Precision in EFT studies for top and Higgs physics

Eleni Vryonidou
CERN TH

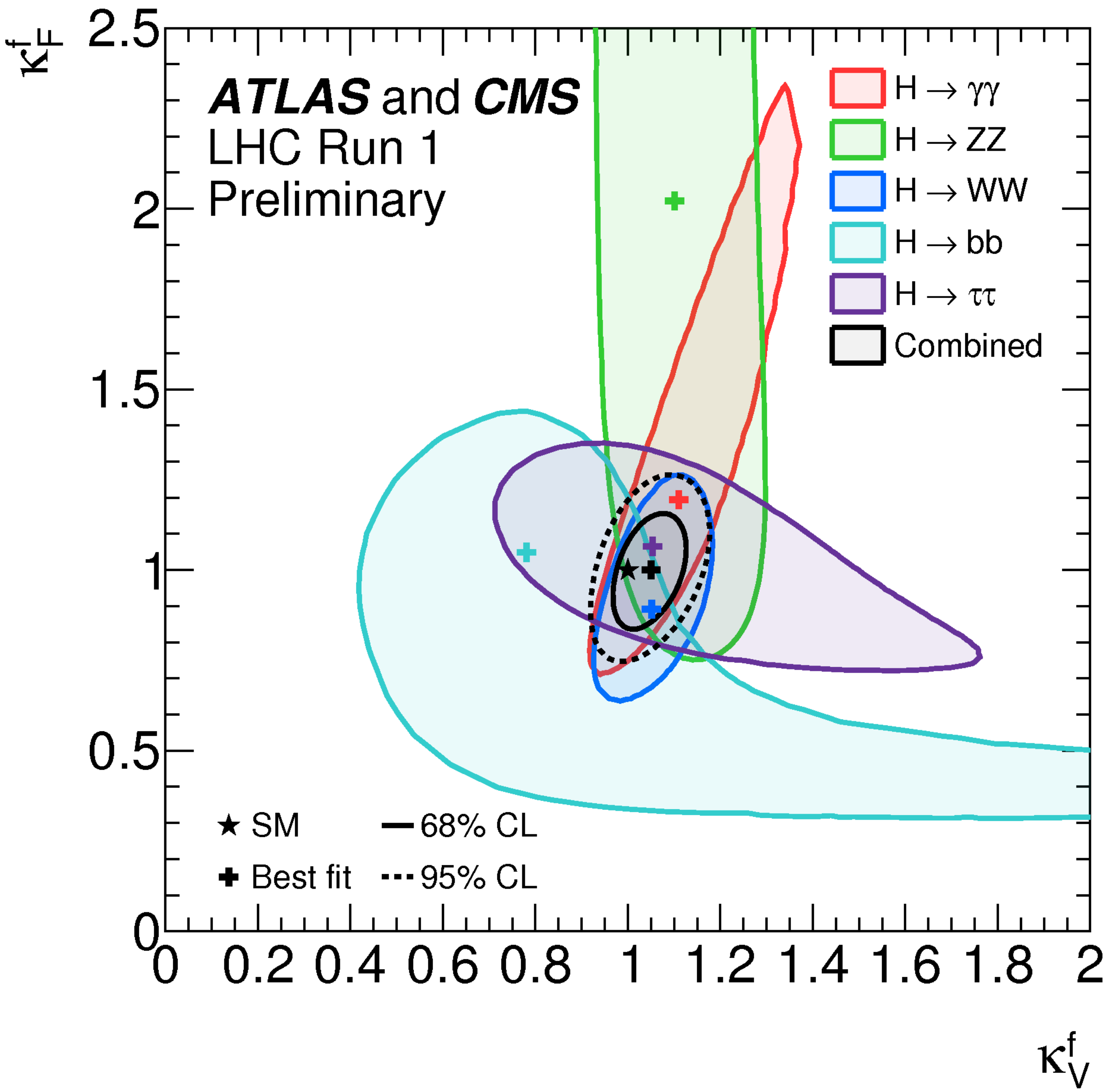
HU Berlin
20/6/19

Outline

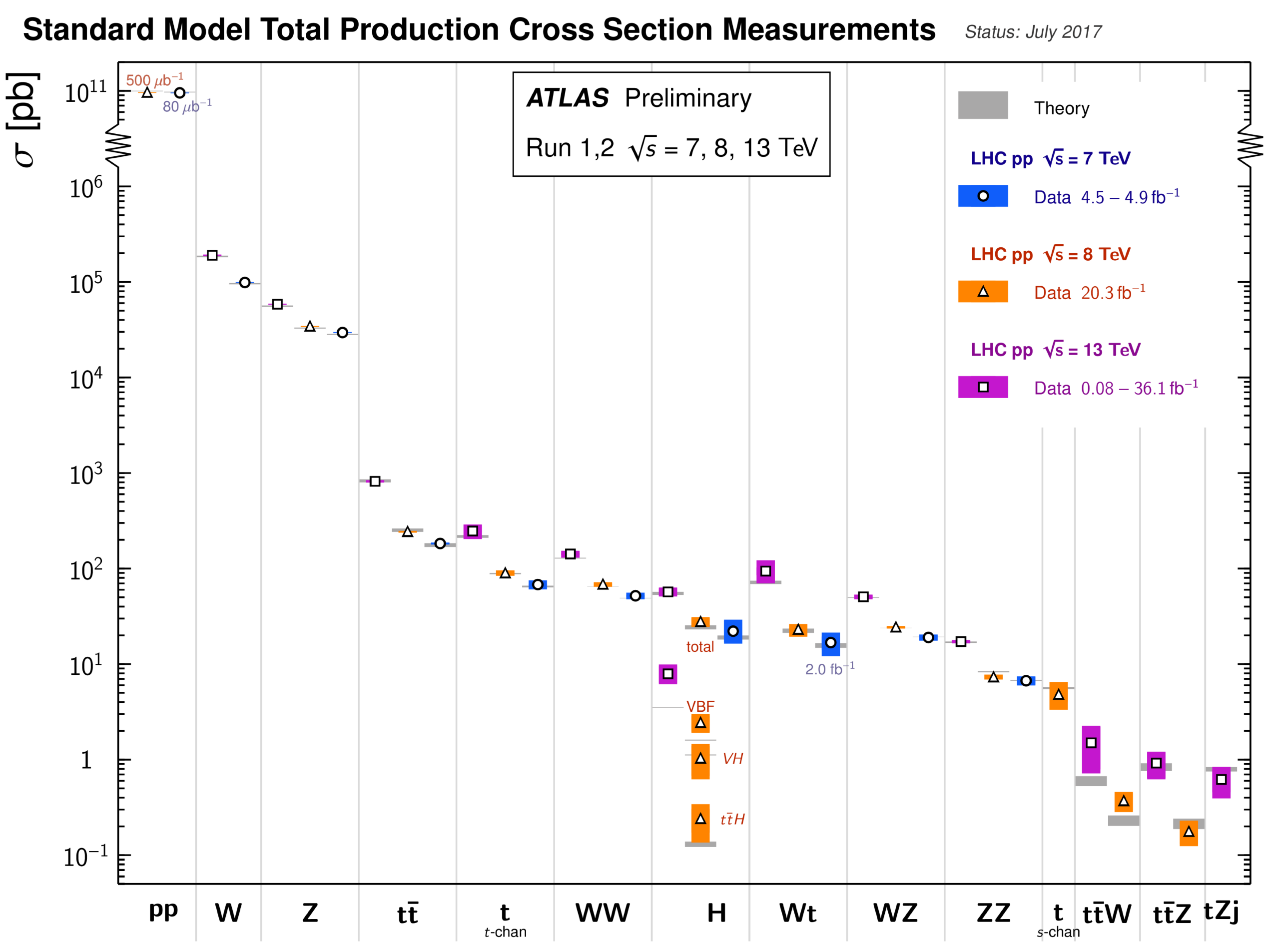
- Introduction to the EFT
- EFT in top quark physics
    - Precision calculations in the EFT
    - Towards global fits in the top sector
- EFT in the top-Higgs sector
    - Top loops in the EFT

LHC: the story so far

Higgs discovery



Rediscovering the SM



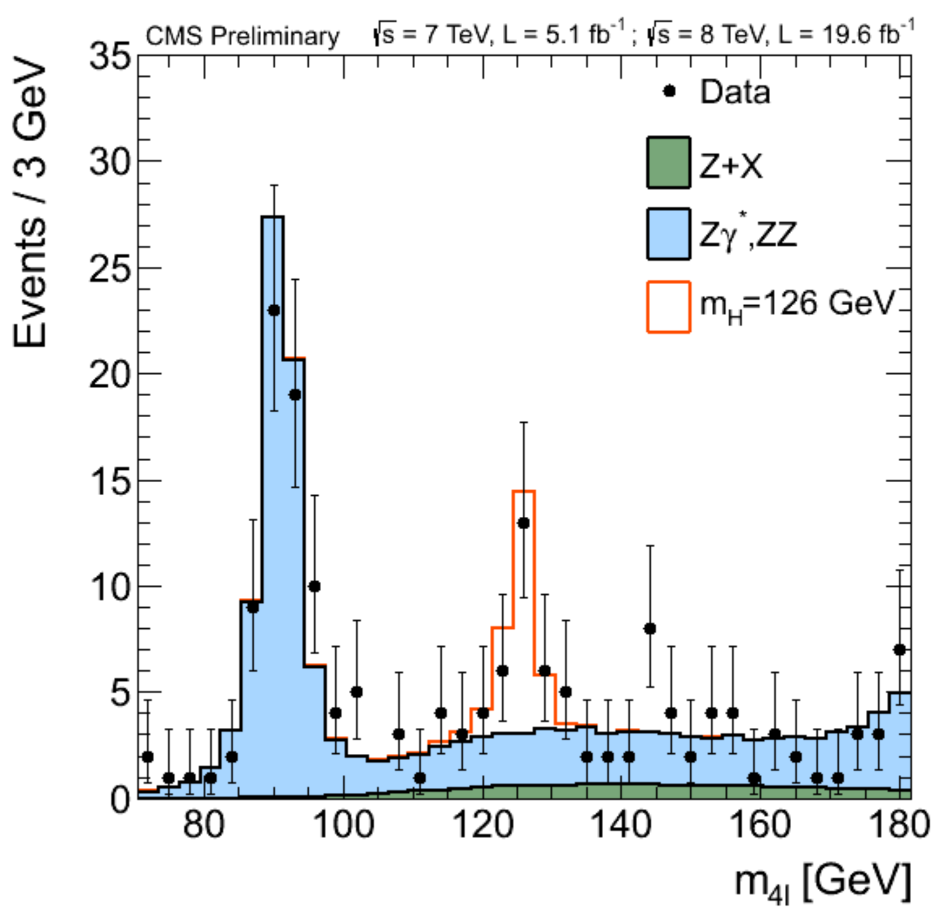
Good agreement with the SM predictions

How to look for new physics?

Model-dependent

SUSY, 2HDM…

New particles



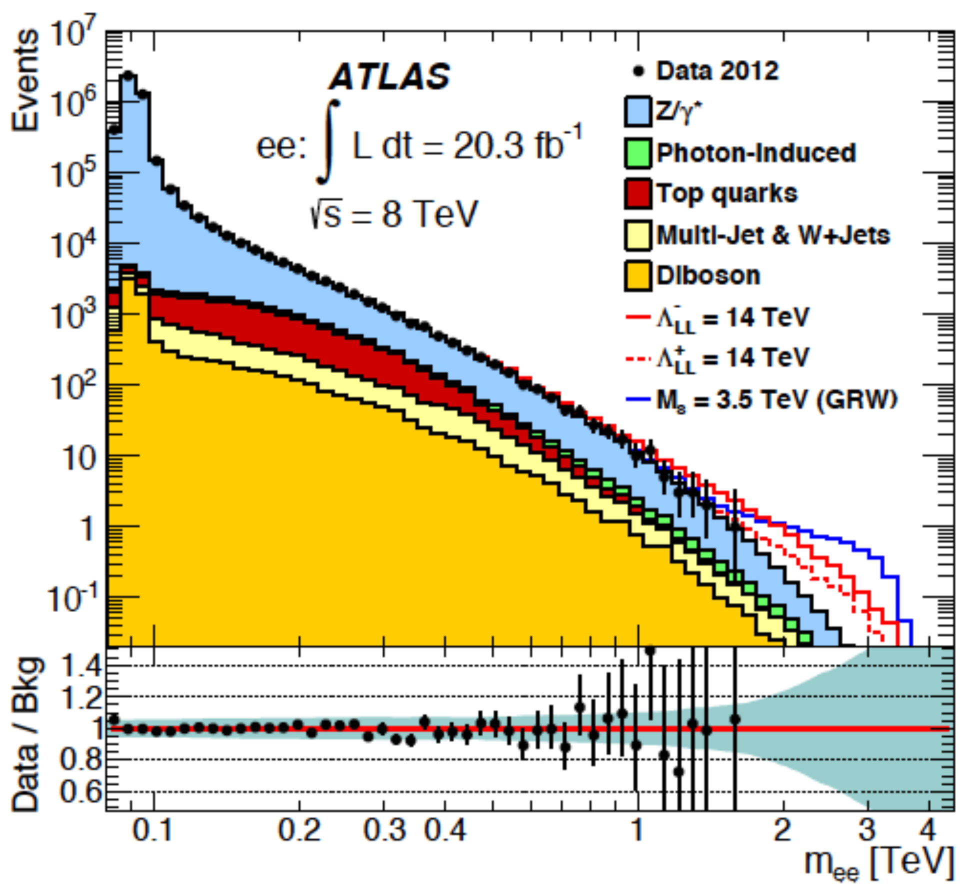
Resonance peaks

Model-Independent

simplified models, EFT

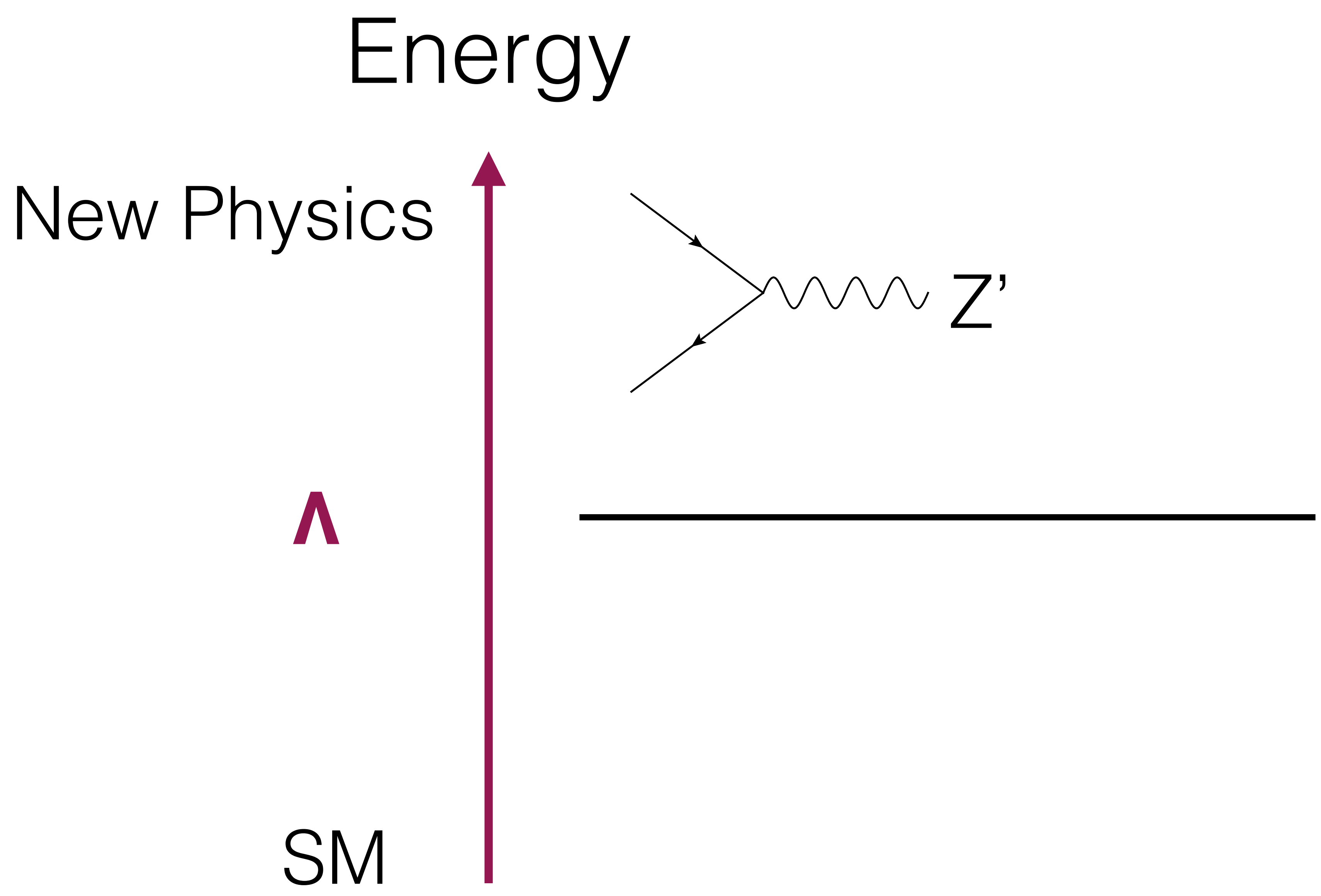
New Interactions of SM particles

anomalous couplings, EFT



Deviations in tails

SMEFT: What is it all about?



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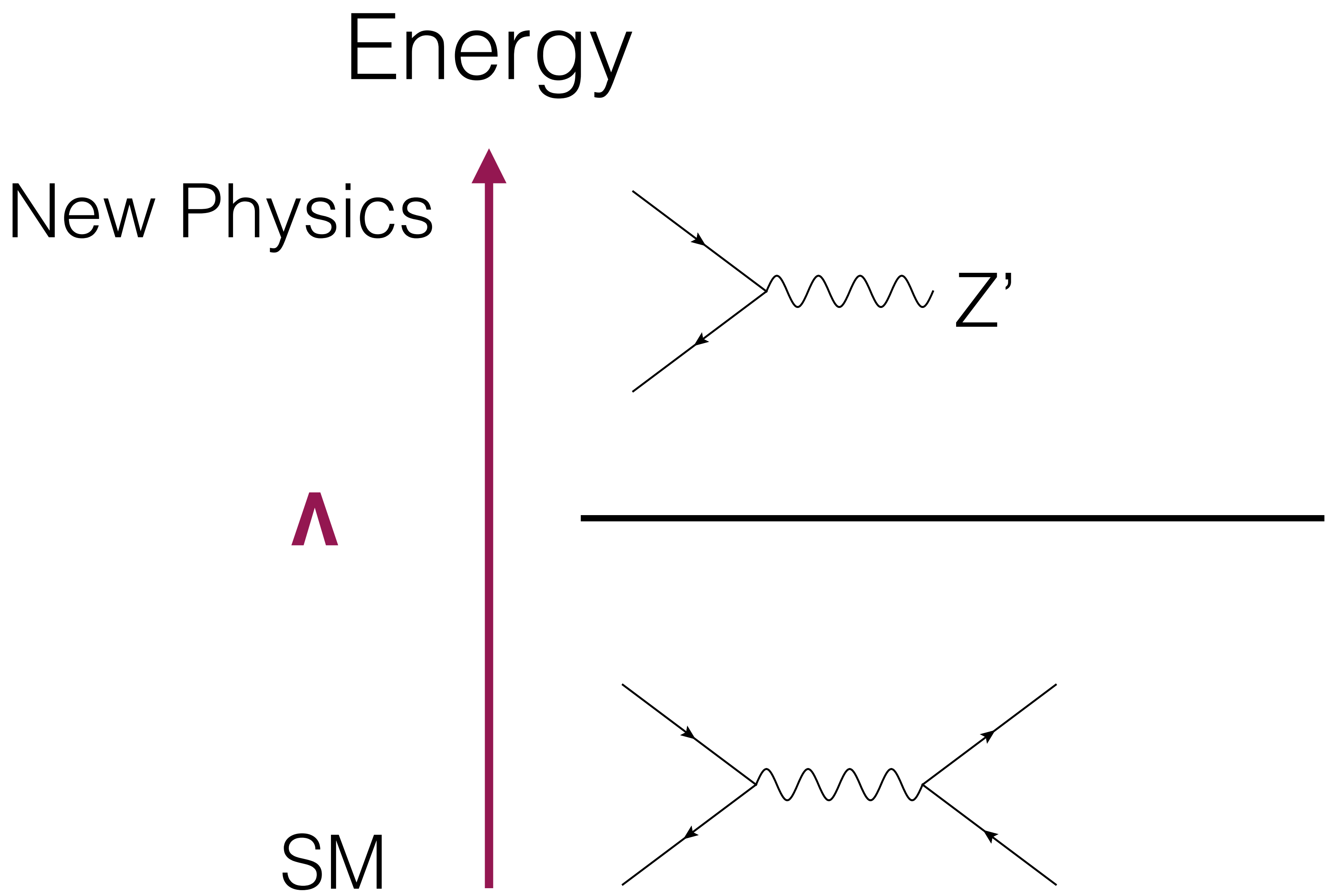

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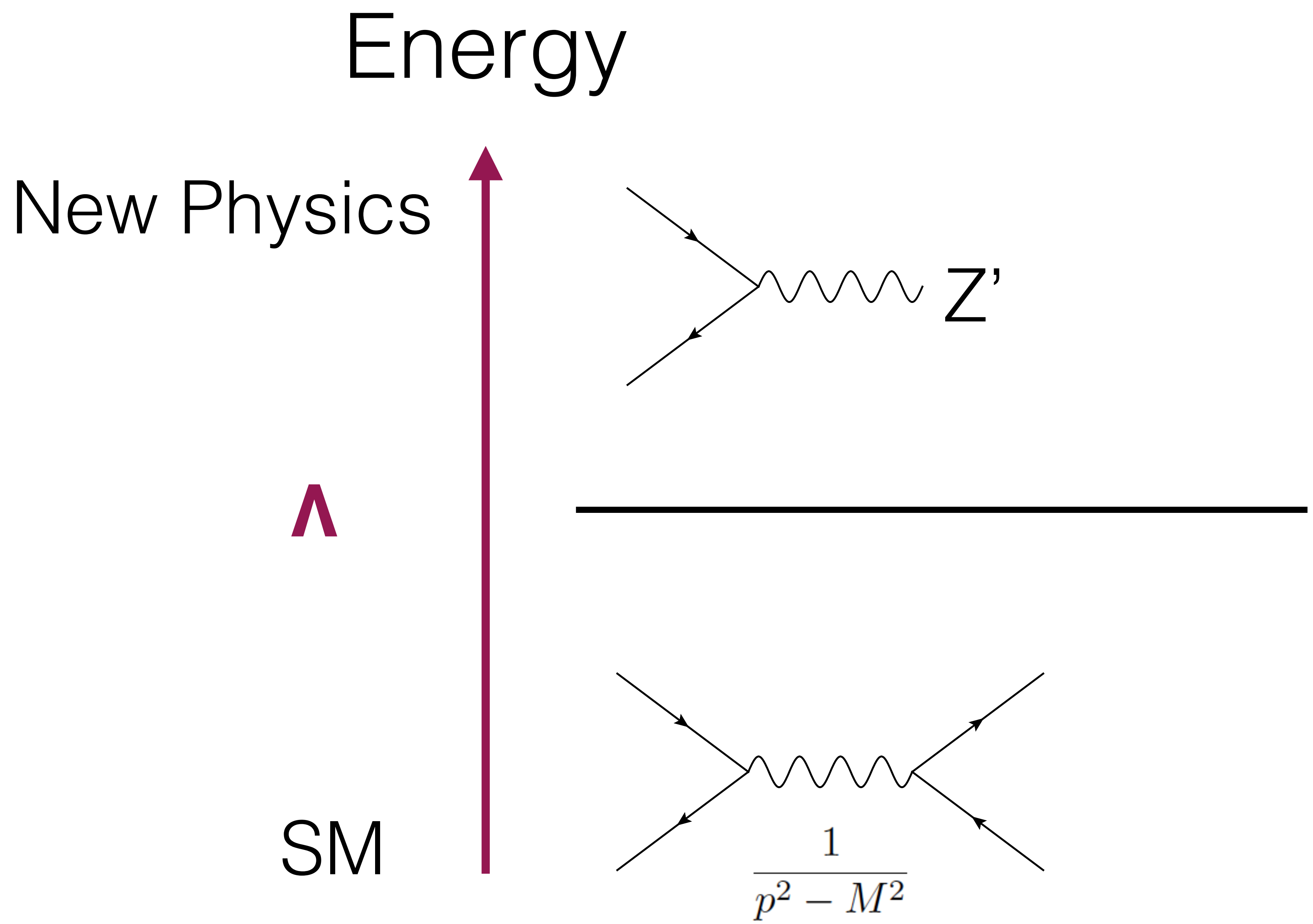

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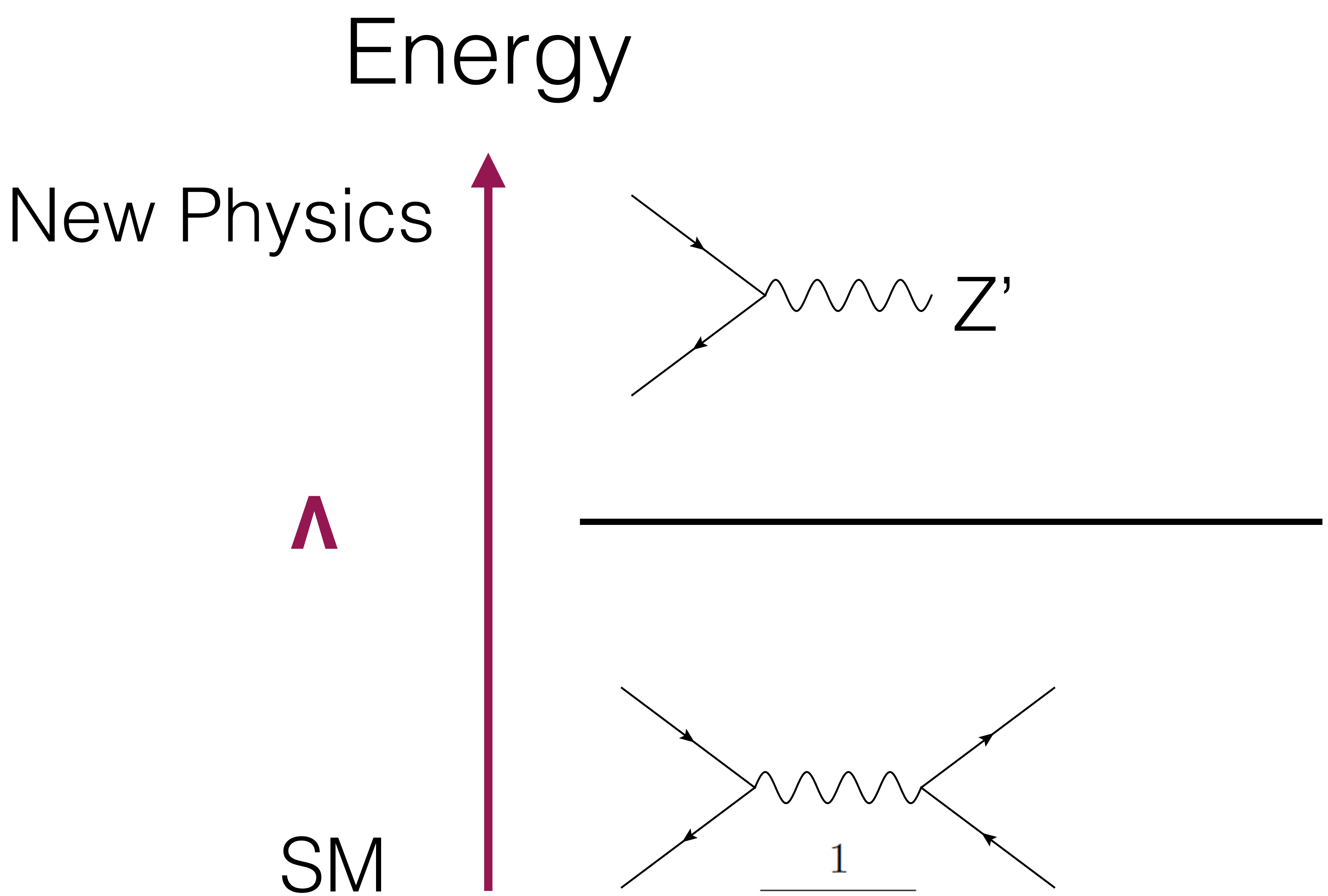

$$\frac{1}{p^2 - M^2}$$

$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

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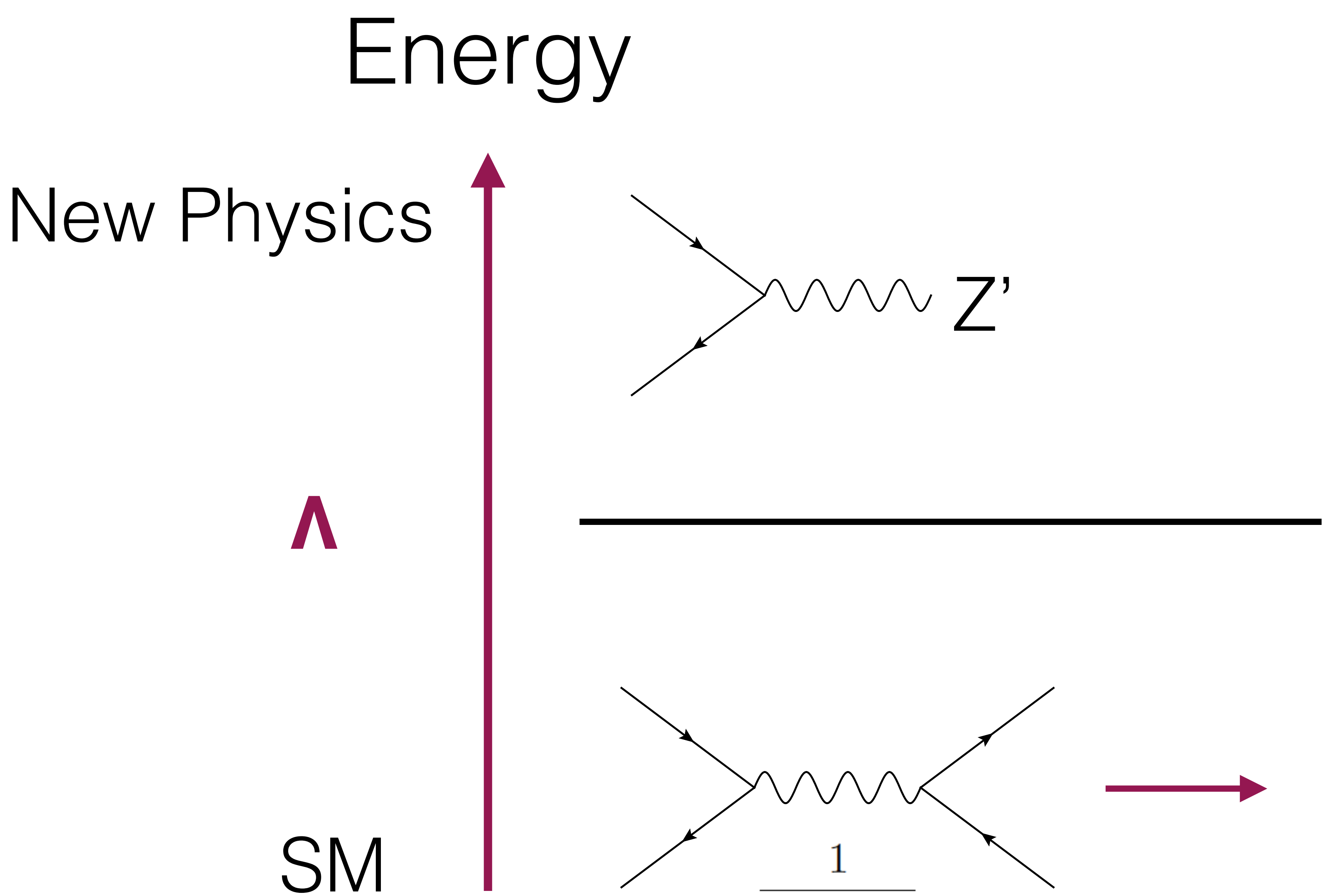

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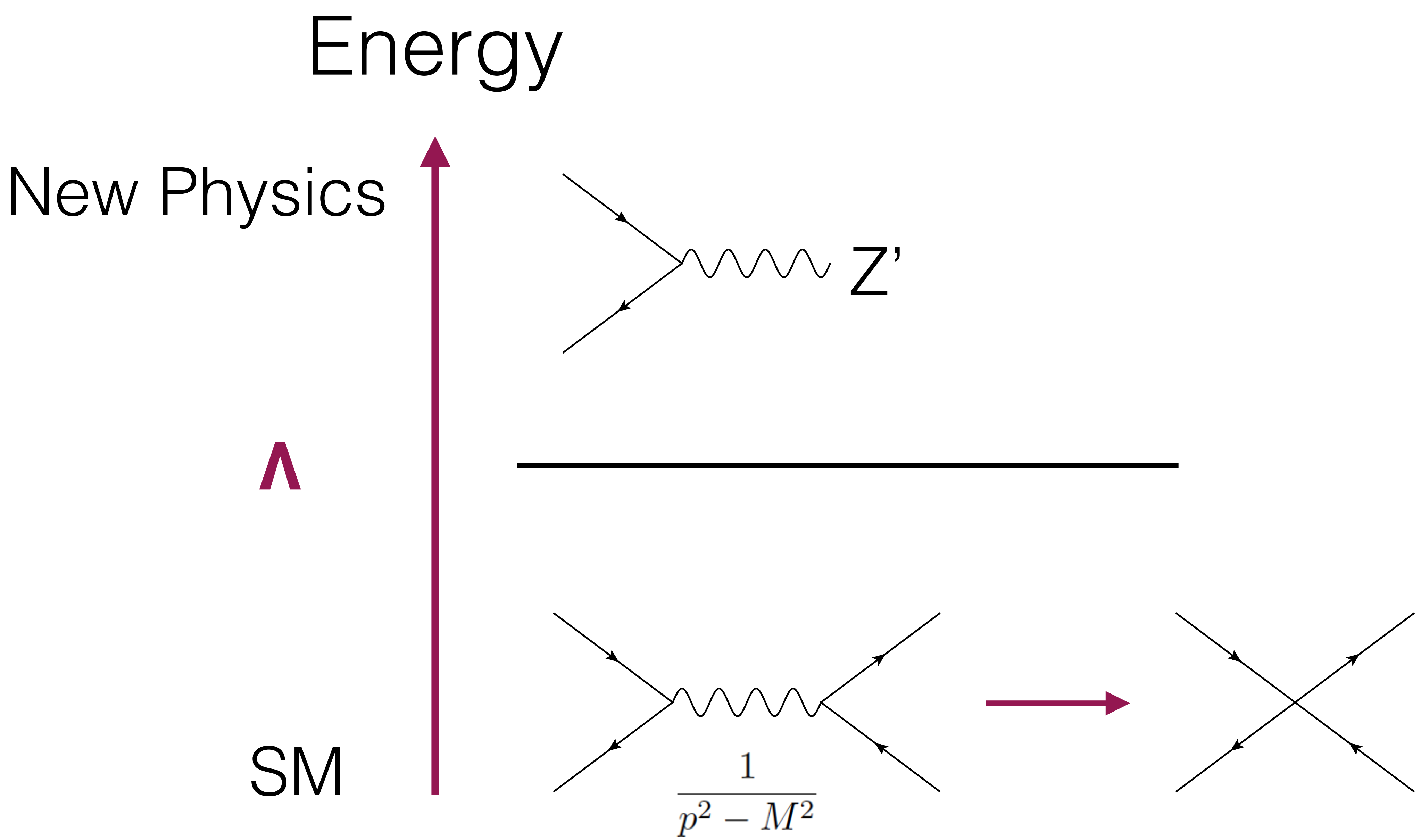

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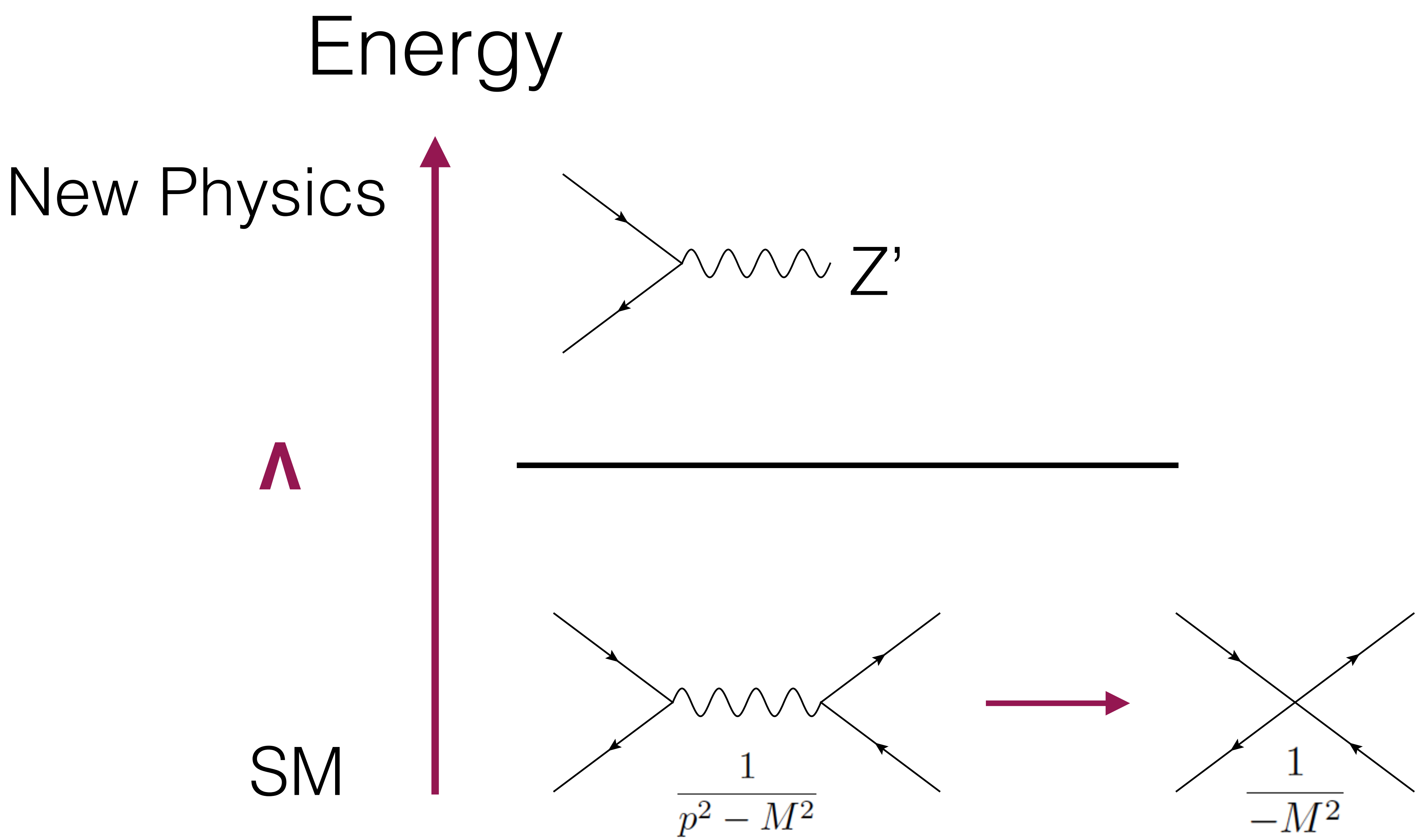

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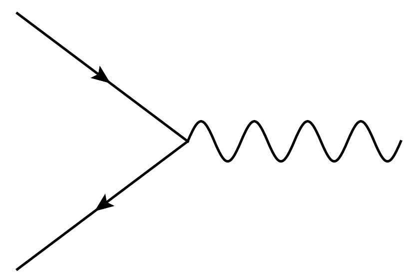
SMEFT: What is it all about?

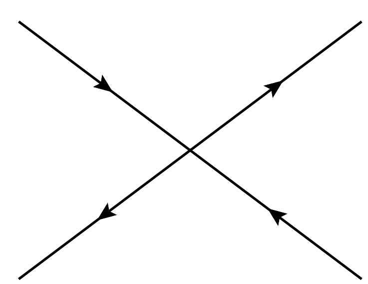
Energy

New Physics



$$\mathcal{L}_{NP}(\varphi, Z')$$

Λ~M



SM

$$\frac{1}{-M^2}$$

$$\mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

$$\mathcal{L}_{Dim6}(\varphi) = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

SMEFT basics

New Interactions of SM particles

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arXiv:1008.4884

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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	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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EFT for top quark interactions

SMEFT vs Anomalous couplings

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu\tau^I Q\right)$$
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$
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$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$\mathcal{L}_{ttZ} = e\bar{u}(p_t)\left[\gamma^\mu\left(C^Z_{1,V}+\gamma_5 C^Z_{1,A}\right)+\frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\left(C^Z_{2,V}+i\gamma_5 C^Z_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu$$

- SMEFT:
  - Gauge invariant ✔
  - Higher-order corrections: renormalisable order by order in 1/Λ ✔

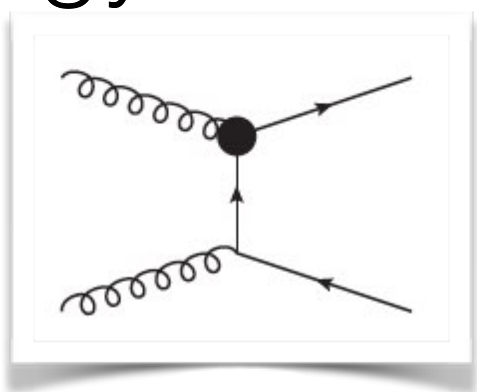
$$\mathcal{O}(\alpha_s)+\mathcal{O}\left(\frac{1}{\Lambda^2}\right)+\mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right)+\cdots$$

  - Complete description-respecting SM symmetries ✔
  - Model Independent ✔

SMEFT in processes with tops

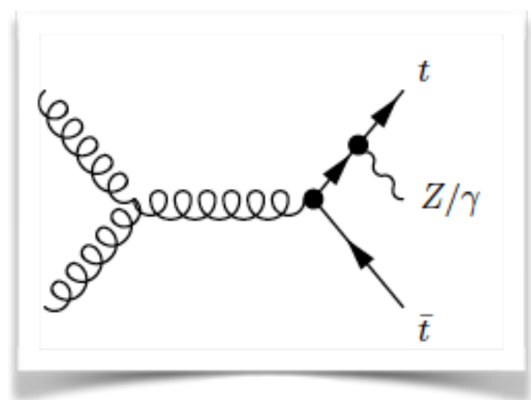
Rich phenomenology:

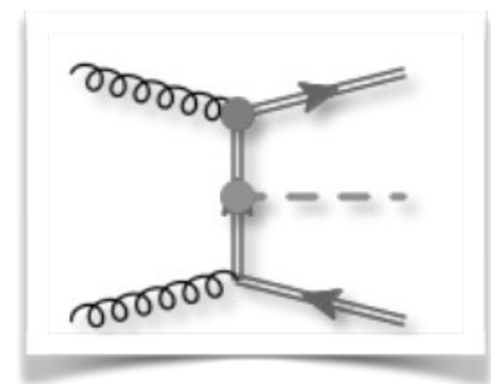
pair production

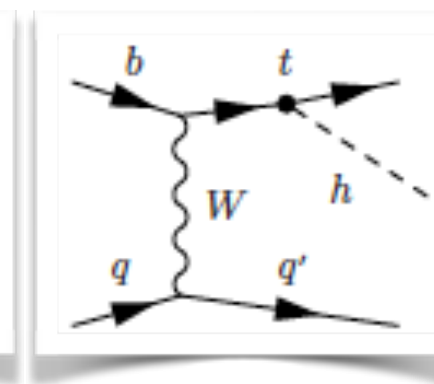


single

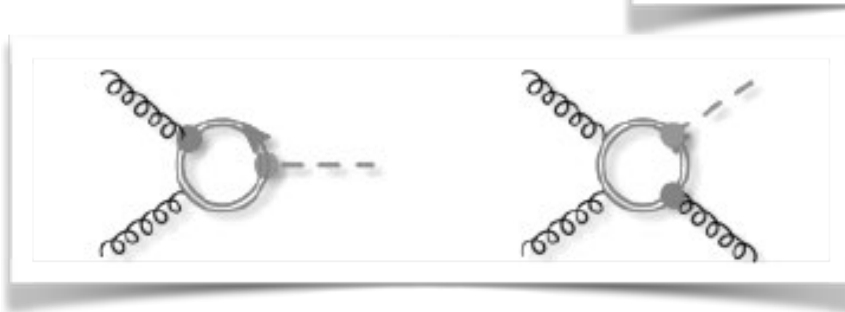
associated production

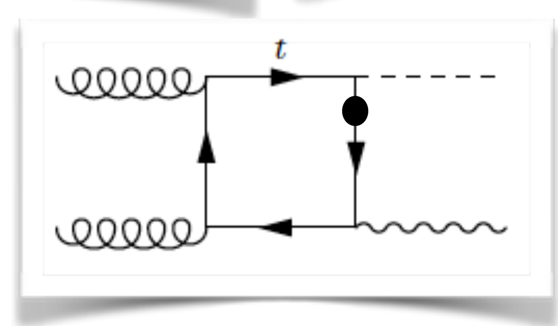


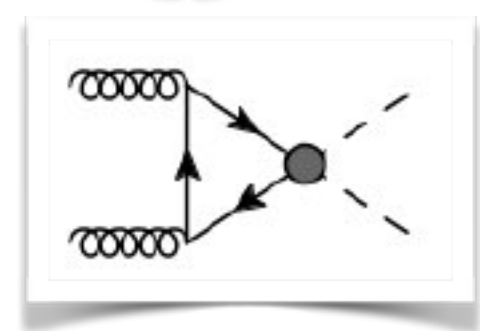




top loops







connection to Higgs physics

Top-quark operators and how to look for them

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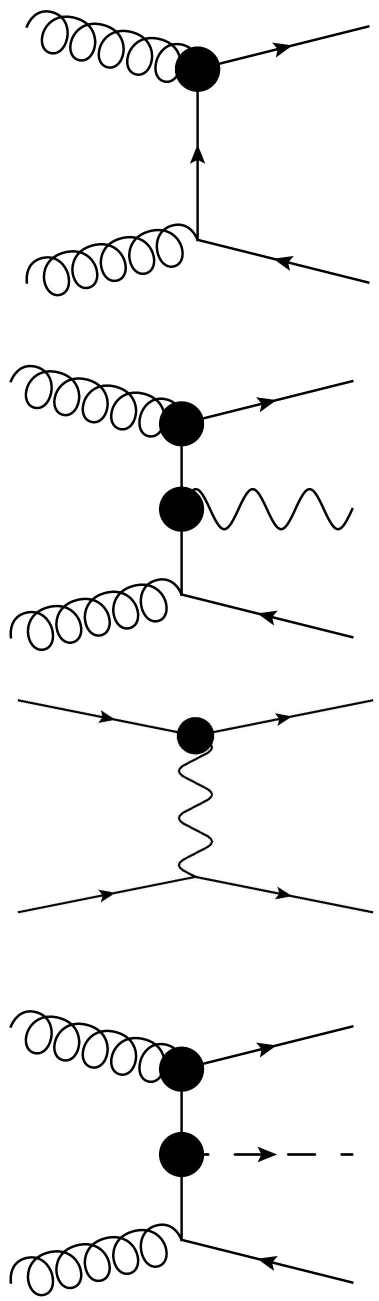
$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}$$



see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

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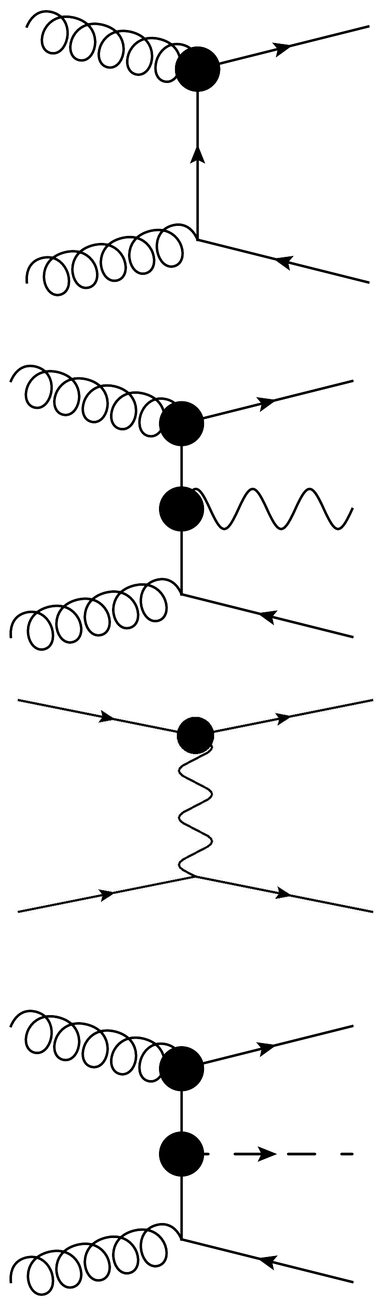

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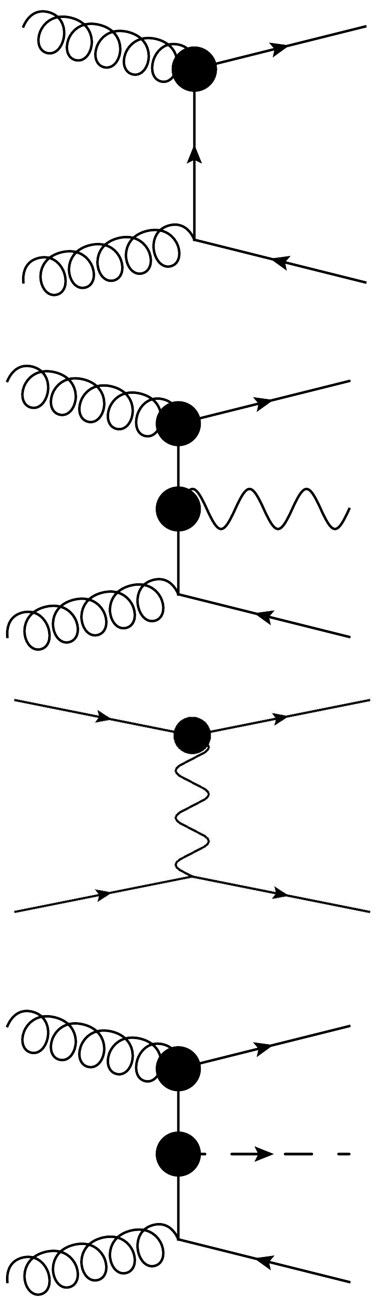

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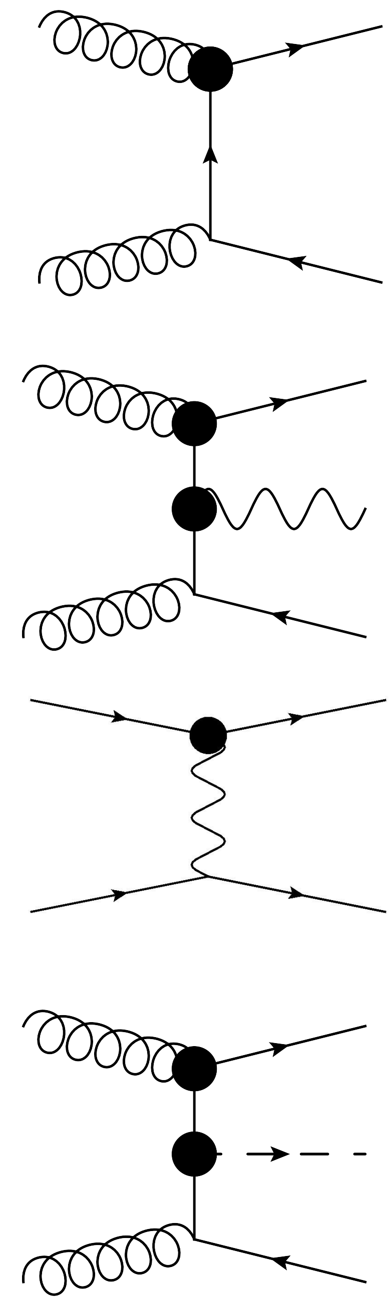

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$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$

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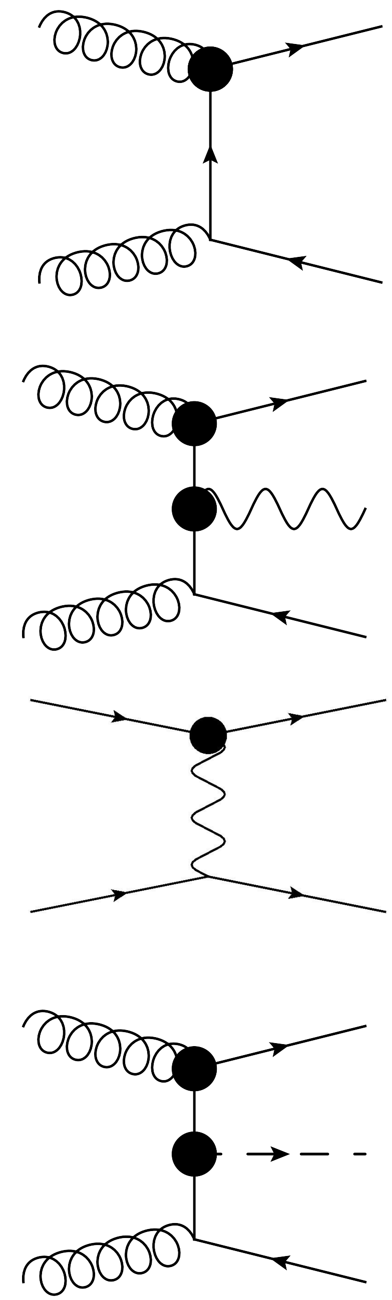

see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

Top-quark operators and how to look for them

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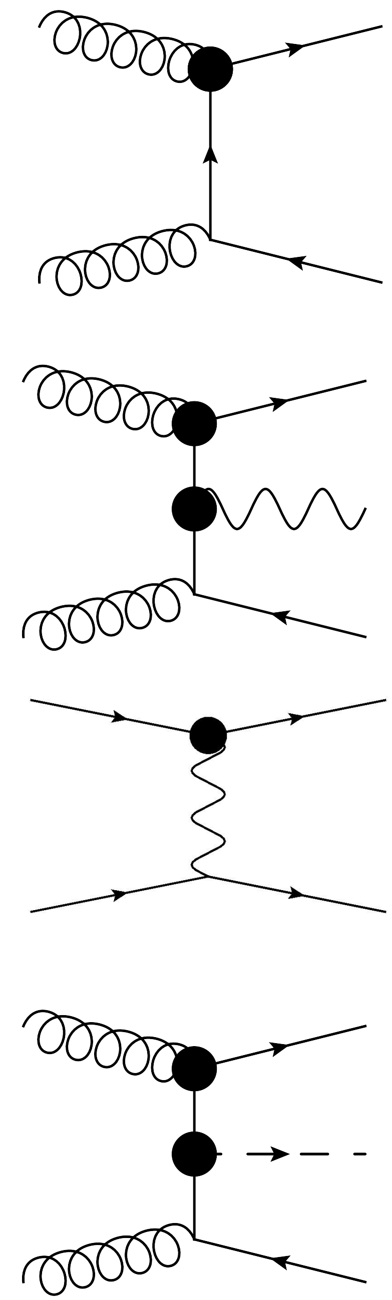

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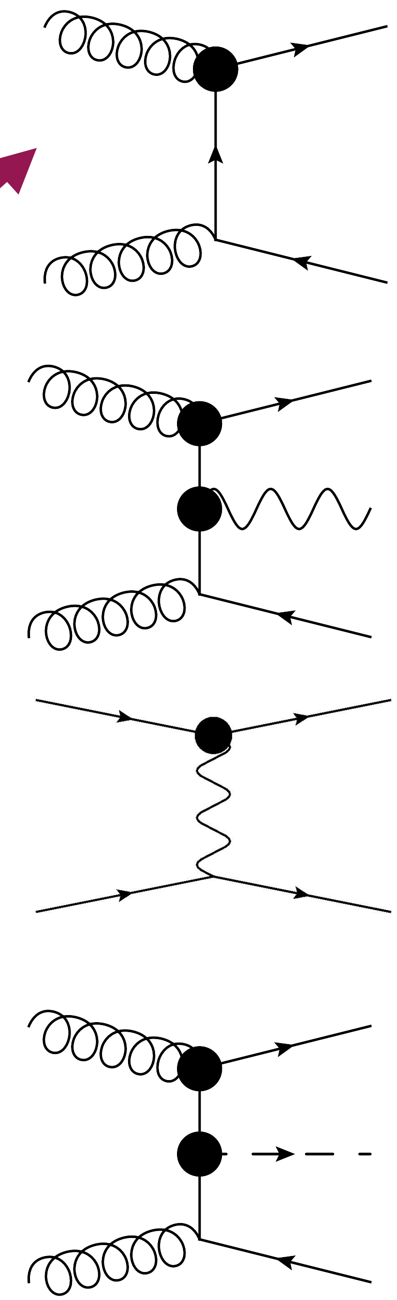

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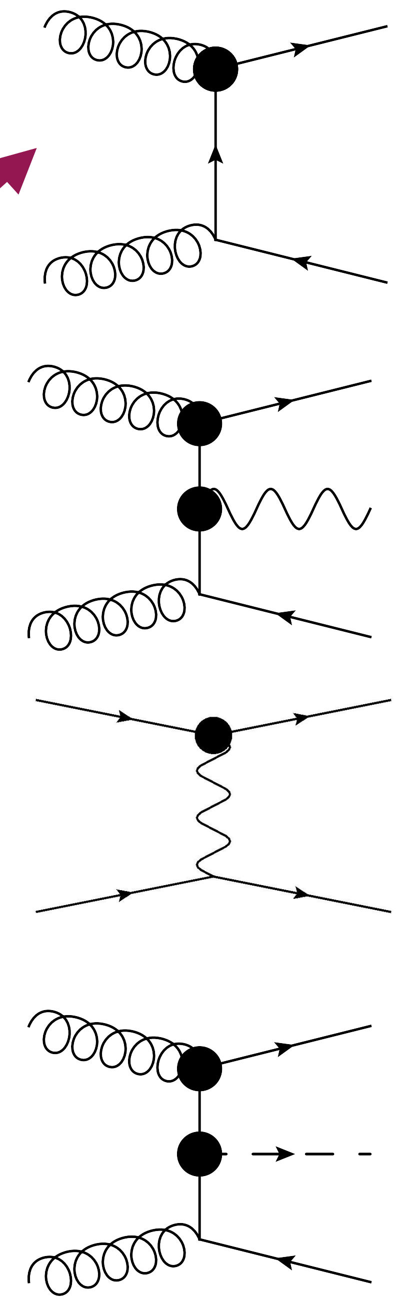

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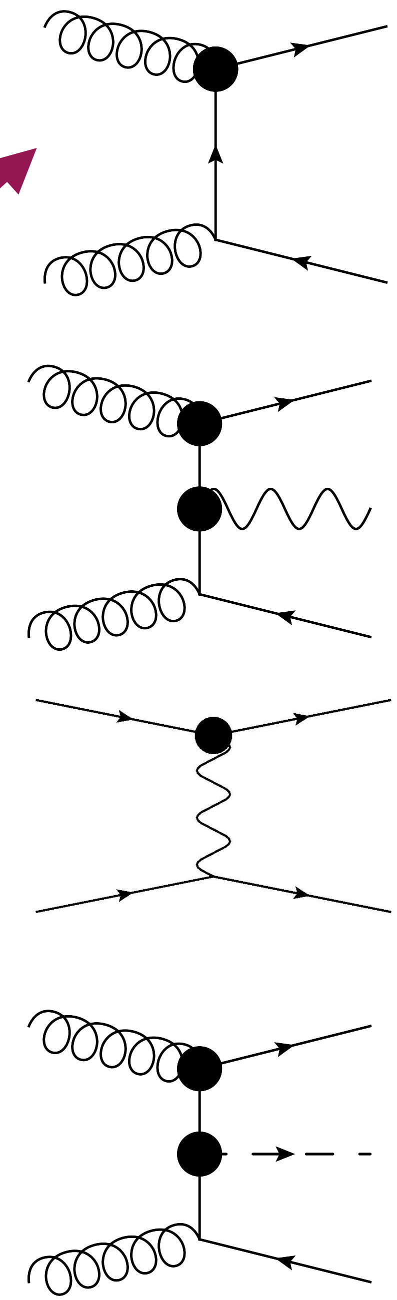

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Operators entering various processes: Global approach needed

What’s next?

Use SMEFT to parametrise and look for deviations from SM predictions

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Cross-sections+differential distributions

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QCD/EW corrections

Need for precision also in SMEFT

Need for precision calculations
Automated tools for the EFT

How can we improve EFT predictions?

- SMEFT@NLO
  - Mixing between operators: anomalous dimension matrix: Jenkins et al arXiv:1308.2627,1310.4838, Alonso et al. 1312.2014
  - Additional operators at NLO: e.g. chromomagnetic dipole in single top production

Recent progress in top physics:

- top pair Franzosi and Zhang (arxiv:1503.08841)
- single top Zhang (arxiv:1601.06163), de Beurs, Laenen, Vreeswijk, EV (arXiv:1807.03576)
- ttZ/γ Bylund, Maltoni, Tsinikos, EV, Zhang (arXiv:1601.08193), Schulze and Rontsch (arXiv:1404.1005)
- ttH Maltoni, EV, Zhang (arXiv:1607.05330)
- tZ/Hj Degrande, Maltoni, Mimasu, EV, Zhang (arXiv:1804.07773)

In practice

UFO model with UV+R2 counterterms
Import to MG5_aMC@NLO
Proceed as in SM case

```
MG5_aMC>import model TEFT
MG5_aMC>generate p p > t t~ z EFT=1 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

Results:
Fixed order NLO
NLO+PS with MC@NLO

Implementation gives:

$$\sigma = \sigma_{\mathrm{SM}} + \underbrace{\sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i}_{\text{interference with SM}} + \underbrace{\sum_{i\leq j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}}_{\text{interference between operators, squared contributions}}.$$

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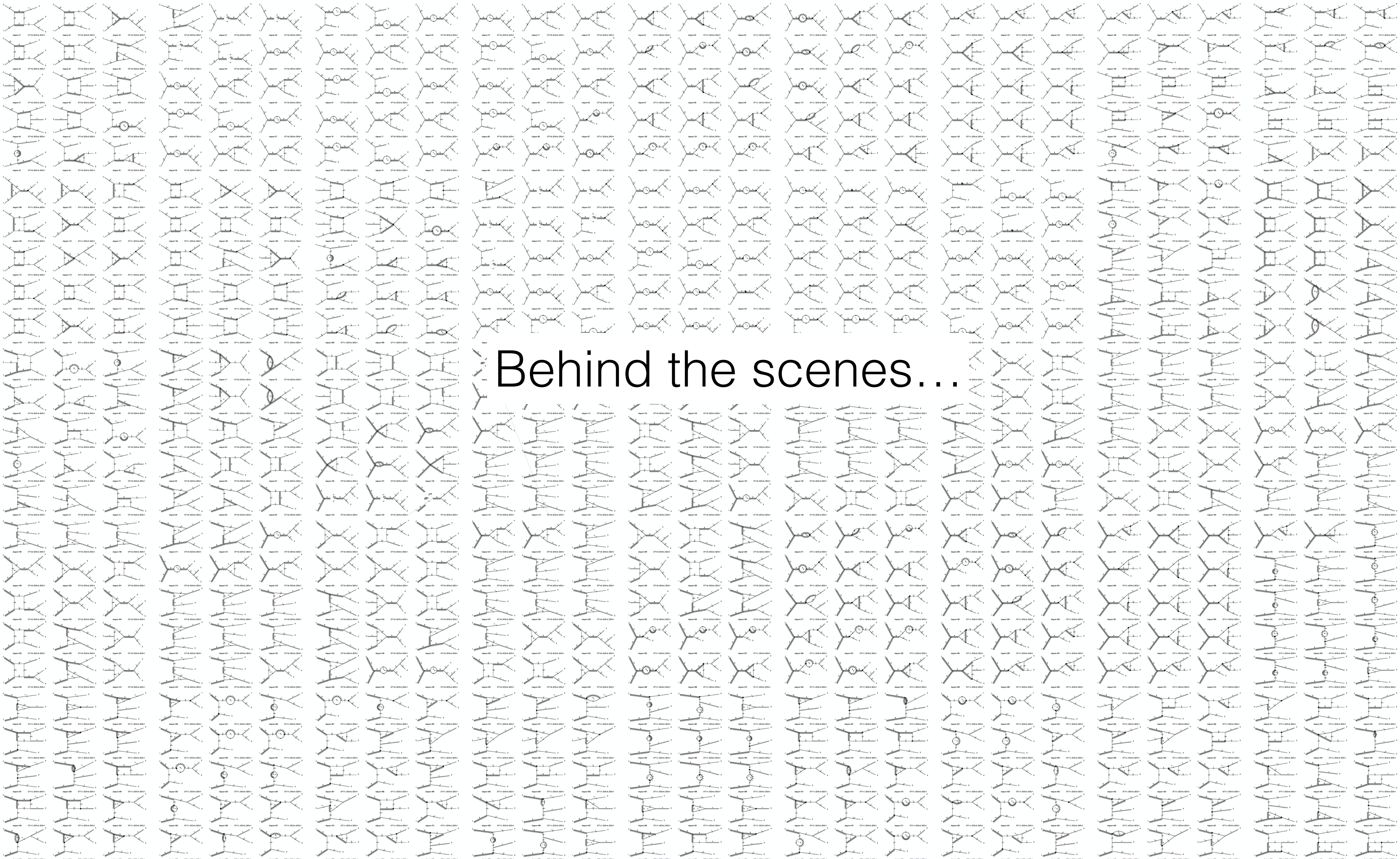

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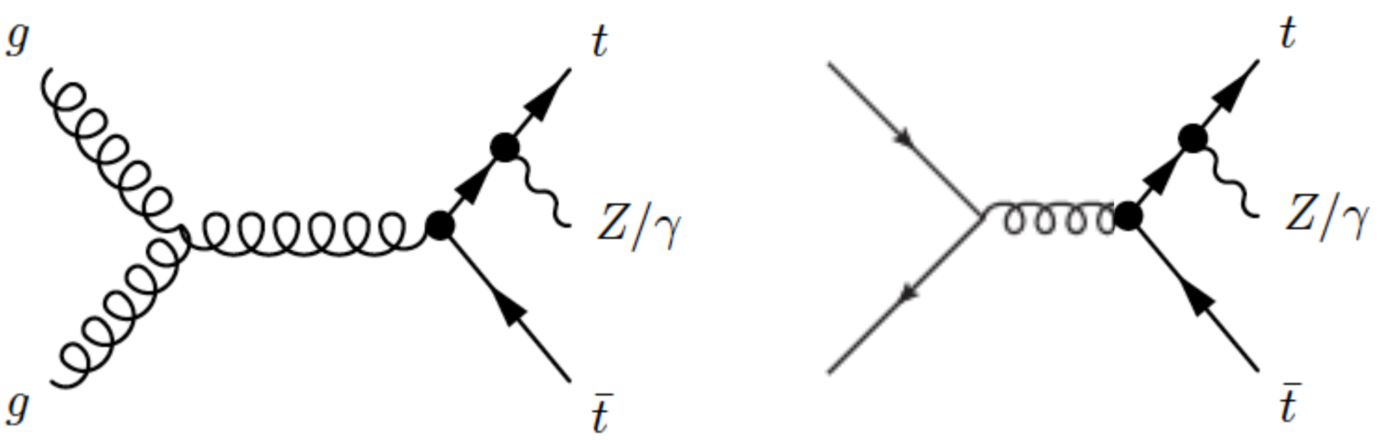
interference with SM

interference between operators, squared contributions

Top production in association with a Z



~900fb at 13 TeV

First measurements at LHC13
CMS-PAS-TOP-16-017, CMS-PAS-TOP-17-005
ATLAS: arXiv:1609.01599
approaching 10% accuracy

Relevant operators

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$
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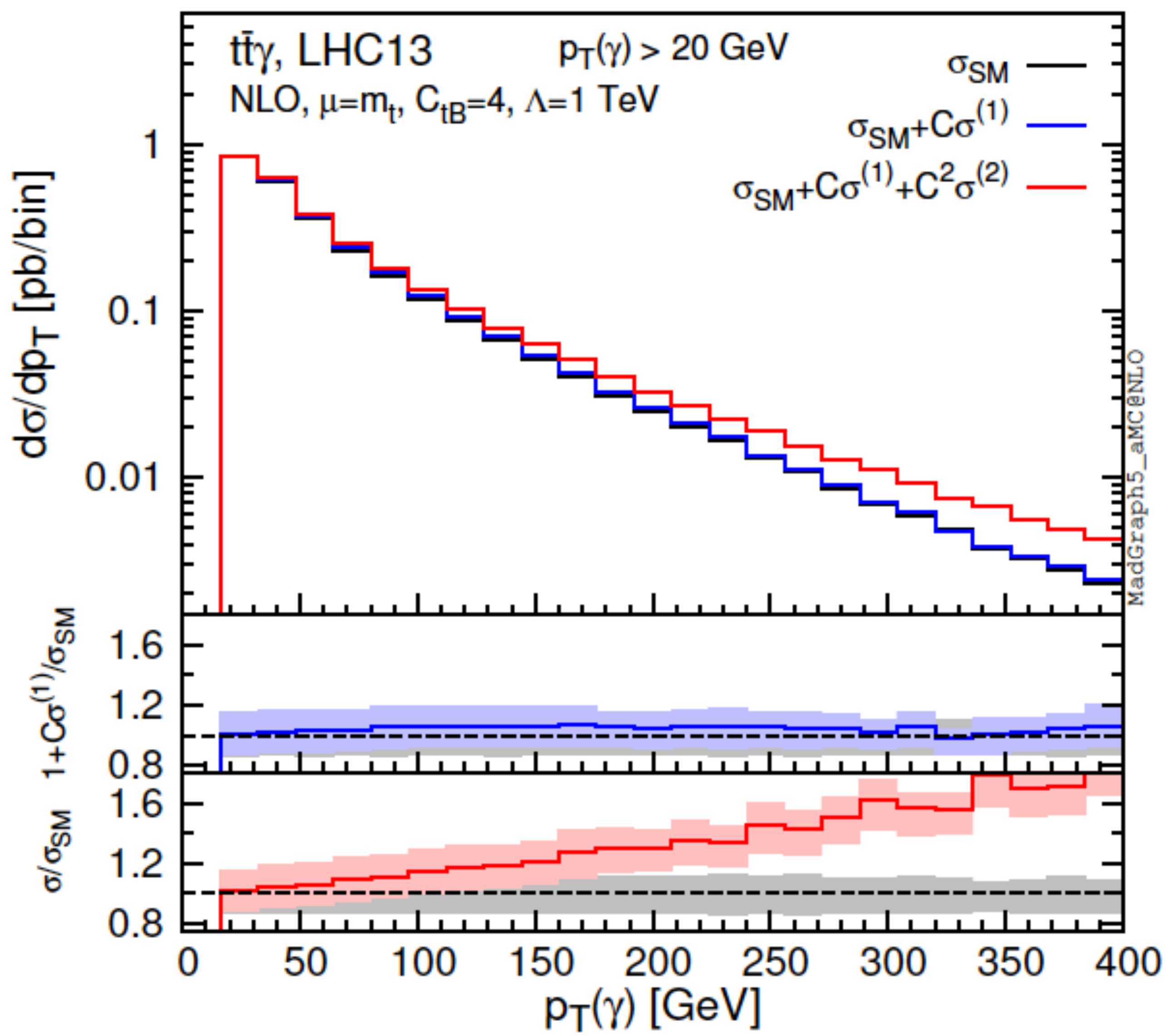
$$\mathcal{L}_{ttZ} = e\bar{u}(p_t)\left[\gamma^\mu\left(C^Z_{1,V}+\gamma_5 C^Z_{1,A}\right)+\frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\left(C^Z_{2,V}+i\gamma_5 C^Z_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu$$

$$C^Z_{1,V} = \frac{1}{2}\left(C^{(3)}_{\varphi Q} - C^{(1)}_{\varphi Q} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W}$$
$$C^Z_{1,A} = \frac{1}{2}\left(-C^{(3)}_{\varphi Q} + C^{(1)}_{\varphi Q} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W}$$
$$C^Z_{2,V} = \left(C_{tW}c_W^2 - C_{tB}s_W^2\right)\frac{2m_t m_Z}{\Lambda^2 s_W c_W}$$
$$C^Z_{2,A} = 0$$

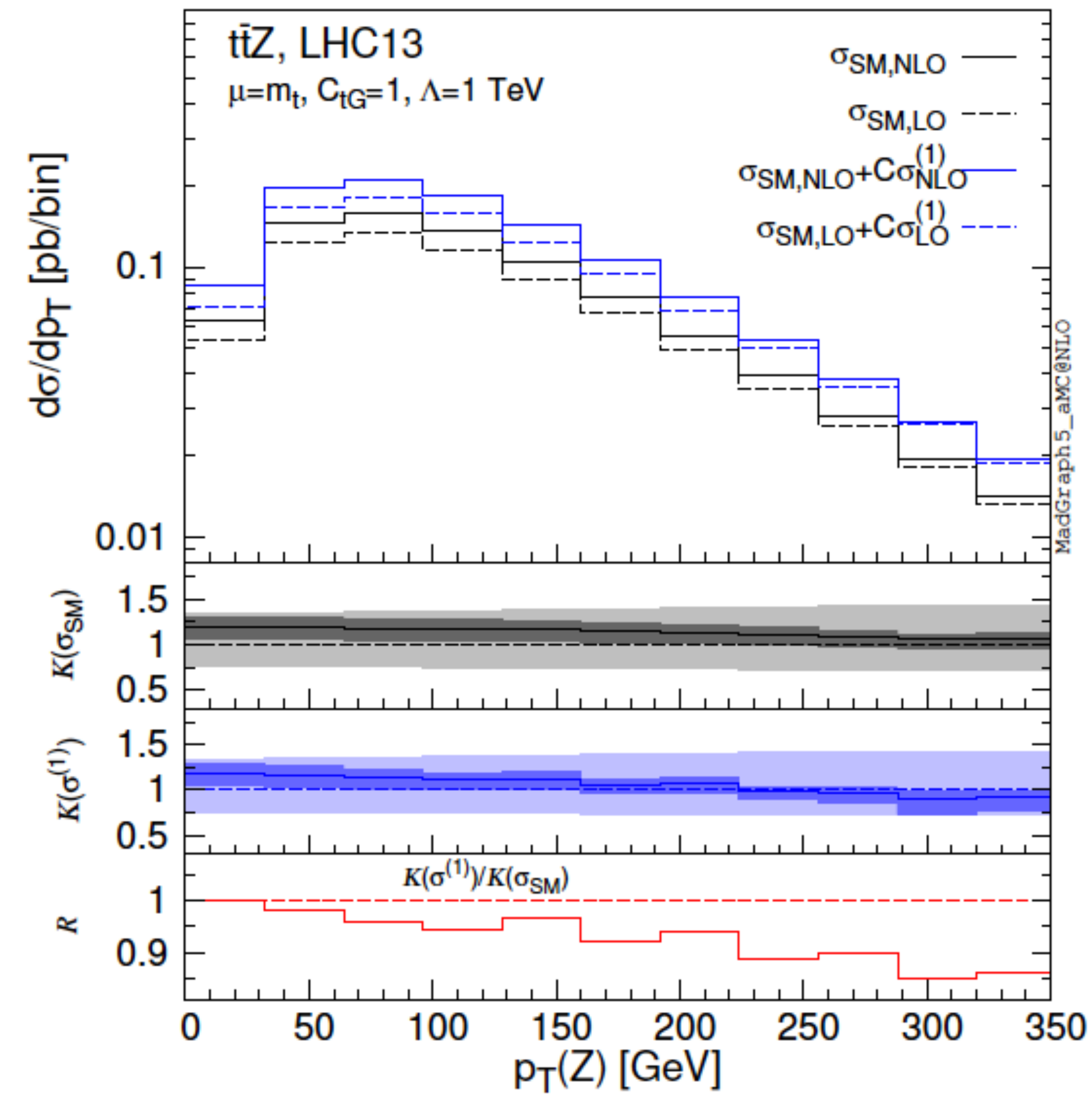
Anomalous coupling approach
top neutral couplings

4-fermion operators
Triple gluon operator
(not discussed here)
Constrained from multijets
Krauss et al arXiv:1611.00767

Differential distributions for tt+V



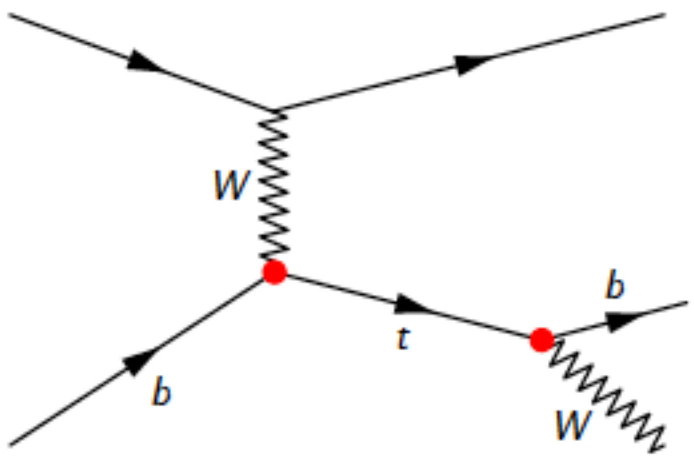
Large contribution at O(1/Λ⁴)

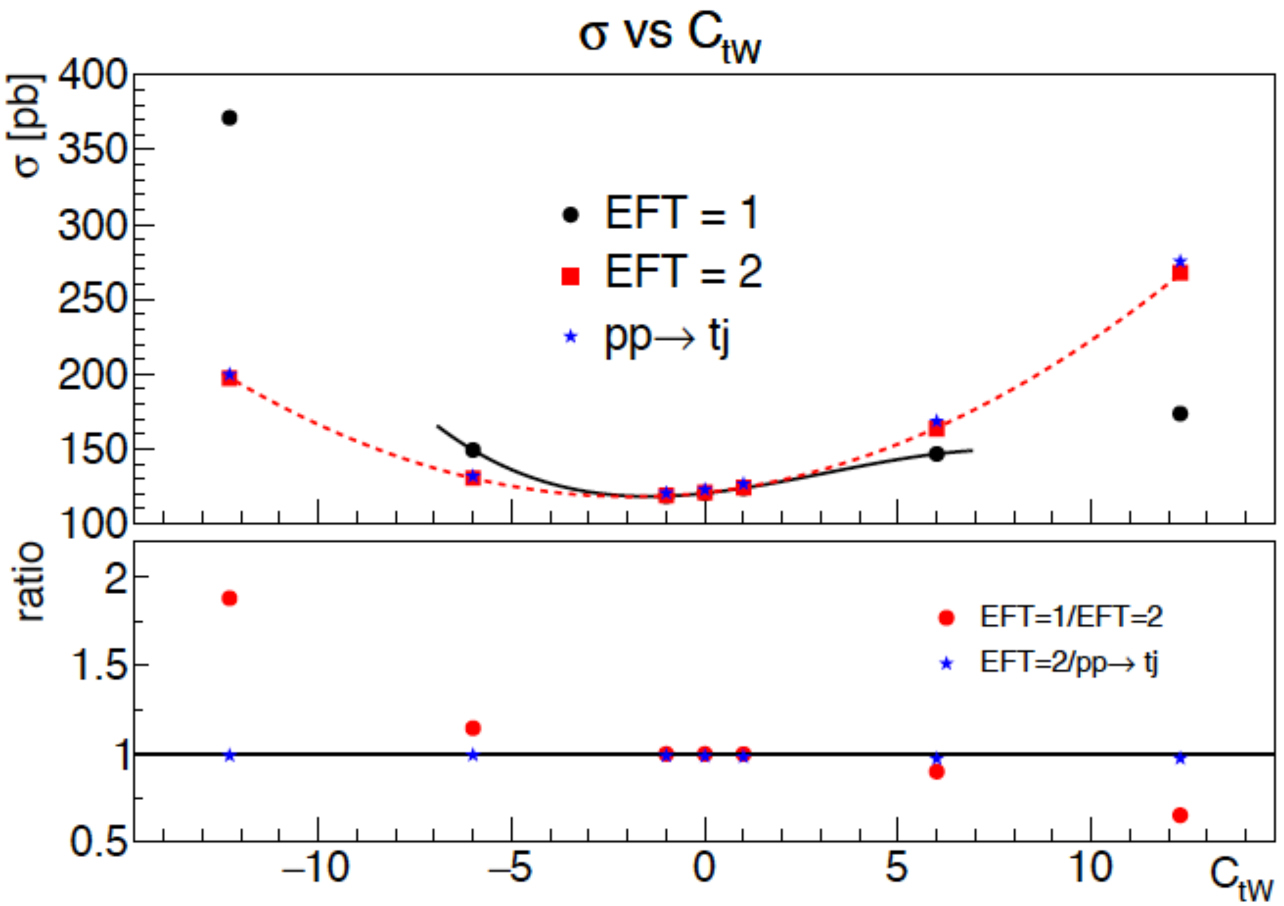


Using SM k-factors is not enough

Bylund et al arXiv:1601.08193

Single top production and decay





- The same EFT couplings enter both the production and decay
- The width of the top enters in the total cross-section calculation

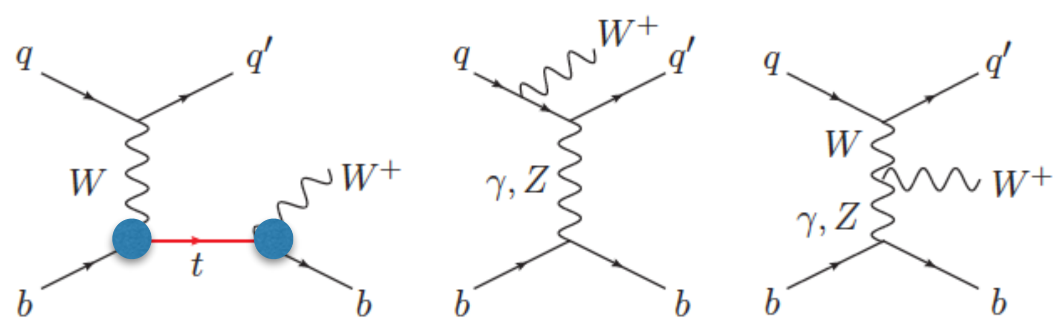
For large values of the coupling allowing two insertions and computing the width of the top consistently is needed to match the Wbj and tj cross-sections

de Beurs, Laenen, Vreeswijk, EV arXiv:1807.03576

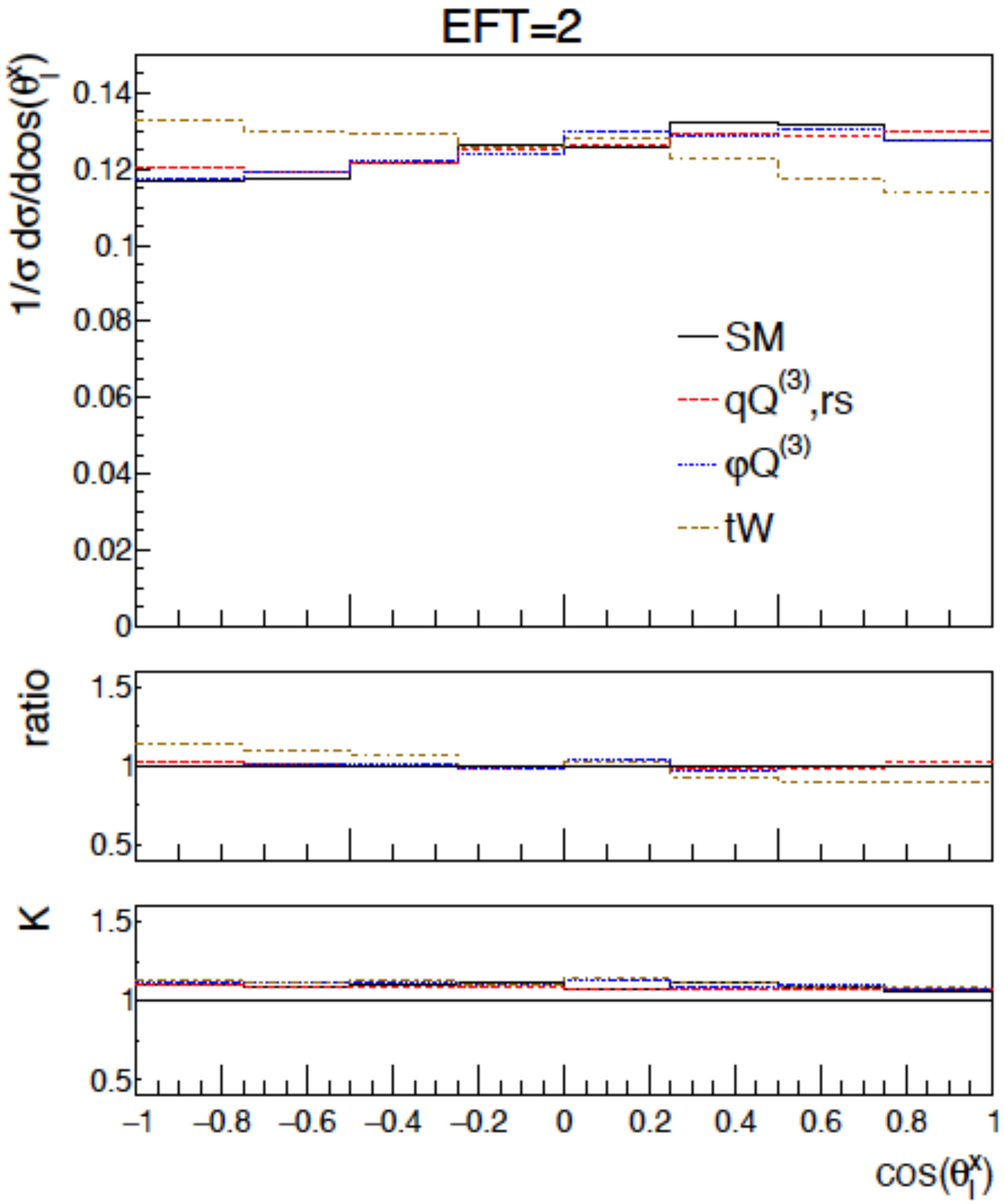
Single top production and decay

Going beyond the narrow width approximation for single top:

- Wbj production with off-shell and interference effects



- Resonant-aware matching to the Parton Shower (arXiv: 1603.01178)
- W decay in MadSpin
- Up to two EFT operator insertions allowed (one in production one in decay)

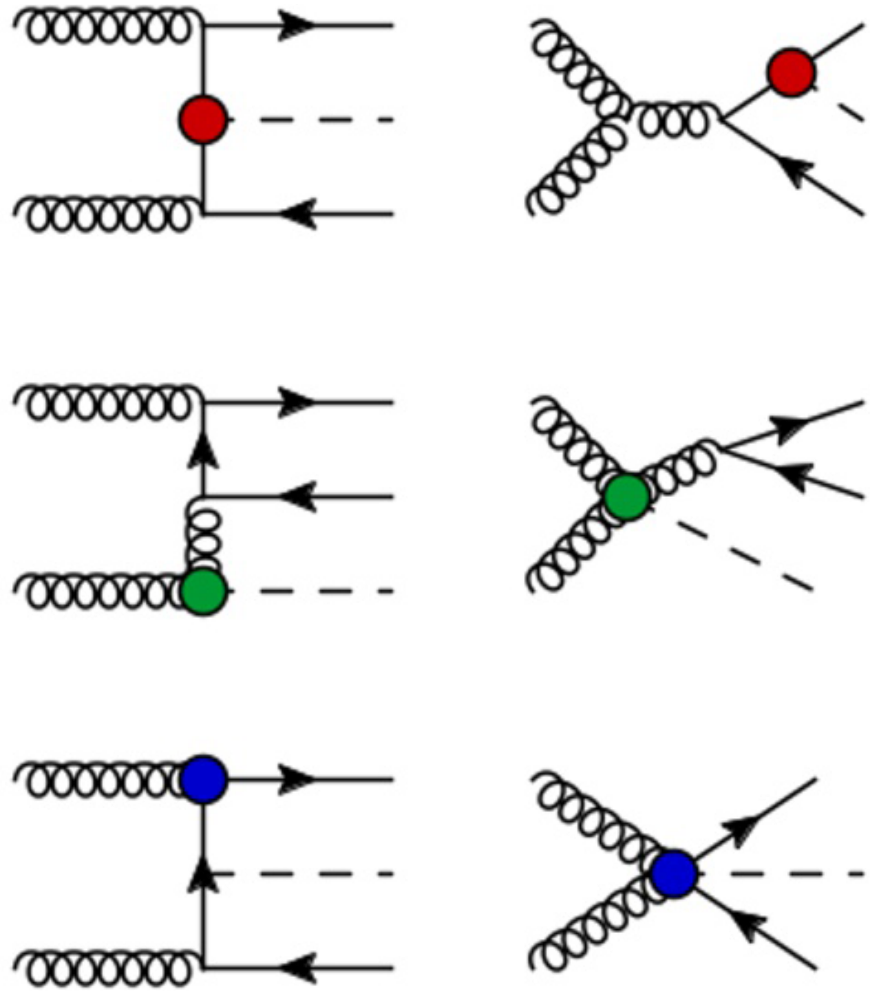


top polarisation angles

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i^z} = \frac{1}{2}\left(1 + a_i P\,\cos\theta_i^z\right)$$

de Beurs, Laenen, Vreeswijk, EV arXiv:1807.03576

ttH in the EFT

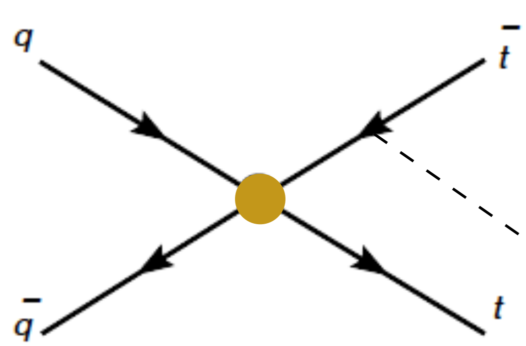


$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

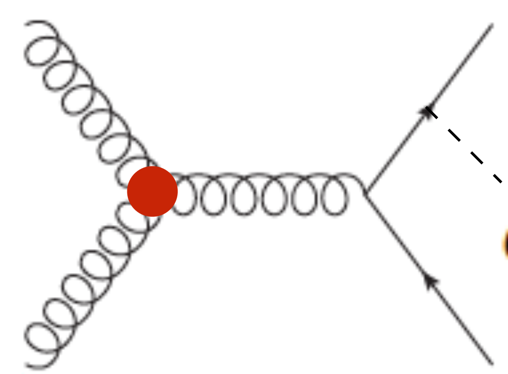
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

At NLO



4-fermion operators

Not in this talk, work in progress
Degrande et al



$$O_G = g_s f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$$

Multijet constraints:
Krauss et al arXiv:1611.00767

ttH@NLO in the EFT

13 TeV	σ NLO	K
σ_{SM}	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	1.09
$\sigma_{t\phi}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	1.13
$\sigma_{\phi G}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	1.39
σ_{tG}	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	1.58
$\sigma_{tG,tG}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	1.42
$\sigma_{t\phi,tG}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	1.37

First systematic study of uncertainties:

- 1) Scale and PDF uncertainties:

Similar to SM

- Reduced scale and PDF uncertainties in the ratio over the SM
- 2) EFT scale uncertainties

$$\sigma_i(\mu_0;\mu) = \Gamma_{ji}(\mu,\mu_0)\sigma_j(\mu)\,.$$

$$\sigma_{ij}(\mu_0;\mu) = \Gamma_{ki}(\mu,\mu_0)\Gamma_{lj}(\mu,\mu_0)\sigma_{kl}(\mu)$$

$$\Gamma_{ij}(\mu,\mu_0) = \exp\left(\frac{-2}{\beta_0}\log\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\gamma_{ij}\right)$$

Cross-sections evaluated at a different scale ($\mu_0/2$, $2\mu_0$) taking into account operator mixing and running

3) C/Λ^2 expansion

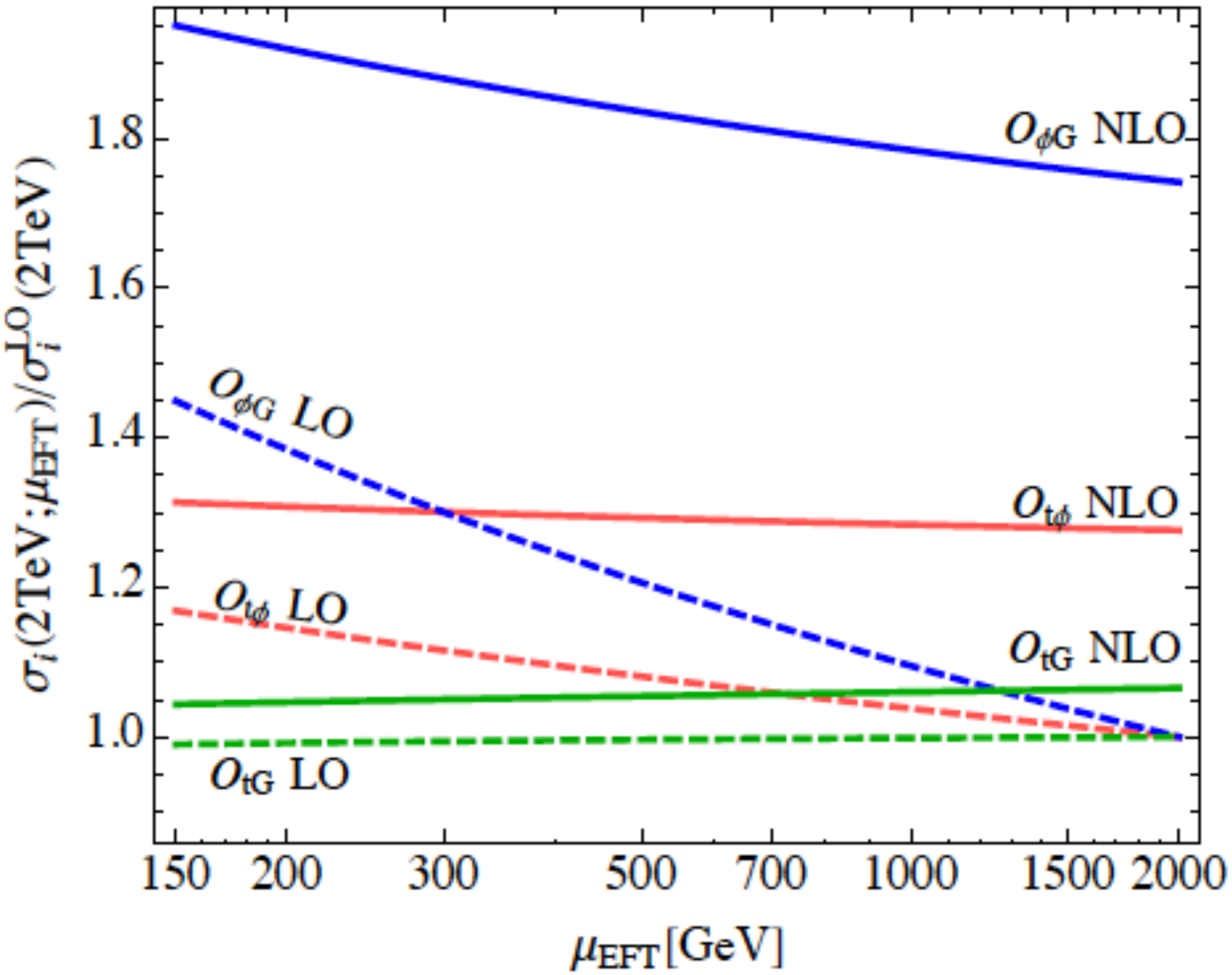
$$\sigma = \sigma_{\rm SM} + \sum_i \frac{C_i^{\rm dim6}}{(\Lambda/1{\rm TeV})^2}\sigma_i^{(\rm dim6)} + \boxed{\sum_{i<j}\frac{C_i^{\rm dim6}C_j^{\rm dim6}}{(\Lambda/1{\rm TeV})^4}\sigma_{ij}^{(\rm dim6)}}$$

Computed

$$\boxed{+\sum_i \frac{C_i^{\rm dim8}}{(\Lambda/1{\rm TeV})^4}\sigma_i^{(\rm dim8)}} + \mathcal{O}(\Lambda^{-6})\,.$$

Needs dim-8 operators (Not included here)
It can computed in some cases
Contino et al arXiv:1604.0644, Hays et al arXiv:1808.00442

A study of RG effects



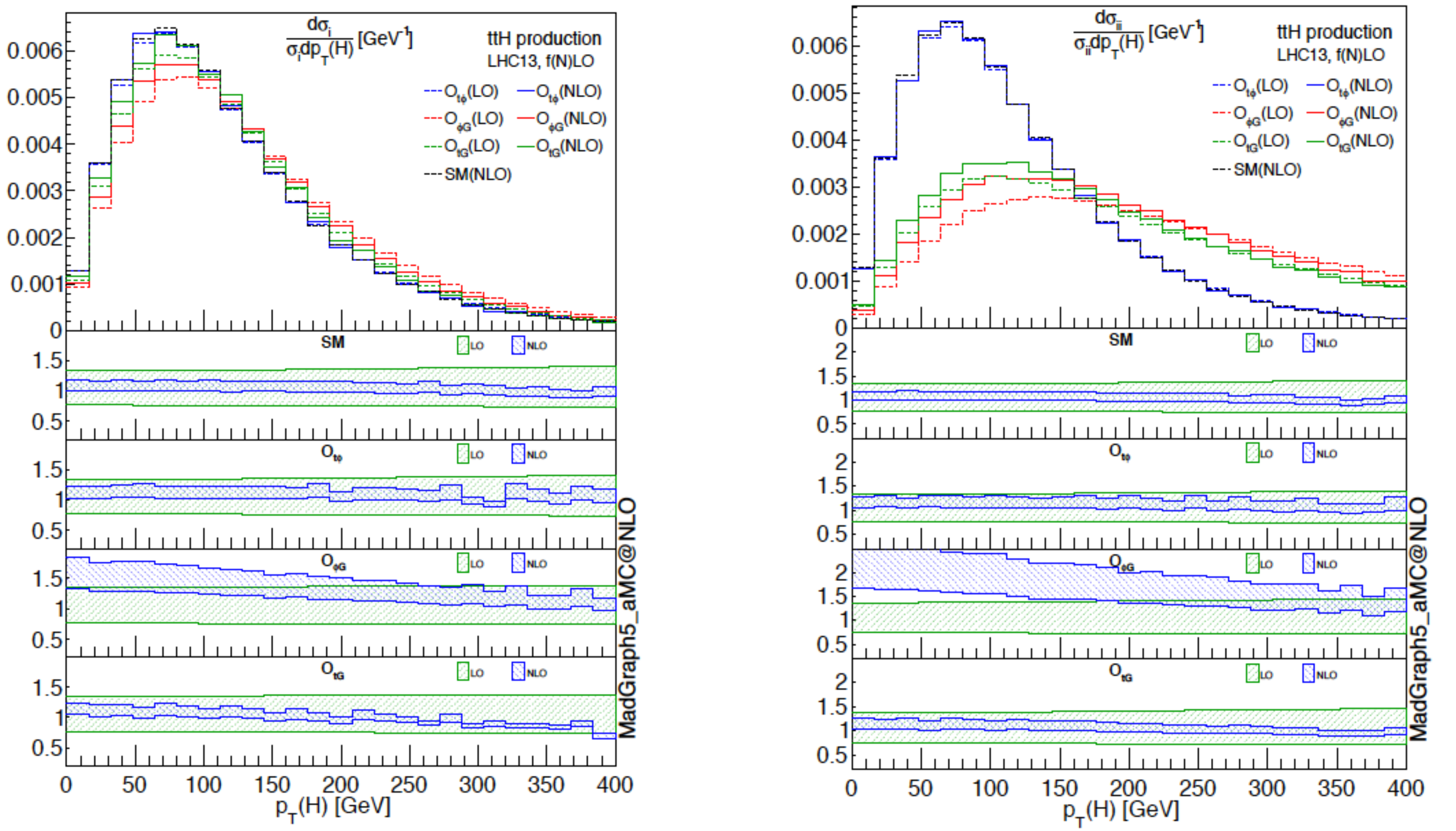
RG corrections not a good approximation to the NLO result, underestimate the NLO corrections

Milder EFT scale dependence at NLO, when mixing effects also taken into account

Comparison of exact NLO with LO improved by 1-loop RG running

Maltoni, EV, Zhang arXiv:1607.05330

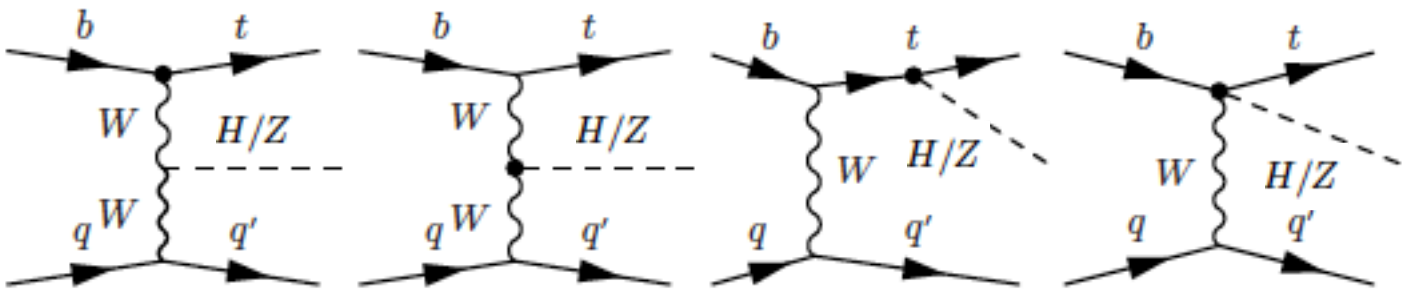
Differential distributions for ttH



NLO: smaller uncertainties, non-flat K-factors
Different shapes for different operators

Maltoni, EV, Zhang arXiv:1607.05330

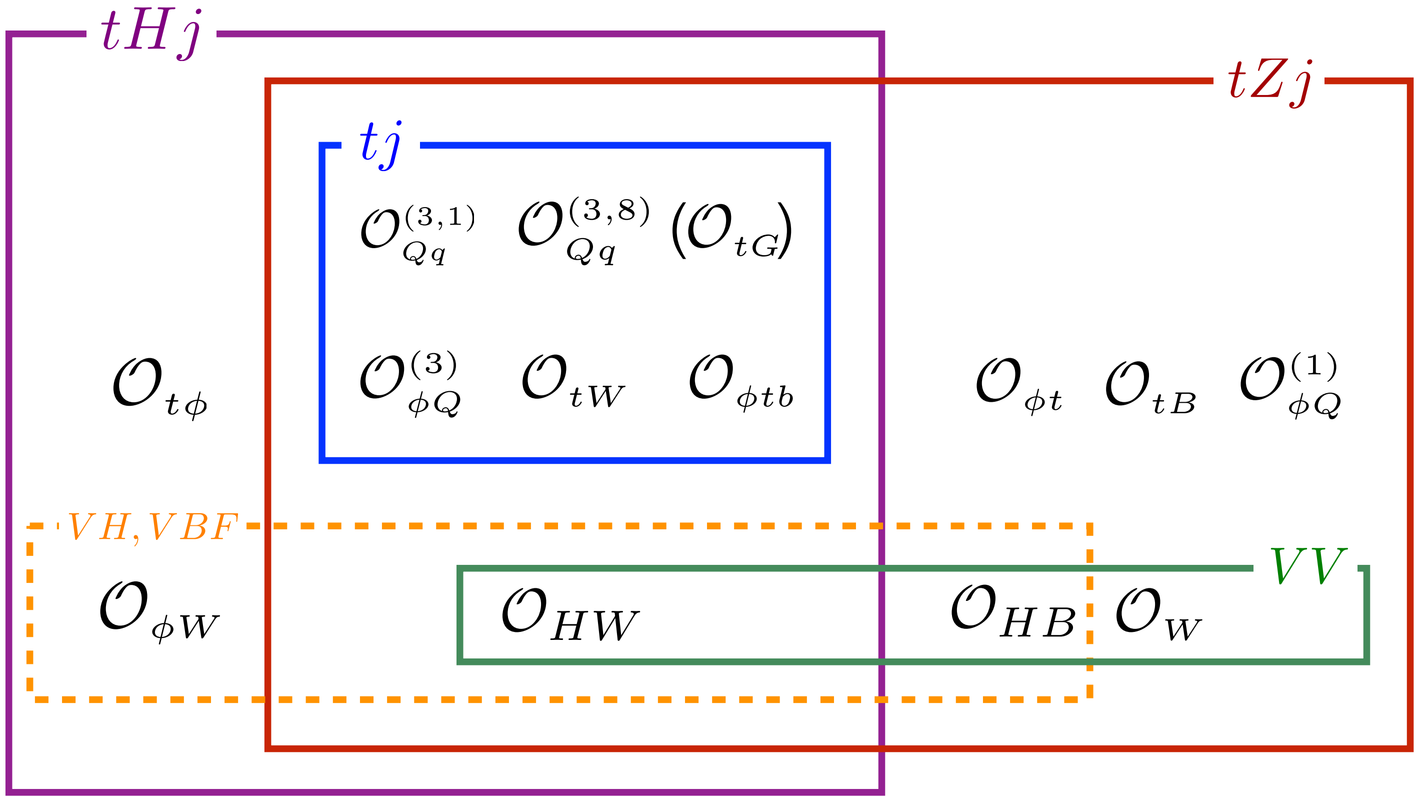
Rare processes: tZj/tHj associated production



Gauge-Higgs

Top couplings

TGC



$\mathcal{O}_W$	$\varepsilon_{IJK}\, W^I_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\,\gamma^\mu \tau^I Q) + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\,\gamma^\mu Q) + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi)\, B^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\,\gamma^\mu t) + \text{h.c.}$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger(\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi}\, D_\mu \varphi)(\bar{t}\,\gamma^\mu b) + \text{h.c.}$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}^{(1)}_{\varphi q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\,\gamma^\mu q_i) + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}^{(3)}_{\varphi q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{q}_i\,\gamma^\mu \tau^I q_i) + \text{h.c.}$
$\mathcal{O}_{tW}$	$i(\bar{Q}\sigma^{\mu\nu} \tau_I\, t)\, \tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{\varphi u}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{u}_i\,\gamma^\mu u_i) + \text{h.c.}$
$\mathcal{O}_{tB}$	$i(\bar{Q}\sigma^{\mu\nu}\, t)\, \tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,1)}_{Qq}$	$(\bar{q}_i\,\gamma_\mu \tau_I q_i)(\bar{Q}\,\gamma^\mu \tau^I Q)$
$\mathcal{O}_{tG}$	$i(\bar{Q}\sigma^{\mu\nu} T_A\, t)\, \tilde{\varphi}\, G^A_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,8)}_{Qq}$	$(\bar{q}_i\,\gamma_\mu \tau_I T_A q_i)(\bar{Q}\,\gamma^\mu \tau^I T^A Q)$

Unique interplay

Pure gauge operators (4): $\mathcal{O}_{\varphi W}, \mathcal{O}_W, \mathcal{O}_{HW}, \mathcal{O}_{HB}$,

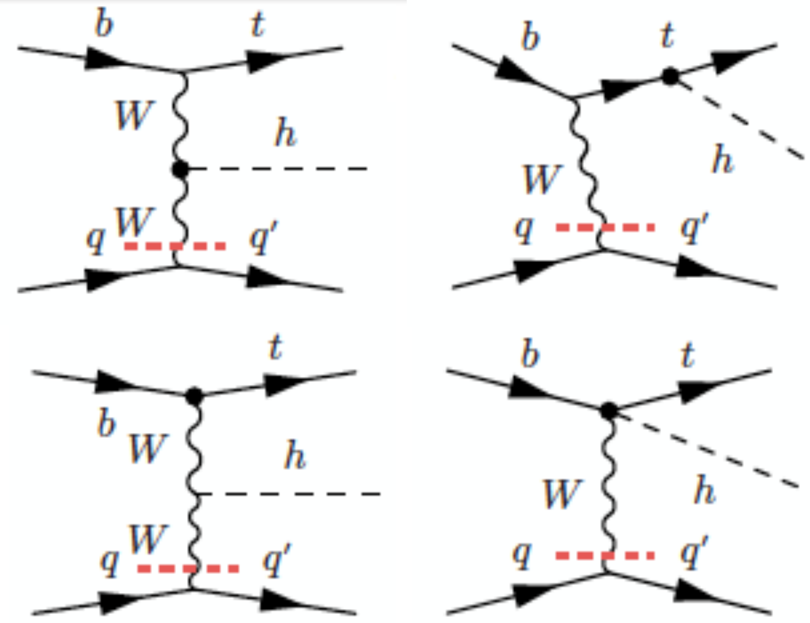
Two-fermion top-quark operators (8): $\mathcal{O}^{(3)}_{\varphi Q}, \mathcal{O}^{(1)}_{\varphi Q}, \mathcal{O}_{\varphi t}, \mathcal{O}_{tW}, \mathcal{O}_{tB}, \mathcal{O}_{tG}, \mathcal{O}_{\varphi tb}, \mathcal{O}_{t\varphi}$

Four-fermion top-quark operators (2): $\mathcal{O}^{(3,1)}_{Qq}, \mathcal{O}^{(3,8)}_{Qq}$.

Helicity amplitudes for subprocesses

bW → tH

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



bW → tZ

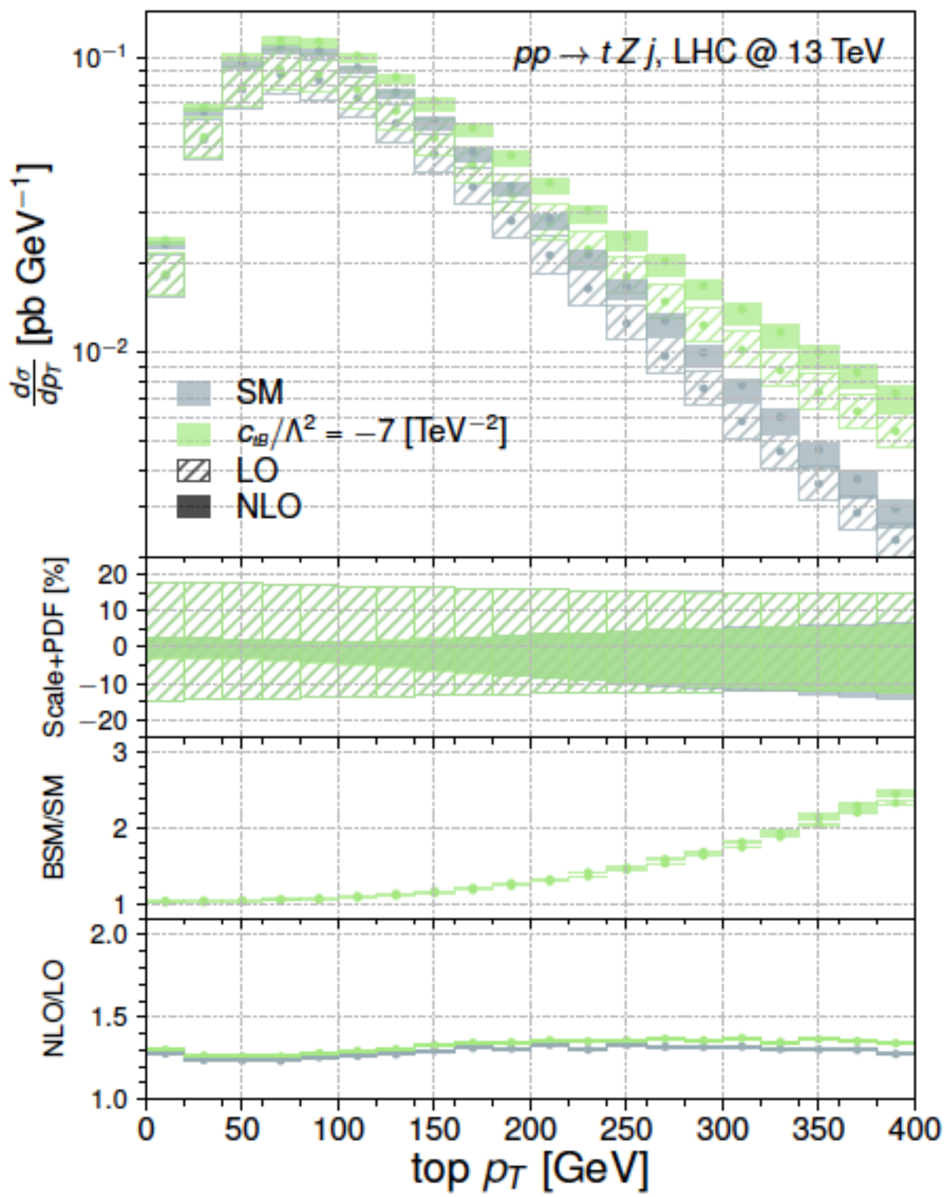
$\lambda_b,\ \lambda_W,\ \lambda_t,\ \lambda_Z$	SM	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$
$-,0,-,0$	s^0	$\boxed{\sqrt{s(s+t)}}$	$-$	$-$	$-$	s^0	s^0	$\sqrt{s(s+t)}$	s^0
$-,0,+,0$	$\frac{1}{\sqrt{s}}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_Z\sqrt{-t}$	$\frac{m_W(2s+3t)}{\sqrt{-t}}$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,-,-,0$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$m_W\sqrt{-t}$	$\frac{1}{\sqrt{s}}$
$-,-,+,0$	$\frac{1}{s}$	s^0	s^0	s^0	s^0	$\boxed{\sqrt{s(s+t)}}$	s^0	s^0	$\frac{1}{\sqrt{s}}$
$-,0,-,-$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$\frac{m_W(ss_W^2+2t)}{\sqrt{-t}}$	$\frac{m_W s}{\sqrt{-t}}$
$-,0,-,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,0,+,-$	s^0	s^0	s^0	$-$	$-$	s^0	s^0	s^0	s^0
$-,0,+,+$	$\frac{1}{s}$	s^0	s^0	s^0	$\boxed{\sqrt{s(s+t)}}$	$\boxed{\sqrt{s(s+t)}}$	$-$	s^0	s^0
$-,+,-,0$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
$-,+,+,0$	s^0	s^0	$-$	$-$	$-$	s^0	$-$	s^0	$\frac{1}{s}$
$-,-,-,-$	s^0	s^0	s^0	$-$	s^0	s^0	s^0	s^0	s^0
$-,-,-,+$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$	s^0	s^0
$-,-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_Z\left(s_W^2 t-3c_W^2(2s+t)\right)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
$-,-,+,+$	$-$	$-$	$-$	$-$	$m_W\sqrt{-t}$	$m_Z\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,-,-$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\boxed{\sqrt{s(s+t)}}$	s^0	s^0
$-,+,-,+$	s^0	s^0	s^0	$-$	$-$	$-$	$-$	s^0	s^0
$-,+,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,+,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$

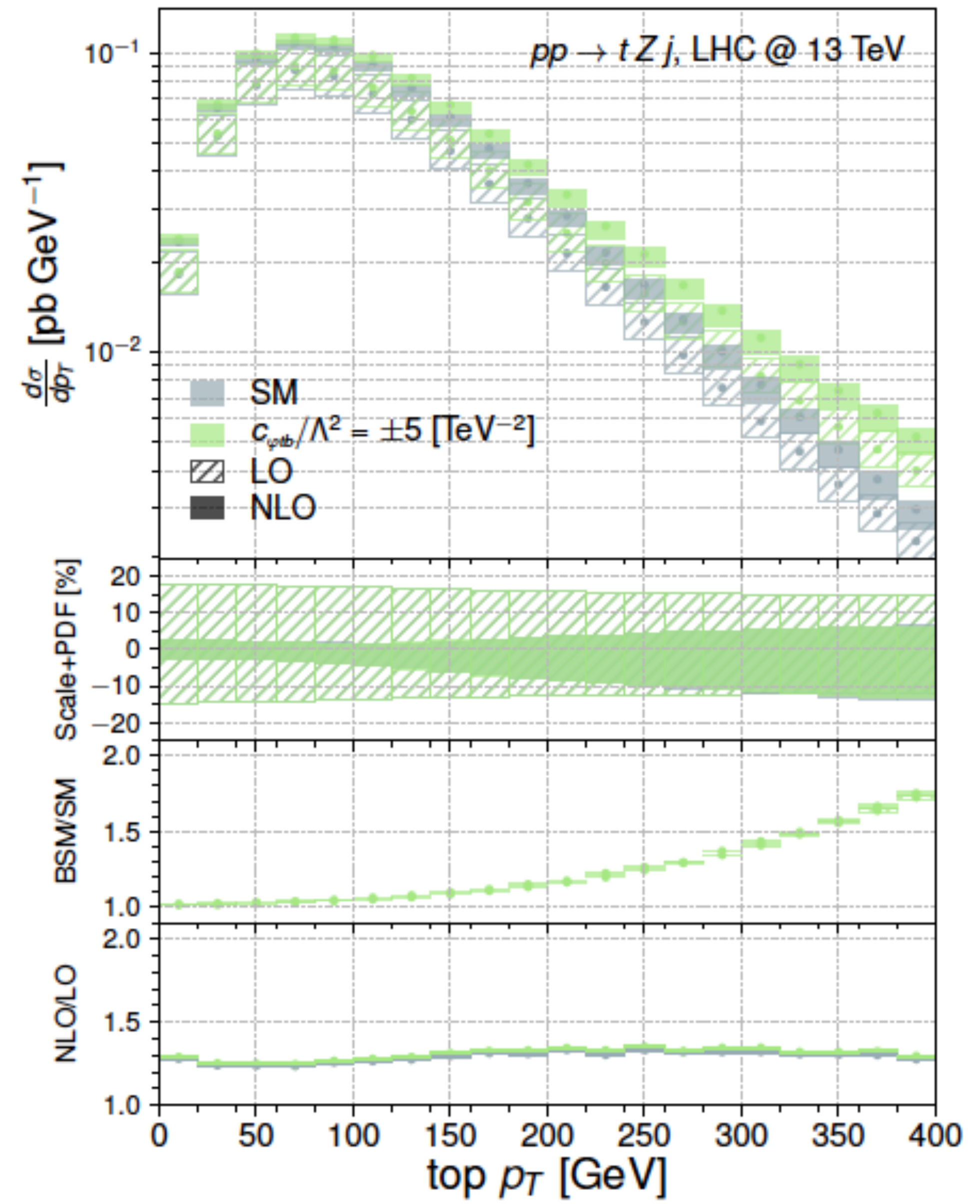
Amplitudes growing with energy as SM cancellations get spoiled ➡

Large deviations
Differential distributions

Differential results

tZj

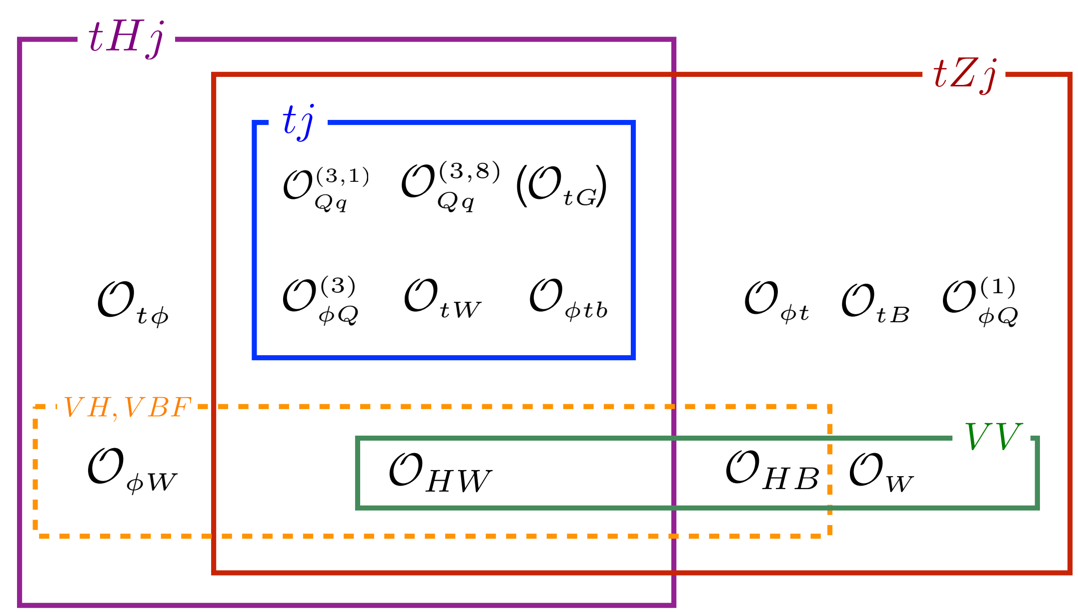




Large deviations in the tails, as expected from helicity amplitudes

Comparison with single top

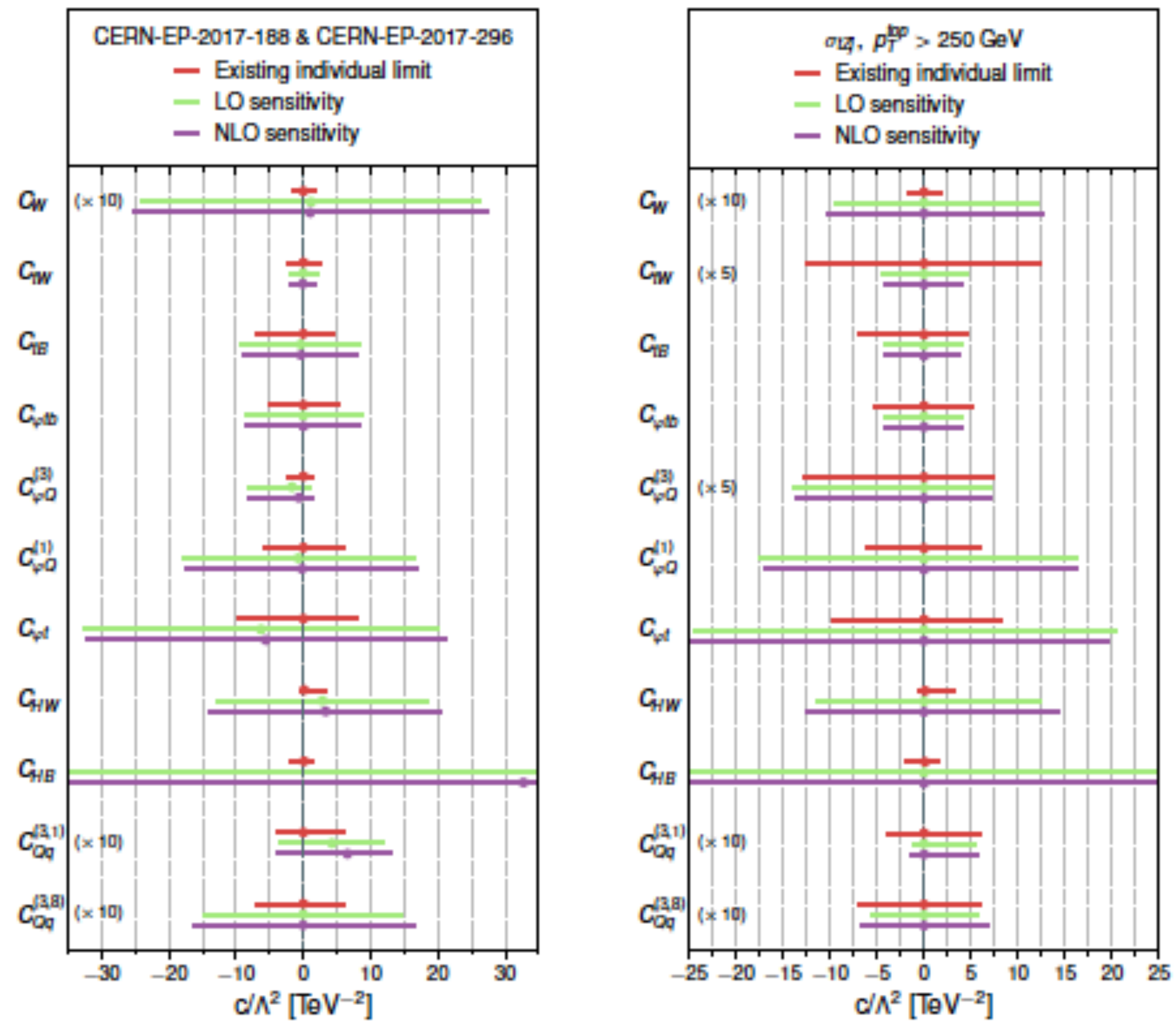
	tj	tj ($p_T^t > 350$ GeV)	tZj	tZj ($p_T^t > 250$ GeV)	tHj
σ_{SM}	224 pb	880 fb	839 fb	69 fb	75.9 fb
r_{tW}	0.0275	0.024	0.016	0.010	0.292
$r_{tW,tW}$	0.0162	0.35	0.095	0.67	0.940
$r_{\varphi Q^{(3)}}$	0.121	0.121	0.192	0.172	-0.132
$r_{\varphi Q^{(3)},\varphi Q^{(3)}}$	0.0037	0.0037	0.029	0.114	0.21
$r_{\varphi tb,\varphi tb}$	0.00090	0.0008	0.0050	0.027	0.050
r_{tG}	0.0003	-0.01	0.00053	-0.0048	-0.0055
$r_{tG,tG}$	0.00062	0.045	0.0027	0.022	0.025
$r_{Qq^{(3,1)}}$	-0.353	-4.4	-0.59	-2.22	-0.39
$r_{Qq^{(3,1)},Qq^{(3,1)}}$	0.126	11.5	0.65	5.1	1.21
$r_{Qq^{(3,8)},Qq^{(3,8)}}$	0.0308	2.73	0.133	1.01	1.08



- Increased sensitivity for dipoles and right-handed current (as expected from helicity analysis)
- 4-fermion operators sensitivity due to higher thresholds can be outperformed by high-pT single top measurements

Current and future sensitivity

Op.	TF (I)	TF (M)	RHCC (I) tree/loop	σ_{ttH} [10]	SFitter (I)	PEWM[2]
$\mathcal{O}_W$					[-0.18, 0.18]	
$\mathcal{O}_{HW}$					[-0.64,3.25]	
$\mathcal{O}_{HB}$					[-2.11,1.57]	
$\mathcal{O}_{\varphi W}$					[-0.39,0.33]	
$\mathcal{O}_{\varphi tb}$			[-5.28,5.28]/[-0.046,0.040]			
$\mathcal{O}_{\varphi Q}^{(3)}$	[-2.59,1.50]	[-4.19,2.00]				-1.0 ± 2.7 [3]
$\mathcal{O}_{\varphi Q}^{(1)}$	[-3.10,3.10]					1.0 ± 2.7
$\mathcal{O}_{\varphi t}$	[-9.78,8.18]					1.8 ± 3.8
$\mathcal{O}_{tW}$	[-2.49,2.49]	[-3.99,3.40]				-0.4 ± 2.4
$\mathcal{O}_{tB}$	[-7.09,4.68]					4.8 ± 10.6
$\mathcal{O}_{tG}$	[-0.24,0.53]	[-1.07,0.99]				
$\mathcal{O}_{t\varphi}$				[-6.5,1.3]	[-18.2,6.30]	
$\mathcal{O}_{Qq}^{(3,1)}$	[-0.40,0.60]	[0.66,1.24]				
$\mathcal{O}_{Qq}^{(3,8)}$	[-4.90,3.70]	[6.06,6.73]				



TopFitter: Buckley et al. arXiv:1512.03360
SFitter: Butter et al. arXiv:1604.03105
PEWM: Zhang et al. arXiv:1201.6670
ttH: Maltoni et al. arXiv:1607.05330
RHCC: Alioli et al. arXiv:1703.04751

tZj measurements:
CMS; PLB 779 (2018) 358-384: 0.75 ± 0.27
ATLAS; CERN-EP-2017-188: 1.31 ± 0.47

Promising for weak dipoles, RHCC and SU(2) current in particular for HL-LHC where high pT data can potentially be used

Rare processes can play a role in a global fit

Towards a complete implementation@NLO

Aim to obtain a complete Monte Carlo implementation based on:

- Warsaw basis
- Degrees of freedom for top operators as in arXiv:1802.07237 (LHCTopWG)

Current status:

- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- Successful validation at LO with dim6top (in turn validated with SMEFTsim)
- 0/2F@NLO operators validated (with previous partial NLO implementations) → **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**
- 4F@NLO operators validation: on-going

Future plans

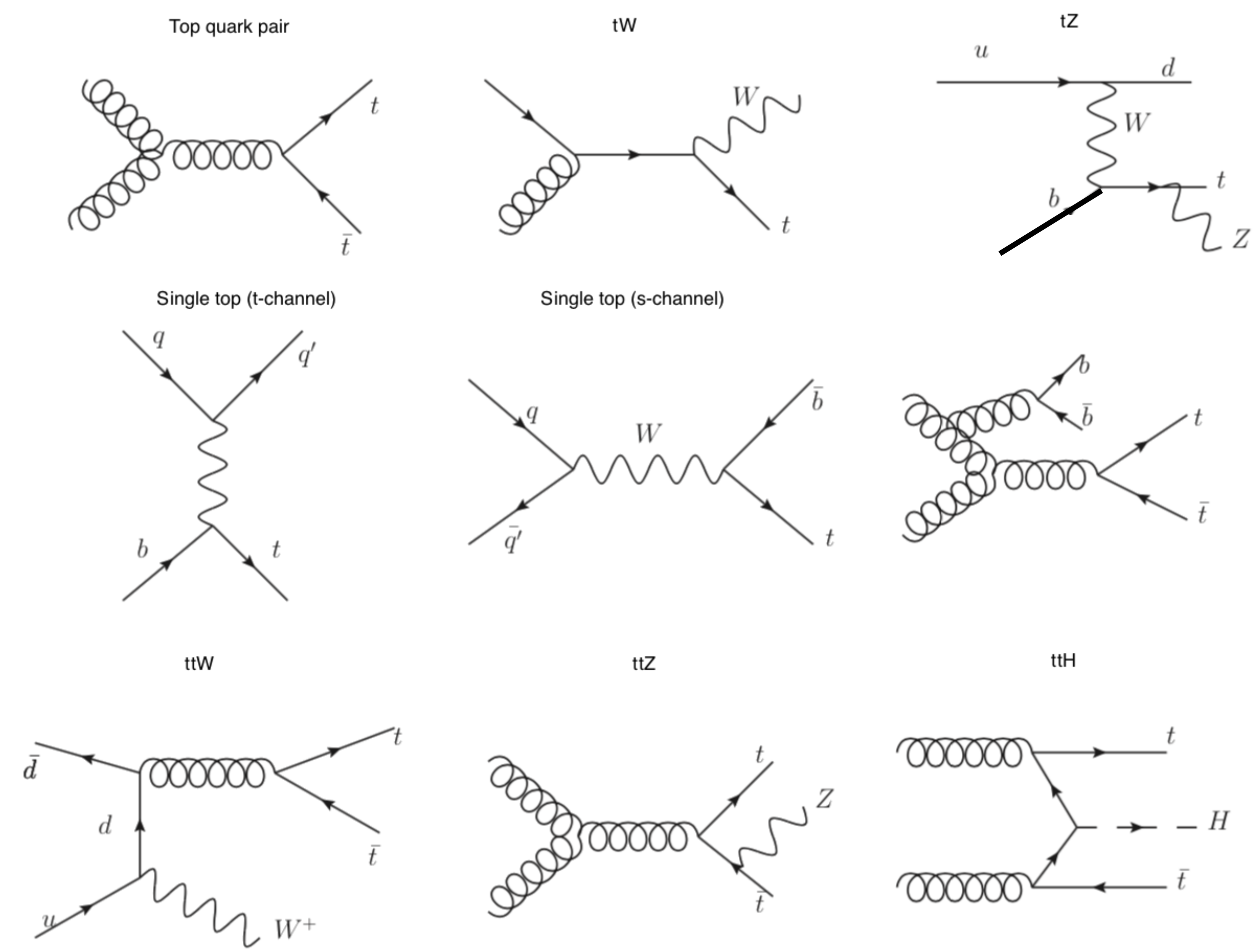
- Full NLO model release (4F@NLO)
- Other flavour assumptions
- CP-violating effects

Work in progress with:
C. Degrande, G. Durieux, F. Maltoni, K. Mimasu, C. Zhang

A first application: A global top fit@NLO

Class	Notation	Degree of Freedom	Operator Definition
	OQQ1	c^1_{QQ}	$2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$
	OQQ8	c^8_{QQ}	$8C^{3(3333)}_{qq}$
	OQt1	c^1_{Qt}	$C^{1(3333)}_{qu}$
	OQt8	c^8_{Qt}	$C^{8(3333)}_{qu}$
$QQQQ$	OQb1	c^1_{Qb}	$C^{1(3333)}_{qd}$
	OQb8	c^8_{Qb}	$C^{8(3333)}_{qd}$
	Ott1	c^1_{tt}	$C^{(3333)}_{uu}$
	Otb1	c^1_{tb}	$C^{1(3333)}_{ud}$
	Otb8	c^8_{tb}	$C^{8(3333)}_{ud}$
	OQtQb1	c^1_{QtQb}	$C^{1(3333)}_{quqd}$
	OQtQb8	c^8_{QtQb}	$C^{8(3333)}_{quqd}$
	O81qq	$c^{1,8}_{Qq}$	$C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$
	O11qq	$c^{1,1}_{Qq}$	$C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$
	O83qq	$c^{3,8}_{Qq}$	$C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$
	O13qq	$c^{3,1}_{Qq}$	$C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$
	O8qt	c^8_{tq}	$C^{8(ii33)}_{qu}$
	O1qt	c^1_{tq}	$C^{1(ii33)}_{qu}$
	O8ut	c^8_{tu}	$2C^{(i33i)}_{uu}$
$QQqq$	O1ut	c^1_{tu}	$C^{(ii33)}_{uu} + \frac{1}{3}C^{(i33i)}_{uu}$
	O8qu	c^8_{Qu}	$C^{8(33ii)}_{qu}$
	O1qu	c^1_{Qu}	$C^{1(33ii)}_{qu}$
	O8dt	c^8_{td}	$C^{8(33ii)}_{ud}$
	O1dt	c^1_{td}	$C^{1(33ii)}_{ud}$
	O8qd	c^8_{Qd}	$C^{8(33ii)}_{qd}$
	O1qd	c^1_{Qd}	$C^{1(33ii)}_{qd}$
	OtG	c_{tG}	$\mathrm{Re}\{C^{(33)}_{uG}\}$
	OtW	c_{tW}	$\mathrm{Re}\{C^{(33)}_{uW}\}$
	ObW	c_{bW}	$\mathrm{Re}\{C^{(33)}_{dW}\}$
	OtZ	c_{tZ}	$\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$
$QQ+V,G,\varphi$	Off	$c_{\varphi tb}$	$\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$
	Ofq3	$c^3_{\varphi Q}$	$C^{3(33)}_{\varphi q}$
	OpQM	$c^-_{\varphi Q}$	$C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$
	Opt	$c_{\varphi t}$	$C^{(33)}_{\varphi u}$
	Otp	$c_{t\varphi}$	$\mathrm{Re}\{C^{(33)}_{u\varphi}\}$

34 d.o.f.
CP-conserving



Rich phenomenology

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Some considerations

- Validity of the EFT expansion: E<Λ
  - Ensure results are not dominated by high energy regions
  - report limits as a function of the max scale probed Contino et al arXiv:1604.06444
- Range of Wilson coefficients:
  - The theory: perturbativity, unitarity, linear or non-linear EFT, UV completion
  - The experimental limits: Think about and use as many processes as possible to extract allowed range

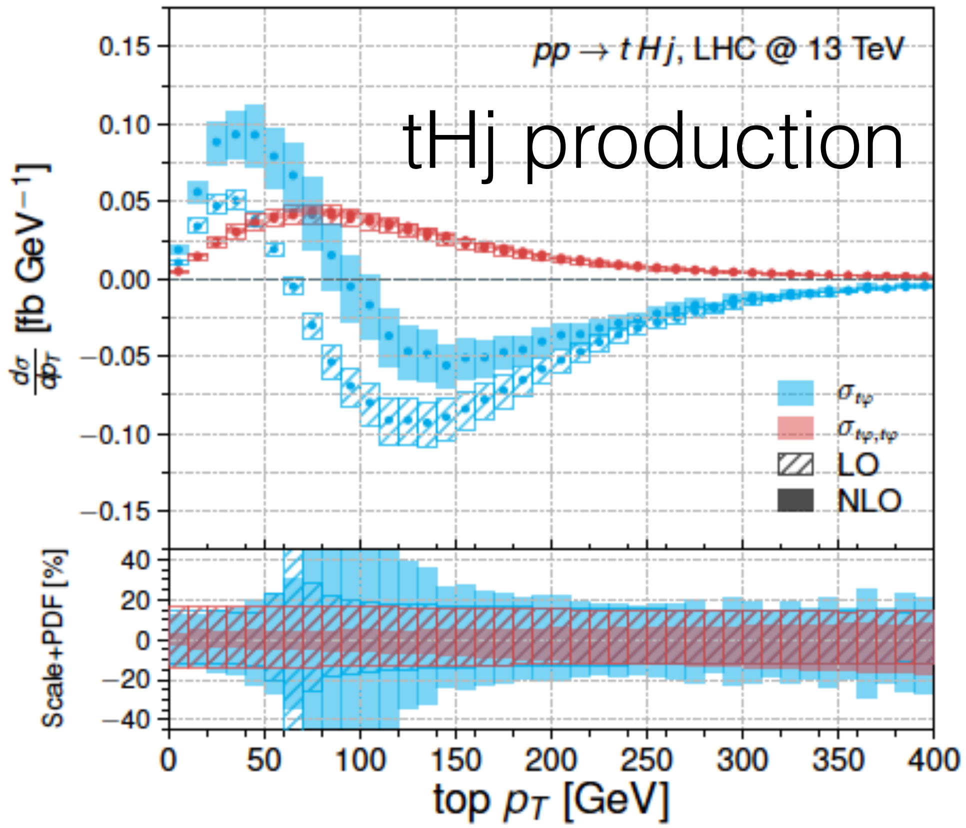
- $1/\Lambda^2$ vs $1/\Lambda^4$ contributions
  - $1/\Lambda^2$ suppressed due to helicity Azatov et al arXiv:1607.05236
  - $1/\Lambda^4$ can be large for loosely constrained operator coefficients/strongly coupled theories

$$C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

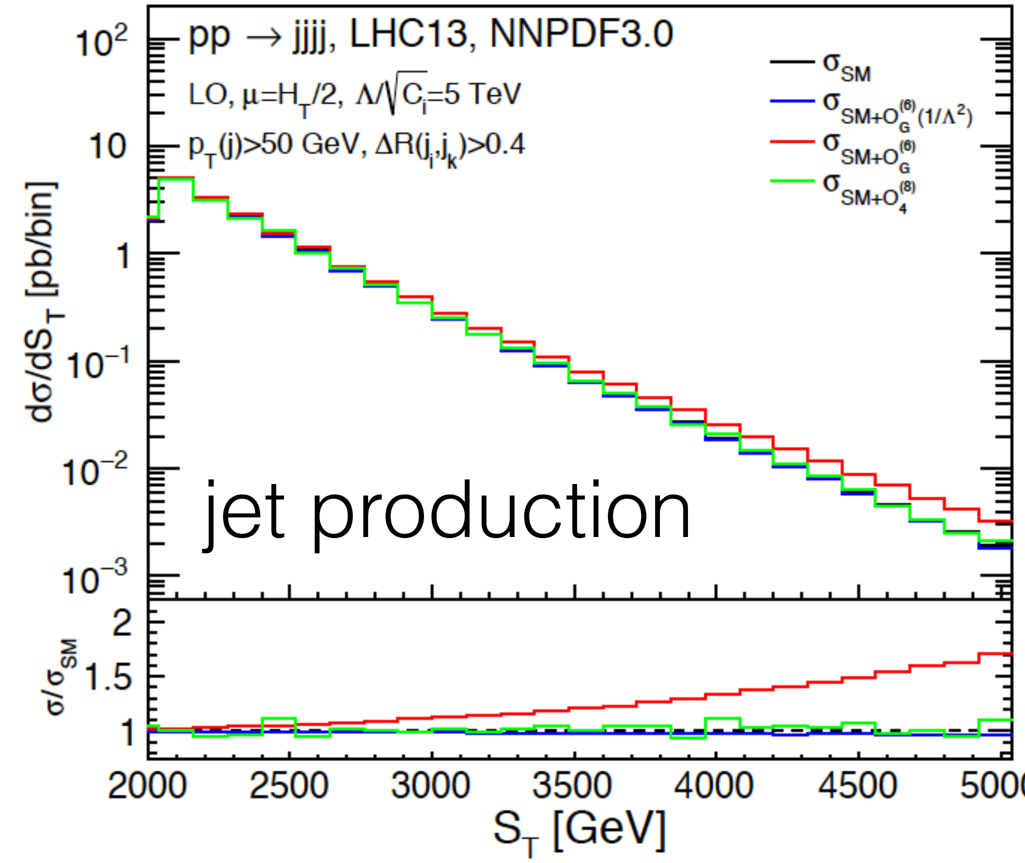
E<Λ satisfied but $O(1/\Lambda^4)$ large for large operator coefficients

$1/\Lambda^2$ vs $1/\Lambda^4$ contributions some examples

1)



2)



$1/\Lambda^2$ is not positive definite
$1/\Lambda^2$ is not suppressed PS point by PS point
$1/\Lambda^2$ is suppressed only when integrating over the PS

$1/\Lambda^2$ is suppressed compared to $1/\Lambda^4$
$1/\Lambda^4$ from dimension-6 much larger than interference of SM with dim-8

3) ttZ production

13TeV	$\mathcal{O}_{tW}$
$\sigma^{(1)}_{i,NLO}$	$-1.7(2)^{+31.3\%}_{-49.1\%}$
$\sigma^{(2)}_{ii,NLO}$	$24.2^{+6.2\%}_{-11.2\%}$

Reasons why the interference is suppressed:
1) An accidental cancellation between the contributions of the gg and qq channels
2) OtW not producing a longitudinal Z

Global fit Setup

Theory

(N)NLO QCD for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions
Parton-level

Global SMEFT fit of the top-quark sector

Methodology

Based on NNPDF
Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Output

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added
Plan to extend to Higgs, gauge sector etc

Observables and theory predictions

Data

Top-pair production
W-helicities

4 tops, ttbb, top-pair associated production

Single top
t-channel, s-channel, tW, tZ

Dataset	n_{dat}
ATLAS_tt_8TeV_ljets [$m_{t\bar{t}}$]	7
CMS_tt_8TeV_ljets [y_t]	10
CMS_tt2D_8TeV_dilep [$(m_{t\bar{t}}, y_t)$]	16
CMS_tt_13TeV_ljets2 [$y_{t\bar{t}}$]	8
CMS_tt_13TeV_dilep [$y_{t\bar{t}}$]	6
CMS_tt_13TeV_ljets_2016 [y_t]	11
ATLAS_WhelF_8TeV	3
CMS_WhelF_8TeV	3
CMS_ttbb_13TeV	1
CMS_tttt_13TeV	1
ATLAS_tth_13TeV	1
CMS_tth_13TeV	1
ATLAS_ttZ_8TeV	1
ATLAS_ttZ_13TeV	1
CMS_ttZ_8TeV	1
CMS_ttZ_13TeV	1
ATLAS_ttW_8TeV	1
ATLAS_ttW_13TeV	1
CMS_ttW_8TeV	1
CMS_ttW_13TeV	1
CMS_t_tch_8TeV_dif	6
ATLAS_t_tch_8TeV [y_t]	4
ATLAS_t_tch_8TeV [$y_{\bar{t}}$]	4
ATLAS_t_sch_8TeV	1
CMS_t_tch_13TeV_dif [y_t]	4
CMS_t_sch_8TeV	1
ATLAS_tW_inc_8TeV	1
CMS_tW_inc_8TeV	1
ATLAS_tW_inc_13TeV	1
CMS_tW_inc_13TeV	1
ATLAS_tZ_inc_13TeV	1
CMS_tZ_inc_13TeV	1
Total	$\boxed{102}$

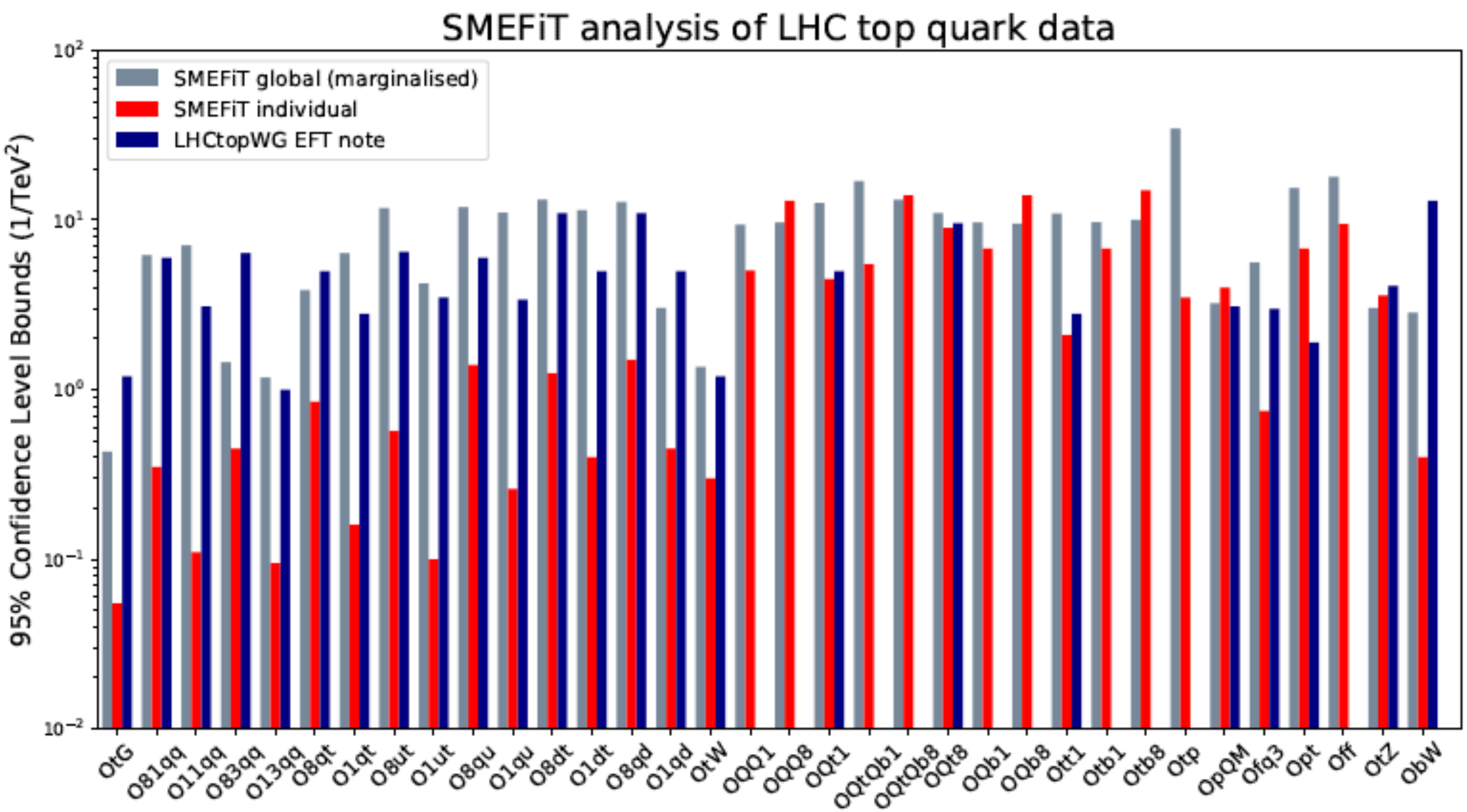
One distribution from each dataset, to avoid double counting

Theoretical predictions

Process	SM	SMEFT
$t\bar{t}$	NNLO QCD	NLO QCD
single-t (t-ch)	NNLO QCD	NLO QCD
single-t (s-ch)	NLO QCD	NLO QCD
tW	NLO QCD	NLO QCD
tZ	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}W(Z)$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}h$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}t\bar{t}$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}b\bar{b}$	NLO QCD	LO QCD + NLO SM K-factors

Baseline fit includes:

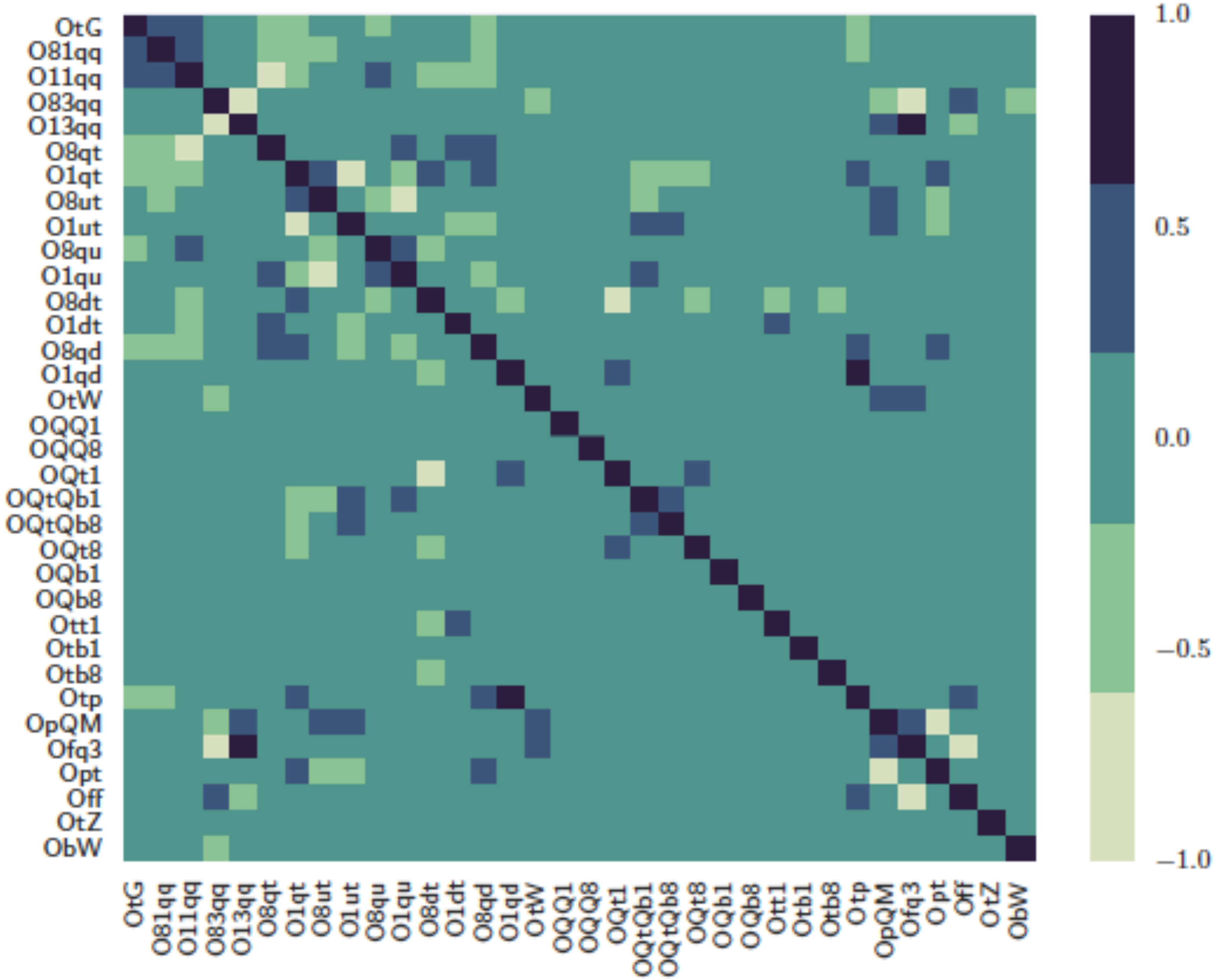
- Best available SM predictions
- NLO EFT predictions
- $O(1/\Lambda^4)$ terms



First limits reported for some operators
Improvement for some operators: e.g. O_{tG}, O^{83}_{qq}, O_{bW}
Individual limits more stringent than marginalised ones

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

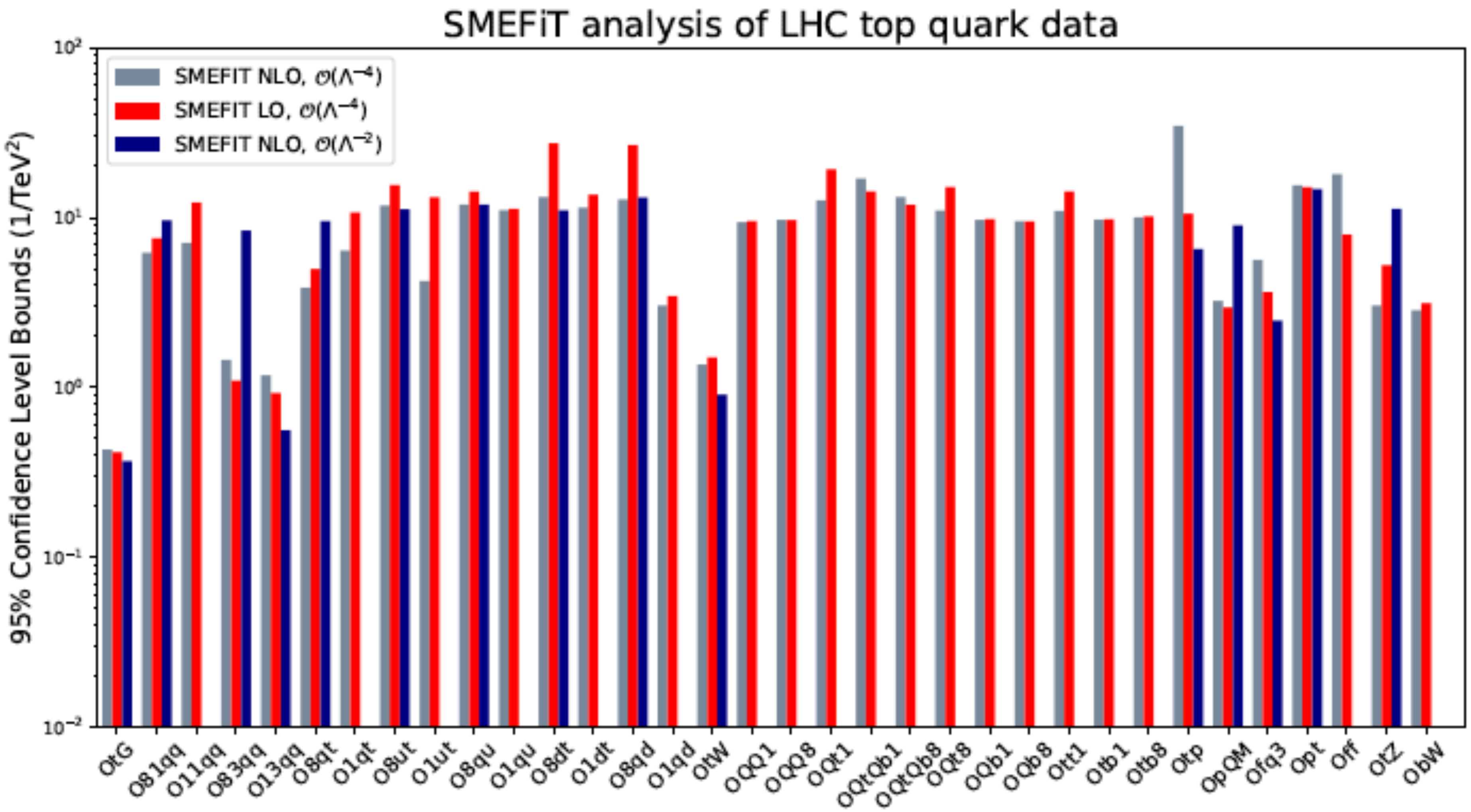
Correlations between EFT coefficients



Strong (anti-)correlations between different operators (ignored by individual constraints)

Impact of higher-order terms

Fit allows to check the impact of NLO QCD corrections and of including the $O(1/\Lambda^4)$ terms



Non-trivial impact of the two effects, can be different operator-by-operator

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

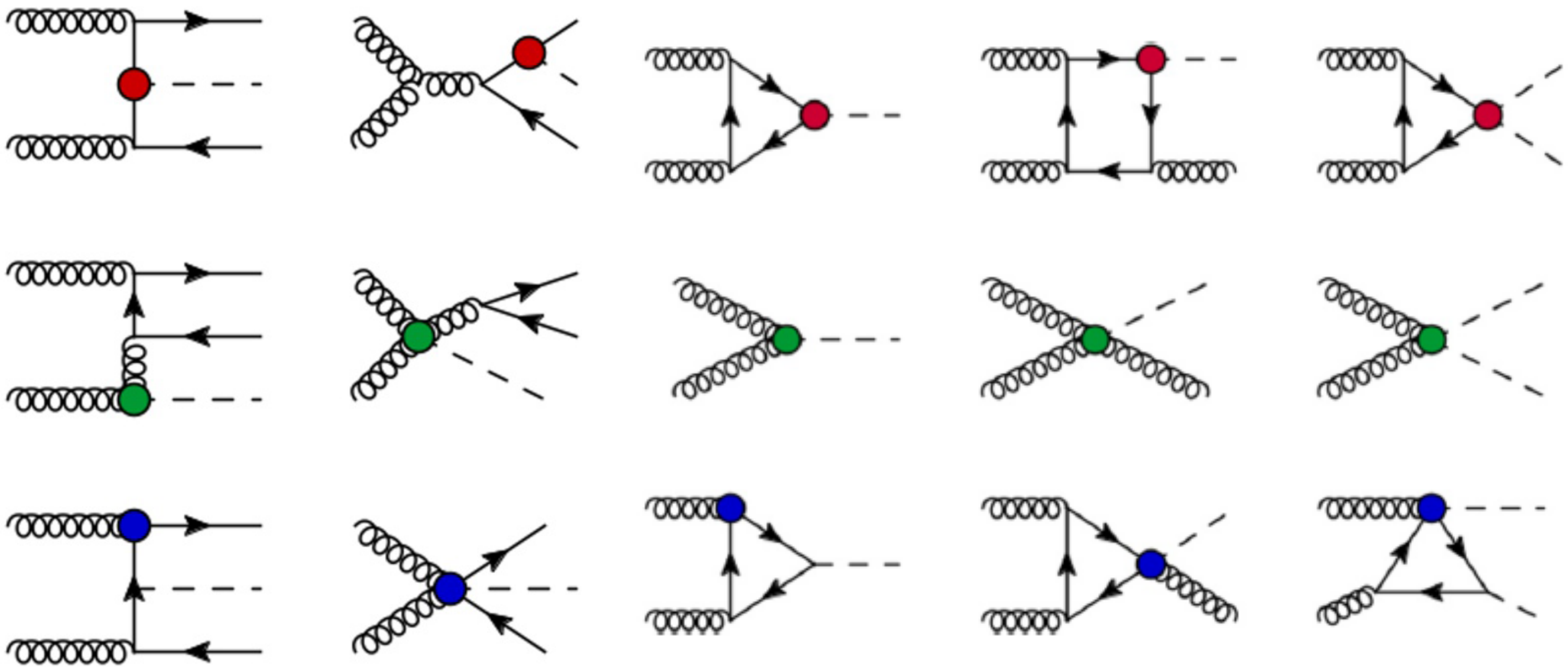
Outline

- Introduction to the EFT
- EFT in top quark physics
  - Precision calculations in the EFT
  - Towards global fits in the top sector
- EFT in the top-Higgs sector
  - Top loops in the EFT

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$



ttH

H, H+j, HH

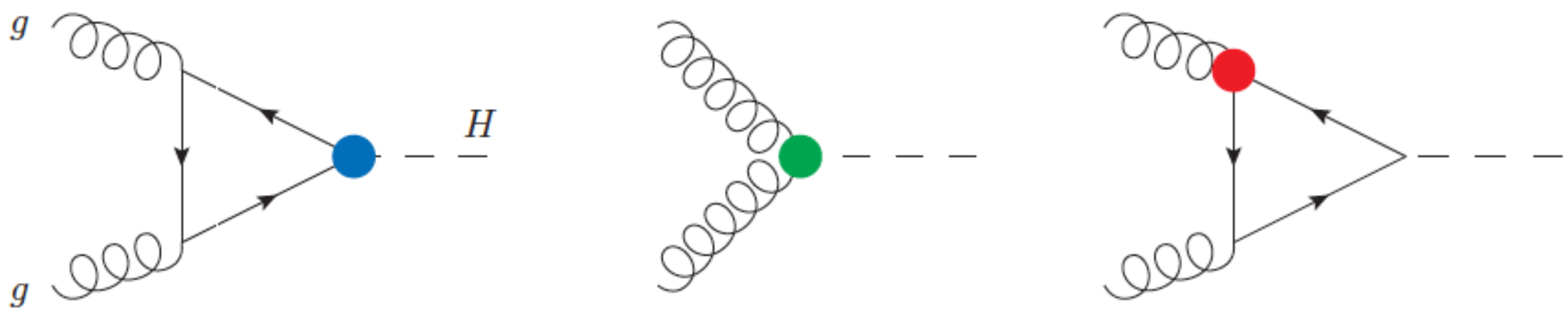
See also
Degrande et al. arXiv:1205.1065
Grojean et al. arXiv:1312.3317
Azatov et al arXiv:1608.00977

Use with 1) ttH and 2) H, H+j to break degeneracy between operators and extract maximal information on these operators

Maltoni, EV, Zhang: arXiv:1607.05330

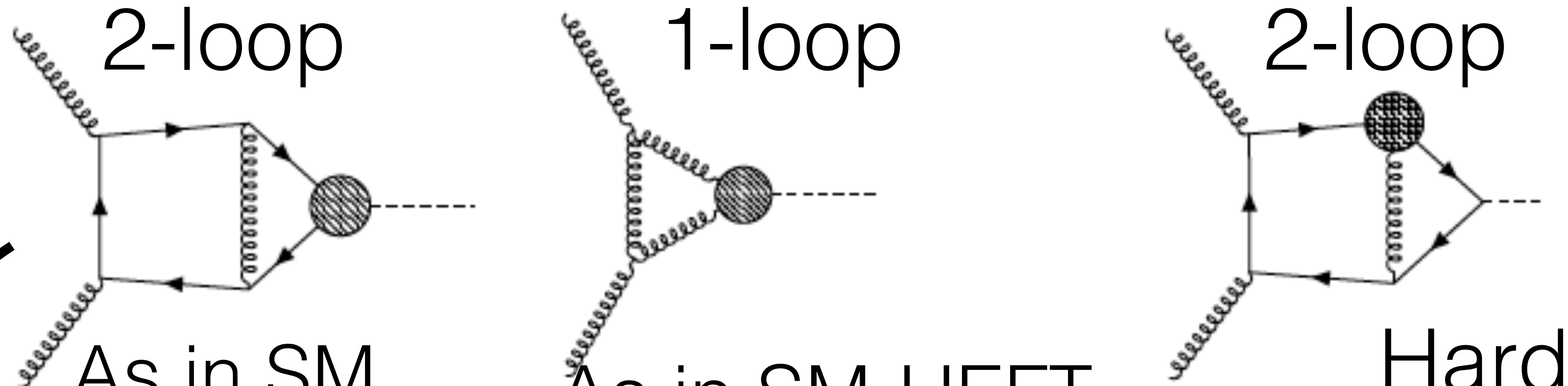
SMEFT in single Higgs production

LO:



$(\Phi^\dagger\Phi)\,\bar{Q}_L\Phi\, q_R$ $(\Phi^\dagger\Phi)\,GG$ $\bar{Q}_L\Phi\,\sigma q_R G$

NLO: 2-loop 1-loop 2-loop



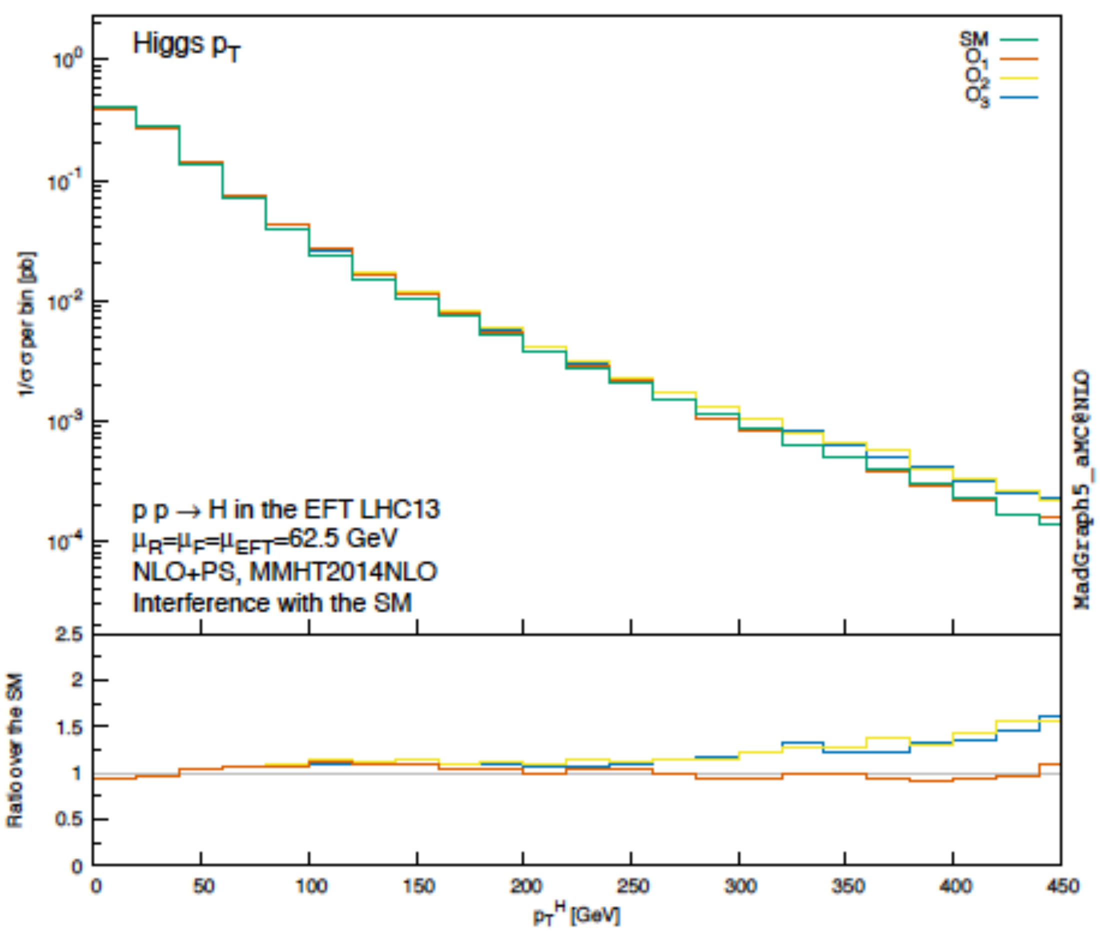
As in SM As in SM-HEFT **Harder**

but master integrals known

13 TeV	σ LO	σ/σ_{SM} LO	σ NLO	σ/σ_{SM} NLO	K
σ_{SM}	$21.3^{+34.0+1.5\%}_{-25.0-1.5\%}$	1.0	$36.6^{+26.4+1.9\%}_{-20.0-1.6\%}$	1.0	1.71
σ_1	$-2.93^{+34.0+1.5\%}_{-25.0-1.5\%}$	-0.138	$-4.70^{+24.8+1.9\%}_{-20.0-1.6\%}$	-0.127	1.61
σ_2	$2660^{+34.0+1.5\%}_{-25.0-1.5\%}$	125	$4130^{+23.9+1.9\%}_{-19.6-1.6\%}$	114	1.55
σ_3	$50.5^{+34.0+1.5\%}_{-25.0-1.5\%}$	2.38	$83.5^{+26.0+1.9\%}_{-20.6-1.6\%}$	2.28	1.65

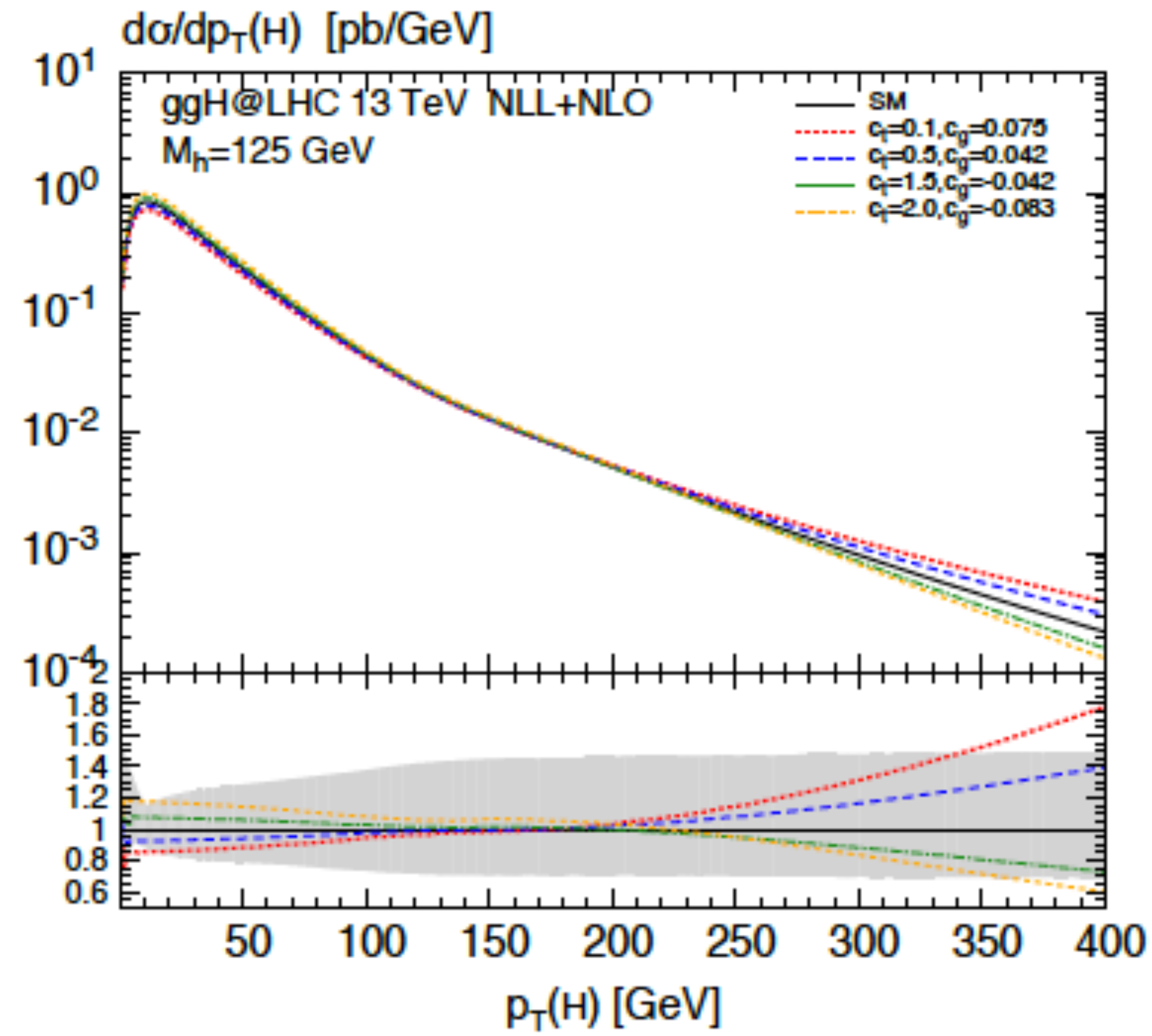
Deutschmann, Duhr, Maltoni, EV
arXiv:1708.00460

SMEFT in Higgs production



Higgs p_T

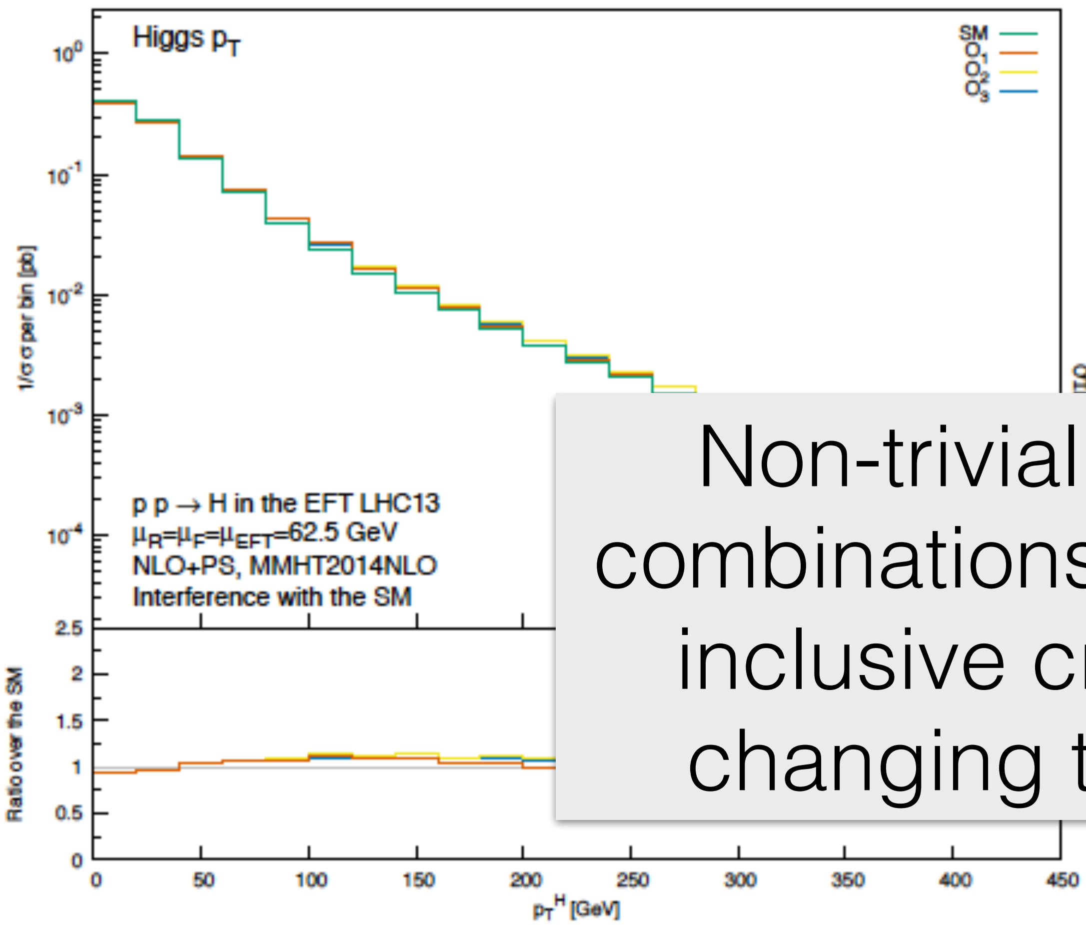
Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

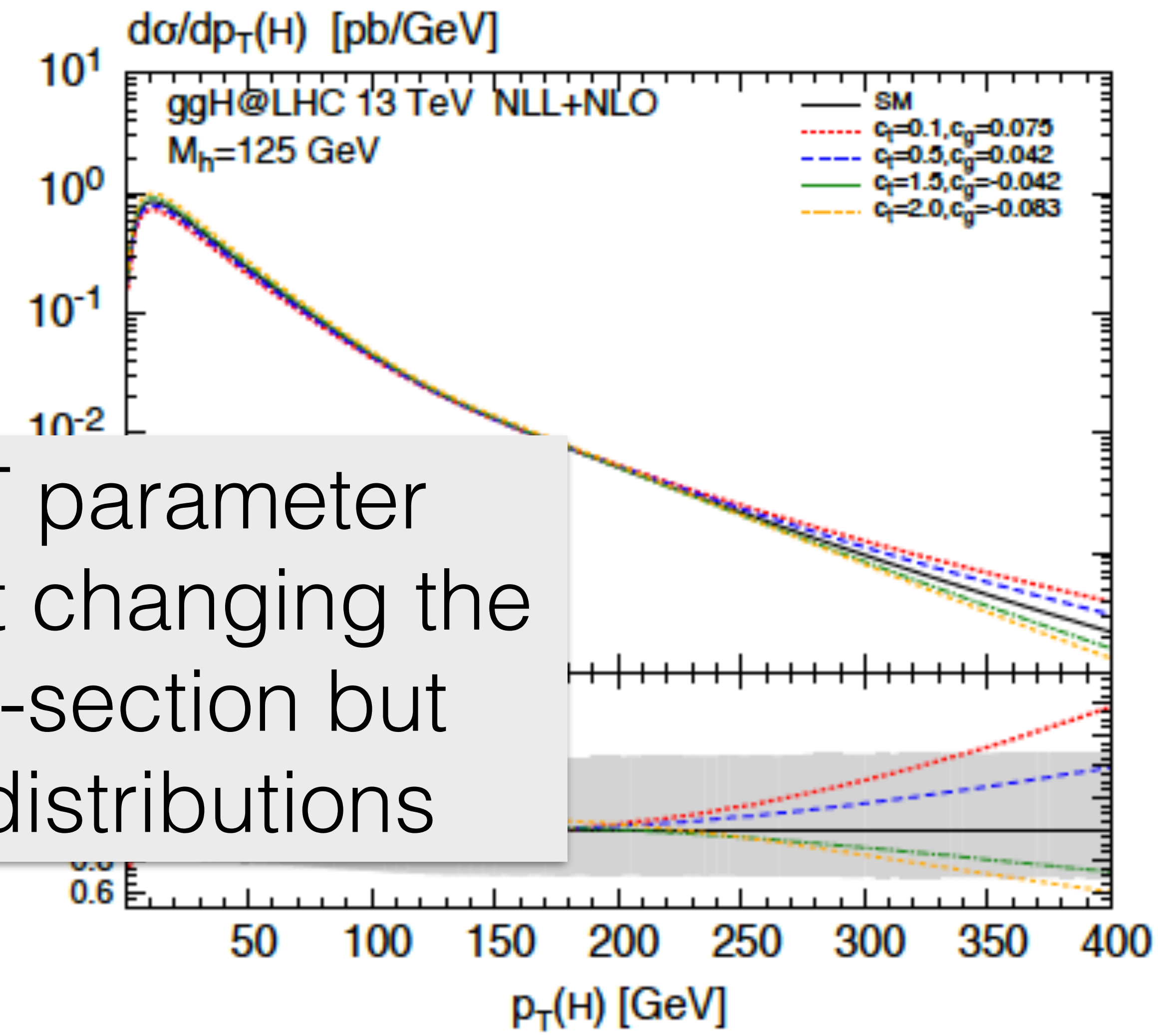


Higgs p_T

Grazzini et al 1612.00283

SMEFT in Higgs production





Non-trivial EFT parameter combinations not changing the inclusive cross-section but changing the distributions

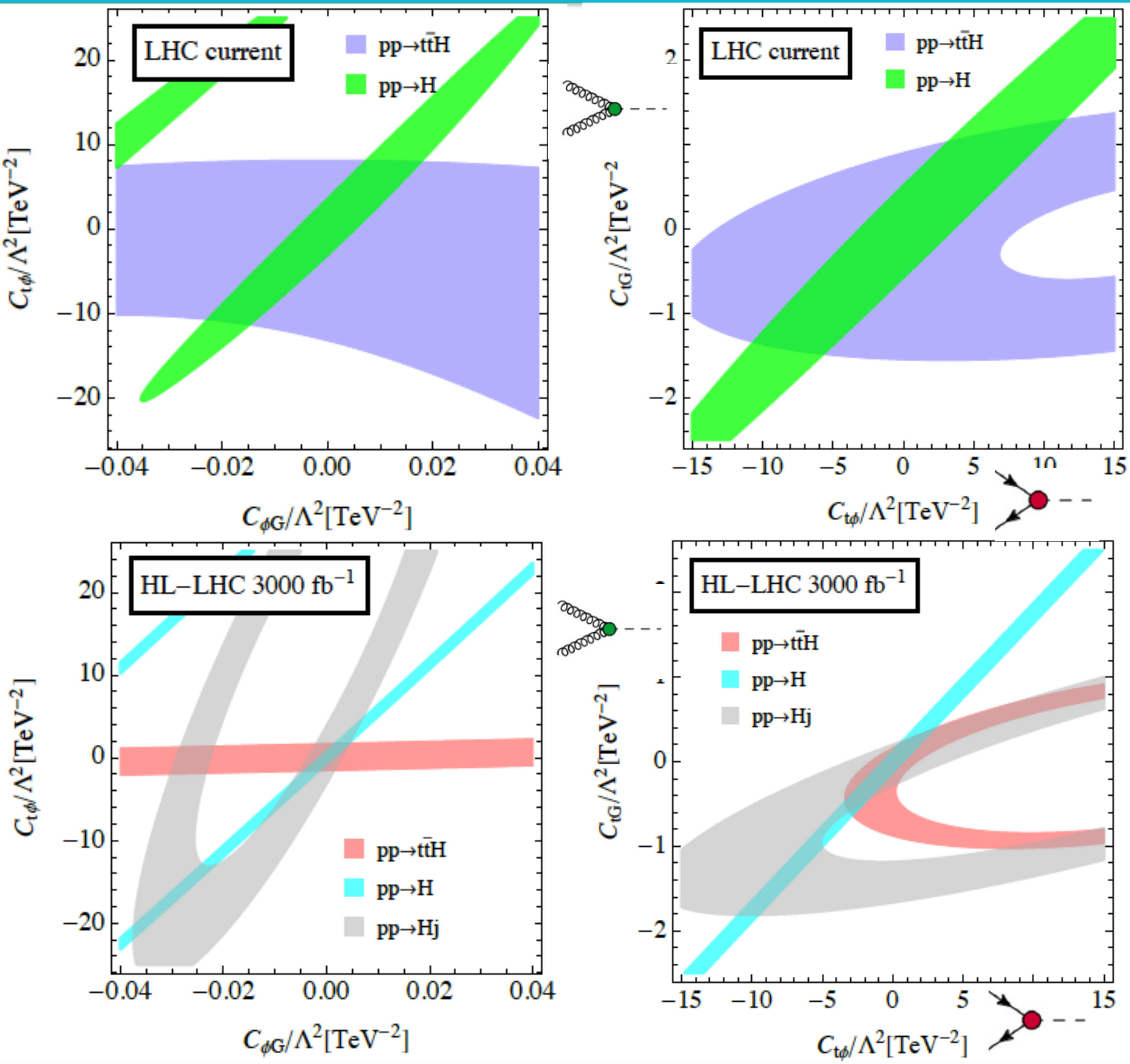
Higgs p_T

Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

Higgs p_T

Grazzini et al 1612.00283

Constraints using two-operator fits



Current limits using LHC measurements

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q}t\right) \tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

14TeV projection 3000 fb^{-1}

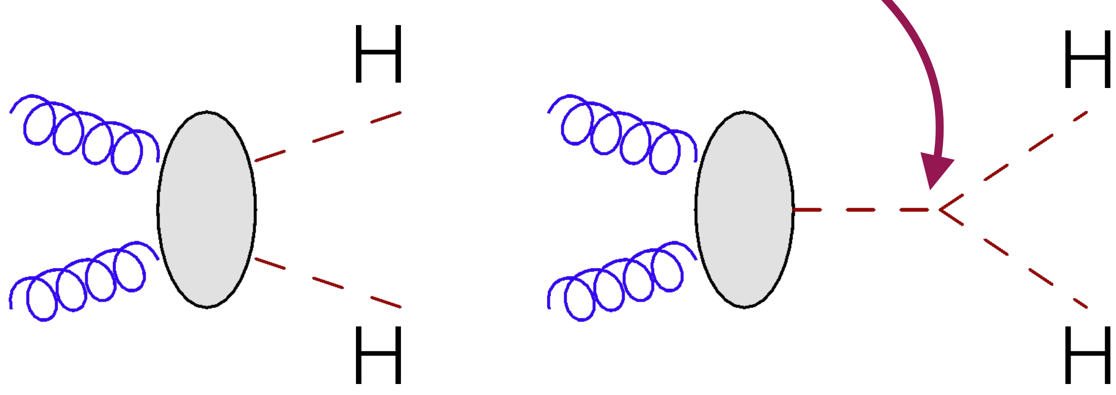
Maltoni, EV, Zhang arXiv: 1607.05330

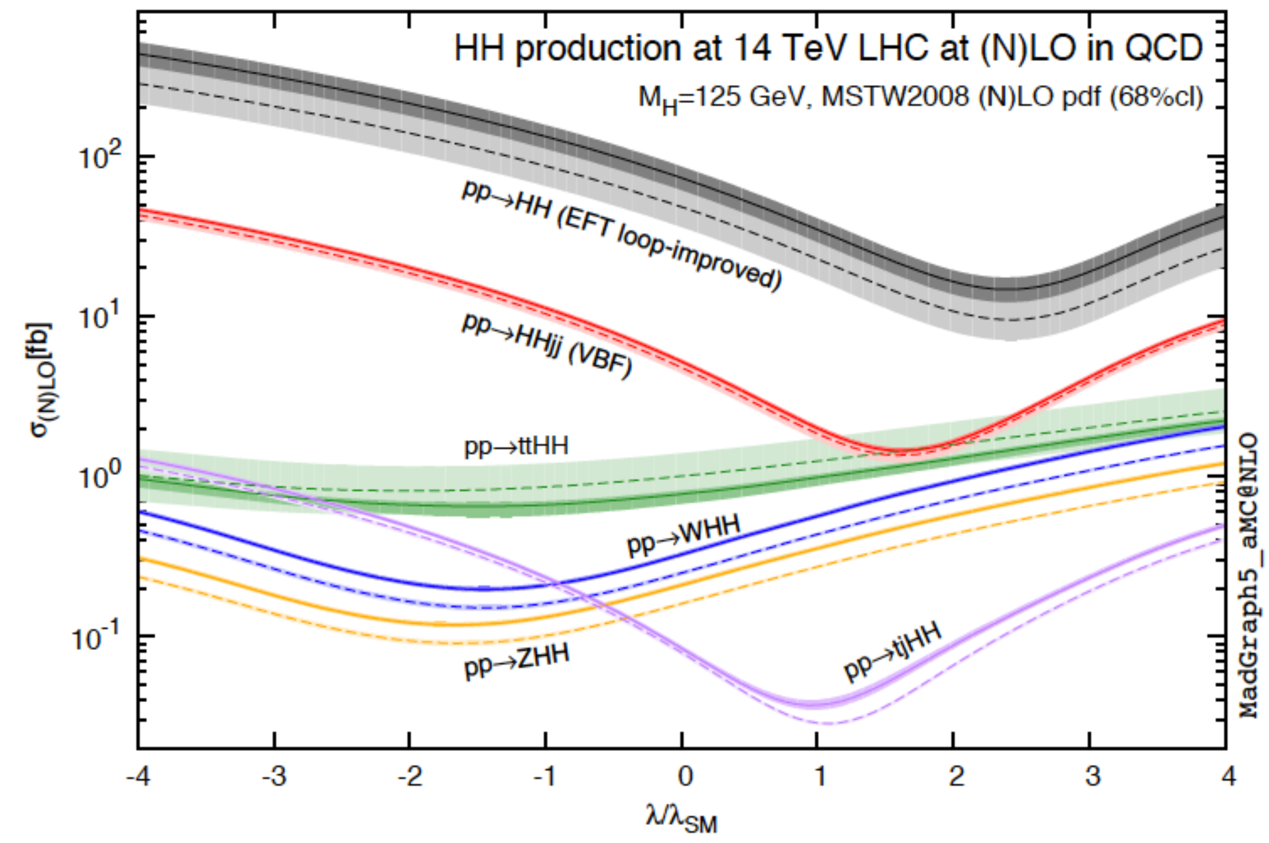
Double Higgs production

The Higgs potential

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

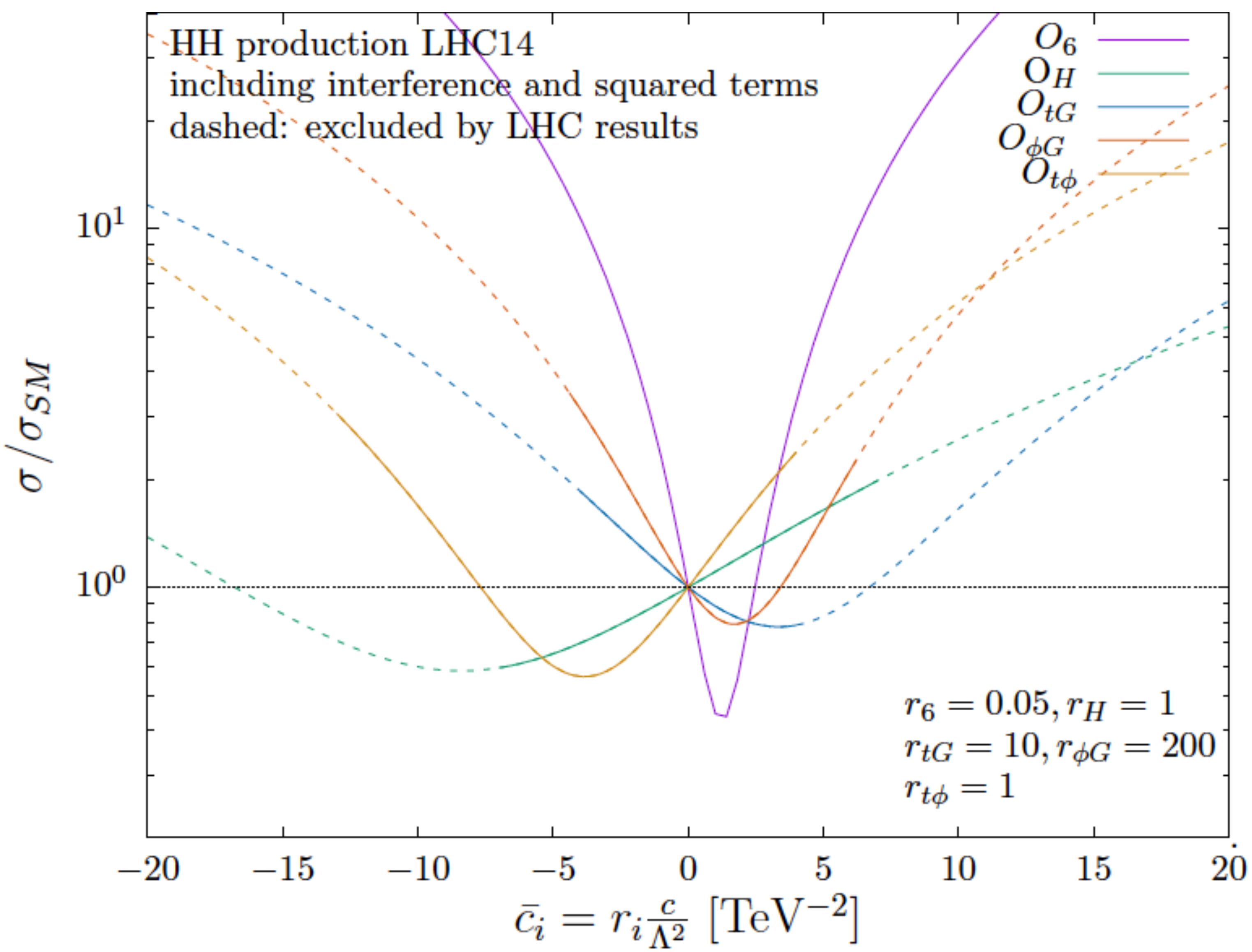


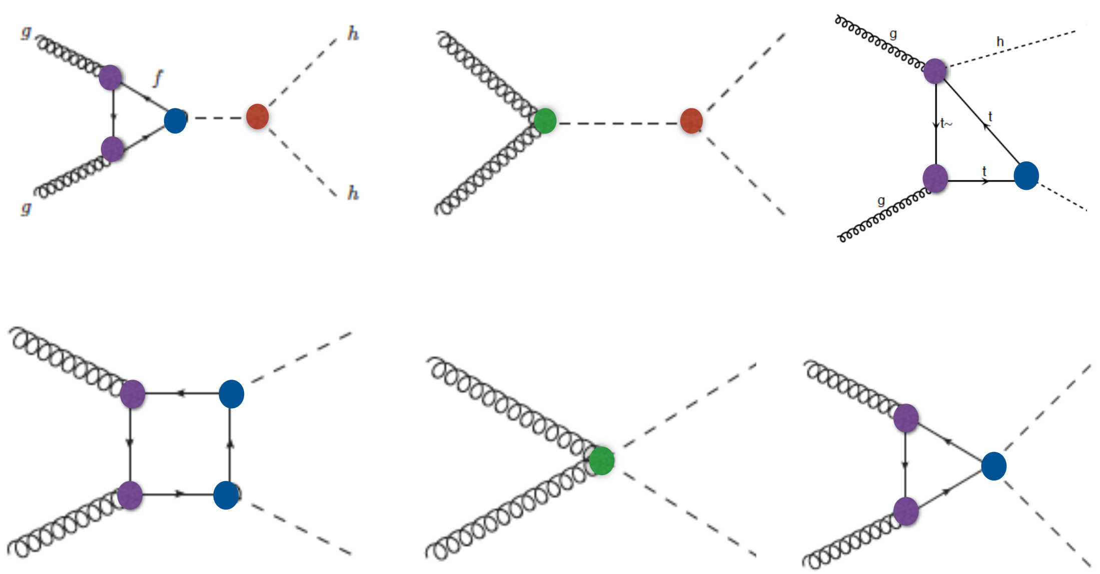


Phys.Lett. B732 (2014) 142-149

A challenging process at the LHC

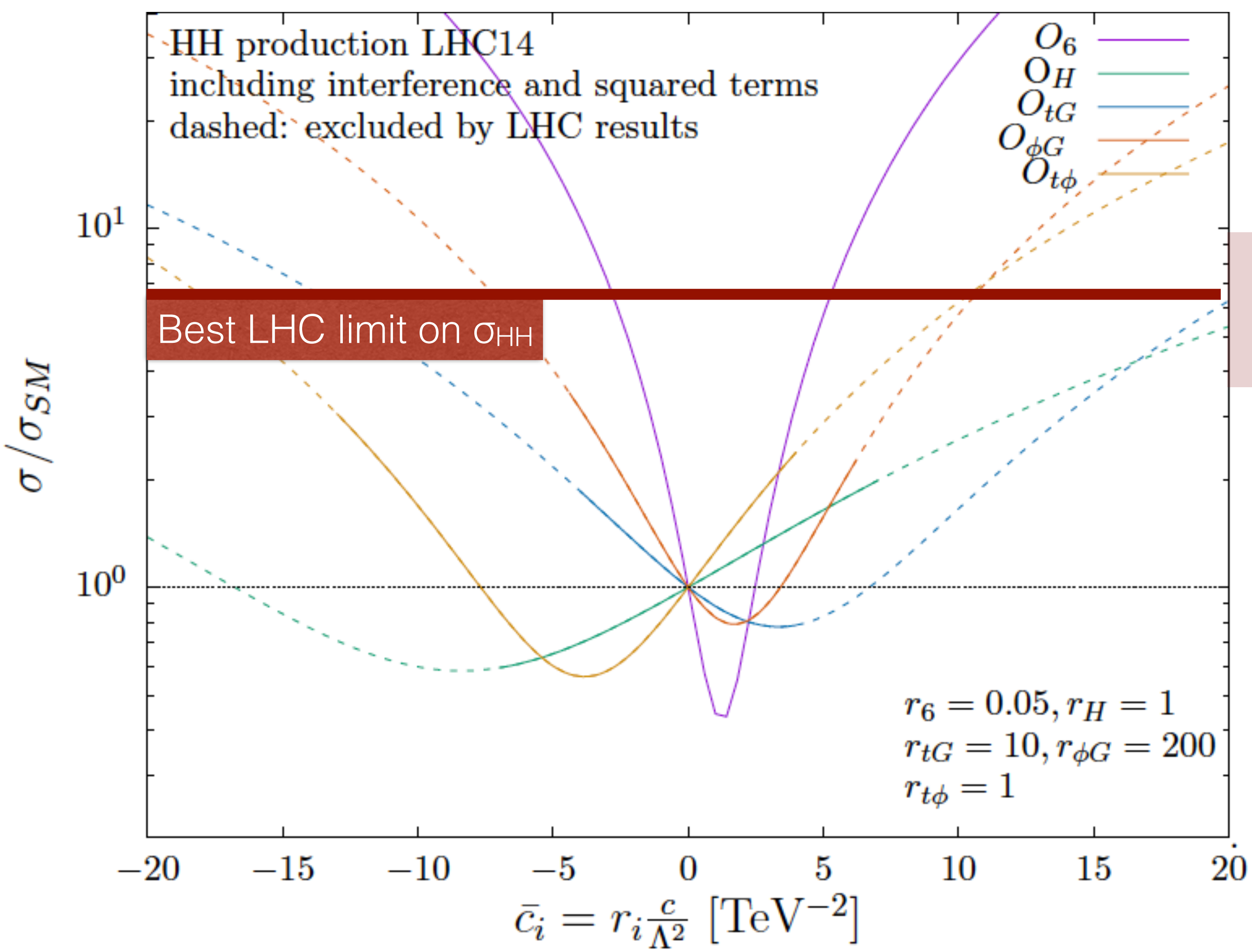
HH in the EFT





top Yukawa, ggh(h) coupling, top-gluon interaction, Higgs self-coupling

HH in the EFT



$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

$$O_6 = -\lambda (\phi^\dagger \phi)^3$$

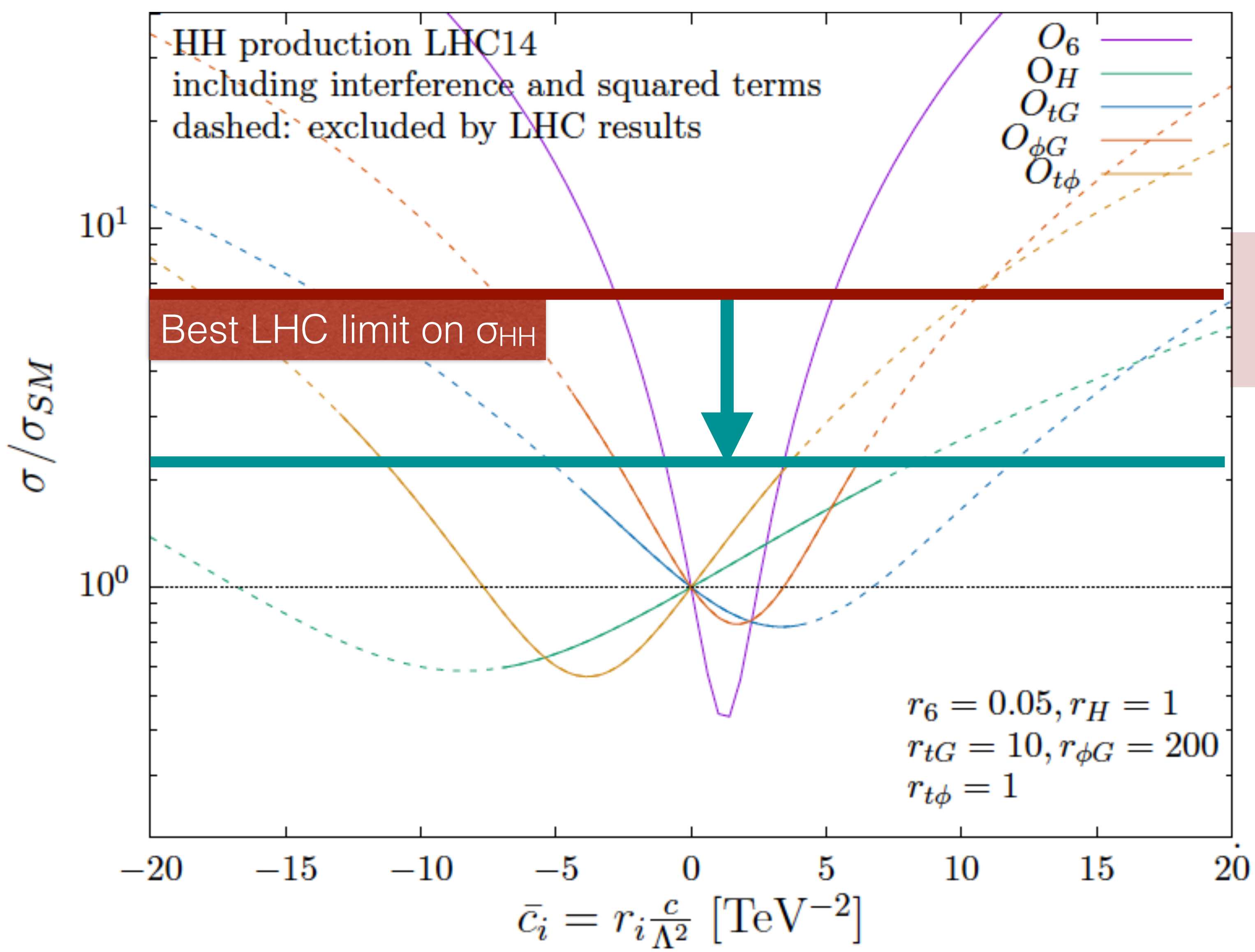
$$O_H = \frac{1}{2} (\partial_\mu (\phi^\dagger \phi))^2$$

top Yukawa, ggh(h) coupling, top-gluon interaction, Higgs self-coupling

The present

Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained “ignoring” other couplings

HH in the EFT



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top Yukawa, ggh(h) coupling, top-gluon interaction, Higgs self-coupling

The present

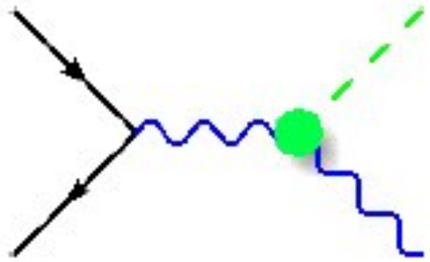
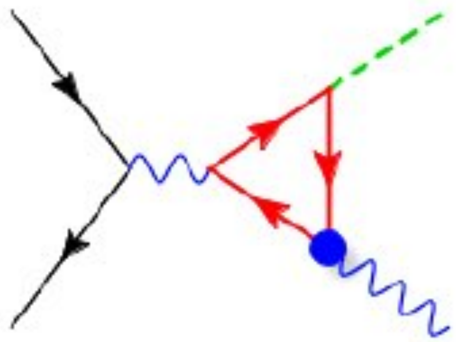
Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained “ignoring” other couplings

The future

Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM

Differential distributions will also be necessary

Going beyond QCD corrections in the EFT

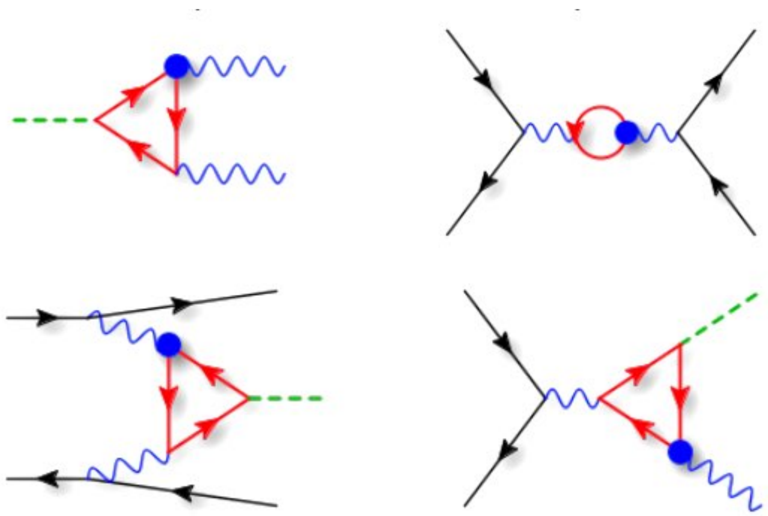
Are we measuring  or  ?

NLO EW in SMEFT may not be small:

$$\mathcal{O}(\alpha_{EW}/\pi \cdot C_t/C_H) \quad \textbf{instead of} \quad \mathcal{O}(\alpha_{EW}/\pi)$$

Weak corrections can be important for unconstrained operators

Towards weak loops in the EFT



+

$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.,$$
$$O_{\varphi Q}^{(3)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\gamma^\mu\tau^I Q),$$
$$O_{\varphi tb} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{t}\gamma^\mu b) + h.c.,$$
$$O_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$
$$O_{\varphi t} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t),$$
$$O_{\varphi Q}^{(1)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q),$$
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$

+

Current constraints

Operator	Top Fitter	RHCC	$\sigma_{t\bar{t}H}$ [28]
$C_{\varphi tb}$		[-5.28,5.28]	
$C_{\varphi Q}^{(3)}$	[-2.59,1.50]		
$C_{\varphi Q}^{(1)}$	[-3.10,3.10]		
$C_{\varphi t}$	[-9.78,8.18]		
C_{tW}	[-2.49,2.49]		
C_{tB}	[-7.09,4.68]		
$C_{t\varphi}$			[-6.5,1.3]

→ Poor knowledge of top couplings leads to uncertainties on Higgs measurements at the LHC:

	$\gamma\gamma$	γZ	bb	WW*	ZZ*	$\tau\tau$	$\mu\mu$
gg	(-100%,1980%)	(-88%,200%)	(-40%,48%)	(-40%,47%)	(-40%,46%)	(-40%,48%)	(-40%,48%)
VBF	(-100%,1880%)	(-88%,170%)	(-6.1%,5.3%)	(-6.8%,6.7%)	(-8.8%,9.2%)	(-6.2%,5.9%)	(-6.2%,5.9%)
WH	(-100%,1880%)	(-88%,170%)	(-5.5%,4.2%)	(-6.1%,5.6%)	(-7.8%,7.9%)	(-5.8%,5.1%)	(-5.8%,5.1%)
ZH	(-100%,1880%)	(-87%,170%)	(-6.5%,5.9%)	(-7.1%,7.1%)	(-9.4%,9.9%)	(-6.8%,6.7%)	(-6.8%,6.7%)

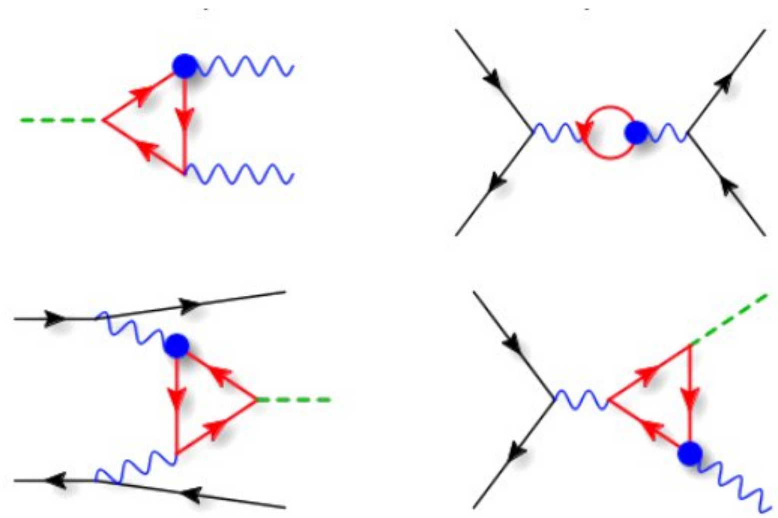
loop-induced

tree-level

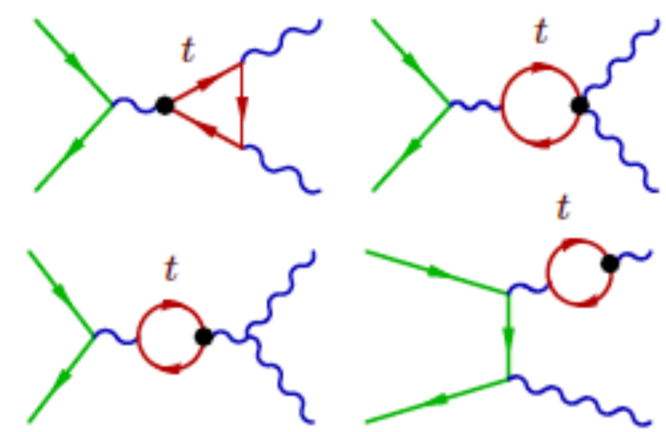
EV, Zhang arXiv:1804.09766

Weak loops in the EFT: Future colliders

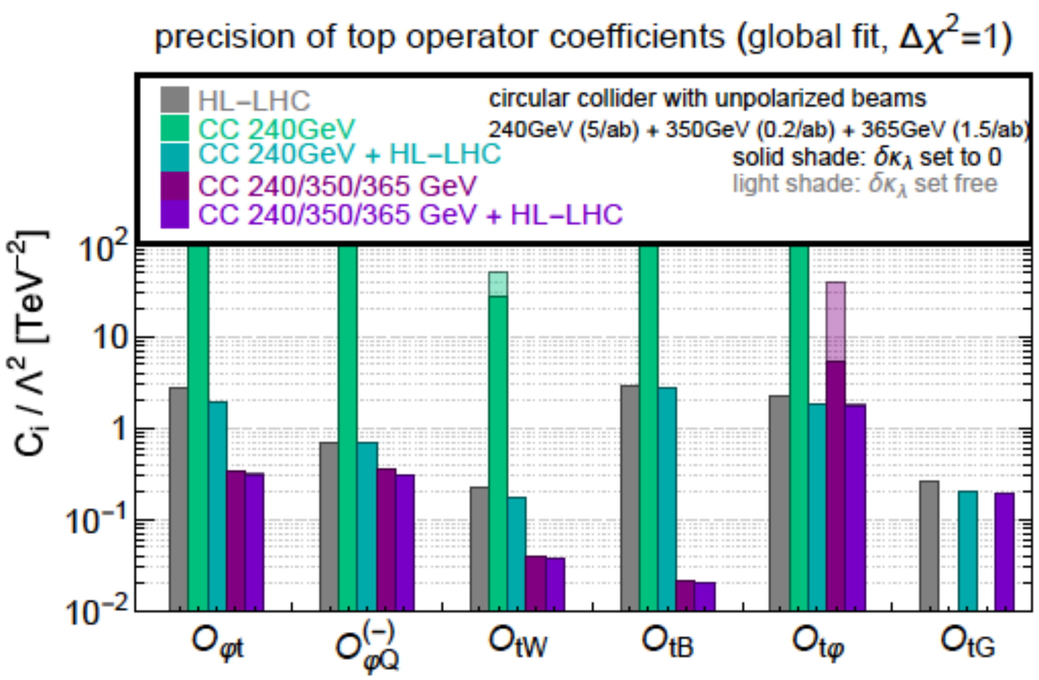
Circular Electron Positron Collider & HL-LHC: Top + Higgs Global Fit

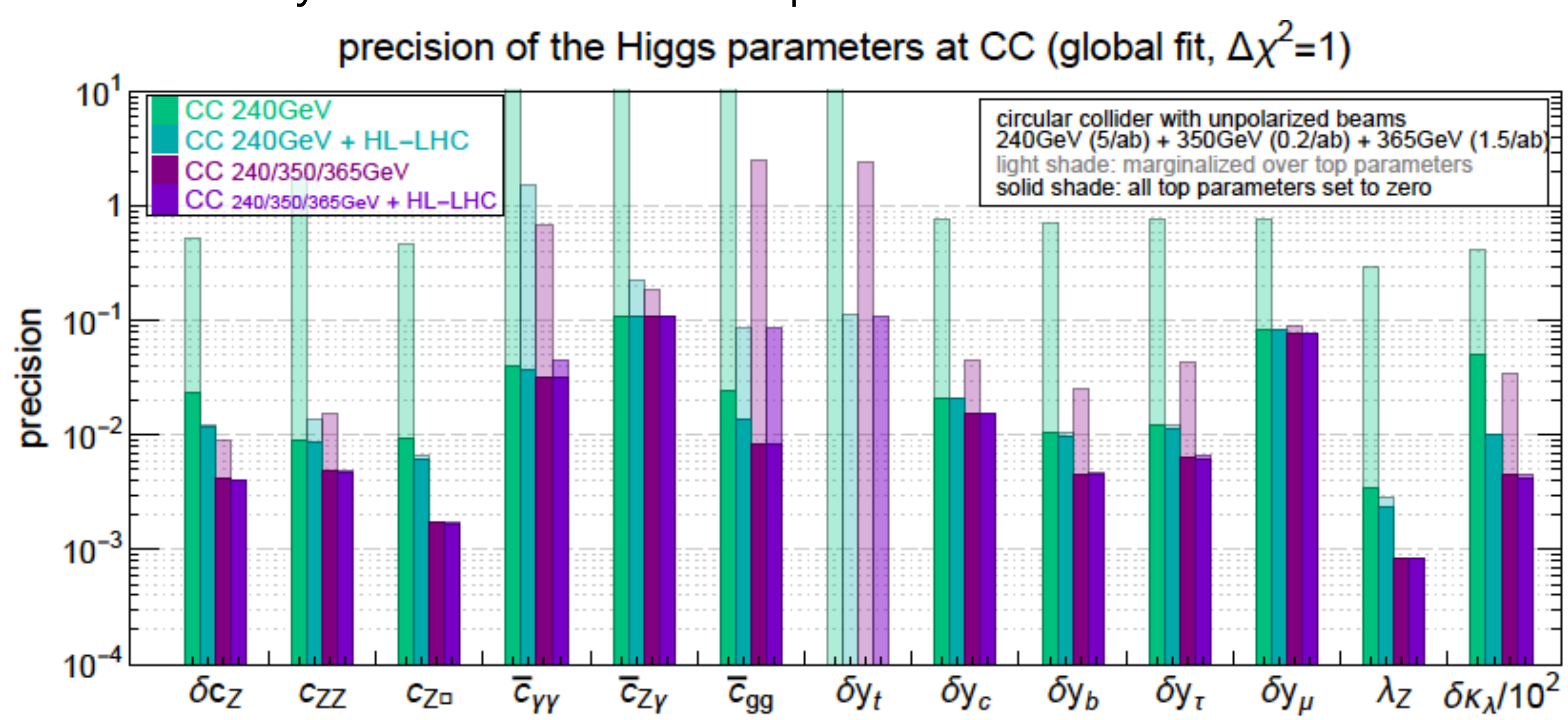


Higgs production and decay



WW production





Durieux, Gu, EV, Zhang arXiv:1809.03520

Outlook

- SMEFT is a consistent way to look for new interactions
- Higher-order corrections needed to match SM precision and experimental accuracy
- Progress in top-quark processes: single top, t(t)+V, t(t)+H as well as in the Monte Carlo automation of these corrections
- QCD corrections important both for total cross-sections and distributions: SM k-factors are not enough
- First global fits results already available: important to include NLO predictions where available and to combine as many processes as possible to extract maximal information
- Electroweak loop corrections can be important, progress towards computing them and assessing their impact

Thank you for your attention