HU Berlin & DESY Zeuthen
joint theory seminar

SMEFT in the EW sector

Ken Mimasu

CP3, UCLouvain

6th February 2020

Part I
Intro & status of SMEFT

The SM success story

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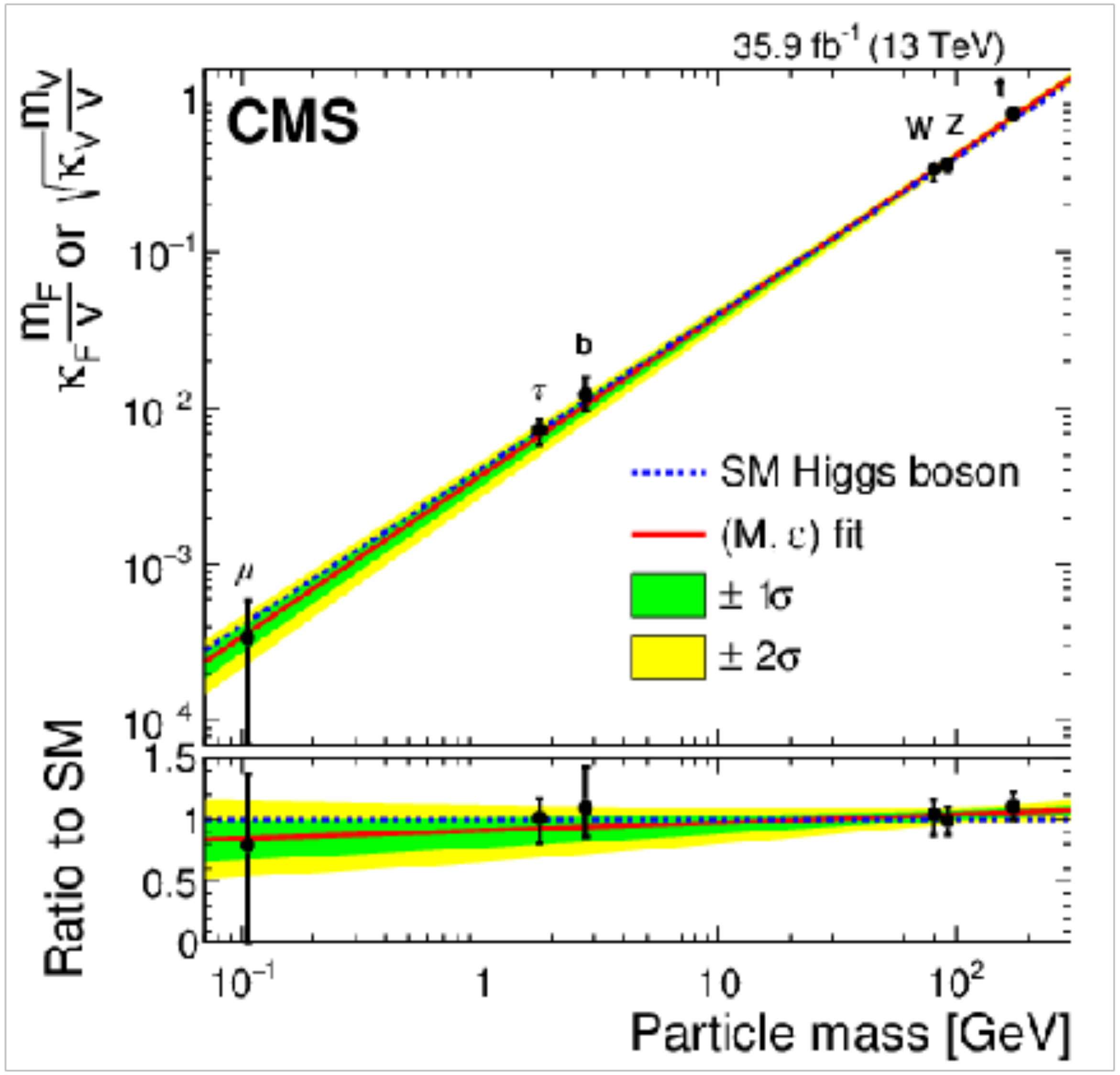
We have found a scalar that couples to mass



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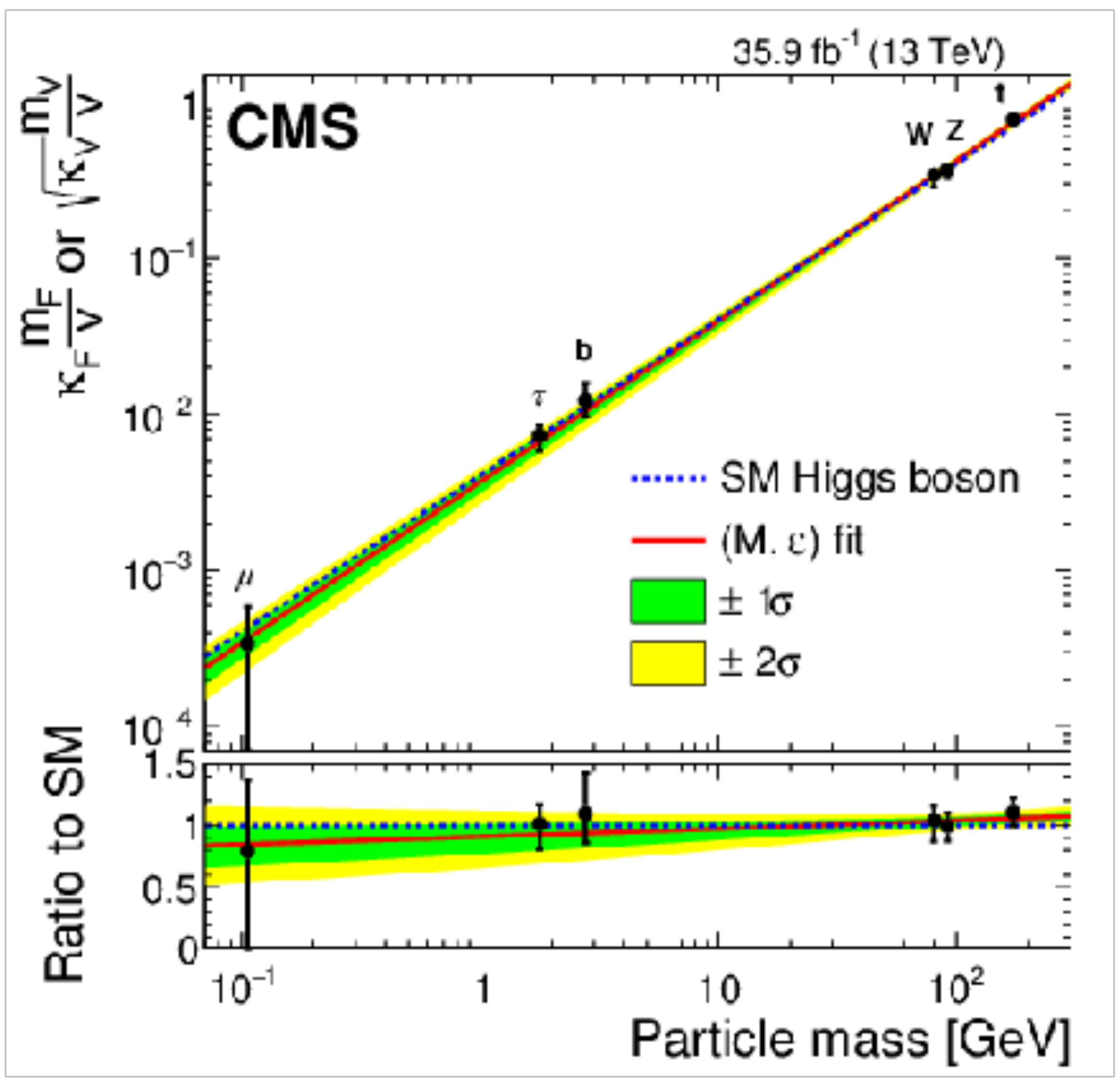

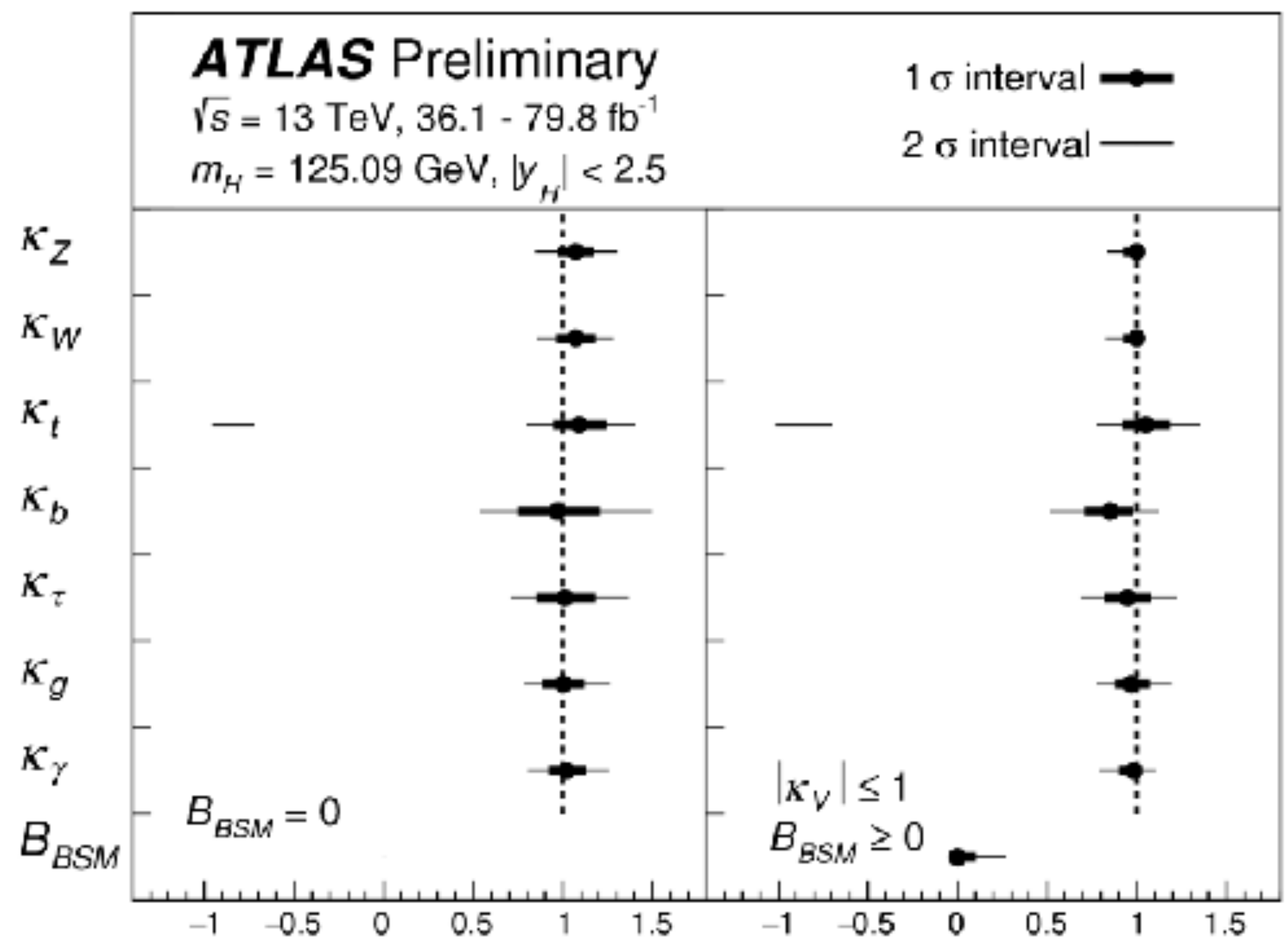

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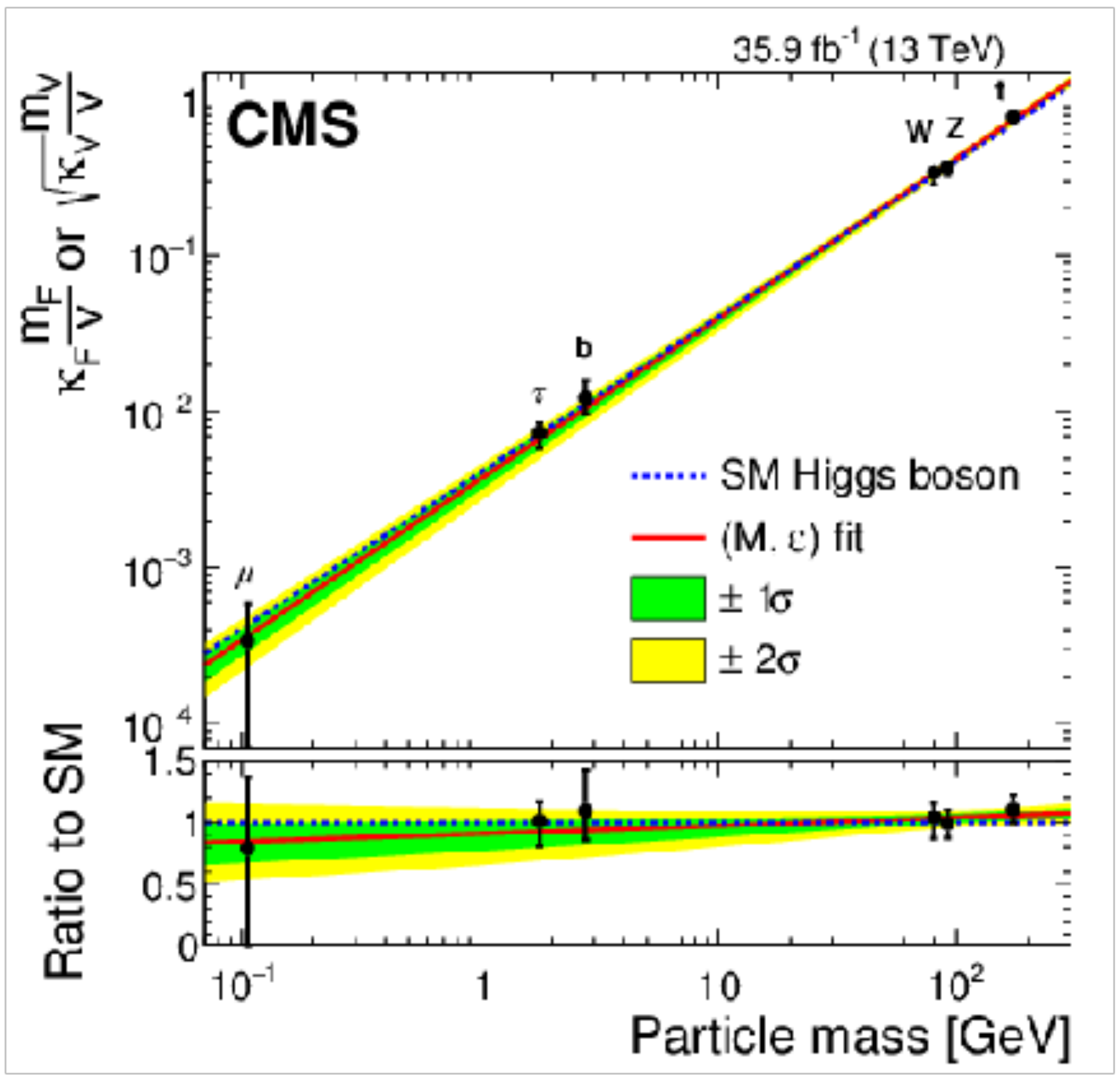

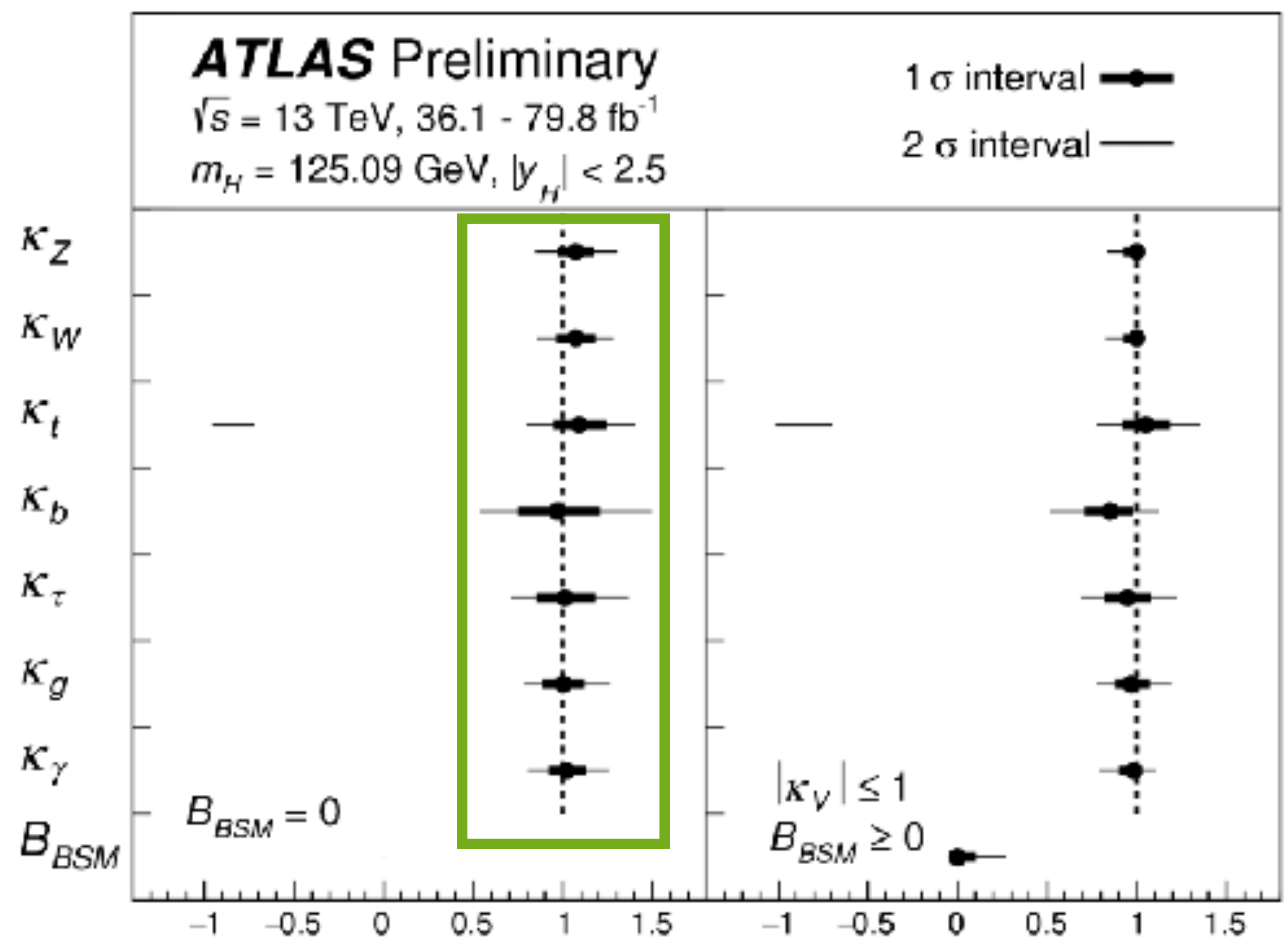

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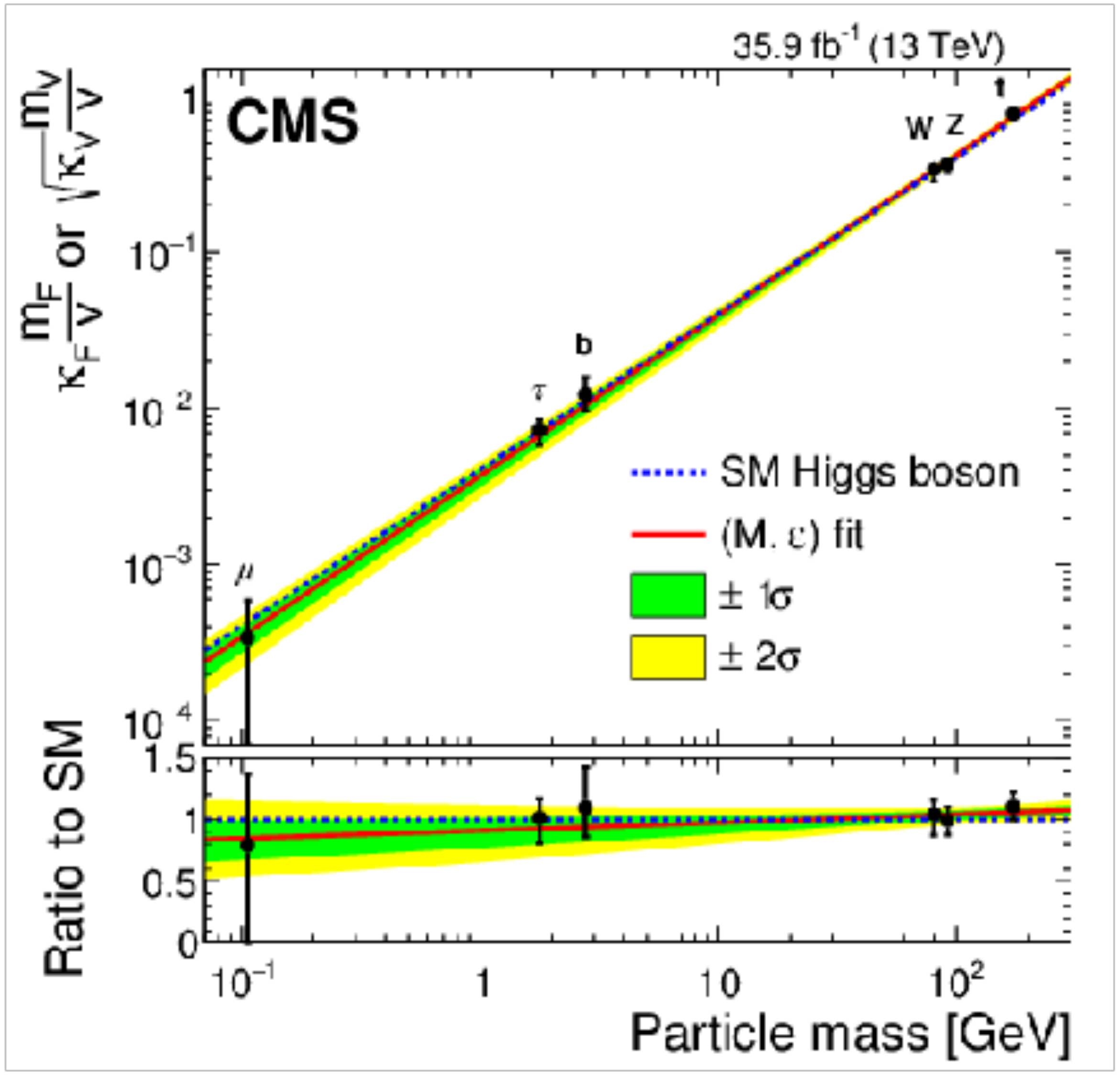

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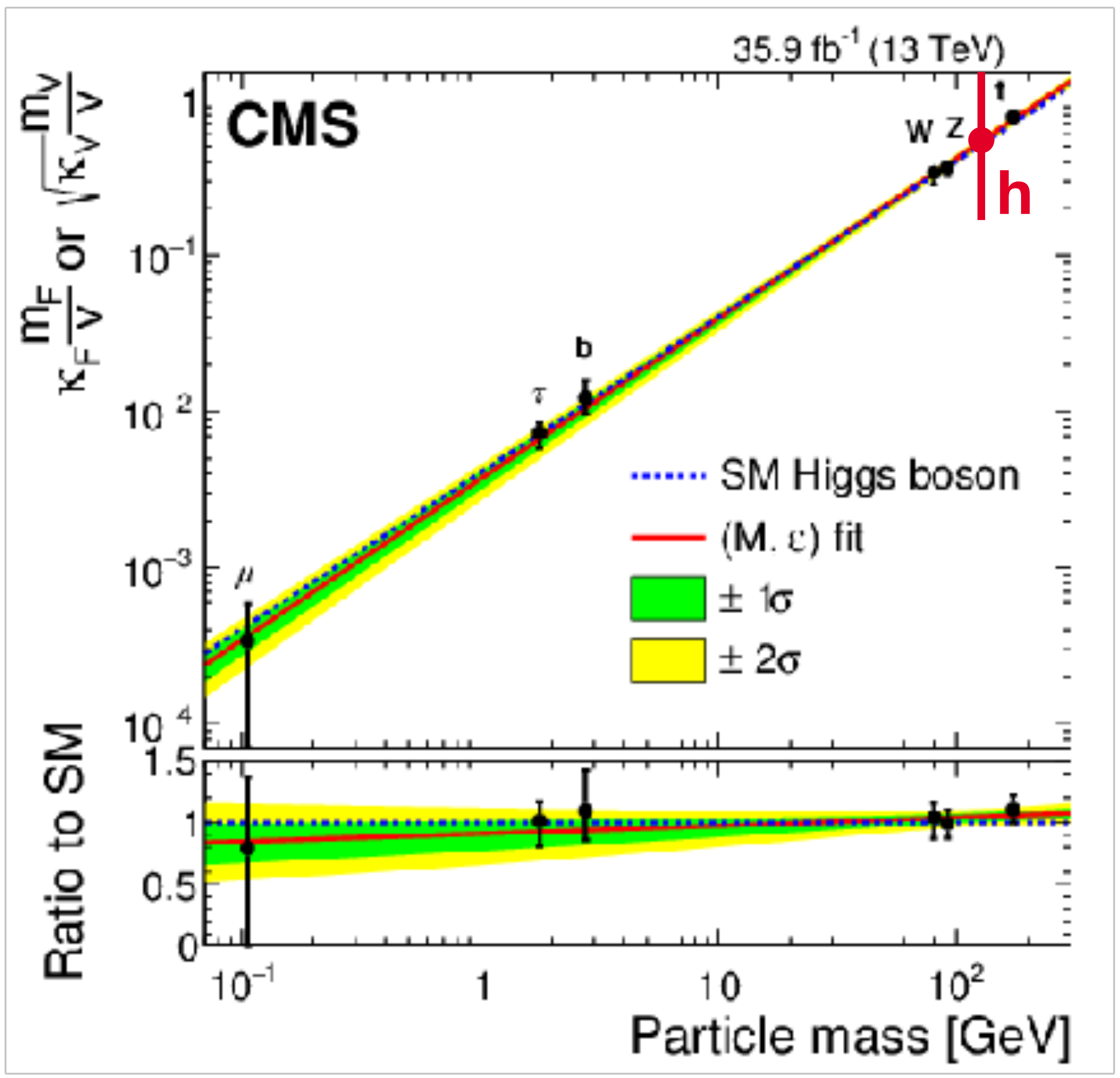

At least *one* missing ingredient…

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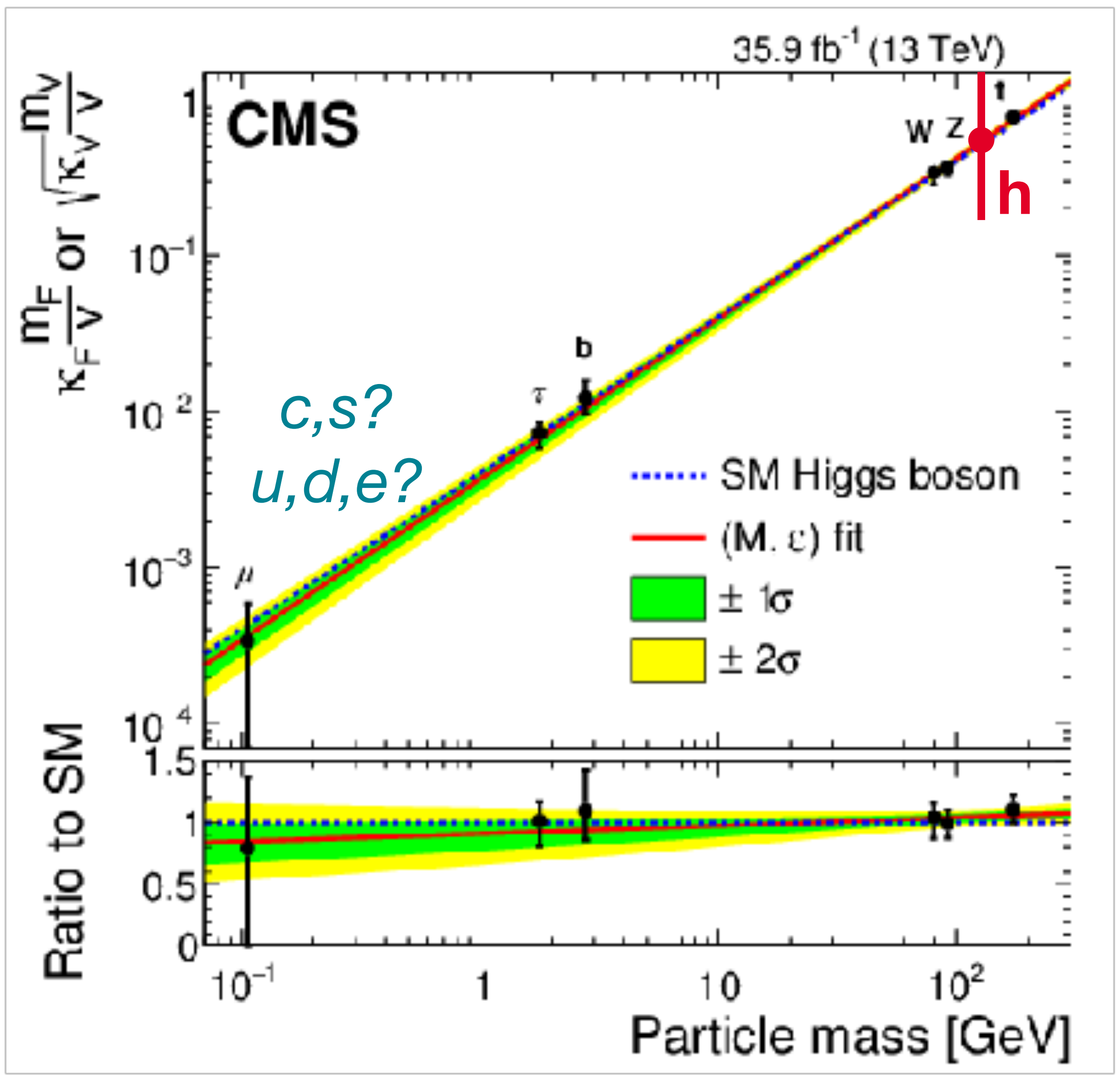

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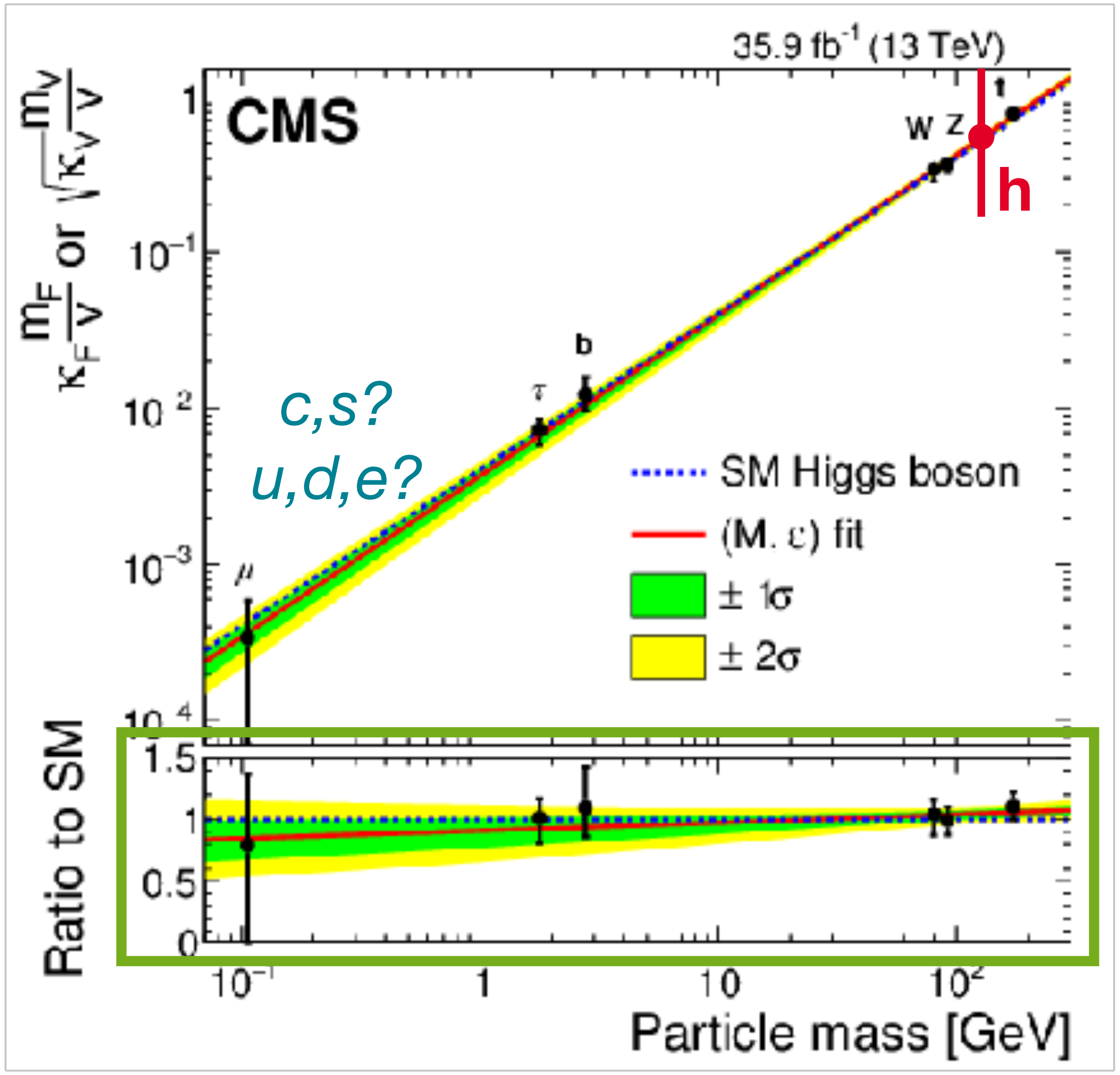

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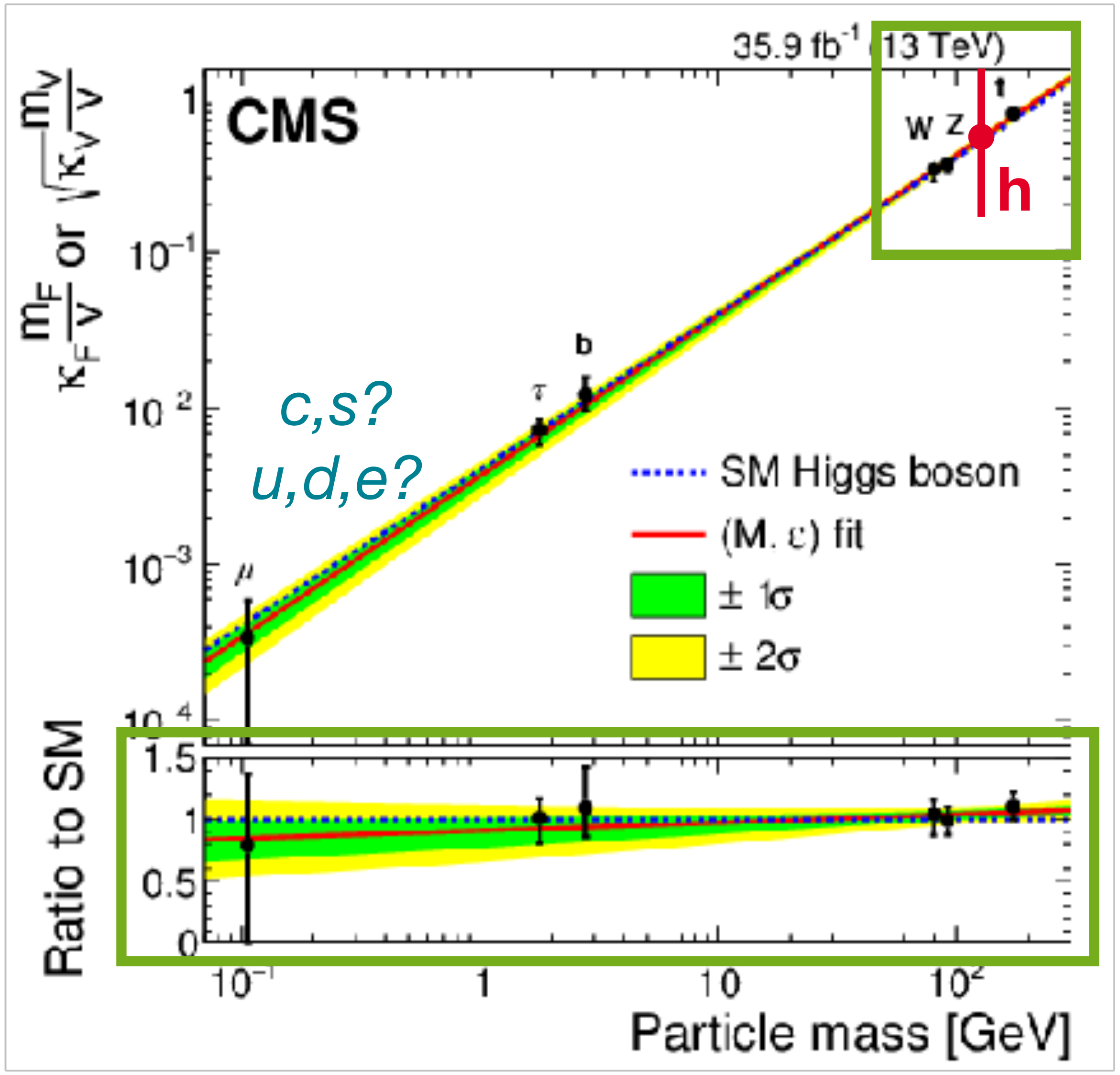
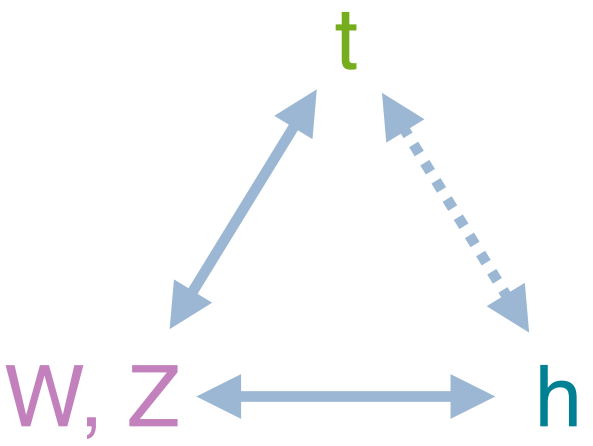


At least *one* missing ingredient…

Still some way to go to pin down precise interactions

The priority mission of the LHC is to characterise the EWSB sector



Big news of 2019

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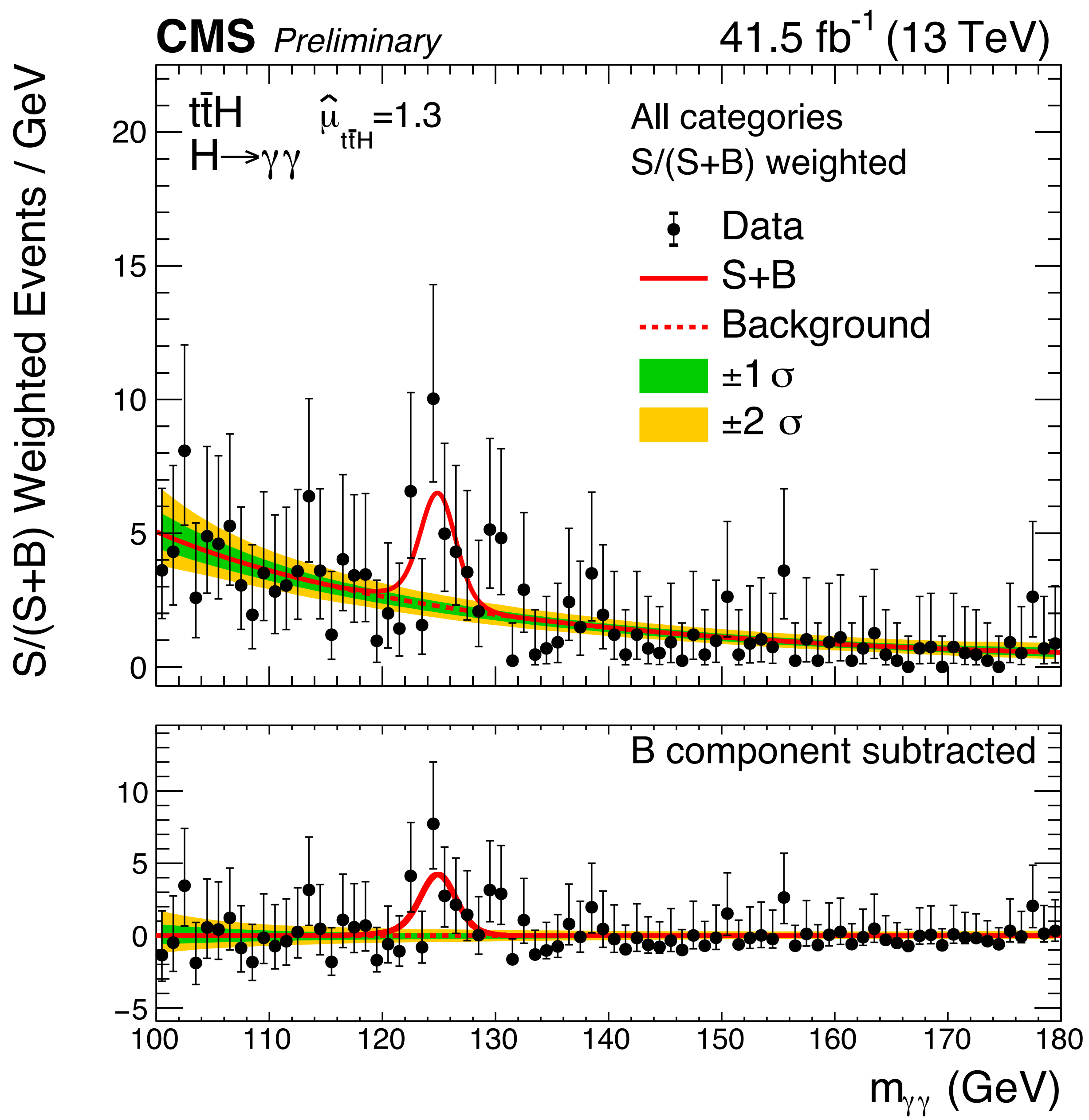
The top couples to the Higgs!



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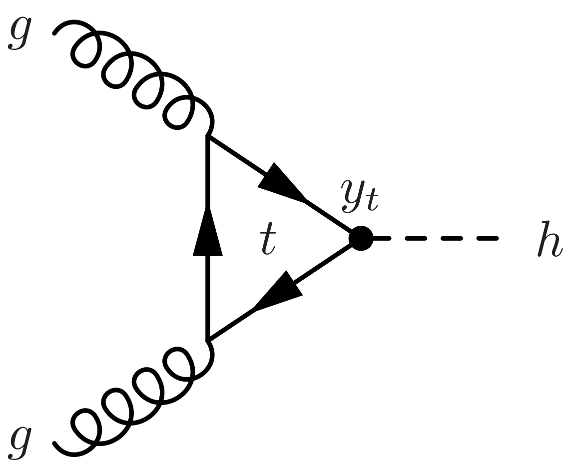

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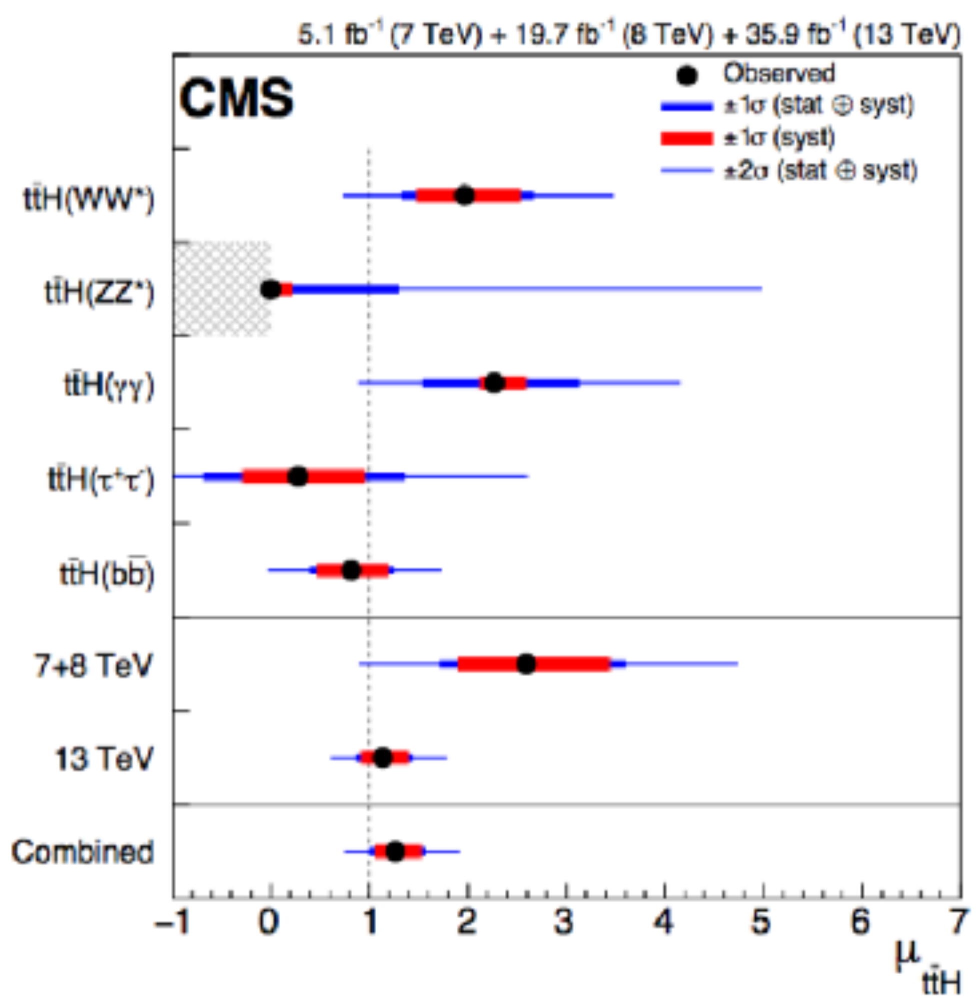

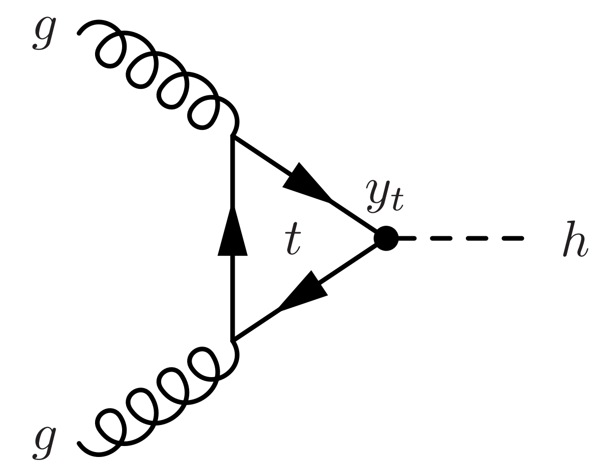

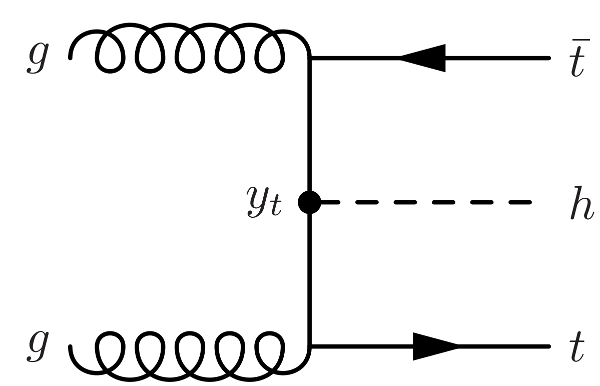

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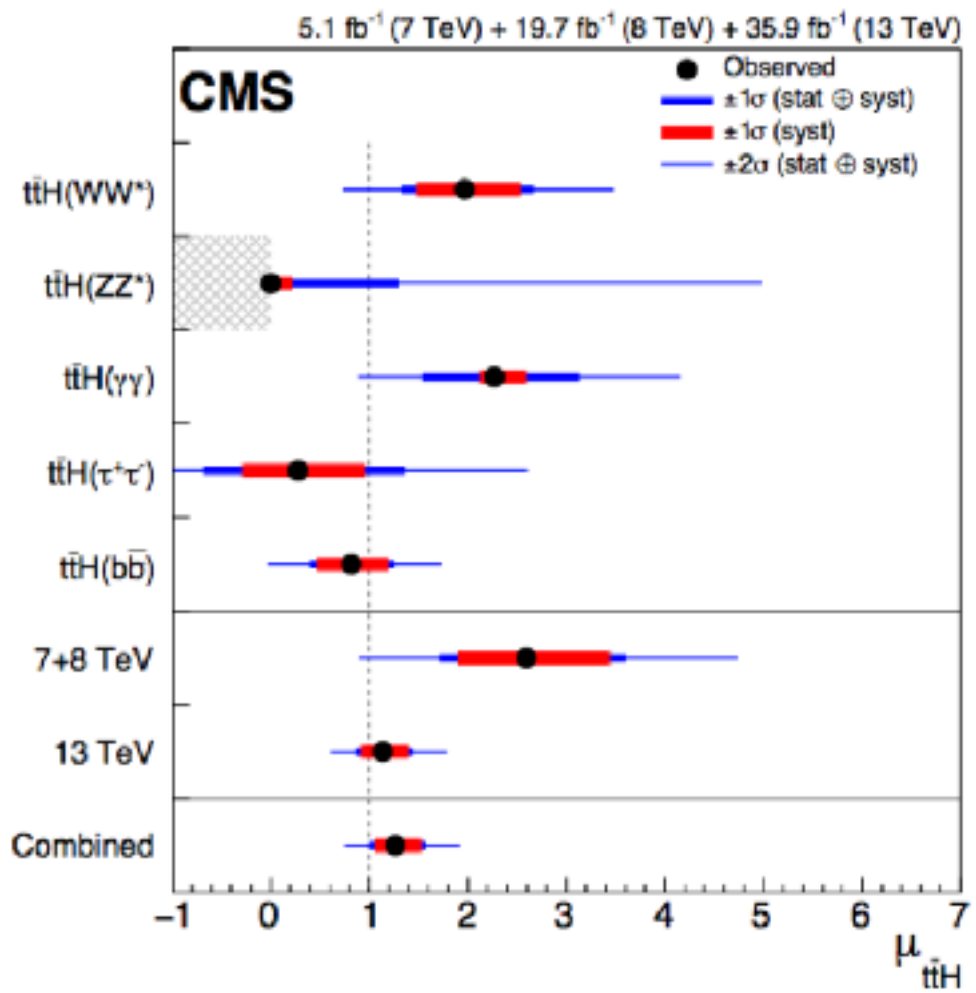

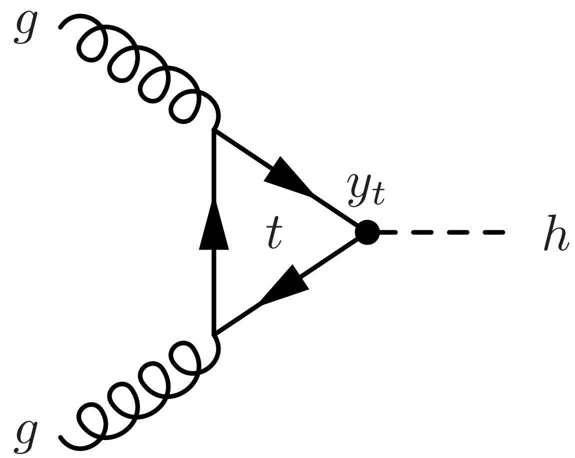

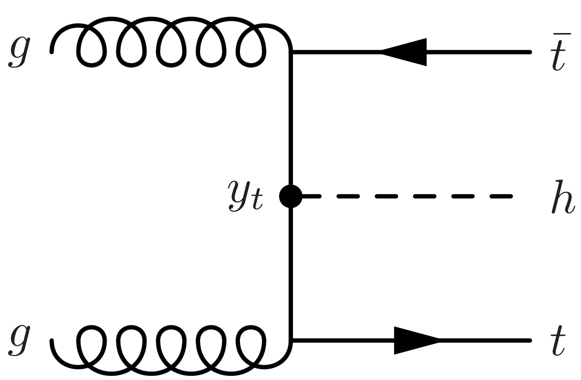

Consistent with SM ~ 100% errors

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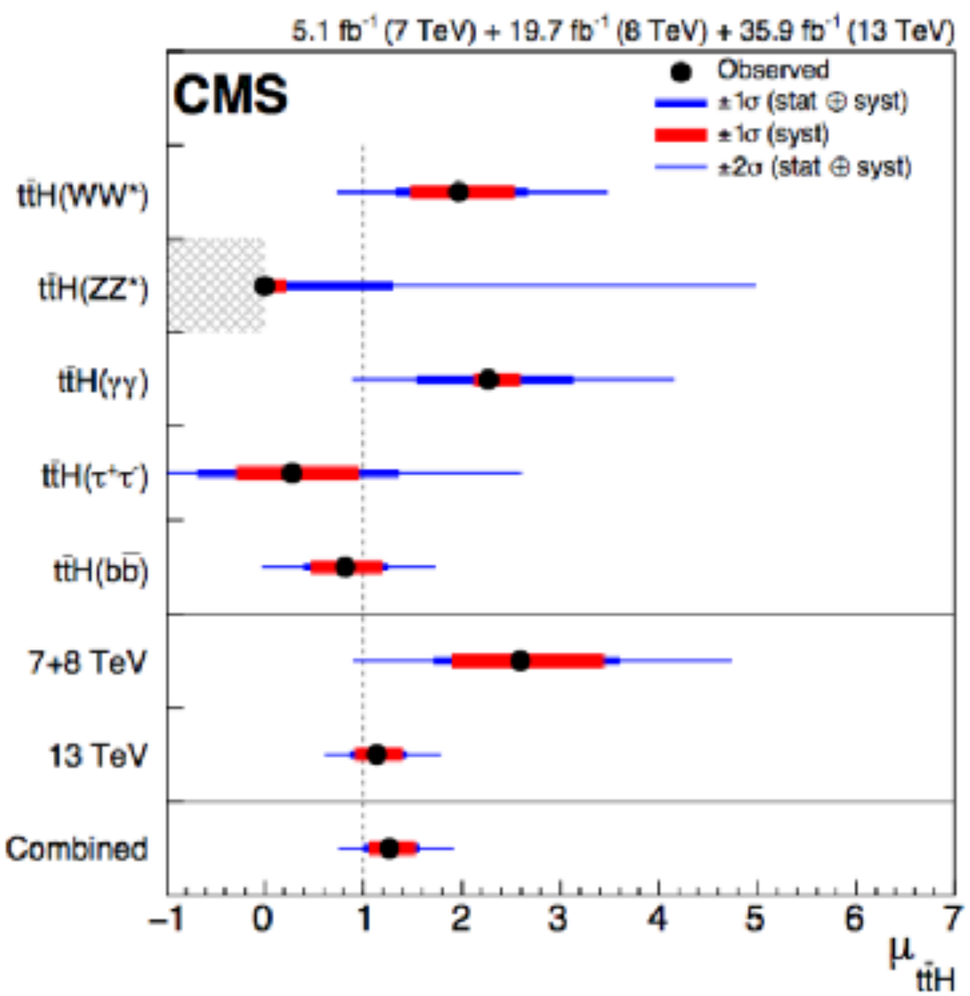

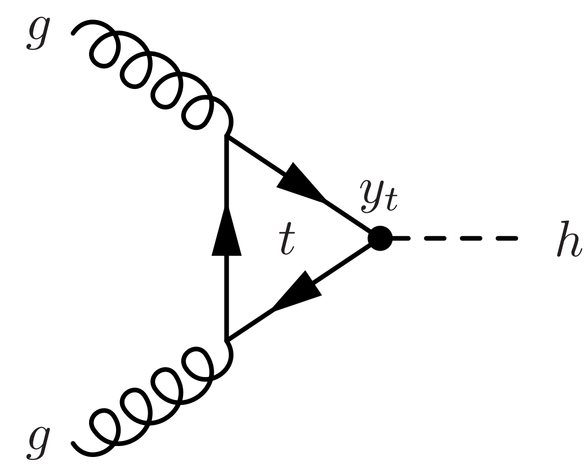

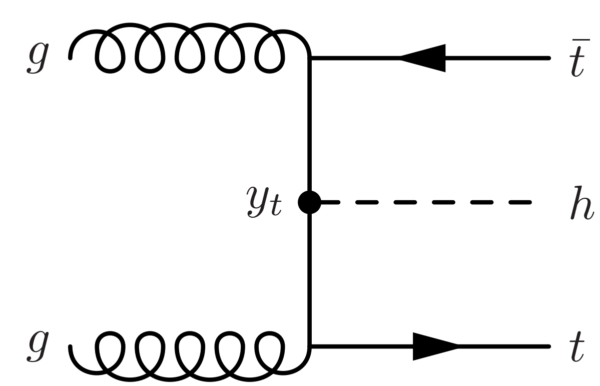

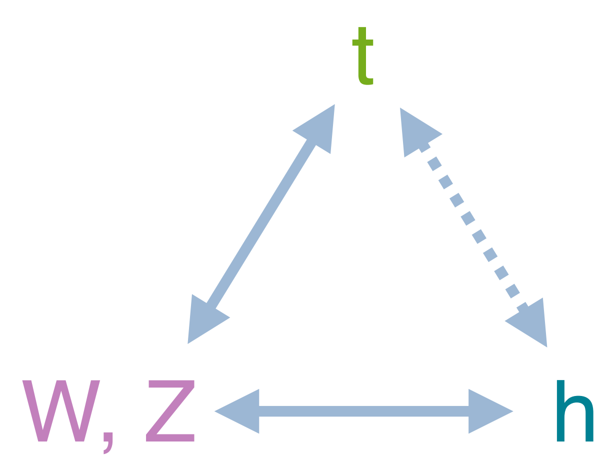

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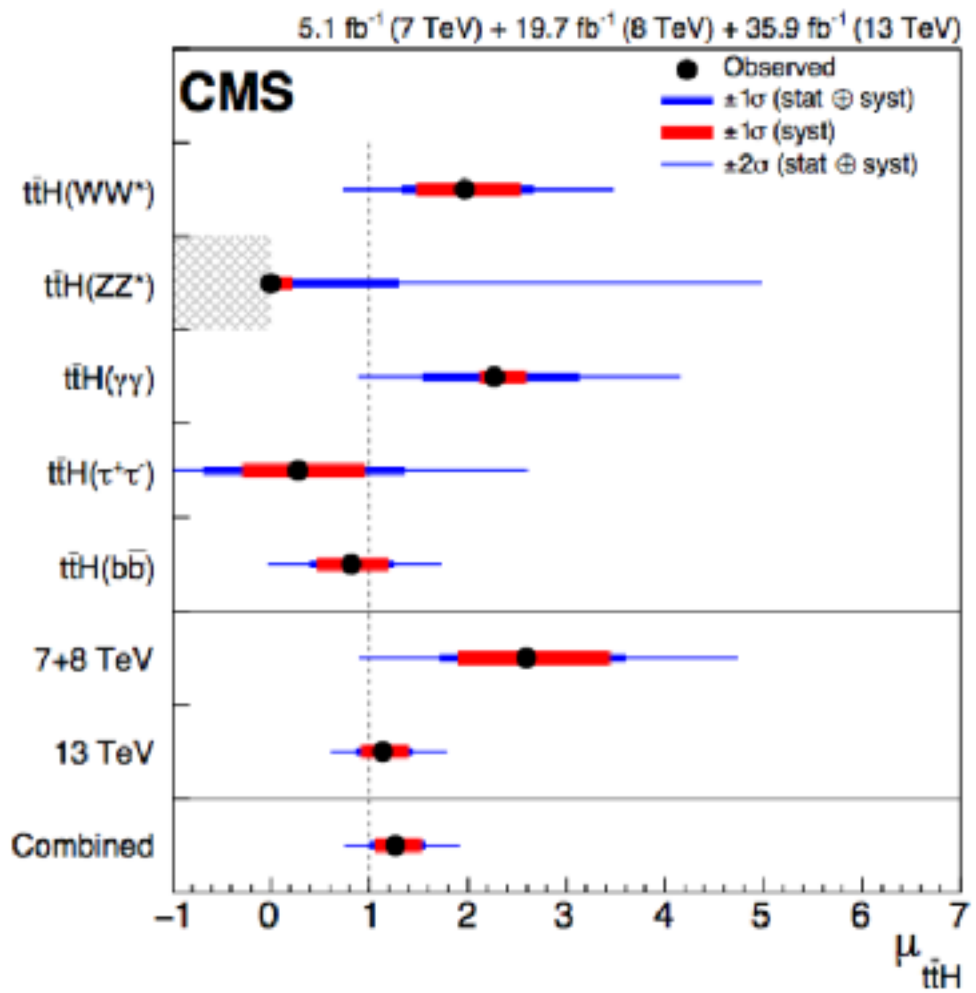

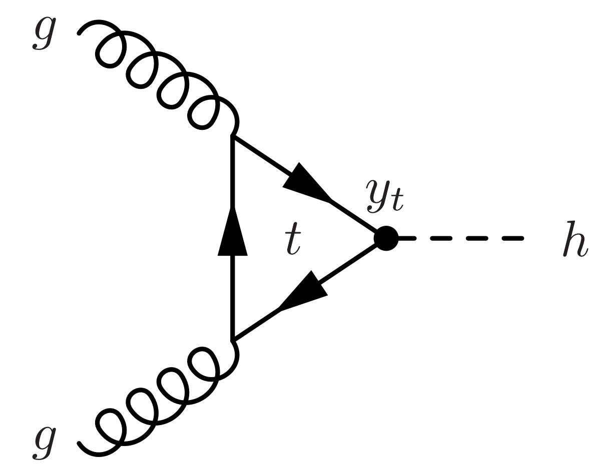

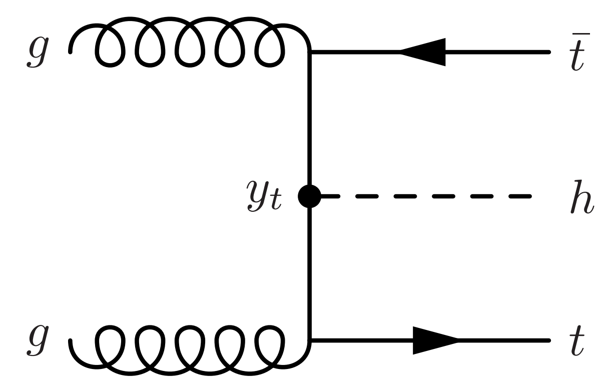

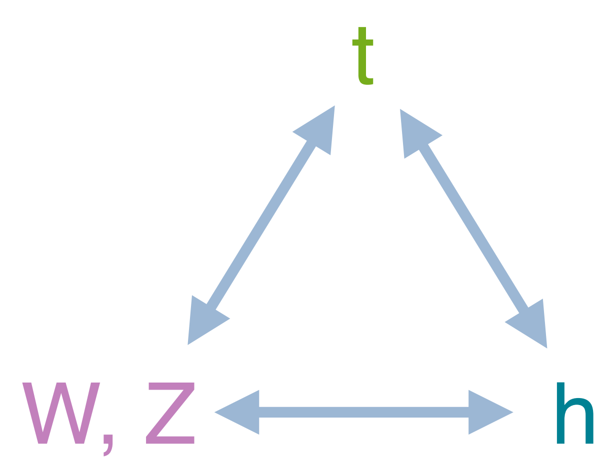

EWSB sector at the LHC

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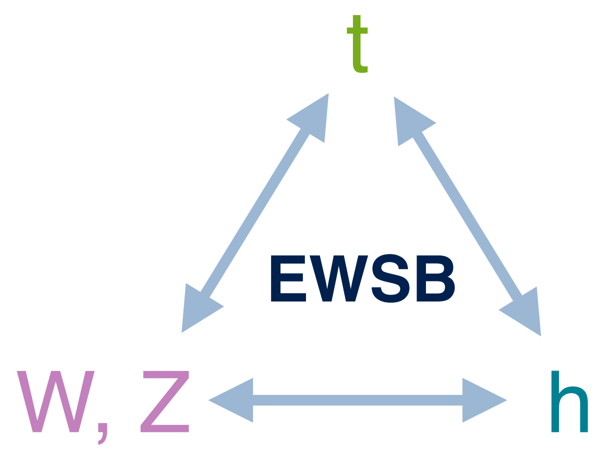
All players are in the game



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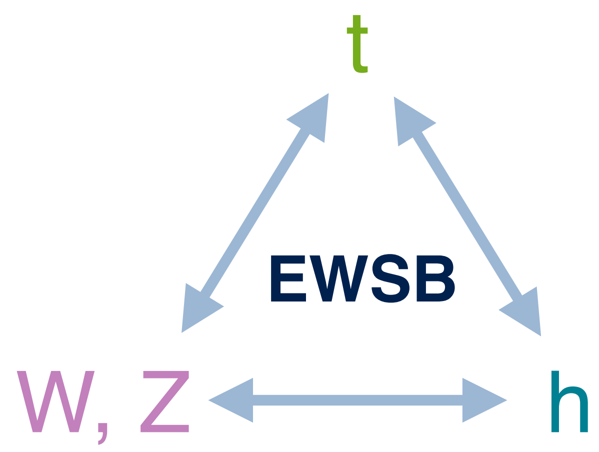
LHC legacy = precise measurements of the interactions that govern EWSB



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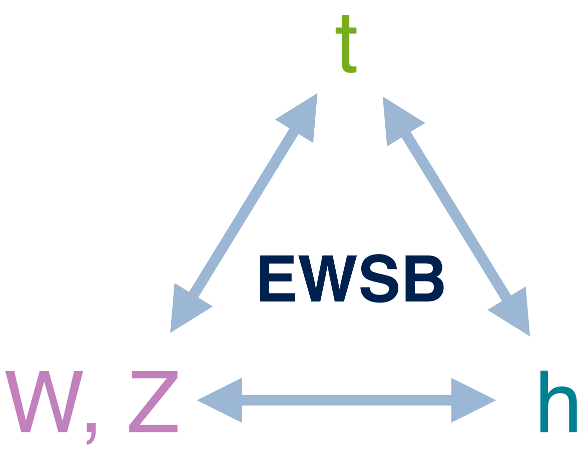

SM is a spontaneously broken, gauge-Yukawa theory

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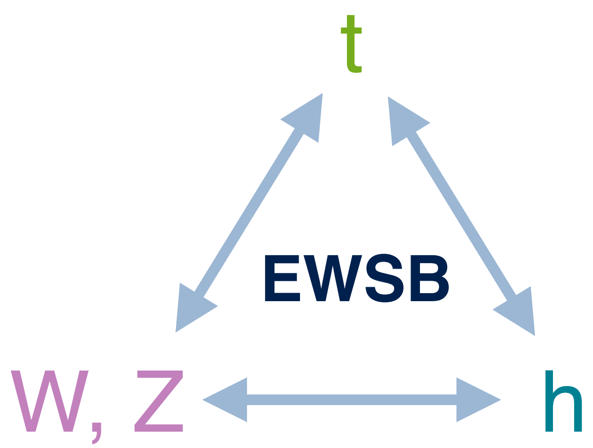

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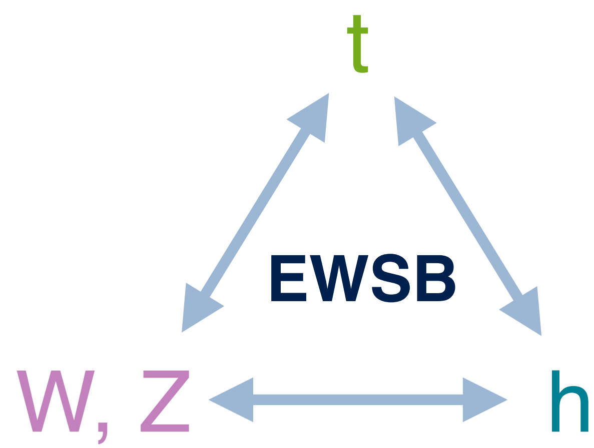

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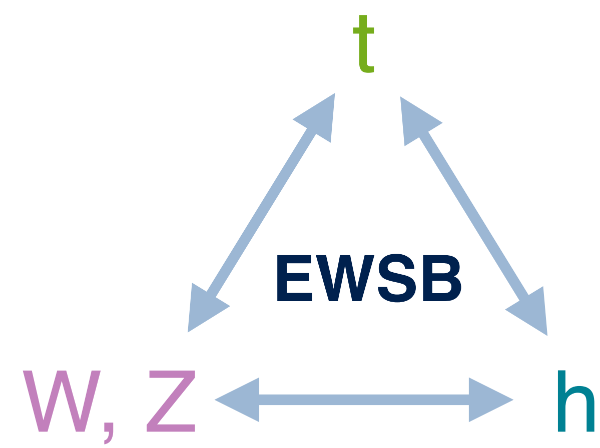

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$$y_f\,\bar{F}_L f_R\,\varphi \qquad (D^\mu\varphi)^\dagger\,(D_\mu\varphi)$$

Mass ↔ Higgs coupling

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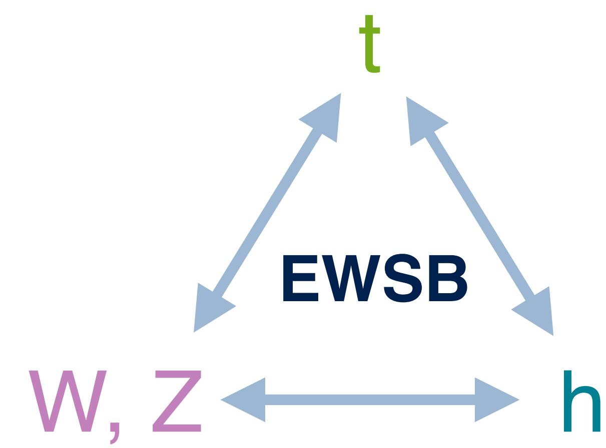

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Self-interactions ↔ Gauge currents

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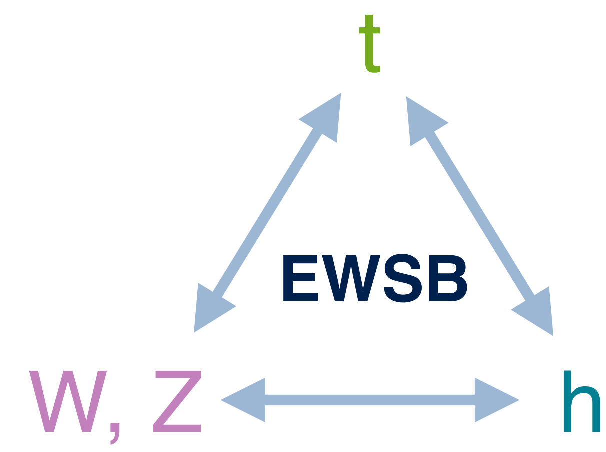

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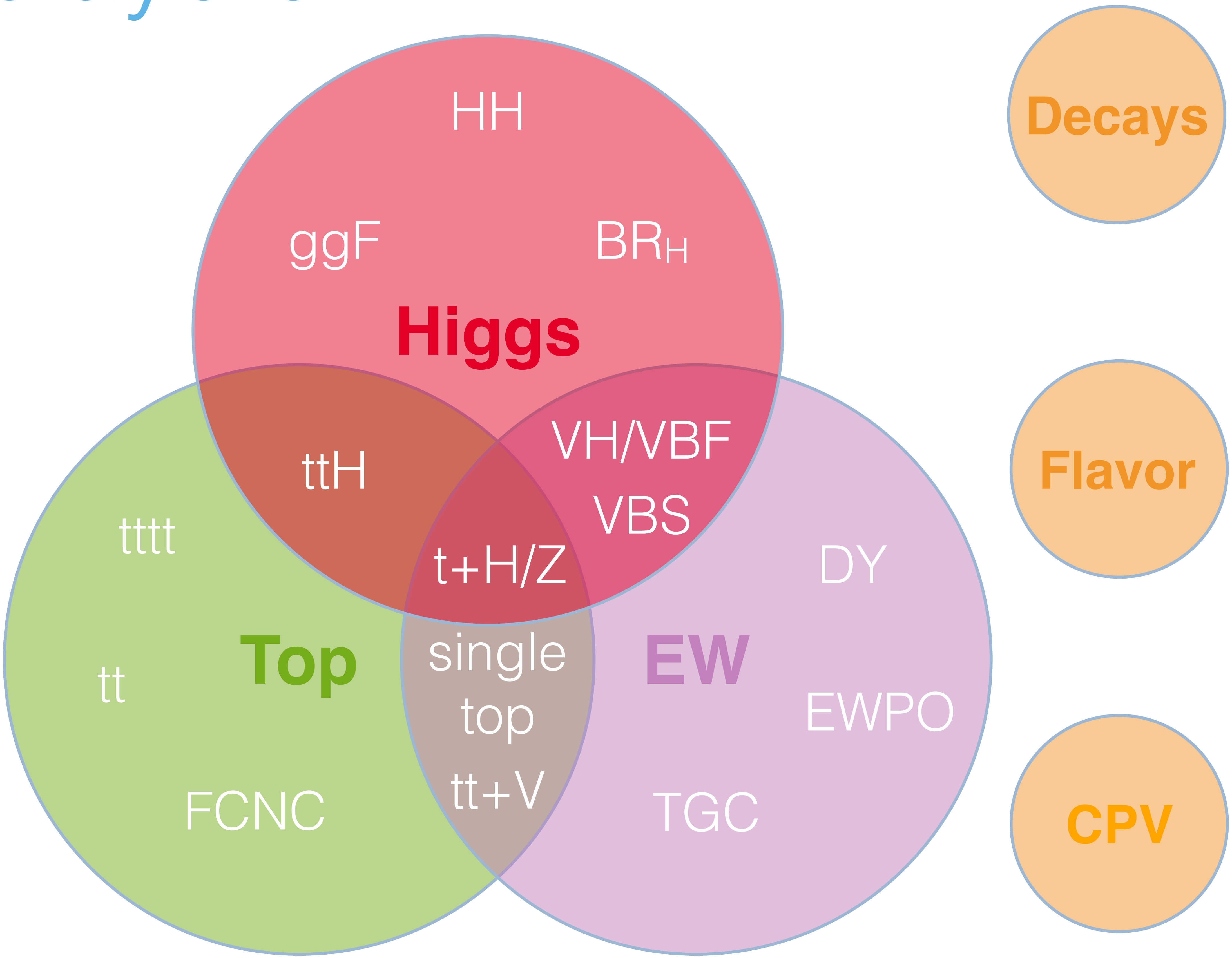
Self-interactions ↔ Gauge currents

Delicate ‘balance’ conserves **unitarity** & **renormalisability**

Key players



HH
ggF
BR$_H$
Higgs
ttH
VH/VBF
VBS
tttt
t+H/Z
DY
Top
single top
EW
tt
EWPO
tt+V
FCNC
TGC
Decays
Flavor
CPV

Quiet at the TeV scale…

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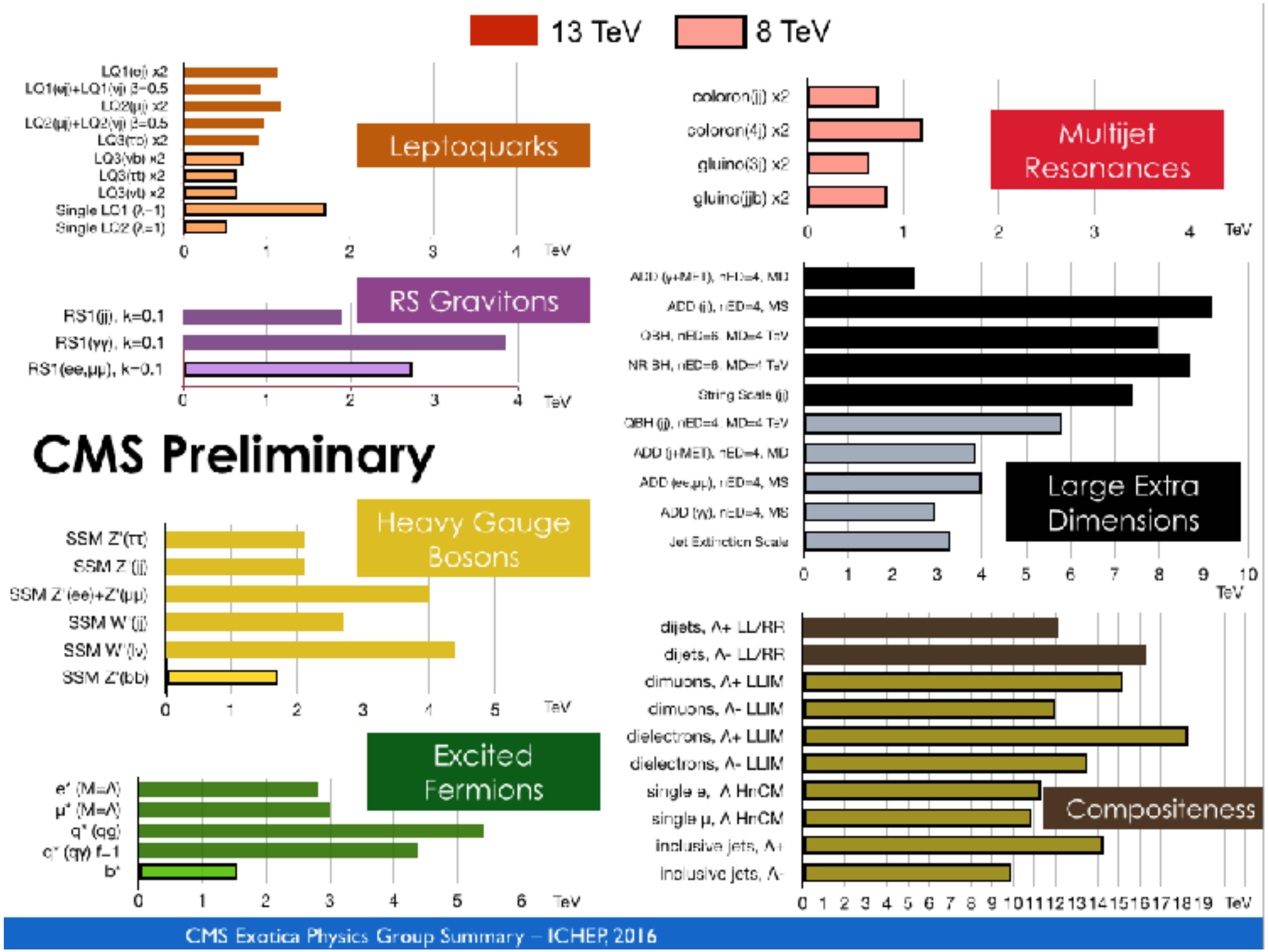

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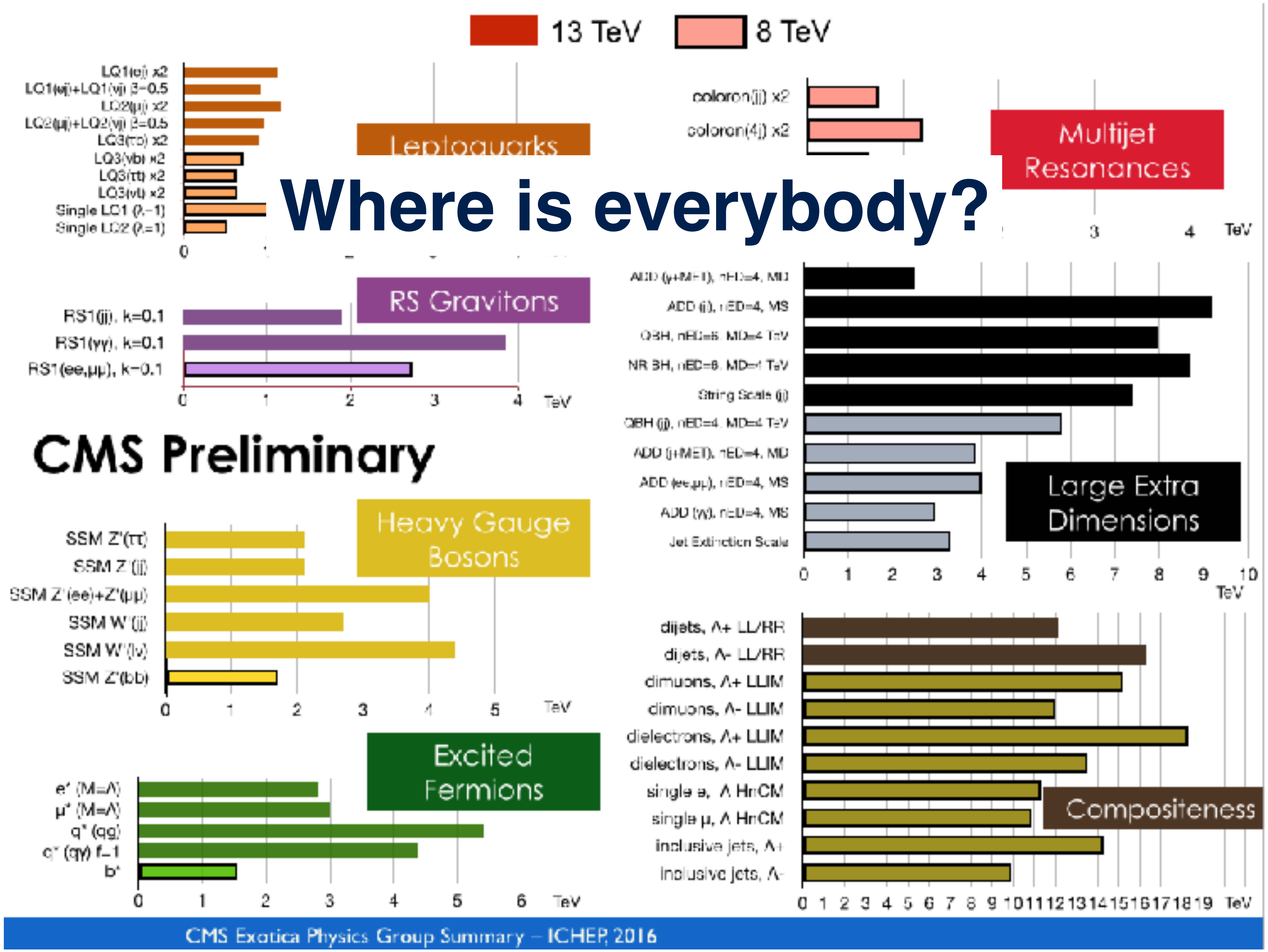

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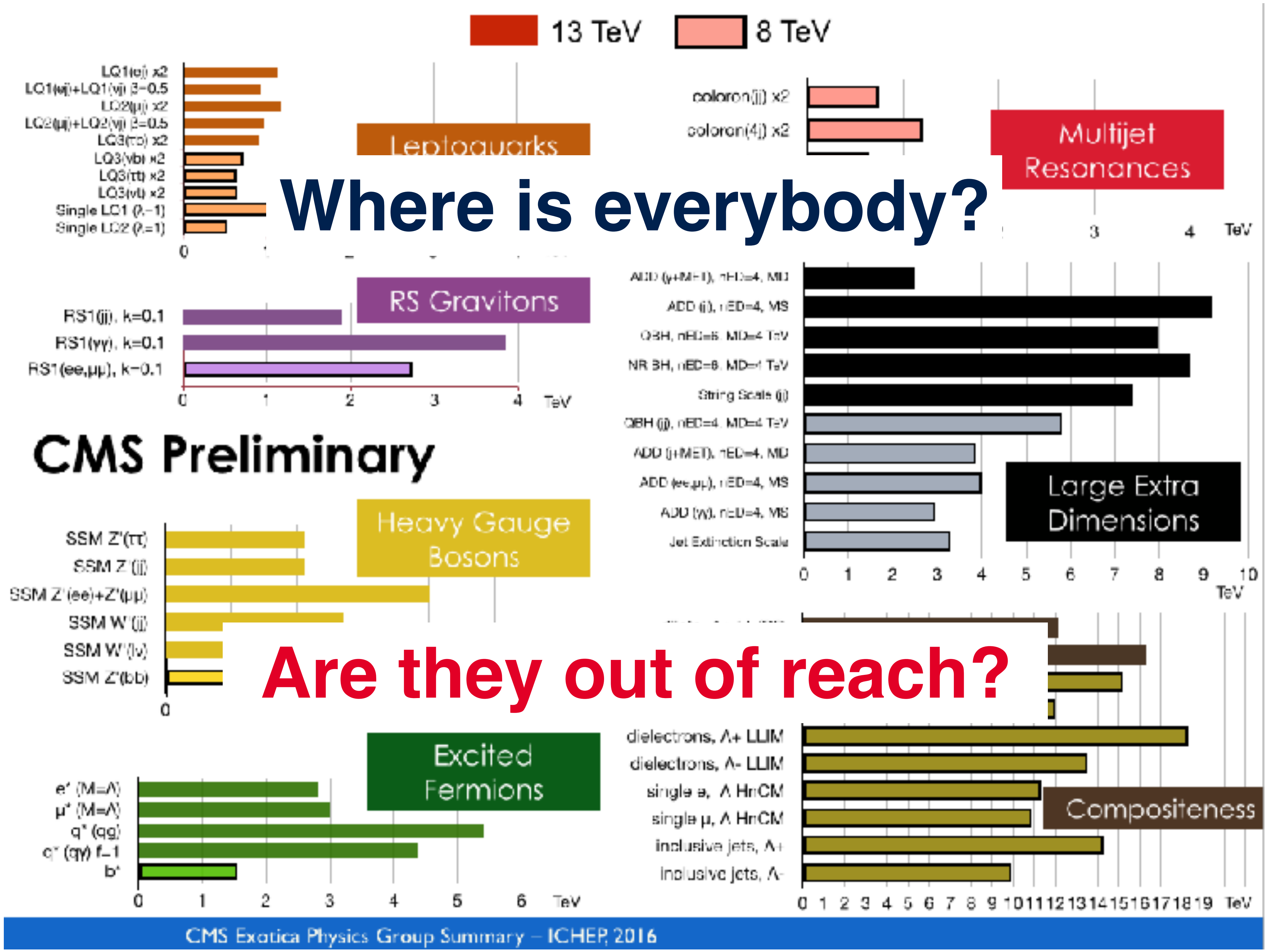

Where is everybody?

Are they out of reach?

Subtle at the TeV scale

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Paradigm shift at the energy frontier for BSM searches

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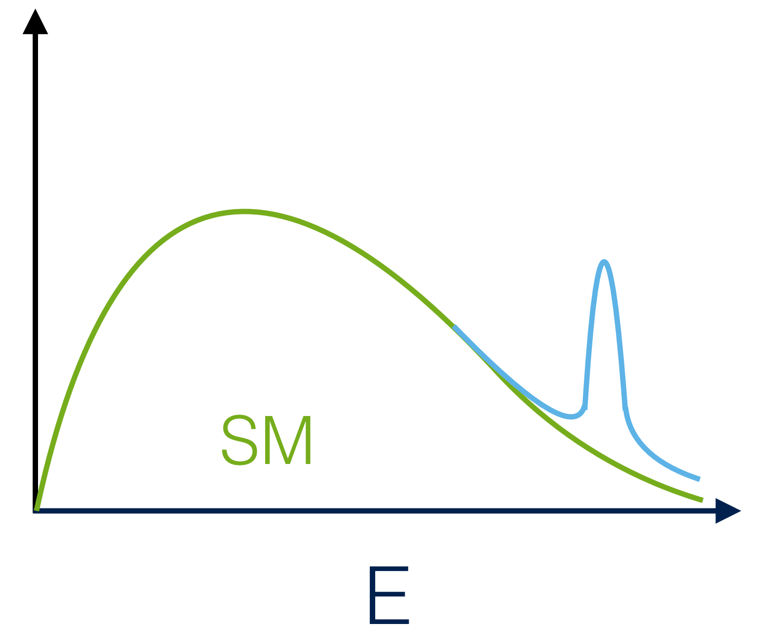
Direct (bump hunts)



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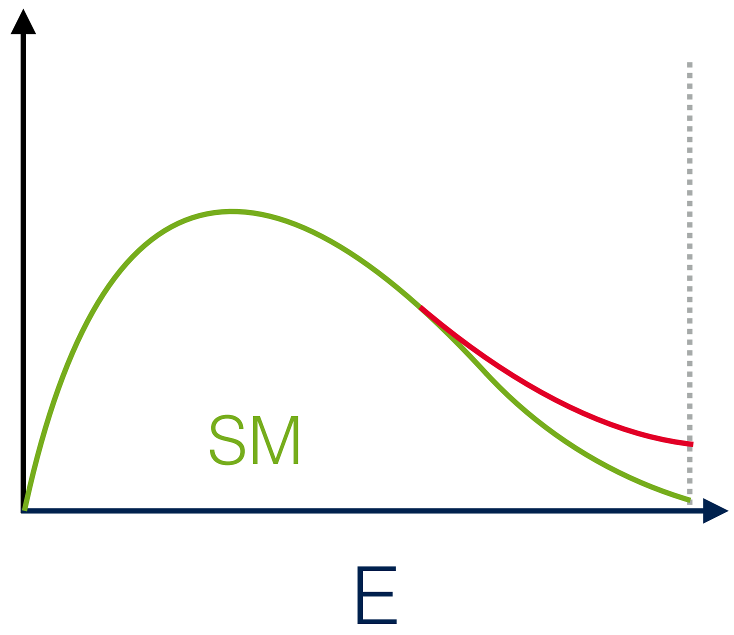

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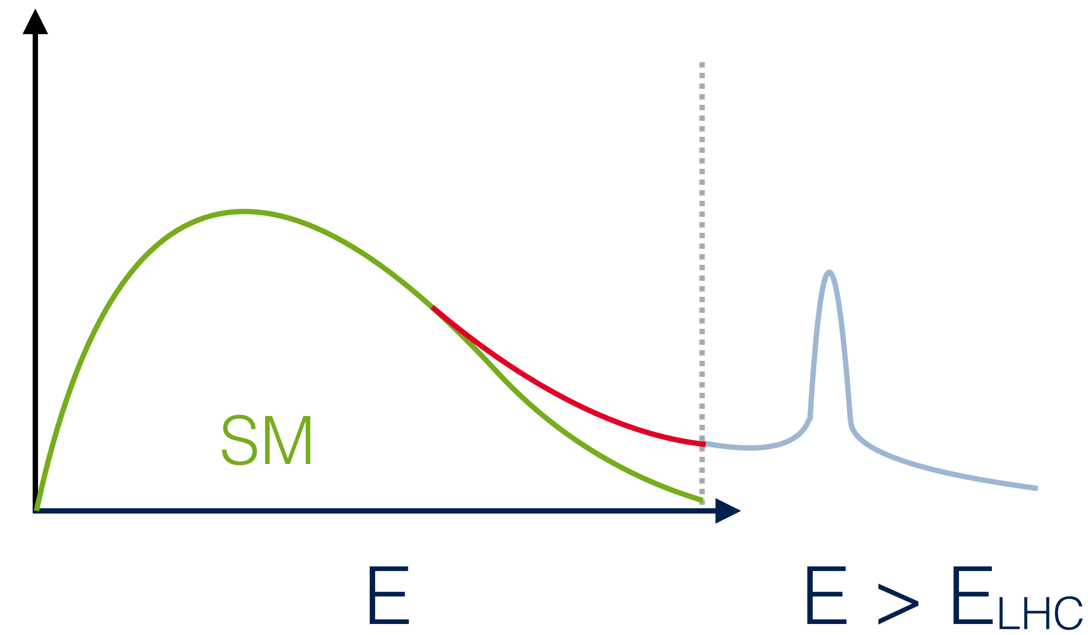

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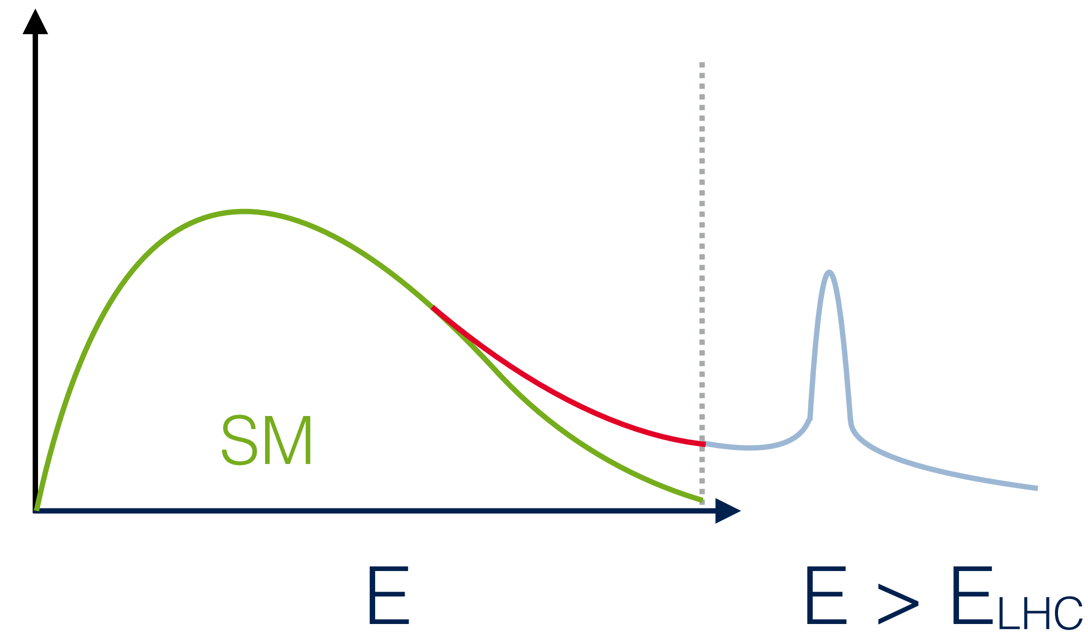

Language that marries
Precision measurements & Heavy new physics

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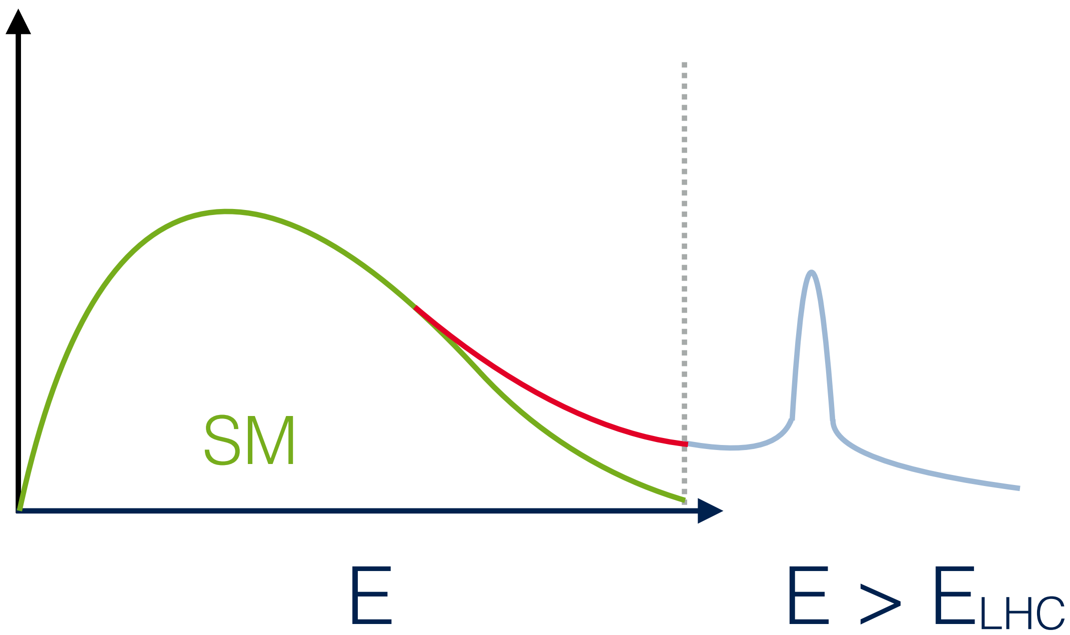

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Standard Model Effective Field Theory (SMEFT)

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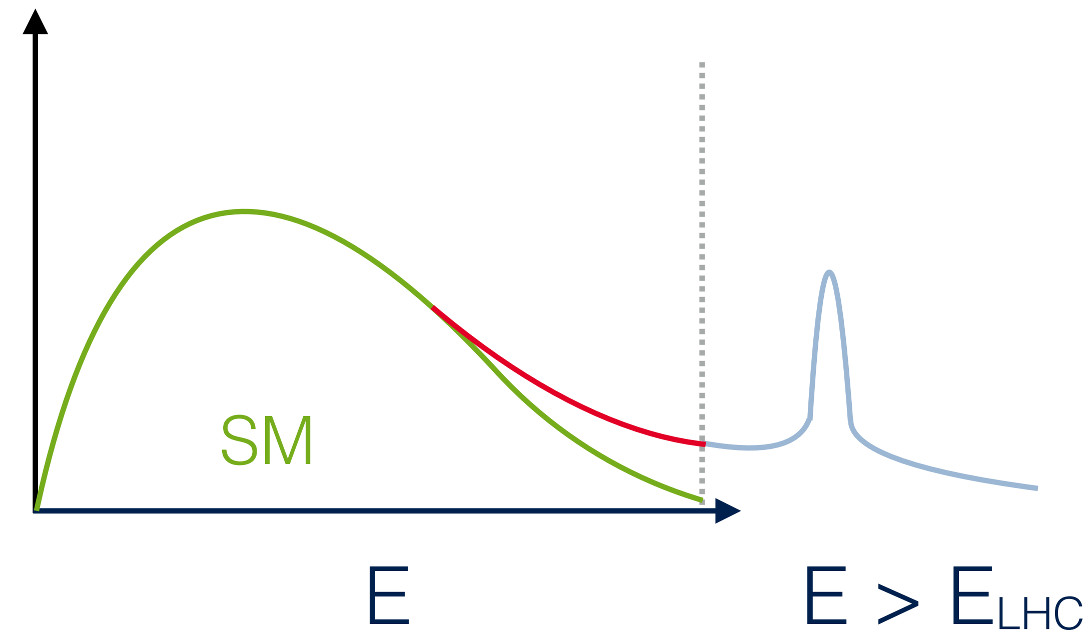

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Standard Model Effective Field Theory (SMEFT)

Encodes a parameter space for deviations from interactions between SM particles

SMEFT: SM v2.0

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Wilsonian approach: world is a low energy EFT

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SMEFT: SM v2.0

Wilsonian approach: world is a low energy EFT

- SM: all relevant ($D < 4$) & marginal ($D = 4$) operators
- SMEFT: tower of irrelevant ($D > 4$) operators

$$
\begin{aligned}
X^3 &: \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho} & \qquad X^2 H^2 &: (\varphi^\dagger \varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a \\
H^6 &: (\varphi^\dagger \varphi)^3 & H^4 D^2 &: (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D^\mu \varphi) \\
\psi^2 H^3 &: (\varphi^\dagger \varphi)^2 (\bar{q}_i \, u_j \, \tilde{\varphi}) & \psi^2 X H &: (\bar{q}_i \, \sigma^{\mu\nu} \, u_j \, \tilde{\varphi}) B_{\mu\nu} \\
\psi^2 H^2 D &: (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \, \gamma^\mu \, q_j) & \psi^4 &: (\bar{q}_i \, \gamma^\mu \, q_j)(\bar{q}_k \, \gamma_\mu \, q_l)
\end{aligned}
$$

SMEFT: SM v2.0

Wilsonian approach: world is a low energy EFT

- SM: all relevant (D < 4) & marginal (D = 4) operators
- SMEFT: tower of irrelevant (D > 4) operators

SM gauge symmetry & linear EWSB

SU(3)$_C$ x SU(2)$_L$ x U(1)$_Y$

$$\varphi = \begin{pmatrix} G^+ \\ v+h+iG^0 \end{pmatrix} : \mathbf{2}_{\frac{1}{2}}$$

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\end{aligned}$$

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More than 'just' a parametrisation of ignorance

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Wilsonian approach: world is a low energy EFT

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More than 'just' a parametrisation of ignorance

- **Unlike** 'Anomalous Couplings'

$$\begin{aligned} X^3 &: \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho} & X^2H^2 &: (\varphi^\dagger\varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a \\ H^6 &: (\varphi^\dagger\varphi)^3 & H^4D^2 &: (\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D^\mu\varphi) \\ \psi^2H^3 &: (\varphi^\dagger\varphi)^2(\bar{q}_i\, u_j\, \tilde{\varphi}) & \psi^2XH &: (\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu} \\ \psi^2H^2D &: (\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{q}_i\, \gamma^\mu\, q_j) & \psi^4 &: (\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l) \end{aligned}$$

SMEFT: SM v2.0

Wilsonian approach: world is a low energy EFT

- SM: all relevant (D < 4) & marginal (D = 4) operators
- SMEFT: tower of irrelevant (D > 4) operators

SM gauge symmetry & linear EWSB

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\varphi = \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} : \mathbf{2}_{\frac{1}{2}}$$

More than 'just' a parametrisation of ignorance

- **Unlike** 'Anomalous Couplings'
- Renormalisable QFT (order-by-order)

$$X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho} \qquad X^2 H^2 : (\varphi^\dagger \varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a$$

$$H^6 : (\varphi^\dagger \varphi)^3 \qquad H^4 D^2 : (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)$$

$$\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{q}_i \, u_j \, \tilde{\varphi}) \qquad \psi^2 X H : (\bar{q}_i \, \sigma^{\mu\nu} \, u_j \, \tilde{\varphi}) B_{\mu\nu}$$

$$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \, \gamma^\mu \, q_j) \qquad \psi^4 : (\bar{q}_i \, \gamma^\mu \, q_j)(\bar{q}_k \, \gamma_\mu \, q_l)$$

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$$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\, \gamma^\mu\, q_j) \qquad \psi^4 : (\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$$

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More than 'just' a parametrisation of ignorance

- **Unlike** 'Anomalous Couplings'
- Finite energy range < Λ
- Renormalisable QFT (order-by-order)
- Well-defined matching procedure

$$X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho} \qquad X^2H^2 : (\varphi^\dagger\varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a$$

$$H^6 : (\varphi^\dagger\varphi)^3 \qquad H^4D^2 : (\varphi^\dagger D^\mu \varphi)^*(\varphi^\dagger D^\mu \varphi)$$

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SU(3)c x SU(2)L x U(1)Y

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SM gauge symmetry & linear EWSB

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aTGC	$X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$X^2H^2 : (\varphi^\dagger\varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a$	ggF
λ_h	$H^6 : (\varphi^\dagger\varphi)^3$	$H^4D^2 : (\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)$	T-param
y_f	$\psi^2H^3 : (\varphi^\dagger\varphi)^2(\bar{q}_i\, u_j\, \tilde{\varphi})$	$\psi^2XH : (\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi})B_{\mu\nu}$	'dipole'
ffZ	$\psi^2H^2D : (\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$	$\psi^4 : (\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$	4F

D=6 operators

‘Warsaw’ basis

[Grzadkowski et al.; JHEP 1010 (2010) 085]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

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$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
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$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
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		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
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$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

Degrees of freedom 76: flavor universal

D=6 operators

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Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^*\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
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$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

Degrees of freedom 76: flavor universal 2499: flavor general

D=6 operators

'Warsaw' basis

[Grzadkowski et al.; JHEP 1010 (2010) 085]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		

Degrees of freedom 76: flavor universal 2499: flavor general

Measure the couplings of the SM at dimension-6 (and beyond)

D=6 operators

'Warsaw' basis

[Grzadkowski et al.; JHEP 1010 (2010) 085]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q^{(1)}_{qq}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q^{(3)}_{qq}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q^{(1)}_{lq}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q^{(3)}_{lq}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q^{(1)}_{qu}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q^{(1)}_{ud}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q^{(8)}_{qu}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q^{(8)}_{ud}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q^{(1)}_{qd}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q^{(8)}_{qd}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q^{(1)}_{quqd}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q^{(8)}_{quqd}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q^{(1)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q^{(1)}_{lequ}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q^{(3)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q^{(3)}_{lequ}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Degrees of freedom   76: flavor universal   2499: flavor general

Measure the couplings of the SM at dimension-6 (and beyond)

Extend the reach of our colliders to NP beyond nominal energy

Strategy

Strategy

Basis

Strategy

Basis

Warsaw, SILH, HISZ, Higgs Basis

Strategy

Basis

Warsaw, SILH, HISZ, Higgs Basis

Flavor assumptions

Universal, diagonal, 3rd gen, general?

Strategy

Basis

Warsaw, SILH, HISZ, Higgs Basis

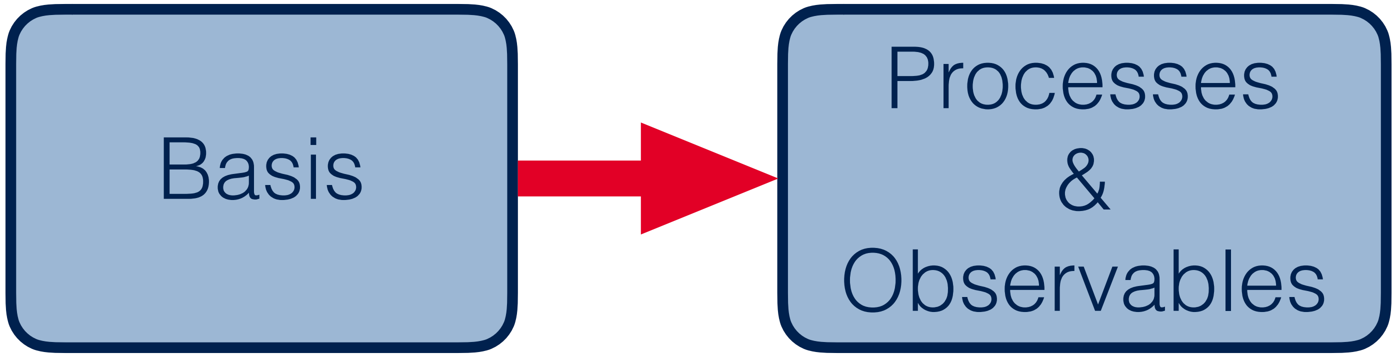
Flavor assumptions

Universal, diagonal, 3rd gen, general?

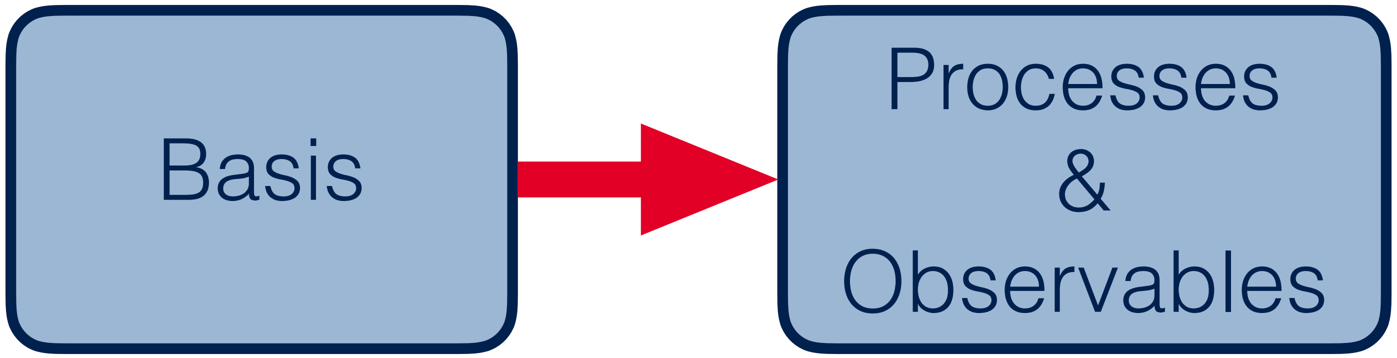
Symmetries

CP, Baryon/Lepton number?

Strategy

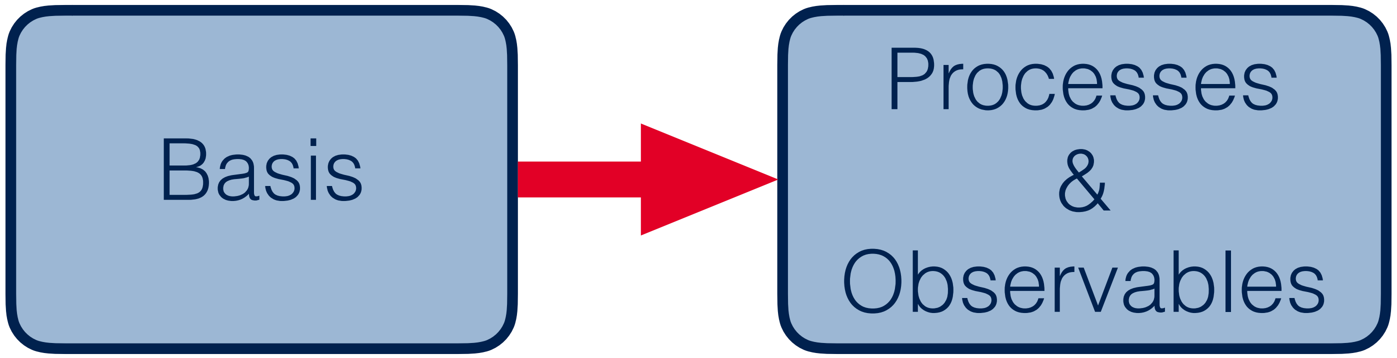


Strategy



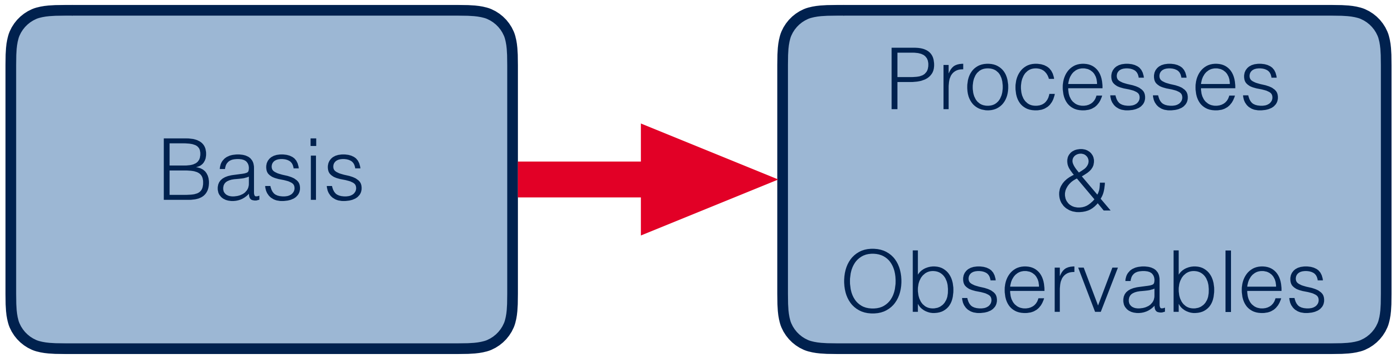
Rate measurements

Strategy



Rate measurements $\sigma_{\text{tot.}}\,, \quad \mu = \dfrac{\sigma}{\sigma_{\text{SM}}}$

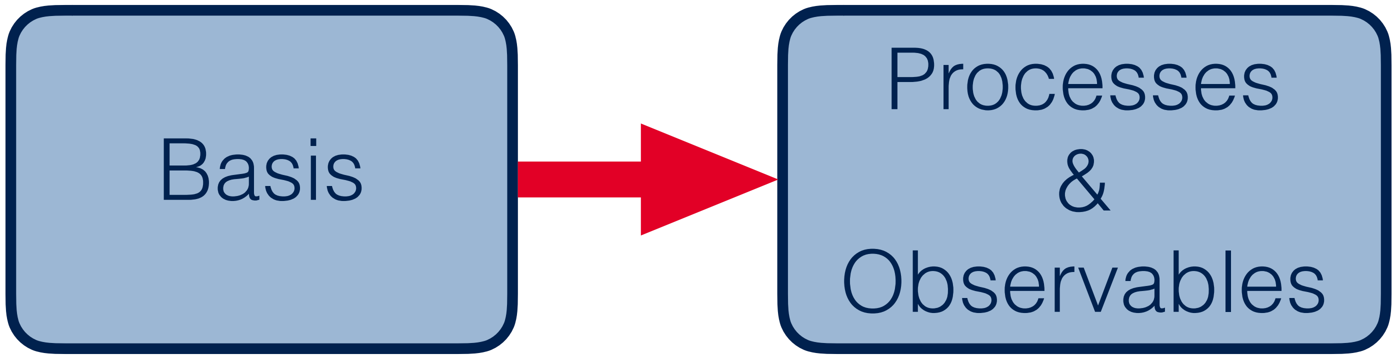
Strategy



Rate measurements $\sigma_{\text{tot.}}, \quad \mu = \frac{\sigma}{\sigma_{\text{SM}}}$

Differential

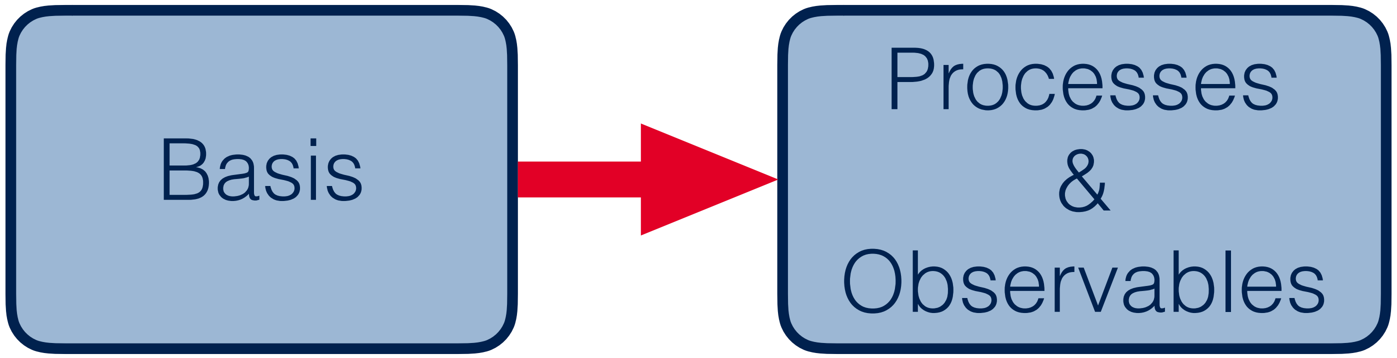
Strategy



Rate measurements $\sigma_{\text{tot.}}\,,\quad \mu = \dfrac{\sigma}{\sigma_{\text{SM}}}$

Differential $\dfrac{d\sigma}{dM_{\text{XX}}}$

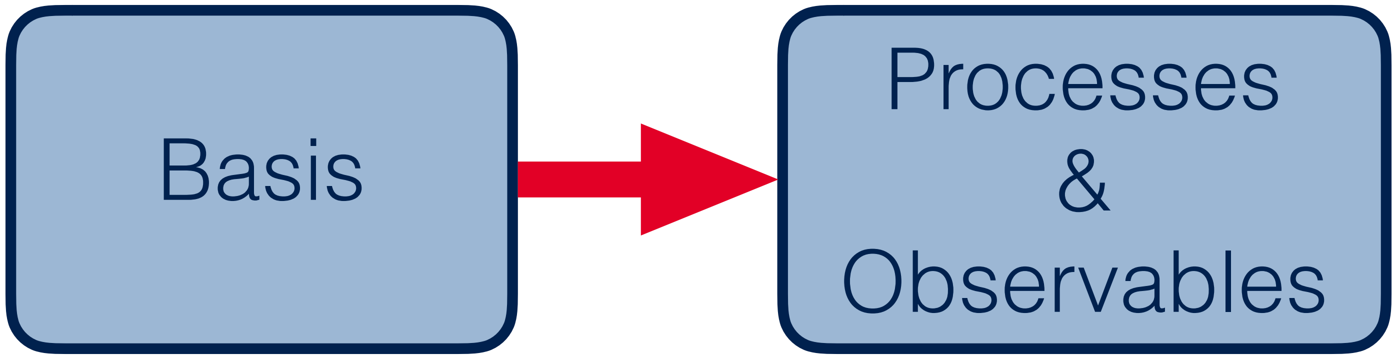
Strategy



Rate measurements $\sigma_{\text{tot.}}\,,\quad \mu = \dfrac{\sigma}{\sigma_{\text{SM}}}$

Differential $\dfrac{d\sigma}{dM_{\text{XX}}}$ *energy, angular*

Strategy

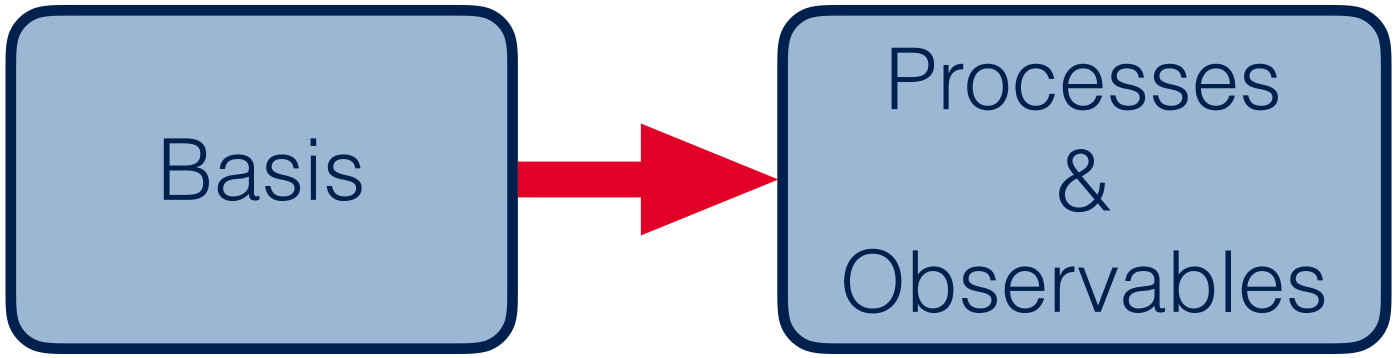


Rate measurements $\sigma_{\text{tot.}}\,, \quad \mu = \dfrac{\sigma}{\sigma_{\text{SM}}}$

Differential $\dfrac{d\sigma}{dM_{\text{XX}}}$ *energy, angular*

High-level

Strategy



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asymmetries

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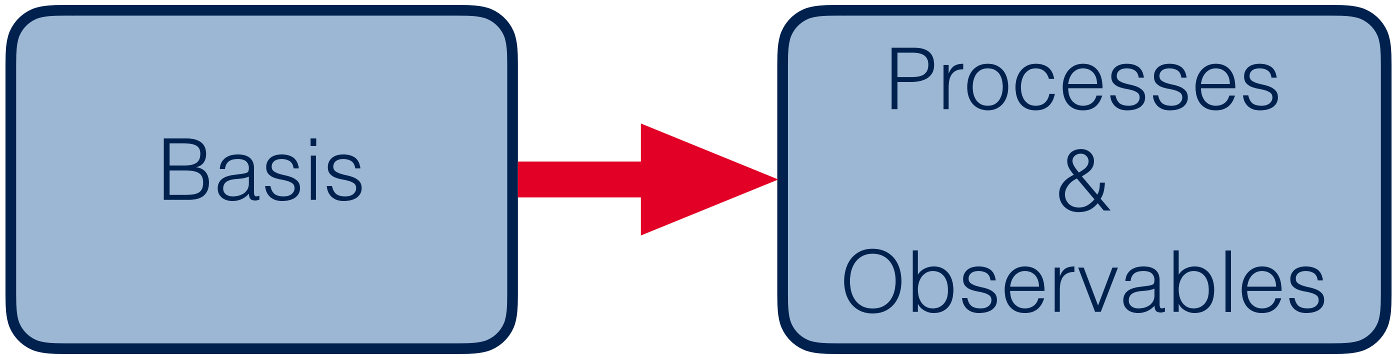

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High-level *optimal observables*

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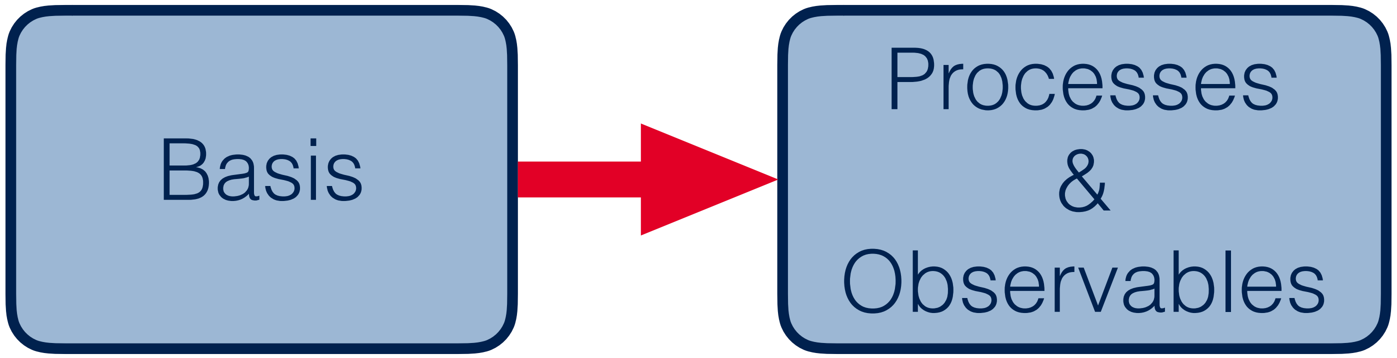

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High-level

asymmetries

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NN-output

Strategy

Strategy

Determine dependence on
Wilson coefficients

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$$\mathcal{O} = \mathcal{O}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}^i_{\rm int} + \sum_{i,j} \frac{c_i\,c_j}{\Lambda^4}\mathcal{O}^{ij}_{\rm sq}$$

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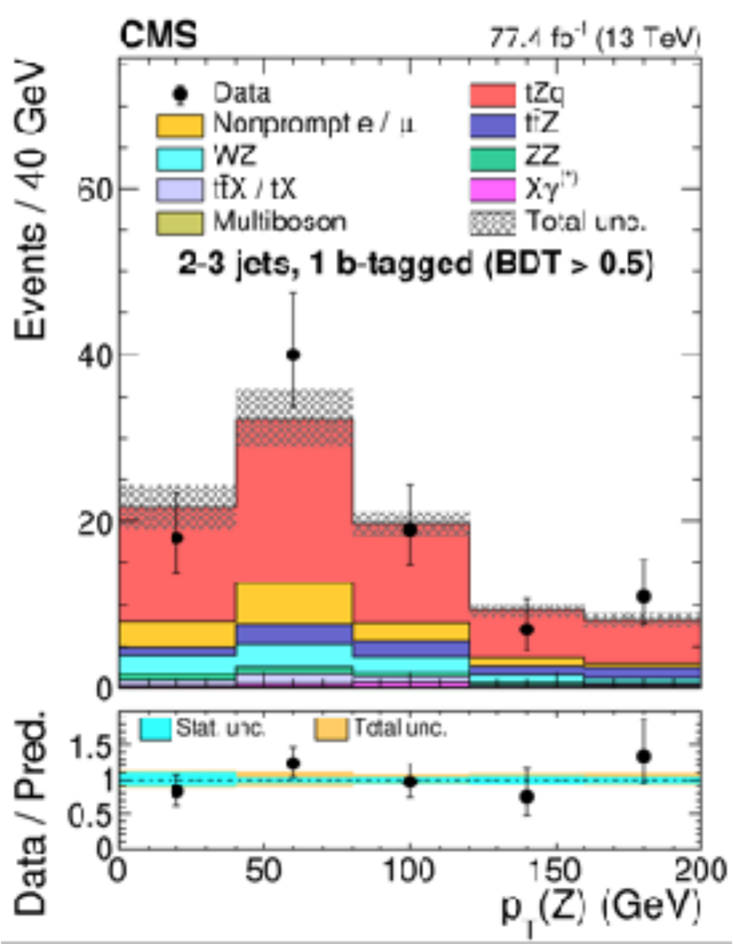
Precise Monte Carlo tools

Strategy

Basis → Processes & Observables → Sensitivity → Measurement



[CMS.; PRL 122 (2019) 132003]

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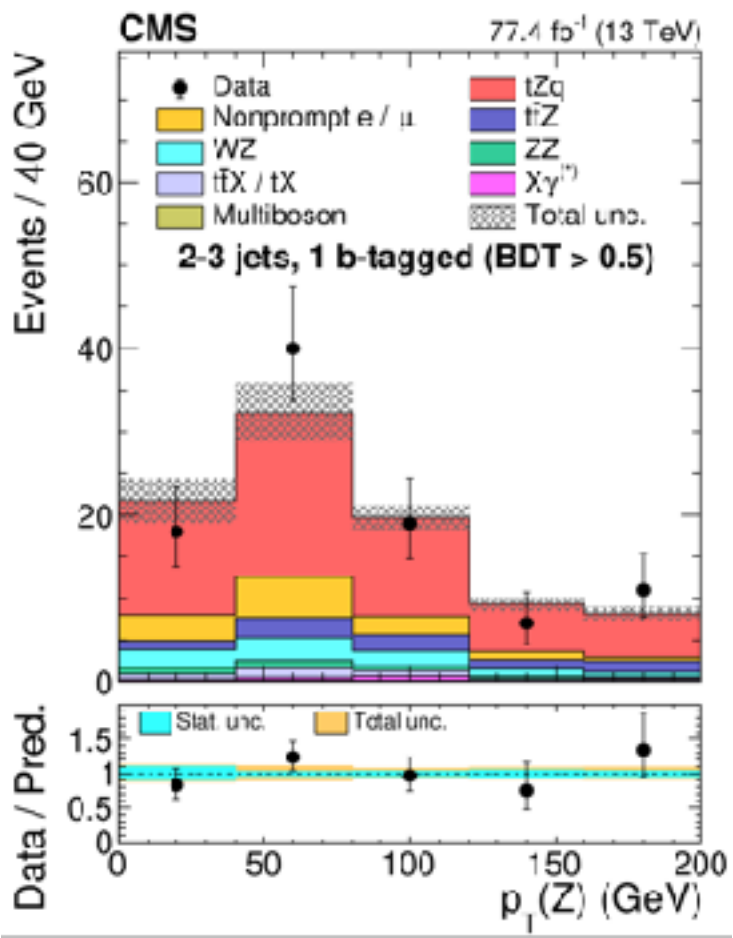
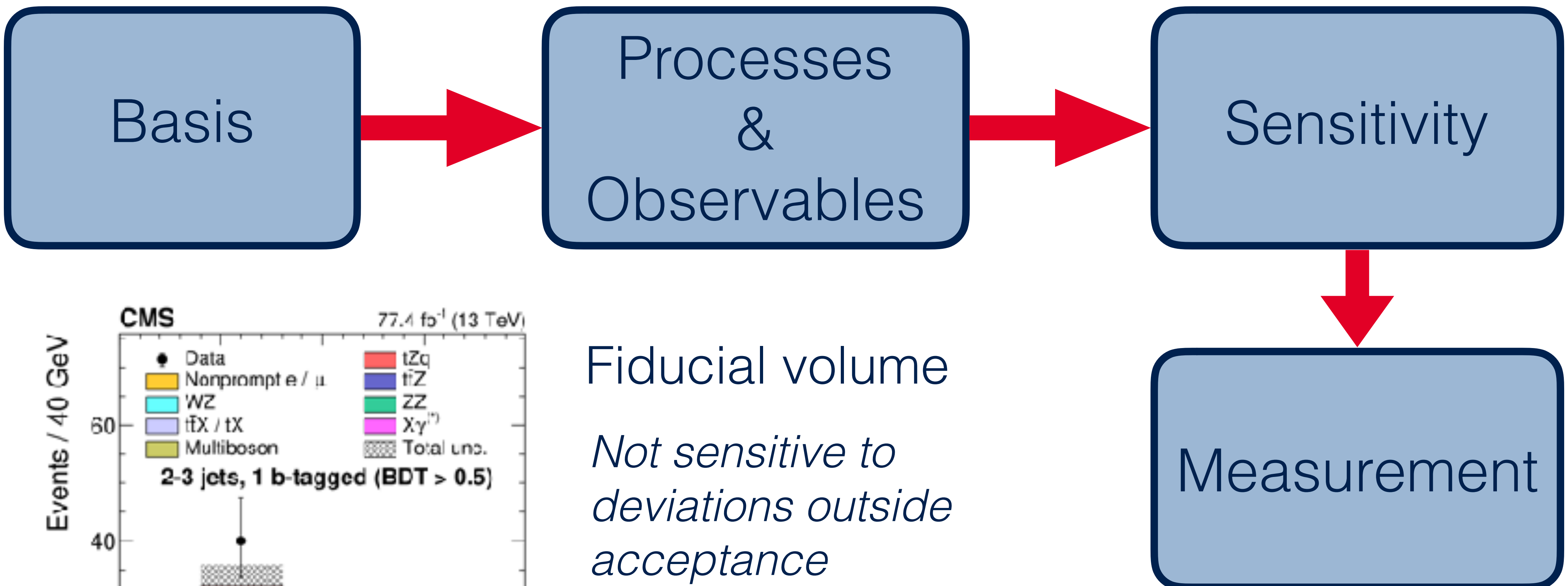


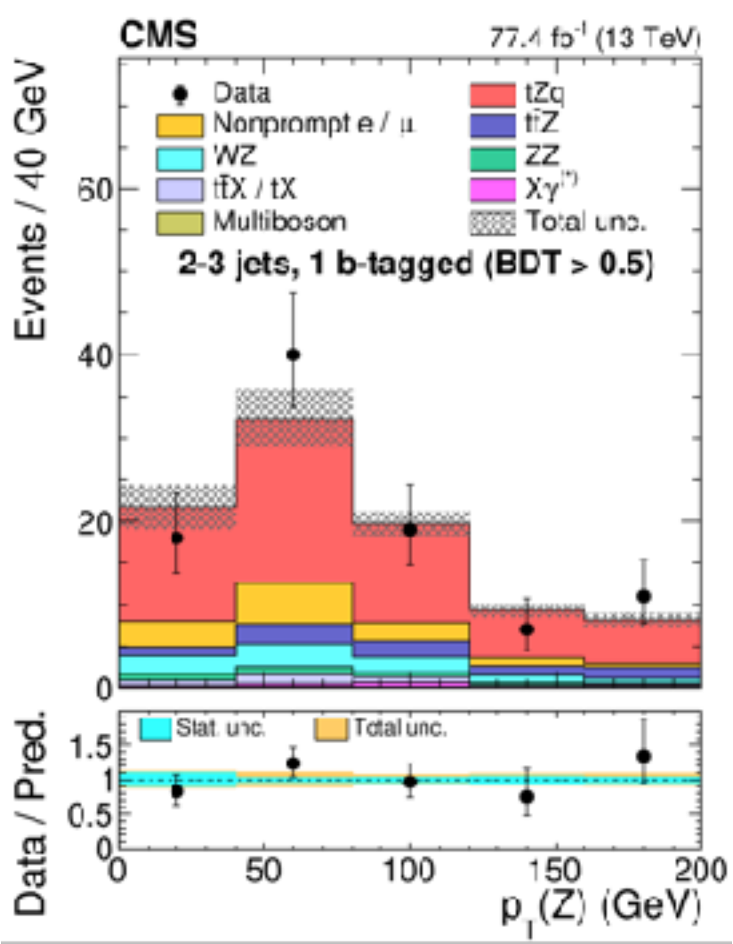
[CMS.; PRL 122 (2019) 132003]

Fiducial volume

Not sensitive to deviations outside acceptance (model dependent)

Strategy





[CMS.; PRL 122 (2019) 132003]

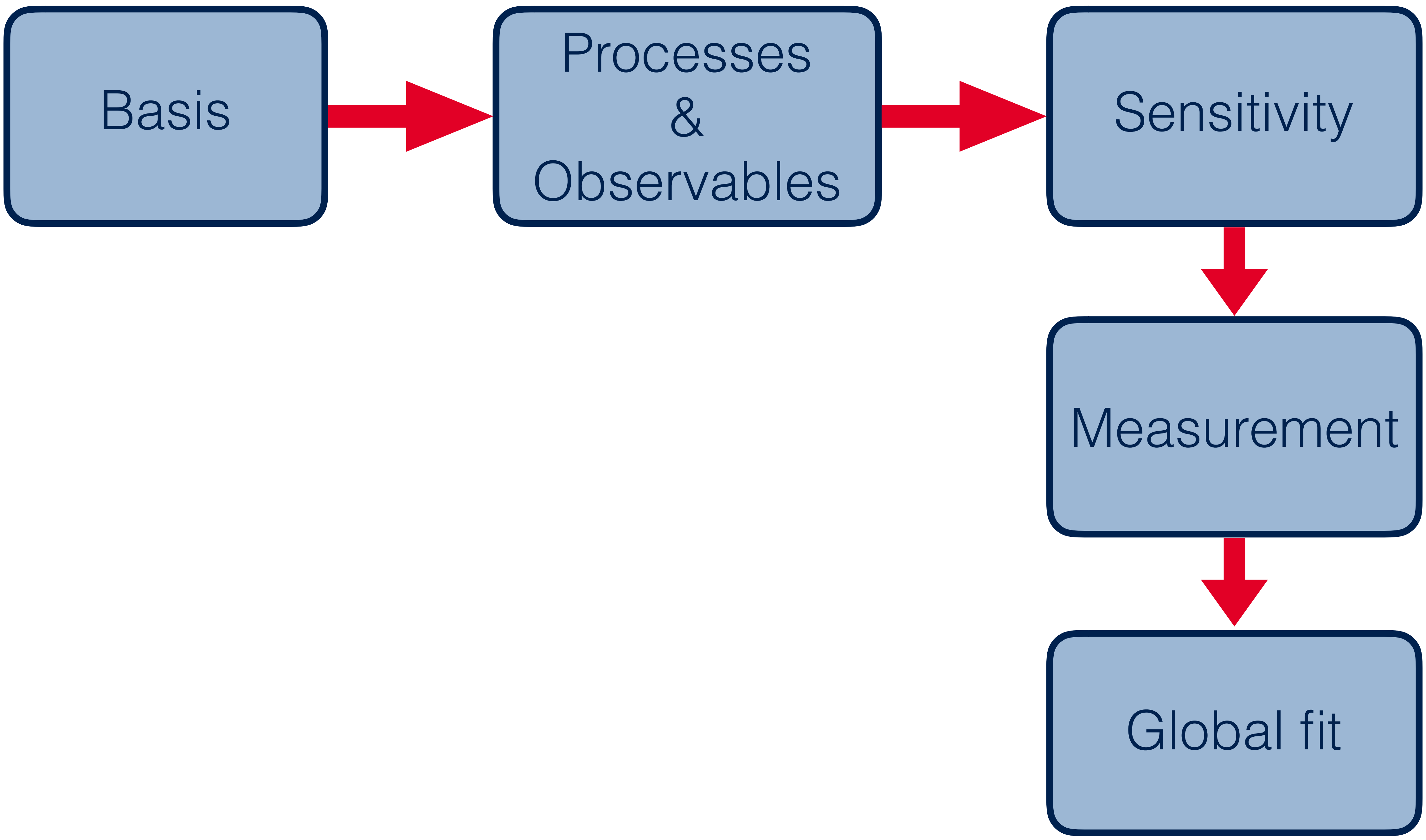
Fiducial volume

Not sensitive to deviations outside acceptance (model dependent)

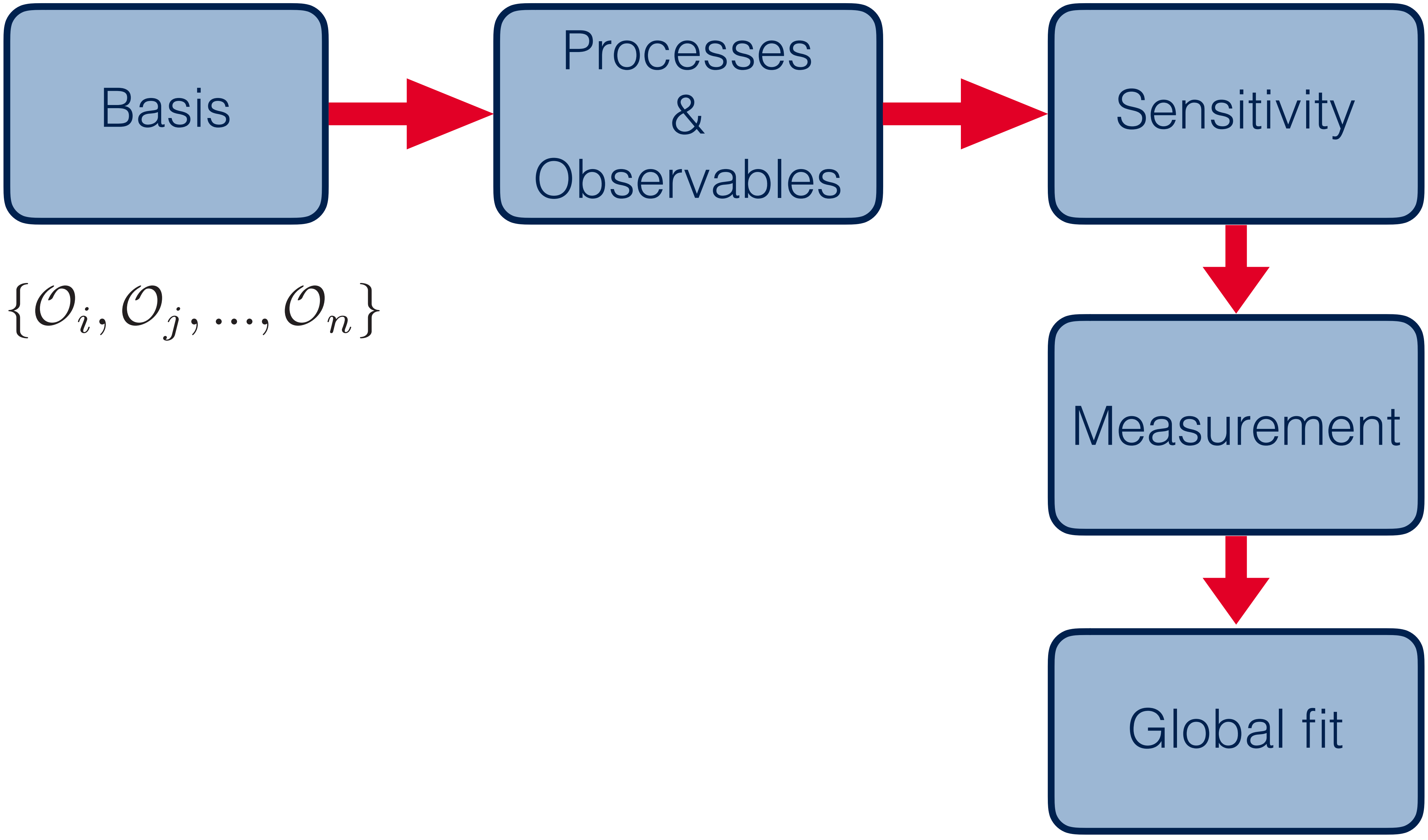
Extract limits

$$c_i \subset [a, b] \;\; [\mathrm{TeV}^{-2}]$$

Strategy

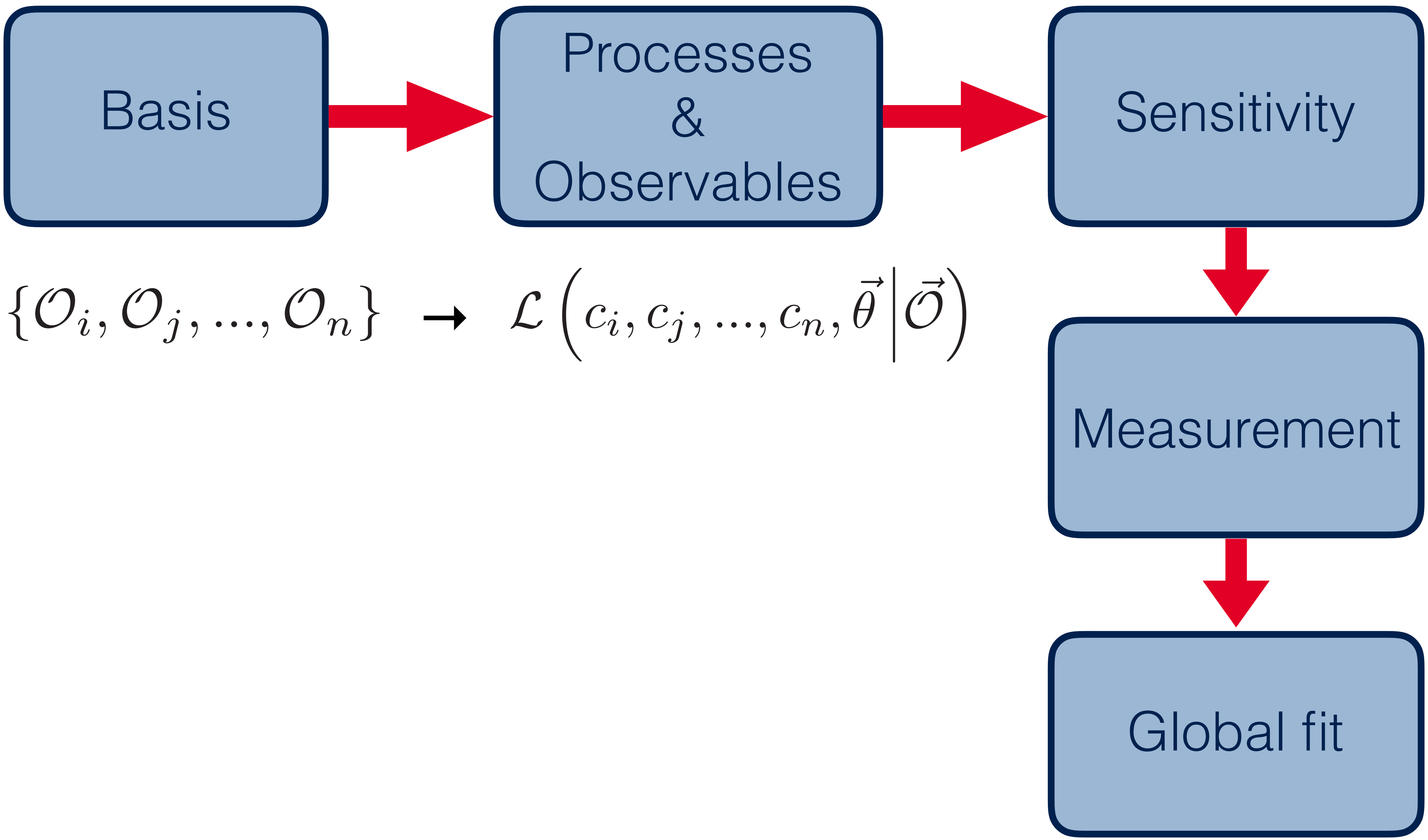

Basis
Processes
&
Observables
Sensitivity
Measurement
Global fit

Strategy



$$\{\mathcal{O}_i, \mathcal{O}_j, ..., \mathcal{O}_n\}$$

Strategy



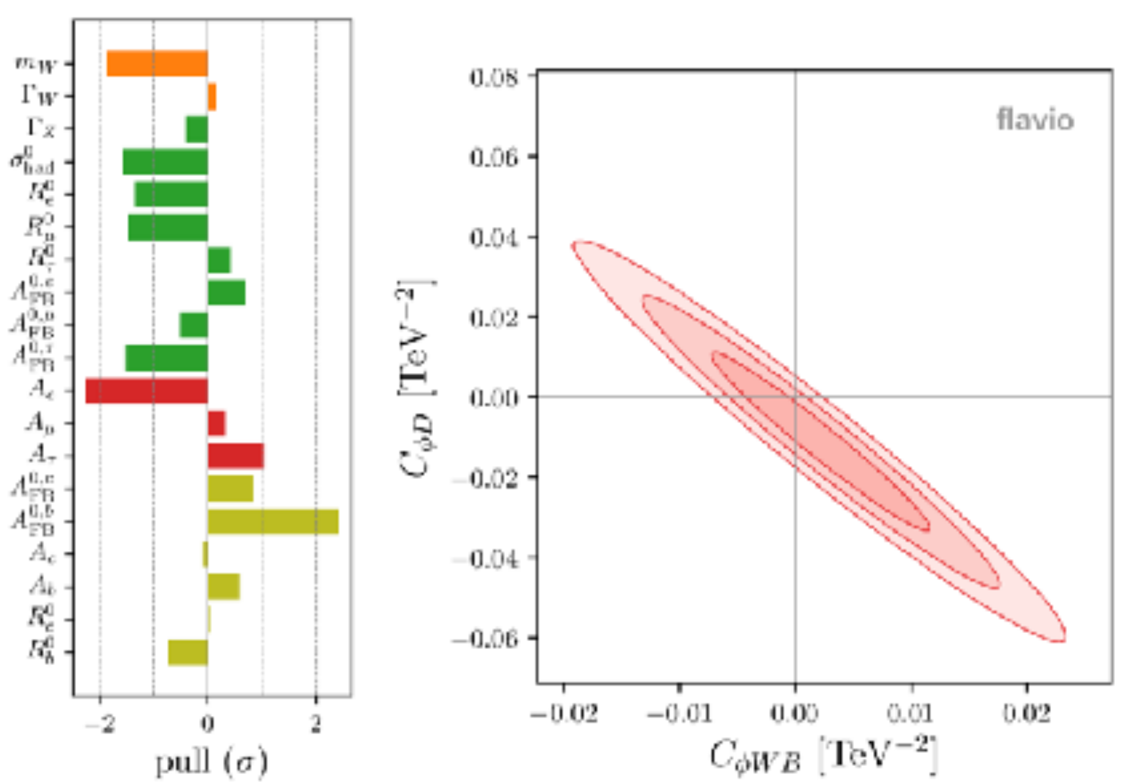
$$\{\mathcal{O}_i, \mathcal{O}_j, \ldots, \mathcal{O}_n\} \rightarrow \mathcal{L}\left(c_i, c_j, \ldots, c_n, \vec{\theta}\,\middle|\,\vec{\mathcal{O}}\right)$$

Strategy

Basis → Processes & Observables → Sensitivity → Measurement → Global fit

$$\{\mathcal{O}_i, \mathcal{O}_j, ..., \mathcal{O}_n\} \rightarrow \mathcal{L}\left(c_i, c_j, ..., c_n, \vec{\theta}\,\middle|\,\vec{\mathcal{O}}\right)$$

[Aebischer et al.; arXiv:1810.07698]



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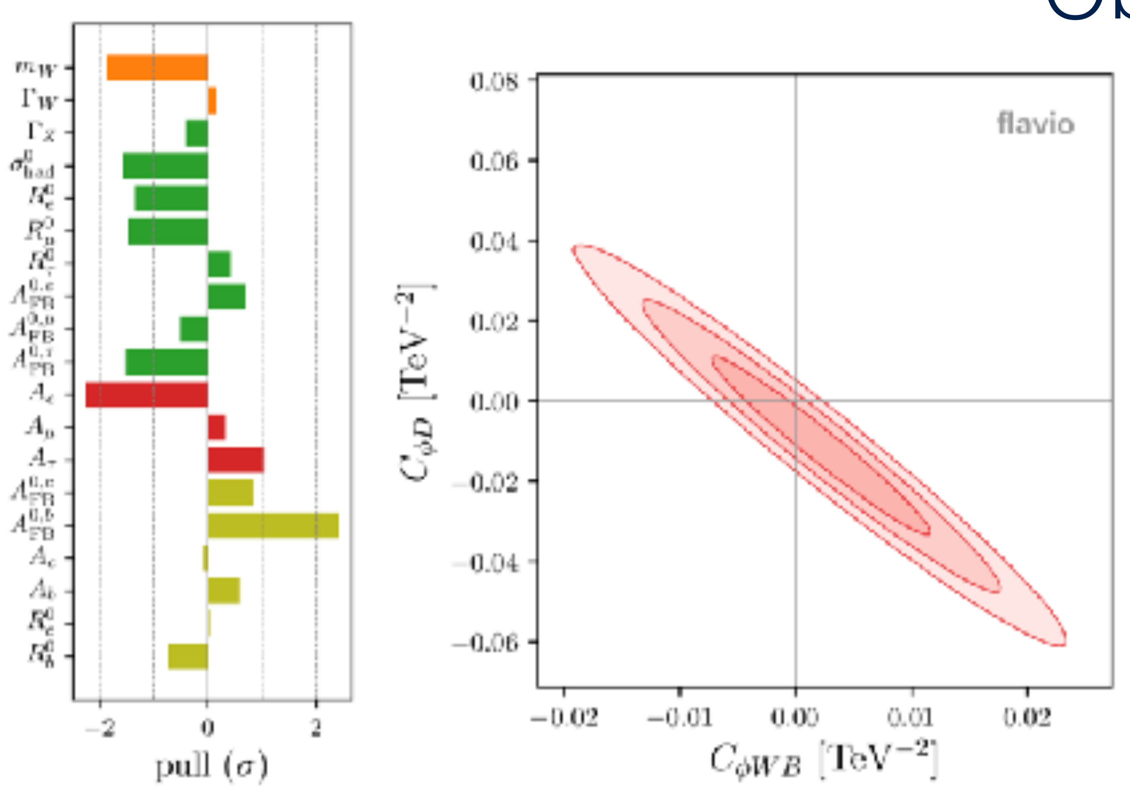
Observations/
Limits



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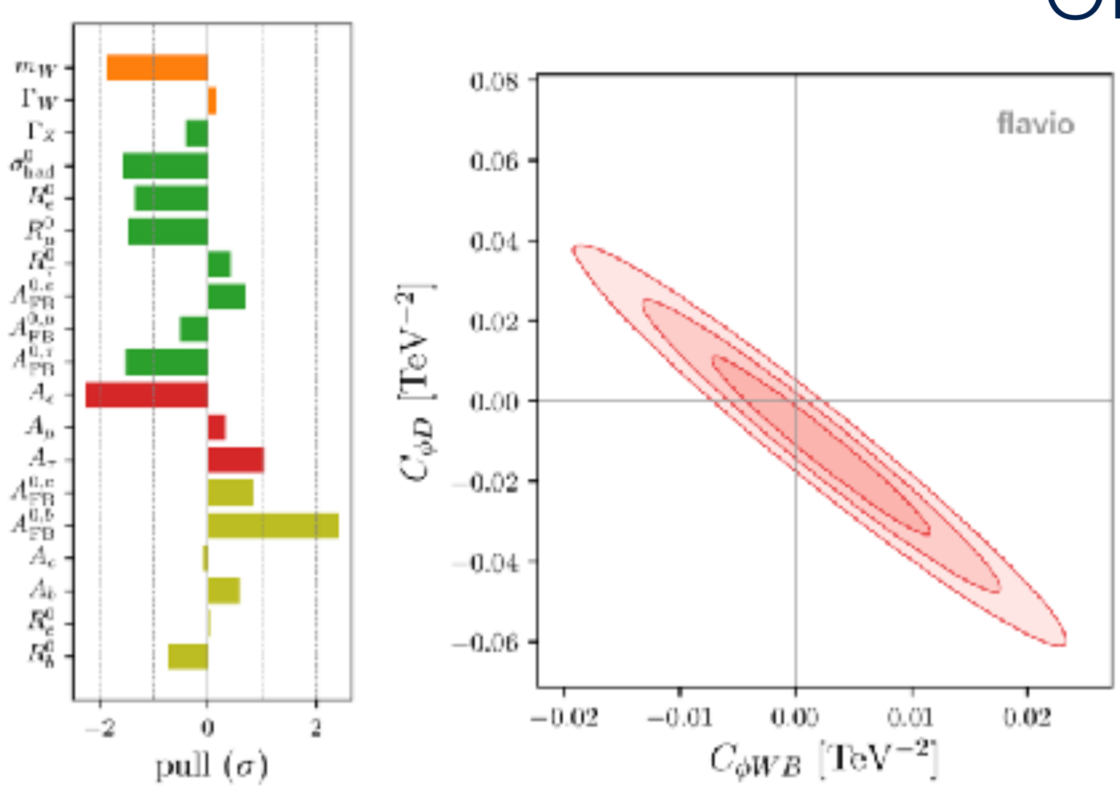
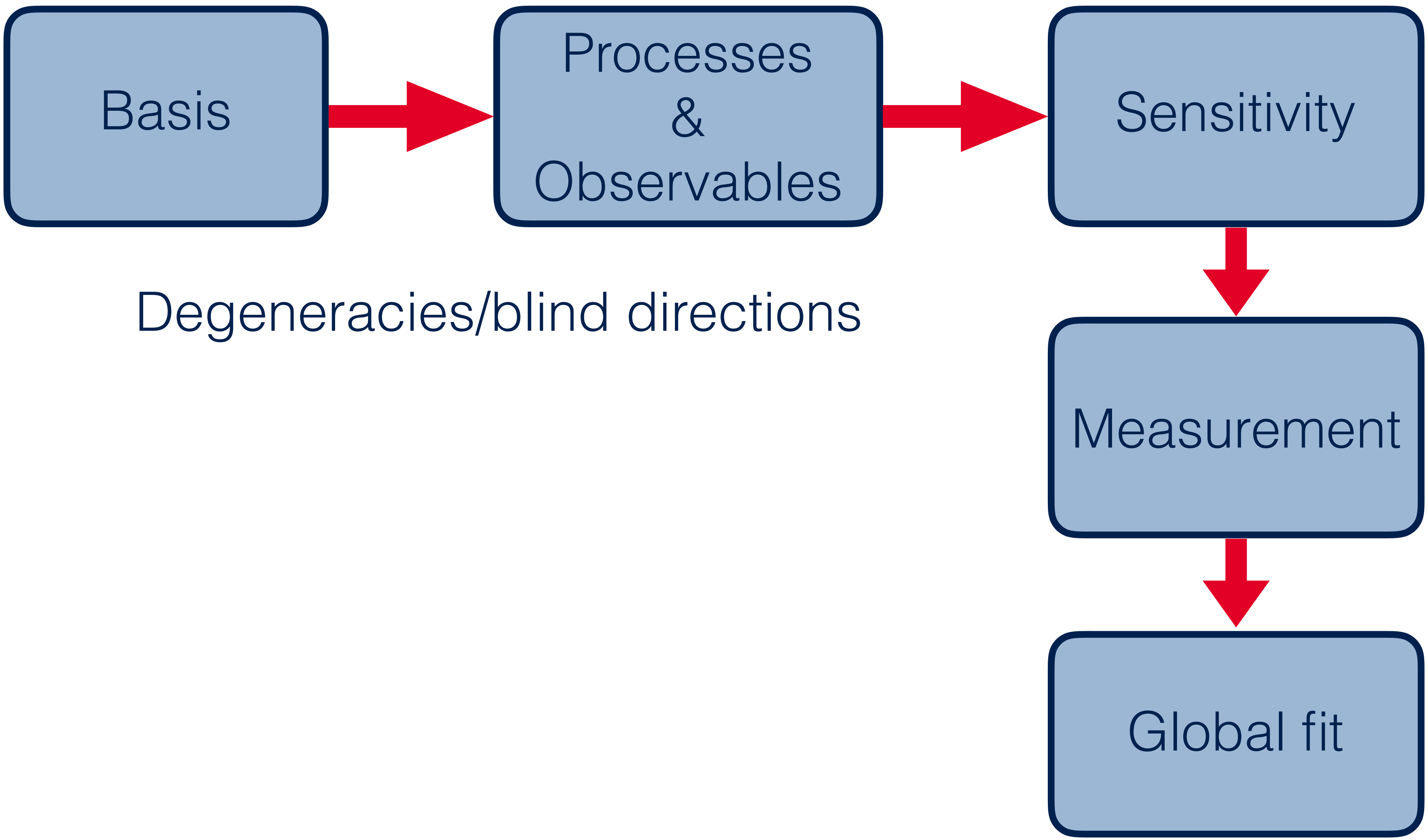


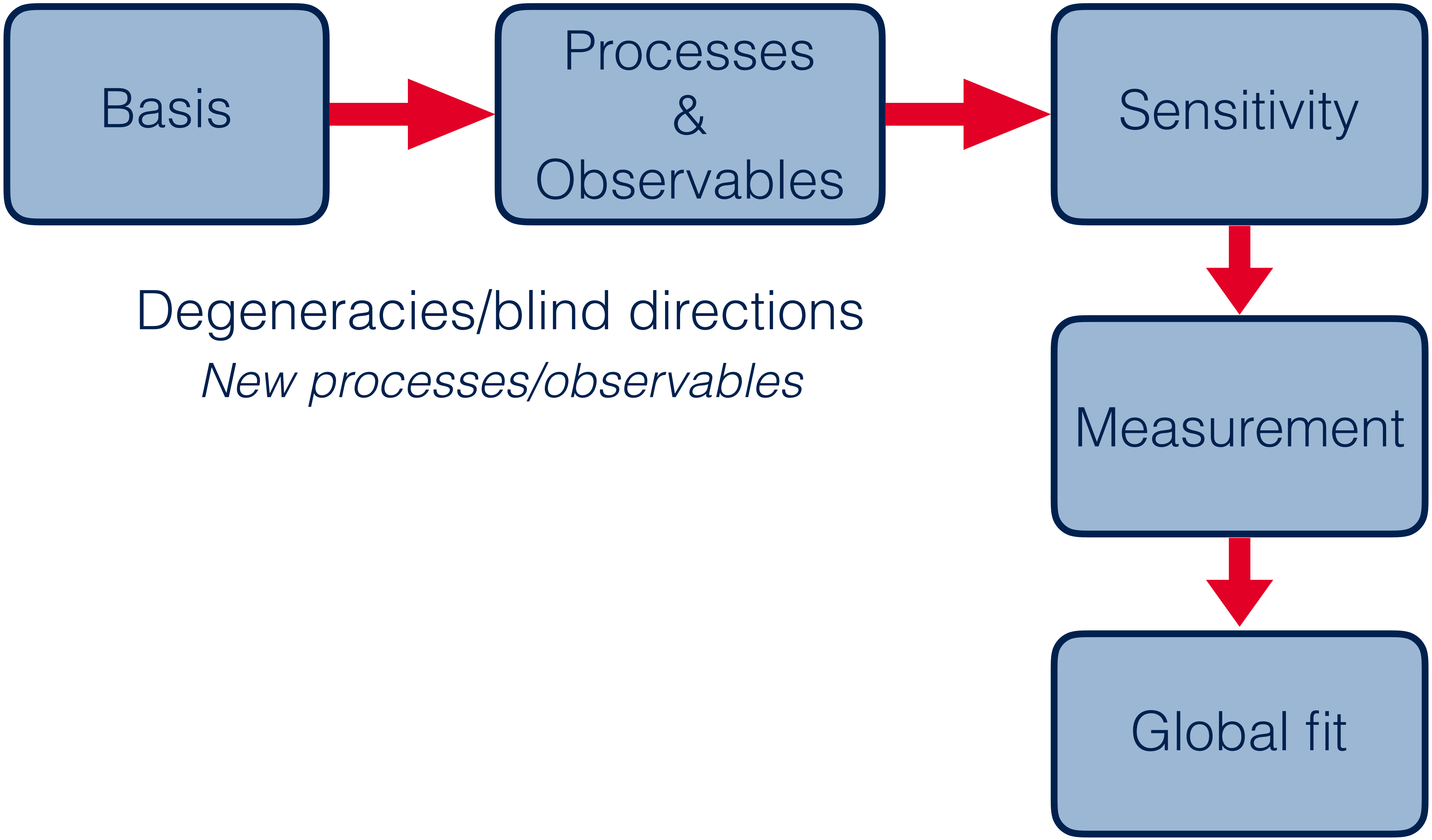
Observations/
Limits

Individual
Marginalised
Pulls,…

Strategy


Basis
Processes
&
Observables
Sensitivity
Degeneracies/blind directions
Measurement
Global fit

Strategy


Basis
Processes & Observables
Sensitivity
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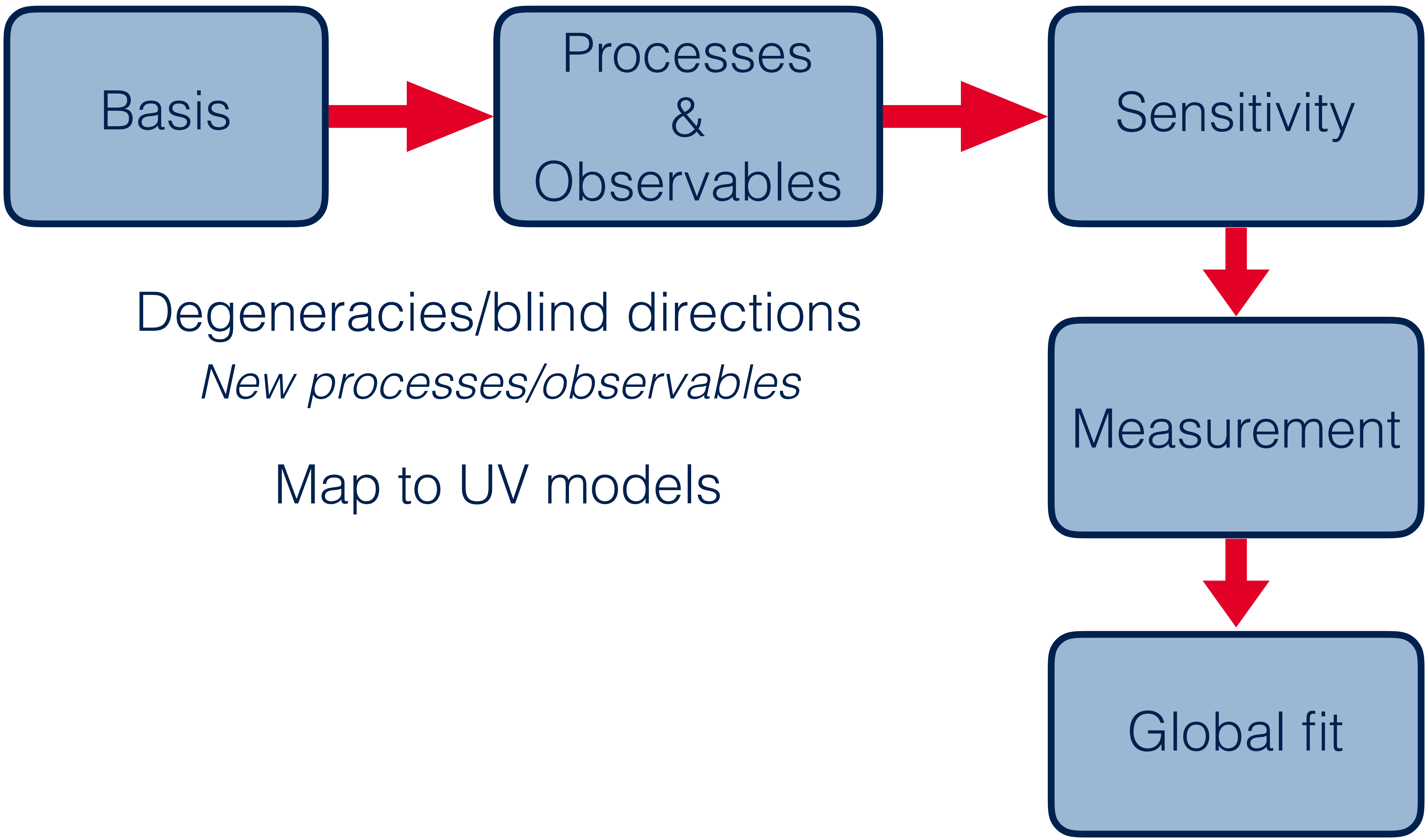
Global fit
Degeneracies/blind directions
New processes/observables

Strategy



Degeneracies/blind directions

New processes/observables

Map to UV models

Strategy

Basis → Processes & Observables → Sensitivity → Measurement → Global fit

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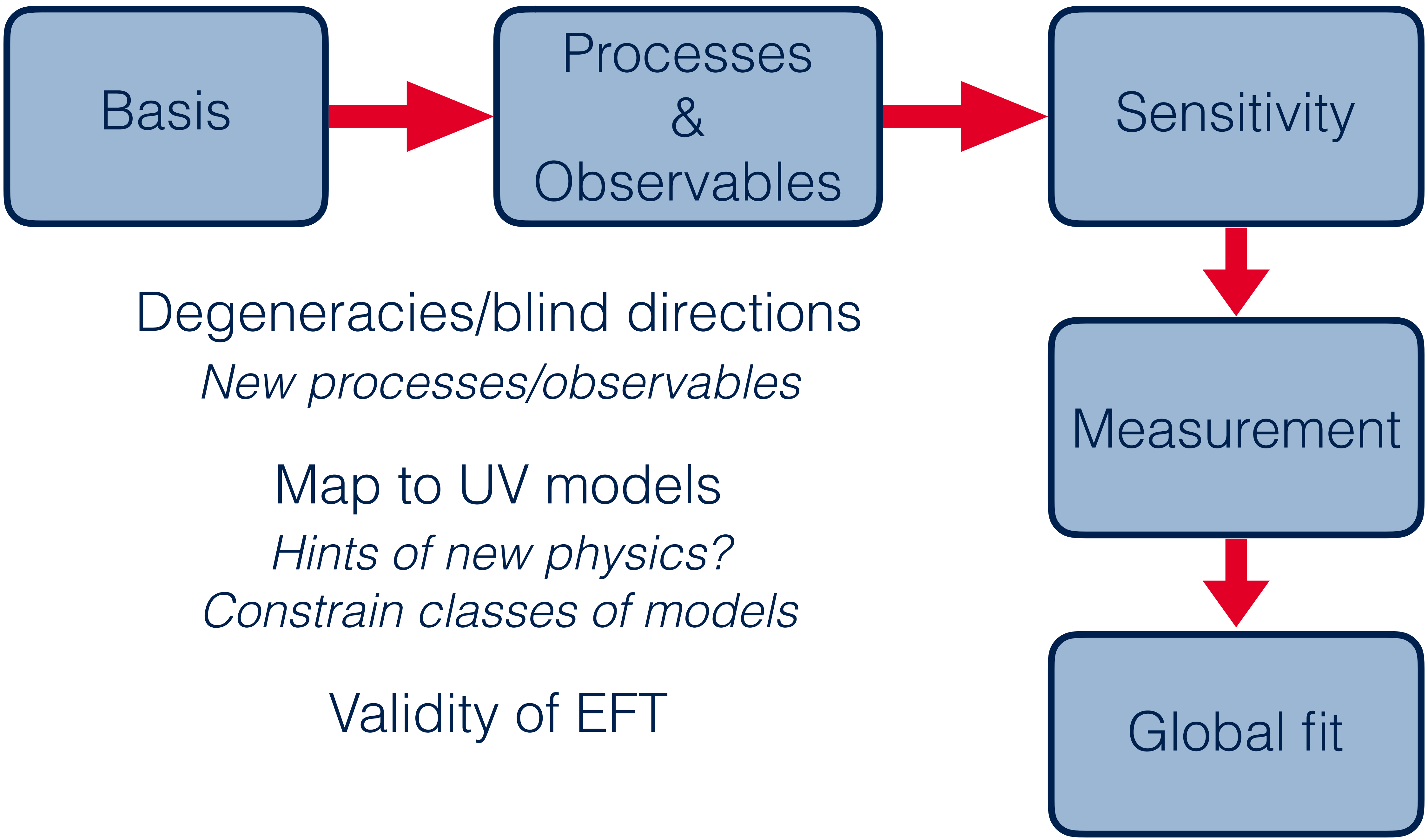
New processes/observables

Map to UV models

Hints of new physics?
Constrain classes of models

Strategy



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Validity of EFT

Strategy

Basis

Processes & Observables

Sensitivity

Measurement

Global fit

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Validity of EFT

***A posteriori**: depends on sensitivity*

Intrinsically model dependent

Global approach

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Global approach essential

- Large parameter space predicting intrinsically small effects
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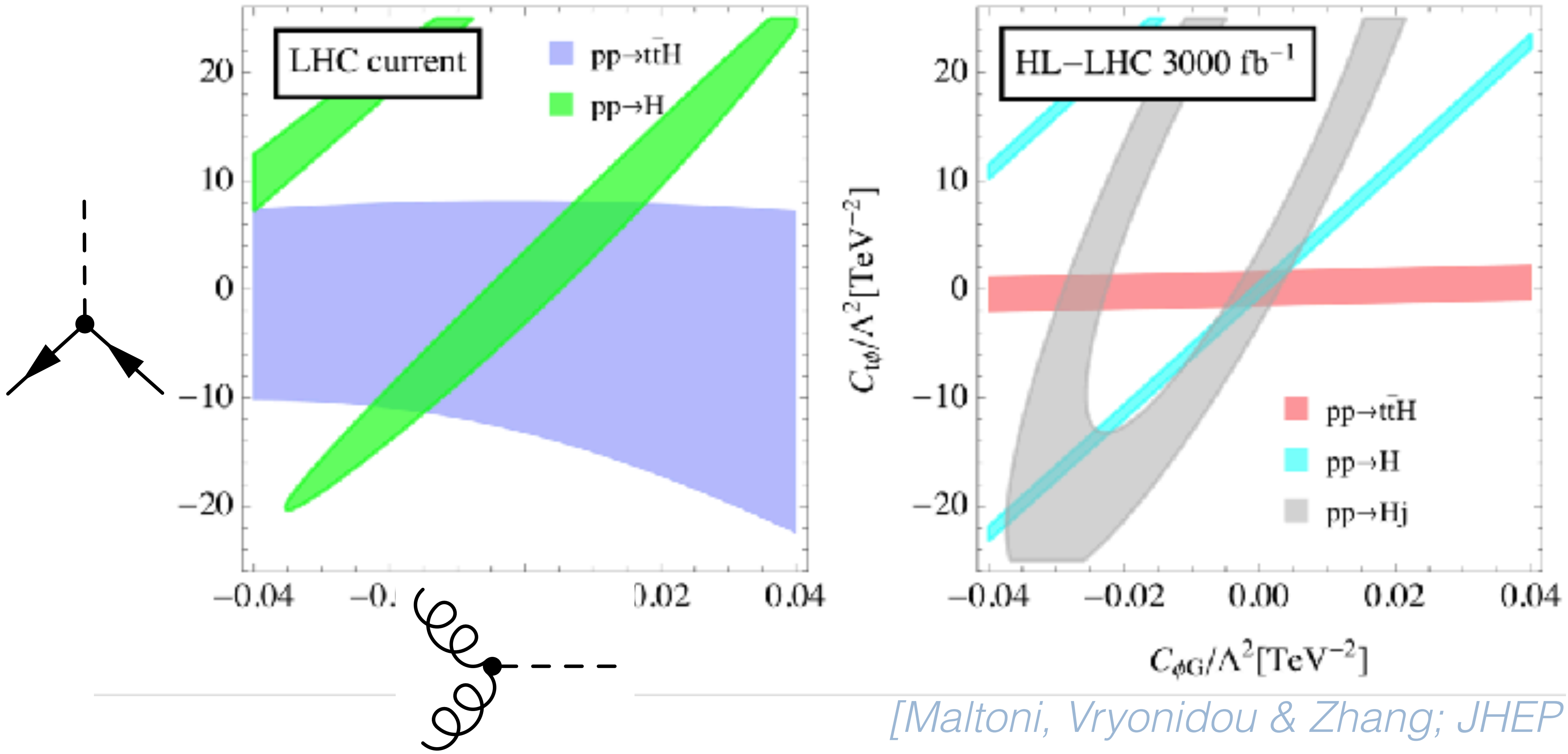
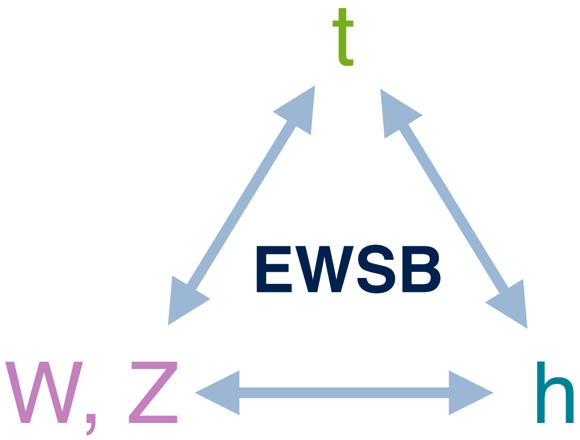


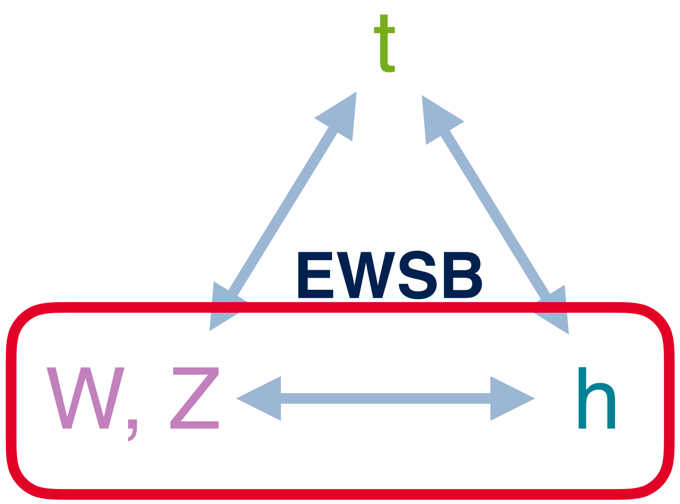
[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

SMEFT for EWSB sector



SMEFT for EWSB sector

Bosonic operators of minimal basis cover deviations in the gauge/Higgs sector



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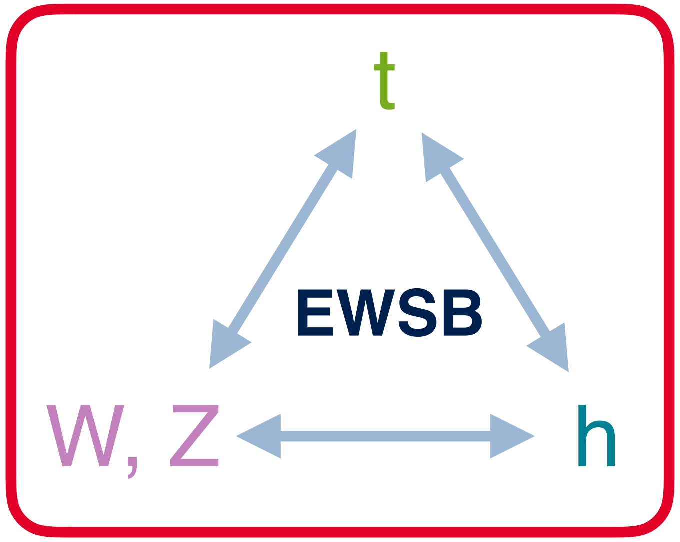
Bosonic operators of minimal basis cover deviations in the gauge/Higgs sector

Including the top → going beyond universal flavor assumption



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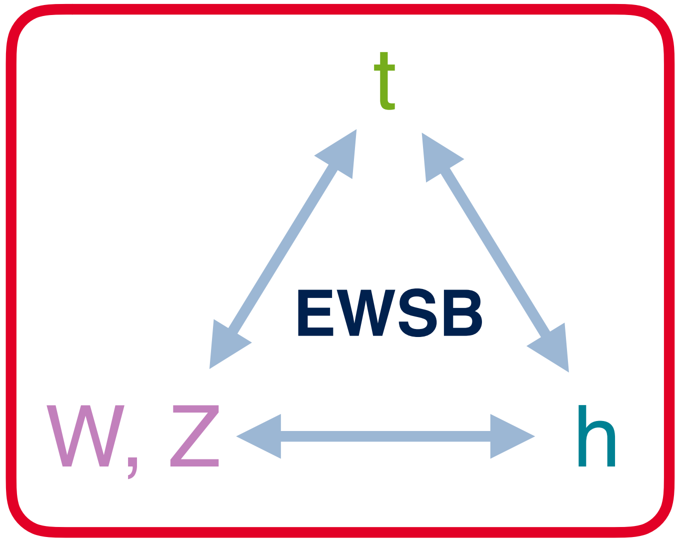

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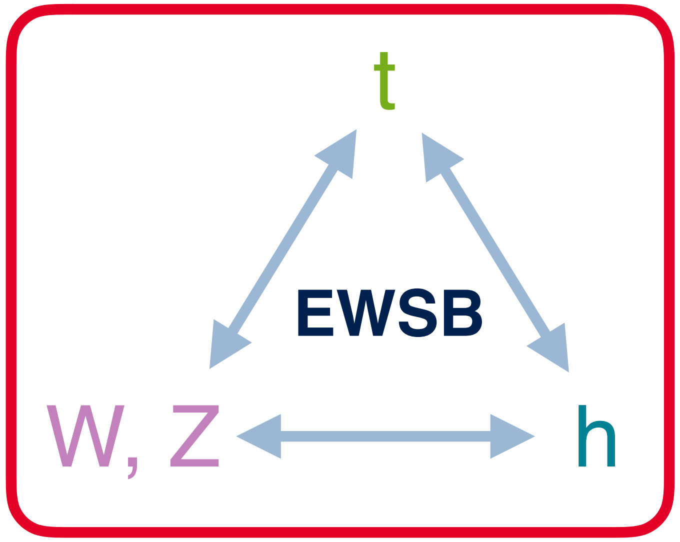

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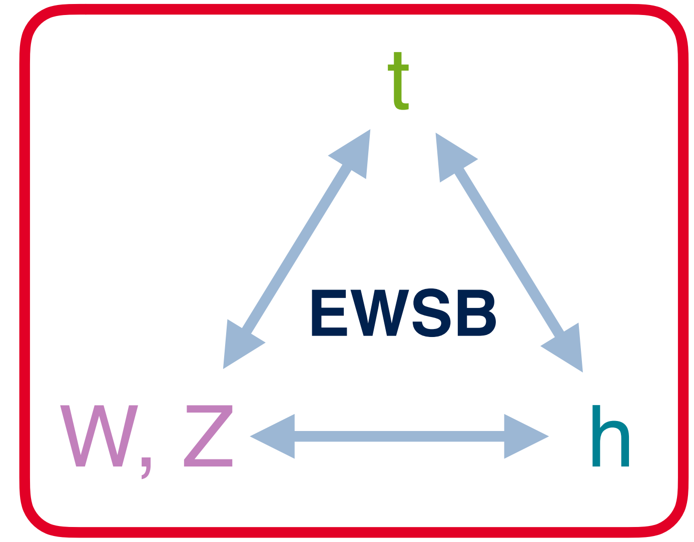

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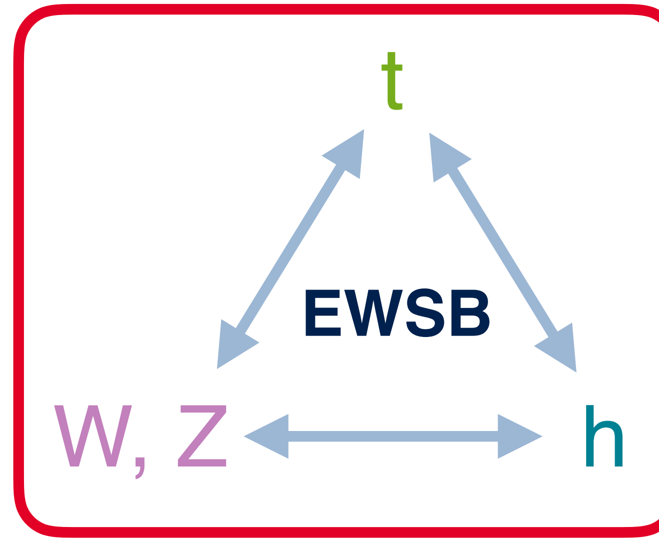

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cf. Minimal flavor violation

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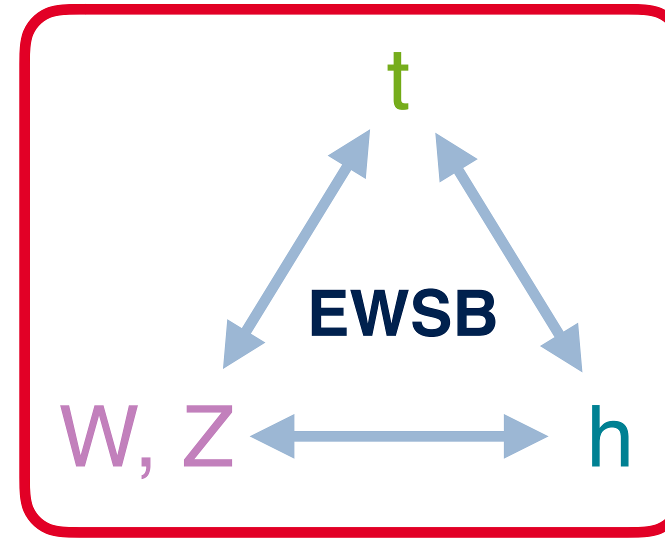

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cf. Minimal flavor violation

Single out independent operators for modified top/EW interactions

$$\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{Q}\, t\, \tilde{\varphi})$$

$$\psi^2 X H : (\bar{Q}\, \sigma^{\mu\nu}\, t\, \tilde{\varphi}) B_{\mu\nu}\ [W^I_{\mu\nu},\, G^a_{\mu\nu}]$$

$$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{Q}\, \gamma^\mu\, Q)\ [(\bar{Q}\, \gamma^\mu \tau^I\, Q),\, (\bar{t}\, \gamma^\mu\, t), ...]$$

$$\psi^4 : (\bar{Q}\, \gamma^\mu\, Q)(\bar{q}\, \gamma_\mu\, q),\, (\bar{Q}\, \gamma^\mu\, Q)(\bar{Q}\, \gamma_\mu\, Q), ...$$

Tools

Tools

Several LO implementations available

- dim6top (LHC Top WG)
  http://feynrules.irmp.ucl.ac.be/wiki/dim6top
  [Aguilar-Saavedra et al.; arXiv:1802.07237]
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Going beyond: **SMEFT@NLO**

[Degrande, Durieux, Maltoni, KM, Vryonidou, Zhang; in preparation]

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Based on:

[Zhang; PRL 116 (2016) 162002]	single-top
[Bylund, Maltoni, Tsinikos, Vryonidou, Zhang; JHEP 1605 (2016) 052]	ttZ & ttγ
[Maltoni, Vryonidou, Zhang; JHEP 1610 (2016) 123]	ttH, ggH, H+j
[Degrande, Fuks, Mawatari, KM, Sanz; EPJC 77 (2017) 4, 262]	VH & VBF
[Degrande, Maltoni, KM, Zhang, Vryonidou; JHEP 1810 (2018) 005]	tZq & tHq

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POWHEG-BOX/MCFM

http://powhegbox.mib.infn.it

- VH NLO QCD + PS for Higgs/EW operators (SILH) *[KM et al.; JHEP 1608 (2016) 039]*
- Drell-Yan & EW Higgs production with more operators *[Alioli et al.; JHEP 08 (2018) 205]*
- WW with TGC & quark vertex operators *[Baglio et al.; PRD 99 (2019) 035029]*
- tt with EW top operator loops *[Martini & Schulze ; arXiv:1911.11244]*
- SMEFT single top *[Neumann & Sullivan.; JHEP 06 (2019) 022]*

Applications: LHC

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Increasing number of EFT interpretations in LHC analyses

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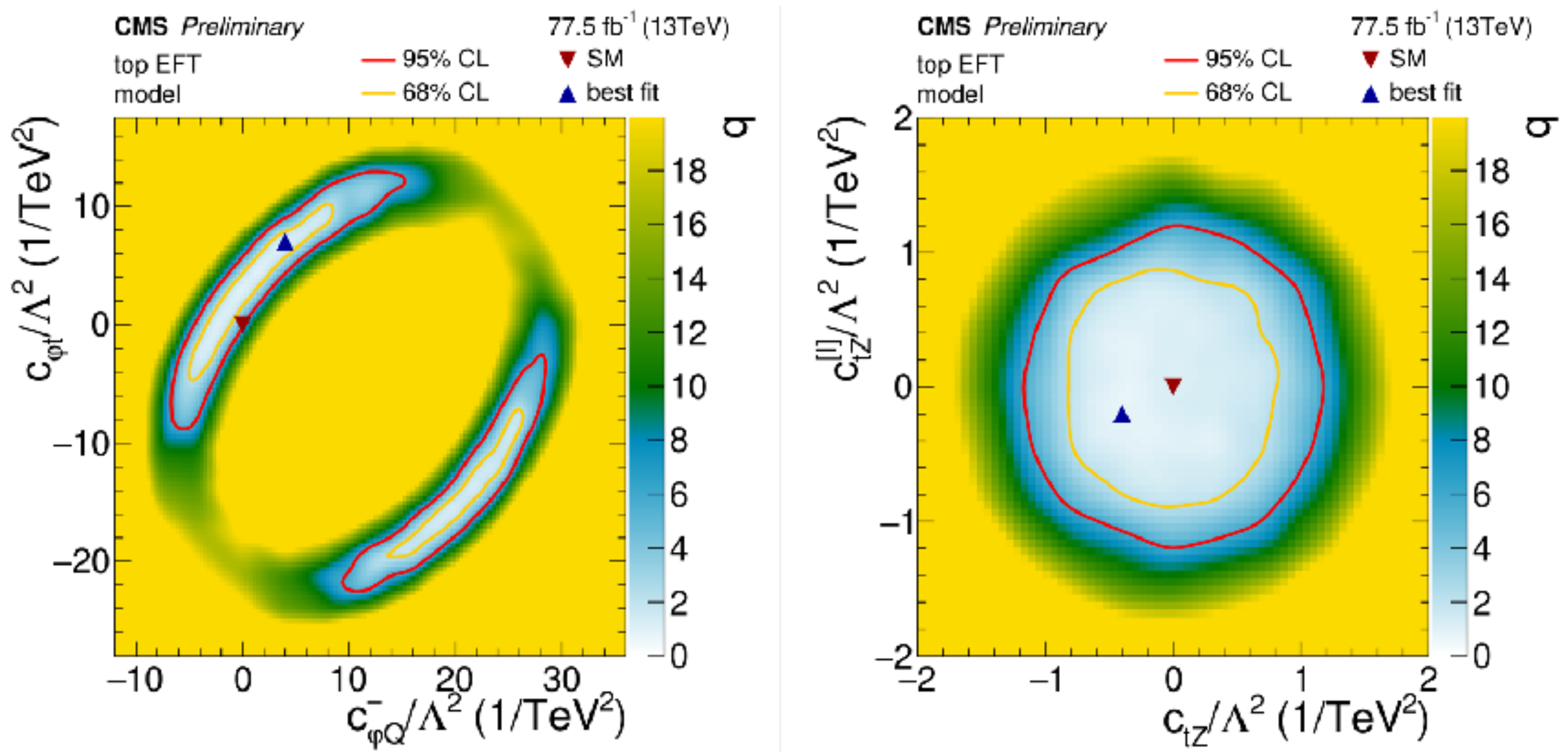

ttZ differential [CMS-PAS-TOP-18-009]

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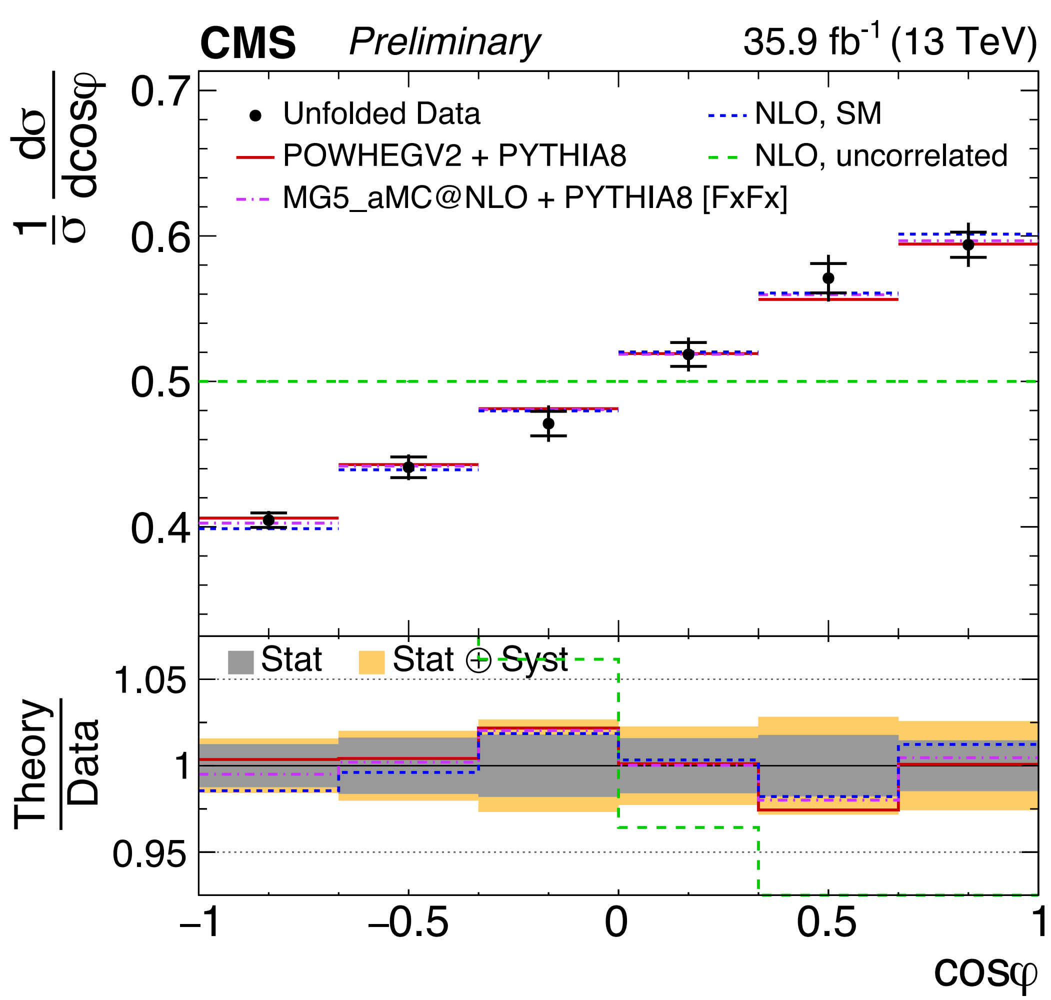

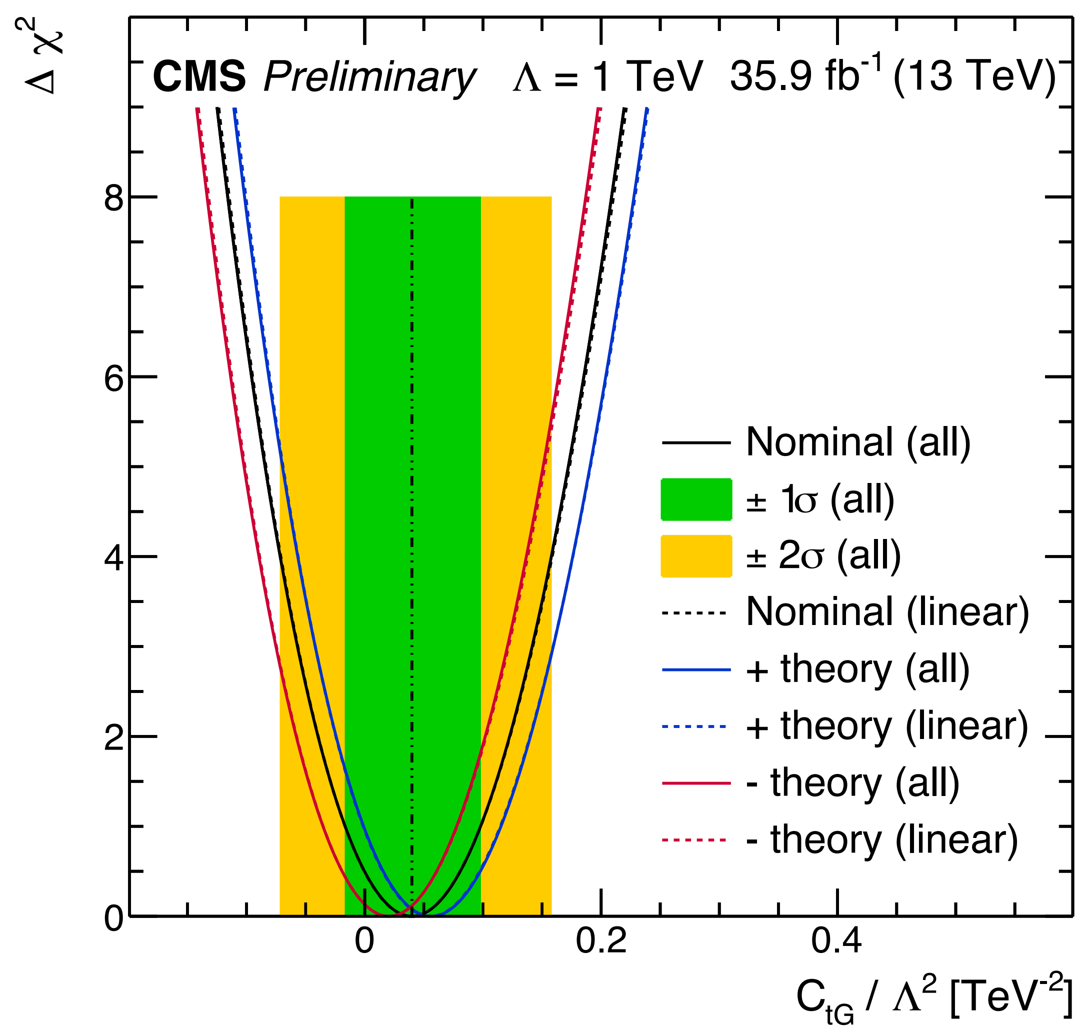

tt polarisation/spin corr. *[CMS-PAS-TOP-18-006]*

Applications: LHC

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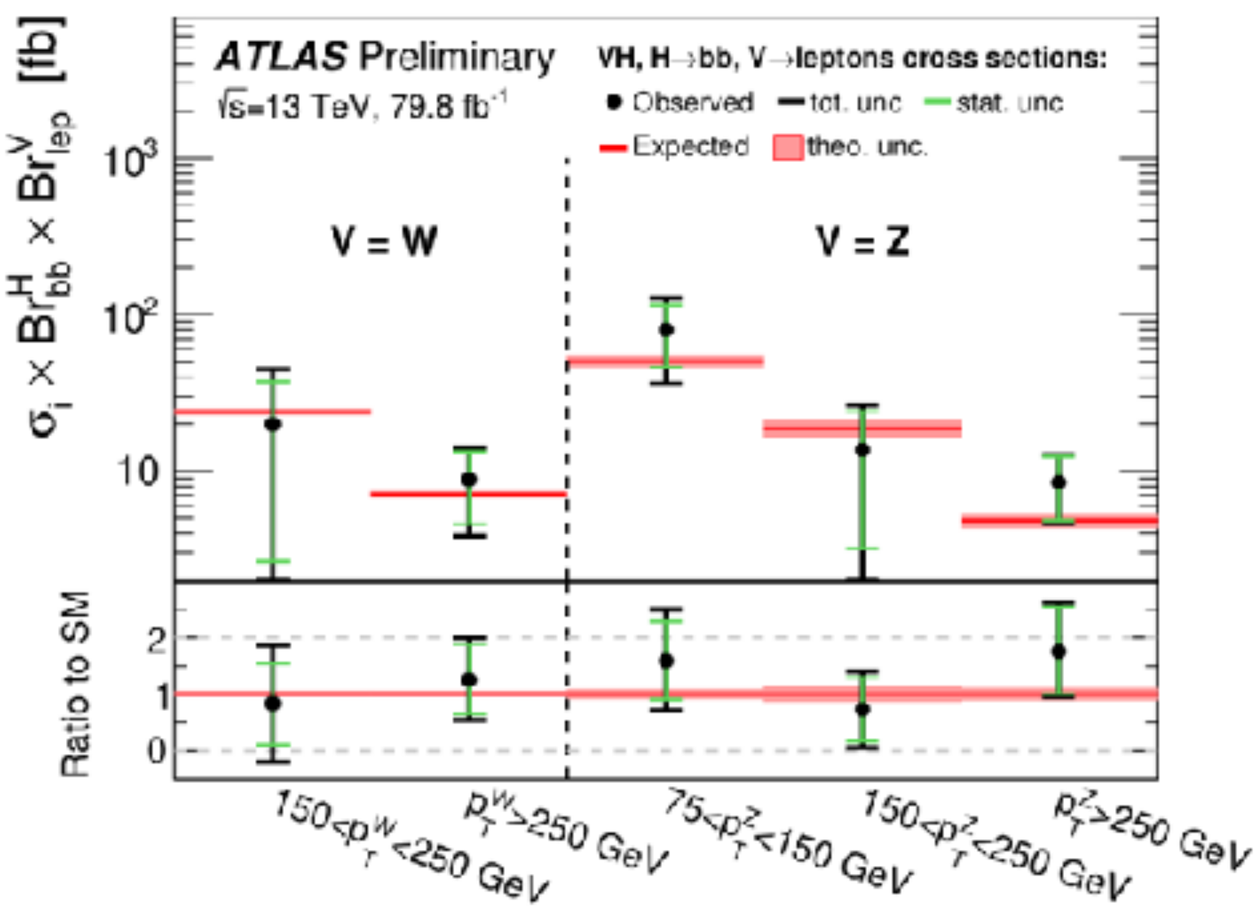

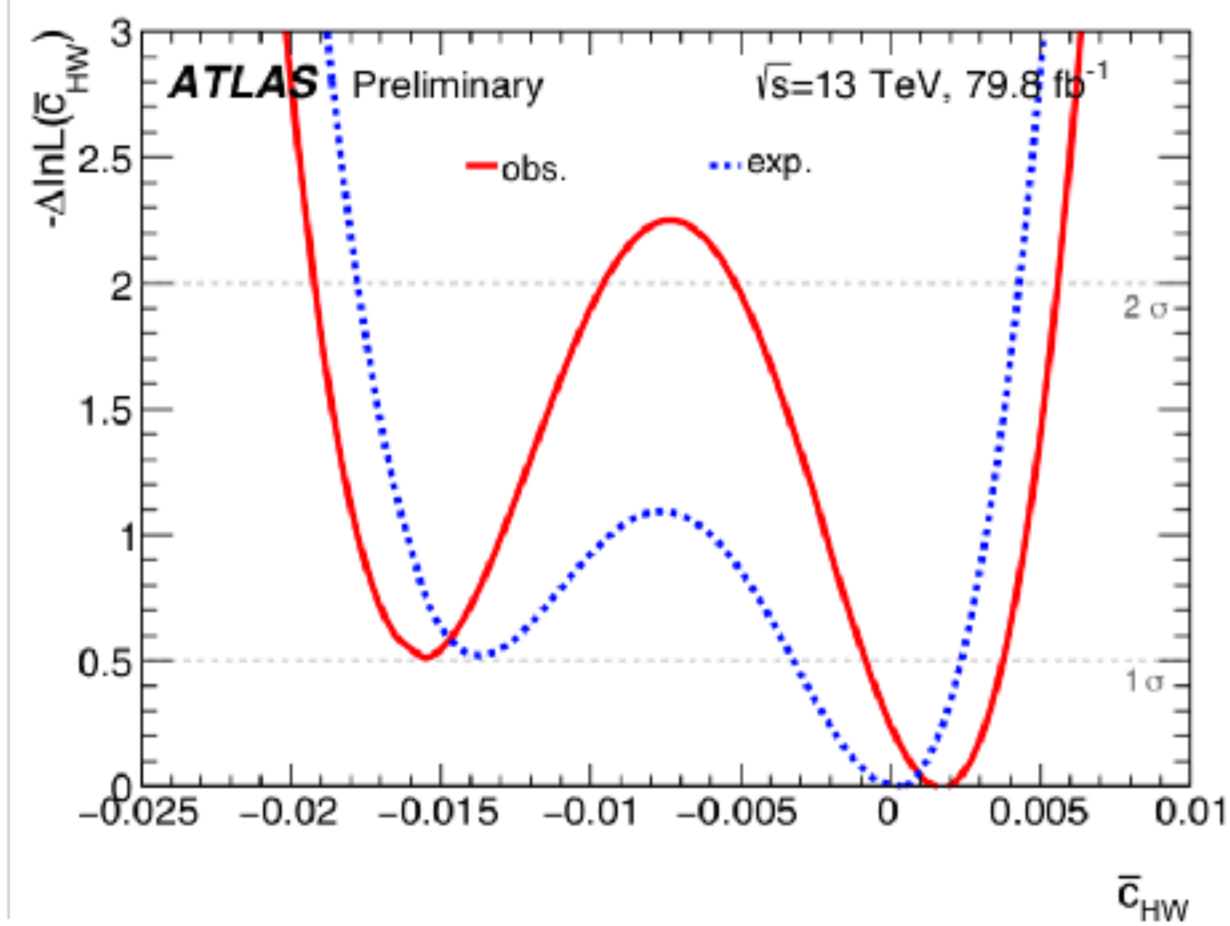

VH STXS *[ATLAS-CONF-2018-053]*

SMEFiT

SMEFiT

State-of-the-art top EFT fit *[Hartland et al.; JHEP 1904 (2019)100]*

SMEFiT

State-of-the-art top EFT fit

[Hartland et al.; JHEP 1904 (2019)100]

- (N)NLO QCD predictions for SM
- Mostly NLO QCD for SMEFT
- 34 Wilson coefficients (dim6top)

4F

c^1_{QQ}	$c^{1,8}_{Qq}$
c^8_{QQ}	$c^{1,1}_{Qq}$
c^1_{Qt}	$c^{3,8}_{Qq}$
c^8_{Qt}	$c^{3,1}_{Qq}$
c^1_{Qb}	c^8_{tq}
c^8_{Qb}	c^1_{tq}
c^1_{tt}	c^8_{tu}
c^1_{tb}	c^1_{tu}
c^8_{tb}	c^8_{Qu}
c^1_{QtQb}	c^1_{Qu}
c^8_{QtQb}	c^8_{td}
	c^1_{td}
	c^8_{Qd}
	c^1_{Qd}

2F

c_{tG}
c_{tW}
c_{bW}
c_{tZ}
$c_{\varphi tb}$
$c^3_{\varphi Q}$
$c^-_{\varphi Q}$
$c_{\varphi t}$
$c_{t\varphi}$

SMEFiT

State-of-the-art top EFT fit

[Hartland et al.; JHEP 1904 (2019)100]

- (N)NLO QCD predictions for SM
- Mostly NLO QCD for SMEFT
- 34 Wilson coefficients (dim6top)

- > 100 7,8,13 TeV LHC measurements
- > 10 production processes

4F

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	c^1_{td}
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$c_{\varphi t}$
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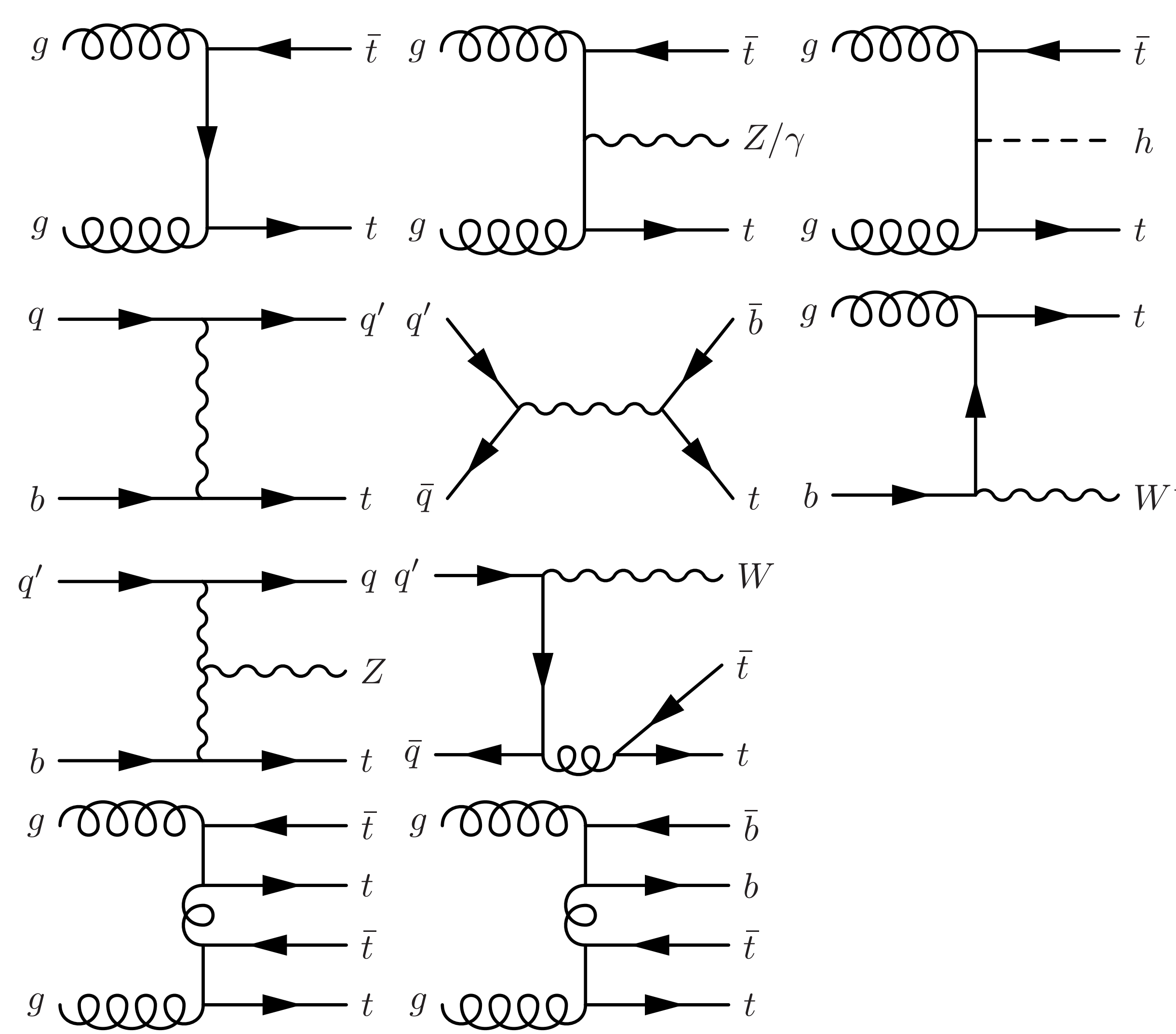

SMEFiT results

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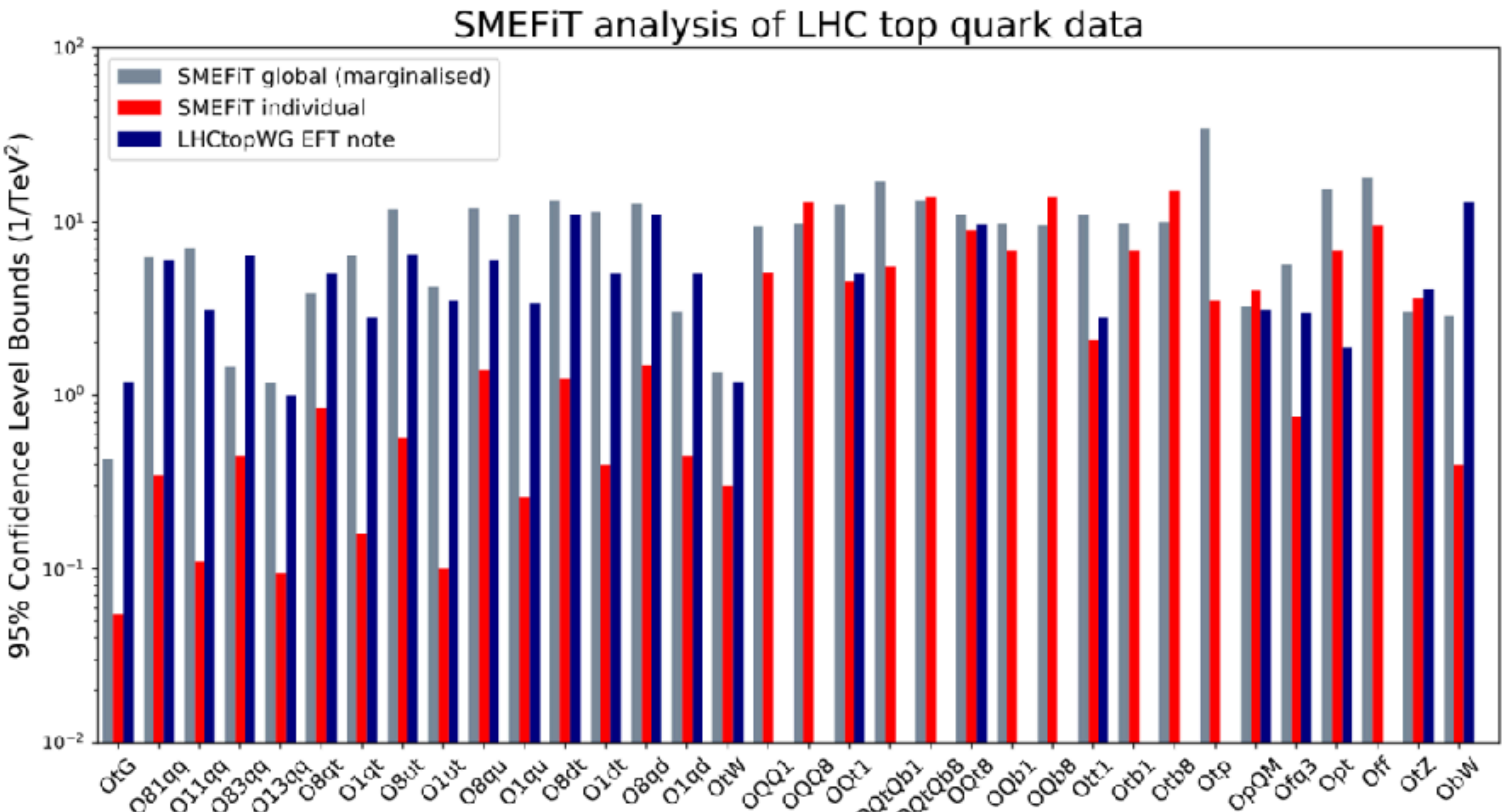

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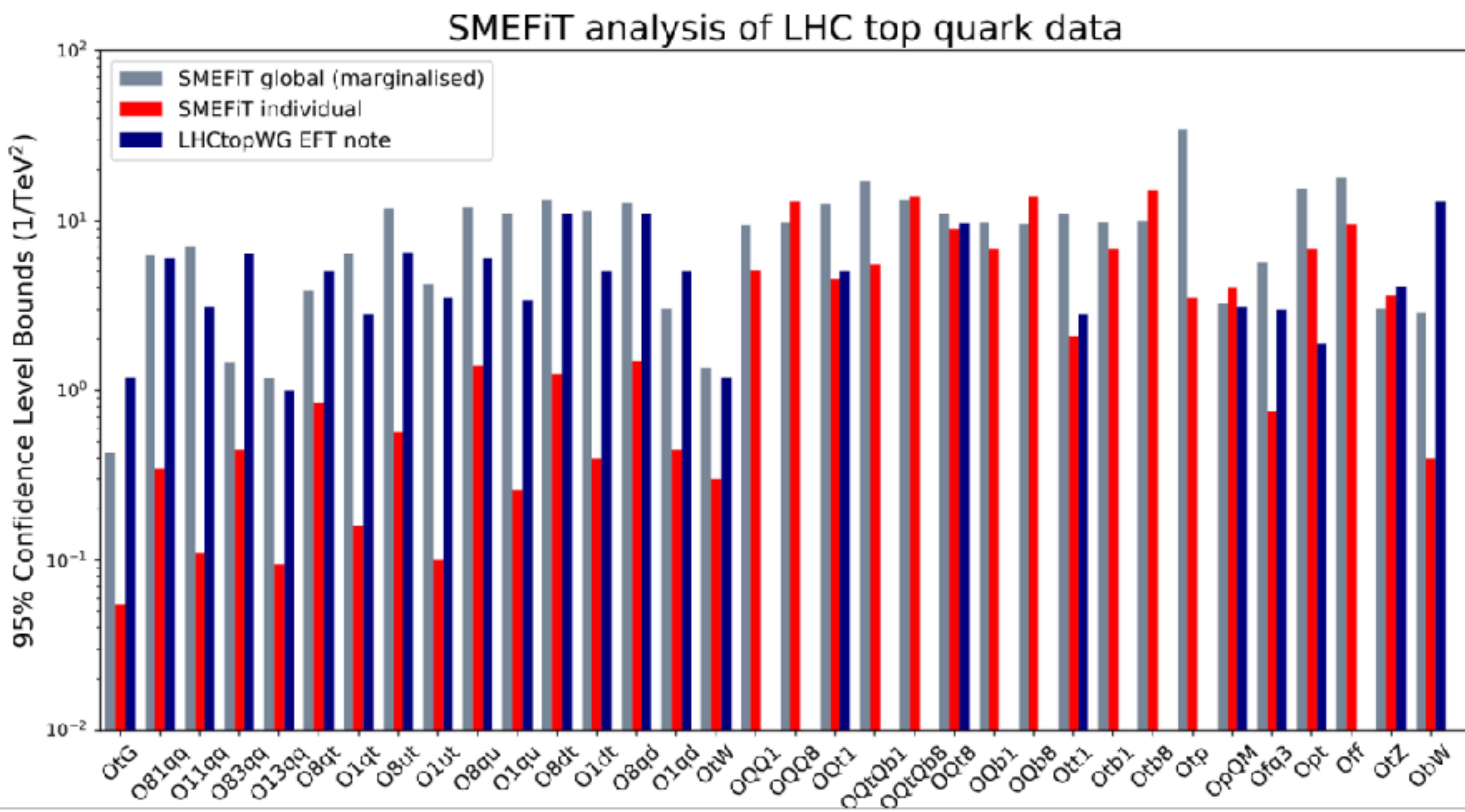

$\Lambda(c=1)$

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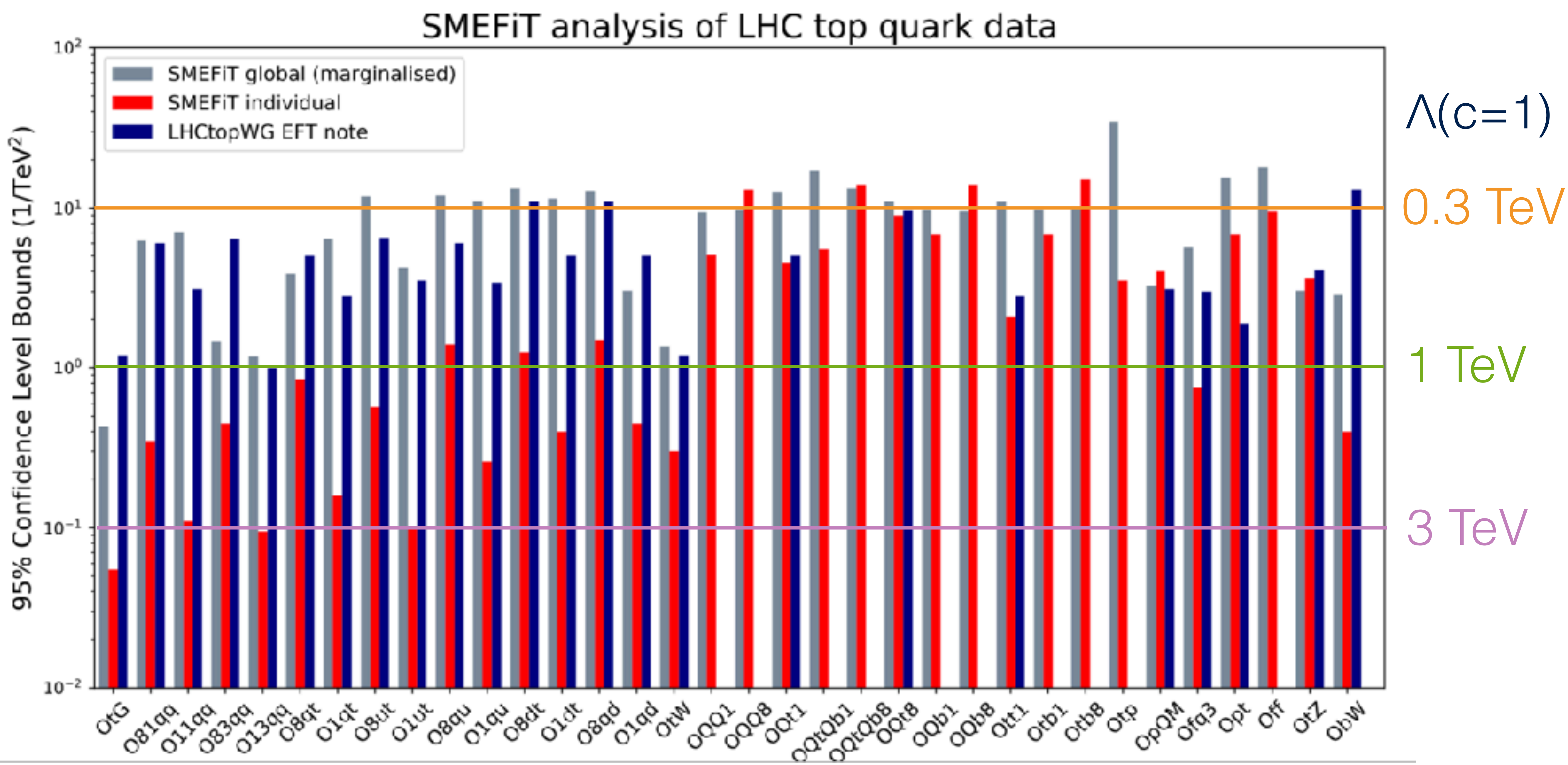
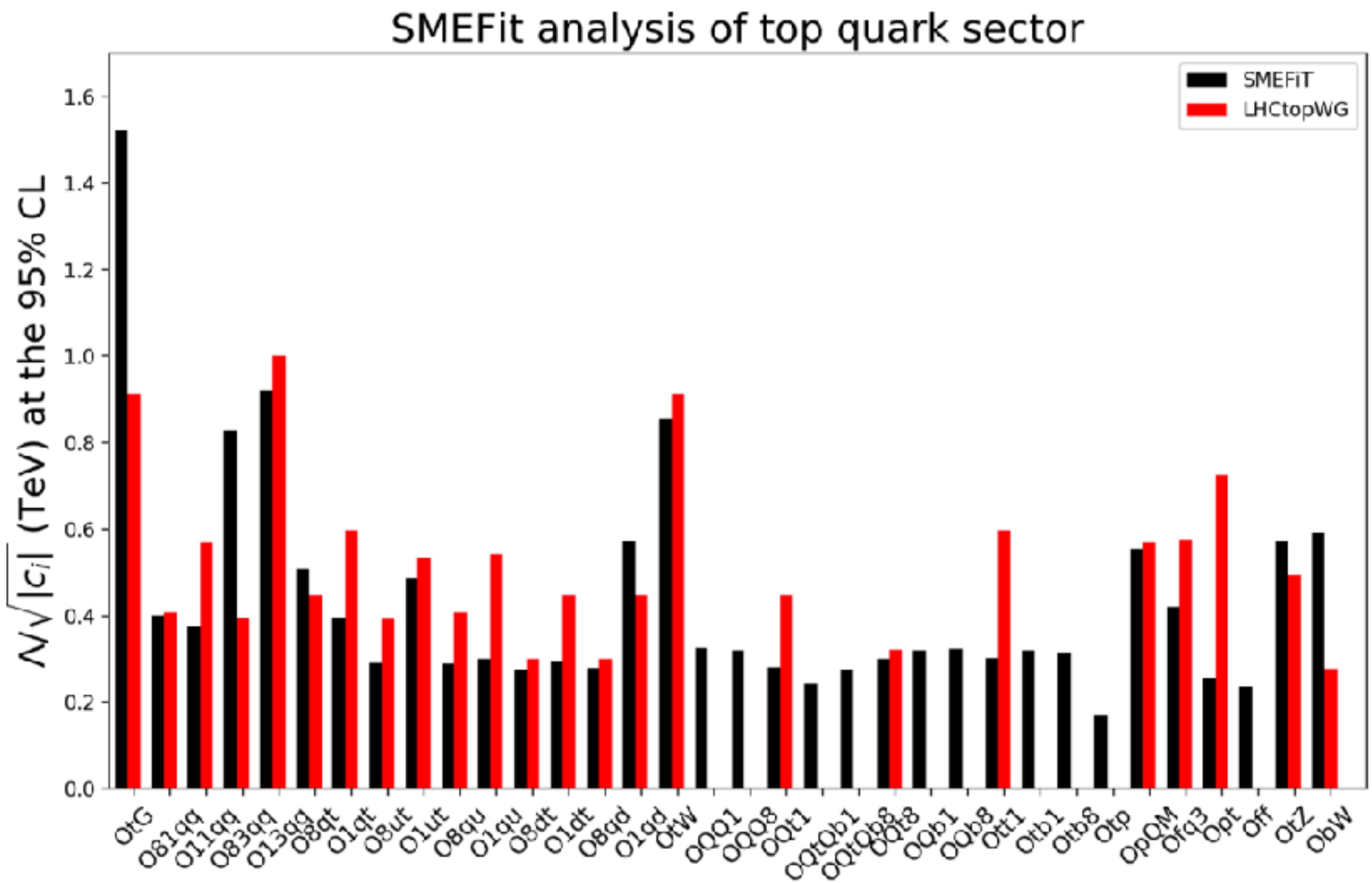


Energy reach



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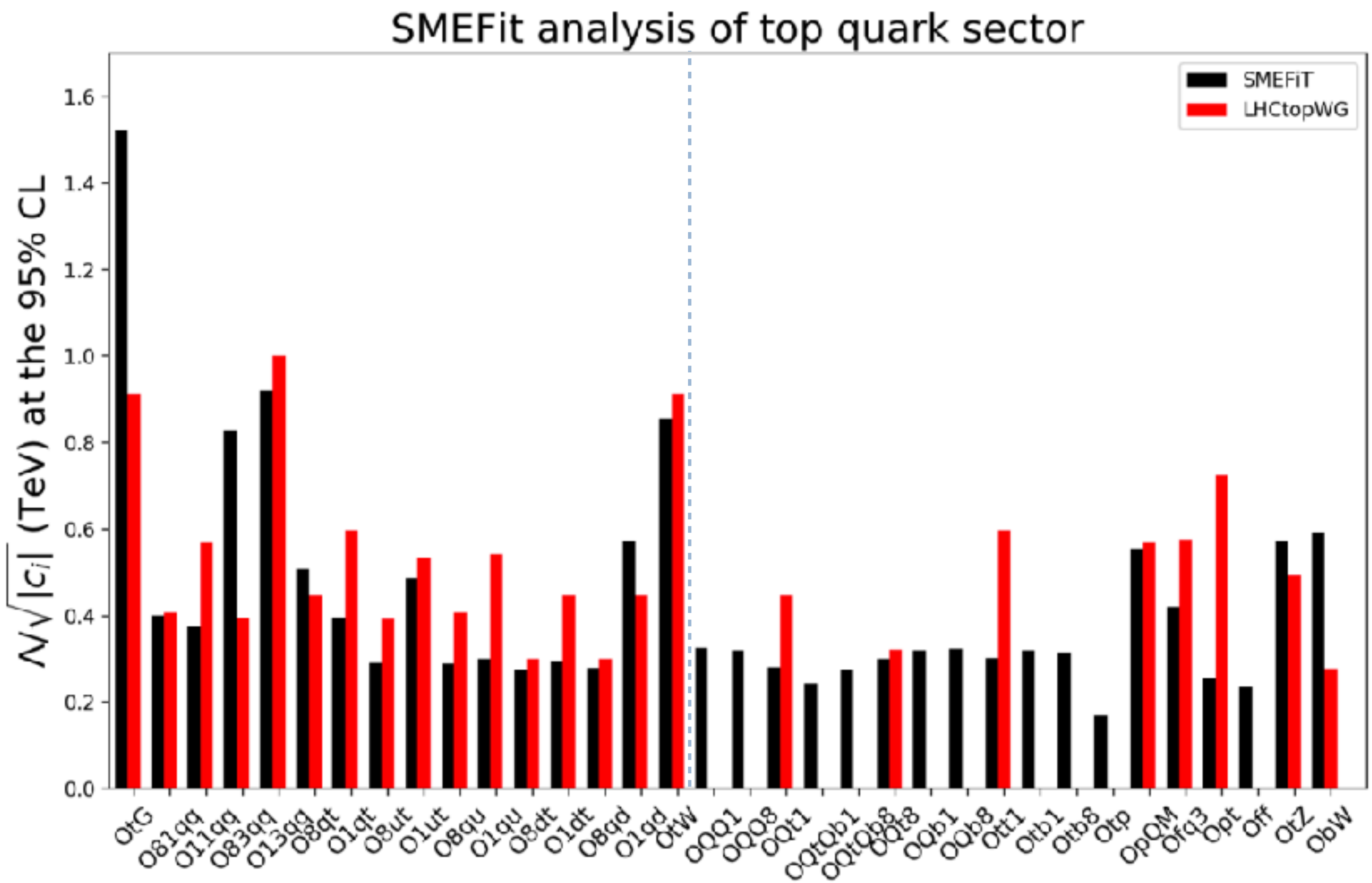

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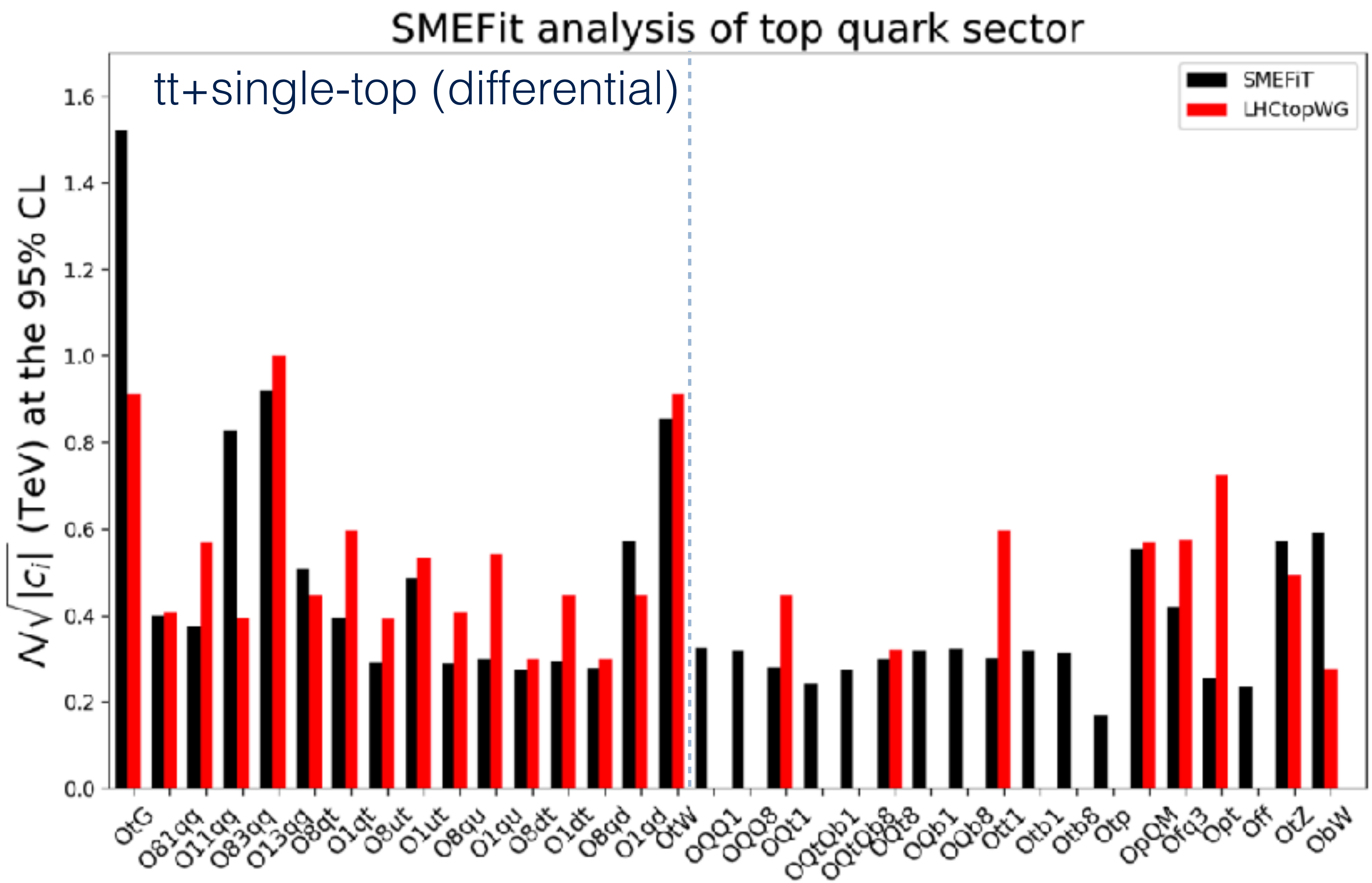

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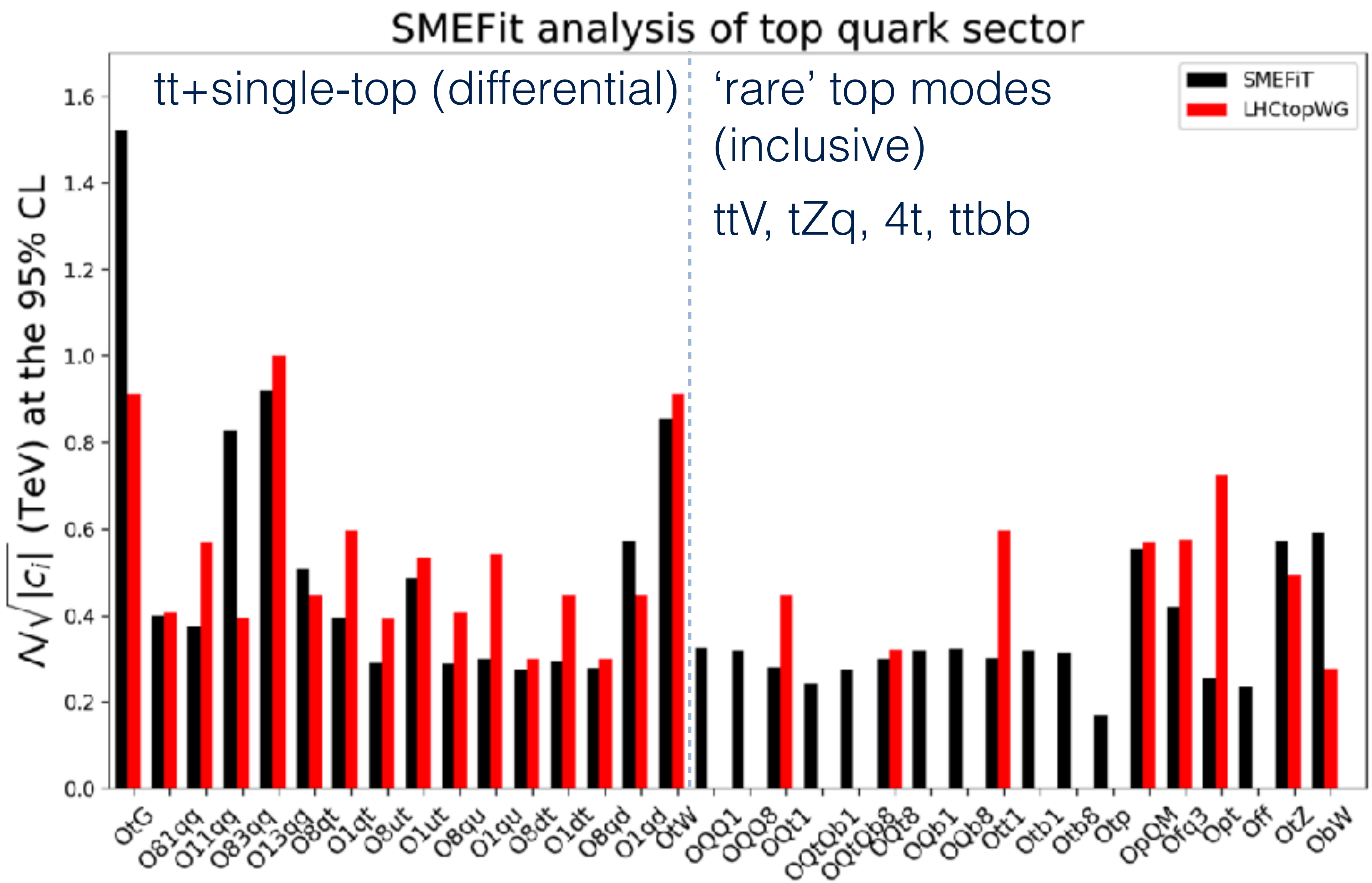

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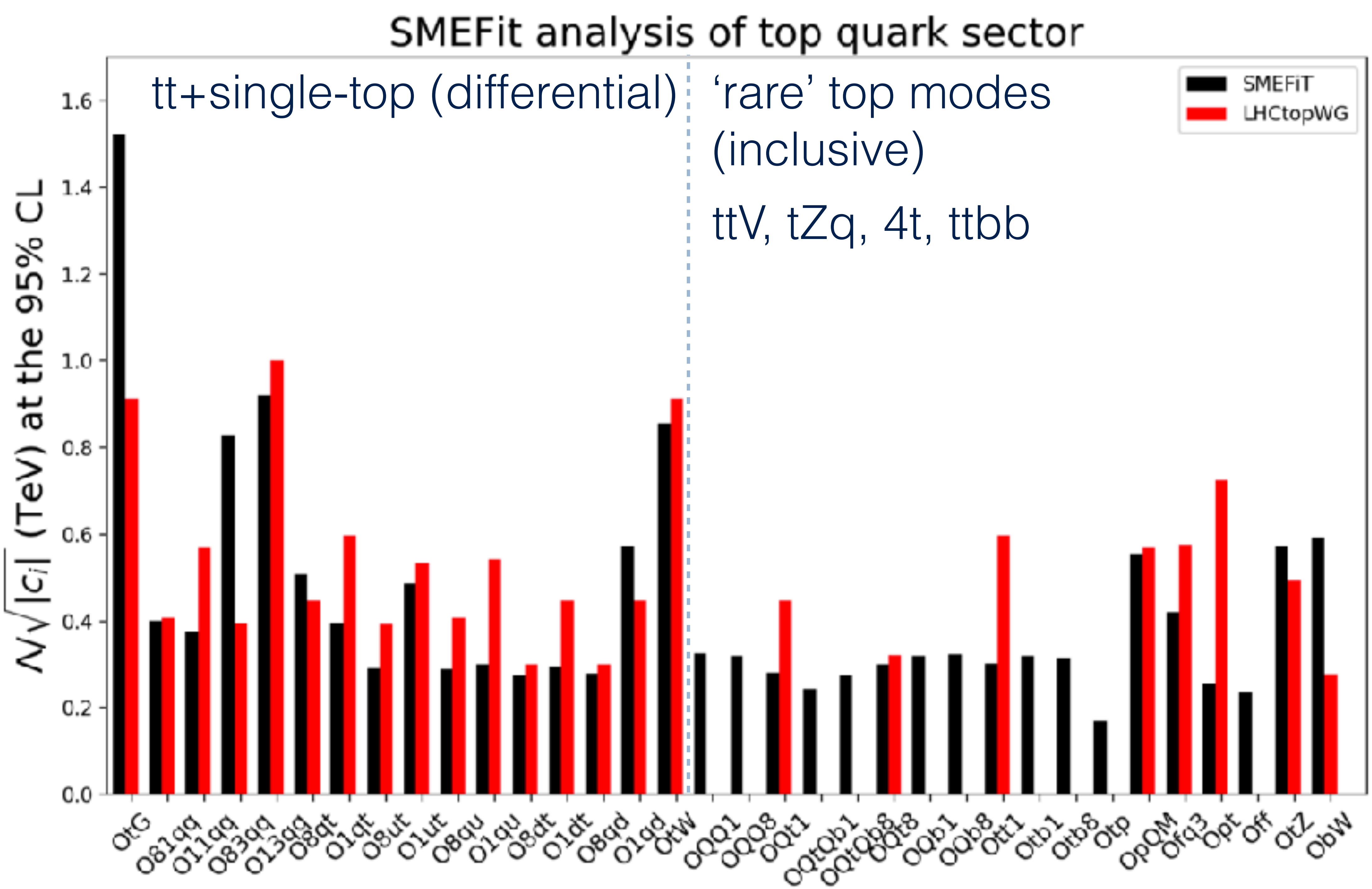

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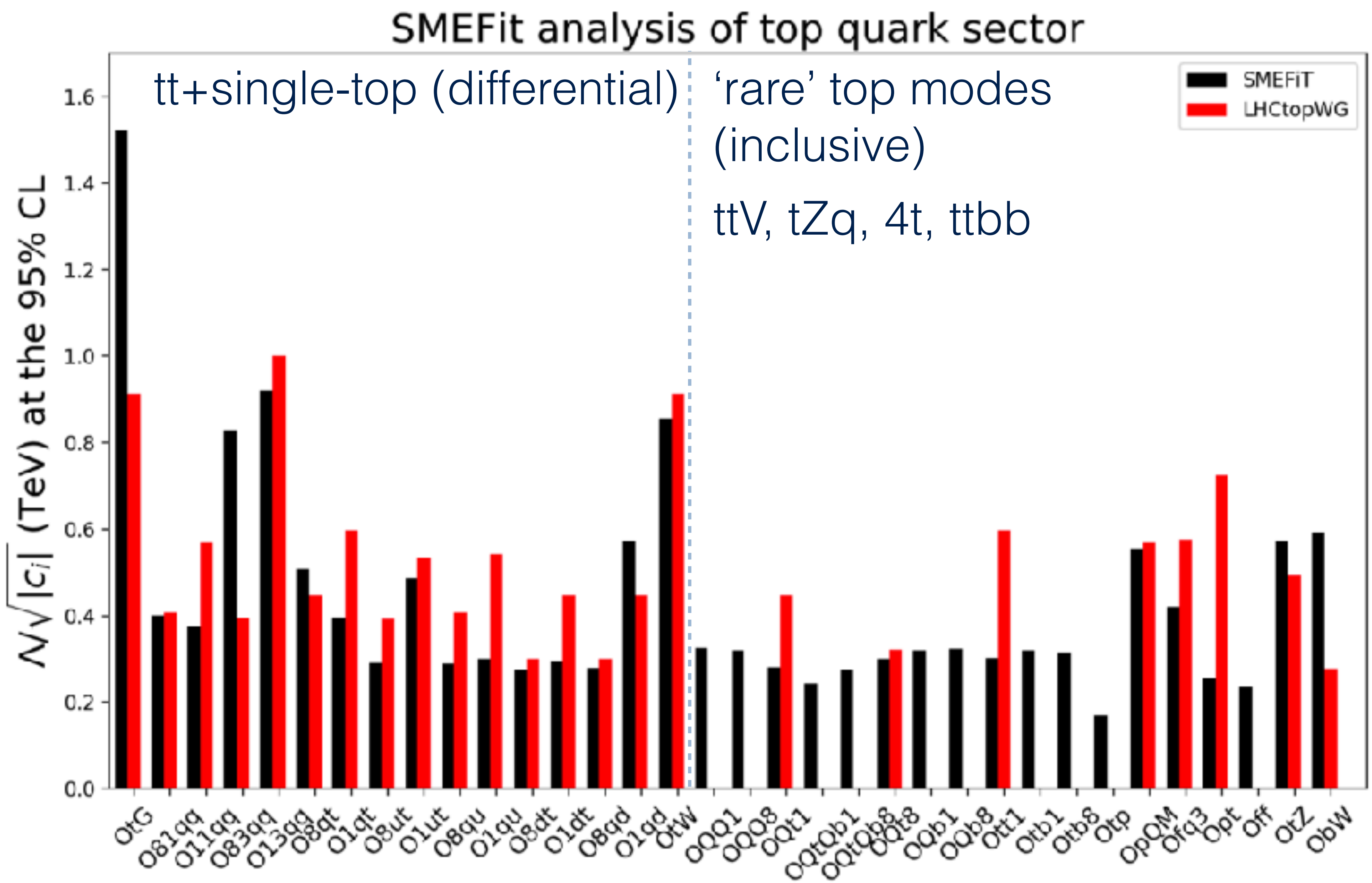

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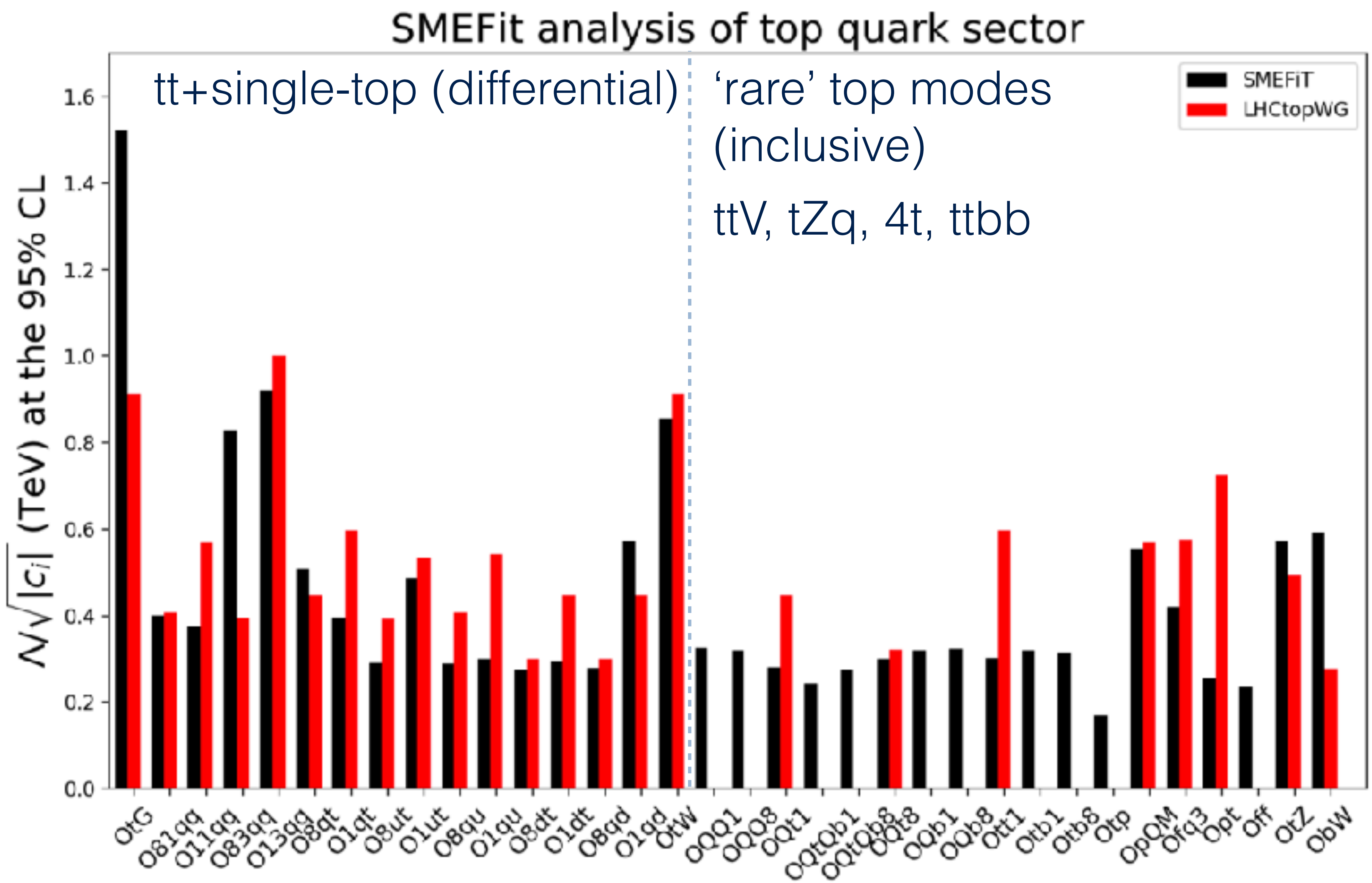

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≲ 150 fb^{-1}

↓

3000 fb^{-1}

Gauge/Higgs sector fit

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Recent global analysis of LEP + LHC Run I & II data

[Ellis et al.; JHEP 1806 (2018)146]

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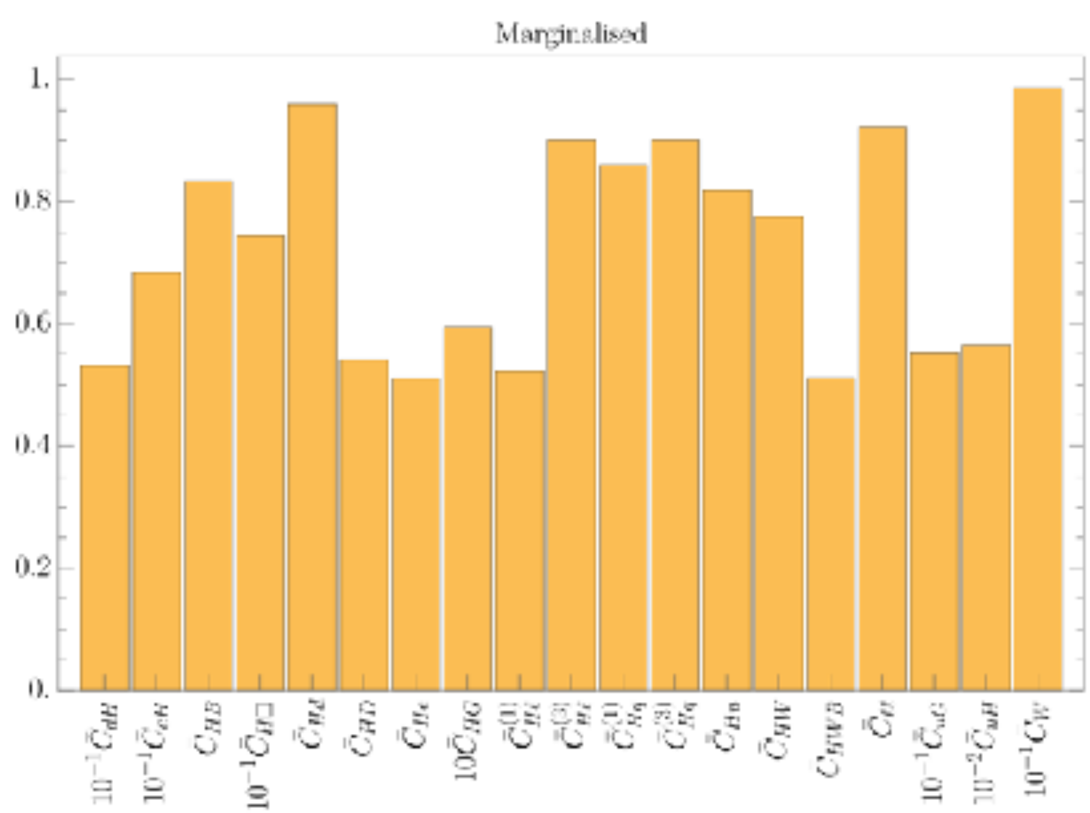

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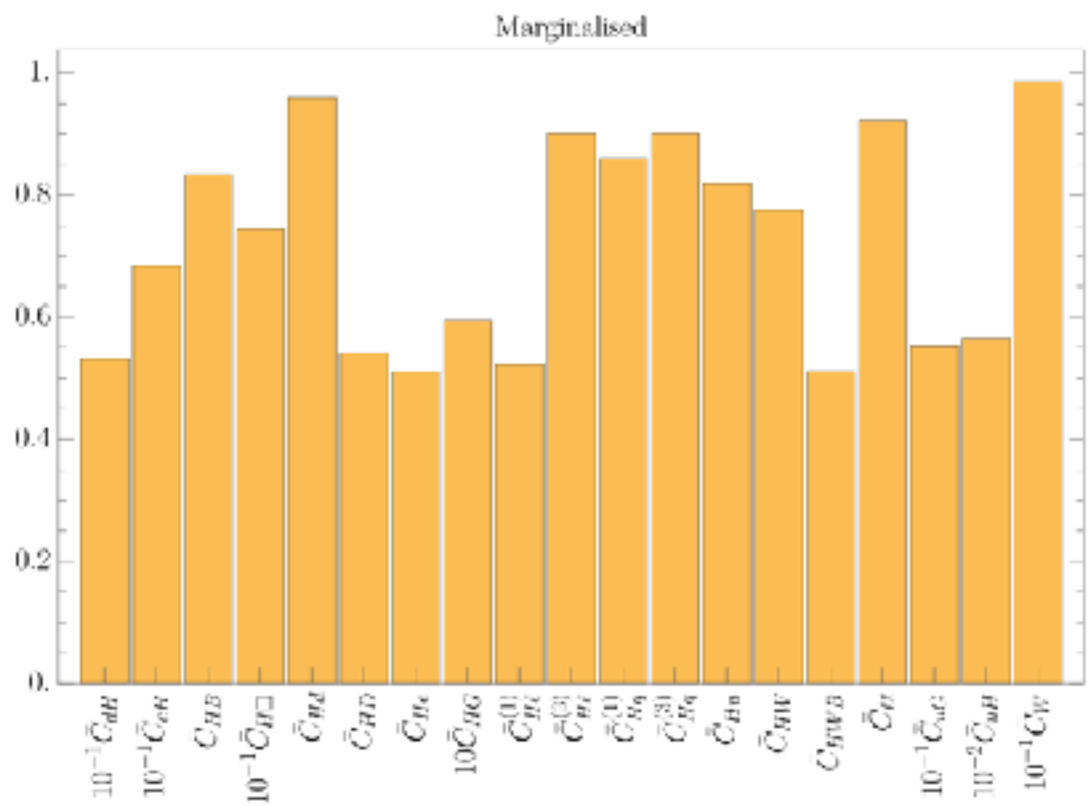

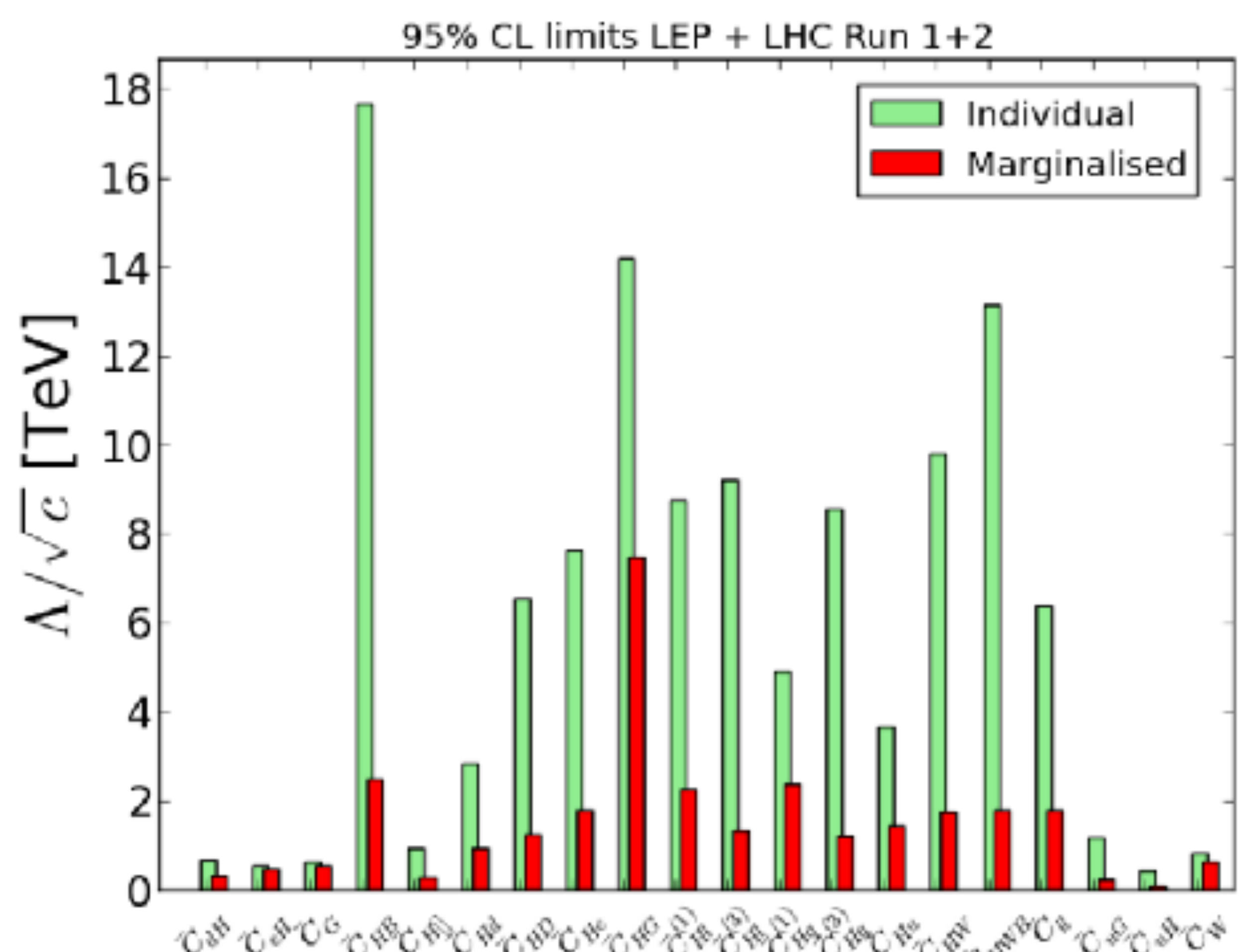

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Recent progress: top operators in EW loops

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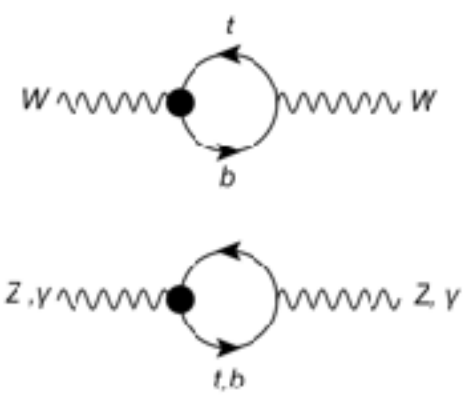

[Zhang, Greiner & Willenbrock; PRD 86 (2012) 014024]

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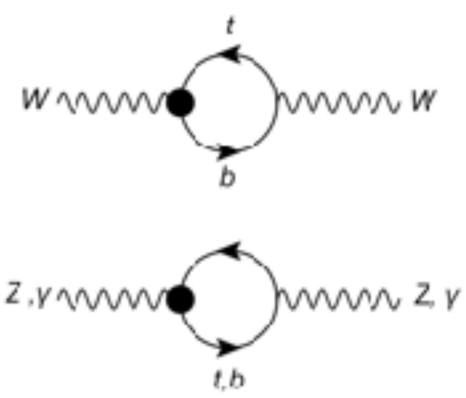

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EW Higgs production & decay

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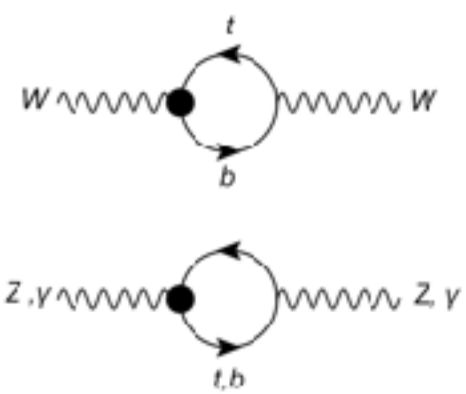

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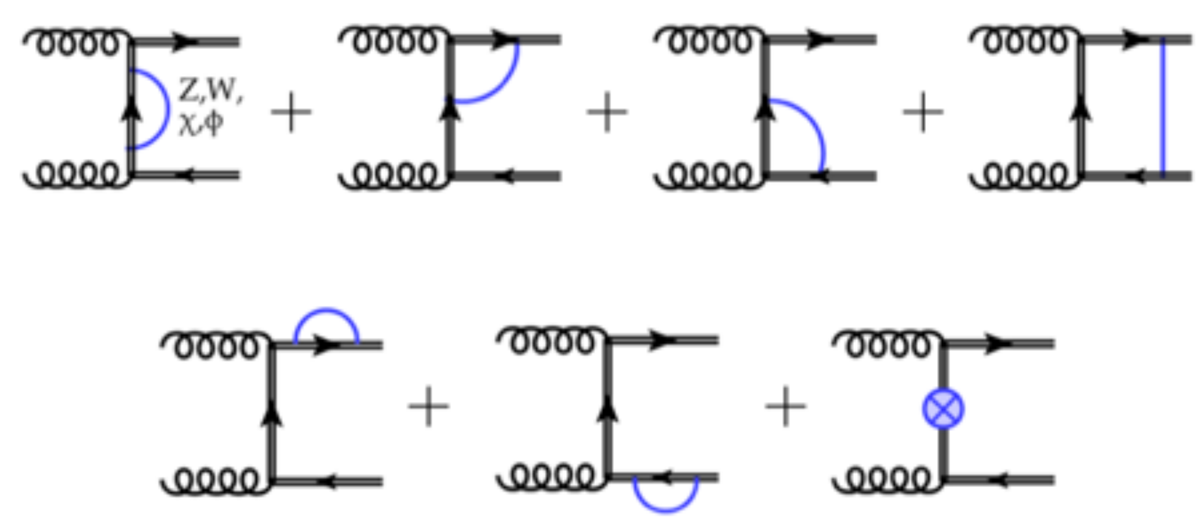
Top pair production



[Martini & Schulze ; arXiv:1911.11244]

Going forward

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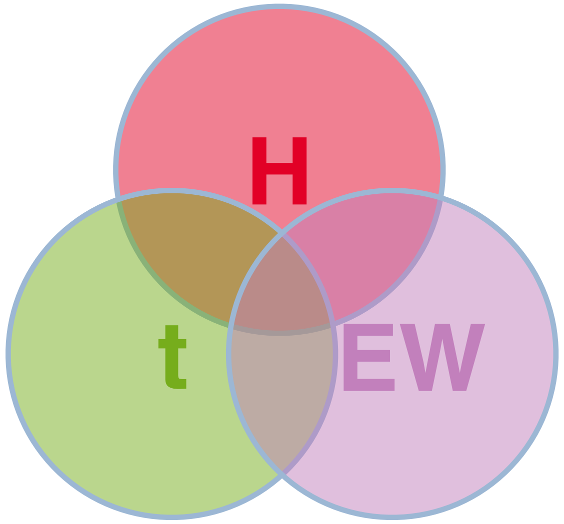

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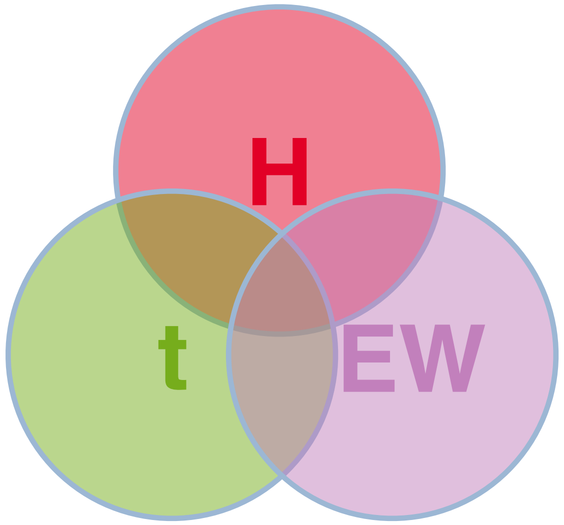

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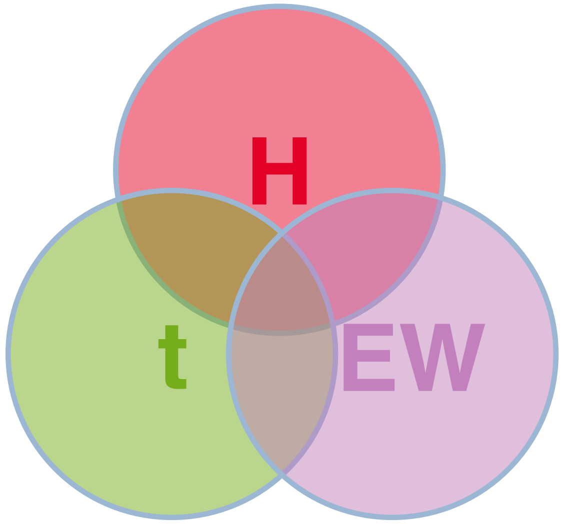

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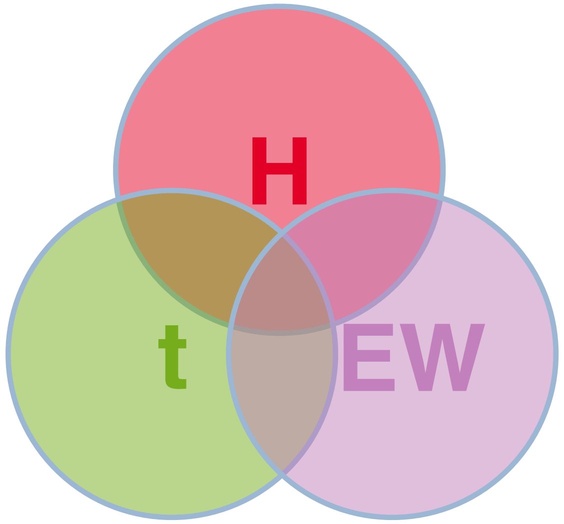

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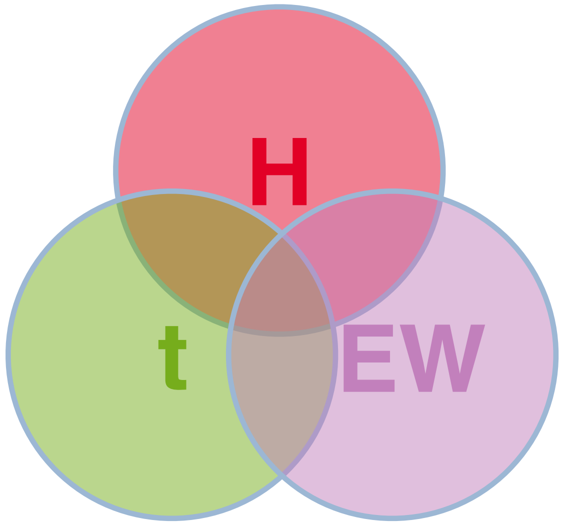

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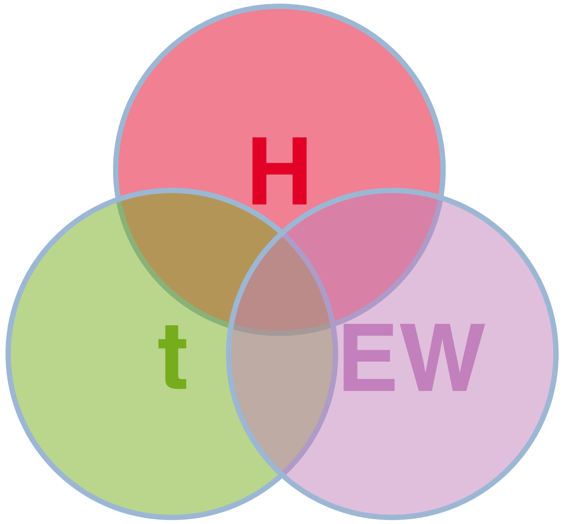

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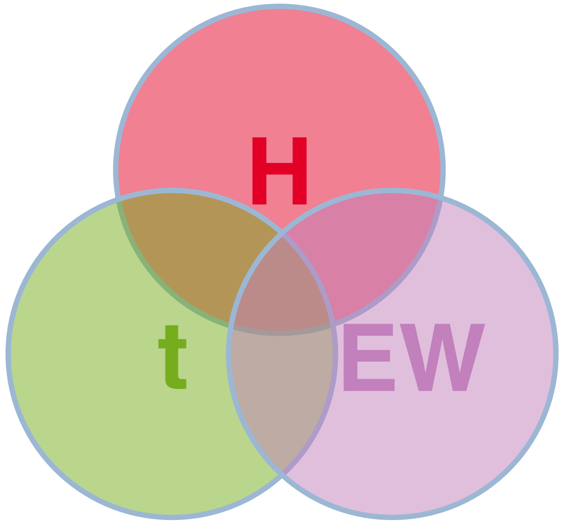

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Thorough programme of sensitivity studies

- Maximise energy growing effects - part II: high energy top quark scattering
- Identify new processes e.g. ttbb - part III: ttbb

Part II
High energy top/EW scattering

High-energy EW tops

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Can we do better?

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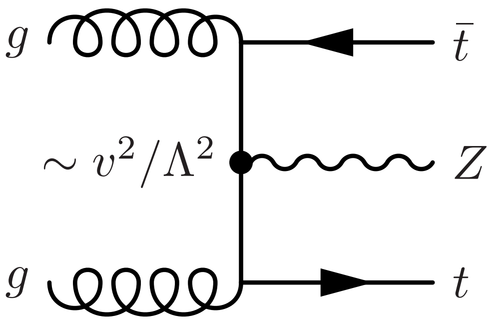

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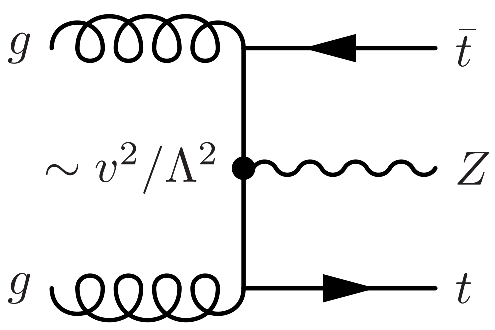

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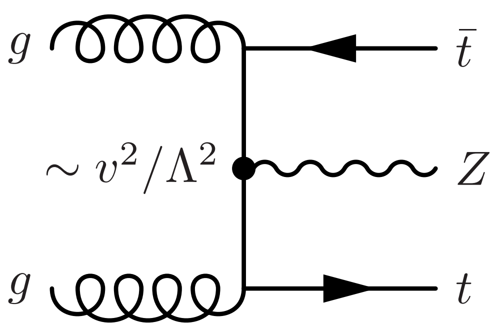

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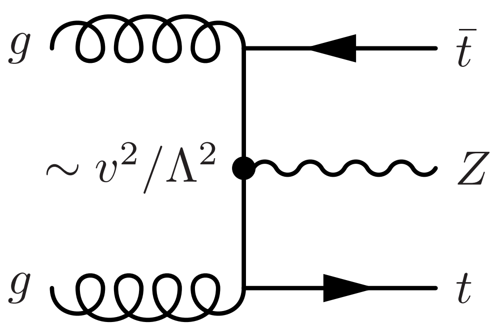

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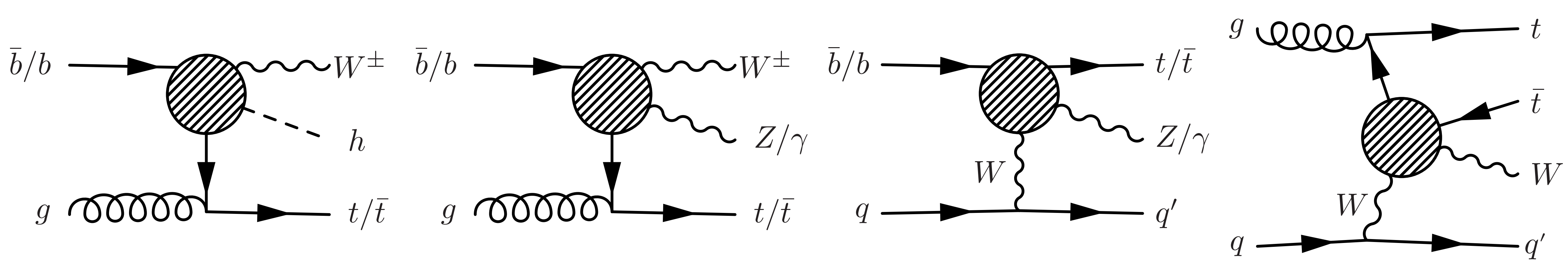

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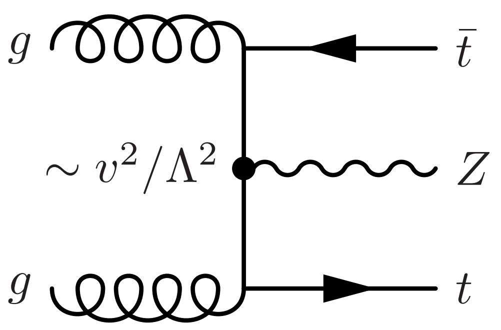

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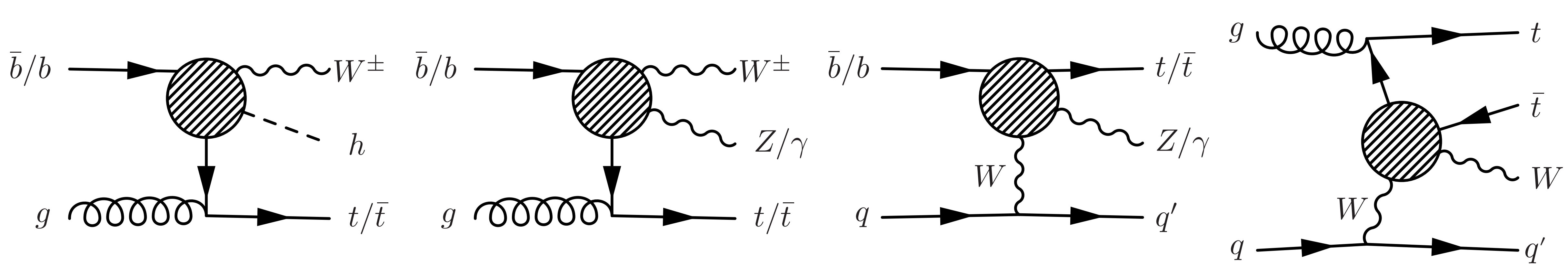

Embed top/EW 2→2 scattering amplitudes

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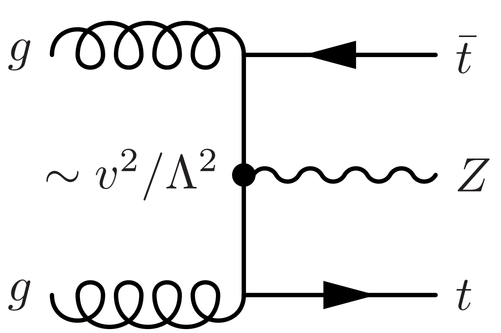

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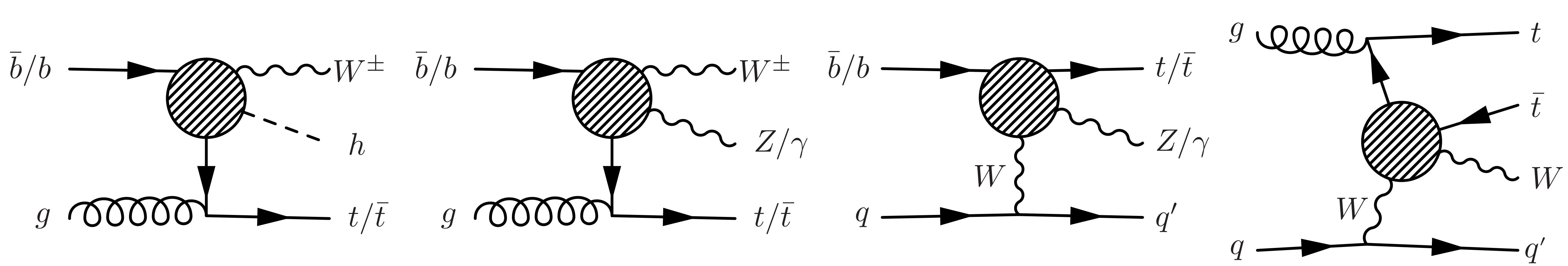

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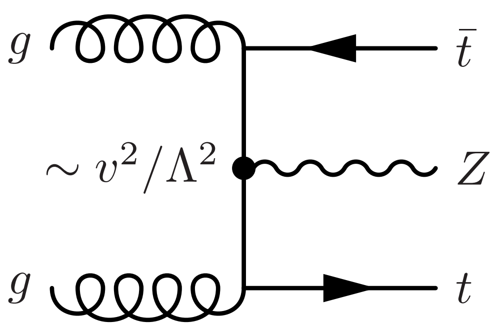

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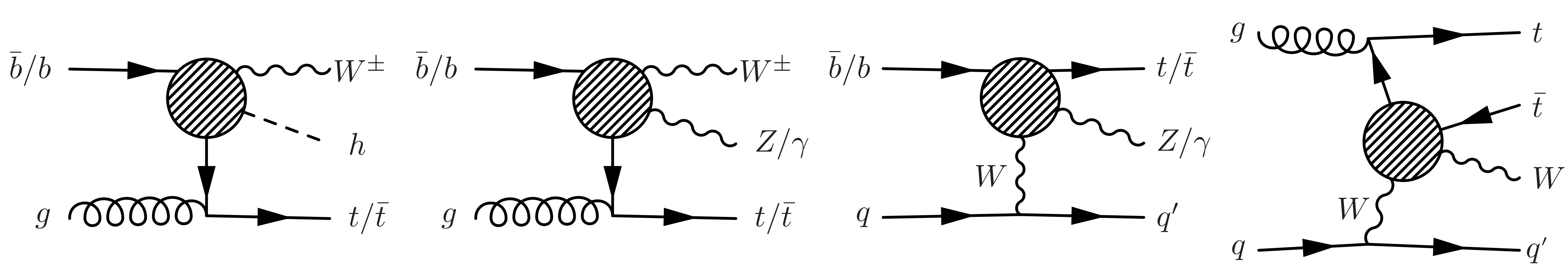

Embed top/EW 2→2 scattering amplitudes

- Probe mixed top/EW/Higgs interactions
- Unitarity violating behaviour (energy growth) ∝ vE, E^2

Analogous to V_L scattering

Scattering unitarity

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$W_L\, W_L \rightarrow W_L\, W_L$: Unitarity 'cancellations' in the SM

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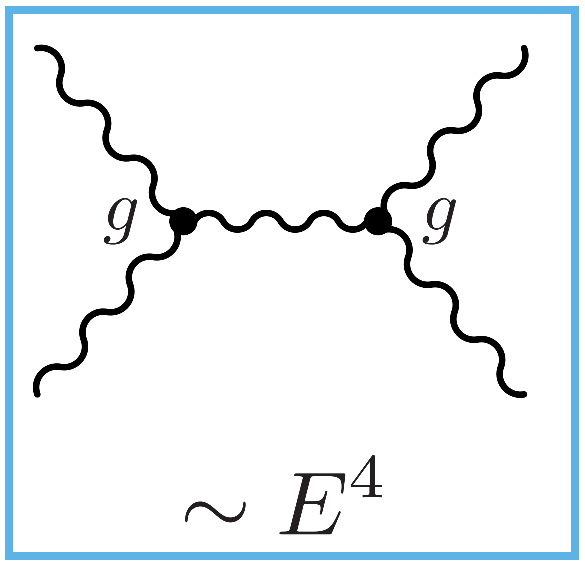

triple-gauge

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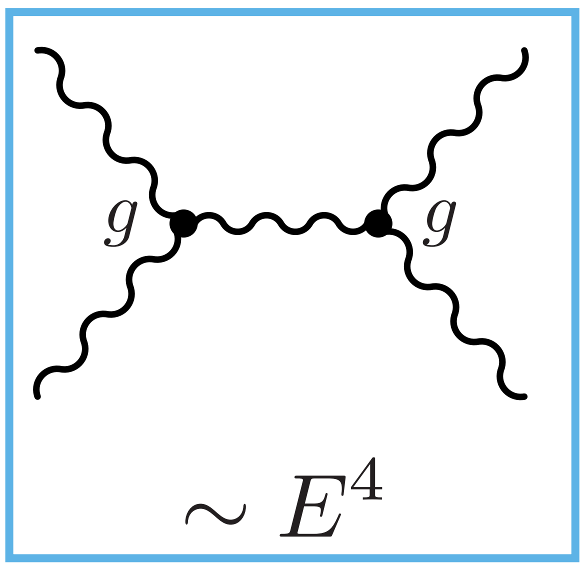

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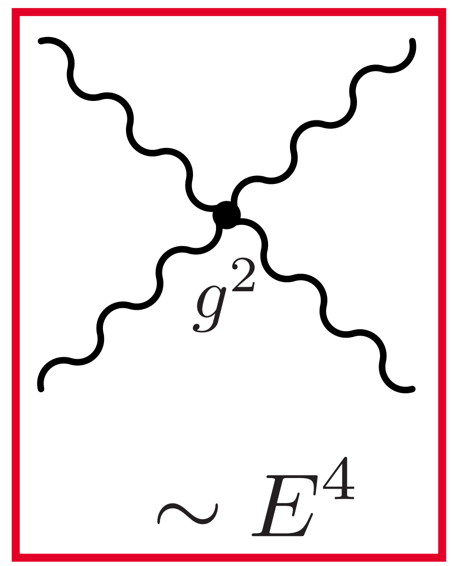
$+$



quartic

$= \sim E^2$

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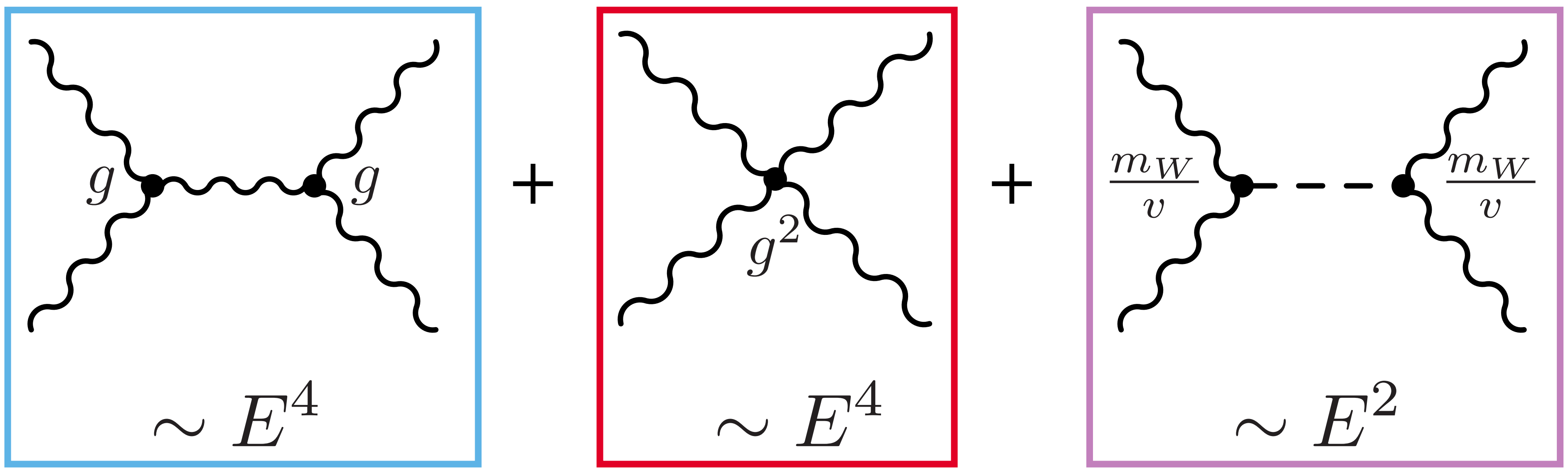

$= \boxed{\sim E^0}$

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EWSB

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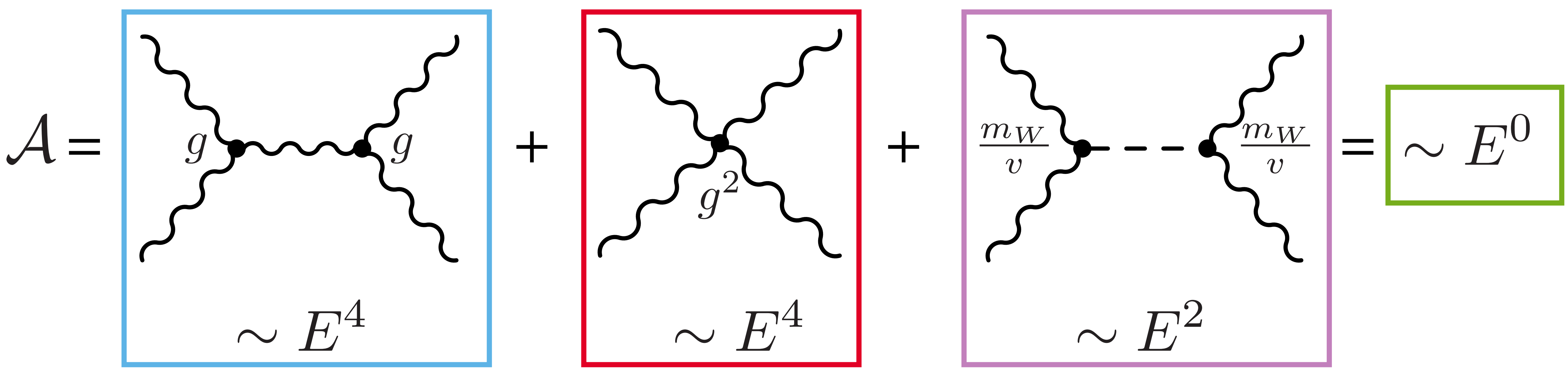

triple-gauge | quartic | EWSB

Diboson (TGC) | VBS (TGC, QGC) | EW Higgs prod./decay

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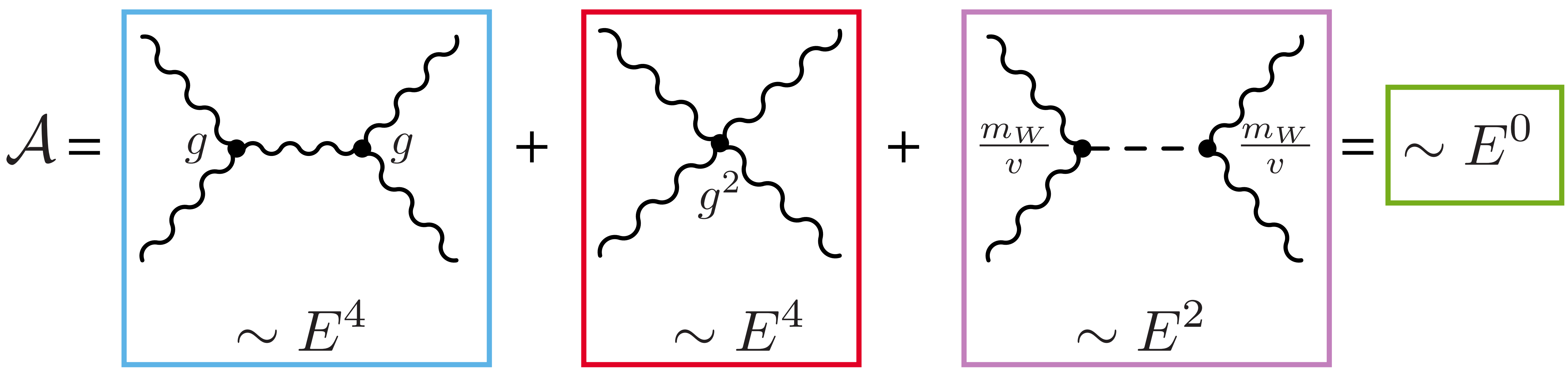

triple-gauge quartic EWSB

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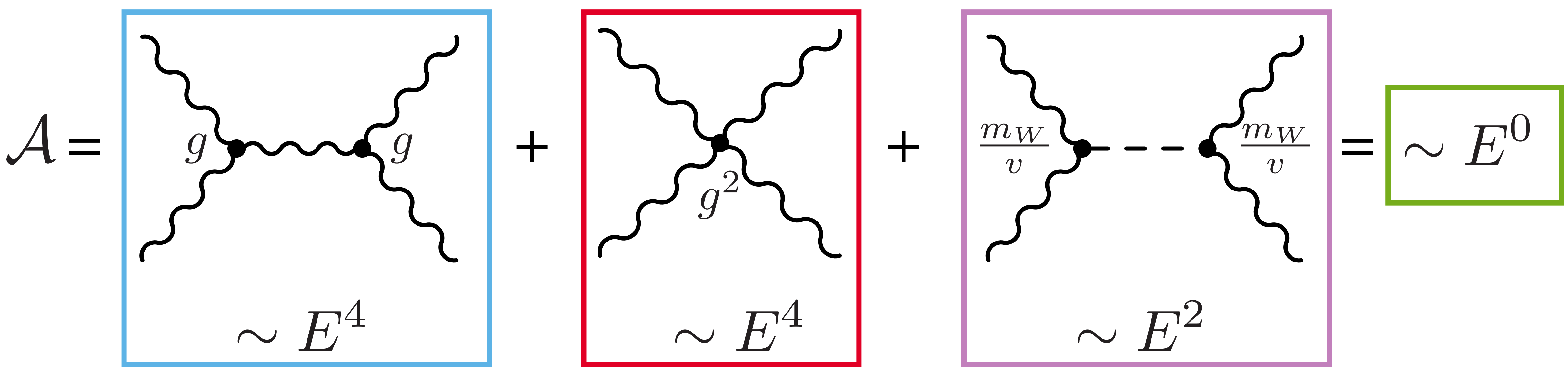

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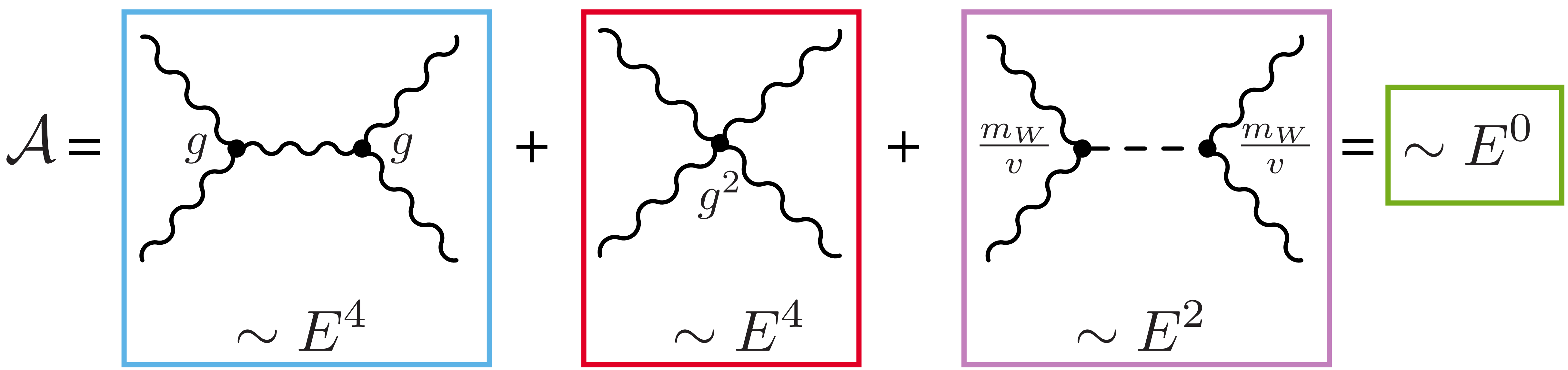

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- Cancellations are a feature of gauge invariance & EWSB mechanism
- E-growth: theory has limited validity range → heavy new physics

Tops and unitarity

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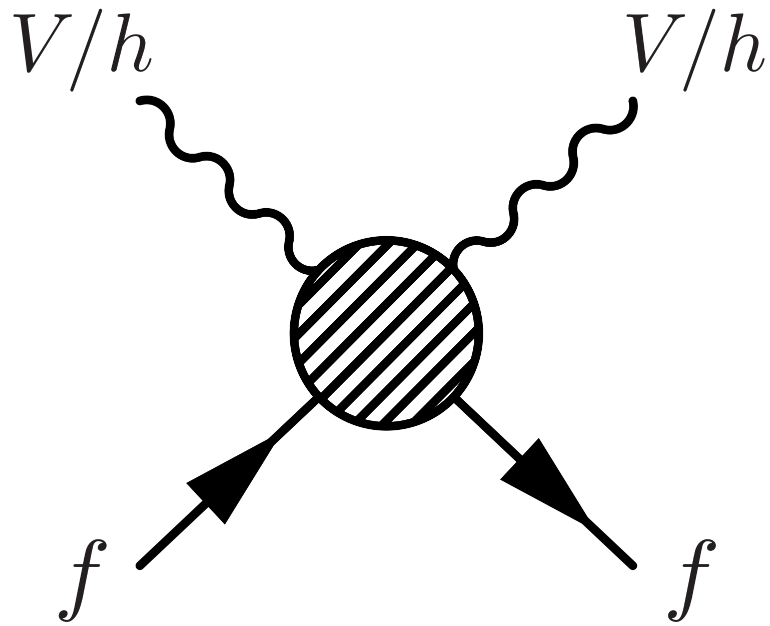
Analogous behaviour in scatterings involving fermions



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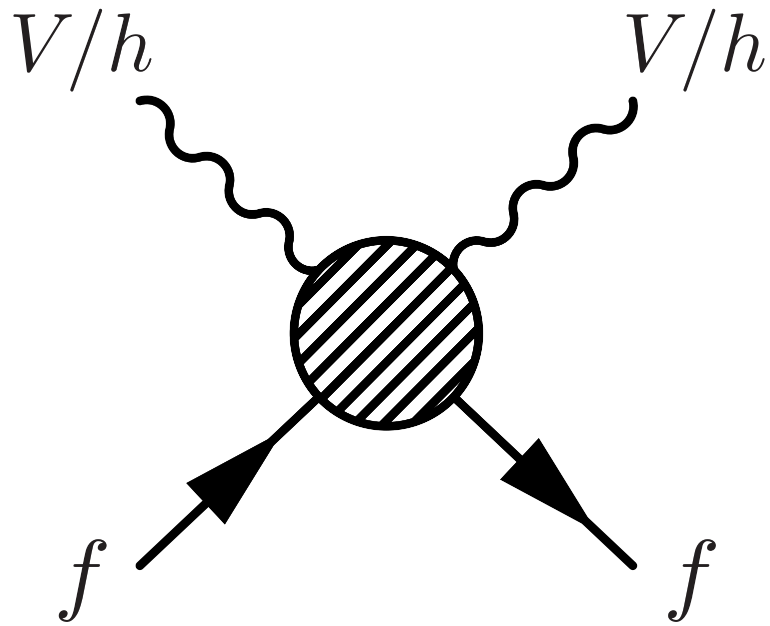

$$\mathcal{A} \sim E^2 \to E^0$$ gauge interactions

Tops and unitarity

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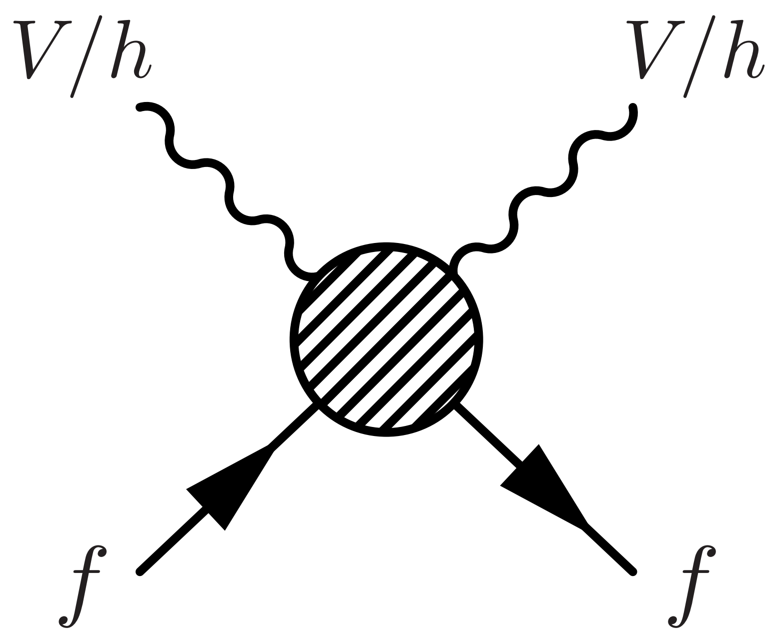

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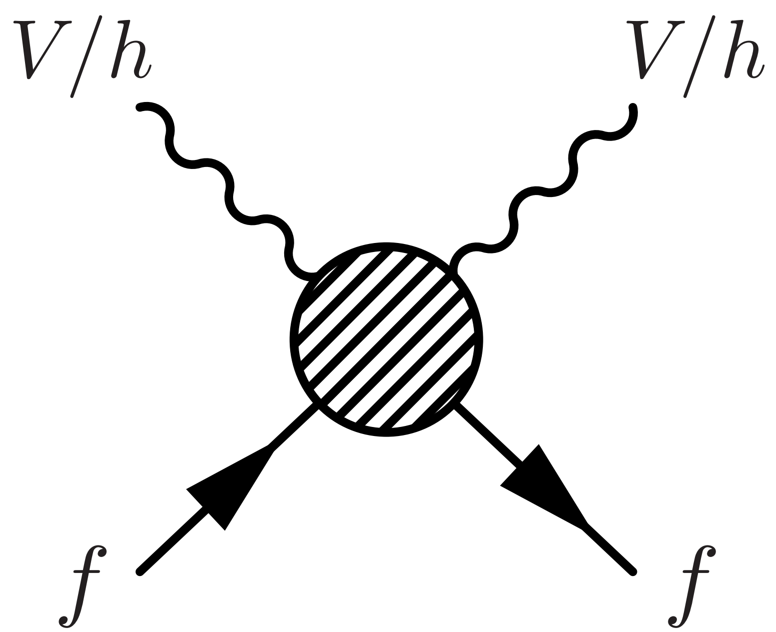

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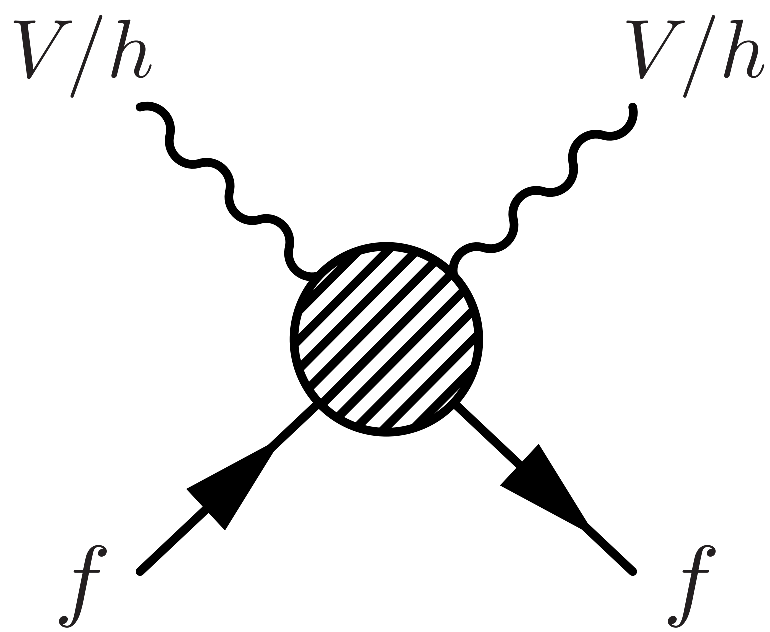

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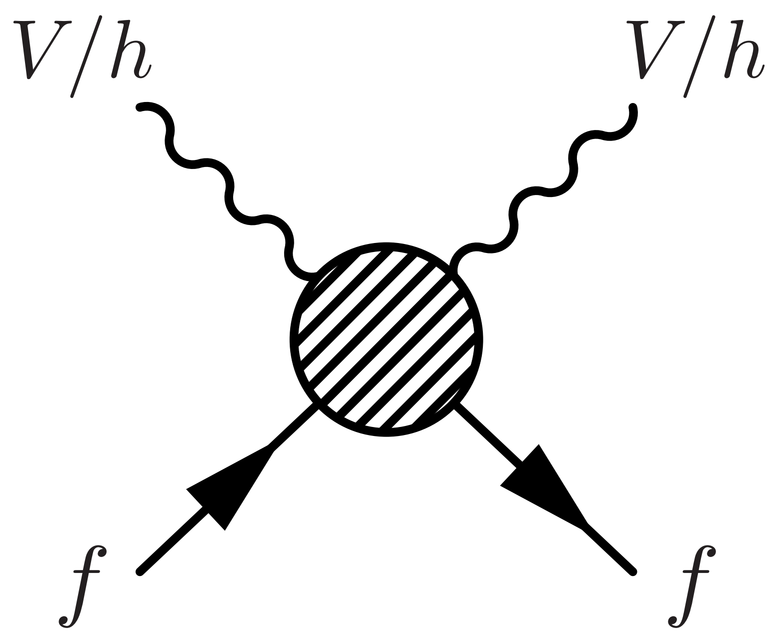

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→ **SM Effective Field Theory**

Energy growth in SMEFT

Energy growth in SMEFT

Dim-6

$$\mathcal{A} \sim \mathcal{A}_{SM}\left(1 + c_i\frac{v^2}{\Lambda^2} + c_j\frac{v\,E}{\Lambda^2} + c_k\frac{E^2}{\Lambda^2}\right)$$

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[Farina et al.; PLB 772 (2017) 210-215]

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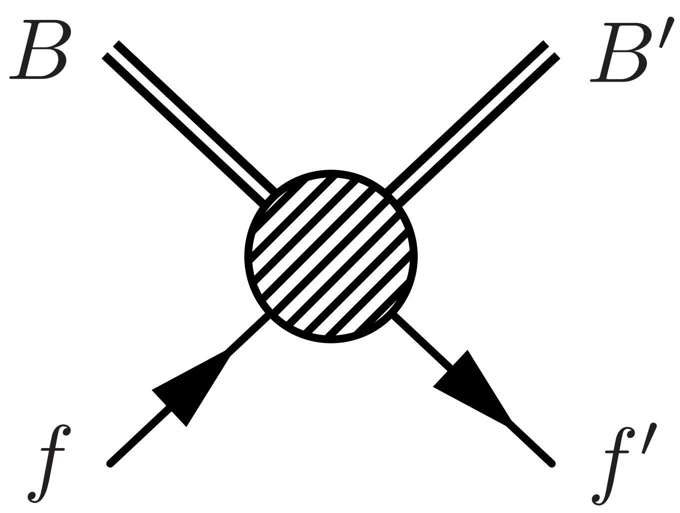
Phenomenologists job: find and exploit them

[Mantani, Maltoni & KM; JHEP 10 (2019) 004]
[Dror et al.; JHEP 01 (2016) 071]

Our study

Our study



	Single-top	Two-top ($t\bar{t}$)
w/o Higgs	$b\,W \to t\,(Z/\gamma)$	$t\,W \to t\,W$ $t\,(Z/\gamma) \to t\,(Z/\gamma)$
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Considered 10, 2 → 2 scattering amplitudes with ≥ one top

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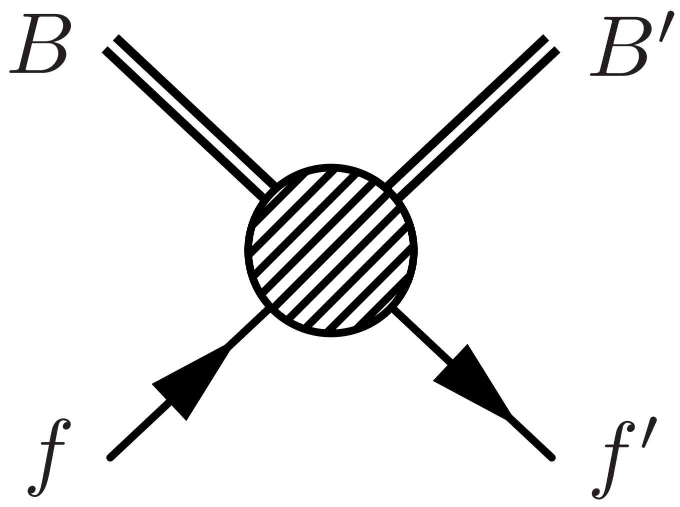

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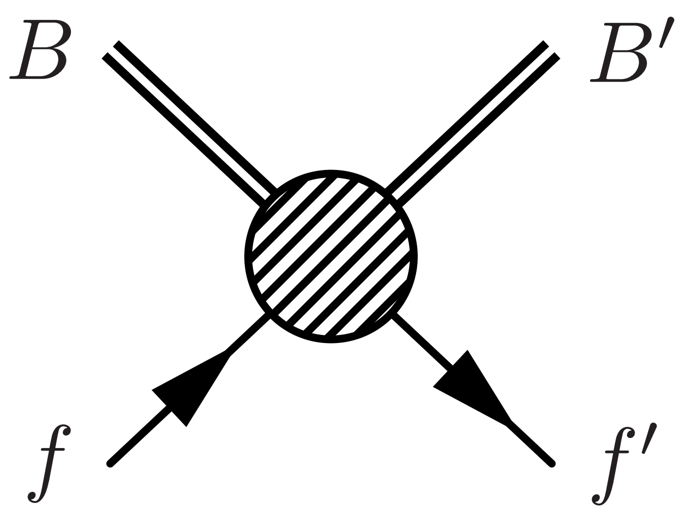

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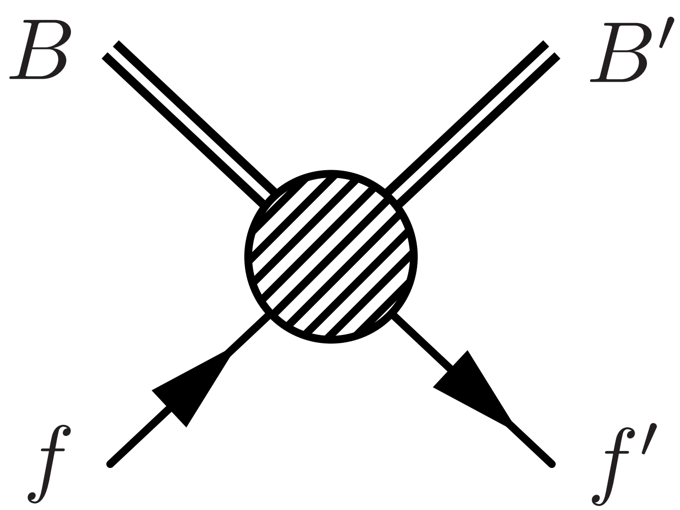

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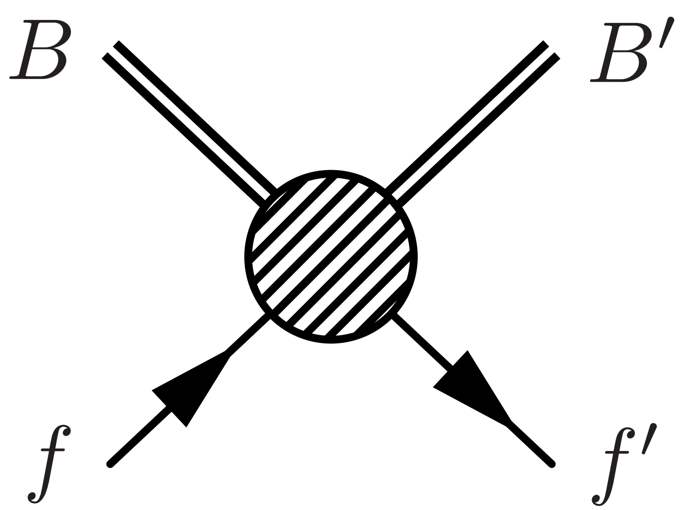

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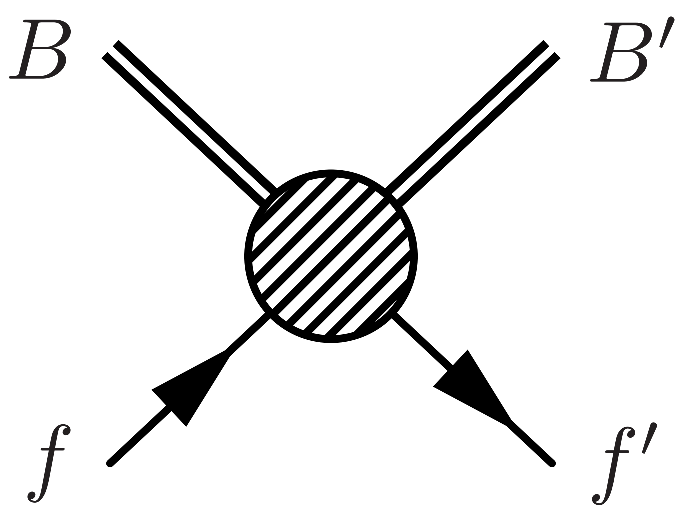

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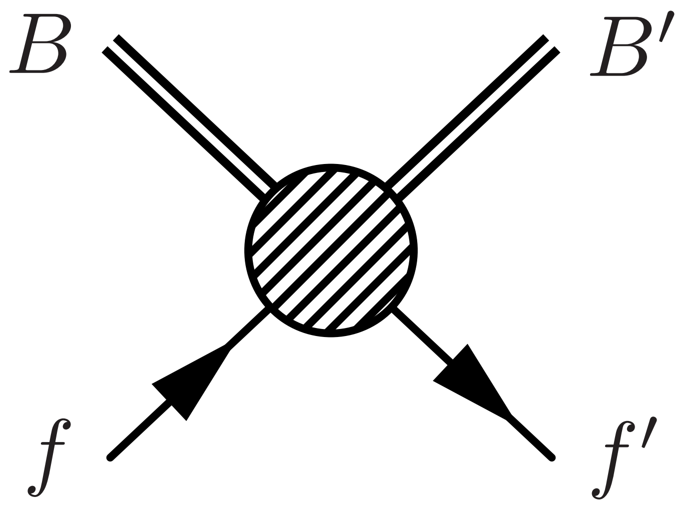

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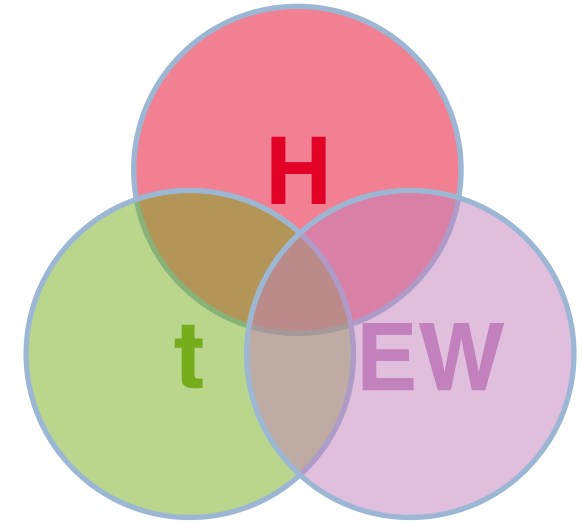
Interesting processes: 'rare' EW top production

tZj, tWj, tHj, tZW, tHW, ttWj, VBF-tt, ttXY…

SMEFT for EWSB



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$\mathcal{O}_{\varphi W}$	$\left(\varphi^{\dagger}\varphi - \frac{v^2}{2}\right) W_{I}^{\mu\nu}\, W^{I}_{\mu\nu}$	$\mathcal{O}_{tW}$	$i(\bar{Q}\sigma^{\mu\nu}\, \tau_{I}\, t)\, \tilde{\varphi}\, W^{I}_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^{\dagger}\varphi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$	$\mathcal{O}_{tB}$	$i(\bar{Q}\sigma^{\mu\nu}\, t)\, \tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^{\dagger}\tau_{I}\varphi)\, B^{\mu\nu}W^{I}_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i(\varphi^{\dagger}\overleftrightarrow{D}_{\mu}\, \tau_{I}\varphi)(\bar{Q}\, \gamma^{\mu}\, \tau^{I} Q)$
$\mathcal{O}_{\varphi D}$	$(\varphi^{\dagger}D^{\mu}\varphi)^{\dagger}(\varphi^{\dagger}D_{\mu}\varphi)$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i(\varphi^{\dagger}\overleftrightarrow{D}_{\mu}\, \varphi)(\bar{Q}\, \gamma^{\mu}\, Q)$
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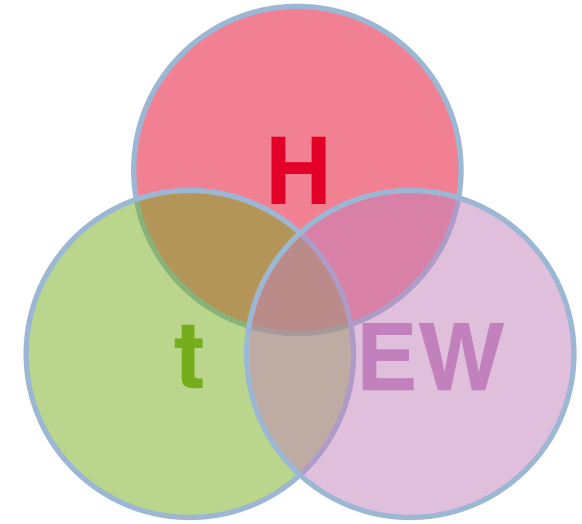

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Relevant dim-6 operators for EW-top scattering

- Warsaw basis with $U(2)_Q$ x $U(2)_u$ x $U(3)_d$ x $U(3)_L$ x $U(3)_e$ flavor symmetry

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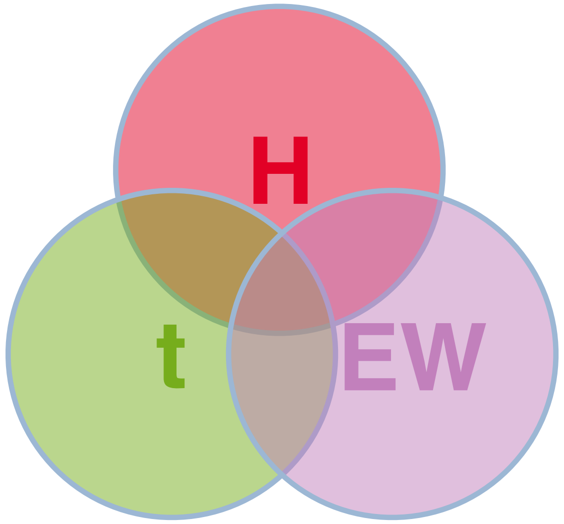

Bosonic

$\mathcal{O}_W$	$\varepsilon_{IJK}\, W^I_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$
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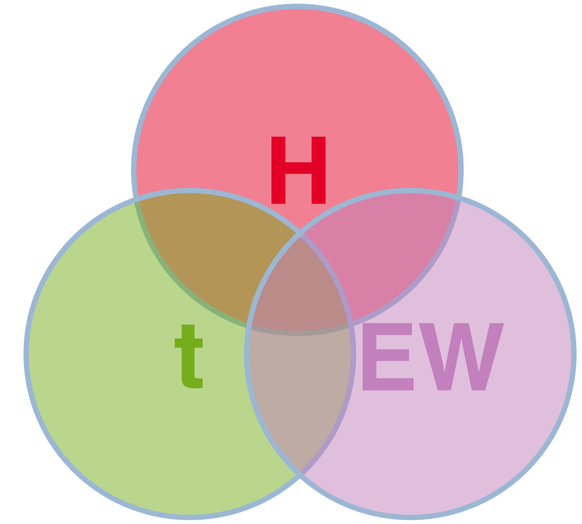

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$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{t}\, \gamma^\mu\, t)$	
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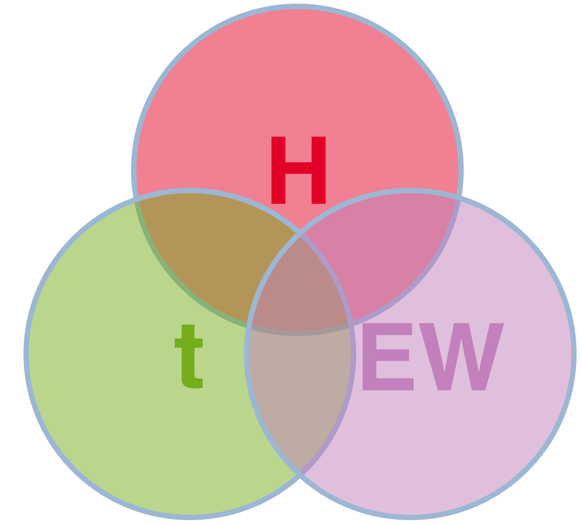

↓more constrained↓

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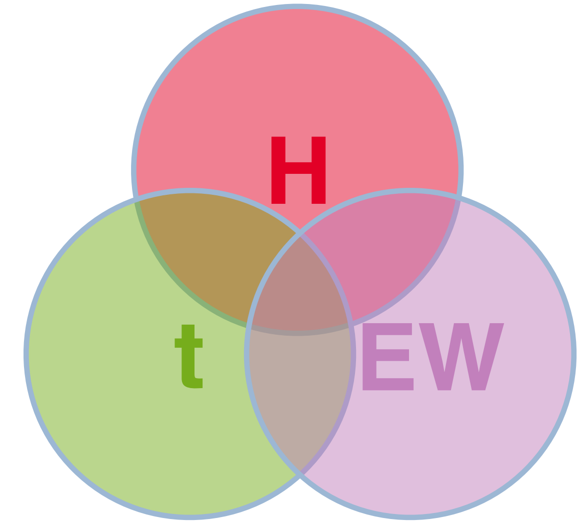
			$\mathcal{O}_{\varphi tb}$	$i\big(\tilde{\varphi}\, D_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, b\big) + \text{h.c.}$	RHCC

Relevant dim-6 operators for EW-top scattering

- Warsaw basis with $U(2)_Q$ x $U(2)_u$ x $U(3)_d$ x $U(3)_L$ x $U(3)_e$ flavor symmetry
- Bosonic + top specific operators

SMEFT for EWSB



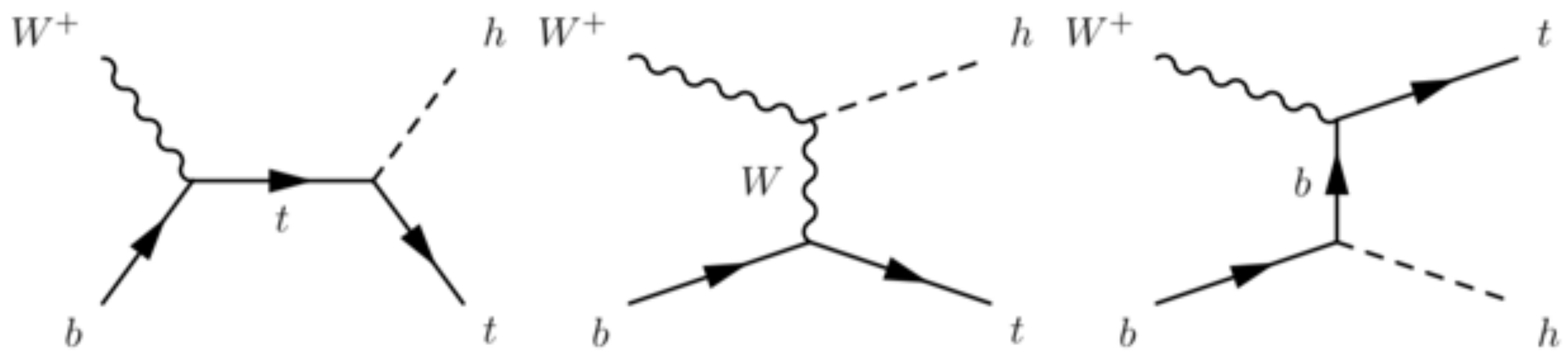
	↓more constrained↓		↓less constrained↓		
Bosonic	$\mathcal{O}_{W}$	$\varepsilon_{IJK}\, W^{I}_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^{\dagger}\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	Yukawa
	$\mathcal{O}_{\varphi W}$	$\left(\varphi^{\dagger}\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_{I}\, W^{I}_{\mu\nu}$	$\mathcal{O}_{tW}$	$i(\bar{Q}\sigma^{\mu\nu}\,\tau_{I}\, t)\, \tilde{\varphi}\, W^{I}_{\mu\nu} + \text{h.c.}$	weak dipoles
	$\mathcal{O}_{\varphi B}$	$\left(\varphi^{\dagger}\varphi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$	$\mathcal{O}_{tB}$	$i(\bar{Q}\sigma^{\mu\nu}\, t)\, \tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$	
	$\mathcal{O}_{\varphi WB}$	$(\varphi^{\dagger}\tau_{I}\varphi)\, B^{\mu\nu} W^{I}_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i(\varphi^{\dagger}\overleftrightarrow{D}_{\mu}\,\tau_{I}\varphi)(\bar{Q}\,\gamma^{\mu}\,\tau^{I}Q)$	currents
	$\mathcal{O}_{\varphi D}$	$(\varphi^{\dagger}D^{\mu}\varphi)^{\dagger}(\varphi^{\dagger}D_{\mu}\varphi)$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i(\varphi^{\dagger}\overleftrightarrow{D}_{\mu}\,\varphi)(\bar{Q}\,\gamma^{\mu}\, Q)$	
	$\mathcal{O}_{\varphi\Box}$	$(\varphi^{\dagger}\varphi)\Box(\varphi^{\dagger}\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^{\dagger}\overleftrightarrow{D}_{\mu}\,\varphi)(\bar{t}\,\gamma^{\mu}\, t)$	
			$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi}\, D_{\mu}\,\varphi)(\bar{t}\,\gamma^{\mu}\, b) + \text{h.c.}$	RHCC

Relevant dim-6 operators for EW-top scattering

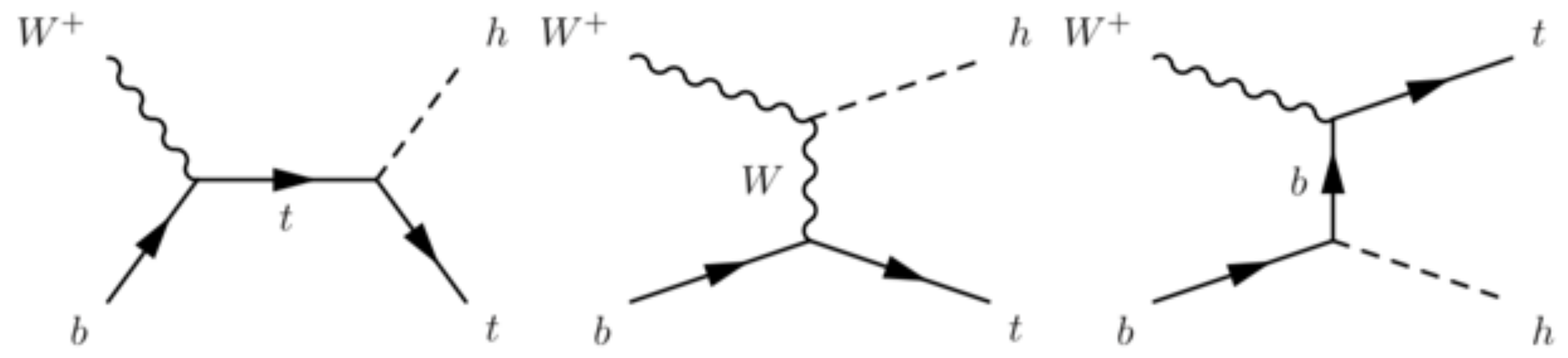
- Warsaw basis with $U(2)_Q$ x $U(2)_u$ x $U(3)_d$ x $U(3)_L$ x $U(3)_e$ flavor symmetry
- Bosonic + top specific operators

Example: $bW^+ \to tH$

Example: bW+ → tH

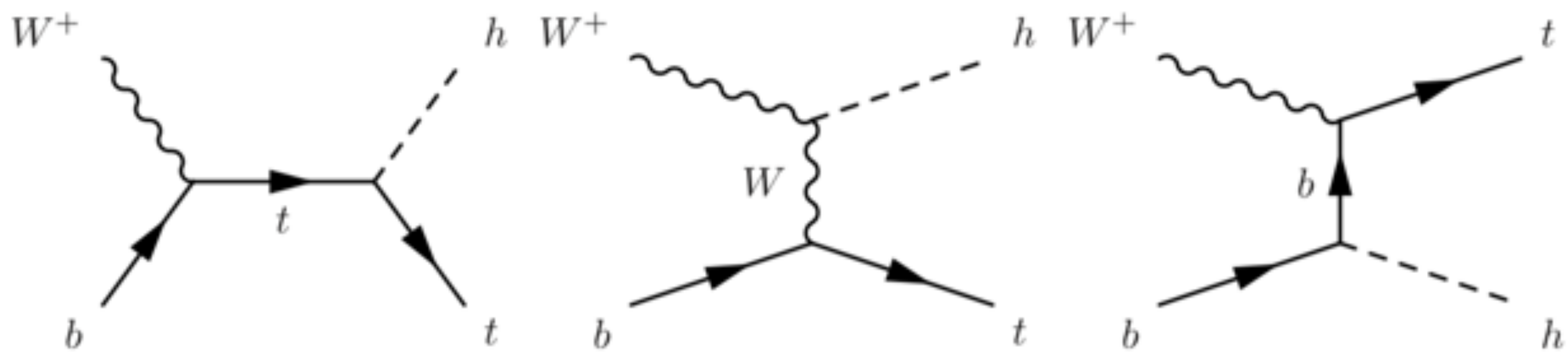


Example: $bW^+ \rightarrow tH$



In the SM, fully left handed, longitudinal W configuration ~ E^0

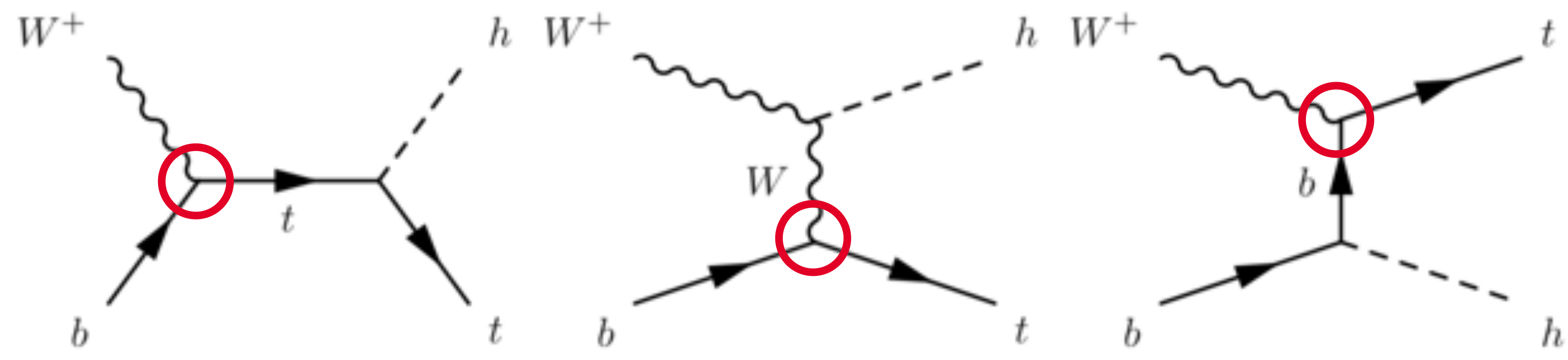
Example: $bW^+ \rightarrow tH$



In the SM, fully left handed, longitudinal W configuration ~ E^0

Anomalous interactions:

Example: $bW^+ \rightarrow tH$

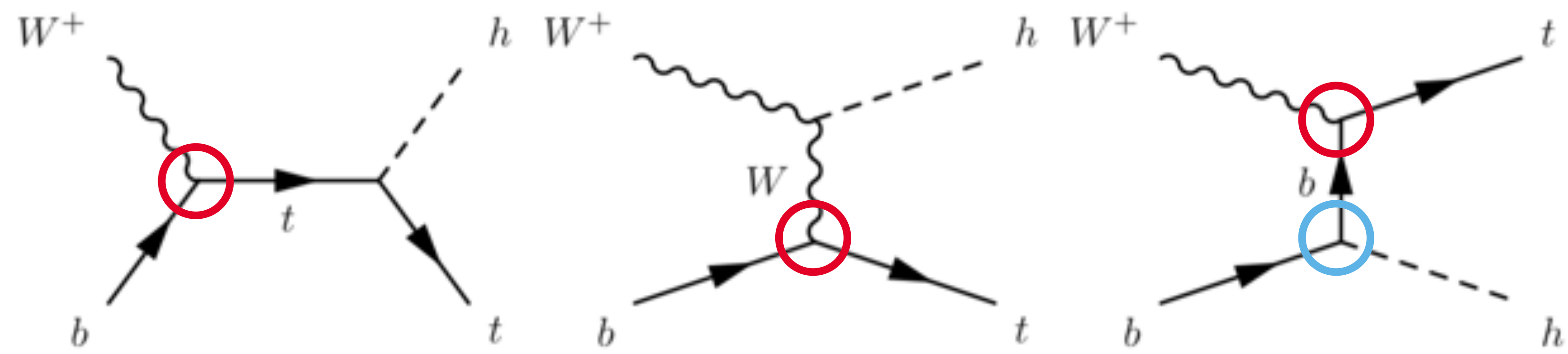


In the SM, fully left handed, longitudinal W configuration ~ E^0

Anomalous interactions:

- tbW vertex: present in all diagrams → overall rescaling ~ E^0

Example: $bW^+ \to tH$

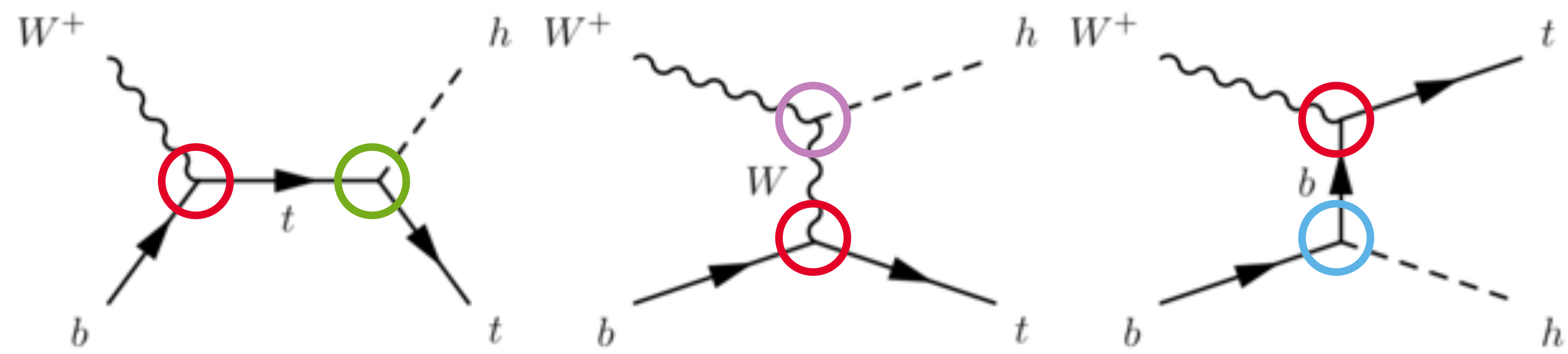


In the SM, fully left handed, longitudinal W configuration ~ E^0

Anomalous interactions:

- tbW vertex: present in all diagrams → overall rescaling ~ E^0
- bbH vertex: ∝ mb → 0

Example: $bW^+ \rightarrow tH$

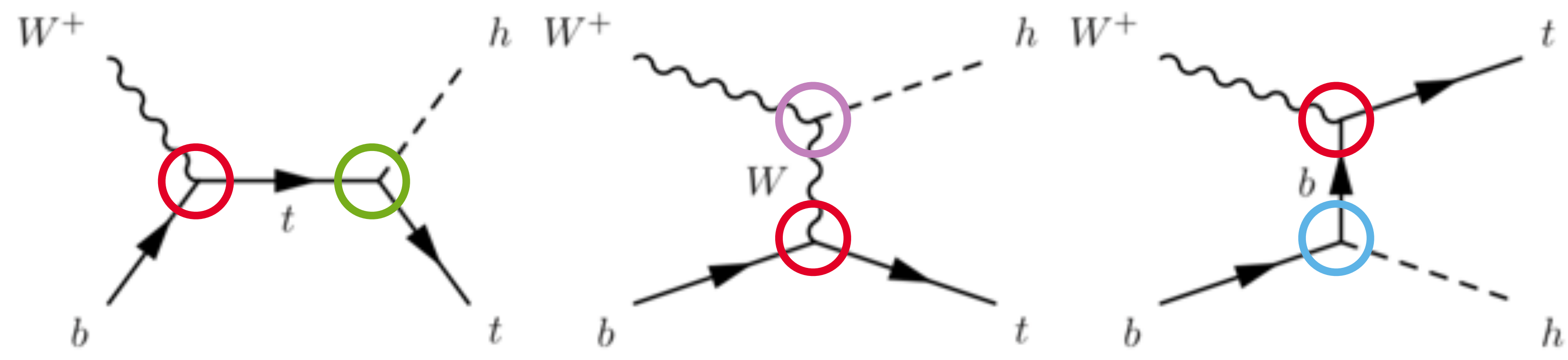


In the SM, fully left handed, longitudinal W configuration ~ E^0

Anomalous interactions:

- tbW vertex: present in all diagrams ➞ overall rescaling ~ E^0
- bbH vertex: ∝ mb ➞ 0
- HWW & ttH interactions: participate in a unitarity cancellation ~ v E

Example: bW$^+$ → tH



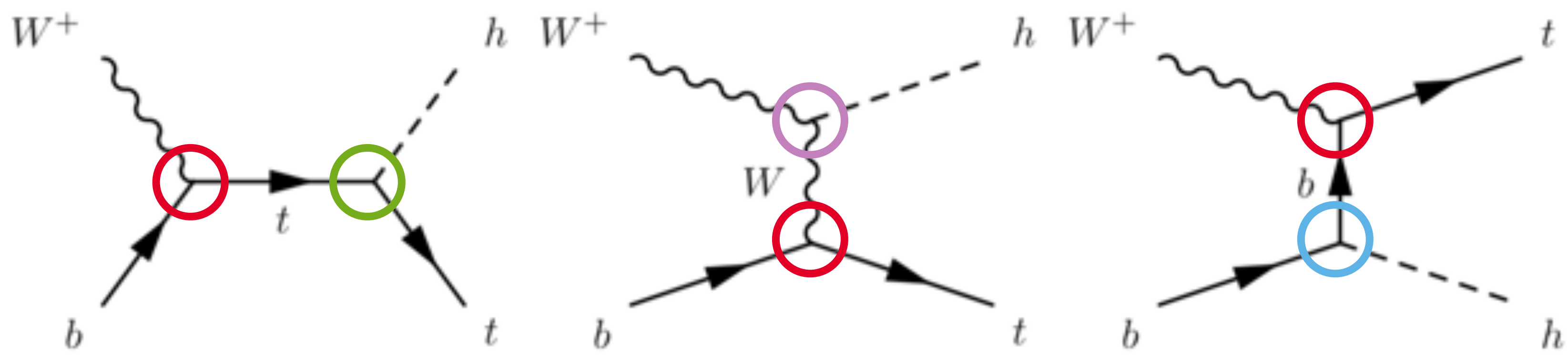
In the SM, fully left handed, longitudinal W configuration ~ E^0

Anomalous interactions:

- tbW vertex: present in all diagrams → overall rescaling ~ E^0
- bbH vertex: ∝ mb → 0
- HWW & ttH interactions: participate in a unitarity cancellation ~ v E

$$\mathcal{A}(b_L, W_L, t_R) \propto \sqrt{-t}(2m_W^2 g_{th} - g_{Wh} m_t)$$

Example: bW⁺→ tH



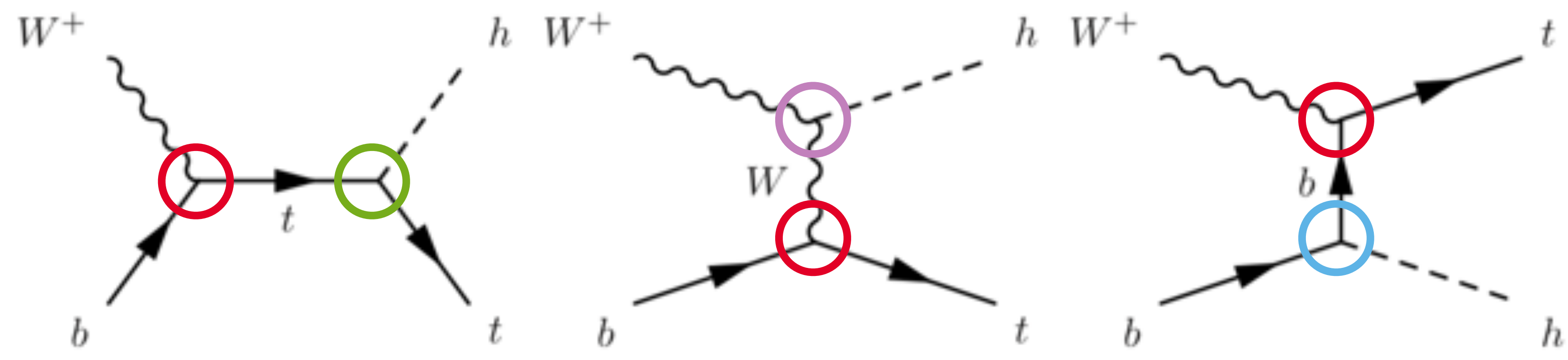
In the SM, fully left handed, longitudinal W configuration ~ E^0

Anomalous interactions:

- tbW vertex: present in all diagrams → overall rescaling ~ E^0
- bbH vertex: ∝ mb → 0
- HWW & ttH interactions: participate in a unitarity cancellation ~ v E

$$\mathcal{A}(b_L, W_L, t_R) \propto \sqrt{-t}(2m_W^2 \boxed{g_{th}} - \boxed{g_{Wh}} m_t)$$

Example: bW⁺ → tH



In the SM, fully left handed, longitudinal W configuration ~ E^0

Anomalous interactions:

- tbW vertex: present in all diagrams → overall rescaling ~ E^0
- bbH vertex: ∝ mb → 0
- HWW & ttH interactions: participate in a unitarity cancellation ~ v E

$$\mathcal{A}(b_L, W_L, t_R) \propto \sqrt{-t}(2m_W^2 \boxed{g_{th}} - \boxed{g_{Wh}} m_t)$$

- Fixing couplings to SM values sends it to E^{-1}

$bW^+ \to tH$ in SMEFT

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+, 0, -$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+, 0, +$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-, -, +$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \to tH$ in SMEFT

SMEFT: many more sources of energy growth

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-,0,-$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+,0,-$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+,0,+$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-,-,+$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-,+,+$	s^0	$-$	$-$	s^0	s^0	s^0
$+,-,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,-,+$	$-$	$-$	$-$	$-$	$-$	$-$
$+,+,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \to tH$ in SMEFT

Helicity configurations

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(3)}_{\varphi Q}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+, 0, -$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+, 0, +$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-, -, +$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \rightarrow tH$ in SMEFT

Helicity configurations

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+, 0, -$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+, 0, +$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-, -, +$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

W_L

$bW^+ \to tH$ in SMEFT

Helicity configurations

	$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(3)}_{\varphi Q}$
W_L	$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
	$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
	$+, 0, -$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
	$+, 0, +$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
W_T	$-, -, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
	$-, -, +$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
	$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
	$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
	$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
	$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
	$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
	$+, +, +$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \rightarrow tH$ in SMEFT

Schematic SM E-dependence down to E^{-2}

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+, 0, -$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+, 0, +$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-, -, +$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \to tH$ in SMEFT

Operators with some degree of growth

$\lambda_b,\, \lambda_W,\, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(3)}_{\varphi Q}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+, 0, -$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+, 0, +$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-, -, +$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \to tH$ in SMEFT

Max growth

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-,0,-$	s^0	s^0	$-$	s^0	s^0	$\boxed{\sqrt{s(s+t)}}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+,0,-$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+,0,+$	$-$	$-$	$\boxed{\sqrt{s(s+t)}}$	$-$	$-$	$-$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-,-,+$	$\frac{1}{s}$	s^0	$-$	$-$	$\boxed{\sqrt{s(s+t)}}$	s^0
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-,+,+$	s^0	$-$	$-$	s^0	s^0	s^0
$+,-,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,-,+$	$-$	$-$	$-$	$-$	$-$	$-$
$+,+,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \rightarrow tH$ in SMEFT

Interfering E-growth: SU(2) current operator

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-,0,-$	$\boxed{s^0}$	s^0	$-$	s^0	s^0	$\boxed{\sqrt{s(s+t)}}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+,0,-$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+,0,+$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-,-,+$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-,+,+$	s^0	$-$	$-$	s^0	s^0	s^0
$+,-,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,-,+$	$-$	$-$	$-$	$-$	$-$	$-$
$+,+,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \to tH$ in SMEFT

Non-interfering / no E growth in interference

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-,0,-$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+,0,-$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+,0,+$	$\boxed{-}$	$-$	$\boxed{\sqrt{s(s+t)}}$	$-$	$-$	$-$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-,-,+$	$\boxed{\frac{1}{s}}$	s^0	$-$	$-$	$\boxed{\sqrt{s(s+t)}}$	s^0
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-,+,+$	s^0	$-$	$-$	s^0	s^0	s^0
$+,-,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,-,+$	$-$	$-$	$-$	$-$	$-$	$-$
$+,+,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \rightarrow tH$ in SMEFT

Non-interfering / no E growth in interference

$\propto m_b$

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-,0,-$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}\,v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}\,m_t$
$+,0,-$	$-$	$-$	$\sqrt{-t}\,m_t$	$-$	$-$	$-$
$+,0,+$	$\boxed{-}$	$-$	$\boxed{\sqrt{s(s+t)}}$	$-$	$-$	$-$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}\,m_t$	$\sqrt{-t}\,m_W$
$-,-,+$	$\boxed{\frac{1}{s}}$	s^0	$-$	$-$	$\boxed{\sqrt{s(s+t)}}$	s^0
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-,+,+$	s^0	$-$	$-$	s^0	s^0	s^0
$+,-,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,-,+$	$-$	$-$	$-$	$-$	$-$	$-$
$+,+,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$\sqrt{-t}\,m_W$	$-$	$-$	$-$

$bW^+ \to tH$ in SMEFT

Non-interfering / no E growth in interference

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(3)}_{\varphi Q}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-tv}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t m_t}$
$+, 0, -$	$-$	$-$	$\sqrt{-t m_t}$	$-$	$-$	$-$
$+, 0, +$	$\boxed{-}$	$-$	$\boxed{\sqrt{s(s+t)}}$	$-$	$-$	$-$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t m_t}$	$\sqrt{-t m_W}$
$-, -, +$	$\boxed{\frac{1}{s}}$	s^0	$-$	$-$	$\boxed{\sqrt{s(s+t)}}$	s^0
$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\sqrt{-t m_W}$	$-$	$-$	$-$

$\propto m_b$

W_T

$bW^+ \rightarrow tH$ in SMEFT

Sub-leading growth ∝ EW scale (m_t, m_W, v)

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(3)}_{\varphi Q}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\boxed{\sqrt{-tv}}$	$-$	$-$	$\boxed{\frac{s m_W}{\sqrt{-t}}}$	$\boxed{\sqrt{-t m_t}}$
$+, 0, -$	$-$	$-$	$\boxed{\sqrt{-t m_t}}$	$-$	$-$	$-$
$+, 0, +$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\boxed{\frac{s m_W}{\sqrt{-t}}}$	$\boxed{\sqrt{-t m_t}}$	$\boxed{\sqrt{-t m_W}}$
$-, -, +$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\boxed{\frac{m_W(s+t)}{\sqrt{-t}}}$	$-$	$-$
$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\boxed{\sqrt{-t m_W}}$	$-$	$-$	$-$

$bW^+ \rightarrow tH$ in SMEFT

Sub-leading growth ∝ EW scale (m_t, m_W, v)

g_{th}

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-,0,-$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\boxed{\sqrt{-tv}}$	$-$	$-$	$\boxed{\frac{sm_W}{\sqrt{-t}}}$	$\boxed{\sqrt{-tm_t}}$
$+,0,-$	$-$	$-$	$\boxed{\sqrt{-tm_t}}$	$-$	$-$	$-$
$+,0,+$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\boxed{\frac{sm_W}{\sqrt{-t}}}$	$\boxed{\sqrt{-tm_t}}$	$\boxed{\sqrt{-tm_W}}$
$-,-,+$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\boxed{\frac{m_W(s+t)}{\sqrt{-t}}}$	$-$	$-$
$-,+,+$	s^0	$-$	$-$	s^0	s^0	s^0
$+,-,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,-,+$	$-$	$-$	$-$	$-$	$-$	$-$
$+,+,-$	$-$	$-$	s^0	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$\boxed{\sqrt{-tm_W}}$	$-$	$-$	$-$

$bW^+ \rightarrow tH$ in SMEFT

No E-growing interference

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\boxed{\frac{1}{\sqrt{s}}}$	$\boxed{\sqrt{-tv}}$	$-$	$-$	$\boxed{\frac{sm_W}{\sqrt{-t}}}$	$\boxed{\sqrt{-tm_t}}$
$+, 0, -$	$\boxed{-}$	$-$	$\boxed{\sqrt{-tm_t}}$	$-$	$-$	$-$
$+, 0, +$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-, -, -$	$\boxed{\frac{1}{\sqrt{s}}}$	$-$	$-$	$\boxed{\frac{sm_W}{\sqrt{-t}}}$	$\boxed{\sqrt{-tm_t}}$	$\boxed{\sqrt{-tm_W}}$
$-, -, +$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-, +, -$	$\boxed{\frac{1}{\sqrt{s}}}$	$-$	$-$	$\boxed{\frac{m_W(s+t)}{\sqrt{-t}}}$	$-$	$-$
$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, +, +$	$\boxed{-}$	$-$	$\boxed{\sqrt{-tm_W}}$	$-$	$-$	$-$

$bW^+ \rightarrow tH$ in SMEFT

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+, 0, -$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+, 0, +$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-, -, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-, -, +$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	s^0
$-, +, -$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$
$-, +, +$	s^0	$-$	$-$	s^0	s^0	s^0
$+, -, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, -, +$	$-$	$-$	$-$	$-$	$-$	$-$
$+, +, -$	$-$	$-$	s^0	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \rightarrow tH$ in SMEFT

$bW^+ \rightarrow tH$ in SMEFT

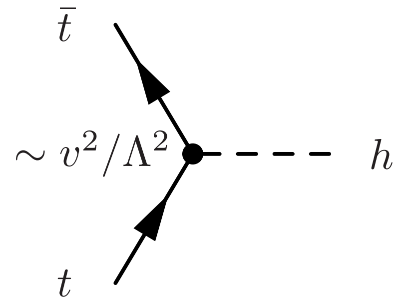
One source of energy growth from modified SM interactions

bW⁺ → tH in SMEFT

One source of energy growth from modified SM interactions

- Yukawa operator: disconnects kinematical mass from coupling to Higgs

$$\mathcal{O}_{t\varphi} = (\varphi^\dagger \varphi)^2 (\bar{Q}\, t\, \tilde{\varphi})$$



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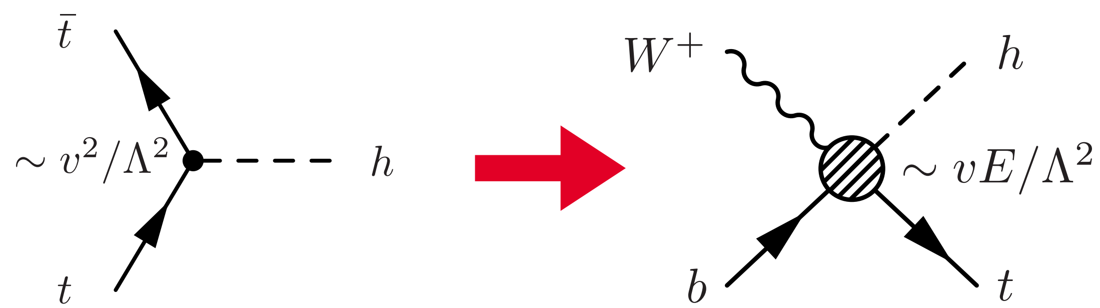

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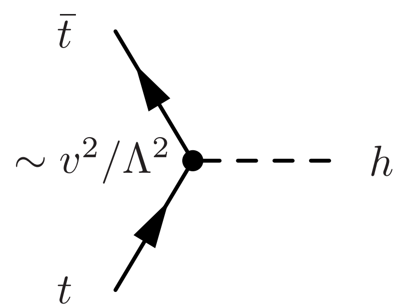

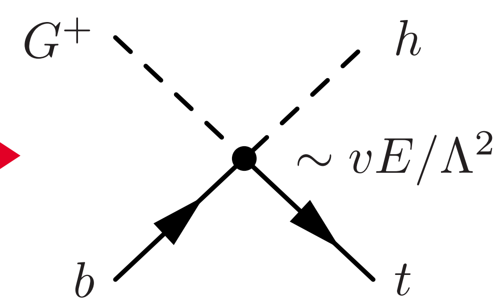

$$\boxed{h\,G^+\,\bar{t}_L\,b_R}$$

- 'Unitarity cancellation' **OR** dim-5 contact-interaction w/ charged Goldstone

$bW^+ \rightarrow tH$ in SMEFT

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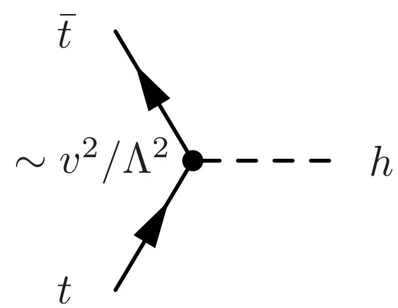
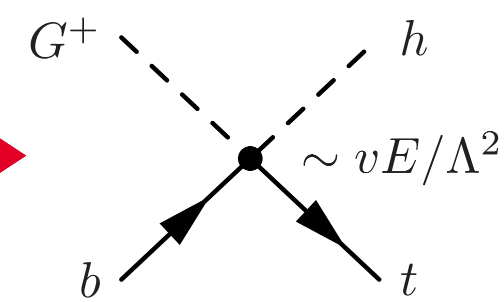
$$\mathcal{O}_{t\varphi} = (\varphi^\dagger\varphi)^2(\bar{Q}\,t\,\tilde{\varphi})$$





$$\boxed{h\,G^+\,\bar{t}_L\,b_R}$$

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Max growth from dim-6 contact-terms

bW+ → tH in SMEFT

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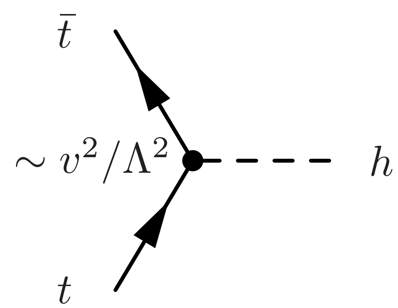
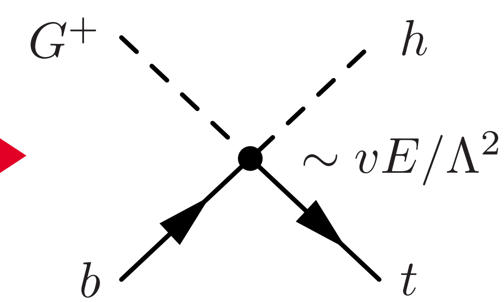


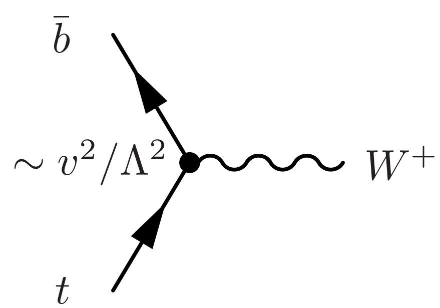


$$\boxed{h\,G^+\,\bar{t}_L\,b_R}$$

- ‘Unitarity cancellation’ **OR** dim-5 contact-interaction w/ charged Goldstone

Max growth from dim-6 contact-terms

$$\mathcal{O}^{(3)}_{\varphi Q} = i(\varphi^\dagger \overleftrightarrow{D}_\mu\,\tau^I\varphi)(\bar{Q}\,\gamma^\mu\,\tau_I\,Q)$$
$$\mathcal{O}_{\varphi tb} = i(\tilde{\varphi}\,D_\mu\varphi)(\bar{t}\,\gamma^\mu\,b) + \mathrm{h.c.}$$



bW+ → tH in SMEFT

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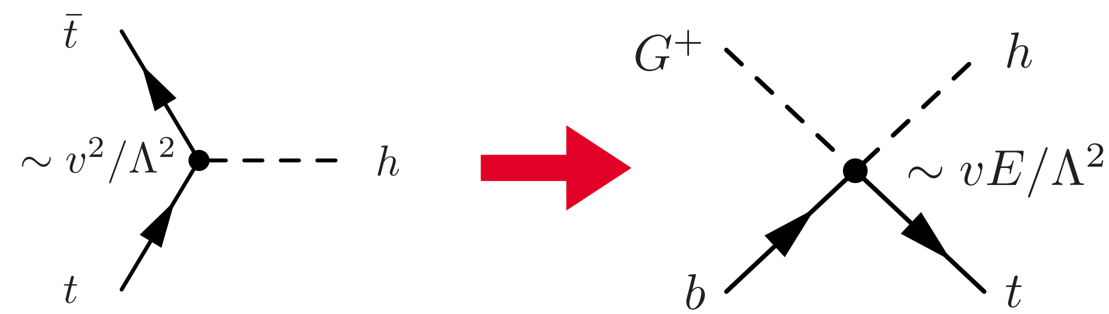
$$\mathcal{O}_{t\varphi} = (\varphi^\dagger\varphi)^2(\bar{Q}\,t\,\tilde{\varphi})$$



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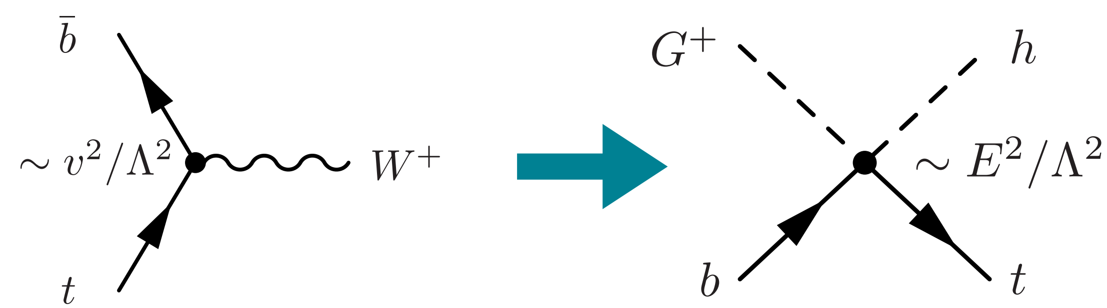
$$\mathcal{O}_{\varphi tb} = i(\tilde{\varphi}\,D_\mu\varphi)(\bar{t}\,\gamma^\mu\,b) + \text{h.c.}$$



$$\boxed{h\,\partial_\mu G^+\,\bar{t}\,\gamma^\mu b}$$

bW⁺ → tH in SMEFT

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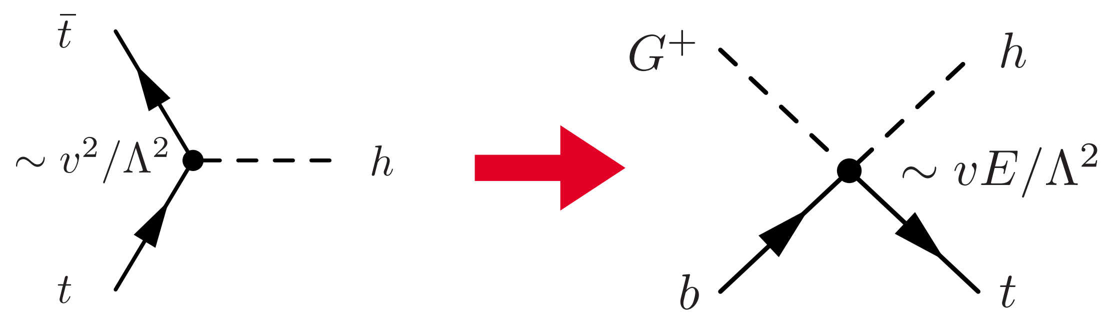
$$\mathcal{O}_{t\varphi} = (\varphi^\dagger\varphi)^2(\bar{Q}\, t\, \tilde{\varphi})$$



$$\boxed{h\, G^+\, \bar{t}_L\, b_R}$$

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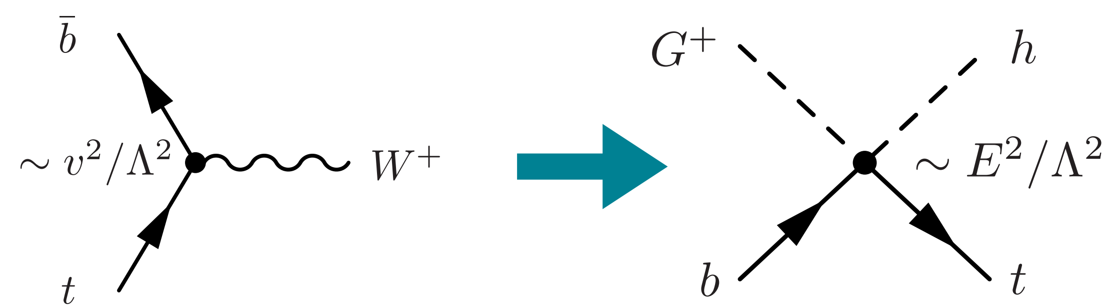
Max growth from dim-6 contact-terms

$$\mathcal{O}^{(3)}_{\varphi Q} = i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau^I \varphi)(\bar{Q}\, \gamma^\mu\, \tau_I\, Q)$$
$$\mathcal{O}_{\varphi t b} = i(\tilde{\varphi}\, D_\mu \varphi)(\bar{t}\, \gamma^\mu\, b) + \text{h.c.}$$



$$\boxed{h\, \partial_\mu G^+\, \bar{t}\, \gamma^\mu b}$$

- No anomalous coupling analogues *(recall Wtb vertex only rescales)*
- Prediction from gauge invariant dim-6 operators

Summary: max growths

Summary: max growths

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$bW \to tZ$	E	–	–	–	E	E^2	–	E^2	E^2	E	E^2	E	E^2
$bW \to t\gamma$	–	–	–	–	E	E^2	–	E^2	E^2	–	–	–	–
$bW \to th$	–	–	–	E	–	–	E	–	E^2	–	E^2	–	E^2

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$
$tW \to tW$	E	E	–	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \to tZ$	E	E	E	E	E	–	E	E^2	E^2	E	E	E
$tZ \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	–	–
$t\gamma \to t\gamma$	–	–	E	E	E	–	–	E	E	–	–	–

two-top w/o Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \to th$	E	–	E	E	E	–	E	E^2	E^2	E^2	E^2	E^2	–
$t\gamma \to th$	–	–	E	E	E	–	–	E^2	E^2	–	–	–	–
$th \to th$	E	E	–	–	–	–	E	–	–	–	–	–	–

two-top w/ Higgs

Summary: max growths

gauge/higgs operators $\Longleftarrow$ $\Longrightarrow$ *top operators*

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$bW \to tZ$	E	–	–	–	E	E^2	–	E^2	E^2	E	E^2	E	E^2
$bW \to t\gamma$	–	–	–	–	E	E^2	–	E^2	E^2	–	–	–	–
$bW \to th$	–	–	–	E	–	–	E	–	E^2	–	E^2	–	E^2

two-top w/o Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$
$tW \to tW$	E	E	–	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \to tZ$	E	E	E	E	E	–	E	E^2	E^2	E	E	E
$tZ \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	–	–
$t\gamma \to t\gamma$	–	–	E	E	E	–	–	E	E	–	–	–

two-top w/ Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \to th$	E	–	E	E	E	–	E	E^2	E^2	E^2	E^2	E^2	–
$t\gamma \to th$	–	–	E	E	E	–	–	E^2	E^2	–	–	–	–
$th \to th$	E	E	–	–	–	–	E	–	–	–	–	–	–

Summary: max growths

gauge/higgs operators $\Longleftarrow$ $\Longrightarrow$ *top operators*

Energy-growing interference

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$bW \to tZ$	E	–	–	–	E	E^2	–	E^2	E^2	E	E^2	E	E^2
$bW \to t\gamma$	–	–	–	–	E	E^2	–	E^2	E^2	–	–	–	–
$bW \to th$	–	–	–	E	–	–	E	–	E^2	–	E^2	–	E^2

two-top w/o Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$
$tW \to tW$	E	E	–	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \to tZ$	E	E	E	E	E	–	E	E^2	E^2	E	E	E
$tZ \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	–	–
$t\gamma \to t\gamma$	–	–	E	E	E	–	–	E	E	–	–	–

two-top w/ Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \to th$	E	–	E	E	E	–	E	E^2	E^2	E^2	E^2	E^2	–
$t\gamma \to th$	–	–	E	E	E	–	–	E^2	E^2	–	–	–	–
$th \to th$	E	E	–	–	–	–	E	–	–	–	–	–	–

Summary: max growths

gauge/higgs operators $\Longleftarrow$ $\Longrightarrow$ *top operators*

Energy-growing interference

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$bW \to tZ$	E	–	–	–	E	E^2	–	E^2	E^2	E	E^2	E	E^2
$bW \to t\gamma$	–	–	–	–	E	E^2	–	E^2	E^2	–	–	–	–
$bW \to th$	–	–	–	E	–	–	E	–	E^2	–	E^2	–	E^2

two-top w/o Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$
$tW \to tW$	E	E	–	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \to tZ$	E	E	E	E	E	–	E	E^2	E^2	E	E	E
$tZ \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	–	–
$t\gamma \to t\gamma$	–	–	E	E	E	–	–	E	E	–	–	–

two-top w/ Higgs

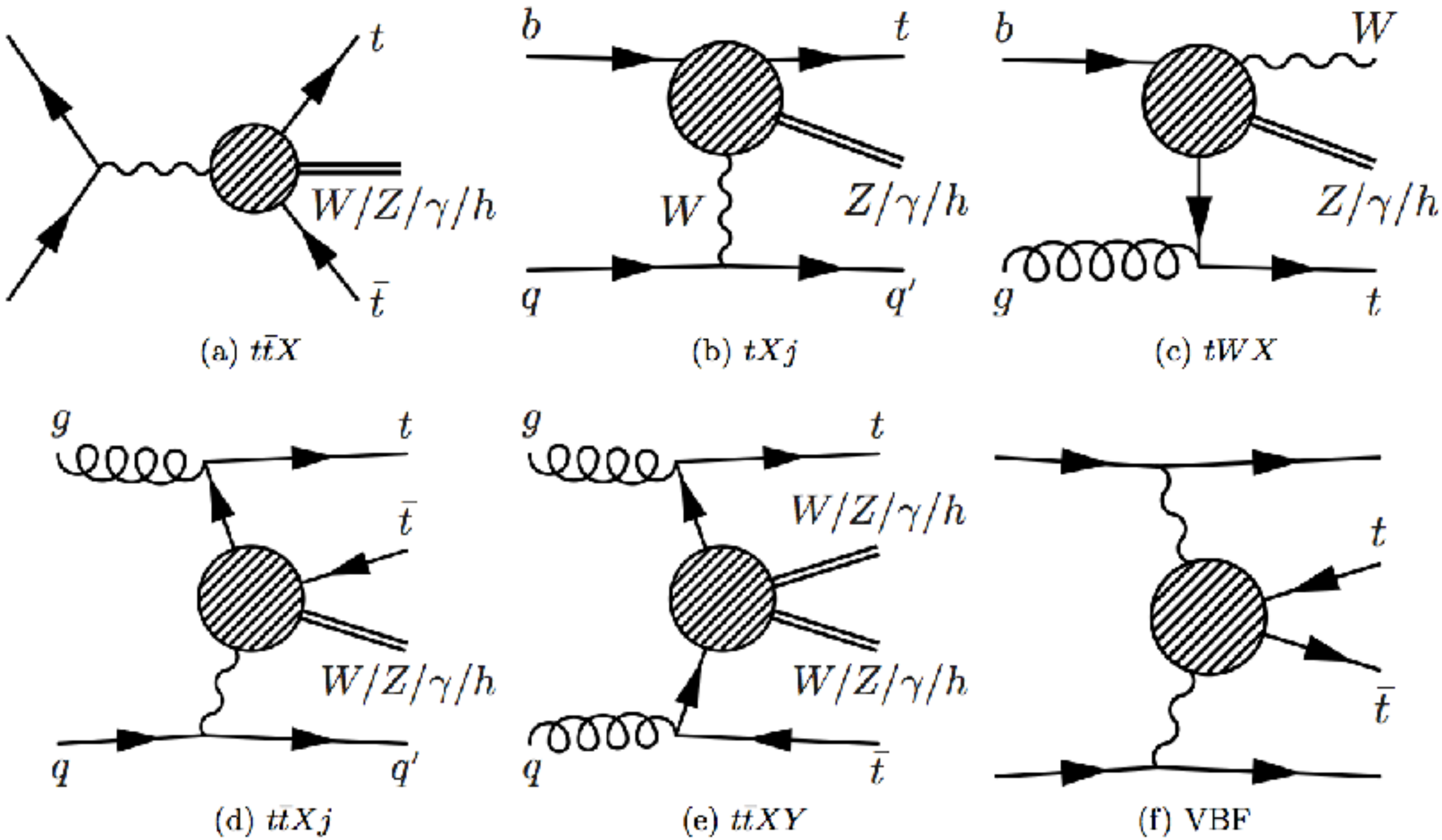
	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \to th$	E	–	E	E	E	–	E	E^2	E^2	E^2	E^2	E^2	–
$t\gamma \to th$	–	–	E	E	E	–	–	E^2	E^2	–	–	–	–
$th \to th$	E	E	–	–	–	–	E	–	–	–	–	–	–

Most top operators show max growth somewhere

- Interfering growth rare, only in longitudinal configurations (c.f. helicity selection)

Embedding the amplitudes

Collider processes: rare top production



(a) $t\bar{t}X$ (b) tXj (c) tWX

(d) $t\bar{t}Xj$ (e) $t\bar{t}XY$ (f) VBF

Embedding the amplitudes

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Collection of ‘sensitivity’ studies, general discussion

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	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
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$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

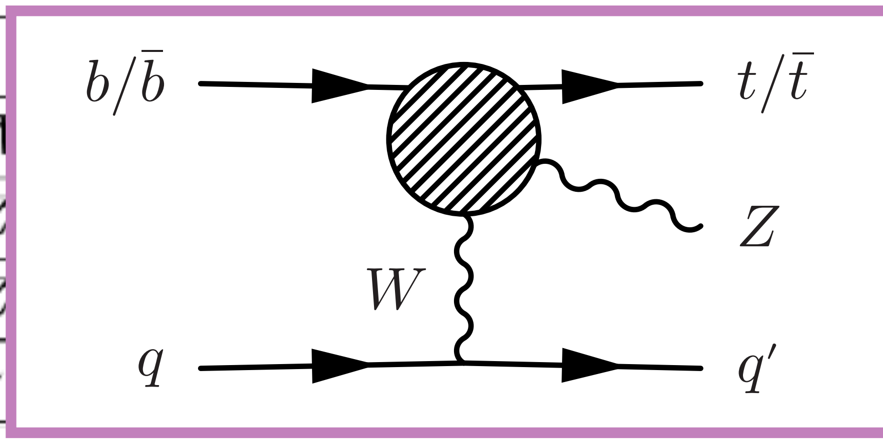
	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

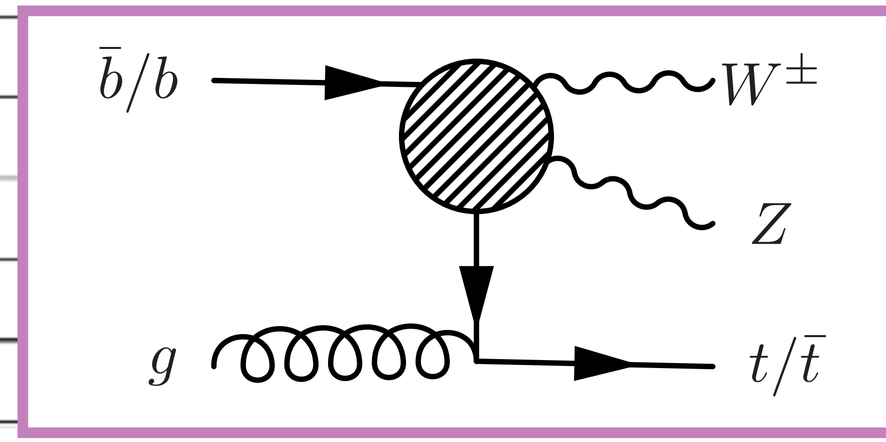
Embedding the amplitudes

Collection of ‘sensitivity’ studies, general discussion

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

	BF
tW	✓
tZ	✓
tZ	✓
$t\gamma$	✓





	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

tZj/tWZ: $bW^+ \rightarrow tZ$

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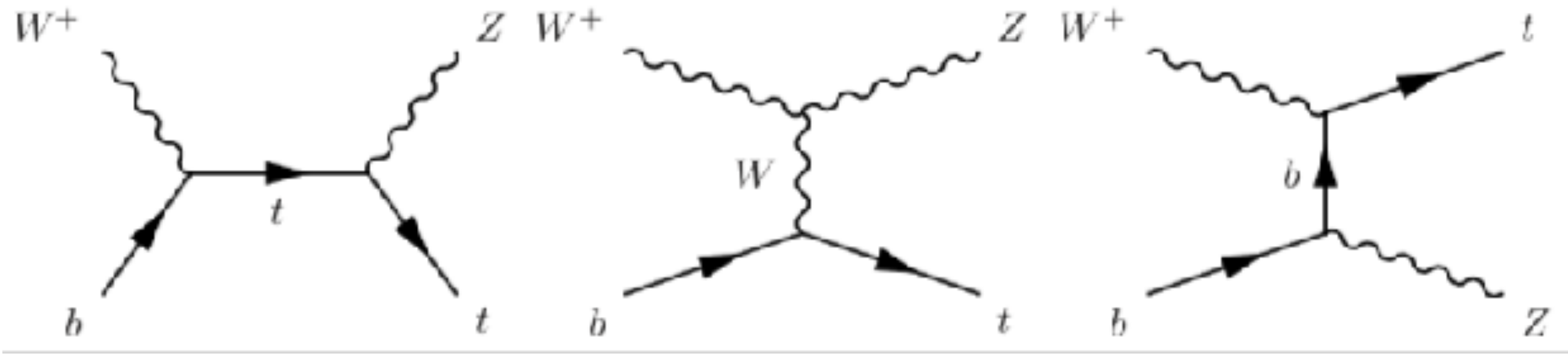
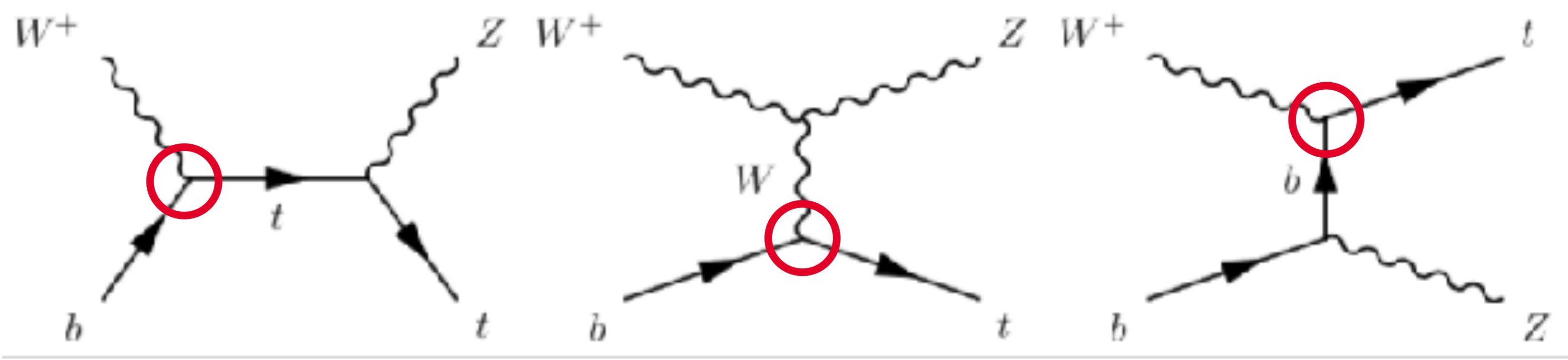
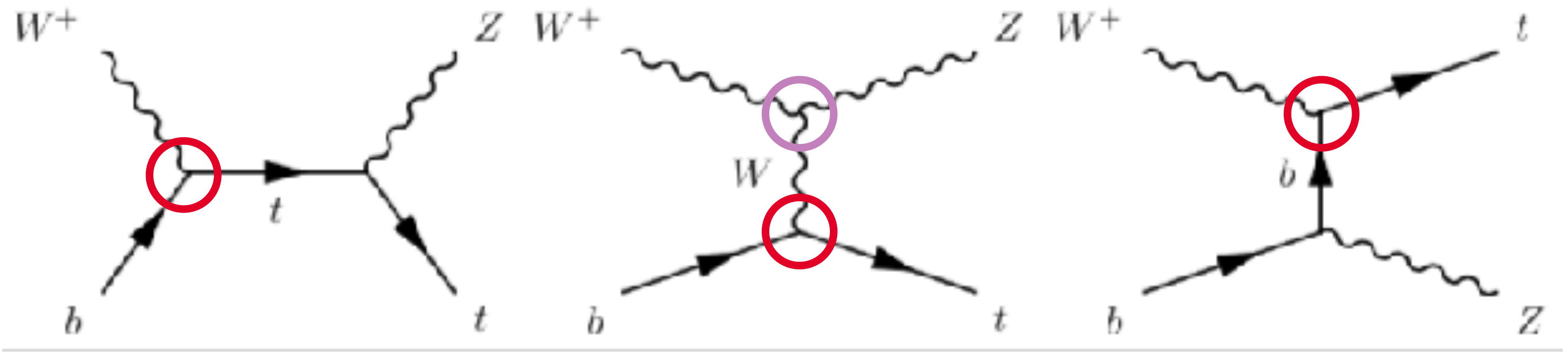


tZj/tWZ: $bW^+ \rightarrow tZ$



tZj/tWZ: $bW^+ \to tZ$



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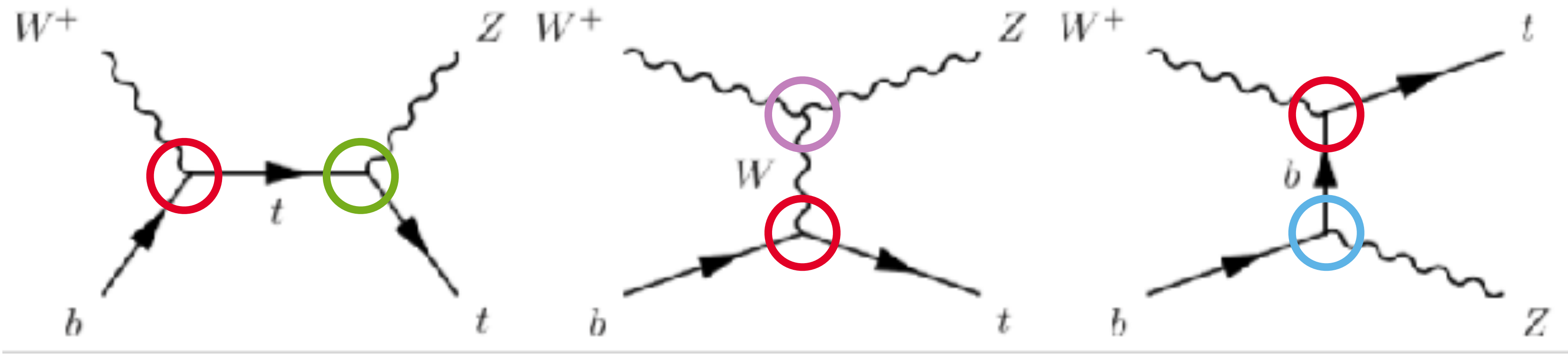

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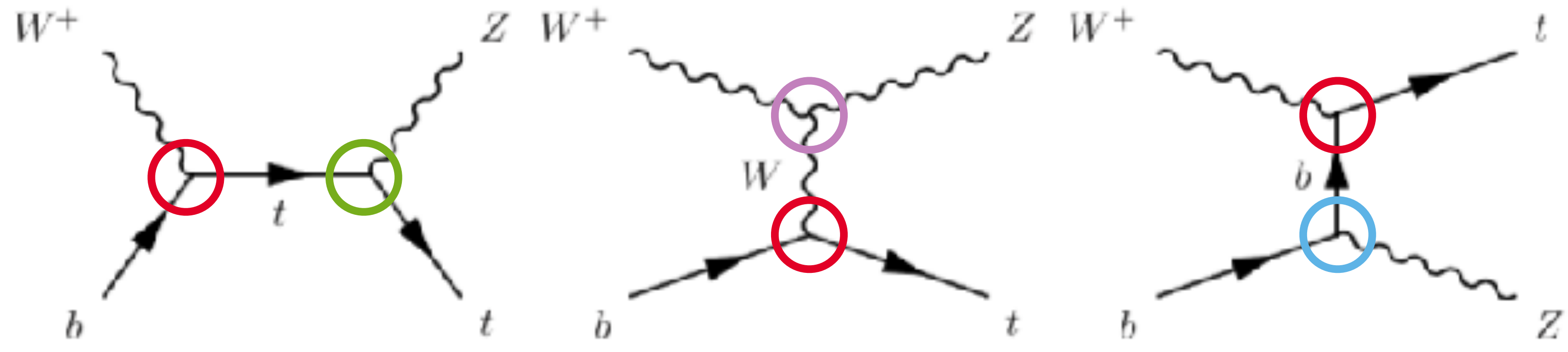
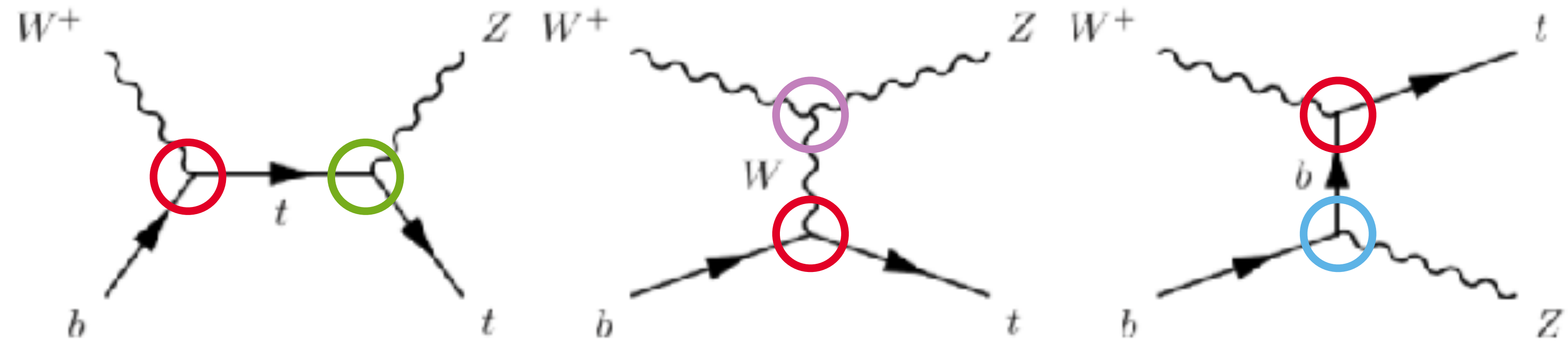


$$\mathcal{A}(b_L, W_0, t_L, Z_0) \propto \sqrt{s(s+t)}\,(g^Z_{b_L} - g^Z_{t_L} + g_{WZ})$$
$$\mathcal{A}(b_L, W_0, t_R, Z_0) \propto \sqrt{-t}\,(2m^2_W(g^Z_{b_L} - g^Z_{t_R} + g_{WZ}) - g_{WZ}m^2_Z)\,.$$

tZj/tWZ: bW⁺ → tZ



$$\mathcal{A}(b_L, W_0, t_L, Z_0) \propto \sqrt{s(s+t)}\,(\boxed{g^Z_{b_L}} - \boxed{g^Z_{t_L}} + \boxed{g_{WZ}})$$
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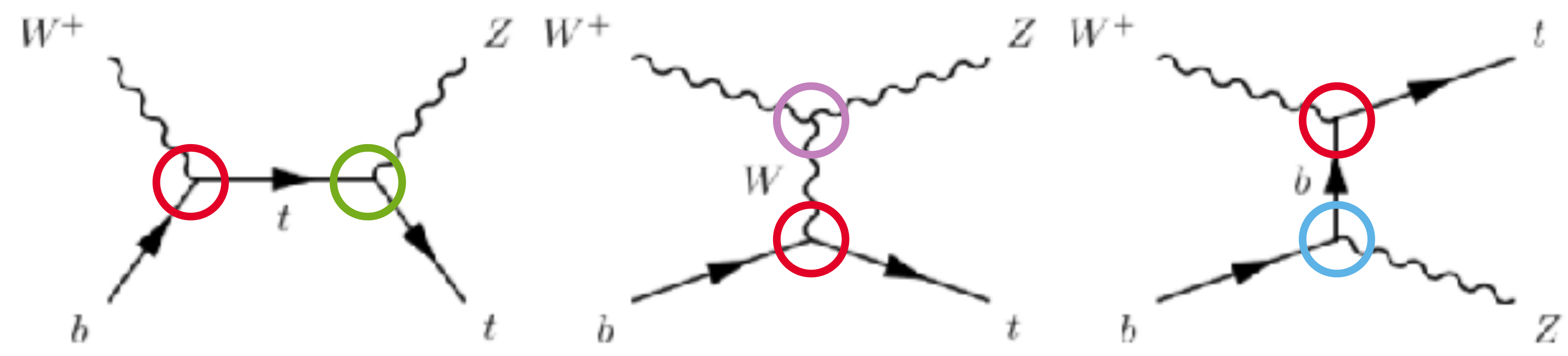

$$\mathcal{A}(b_L, W_0, t_L, Z_0) \propto \sqrt{s(s+t)}\,\left(\boxed{g^Z_{b_L}} - \boxed{g^Z_{t_L}} + \boxed{g_{WZ}}\right)$$
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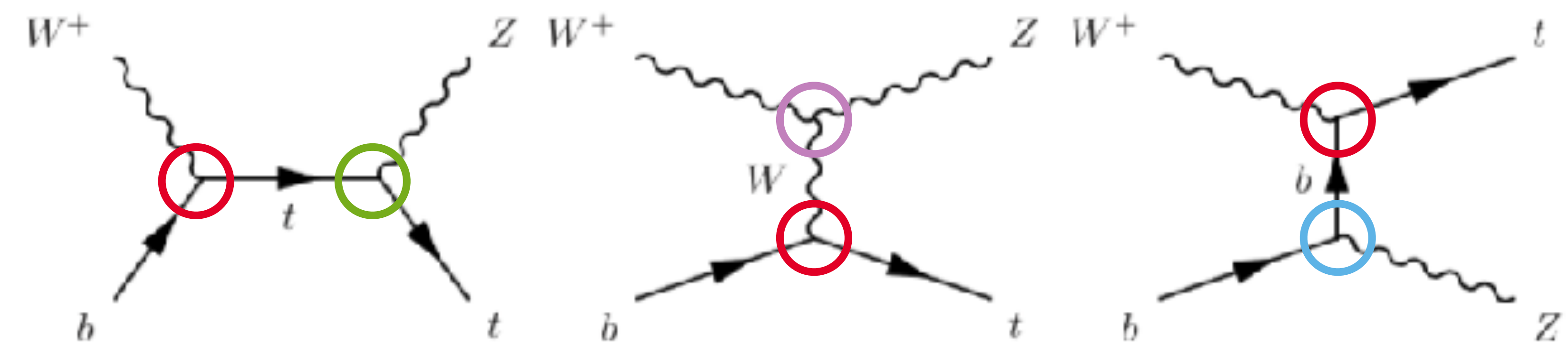
tZj/tWZ: bW⁺→ tZ



$$\mathcal{A}(b_L, W_0, t_L, Z_0) \propto \sqrt{s(s+t)}\,\left(\boxed{g^Z_{b_L}} - \boxed{g^Z_{t_L}} + \boxed{g_{WZ}}\right)$$

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$\lambda_b,\ \lambda_W,\ \lambda_t,\ \lambda_Z$	SM	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(3)}_{\phi Q}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}^{(1)}_{\phi Q}$
$-,0,-,0$	s^0	$-$	s^0	$\sqrt{s(s+t)}$	$-$	$-$
$-,0,+,0$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}m_W$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_t$	$\sqrt{-t}m_t$
$+,0,-,0$	$-$	$-$	$-$	$-$	$-$	$-$
$+,0,+,0$	$-$	$-$	$-$	$-$	$-$	$-$
$-,-,-,0$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$
$-,-,+,0$	$\frac{1}{s}$	s^0	$\sqrt{s(s+t)}$	s^0	s^0	s^0

many more

Top/EW interactions

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Top quark interactions are relatively poorly known

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- Simplest processes: ttZ, ttH, ttγ have been measured

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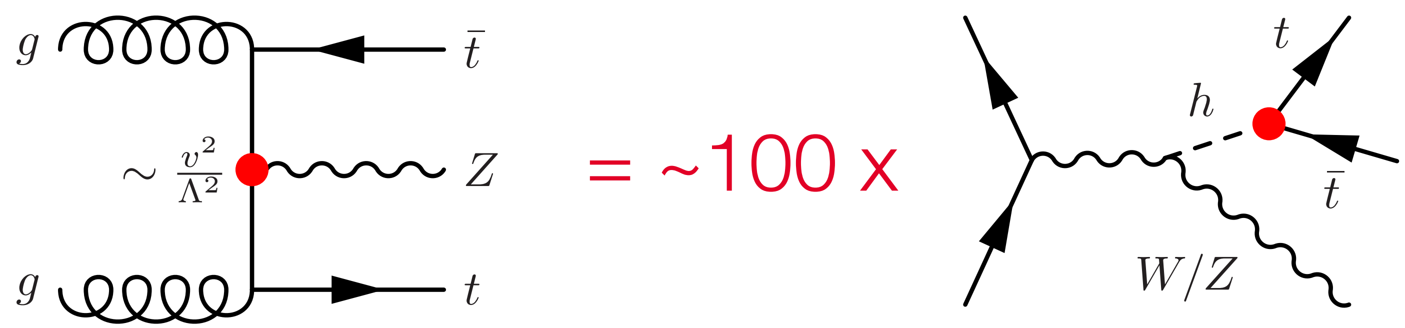
- Dominantly QCD-induced: modified interactions do not lead to E-growth
- EW contribution involves off-shell intermediate states: suppress E-growth



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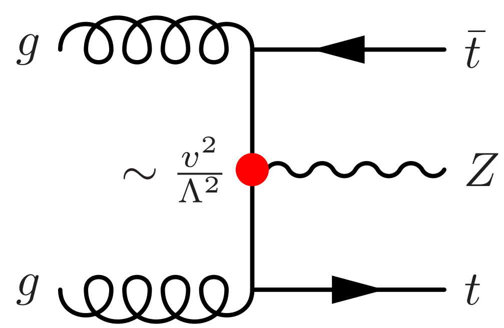
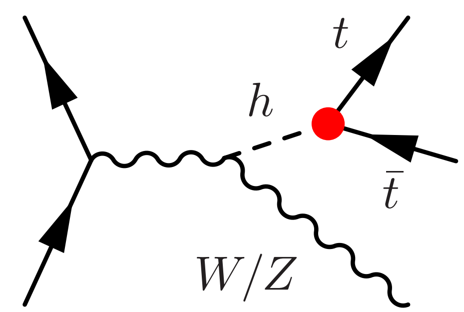


= ~100 x



Motivates alternative channel: single top + Z(W)

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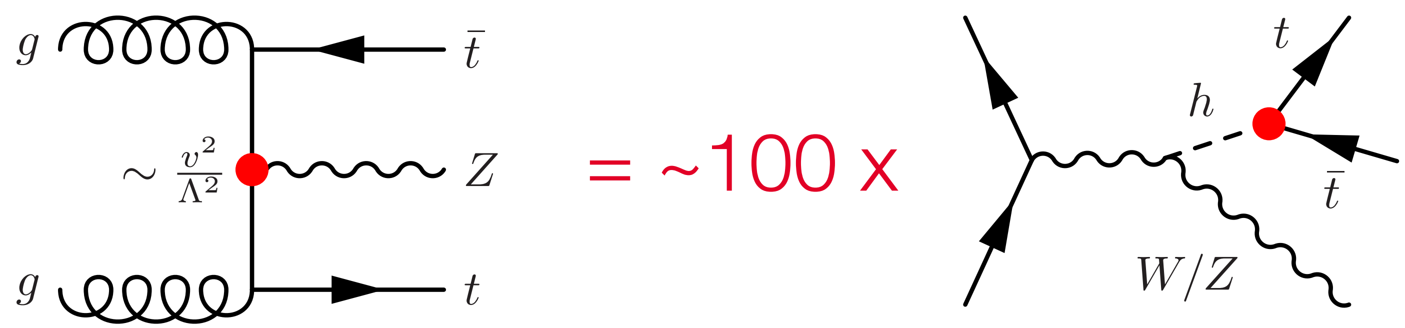

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- LHC has recently measured tZj > 5σ

[CMS Collaboration; PRL 122 (2019) 132003]
[ATLAS Collaboration; ATLAS-CONF-2019-043]

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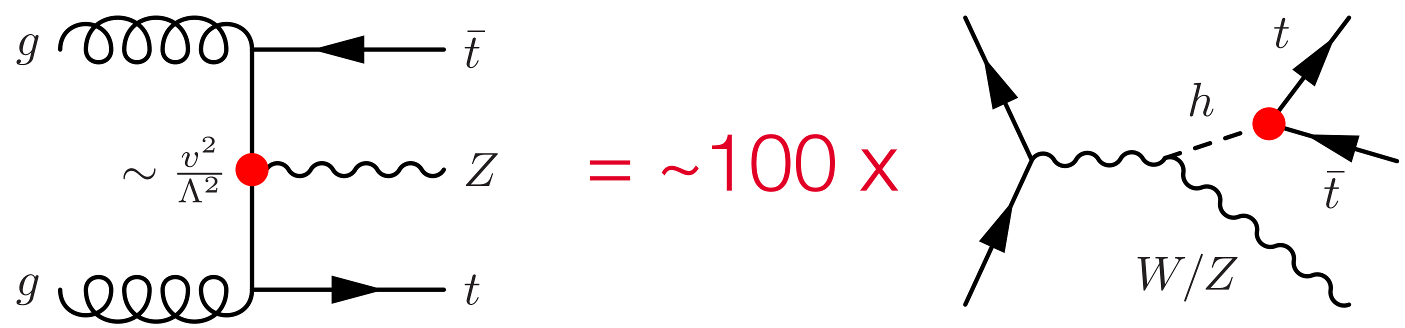


Motivates alternative channel: single top + Z(W)

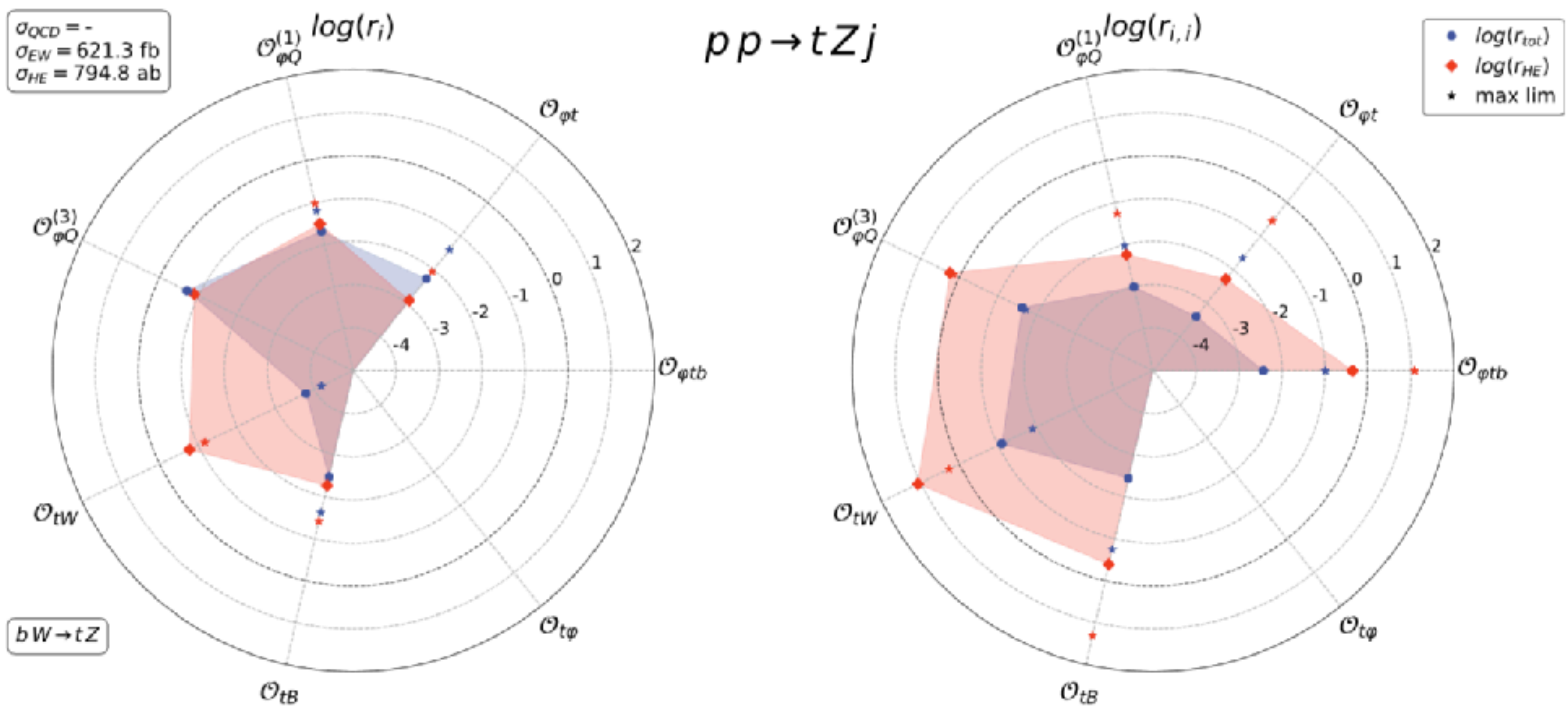
- LHC has recently measured tZj > 5σ

[CMS Collaboration; PRL 122 (2019) 132003]
[ATLAS Collaboration; ATLAS-CONF-2019-043]

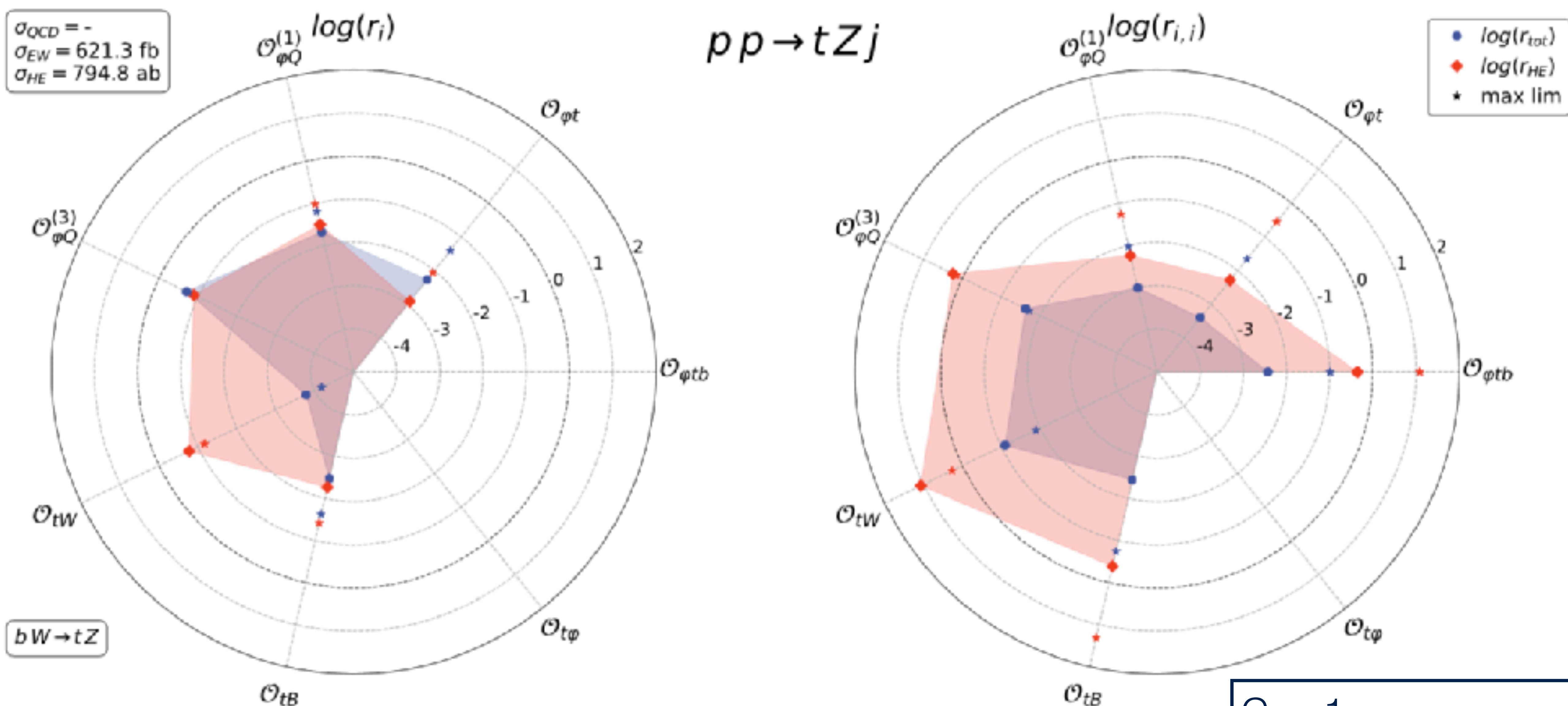
- Previous study showed promising sensitivity to E-growing effects from modified ttZ/bbZ/WWZ interactions (same for tHj)

[Degrande, Maltoni, KM, Vryonidou, Zhang; JHEP 1810 (2018) 005]

tZj total & high energy xs

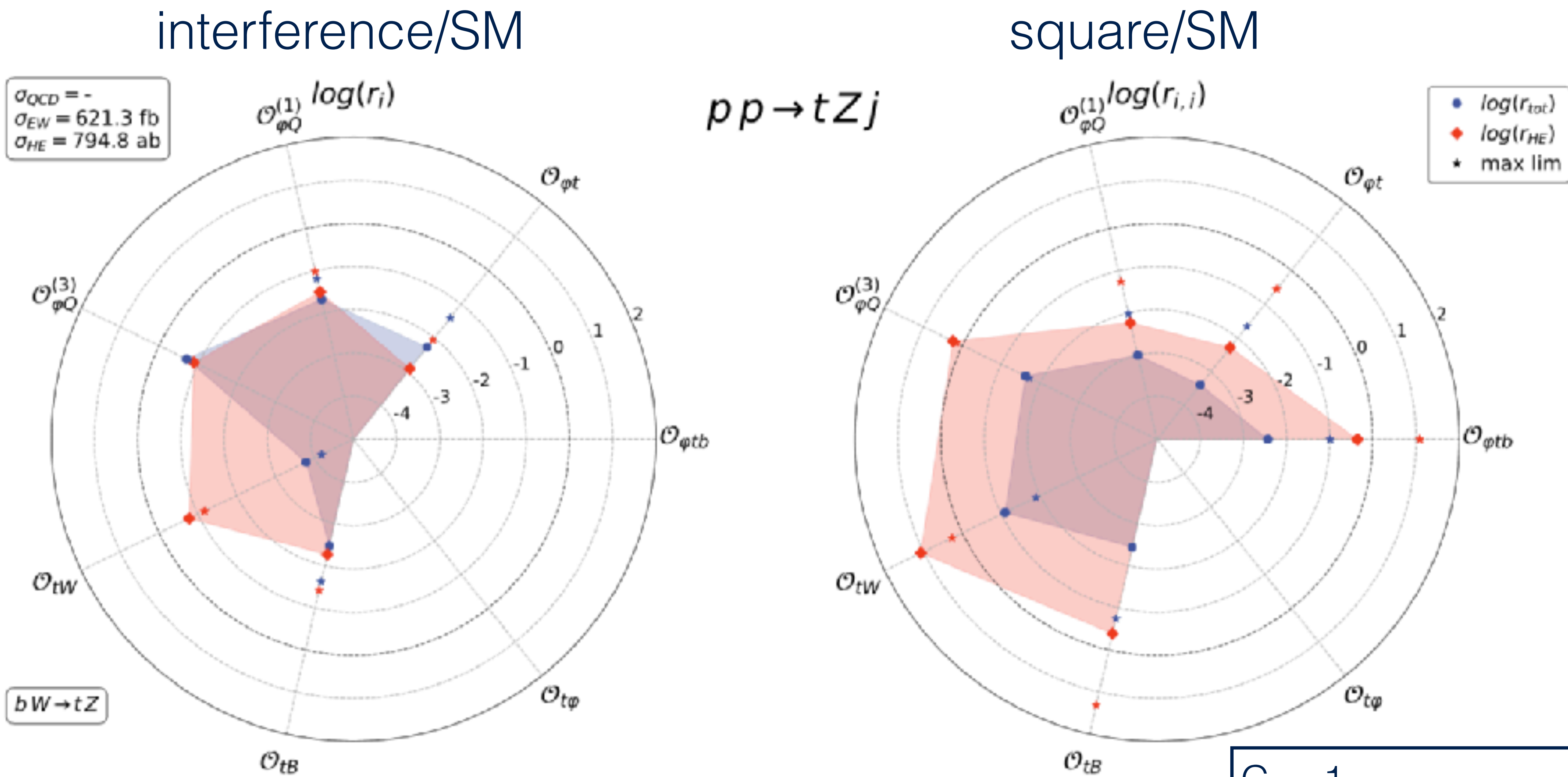


tZj total & high energy xs



C_i = 1
Inclusive
p_T (Z)> 500 GeV

tZj total & high energy xs



C_i = 1
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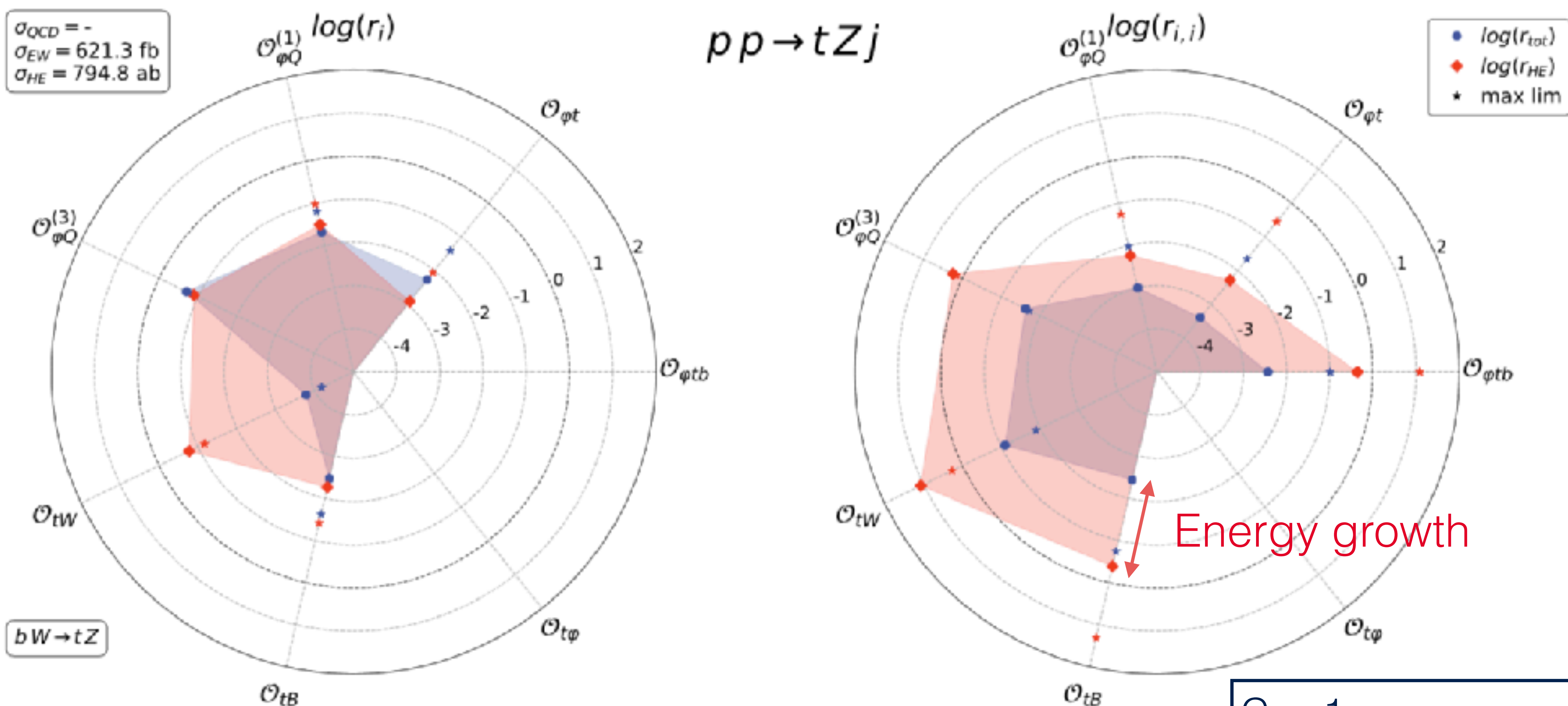
tZj total & high energy xs

interference/SM

square/SM



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tZj total & high energy xs

interference/SM

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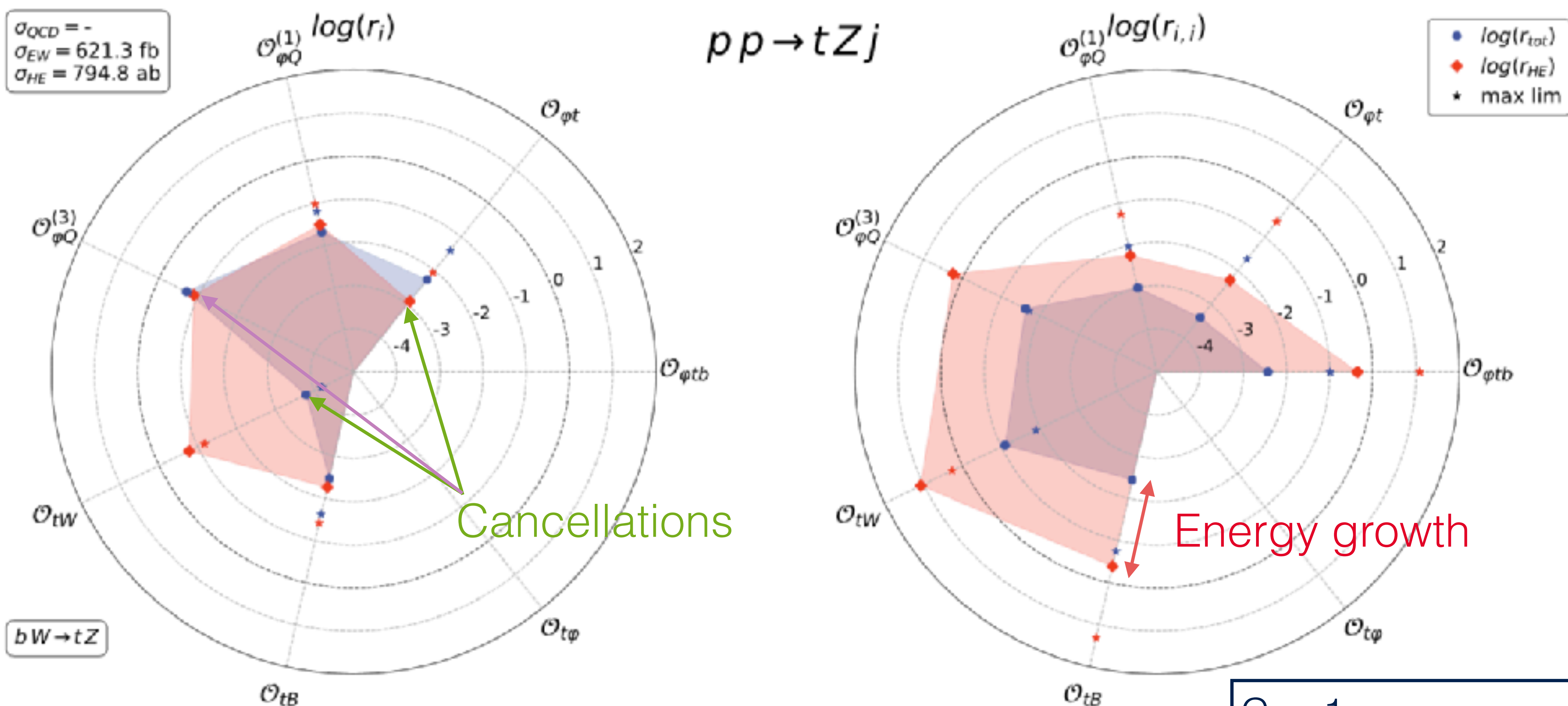
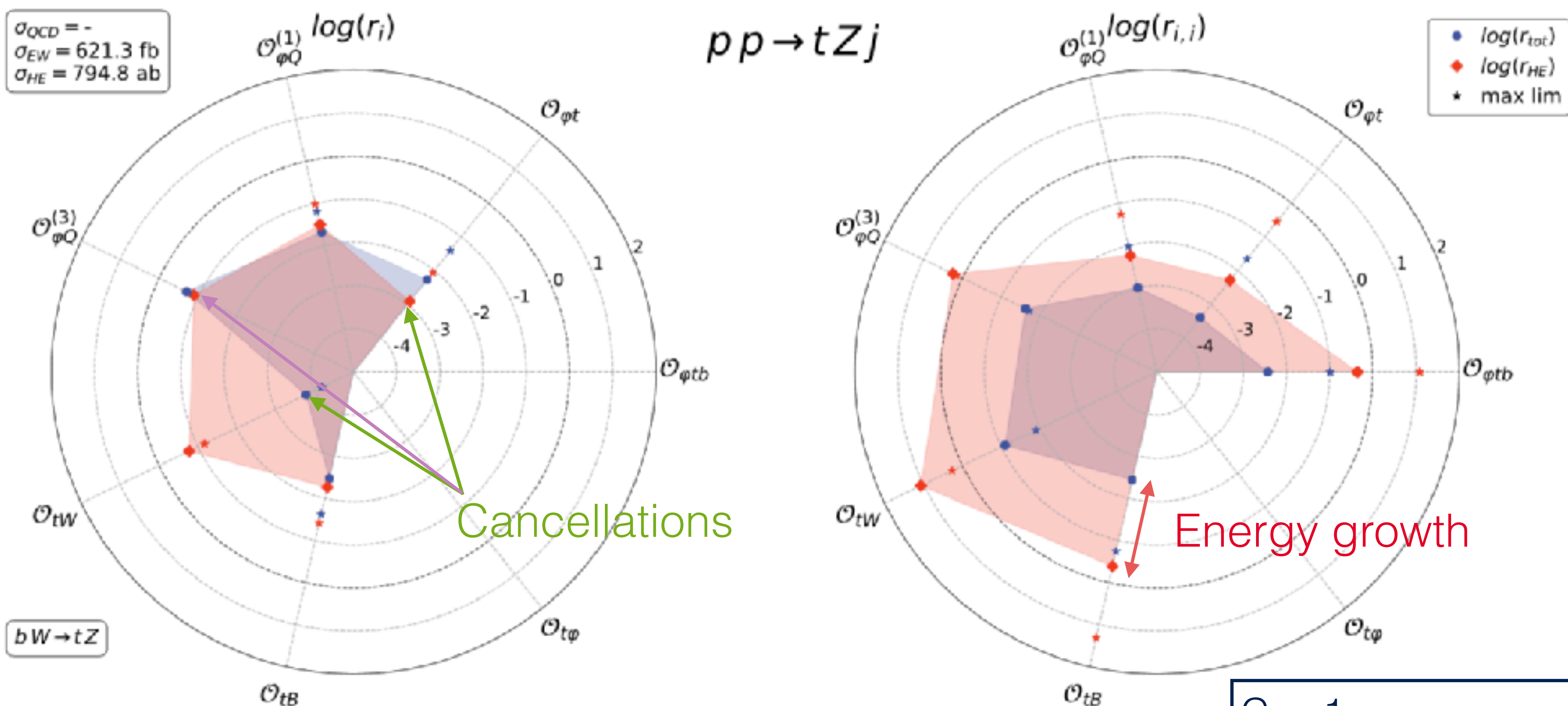


C_i = 1
Inclusive
p_T (Z)> 500 GeV

tZj total & high energy xs

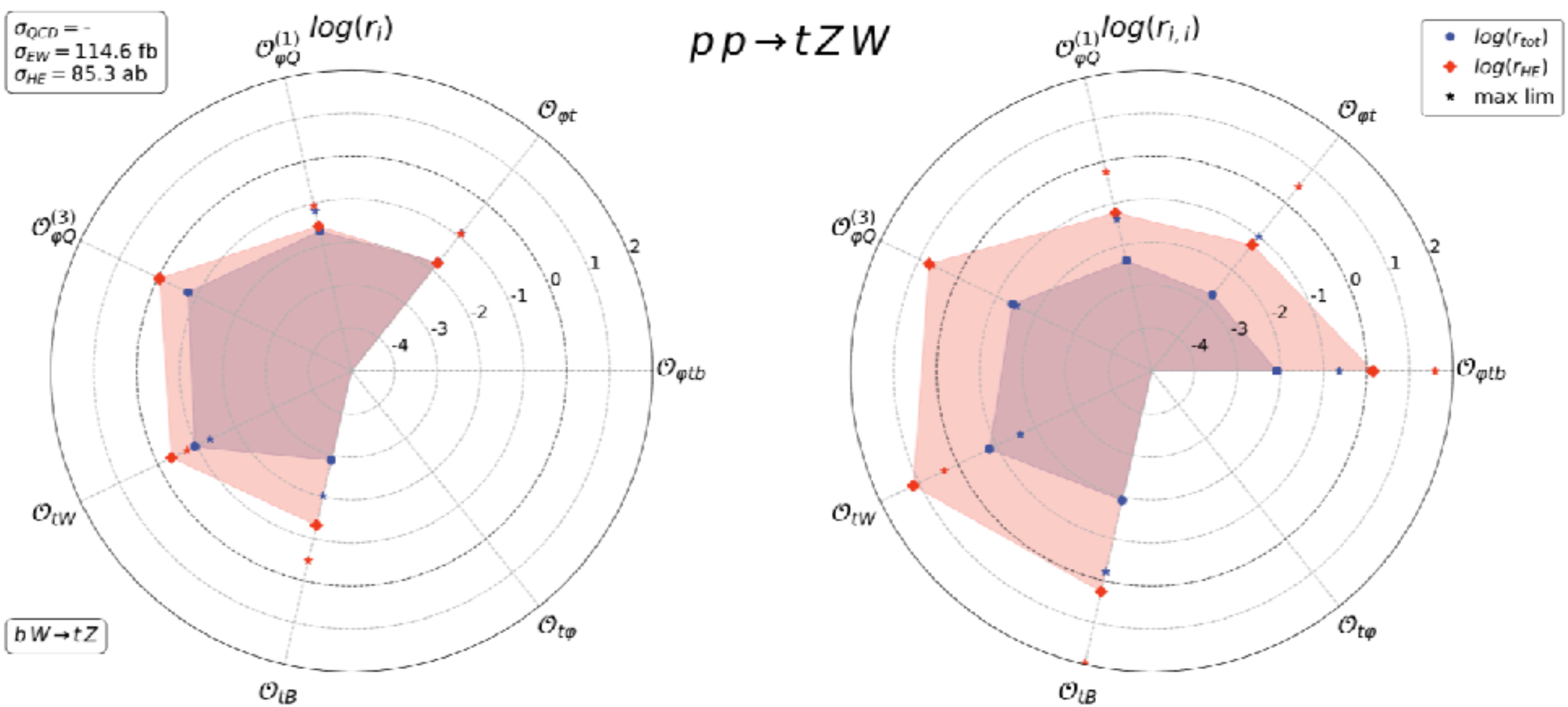
interference/SM | square/SM



Expected growth from 2→2 absent!

C_i = 1
Inclusive
p_T (Z)> 500 GeV

tZW total & high energy xs

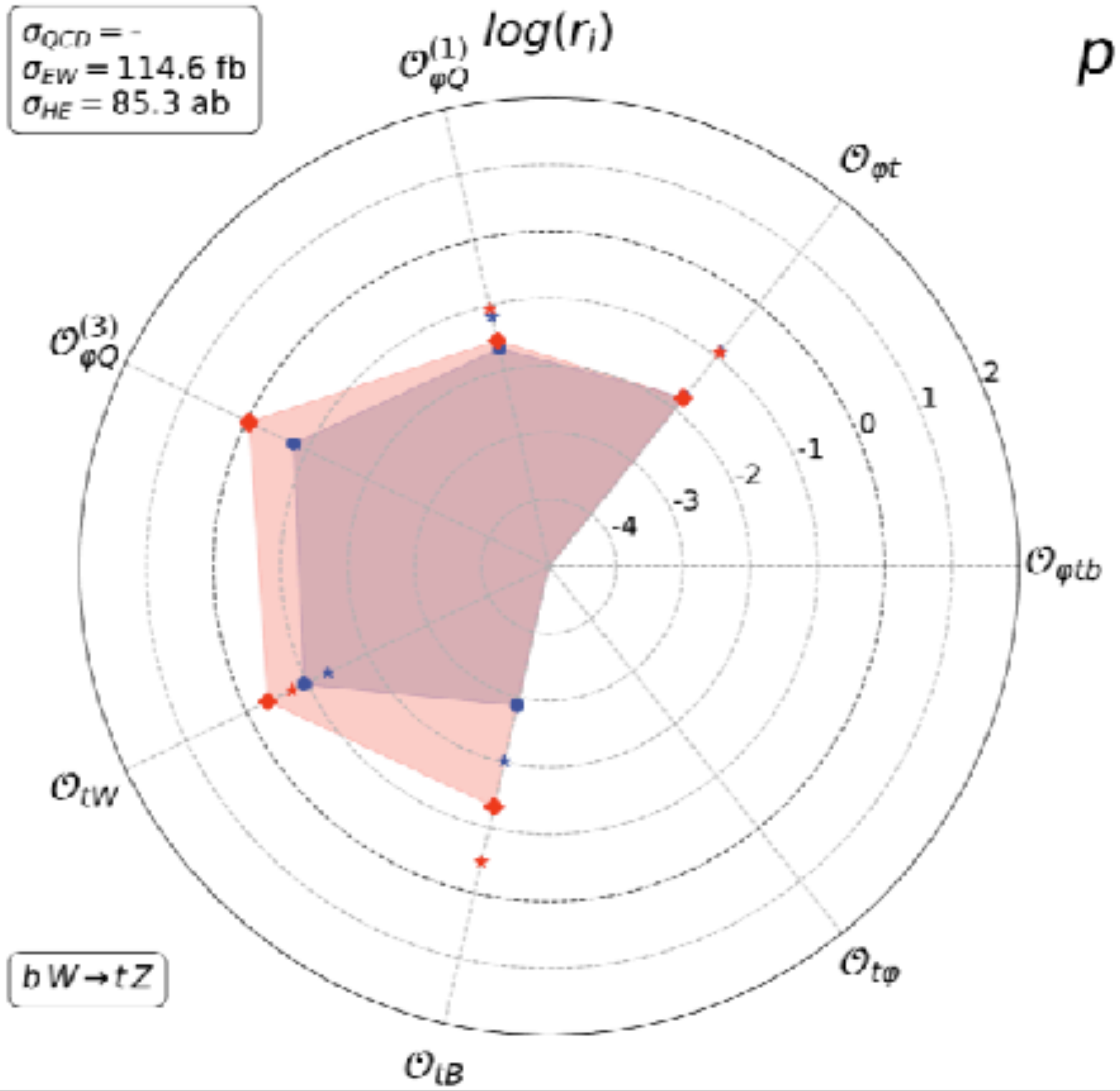


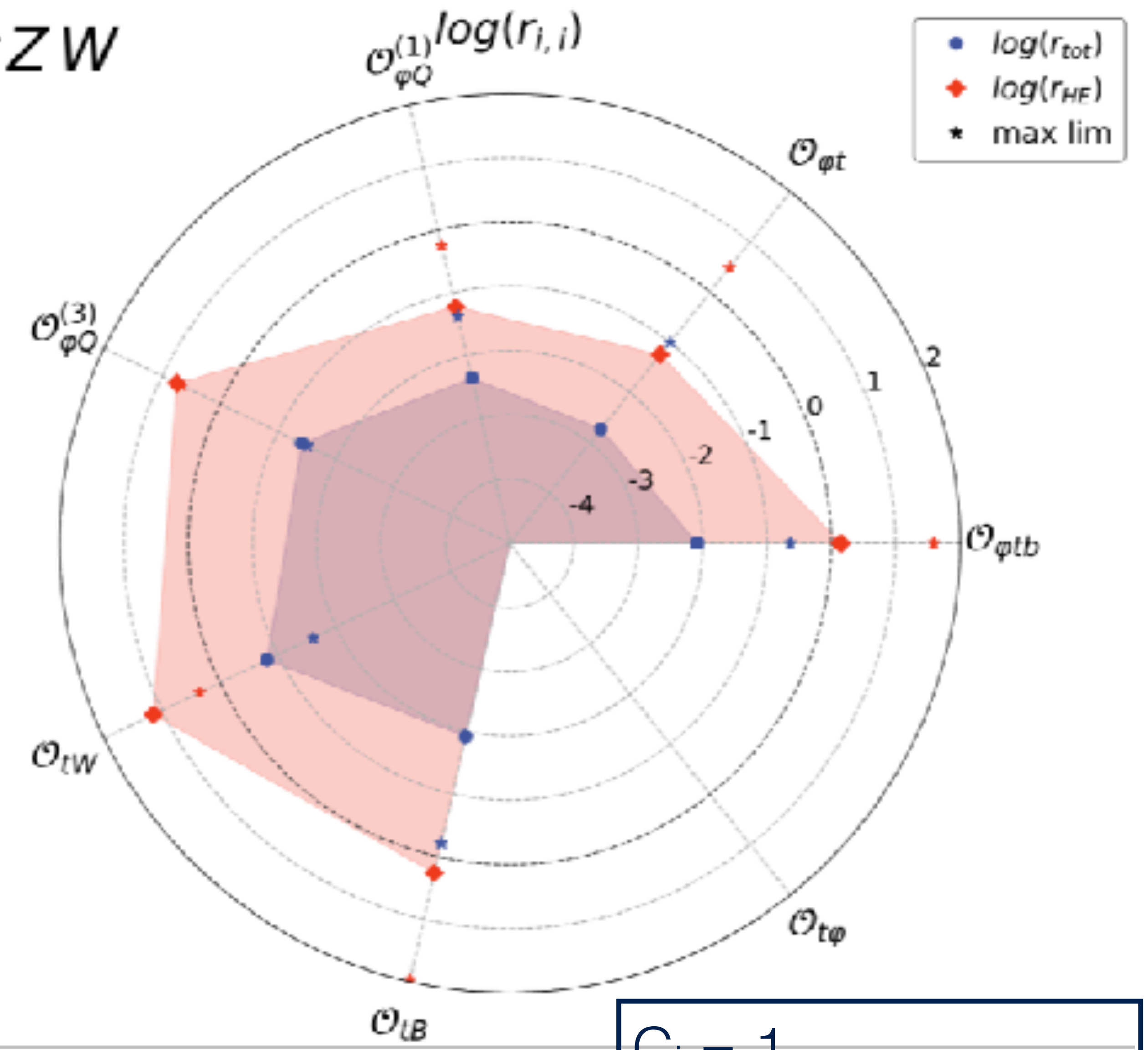
tZW total & high energy xs

interference/SM

square/SM

$pp \rightarrow tZW$

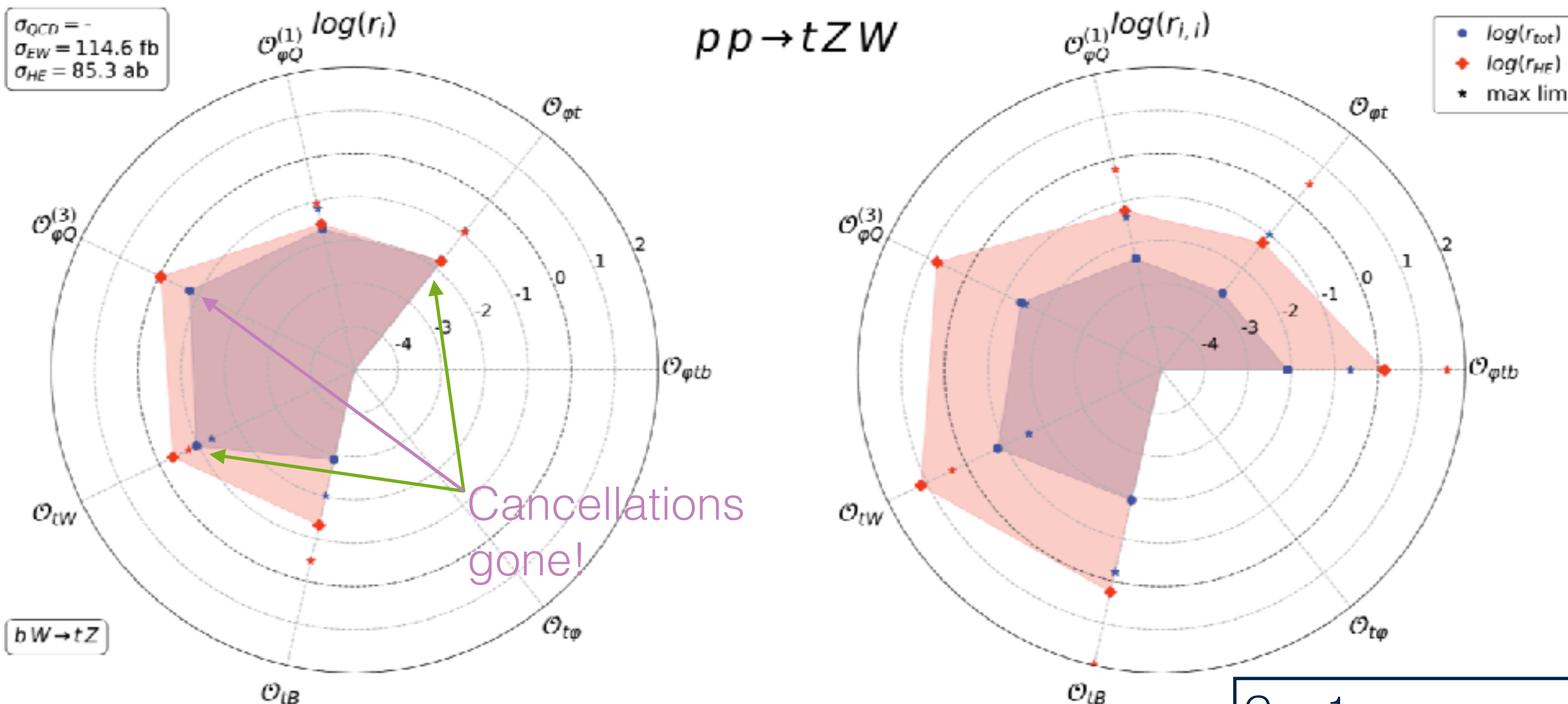




$C_i = 1$
Inclusive
p_T (W,Z)> 500 GeV

tZW total & high energy xs

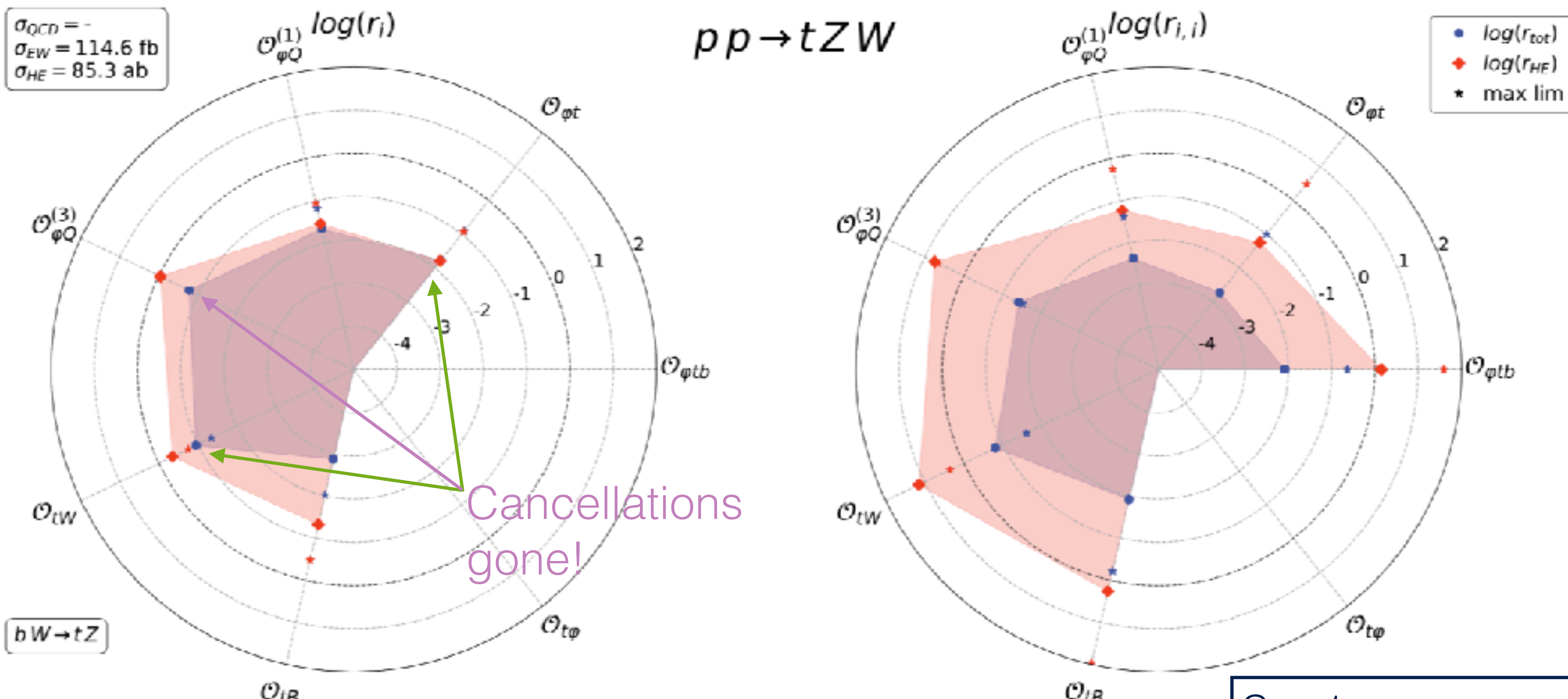
interference/SM — square/SM



$C_i = 1$
Inclusive
p_T (W,Z)> 500 GeV

tZW total & high energy xs

interference/SM   square/SM

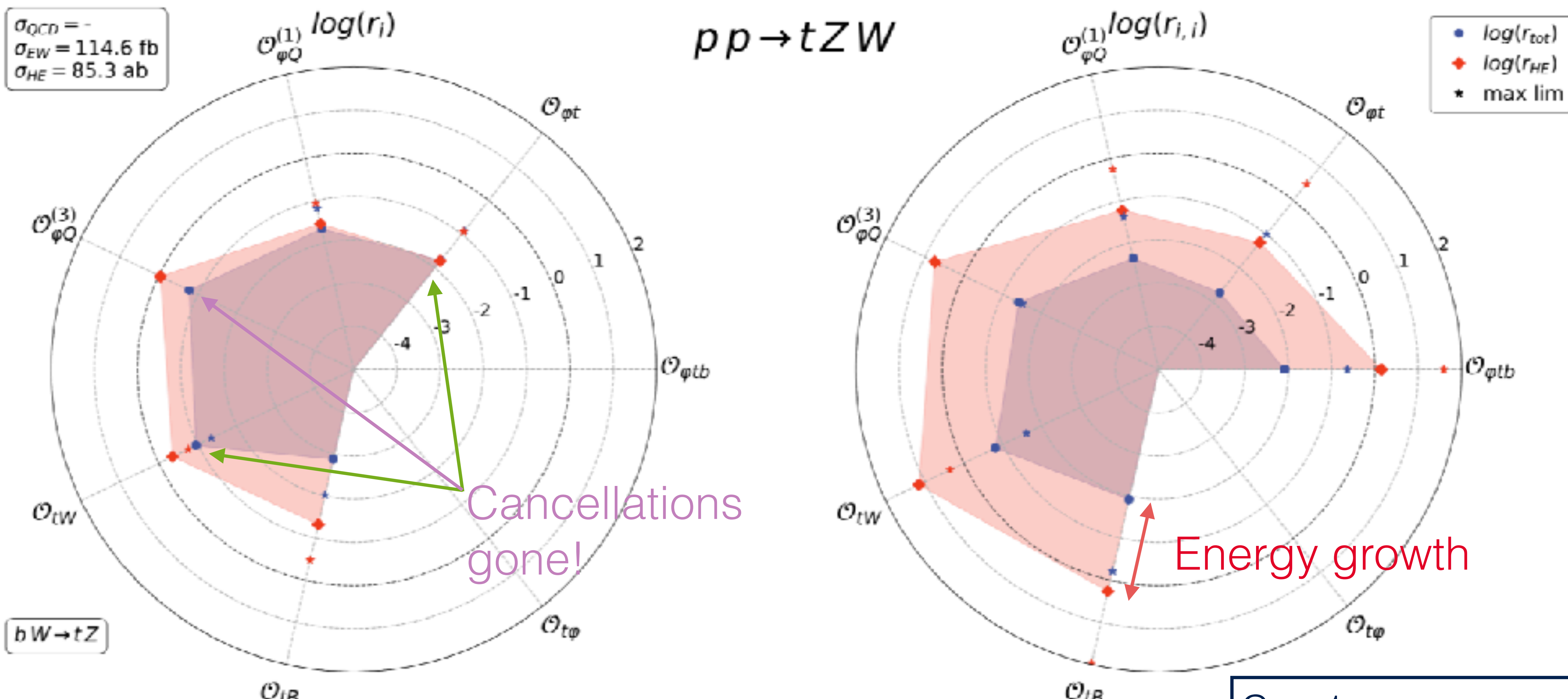


C_i = 1
Inclusive
p_T (W,Z)> 500 GeV

Expected growth is there!

tZW total & high energy xs

interference/SM　　　　square/SM

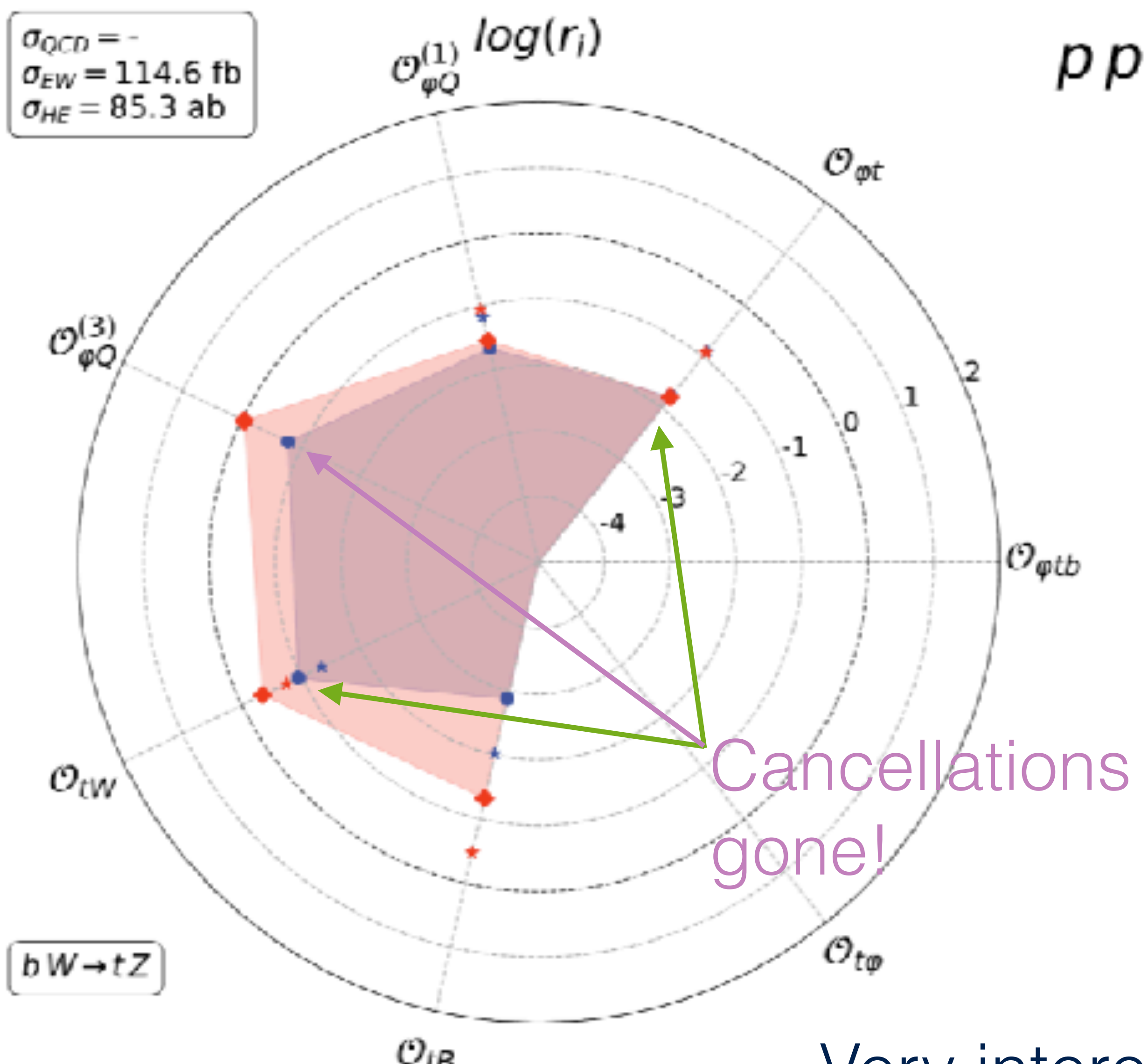


$C_i = 1$
Inclusive
p_T (W,Z)> 500 GeV

Expected growth is there!

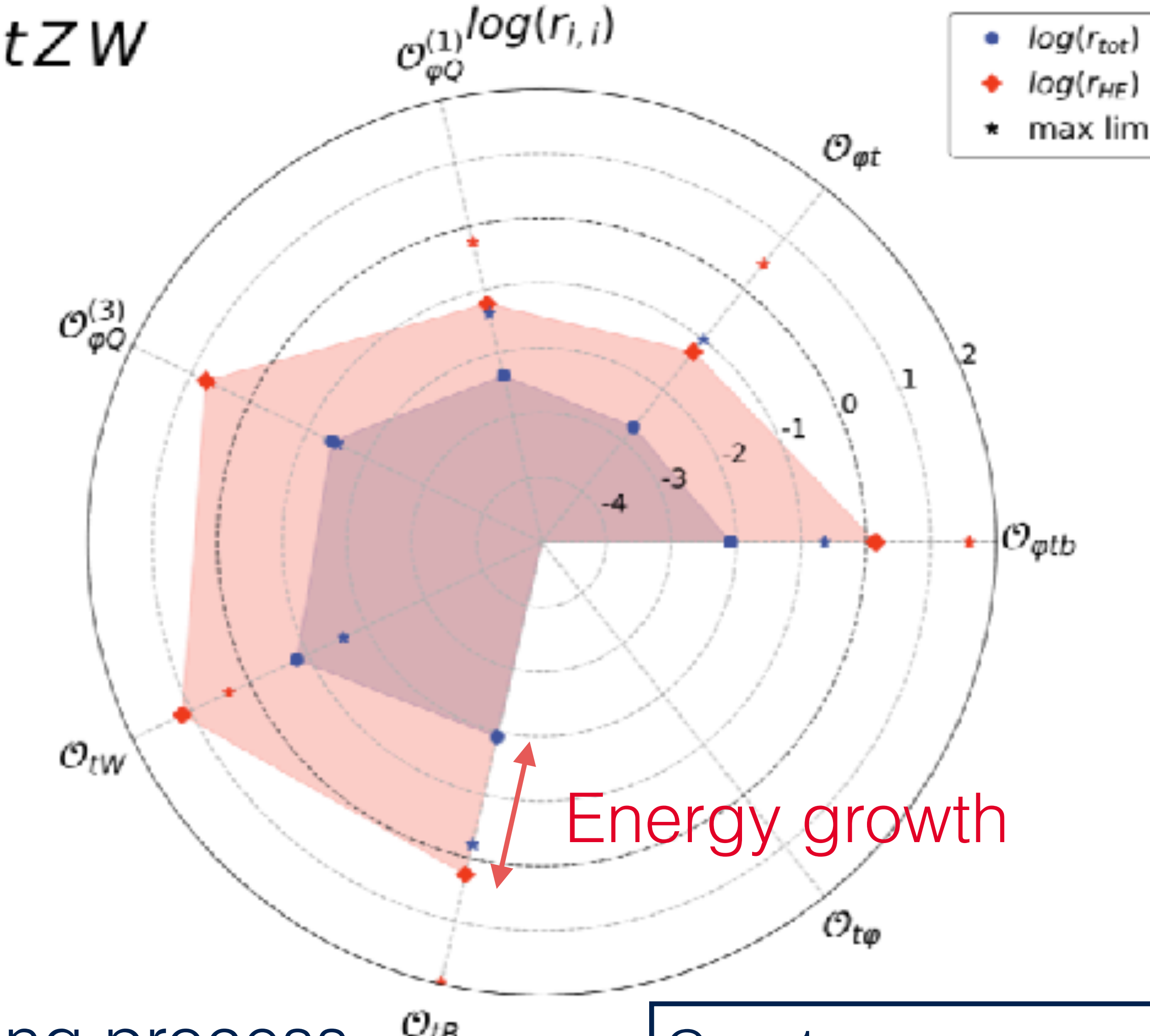
tZW total & high energy xs

interference/SM



$p\,p \to t\,Z\,W$

square/SM

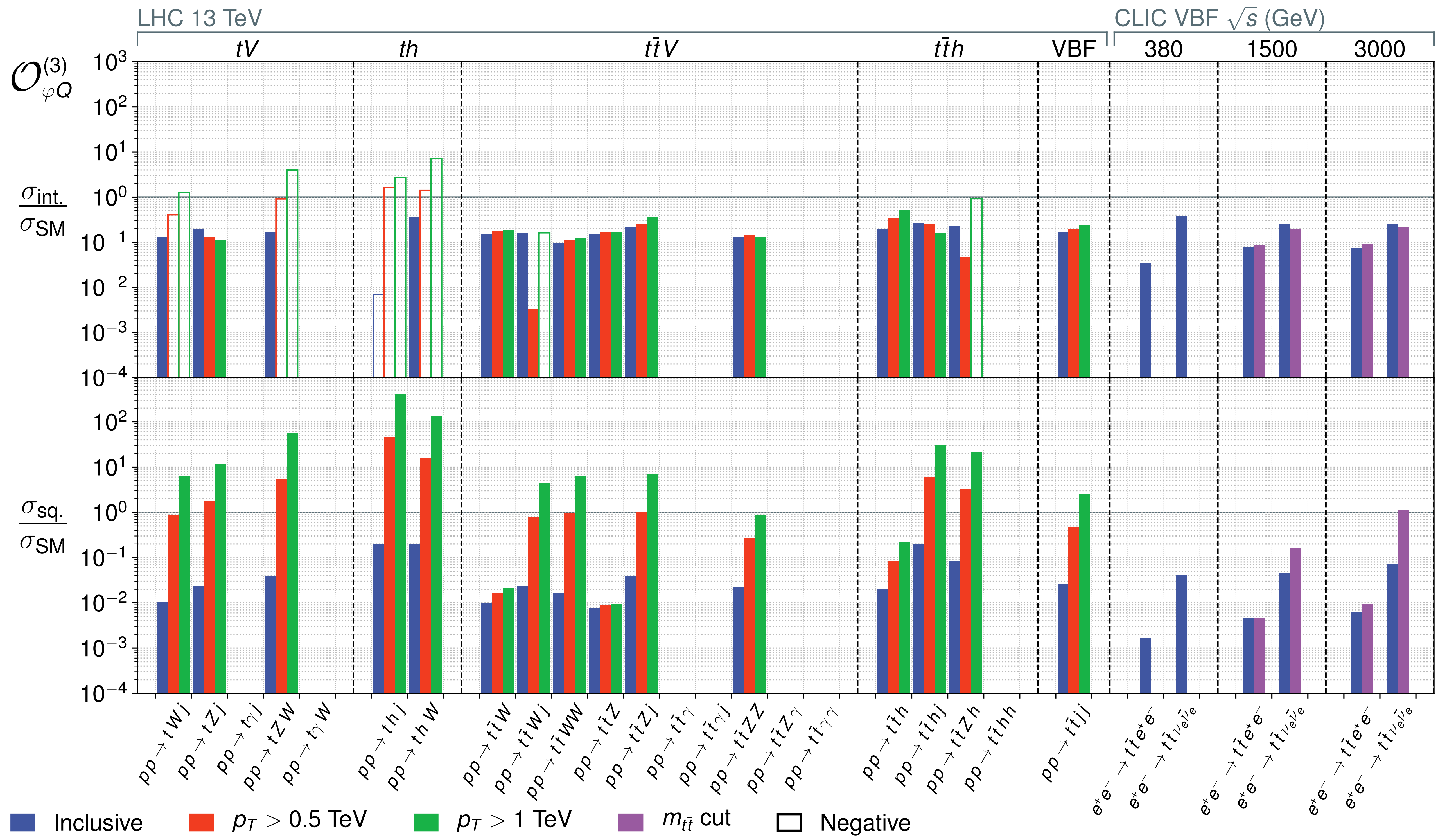


Expected growth is there!

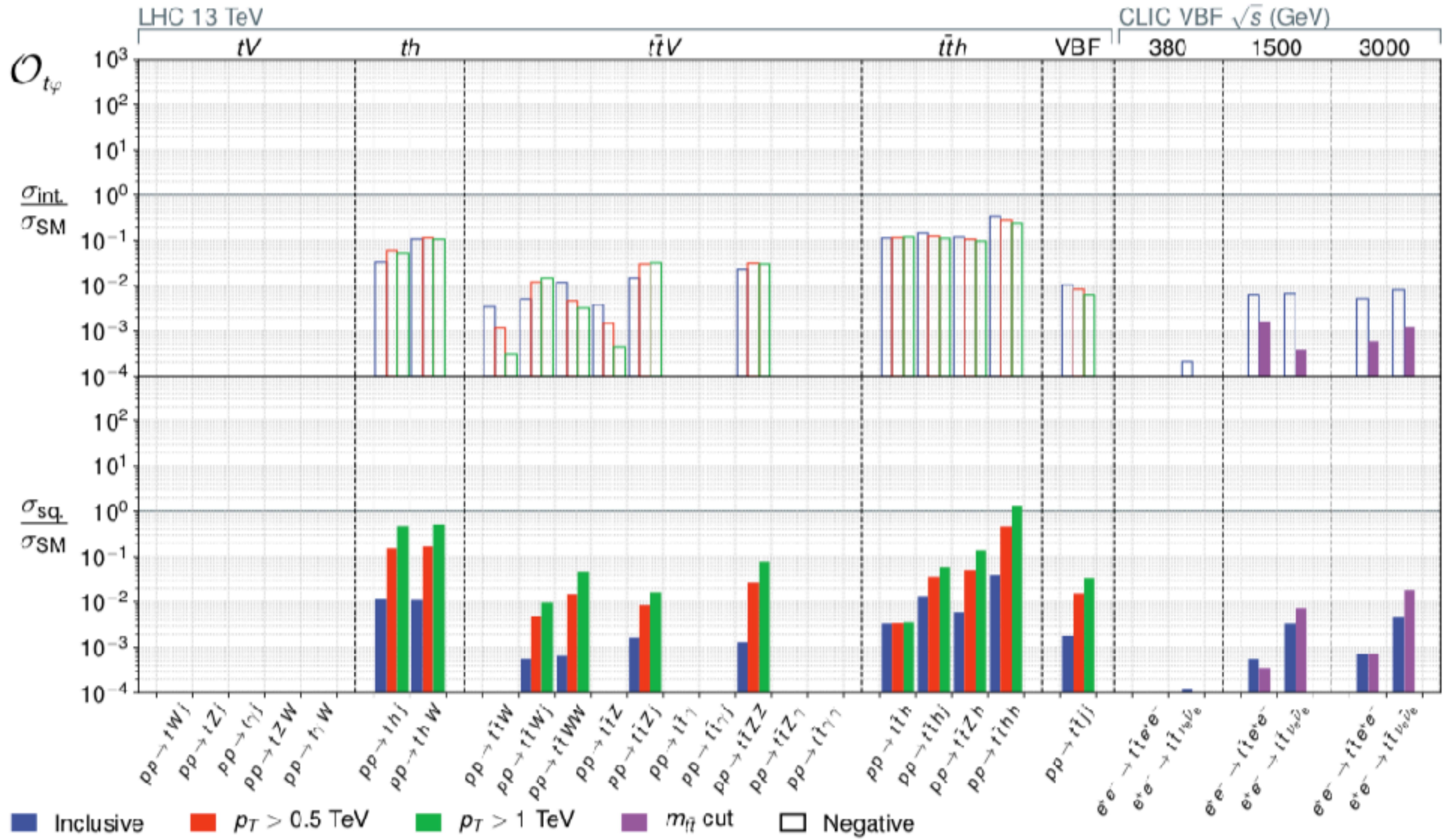
Very interesting process that should be measured at the LHC

$C_i = 1$
Inclusive
p_T (W,Z)> 500 GeV

Charged current operator



Yukawa operator



Embedding the amplitudes

'Future collider' amplitudes & processes

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

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'Future collider' amplitudes & processes

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

ttZh: LHC vs FCC-hh

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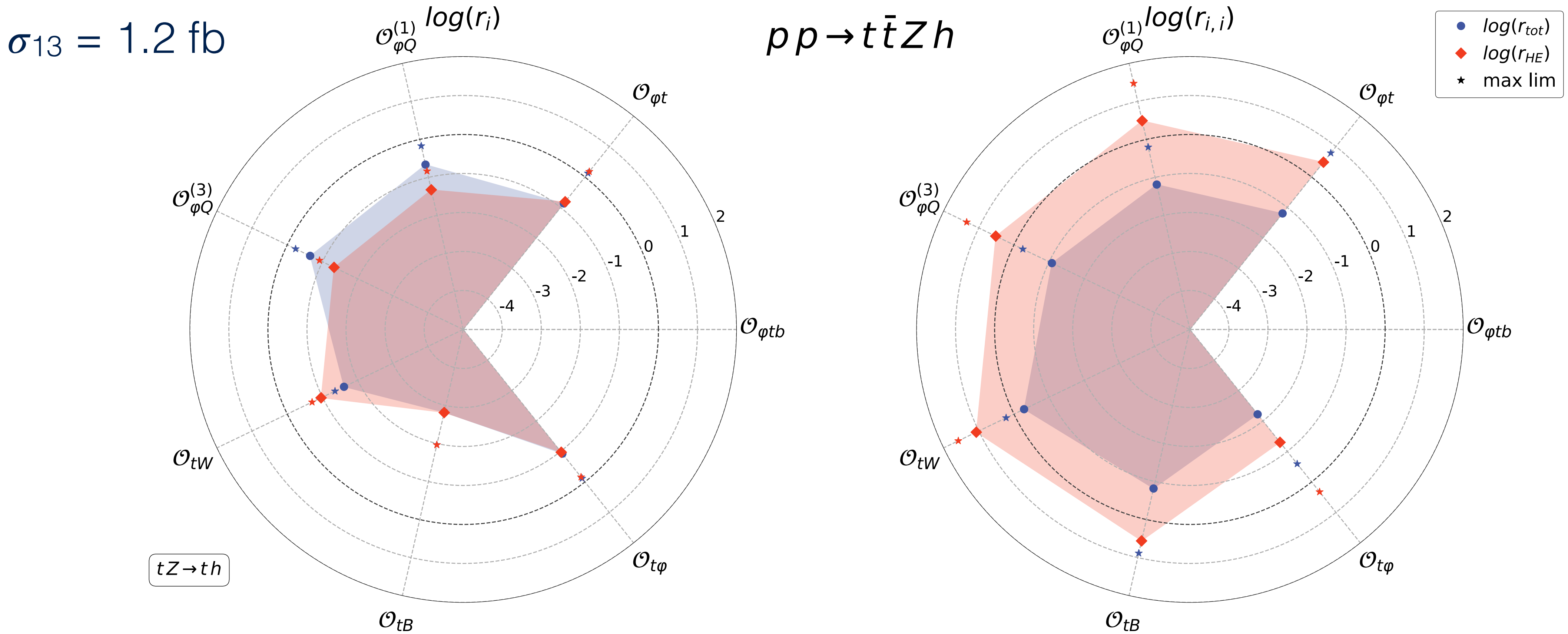
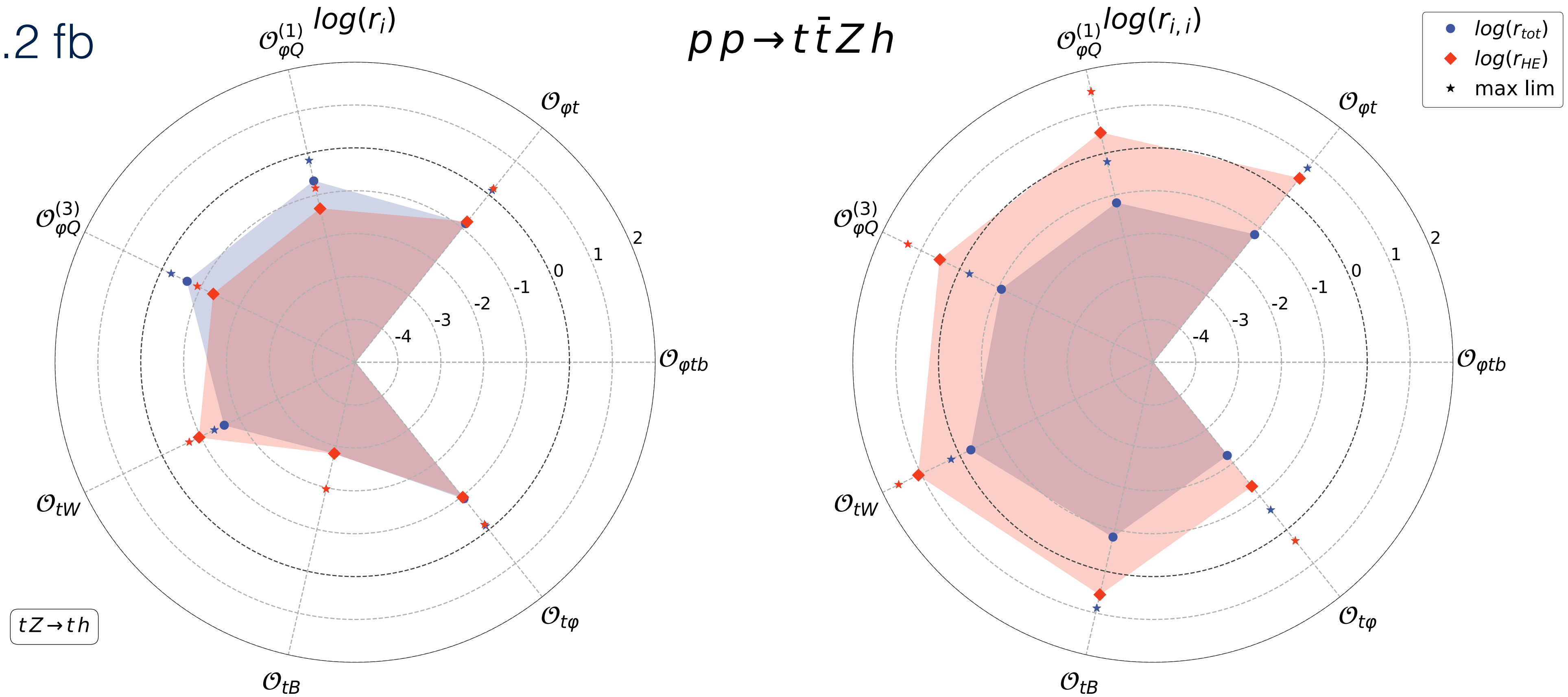


ttZh: LHC vs FCC-hh

High energy: p_T (Z,h) > 500 GeV

σ_{13} = 1.2 fb



ttZh: LHC vs FCC-hh

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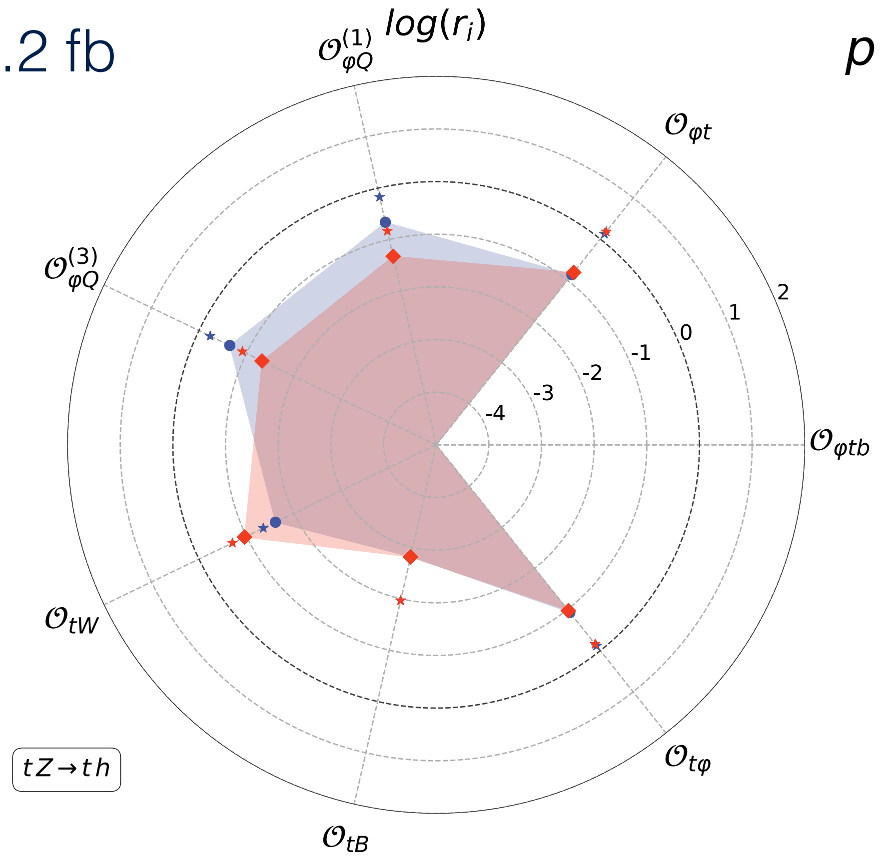
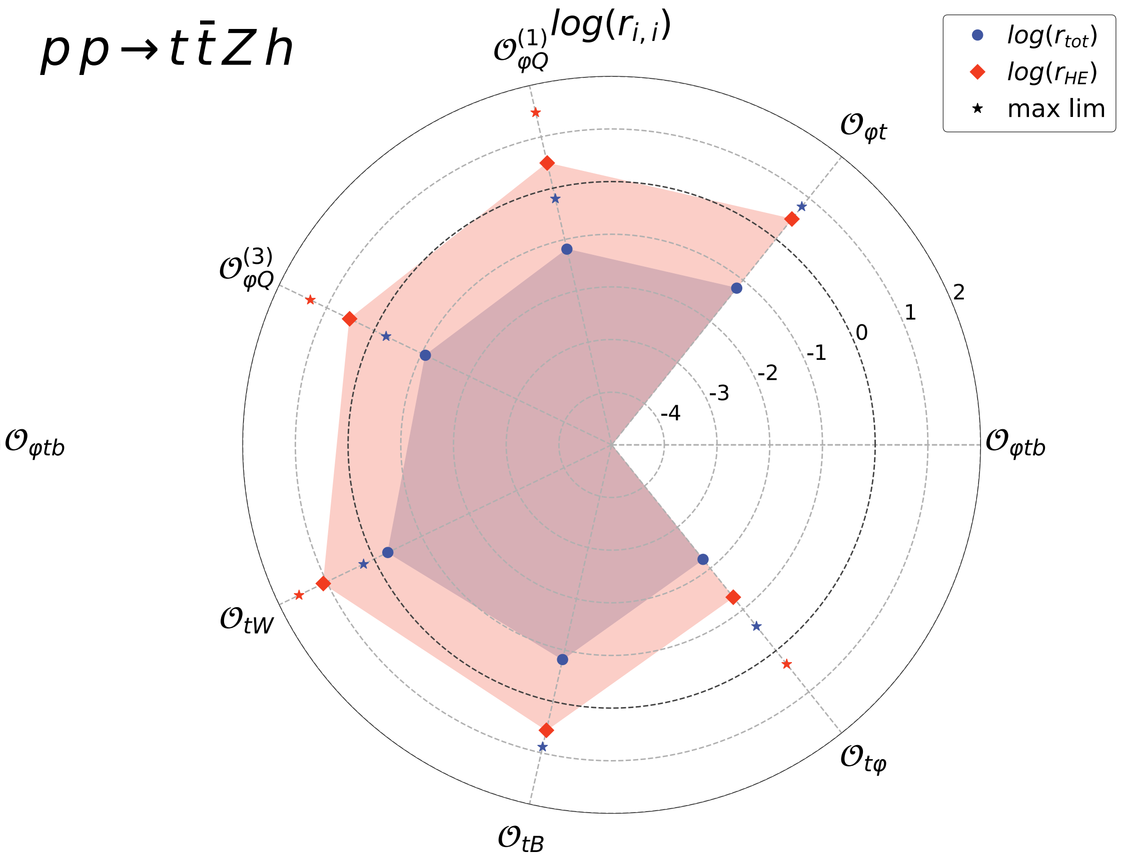
σ_{13} = 1.2 fb

Interference: phase space cancellations



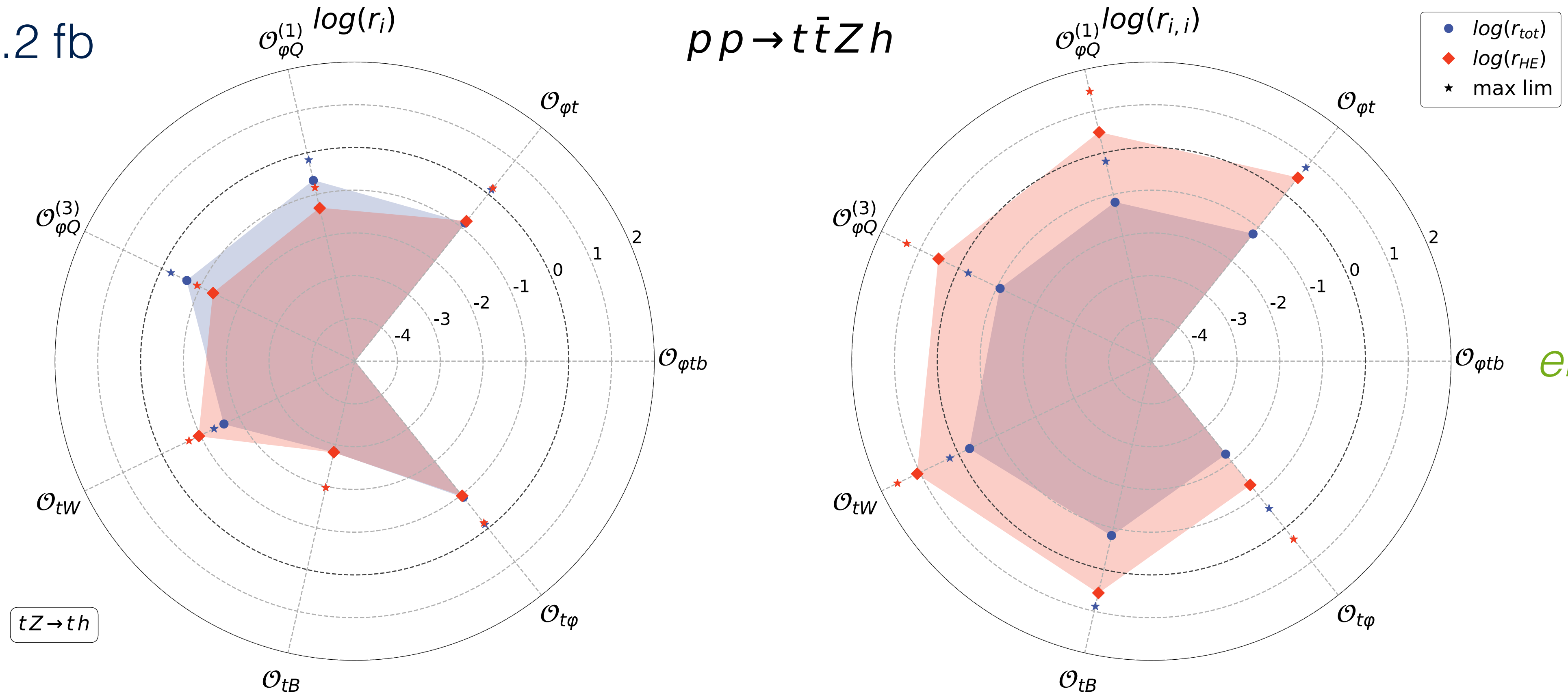


ttZh: LHC vs FCC-hh

High energy: $p_T\,(Z,h) > 500$ GeV

$\sigma_{13} = 1.2$ fb

Interference: phase space cancellations



Quadratic: energy growth & O(1-10)

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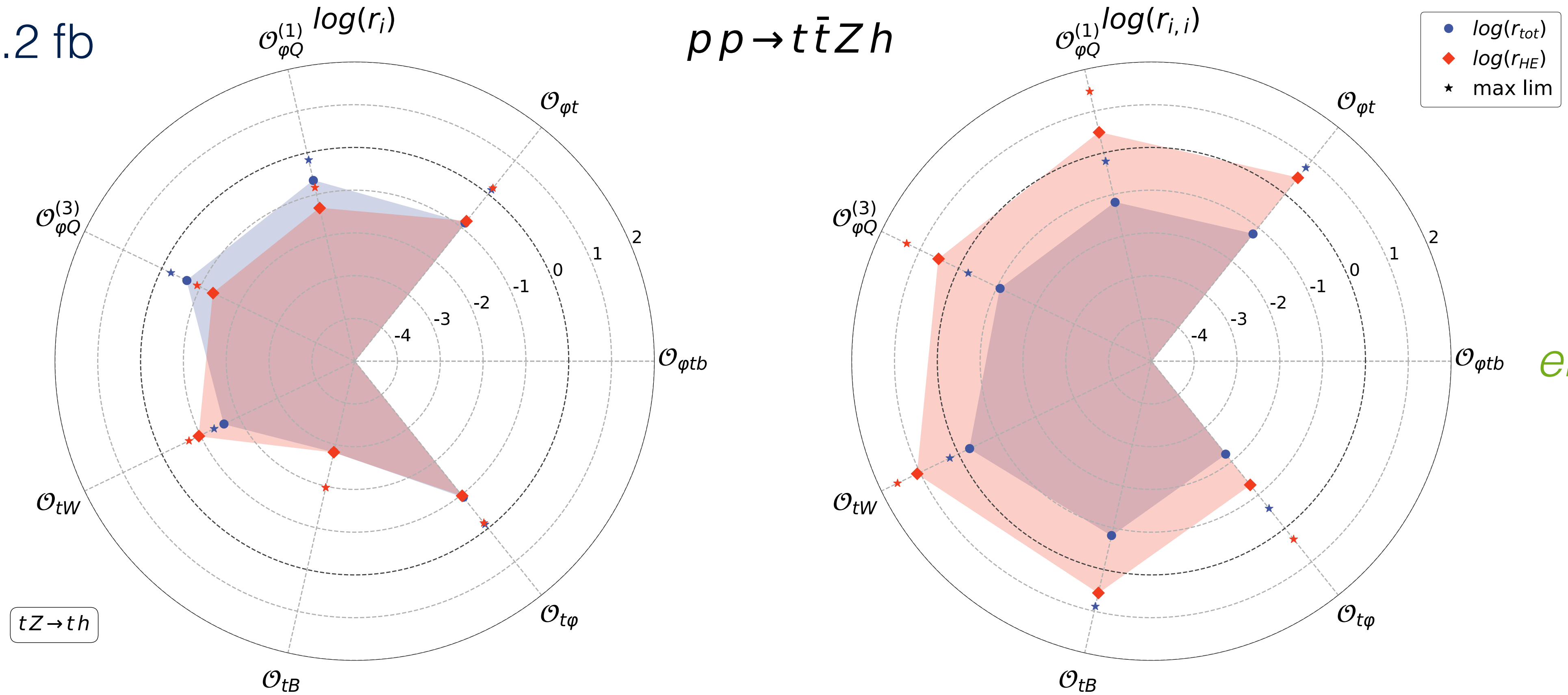

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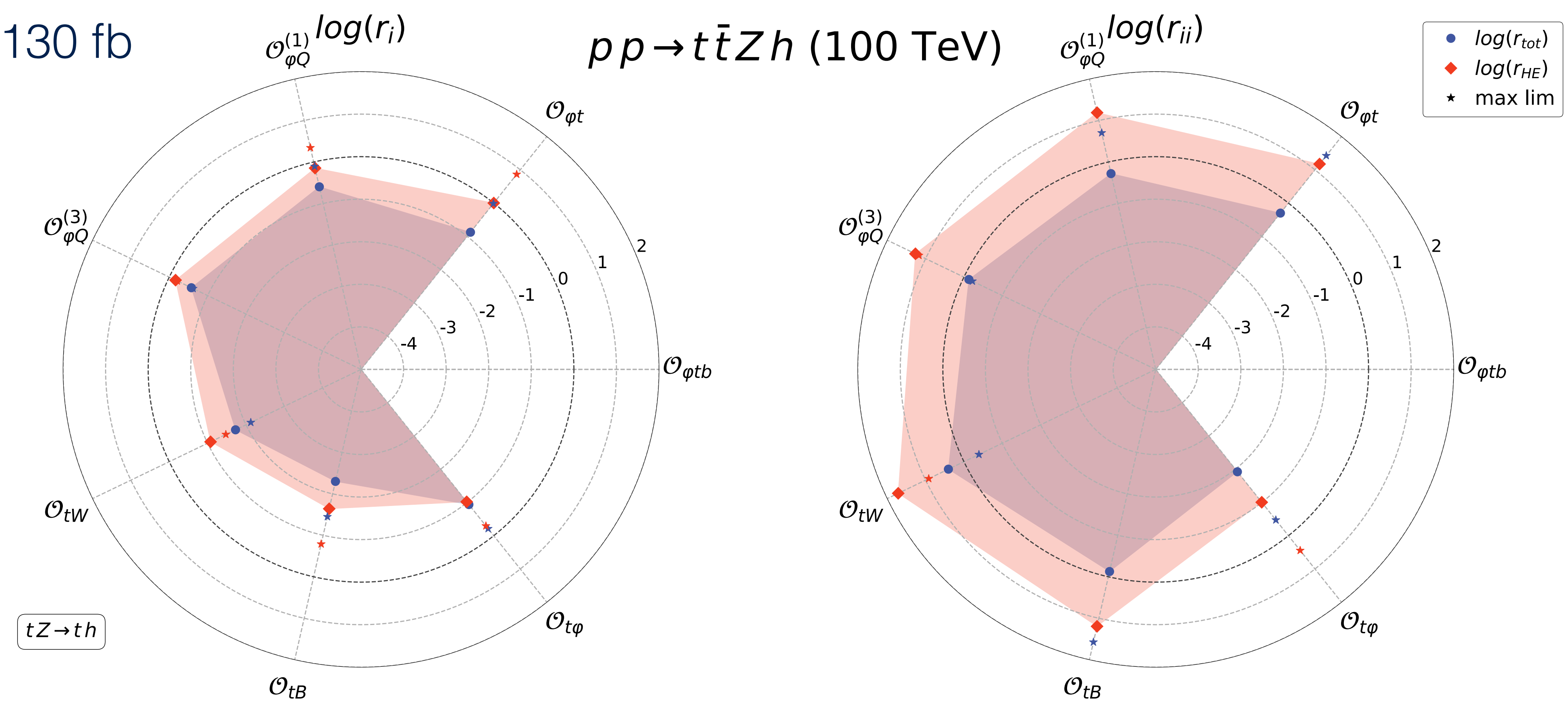
σ_{100} = 130 fb



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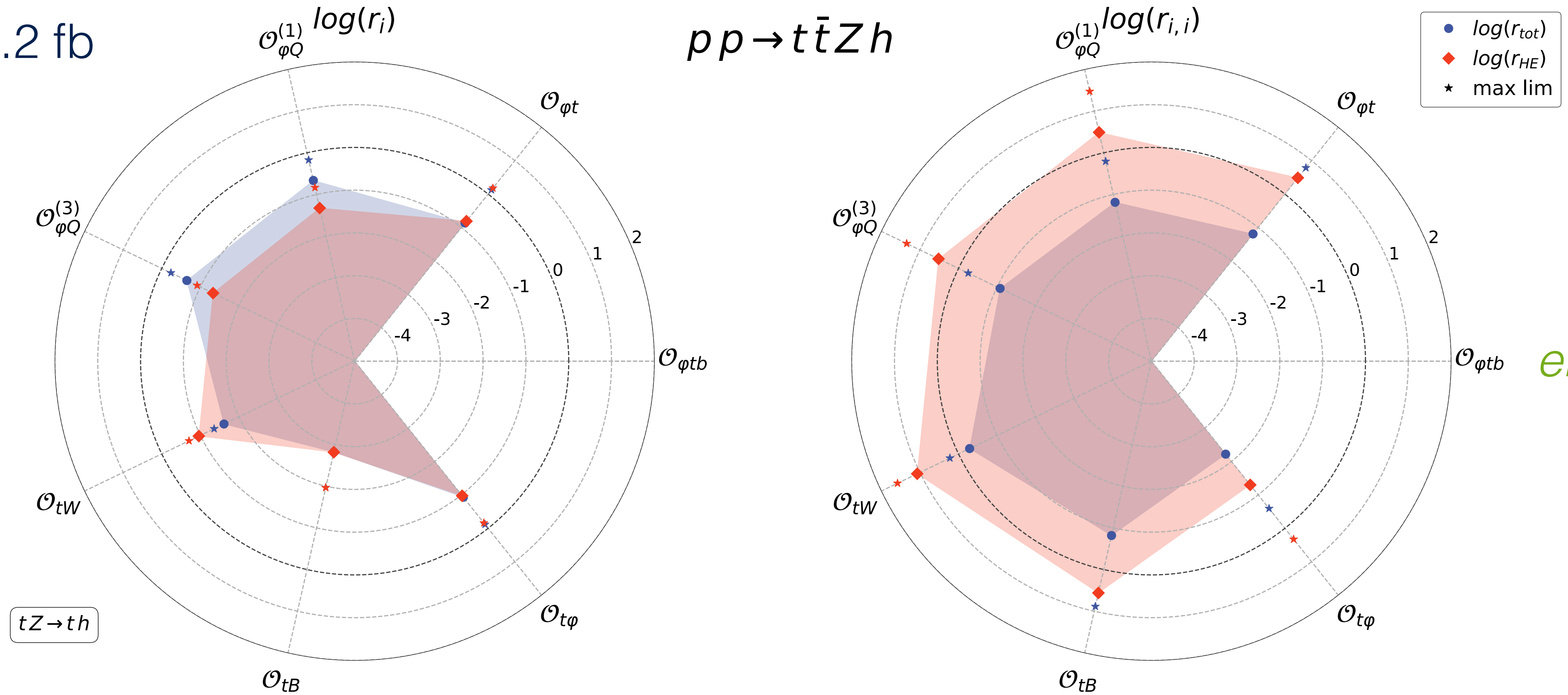

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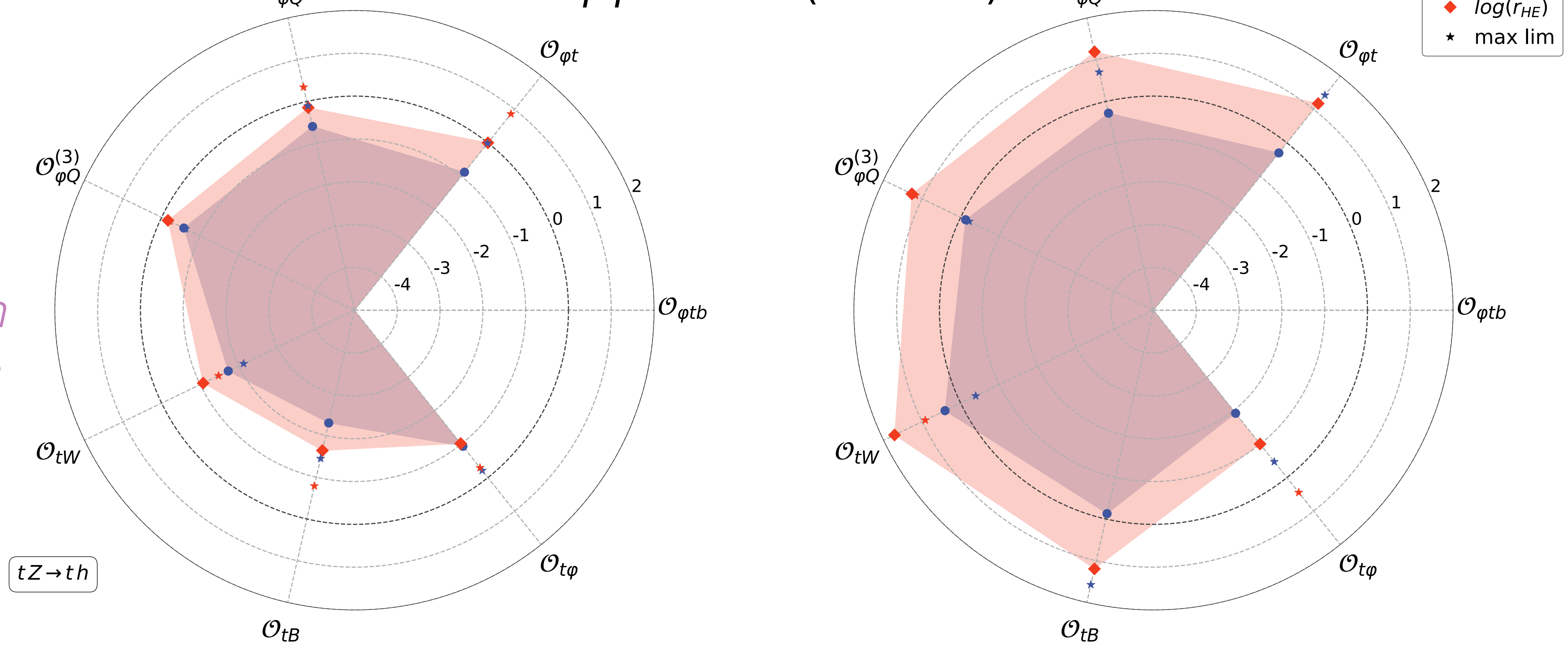
Interference: energy growth & O(1) effects



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$pp \to t\bar{t}Zh$

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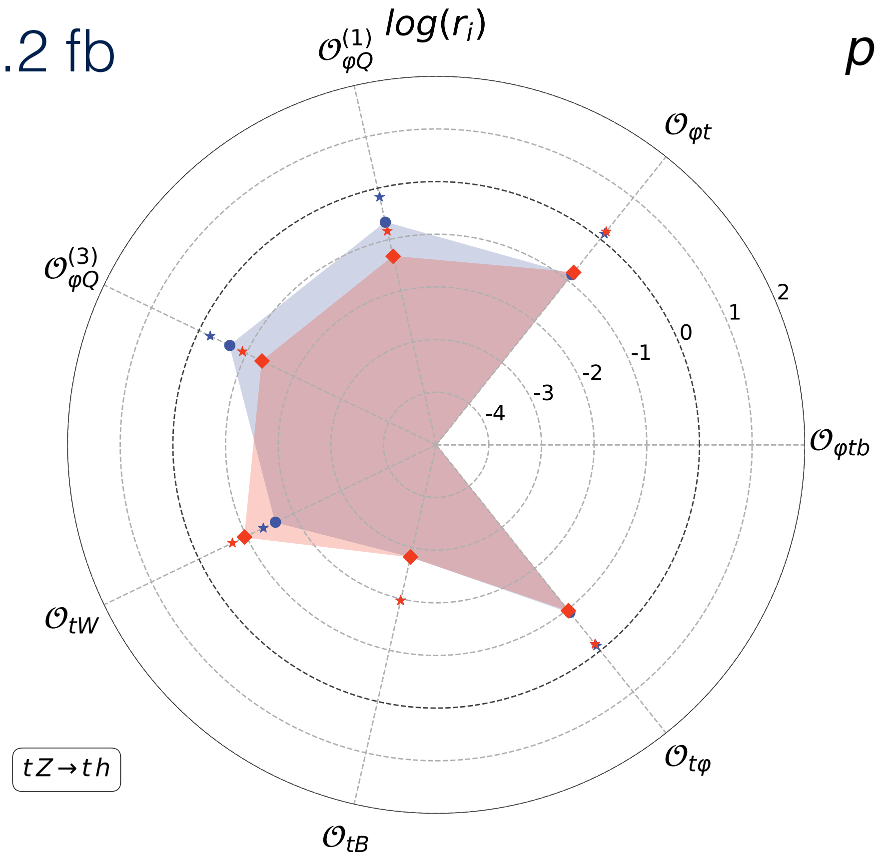
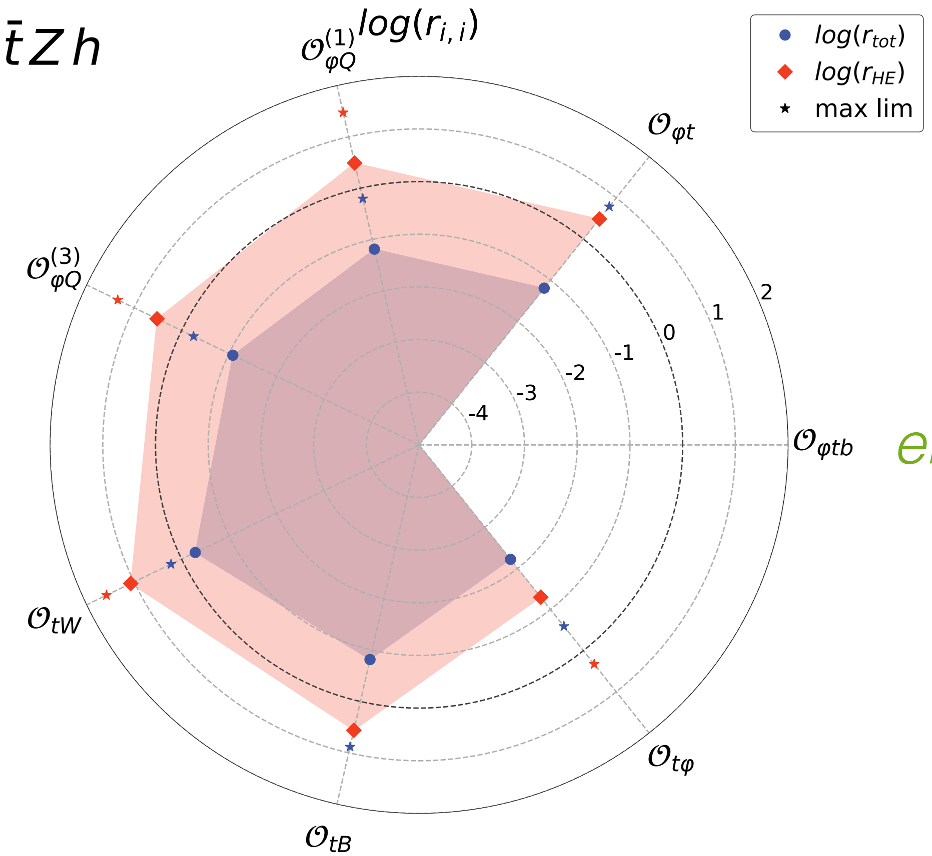


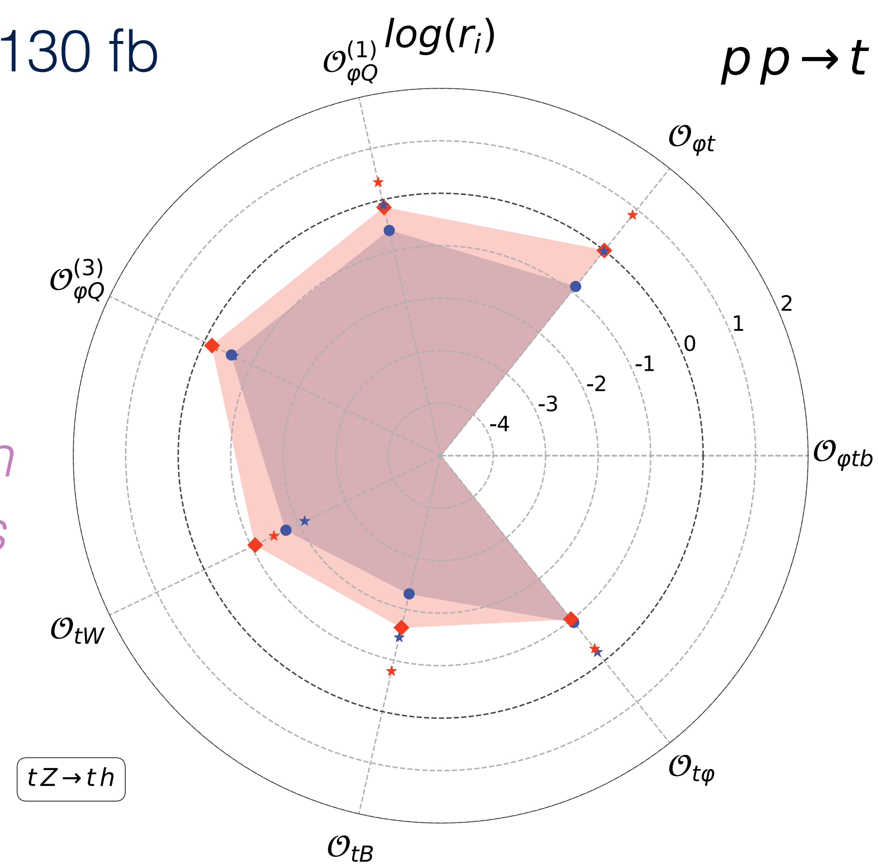


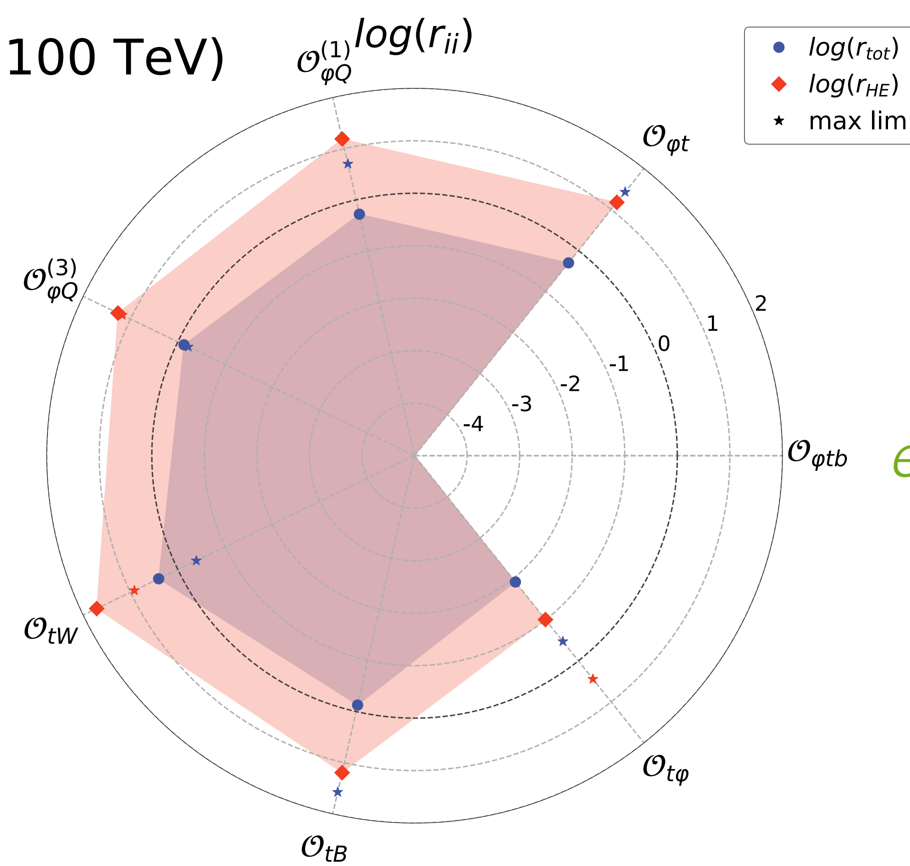
Quadratic: energy growth & O(1-10)

σ_{100} = 130 fb

$pp \to t\bar{t}Zh$ (100 TeV)

Interference: energy growth & O(1) effects





Quadratic: energy growth & O(10-100)

High-energy EW tops

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Sometimes, need to go beyond 4-point scattering

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- Yukawa & Triple Higgs operators (3 & 6 Higgs fields)

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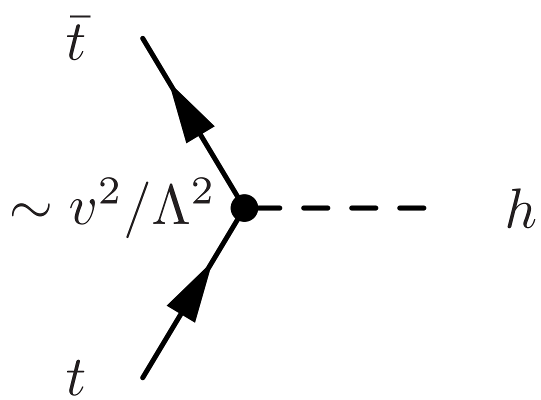
$$(\varphi^\dagger\varphi)^2(\bar{Q}\,t\,\tilde{\varphi})$$



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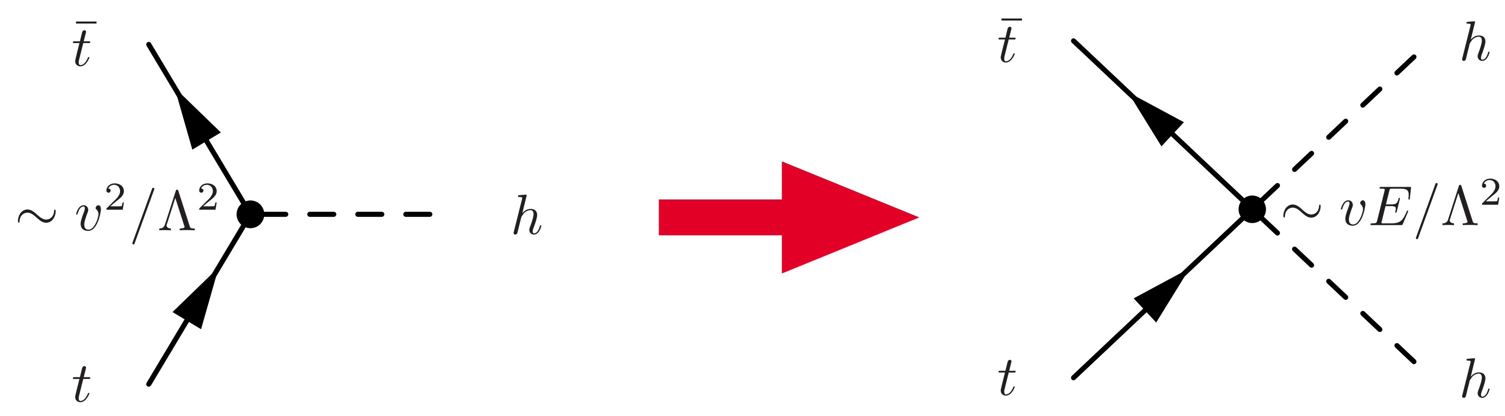

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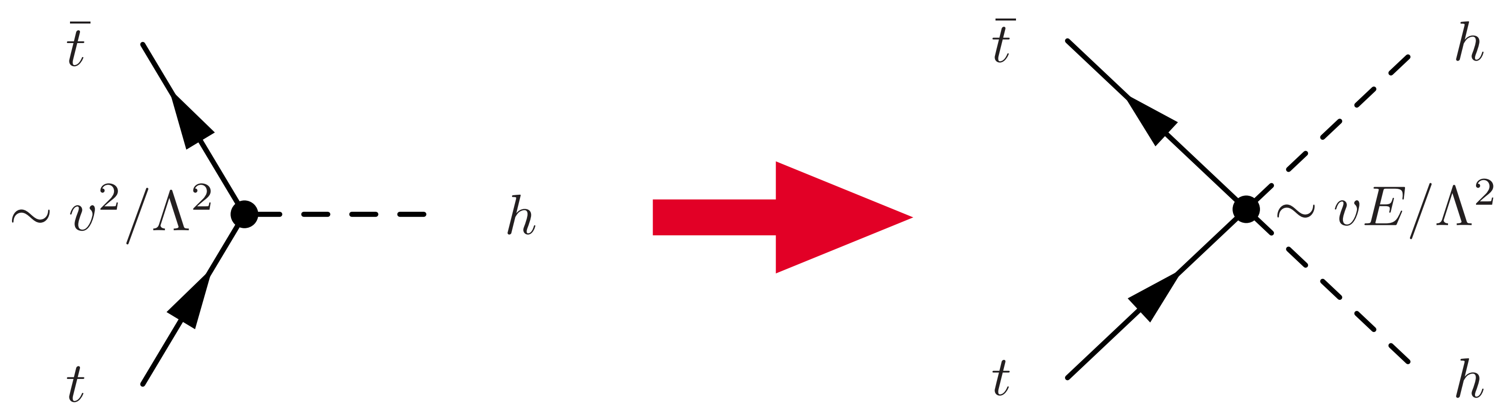

$$
\begin{aligned}
t\,h &\to t\,h \\
t\,W_L &\to t\,W_L \\
t\,Z_L &\to t\,Z_L \\
b\,W_L &\to t\,h
\end{aligned}
$$

High-energy EW tops

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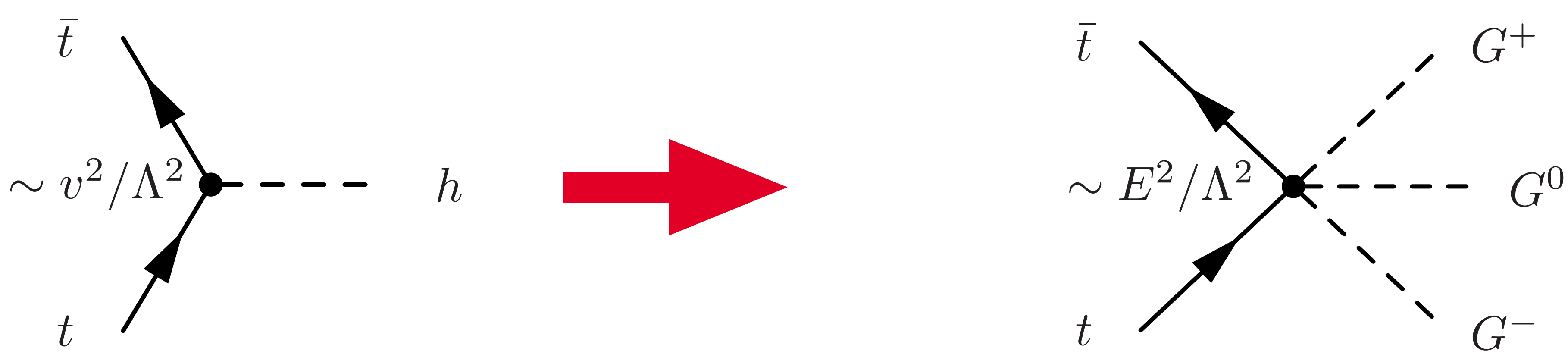

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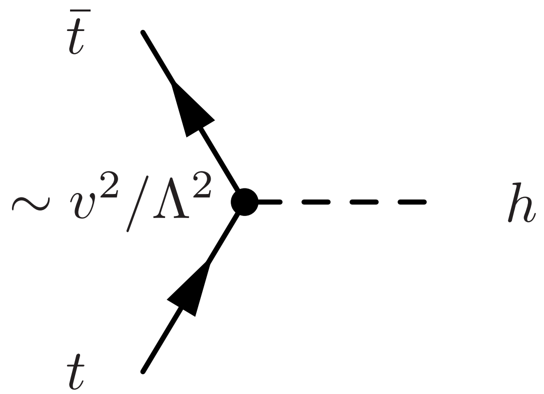

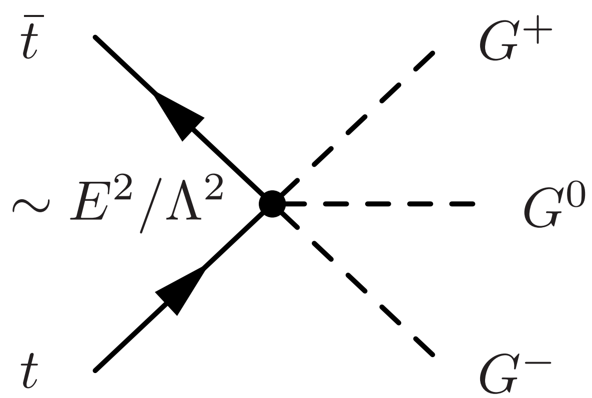

Essential prediction of **SMEFT**

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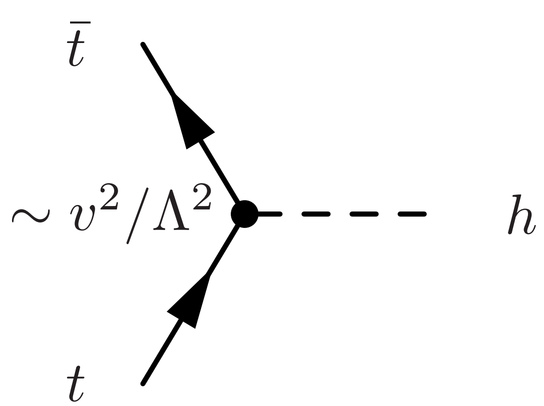

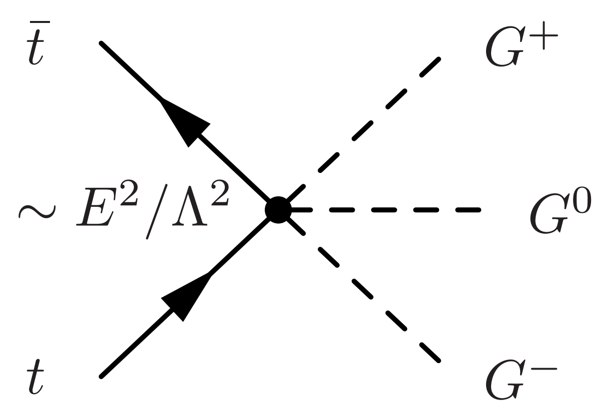

Essential prediction of **SMEFT**

- Higgs & Goldstones in the same multiplet

$$\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix} -iG^+ \\ v+h+iG^0 \end{pmatrix}$$

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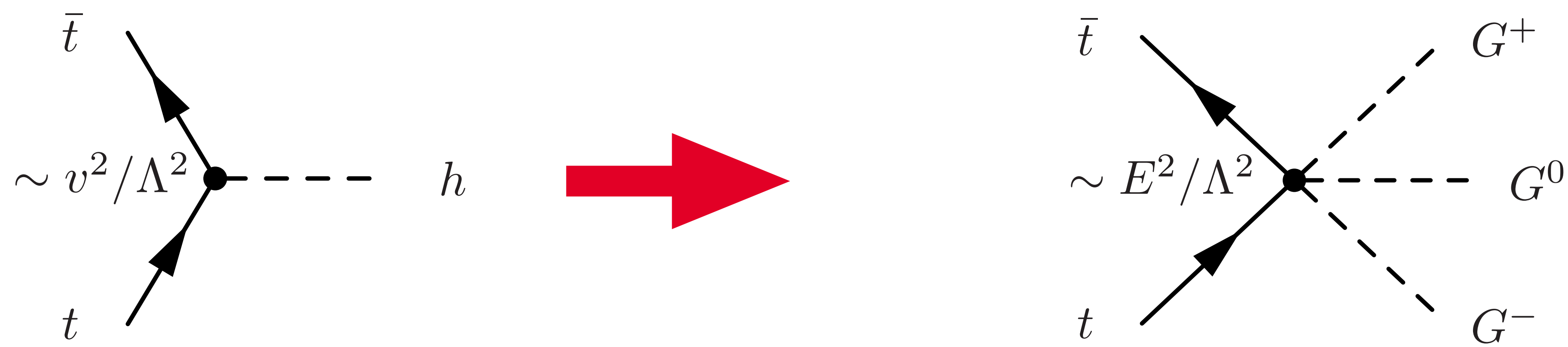

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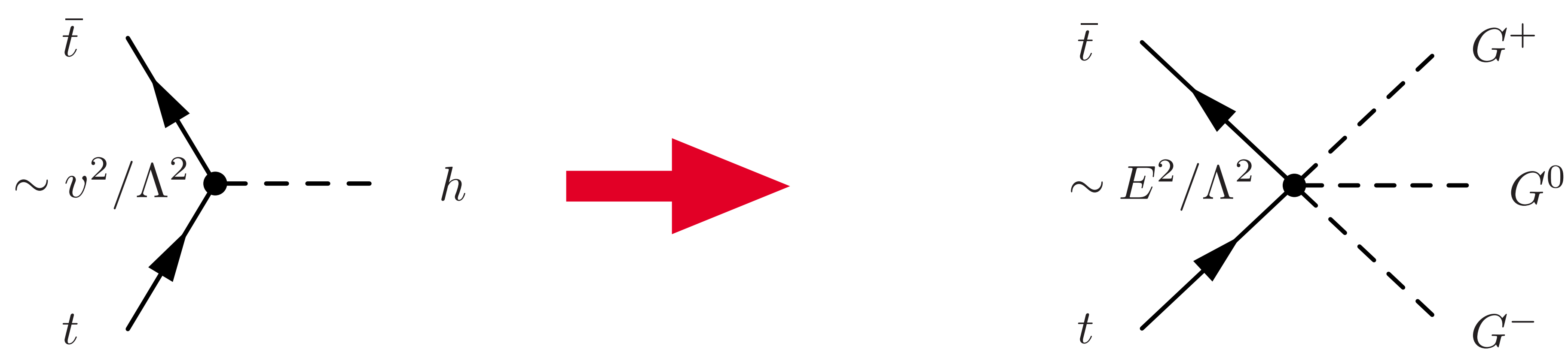

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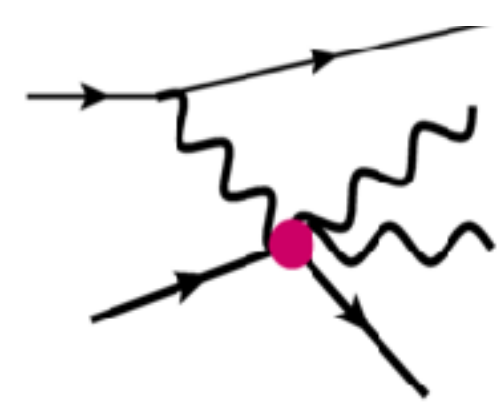


[Henning et al.; PRL 123 (2019), no.18 181801]

Part III
Pinpointing four fermion operators in ttbb

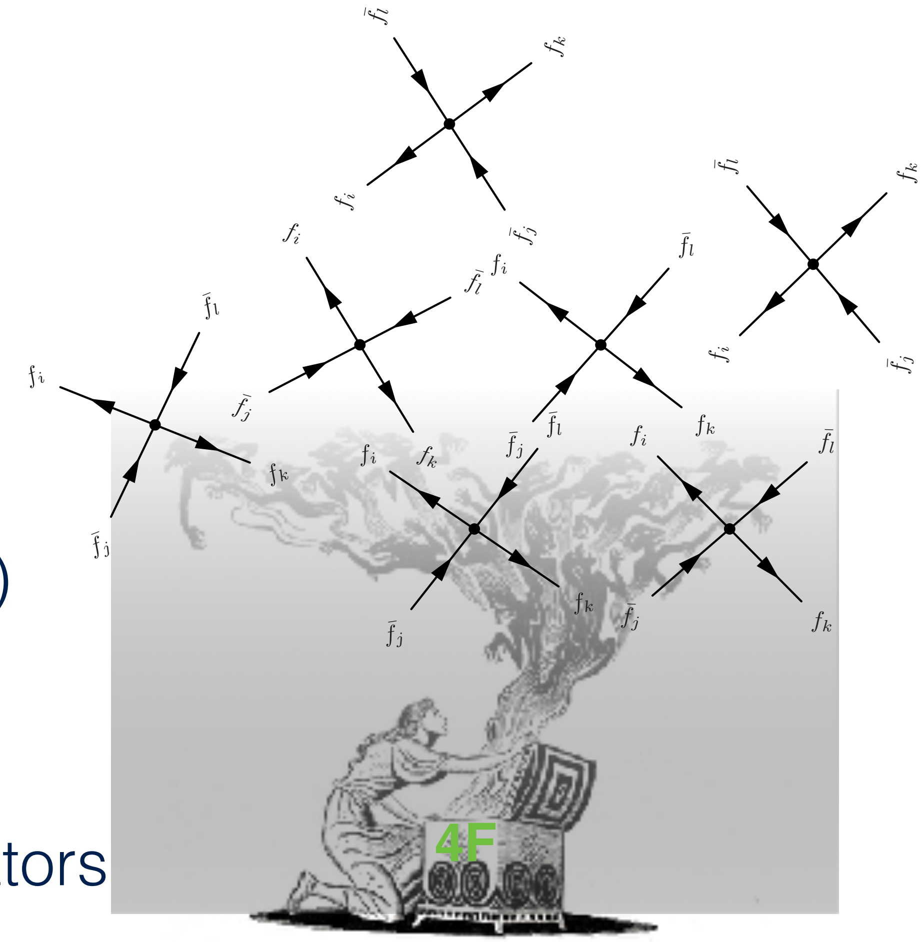
Four fermions

Pandora's box of EFT

- Many flavor indices (mostly flavor violating)

In the top/EW SMEFT:

- U(3)^3 x U(2)^2 flavor assumption ~ 30 operators

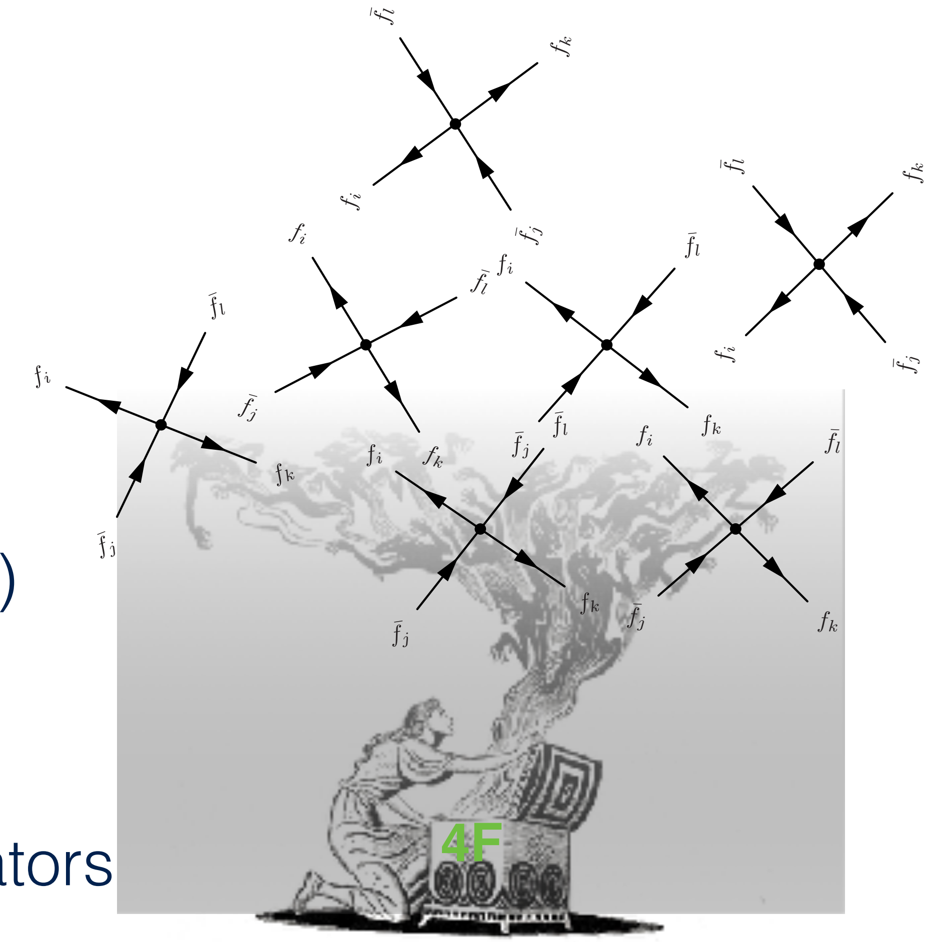


3rd gen. only

3rd gen. + universal light gen.

universal light gen.

Four fermions



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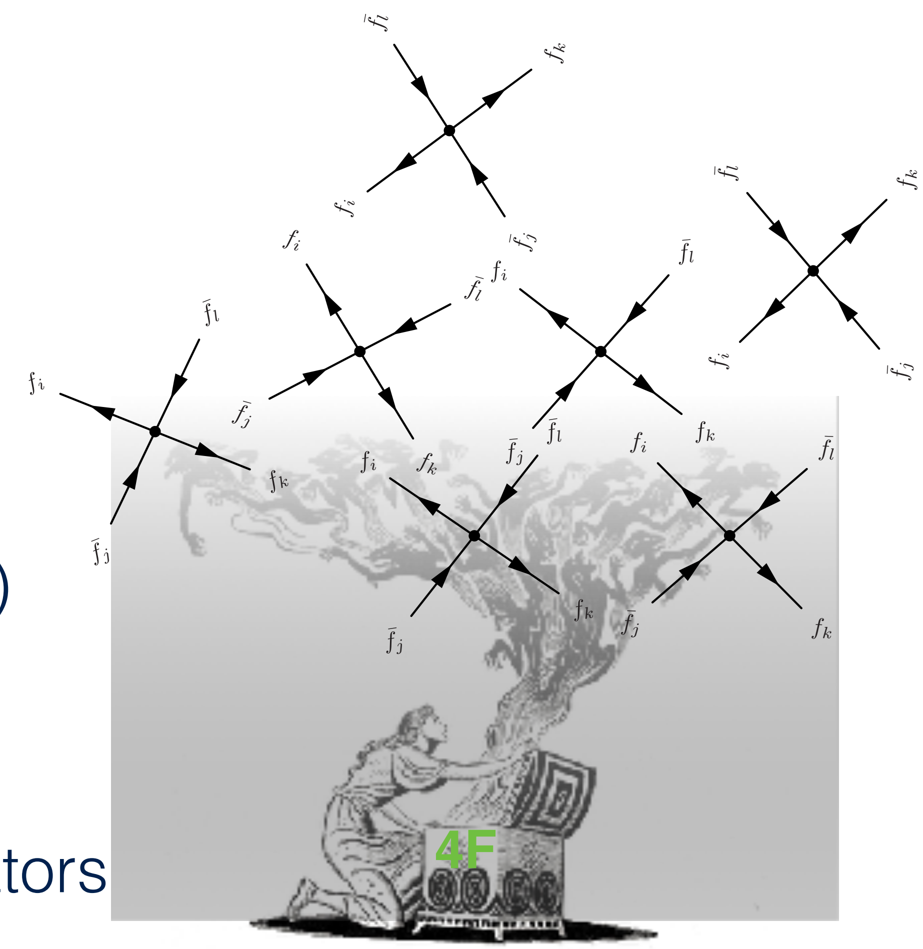

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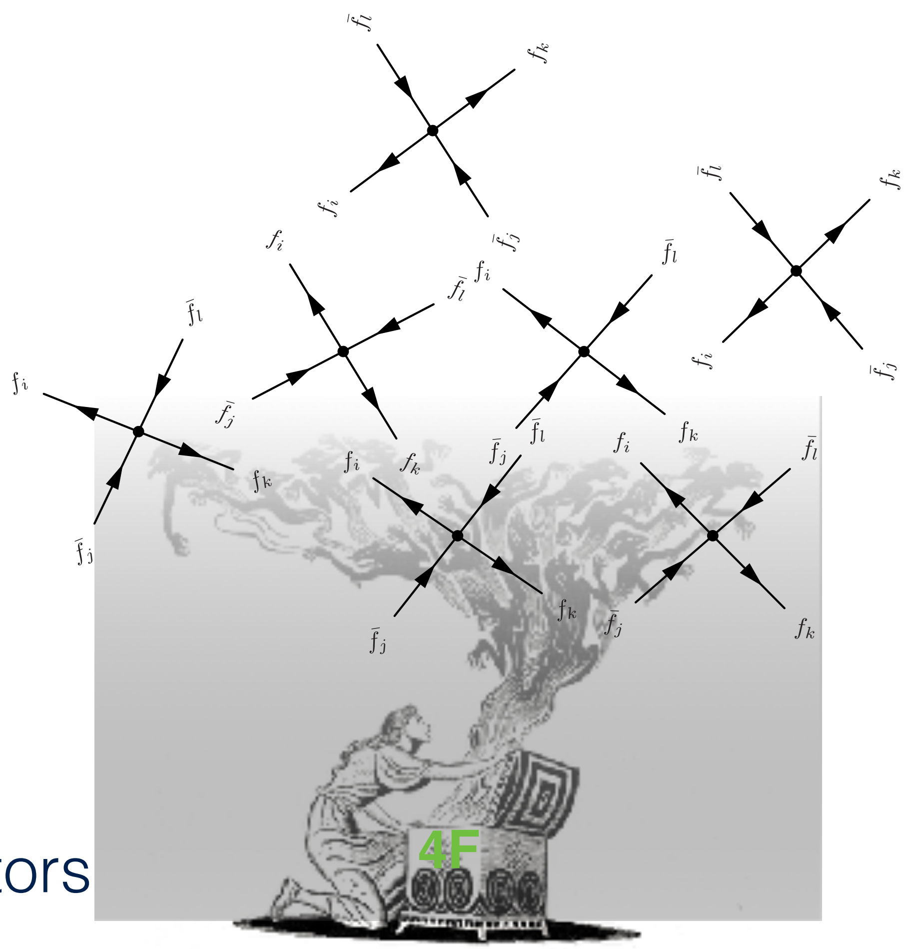

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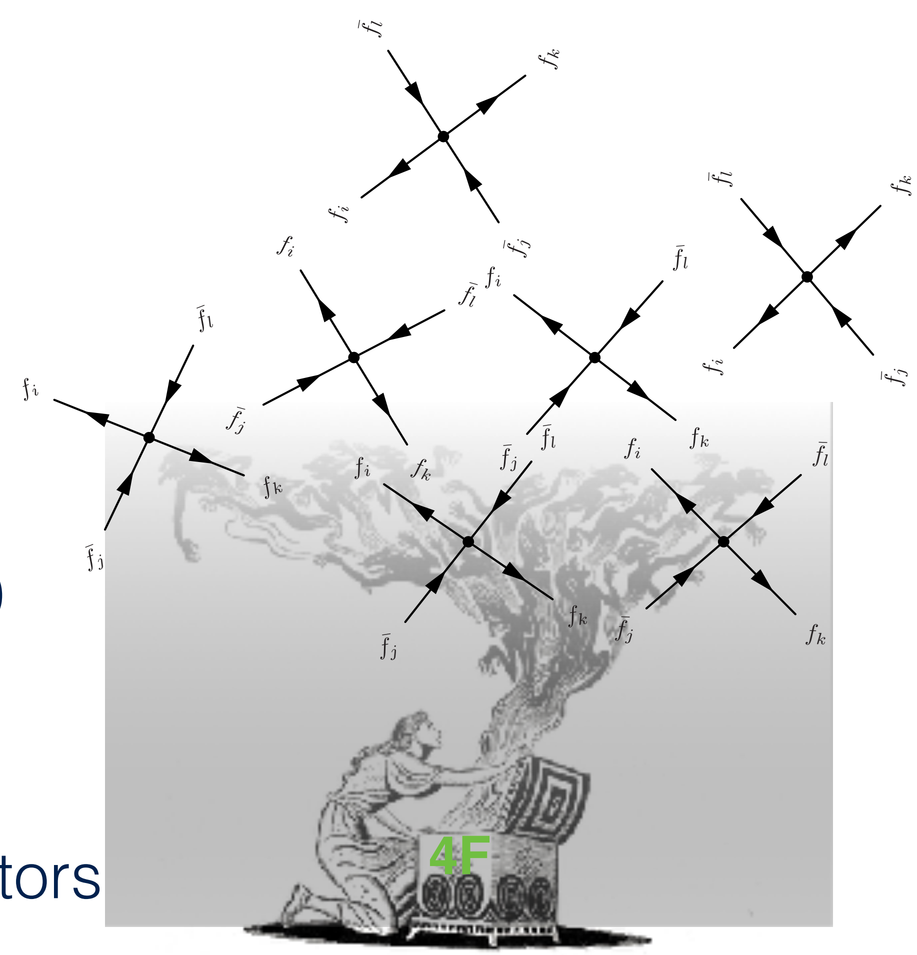

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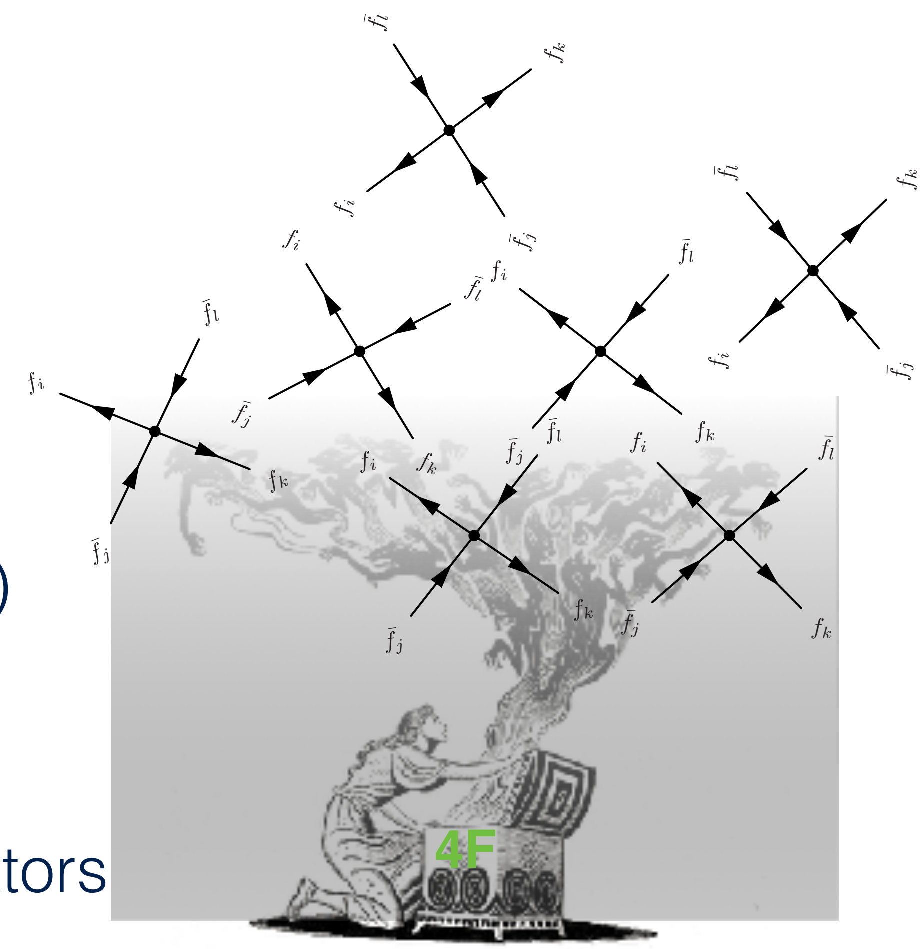

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Can contribute to virtually any top-quark process

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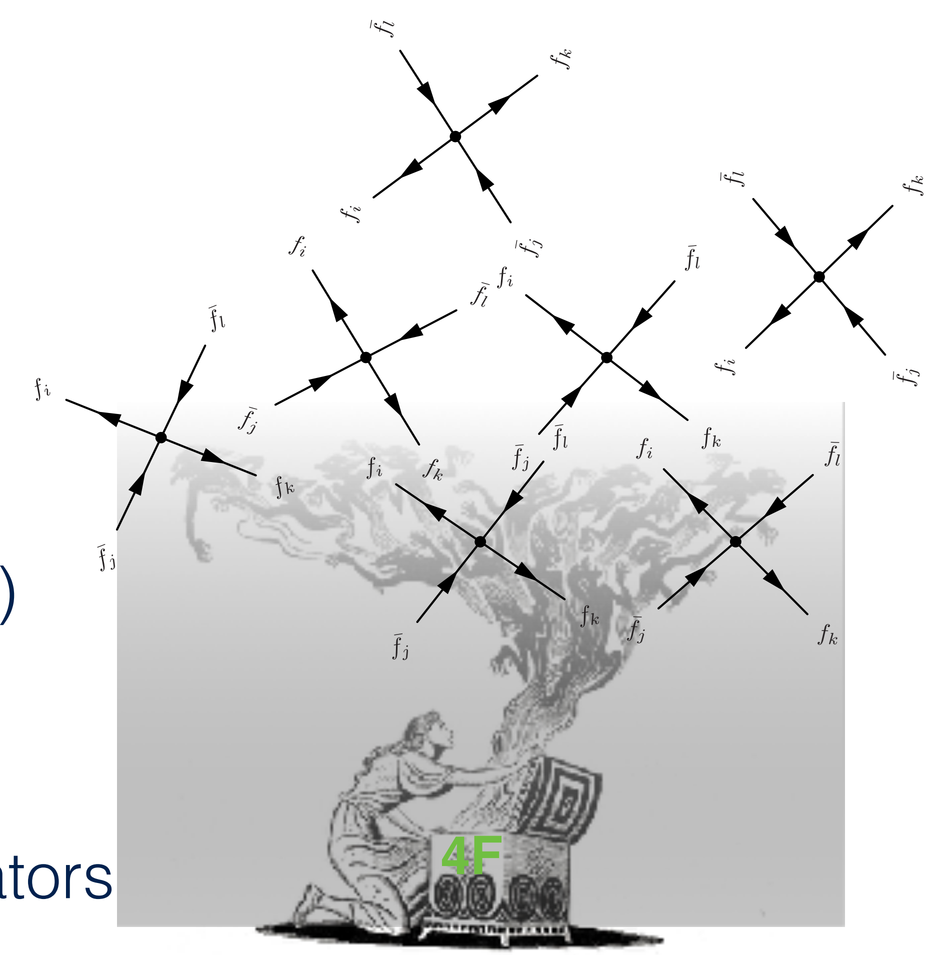

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Can contribute to virtually any top-quark process

tt, tt+W/Z/H/γ, single-top(+X), 4top, ttbb, ttjj

Four-heavy operators

Generated by heavy new physics coupled to 3rd gen.

- Top mass generation
- Z'/Composite dynamics

Contain tttt, ttbb & bbbb interactions

- Color single/triplet
- Scalar/vector currents
- L/R chiral currents

Partly constrained by four top production at the LHC

- • $O^1_{QQ} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{Q}\,\gamma^\mu\,Q)\,,$
- • $O^8_{QQ} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{Q}\,\gamma^\mu\,T^A\,Q)\,,$
- • $O^1_{tt} = (\bar{t}\,\gamma_\mu\,t)\,(\bar{t}\,\gamma_\mu\,t)\,,$
- $O^1_{tb} = (\bar{t}\,\gamma_\mu\,t)\,(\bar{b}\,\gamma_\mu\,b)\,,$
- $O^8_{tb} = (\bar{t}\,\gamma_\mu T^A\,t)\,(\bar{b}\,\gamma_\mu\,T^A\,b)\,,$
- • $O^1_{Qt} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{t}\,\gamma^\mu\,t)\,,$
- • $O^8_{Qt} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{t}\,\gamma^\mu\,T^A\,t)\,,$
- $O^1_{Qb} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{b}\,\gamma^\mu\,b)\,,$
- $O^8_{Qb} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{b}\,\gamma^\mu\,T^A\,b)\,,$
- $O^1_{QtQb} = (\bar{Q}\,t)\,\varepsilon\,(\bar{Q}\,b)\,,$
- $O^8_{QtQb} = (\bar{Q}\,T^A\,t)\,\varepsilon\,(\bar{Q}\,T^A\,b)$

• contributes to four top

Four top production

Very rare process at the LHC ~ 9 fb

- LHC is at the edge of discovery (2.6 σ) *[CMS; EPJC 80 (2020) no.2, 75]*

Not yet a precision measurement

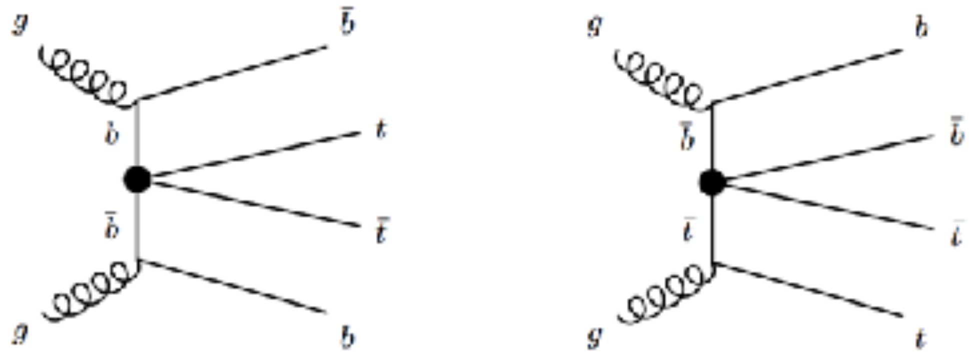
- Sensitive to four-heavy & two-heavy operators
- High mass threshold ~ 700 GeV

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\mathrm{tt}}$	$[-2.0, 1.9]$	$[-2.2, 2.1]$
$\mathcal{O}^1_{\mathrm{QQ}}$	$[-2.0, 1.9]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{\mathrm{Qt}}$	$[-3.4, 3.3]$	$[-3.7, 3.5]$
$\mathcal{O}^8_{\mathrm{Qt}}$	$[-7.4, 6.3]$	$[-8.0, 6.8]$

[CMS; JHEP 1911 (2019) 082]

4 out of 14 relevant
degrees of freedom

ttbb production



Less rare process at the LHC ~ 3 pb

- Measured at the LHC with ~ 30% accuracy [CMS; PLB 776 (2018) 355-378]
- Major background for ttH →bb
- Challenging process for MC predictions in SM [Jezo et al.,EPJC 78 (2018) 6, 502]
- Turn it around into a new physics signature

Affected by 13 out of 14 operators [Degrande et al.; JHEP 03 (2011) 125]

- Some of which have never been constrained before

[D'Hondt, Mariotti, KM, Moortgat, Zhang; JHEP 1811 (2018) 131]

Exploratory study of 4 heavy quark operators in ttbb

- New limits & future projections from EFT-optimised, differential analyses
- New & complementary information w.r.t 4 top measurement

ttbb in SMEFT

Operator	$t\bar{t}b\bar{b}$	$t\bar{t}t\bar{t}$
$O^1_{QQ} = \frac{1}{2}(\bar{Q}\,\gamma_\mu\,Q)\,(\bar{Q}\,\gamma^\mu\,Q)$,	✓	✓
$O^8_{QQ} = \frac{1}{2}(\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{Q}\,\gamma^\mu\,T^A\,Q)$,	✓	✓
$O^1_{tb} = (\bar{t}\,\gamma_\mu\,t)\,(\bar{b}\,\gamma_\mu\,b)$,	✓	
$O^8_{tb} = (\bar{t}\,\gamma_\mu T^A\,t)\,(\bar{b}\,\gamma_\mu\,T^A\,b)$,	✓	
$O^1_{tt} = (\bar{t}\,\gamma_\mu\,t)\,(\bar{t}\,\gamma_\mu\,t)$,		✓
$O^1_{bb} = (\bar{b}\,\gamma_\mu\,b)\,(\bar{b}\,\gamma_\mu\,b)$,		
$O^1_{Qt} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{t}\,\gamma^\mu\,t)$,	✓	✓
$O^8_{Qt} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{t}\,\gamma^\mu\,T^A\,t)$,	✓	✓
$O^1_{Qb} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{b}\,\gamma^\mu\,b)$,	✓	
$O^8_{Qb} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{b}\,\gamma^\mu\,T^A\,b)$,	✓	
$O^1_{QtQb} = (\bar{Q}\,t)\,\varepsilon\,(\bar{Q}\,b)$,	✓	
$O^8_{QtQb} = (\bar{Q}\,T^A\,t)\,\varepsilon\,(\bar{Q}\,T^A\,b)$.	✓	

degeneracy in four-top

$$C^{(+)}_{QQ} = \frac{1}{2}C^1_{QQ} + \frac{1}{6}C^8_{QQ}$$

Virtues of ttbb

- New sensitivity to 4Q operators
- Breaks degeneracy from four-top
- Sufficiently large cross section to exploit differential observables

Fiducial cross section

Fiducial cross section

[CMS; PLB 776 (2018) 355-378]

Fiducial (acceptance)

Unfolded to full PS (assuming SM)

Phase space		$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible	Measurement	$0.088 \pm 0.012 \pm 0.029$	$3.7 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
	SM (POWHEG)	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	Measurement	$4.0 \pm 0.6 \pm 1.3$	$184 \pm 6 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
	SM (POWHEG)	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

Fiducial cross section

[CMS; PLB 776 (2018) 355-378]

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LO simulation with MG5_aMC@NLO:

https://feynrules.irmp.ucl.ac.be/wiki/dim6top
[Aguilar-Saavedra et. al; CERN-LPCC-2018-01]

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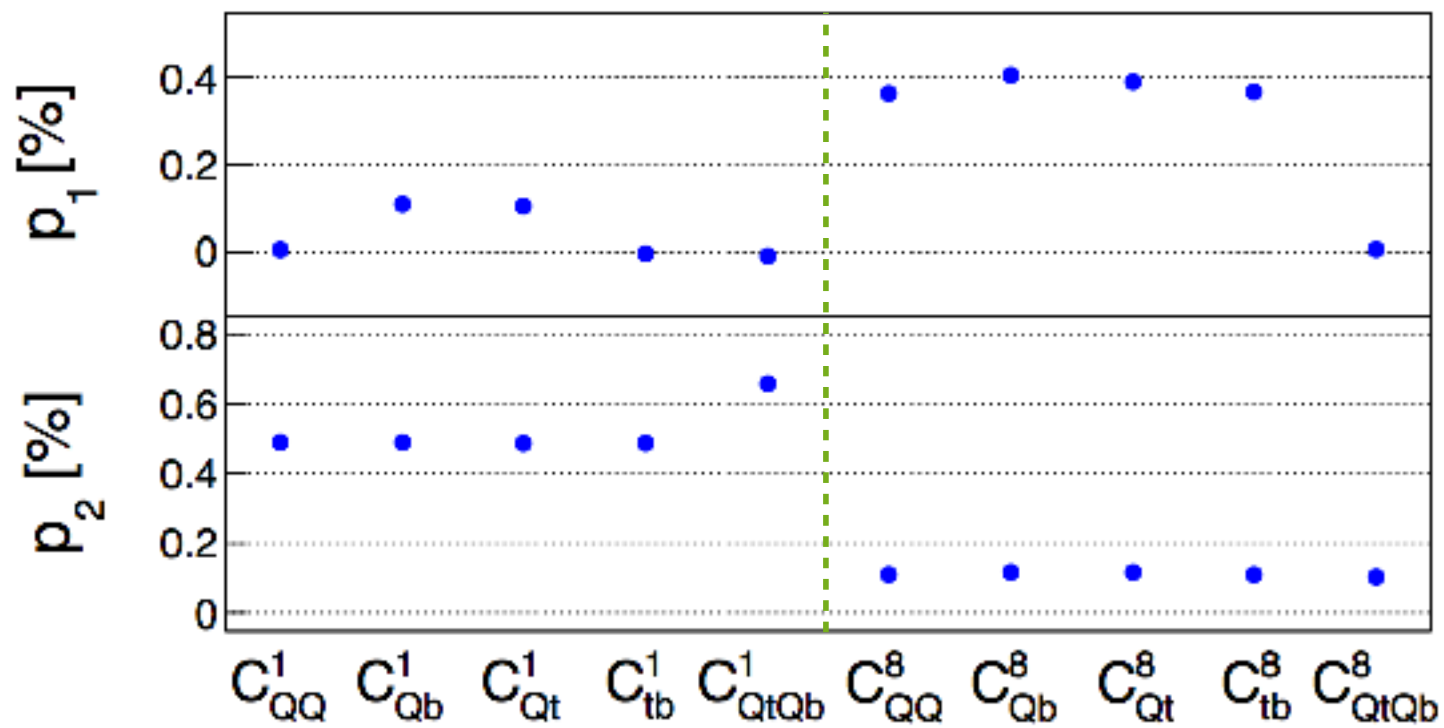
[Aguilar-Saavedra et. al; CERN-LPCC-2018-01]

$$\sigma_{fit} = \sigma_{SM}\left(1 + p_1 \cdot C_i + p_2 \cdot C_i^2\right)$$

Singlets: no interference with SM

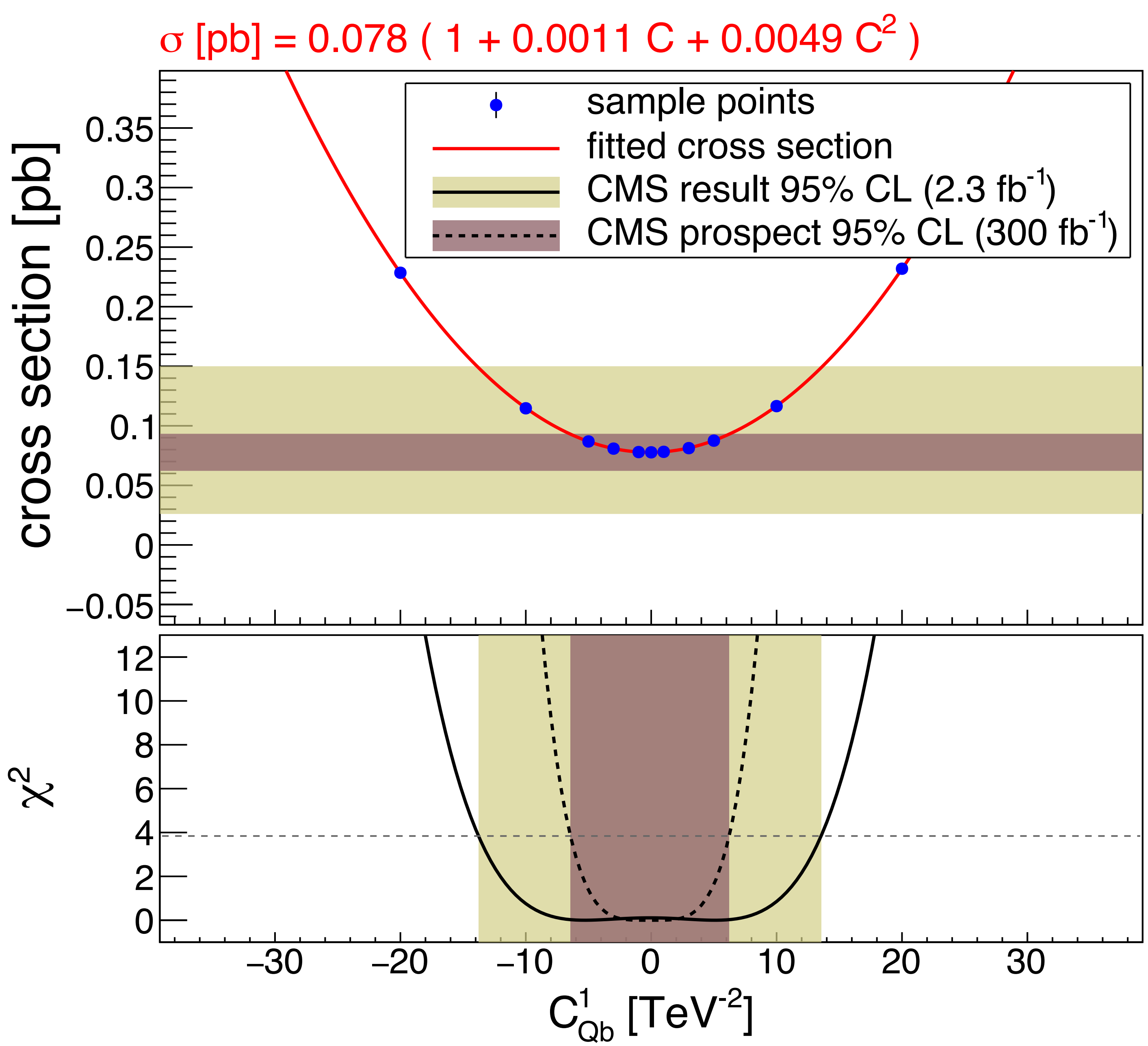
Octets: interference with SM, quadratic piece suppressed by colour factors



Fiducial cross section

Case study: one operator at a time

σ_{CMS} = 88 ±12(*stat.*) ±29(*syst.*) fb [LHC13, 2.3 fb^{-1}]



- Limits from current measurement
- 300 fb^{-1} projections assuming 10% systematic uncertainty

Tail of ttbb

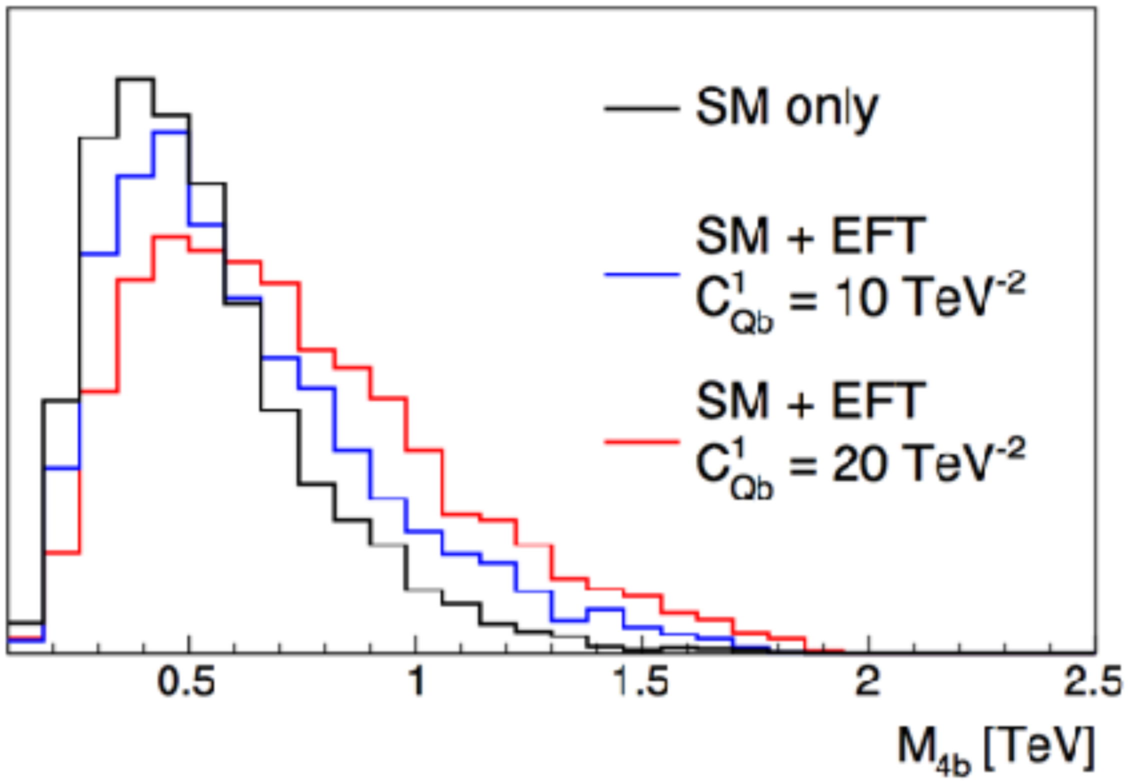
Case study: one operator at a time

Tail of ttbb

Case study: one operator at a time

High energy kinematic variable: M_{4b}

- Invariant mass of 4 b-jets
- Improves sensitivity to 4F operators
- From events below 1.5 TeV
- Set upper threshold M_{cut} = 2 TeV



Tail of ttbb

Case study: one operator at a time

Reconstructed-level selection
2 leptons, pT>20 GeV, |η|<2.5
≥ 4 jets, pT>30 GeV, |η|<2.5
2 b-tags
Min ΔR(l, jet) assigned to tops
MET > 30 GeV

High energy kinematic variable: M_{4b}

- Invariant mass of 4 b-jets
- Improves sensitivity to 4F operators
- From events below 1.5 TeV
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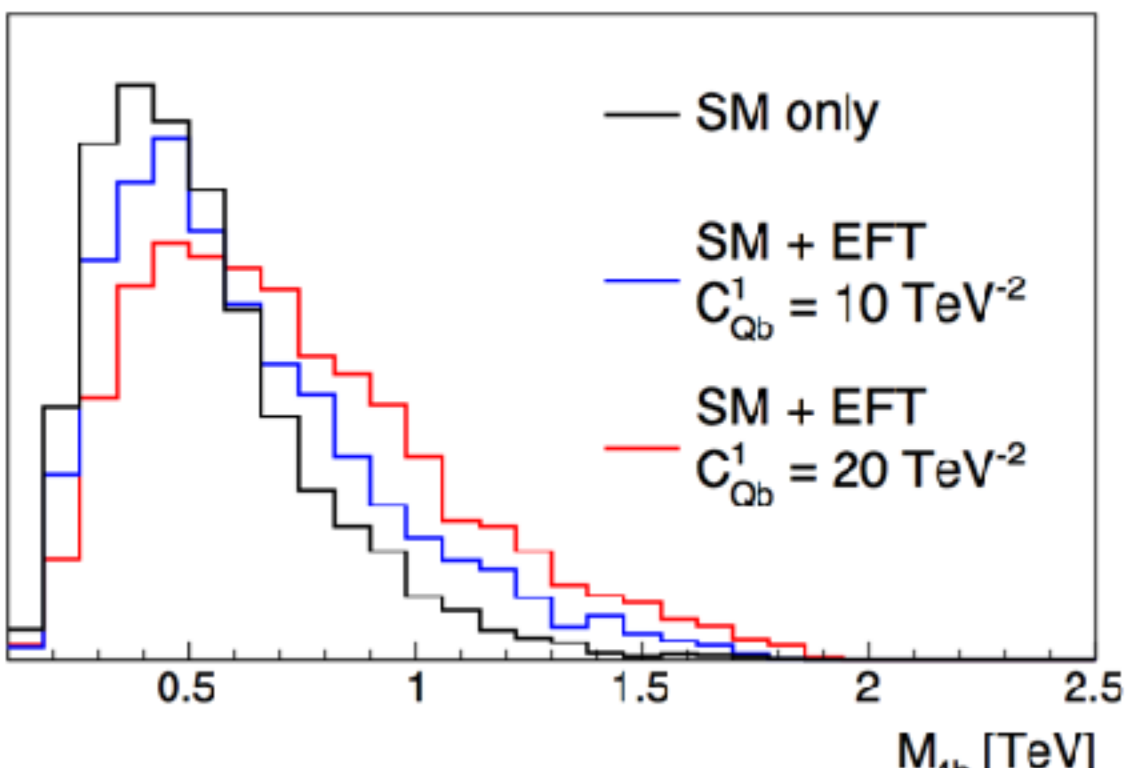

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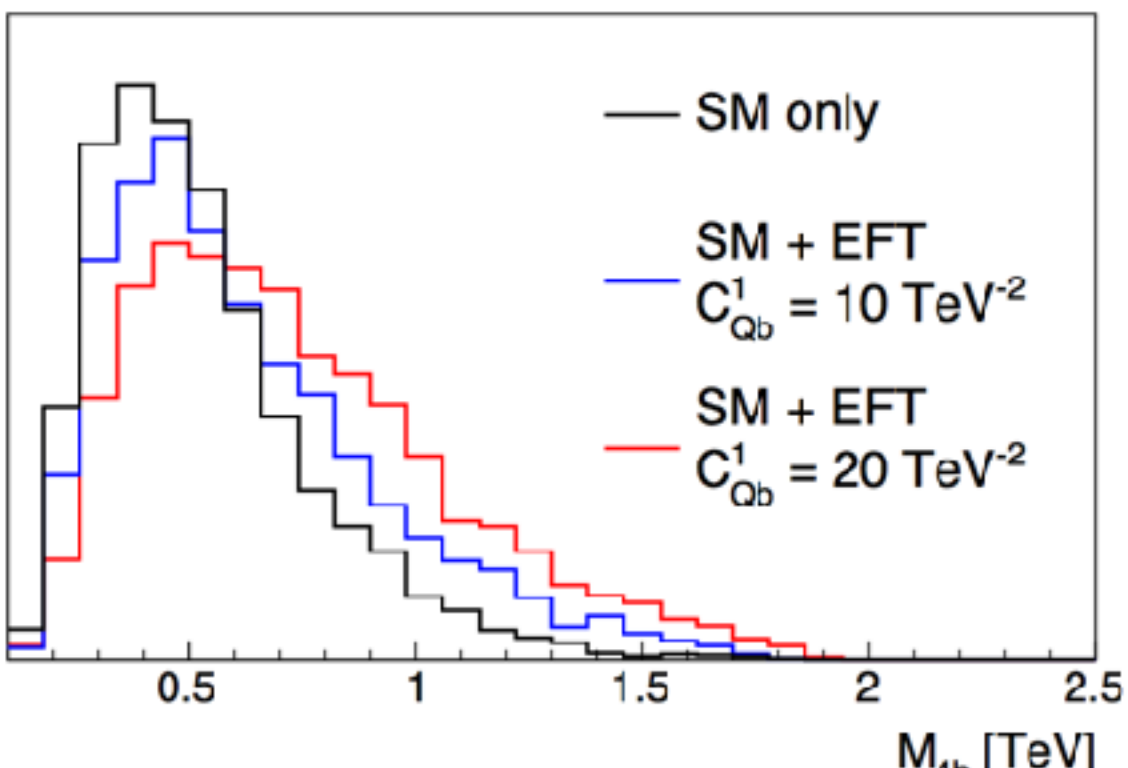
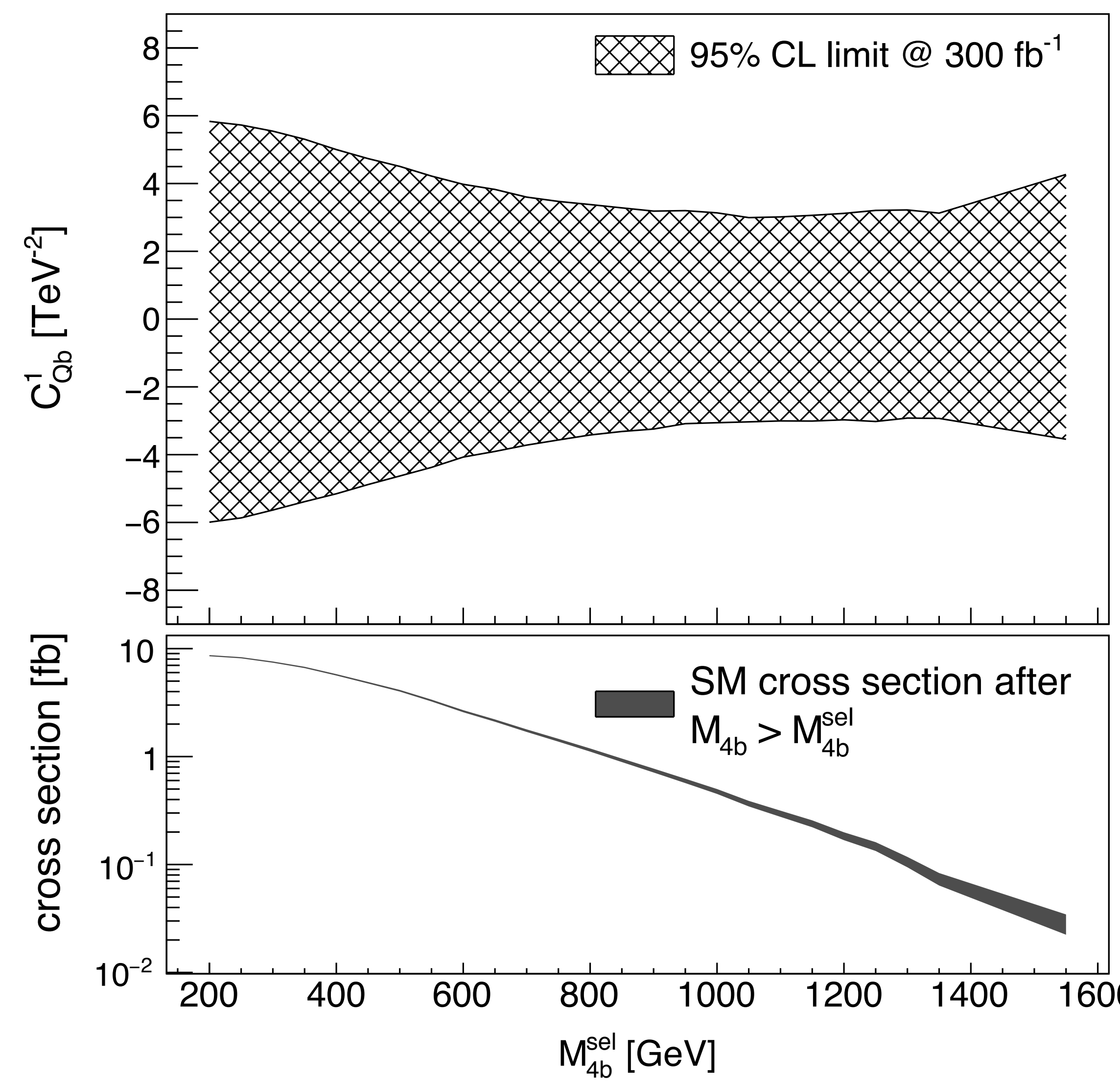


LHC@13 TeV, 300 fb^{-1}



Learning effective operators

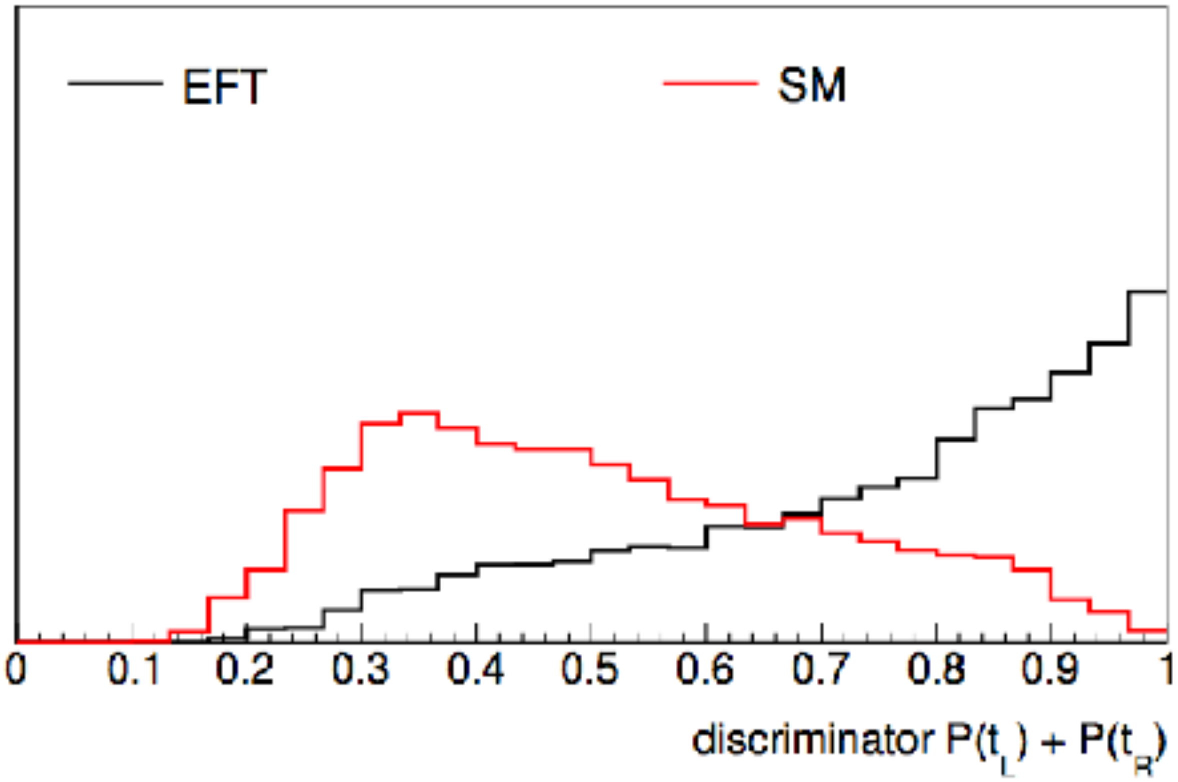
Case study: one operator at a time

Learning effective operators

Case study: one operator at a time

18 kinematical observables

p_T, M_{ij}, ΔR_{ij}, … NN classifier



Learning effective operators

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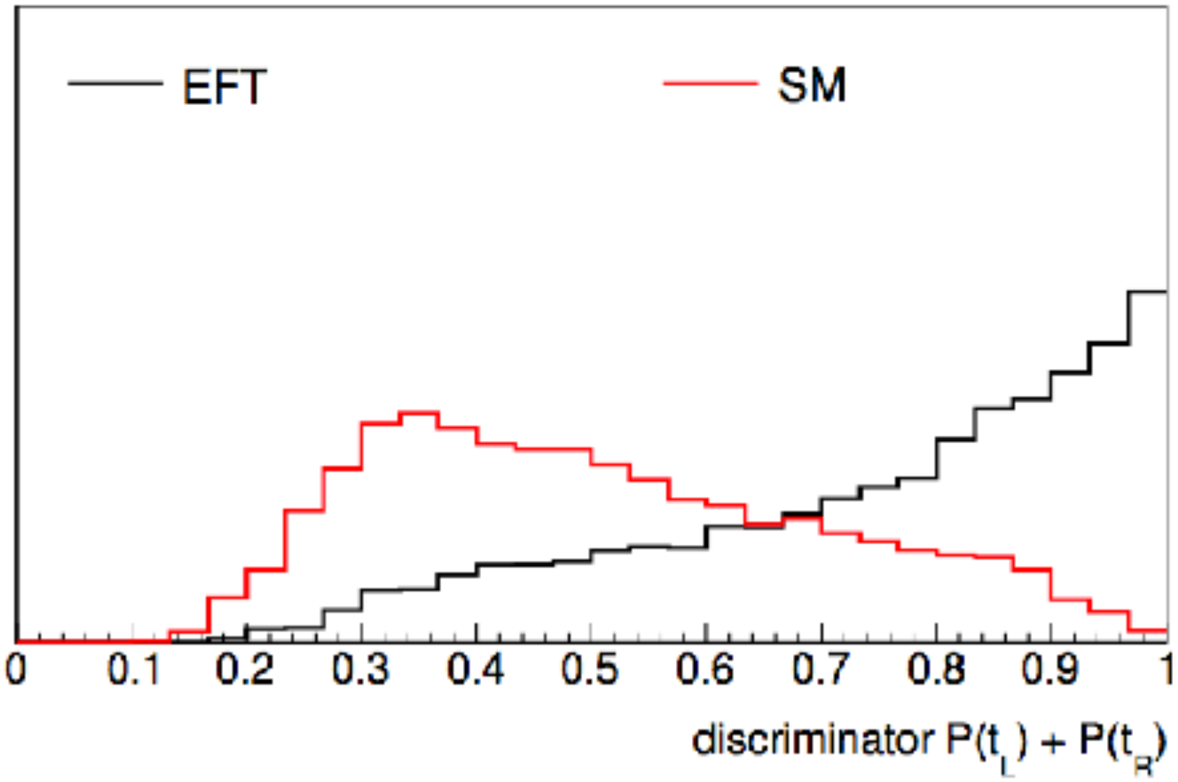

Cut or Template fit on discriminant

Learning effective operators

Case study: one operator at a time

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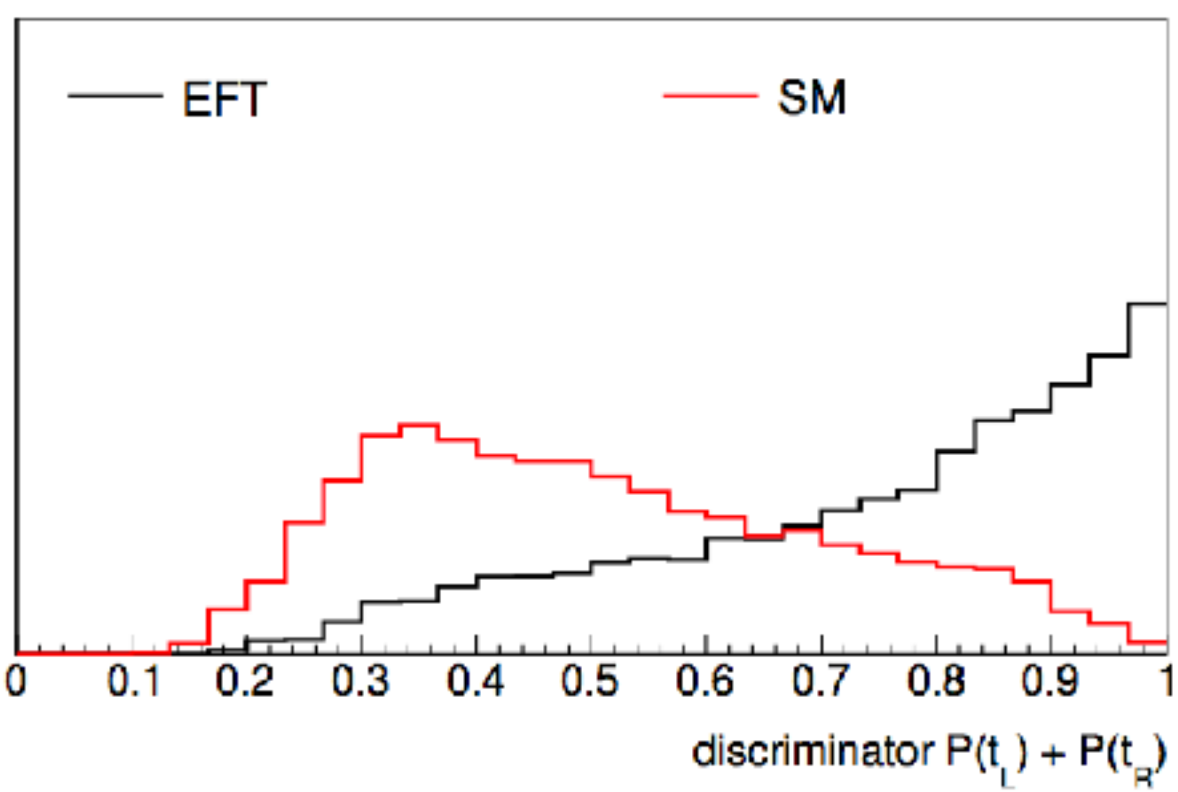
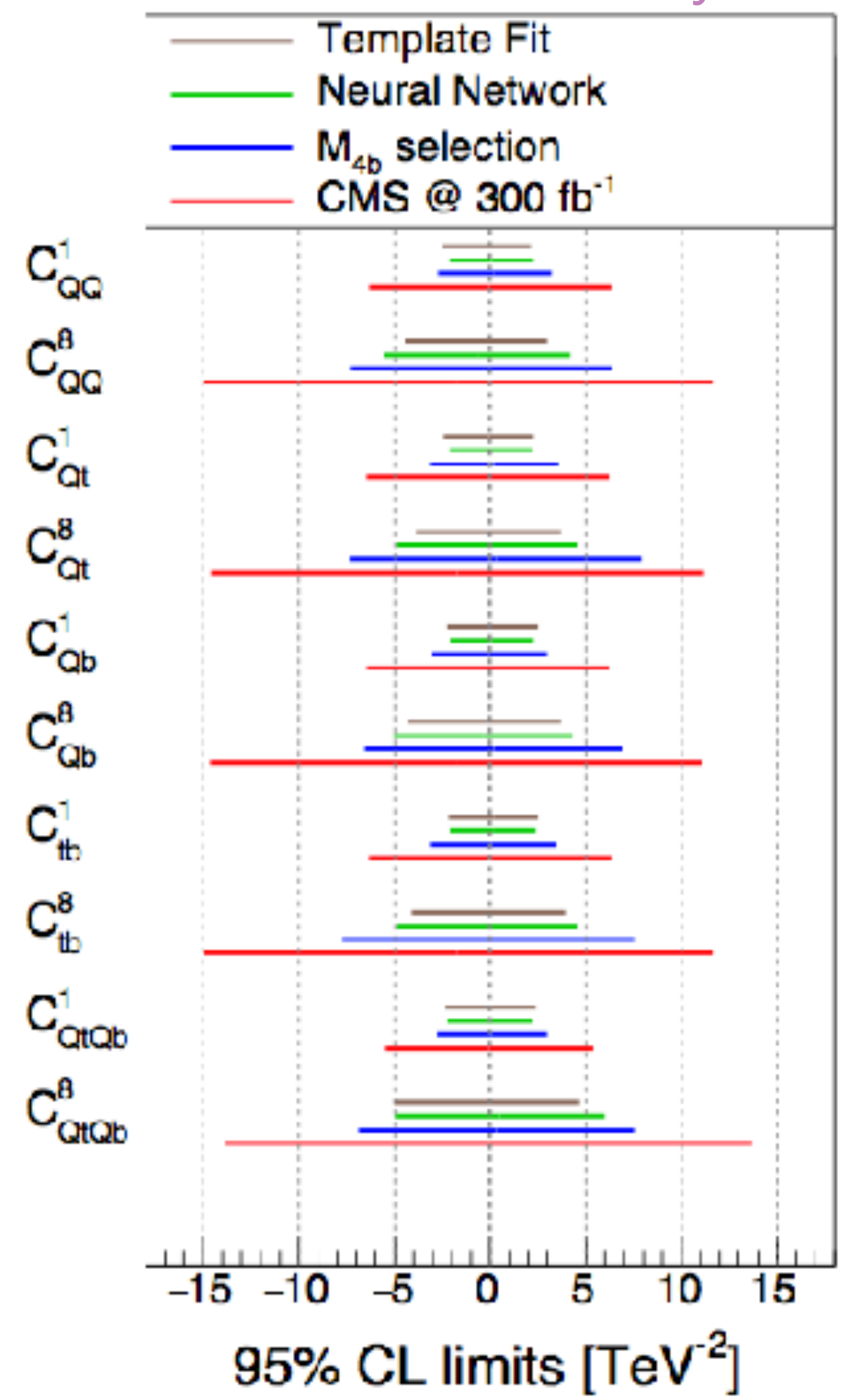


Cut or Template fit on discriminant

Limit summary



Comparing to 4 top

Case study: one operator at a time

[Zhang; Chin. Phys. C42 (2018) 023104]

300 fb^{-1} projections from 4-top

Our study

Operator	4-top ($M_{\rm cut} = 2\,\mathrm{TeV}$)	4-top ($M_{\rm cut} = 3\,\mathrm{TeV}$)	4-top ($M_{\rm cut} = 4\,\mathrm{TeV}$)	this work ($M_{\rm cut} = 2\,\mathrm{TeV}$)
C^1_{QQ}	$[-3.9, 3.5]$	$[-2.9, 2.6]$	$[-2.8, 2.5]$	$[-2.1, 2.3]$
C^8_{QQ}	$[-11.8, 10.5]$	$[-8.8, 7.8]$	$[-8.4, 7.4]$	$[-4.5, 3.1]$
C^1_{Qt}	$[-3.2, 3.3]$	$[-2.4, 2.4]$	$[-2.2, 2.3]$	$[-2.1, 2.3]$
C^8_{Qt}	$[-7.4, 5.8]$	$[-5.4, 4.3]$	$[-5.1, 4.1]$	$[-3.9, 3.8]$

Competitive/better individual limits from ttbb!

Pinpointing operators

[S. Moortgat; IRN Terascale meeting 09/2018]

Pinpointing operators

More than one operator on at once

[S. Moortgat; IRN Terascale meeting 09/2018]

Pinpointing operators

More than one operator on at once

- Multi-class output architecture for the neural network

[S. Moortgat; IRN Terascale meeting 09/2018]

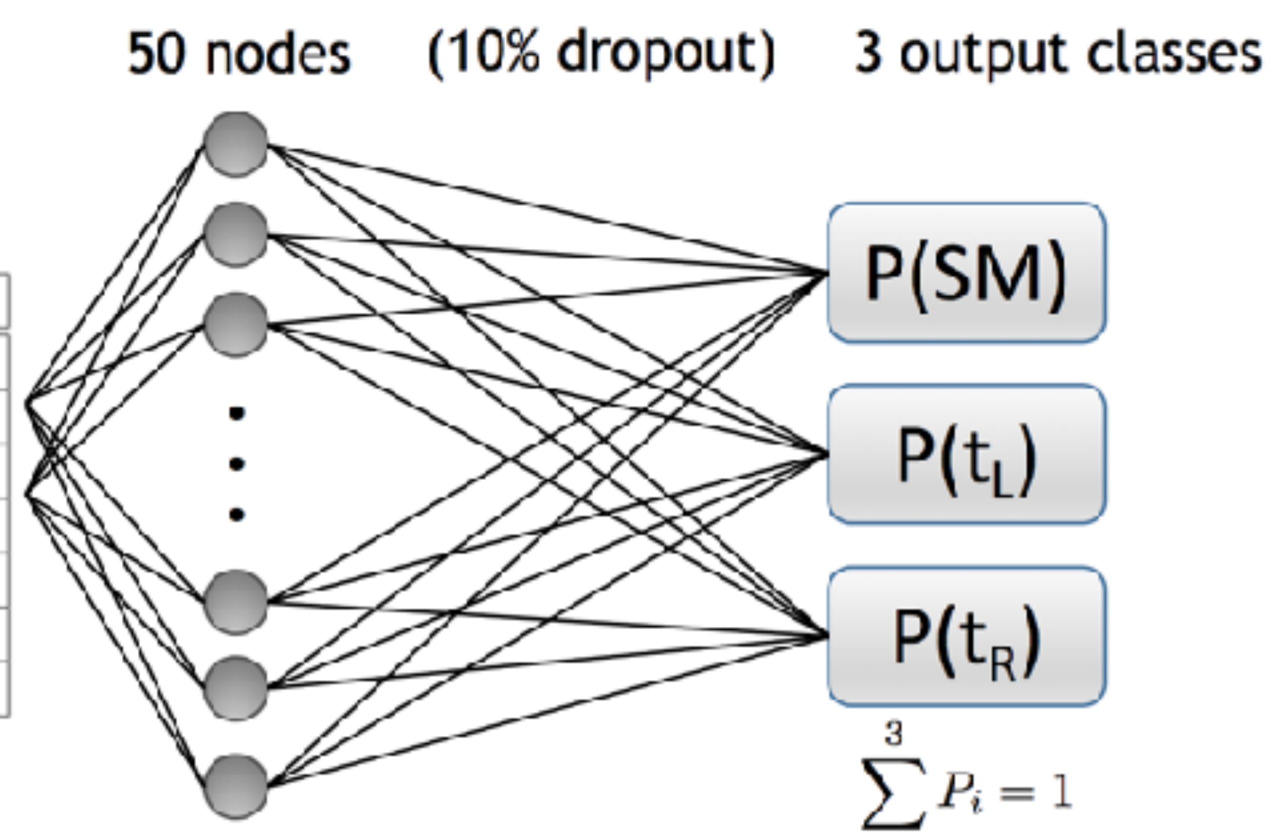
Pinpointing operators

More than one operator on at once

- Multi-class output architecture for the neural network

18 kinematic input observables

ΔR	m_{inv}	p_T
$\Delta R(\ell_1,\ell_2)$	$m_{inv}(\ell_1,\ell_2)$	$p_T(\ell_1)$
$\Delta R(b_1,b_2)$	$m_{inv}(b_1,b_2)$	$p_T(\ell_2)$
$\Delta R(b_1,\ell_2)$	$m_{inv}(b_1,\ell_2)$	$p_T(b_1)$
$\Delta R(b_2,\ell_1)$	$m_{inv}(b_2,\ell_1)$	$p_T(b_2)$
$\Delta R(add_1,add_2)$	$m_{inv}(add_1,add_2)$	$p_T(add_1)$
	$m_{inv}(b_1,b_2,add_1,add_2)$	$p_T(add_2)$
	$m_{inv}(\ell_1,\ell_2,b_1,b_2,add_1,add_2)$	



$$\sum_{i=1}^{3} P_i = 1$$

[S. Moortgat; IRN Terascale meeting 09/2018]

Pinpointing operators

More than one operator on at once

- Multi-class output architecture for the neural network
- Trained to identify SM vs left-handed vs right-handed top operators

18 kinematic input observables

ΔR	m_{inv}	p_T
$\Delta R(\ell_1,\ell_2)$	$m_{inv}(\ell_1,\ell_2)$	$p_T(\ell_1)$
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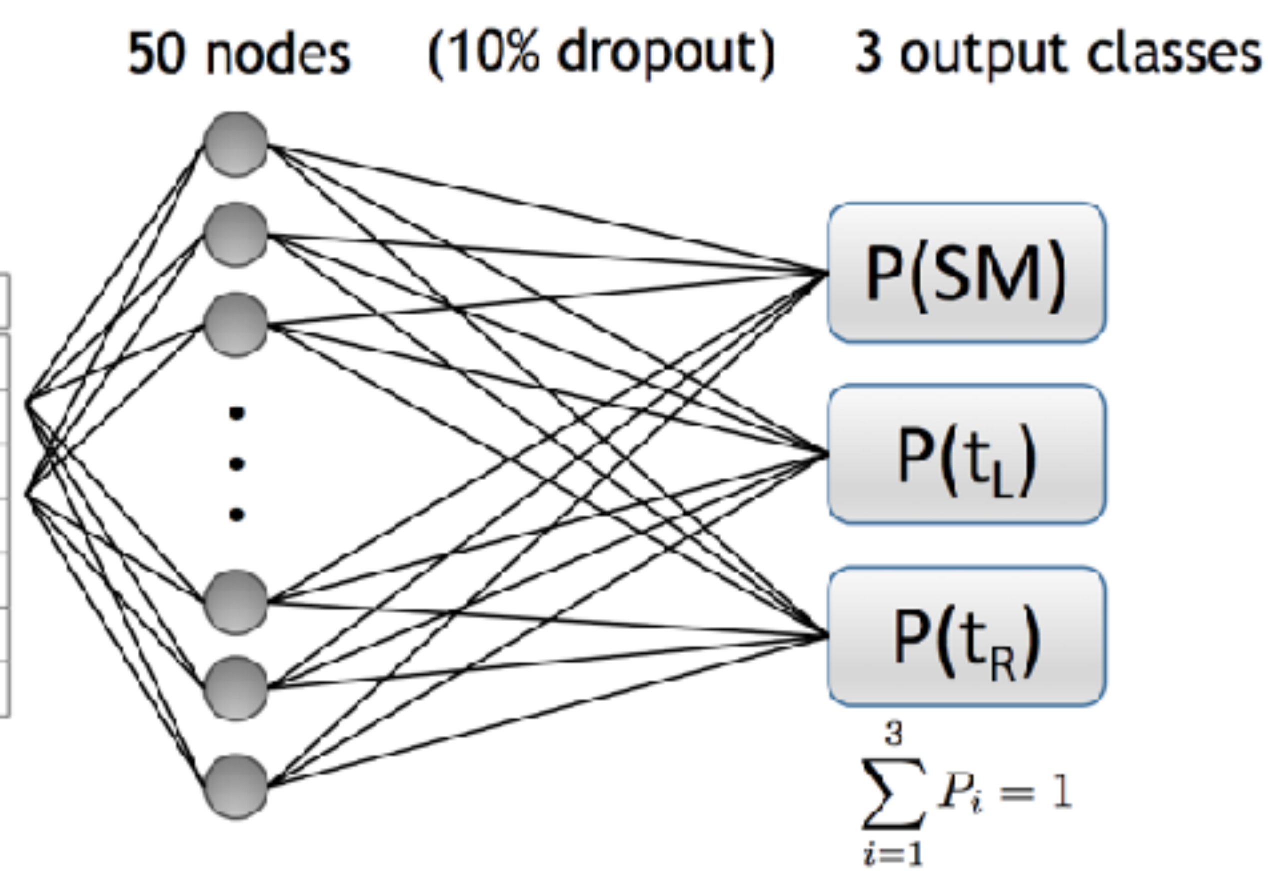

[S. Moortgat; IRN Terascale meeting 09/2018]

Pinpointing operators

Pinpointing operators

Combined discriminants
P(SM), P(t_R) & P(t_L)

	Desired Discrimination	**Combined NN Output used for limits**
only t_L operator	SM vs t_L	$\frac{P(t_L)}{P(t_L)+P(SM)}$
only t_R operator	SM vs t_R	$\frac{P(t_R)}{P(t_R)+P(SM)}$
including both t_L and t_R operators	EFT vs SM	$P(t_L) + P(t_R)$
	t_L vs t_R	$\frac{P(t_L)}{P(t_L)+P(t_R)}$

Pinpointing operators

Combined discriminants
P(SM), P(tR) & P(tL)

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only t_L operator	SM vs t_L	* $\frac{P(t_L)}{P(t_L)+P(SM)}$
only t_R operator	SM vs t_R	* $\frac{P(t_R)}{P(t_R)+P(SM)}$
including both t_L and t_R operators	EFT vs SM	$P(t_L)+P(t_R)$
	t_L vs t_R	* $\frac{P(t_L)}{P(t_L)+P(t_R)}$

*One operator at a time

*Left & Right handed at once

Pinpointing operators

Combined discriminants
P(SM), $P(t_R)$ & $P(t_L)$

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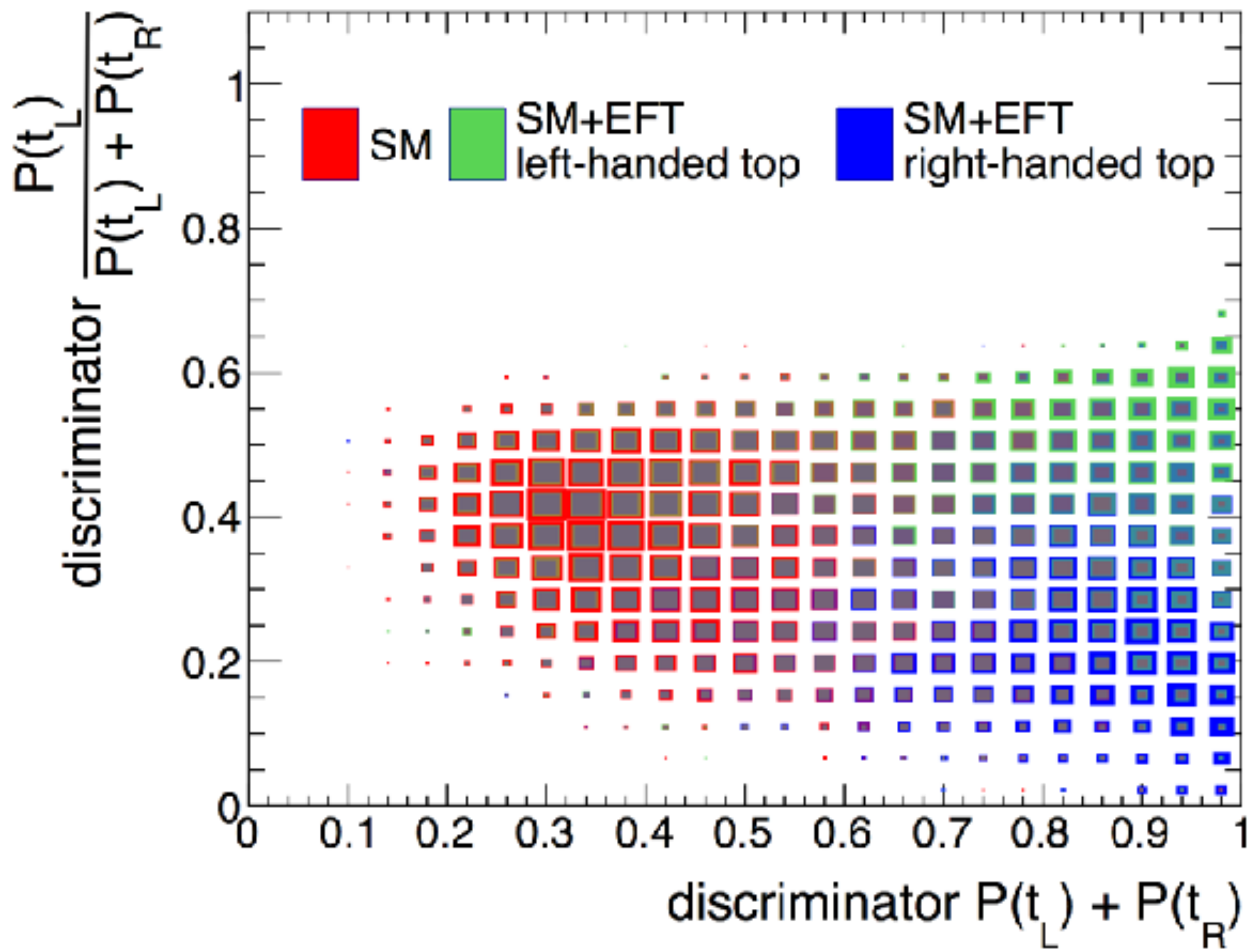
		*
	t_L vs t_R	$\frac{P(t_L)}{P(t_L)+P(t_R)}$

*One operator at a time

*Left & Right handed at once

2D discriminant

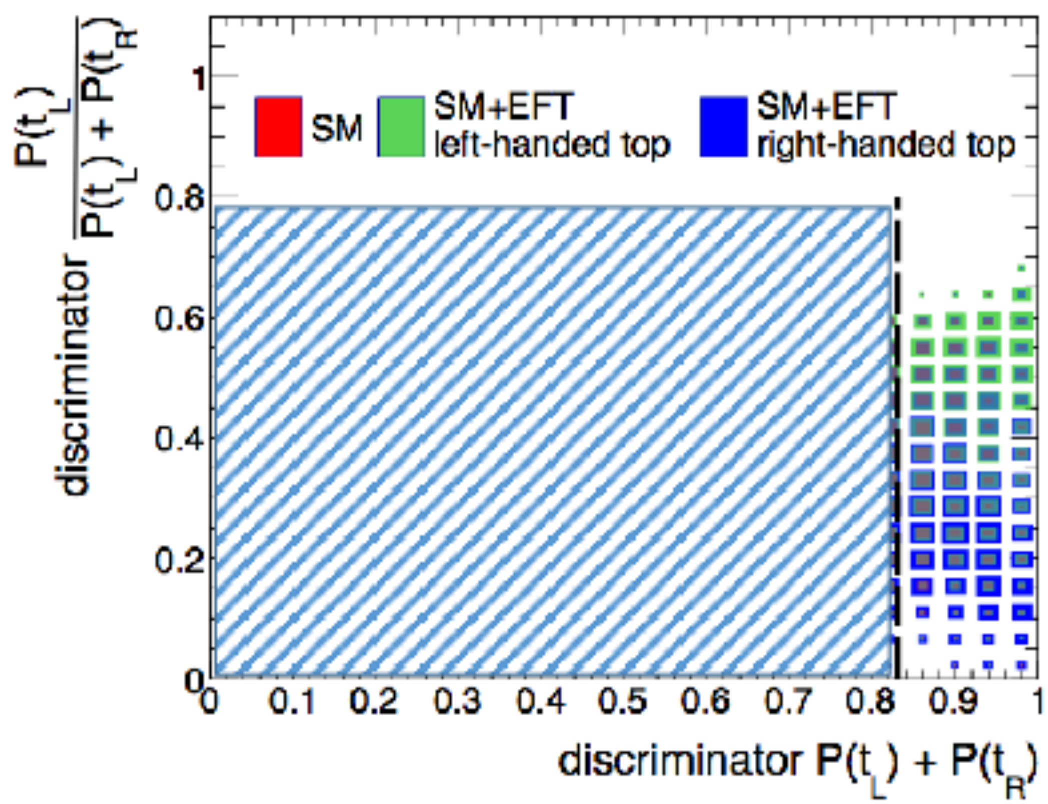
SM vs. EFT ⊗ t_L vs. t_R

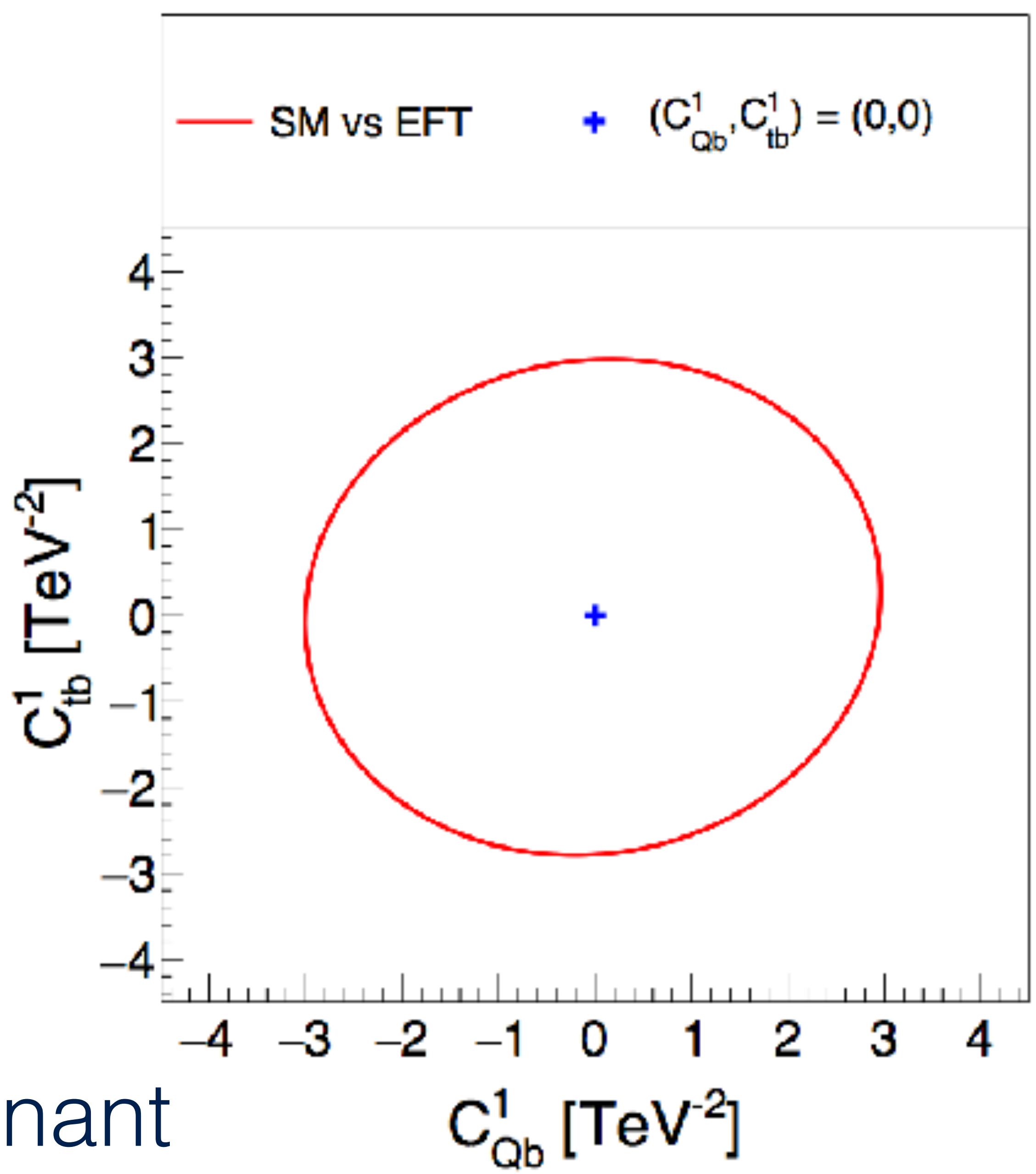


Pinpointing operators

Two operators at a time

95% CL region, 300 fb^{-1}





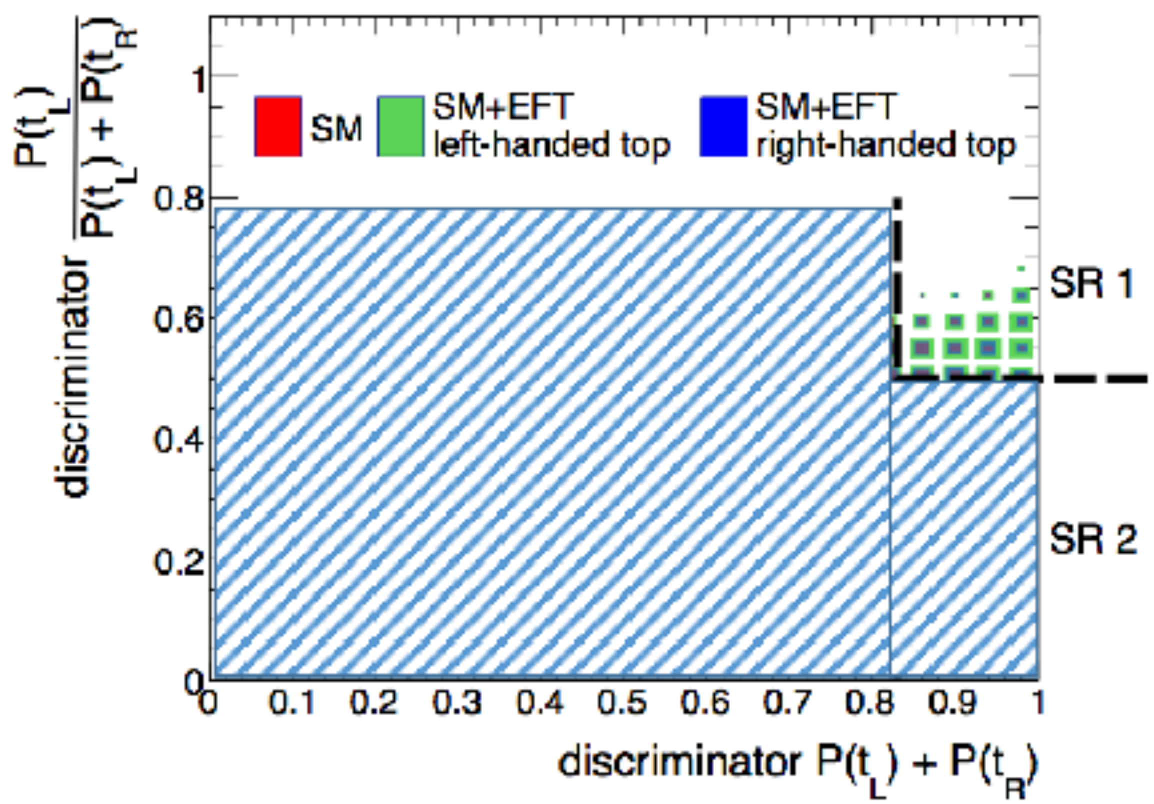
A) SM observation:
$(C_{Qb}, C_{tb}) = (0.,0.)$

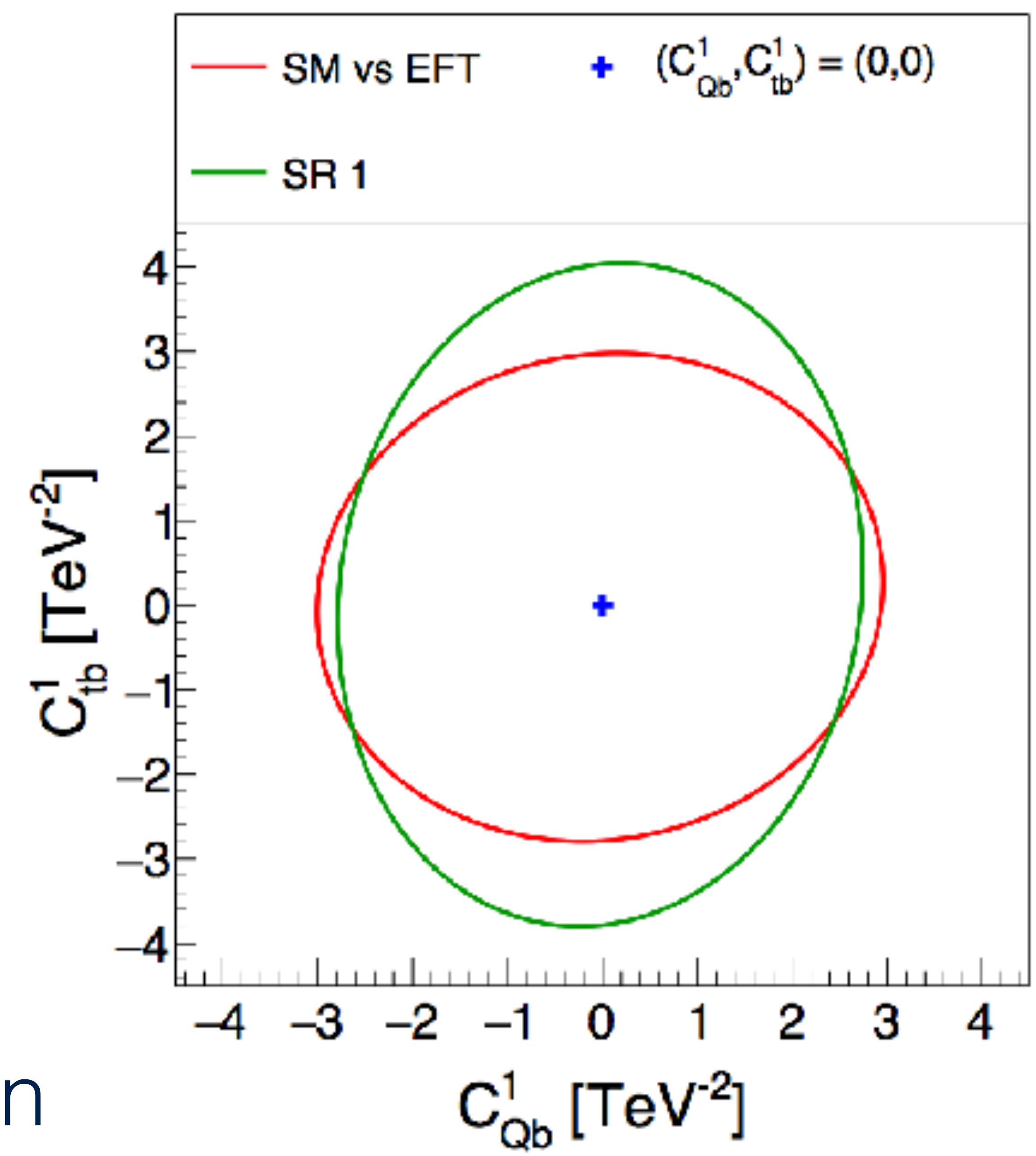
1D cut on SM vs EFT discriminant

Pinpointing operators

Two operators at a time

95% CL region, 300 fb^{-1}





A) SM observation:
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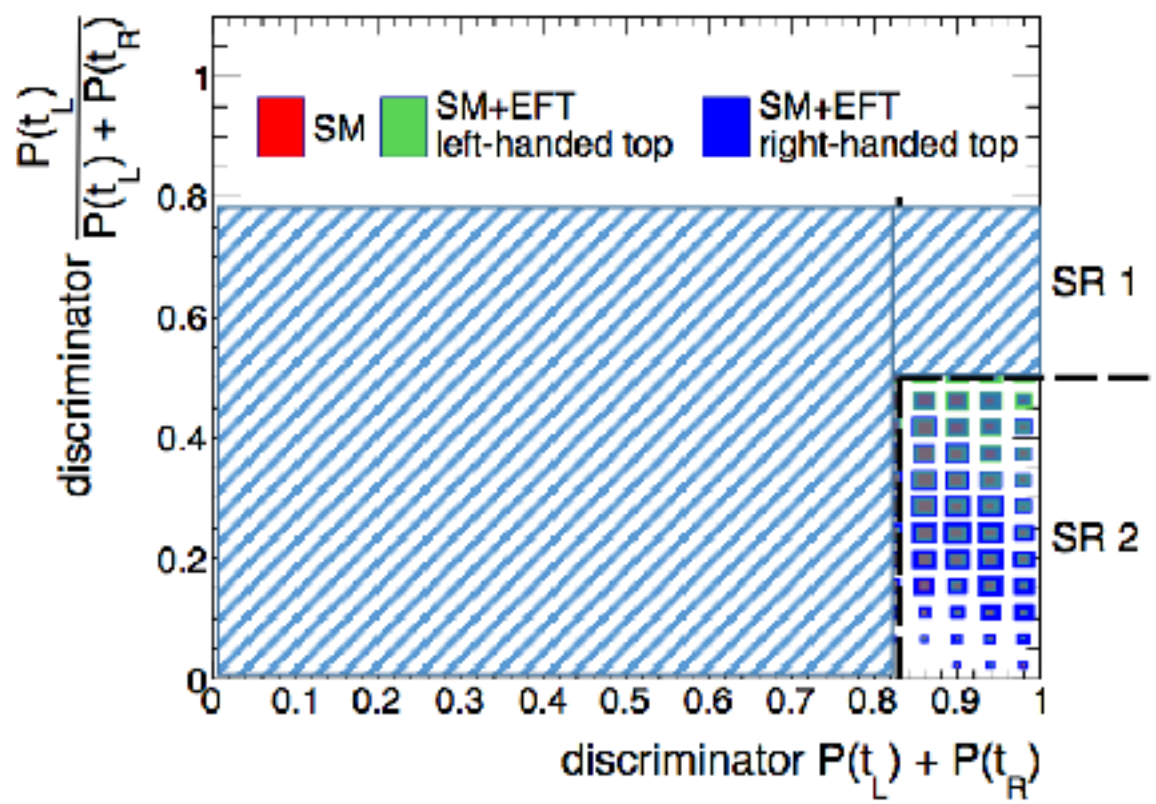
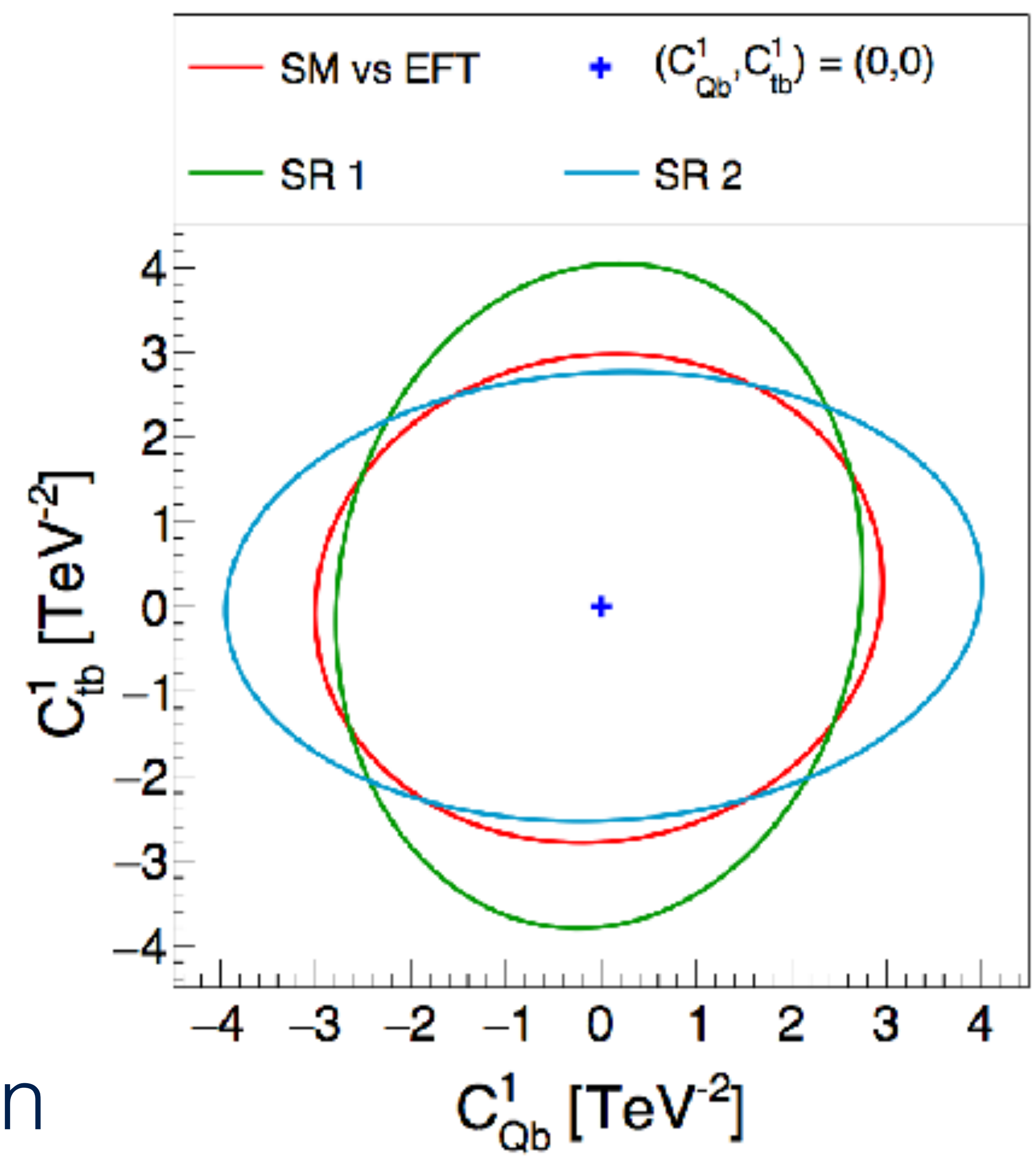
2D cut for t_L-rich signal region

Pinpointing operators

Two operators at a time

95% CL region, 300 fb^{-1}





A) SM observation:
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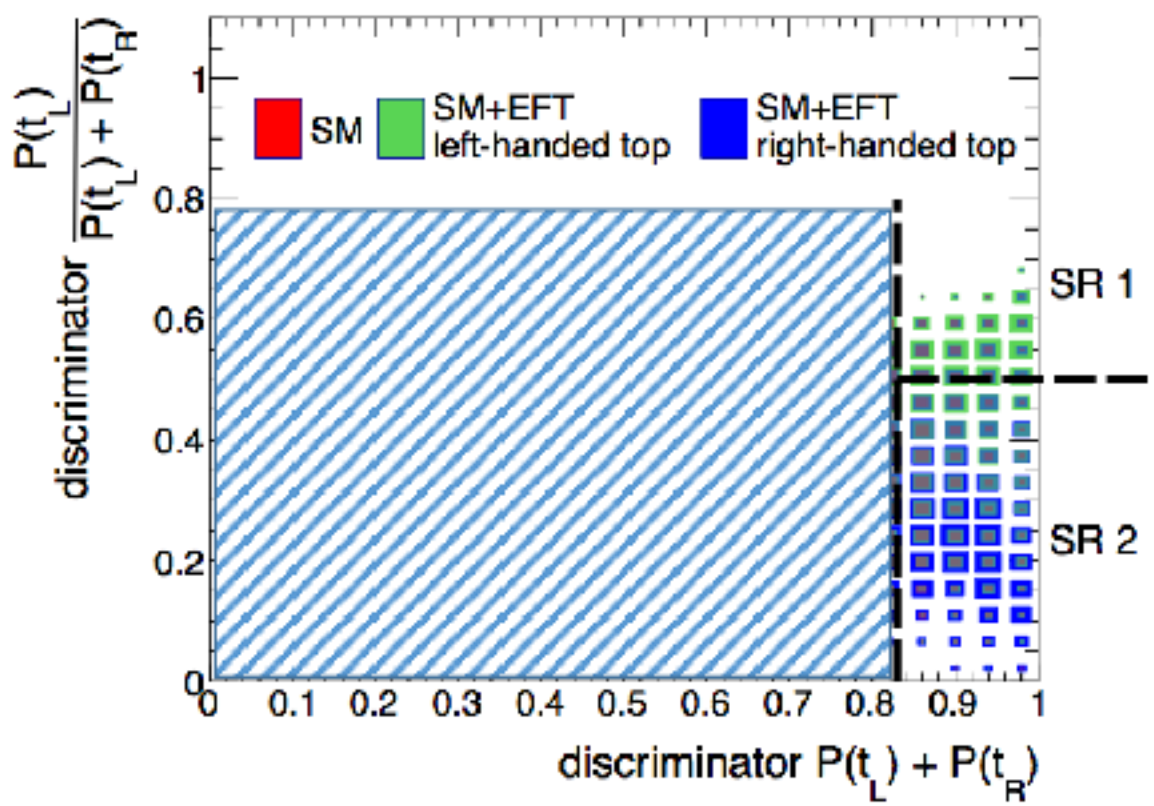
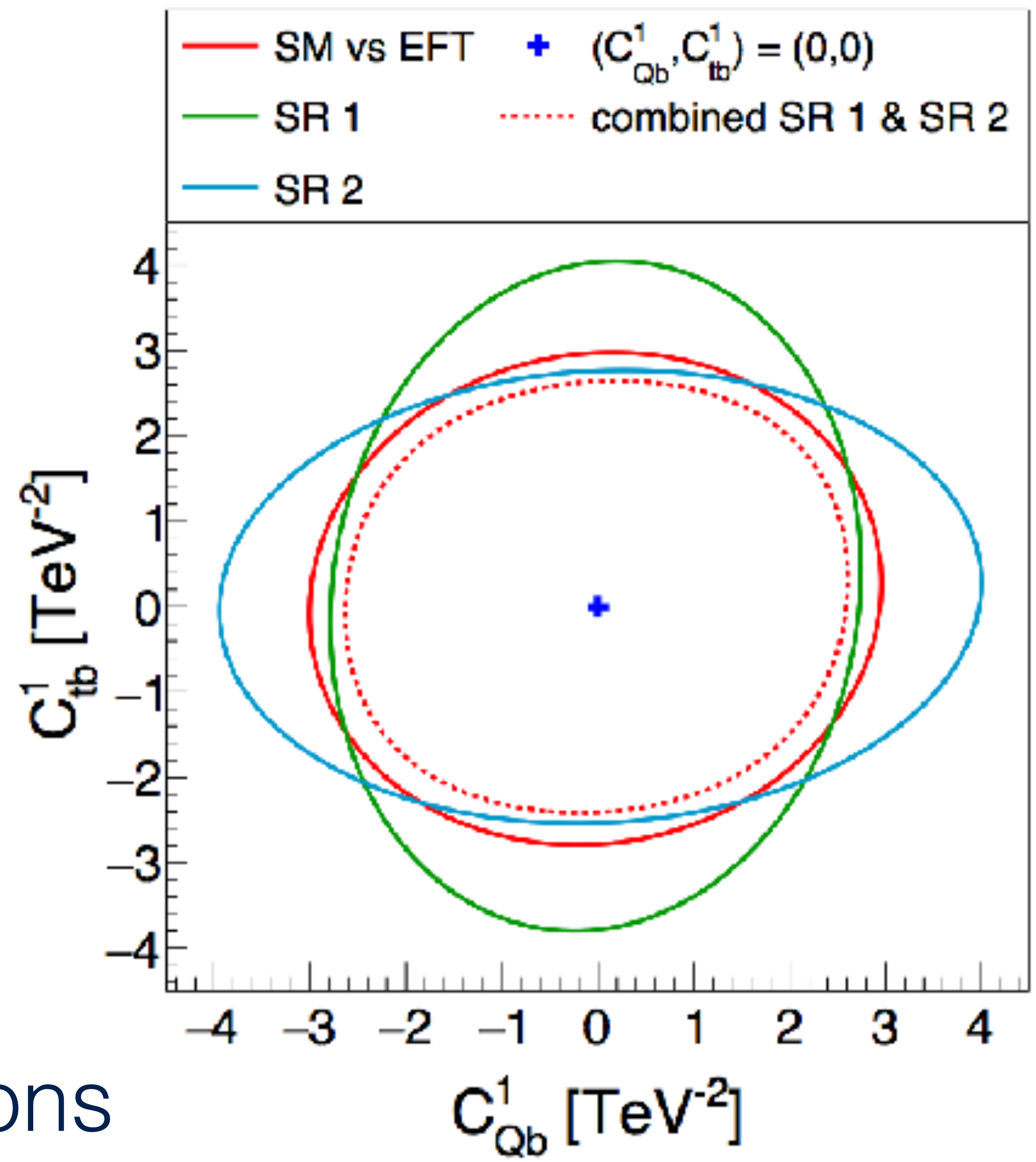
2D cut for t_R-rich signal region

Pinpointing operators

Two operators at a time

95% CL region, 300 fb^{-1}





A) SM observation:
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Combining t_L & t_R signal regions

Pinpointing operators

Two operators at a time

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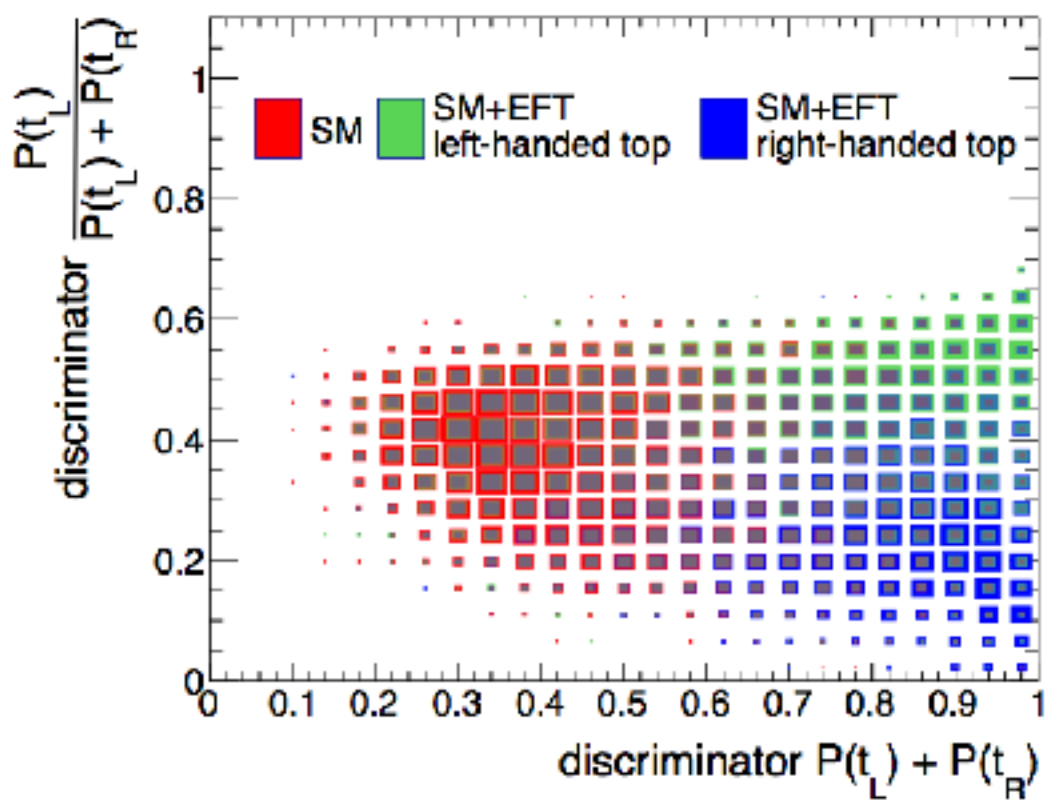

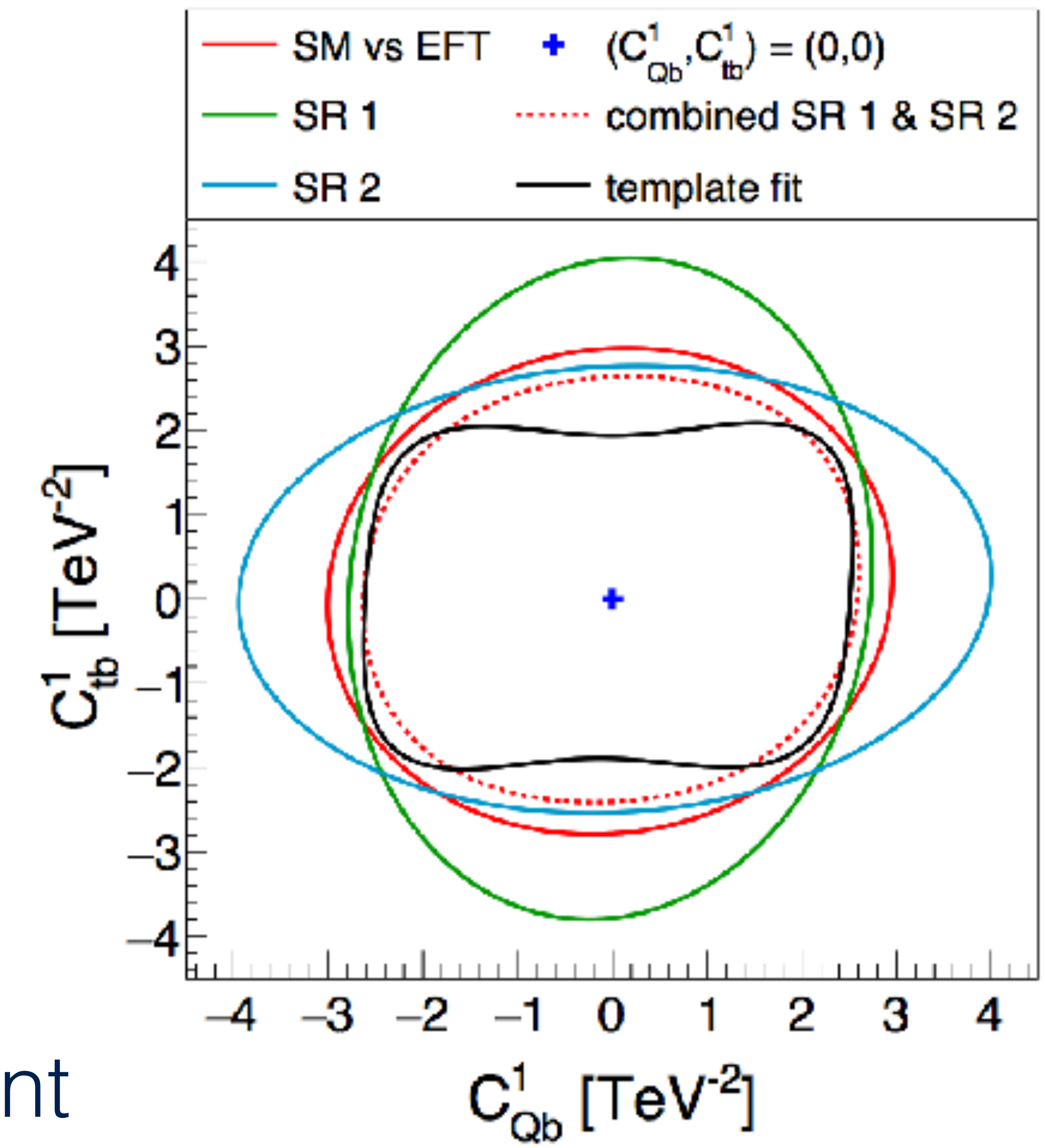

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Template fit to 2D discriminant

Pinpointing operators

Two operators at a time

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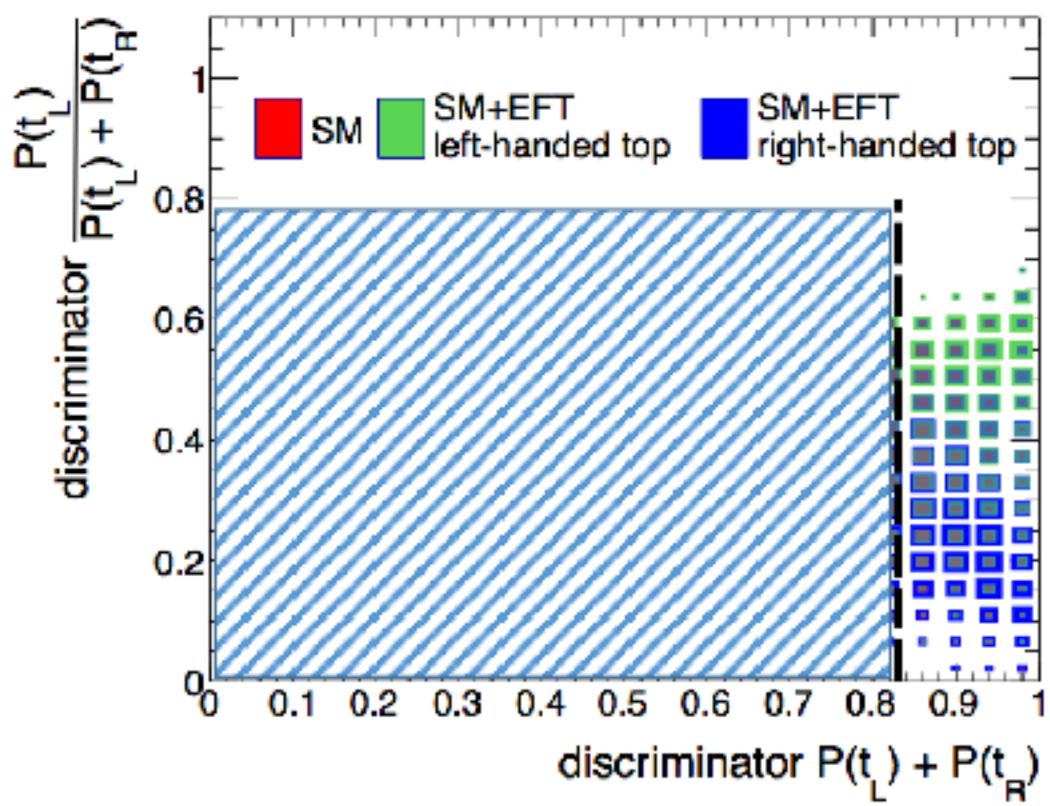

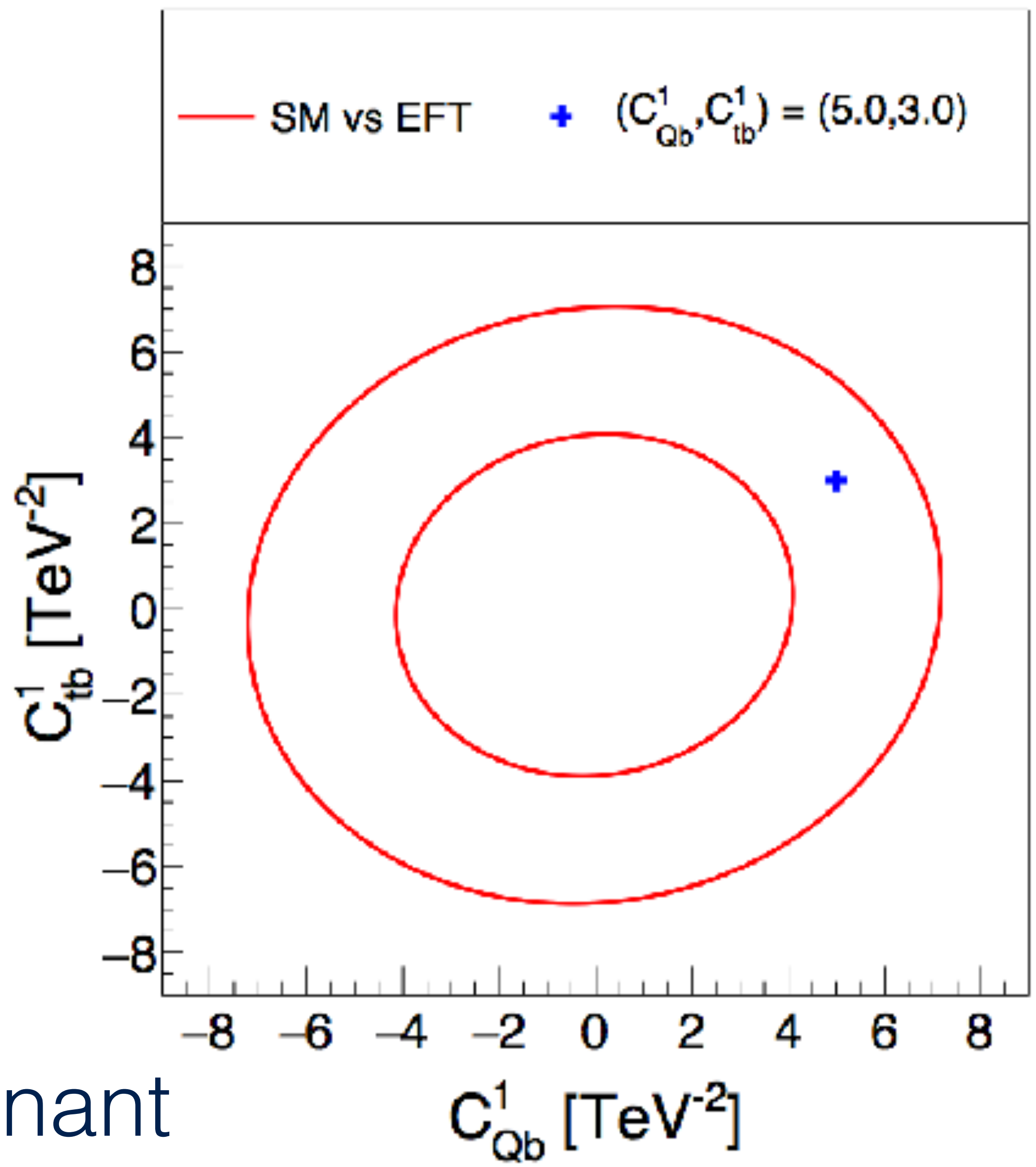

B) BSM observation:
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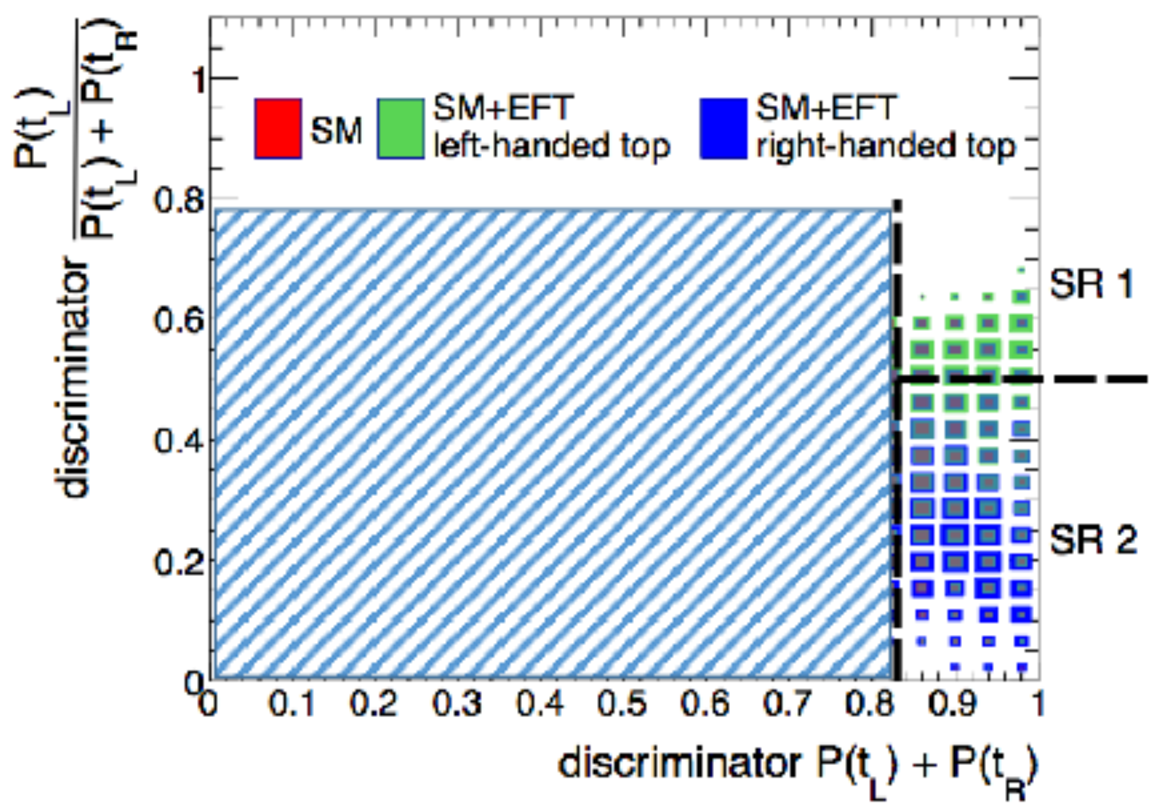
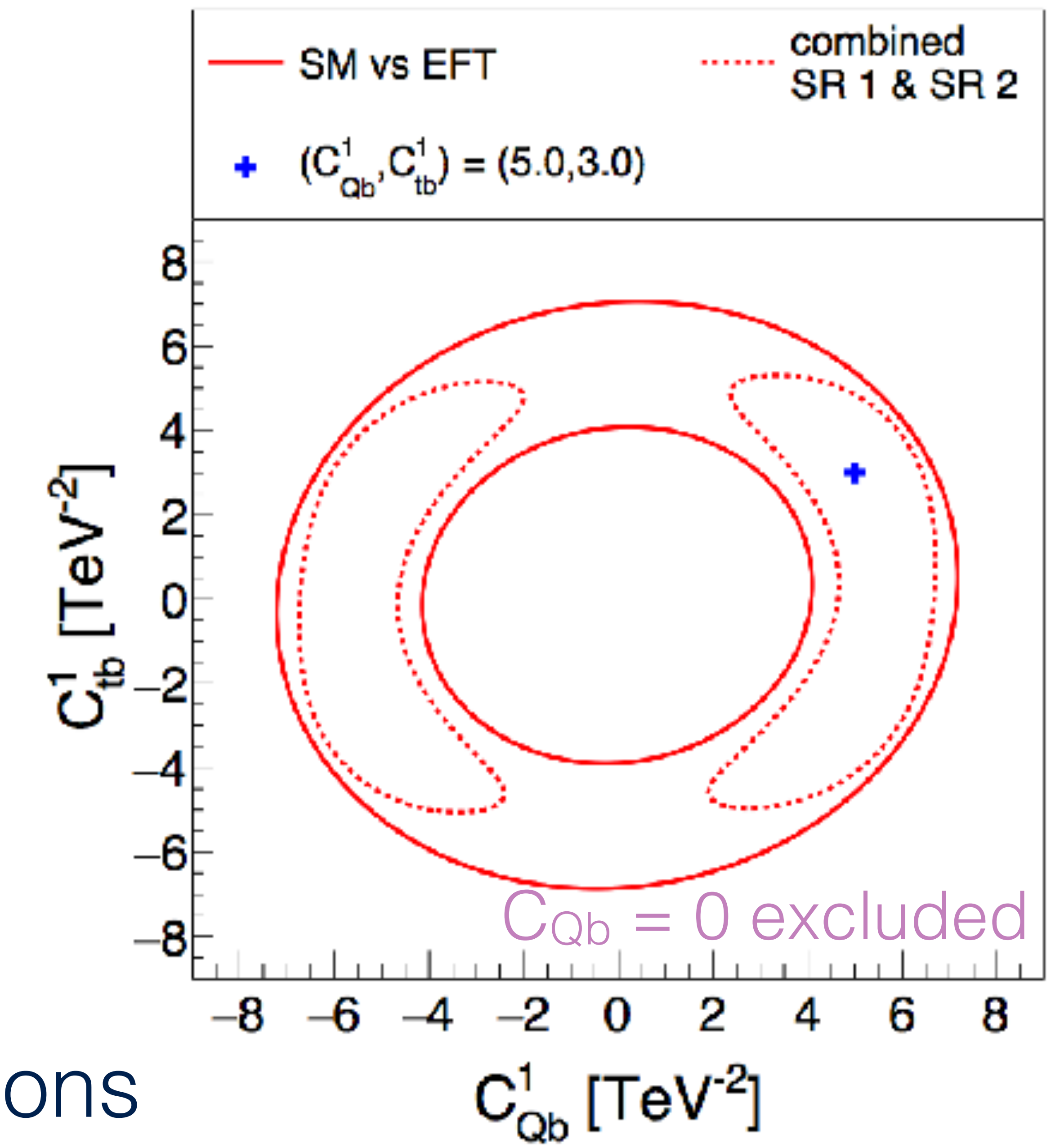
1D cut on SM vs EFT discriminant

Pinpointing operators

Two operators at a time

95% CL region, 300 fb^{-1}





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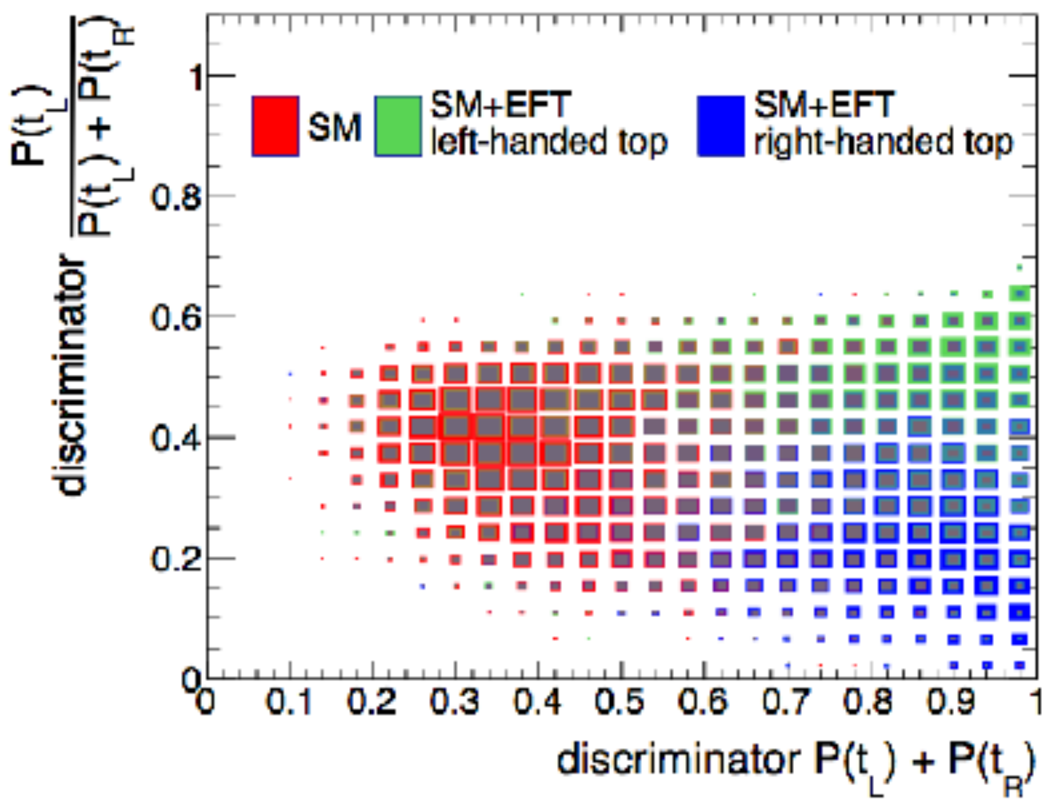

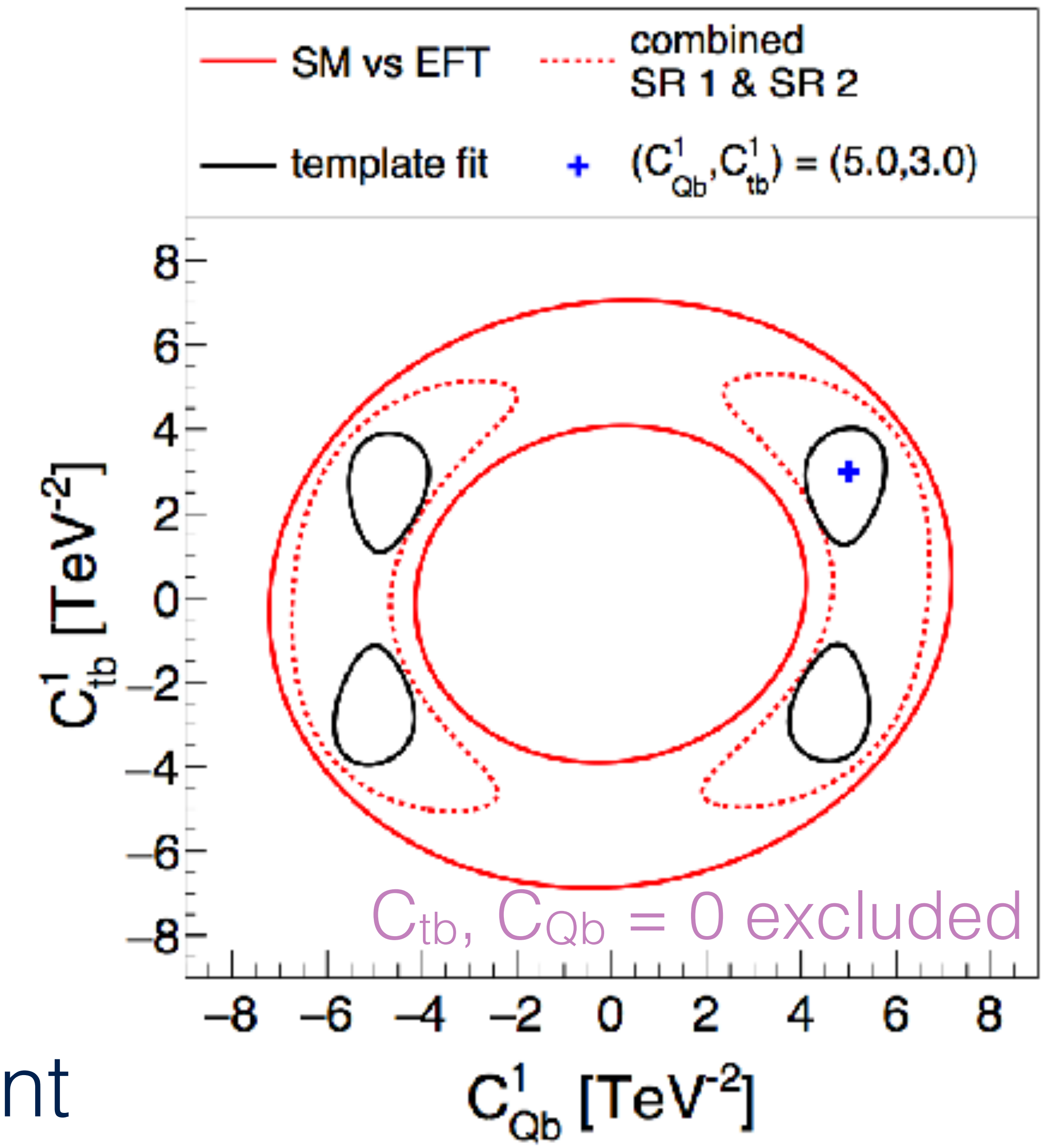

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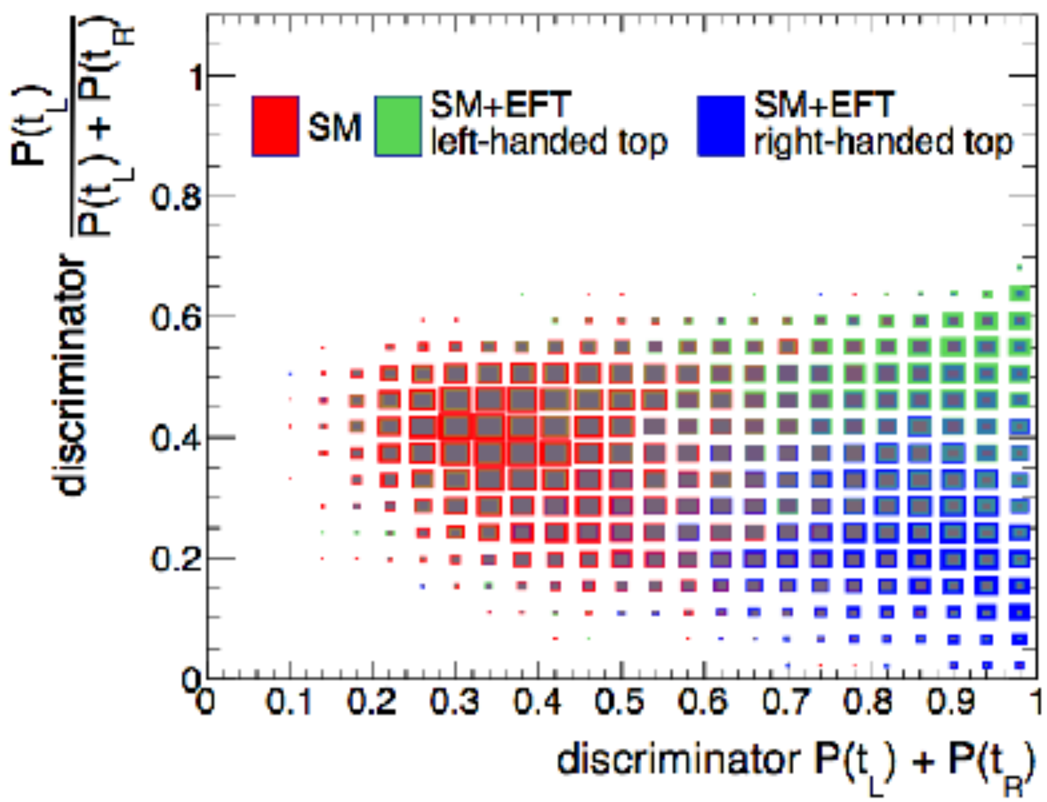

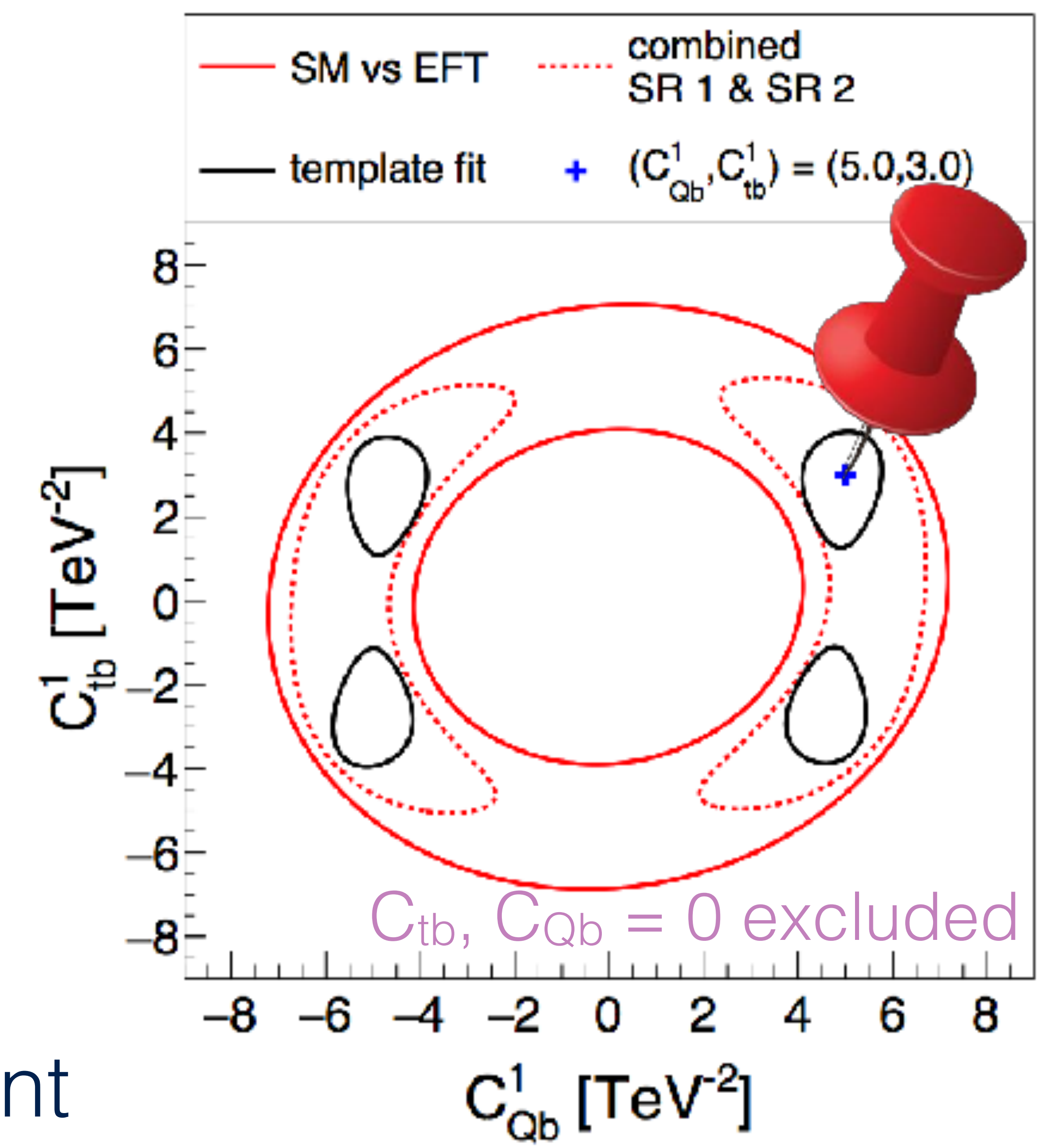

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Template fit to 2D discriminant

Conclusions

SMEFT is a thriving field at the LHC

Opportune time to study EWSB sector in full

- Healthy, ongoing dialogue between theory and experiment
- Precision MC tools available
- Global top/Higgs/EW fit on the way!
- New insight into the origin of EWSB

Challenges & open questions

- How to deal with sig/bkg/statistical overlap in global fits

Roadmap for the future

- High energy EW-top quark production
- Thorough programme of sensitivity studies at the LHC & beyond

Backup

The top is special

The top is special

The top couples to the Higgs, **strongly**: $y_t \sim 1$

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- Heaviest known particle in the SM

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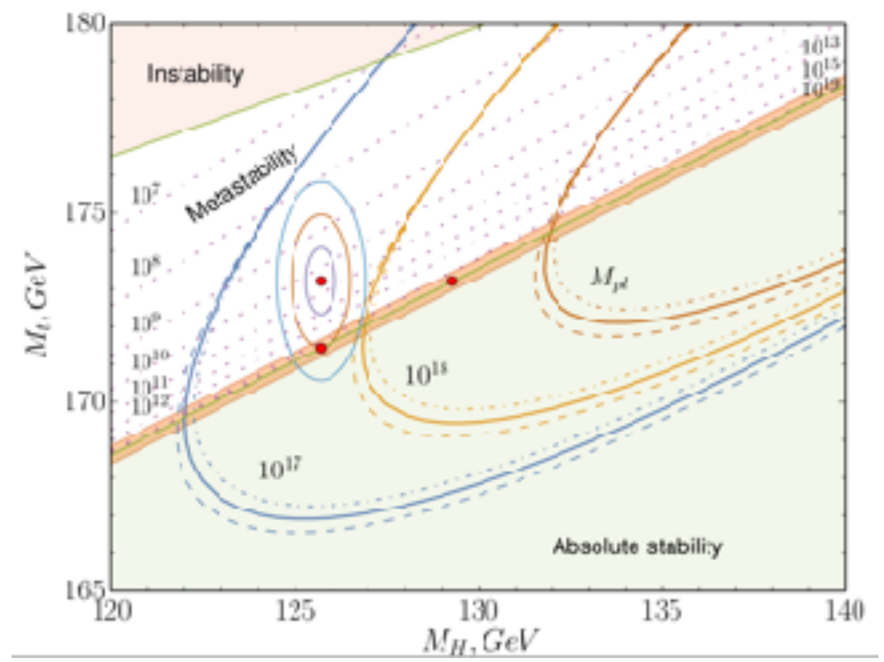
- Its mass may determine the fate of our universe…
  [Bednyakov et al.; PRL 115 (2015) 201802],…



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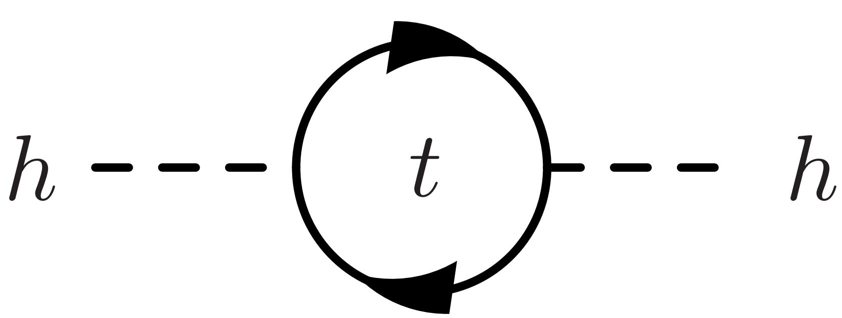
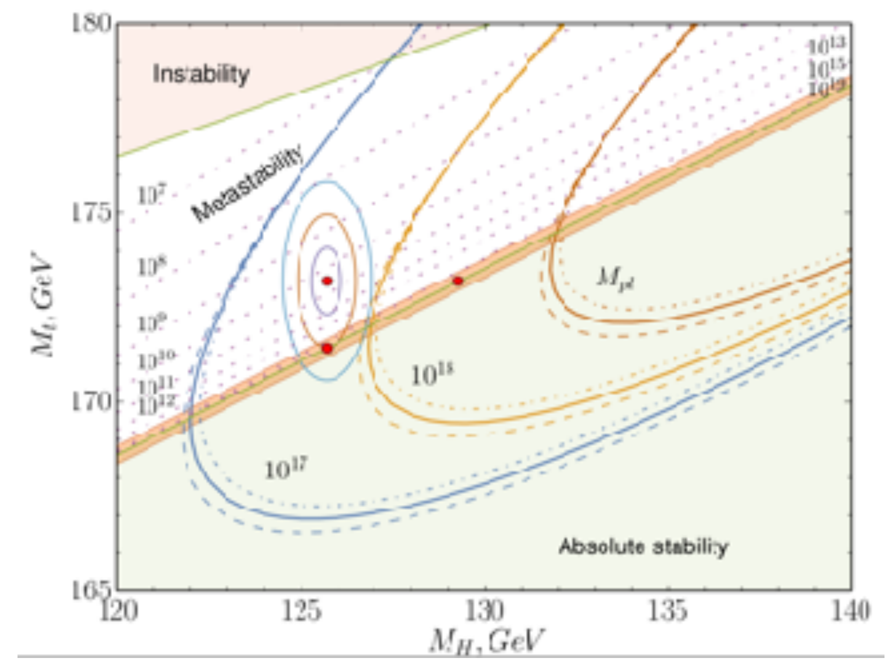
- Key role in BSM physics addressing radiative stability of m_h





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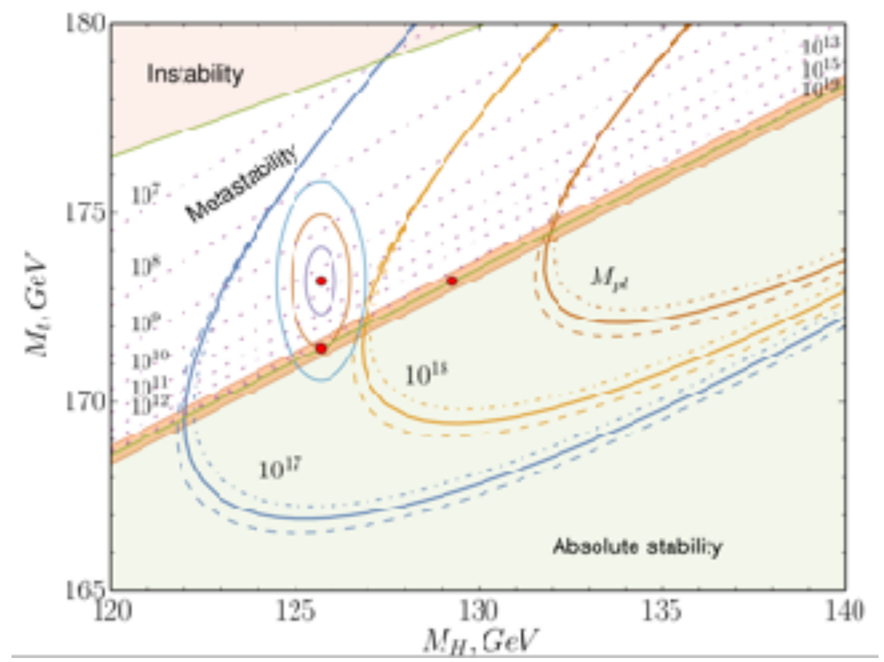

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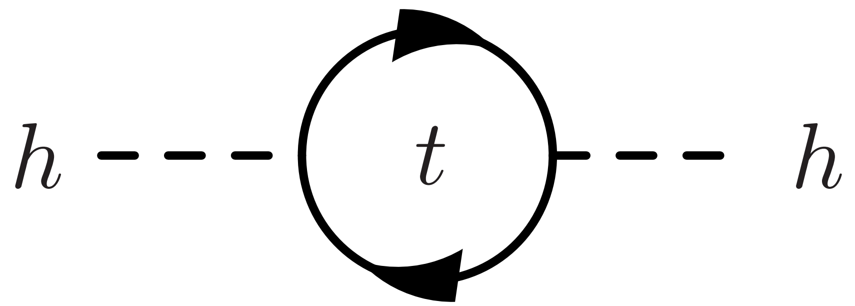

The LHC is a **top factory**

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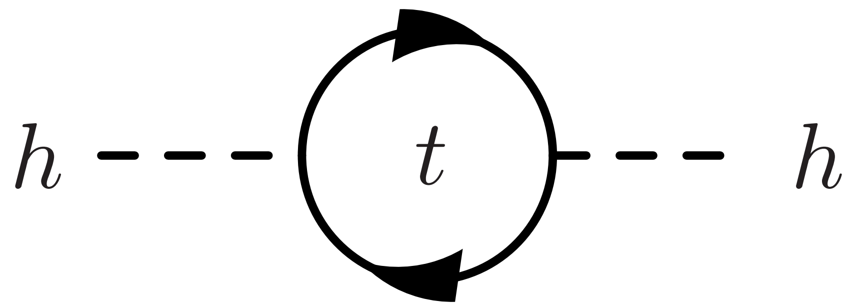

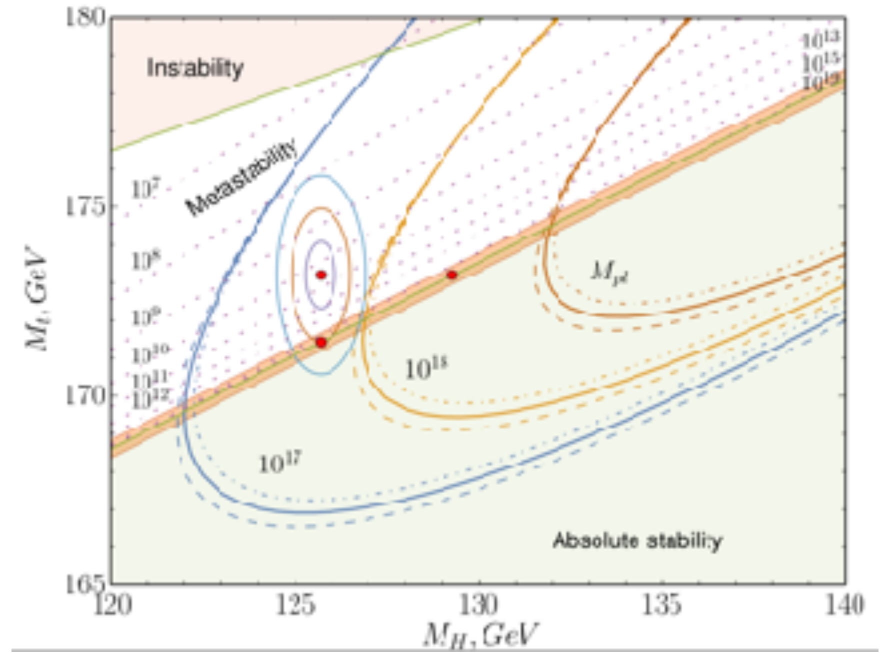

10^9 top pairs

The LHC is a **top factory**

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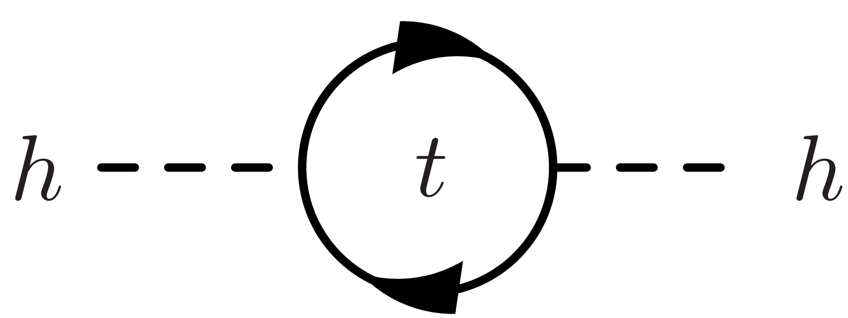

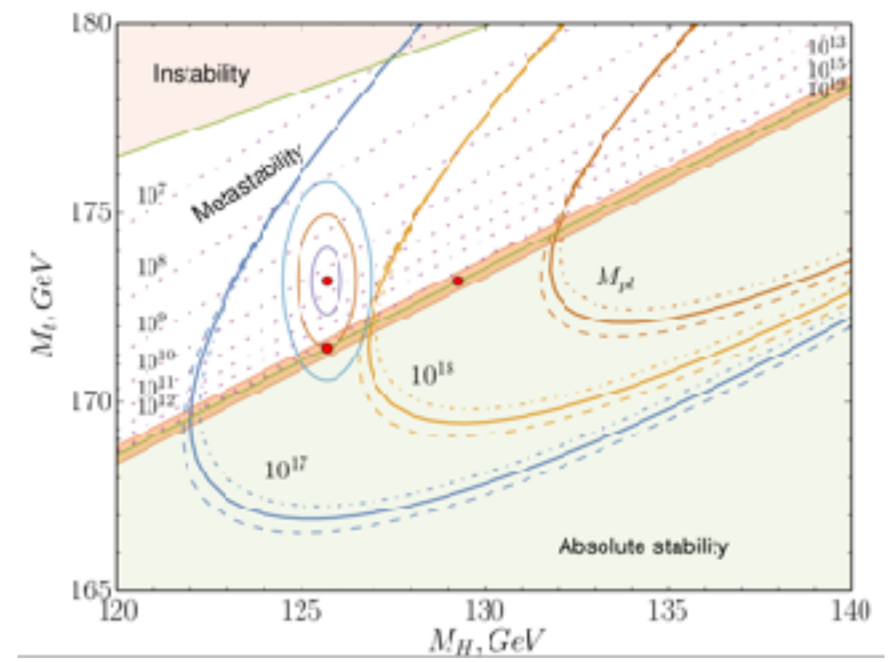

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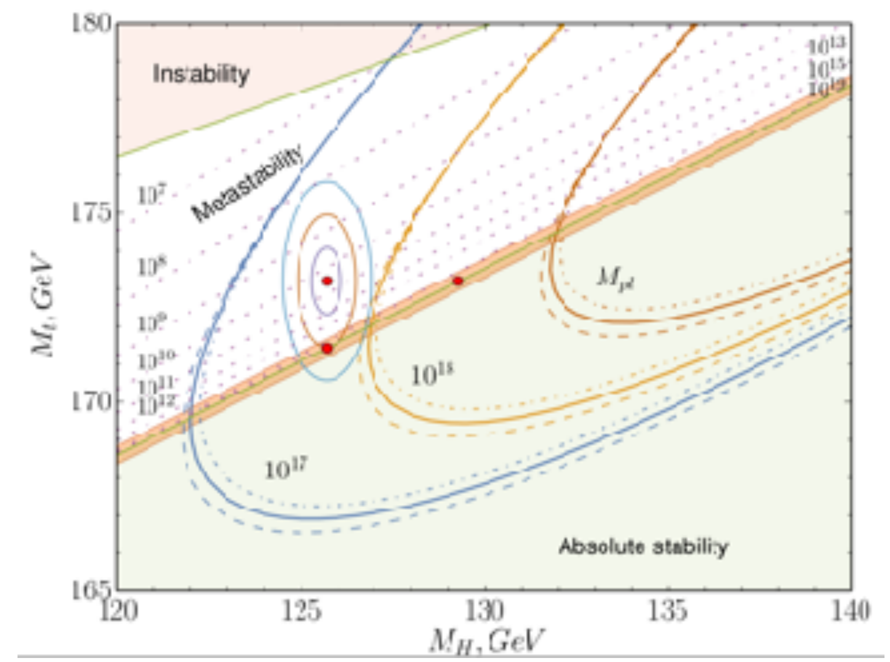

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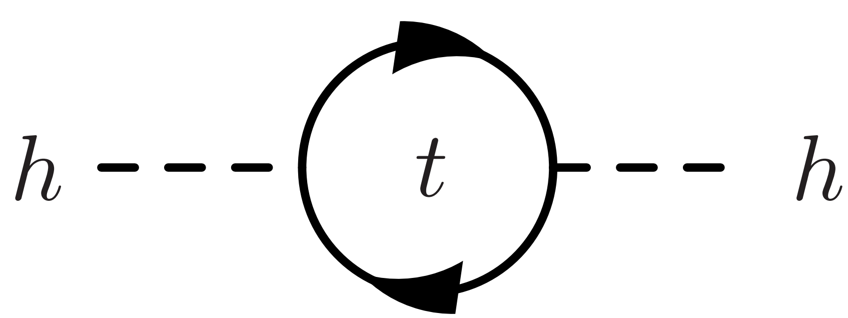

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10^7 tt+W/Z/γ

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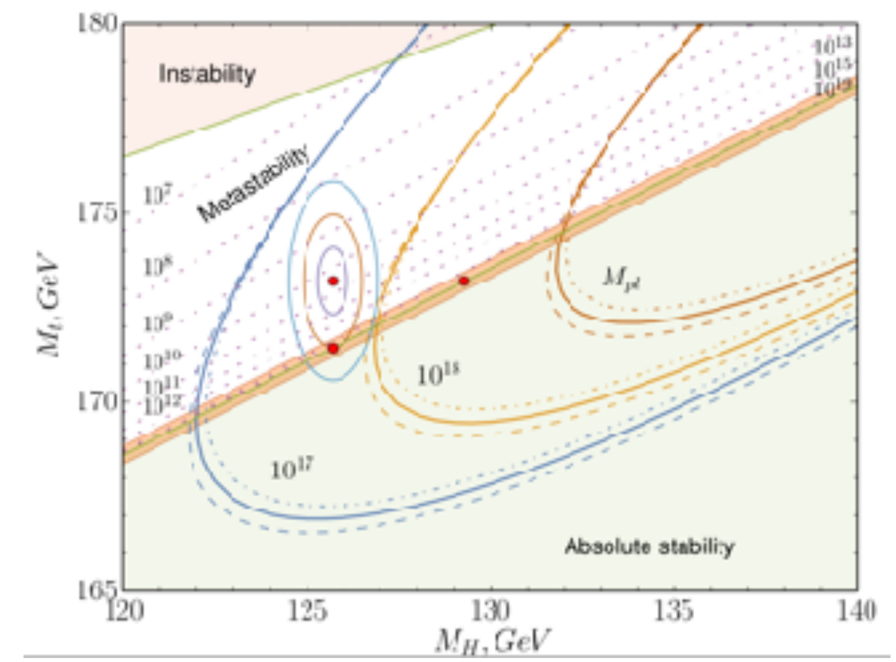

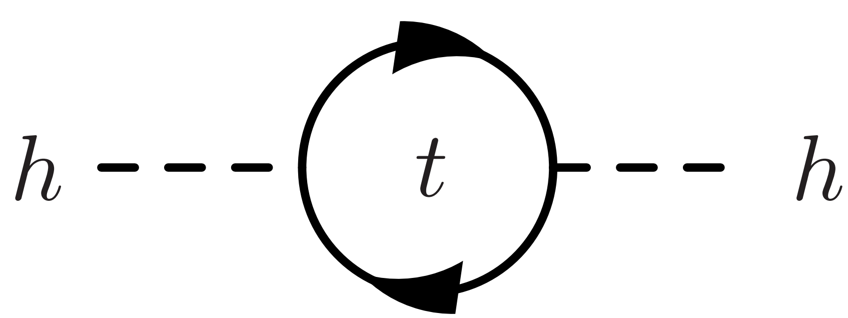

10^9 top pairs

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The LHC is a **top factory**

10^7 tt+W/Z/γ

10^6 ttH

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  [Bednyakov et al.; PRL 115 (2015) 201802],…
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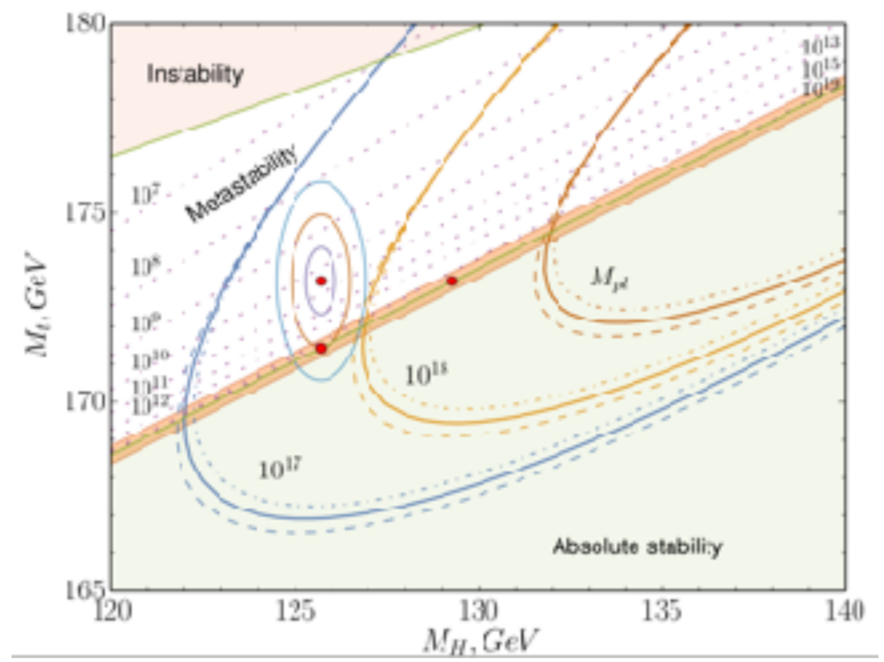

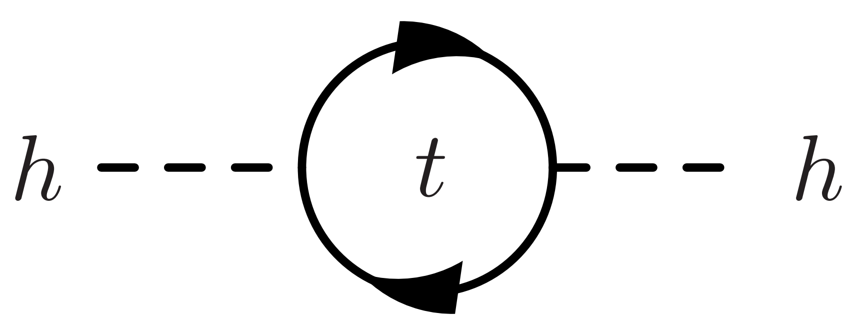

10^9 top pairs

10^8 single top

The LHC is a **top factory**

10^7 tt+W/Z/γ

10^6 ttH 10^4 tttt

The top is special

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It couples to EW gauge bosons

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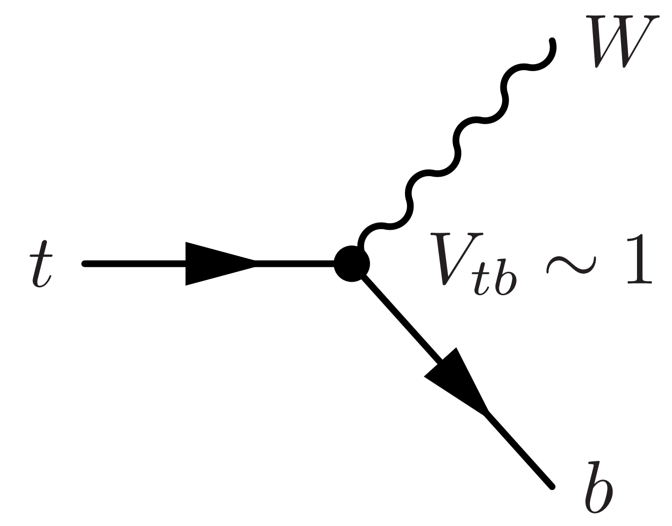
It couples to EW gauge bosons

Through its **decay**



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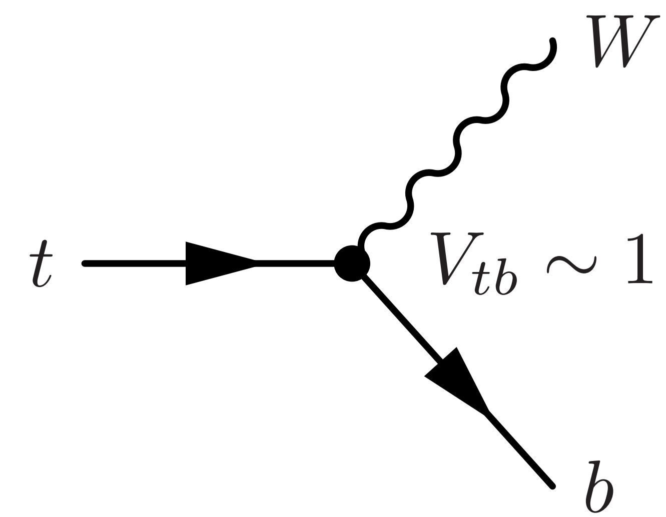
Through its **decay**

- Clean, single Wb channel (V_{tb} ~1)



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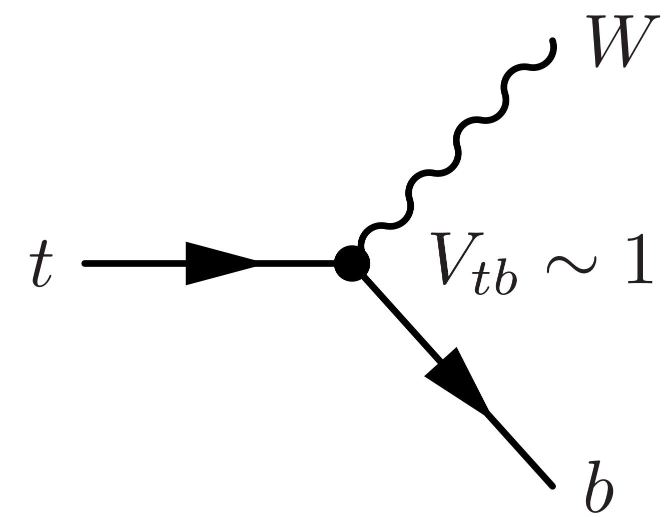

- Clean, single Wb channel (V_{tb} ~1)
- Before hadronisation → it is 'free'

$$\tau_t = \frac{h}{\Gamma_t} \sim 5 \times 10^{-25} s \quad \ll \quad \tau_{\text{had.}} = \frac{h}{\Lambda_{\text{QCD}}} \sim 2 \times 10^{-24} s$$

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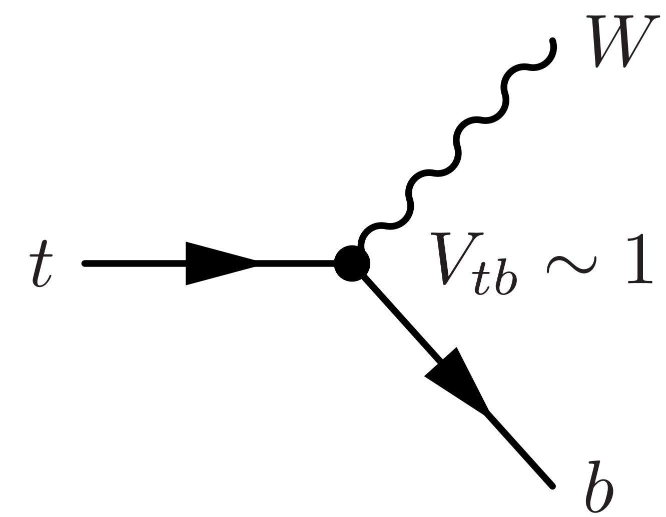

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$$\frac{1}{\Gamma_t}\frac{d\Gamma_{t_\pm}}{d\cos\theta_\ell} \propto (1 \pm \cos\theta_\ell)$$

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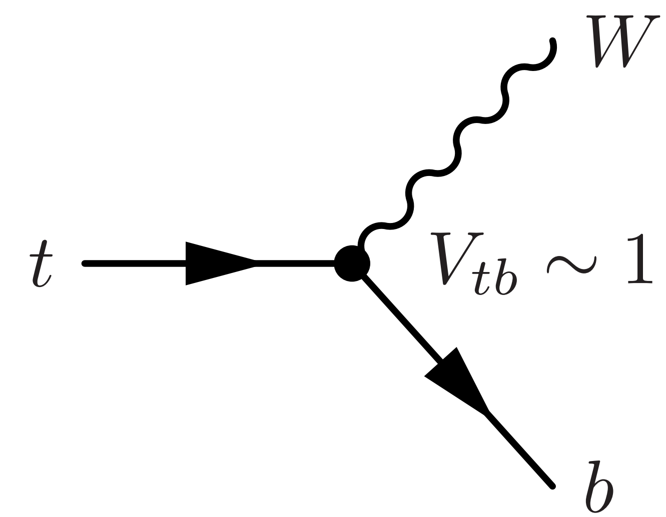

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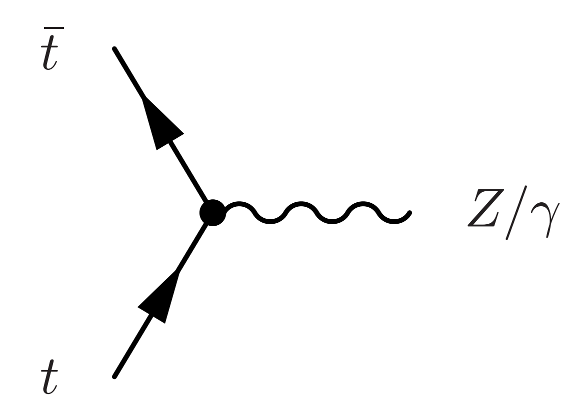
Neutral gauge interactions less well-known



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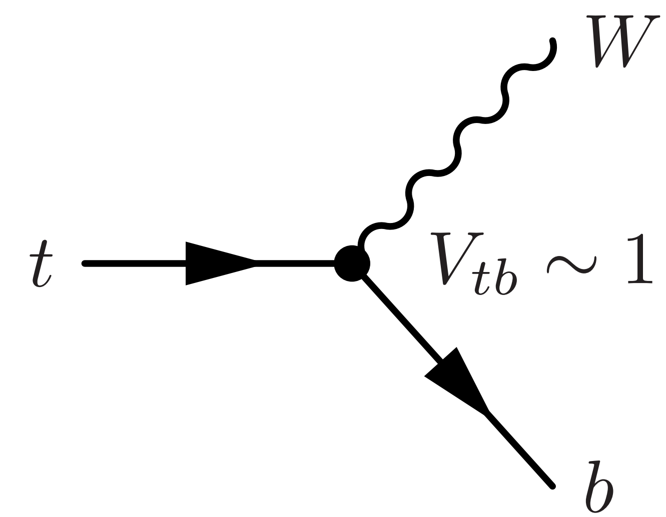

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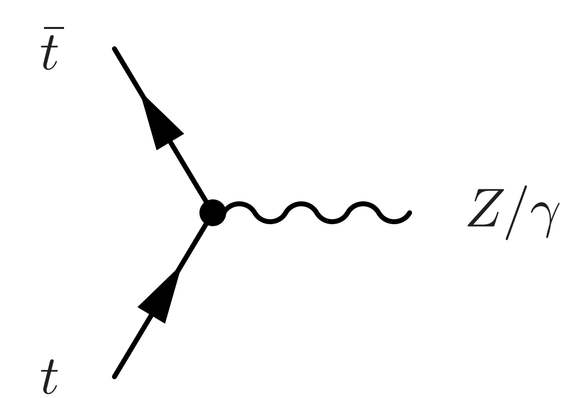

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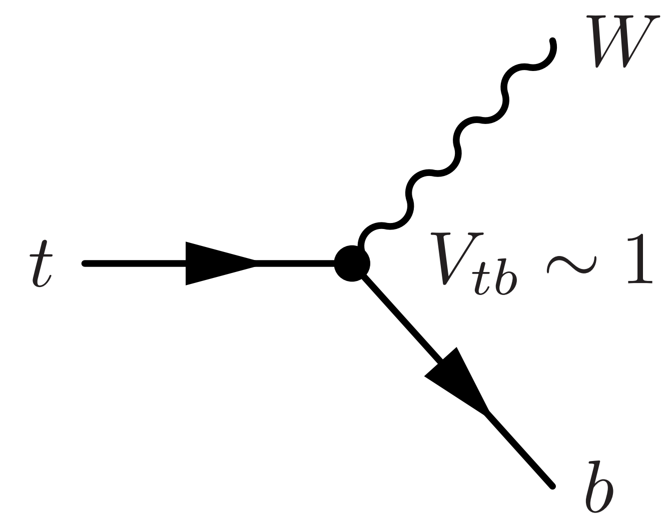

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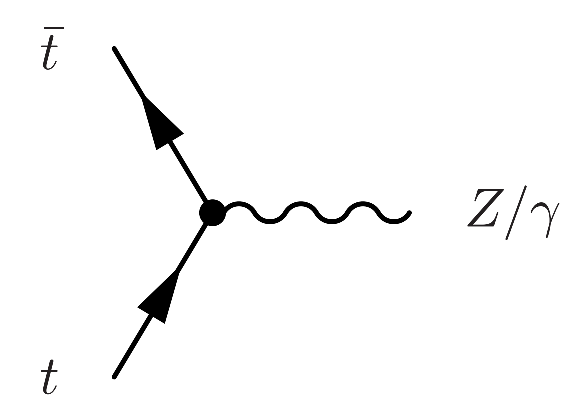
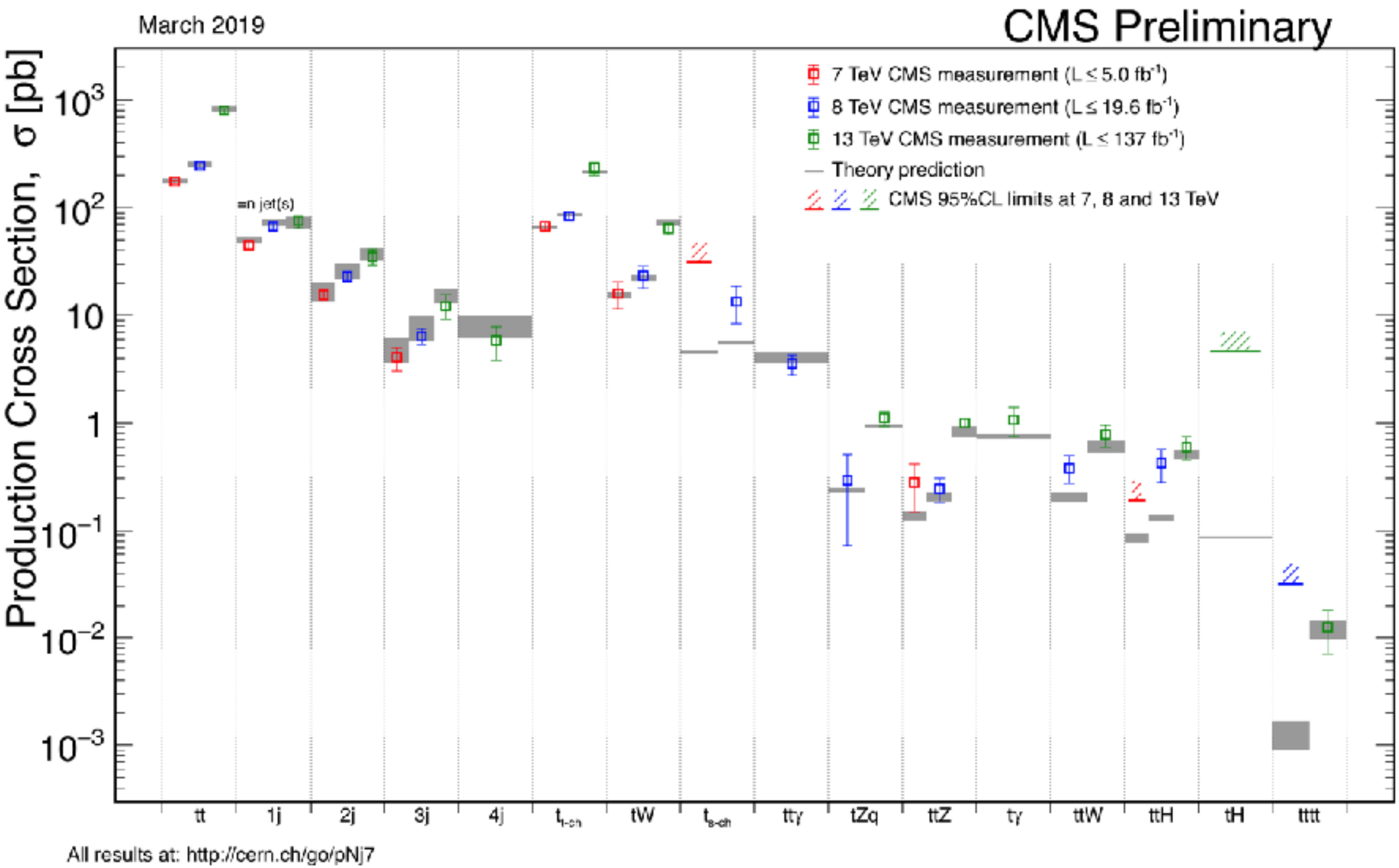


- Measured ttZ, ttγ for the first time at the LHC
- 2019: precision around 10%

LHC top measurements



SMEFT

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Heavy new states are integrated out → local operators built out of SM fields

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Operator expansion: $\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$ → more fields / derivatives

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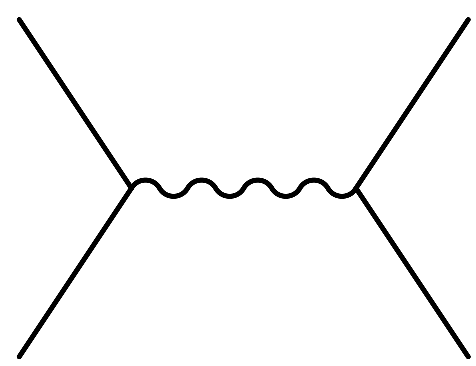

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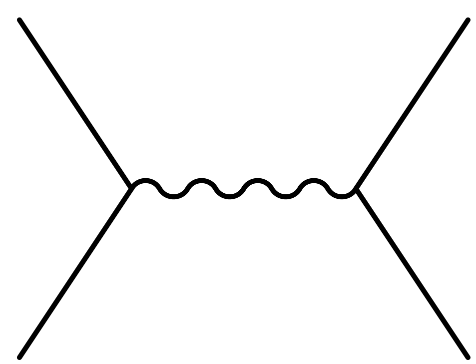
$$\frac{g^2}{p^2 - M^2}$$



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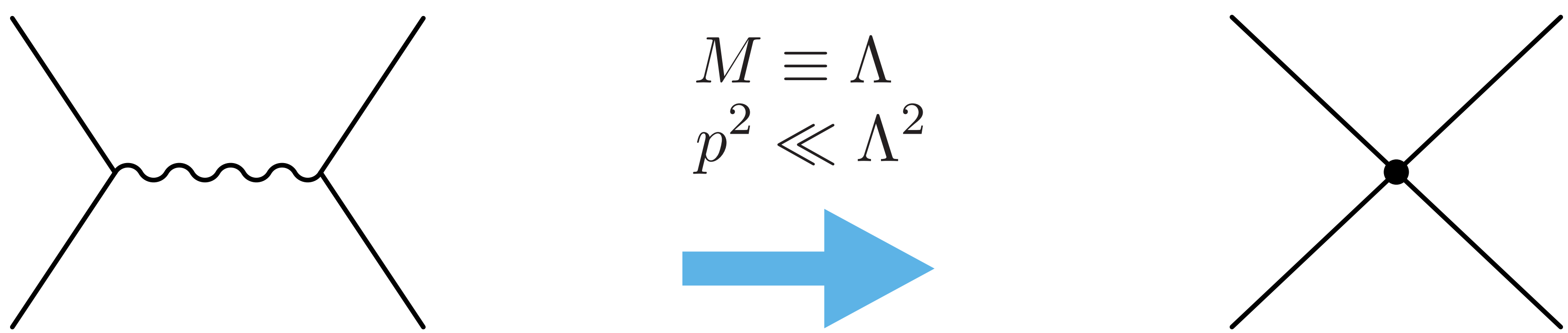

$$M \equiv \Lambda$$
$$p^2 \ll \Lambda^2$$

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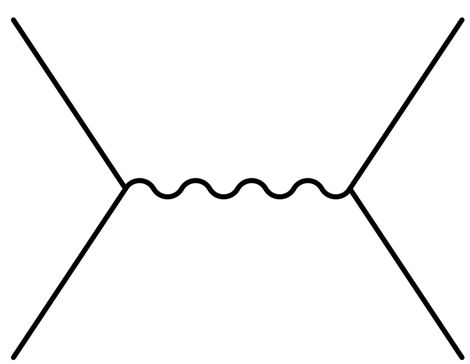
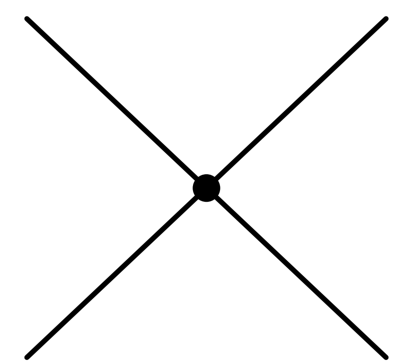


$$\xrightarrow[\;]{M \equiv \Lambda,\; p^2 \ll \Lambda^2}$$



$$-\frac{g^2}{\Lambda^2}\left[1 + \frac{p^2}{\Lambda^2} + \frac{p^4}{\Lambda^4} + \cdots\right]$$

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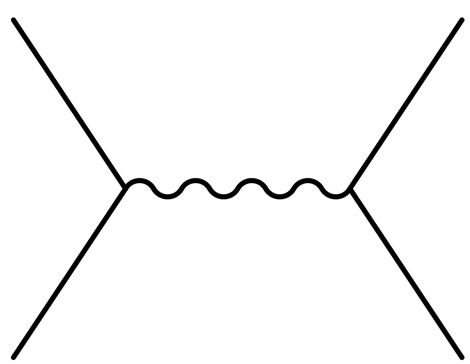

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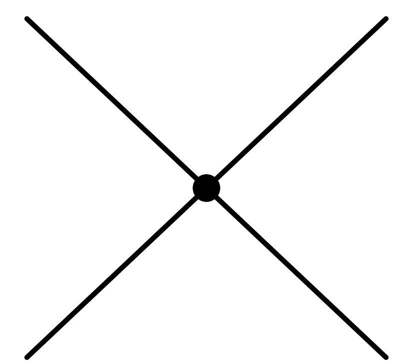

D=6 $\boxed{-\frac{g^2}{\Lambda^2}\left[1\right.}\left.+\frac{p^2}{\Lambda^2}+\frac{p^4}{\Lambda^4}+\cdots\right]$

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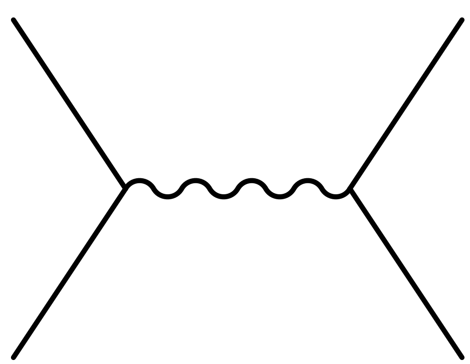

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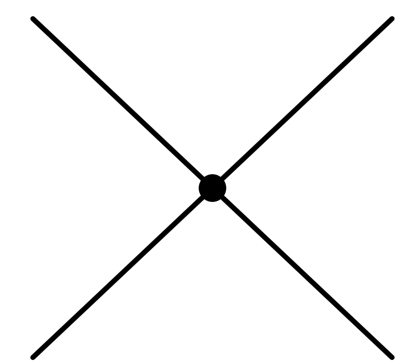

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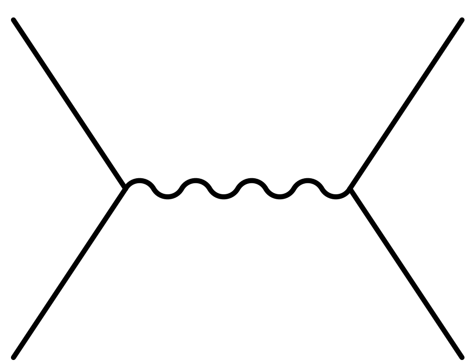

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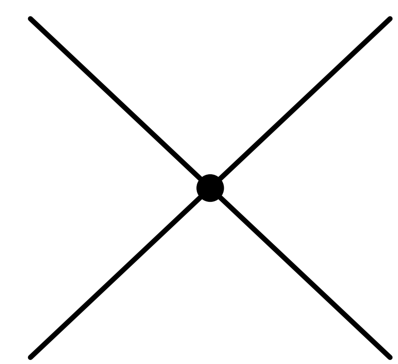

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$$\psi^4 \, : \, G_F \equiv \frac{c}{\Lambda^2} \sim \frac{g^2}{m_W^2}$$

top/EW couplings in SMEFT

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Current operators

$$\psi^2 H^2 D: \;(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\,\gamma^\mu\, Q)\;[(\bar{Q}\,\gamma^\mu \tau^I\, Q),\;(\bar{t}\,\gamma^\mu\, t), ...]$$

$$\to \frac{v^2}{\Lambda^2}\left[Z_\mu\,\bar{t}\gamma^\mu t,\; W^+_\mu \bar{t}\gamma^\mu b\right]$$

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- Shift SM Z, W couplings to fermion currents
- Photon (gluon) interaction protected by $U(1)_{QED(QCD)}$

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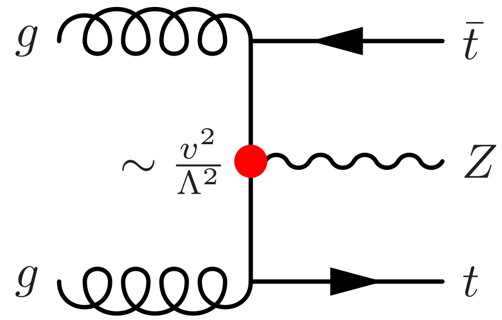

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Overall rescaling of rate

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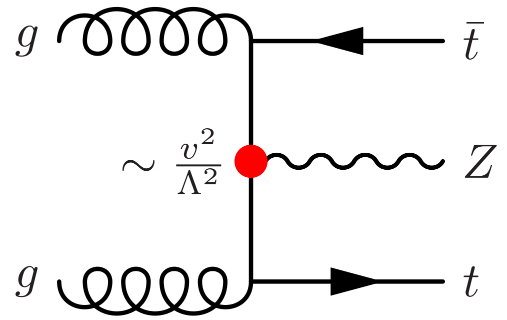

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Dipole operators

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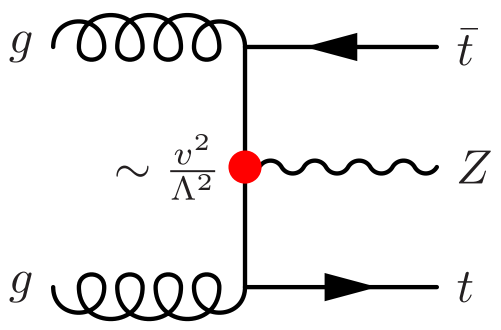

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- Helicity-flip, p-dependent Z, W, γ & g couplings
- Energy growth: $p_T(V)$ tails, V-polarisation

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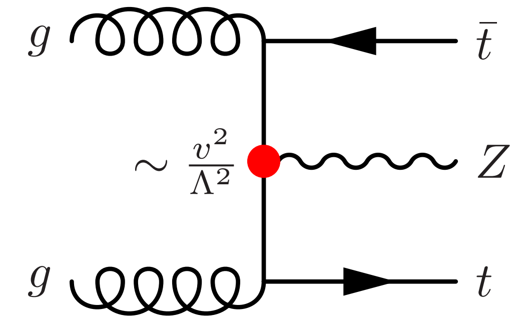

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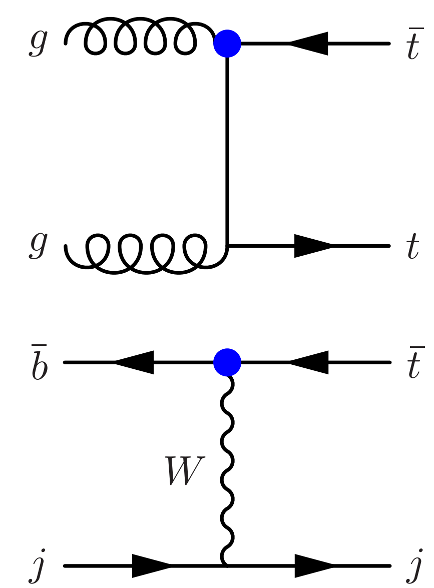

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Yukawa operator

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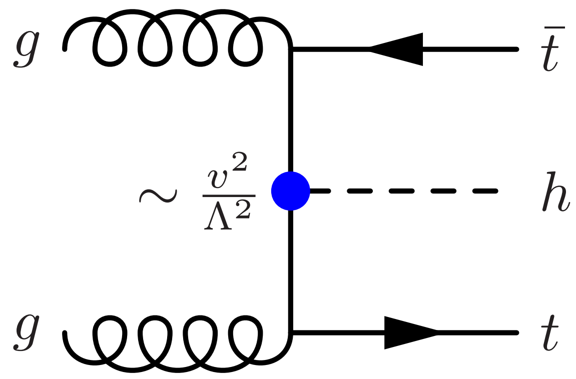

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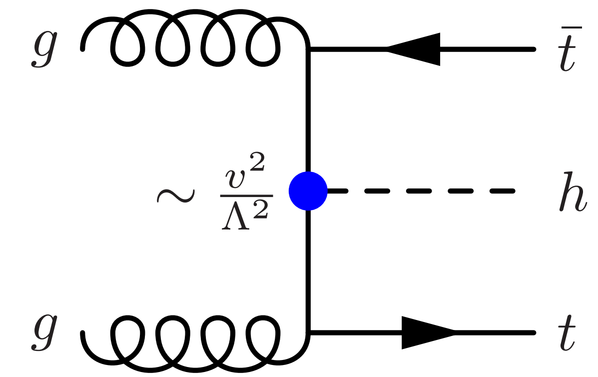

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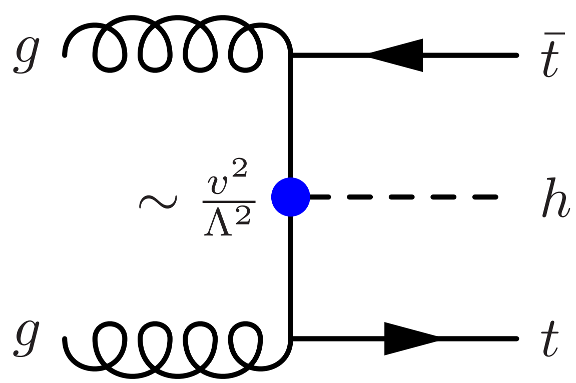
Four-fermion operators

$$\psi^4 : \; (\bar{Q}\,\gamma^\mu\, Q)(\bar{q}\,\gamma_\mu\, q),\; (\bar{Q}\,\gamma^\mu\, Q)(\bar{Q}\,\gamma_\mu\, Q), \ldots$$

$$\to \frac{1}{\Lambda^2}\Big[\, (\bar{t}\gamma^\mu t)\,(\bar{q}\gamma_\mu q)\,,\; (\bar{t}\gamma^\mu b)\,(\bar{q}\gamma_\mu q')$$

$$(\bar{t}\gamma^\mu t)\,(\bar{t}\gamma_\mu t)\,,\; (\bar{t}\gamma^\mu t)\,\big(\bar{b}\gamma_\mu b\big)\,, \ldots\Big]$$

top/EW couplings in SMEFT



Yukawa operator

$$\psi^2 H^3 \,:\, (\varphi^\dagger \varphi)^2 (\bar{Q}\, t\, \tilde{\varphi})$$

$$\rightarrow \frac{v^2}{\Lambda^2} \bar{t}_L t_R\, h + \mathrm{h.c.}$$

- Disconnects kinematical mass from Yukawa coupling
- ttH + ggF(indirect)

Four-fermion operators

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- Contact terms between four light/heavy quarks
- top pair+asymmetries & single top

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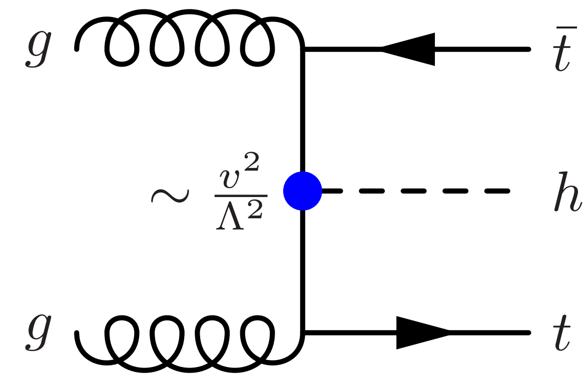

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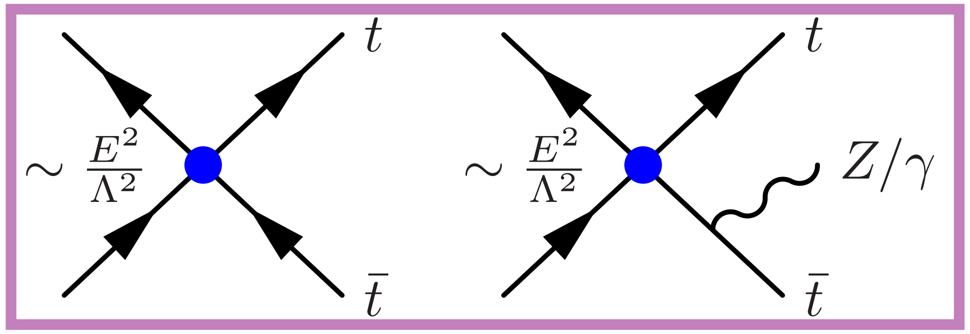

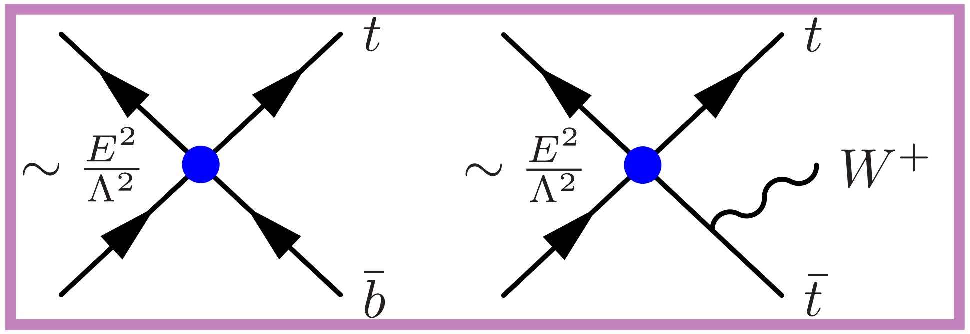

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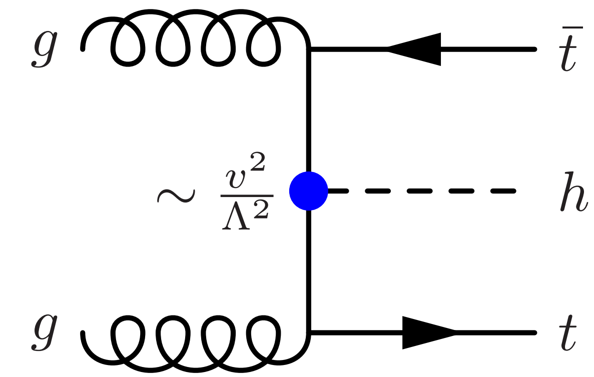

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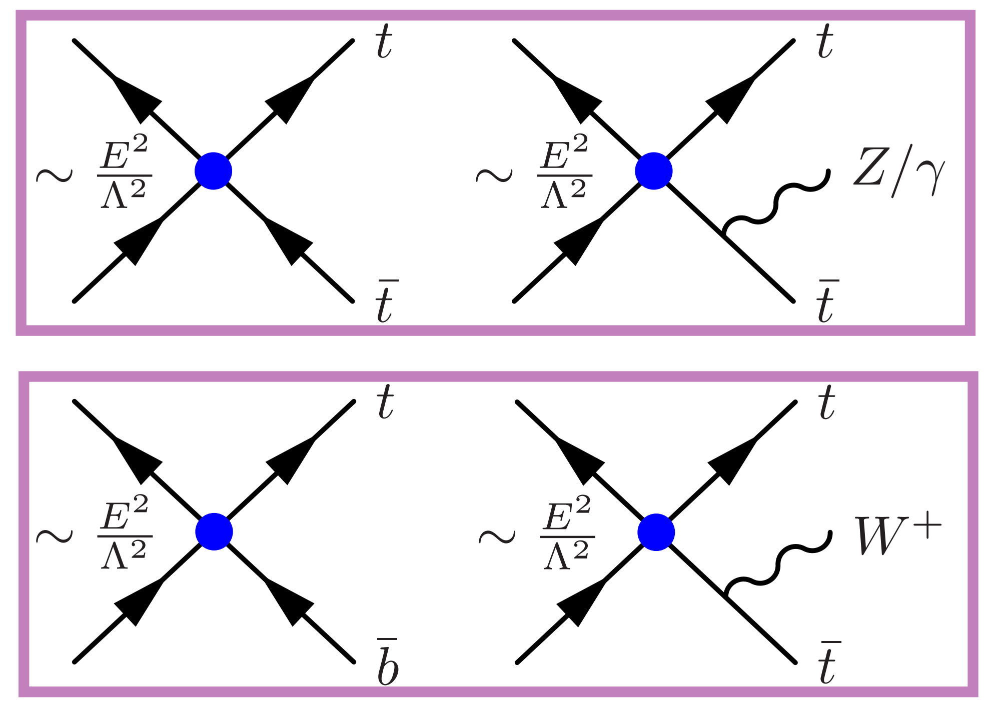

QQQQ → 4 top & ttbb

Signal/background

Signal/background

Challenge for SMEFT interpretation of top/EW measurements

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- **Complex**, high-multiplicity final state: b-jets, leptons, forward jets

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$t\bar{t}Z(\ell^+\ell^-)$	$t\bar{t}W$, $t\bar{t}H$, tZj, WZ,...
$t\bar{t}H(b\bar{b})$	$t\bar{t}Z$, $t\bar{t}b\bar{b}$, $t\bar{t}W$, tZj,...
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$t\bar{t}H(\tau^+\tau^-)$	$t\bar{t}W(W)$, $t\bar{t}Z$,...
tZj	$t\bar{t}V$, tHj, tHW, tZW,...
tHj	$t\bar{t}H$, $t\bar{t}Z$, $t\bar{t}b\bar{b}$, $t\bar{t}W$, tZj,...
$t\bar{t}t\bar{t}$	$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$,...

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Global fit nightmare

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Combined, multi-channel searches: tt+tj+ttX+tX

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"Global measurements for global fits"

Global measurements

Global measurements

Search for new physics in top quark production in dilepton final states in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration*

[CMS-TOP-17-020]

There is hope…

Global measurements

Search for new physics in top quark production in dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Simultaneous tt and tW signal region

Global measurements

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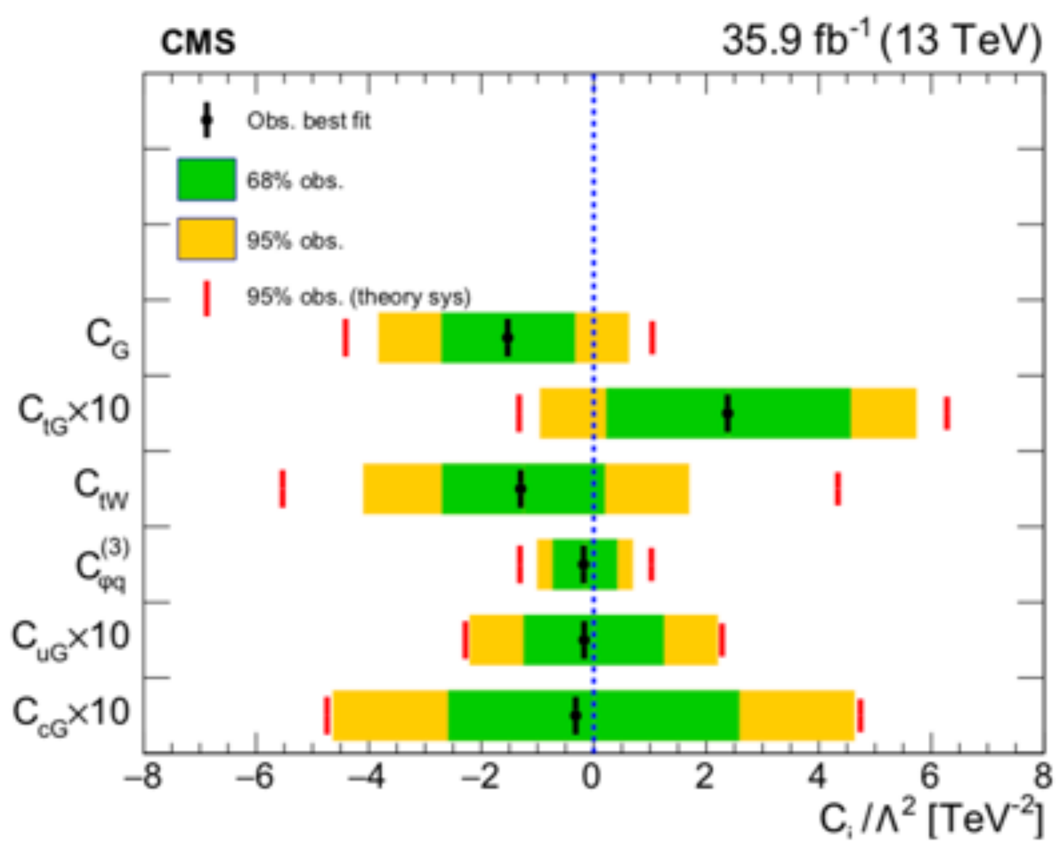
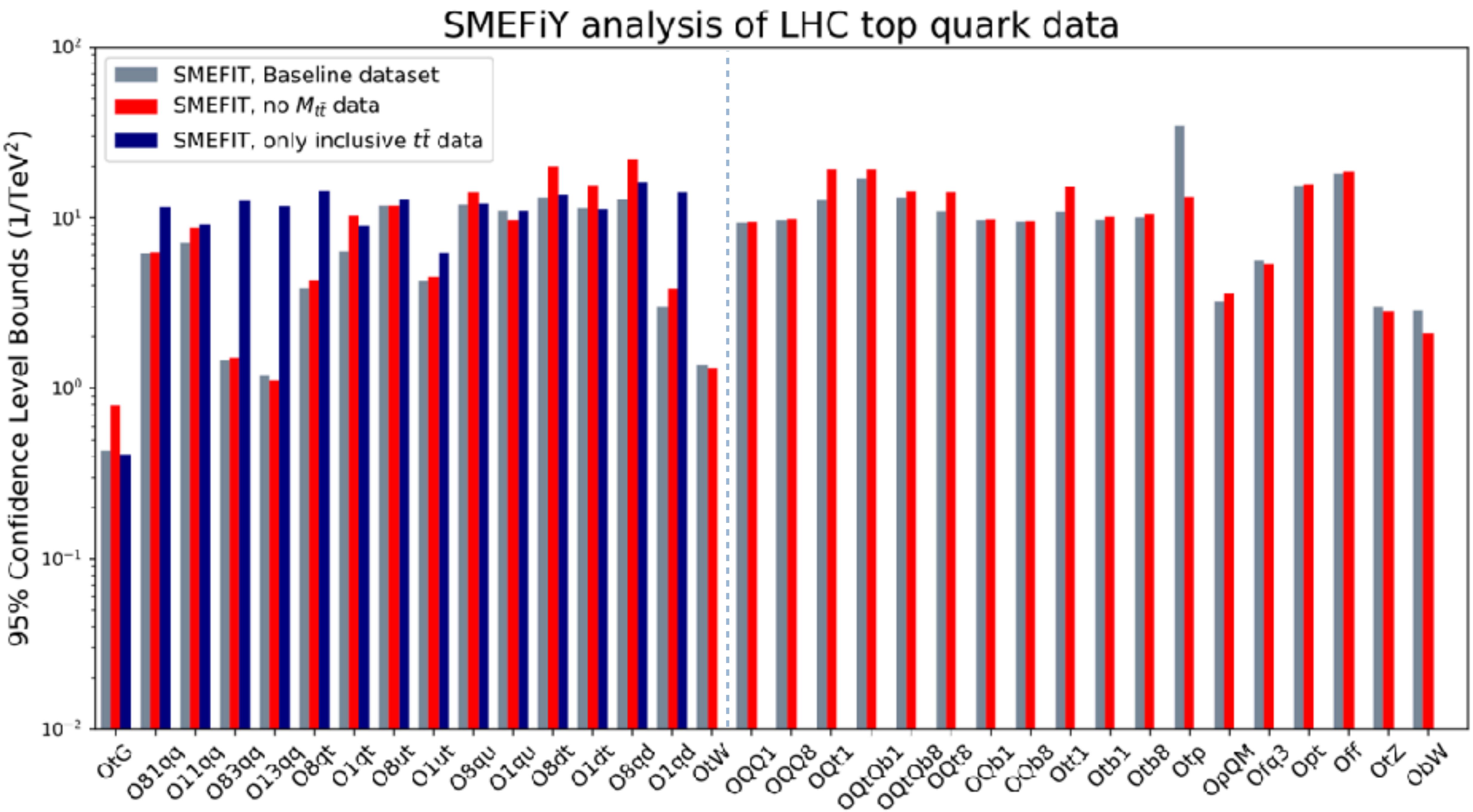
Simultaneous tt and tW signal region

Bonus: EFT interpretation!



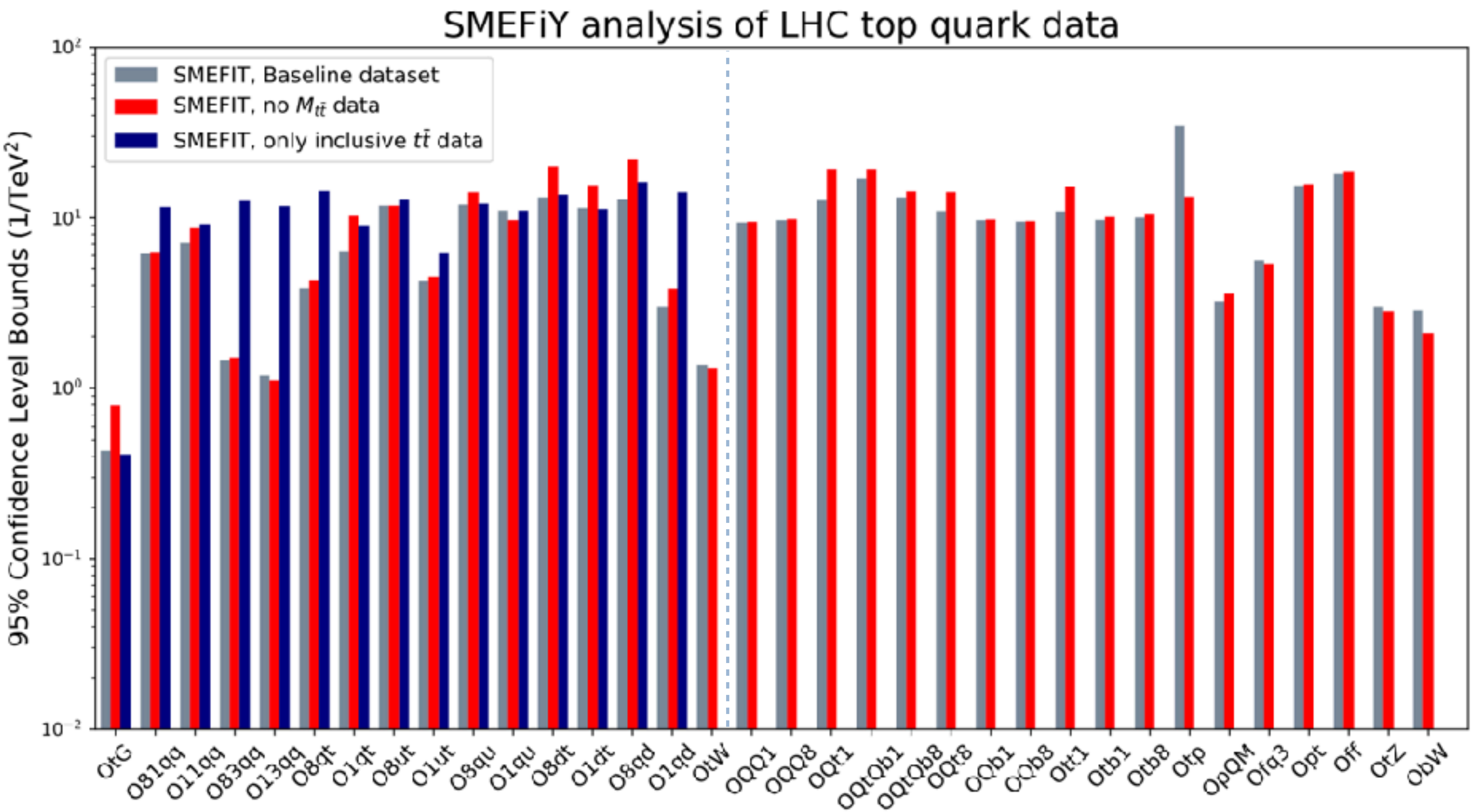
Validity



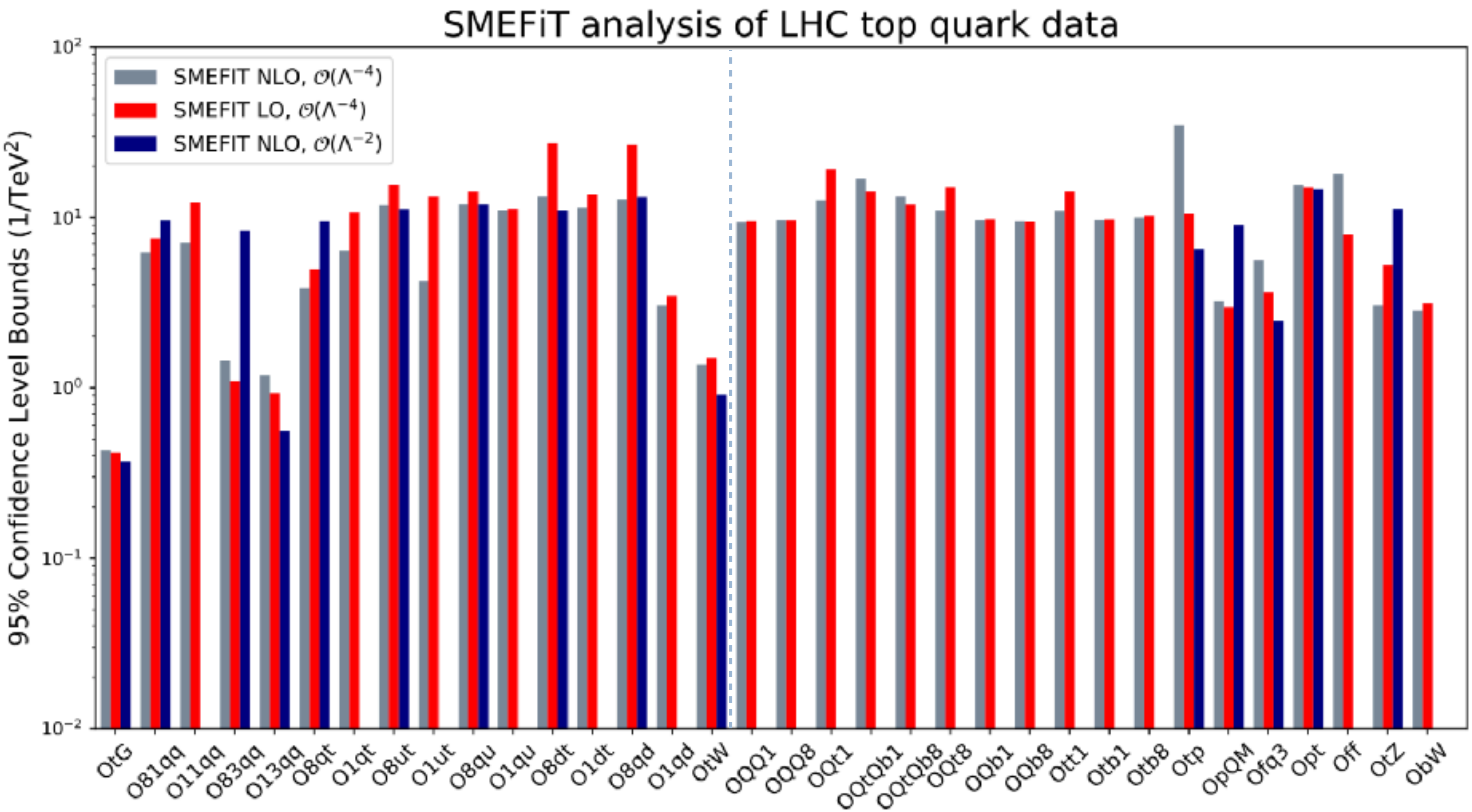
SMEFiY analysis of LHC top quark data
SMEFIT, Baseline dataset
SMEFIT, no $M_{t\bar{t}}$ data
SMEFIT, only inclusive $t\bar{t}$ data
95% Confidence Level Bounds (1/TeV^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
OtG O81qq O11qq O83qq O13qq O8qt O1qt O8ut O1ut O8qu O1qu O8dt O1dt O8qd O1qd OtW OQQ1 OQQ8 OQt1 OQtQb1 OQtQb8 OQt8 OQb1 OQb8 Ott1 Otb1 Otb8 Otp OpQM Ofq3 Opt Off OtZ ObW

Validity

Check impact of high energy by removing differential M_{tt} bins

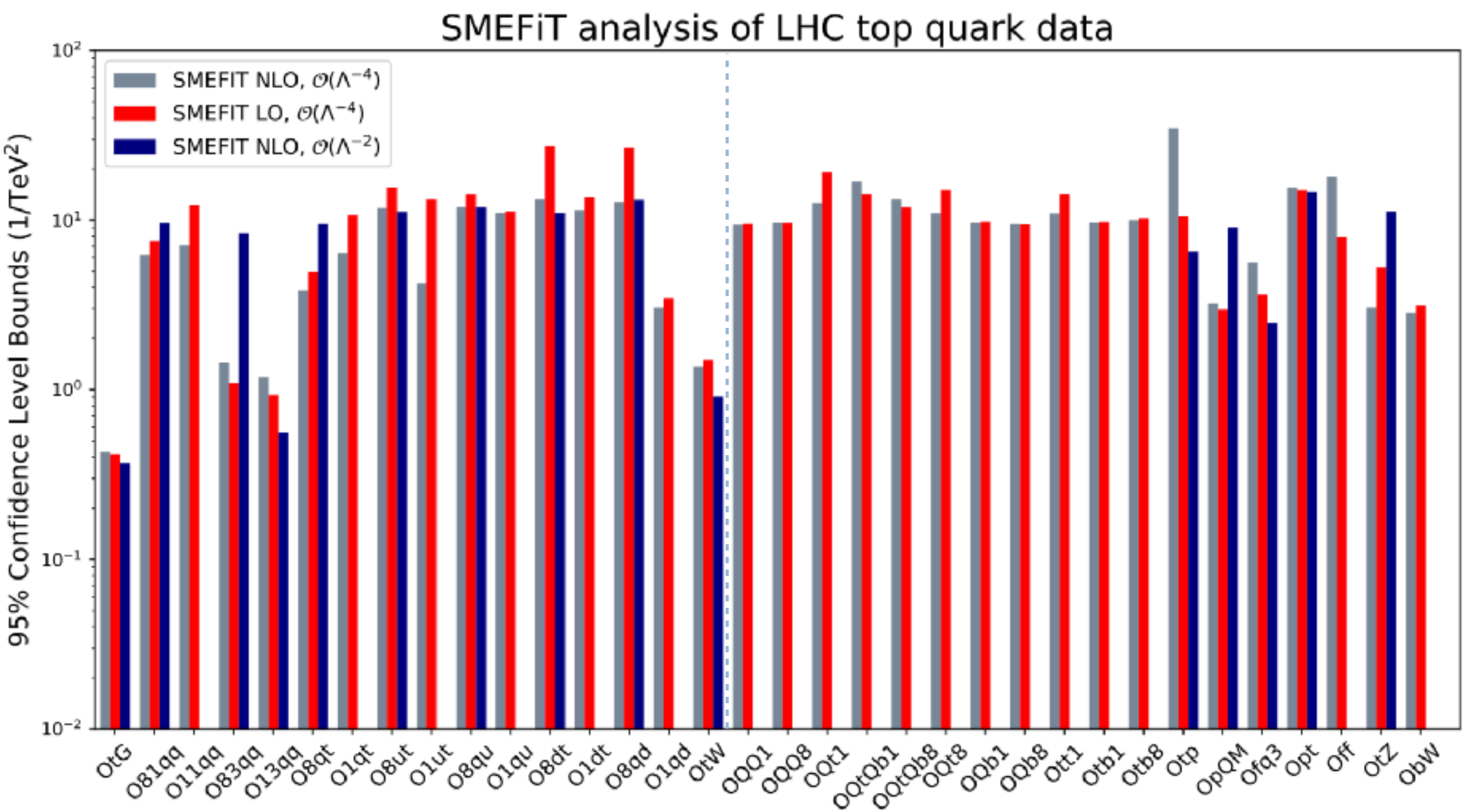


Higher orders



Higher orders

Impact of NLO and $1/\Lambda^4$



Higher orders

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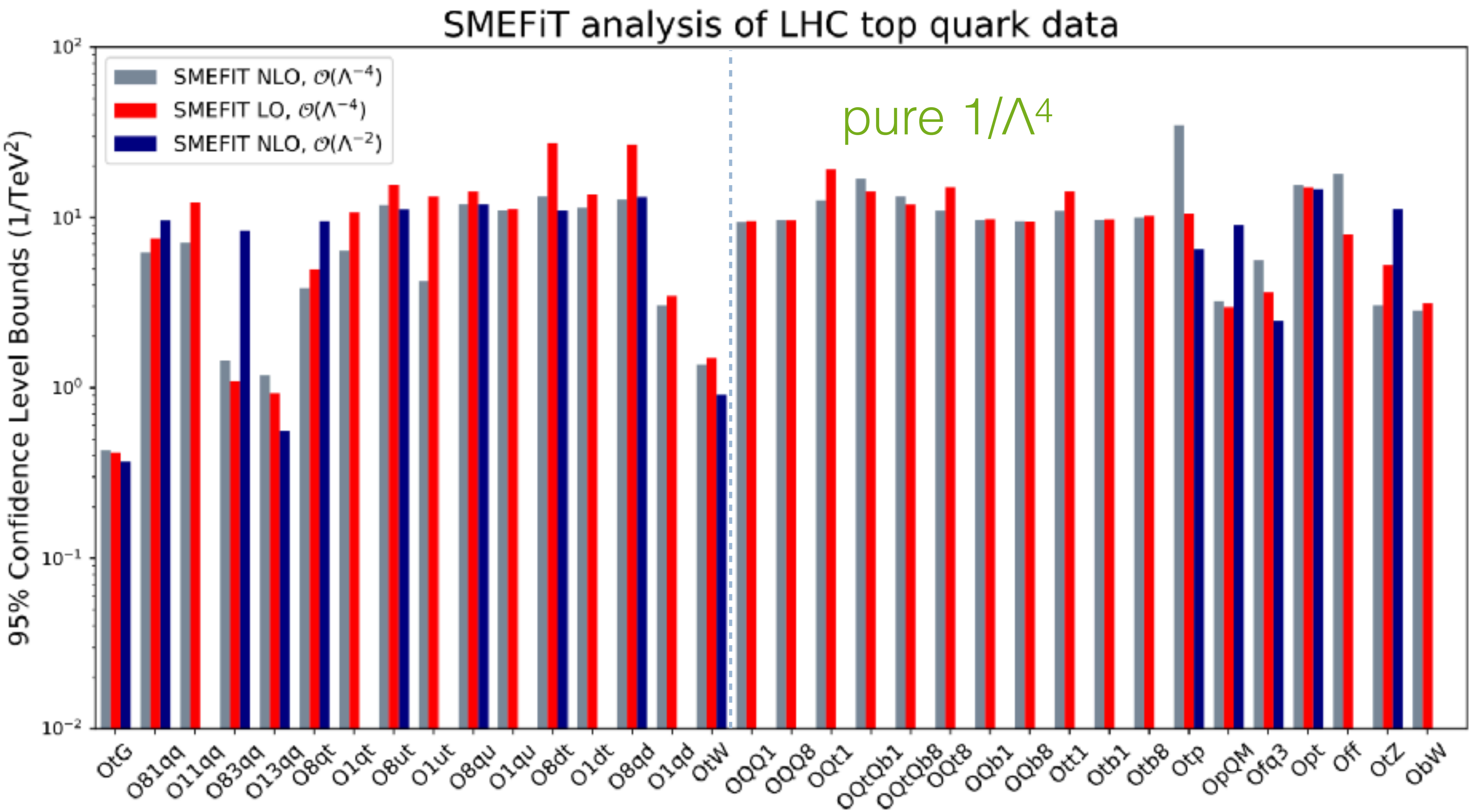
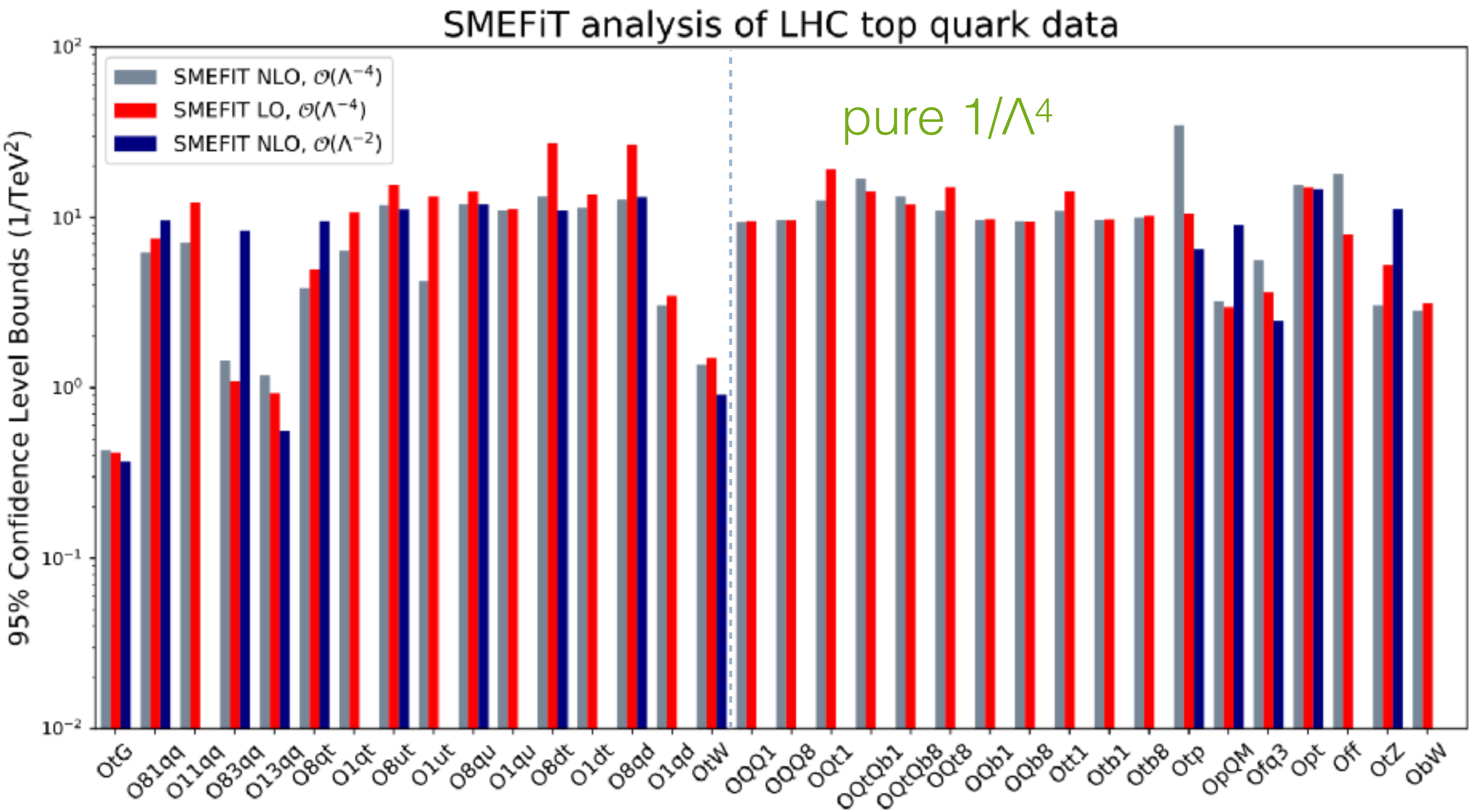


Higher orders

Impact of NLO and $1/\Lambda^4$ LO vs NLO

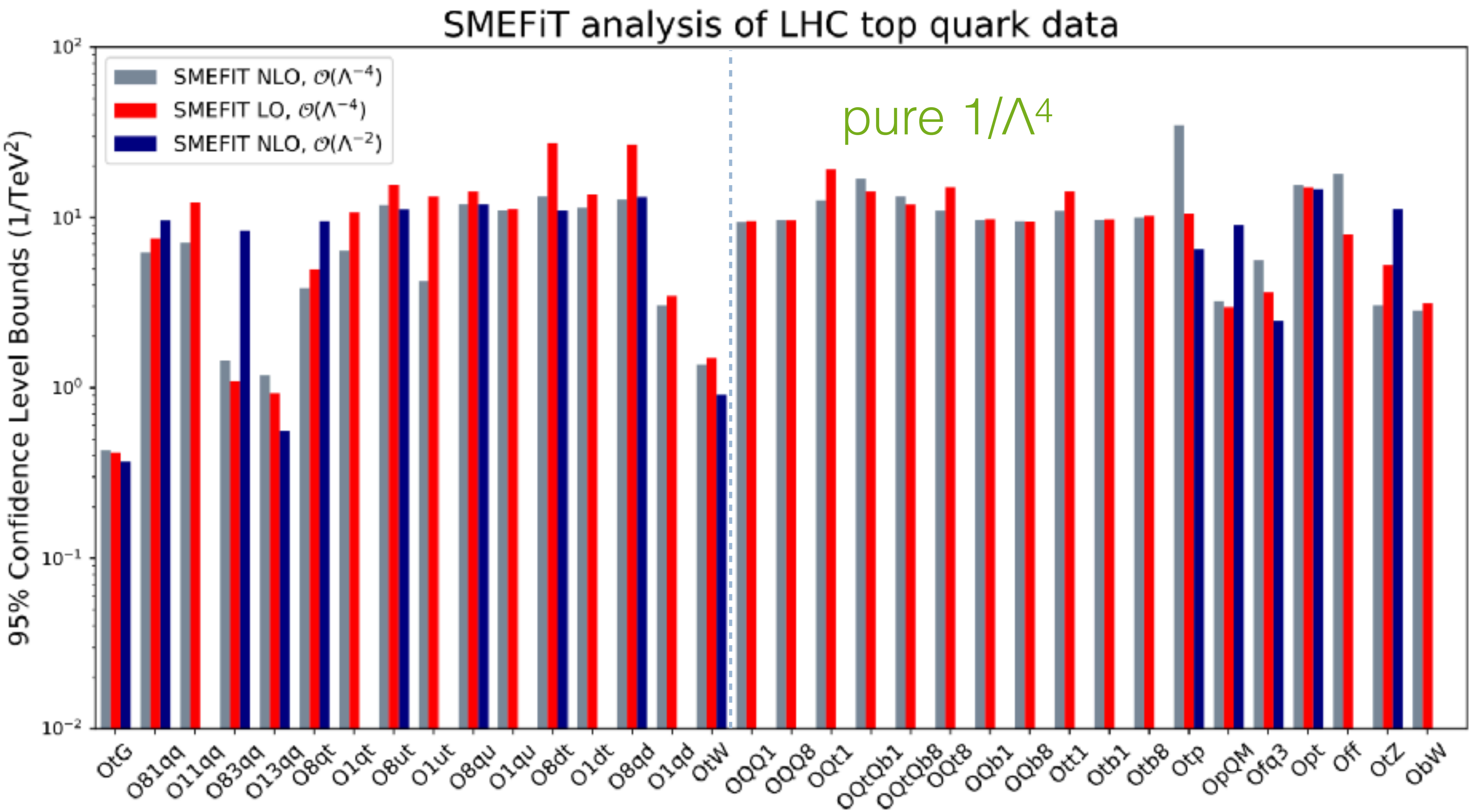


Higher orders

$$\mathcal{O} = \mathcal{O}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}^i_{\mathrm{int}} + \sum_{i,j} \frac{c_i\, c_j}{\Lambda^4}\mathcal{O}^{ij}_{\mathrm{sq}}$$

Impact of NLO and $1/\Lambda^4$

LO vs NLO $\quad$ $1/\Lambda^2$ vs $1/\Lambda^4$



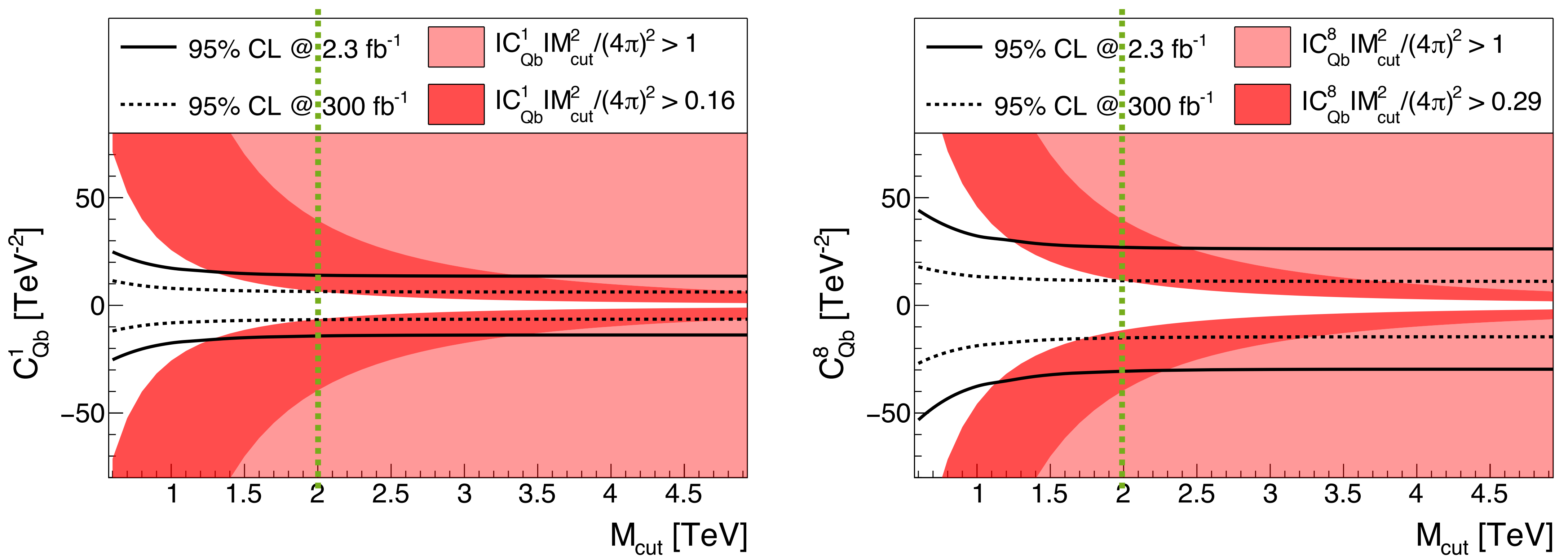
Validity & M_{cut}

M_{cut} < 2 TeV required for all energy scales of the process

- Valid interpretation for $\Lambda_{NP} > M_{cut}$

Tree-level matching: $c/\Lambda^2 \sim g^{*2}/\Lambda_{NP}^2$

- Dim-6 EFT contribution to amplitude scales at most ~ $c(E/\Lambda)^2$
- NP perturbativity bound: $c(E/\Lambda)^2 < (4\pi)^2$



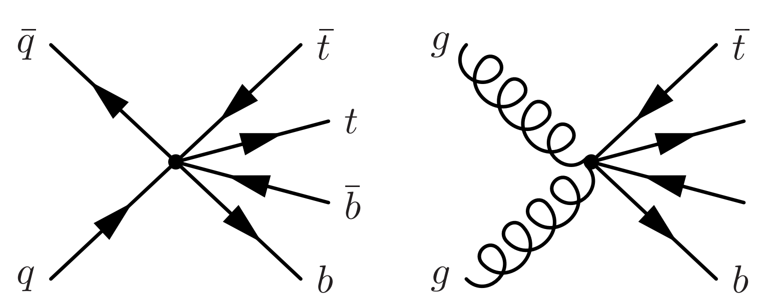
Dimension 8 in ttbb

Sensitivity dominated by EFT squared ($1/\Lambda^4$) terms

- Non-interference due to colour
- Large Wilson coefficients ~ strong coupling regime $\quad \dfrac{C^{(6)}E^2}{\Lambda^2} \gtrsim 1$

Are higher dimension operators relevant?

D=10 D=8



As long as $E < \Lambda$

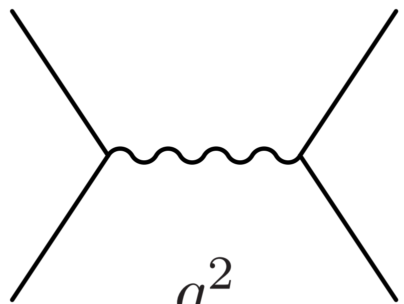
- 6 fermion operators: at least dim-10 ~ $(E/\Lambda)^6$
- Dim-8 four fermion operators ~ $(E/\Lambda)^4$

schematically: $ffffD_\mu D_\nu$ & $ffffG_{\mu\nu}$

one coupling & one scale power counting:

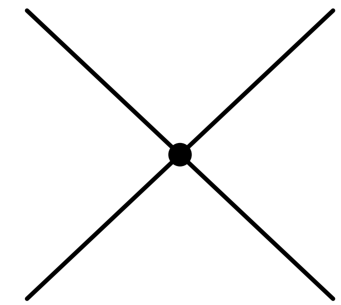
$$\mathcal{L}_{\rm EFT} = \frac{\Lambda_{NP}^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda_{NP}}, \frac{g_* H}{\Lambda_{NP}}, \frac{g_* f_{L,R}}{\Lambda_{NP}^{3/2}}, \frac{g F_{\mu\nu}}{\Lambda_{NP}^2}\right)$$

Power counting



$$\frac{g^2}{p^2 - M^2}$$

$p^2 \ll \Lambda^2$



$$\boxed{-\frac{g^2}{\Lambda^2}\Big[1}\ \boxed{+\frac{p^2}{\Lambda^2}}+\frac{p^4}{\Lambda^4}+\cdots\Big]$$

D=6 D=8 $\frac{C_{4F}^{(6)}}{\Lambda^2} \sim \frac{C_{4F}^{(8)}}{\Lambda^2} \sim \frac{g_*^2}{M^2}$

dim-6 interference: $\frac{g_s^6 g_*^2 E^2}{\Lambda_{NP}^2}$

dim-6 quadratic term: $\frac{g_s^4 g_*^4 E^4}{\Lambda_{NP}^4}$

$\boxed{(g_*/g_s)^2 E^2/\Lambda_{NP}^2 \approx 1 \rightarrow \text{SQ} \sim \text{INT}}$

g* enhancement

$ffffD_\mu D_\nu$ $\frac{C_i^{(8)}}{\Lambda^2} \sim \frac{g_*^2}{M^2}$

$ffffG_{\mu\nu}$ $\frac{C_i^{(8)}}{\Lambda^2} \sim \frac{g_*^2 g_s}{M^2}$

ttbb operator + 2 derivatives

gttbb contact term

ggttbb contact term

dim-8 interference: $\frac{g_s^6 g_*^2 E^4}{\Lambda_{NP}^4}$

no g* enhancement