Probing the Higgs potential at colliders

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Work in collaboration with:

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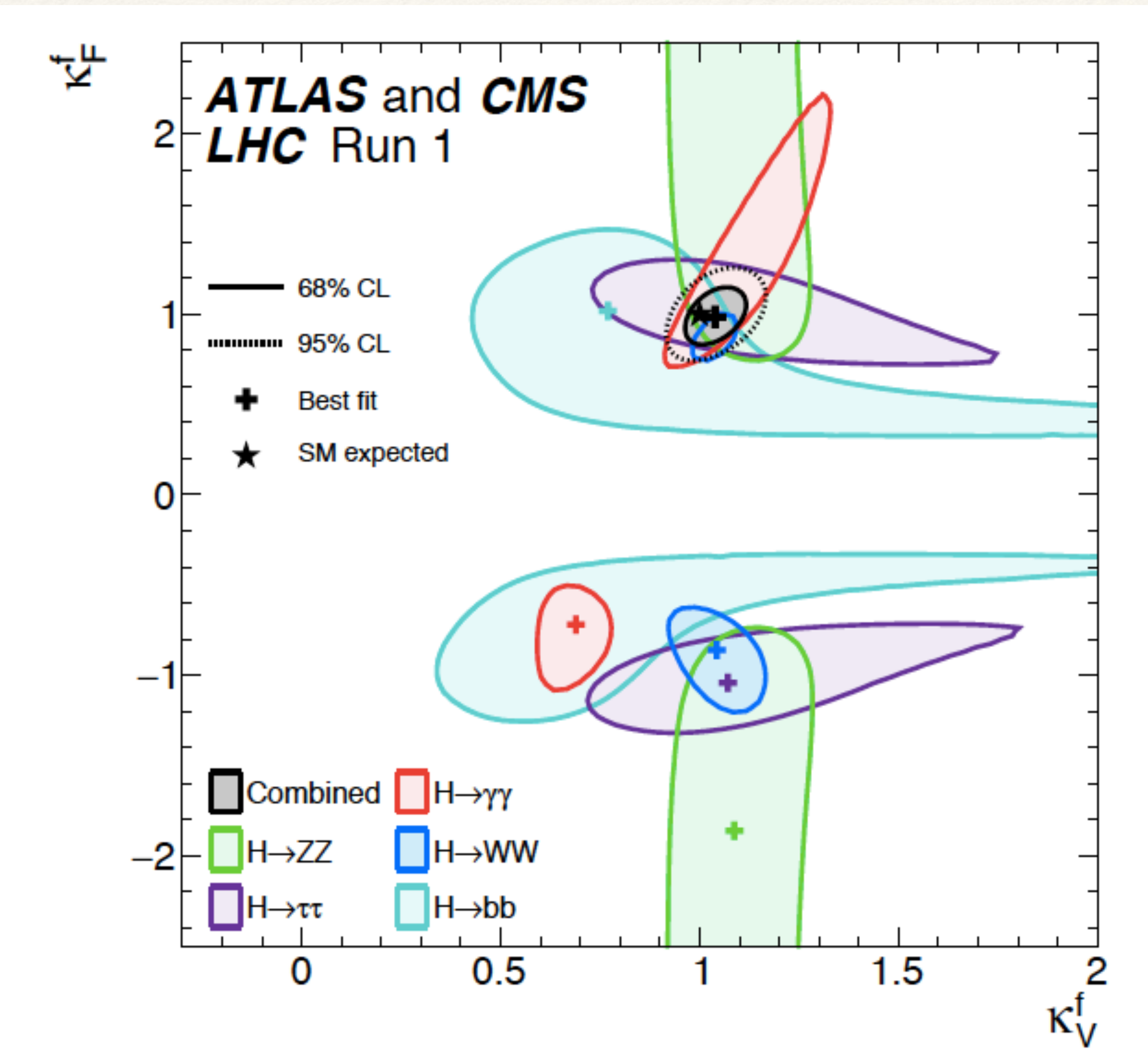
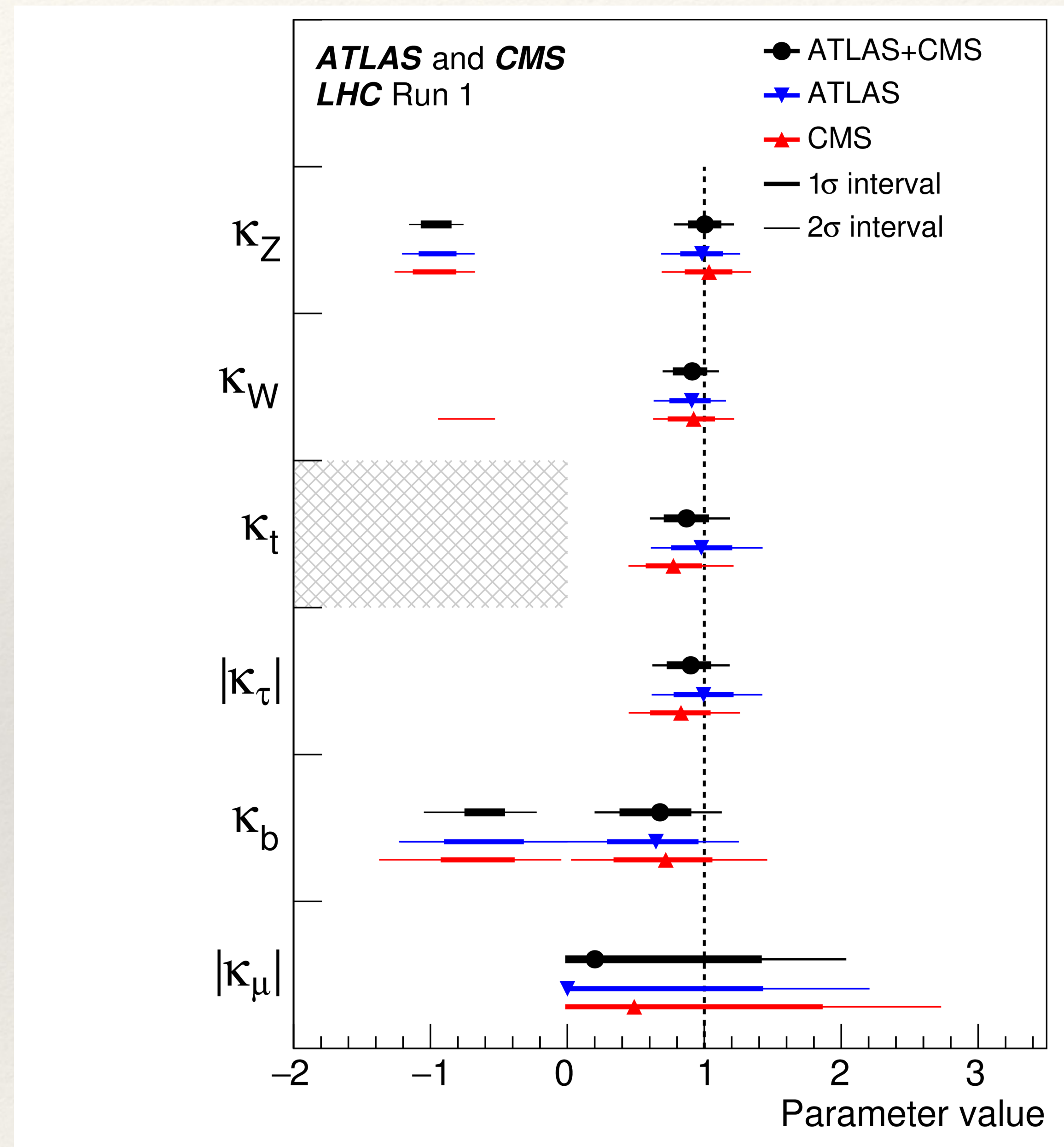
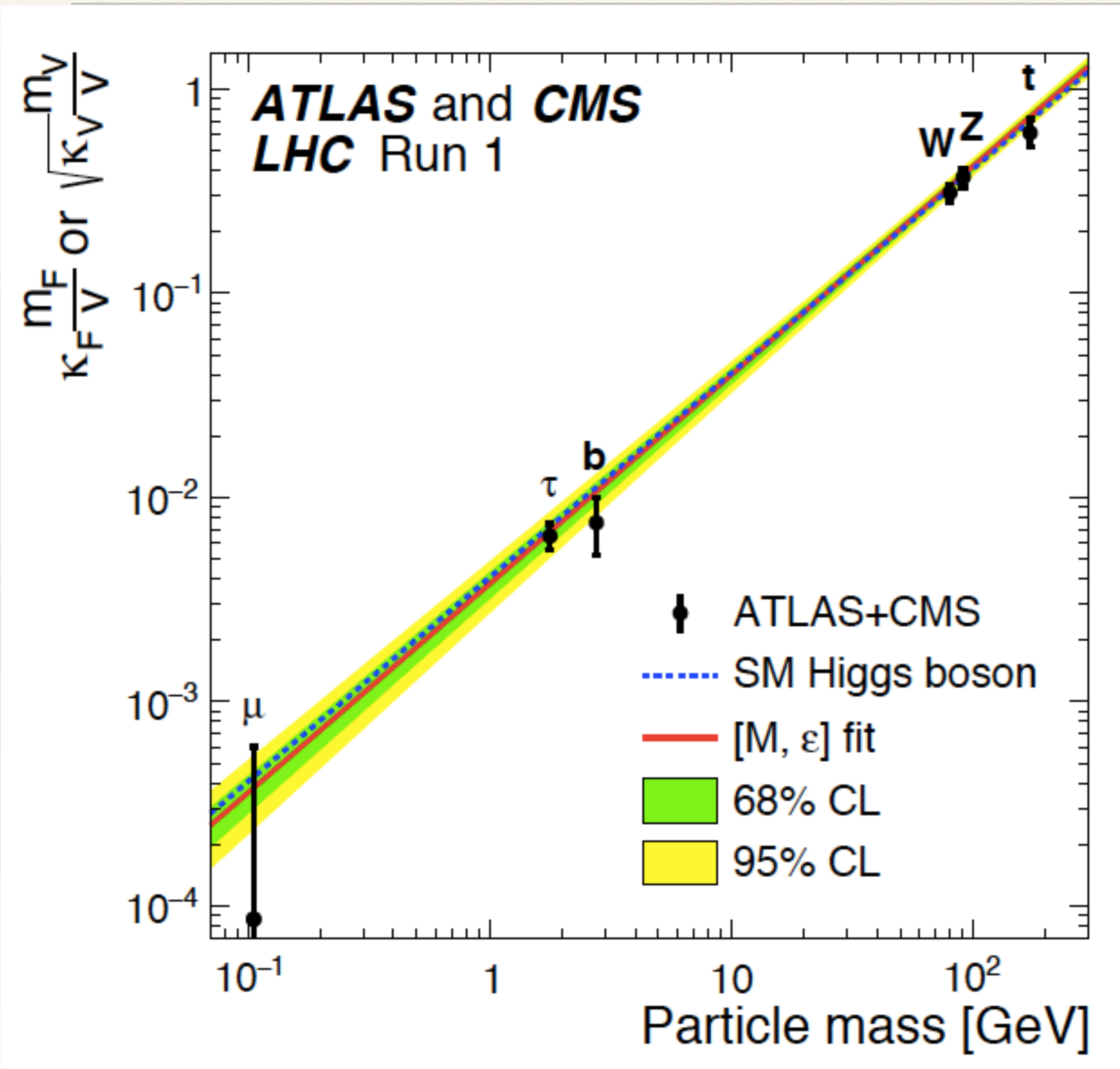
Higgs couplings



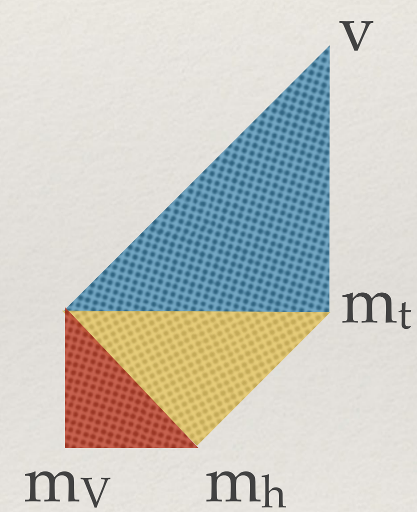


Data points agree with SM hypothesis at the 20-30% level

Higgs couplings



$$\frac{v}{m_t} = \frac{m_t}{m_h} = \frac{m_h}{\bar{m}_V} = \sqrt{2}$$



$$r = 2^{\frac{2\theta}{\pi}}$$

SM logarithmic spiral

Higgs potential 101

A low-energy parametrisation of the Higgs potential

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \ldots$$

In the Standard Model:

$$V^{\mathrm{SM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \quad \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \quad \begin{cases} \lambda_3^{\mathrm{SM}} = \lambda \\ \lambda_4^{\mathrm{SM}} = \lambda \end{cases}$$

i.e., fixing v and m_H , uniquely determines both λ_3 and λ_4 .

That means that by measuring λ_3 and λ_4 one can test the SM, yet to interpret deviations, one needs to "deform it", i.e. needs to consider a well-defined BSM extension. Such extensions will necessarily depend on TH assumptions.

Higgs potential 101

To go Beyond the SM, one can parametrise a generic potential by expanding it in series:

$$V^{\mathrm{BSM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + \sum_n \frac{c_{2n}}{\Lambda^{2n-4}}(\Phi^\dagger\Phi - \frac{v^2}{2})^n$$

so that the basic relations remain the same as in the SM:

$$\begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases}$$

while the λ_3 and λ_4 are modified with respect to the SM values:

$$\begin{cases} \lambda_3 = \kappa_\lambda \lambda_3^{\mathrm{SM}} \\ \lambda_4 = \kappa_{\lambda_4} \lambda_4^{\mathrm{SM}} \end{cases}$$

So for example: adding c_6 only

$$\begin{cases} \kappa_\lambda = 1 + \dfrac{c_6 v^2}{\lambda\Lambda^2} \\ \kappa_{\lambda_4} = 1 + \dfrac{6 c_6 v^2}{\lambda\Lambda^2} = 6\kappa_\lambda - 5 \end{cases}$$

i.e., in this case λ_3 and λ_4 are related.

Model dependence and max size of the trilinear

Direct measurements are "by definition" less model dependent than indirect ones. It is therefore important to clearly assess what are the issues that impact both direct and indirect, and what are those impacting only or especially the indirect.

Questions:

1. What are the NP scenarios that can be probed via a given measurement?
2. How large can λ_3 be?
3. Is it possible to have λ_3 significantly different from the SM, with all other Higgs couplings being close to the SM values?

Answers to these questions frame all possible interpretations of direct and indirect measurements and need to be kept in mind when sensitivity comparisons are made.

Model dependence and max size of the trilinear

A few recent studies/results (note: each with its own theoretical assumptions):

- L. Di Luzio, R. Gröber, M. Spannowsky 1704.02311:

  hh → hh partial wave unitarity
  hhh one-loop $(\lambda_3)^3$ corrections $\Longrightarrow$ $|k_\lambda| \lesssim 6$

- If we start with $V^{SM}=0$, but couple the Higgs with a singlet scalar S, then CW potential would give (M. Perelstein) :

$$V^{\mathrm{CW}} = \frac{N_S \xi_0^2 h^4}{64\pi^2}\left(\log\frac{h^2}{v^2} - \frac{1}{2}\right) \Longrightarrow k_\lambda \lesssim 5/3$$

- Di Vita et al. 1704.01953:

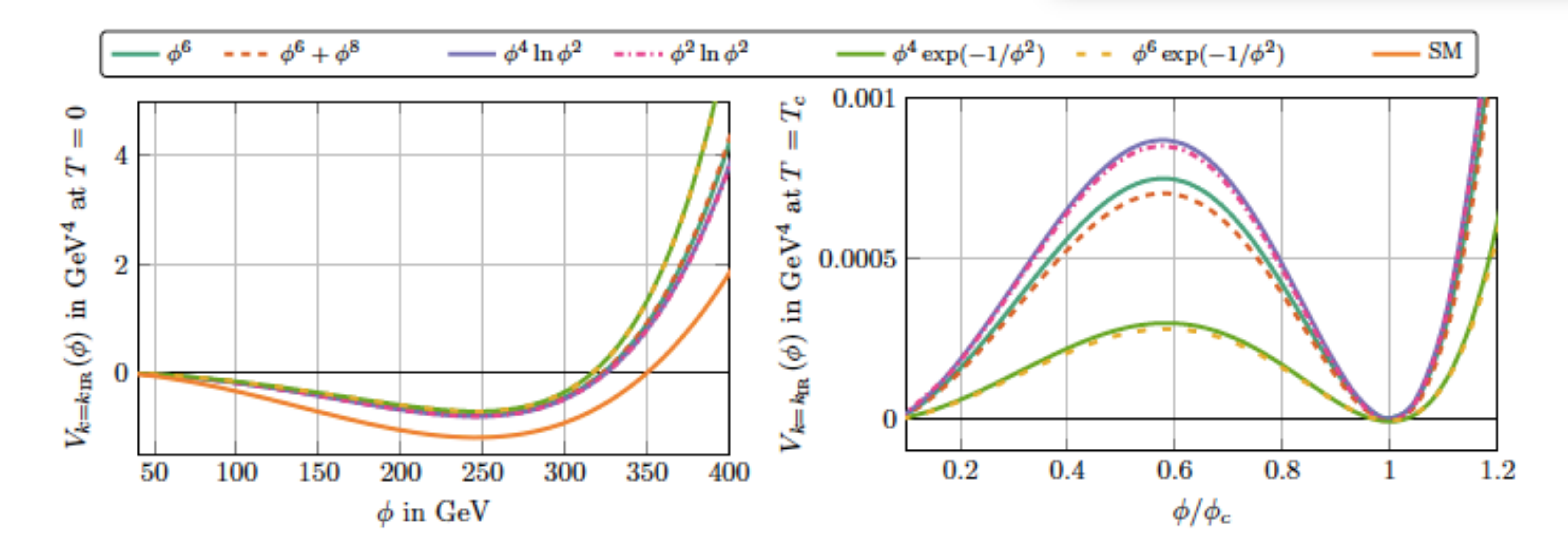
  Higgs portal with tuning, leaves all H couplings close to the SM and allows $|k_\lambda| \lesssim 6$.

- Falkowski and Rattazzi (by now famous yet private note):

  Validity of a theory with ONLY self-coupling deformations is studied through unitarity and can be up to several TeV's for deformation of order $|k_\lambda| \lesssim 10$.

Model dependence and max size of the trilinear

A very recent paper by Tilman and collaborators: Reichert et al. 1711.00019 a series modifications of the Higgs potential are studies:



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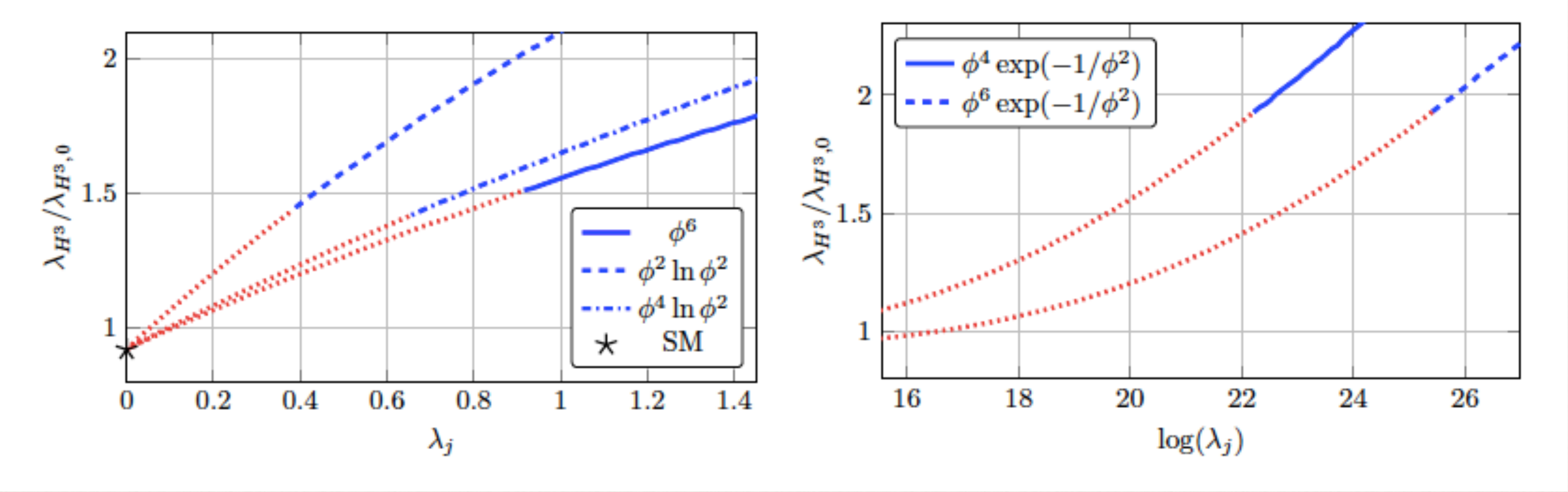
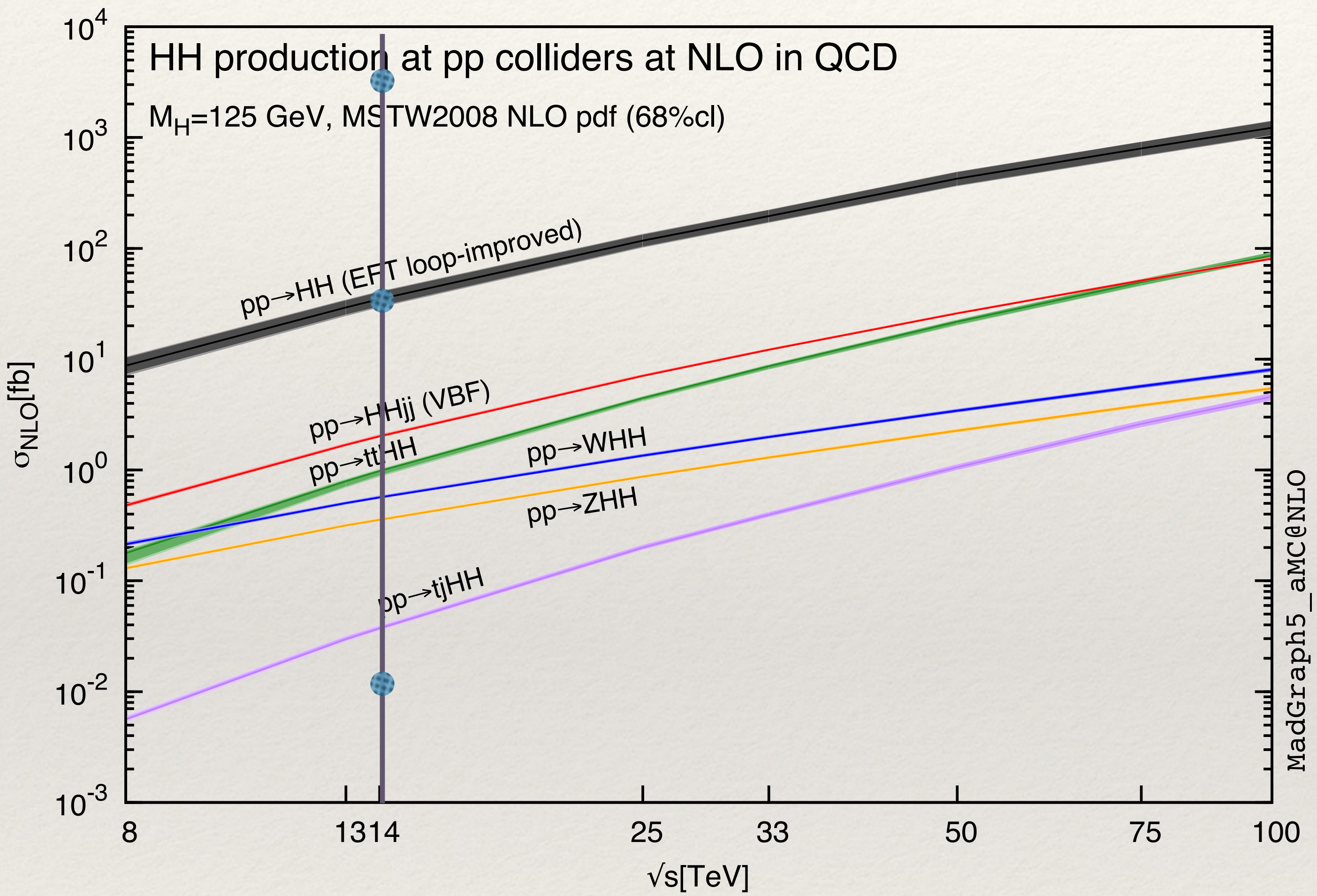


HH at the LHC

[Frederix et al. '14]



At 14 TeV from gg fusion:

$$\sigma_H = 55 \text{ pb}$$

$$\sigma_{HH} = 44 \text{ fb}$$

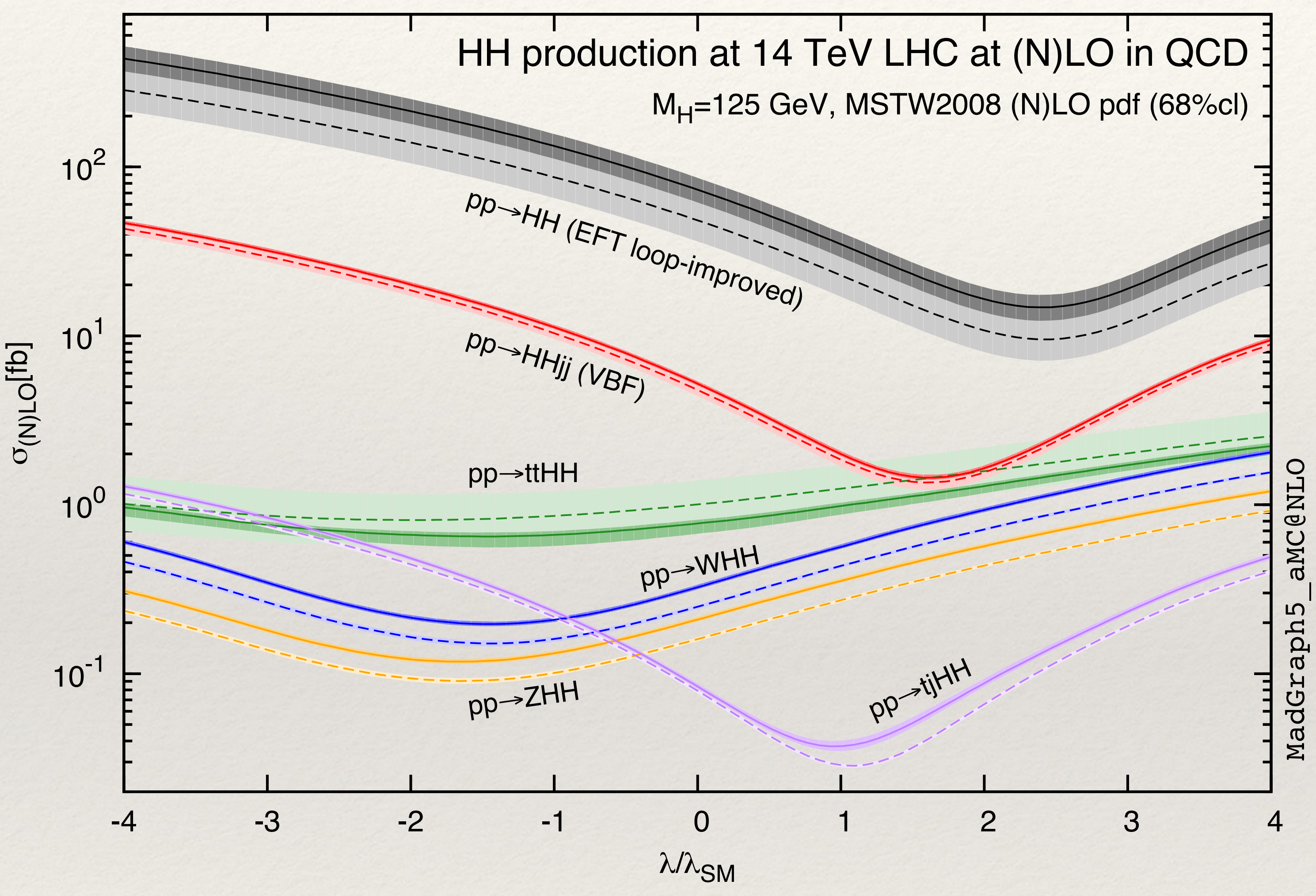
$$\sigma_{HHH} = 110 \text{ ab}$$

As in single Higgs many channels contribute in principle.

Cross sections for HH(H) increase by a factor of 20(60) at a FCC.

HH at the LHC

[Frederix et al. '14]



HH at the LHC

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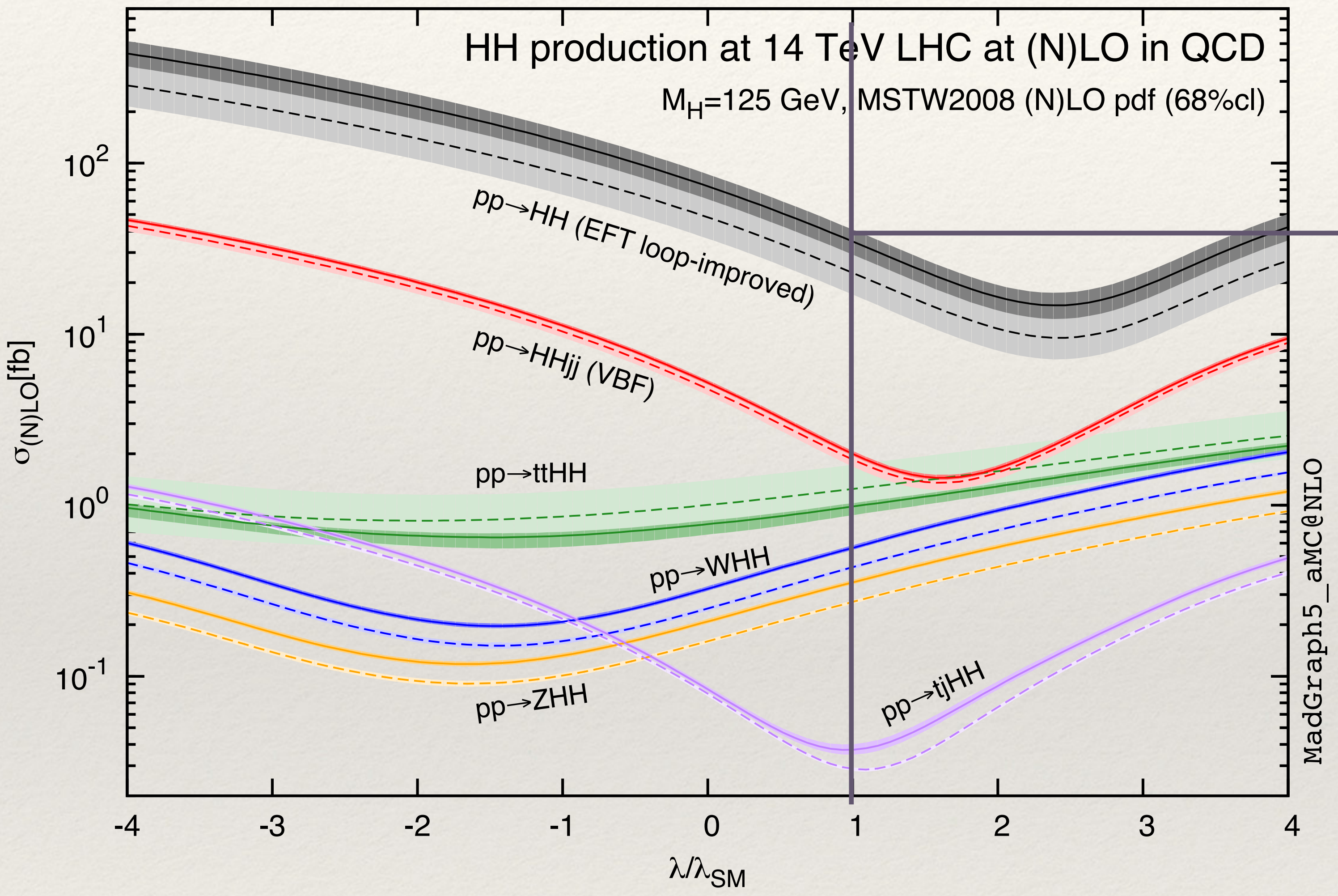
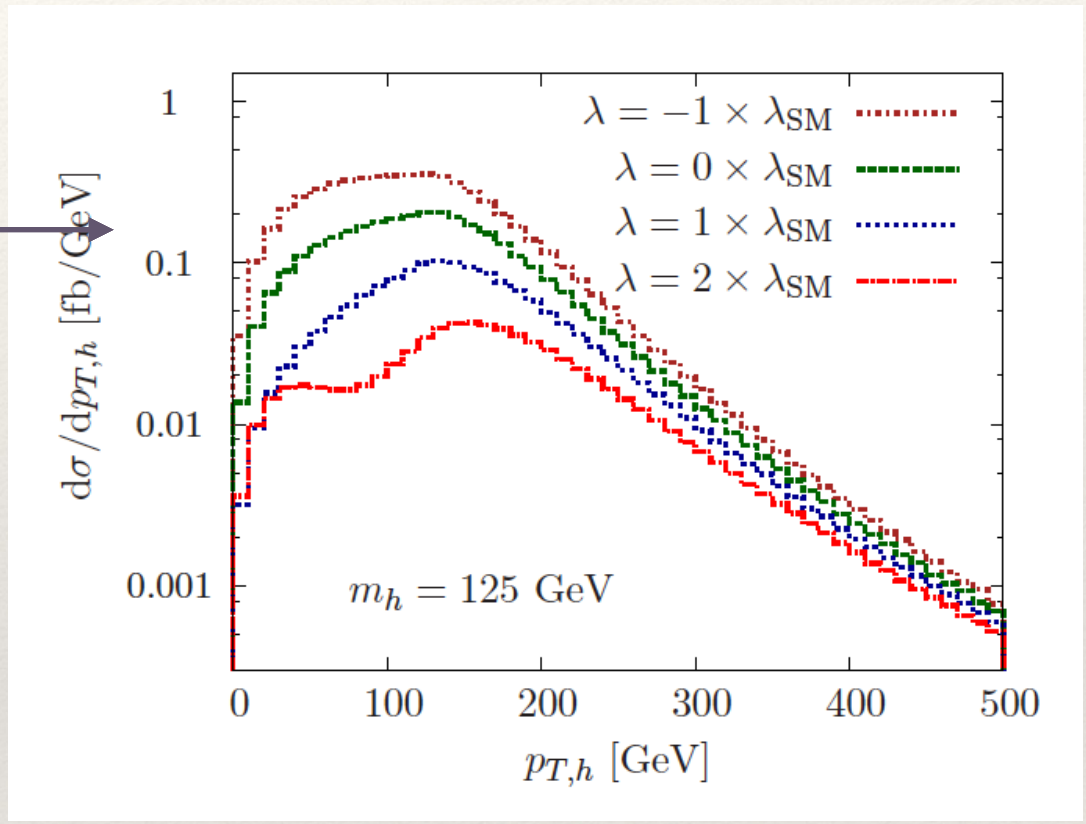


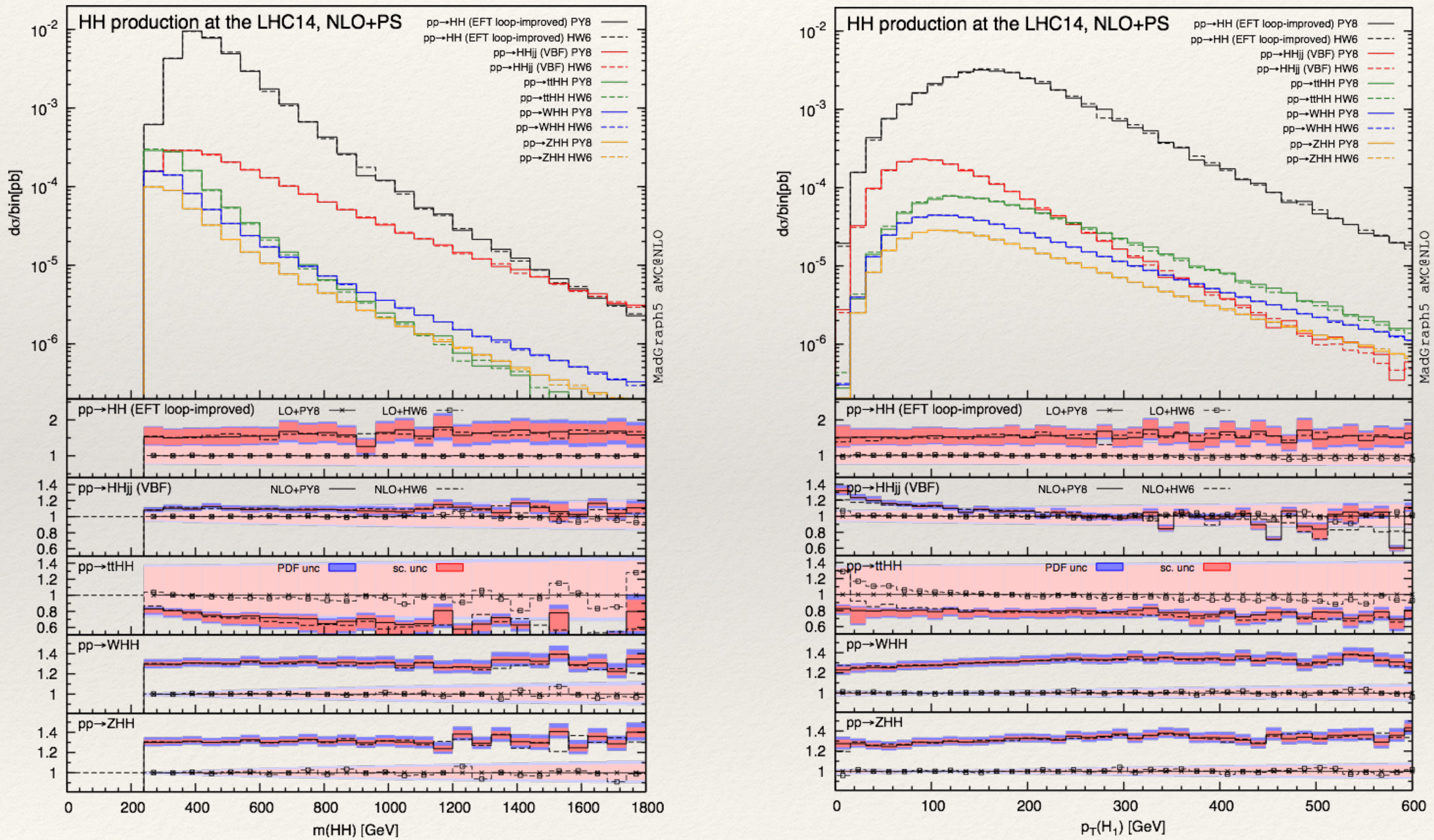
Degenerate solutions:



use differential information

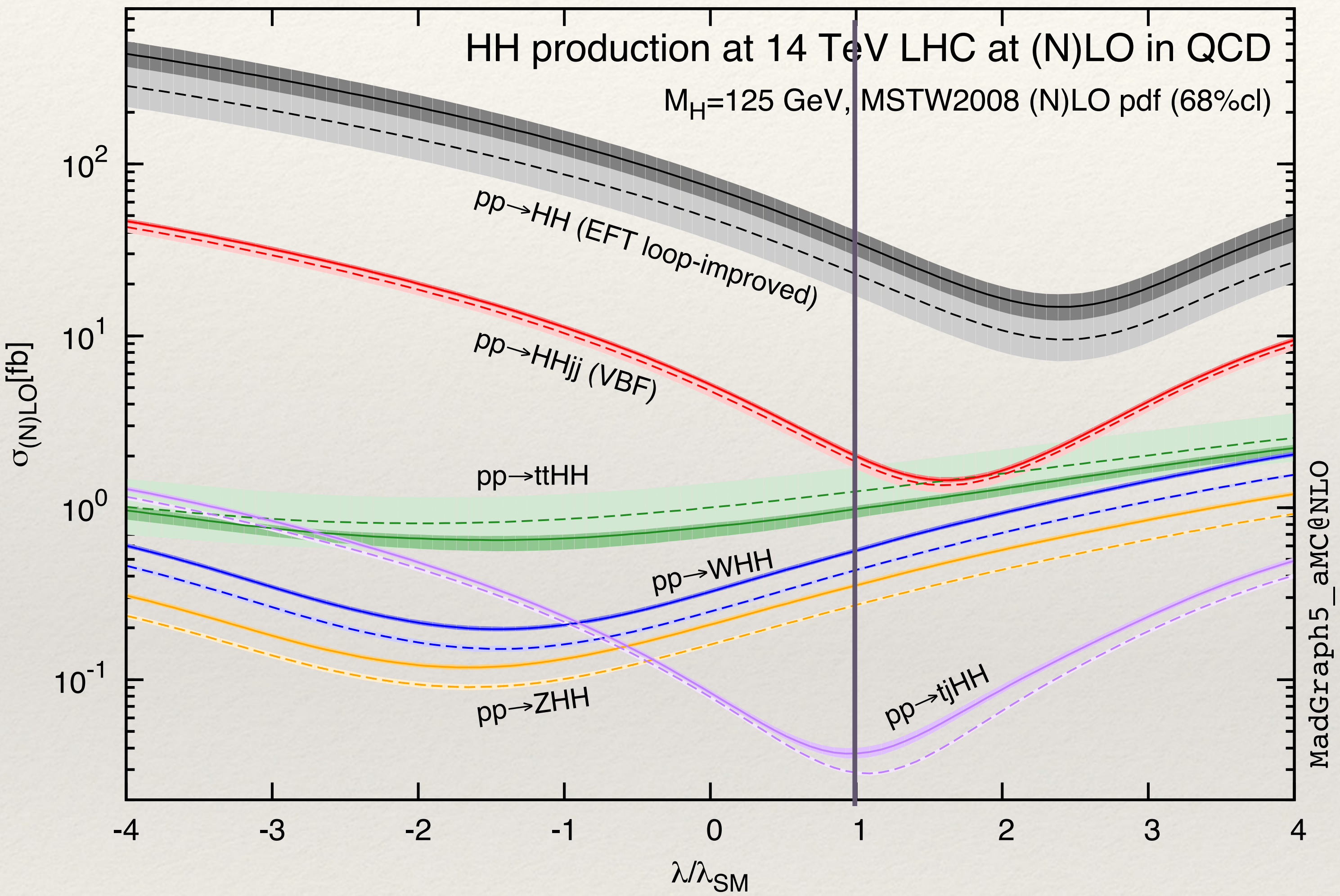
HH at the LHC

[Frederix et al. '14]



HH at the LHC

[Frederix et al. '14]



Note: due to shape changes, it is not straightforward to infer a bound on λ_3 from σ(HH), even when $\sigma_{BSM}=\sigma(\lambda_3)$ only is assumed.

Many channels, but small cross sections.

Current limits are on σ_{SM} ($gg\to HH$) channel in various H decay channels:

CMS : $\sigma/\sigma_{SM} < 19$ ($bb\gamma\gamma$) [EPS2017]
ATLAS : $\sigma/\sigma_{SM} < 30$ (bbbb)
CMS : $\sigma/\sigma_{SM} < 28$ (bbtt)

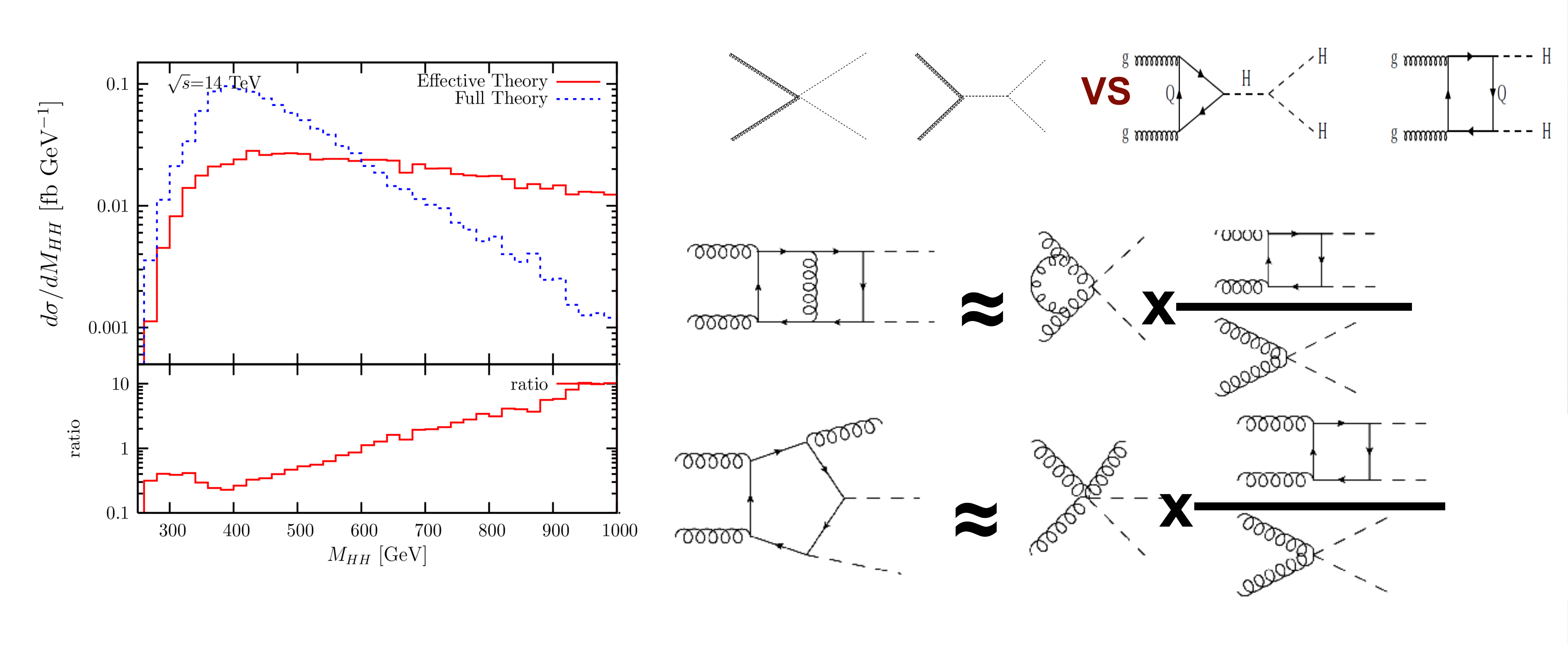
Remarks:

1. Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
2. The current most common assumption is just a change of λ_3 which leads to a change in σ as well as of distributions:

$$\sigma = \sigma_{\rm SM}[1 + (\kappa_\lambda - 1)A_1 + (\kappa_\lambda^2 - 1)A_2]$$

HH in gluon-gluon fusion beyond LO

Beyond LO: The early times (1998-2013)
Hpair approach: [Dawson, Dittmaier, Spira hep-ph/9805244]
NLO corrections in the EFT

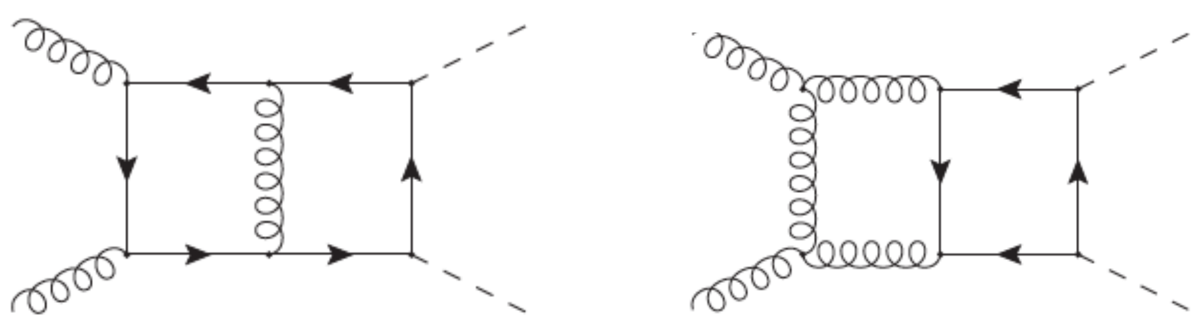


HEFT fails to reproduce the differential distributions

Includes LO cross-section with full top-mass dependence. Improvements (FT_{appox}) includes also real corrections.

Recent theory highlights

HH@NLO: New computation in 2016: major technical achievement in 2-loop computations.
[Borowka et al 1604.06447 and 1608.04798]
NLO computation for gluon fusion with the exact top mass dependence complete



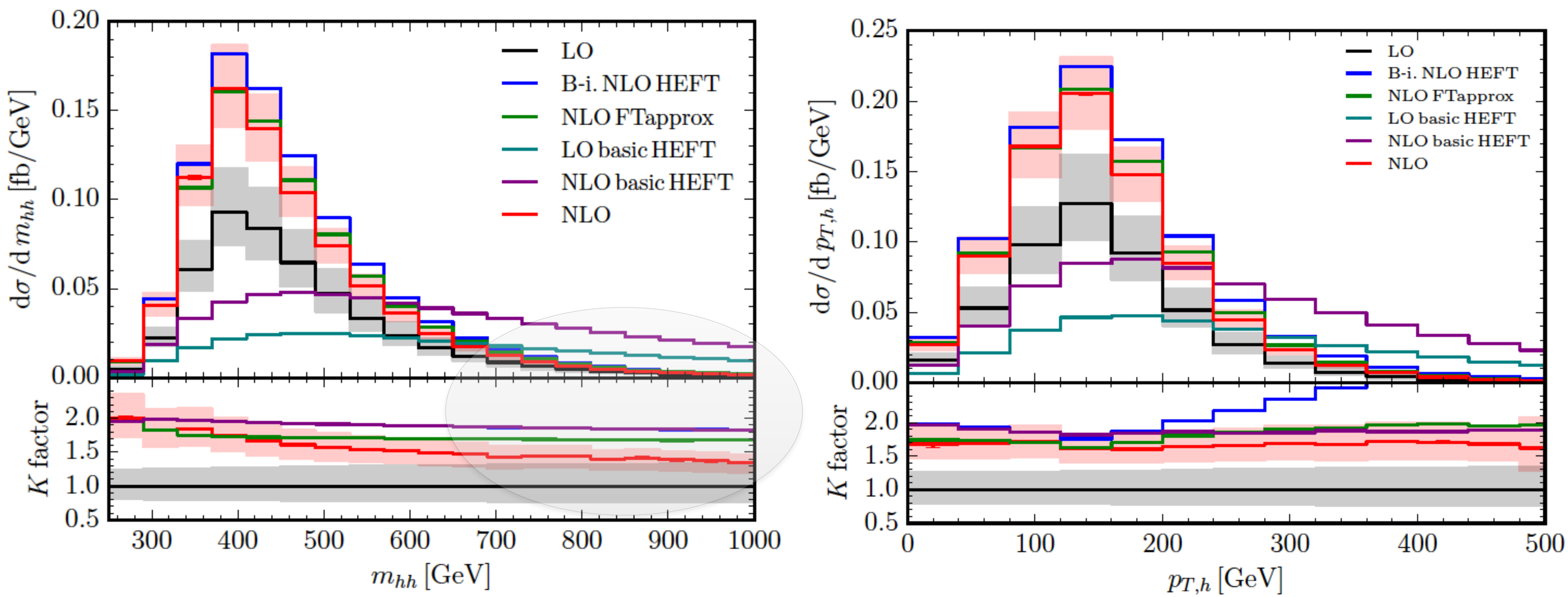
2-loop amplitudes computed with
GOSAM-2L REDUZE SECDEC 3
Numerical evaluation of integrals

$\sqrt{s}$	LO	B-i. NLO HEFT	NLO FT$_{approx}$	NLO
14 TeV	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$34.26^{+14.7\%}_{-13.2\%}$	$32.91^{+13.6\%}_{-12.6\%}$

-14%

-4%

Differential distributions at NLO



[Borowka et al arXiv:1604.06447 and 1608.04798]

- Exact NLO result softer than all other approximations in high mhh region (up to ~20% difference)
- FTapprox in MG5_aMC good for high pT (boosted searches)
- Exact NLO+PS implementation: in progress

SM HH Outlook

- Next step:

Phenomenology with a ~40fb (gluon fusion) cross-section: Not easy

- Which are the promising decay channels to observe the process?

  Recent progress with boosted techniques

  - bb$\gamma\gamma$ (arxiv:1212.5581)
  - bb$\tau\tau$ (arxiv:1206.5001, arxiv:1212.5581)
  - bbWW (arxiv:1209.1489, arxiv:1212.5581)
  - bbbb (arxiv:1404.7139)

- Prospects for the measurement of the trilinear Higgs coupling?
  - Optimistic estimate of 30% accuracy with 3000 fb-1 at 14 TeV (arxiv:1404.7139)
- Prospects in other channels? ttHH arxiv:1409.8074, VBF: arxiv:1506.08008

SM HH Outlook

- Recent experimental studies with 3 iab at 14 TeV

ATLAS 4b :

expected HL-LHC limit on λ_{3h} :

$0.2 < \lambda_{3h}/\lambda_{SM} < 7.0$ @ 95 % C.L.

ATLAS 2b2gamma :

expected HL-LHC limit on λ_{3h} :

$-0.8 < \lambda_{3h}/\lambda_{SM} < 7.7$ @ 95 % C.L.

Lessons so far

- Determining the self coupling from HH production is hard: small cross sections, huge backgrounds, mild dependence on k_λ .
- Accurate and precise predictions for cross sections and distributions are needed.
- Smart and new experimental and analysis techniques need to be considered.
- HH cross sections do also depend on single Higgs couplings, in particular of those with the top quark!

Dim=6 SM Lagrangian

[Grzadkowski et al, 10]

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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalizable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ

The EFT approach: managing unknown unknowns

- Very powerful approach.
- Note, however, that it only makes sense if a **global constraining strategy** is used to extract information from the data:
  - assume all couplings might not be zero at the EW scale.
  - identify the operators entering each observable.
  - find enough observables (cross sections, BR’s, distributions,…) to constrain all operators.
  - solve the (linear+quadratic) system.
  - hierarchical approach on the couplings.

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

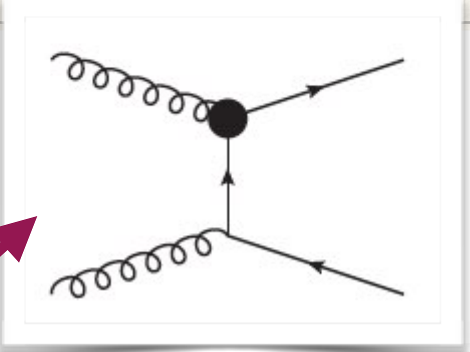
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

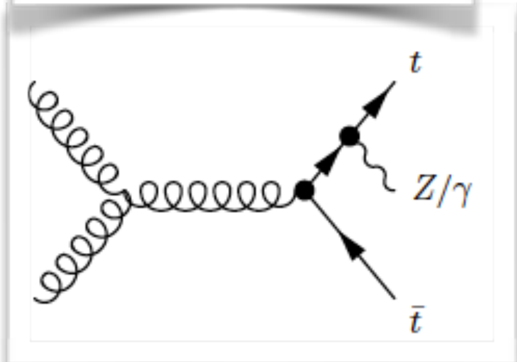
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

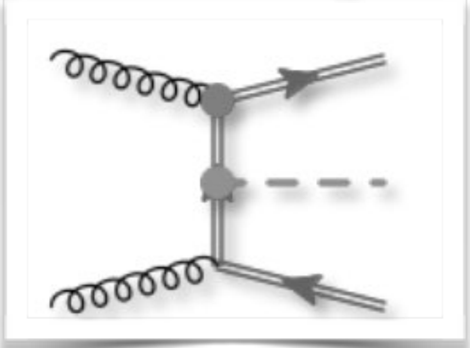
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

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

$$O_{t\varphi} = y_t^3(\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi}t$$







+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

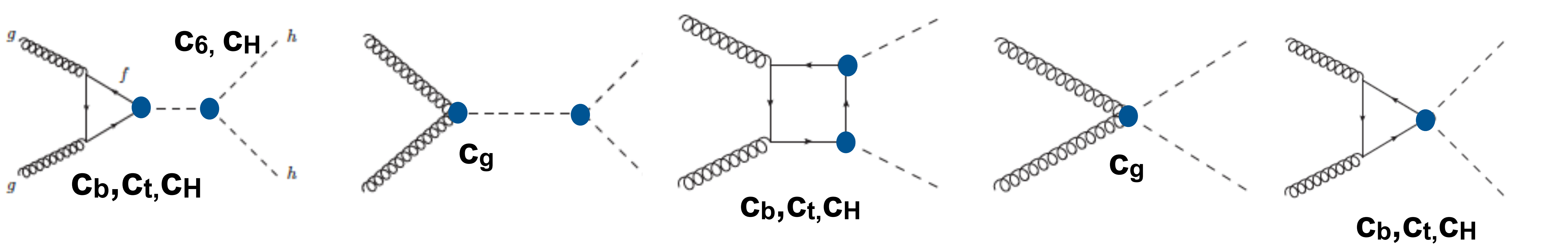
HH production in the EFT

$$
\begin{aligned}
\mathcal{L}_{h^n} = & -\mu^2|H|^2 - \lambda|H|^4 - \left(y_t \bar{Q}_L H^c t_R + y_b \bar{Q}_L H b_R + \text{h.c.}\right) \\
& + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda|H|^6 + \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu}G^{\mu\nu}_a \\
& - \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \text{h.c.}\right),
\end{aligned}
$$

[Goertz et al. arxiv:1410.3471]
[Contino et al. arXiv:1502.00539]

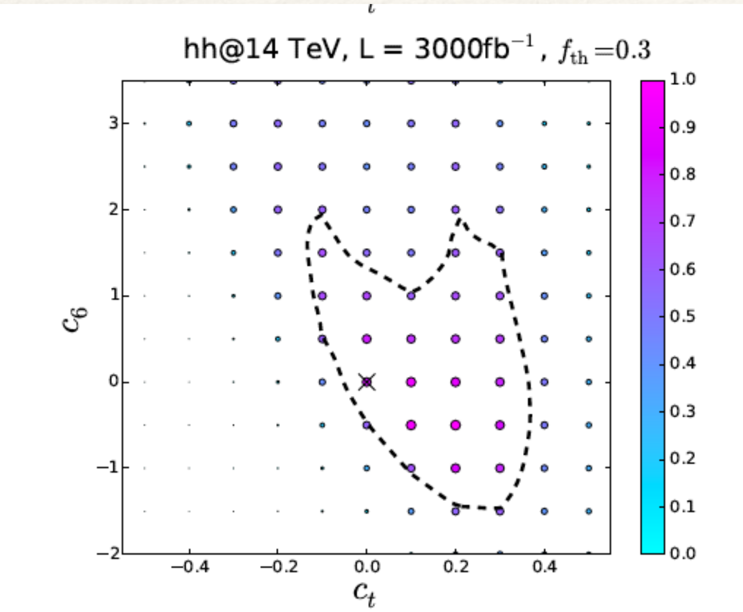
EFT approach: No additional light states
Dimension-6 operators suppressed by scale Λ

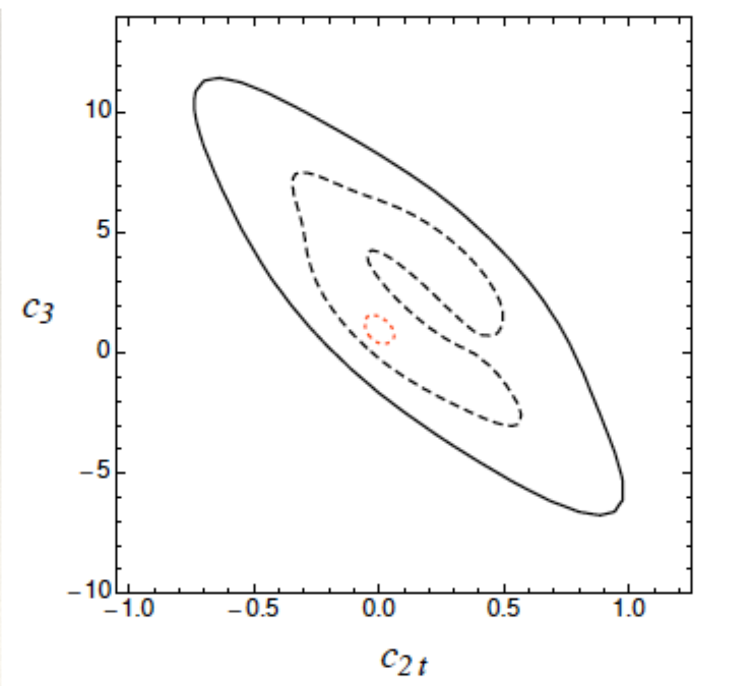
$$
\begin{aligned}
\mathcal{L}_{hh} = & -\frac{m_h^2}{2v}\left(1 - \frac{3}{2}c_H + c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1 - \frac{25}{3}c_H + 6c_6\right)h^4 \\
& + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right) G^a_{\mu\nu}G^{\mu\nu}_a \\
& - \left[\frac{m_t}{v}\left(1 - \frac{c_H}{2} + c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1 - \frac{c_H}{2} + c_b\right)\bar{b}_L b_R h + \text{h.c.}\right] \\
& - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2} - \frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2} - \frac{c_H}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right],
\end{aligned}
$$



5 parameters:c6, cH, cb,ct,cg

Results of previous HH EFT pheno studies





Prospects for HL-LHC

[Goertz et al arxiv:1410.3471] focussing on bbττ

model	$L = 600\ \text{fb}^{-1}$	$L = 3000\ \text{fb}^{-1}$
c_6-only	$c_6 \in (-0.5, 0.8)$	$c_6 \in (-0.4, 0.4)$
full	$c_6 \gtrsim -1.3$	$c_6 \gtrsim -1.2$
$c_6 - c_t - c_\tau - c_b$	$c_6 \gtrsim -2.0$	$c_6 \in (-1.8, 2.3)$

Similarly in [Azatov et al. arxiv:1502.00539] focussing on bbγγ

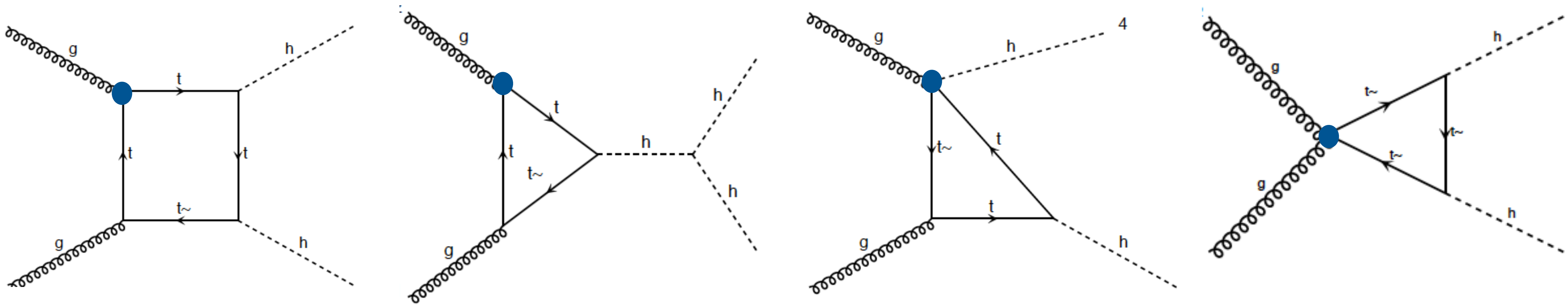
Prospects for c6:

LHC_{14}	HL-LHC	FCC_{100}
$[-1.2, 6.1]$	$[-1.0, 1.8] \cup [3.5, 5.1]$	$[-0.33, 0.29]$
$300\ \text{fb}^{-1}$	$3\ \text{ab}^{-1}$	$3\ \text{ab}^{-1}$

HH production in the EFT : the chromo

Chromomagnetic operator is also contributing [Maltoni, EV, Zhang: arXiv:1607.05330]

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



Needs to be taken into account in the context of a global EFT analysis for HH
Constraints from top pair production at NLO:

C_{tg}= [-0.42,0.30] [Zhang and Franzosi arxiv:1503.08841]

How much does this operator contribute to HH?

HH production in the EFT : the chromo

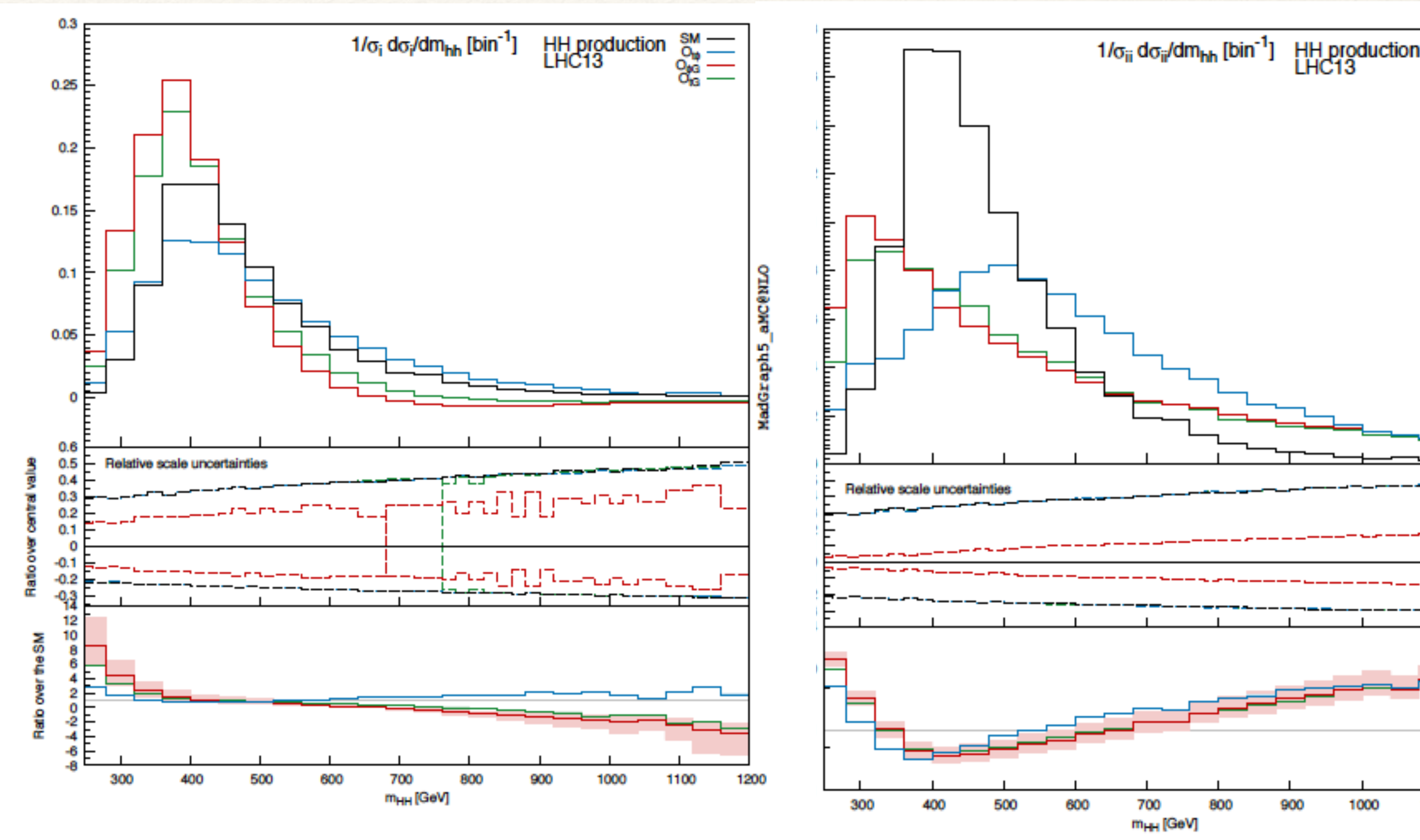
[Maltoni, EV, Zhang: arXiv:1607.05330]

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

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

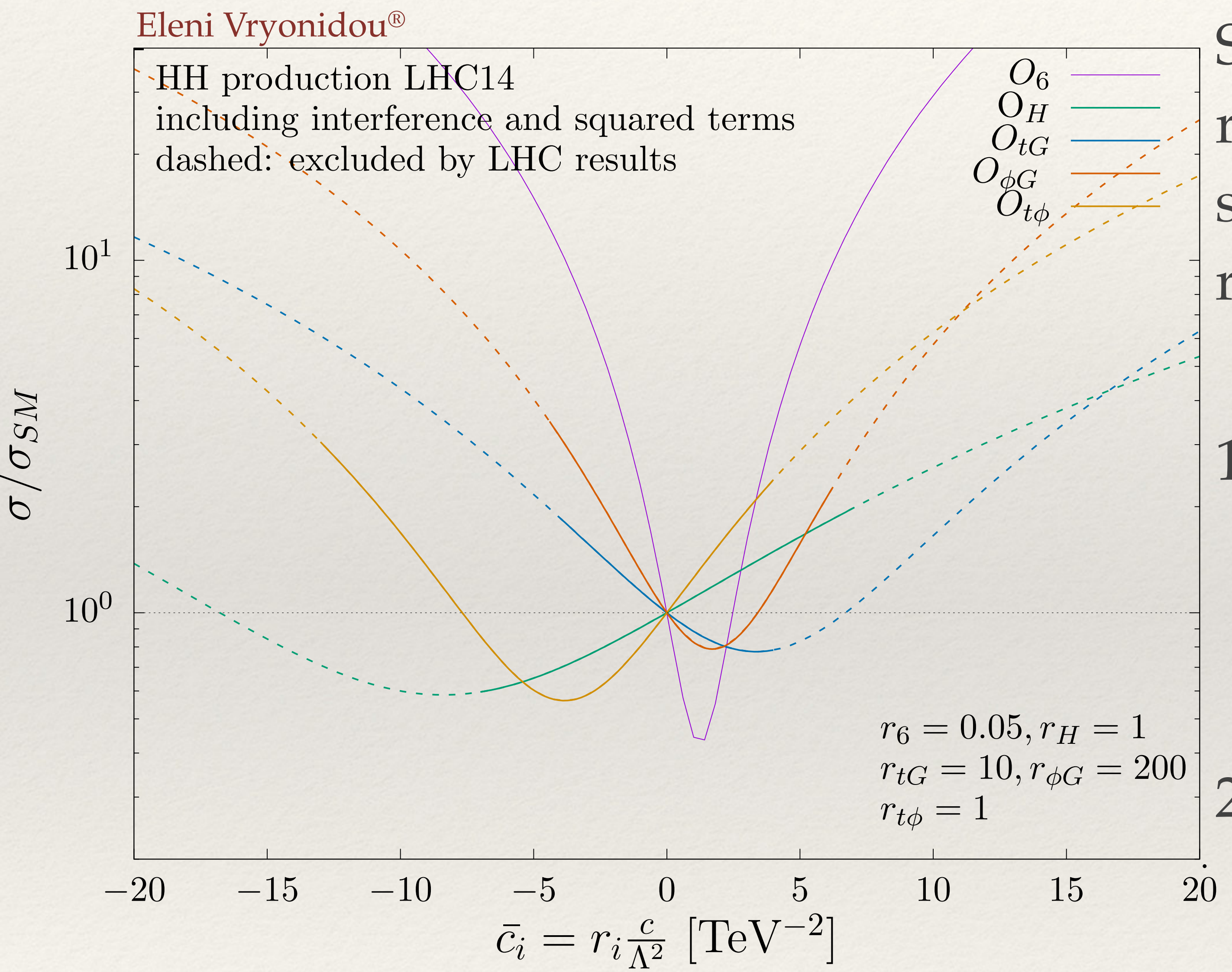
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

13 TeV	σ/σ_{SM} LO
σ_{SM}	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$0.227^{+0.00114+0.0116}_{-0.000918-0.0101}$
$\sigma_{\phi G}$	$-47.3^{+6.18+3.707}_{-6.14-4.42}$
$\boxed{\sigma_{tG}}$	$\boxed{-1.356^{+0.0271+0.161}_{-0.0225-0.051}}$
$\sigma_{t\phi,t\phi}$	$0.0293^{+0.000727+0.0031}_{-0.000584-0.0026}$
$\sigma_{\phi G,\phi G}$	$2856.2^{+743.3+552}_{-628.5-425}$
$\boxed{\sigma_{tG,tG}}$	$\boxed{1.940^{+0.0650+0.198}_{-0.0477-0.493}}$
$\sigma_{t\phi,\phi G}$	$-11.83^{+1.39+1.42}_{-1.41-1.77}$
$\sigma_{t\phi,tG}$	$-0.340^{+0.000238+0.064}_{-0.000438-0.047}$
$\sigma_{\phi G,tG}$	$147.5^{+20.83+20.7}_{-18.86-31.4}$



To be investigated: the impact of the chromomagnetic operator in EFT analyses that focus on the extraction of the triple Higgs coupling λ

HH sensitivity in the SMEFT



Sensitivity plot of σ(HH) in terms of the five relevant operators. Coefficients are rescaled so that the ranges are comparable. The range of c_6 is commensurate to that of $k_{\lambda 3}$.

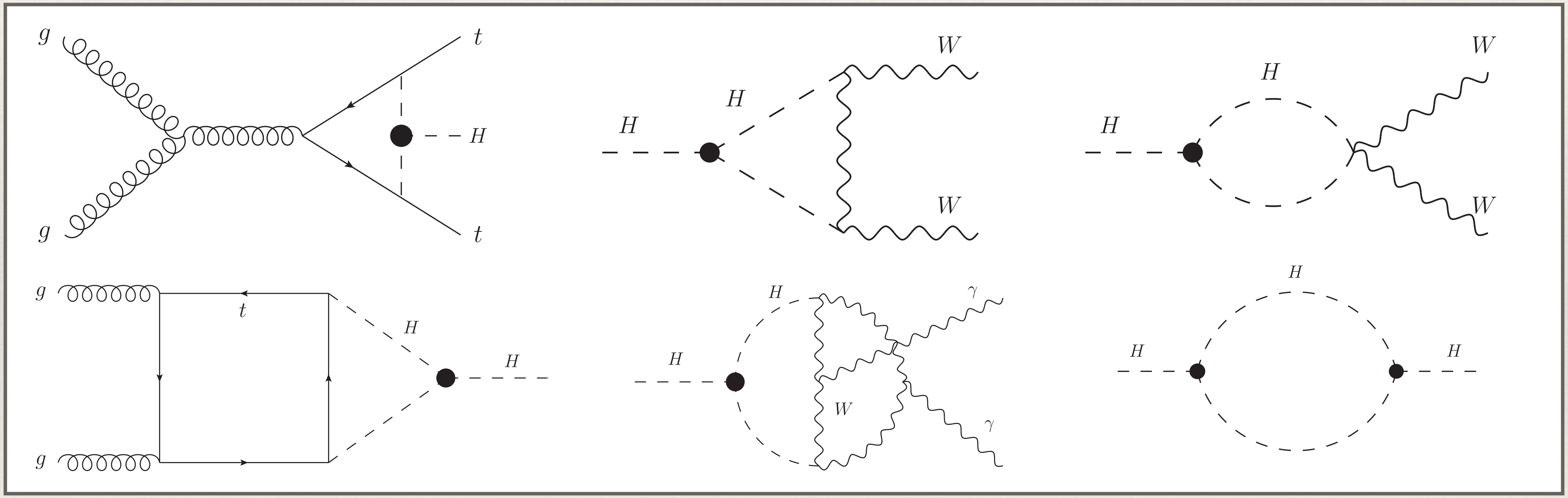
1. An accurate measurement of the Higgs self-couplings will depend on our ability to bound several (top-related) SMEFT operators: O_{tG},$O_{\varphi G}$,$O_{t\varphi}$.
2. Given the current constraints on σ(HH), the Higgs self-coupling can be constrained "ignoring" the other EFT couplings.

Question

Is there any other way of getting independent (and useful) information on the Higgs self-interactions at the LHC?

The idea

1) Exploit the dependence of single-Higgs (total and differential) cross sections and decay rates on the self couplings at NLO (EW) level:



2) Combine all the information (rates and distributions) coming from the relevant single Higgs channels in a global way.

Indirect approach: progress

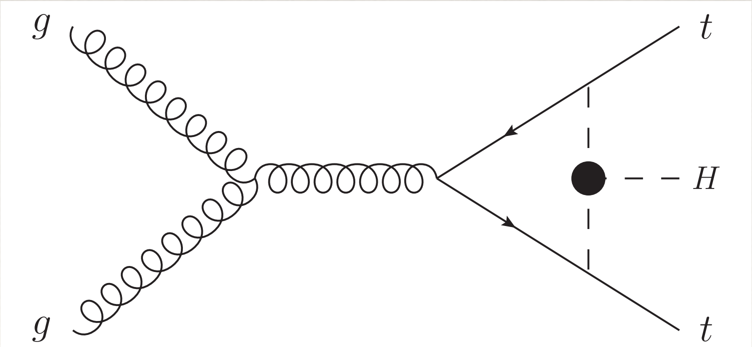
Ref	Authors	Processes	Comments
1312.3322	M.McCullough	e+e- → ZH	applications at future colliders
1607.03773	M.Gorbahn, U.Haisch	gg→H, H→$\gamma\gamma$	approx. two-loop results mh →0
1607.04251	G.Degrassi, P.P. Giardino, F.M., D.Pagani	gg→H,WH,ZH,VBF, ttH H→$\gamma\gamma$,WW*/ZZ*→4l, gg	total and diff.
1610.05771	W.Bizon, M.Gorbahn, U.Haisch, G.Zanderighi	WH,ZH,VBF	total and diff. + effects of QCD corrections
1702.01737	G. Degrassi, M. Fedele, P.P. Giardino	EWPO	two-loop effects
1702.07678	G. Kribs, A. Maier, H. Rzehak, M. Spannowksy, P. Waite	EWPO	two-loop effects
1704.01953	S. Di Vita, C. Grojean, G. Panico, M. Riembau, T. Vantalon	Direct+indirect	global fit in the EFT including differential
1709.08649	F. Maltoni, D. Pagani, A. Shivaji, X. Zhao	VBF, VH, tHj ttH and H→4l.	Differential distributions with EW corrections. Release of MC codes
1711.03978	Di Vita, et al.	e+e- → ZH , ZHH	Future colliders

Master formula

$$\delta\sigma \equiv \frac{\sigma_{\rm NLO} - \sigma_{\rm NLO}^{\rm SM}}{\sigma_{\rm LO}} = (\kappa_\lambda - 1)\boxed{C_1} + (\kappa_\lambda^2 - 1)\boxed{C_2}$$

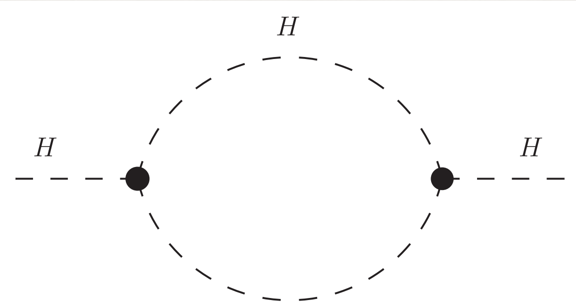
Process and kinetic dependent

$$C_1^\sigma = \frac{\sum_{i,j} \int dx_1 dx_2 f_i(x_1) f_j(x_2)\, 2\Re\left(\mathcal{M}_{ij}^{0*}\mathcal{M}^1_{\lambda_3^{\rm SM},ij}\right) d\Phi}{\sum_{i,j} \int dx_1 dx_2 f_i(x_1) f_j(x_2)\, |\mathcal{M}_{ij}^0|^2 d\Phi}$$



overall and universal

$$C_2 = \frac{\delta Z_H}{(1 - \kappa_\lambda^2 \delta Z_H)}$$



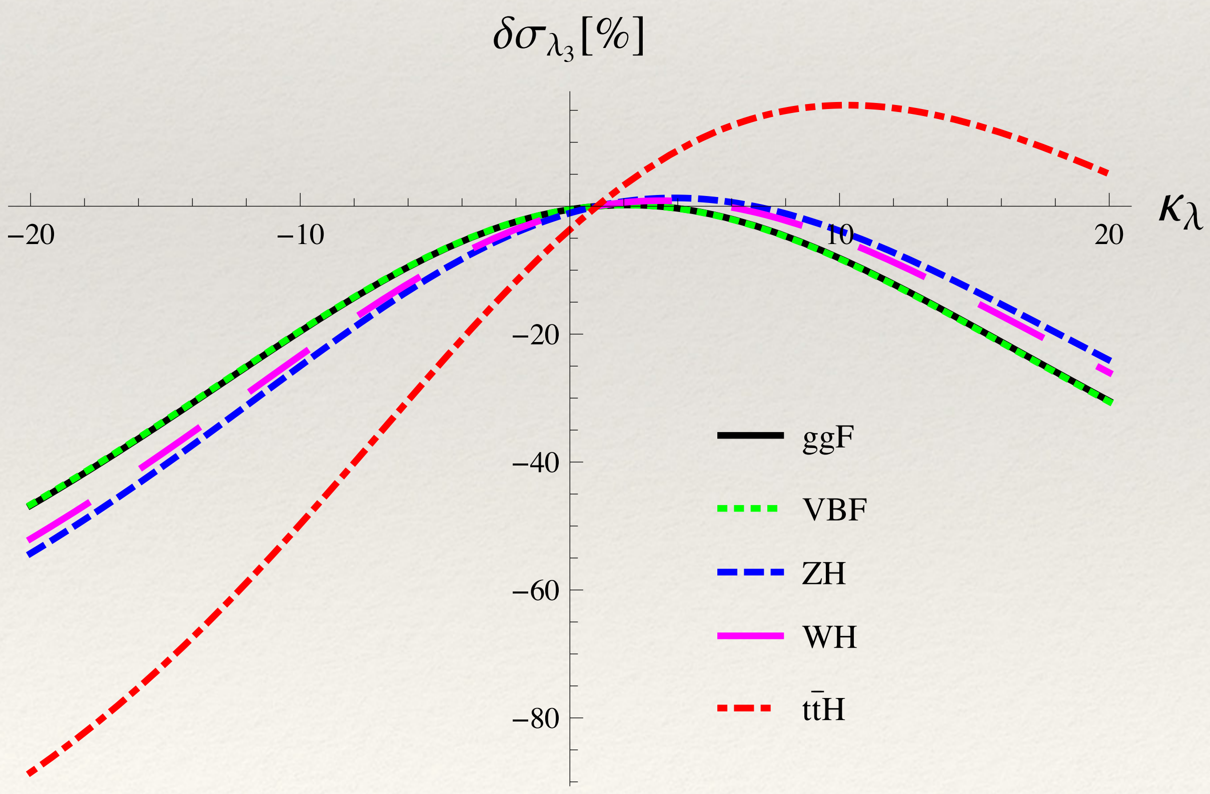
Similar (but simpler) formula for C_1 of decay widths.
Note that branching ratios do not depend on C_2

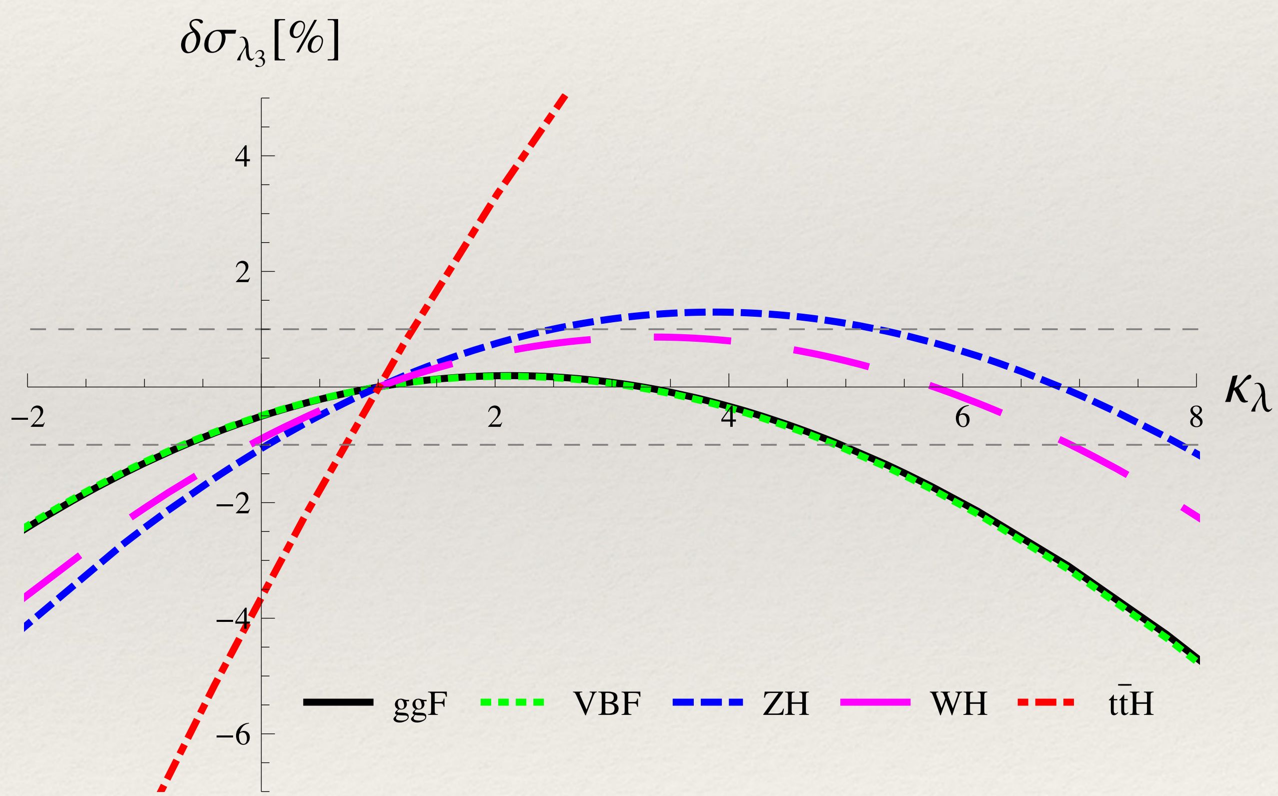
Results : total cross sections

$$\delta\sigma = (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2$$

$$C_2 = -9.514 \cdot 10^{-4} \text{ for } \kappa_\lambda = \pm 20$$
$$C_2 = -1.536 \cdot 10^{-3} \text{ for } \kappa_\lambda = 1$$

$C_1^\sigma[\%]$	ggF	VBF	WH	ZH	$t\bar{t}H$
8 TeV	0.66	0.65	1.05	1.22	3.78
13 TeV	0.66	0.64	1.03	1.19	3.51





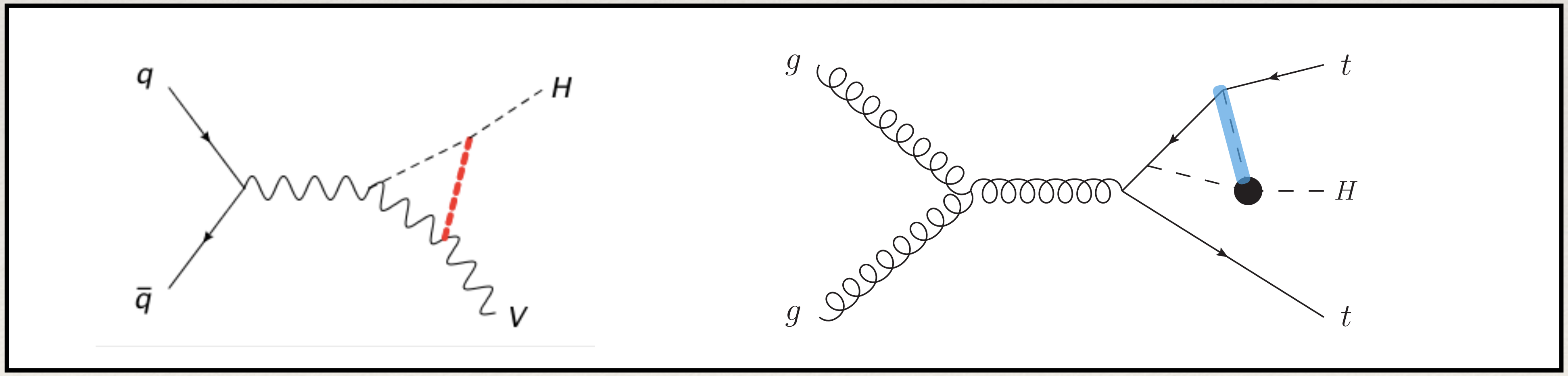
Results : differential production

$C_1^\sigma[\%]$	25 GeV	50 GeV	100 GeV	200 GeV	500 GeV
WH	1.71 (0.11)	1.56 (0.34)	1.29 (0.72)	1.09 (0.94)	1.03 (0.99)
ZH	2.00 (0.10)	1.83 (0.33)	1.50 (0.71)	1.26 (0.94)	1.19 (0.99)
$t\bar{t}H$	5.44 (0.04)	5.14 (0.17)	4.66 (0.48)	3.95 (0.84)	3.54 (0.99)

$$p_T(H) < p_{T,\mathrm{cut}}$$

$C_1^\sigma[\%]$	1.1	1.2	1.5	2	3
WH	1.78 (0.17)	1.60 (0.36)	1.32 (0.70)	1.15 (0.89)	1.06 (0.97)
ZH	2.08 (0.19)	1.86 (0.38)	1.51 (0.72)	1.31 (0.90)	1.22 (0.98)
$t\bar{t}H$	8.57 (0.02)	7.02 (0.10)	5.11 (0.43)	4.12 (0.76)	3.64 (0.94)

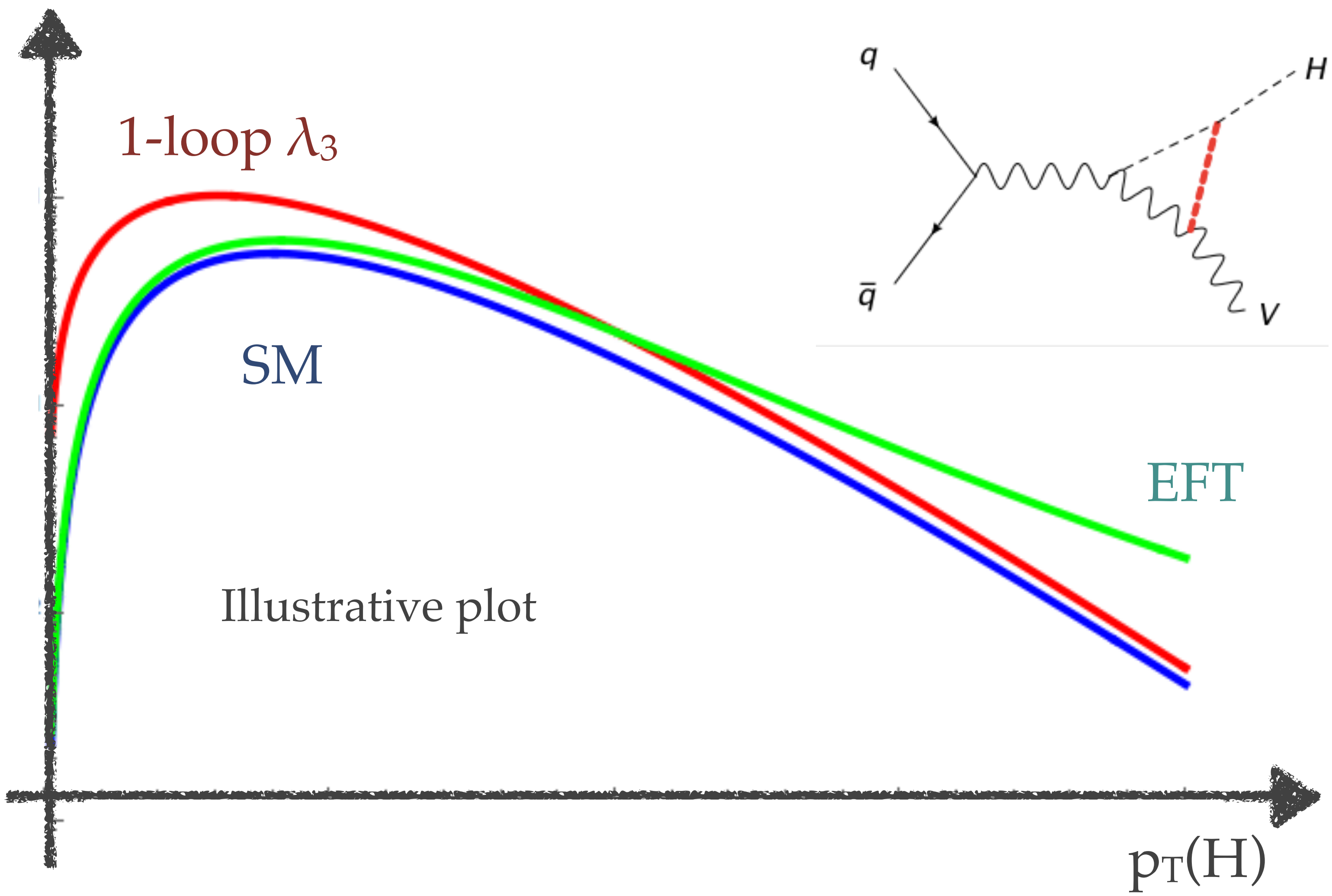
$$m_{\mathrm{tot}} < K \cdot m_{\mathrm{thr}}$$

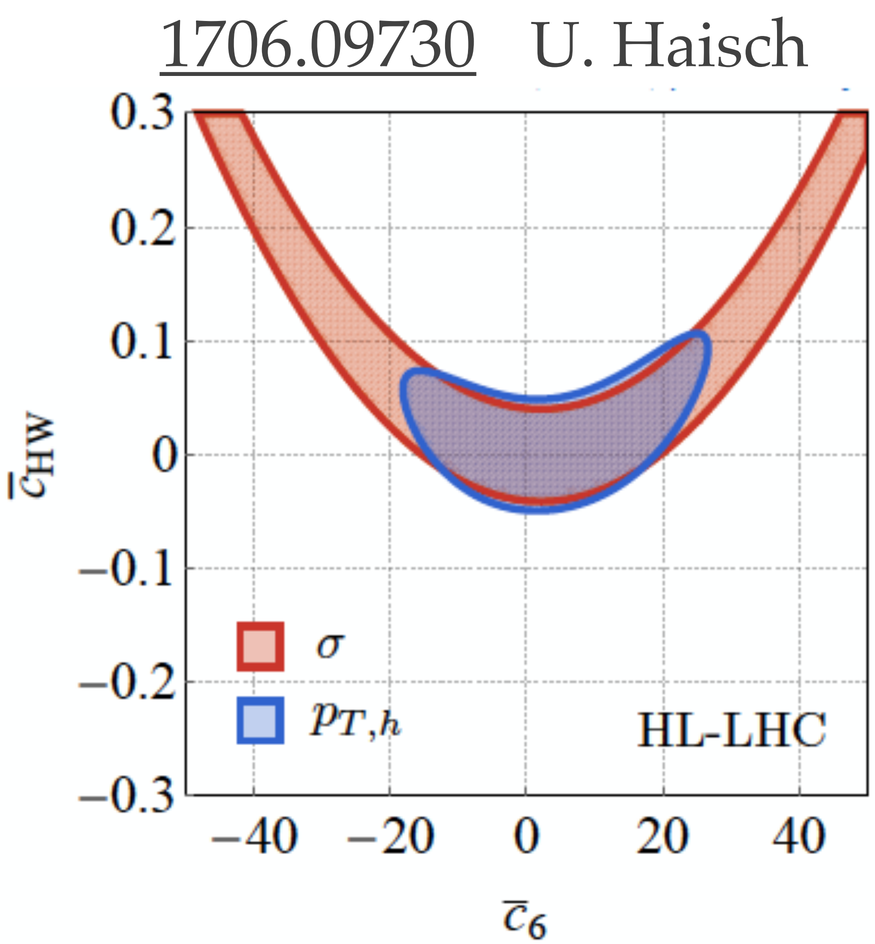


The largest effects are **non-local** and **at threshold**: corrections to ttH and HV processes can be seen as induced by a Yukawa potential, giving a "Sommerfeld enhancement" when the final states are non relativistic.

Differential information

Calculations: 1607.04251 1610.05771 1709.08649 Used in the fit: 1704.01953

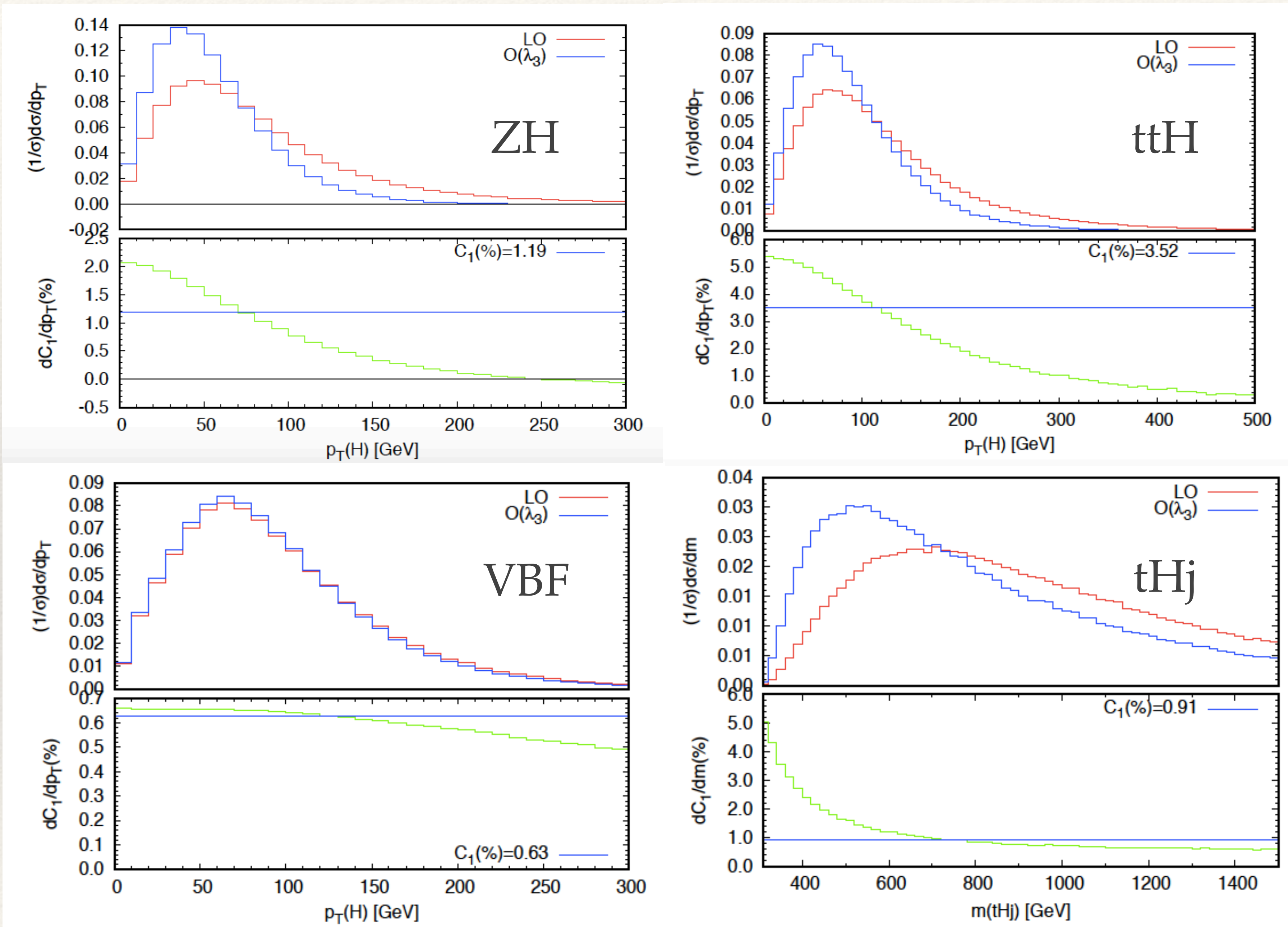




The largest effects are **non-local** and **at threshold**: corrections to ttH and HV processes can be seen as induced by a Yukawa potential. EFT (at LO) gives **local** effects and **in the tails.**

Differential information

1709.08649

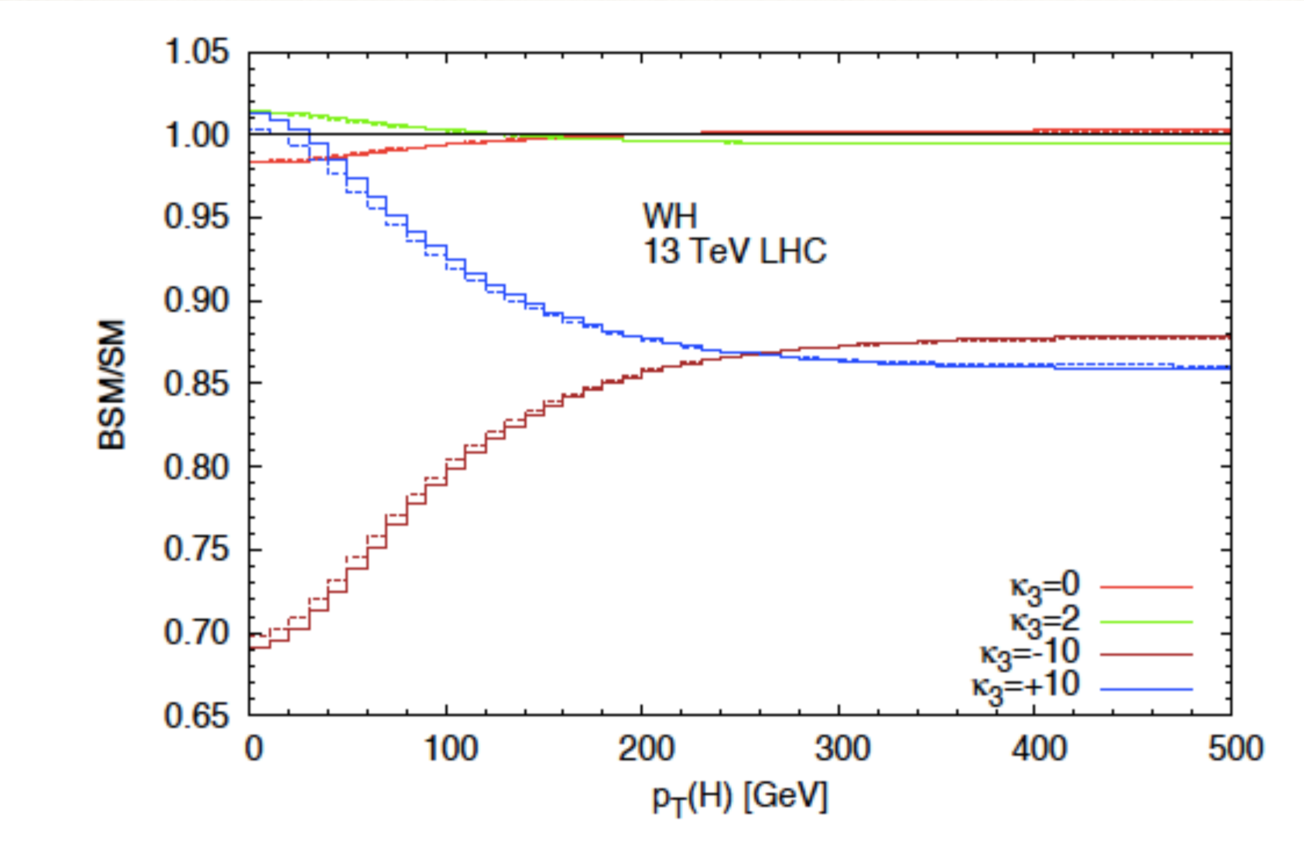


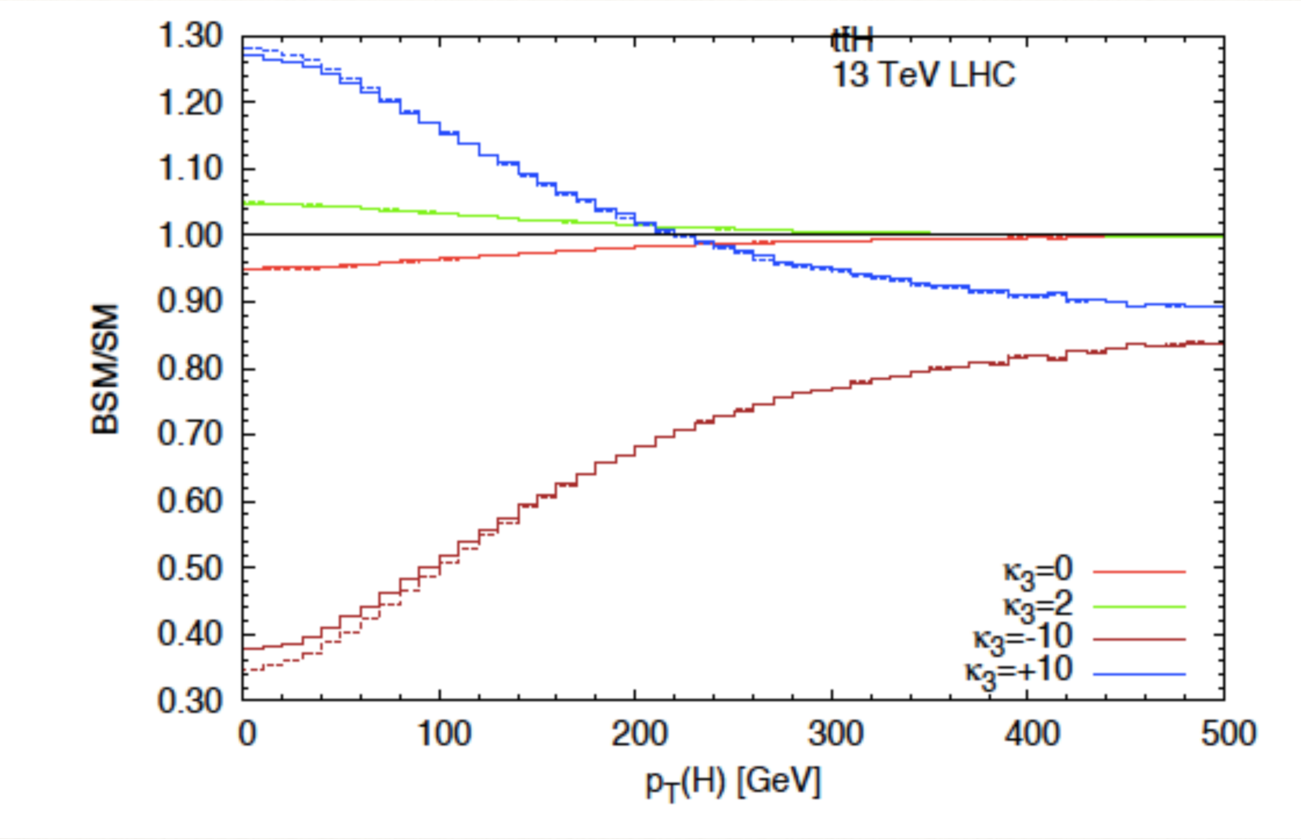
Codes to reweight SM events to include the 1-loop λ_3 in VH,VBF, ttH, tHj available HERE.

Differential information

1709.08649

Inclusion of the EW corrections: $$\Sigma_{\rm NLO}^{\rm BSM} = Z_H^{\rm BSM}\Big[\Sigma_{\rm LO}\left(1+\kappa_3 C_1+\delta Z_H+\delta_{\rm EW}\big|_{\lambda_3=0}\right)\Big]$$



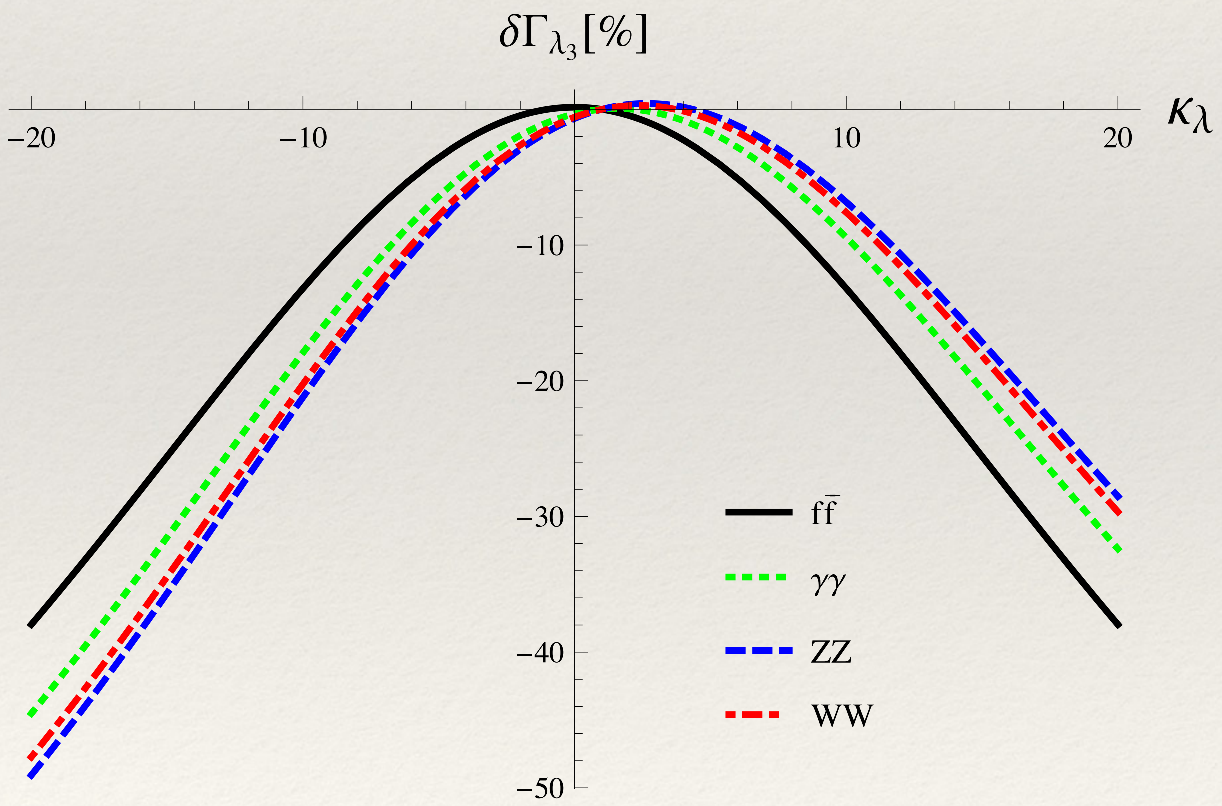


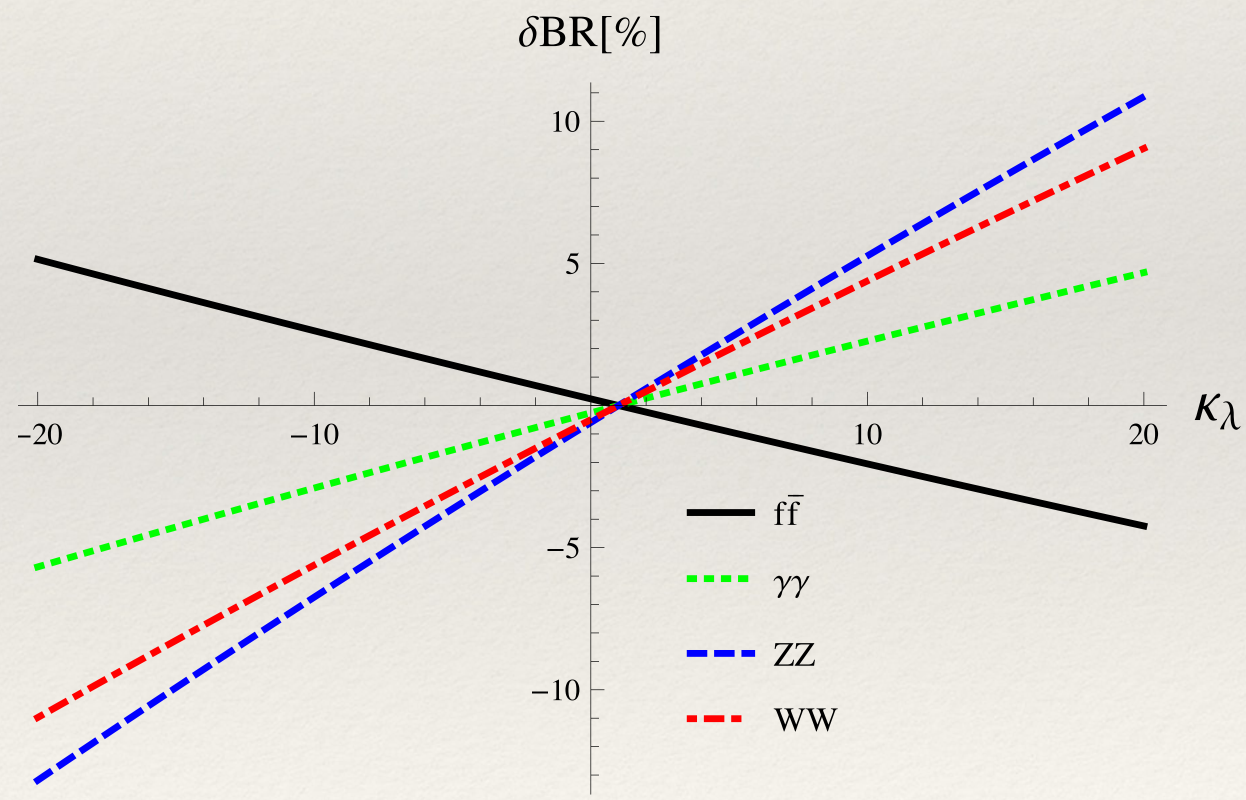
Note: Differential study for H→4l also including EW corrections, available. Differential effects in H→4l from k_λ are very small.

Results: Decay rates

$$\delta \mathrm{BR}_{\lambda_3}(i) = \frac{(\kappa_\lambda - 1)(C_1^\Gamma(i) - C_1^{\Gamma_{\rm tot}})}{1 + (\kappa_\lambda - 1)C_1^{\Gamma_{\rm tot}}}$$

$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

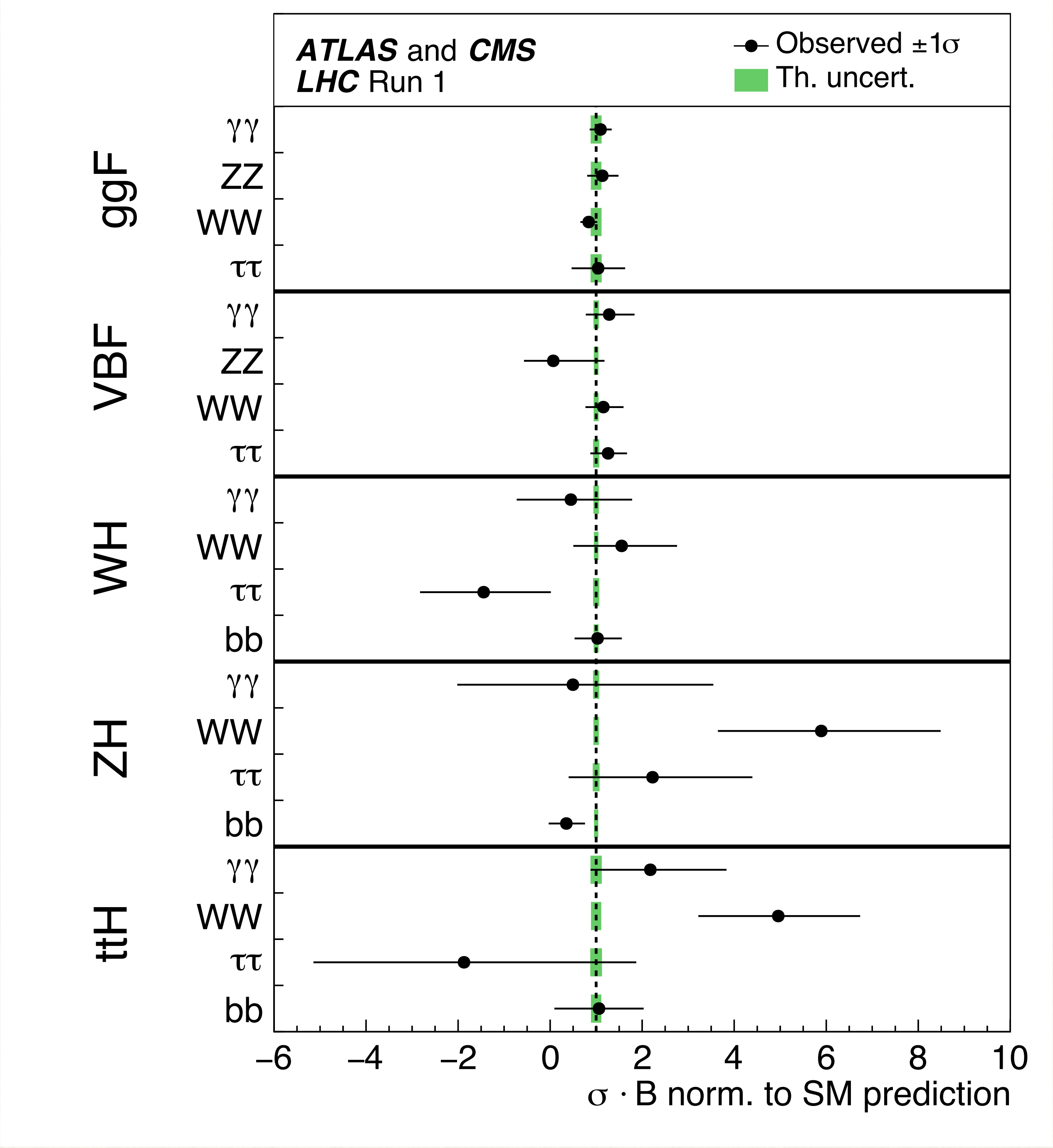




Further questions

- Is the sensitivity of the various processes large enough to set constraints?
- Can we start to exploit such a sensitivity **now**, to close the gap between the current bounds ($|k_\lambda| \lesssim$ 10-20) and the EFT-relevant region ($-2 \lesssim k_\lambda \lesssim 4$)?
- What are the minimal theoretical assumptions that are needed to guarantee that the interpretations at large values of k_λ are robust?

The first global sensitivity study



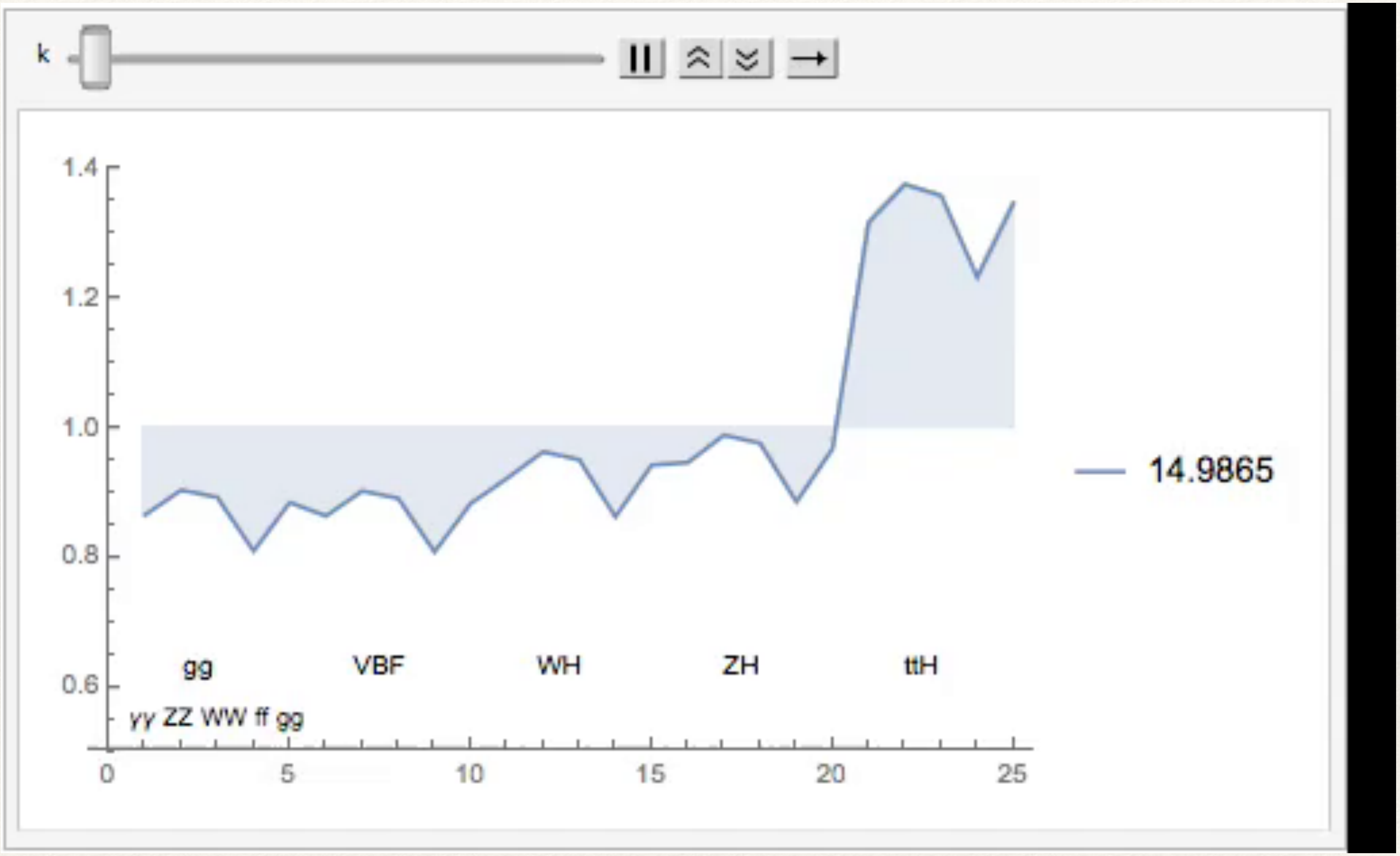
We have performed a first sensitivity study using the 8 TeV data on rates and projecting on the future LHC measurements.
We performed a one-parameter fit, assuming the other Higgs couplings to be SM like.

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

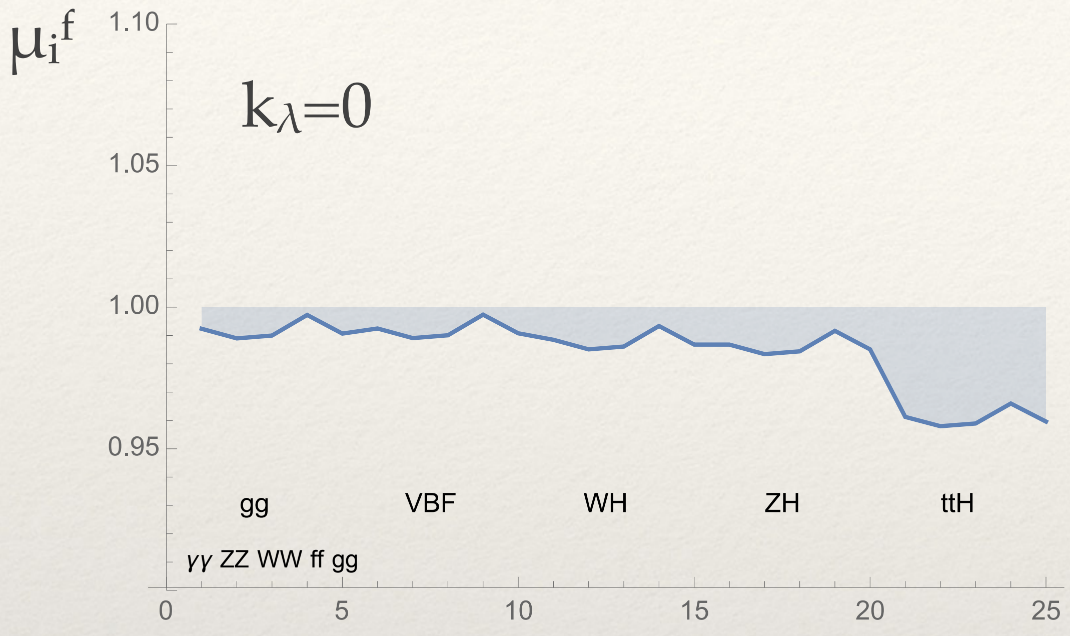
$$\mu_i = 1 + \delta\sigma_{\lambda_3}(i)$$

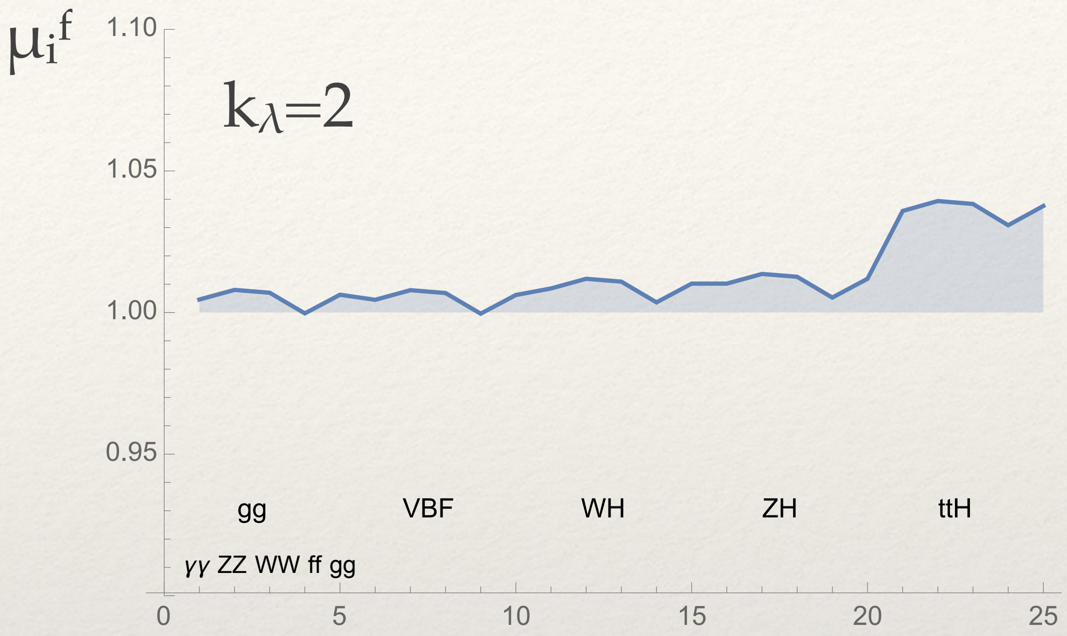
$$\mu^f = 1 + \delta \mathrm{BR}_{\lambda_3}(f)$$

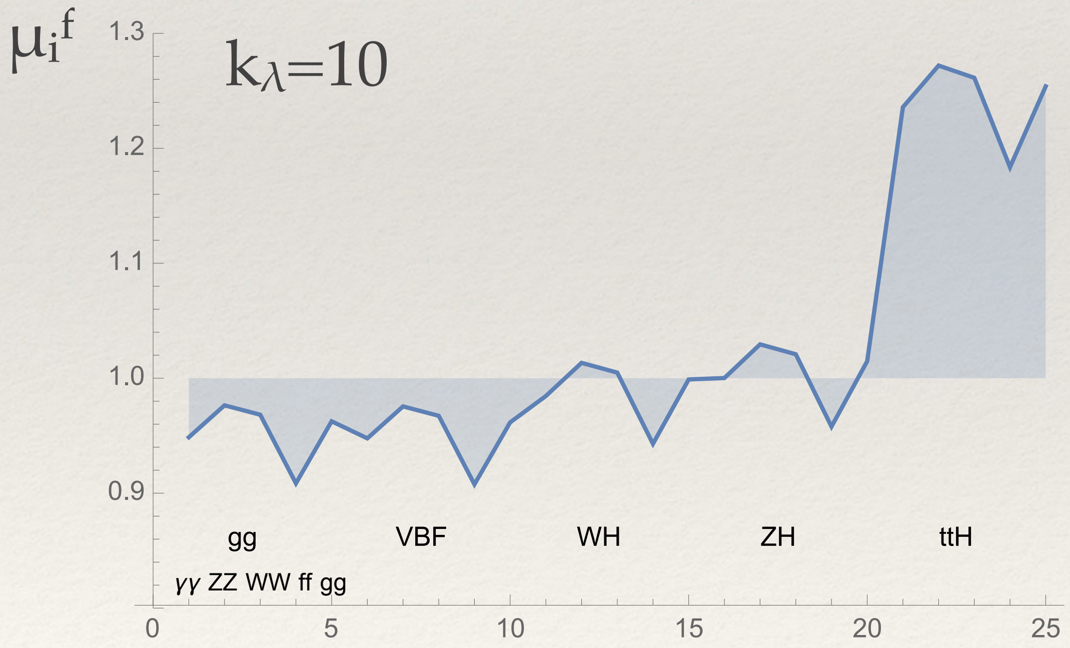
Rates: $\mu_i^f(k_\lambda)$

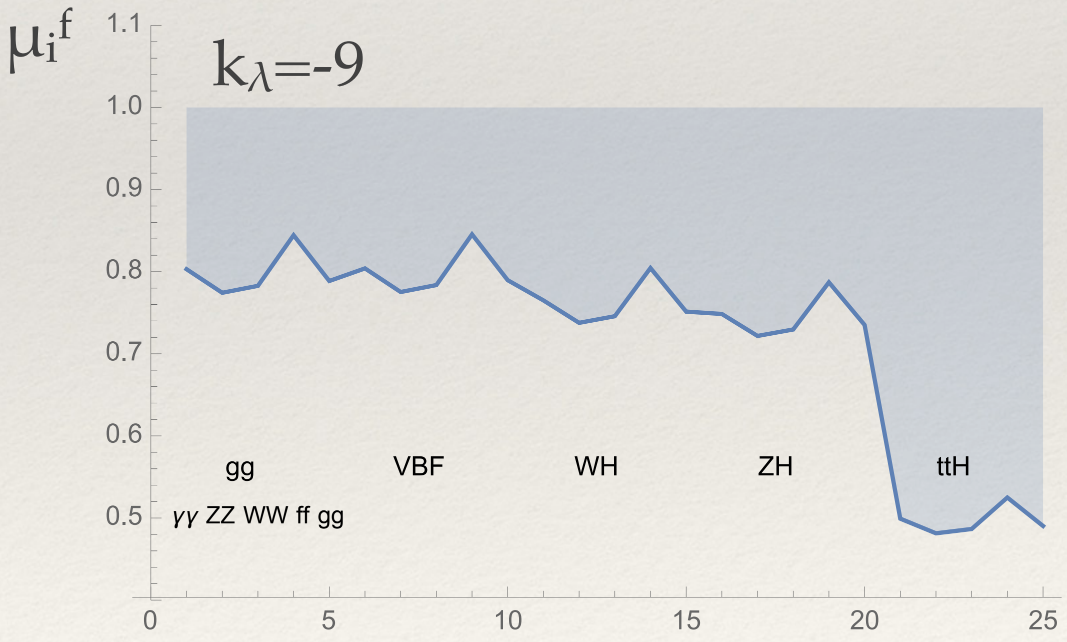


Rates: $\mu_i^f(k_\lambda)$





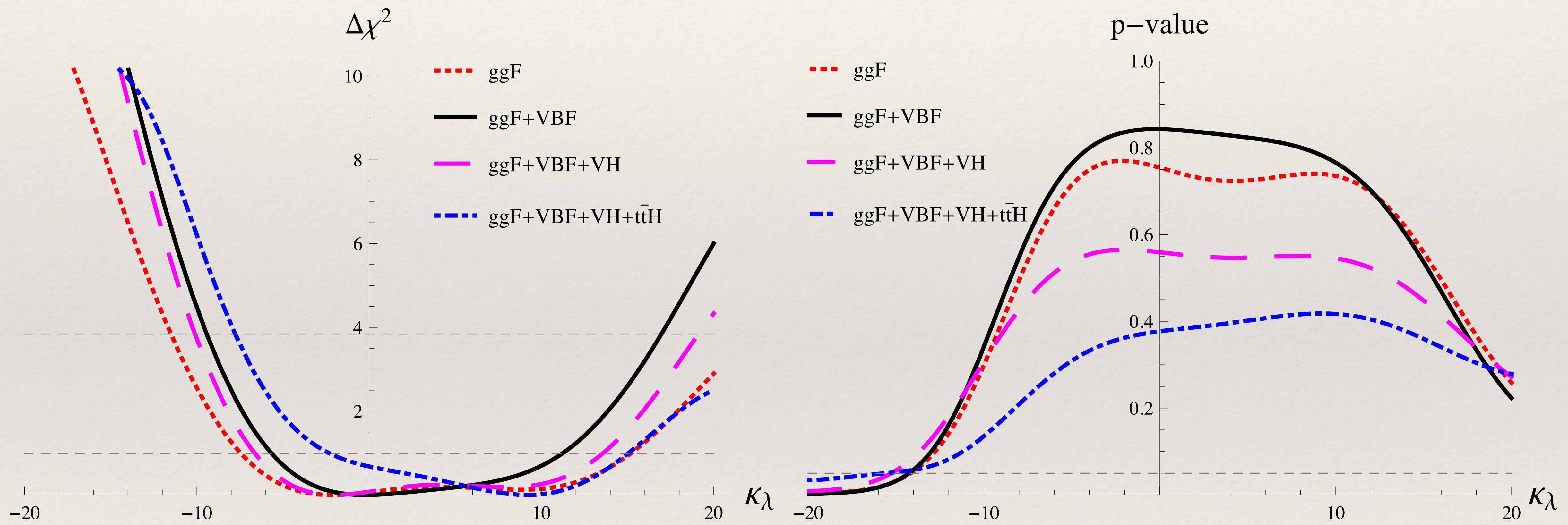




An animation can be found here

The first global sensitivity study

Minimization of $$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$



P_2: ggF+VBF ➡ $\kappa_\lambda^{\text{best}} = -0.24\,, \quad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \quad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$

$p\text{-value}(\kappa_\lambda) = 1 - F_{\chi^2_{(n)}}(\chi^2(\kappa_\lambda))$ ➡ $\kappa_\lambda < -14.3$ Excluded at more than 2σ

Indirect vs direct

Indirect: $\kappa_\lambda^{2\sigma} = [-9.4, 17.0]$ In-house TH fit on 8 TeV 1607.04251

Direct: $\kappa_\lambda^{2\sigma} = [-8.82, 15.04]$ HH -> b b gamma gamma HIG-17-008

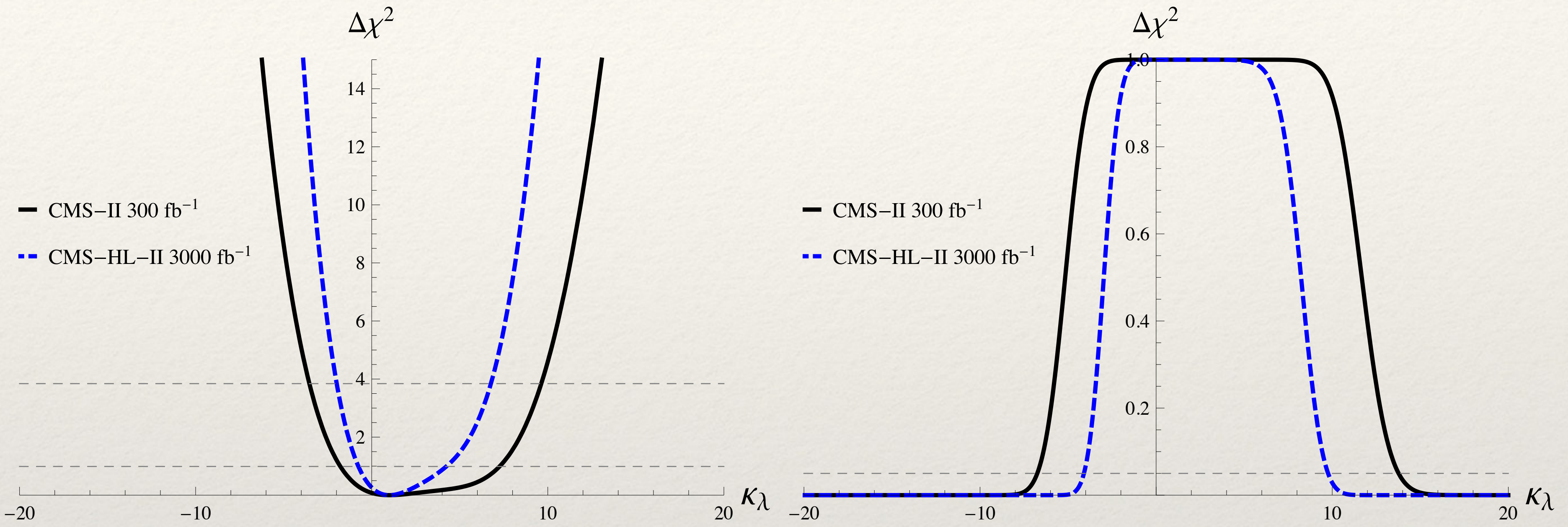
Both interpretations assume all other Higgs couplings to be SM-like.

Future runs

Exercise 0:

$$\bar{\mu}_i^f = 1$$

$$\kappa_\lambda^{\text{best}} = 1$$



$\boxed{\text{“CMS-II” (300 fb}^{-1})}$

$$\kappa_\lambda^{1\sigma} = [-1.8, 7.3]\,, \qquad \kappa_\lambda^{2\sigma} = [-3.5, 9.6]\,, \qquad \kappa_\lambda^{p>0.05} = [-6.7, 13.8]$$

$\boxed{\text{“CMS-HL-II” (3000 fb}^{-1})}$

$$\kappa_\lambda^{1\sigma} = [-0.7, 4.2]\,, \qquad \kappa_\lambda^{2\sigma} = [-2.0, 6.8]\,, \qquad \kappa_\lambda^{p>0.05} = [-4.1, 9.8]$$

The first global sensitivity study at 8 TeV: inclusion of EWPO

m_w and the effective sine are obtained from α, G_μ and m_z via

$$m_W^2 = \frac{\hat\rho\, m_Z^2}{2}\left\{1+\left[1-\frac{4\hat A^2}{m_Z^2\hat\rho}(1+\Delta\hat r_W)\right]^{1/2}\right\}$$

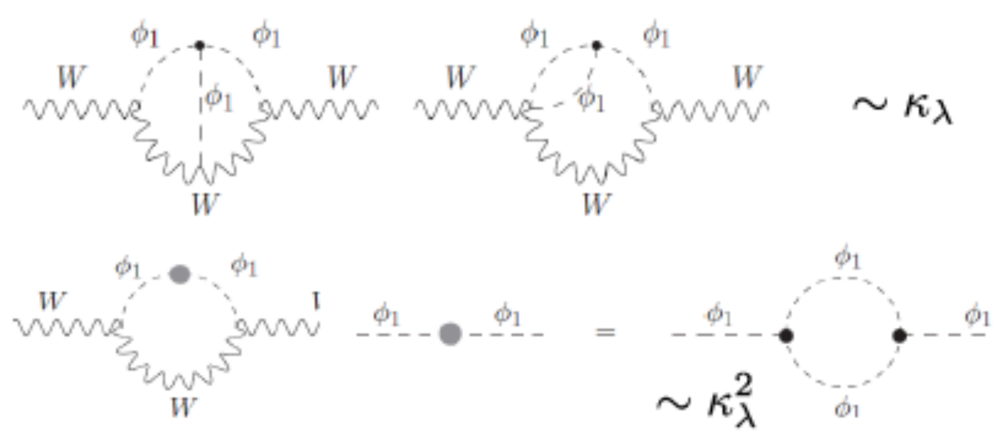
$$\sin^2\theta_{\rm eff}^{\rm lep} \sim \frac{1}{2}\left\{1-\left[1-\frac{4\hat A^2}{m_Z^2\hat\rho}(1+\Delta\hat r_W)\right]^{1/2}\right\}$$

$$\begin{aligned}\hat A &= (\pi\hat\alpha(m_Z)/(\sqrt{2}G_\mu))^{1/2}\\ \hat\alpha(m_Z) &= \frac{\alpha}{1-\Delta\hat\alpha(m_Z)}\\ \frac{G_\mu}{\sqrt2} &= \frac{\pi\hat\alpha(m_Z)}{2m_W^2\hat s^2}(1+\Delta\hat r_W)\\ \hat\rho &= \frac{1}{1-Y_{\overline{MS}}}\end{aligned}$$

λ_3-dependent contributions appear at two-loop in the W and Z self-energies

$$\Delta\hat r_W^{(2)} = \frac{\mathrm{Re}\,A_{WW}^{(2)}(m_W^2)}{m_W^2}-\frac{A_{WW}^{(2)}(0)}{m_W^2}+\dots$$

$$Y_{\overline{MS}}^{(2)} = \mathrm{Re}\left[\frac{A_{WW}^{(2)}(m_W^2)}{m_W^2}-\frac{A_{ZZ}^{(2)}(m_Z^2)}{m_Z^2}\right]+\dots$$



[1702.01737](#)

see also

[1702.07678](#)

[Talk](#) by G. Degrassi at EPS

The first global sensitivity study at 8 TeV: inclusion of EWPO

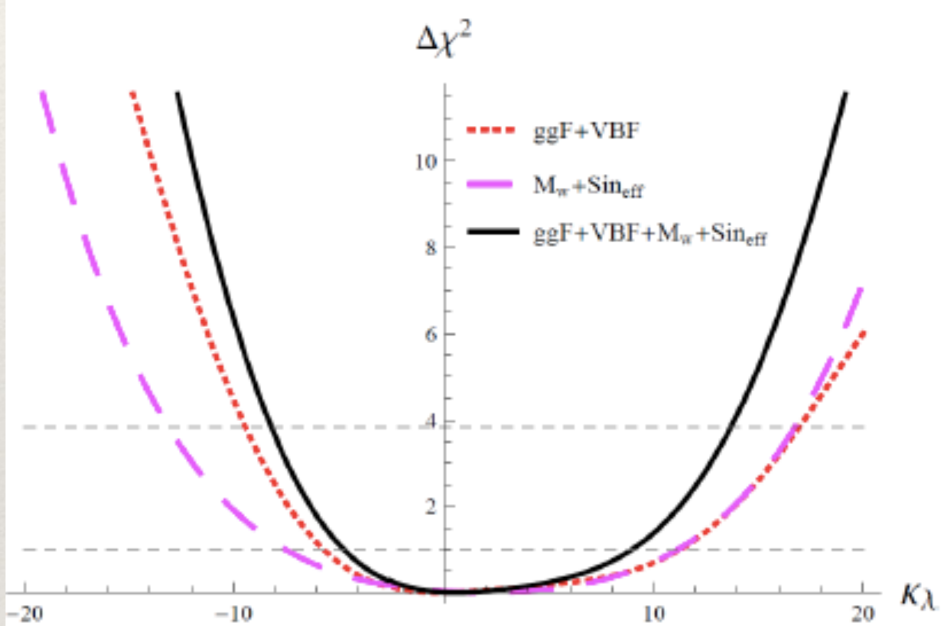
$$O = O^{\rm SM}\left[1 + (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2\right]$$

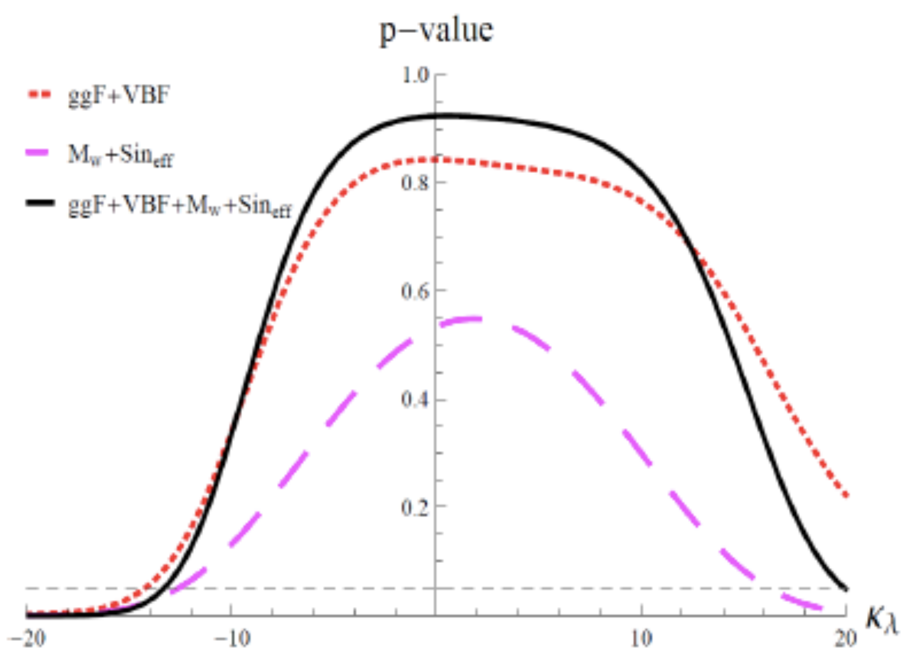
	C_1	C_2
m_W	6.27×10^{-6}	-1.72×10^{-6}
$\sin^2\theta_{\rm eff}^{\rm lep}$	-1.56×10^{-5}	4.55×10^{-6}

1702.01737

see also

1702.07678





P.O. + ggF +VBF $\quad \kappa_\lambda^{\rm best} = 0.5\,, \quad \kappa_\lambda^{1\sigma} = [-4.7, 8.9]\,, \quad \kappa_\lambda^{2\sigma} = [-8.2, 13.7]$

$p > 0.05 \quad \kappa_\lambda > -13.3, \quad \kappa_\lambda < 20$

ggF + VBF $\quad \kappa_\lambda^{\rm best} = -0.24\,, \quad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \quad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$

$p > 0.05 \quad \kappa_\lambda > -14.3$

Talk by G. Degrassi at EPS

Combining H (total+diff), HH and EWPO

1704.01953

SM Effective Field Theory framework

Write down all the possible operators, let H→h+v, write lagrangian in mass eigenstates basis performing field redefinitions and couplings shifts, ... [see HXSWG YR4; Falkowski '14]

SM tensor structures

"SM" tensor structures

4 New tensor structures

10 Independent couplings

8 Dependent couplings

$$\mathcal{L} \supset \frac{h}{v}\Big[\delta c_w \frac{g^2 v^2}{2} W_\mu^+ W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu$$

$$+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W^{-\mu\nu} + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W^{+\mu\nu} + \text{h.c.}\right) + \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu}$$

$$+ c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu}\Big]$$

$$+ \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}_{gg}^{(2)}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu} - \sum_f \left[m_f \left(\delta y_f \frac{h}{v} + \delta y_f^{(2)}\frac{h^2}{2v^2}\right)\bar{f}_R f_L + \text{h.c.}\right]$$

$$- (\kappa_\lambda - 1)\lambda_3^{SM} v h^3$$

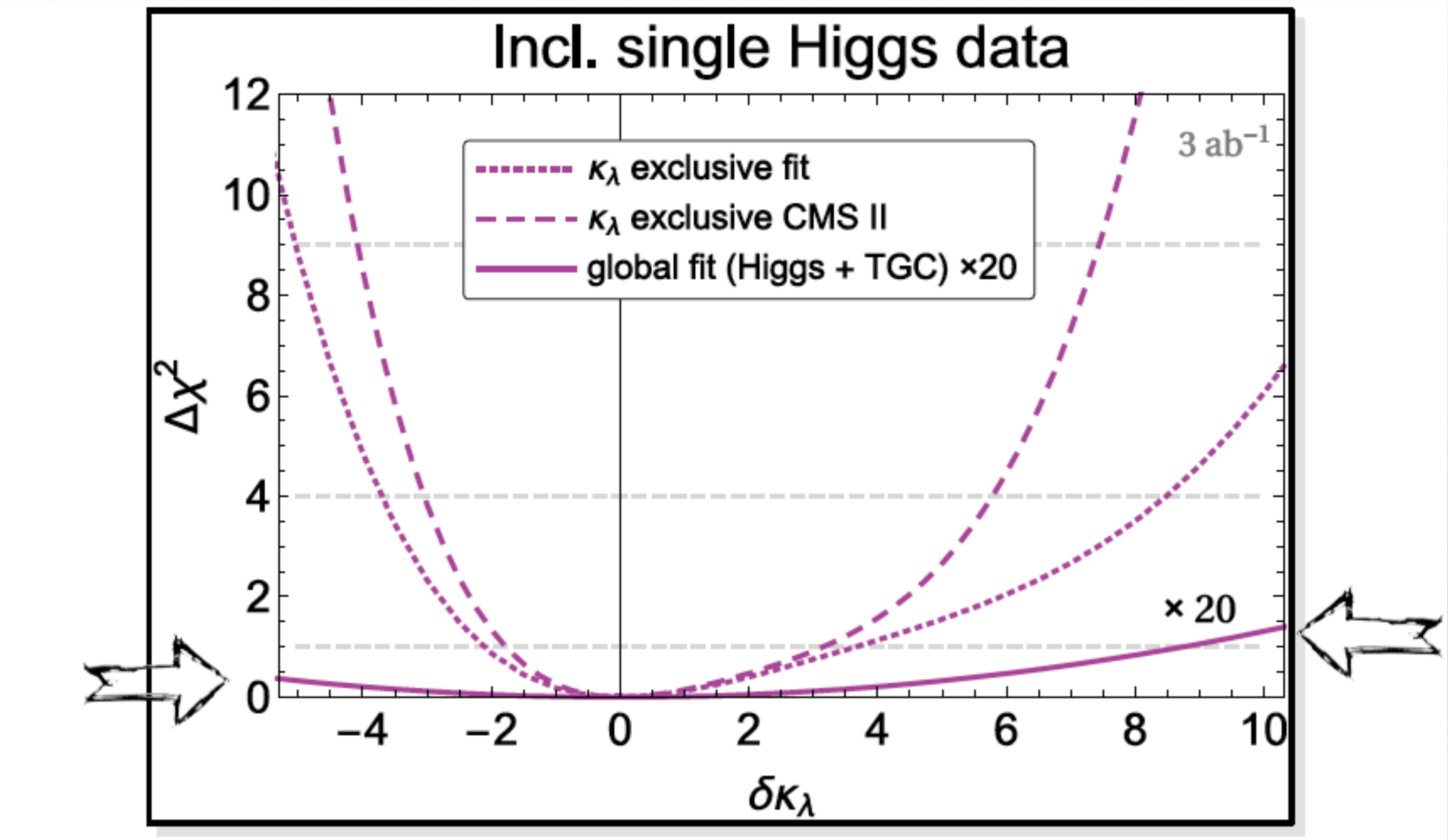
f=t,b,τ

Assuming for simplicity: only dim-6 operators, flavor universality, no CP-odd operators, no dipole operators and no Ψ⁴ operators involving light quarks

Talk by S. Di Vita in the kick-off WG2 meeting

Combining H (total+diff), HH and EWPO

1704.01953



One flat direction with inclusive observables.

Combining H (total+diff), HH and EWPO

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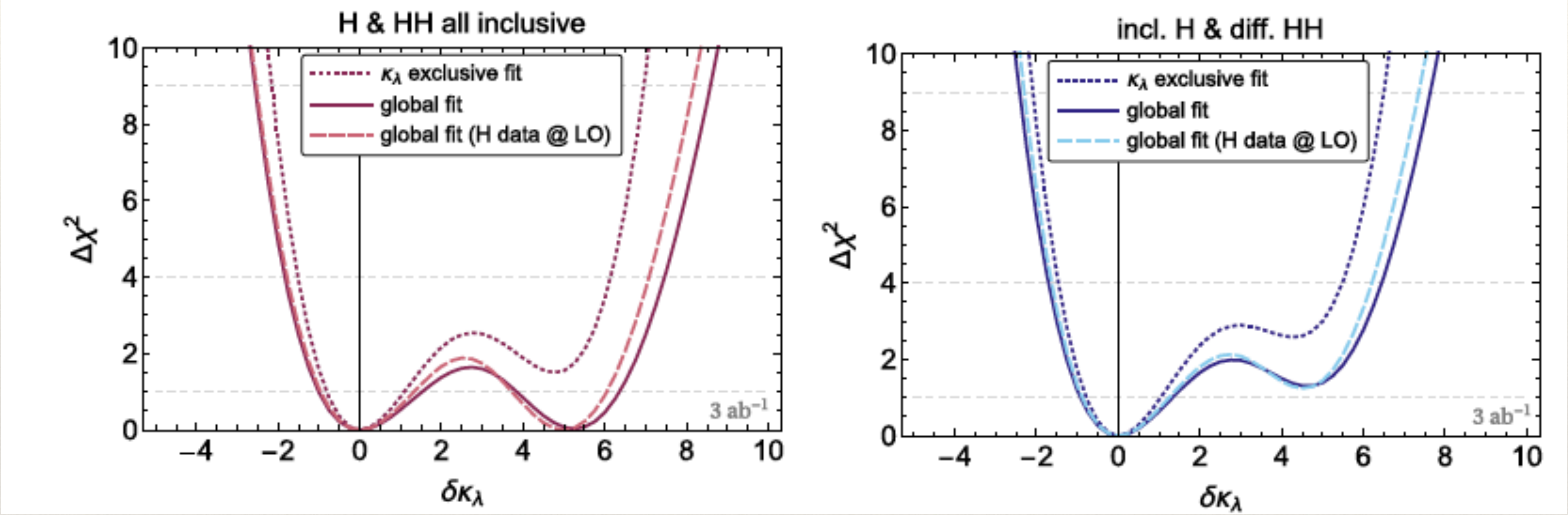
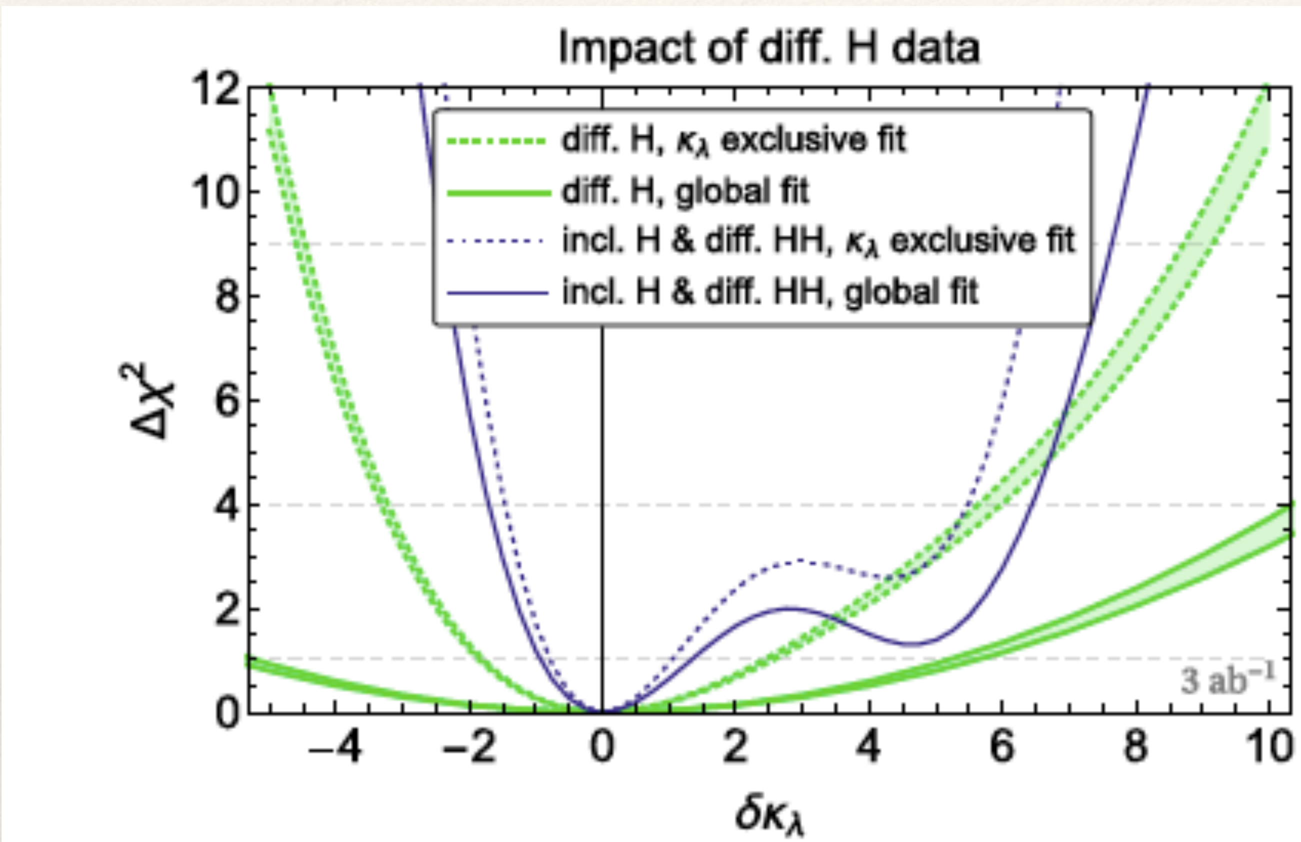


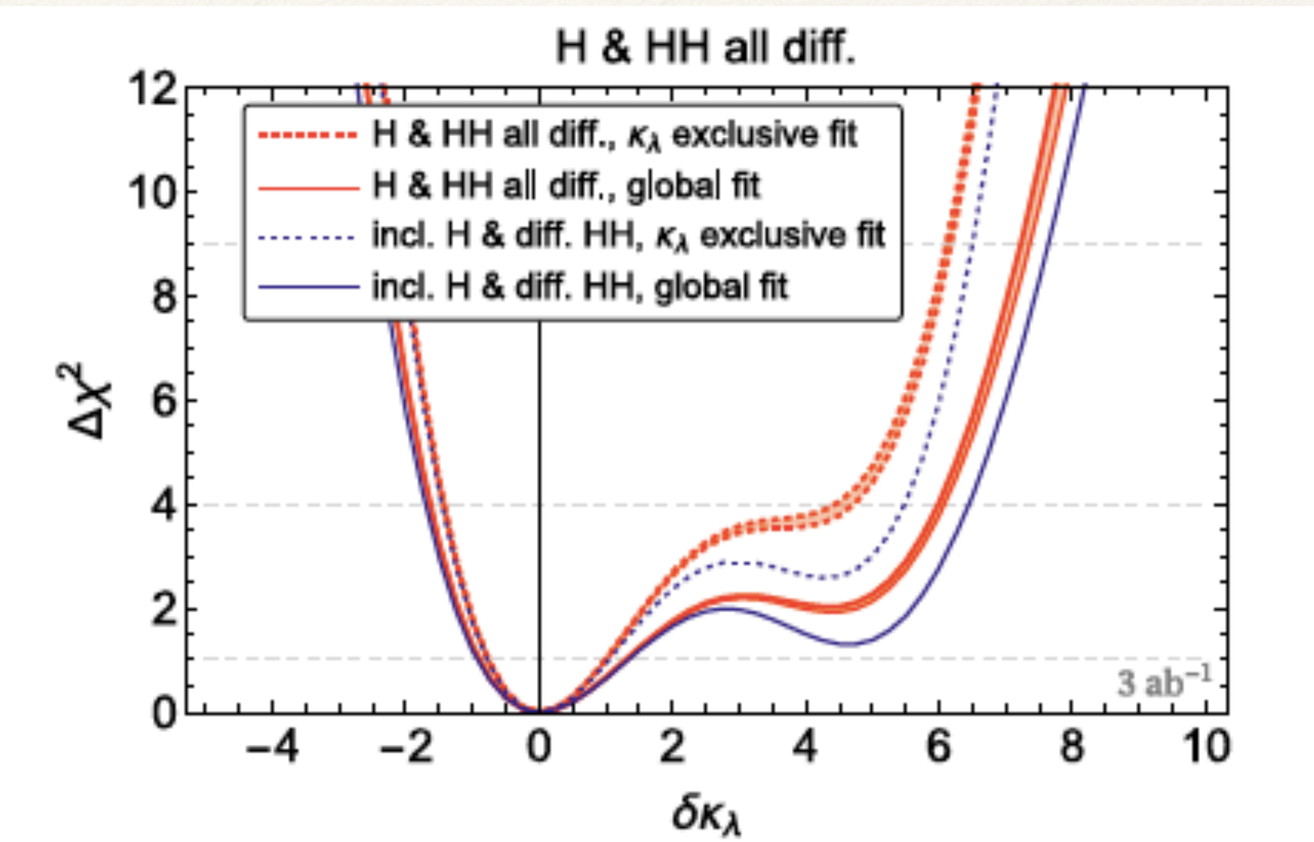
Double Higgs drives the bound on k_λ while, single-Higgs observables are essential to constrain the other coefficients deforming HH production.

Differential m(HH) removes the degeneracy with the second minimum

Combining H (total+diff), HH and EWPO

[1704.01953](1704.01953)





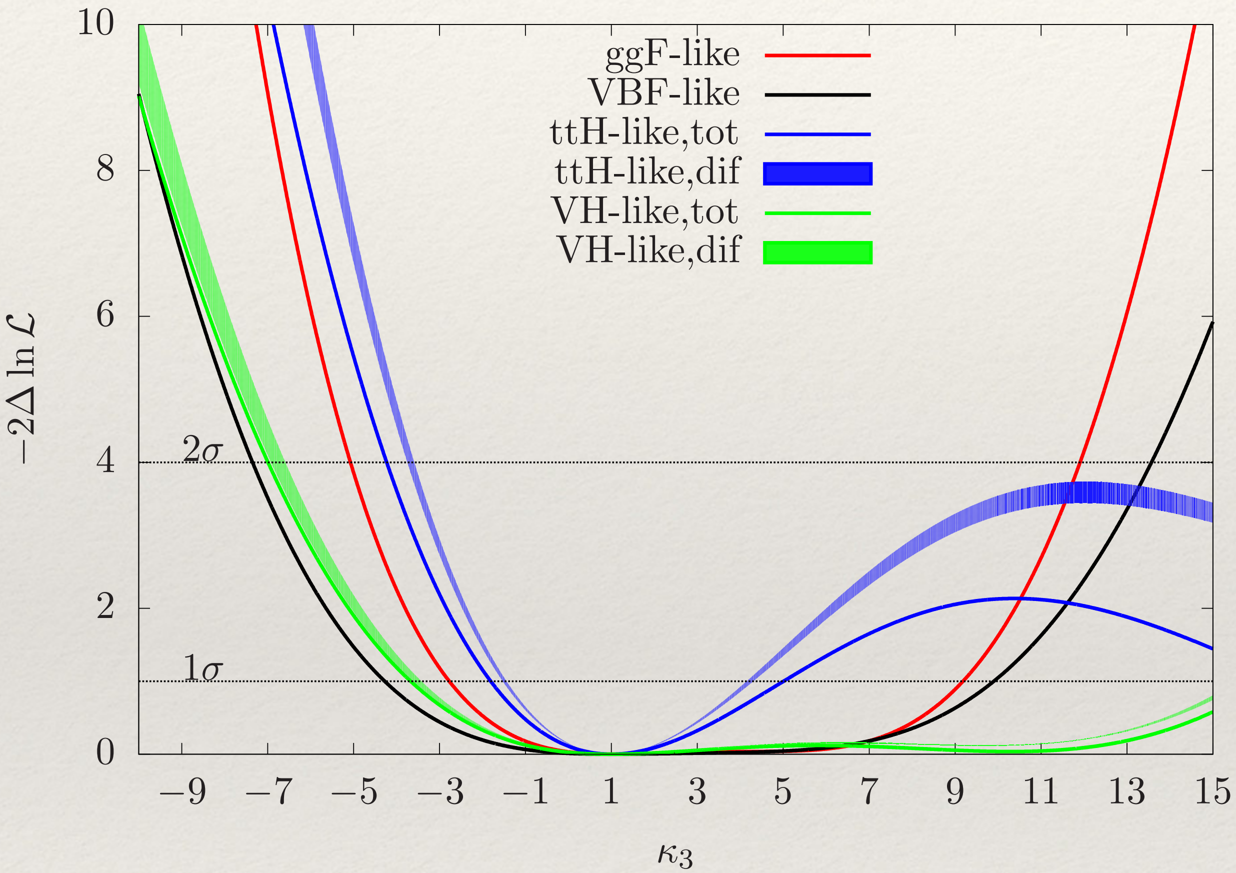
The inclusion of differential information in single-Higgs observables seems promising, but better experimental estimates are required

Combining differential information from single- and double-Higgs, the second minimum is futher lifted.

Sensitivity study: k_t, k_V,k_λ

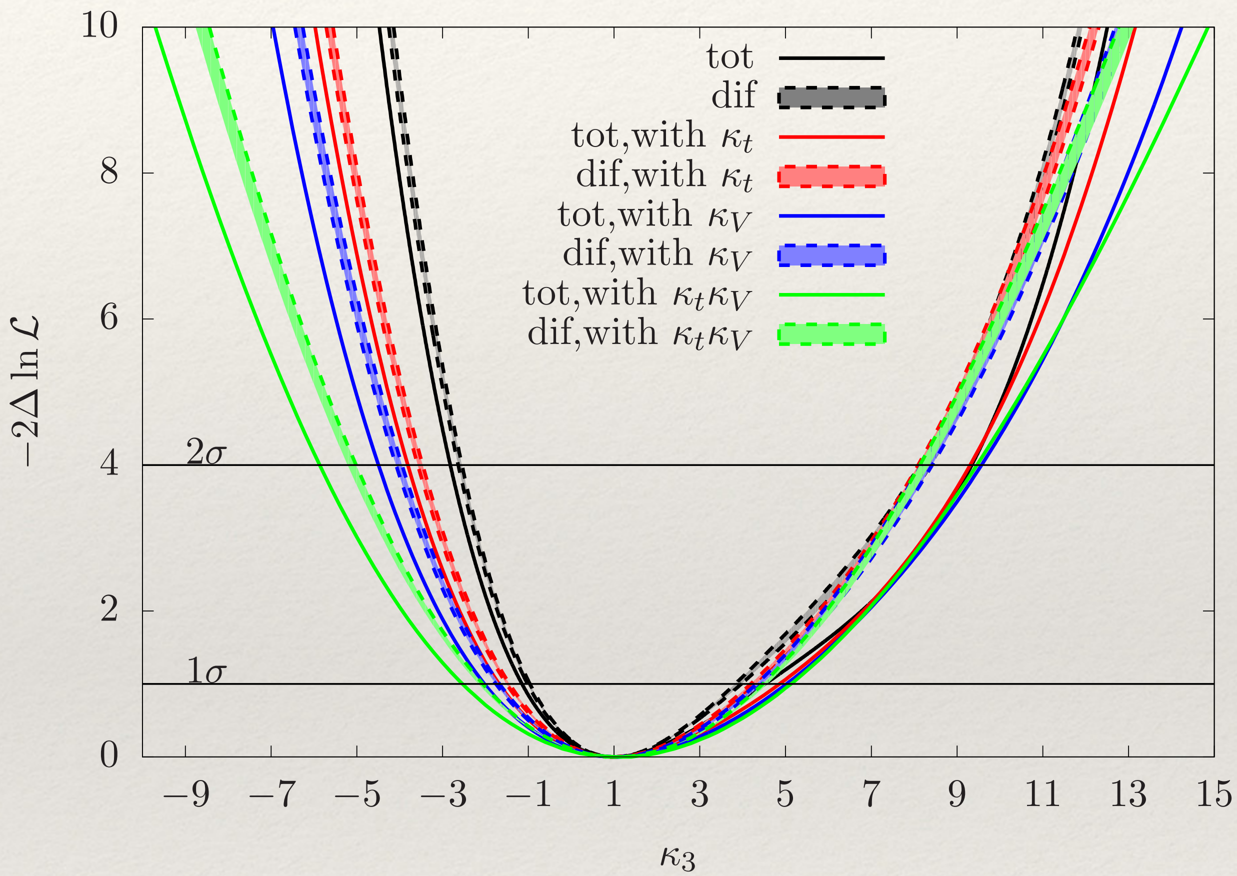
[1709.08649](https://arxiv.org/abs/1709.08649)

3 ab^{-1}



Sensitivity process-by-process to k_λ only

3 ab^{-1}



Black: Global on k_λ . Red: only, k_λ,k_t only.

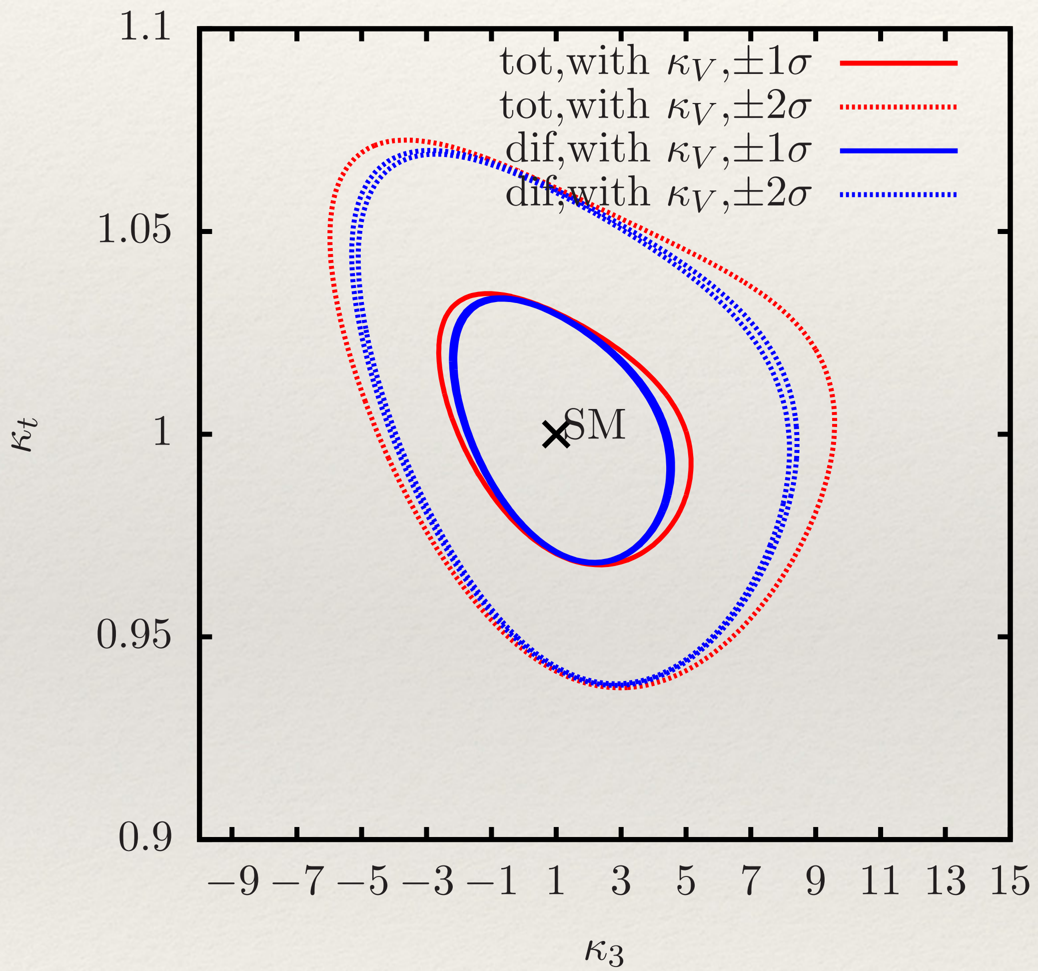
Blue: k_λ,k_V only. Green: all three.

With statistical, theoretical and systematic uncertainties

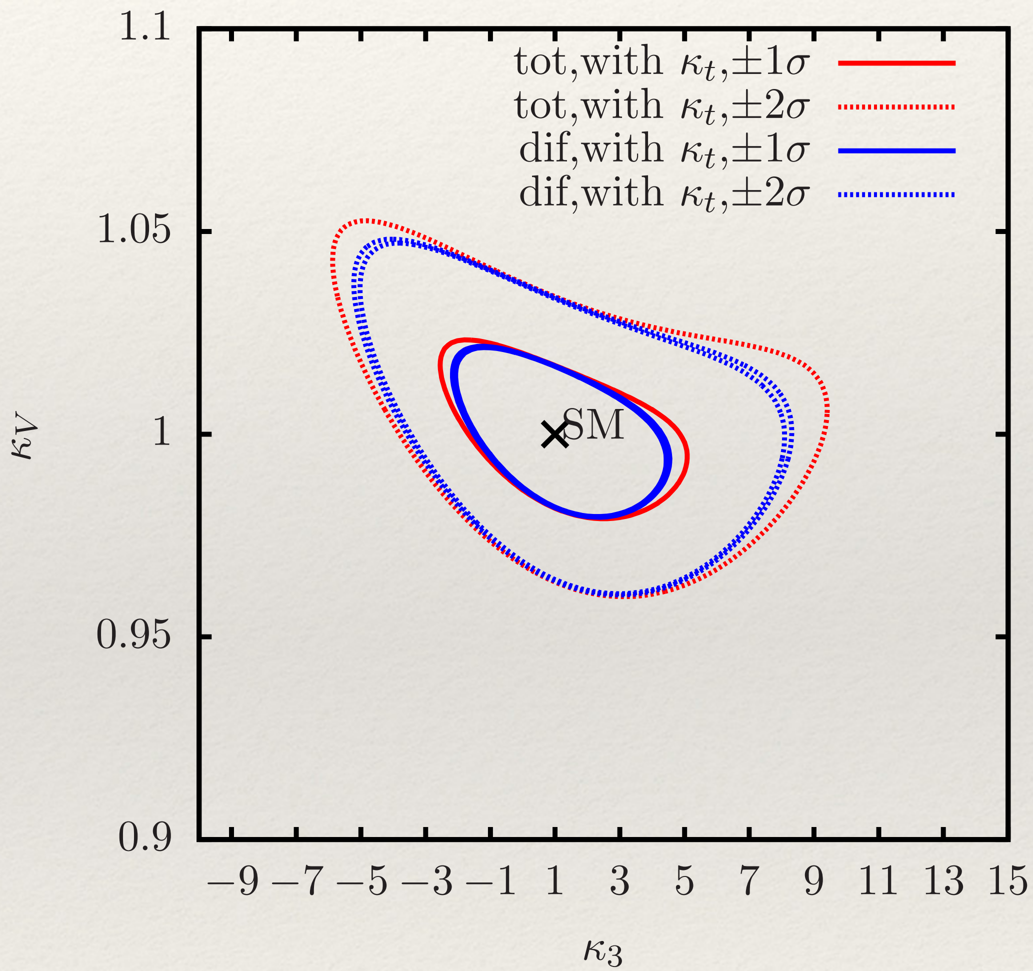
Sentivity study: k_t, k_v,$k\lambda$

1709.08649

3 ab^{-1}



3 ab^{-1}



Global on k_t, k_v, k_l , projected on 2D regions.

With statistical, theoretical and systematic uncertainties

Conclusions and Outlook

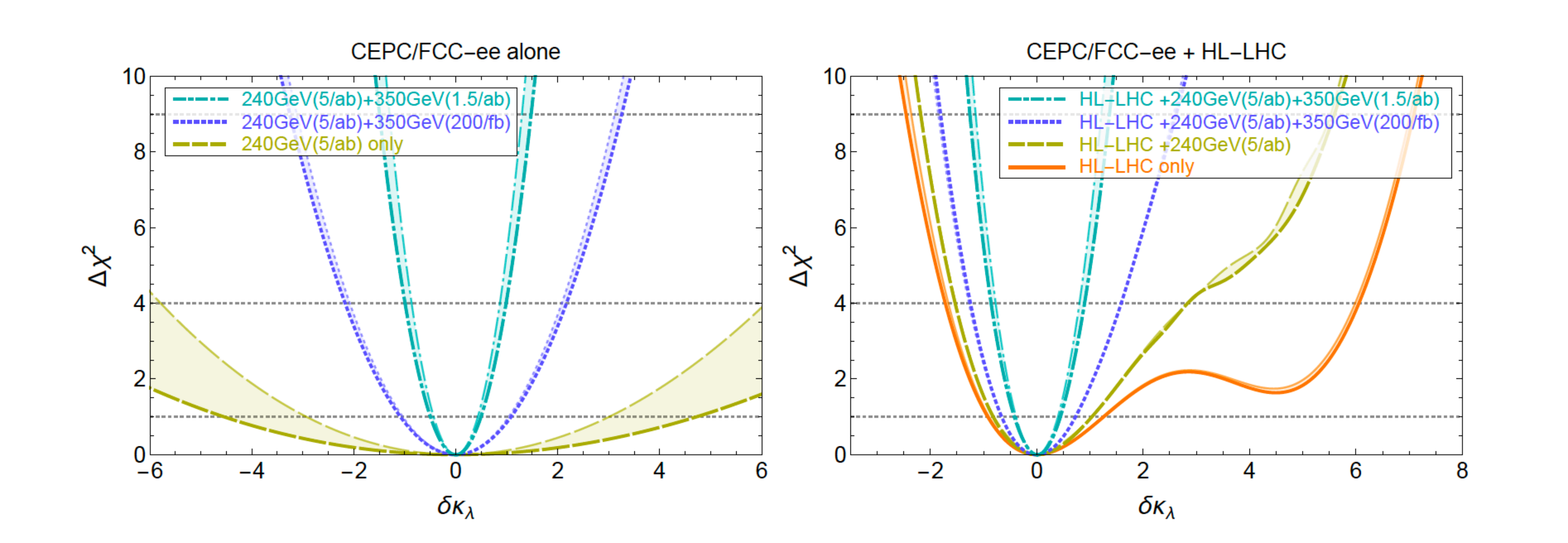
- The determination of the Higgs self coupling is certainly one of the high-priority studies at the LHC.
- Measuring double H production is difficult and extracting information on the self coupling from it even more difficult as it also depends crucially on all other couplings.
- We have put forward the idea of using the global sensitivity of single-Higgs processes at NLO to the Higgs trilinear coupling to gather information on the Higgs potential. Our first exploration shows that the method is promising and could become complementary to that of the direct HH measurements. Independent studies support this conclusion.

Conclusions and Outlook

- Theory progress has been made on several fronts:
  - Understanding whether EFT vs anomalous coupling approaches differ (they don't for the calculations considered so far). More studies on going for other observables/computations.
  - Understanding the model dependence and how large $|\lambda_3|$ can be (with the other Higgs couplings staying close to SM values) in concrete models. Some of the results affect both direct and indirect interpretation of the measurements. More studies welcome and on going.
  - Covering all the set of single Higgs processes, improving the precision and identifying the most promising observables. MC codes for VBF, VH, ttH, tHj are now publicly available.
  - Studying the sensitivity of the global fits in the EFT and in simplified scenarios. Including also differential information and other measurements allows in principle to lift all degeneracies even in quite general cases. Justification of simplified scenarios?

Lepton colliders

1711.03978



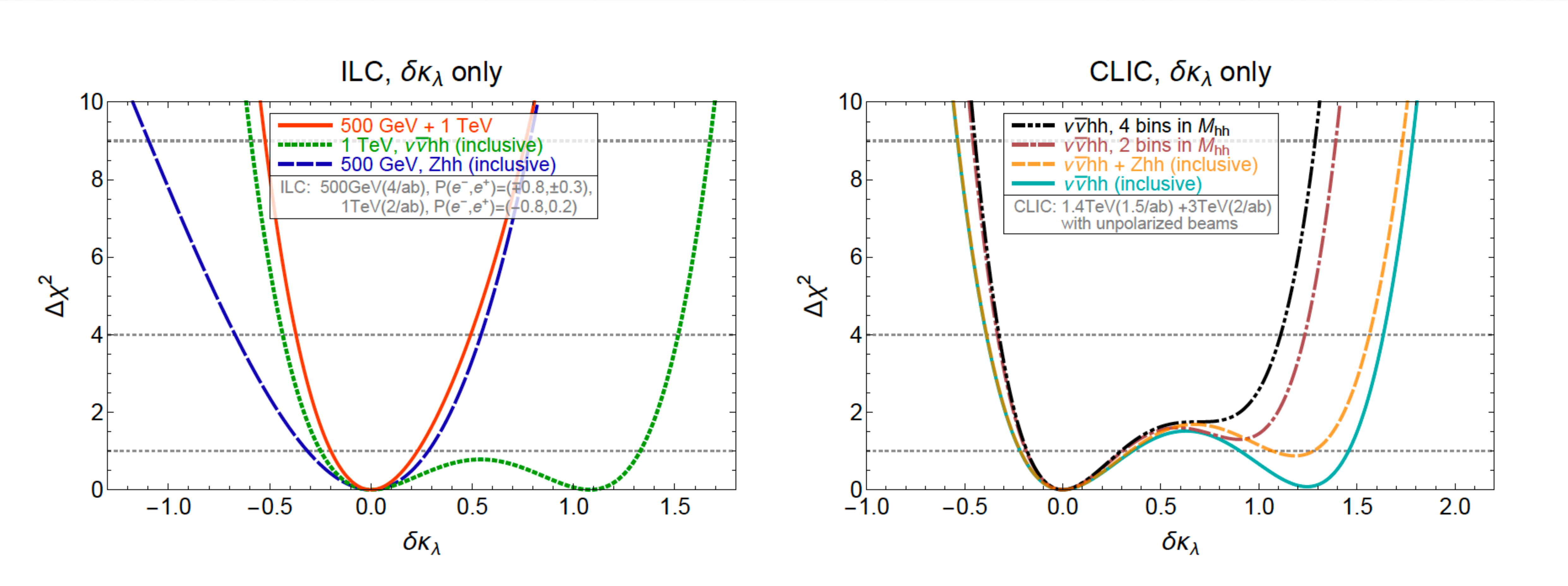
Lepton colliders

1711.03978

	lepton collider alone		lepton collider + HL-LHC	
	non-zero aTGCs	zero aTGCs	non-zero aTGCs	zero aTGCs
HL-LHC alone			[−0.92, +1.26]	[−0.90, +1.24]
CC 240 GeV ($5\,\mathrm{ab}^{-1}$)	[−4.55, +4.72]	[−2.93, +3.01]	[−0.81, +1.04]	[−0.82, +1.03]
+350 GeV ($200\,\mathrm{fb}^{-1}$)	[−1.08, +1.09]	[−1.04, +1.04]	[−0.66, +0.76]	[−0.66, +0.74]
+350 GeV ($1.5\,\mathrm{ab}^{-1}$)	[−0.50, +0.49]	[−0.43, +0.43]	[−0.43, +0.44]	[−0.39, +0.40]
ILC 250 GeV ($2\,\mathrm{ab}^{-1}$)	[−5.72, +5.87]	[−5.39, +5.62]	[−0.85, +1.13]	[−0.85, +1.12]
+350 GeV ($200\,\mathrm{fb}^{-1}$)	[−1.26, +1.26]	[−1.18, +1.18]	[−0.72, +0.83]	[−0.71, +0.80]
+350 GeV ($1.5\,\mathrm{ab}^{-1}$)	[−0.64, +0.64]	[−0.56, +0.56]	[−0.52, +0.54]	[−0.48, +0.50]

Lepton colliders

1711.03978



Lepton colliders

1711.03978