Higgs and Top

Cen Zhang

Institute of High Energy Physics
Chinese Academy of Sciences

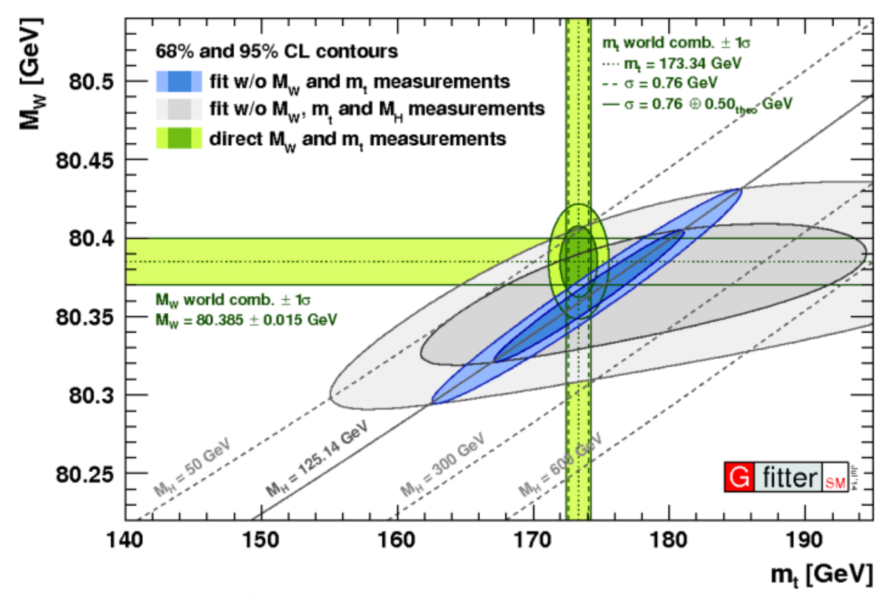
CLHCP 11/7/2020

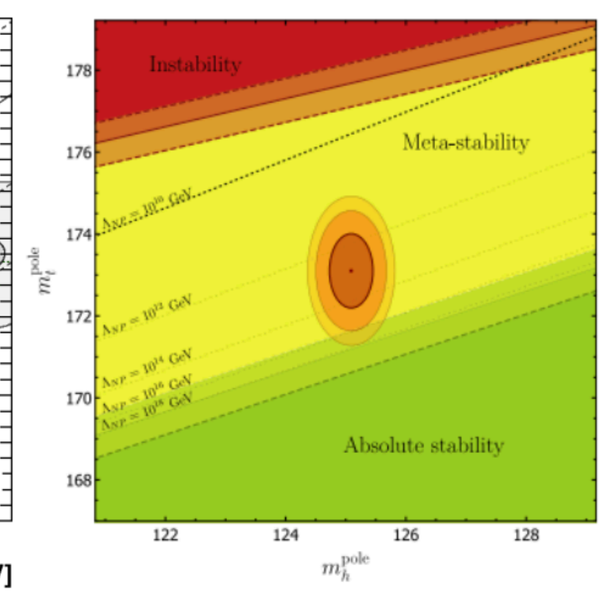
Outline

- Top and Higgs from the EFT perspective. With a focus on:
  - Their interplays at the LHC
  - New theory ideas/tools
  - Global approach
- Will not cover the BSM perspective (see talk by Jia Liu) and the SM theory progresses (see talk by Jian Wang)

Top Quark: A Unique Particle

- **Top quark is the heaviest elementary particle: 172.9±0.4 GeV → y_t=0.994±0.002 (near-unity Yukawa)**
- **Decays (τ_t~0.5x10^{-24}s) before hadronizing & spin-decorrelation →** Bare quark properties, maintains spin-correlation in decay products
- Uniqueness of its phenomenology basically comes from its large mass.
- Large corrections to Electroweak observables.
- Dominant contributions in the Higgs potential → e.g. insights to its origin as well as the lifetime of the Universe



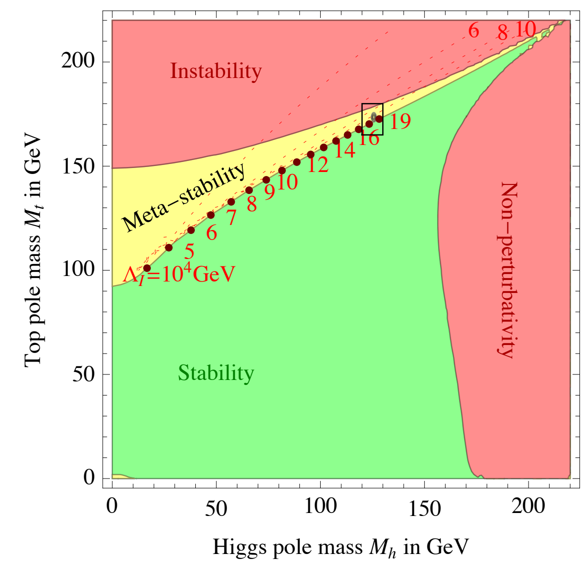


A. Andreassen et al., PRD 97, 056006 (2018)

Talk by Hideki Okawa

The top is special

- **It is rich.** It is the elementary particle with the largest mass so far.
- **It is strong.** $m_{top} = y_t v/\sqrt{2} \approx 174\ \mathrm{GeV} \Rightarrow y_t \approx 1$
- **It is naked.** $\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \cdot 10^{-24}\ s$
  $\tau_{flip} \approx h\, m_t / \Lambda_{QCD}^2 >> \tau_{had}$
  $\tau_{top} \approx h/\Gamma_{top} = 1/(G_F\, m_t^3 |V_{tb}|^2/8\pi\sqrt{2}) \approx 5 \cdot 10^{-25}\ s$
- **It is popular.** σ(tt)~1nb @ LHC13
- **It goes beyond (the SM).** $$\delta m_H^2 = -\frac{3 G_F m_t^2 \Lambda^2}{2\sqrt{2}\pi^2}$$



$$\lambda(M_{Pl}) = -0.0113 - 0.0065(m_t/\mathrm{GeV} - 173.10)$$

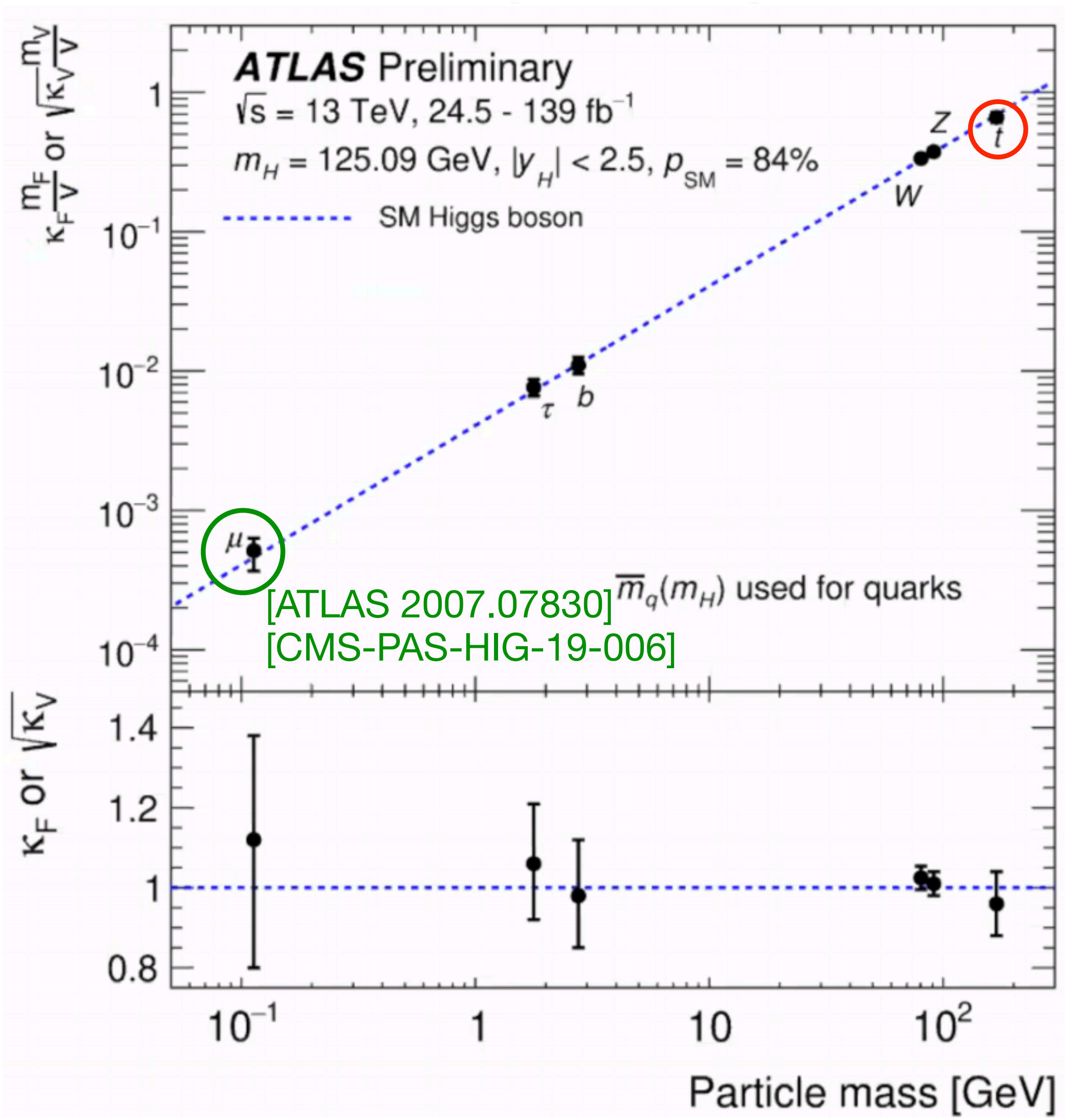
The top is special

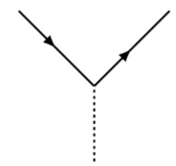
1. **It is rich** m_t~173GeV
2. **It is strong** y_t~1
3. **It is naked** t_{decay}>t_{had}
4. **It is popular** σ_{tt}~1nb @ LHC$_{13}$ top is sensitive to QCD&EW
5. **It goes beyond**

$$\delta m_H^2 = -\frac{3G_F m_t^2 \Lambda^2}{2\sqrt{2}\pi^2} \quad \lambda(M_{Pl}) = -0.0113 - 0.0065(m_t/\text{GeV} - 173.10)$$

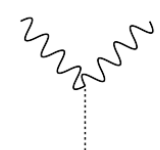
1. **He is rich**
2. **He is strong**
3. **He is (often) naked**
4. **He is (un)popular**
5. **He goes beyond (reason)**

The Top-Higgs coupling in SM





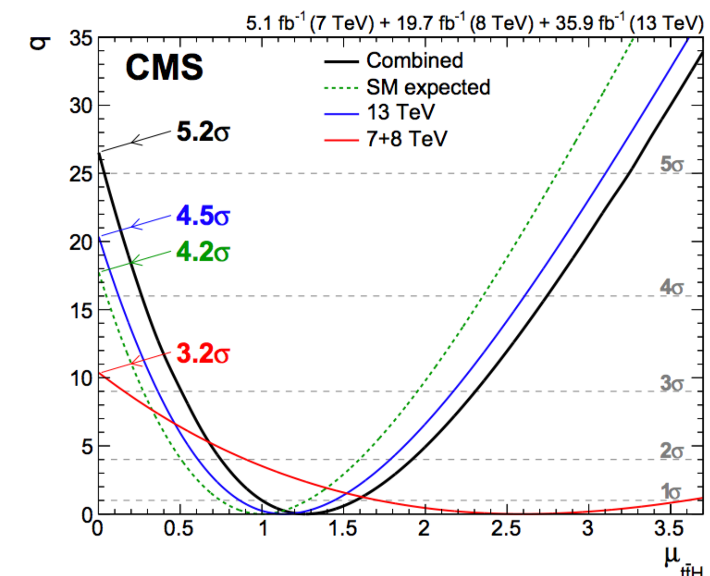
$$i\, m_f / v$$

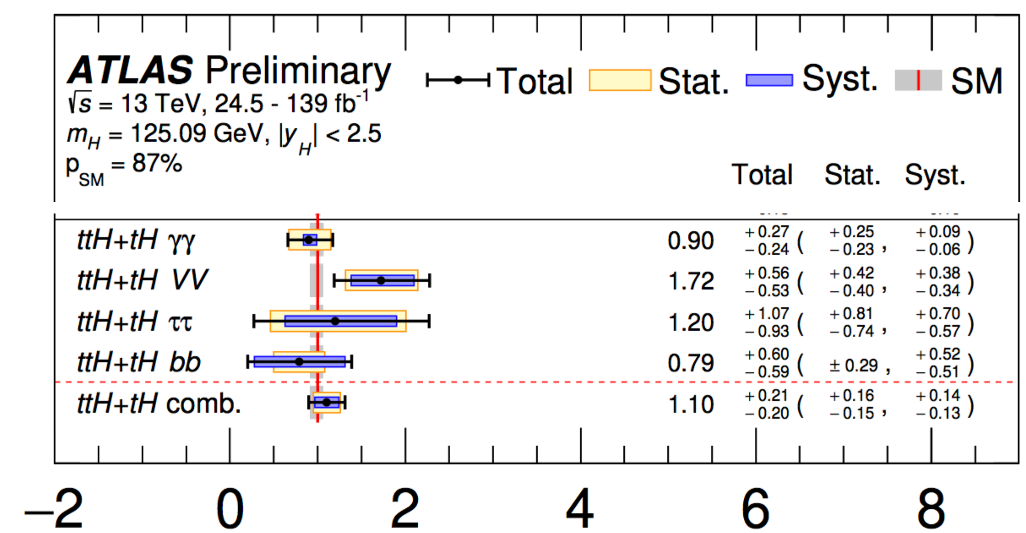


$$i g m_W g_{\mu\nu} = 2 i v g_{\mu\nu} \cdot m_W^2 / v^2$$

$$i g \frac{m_Z}{\cos\theta_W} g_{\mu\nu} = 2 i v g_{\mu\nu} \cdot m_Z^2 / v^2$$

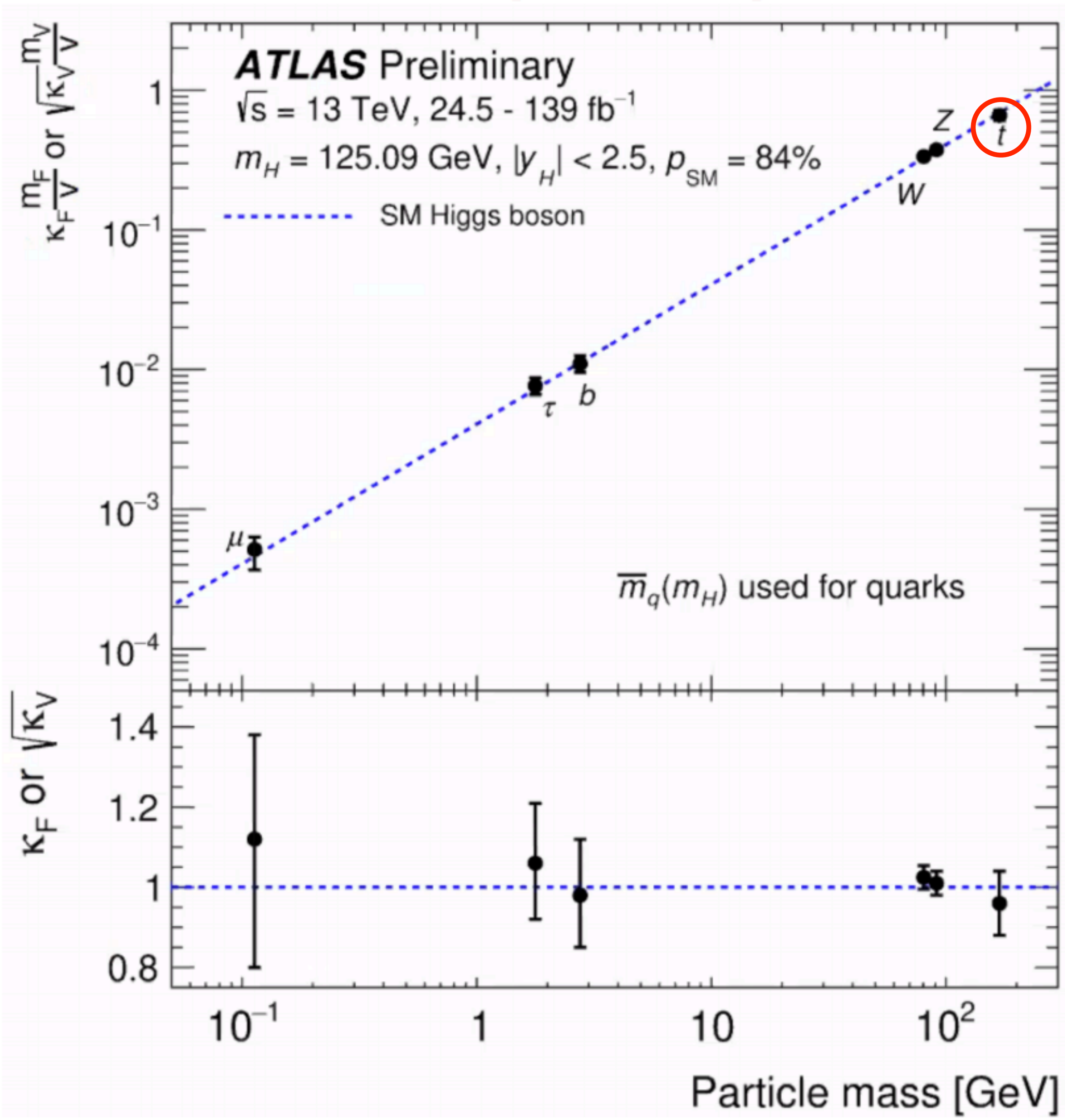
Unique mass generation mechanism for fermions and vectors.

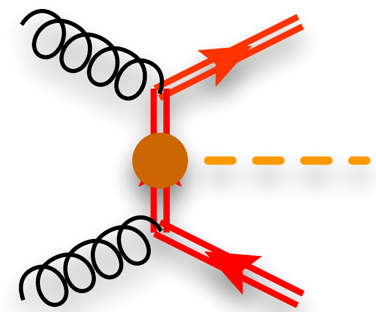




- Mass generation with gauge invariance
- Top is a window to EWSB: enhanced couplings to Goldstone. Higher-dim terms give effects **growing with energy**.

The Top-Higgs coupling beyond SM





SM at dim-4:

$$m_t = \frac{y_t}{\sqrt{2}} = 173\text{GeV} \longrightarrow y_t = 0.99$$

SM at dim-6, SMEFT:

$$\mathcal{L}_{\mathrm{dim}-4} + \frac{C_{t\phi}}{\Lambda^2}(\bar{Q}t)(\phi^\dagger\phi)\tilde{\phi}$$

$$\delta y_t = \frac{C_{t\phi}v^2}{\sqrt{2}\Lambda^2}$$

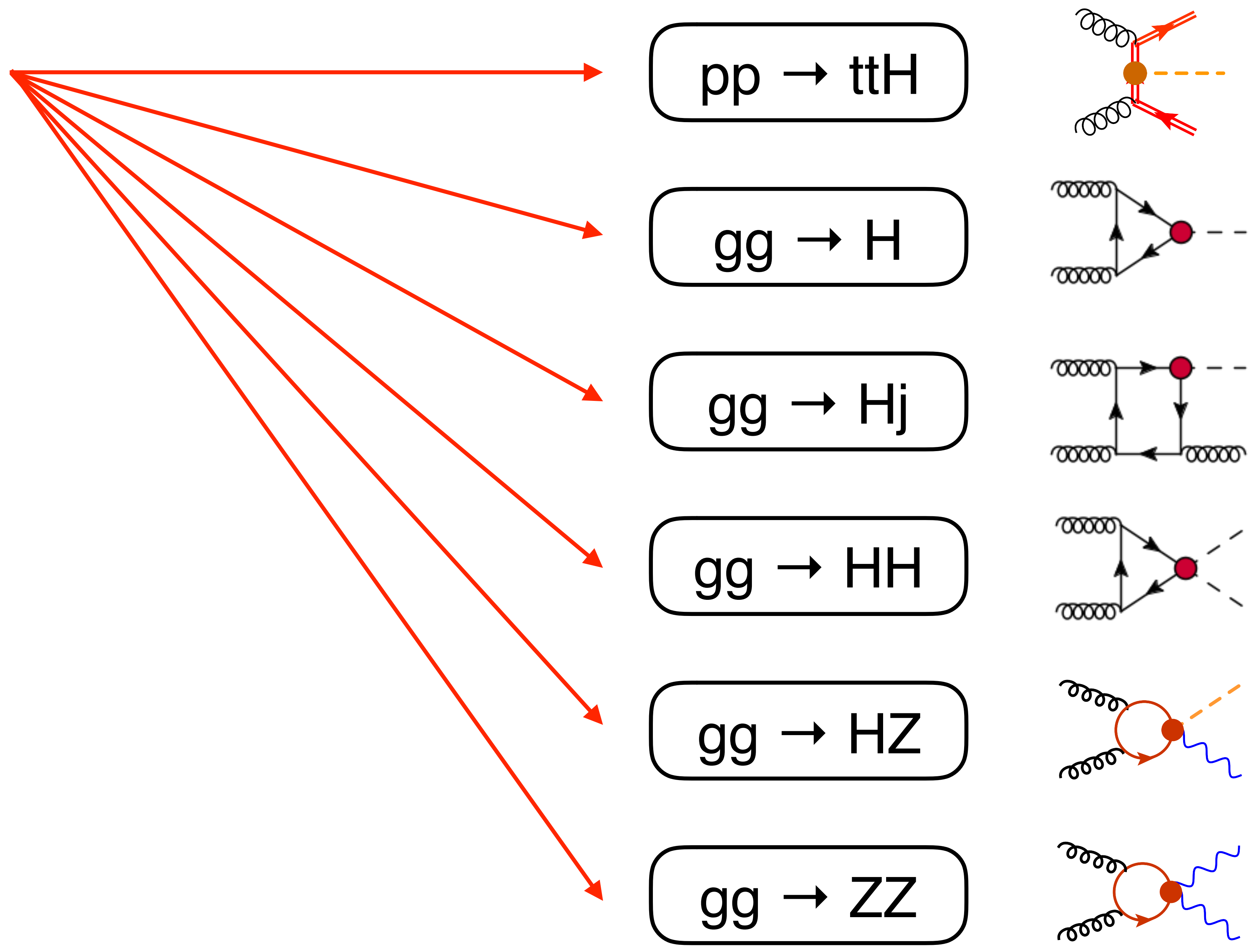
Minimal deviation from SM, with:

- Mass generation with gauge invariance
- Unitarity (up to a predefined scale Λ)
- Perturbativity/renormalizability

See [Ren, Wu, Yang, '19] [Cao, Xie, Zhang, Zhang, '20] for CP test in ttH

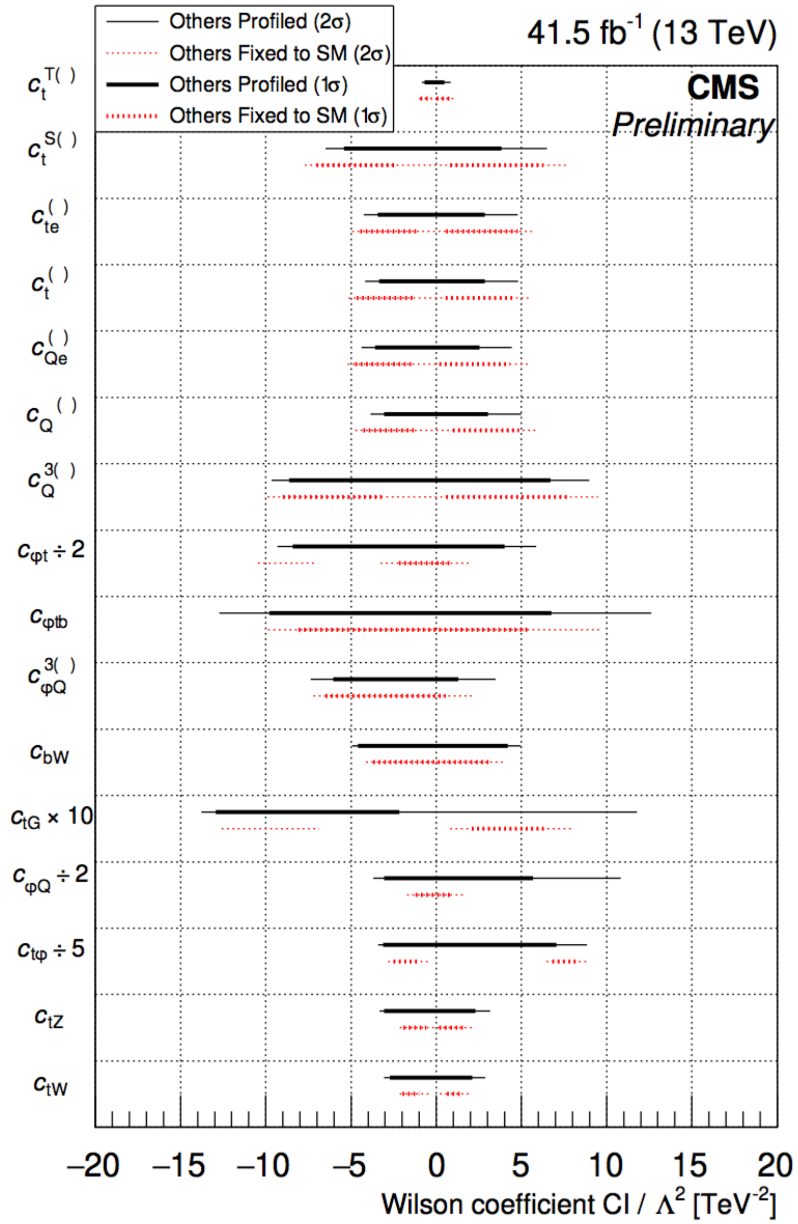
Ideally:

$$\frac{C_{t\phi}}{\Lambda^2}(\bar{Q}t)(\phi^\dagger\phi)\tilde{\phi}$$

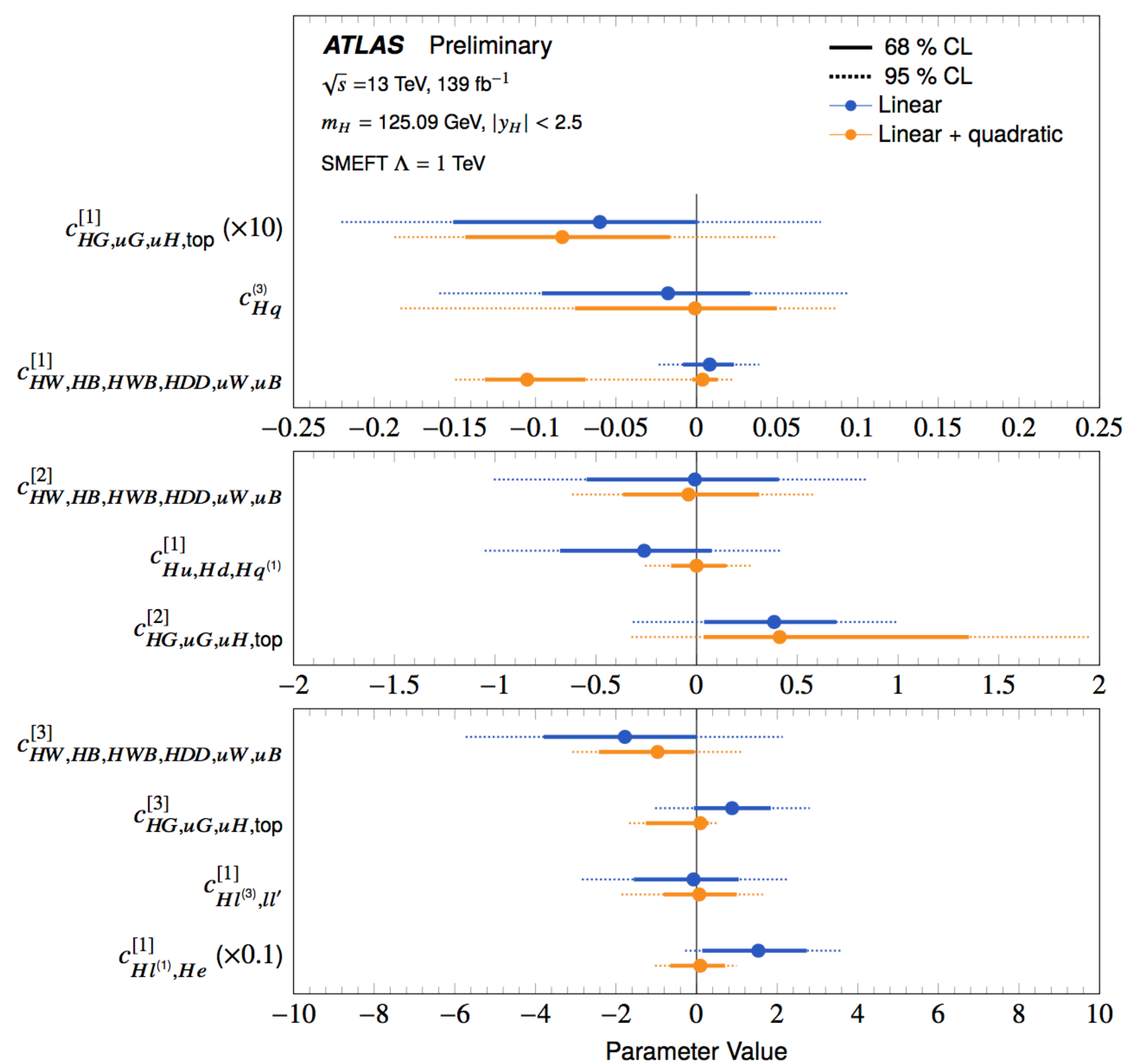


Global SMEFT approach

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i^{(6)} O_i^{(6)}}{\Lambda^2} + \sum_i \frac{f_i^{(8)} O_i^{(8)}}{\Lambda^4} + \cdots$$

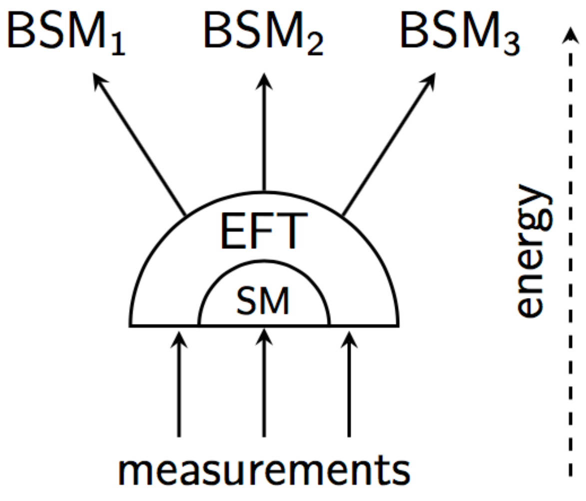


ATLAS-CONF-2020-053



Global SMEFT approach

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{f_i^{(6)} O_i^{(6)}}{\Lambda^2} + \sum_i \frac{f_i^{(8)} O_i^{(8)}}{\Lambda^4} + \cdots$$



Dim-6 operators are present in different sectors:
Higgs, Top, Electroweak, Flavor…

A global SMEFT allows to:

- **Maximize the information from measurements**, and at the same time keep some model-independence.
- **Investigate the interplay between different measurements** (from different SM sectors, e.g. Higgs and Top).

In reality:

$$\frac{C_{t\phi}}{\Lambda^2}(\bar{Q}t)(\phi^\dagger\phi)\tilde{\phi}$$

Top-EW

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

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

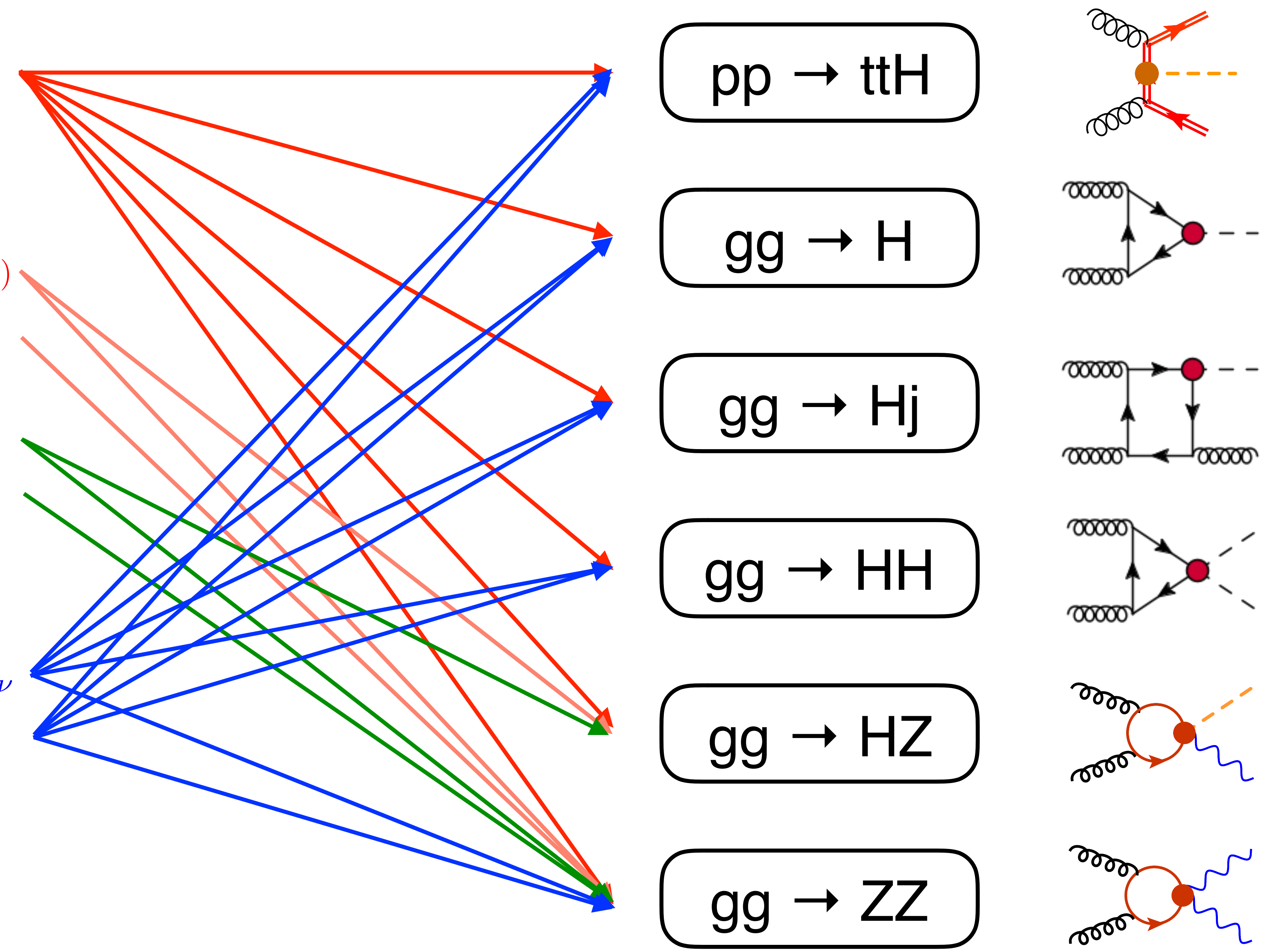
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

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

QCD

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

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



More operators

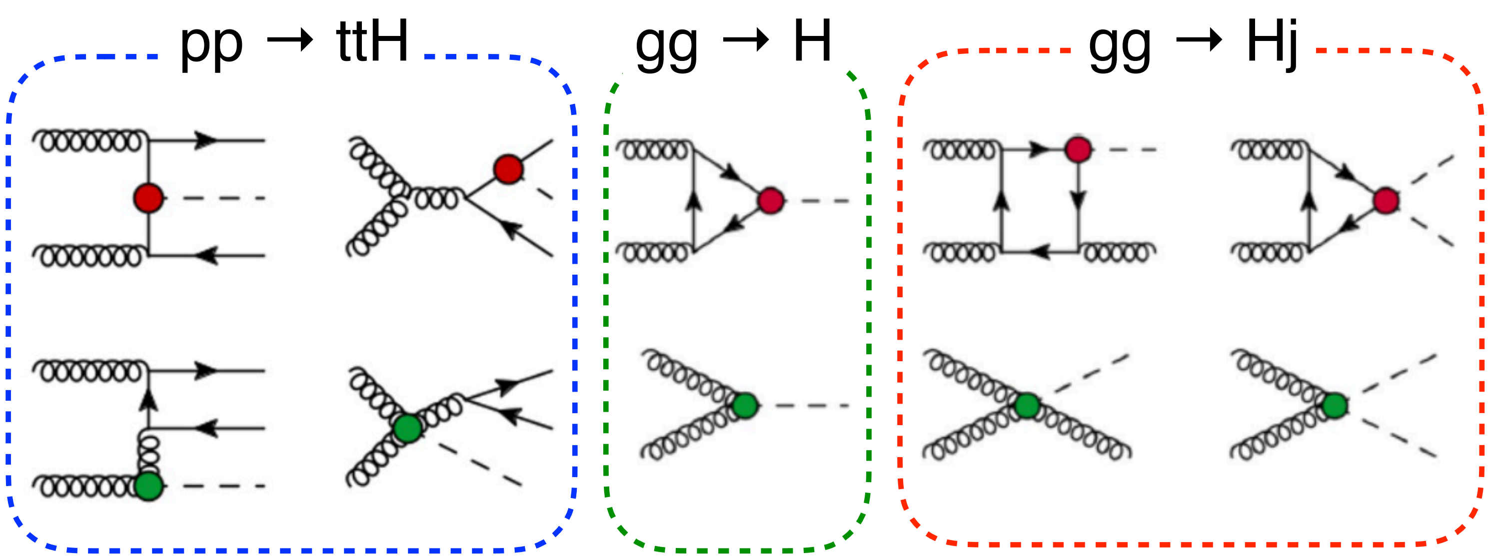
More measurements

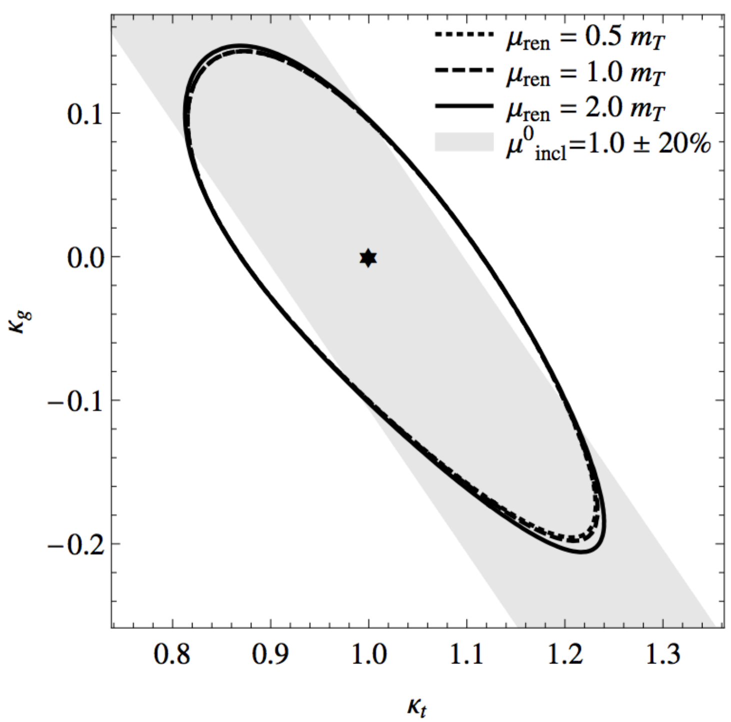
Start from two interactions

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

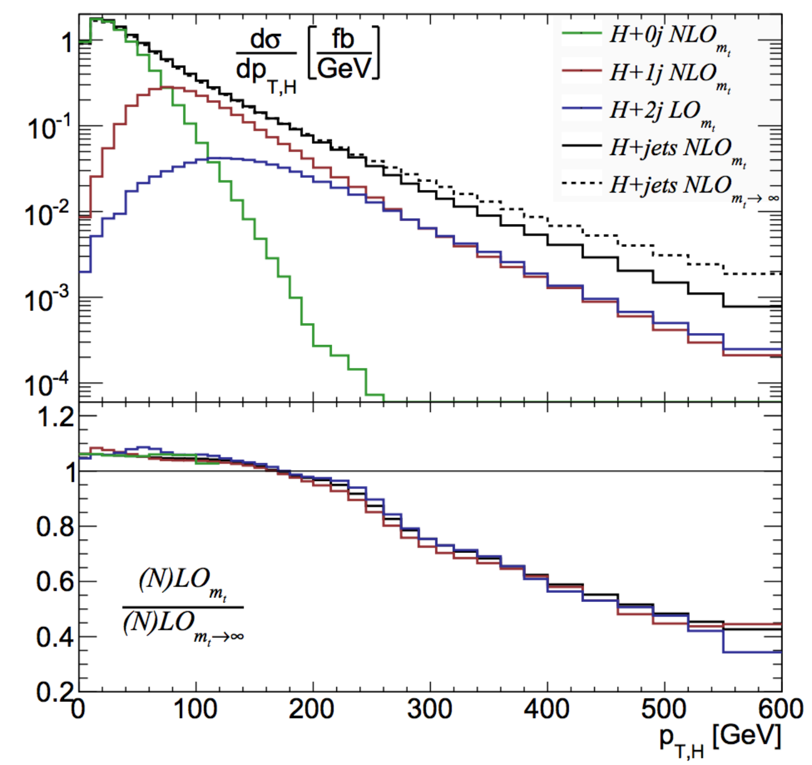
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

Use with multiple channels to break degeneracy, and extract maximal information from measurements



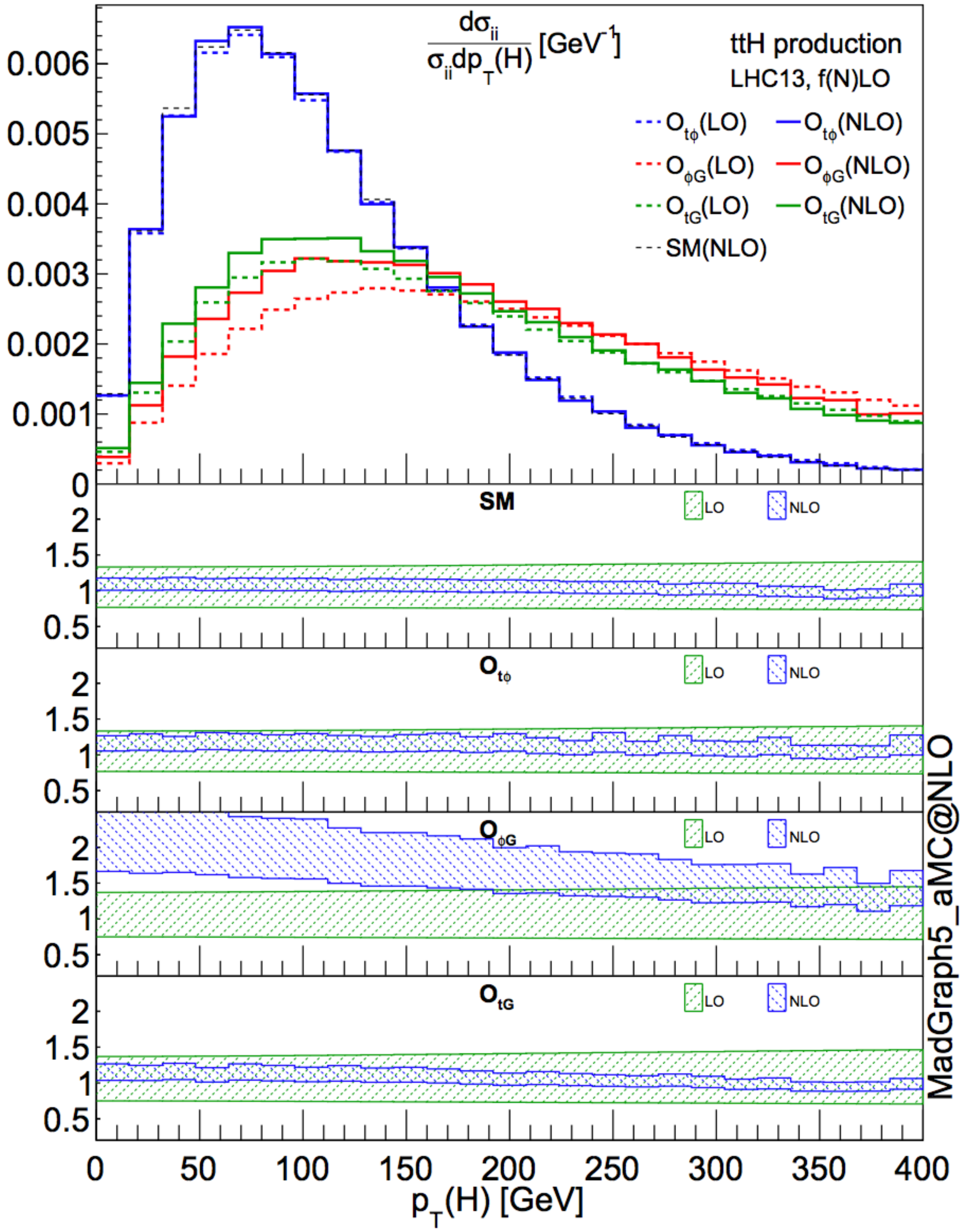


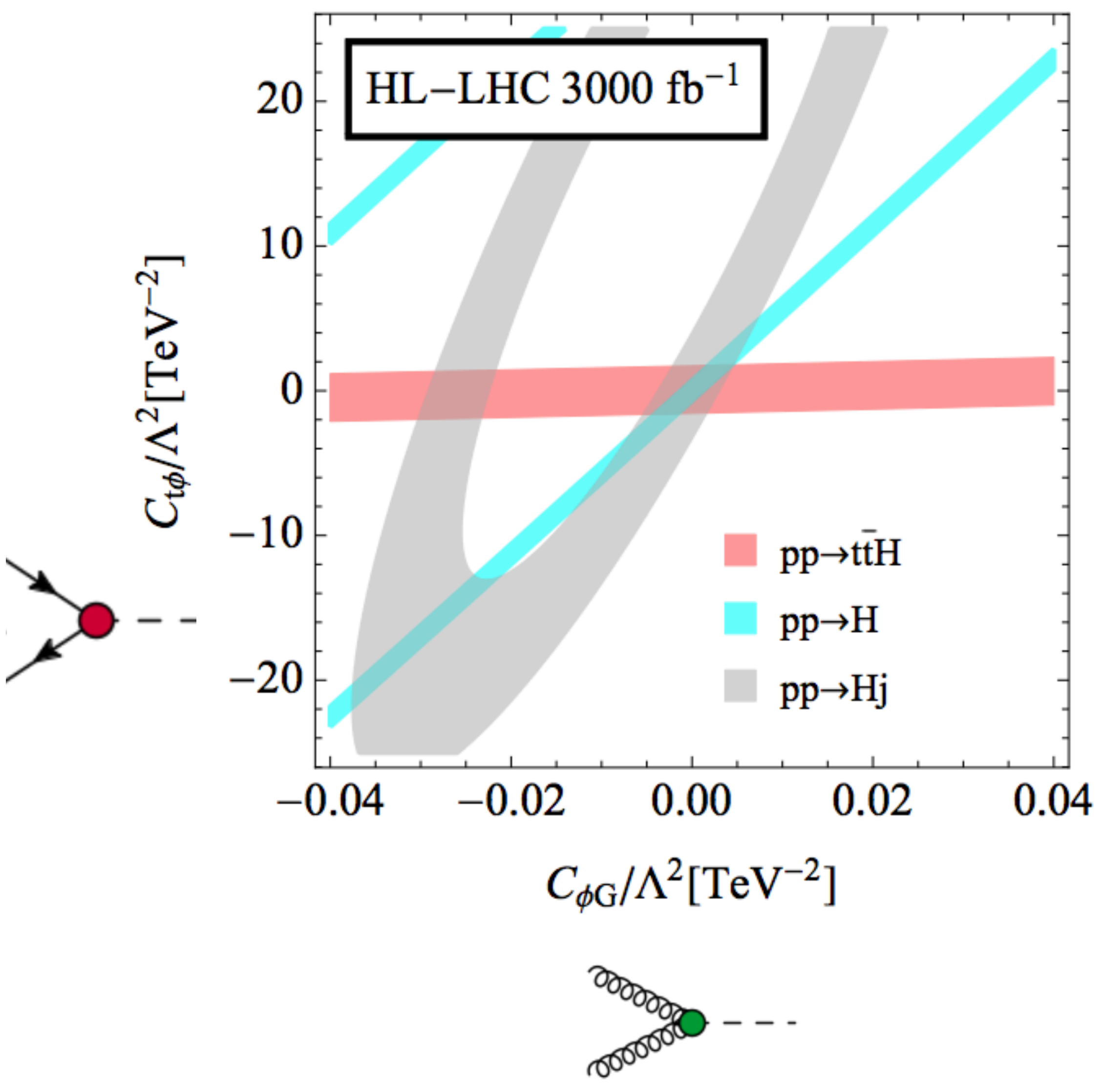
[C. Grojean et al., 1312.3317]



[M. Buschmann et al., 1410.5806]

Differential information

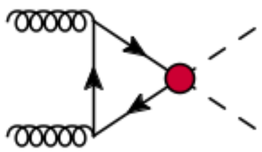




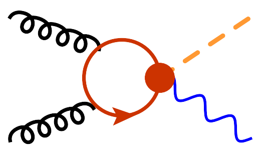
[Vryonidou, Maltoni, CZ, 1607.05330]

More possibilities

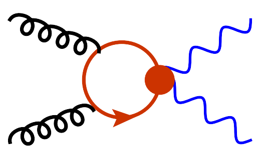
Other gg-initiated channels that resolve the loop / break degeneracy

HH 

Sensitive to ttH (ttHH contact term)
[Goertz, Papaefstathiou, Yang, Zurita, 1410.3471]

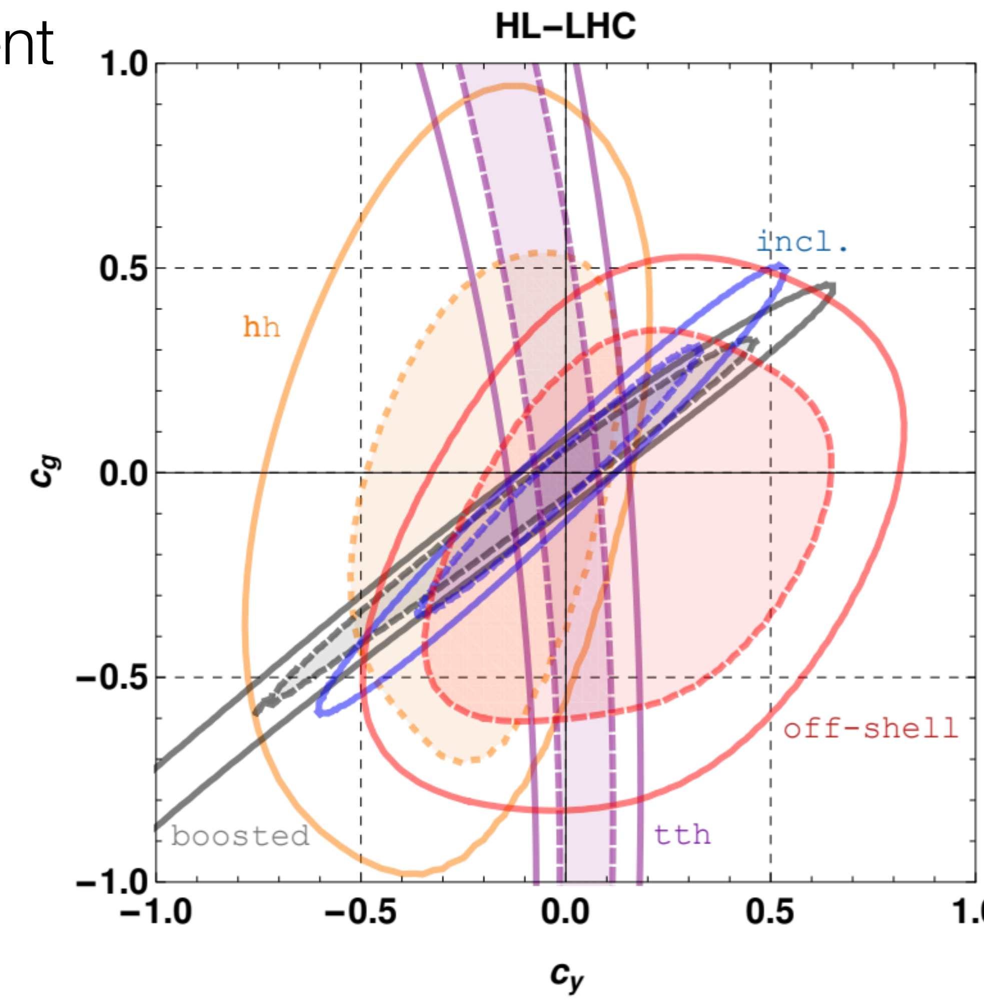
HZ 

Insensitive to ggH (and dipole);
Probe **ttZ** with energy enhancement

ZZ 

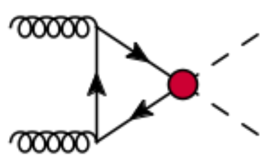
Probe **ttZ** (and ggH) with
less (more) energy enhancement
(See talk by Bin Yan)

[A. Azatovet al., 1608.00977]



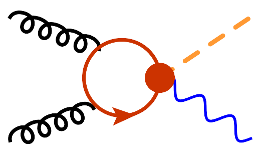
More possibilities

Other gg-initiated channels that resolve the loop / break degeneracy

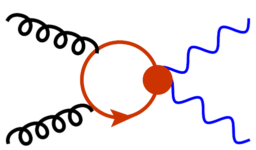
HH 

Sensitive to ttH (ttHH contact term)

[Goertz, Papaefstathiou, Yang, Zurita, 1410.3471]

HZ 

Insensitive to ggH (and dipole);
Probe **ttZ** with energy enhancement

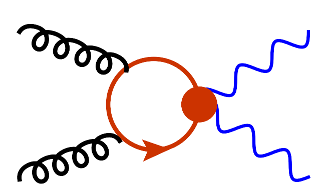
ZZ 

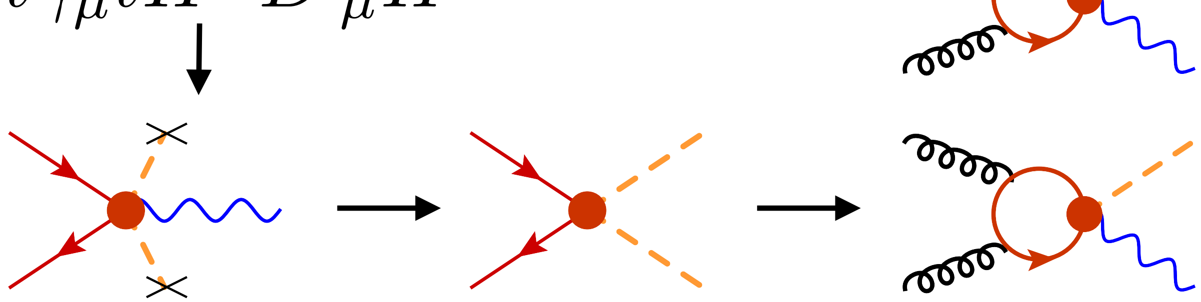
Probe **ttZ** (and ggH) with
less (more) energy enhancement

(See talk by Bin Yan)

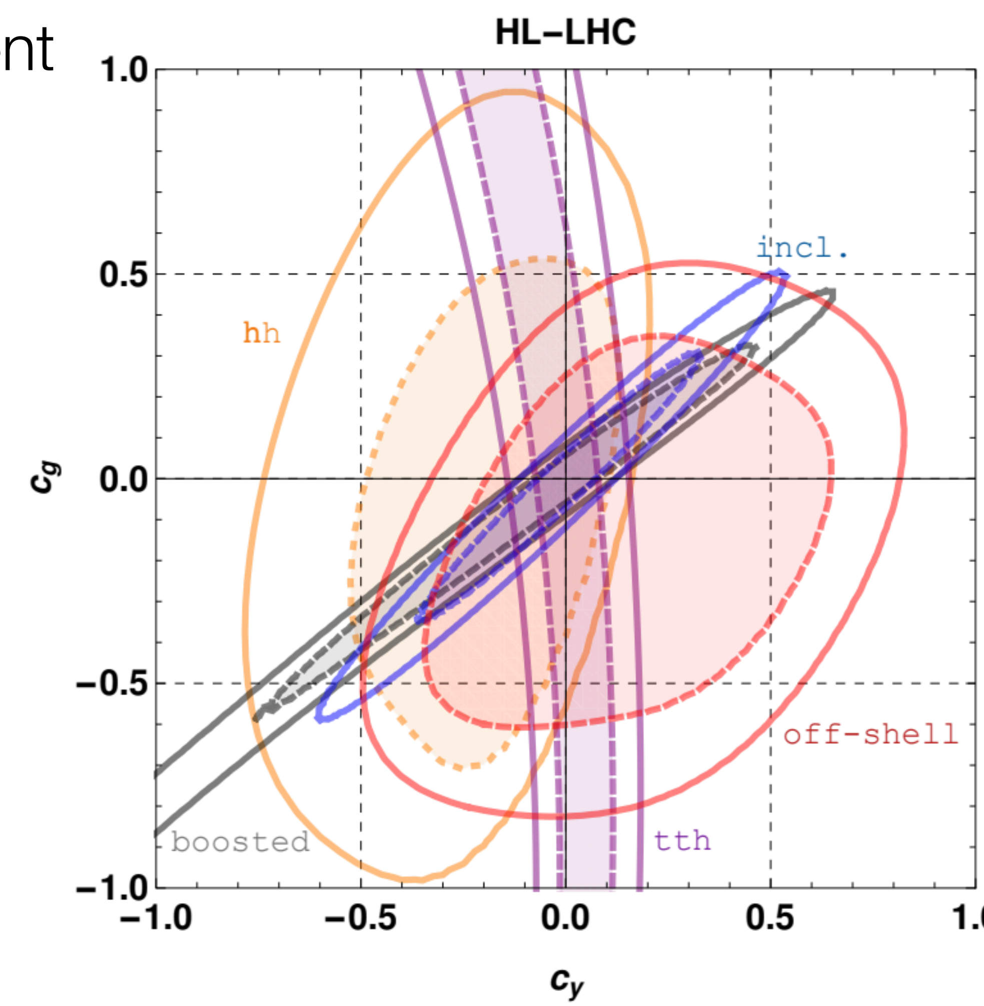
ttZ vertex

$$\bar{t}\gamma_\mu t H^\dagger \overleftrightarrow{D}_\mu H$$





[A. Azatovet al., 1608.00977]



Connecting top, Higgs, and EW in SMEFT

SM Lagrangian is the most general renormalizable one. Couplings are all fixed by a few input parameters (G_F, m_W, m_Z, a_S…)

- **To deviate from SM couplings, need the Higgs vev to reduce dim-6 terms down to dim-4 SM-like couplings.**
- Vev <-> H <-> Goldstone <-> Longitudinal modes of massive boson.

W,Z

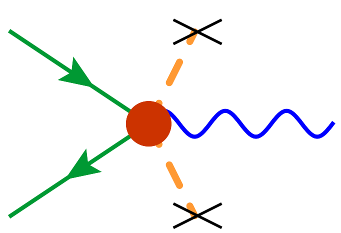
$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} -i(\phi^1 - i\phi^2) \\ v + (h + i\phi^3) \end{pmatrix}$$

  - Non-Higgs measurements (through vev) are connected to Higgs couplings.
  - Higgs can be used as a tool to probe EW/top sectors.
  - Activating vev -> H/Goldstone gives rise to energy-enhanced sensitivity. v^2 -> E^2
  - Top has a strong coupling to Goldstones and is a window to EWSB.
  - More interplay in loops.

Higgs as a probe of EW sector

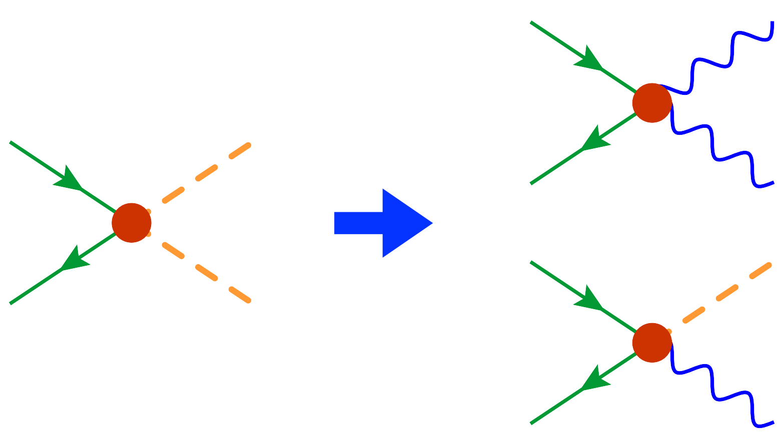
qqZ $\mathcal{O}_u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$

Constrained in EWPO, by $H \to v/\sqrt{2}$



$$\frac{v^2}{\Lambda^2}$$

What if H is active, by $H \to h/\sqrt{2}$?



$$\frac{s}{\Lambda^2}$$

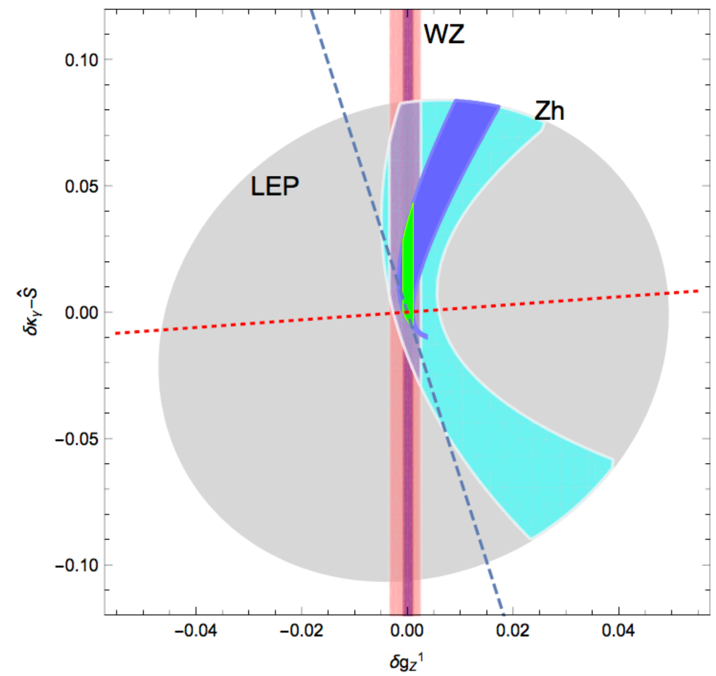


FIG. 2: We show in light blue (dark blue) the projection for the allowed region with 300 fb^{-1} (3 ab^{-1}) data from the $pp \to Zh$ process for universal models in the $\delta\kappa_\gamma - \hat{S}$ vs δg_1^Z plane. The allowed region after LEP bounds (taking the TGC $\lambda_\gamma = 0$, a conservative choice) are imposed is shown in grey. The pink (dark pink) region corresponds to the projection from the WZ process with 300 fb^{-1} (3 ab^{-1}) data derived in Ref. [20] and the purple (green) region shows the region that survives after our projection from the Zh process is combined with the above WZ projections with 300 fb^{-1} (3 ab^{-1}) data.

[R. Franceschini et al. 1712.01310]

[S. Banerjee et al. 1807.01796]

[C. Grojean et al. 1810.05149]

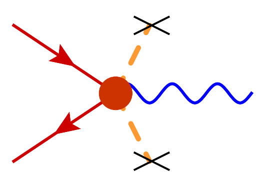
ttZ vs ttWj

$$\bar{t}\gamma_\mu t H^\dagger \overleftrightarrow{D}_\mu H$$

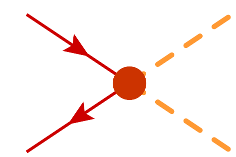
H -> vev

$\delta \sim \frac{v^2}{\Lambda^2}$

ttZ coupling
from tt+Z production



H -> Goldstone



$\delta \sim \frac{E^2}{\Lambda^2}$

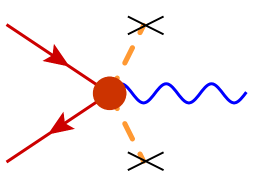
i.e. tW>tW scattering?

ttZ vs ttWj

$$\bar{t}\gamma_\mu t H^\dagger \overleftrightarrow{D}_\mu H$$

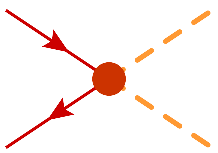
$\delta \sim \frac{v^2}{\Lambda^2}$

ttZ coupling
from tt+Z production



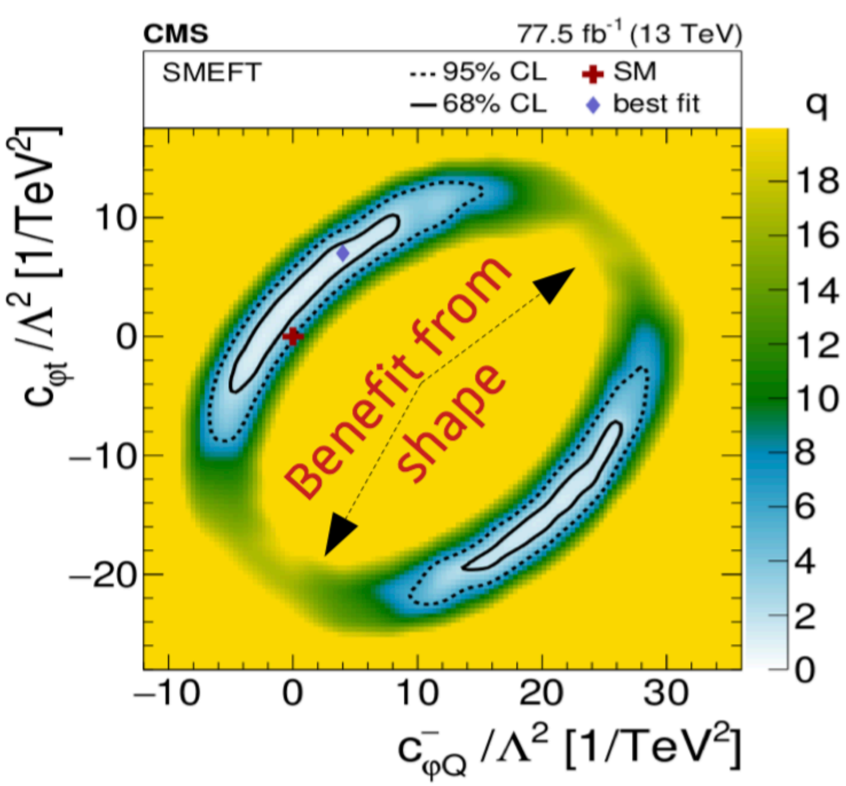
H -> vev

H -> Goldstone



$\delta \sim \frac{E^2}{\Lambda^2}$

i.e. tW>tW scattering?



[CMS JHEP03(2020)056]

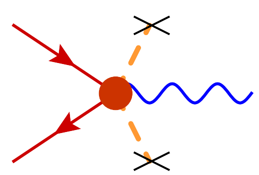
ttZ vs ttWj

$$\bar{t}\gamma_\mu t H^\dagger \overleftrightarrow{D}_\mu H$$

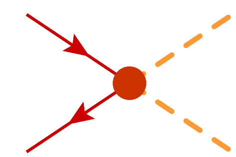
$\delta \sim \frac{v^2}{\Lambda^2}$

ttZ coupling
from tt+Z production

H -> vev

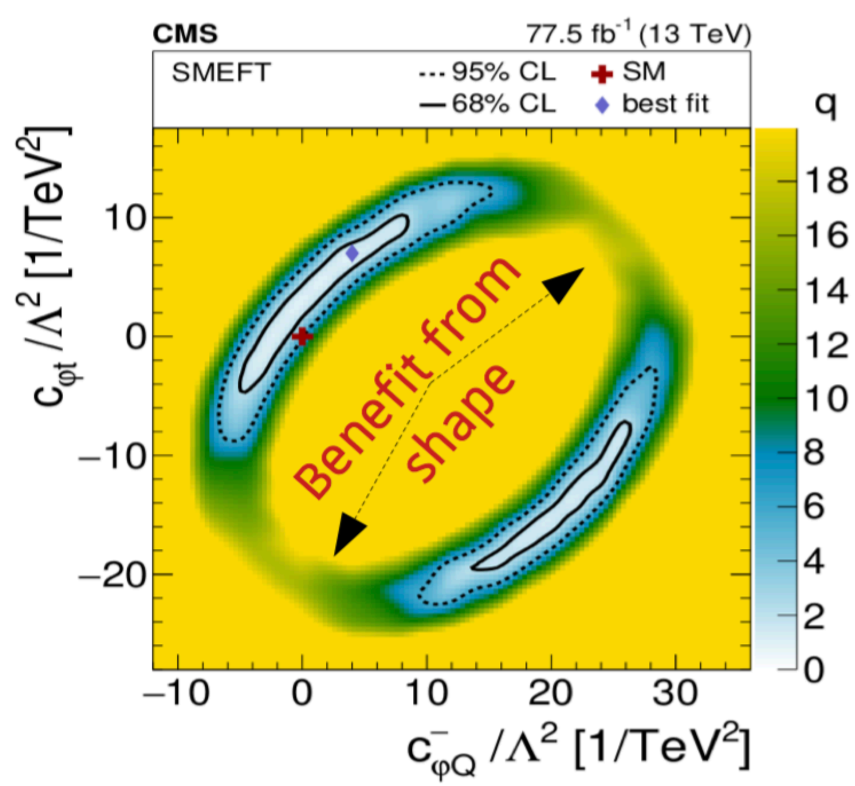


H -> Goldstone

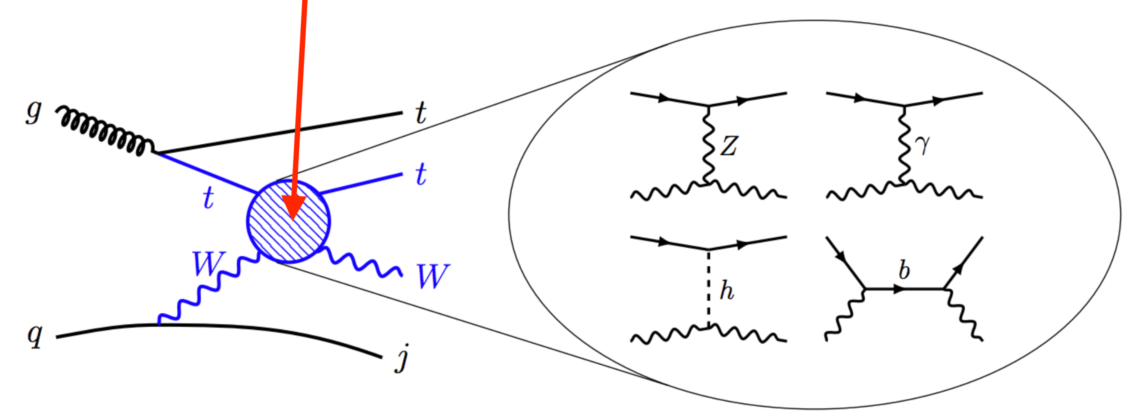


$\delta \sim \frac{E^2}{\Lambda^2}$

i.e. tW>tW scattering?



[CMS JHEP03(2020)056]



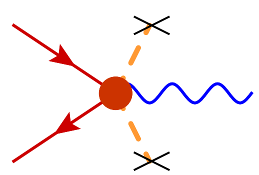
ttZ vs ttWj

$$\bar{t}\gamma_\mu t H^\dagger \overleftrightarrow{D}_\mu H$$

H -> vev

$\delta \sim \frac{v^2}{\Lambda^2}$

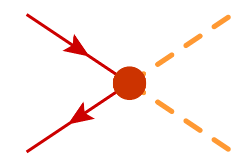
ttZ coupling
from tt+Z production

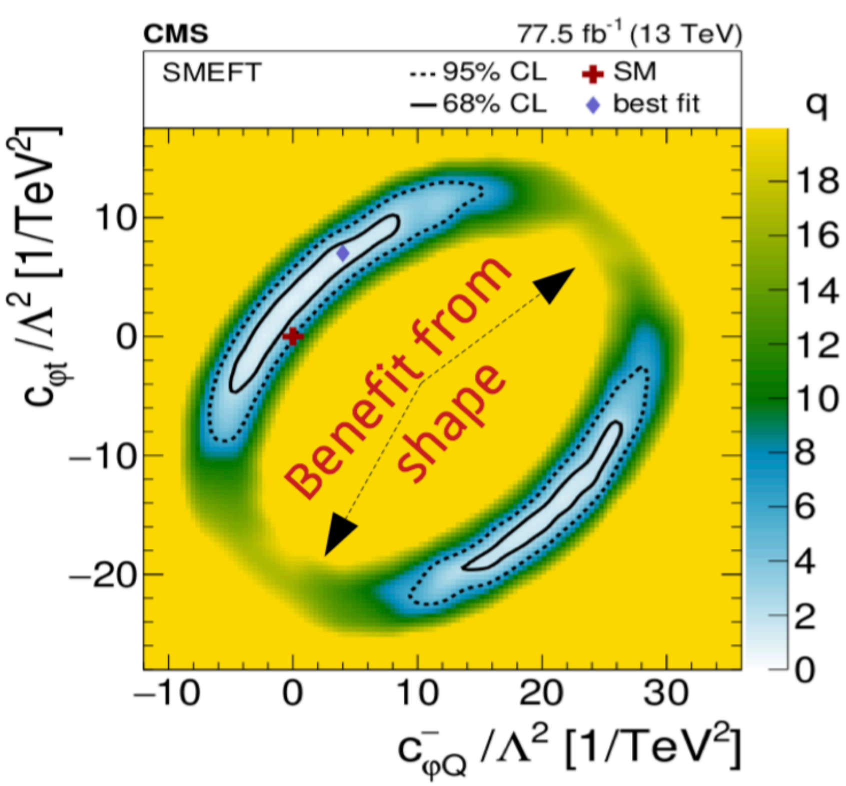


H -> Goldstone

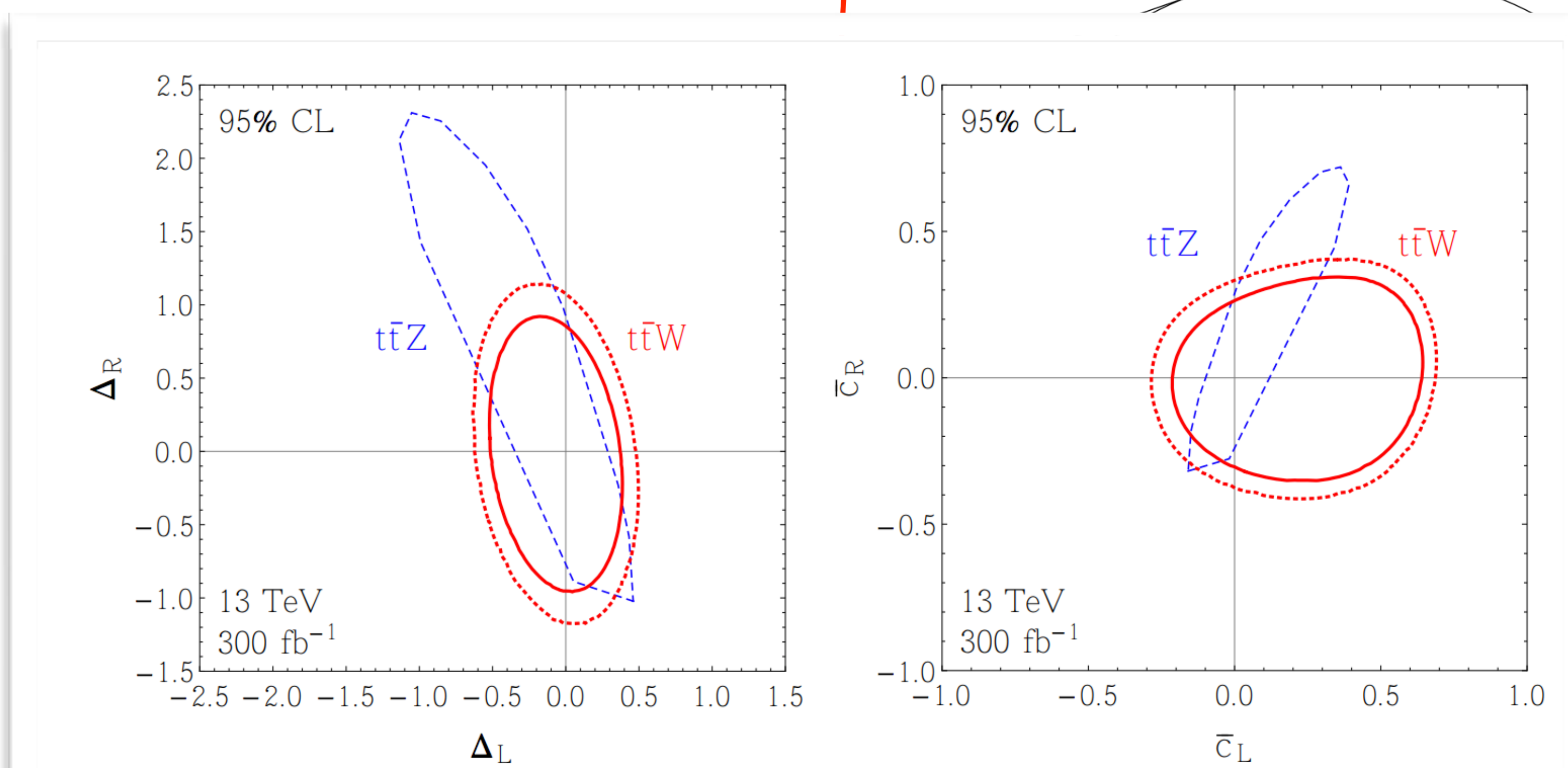
$\delta \sim \frac{E^2}{\Lambda^2}$

i.e. tW>tW scattering?





[CMS JHEP03(2020)056]

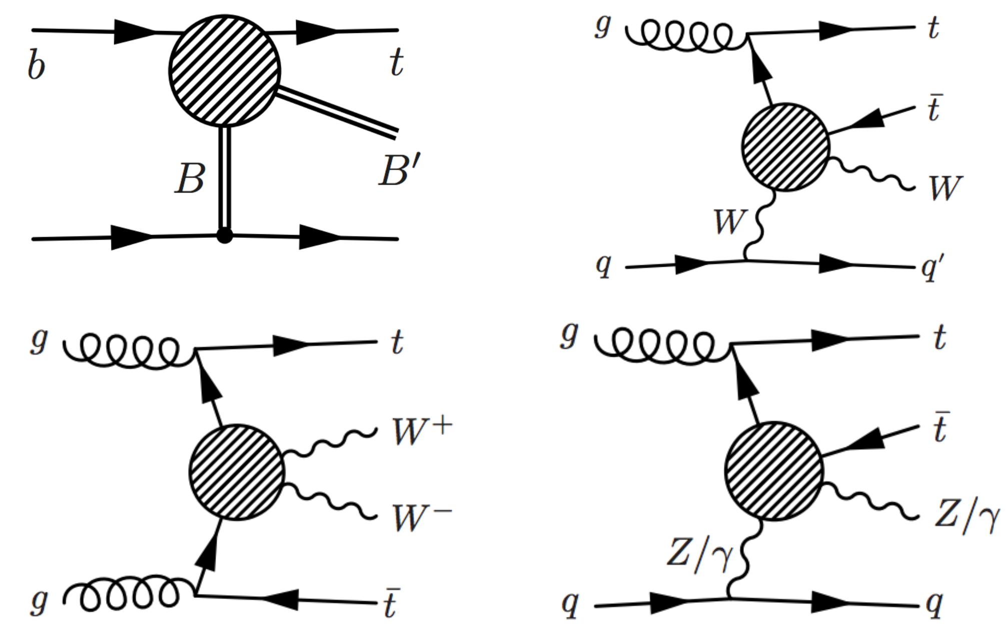


[J. Dror et al., 1511.03674]

More high energy tops

	Single-top		Two-top ($t\bar{t}$)	
w/o Higgs	$b\,W \to t\,(Z/\gamma)$	(4.1.1)	$t\,W \to t\,W$	(5.1.1)
			$t\,(Z/\gamma) \to t\,(Z/\gamma)$	(5.1.4)
w/ Higgs	$b\,W \to t\,h$	(4.2.1)	$t\,(Z/\gamma) \to t\,h$	(5.2.1)
			$t\,h \to t\,h$	(5.2.4)

Helicity amplitudes computed, and energy-growing channels identified



- **tZW and tZj optimal to access b W to t Z.**
- **tHW and tHj optimal for b W to t H.**
- **ttX processes are challenging because suppressed by s-channel propagator.**
- **Adding a jet increase the sensitivity (J. A. Dror et al. arXiv:1511.03674).**
- **ttXY and VBF-tt are promising but rate-limited (e+ e- collider for VBF).**
- **t Z to t H and t H to t H are the most difficult (future colliders).**

Mantani, talk at EPSHEP 2019
[Maltoni, Mantani, Mimasu, 1904.05637]

Single top+Higgs/Z: helicity amplitudes

[Degrande et al.; JHEP 1810 (2018) 005]

tHj 2>2 sub-amplitude: bW>tH

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

$\mathcal{O}_{\phi tb}, \ \lambda_b = +$

λ_t \ λ_W	0	$+$	$-$
$+$	$\sqrt{s(s+t)}$	$m_W\sqrt{-t}$	$\frac{1}{\sqrt{s}}$
$-$	$m_t\sqrt{-t}$	s^0	s^0

Single top+Higgs/Z: helicity amplitudes

[Degrande et al.; JHEP 1810 (2018) 005]

tZj 2>2 sub-amplitude: bW>tZ

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

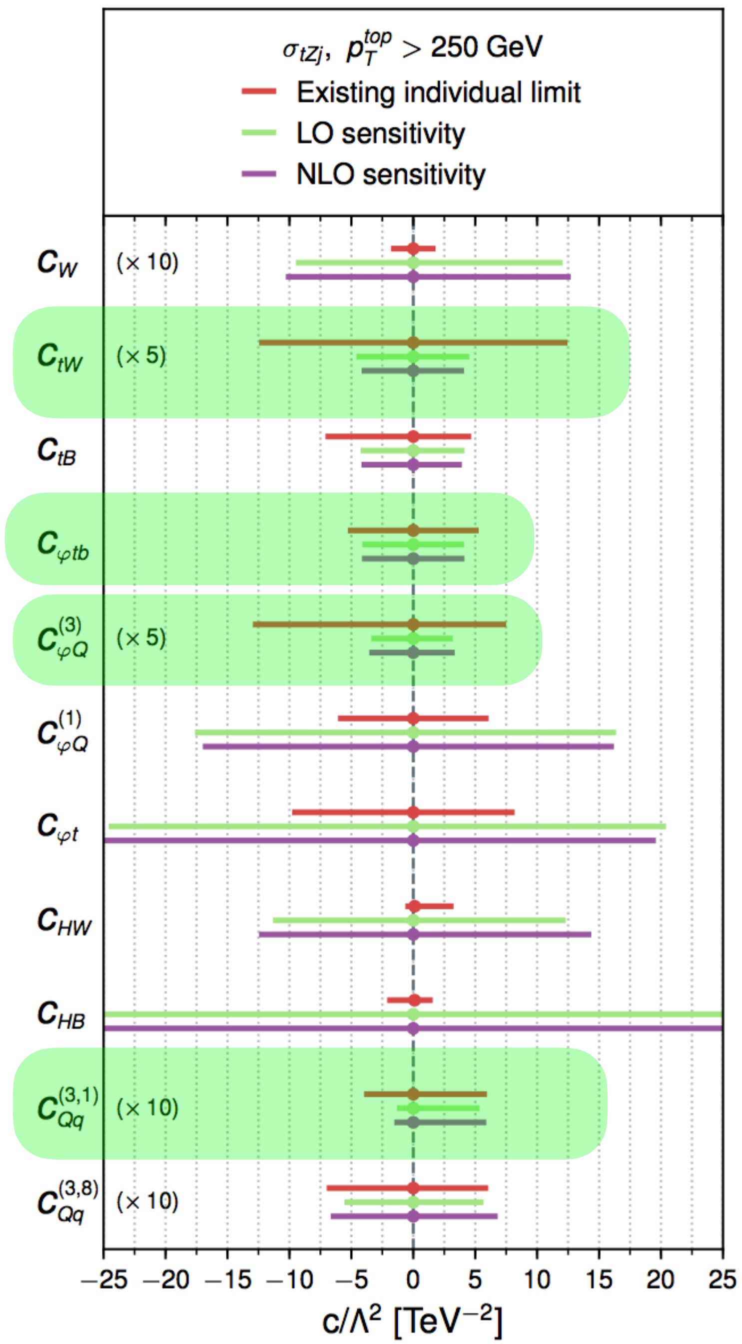
$\mathcal{O}_{\phi tb},\ \lambda_b, \lambda_t = +, +$

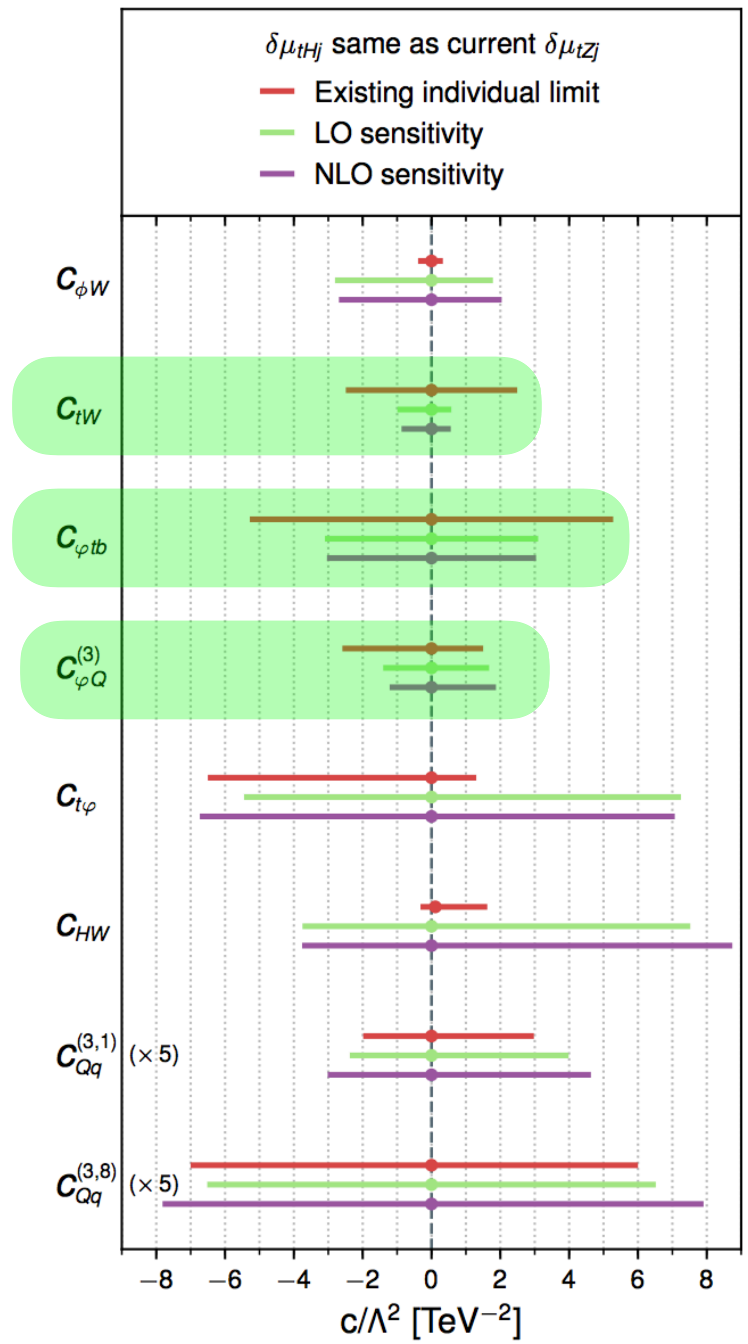
λ_Z \ λ_W	0	$+$	$-$
0	$\sqrt{s(s+t)}$	$m_W\sqrt{-t}$	$-$
$+$	$m_Z\sqrt{-t}$	s^0	$-$
$-$	$-$	$-$	s^0

$\mathcal{O}_{\phi tb},\ \lambda_b, \lambda_t = +, -$

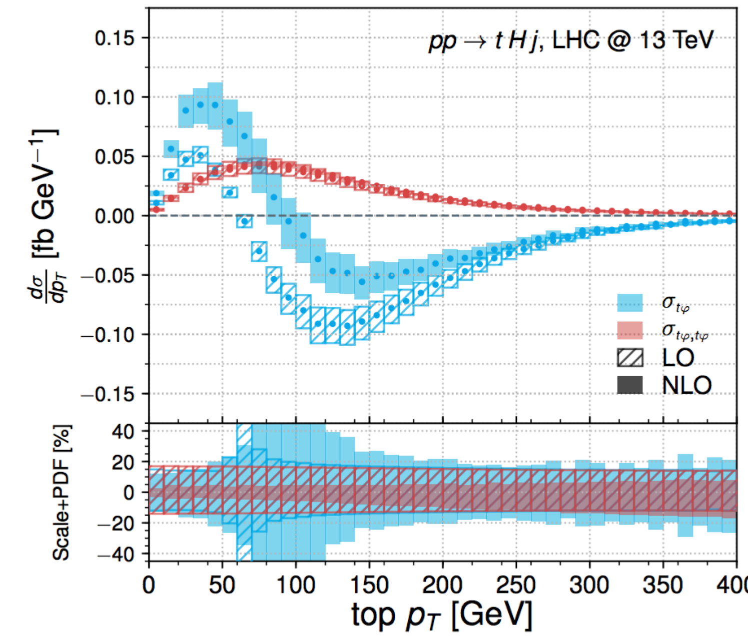
λ_Z \ λ_W	0	$+$	$-$
0	$-$	$-$	s^0
$+$	s^0	$-$	$-$
$-$	s^0	$-$	$-$

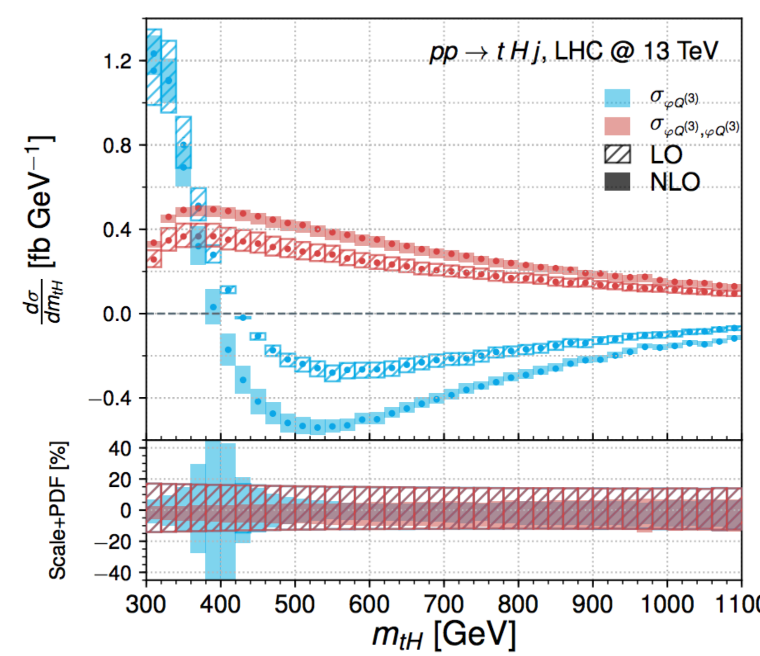
Single top+Higgs/Z: helicity amplitudes





NLO matters

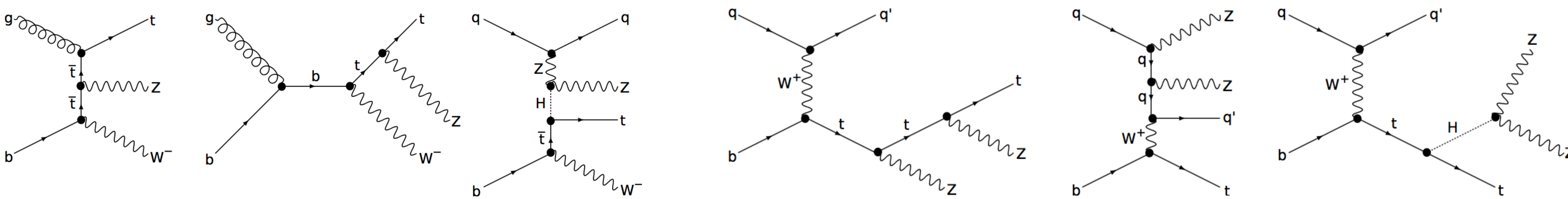




More high energy tops (t+2V!)

Cross section measurements of processes with a single top quark and two vector bosons with the CMS experiment

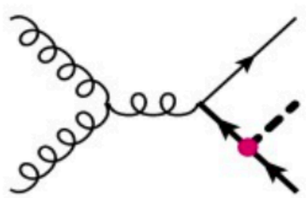
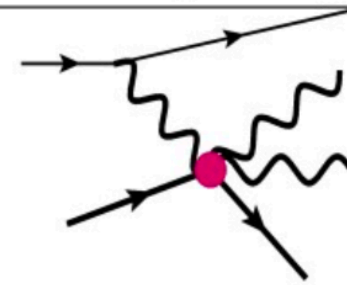
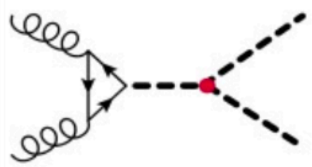
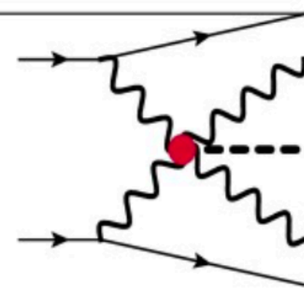
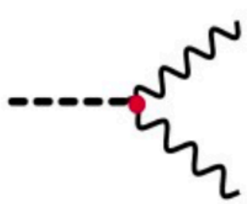
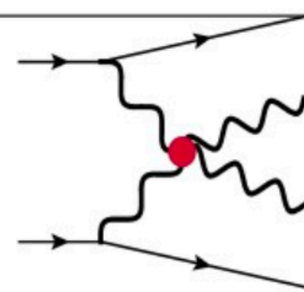
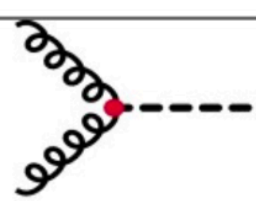
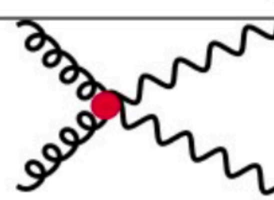
[Tommy Tschida]



C_i	Limit on C_i (TeV^{-2})			
	individual [37]	marginalised [37]	Run-II	Run-III
C_{tZ}	[-2.8,4.5]	[-2.1,4.0]	[-2.95,3.03]	[-2.33,2.42]
C_{tW}	[-0.4,0.2]	[-1.8,0.9]	[-1.32,1.87]	[-1.00,1.56]
$C_{\phi t}$	[-6.4,7.3]	[-13.0,18.0]	[-20.70,11.68]	[-17.67,8.65]
$C_{\phi tb}$	[-9.4,9.5]	[-27.0,8.7]	[-7.97,7.95]	[-6.33,6.32]
$C_{\phi Q}^{(3)}$	[-0.9,0.6]	[-5.5,5.8]	[-5.52,1.66]	[-5.02,1.15]
$C_{\phi Q}^{-}$	[-4.2,3.9]	[-3.5,3.0]	[-12.72,8.57]	[-10.63,6.48]

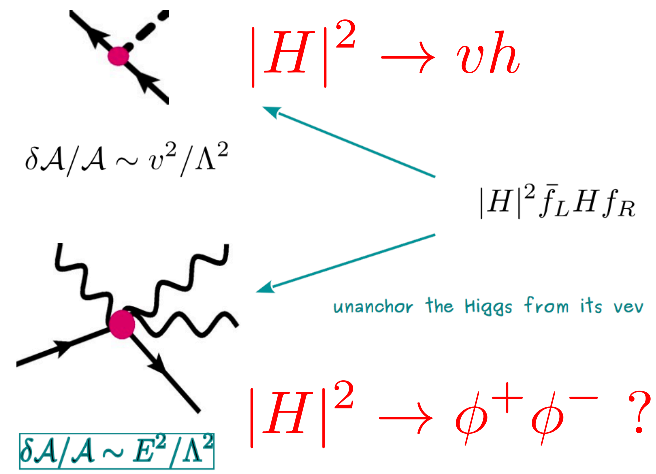
Table 8.1: The Run-II and Run-III limits of the Wilson coefficients in comparison with the individual and marginalised limits of a recent global EFT fit [37].

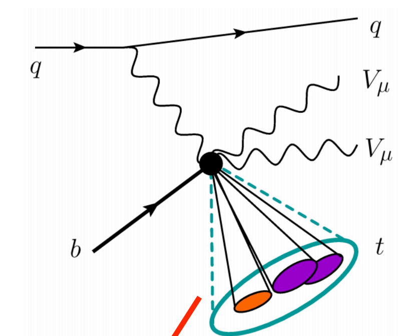
Higgs at off-shell

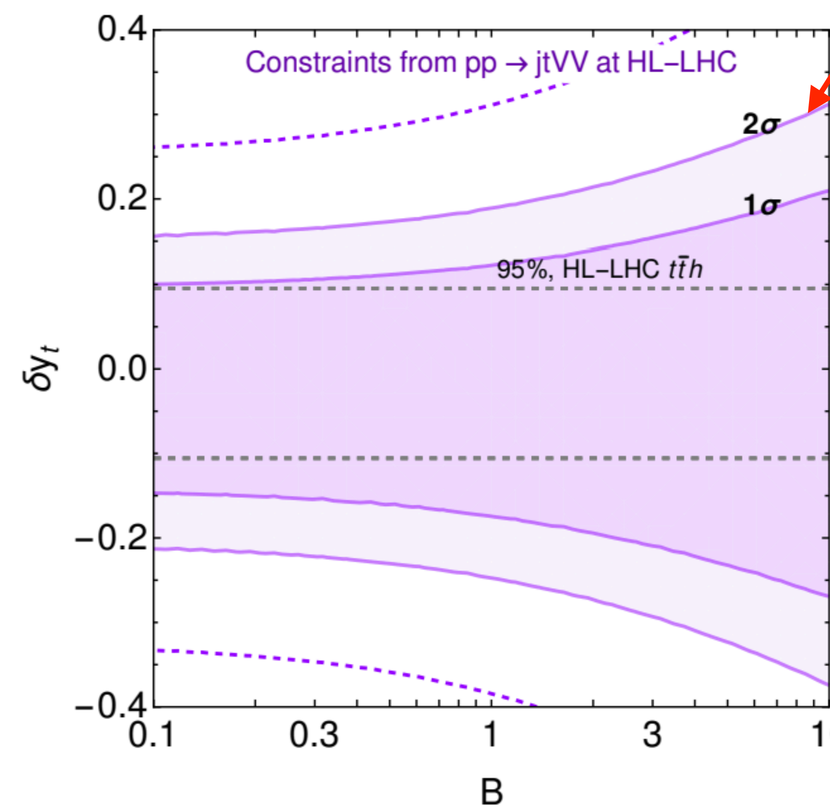
		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

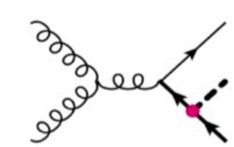
[Henning, Lombardo, Riembau, Riva 1812.09299]

(See talk by Junmou Chen)





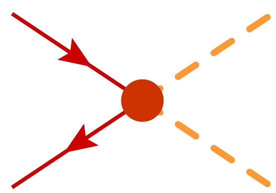


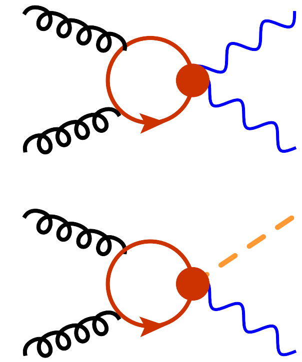


Top loops

Recall the ttϕϕ term from opening the ttZ operator:

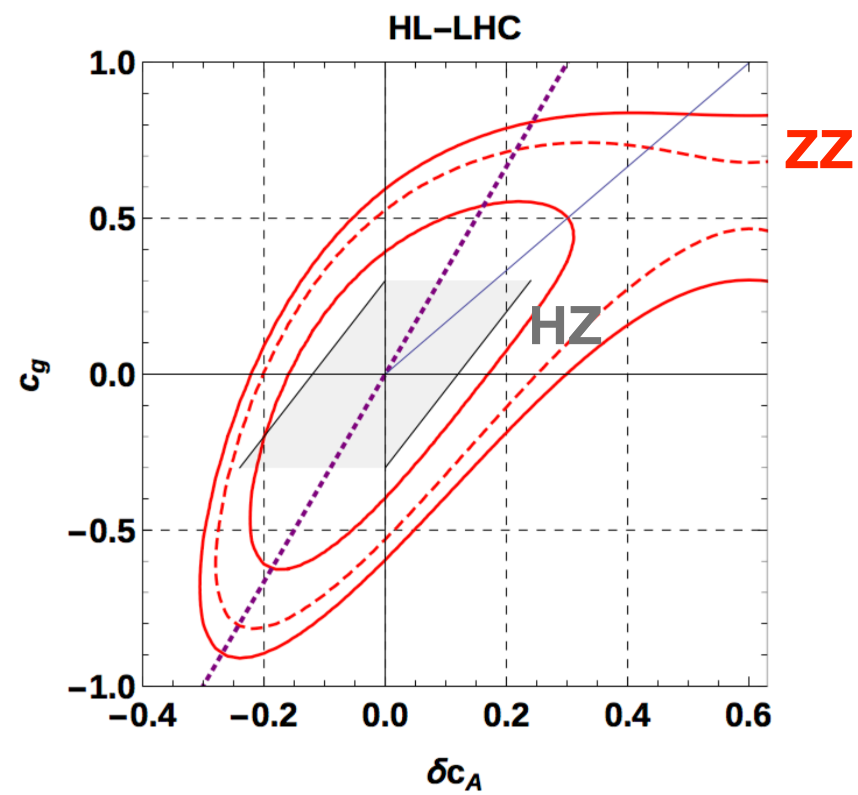
$$\bar{t}\gamma_\mu t H^\dagger \overleftrightarrow{D}_\mu H$$

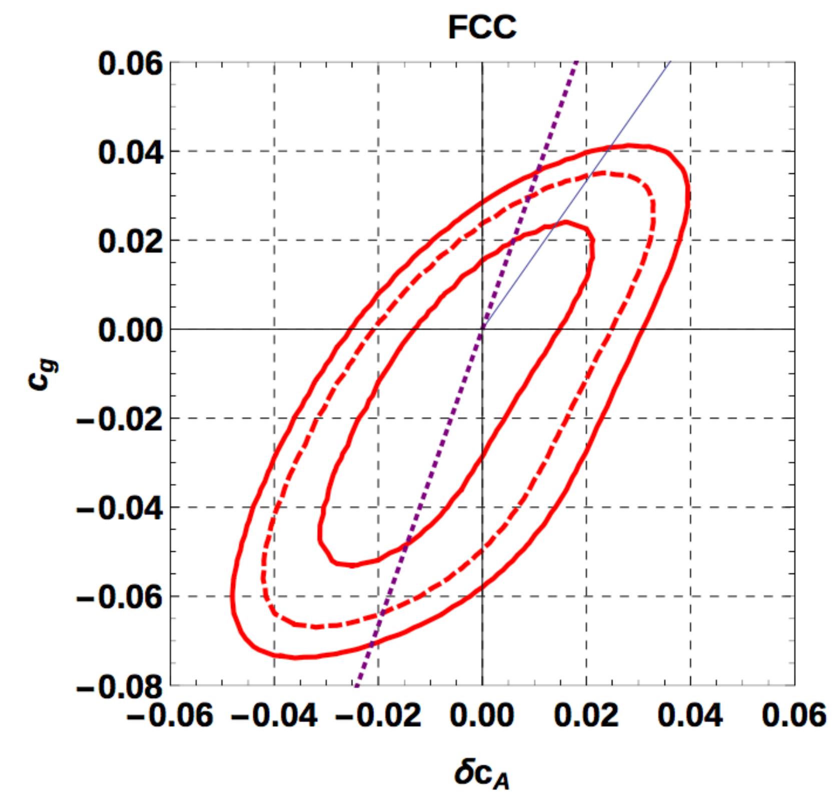




ttZ @ HL-LHC:
$\delta c_A \lesssim 0.2$

Instead of embedding in pp>ttWj, could also use loops:



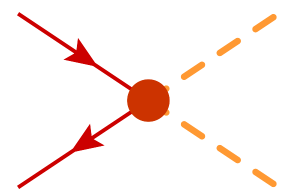


[Azatov, Grojean, Paul, Salvioni ’16]
[Englert, Rosenfeld, Spannowsky, Tonero ’16]

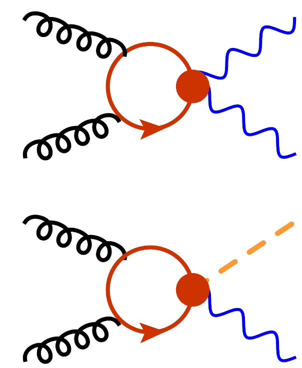
Top loops

Recall the ttϕϕ term from opening the ttZ operator:

$$\bar{t}\gamma_\mu t H^\dagger \overleftrightarrow{D}_\mu H$$



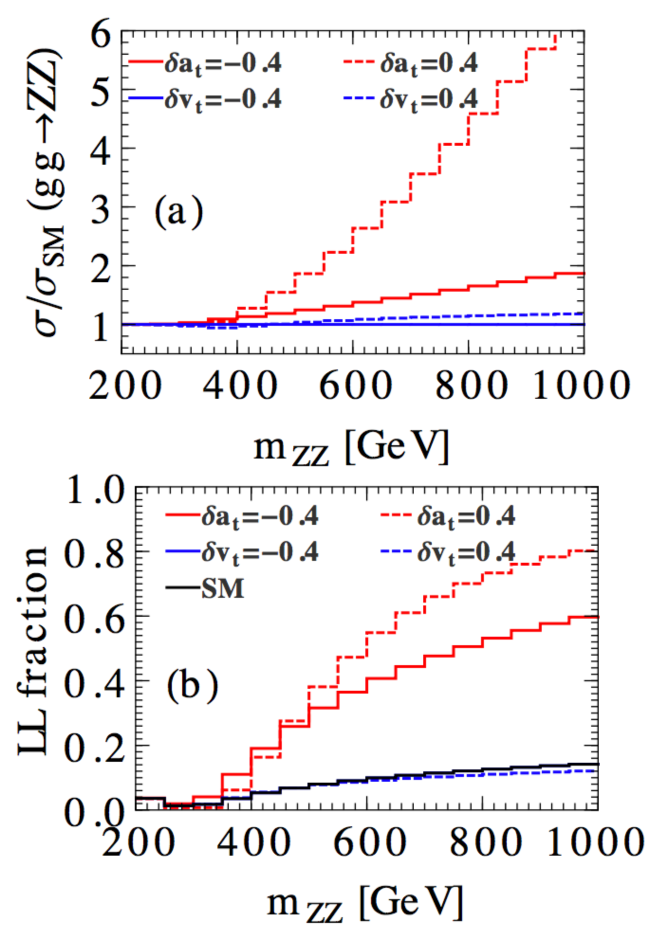
ttZ @ HL-LHC:
$\delta c_A \lesssim 0.2$

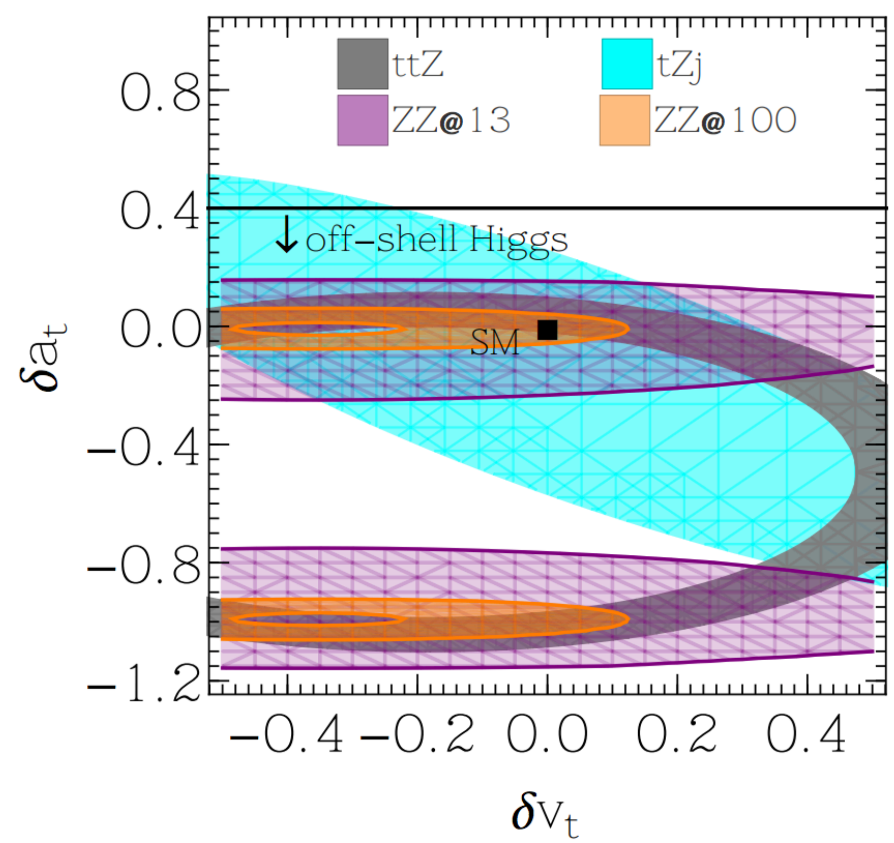


Instead of embedding in pp>ttWj, could also use loops:

Using Z boson polarization to identify the Goldstone modes **[Cao, Yan, Yuan, Zhang '20]**

(See talk by Bin Yan)





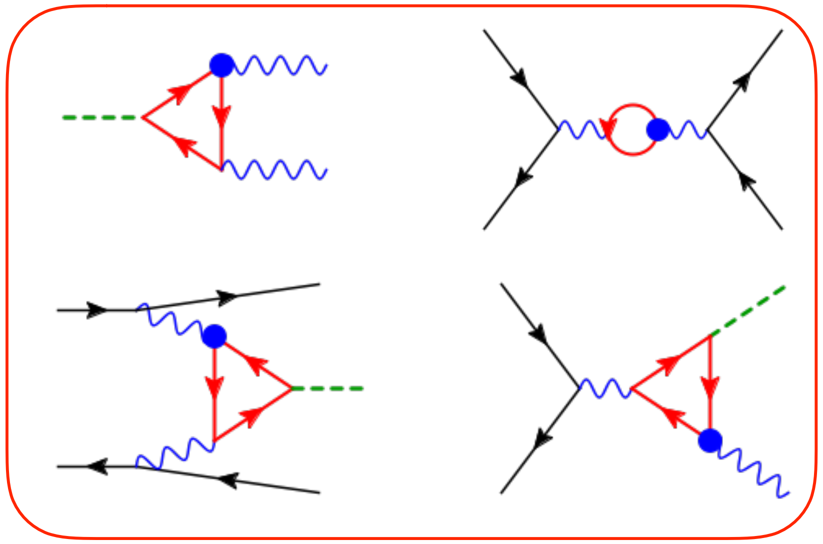
See also

[He, Wan, Wang '19]
Constraining HZZ couplings

[Lee, Park, Qian '18]
Other BSM scenarios in $V_L V_L$ mode

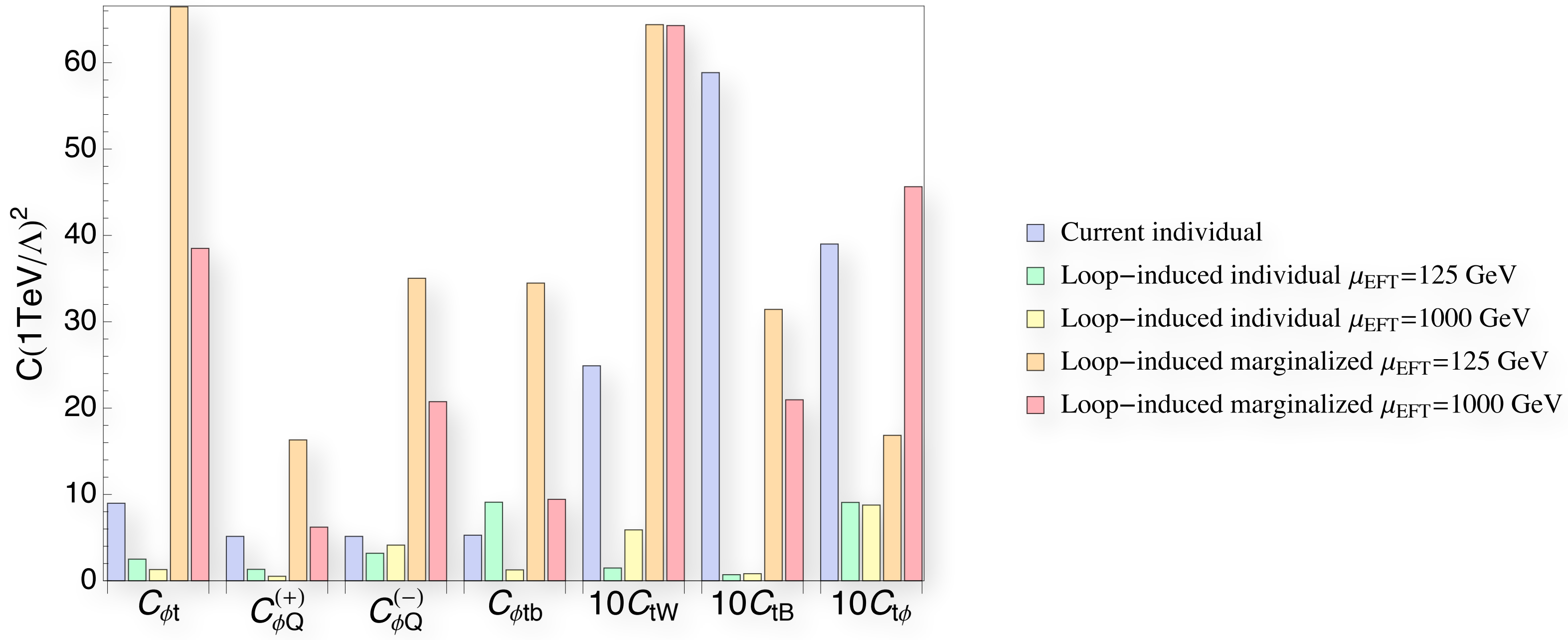
Top loops: EW

Most Higgs channels involve top couplings through loops, and some top-EW couplings are not well constrained.



1) Indirectly constraint top couplings

[Vryonidou, CZ '18]



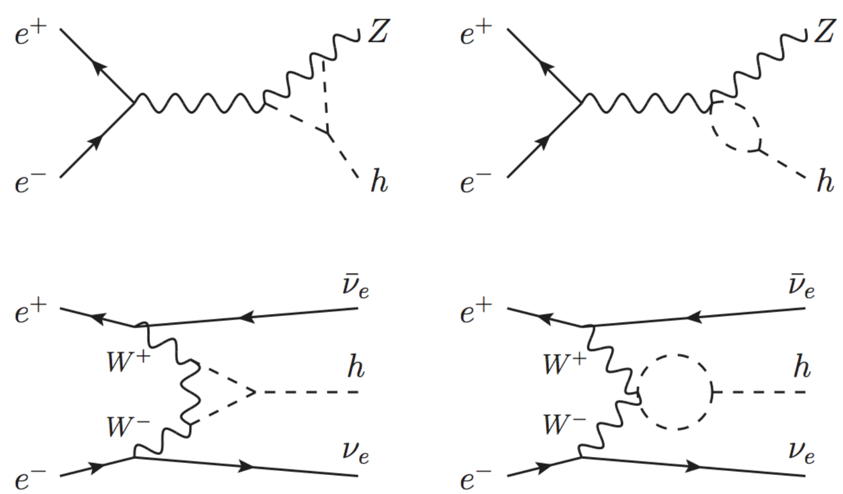
2) Degrading the Higgs precision (within current limits)

	$\gamma\gamma$	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%)

See also [Vryonidou, Gu, Vryonidou, CZ, '18] [Jung, Lee, Perello, Tian, Vos, '20] for future CEPC and ILC cases

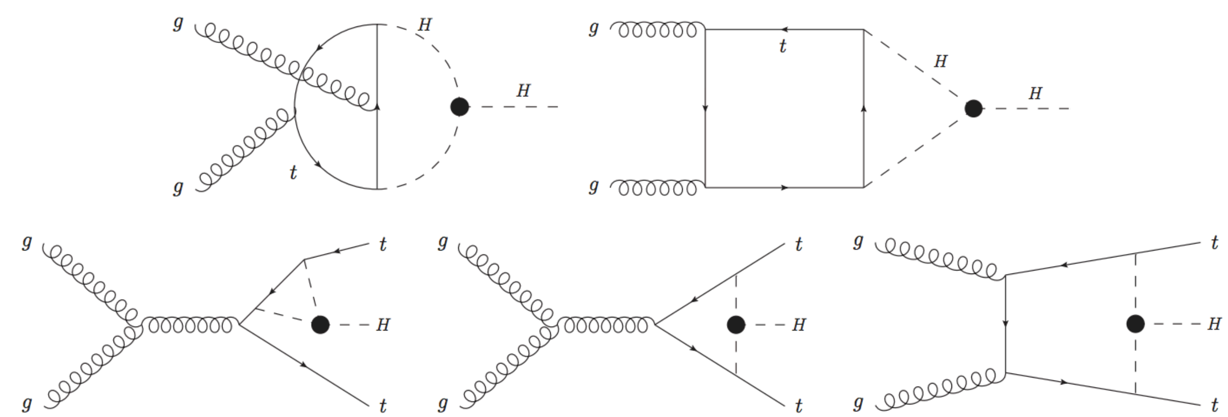
"Higgs loop": The trilinear Higgs coupling κ_λ

At the ee colliders



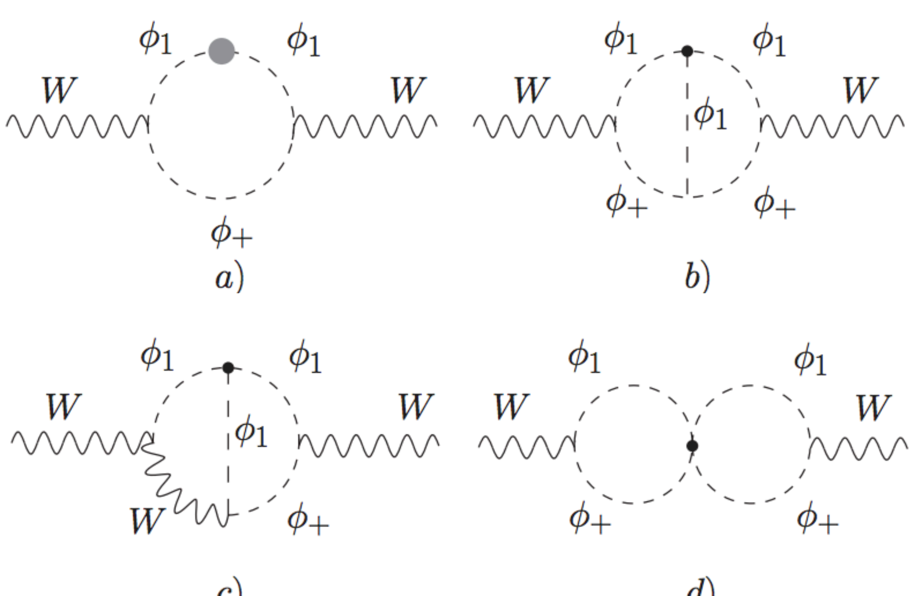
[M. McCullough, '13] [S. D. Vita et al., '17]

At the LHC



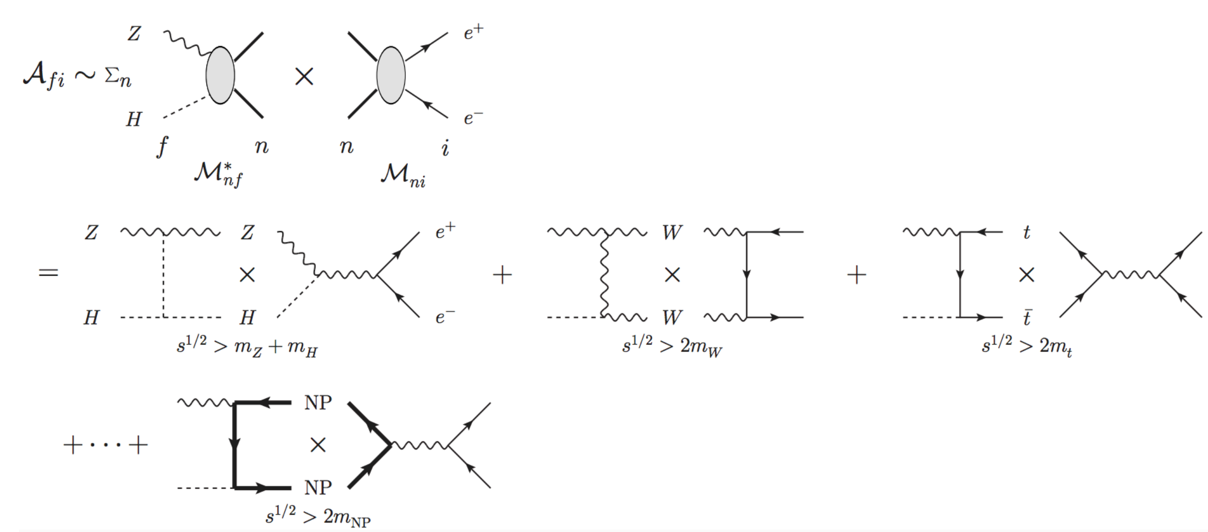
[G. Degrassi et al., '16] [Gorbahn&Haisch, '16]

Using EWPO at **2 loop**



[Degrassi, Fedele, Giardino 1702.01737]

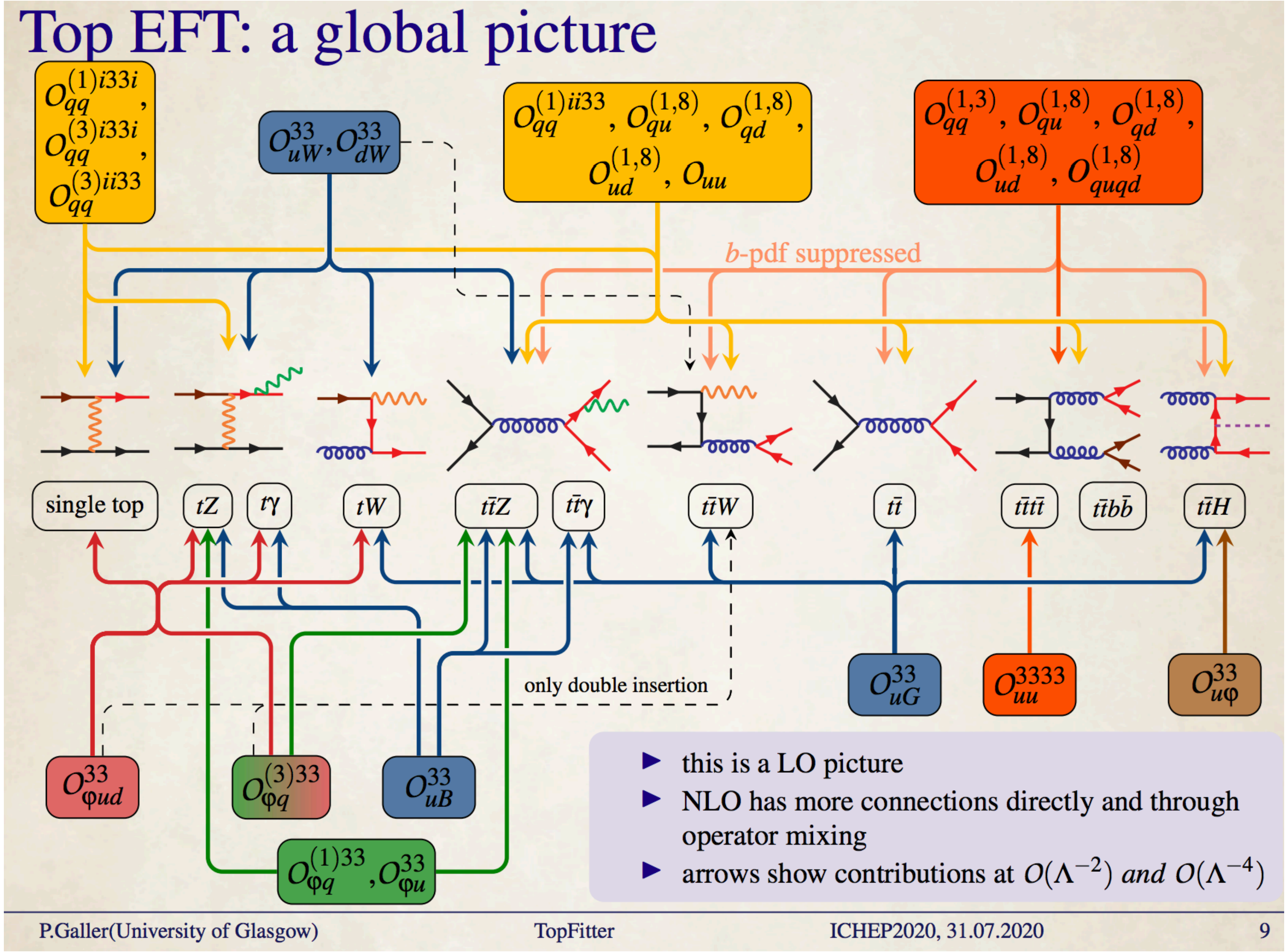
"Loop-exclusive observables"



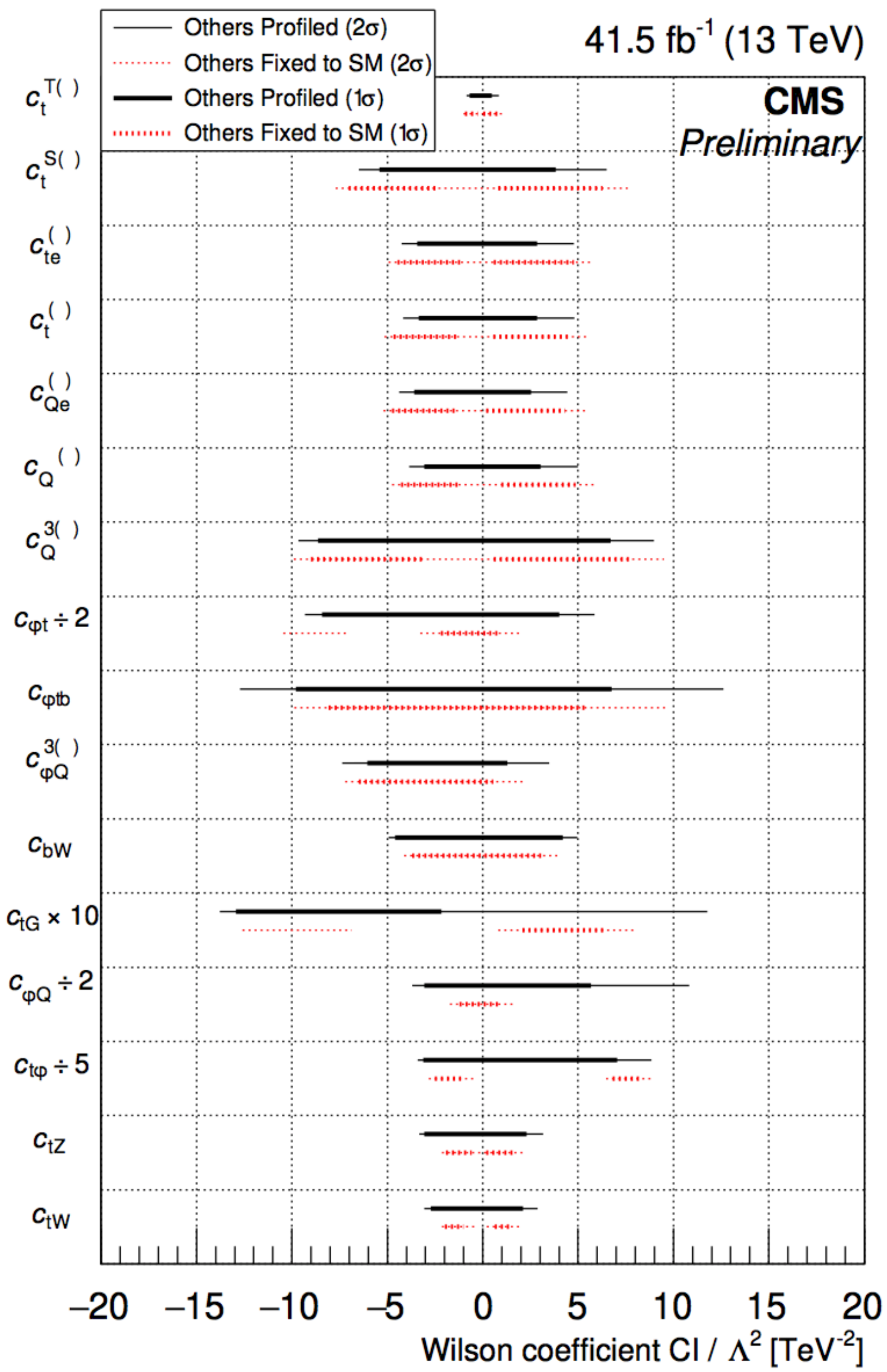
[J. Nakamura & A. Shivaji 1812.01576]

The way ahead

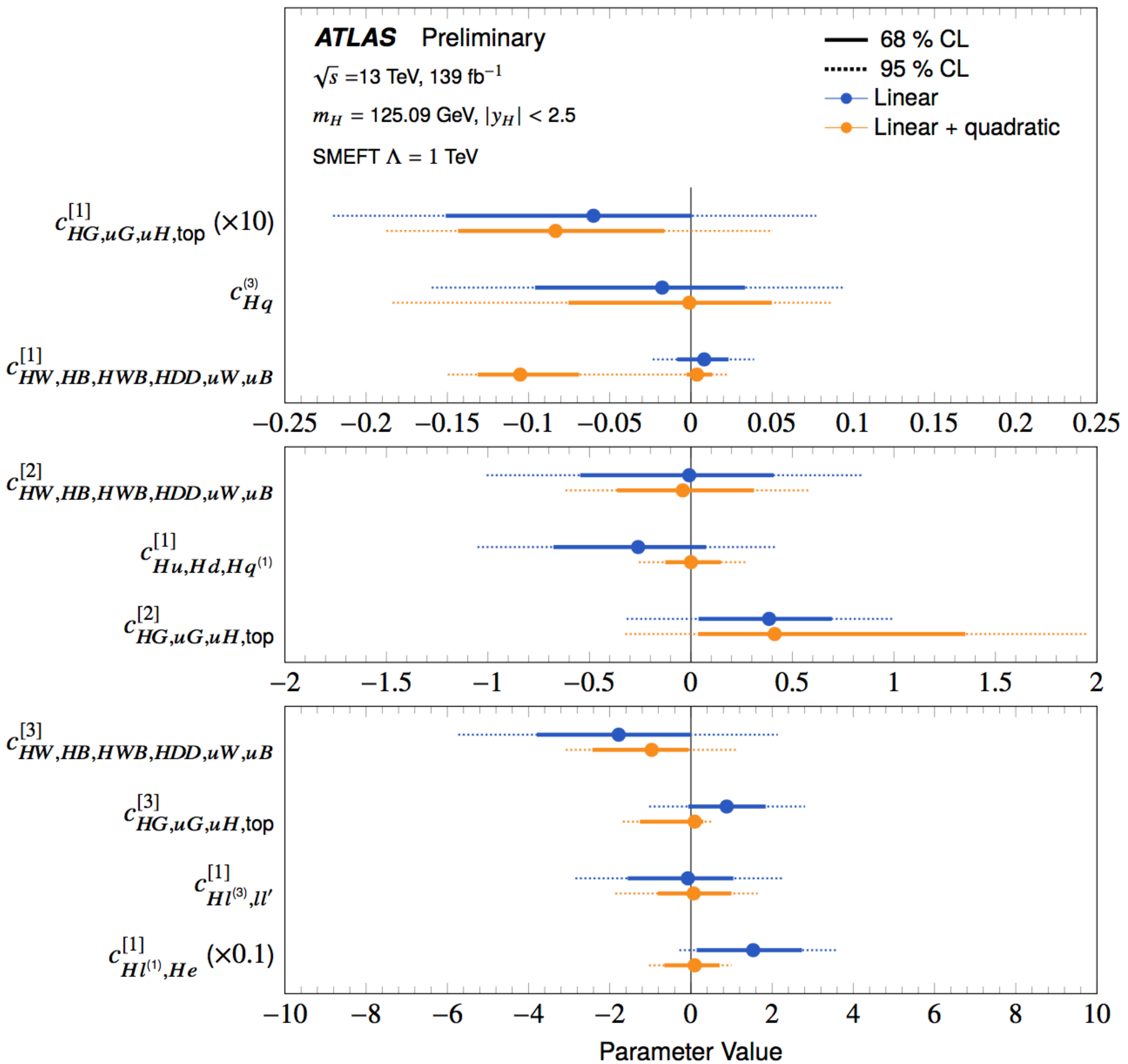
- Pattern of deformations enter many observables in a correlated way.
- **Global fit** is the only way to capture all info and at the same time providing truly model-independent interpretation.
- Will need precise prediction for a wide range of channels.
- Which incorporate predictions in SM (for reach) and in SMEFT (for interpretation and loop-induced channels).



The way ahead



CMS PAS TOP-19-001



ATLAS-CONF-2020-053

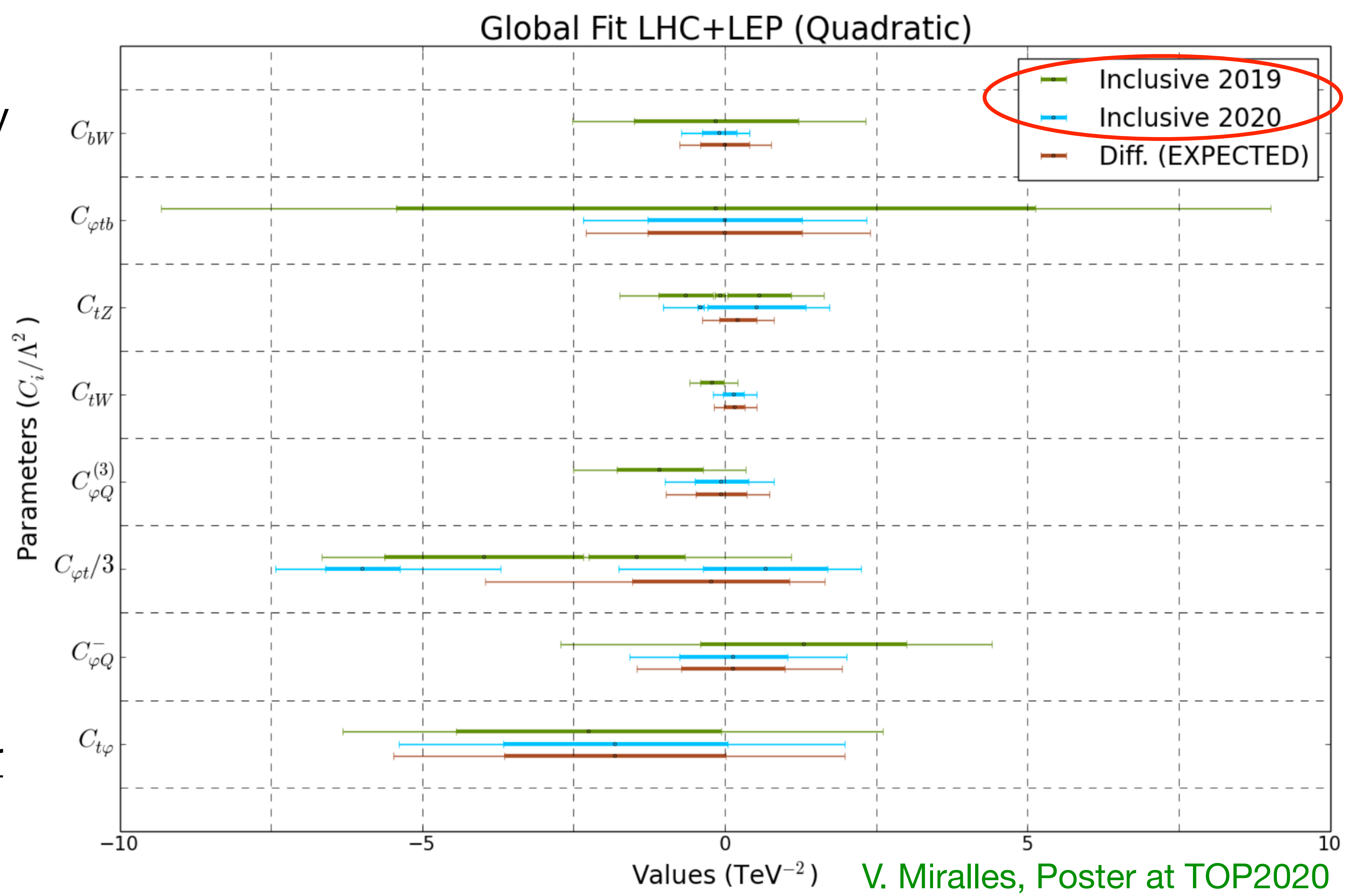
See also talk by Xuyang Gao and many others

The way ahead

- Pattern of deformations enter many observables in a correlated way.
- **Global fit** is the only way to capture all info and at the same time providing truly model-independent interpretation.
- Will need precise prediction for a wide range of channels.
- Which incorporate predictions in SM (for reach) and in SMEFT (for interpretation and loop-induced channels).

THE TOP-QUARK EW COUPLINGS AFTER LHC RUN2

G. Durieux,[1] M. Miralles,[2] V. Miralles,[2] M. Moreno Llácer, [2] A. Peñuelas, [2] M. Perelló,[2] M. Vos,[2] C. Zhang,[3]
[1] Physics Department, Technion-Israel Institute of Technology, [2] Universitat de València and CSIC, [3]Institute of High Energy Physics, Chinese Academy of Sciences



V. Miralles, Poster at TOP2020

Precision in SM

- NNLO spin correlation [Czakon, Mitov, Poncelet ’20]
- ttbar coulomb corrections in [L.-L. Yang et al. ’20]
- NLO ttW [G. Bevilacqua et al. ’20] [Denner & Pellicciolí ’20]
- NLO tt+gamma [G. Bevilacqua et al. ’20]
- Higgs 3 loop finite mass [Czakon, Niggetiedt ’20] [Praise, Usovitsch ’20]
- Higgs 4 loop large mass expansion [J. Davies et al. ’19]
- ……
- Talks by Jian Wang, Tao Liu, Yang Zhang, Xiao Liu, …

Precision in SMEFT: automatic NLO

Automatic NLO+PS for all processes/operators

```
MG5_aMC>import model SMEFT
MG5_aMC>generate p p > t t~ H NP=2 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

arXiv.org > hep-ph > arXiv:2008.11743

Search...

Help | Advanced

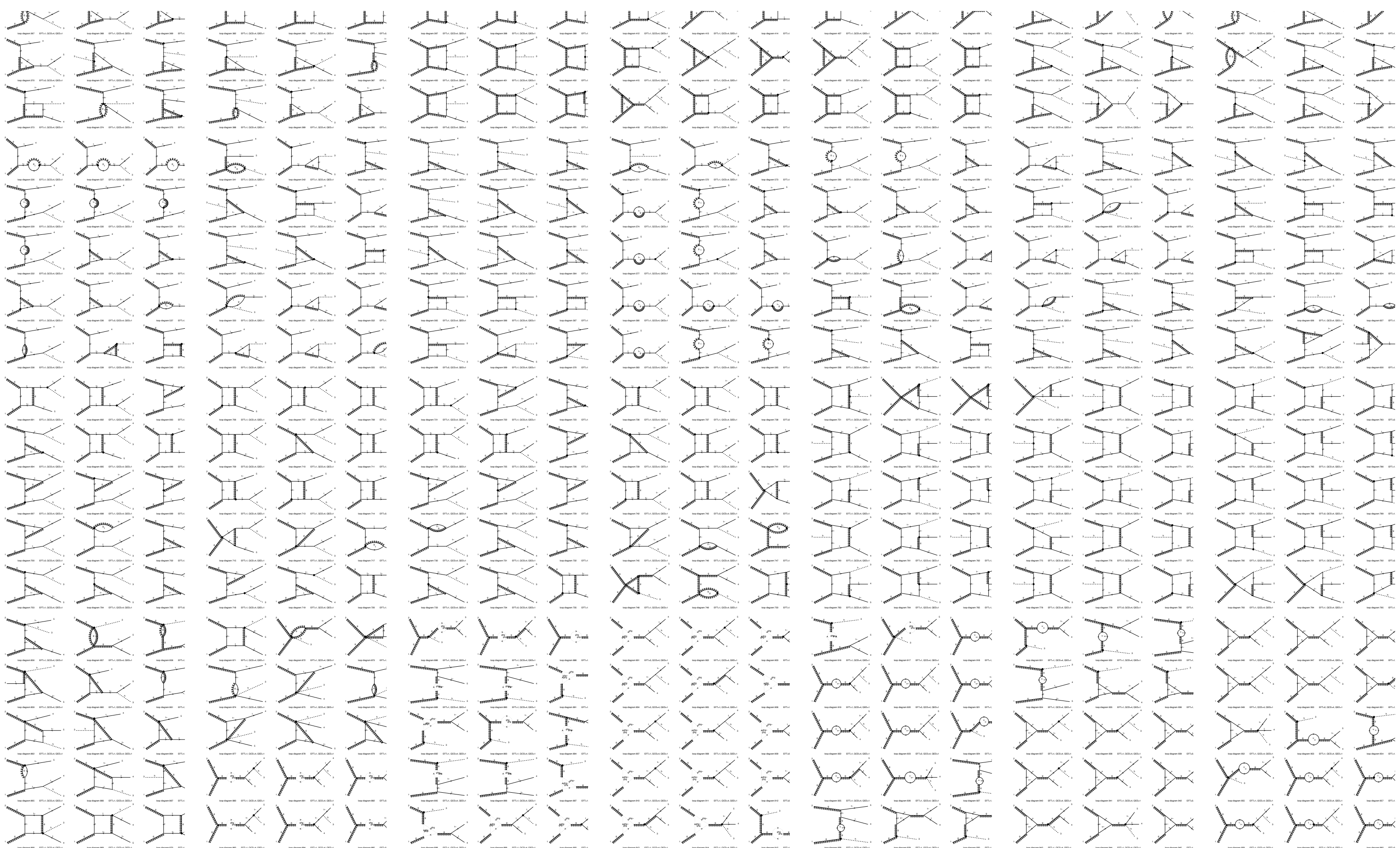
High Energy Physics – Phenomenology

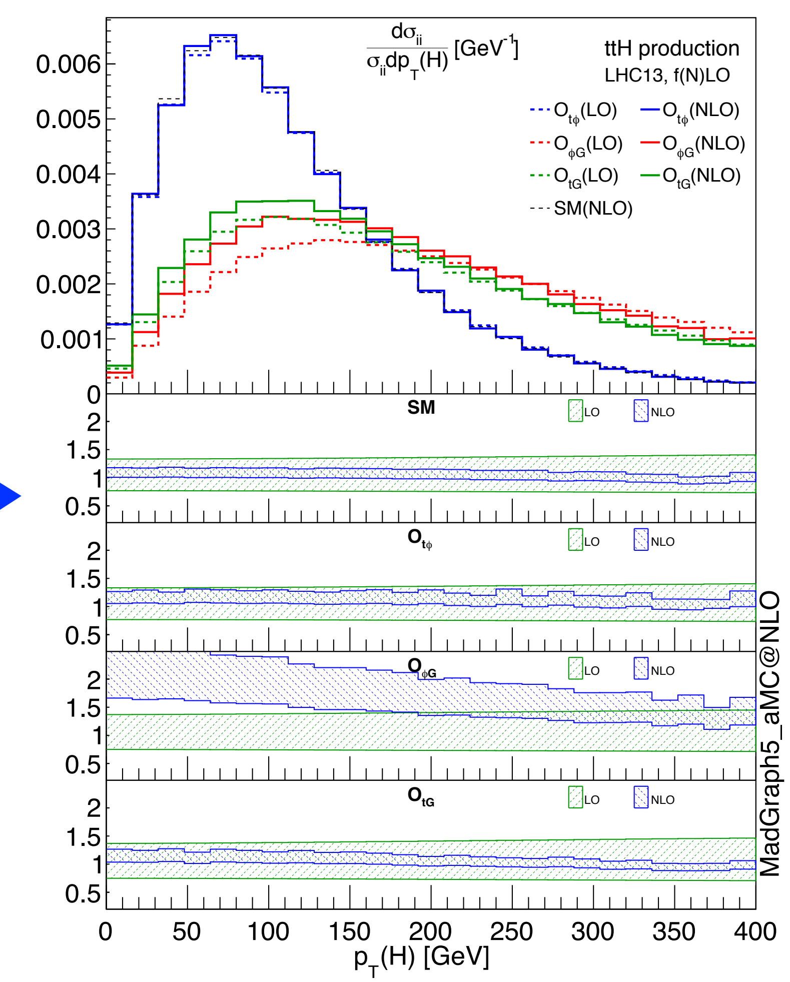
[Submitted on 26 Aug 2020]

Automated one-loop computations in the SMEFT

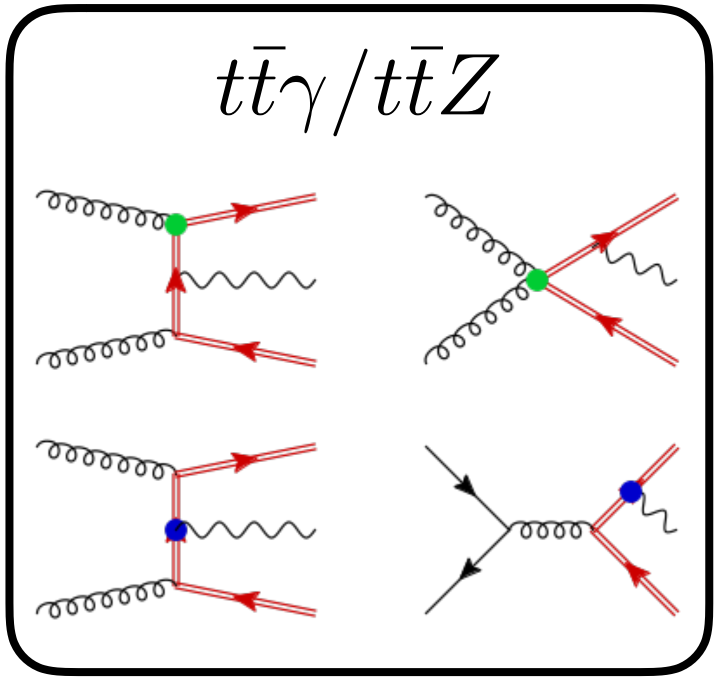
Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou, Cen Zhang

We present the automation of one-loop computations in the standard-model effective field theory at dimension six. Our implementation, dubbed SMEFT@NLO, contains ultraviolet and rational counterterms for bosonic, two- and four-fermion operators. It presently allows for fully differential predictions, possibly matched to parton shower, up to one-loop accuracy in QCD. We illustrate the potential of the implementation with novel loop-induced and next-to-leading order computations relevant for top-quark, electroweak, and Higgs-boson phenomenology at the LHC and future colliders.

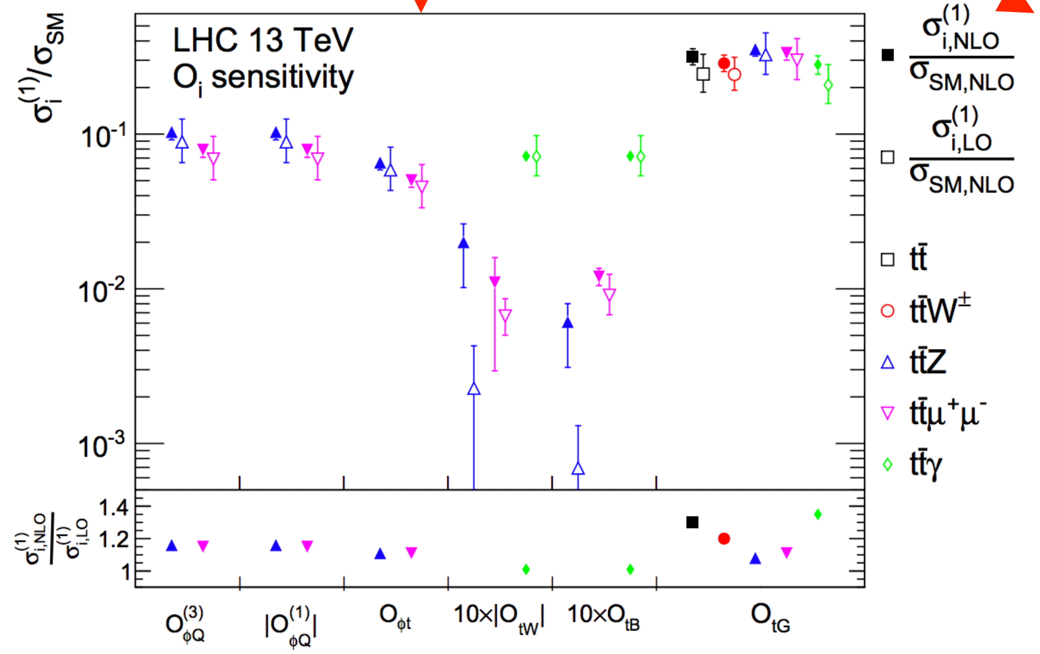


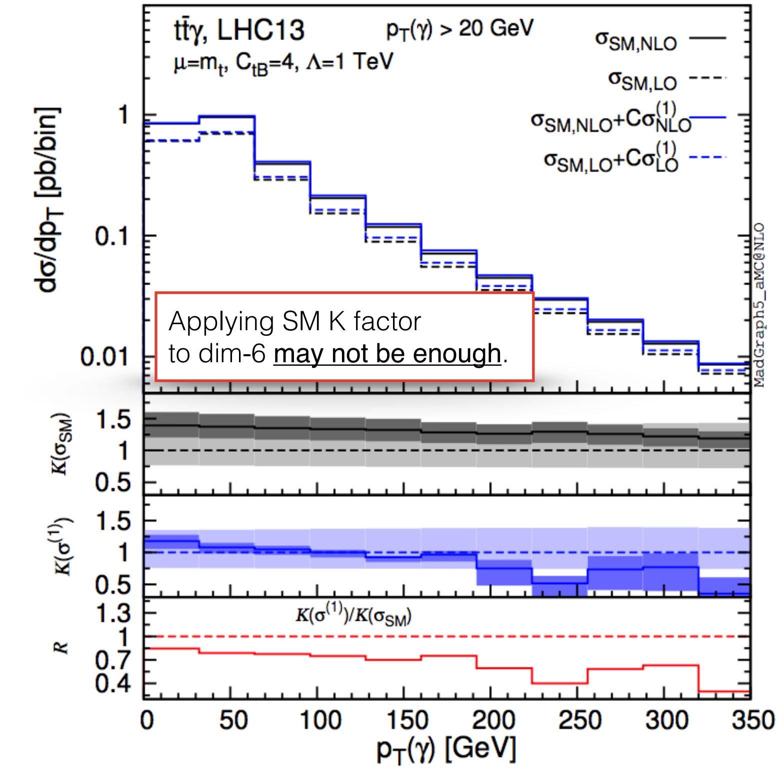


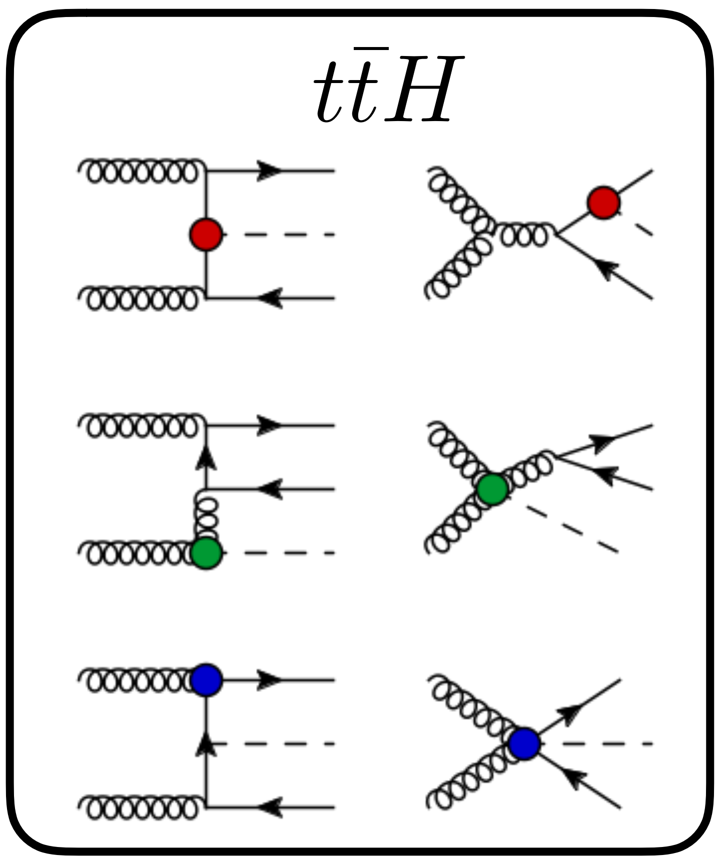
Non-universal K-factors
in rates and distributions

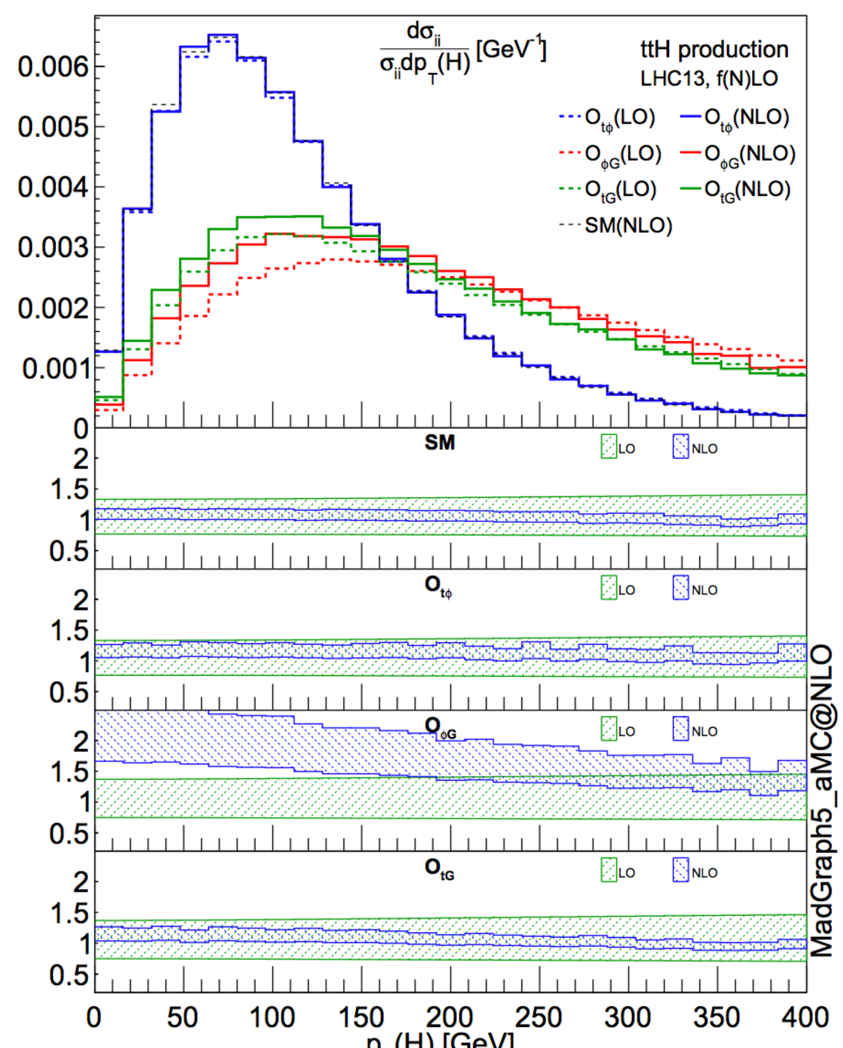


[Bylund et al.; JHEP 1605 (2016) 052]









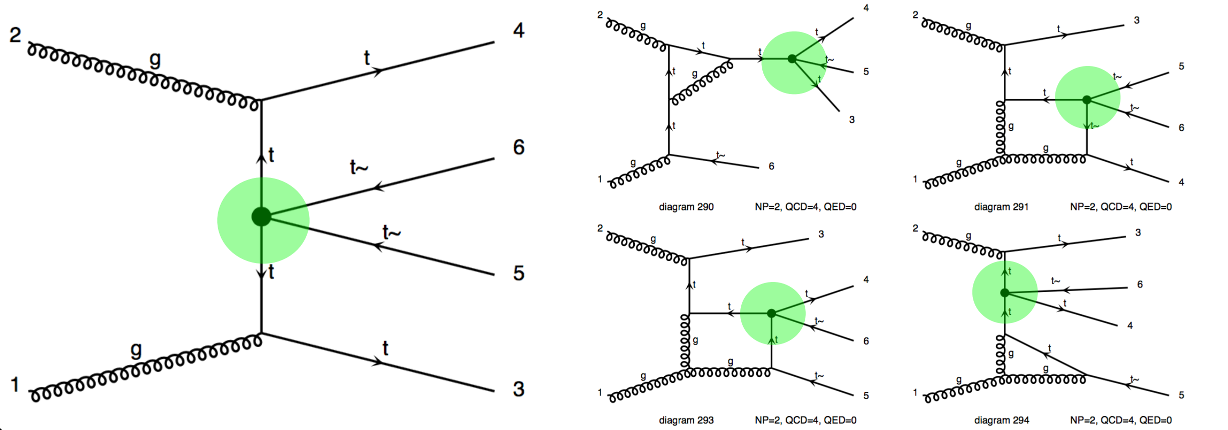
[Maltoni, Vryonidou, CZ; JHEP 1610 (2016) 123]

Rates

13 TeV	σ LO	σ NLO	K
σ_{SM}	$0.464^{+0.161}_{-0.11}$	$0.507^{+0.03}_{-0.04}$	1.09
$\sigma_{t\phi}$	$-0.055^{+0.0}_{-0.0}$	$-0.062^{+0.}_{-0.}$	1.13
$\sigma_{\phi G}$	$0.627^{+0.22}_{-0.15}$	$0.872^{+0.13}_{-0.12}$	1.39
σ_{tG}	$0.470^{+0.16}_{-0.11}$	$0.503^{+0.02}_{-0.04}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0016^{+0.0}_{-0.0}$	$0.0019^{+0.0}_{-0.0}$	1.17
$\sigma_{\phi G,\phi G}$	$0.646^{+0.27}_{-0.17}$	$1.021^{+0.20}_{-0.17}$	1.58
$\sigma_{tG,tG}$	$0.645^{+0.27}_{-0.17}$	$0.674^{+0.03}_{-0.06}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.037^{+0.0}_{-0.0}$	$-0.053^{+0.}_{-0.}$	1.42
$\sigma_{t\phi,tG}$	$-0.028^{+0.0}_{-0.0}$	$-0.031^{+0.}_{-0.}$	1.10
$\sigma_{\phi G,tG}$	$0.627^{+0.25}_{-0.16}$	$0.859^{+0.12}_{-0.12}$	1.37

[Degrande et al., 2008.11743]

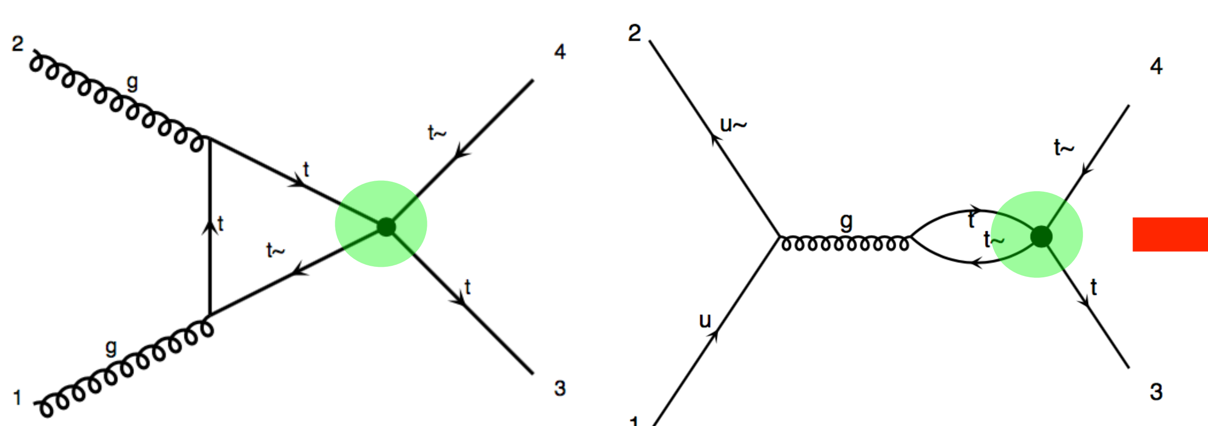
pp -> 4 top 4.3 sigma evidence, ATLAS-CONF-2020-013



c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO	K	$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO	K
c^8_{QQ}	$0.126^{+61\%}_{-35\%}$	$0.089^{+8\%}_{-66\%}$	0.71	$0.170^{+53\%}_{-32\%}$	$0.165^{+3\%}_{-26\%}$	0.97
c^8_{Qt}	$0.421^{+63\%}_{-35\%}$	$0.295^{+9\%}_{-69\%}$	0.70	$0.498^{+52\%}_{-32\%}$	$0.333^{+15\%}_{-75\%}$	0.67
c^1_{QQ}	$0.373^{+62\%}_{-35\%}$	$0.20(1)^{+23\%}_{-115\%}$	0.53	$1.513^{+53\%}_{-32\%}$	$1.40^{+3\%}_{-32\%}$	0.93
c^1_{Qt}	$-0.007(1)^{+88\%}_{-84\%}$	$-0.14(3)^{+83\%}_{-40\%}$	21	$2.061^{+53\%}_{-32\%}$	$1.89^{+3\%}_{-33\%}$	0.92
c^1_{tt}	$0.741^{+61\%}_{-35\%}$	$0.42(3)^{+18\%}_{-101\%}$	0.57	$6.08^{+53\%}_{-32\%}$	$5.65^{+3\%}_{-30\%}$	0.93

LHC 13 SM = 13.9 fb

ttbar: loop sensitivity to four-top-quark operators



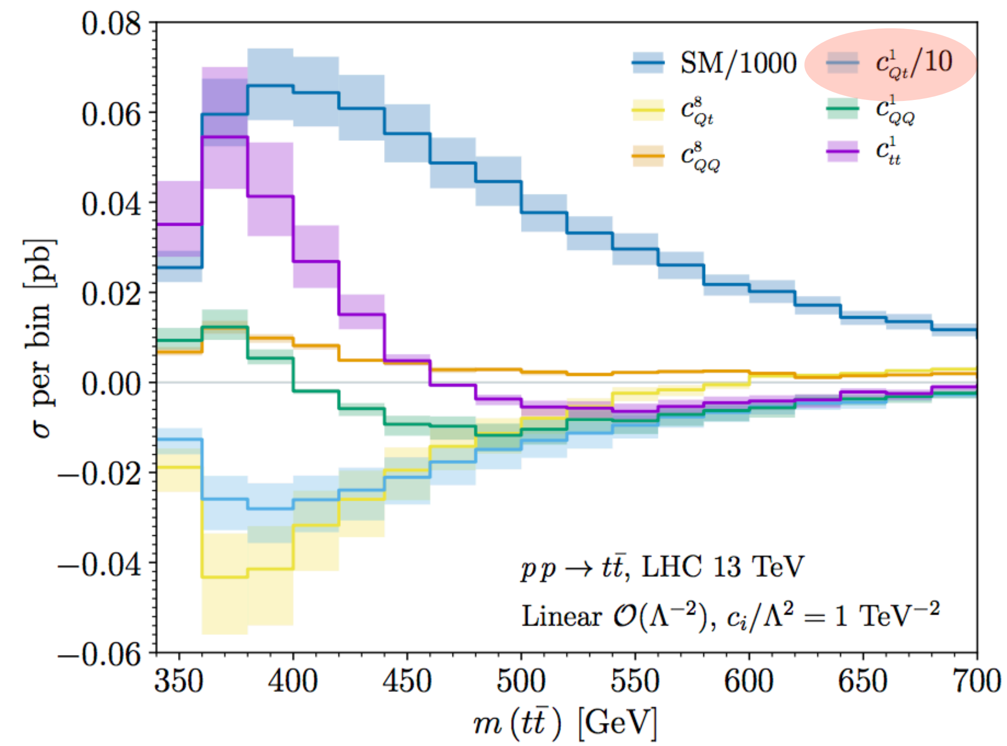


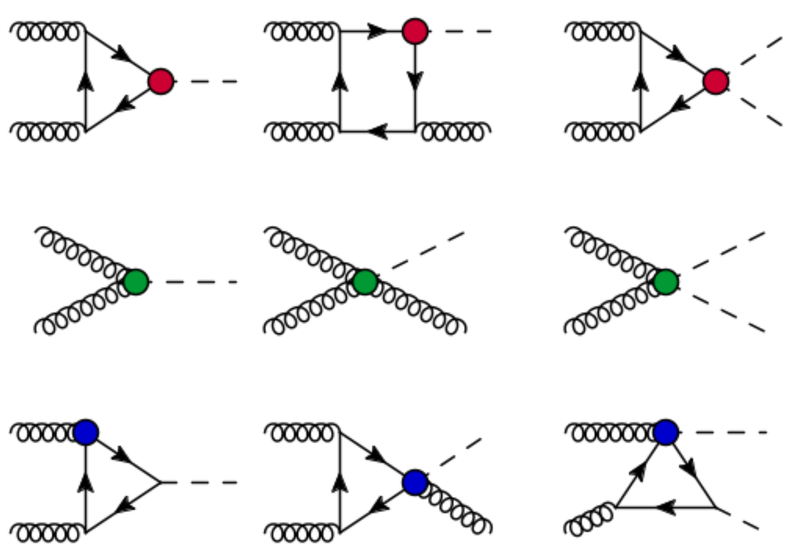
FIG. 1. $t\bar{t}$ invariant-mass distribution of the interference between four-heavy operators and the SM.

qqtt (2 light 2 heavy) operators, tree

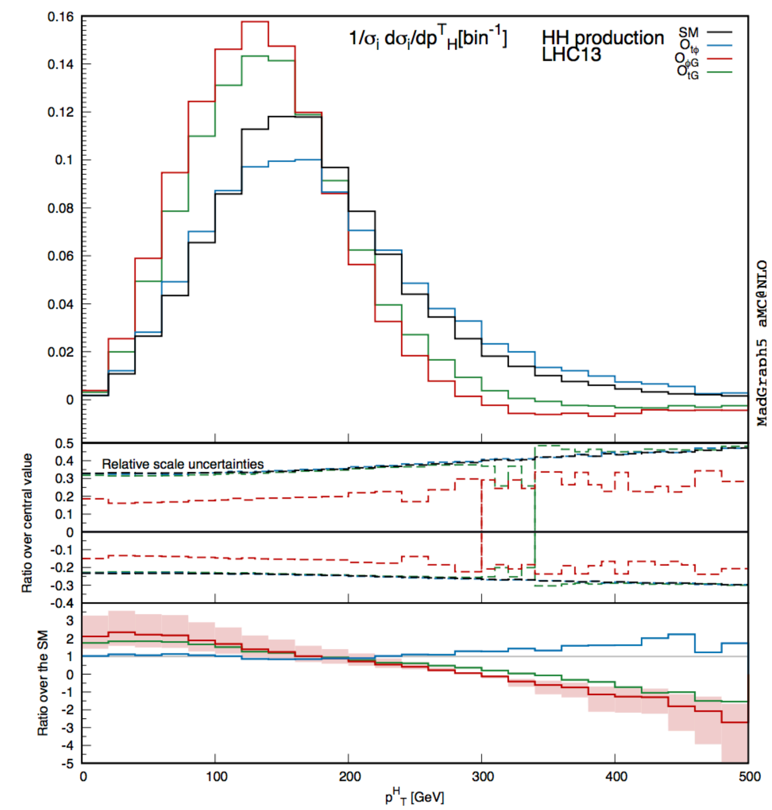
c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO		$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO
c^8_{tu}	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$		$1.04^{+6\%}_{-5\%}$	$1.03^{+2\%}_{-2\%}$
c^8_{td}	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$		$0.577^{+6\%}_{-5\%}$	$0.611^{+3\%}_{-2\%}$
c^8_{tq}	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.29^{+3\%}_{-2\%}$
c^8_{Qu}	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$		$1.04^{+6\%}_{-5\%}$	$0.798^{+3\%}_{-3\%}$
c^8_{Qd}	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$		$0.58^{+6\%}_{-5\%}$	$0.485^{+2\%}_{-2\%}$
$c^{8,1}_{Qq}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.69^{+3\%}_{-3\%}$
$c^{8,3}_{Qq}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.57^{+2\%}_{-2\%}$
c^8_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^8_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c^1_{QQ}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c^1_{Qt}	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c^1_{tt}	×	$0.215^{+23\%}_{-18\%}$		×	×

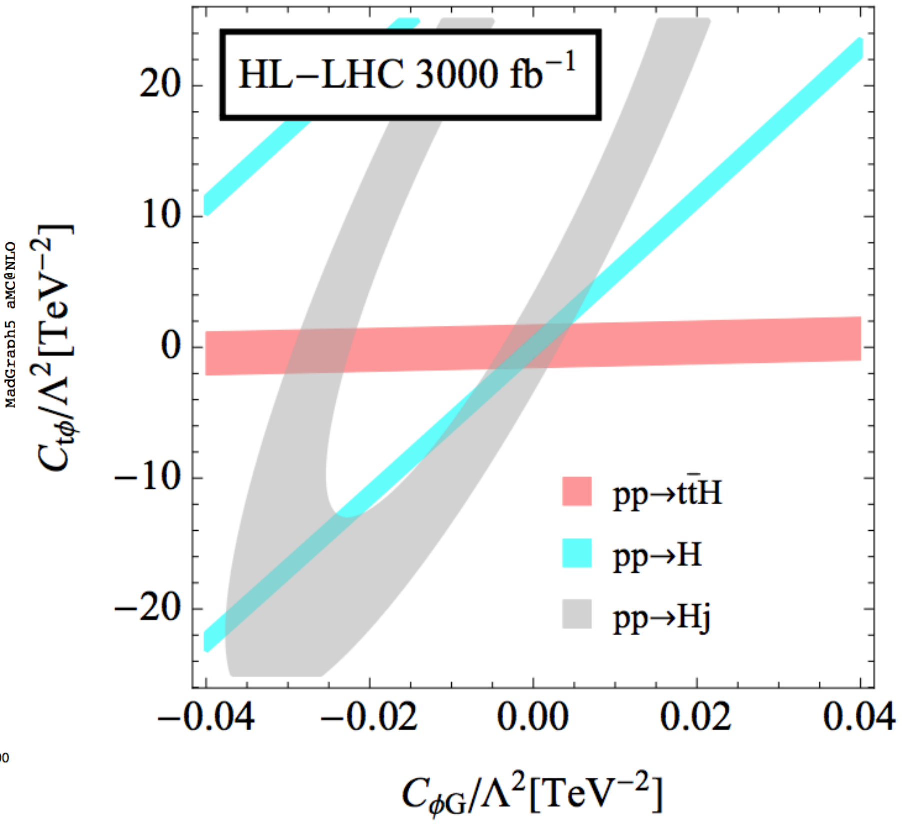
tttt (4 heavy) operators, loop

LHC 13, SM(NLO) = 744, [x]: EW interference loop-sensitivity, **gg -> H/Hj/HH**

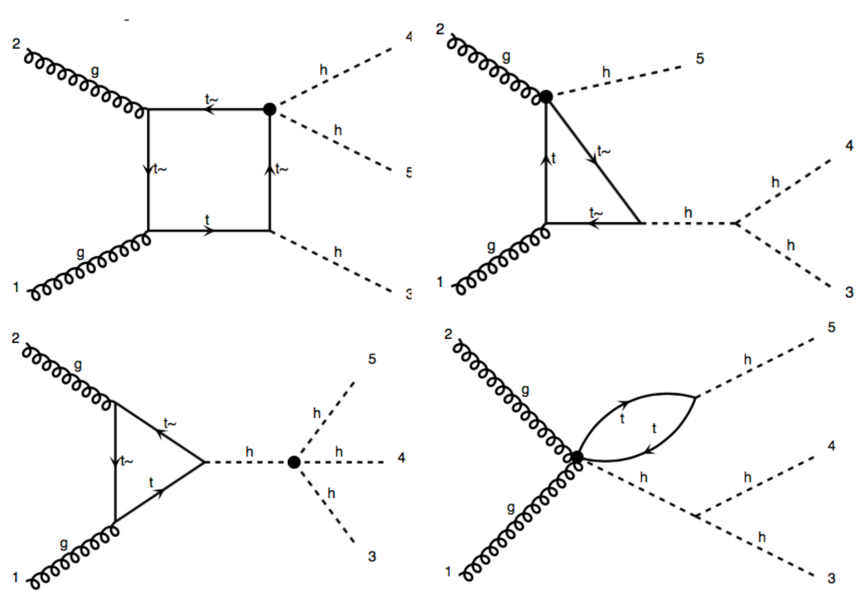


[Maltoni, Vryonidou, CZ; JHEP 1610 (2016) 123]





gg -> H/HH/HHH



[Degrande et al., 2008.11743]

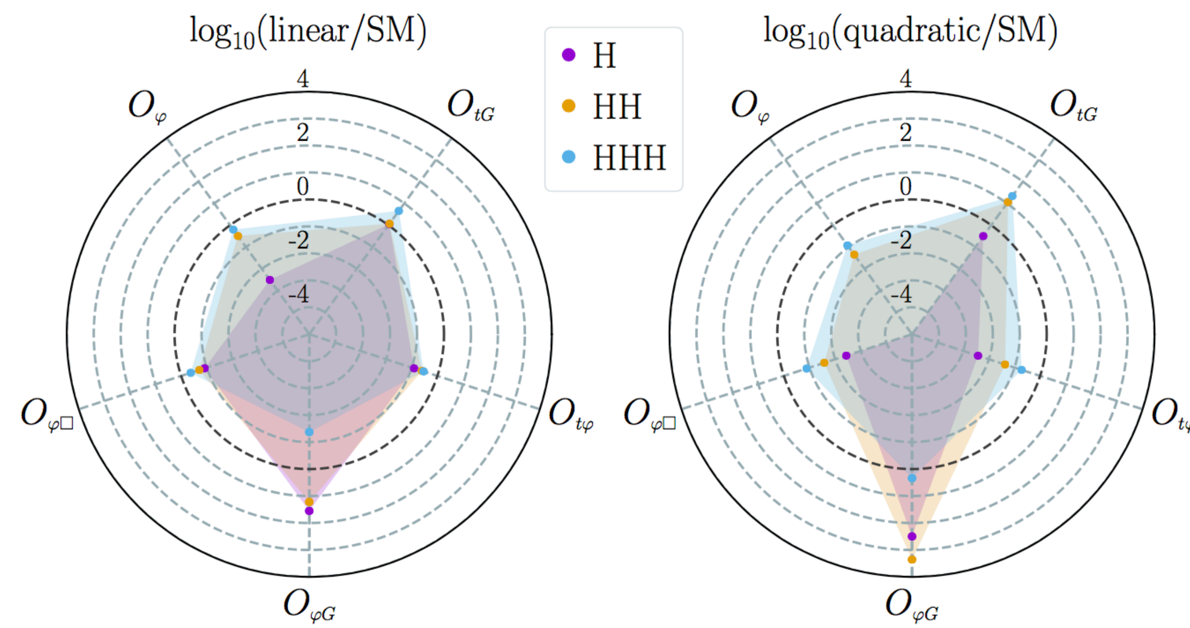
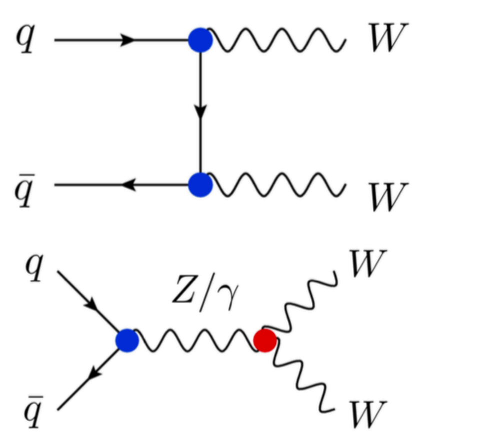


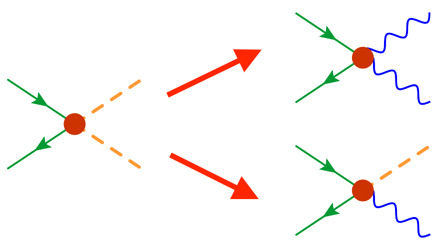
FIG. 3. Linear and quadratic contributions of the five relevant operators to H, HH, and HHH production at a future 100 TeV pp collider, normalised by the corresponding SM predictions.

The projected FCC-hh reach: 1%, 5% and 50% on H, HH and HHH

Diboson, TGC/qqV



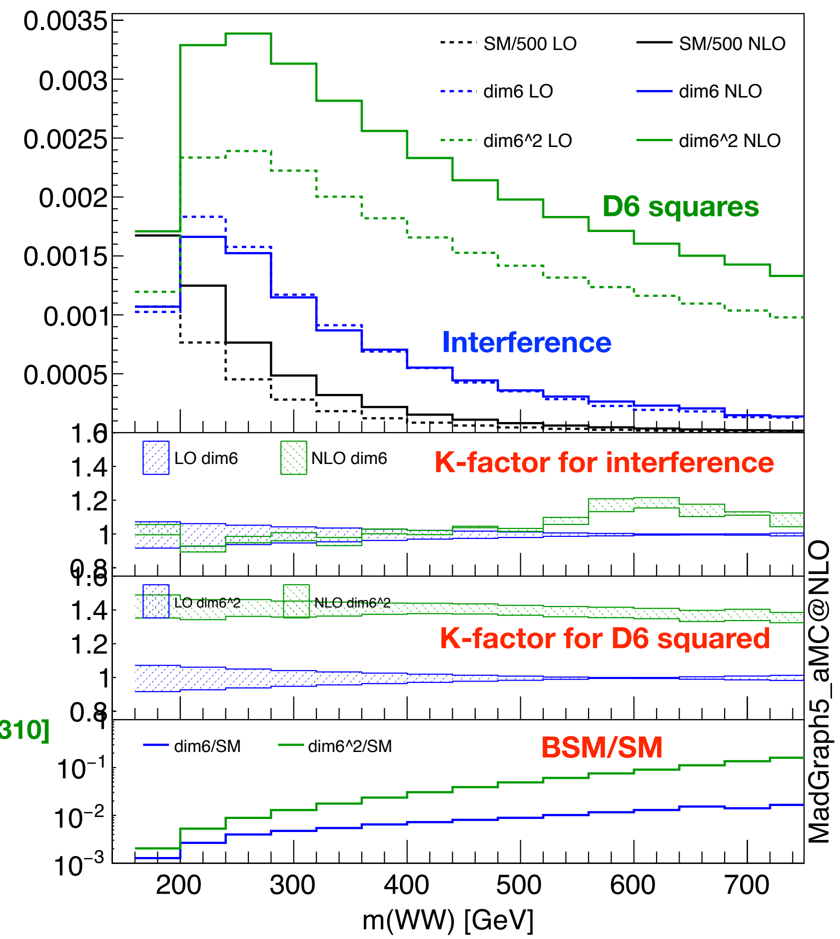
$$\mathcal{O}_L^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$

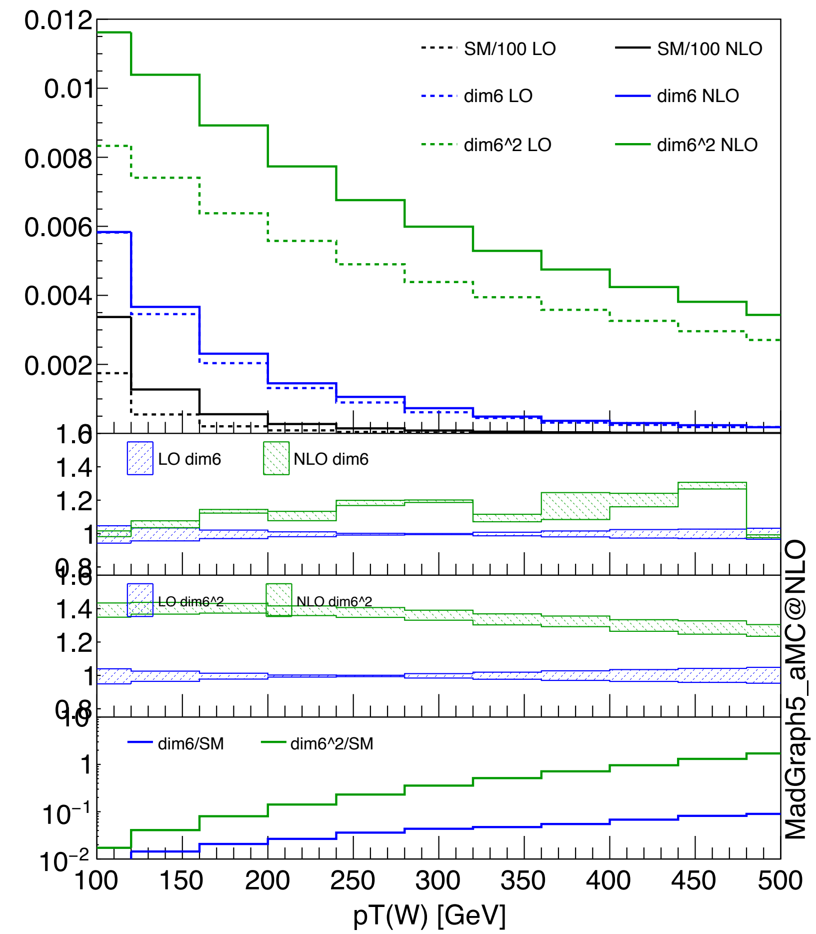


[R. Franceschini et al. 1712.01310]

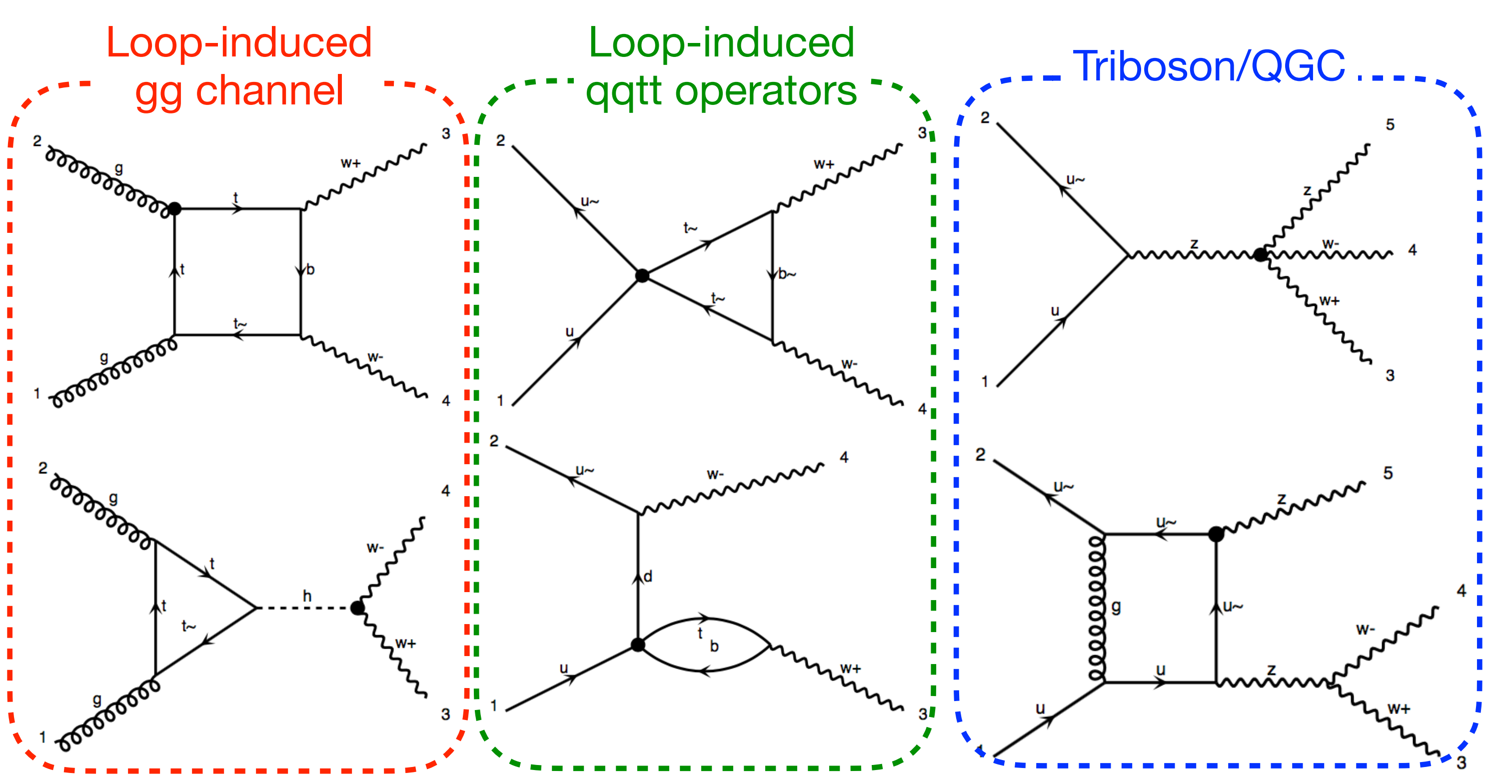
[S. Banerjee et al. 1807.01796]

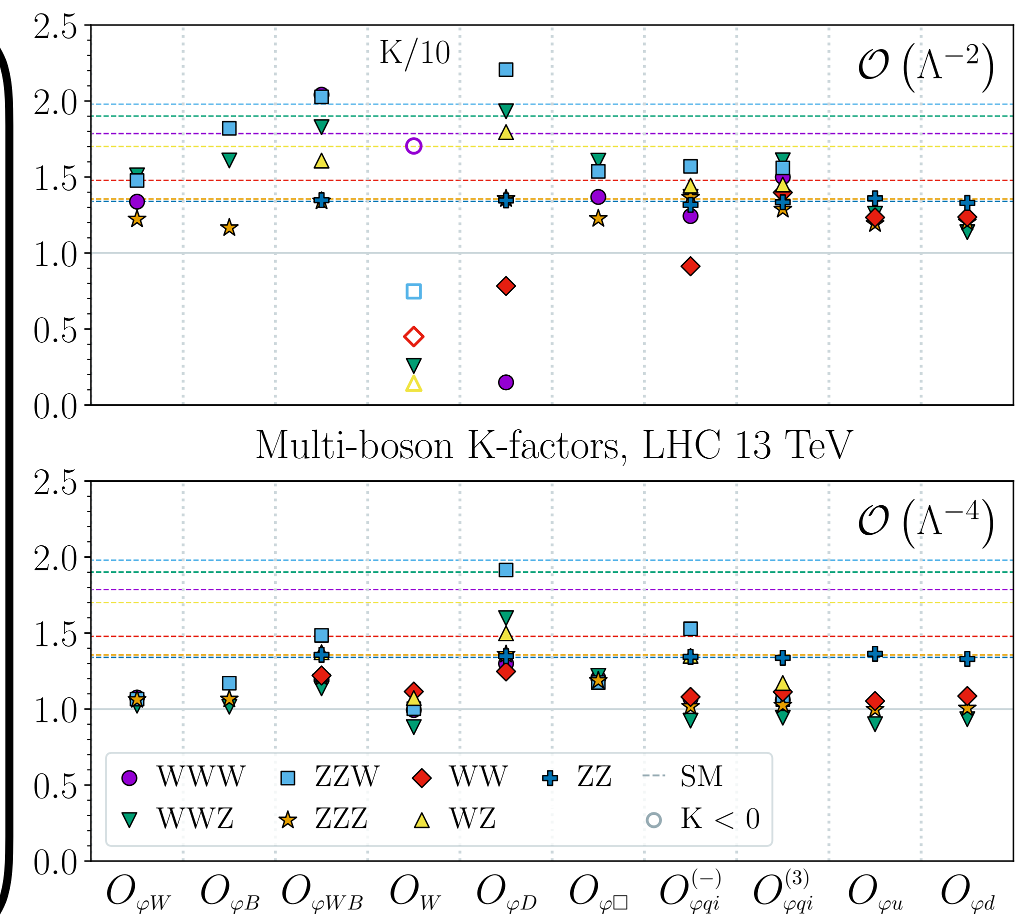
[C. Grojean et al. 1810.05149]





Diboson + multiboson: WW/WZ/ZZ/WWW/WWZ/ZZW/ZZZ



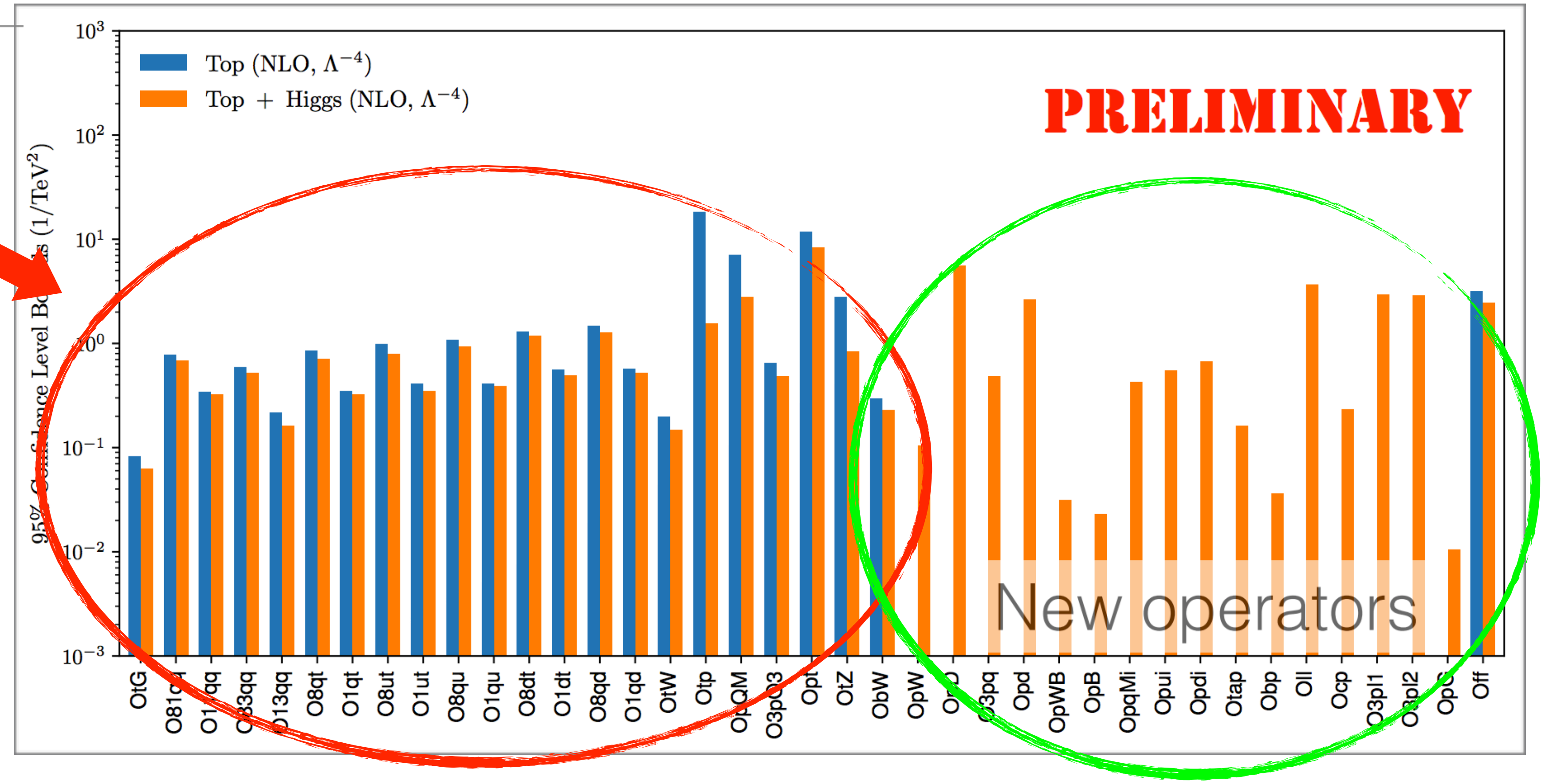


5.7σ from CMS; talk by Zhijun Liang

[Degrande et al., 2008.11743]

Towards global SMEFT fit @ NLO

- Global fit in the top-quark sector: SMEFiT **[Hartland et al. ’19]**
  - Exactly where automation is crucial
- Now being extended to add Higgs/diboson data



Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou and CZ in progress

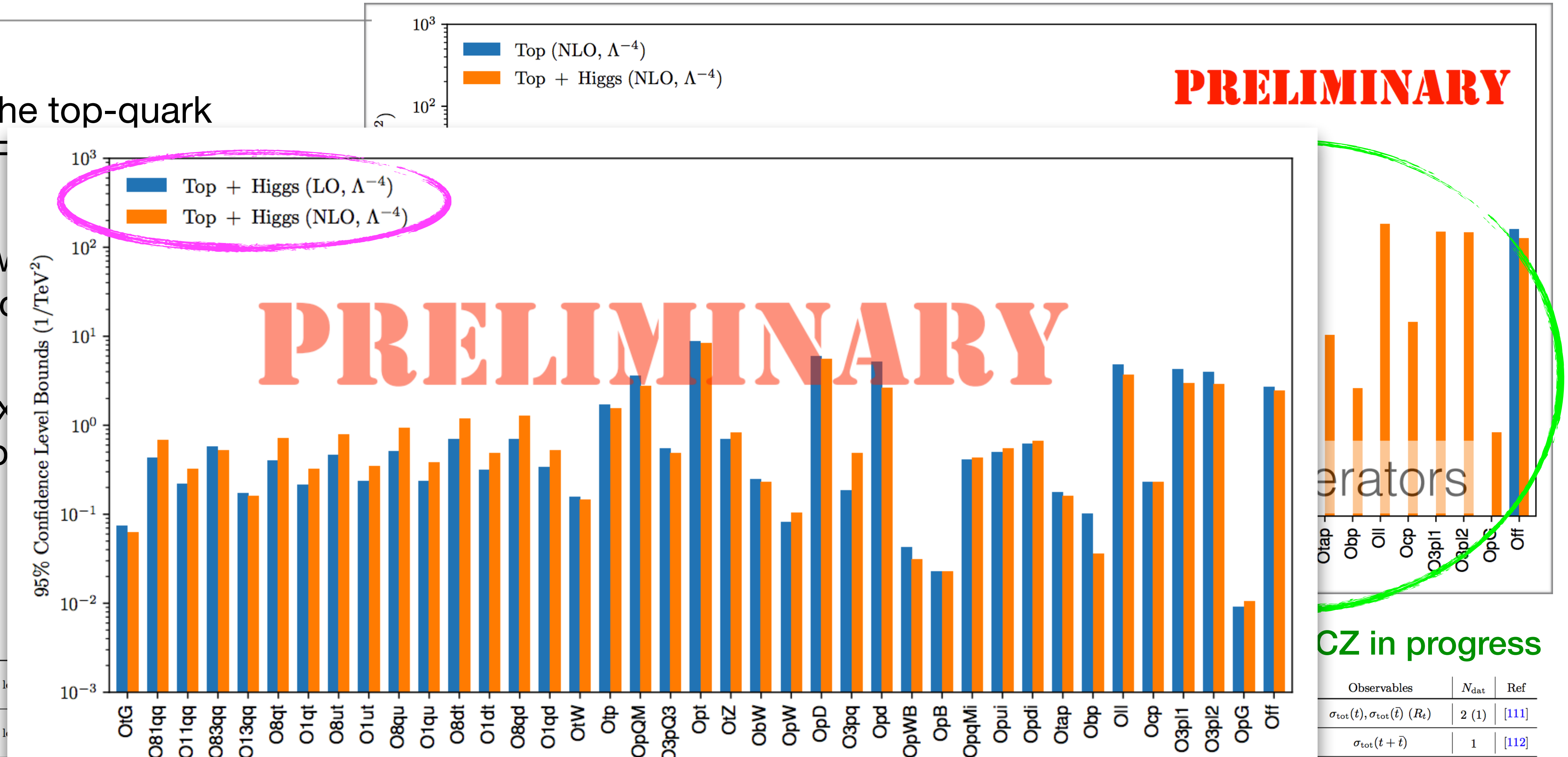
Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
$t\bar{t}$	ATLAS_tt_8TeV_ljets	8 TeV	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	5, 8, 7, 5	[94]
$t\bar{t}$	CMS_tt_8TeV_ljets	8 TeV	lepton+jets	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	10, 8, 7, 10	[95]
$t\bar{t}$	CMS_tt2D_8TeV_dilep	8 TeV	dileptons	$d^2\sigma/dy_t dp_t^T$, $d^2\sigma/dy_t dm_{t\bar{t}}$, $d^2\sigma/dp_{t\bar{t}}^T dm_{t\bar{t}}$, $d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$	16, 16, 16, 16	[96]
$t\bar{t}$	CMS_tt_13TeV_ljets	13 TeV	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	7, 9, 8, 6	[99]
$t\bar{t}$	CMS_tt_13TeV_ljets2	13 TeV	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	11, 12, 10, 10	[101]
$t\bar{t}$	CMS_tt_13TeV_dilep	13 TeV	dileptons	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	8, 6, 6, 8	[102]
$t\bar{t}$	ATLAS_WhelF_8TeV	8 TeV	W helicity fract	F_0, F_L, F_R	3	[97]
$t\bar{t}$	CMS_WhelF_8TeV	8 TeV	W helicity fract	F_0, F_L, F_R	3	[98]

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
$t\bar{t}b\bar{b}$	CMS_ttbb_13TeV	13 TeV	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[103]
$t\bar{t}t\bar{t}$	CMS_tttt_13TeV	13 TeV	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[104]
$t\bar{t}Z$	CMS_ttZ_8_13TeV	8+13 TeV	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	2	[105, 106]
$t\bar{t}Z$	ATLAS_ttZ_8_13TeV	8+13 TeV	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	2	[107, 108]
$t\bar{t}W$	CMS_ttW_8_13TeV	8+13 TeV	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	2	[105, 106]
$t\bar{t}W$	ATLAS_ttW_8_13TeV	8+13 TeV	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	2	[107, 108]
$t\bar{t}H$	CMS_tth_13TeV	13 TeV	signal strength	$\mu_{t\bar{t}H}$	1	[109]
$t\bar{t}H$	ATLAS_tth_13TeV	13 TeV	total xsec	$\sigma_{\rm tot}(t\bar{t}H)$	1	[110]

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
Single t	CMS_t_tch_8TeV_inc	8 TeV	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[111]
Single t	CMS_t_sch_8TeV	8 TeV	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[112]
Single t	ATLAS_t_sch_8TeV	8 TeV	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[113]
Single t	ATLAS_t_tch_8TeV	8 TeV	t-channel	$d\sigma(tq)/dp_T^t, d\sigma(\bar{t}q)/dp_T^{\bar{t}}$ $d\sigma(tq)/dy_t, d\sigma(\bar{t}q)/dy_t$	5, 4 4, 4	[114]
Single t	ATLAS_t_tch_13TeV	13 TeV	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[115]
Single t	CMS_t_tch_13TeV_inc	13 TeV	t-channel	$\sigma_{\rm tot}(t+\bar{t})$ (R_t)	1 (1)	[116]
Single t	CMS_t_tch_8TeV_dif	8 TeV	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\|y^{(t+\bar{t})}\|$	6 6	[117]
Single t	CMS_t_tch_13TeV_dif	13 TeV	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\|y^{(t+\bar{t})}\|$	4 4	[118]
tW	ATLAS_tW_inc_8TeV	8 TeV	inclusive	$\sigma_{\rm tot}(tW)$	1	[119]
tW	CMS_tW_inc_8TeV	8 TeV	inclusive	$\sigma_{\rm tot}(tW)$	1	[120]
tW	ATLAS_tW_inc_13TeV	13 TeV	inclusive	$\sigma_{\rm tot}(tW)$	1	[121]
tW	CMS_tW_inc_13TeV	13 TeV	inclusive	$\sigma_{\rm tot}(tW)$	1	[122]
tZ	CMS_tZ_inc_13TeV	13 TeV	inclusive	$\sigma_{\rm fid}(Wbl^+l^-q)$	1	[123]
tZ	ATLAS_tZ_inc_13TeV	13 TeV	inclusive	$\sigma_{\rm tot}(tZq)$	1	[124]

Towards global SMEFT fit @ NLO

- Global fit in the top-quark sector: SMEF
  [Hartland et
  - Exactly w automatic
- Now being ex Higgs/diboso



Process	Dataset	$\sqrt{s}$				
$t\bar{t}$	ATLAS_tt_8TeV_ljets	8 TeV	l			
$t\bar{t}$	CMS_tt_8TeV_ljets	8 TeV	l			
$t\bar{t}$	CMS_tt2D_8TeV_dilep	8 TeV	dileptons	$d^2\sigma/dy_t dp_t^T$, $d^2\sigma/dy_t dm_{t\bar{t}}$, $d^2\sigma/dp_{t\bar{t}}^T dm_{t\bar{t}}$, $d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$	16, 16, 16, 16	[96]
$t\bar{t}$	CMS_tt_13TeV_ljets	13 TeV	lepton+jets	$d\sigma/d\lvert y_t\rvert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\lvert y_{t\bar{t}}\rvert$	7, 9, 8, 6	[99]
$t\bar{t}$	CMS_tt_13TeV_ljets2	13 TeV	lepton+jets	$d\sigma/d\lvert y_t\rvert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\lvert y_{t\bar{t}}\rvert$	11, 12, 10, 10	[101]
$t\bar{t}$	CMS_tt_13TeV_dilep	13 TeV	dileptons	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	8, 6, 6, 8	[102]
$t\bar{t}$	ATLAS_WhelF_8TeV	8 TeV	W helicity fract	F_0, F_L, F_R	3	[97]
$t\bar{t}$	CMS_WhelF_8TeV	8 TeV	W helicity fract	F_0, F_L, F_R	3	[98]

$t\bar{t}b\bar{b}$	CMS_ttbb_13TeV	13 TeV	total xsec	$\sigma_{tot}(t\bar{t}b\bar{b})$	1	[103]
$t\bar{t}t\bar{t}$	CMS_tttt_13TeV	13 TeV	total xsec	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[104]
$t\bar{t}Z$	CMS_ttZ_8_13TeV	8+13 TeV	total xsec	$\sigma_{tot}(t\bar{t}Z)$	2	[105, 106]
$t\bar{t}Z$	ATLAS_ttZ_8_13TeV	8+13 TeV	total xsec	$\sigma_{tot}(t\bar{t}Z)$	2	[107, 108]
$t\bar{t}W$	CMS_ttW_8_13TeV	8+13 TeV	total xsec	$\sigma_{tot}(t\bar{t}W)$	2	[105, 106]
$t\bar{t}W$	ATLAS_ttW_8_13TeV	8+13 TeV	total xsec	$\sigma_{tot}(t\bar{t}W)$	2	[107, 108]
$t\bar{t}H$	CMS_tth_13TeV	13 TeV	signal strength	$\mu_{t\bar{t}H}$	1	[109]
$t\bar{t}H$	ATLAS_tth_13TeV	13 TeV	total xsec	$\sigma_{tot}(t\bar{t}H)$	1	[110]

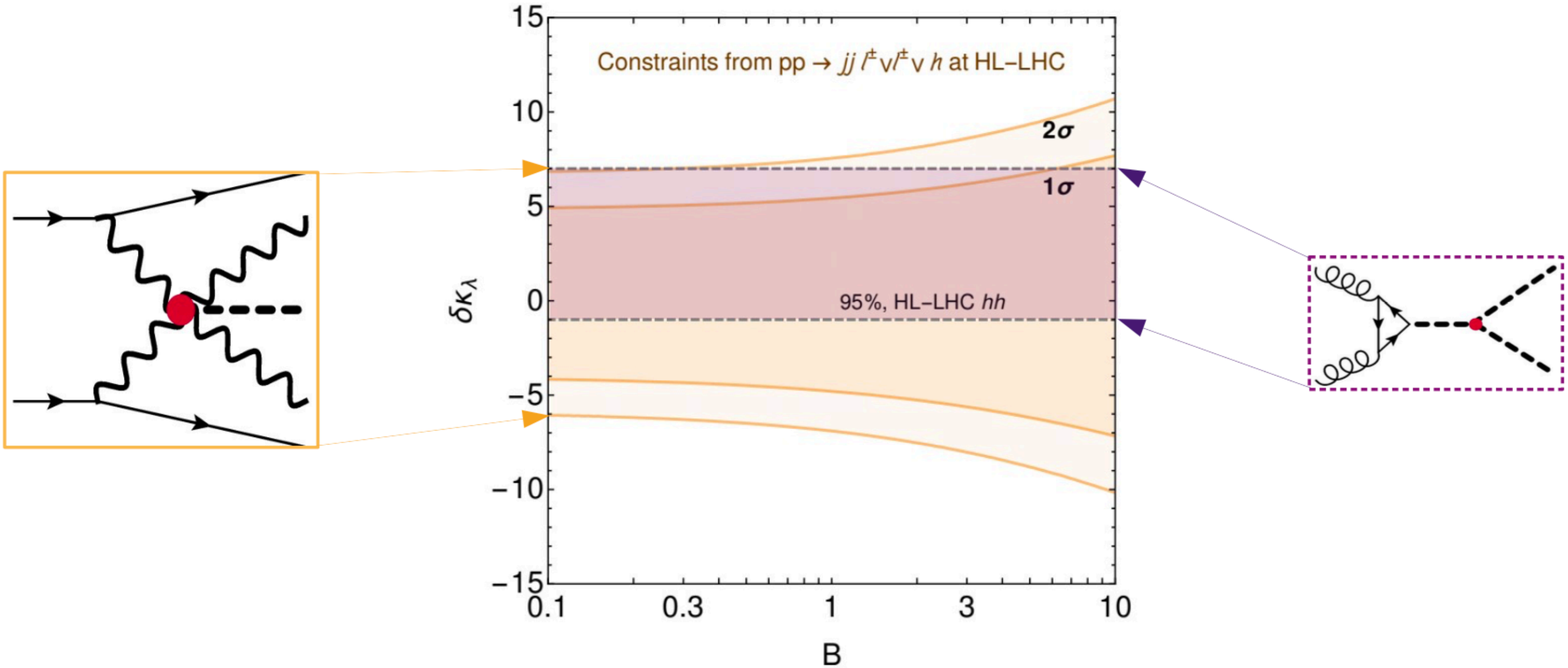
				Observables	N_{dat}	Ref
				$\sigma_{tot}(t), \sigma_{tot}(\bar{t})$ (R_t)	2 (1)	[111]
				$\sigma_{tot}(t+\bar{t})$	1	[112]
Single t	ATLAS_t_sch_8TeV	8 TeV	s-channel	$\sigma_{tot}(t+\bar{t})$	1	[113]
Single t	ATLAS_t_tch_8TeV	8 TeV	t-channel	$d\sigma(tq)/dp_T^t, d\sigma(\bar{t}q)/dp_T^{\bar{t}}$ $d\sigma(tq)/dy_t, d\sigma(\bar{t}q)/dy_t$	5, 4 4, 4	[114]
Single t	ATLAS_t_tch_13TeV	13 TeV	t-channel	$\sigma_{tot}(t), \sigma_{tot}(\bar{t})$ (R_t)	2 (1)	[115]
Single t	CMS_t_tch_13TeV_inc	13 TeV	t-channel	$\sigma_{tot}(t+\bar{t})$ (R_t)	1 (1)	[116]
Single t	CMS_t_tch_8TeV_dif	8 TeV	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	6 6	[117]
Single t	CMS_t_tch_13TeV_dif	13 TeV	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	4 4	[118]
tW	ATLAS_tW_inc_8TeV	8 TeV	inclusive	$\sigma_{tot}(tW)$	1	[119]
tW	CMS_tW_inc_8TeV	8 TeV	inclusive	$\sigma_{tot}(tW)$	1	[120]
tW	ATLAS_tW_inc_13TeV	13 TeV	inclusive	$\sigma_{tot}(tW)$	1	[121]
tW	CMS_tW_inc_13TeV	13 TeV	inclusive	$\sigma_{tot}(tW)$	1	[122]
tZ	CMS_tZ_inc_13TeV	13 TeV	inclusive	$\sigma_{fid}(Wbl^+l^-q)$	1	[123]
tZ	ATLAS_tZ_inc_13TeV	13 TeV	inclusive	$\sigma_{tot}(tZq)$	1	[124]

Summary

- With Run II finished, and Run III, HL/HE-LHC, future CC/LC waiting ahead, we are entering a phase where we can better see how top and Higgs are connected with each other and with the rest of the SM, even in the context of searching for BSM.
- New ideas to benefit from these connections, including but not limited to:
  - Exploring the E^2/Λ^2 effects by activating H/Goldstone fields, and embedding the core process in multi particle production.
  - Loop-induced channels further open up new possibilities.
- SMEFT framework well understood, (NLO) tools are available, with which many new ideas/observables/calculations have been proposed and investigated, in case studies, with certain TH assumptions or restrictions, to demonstrate that how and what we can learn by connecting different sectors in the SMEFT.
- Yet, we should keep in mind that a global perspective is very important in such a situation, and we need it to quantify the actual benefit, to answer more realistic questions, and to provide useful inputs for future strategies.

Thank you

Higgs self-coupling

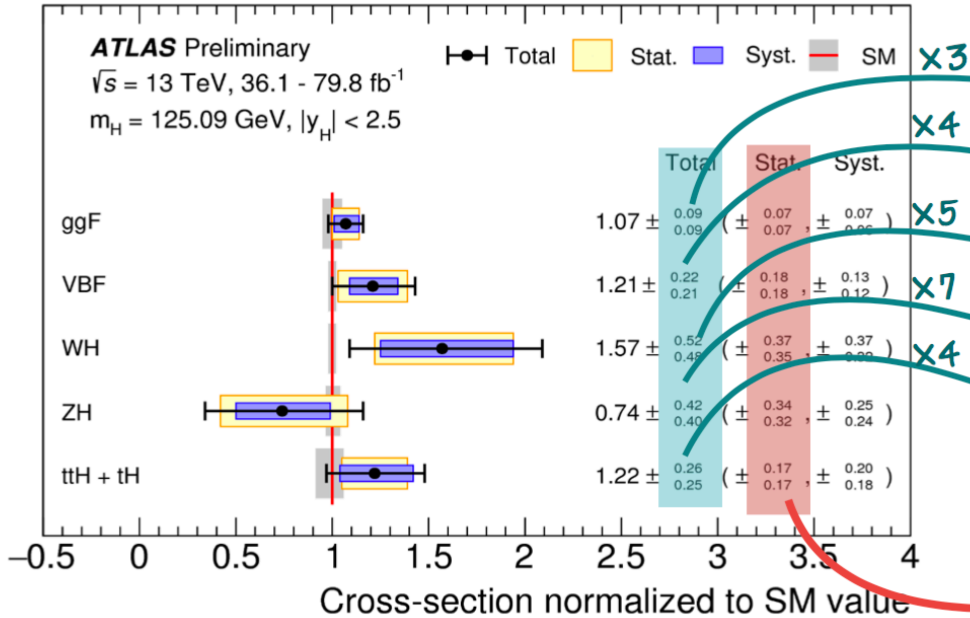


- 50-ish events in the SM
- Irreducible background negligible
- Background from ttjj with lepton misidentification under control
- Backgorund from fake leptons is potentially the dominant one.
  We parametrize it with **#back = B x #signal.**
- Rough cut-and-count analysis gives competitive results with double higgs production

28

Talk by M. Riembau

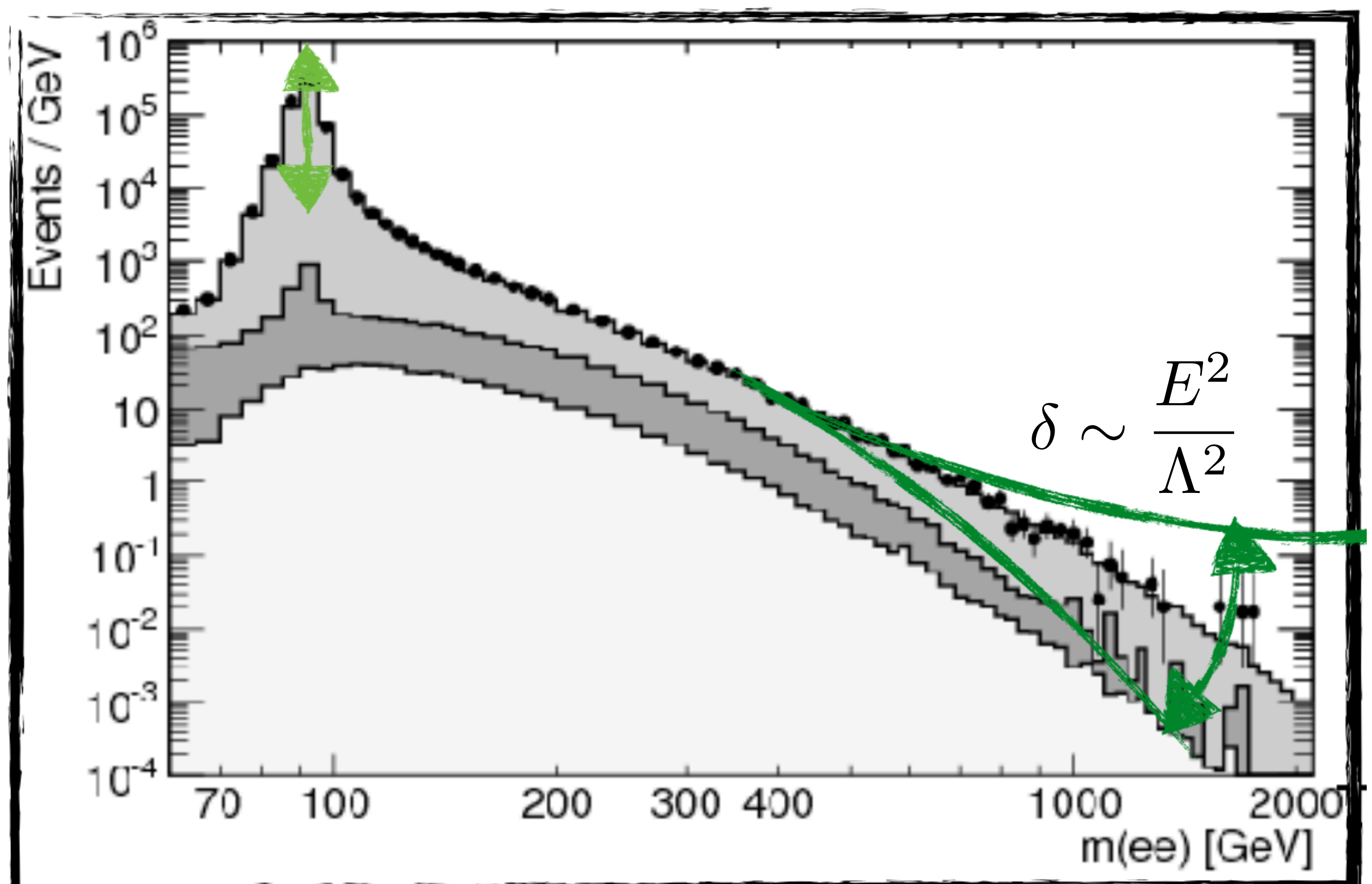
HL-LHC projections:



ATLAS

		3000 fb^{-1} uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
σ_{ggH}	S1	3.5	0.8	2.1	2.1	1.6
	S2	2.4	0.8	1.7	1.2	1.0
σ_{VBF}	S1	5.5	2.0	2.7	3.7	2.1
	S2	4.2	2.0	2.3	2.2	1.7
σ_{WH}	S1	9.3	4.0	4.0	5.1	5.4
	S2	7.7	4.0	3.4	3.3	4.5
σ_{ZH}	S1	6.2	3.4	2.4	3.4	3.0
	S2	4.8	3.4	1.8	2.0	2.1
σ_{ttH}	S1	6.7	1.9	3.1	3.7	4.3
	S2	5.3	1.9	2.8	2.4	3.3

Talk by M. Riembau



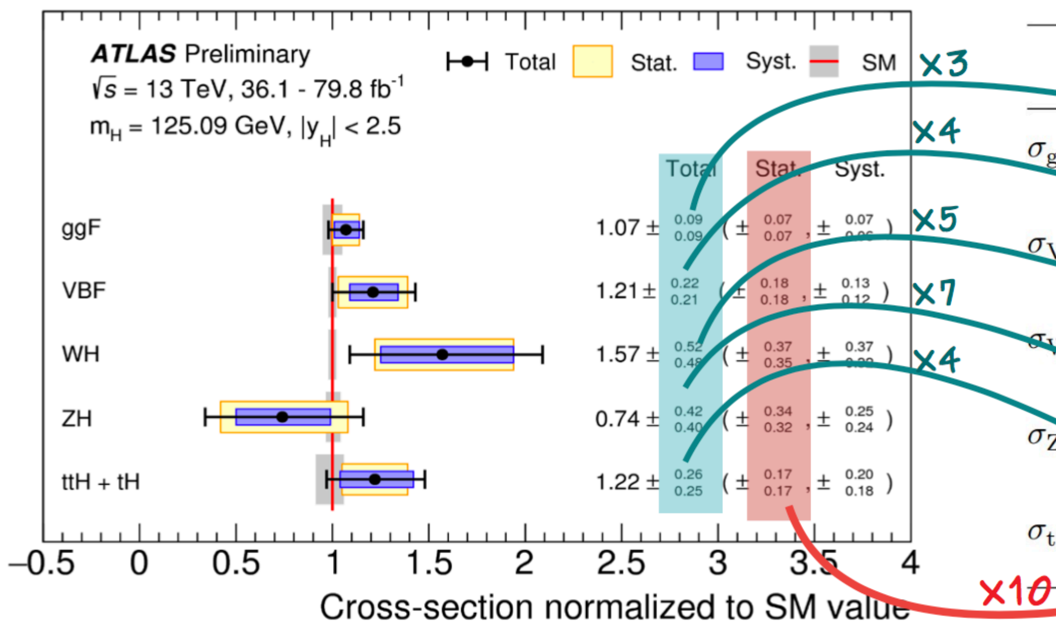
$$\delta \sim \frac{E^2}{\Lambda^2}$$

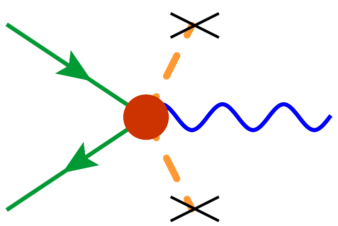
Talk by F. Riva, EPSHEP 2019

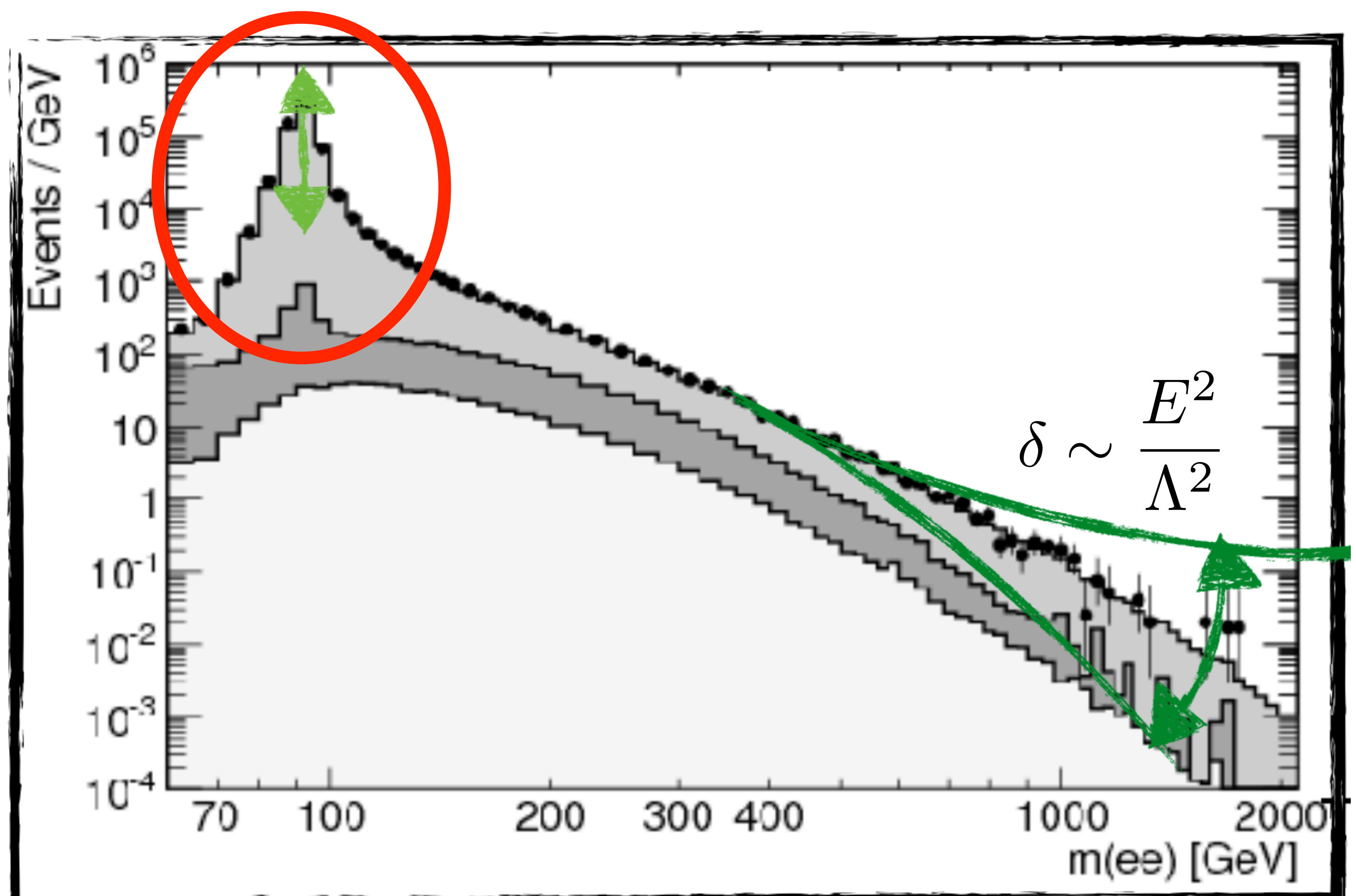
HL–LHC projections:

ATLAS						
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
σ_{ggH}	S1	3.5	0.8	2.1	2.1	1.6
	S2	2.4	0.8	1.7	1.2	1.0
σ_{VBF}	S1	5.5	2.0	2.7	3.7	2.1
	S2	4.2	2.0	2.3	2.2	1.7
σ_{WH}	S1	9.3	4.0	4.0	5.1	5.4
	S2	7.7	4.0	3.4	3.3	4.5
σ_{ZH}	S1	6.2	3.4	2.4	3.4	3.0
	S2	4.8	3.4	1.8	2.0	2.1
σ_{ttH}	S1	6.7	1.9	3.1	3.7	4.3
	S2	5.3	1.9	2.8	2.4	3.3

Talk by M. Riembau



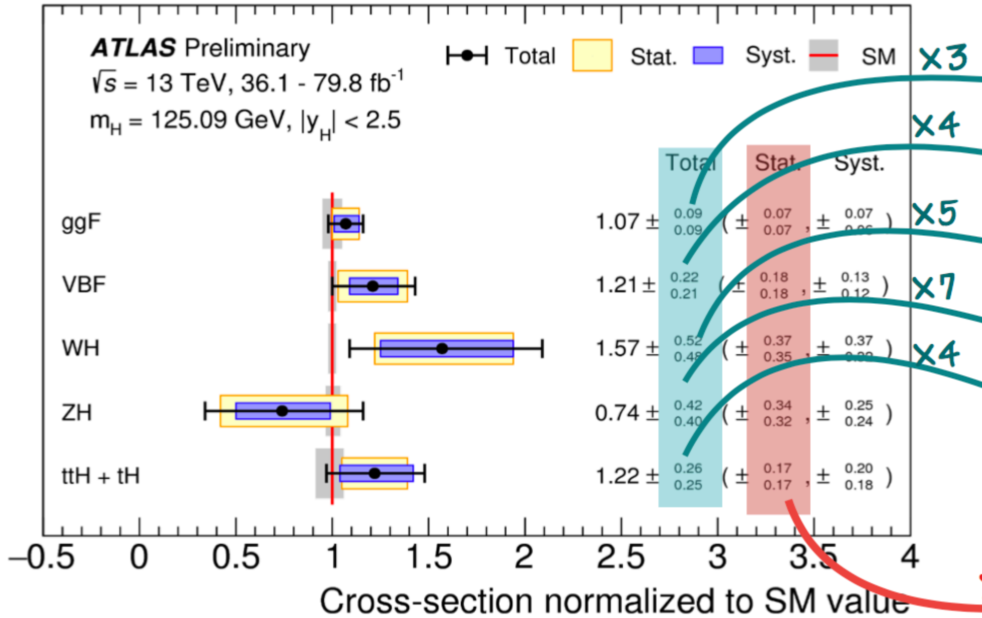




More standard channels, e.g. Z-pole, Higgs/top on-shell couplings…

- Big statistics
- Good precision
- Less sensitive to BSM
- Limited by systematics

Talk by F. Riva, EPSHEP 2019



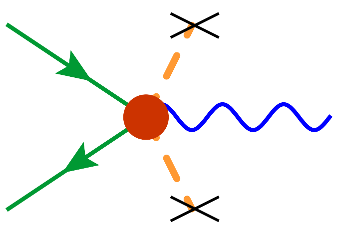
HL–LHC projections:

ATLAS

3000 fb^{-1} uncertainty [%]

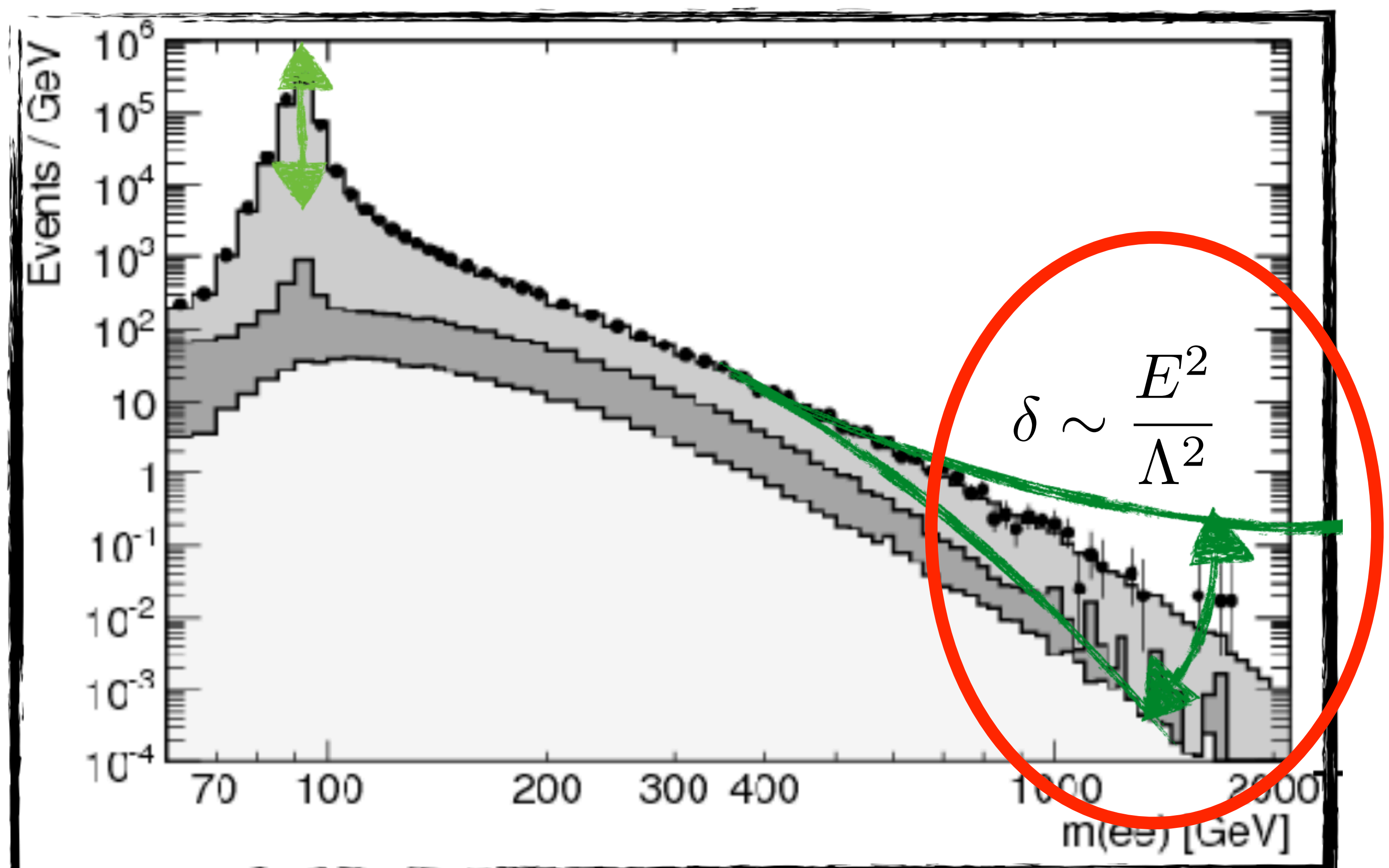
		Total	Stat	Exp	SigTh	BkgTh
σ_{ggH}	S1	3.5	0.8	2.1	2.1	1.6
	S2	2.4	0.8	1.7	1.2	1.0
σ_{VBF}	S1	5.5	2.0	2.7	3.7	2.1
	S2	4.2	2.0	2.3	2.2	1.7
σ_{WH}	S1	9.3	4.0	4.0	5.1	5.4
	S2	7.7	4.0	3.4	3.3	4.5
σ_{ZH}	S1	6.2	3.4	2.4	3.4	3.0
	S2	4.8	3.4	1.8	2.0	2.1
σ_{ttH}	S1	6.7	1.9	3.1	3.7	4.3
	S2	5.3	1.9	2.8	2.4	3.3

Talk by M. Riembau

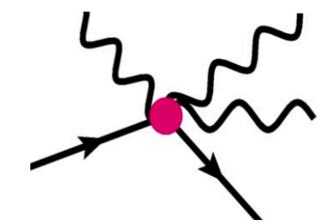


More standard channels, e.g. Z-pole, Higgs/top on-shell couplings…

- Big statistics
- Good precision
- Less sensitive to BSM
- Limited by systematics



Talk by F. Riva, EPSHEP 2019



$$\frac{\delta\sigma(\hat{s})}{\sigma_{SM}(\hat{s})} \sim \delta g_i \frac{\hat{s}}{m_Z^2}\,.$$

30% in $\delta\sigma$, at 1 TeV,
$\Rightarrow$ 0.3% in couplings

- Small statistics
- Bad precision
- More sensitive to BSM
- Less limited by syst.
- Important to identify the right channel which has the energy-growth

SMEFT

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- Pattern of SM deviations enter <u>many observables</u> in a <u>correlated</u> way.
- To be identified with **<u>global fit</u>** methods

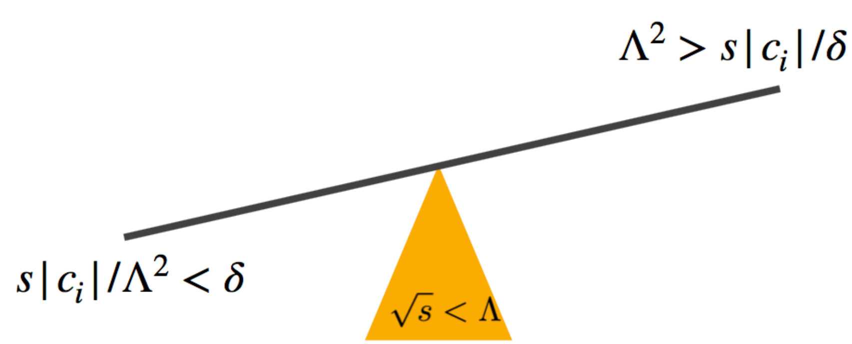
SMEFT

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- Pattern of SM deviations enter <u>many observables</u> in a <u>correlated</u> way.
- To be identified with <u>**global fit**</u> methods

Sensitivity:

- Most precise/accurate experimental measurements with uncertainties and correlations.
- Most precise SM predictions for observables: NLO, NNLO, N3LO...



SMEFT

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

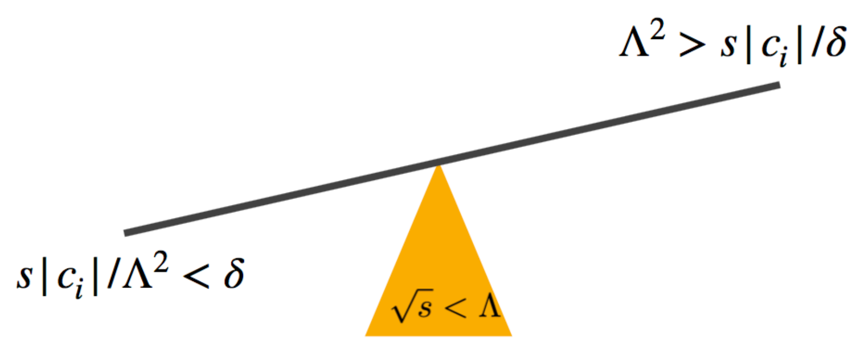
- Pattern of SM deviations enter many observables in a correlated way.
- To be identified with **global fit** methods

Sensitivity:

- Most precise/accurate experimental measurements with uncertainties and correlations.
- Most precise SM predictions for observables: NLO, NNLO, N3LO...

Interpretation:

- relies on sizes/ correlations of the $c^{(6)}$'s. Their determination requires the most precise SMEFT predictions.

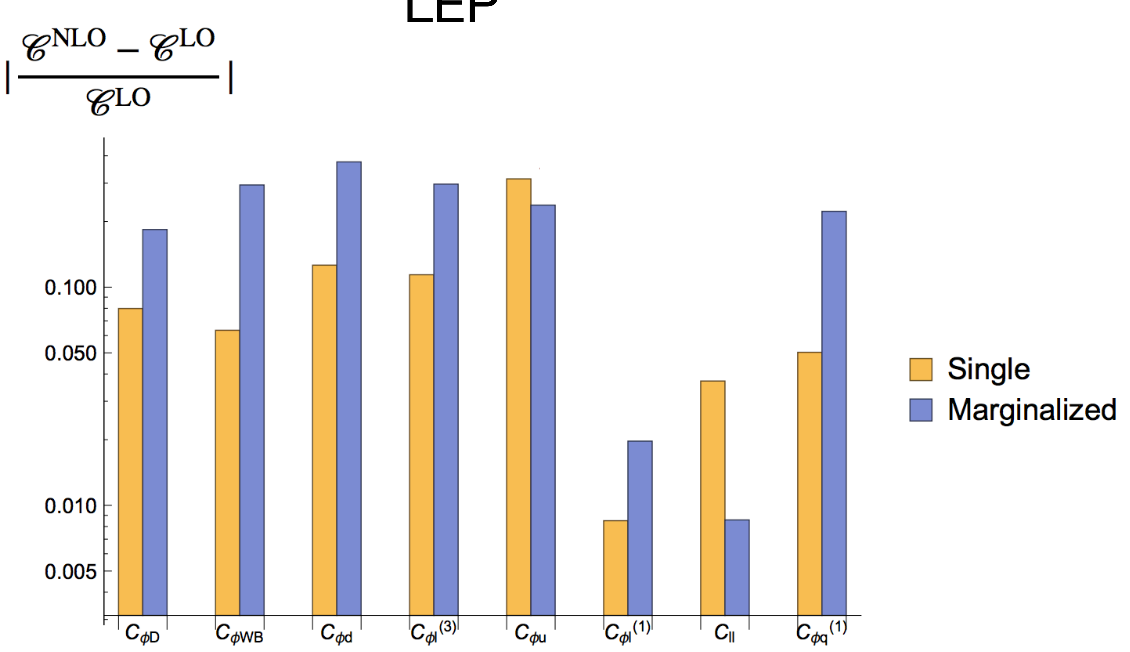


SMEFT at higher order

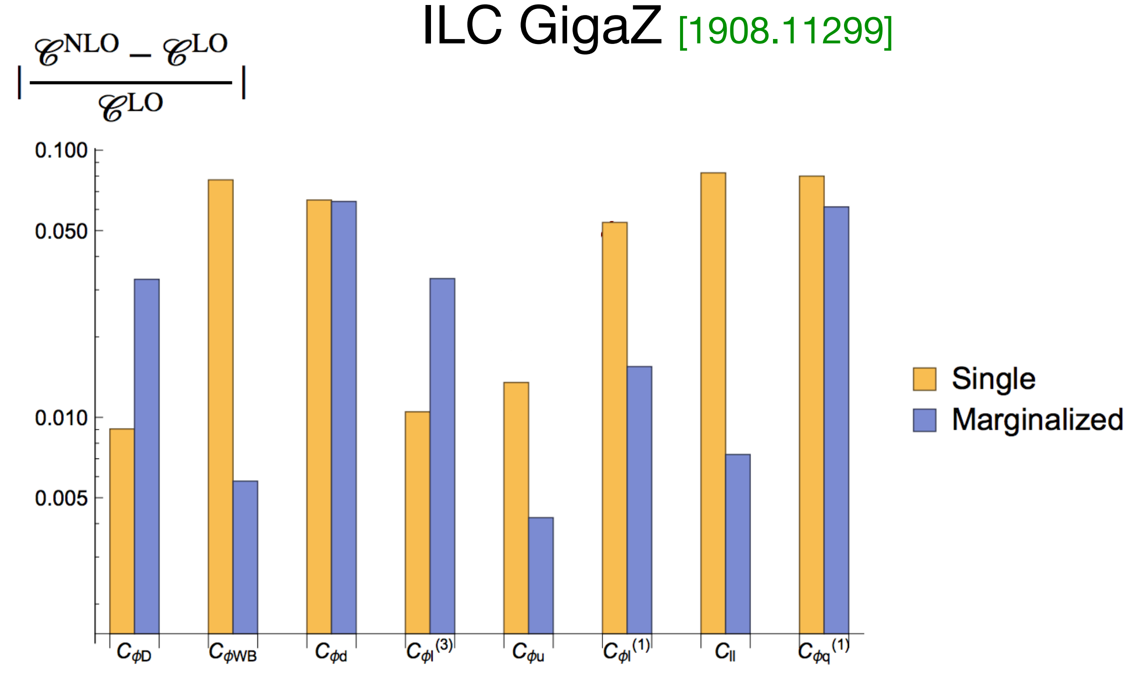
Higher orders in SMEFT allows

- Accuracy
  - In case of no deviation found:

LEP



ILC GigaZ [1908.11299]



EWPO fit
[Dawson, Giardino '19]

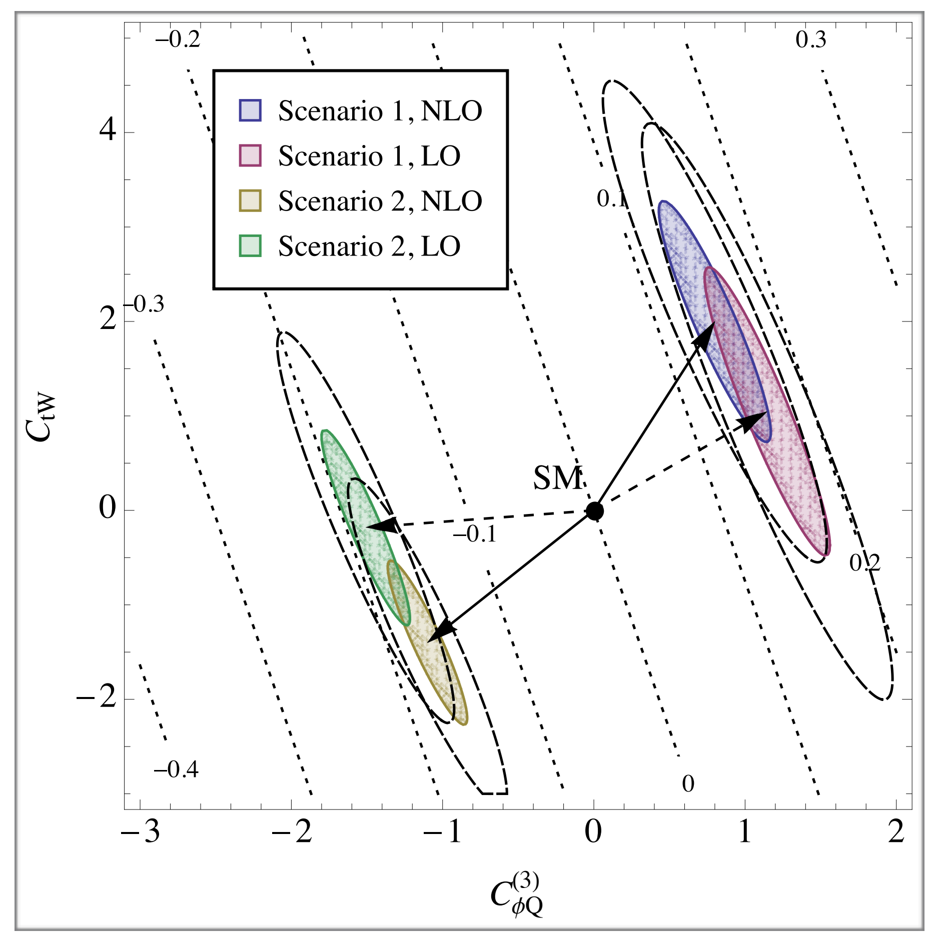
Even EW corrections lead to ~20% difference

SMEFT at higher order

Higher orders in SMEFT allows

- Accuracy
  - In case of a deviation, changes our interpretation of the nature of BSM

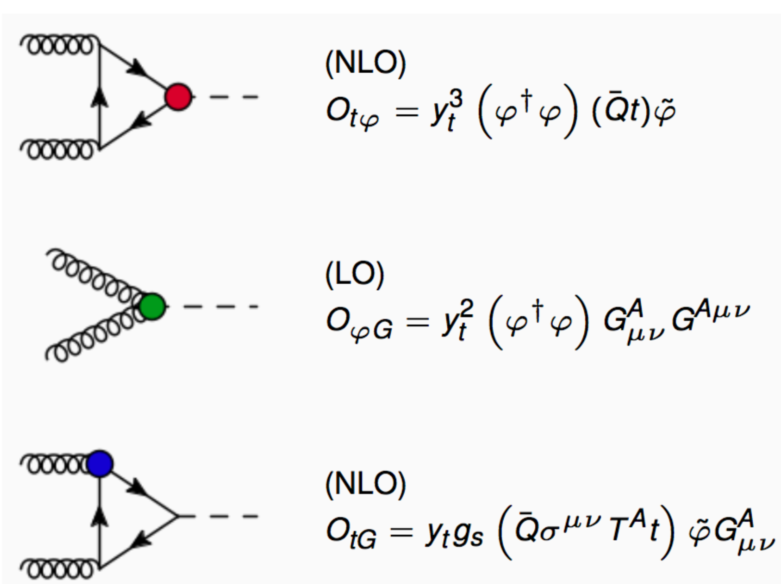
- QCD corrections to shapes can lead to bias in fitting results.
- E.g. in single top, in case of 15% (hypothetical) deviations observed in future, LO/NLO lead to a different direction of deviation from SM.

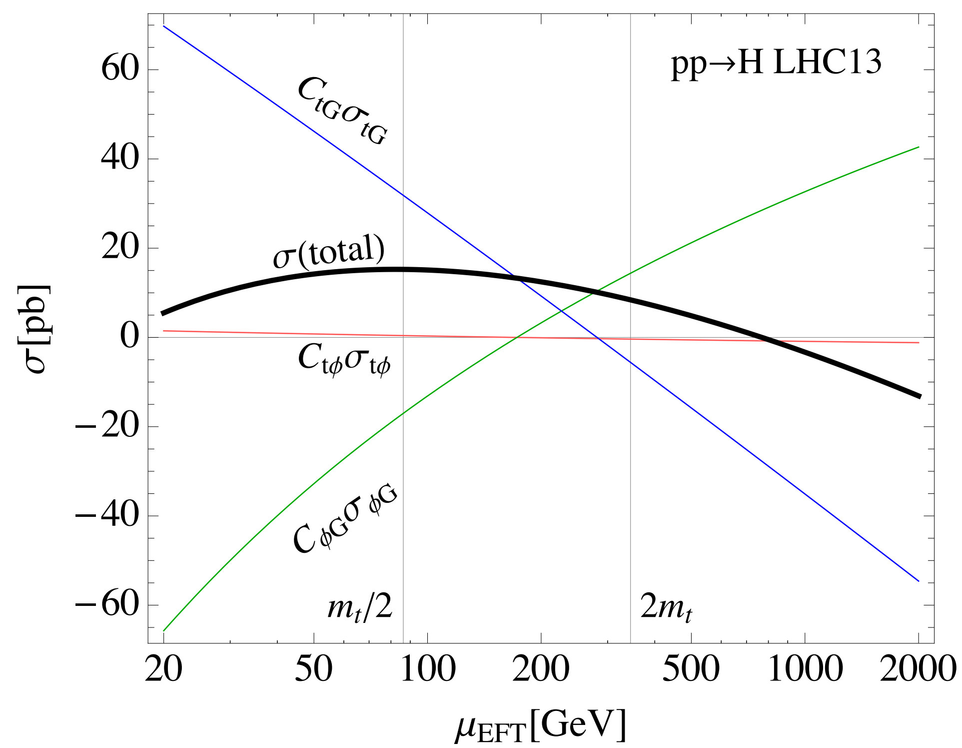


SMEFT at higher order

Higher orders in SMEFT allows

- Accuracy
- Precision: scale uncertainty improved order by order.
  - Only if all operators along with their mixing/running taken into account.





$$C_{tG} = 1,\ C_{t\varphi} = C_{\varphi G} = 0 \text{ at } m_t$$

- Contribution from one operator may become the contribution from a different operator, as the scale changes.
- Only a **global (fitting) approach** could make sense.

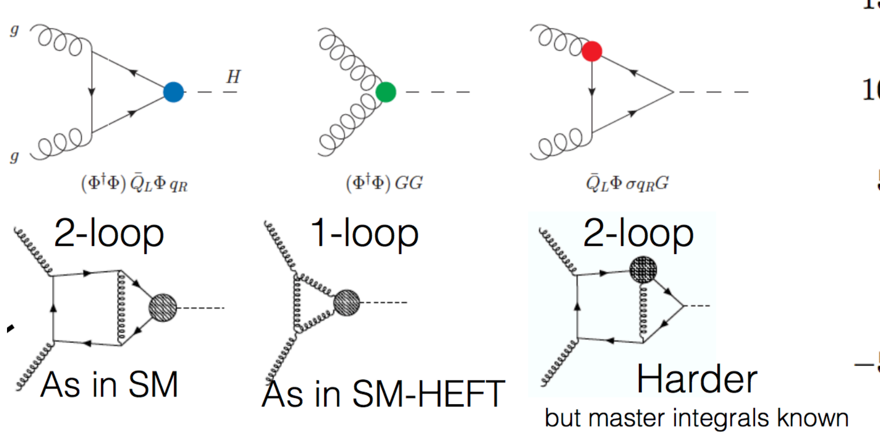
[Vryonidou, Maltoni, CZ, '16]

SMEFT at higher order

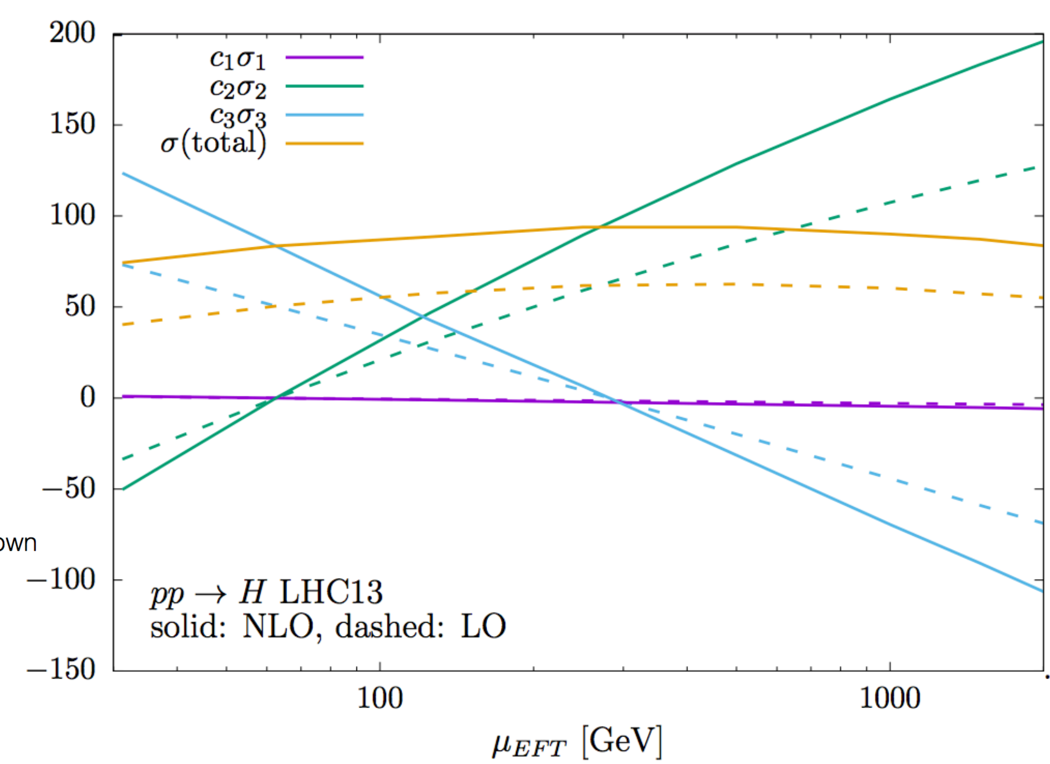
Higher orders in SMEFT allows

- Accuracy
- Precision: scale uncertainty improved order by order.
  - Only if all operators along with their mixing/running taken into account.

$LO \Downarrow$



$NLO \Uparrow$



SMEFT prediction can be improved order by order, provided that all relevant operators are summed up.

[Deutschmann, Duhr, Maltoni, Vryonidou, '17]

SMEFT at higher order

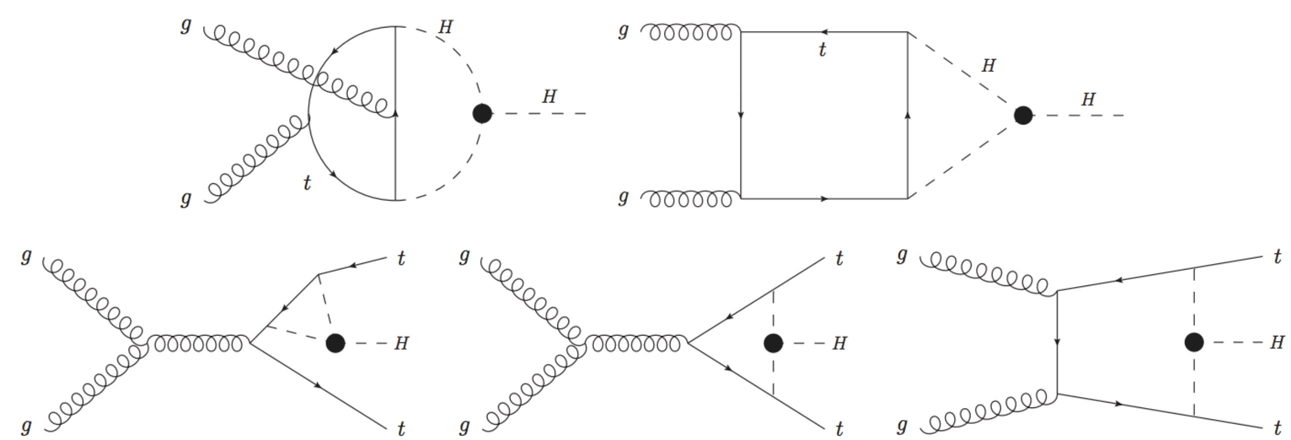
Higher orders in SMEFT allows

- Accuracy
- Precision
- Improved sensitivity
  - Accurate knowledge of the deviations (shapes, correlation between observables, etc.) can be the key to disentangle the (SMEFT type) indirect BSM effects from SM.
    - Multi-variable analyses always benefit from accurate knowledge of the signal.
  - Loop-induced new sensitivity.

Loop-induced sensitivity, e.g. to trilinear H coupling

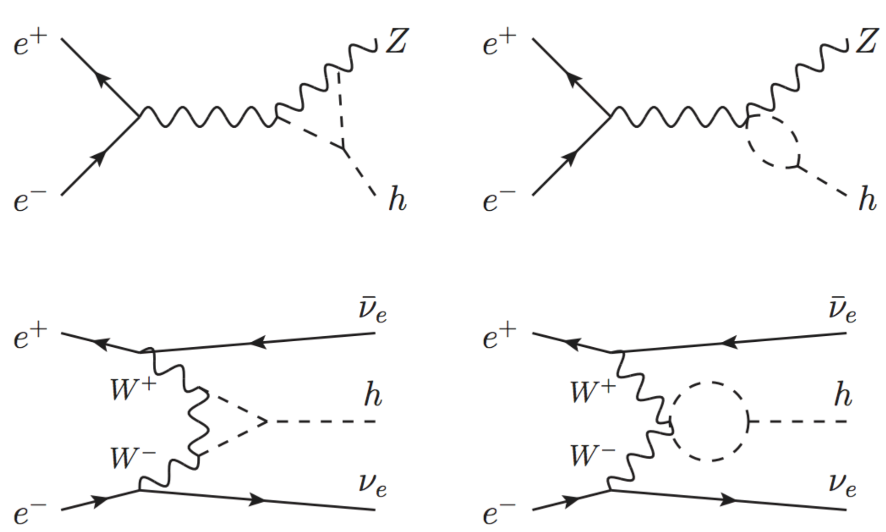
- Some times operators could first show up at 1-loop.
- This could imply new chances to measure certain coefs. that are difficult at LO.
- The trilinear Higgs coupling, κ_λ, is a well-known example.

At the LHC:



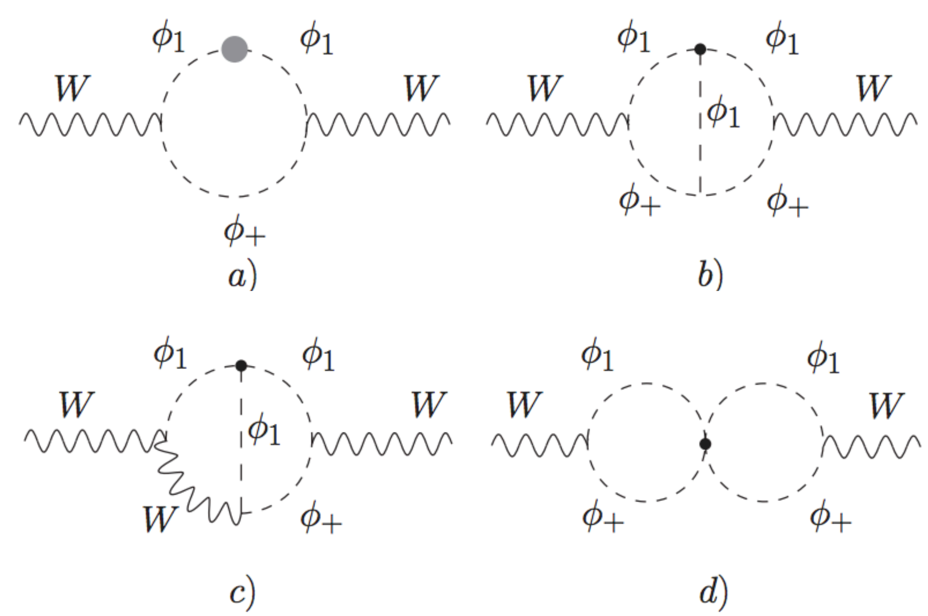
[G. Degrassi et al., '16] [Gorbahn&Haisch, '16]

At the ee colliders:



[M. McCullough, '13] [S. D. Vita et al., '17]

Using EWPO at 2 loop:

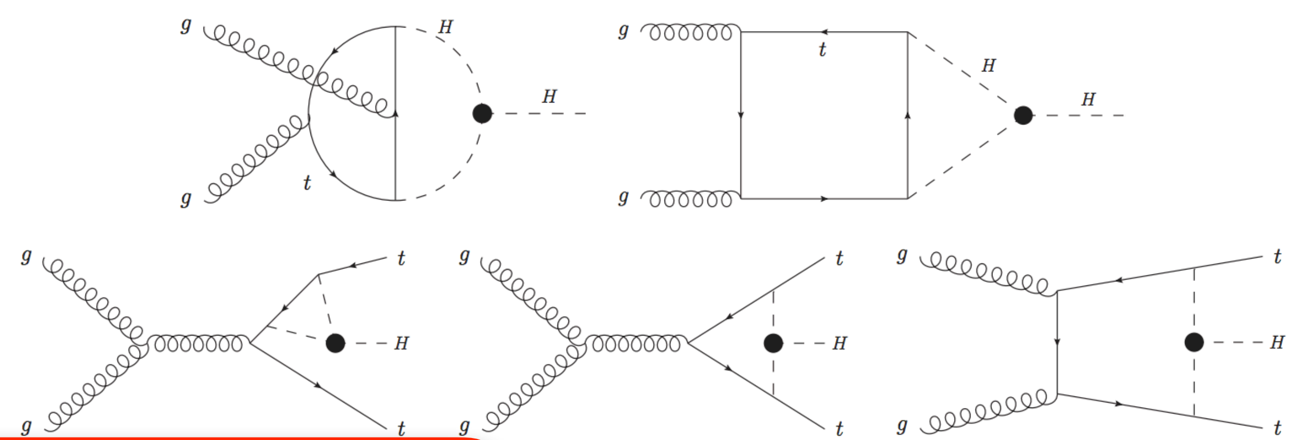


[Degrassi, Fedele, Giardino 1702.01737]

Loop-induced sensitivity, e.g. to trilinear H coupling

- Some times operators could first show up at 1-loop.
- This could imply new chances to measure certain coefs. that are difficult at LO.
- The trilinear Higgs coupling, κ_λ, is a well-known example.

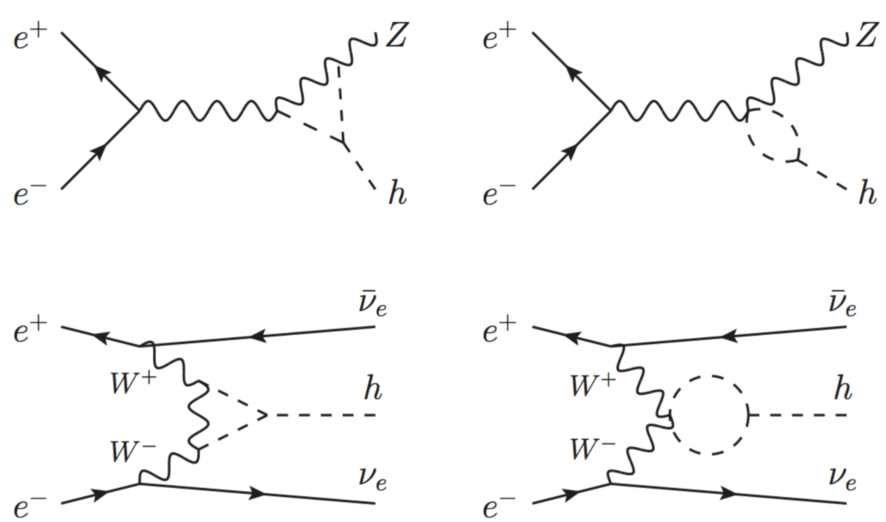
At the LHC:



Aren't these "indirect"?

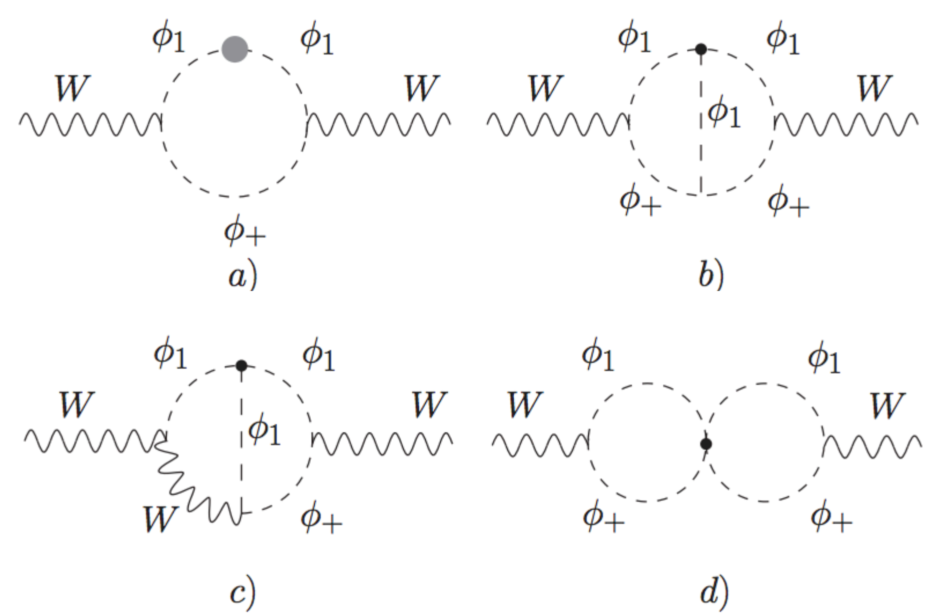
al., '16] [Gorbahn&Haisch, '16]

At the ee colliders:



[M. McCullough, '13] [S. D. Vita et al., '17]

Using EWPO at 2 loop:



[Degrassi, Fedele, Giardino 1702.01737]

Loop-induced sensitivity: from indirect to direct

- Two "solutions".
  global fit.

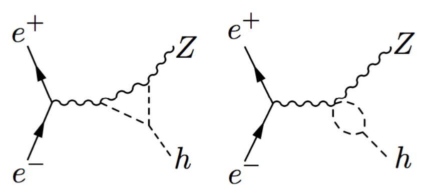
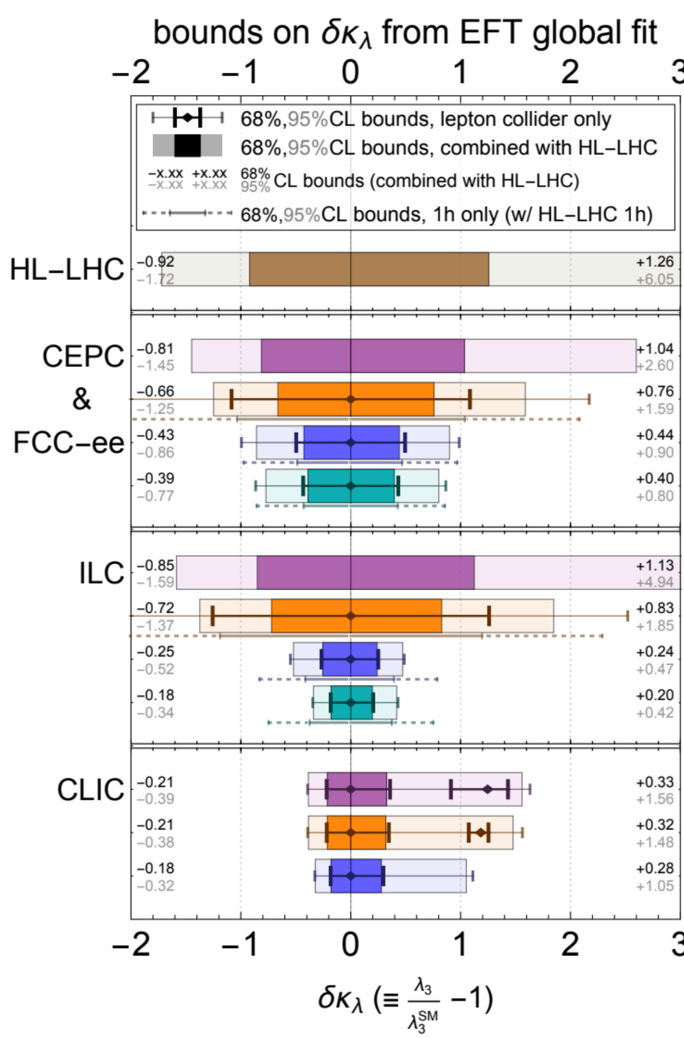


FIG. 1: NLO vertex corrections to the associated production cross section which depend on the Higgs self-coupling. These terms lead to a linear dependence on modifications of the self-coupling δ_h.

~20% sensitivity

[M. McCullough; 1312.3322]



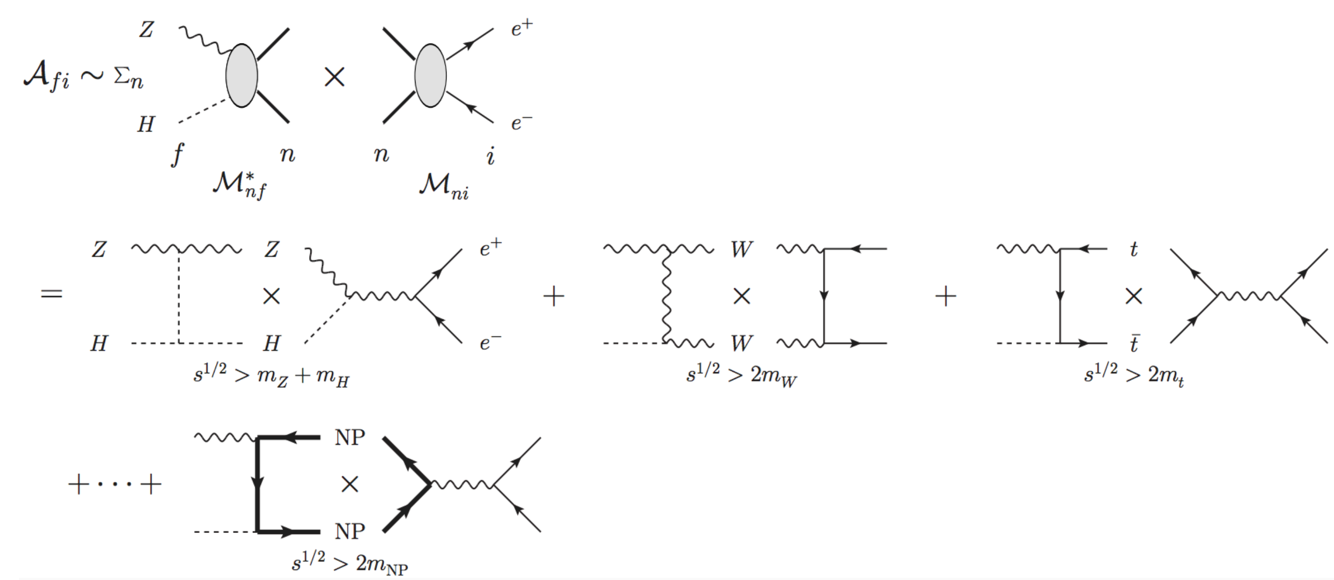
(partially NLO) global fit
to include H loops

[S. Di Vita et al. 1711.03978]

- or clever observables

[J. Nakamura & A. Shivaji 1812.01576]

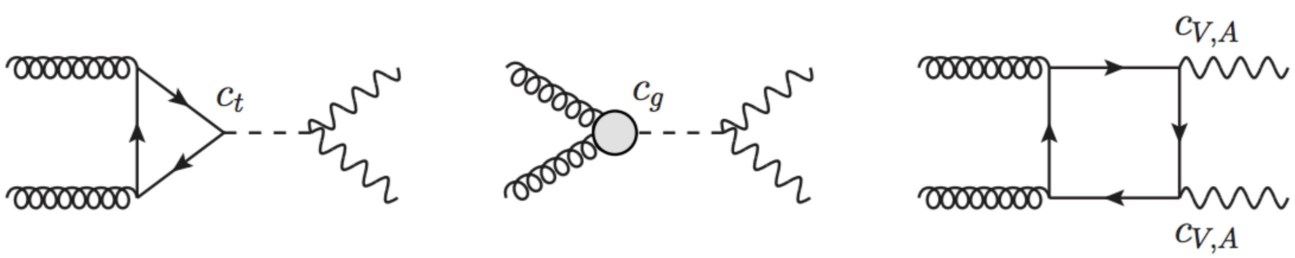
If T (or equally CP) is conserved, T-odd observables are proportional to the **absorptive** part



Heavy NP particles / tree level EFT operators are filtered out

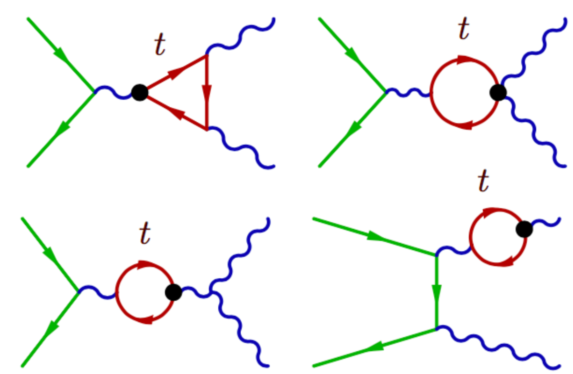
More loop-induced sensitivities

Diboson sensitivity to top couplings



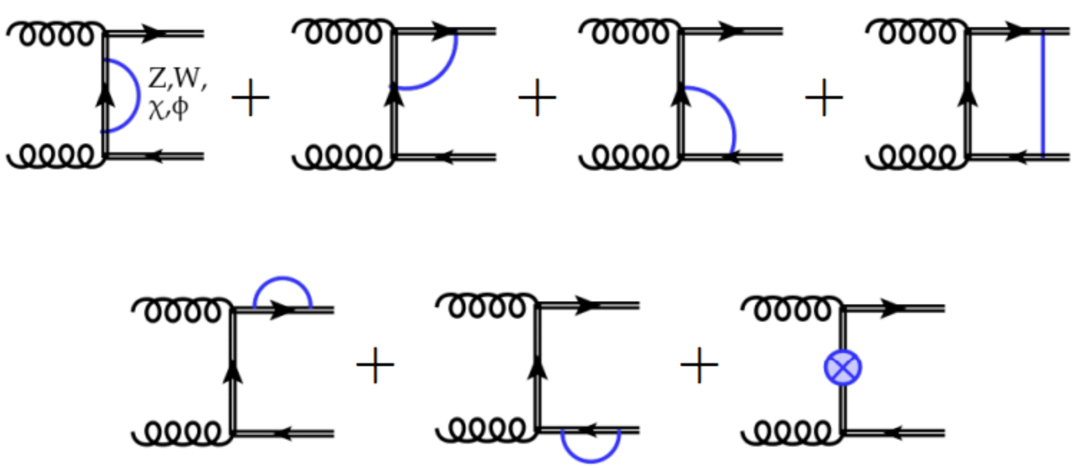
[Azatov, Grojean, Paul, Salvioni '16] [Q.-H. Cao et al. '20]

Higgs/EW sensitivity to top couplings (EW loops)



[Durieux, Gu, Vryonidou, CZ '18]

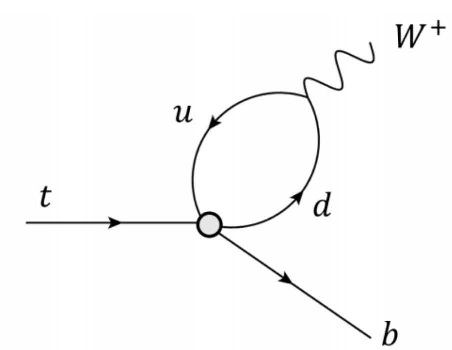
ttbar sensitivity to EW top couplings (via EW loops)



[T. Martini and M. Schulze'19]

And many more…

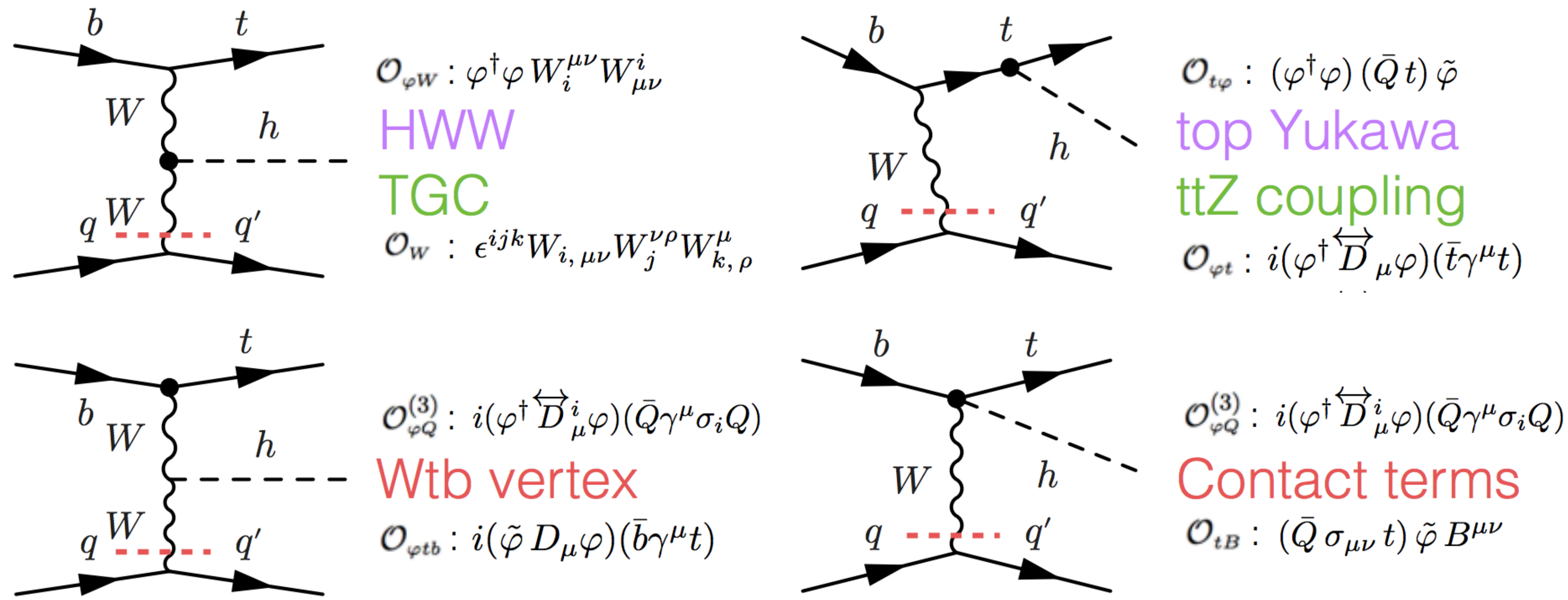
Top decay sensitivity to four-fermion interactions



[Boughezal et al.; 1907.00997]

Single top+Higgs/Z

tHj (tZj = h→Z)



- The tXj channels access the 2 → 2 sub-amplitudes, probe the energy dependence due to unitarity cancellation spoiled by BSM effects, and reveal the rich interplay between EFT operators from different sectors.
- See also [Maltoni,Paul,Stelzer,Willenbrock,'01] [Biswas,Gabrielli,Mele,12] [Farina,Grojean,Maltoni,Salvioni,Thamm,'12][Demartin,Maltoni,Mawatari,Zaro,'15] [Dror,Farina,Salvioni,Serra,'16]