Precision in EFT studies for top-quark physics

Eleni Vryonidou
CERN TH

Based on arXiv: 1601.08193, 1607.05330 and 1708.00460
and ongoing work

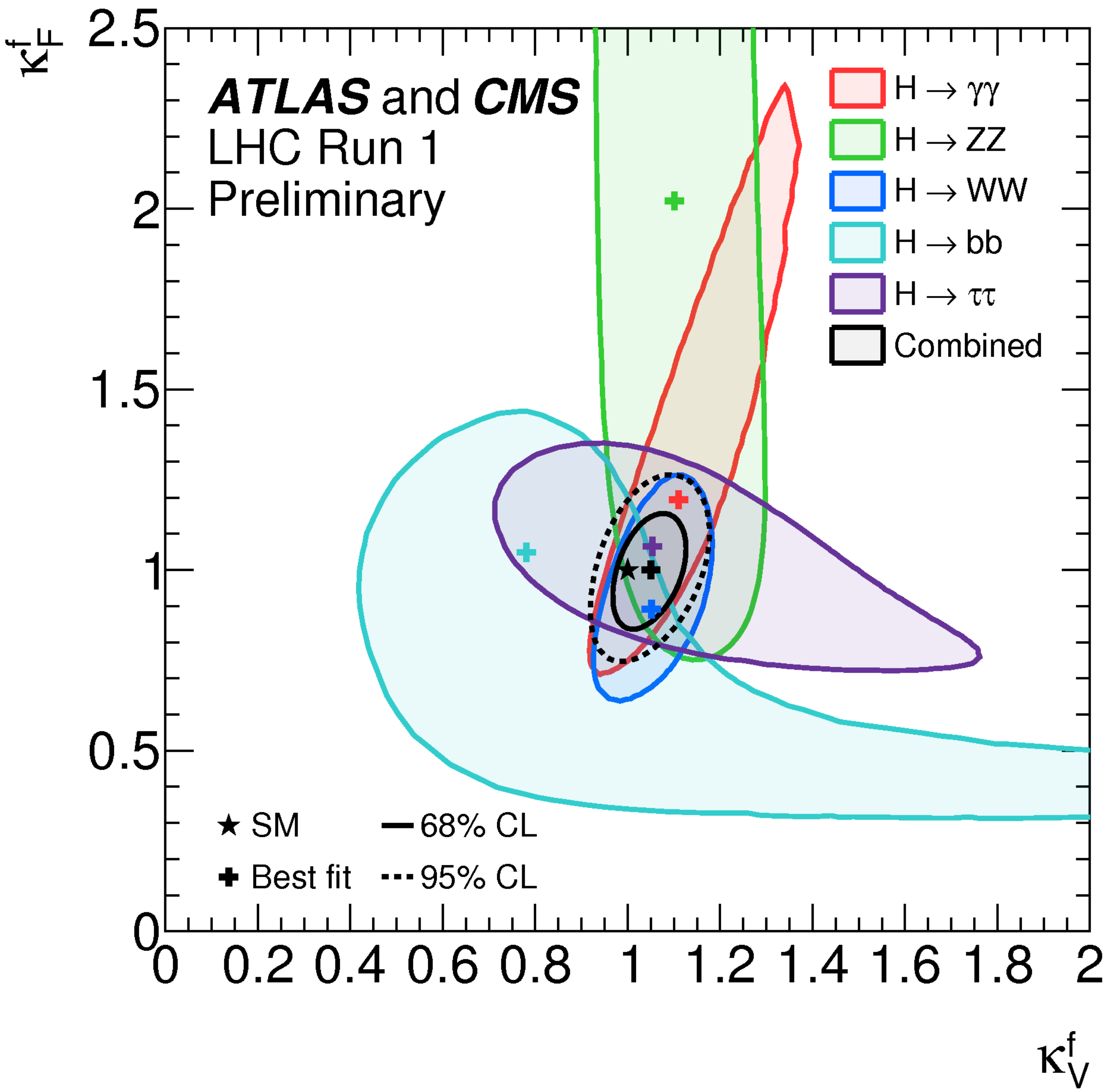
Cambridge
06/10/17

Outline

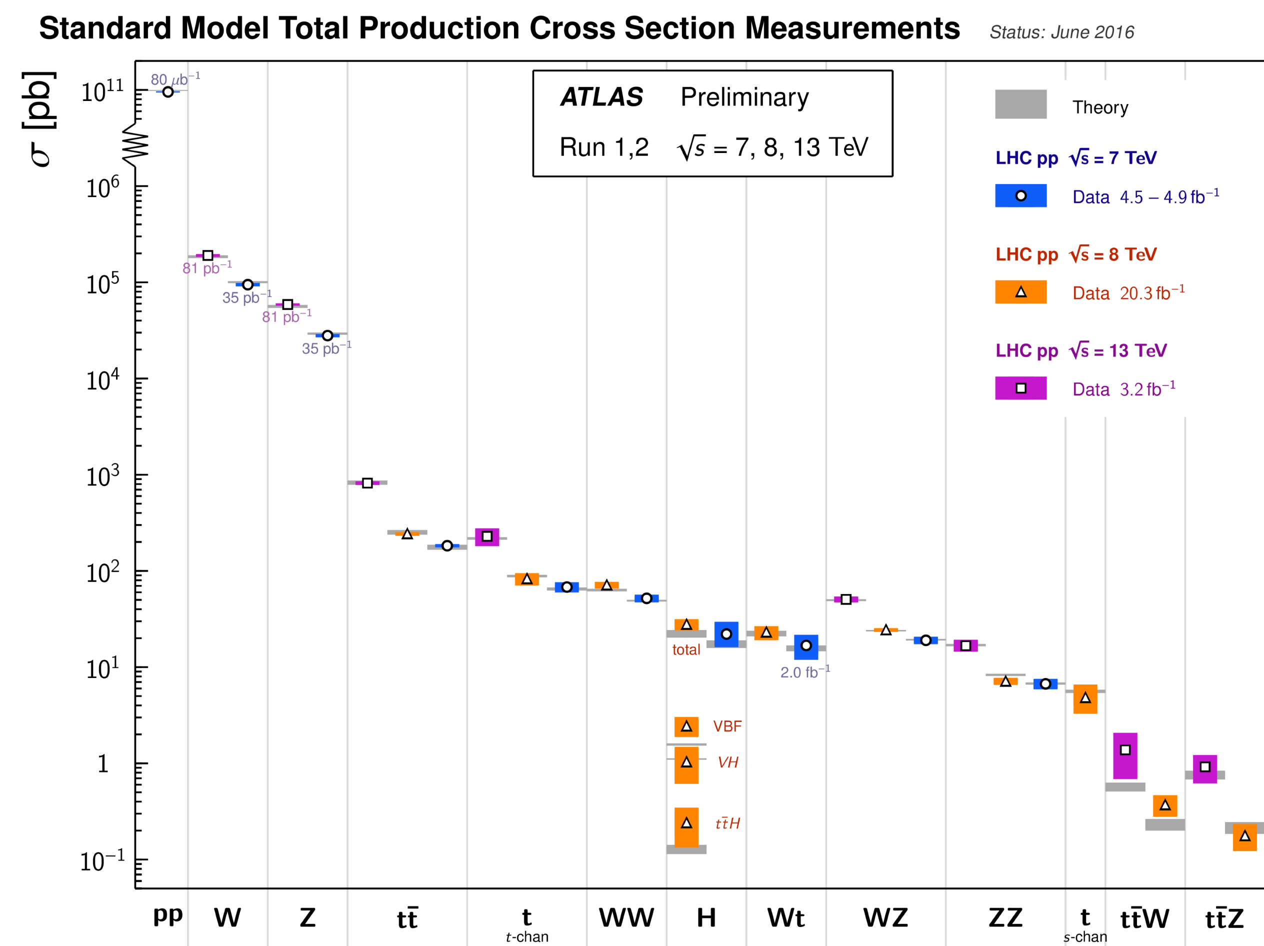
- Introduction to the EFT
- EFT in top quark physics
  - Precision calculations in the EFT
- EFT in the top-Higgs sector
  - Constraining dimension-6 operators

LHC: the story so far

Higgs discovery



Rediscovering the SM



Good agreement with the SM predictions

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How to look for new physics?

Model-dependent

SUSY, 2HDM…

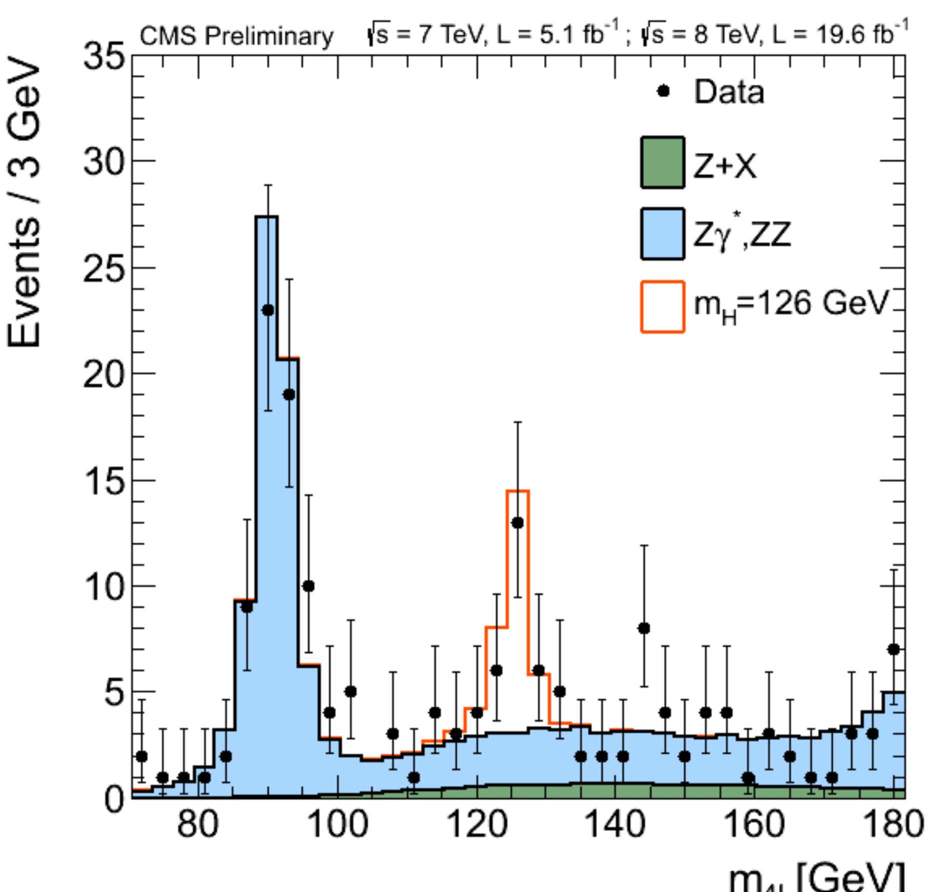
New particles

Model-Independent

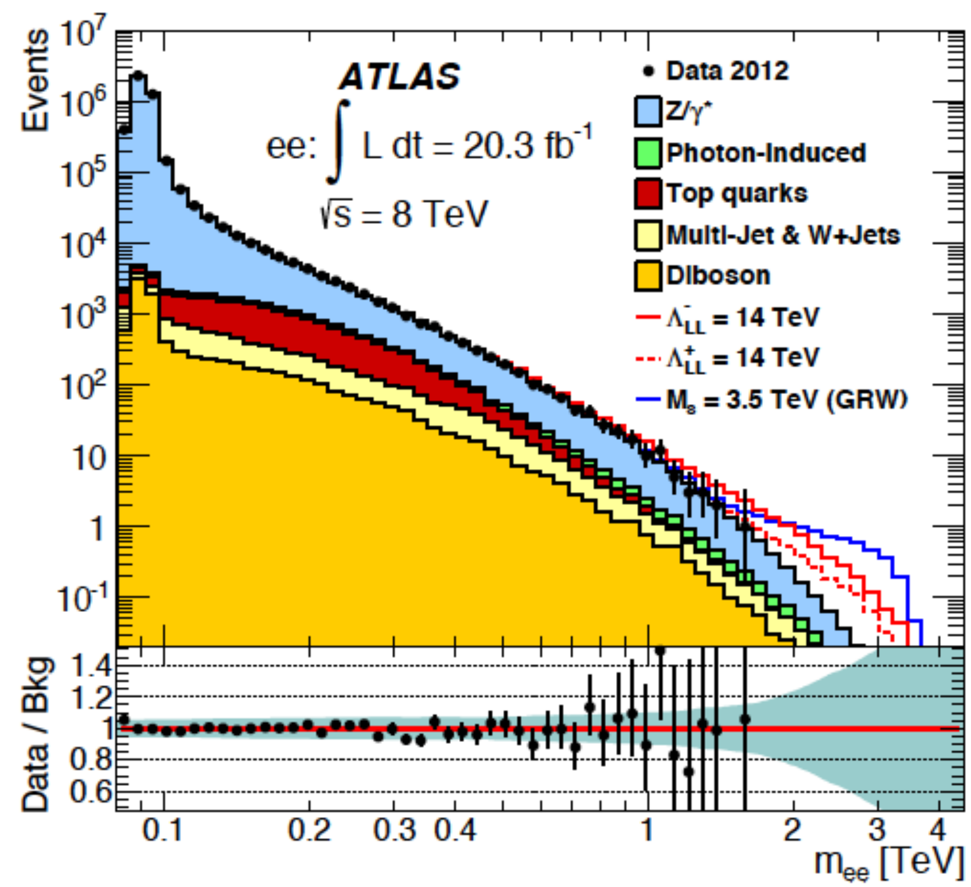
simplified models,EFT

New Interactions of SM particles

anomalous couplings, EFT



Resonance peaks



Deviations in tails

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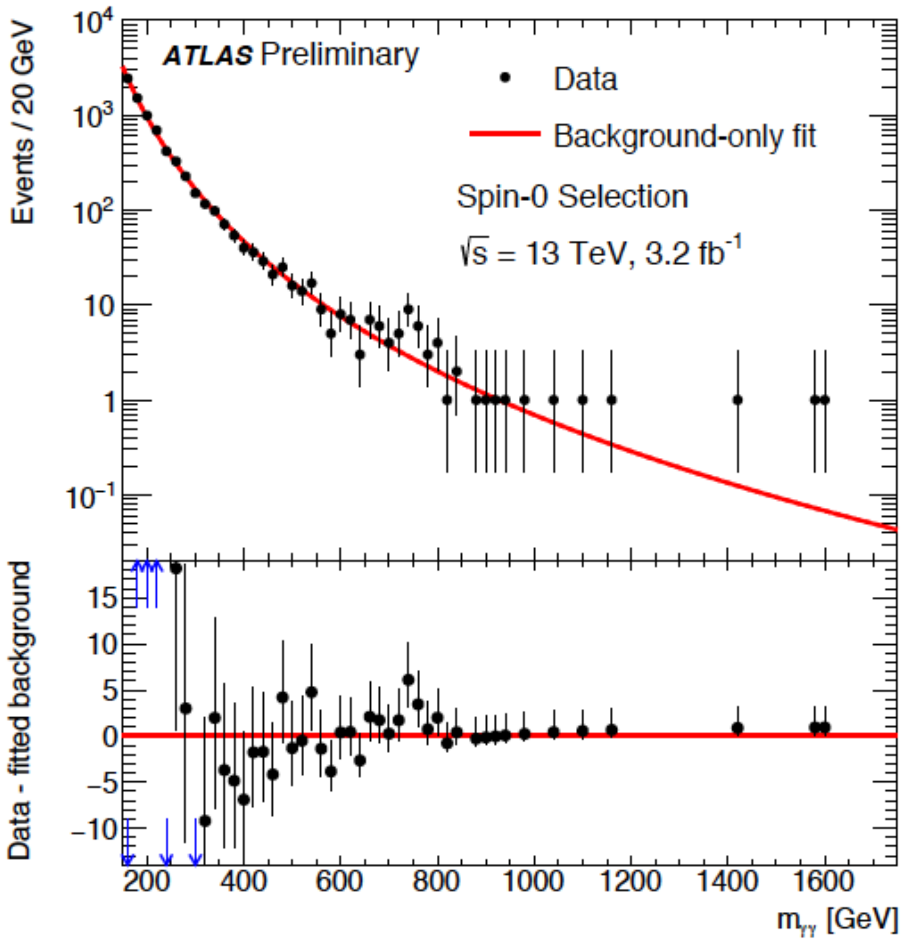

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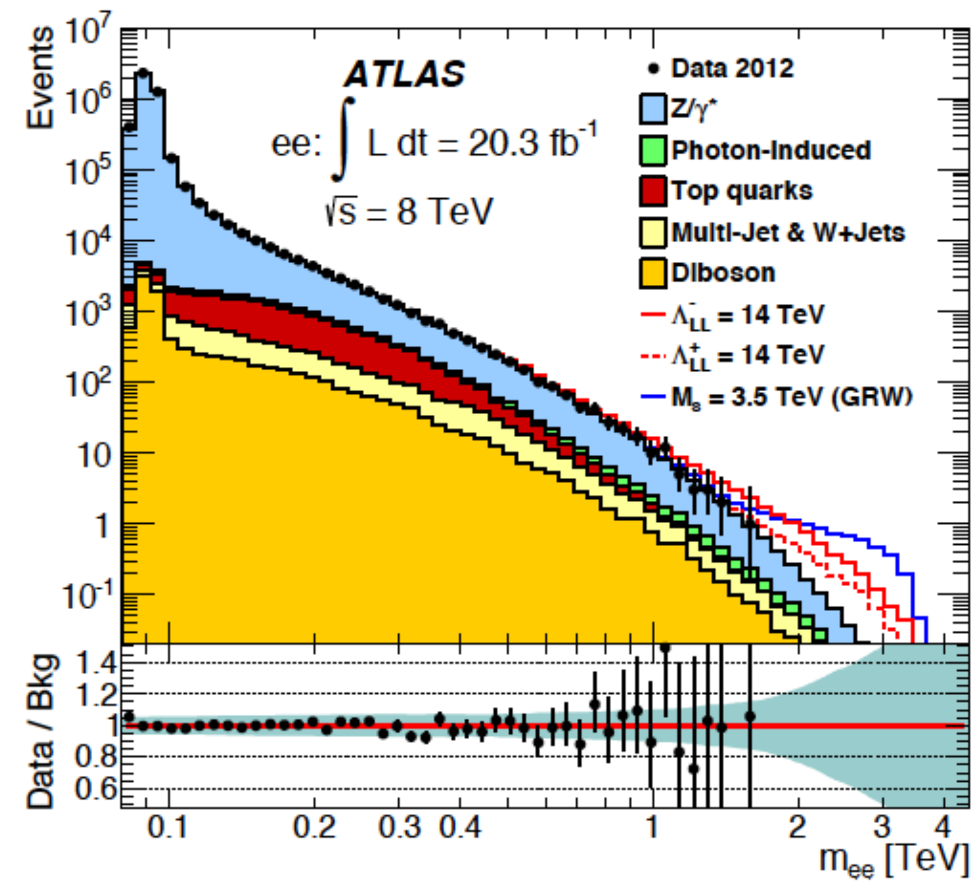

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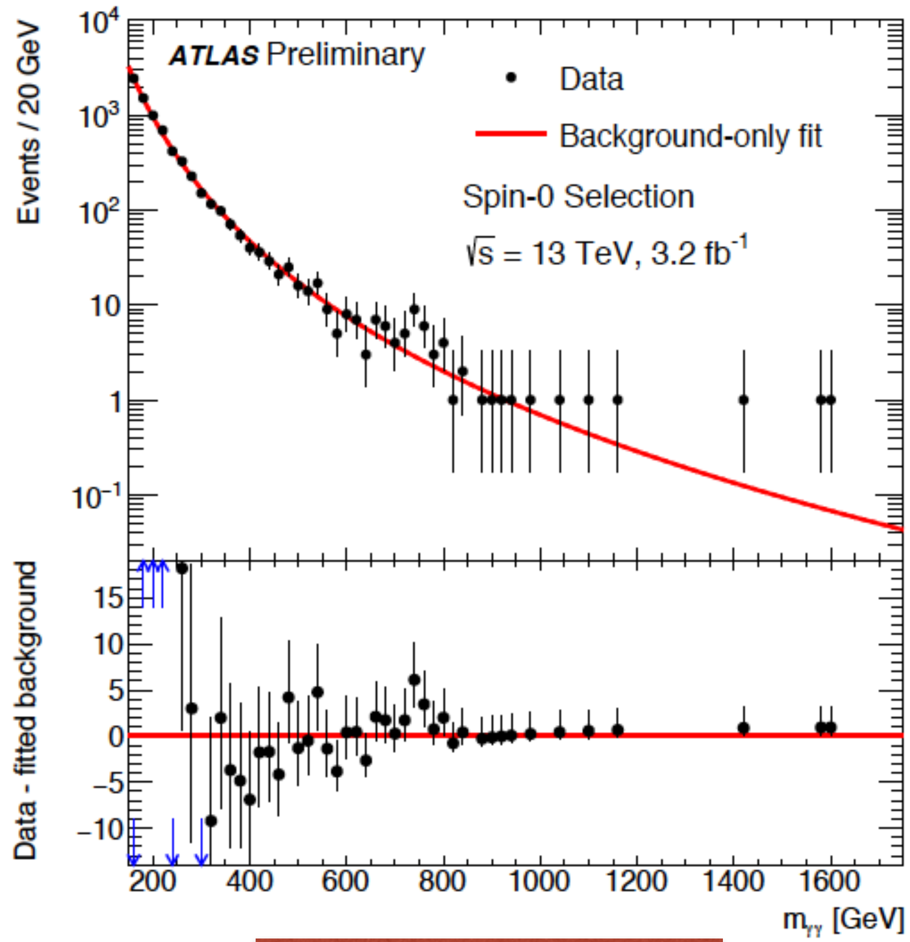

A new particle?

Model-Independent

simplified models,EFT

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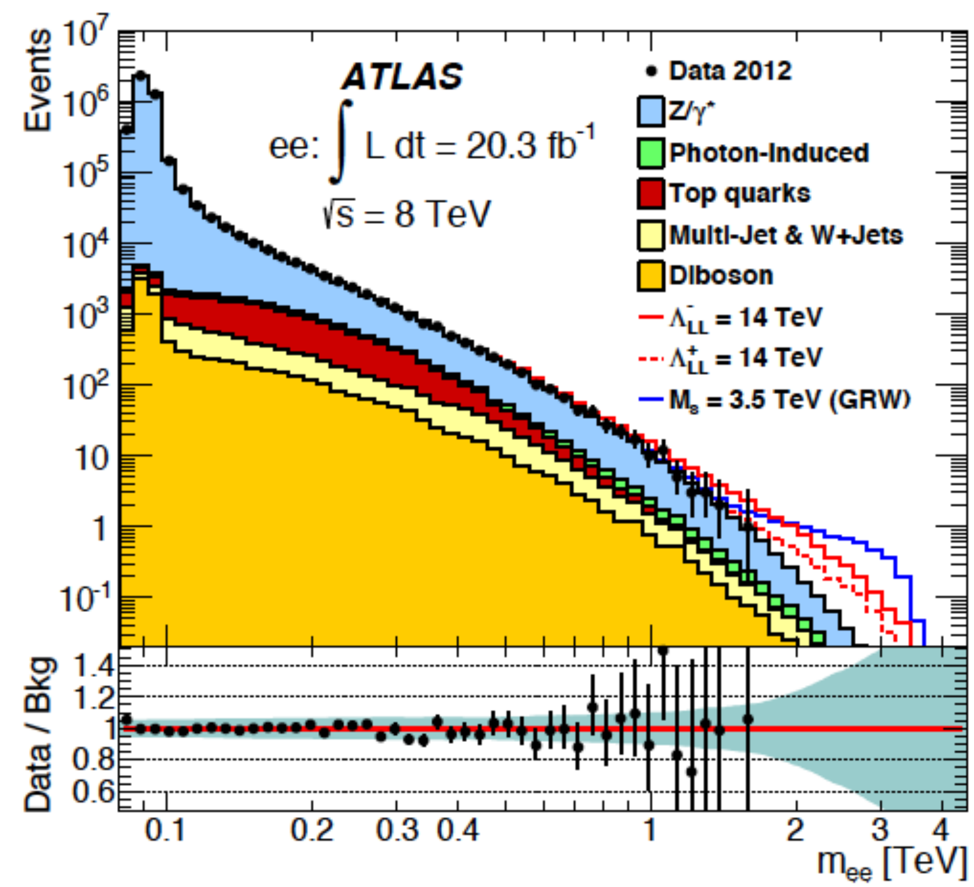
anomalous couplings, EFT



Deviations in tails

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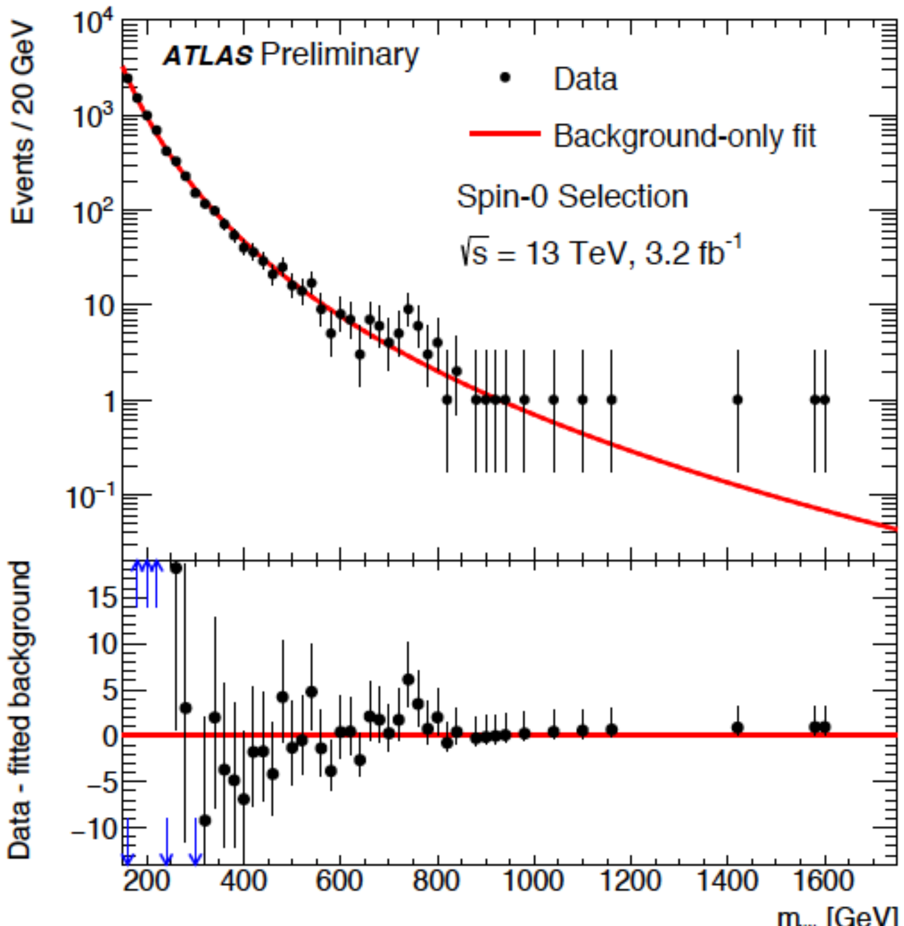

~~A new particle?~~

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simplified models,EFT

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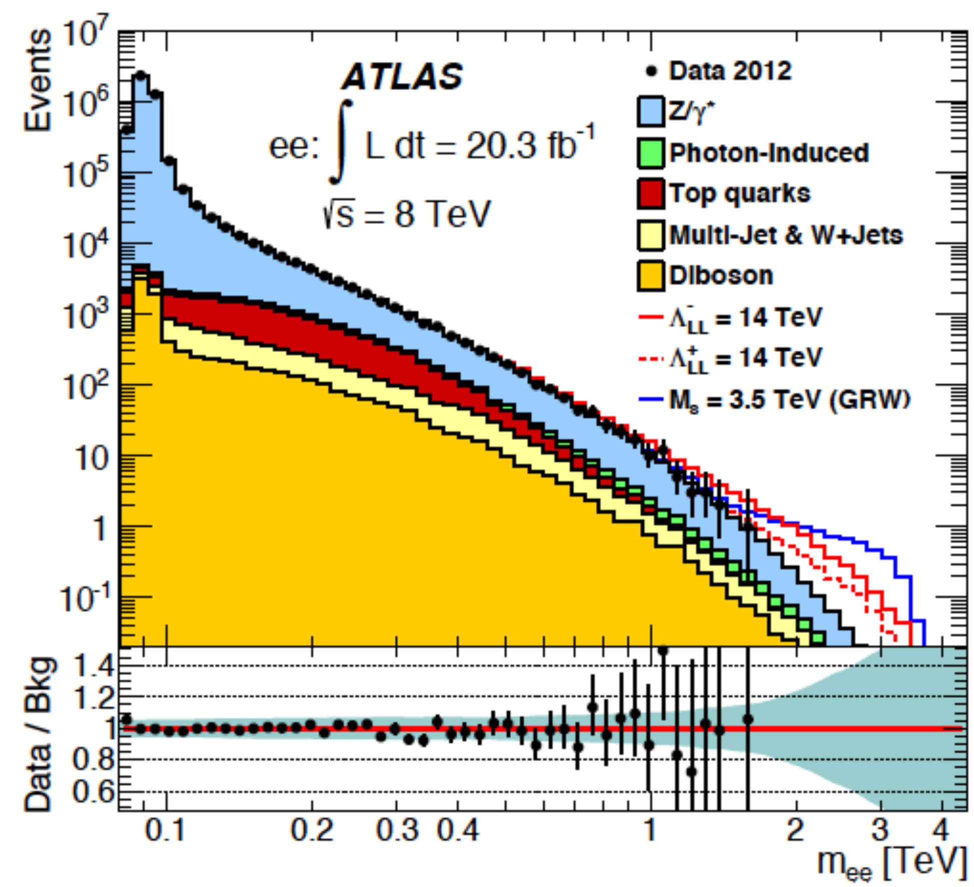
anomalous couplings, EFT



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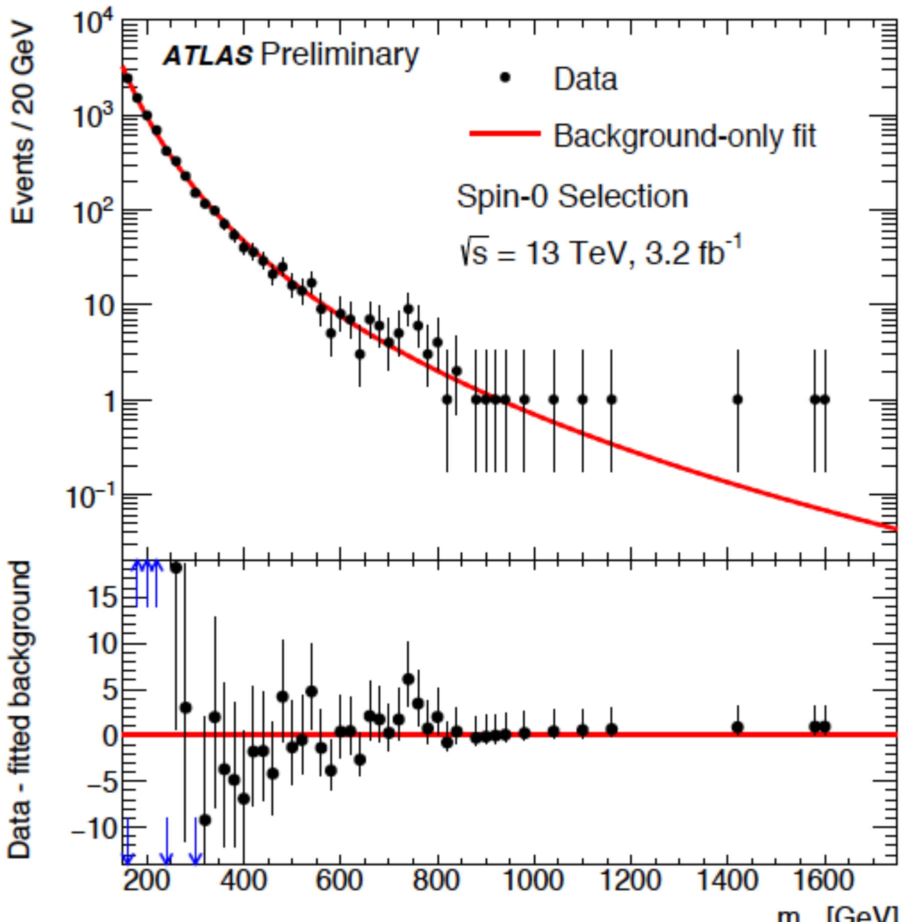

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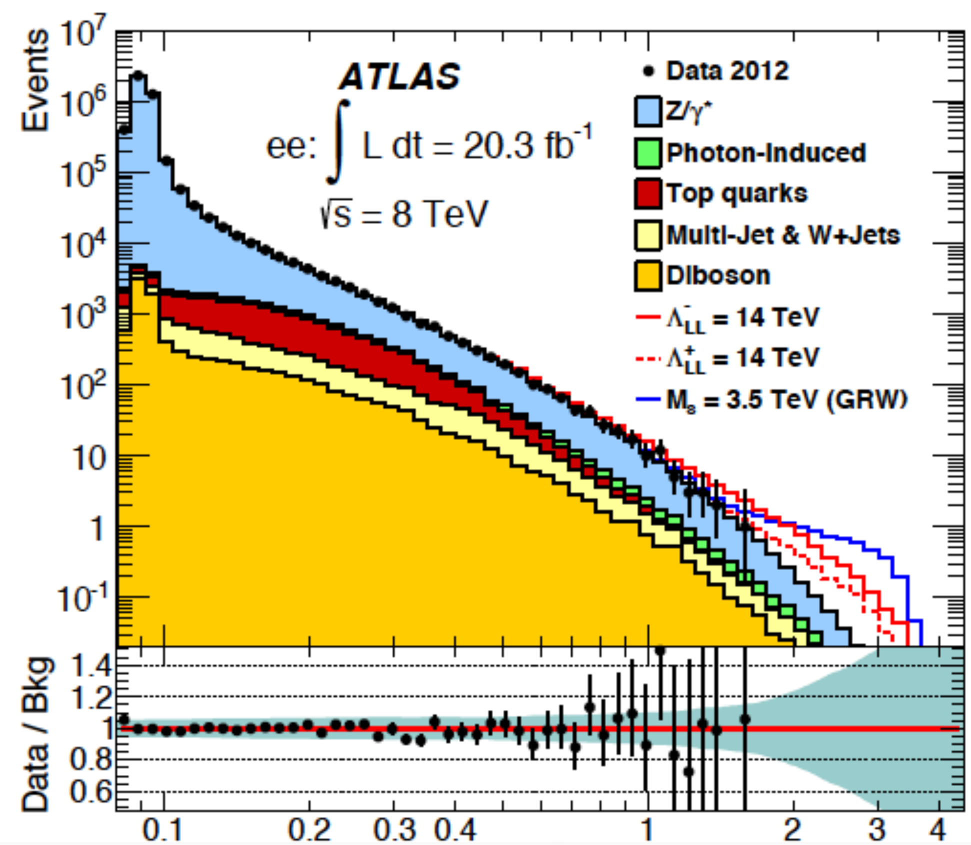

$$\mathcal{L}_{\mathrm{Eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

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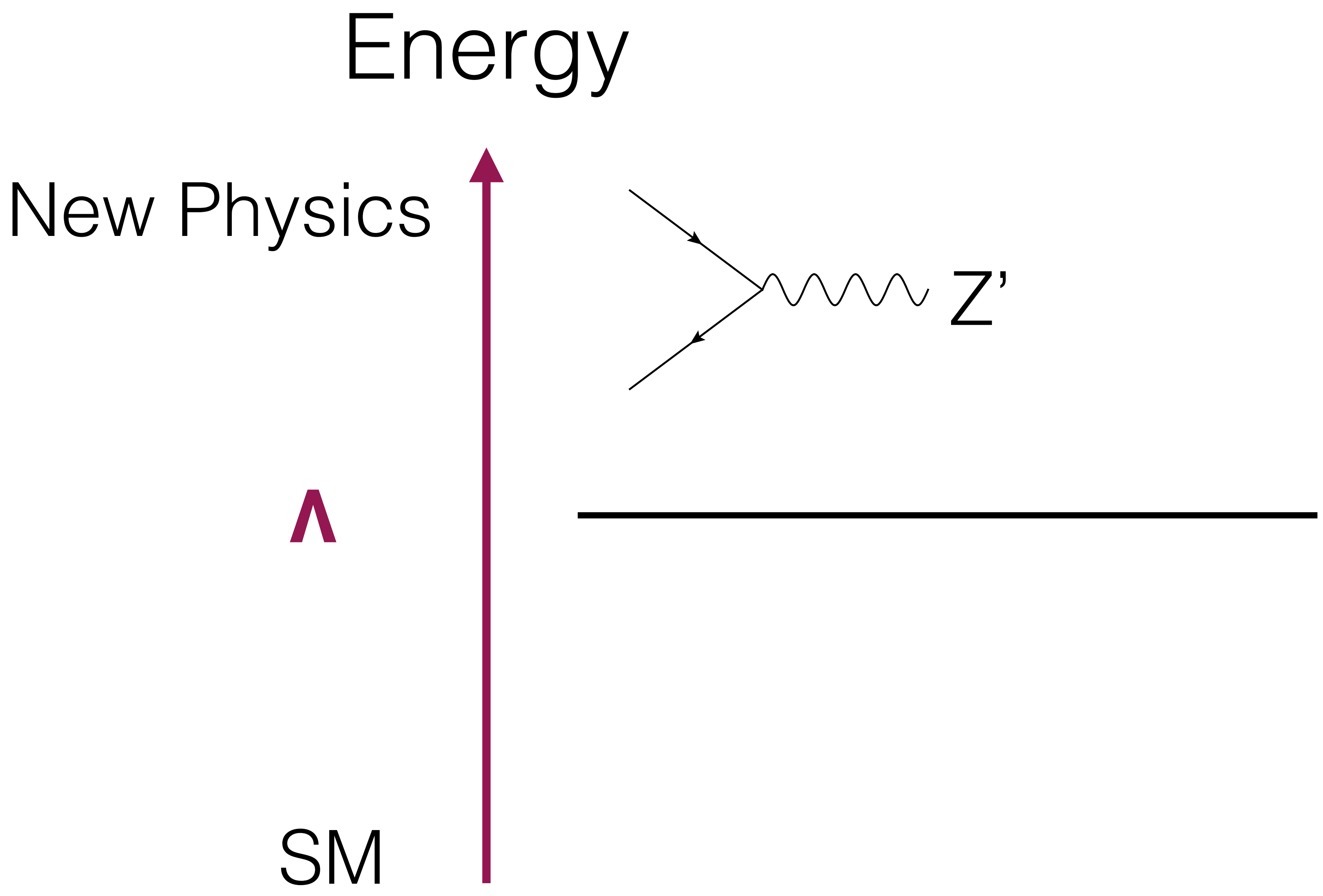
SMEFT: What is it all about?



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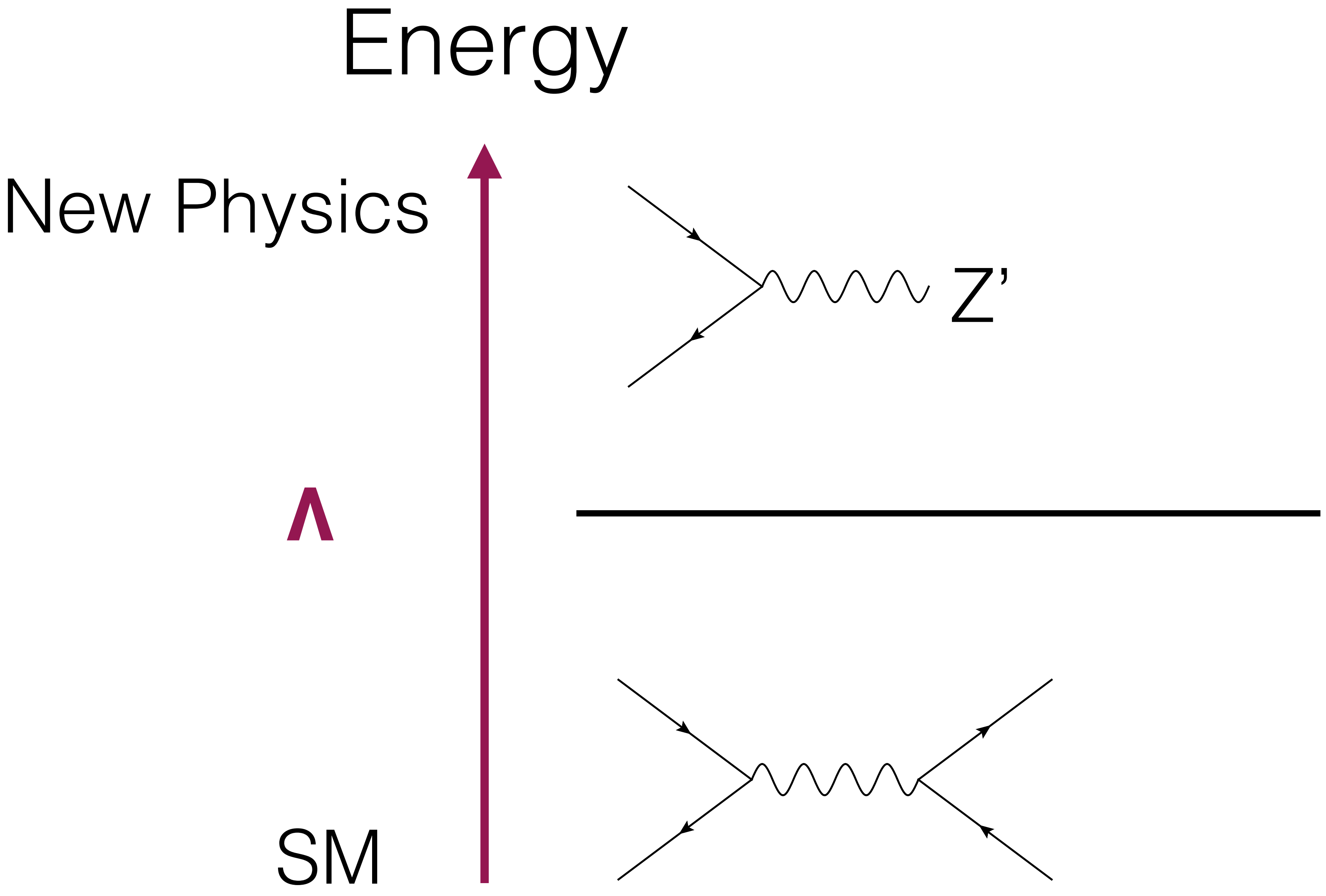

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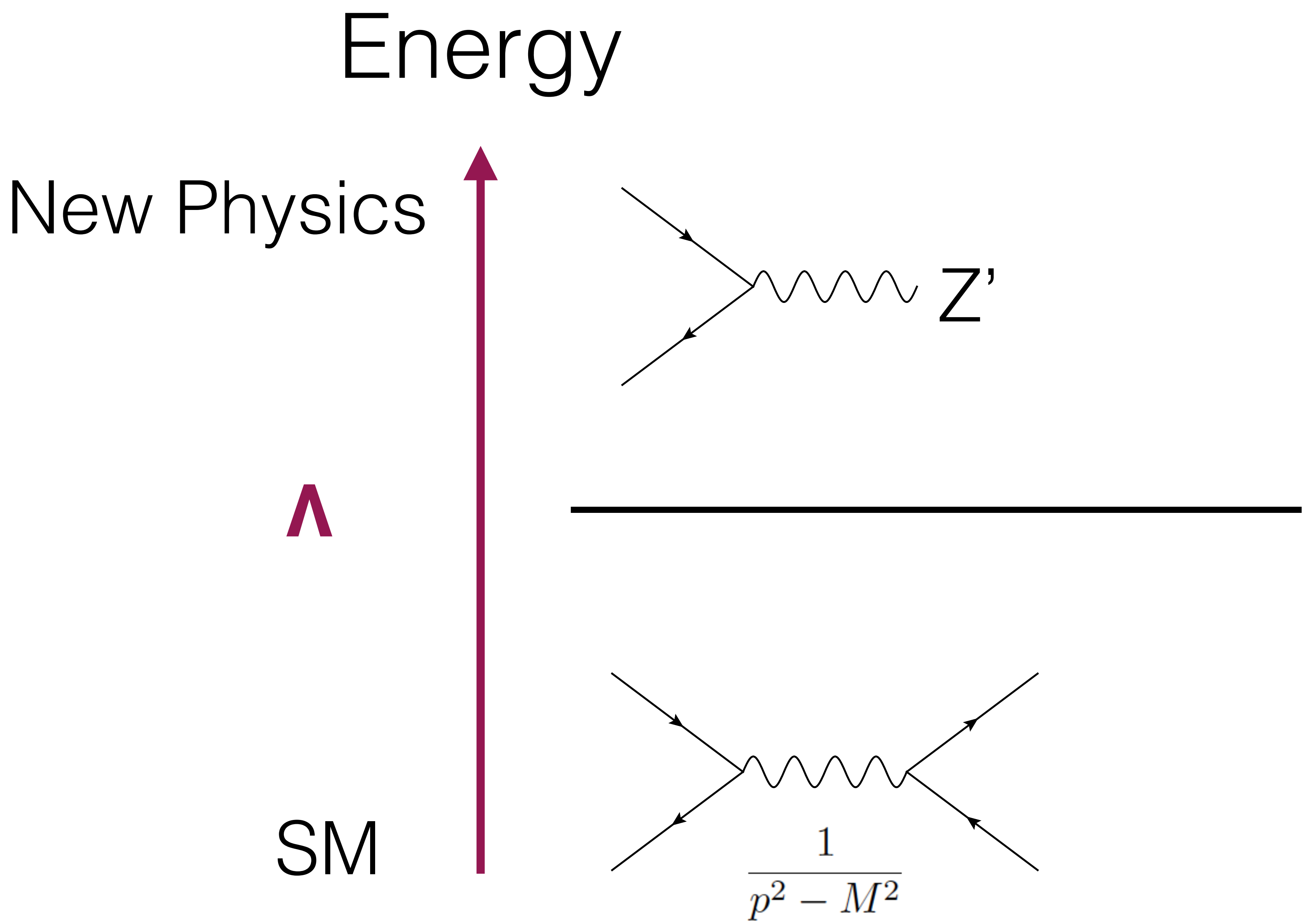

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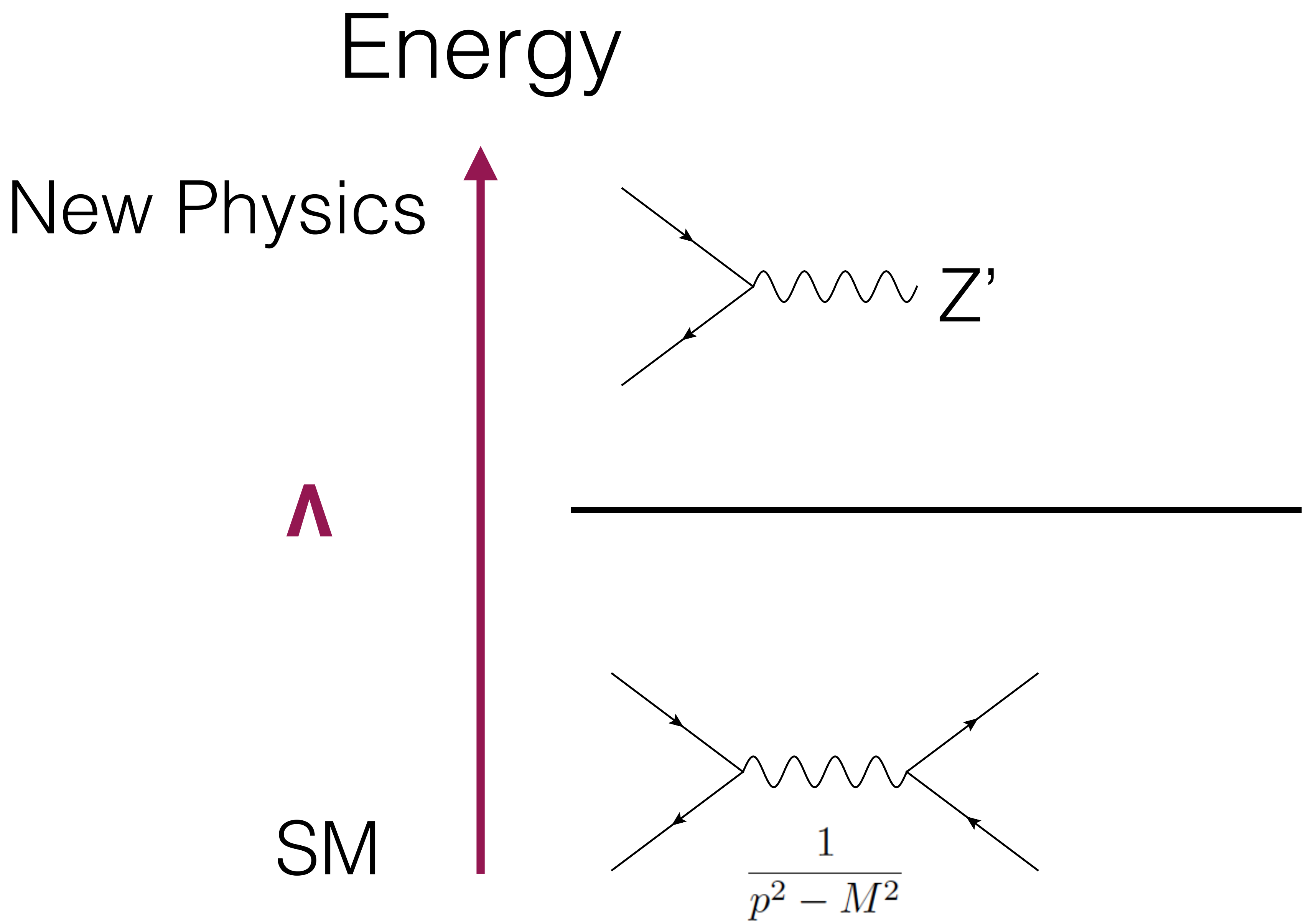

$$\frac{1}{p^2-M^2} = \frac{1}{-M^2}\left[1+\left(\frac{p^2}{M^2}\right)+\left(\frac{p^2}{M^2}\right)^2+\cdots\right]$$

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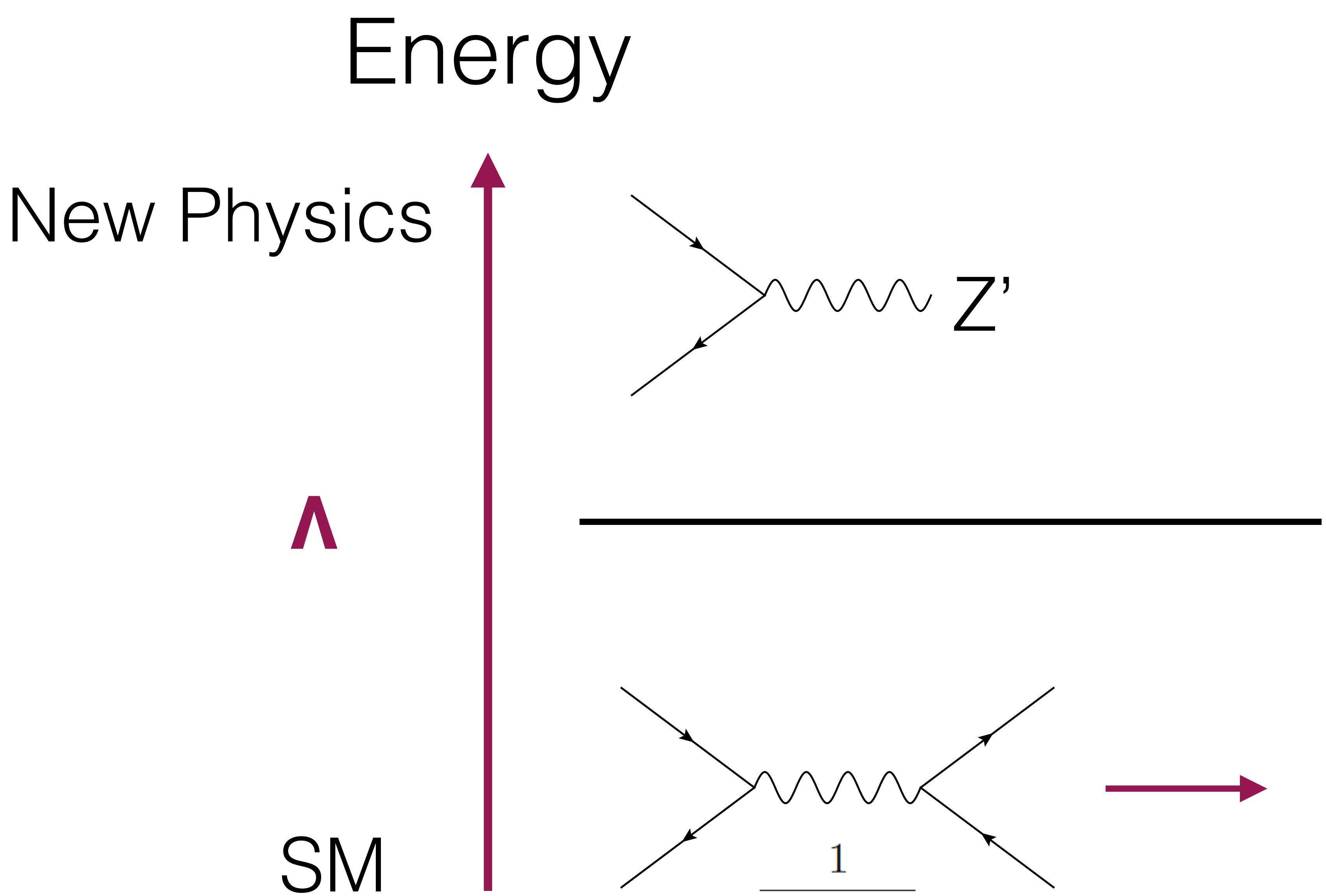

$$\frac{1}{p^2 - M^2}$$

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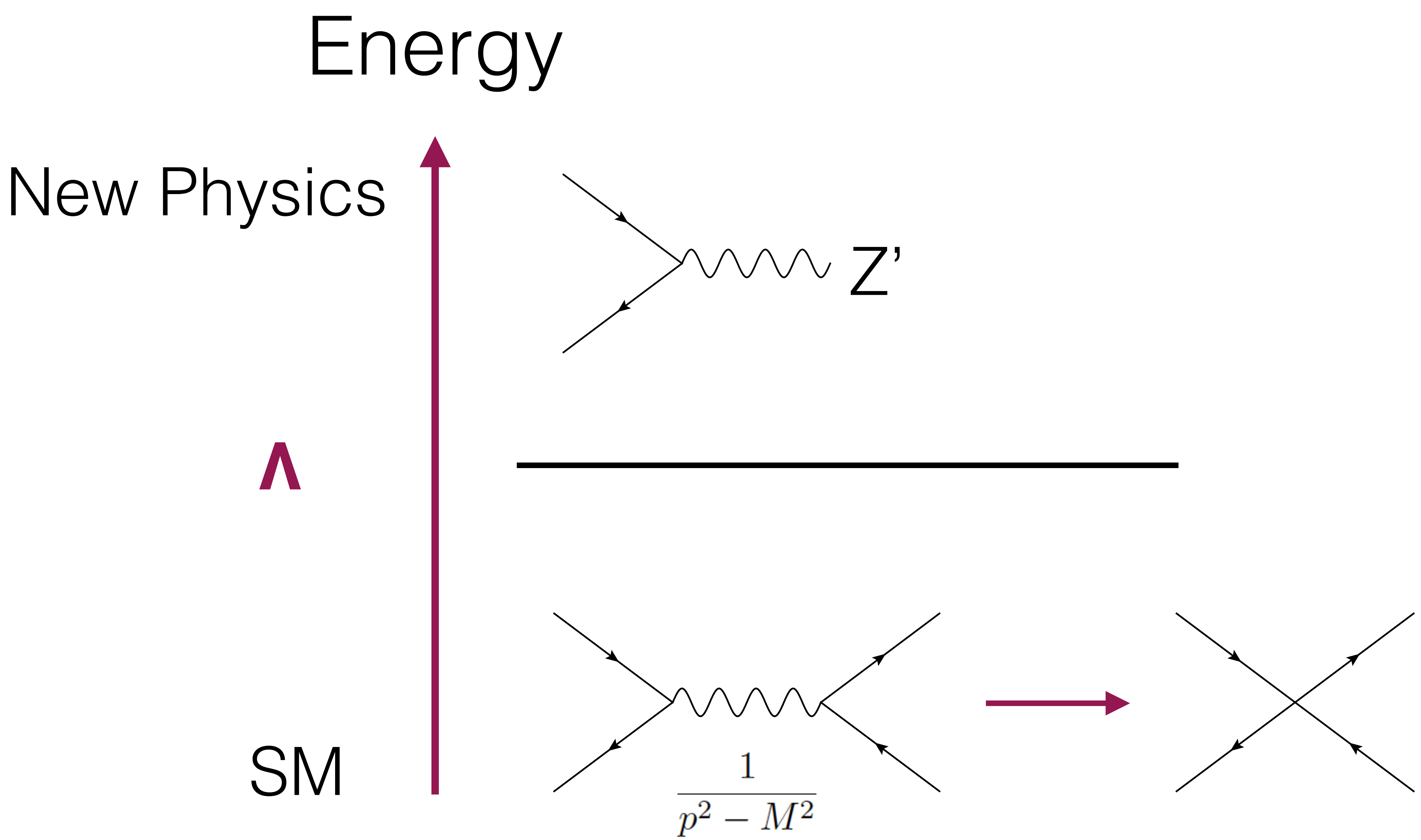

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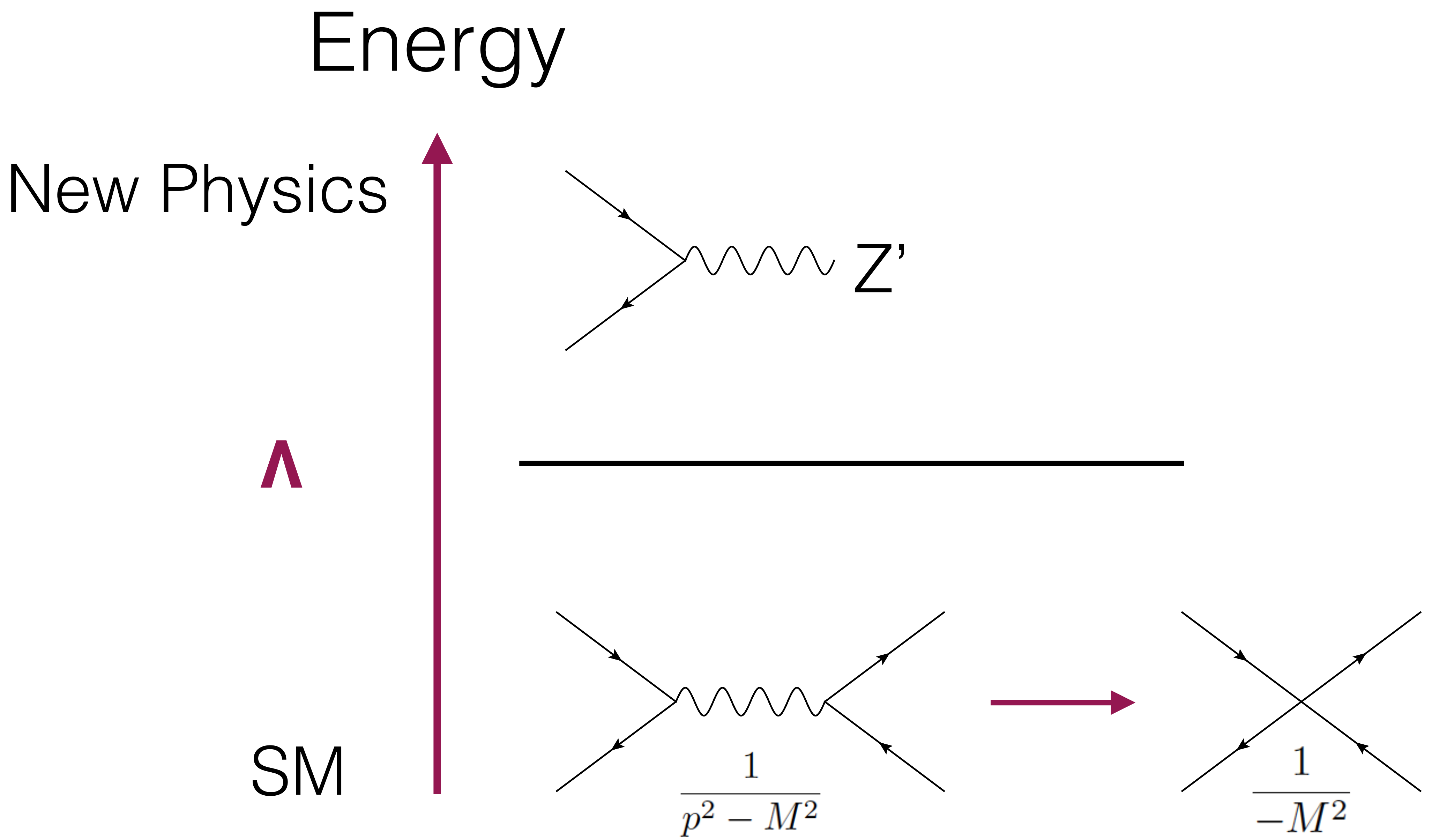

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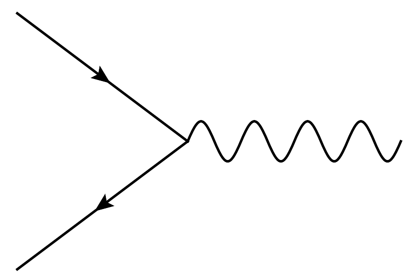
SMEFT: What is it all about?

Energy

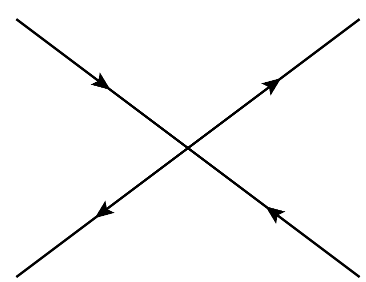
New Physics



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

Λ=M

SM



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

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

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

SMEFT

- BSM? New Interactions of SM particles

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

- 59(3045) operators at dim-6: Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

  Grzadkowski et al arxiv:1008.4884

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

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

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

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

Top quark interactions

SMEFT vs Anomalous couplings

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

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

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

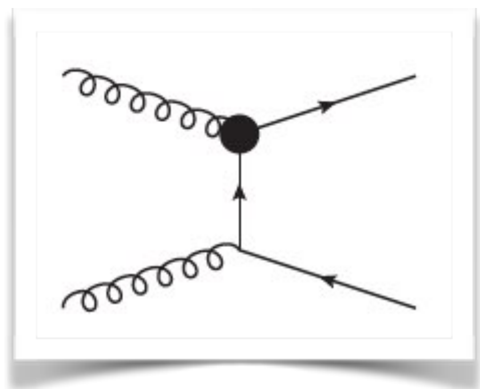
$$\mathcal{O}(\alpha_s) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \cdots$$

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

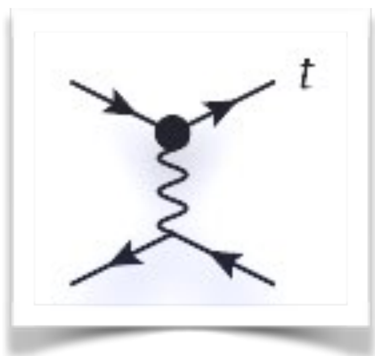
SMEFT in processes with tops

Rich phenomenology:

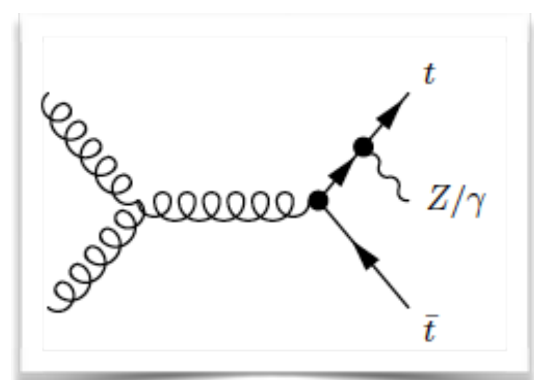
pair production

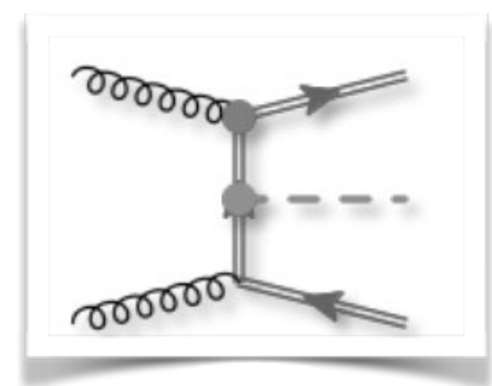


single

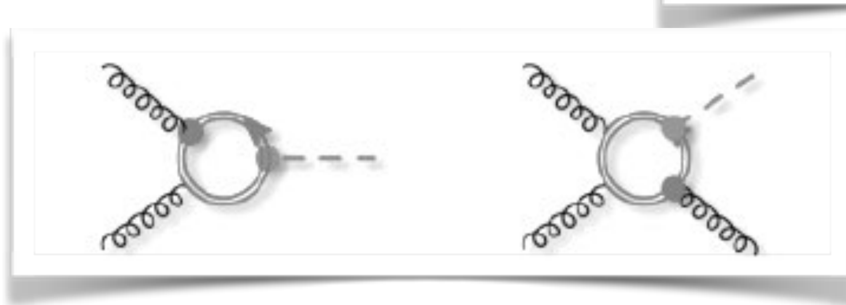


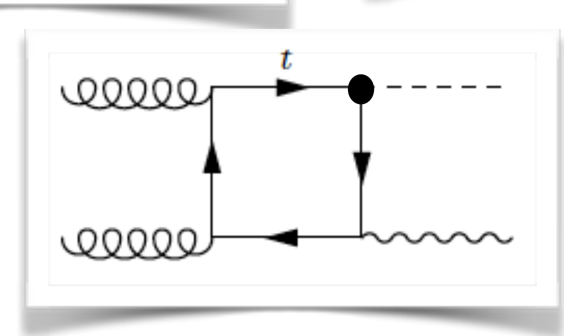
associated production

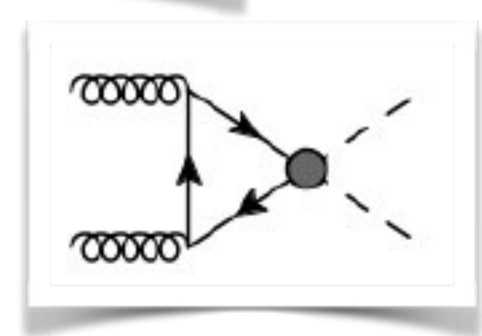




top loops







Top-quark operators and how to look for them

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

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

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

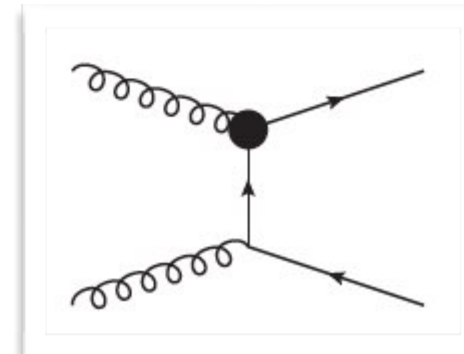
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

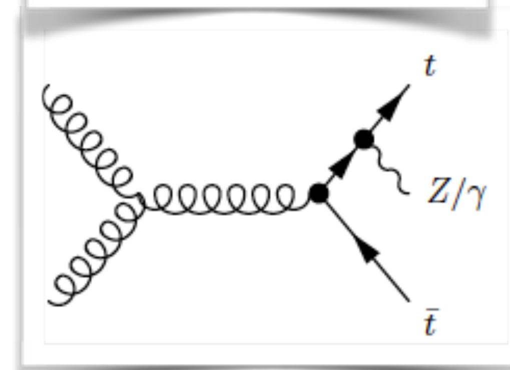
$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$

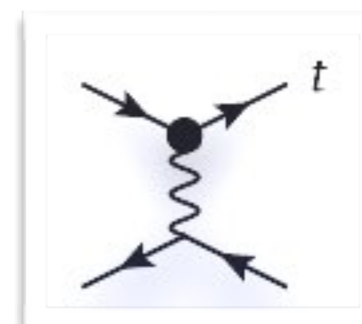
see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

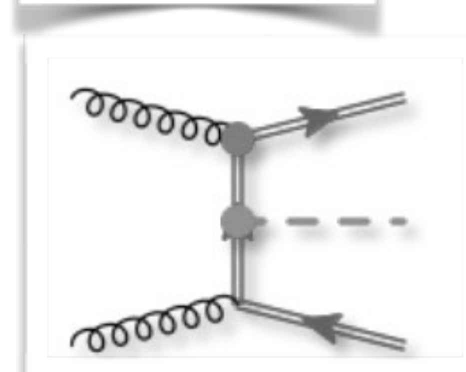
+four-fermion operators

+non-top operators (mixing)









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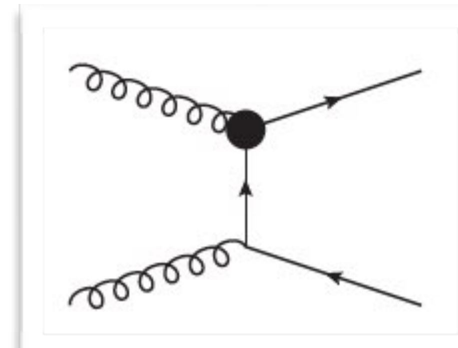

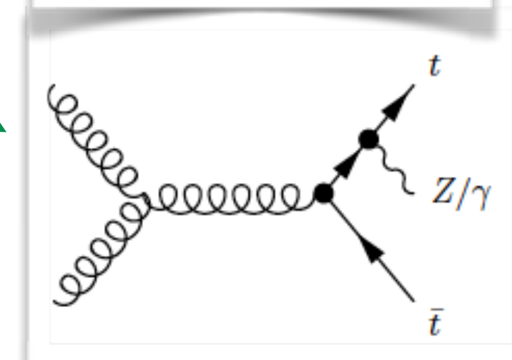

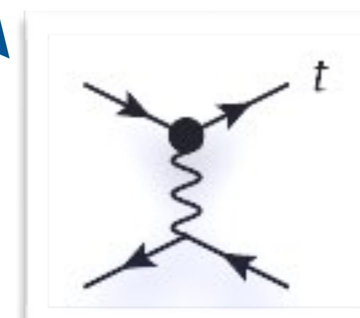

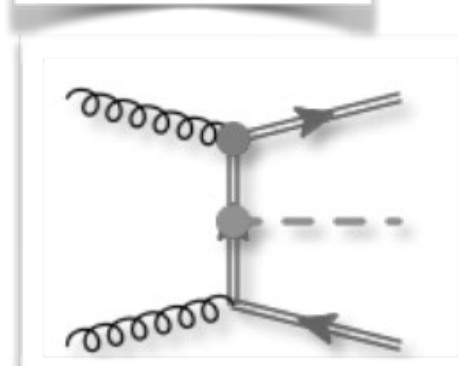

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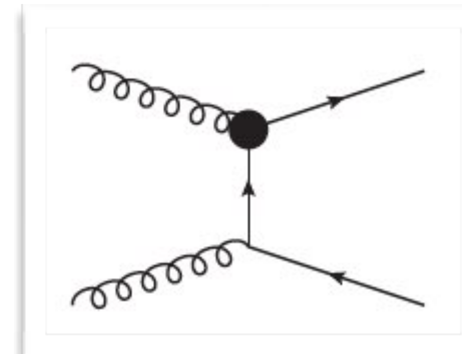

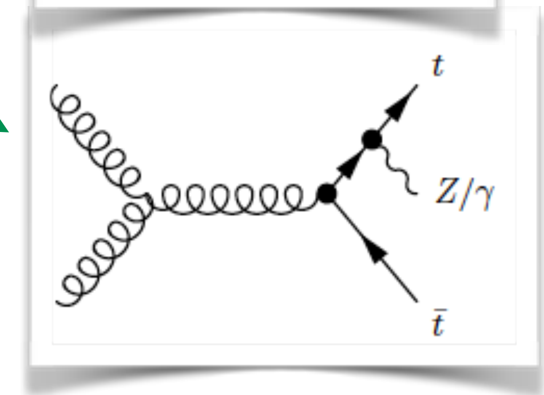

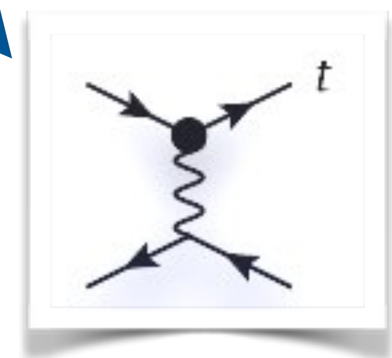

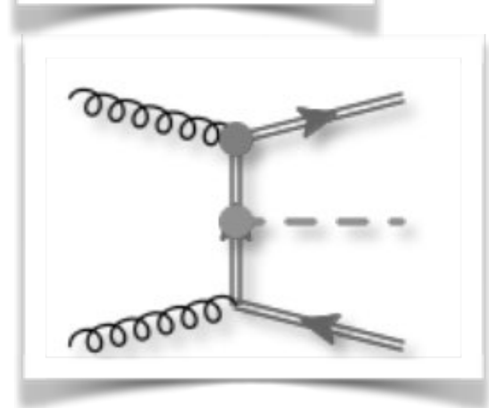

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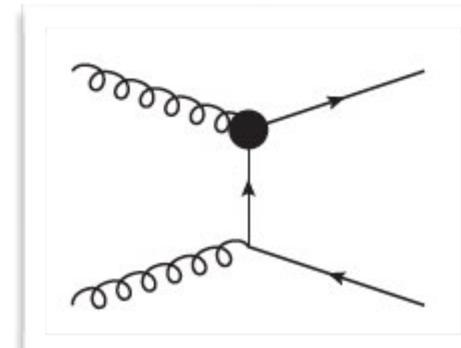

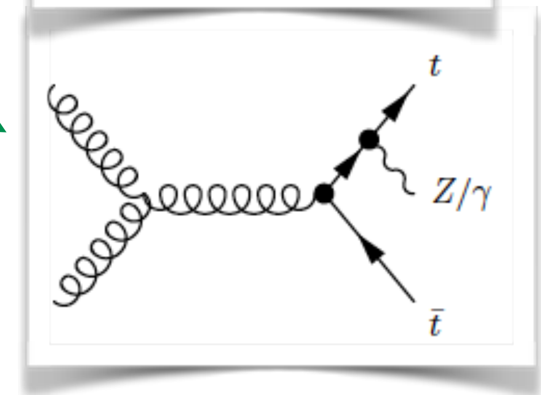

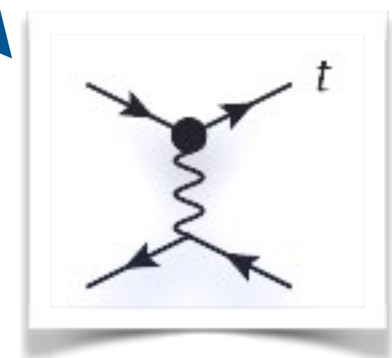

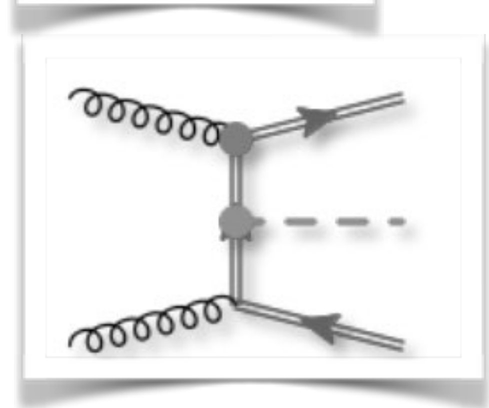

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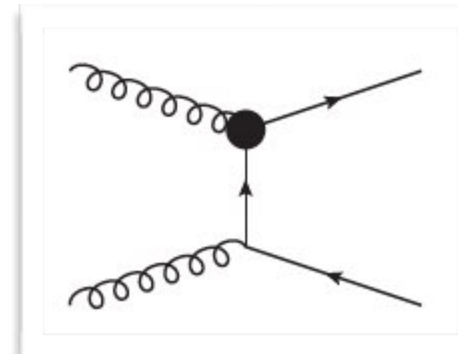

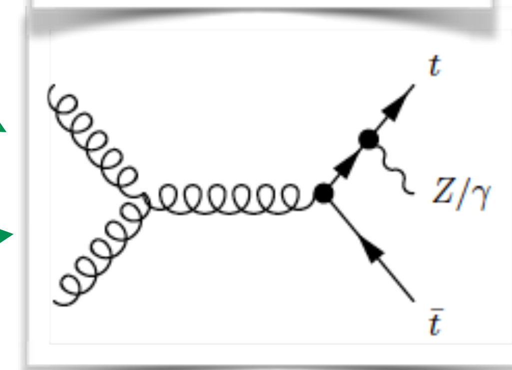

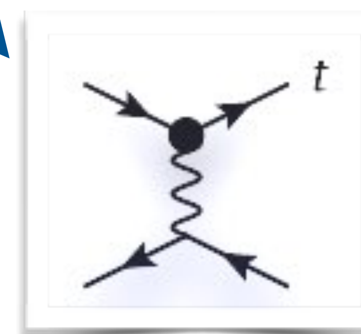

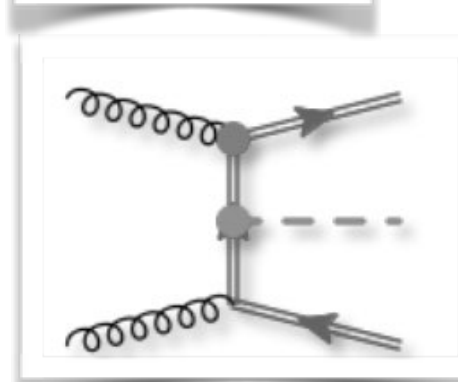

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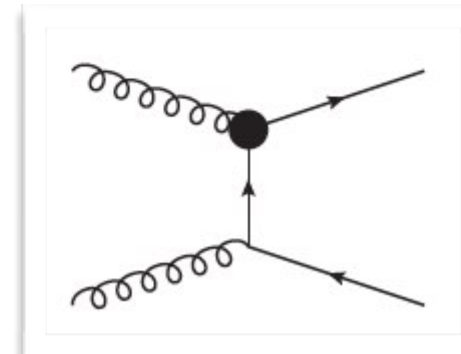

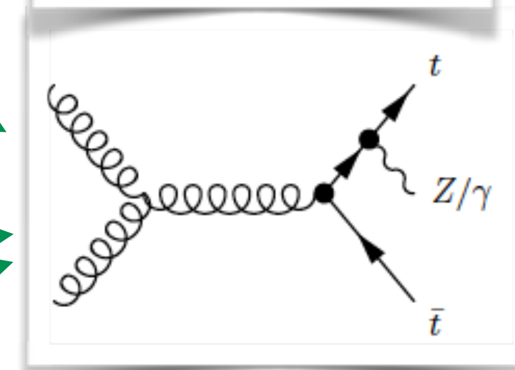

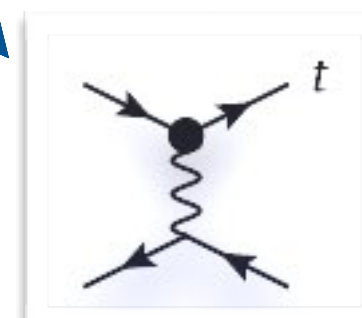

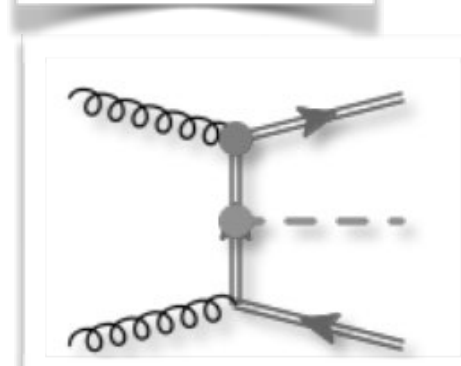

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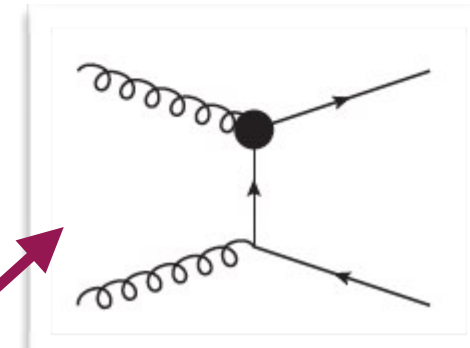

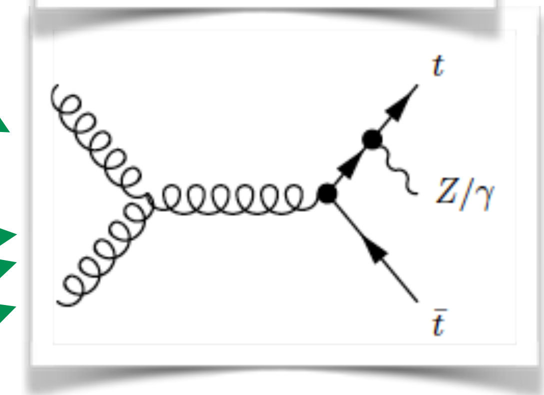

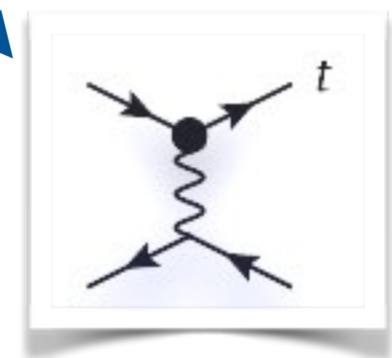

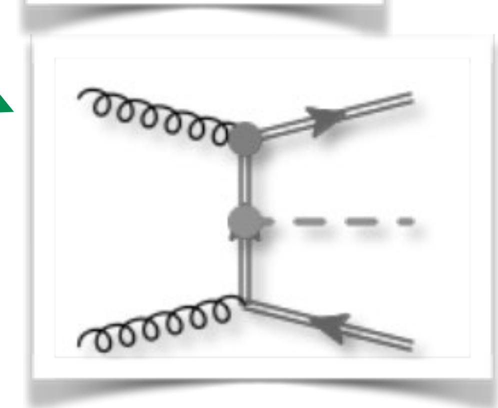

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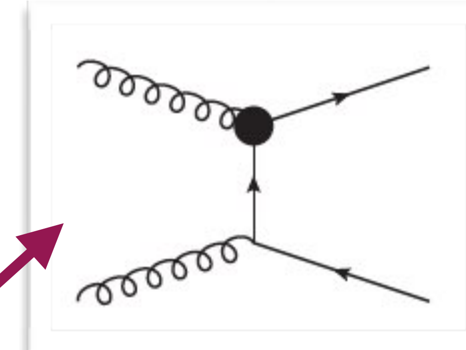

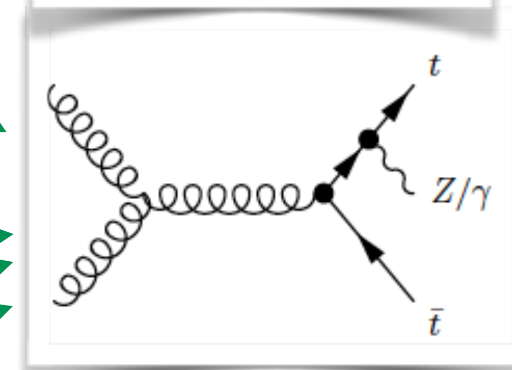

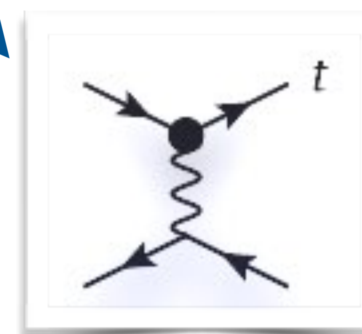

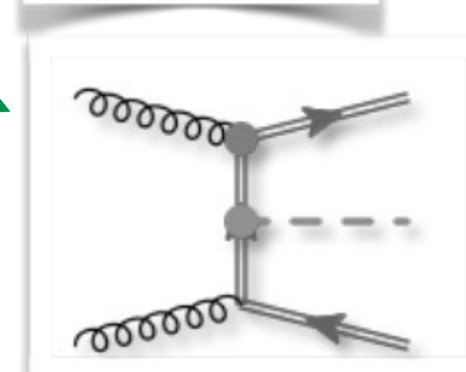

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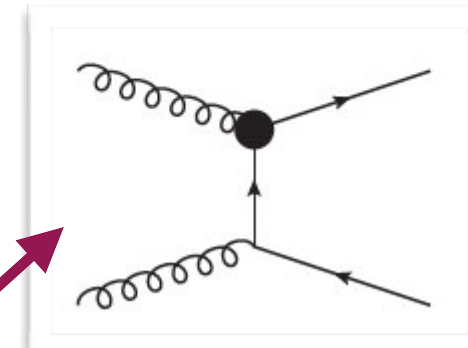

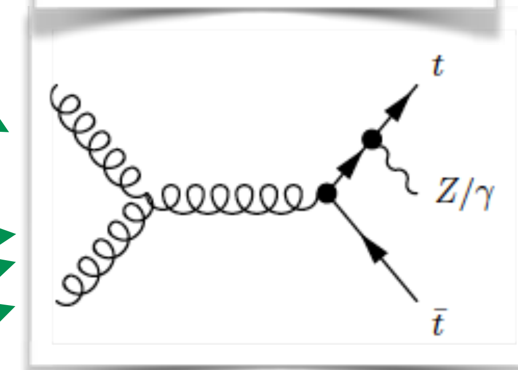

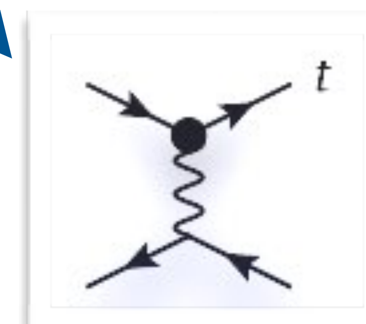

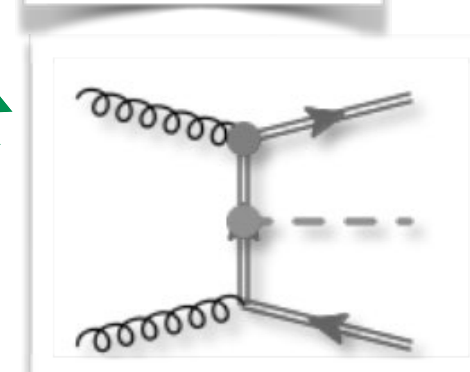

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Operators entering various processes: Global approach needed

Towards global fits

EFT only makes sense if we follow a global approach

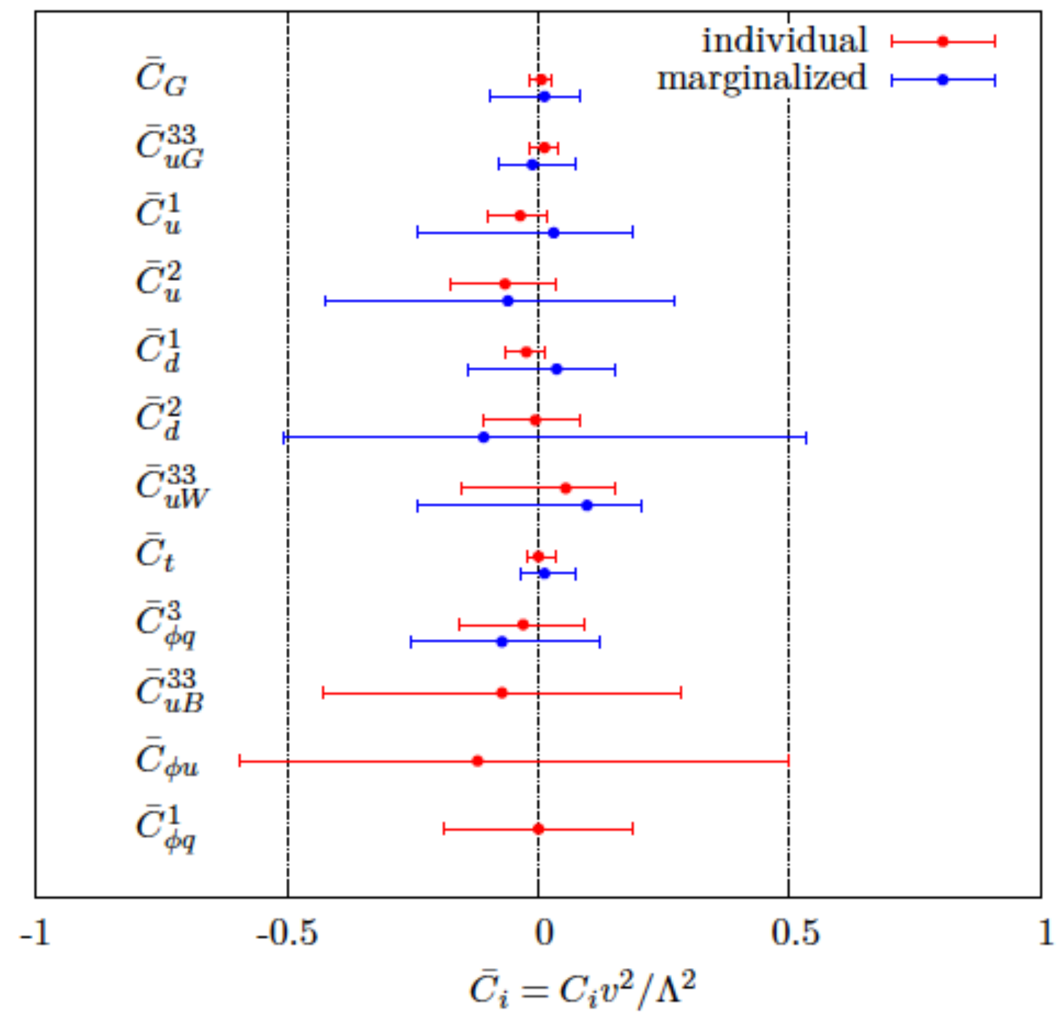
First work towards global fits:

Buckley et al arxiv:1506.08845 and 1512.03360

(N)NLO SM + LO EFT

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production			
Total cross-sections:			
ATLAS	7	lepton+jets	1406.5375
ATLAS	7	dilepton	1202.4892
ATLAS	7	lepton+tau	1205.3067
ATLAS	7	lepton w/o b jets	1201.1889
ATLAS	7	lepton w/ b jets	1406.5375
ATLAS	7	tau+jets	1211.7205
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573
ATLAS	8	dilepton	1202.4892
CMS	7	all hadronic	1302.0508
CMS	7	dilepton	1208.2761
CMS	7	lepton+jets	1212.6682
CMS	7	lepton+tau	1203.6810
CMS	7	tau+jets	1301.5755
CMS	8	dilepton	1312.7582
CDF + DØ	1.96	Combined world average	1309.7570
Single top production			
ATLAS	7	t-channel (differential)	1406.7844
CDF	1.96	s-channel (total)	1402.0484
CMS	7	t-channel (total)	1406.7844
CMS	8	t-channel (total)	1406.7844
DØ	1.96	s-channel (total)	0907.4259
DØ	1.96	t-channel (total)	1105.2788
Associated production			
ATLAS	7	$t\bar{t}\gamma$	1502.00586
ATLAS	8	$t\bar{t}Z$	1509.05276
CMS	8	$t\bar{t}Z$	1406.7830

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Differential cross-sections:			
ATLAS	7	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	1407.0371
CDF	1.96	$M_{t\bar{t}}$	0903.2850
CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
DØ	1.96	$M_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	1401.5785
Charge asymmetries:			
ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
Top widths:			
DØ	1.96	Γ_{top}	1308.4050
CDF	1.96	Γ_{top}	1201.4156
W-boson helicity fractions:			
ATLAS	7		1205.2484
CDF	1.96		1211.4523
CMS	7		1308.3879
DØ	1.96		1011.6549
Run II data			
CMS	13	$t\bar{t}$ (dilepton)	1510.05302



Tevatron and LHC data

Cross-sections and distributions

E.Vryonidou

What's next?

Use SMEFT to parametrise and look for deviations from SM predictions

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→

Use as many experimental measurements as possible Cross-sections+differential distributions

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Use the best SM predictions
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Need for precision also in SMEFT

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Use as many experimental measurements as possible
Cross-sections+differential distributions

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Need for precision also in SMEFT

Need for precision calculations
Automated tools for the EFT

How can we improve the EFT predictions?

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

Recent progress:

- top pair production: Franzosi and Zhang (arxiv:1503.08841)
- single top production: C. Zhang (arxiv:1601.06163)
- ttZ/γ: O. Bylund, F. Maltoni, I. Tsinikos, EV, C. Zhang (arXiv:1601.08193)
- ttH: F. Maltoni, EV, C. Zhang (arXiv:1607.05330)

All automated within MadGraph5_aMC@NLO
R2+UV counterterms: NLOCT Degrande (arxiv:1406.3030)

In practice

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

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

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

Implementation allows the

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

E.Vryonidou

In practice

In practice

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

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

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

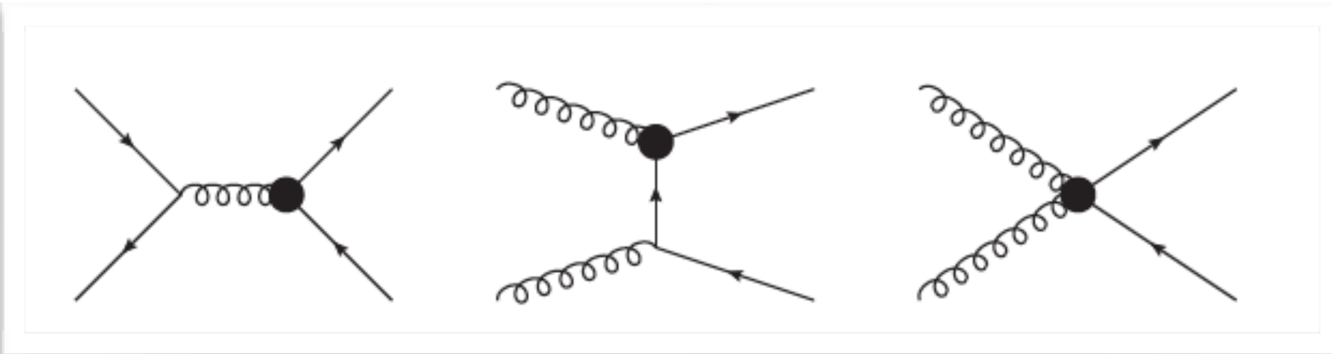
Implementation allows the

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1{\rm TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \le j} \frac{1{\rm TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

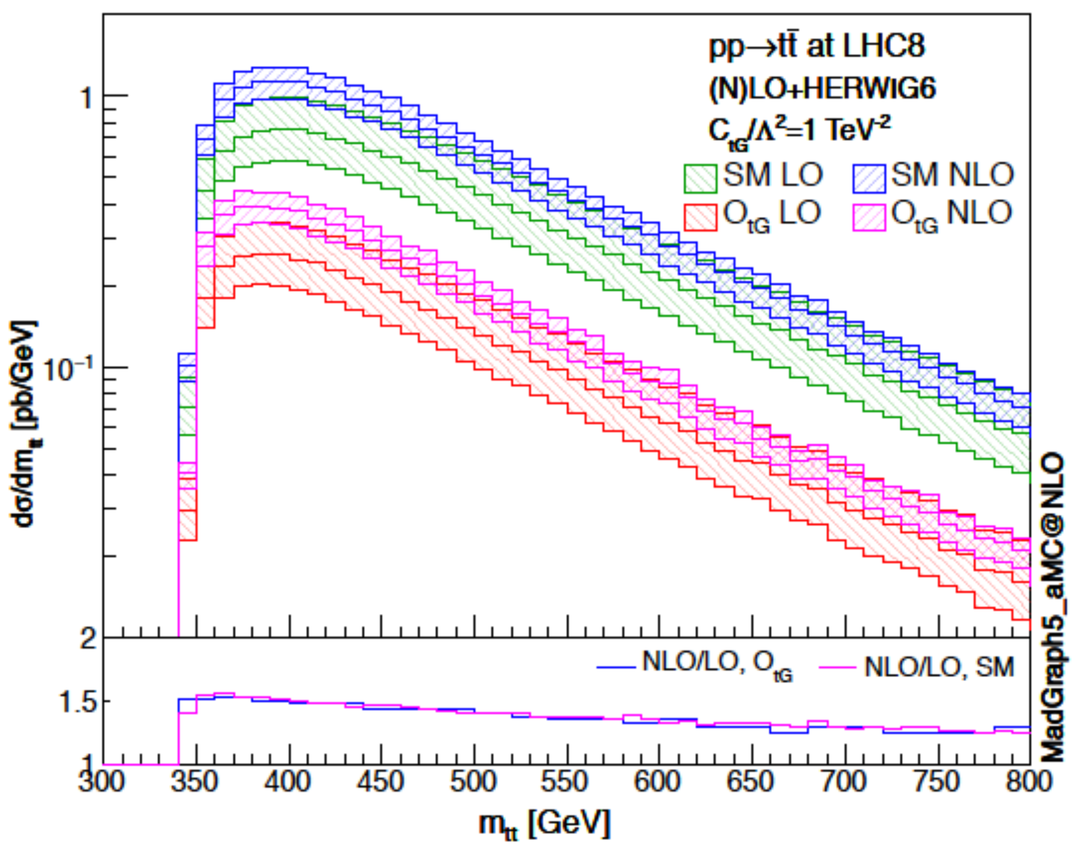
interference

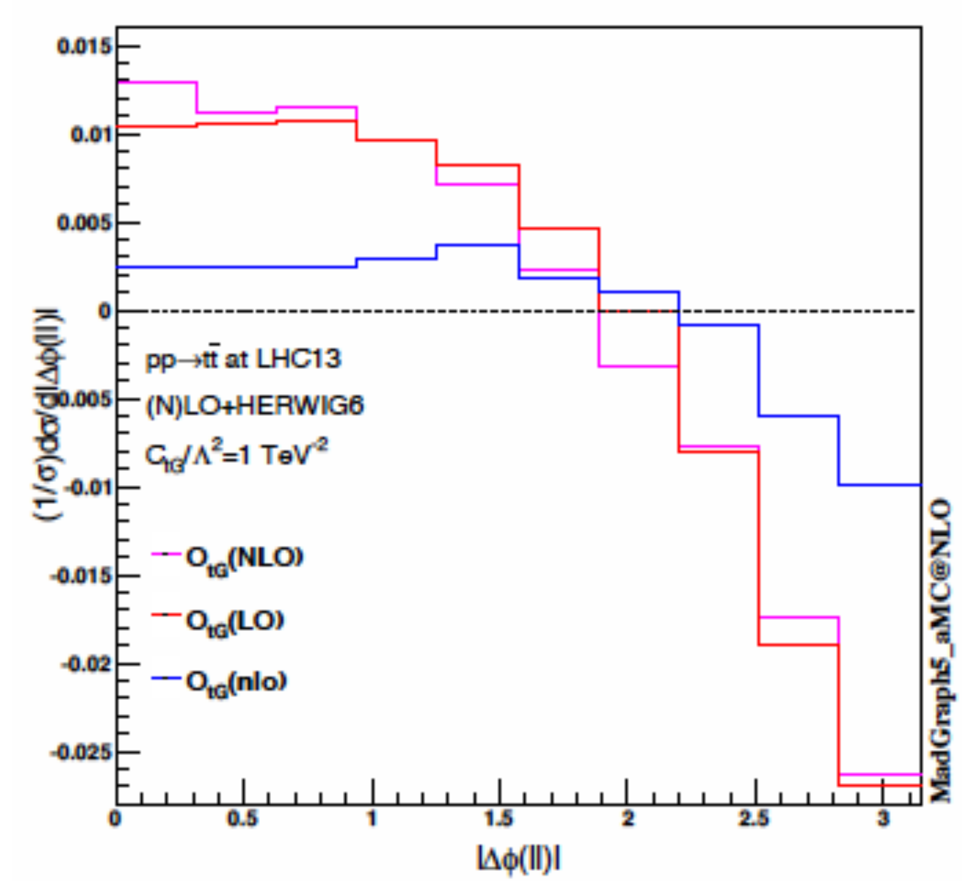
interference between operators, squared

First example: top-pair production



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





Zhang and Franzosi
arXiv:1503.08841

Limits on c_{tG}/Λ^2 using total cross section

	LO [TeV^{-2}]	NLO [TeV^{-2}]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

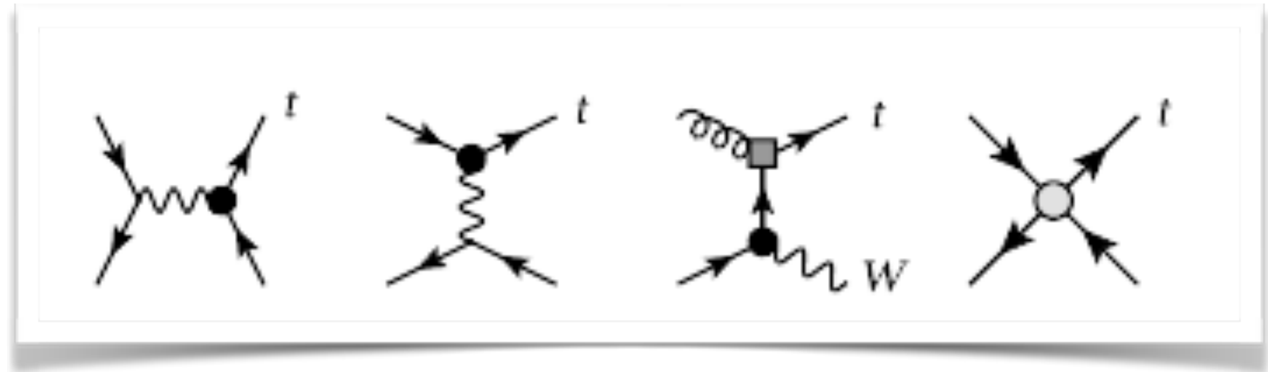
single top production

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

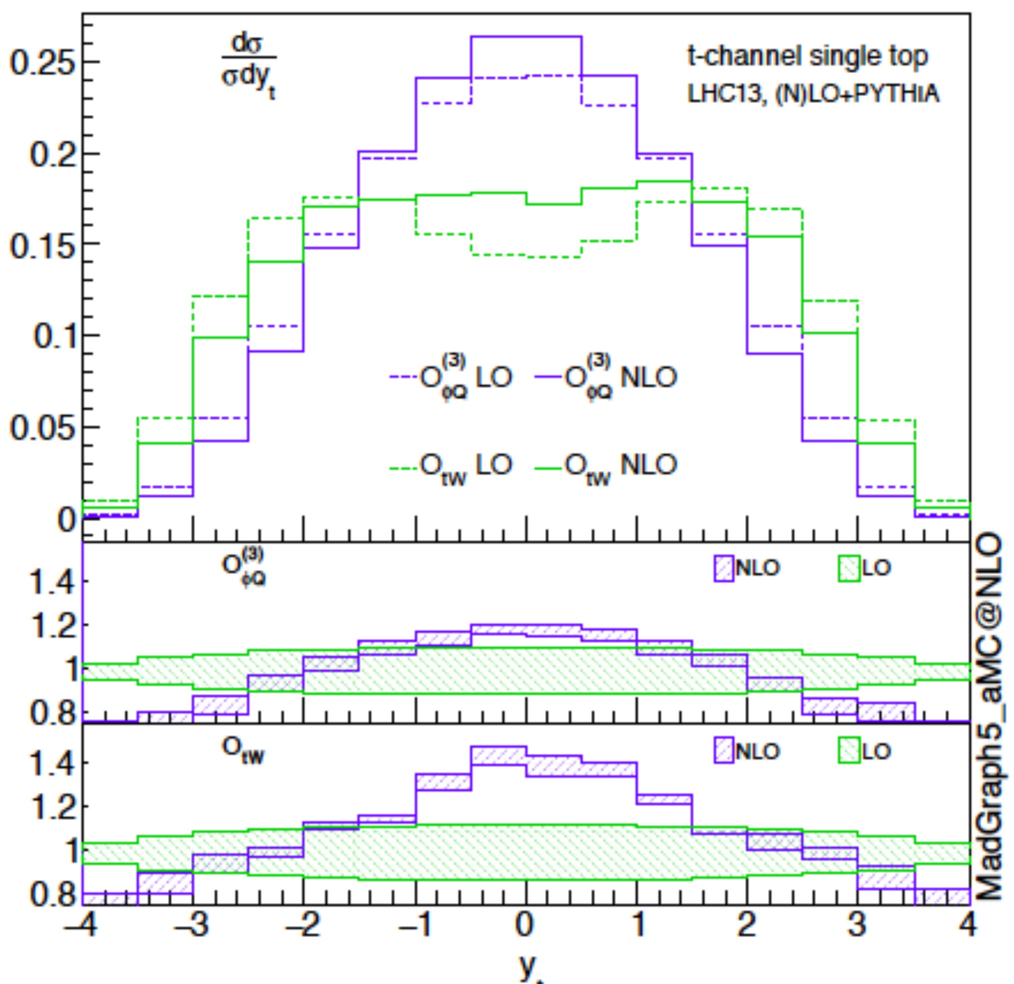
$$O_{tW} = y_t g_W (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W_{\mu\nu}^I$$

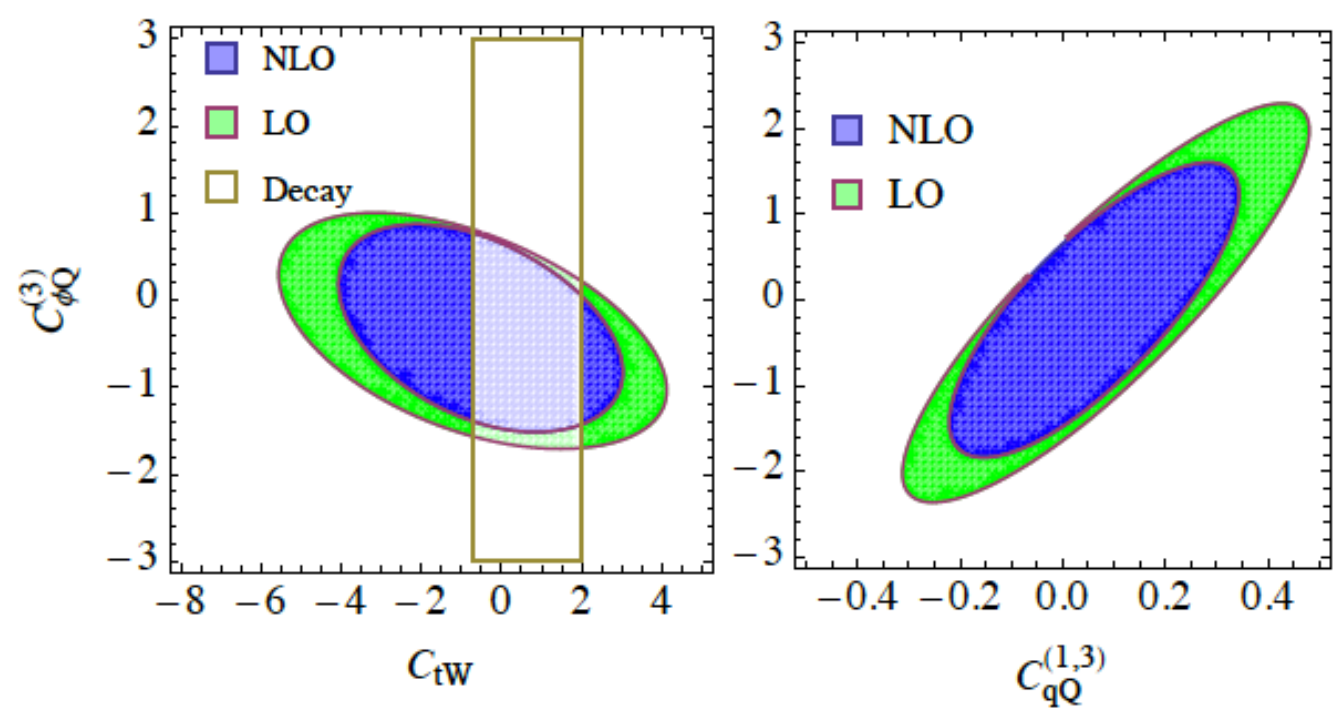
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G_{\mu\nu}^A$$

$$O_{qQ,rs}^{(3)} = (\bar{q}_r \gamma_\mu \tau^I q_s)(\bar{Q}\gamma^\mu \tau^I Q)$$



One four-fermion contributing at 1/Λ²



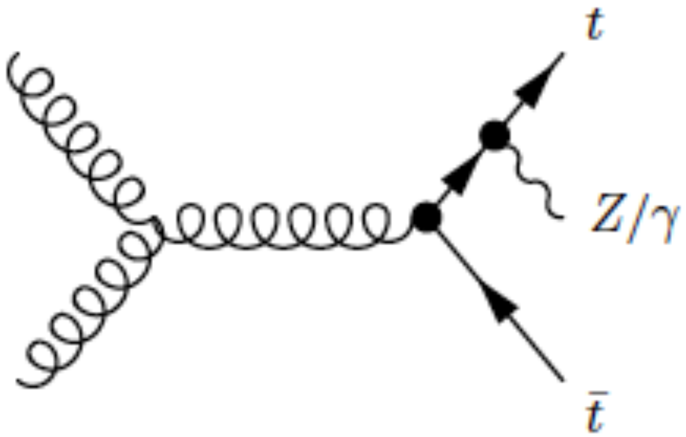


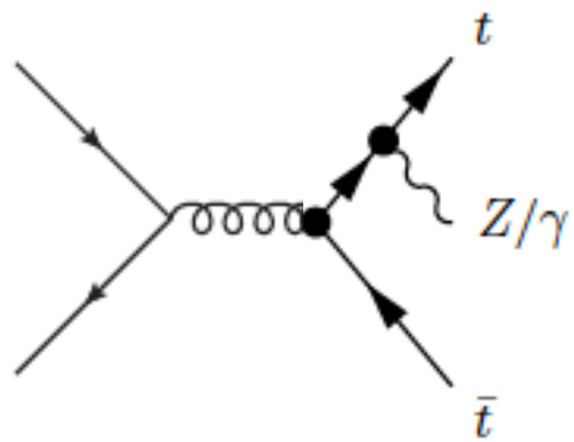
C. Zhang (arxiv:1601.06163)

NLO corrections:

- Impact on distributions
- Impact on limits

Top-pair+Z





~900fb at 13 TeV

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

Relevant operators

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

4-fermion operators
Triple gluon operator
(not discussed here)

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

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

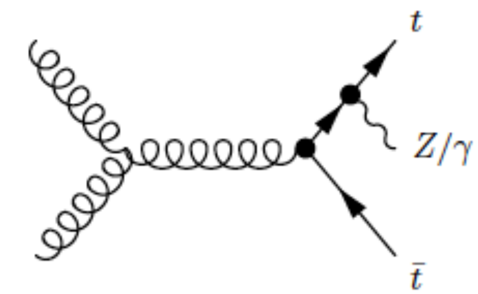
Anomalous coupling approach

Top-pair+Z

13TeV	$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tW}$
$\sigma_{i,LO}^{(1)}$	$286.7^{+38.2\%}_{-25.5\%}$	$78.3^{+40.4\%}_{-26.6\%}$	$51.6^{+40.1\%}_{-26.4\%}$	$-0.20(3)^{+88.0\%}_{-230.0\%}$
$\sigma_{i,NLO}^{(1)}$	$310.5^{+5.4\%}_{-9.7\%}$	$90.6^{+7.1\%}_{-11.0\%}$	$57.5^{+5.8\%}_{-10.3\%}$	$-1.7(2)^{+31.3\%}_{-49.1\%}$
K-factor	1.08	1.16	1.11	8.5
$\sigma_{ii,LO}^{(2)}$	$258.5^{+49.7\%}_{-30.4\%}$	$2.8(1)^{+39.7\%}_{-26.9\%}$	$2.9(1)^{+39.7\%}_{-26.7\%}$	$20.9^{+44.3\%}_{-28.3\%}$
$\sigma_{ii,NLO}^{(2)}$	$244.5^{+4.2\%}_{-8.1\%}$	$3.8(3)^{+13.2\%}_{-14.4\%}$	$3.9(3)^{+13.8\%}_{-14.6\%}$	$24.2^{+6.2\%}_{-11.2\%}$

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

- Different k-factors for different operators
- Small contribution from O_{tW} and O_{tB} at $O(1/\Lambda^2)$ but large at $O(1/\Lambda^4)$: Does this make sense in the context of the EFT? To be checked on a case-by-case basis



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

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

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

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

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

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

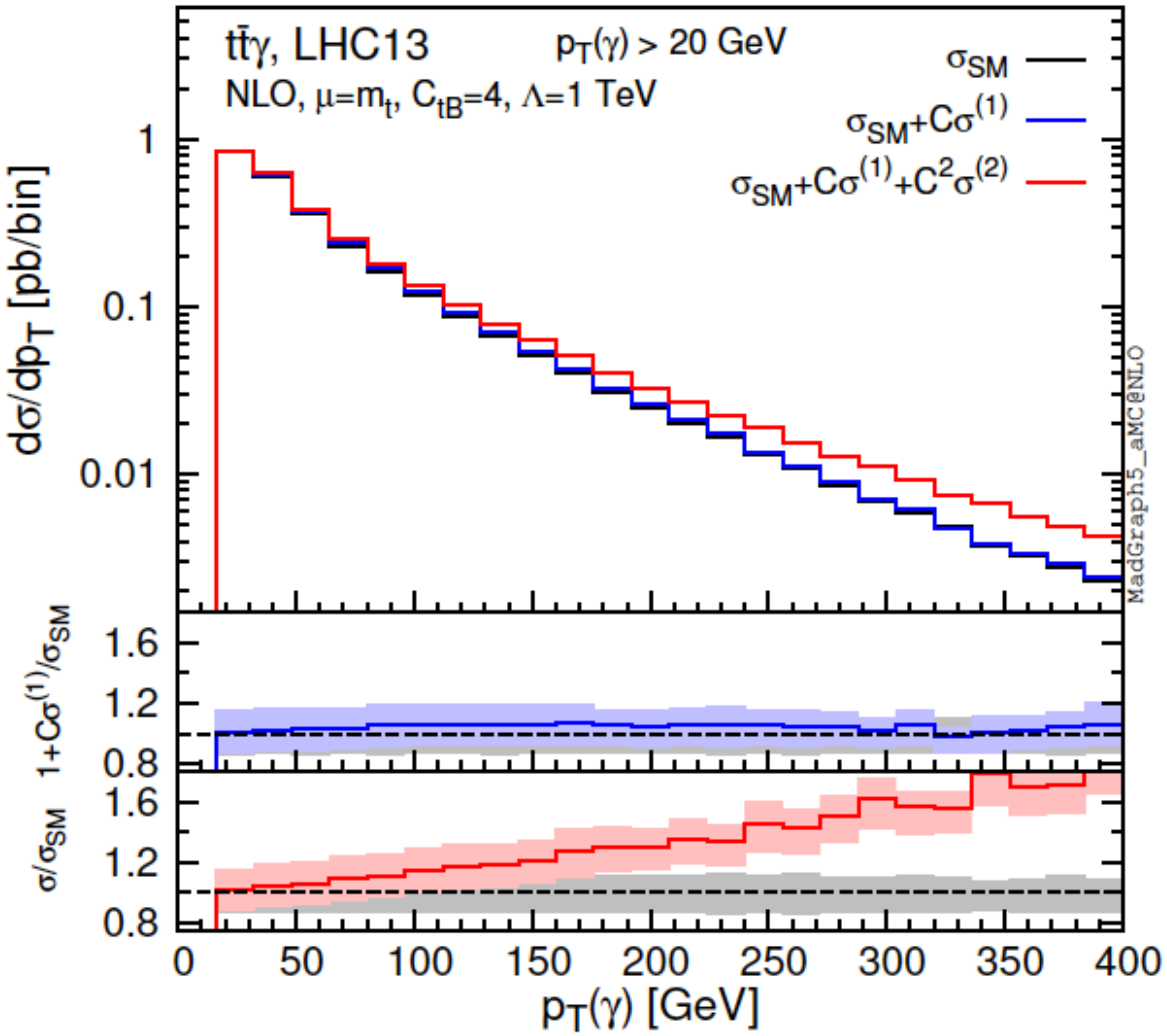
Anomalous dimension matrix:
O_{tW}, O_{tB}, O_{tG}

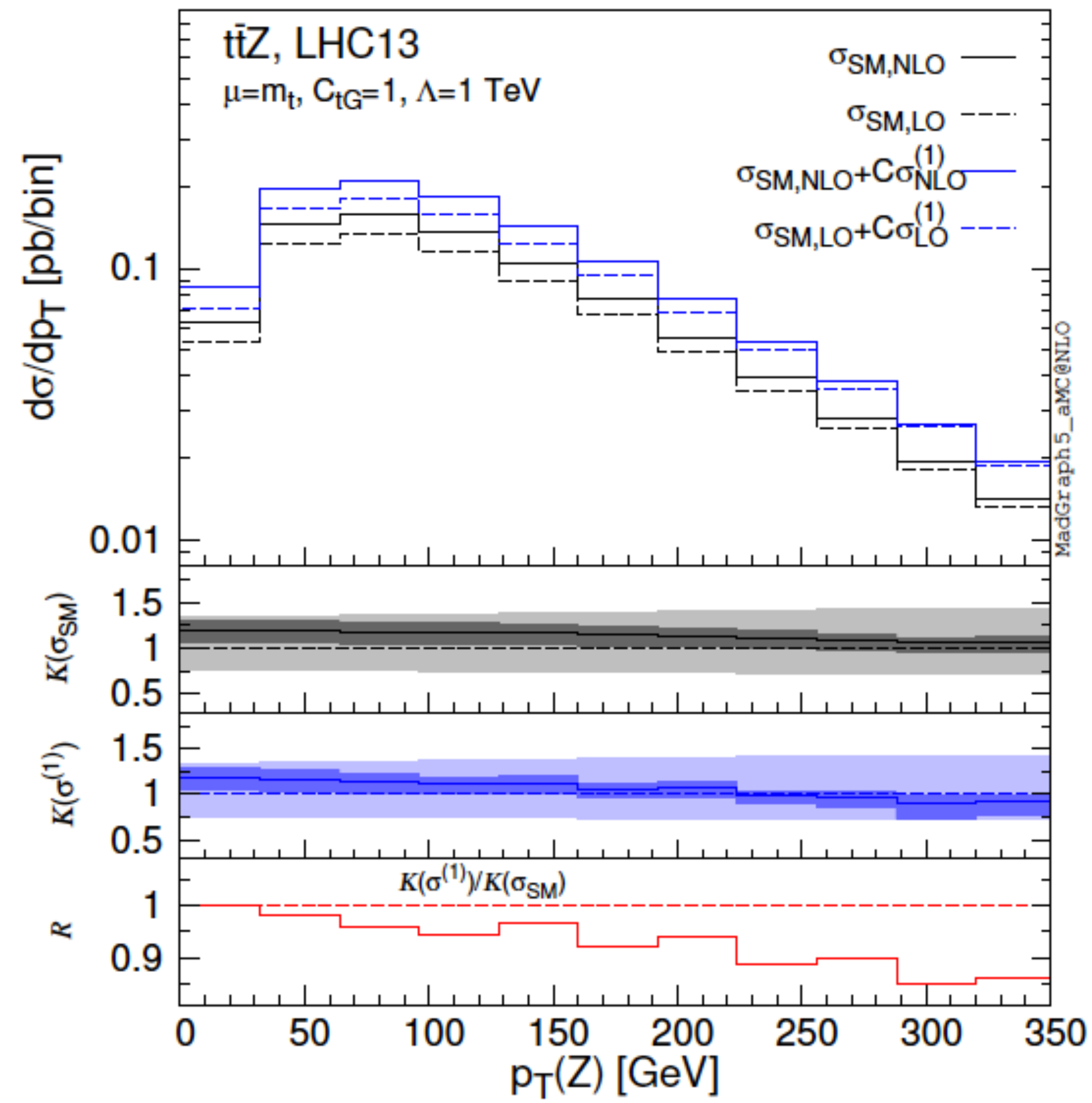
$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} \end{pmatrix}$$

E.Vryonidou

Bylund et al arXiv:1601.08193

Differential distributions for tt+V





Large contribution at $O(1/\Lambda^4)$ rising with energy

Using SM k-factors is not enough

arXiv:1601.08193

Some considerations

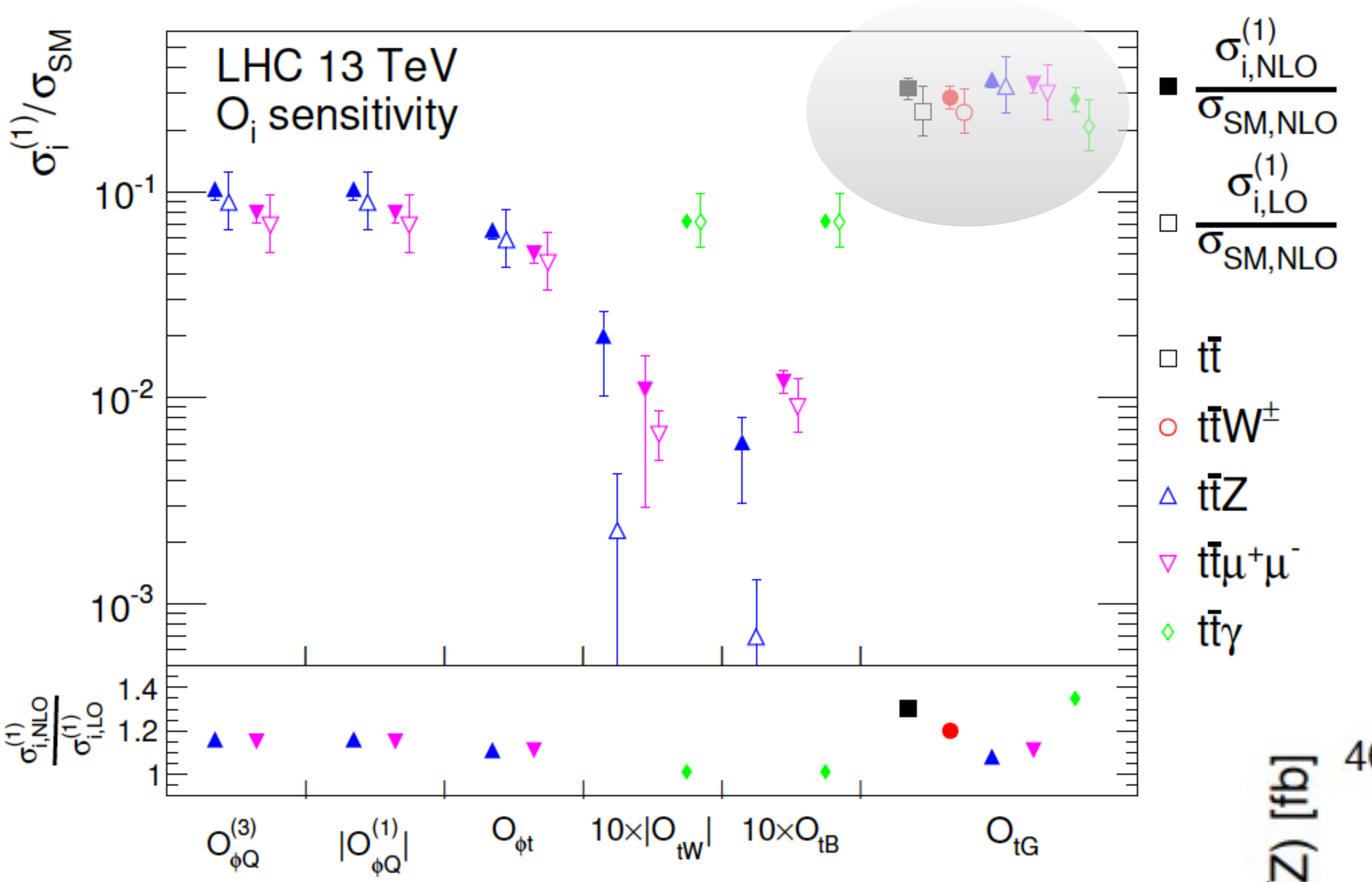
- Theory uncertainties:
  - SM: factorisation and renormalisation scale, PDF uncertainties
  - EFT: as in SM but also EFT scale c(μ), running and mixing
  - EFT expansion: dimension-8 operators
- Validity of the EFT expansion: E<Λ, report limits as a function of the max scale probed: Contino et al arXiv:1604.06444
- $1/\Lambda^2$ vs $1/\Lambda^4$ contributions
  - $1/\Lambda^2$ suppressed due to helicity: Azatov et al arXiv:1607.05236
  - $1/\Lambda^4$ can be large for loosely constrained operator coefficients/strongly coupled theories

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

EFT condition satisfied but $O(1/\Lambda^4)$ large for large operator coefficients

- Range of Wilson coefficients:
  - The theory: perturbativity, unitarity, linear or non-linear EFT, UV completion
  - The experimental limits: Think about and use as many processes as possible

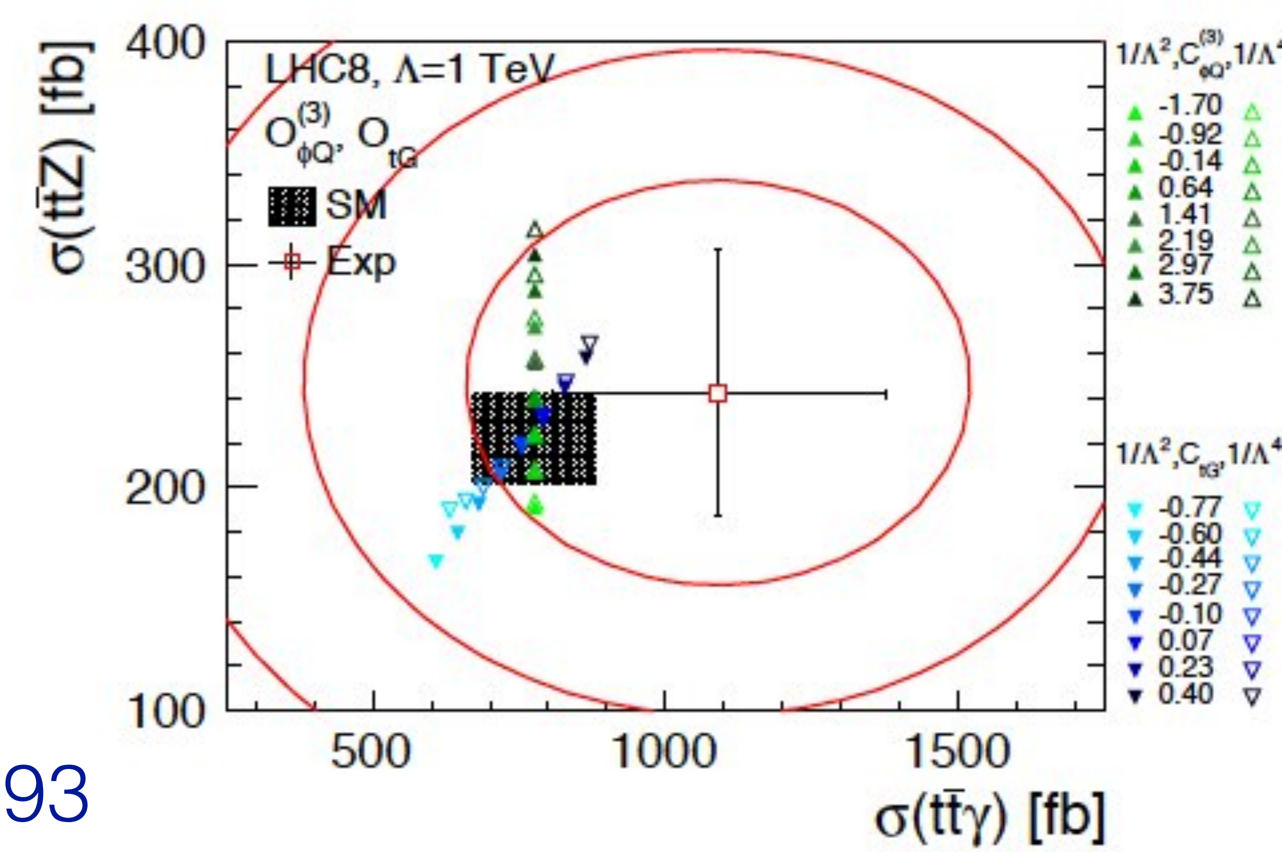
A sensitivity study



Chromomagnetic operator affecting all processes in the same way

LHC measurements of ttV processes can set constraints on the Wilson coefficients

See also: Schulze et al. arXiv:1404.1005, 1501.05939, 1603.08911 in the anomalous coupling framework



arXiv:1601.08193

Top operators in loops: HZ in gluon fusion

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

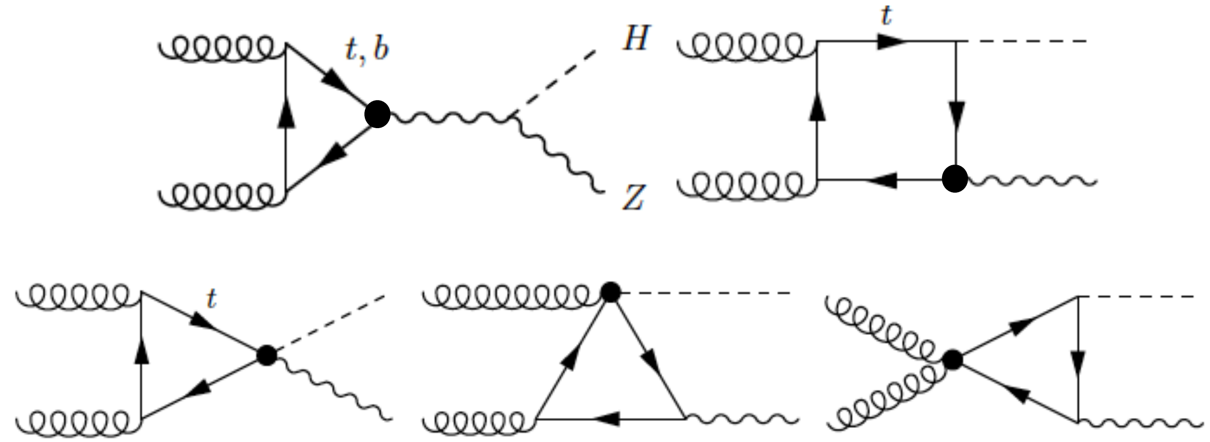
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$

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

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

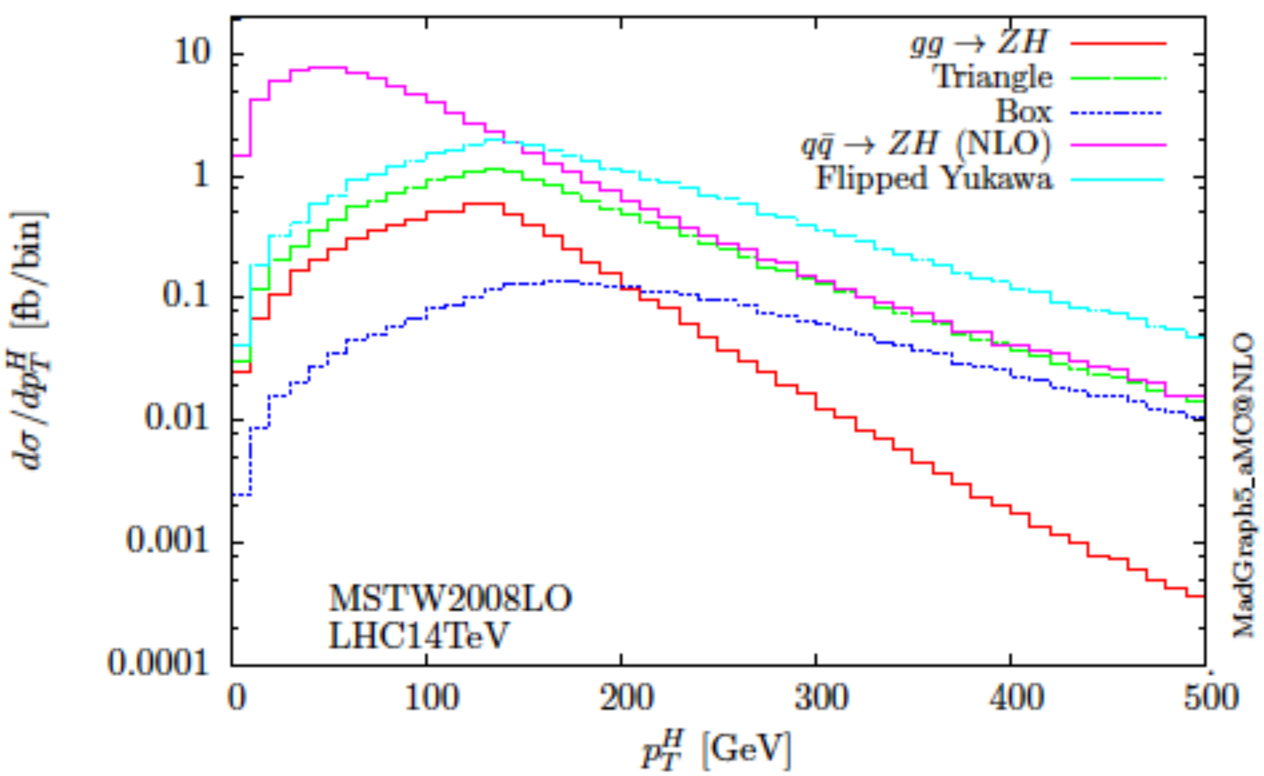
$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$

+HZZ operators



10% of the SM NNLO HZ cross section

Gluon-fusion contribution to HZ production affected by the operators changing gtt, ttZ and ttH → Additional information

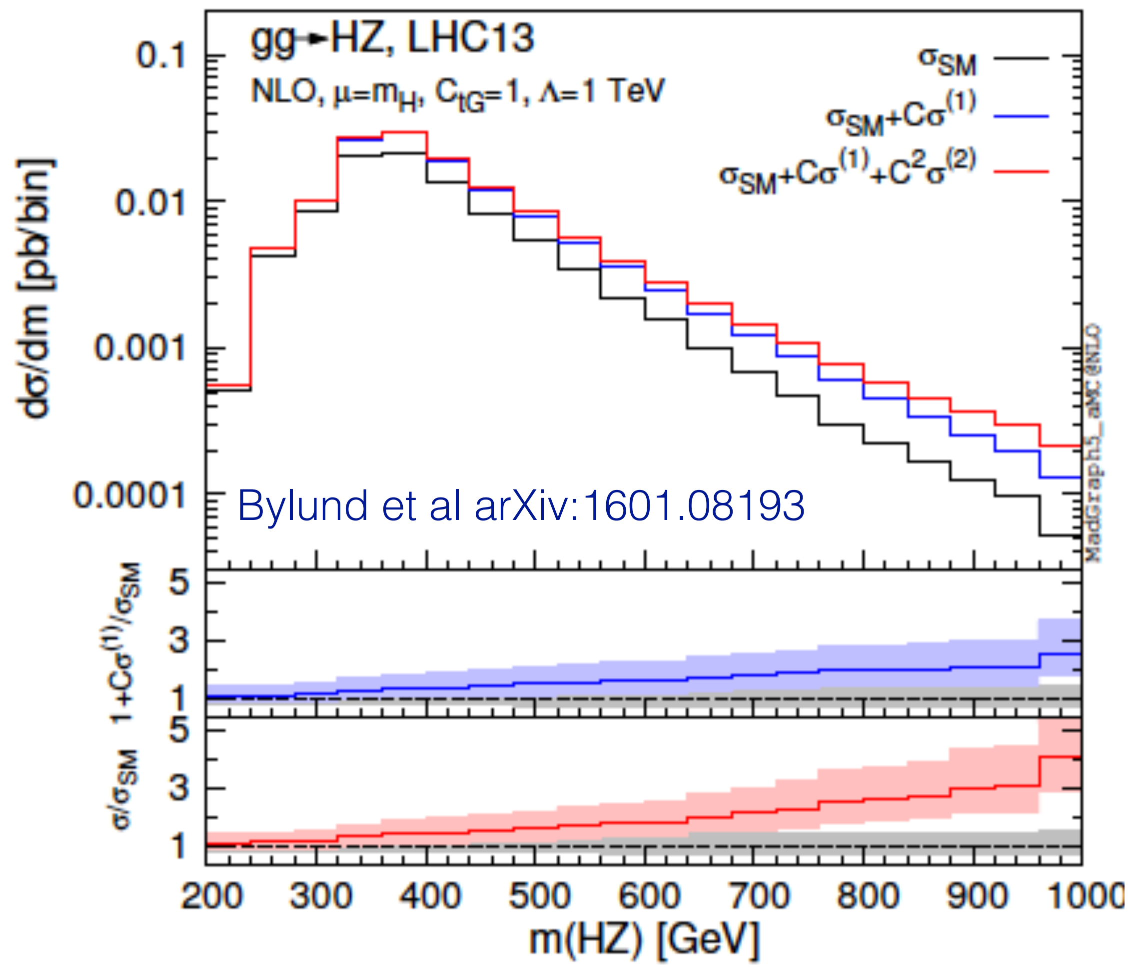


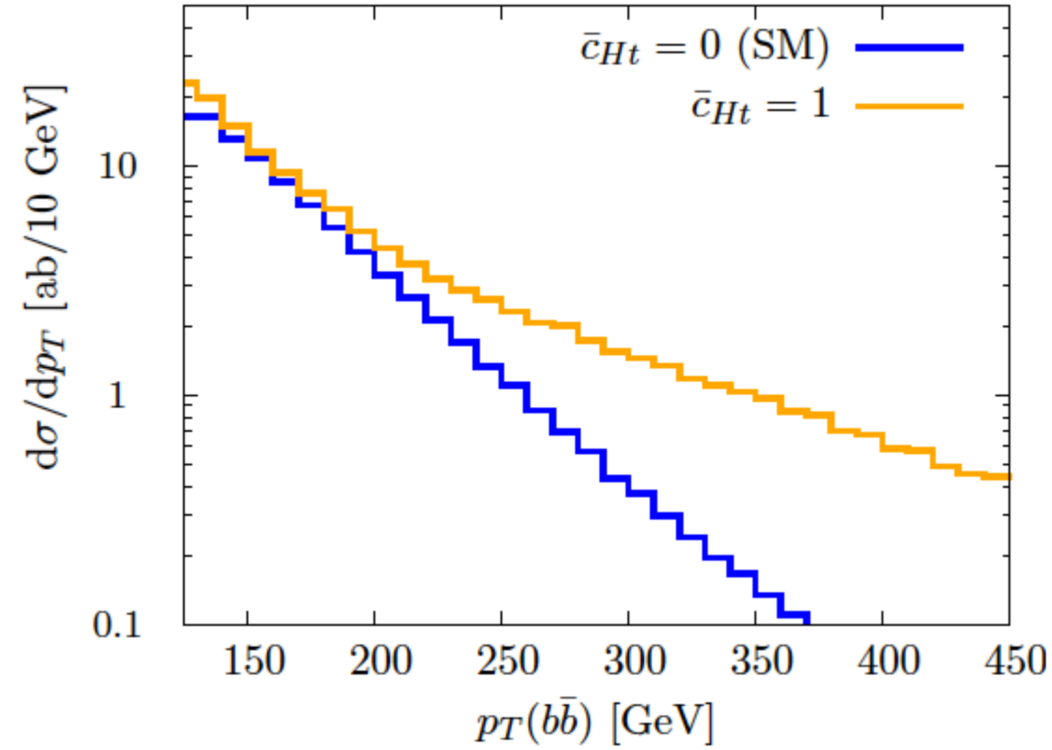
[fb]	SM		O_{tG}	$O^{(1)}_{\phi Q}$
13TeV	$93.6^{+34.3\%}_{-23.8\%}$	$\sigma_i^{(1)}$	$34.6^{+35.2\%}_{-24.5\%}$	$5.91^{+36.4\%}_{-24.9\%}$
		$\sigma_{ii}^{(2)}$	$6.09^{+39.2\%}_{-26.1\%}$	$0.182^{+40.2\%}_{-26.6\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.370^{+0.7\%}_{-0.9\%}$	$0.0631^{+1.6\%}_{-1.5\%}$
		$\sigma_{ii}^{(2)}/\sigma_i^{(1)}$	$0.176^{+2.9\%}_{-2.1\%}$	$0.0309^{+2.8\%}_{-2.2\%}$

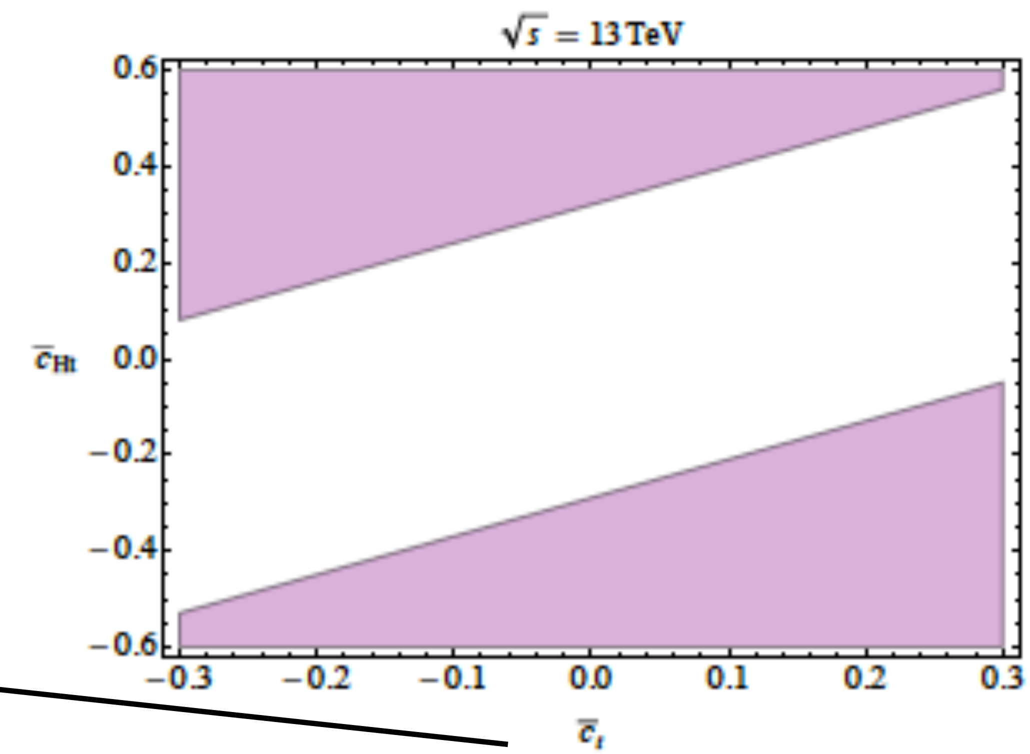
Sensitive to the relative phase of the top and Z Higgs couplings

No contributions from the electroweak dipole operators due to charge conjugation invariance

HZ in gluon fusion







Differential information important

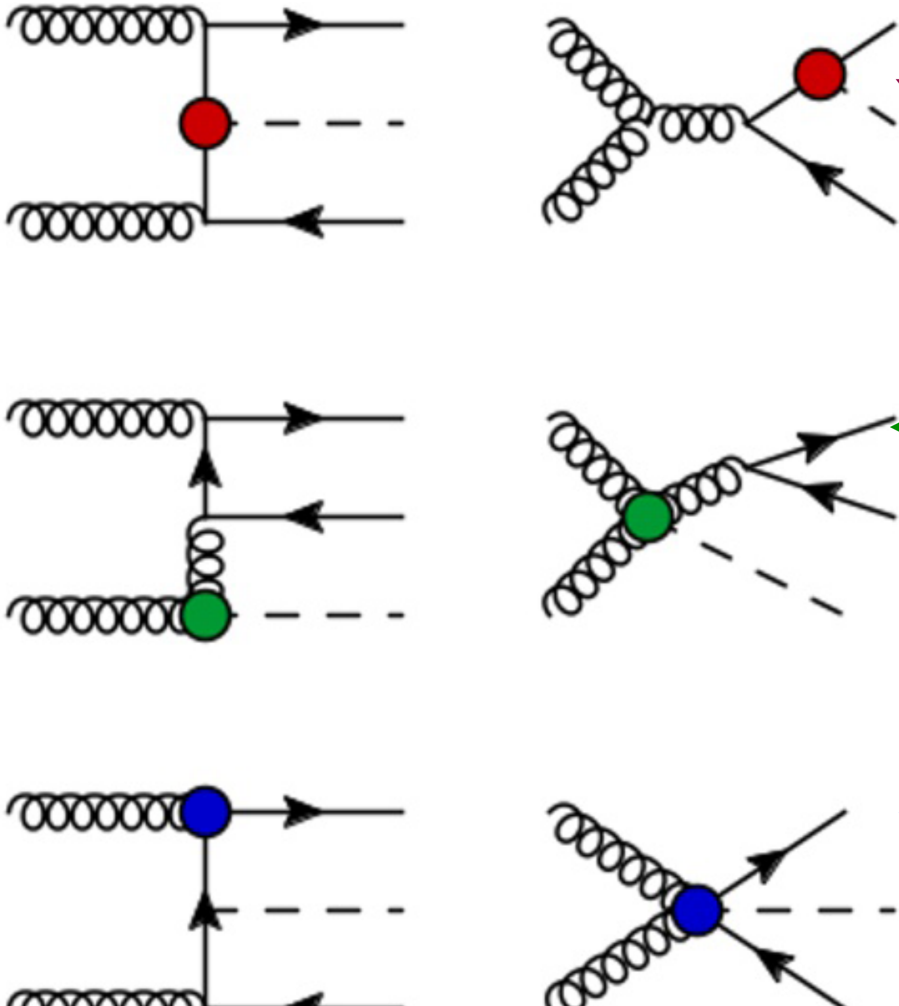
$$\mathcal{O}_{Ht} = \frac{i\bar{c}_{Ht}}{v^2}(\bar{t}_R\gamma^\mu t_R)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\,,$$

$$\mathcal{O}_t = -\,\frac{\bar{c}_t}{v^2} y_t \Phi^\dagger\Phi\,\Phi^\dagger \cdot \bar{Q}_L\, t_R + \text{h.c.}$$

E.Vryonidou

Englert et al arXiv:1603.05304

ttH in the EFT

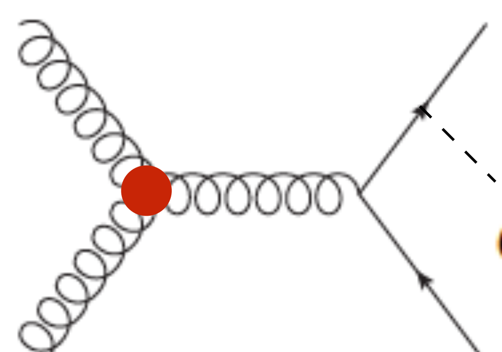


$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}$$

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

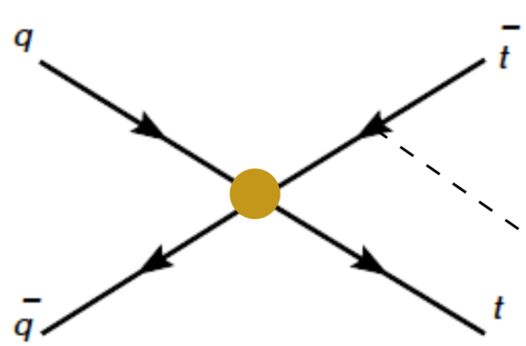
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

At NLO in this talk



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

Multijet constraints:
Krauss et al arXiv:1611.00767



4-fermion operators

Not in this talk, work in progress

E.Vryonidou

ttH@NLO

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

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu) \qquad \begin{array}{c} (O_{t\phi}, O_{\phi G}, O_{tG}) \\ \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix} \end{array}$$

Alonso et al. arxiv:1312.2014

dim-6	dim-5	dim-4
O_{tG}	$O_{\phi G}$	$O_{t\phi}$

Higher-dimension operators mix into lower-dimension ones

Setup allows computation of:

$$\sigma = \sigma_{\mathrm{SM}} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2}C_i\sigma_i + \sum_{i\le j}\frac{1\mathrm{TeV}^4}{\Lambda^4}C_iC_j\sigma_{ij}.$$

interference with SM

interference between operators, squared contributions

E.Vryonidou

Cross-section results (1)

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

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1\text{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

- Different K-factors for different operators, different from the SM
- Large $1/\Lambda^4$ contribution for the chromomagnetic operator
- Constraints from top pair production: c_{tG}=[-0.42,0.30] Franzosi and Zhang arxiv:1503.08841
- Global approach needed to consistently extract information on coefficients within the SMEFT framework

Cross-section results (2)

13 TeV	σ NLO	$\sigma/\sigma_{\rm SM}$ NLO	K
$\sigma_{\rm SM}$	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$	1.09
$\sigma_{t\phi}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	$-0.123^{+0.001+0.001+0.000}_{-0.001-0.002-0.000}$	1.13
$\sigma_{\phi G}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	$1.722^{+0.146+0.073+0.004}_{-0.089-0.068-0.005}$	1.39
σ_{tG}	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	$0.991^{+0.004+0.003+0.000}_{-0.010-0.006-0.001}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	$0.0037^{+0.0001+0.0002+0.0000}_{-0.0000-0.0001-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	$2.016^{+0.267+0.190+0.021}_{-0.178-0.167-0.027}$	1.58
$\sigma_{tG,tG}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	$1.328^{+0.011+0.008+0.014}_{-0.038-0.014-0.018}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	$-0.105^{+0.006+0.006+0.000}_{-0.009-0.007-0.000}$	1.42
$\sigma_{t\phi,tG}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	$-0.061^{+0.000+0.000+0.000}_{-0.000-0.001-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	$1.691^{+0.137+0.042+0.013}_{-0.097-0.039-0.017}$	1.37

First systematic study of uncertainties:

- 1) Scale and PDF uncertainties:

Similar to SM

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

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

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

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

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

3) C/Λ^2 expansion

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

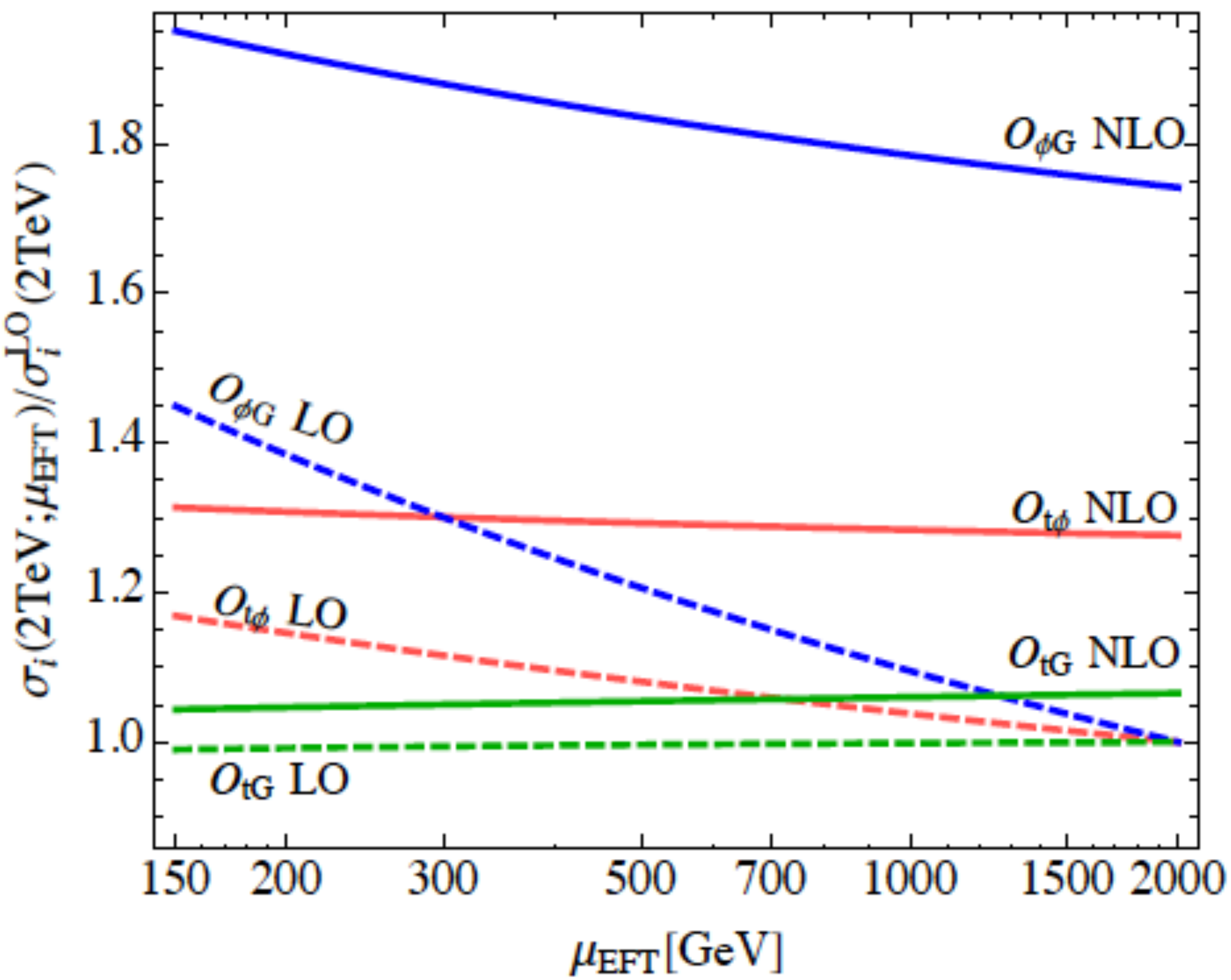
$$\boxed{+\sum_i \frac{C_i^{\rm dim8}}{(\Lambda/1{\rm TeV})^4}\sigma_i^{\rm (dim8)}} + \mathcal{O}(\Lambda^{-6})\,.$$

Included

Needs dim-8 operators (Not included here)
But it can be estimated using a cut-off
Contino et al arXiv:1604.0644

E.Vryonidou

A study of RG effects

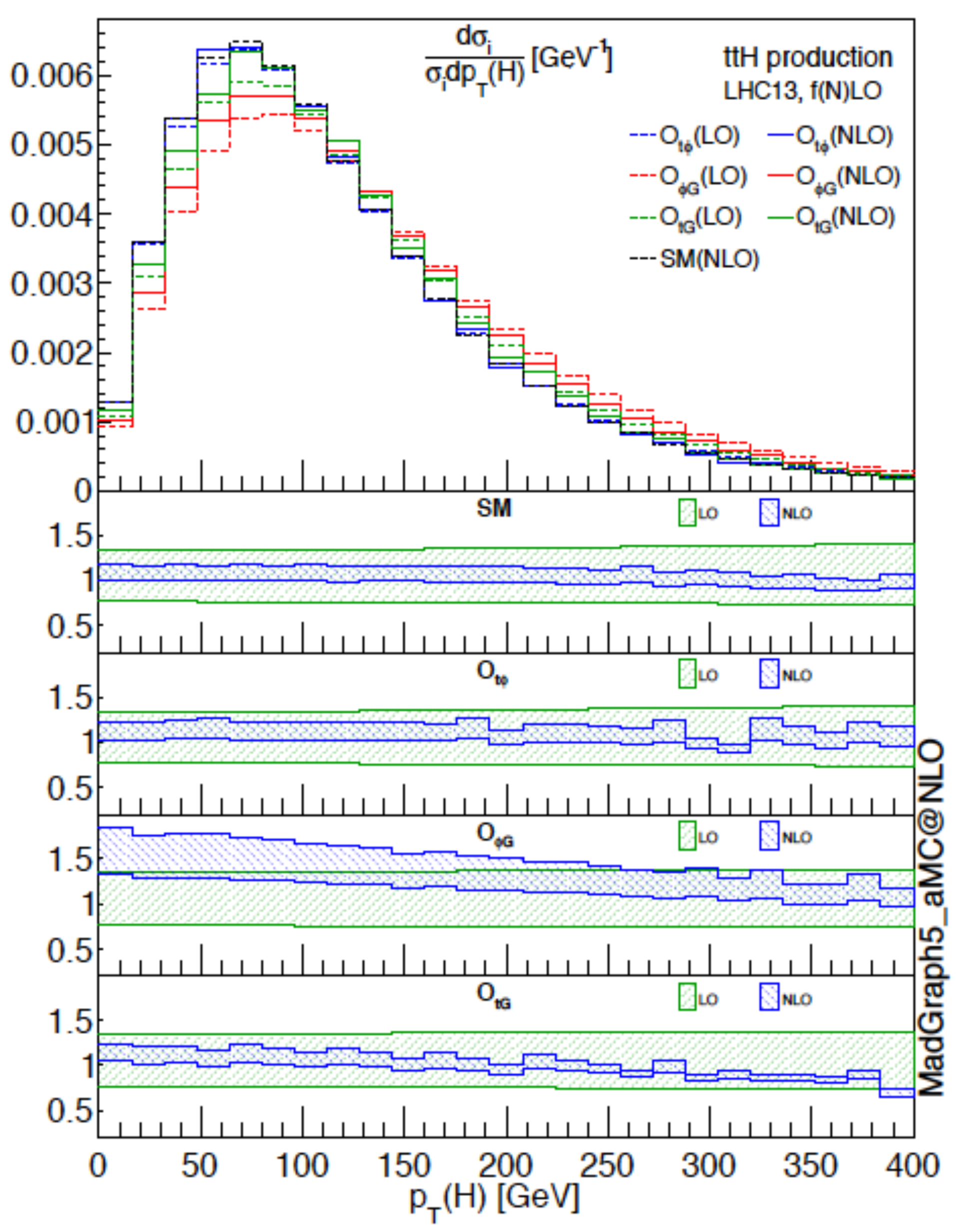


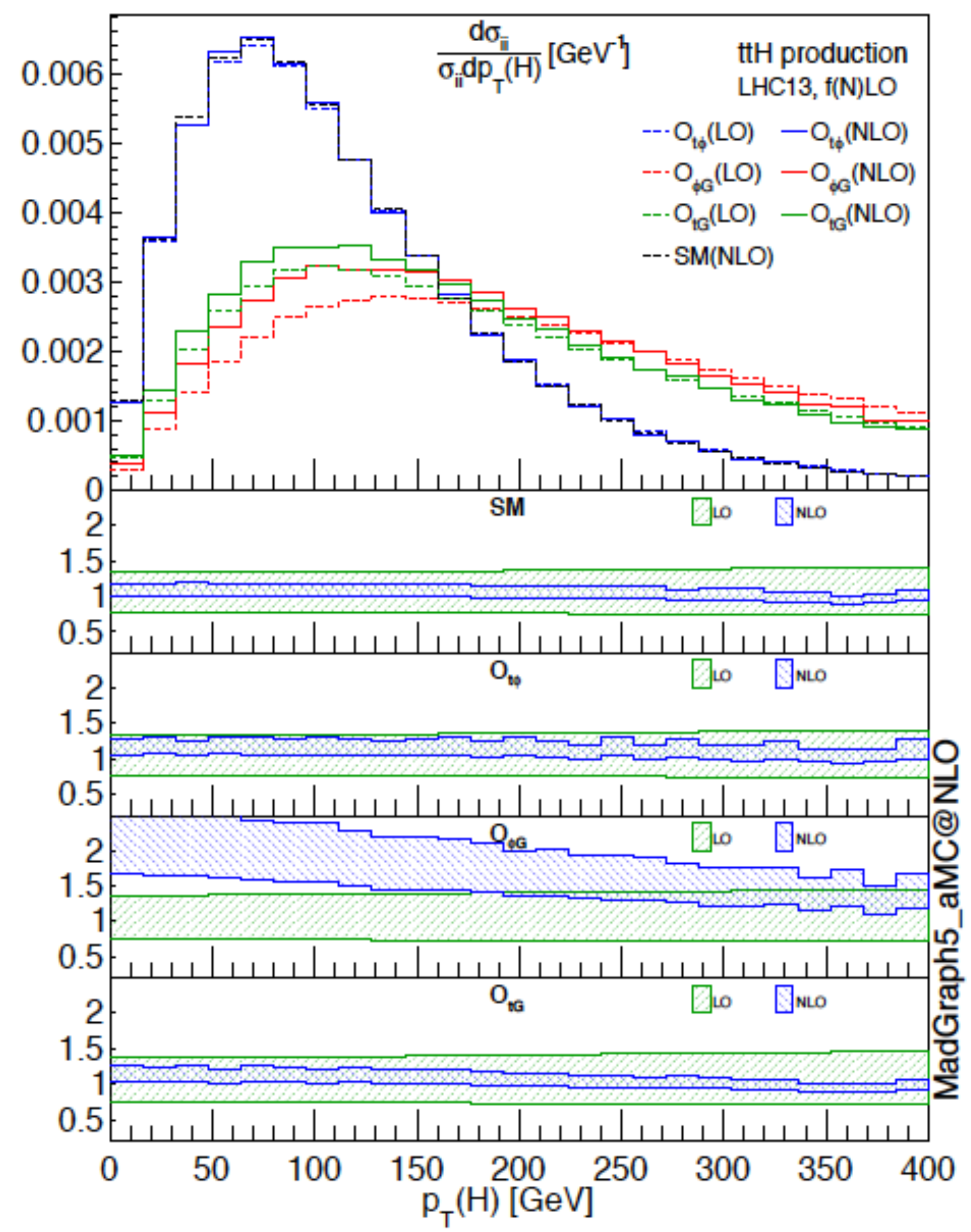
RG corrections not a good approximation to the NLO result, underestimate the NLO corrections

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

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

Differential distributions for ttH





NLO: smaller uncertainties, non-flat K-factors

Different shapes for different operators for the squared terms

Maltoni, EV, Zhang arXiv:1607.05330

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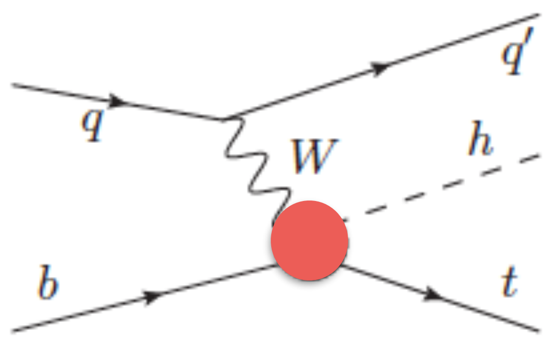
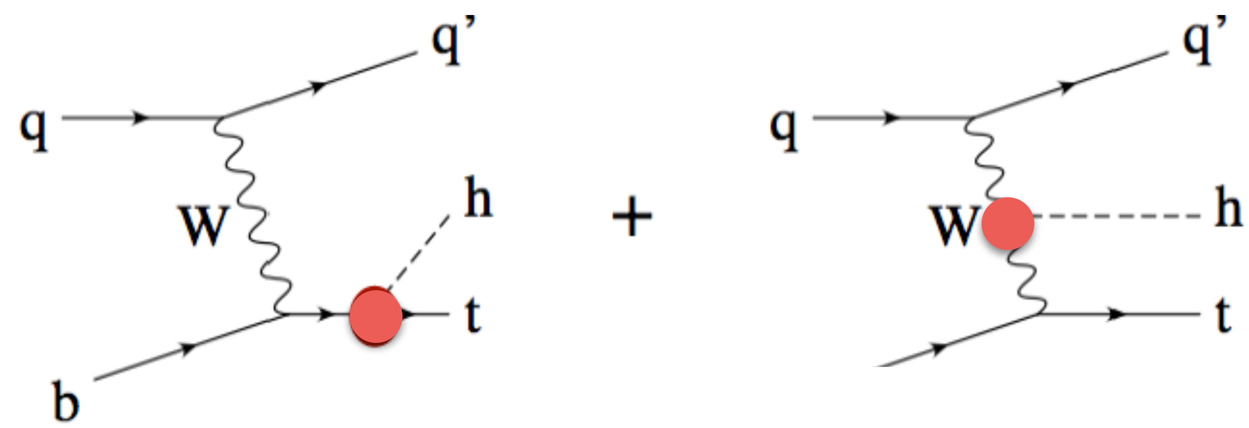
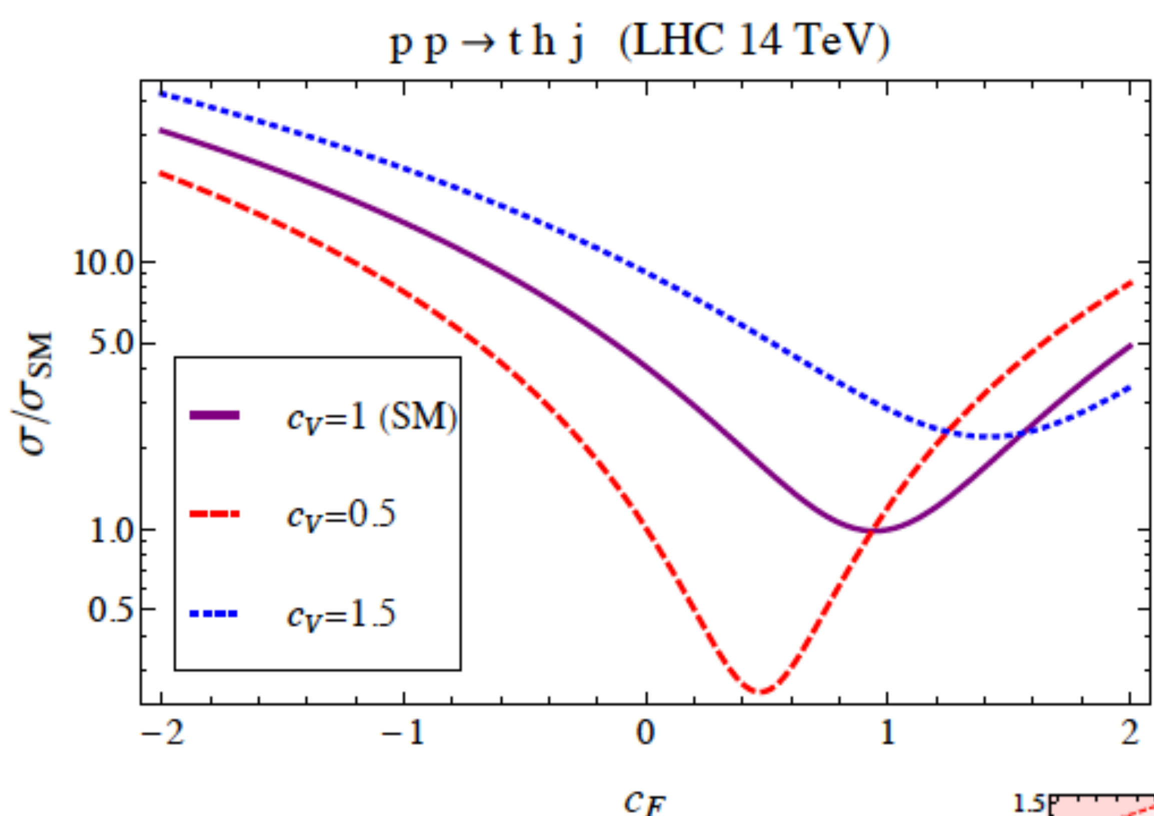
single top+Higgs

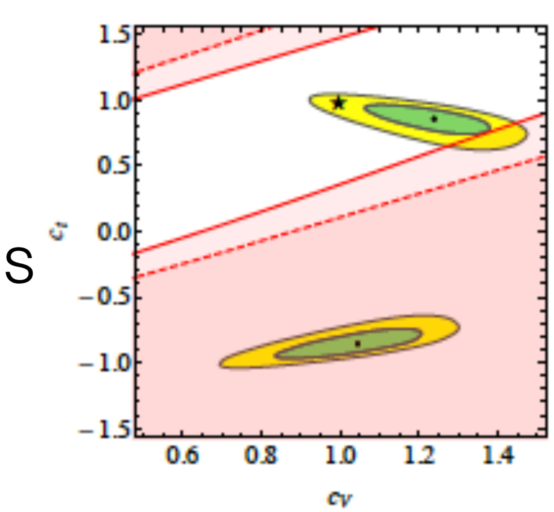


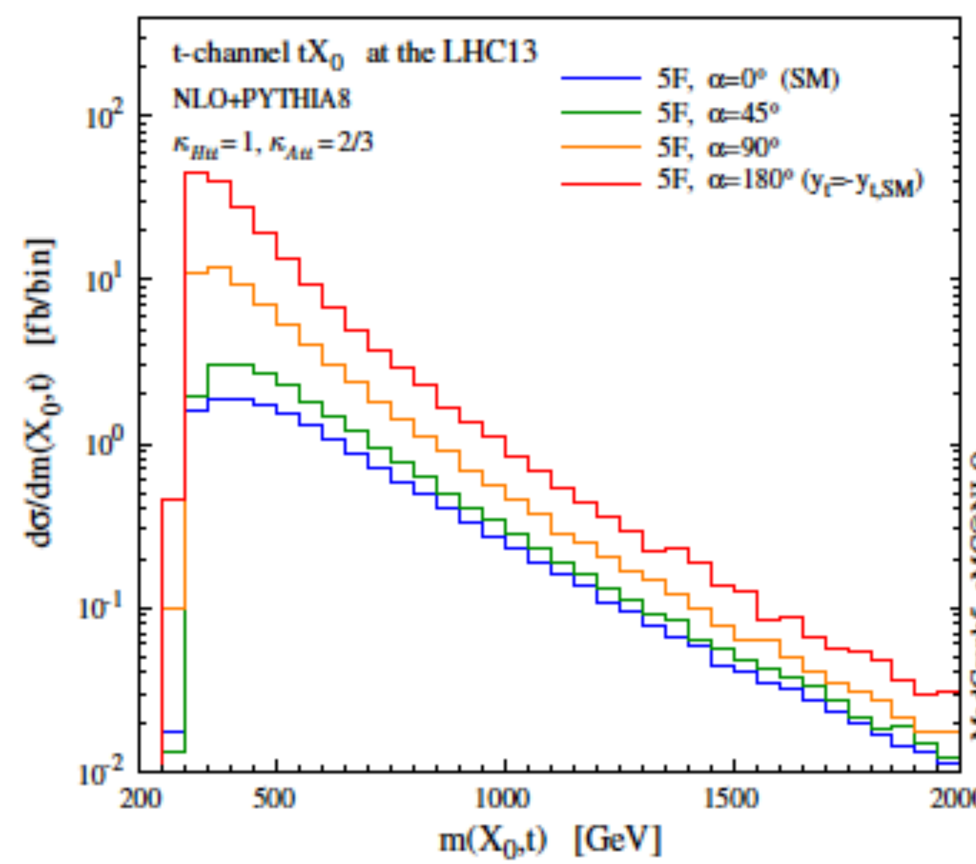


SM
~70fb at 13TeV



Farina et al 1211.3736
A probe of the relative sign
of the Htt and HWW couplings





Higgs characterisation
Demartin et al. arXiv:1504.00611

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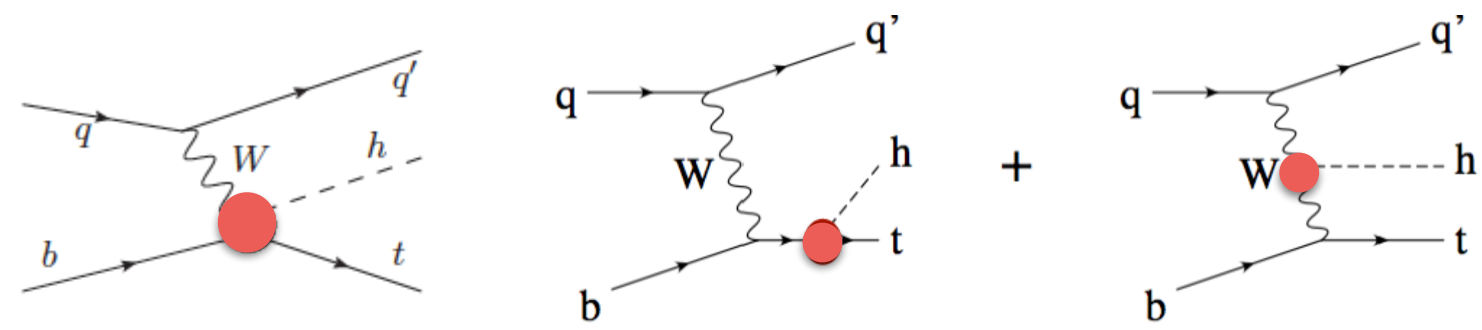
single top+Higgs in the EFT



operator	tH jinter	tH jsquare
$\mathcal{O}_{\phi W}$	0.00693	0.00439
$\mathcal{O}_{\phi D}$	-0.0012	0.0000091
$\mathcal{O}_{\phi WB}$	0.00319	0.000150
$\mathcal{O}_{t\phi}$	-0.00105	0.000485
$\mathcal{O}_{tW}$	0.00872	0.0108
$\mathcal{O}^{(3)}_{\phi dQL}$	-0.000449	0.000552
$\mathcal{O}^{(3)}_{\phi dq}$	-0.00169	0.00233

Higgs weak boson couplings

Top Yukawa

Top weak couplings

$$\mathcal{O}_{\phi D} = \left(\phi^\dagger D_\mu \phi\right)^\dagger \left(\phi^\dagger D^\mu \phi\right)$$

$$\mathcal{O}_{\phi W} = \left(\phi^\dagger \phi - \tfrac{v^2}{2}\right) W_i^{\mu\nu} W^i_{\mu\nu}$$

$$\mathcal{O}_{\phi WB} = \left(\phi^\dagger W^{\mu\nu} \phi\right) B_{\mu\nu}$$

$$\mathcal{O}_{t\phi} = \left(\phi^\dagger \phi - \frac{v^2}{2}\right) \bar{Q}_L t_R \tilde{\phi}$$

$$\mathcal{O}_{tW} = Q_L \sigma_{\mu\nu} W^{\mu\nu} t_R \phi,$$

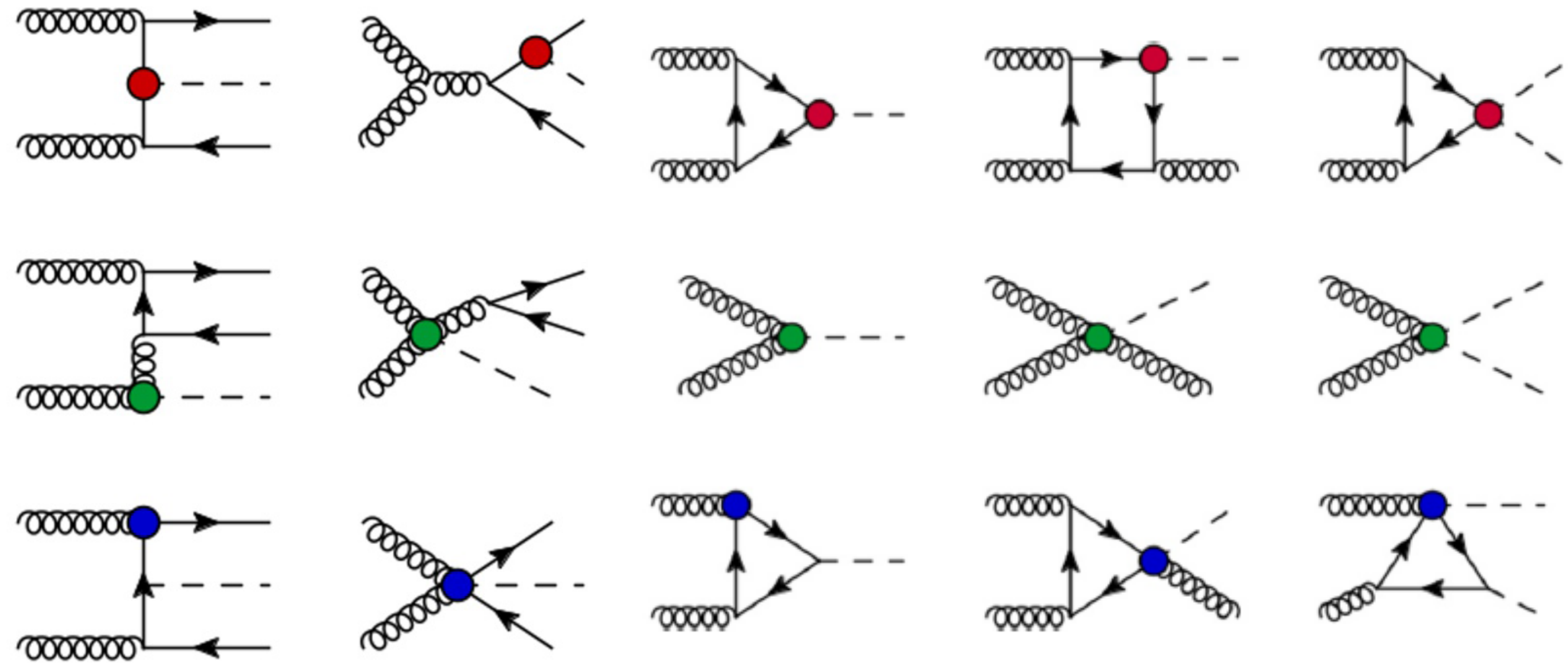
$$\mathcal{O}^{(3)}_{\phi dq} = i\left(\phi^\dagger i \overleftrightarrow{D}^i_\mu \phi\right) \bar{q}_L \gamma^\mu \sigma^i q_L$$

$$\mathcal{O}^{(3)}_{\phi dQ_L} = i\left(\phi^\dagger i \overleftrightarrow{D}^i_\mu \phi\right) \bar{Q}_L \gamma^\mu \sigma^i Q_L$$

NLO QCD computation including all operators in progress:
Degrande, Maltoni, Mimasu, EV, Zhang

Top and Higgs

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



ttH

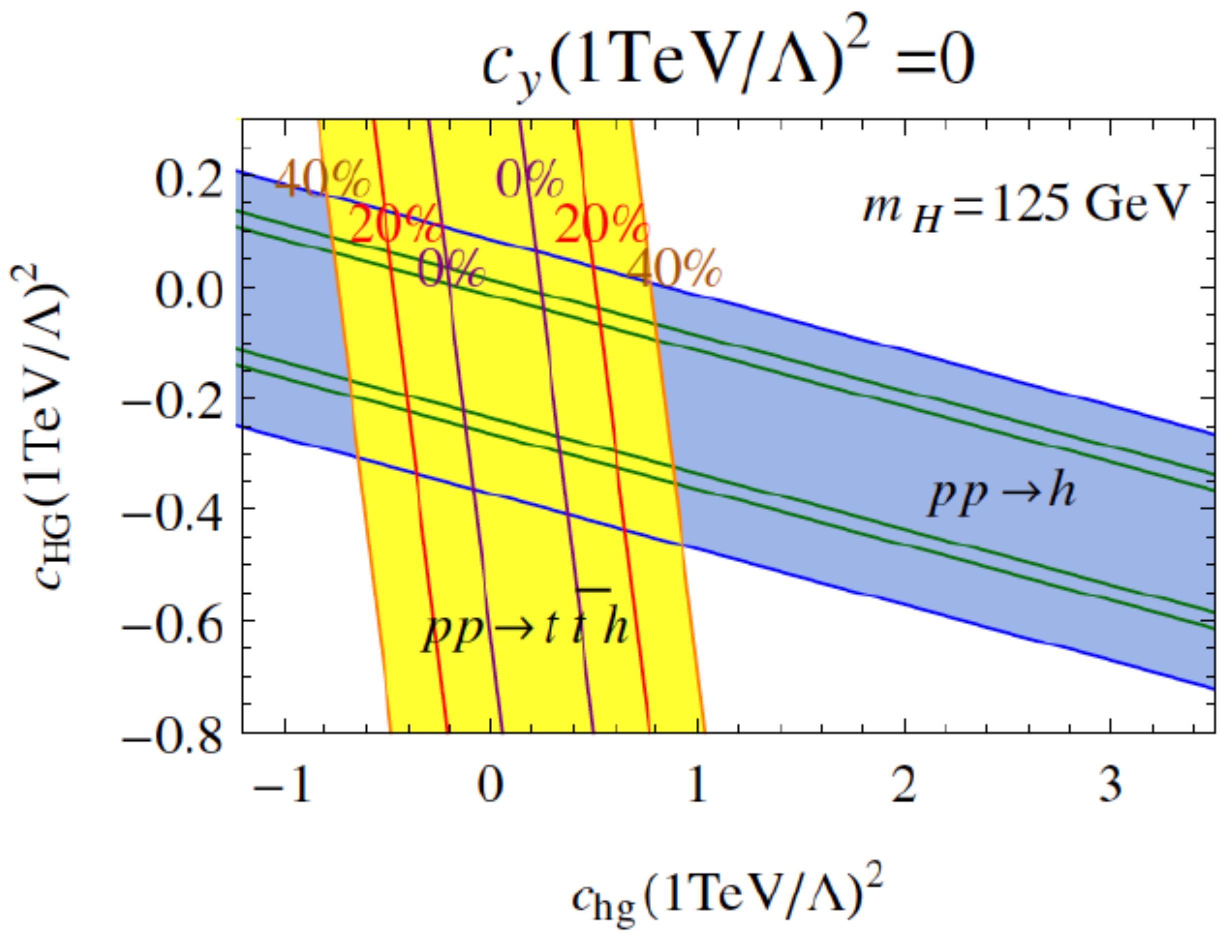
H, H+j, HH

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

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

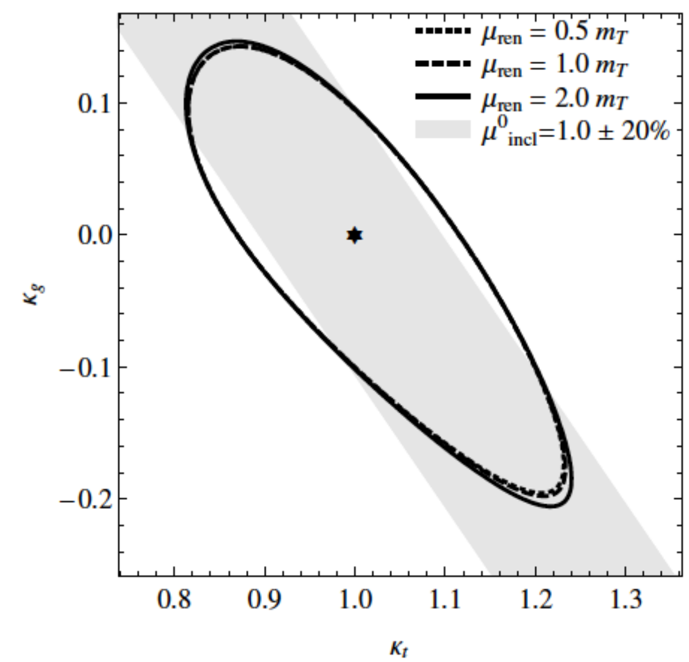
Maltoni, EV, Zhang: arXiv:1607.05330

Breaking the degeneracy between $O_{\phi G}$ and $O_{t\phi}$

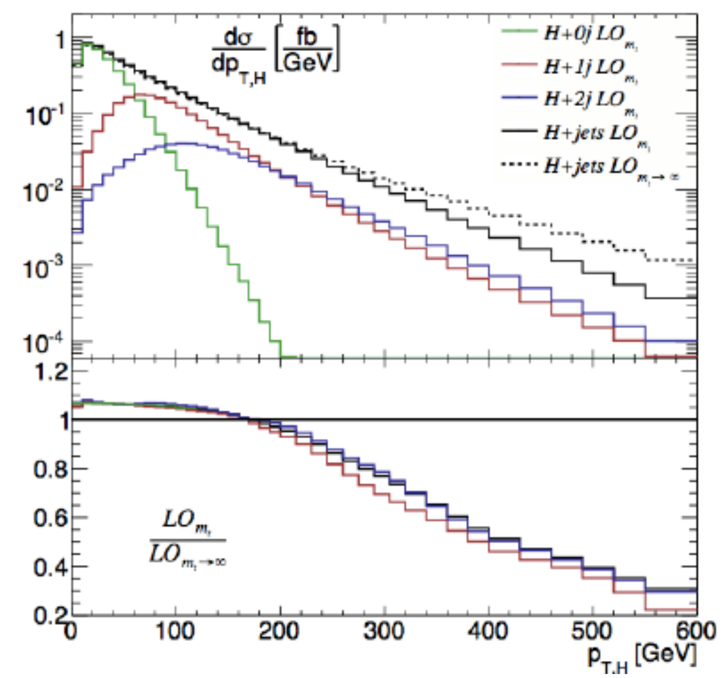


Degrande et al 1205.1065

Use ttH



Grojean et al 1312.3317

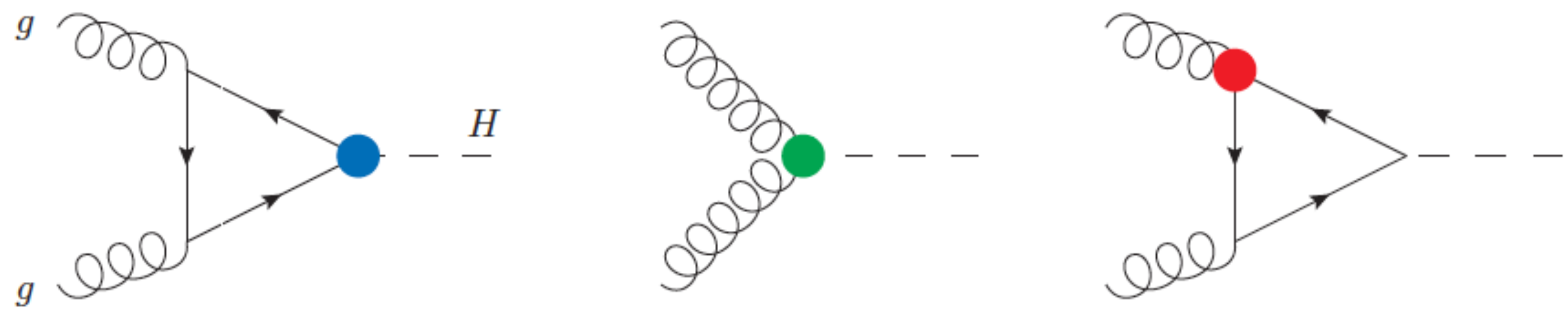


Buschmann et al arXiv:1410.5806

Use boosted Higgs

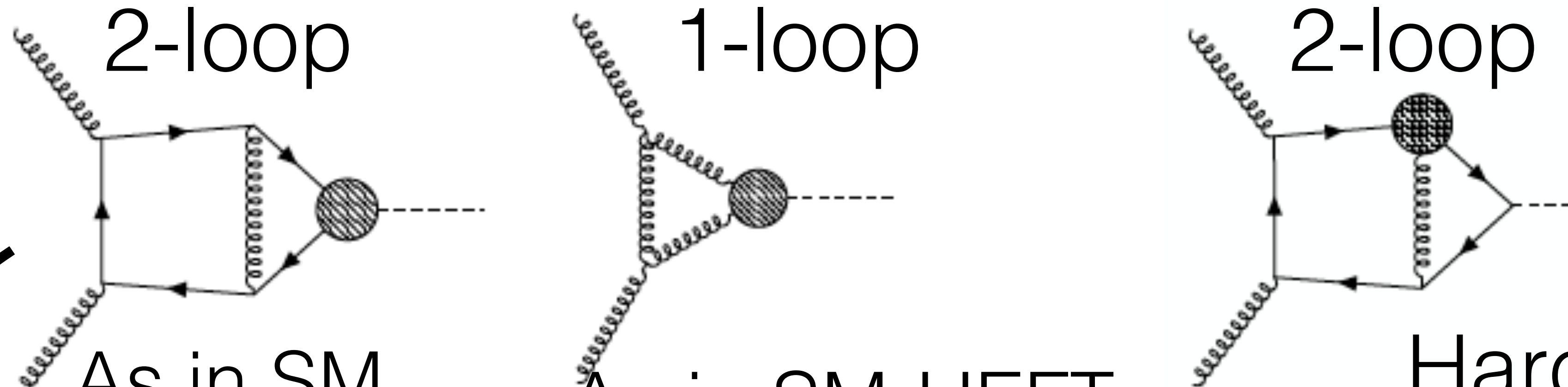
SMEFT in single Higgs production

LO:



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

NLO: 2-loop 1-loop 2-loop



As in SM

As in SM-HEFT

Harder

but master integrals known

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

Deutschmann, Duhr, Maltoni, EV arXiv: 1708.00460

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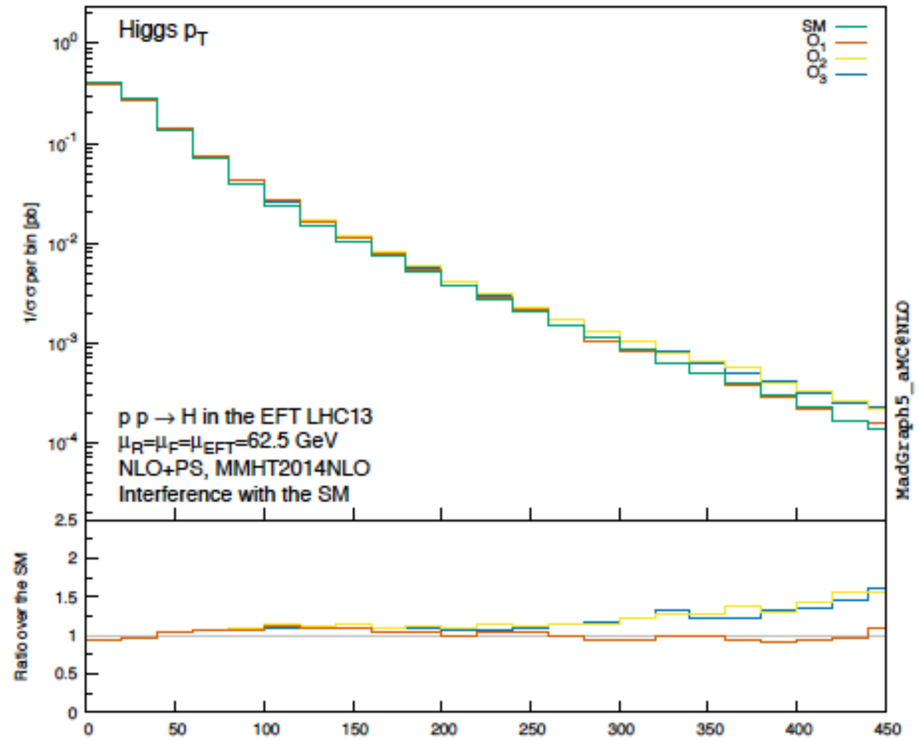
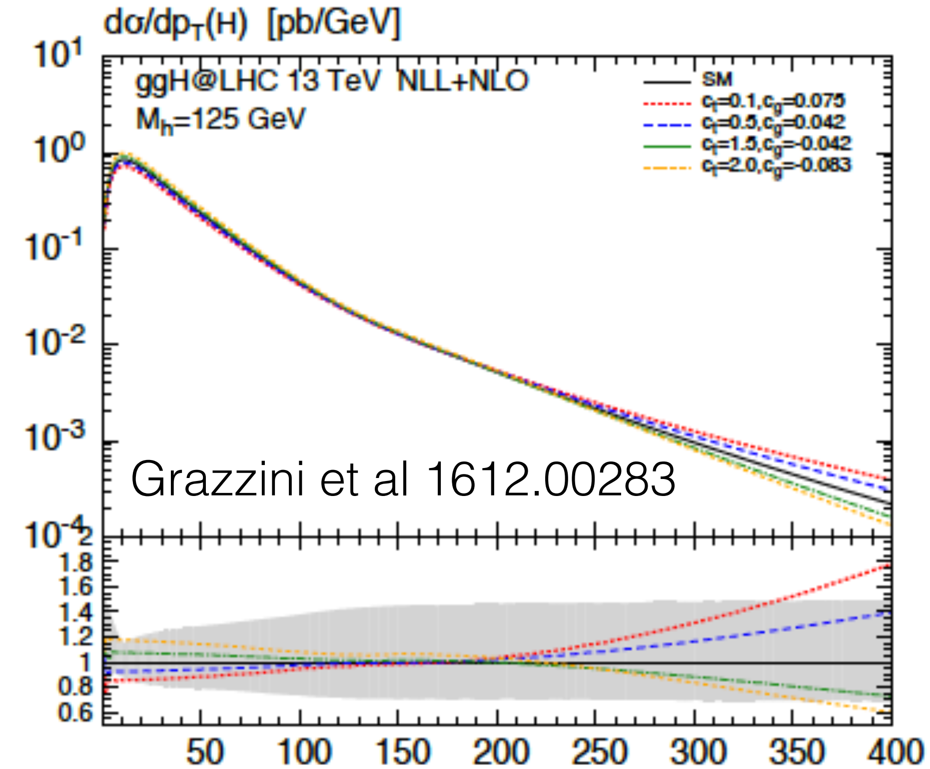
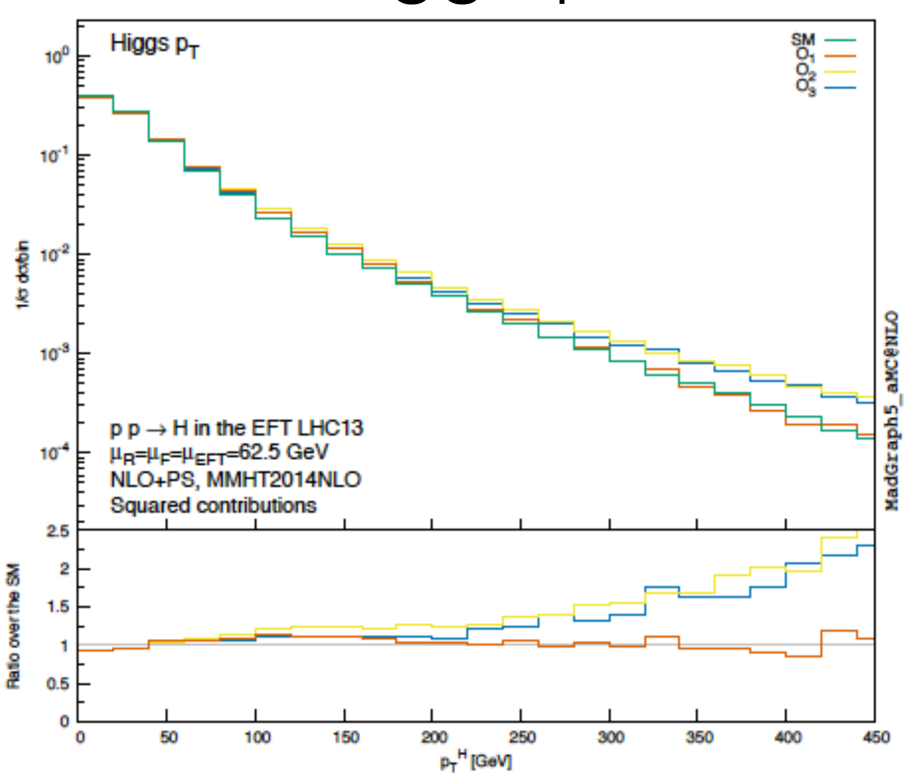
SMEFT in Higgs production

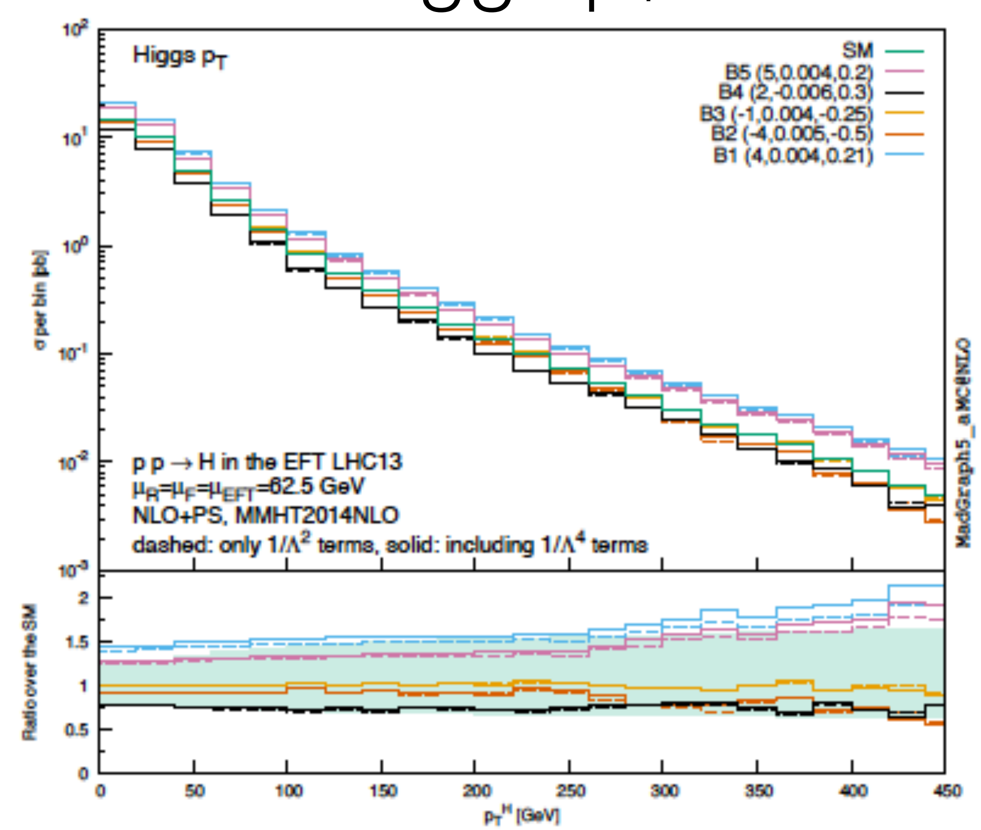




Higgs p$_T$

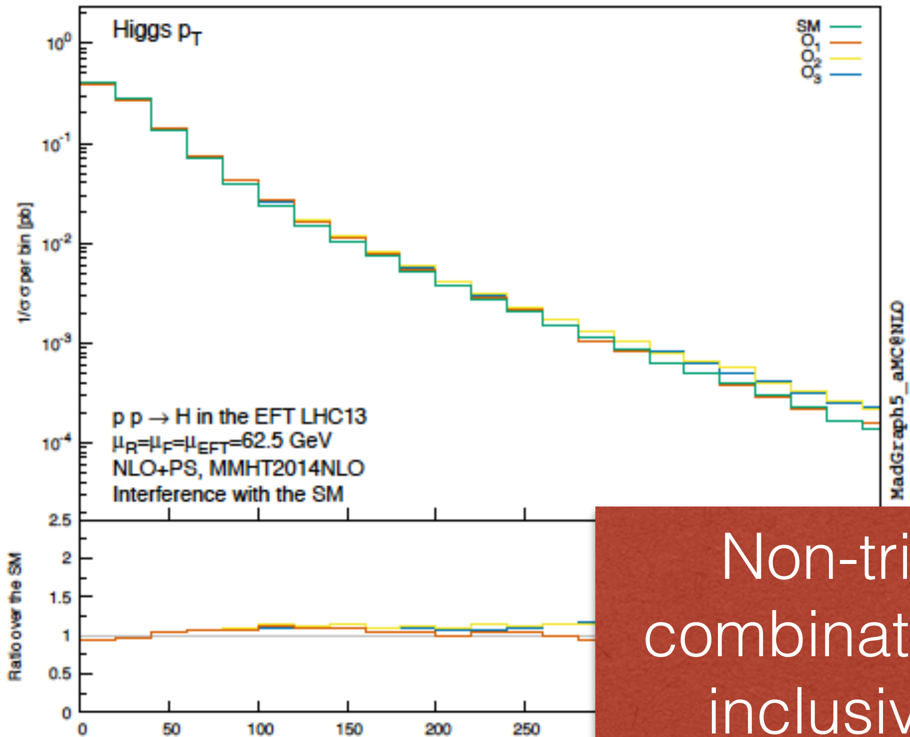
Higgs p$_T$

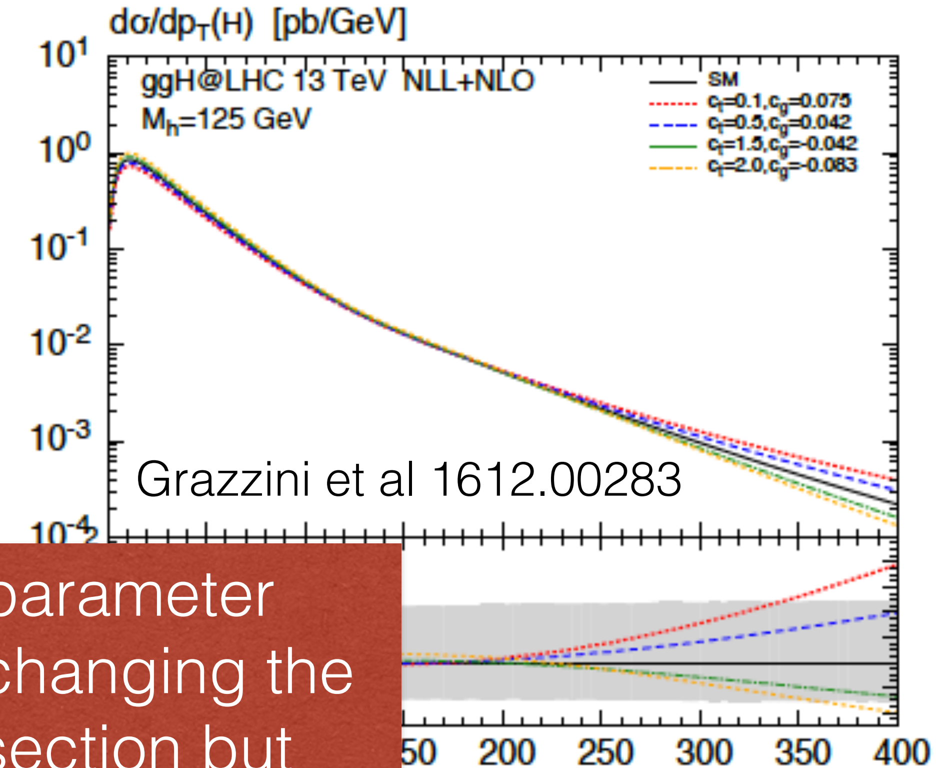




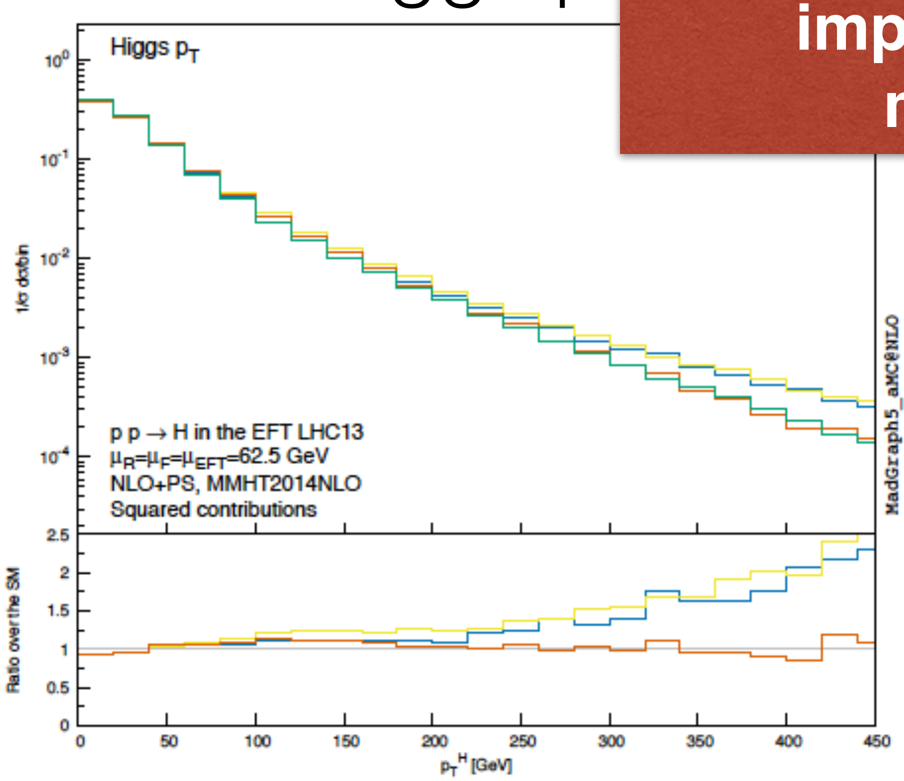
Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

SMEFT in Higgs production

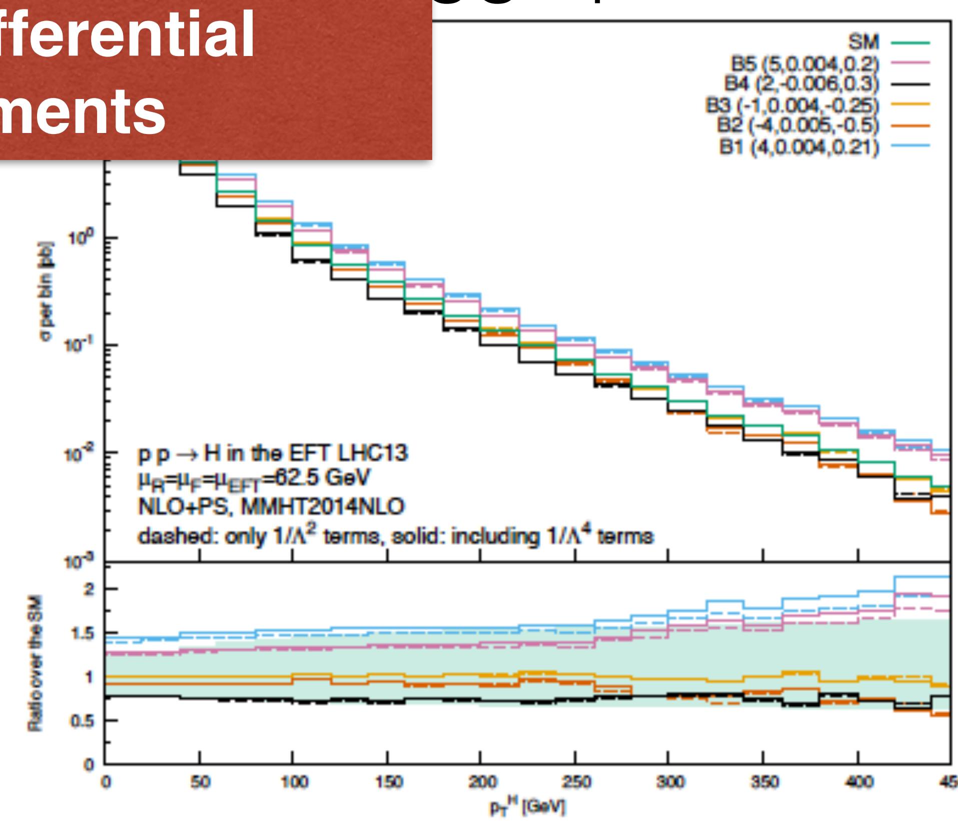




Higgs p_T



...ggs p_T

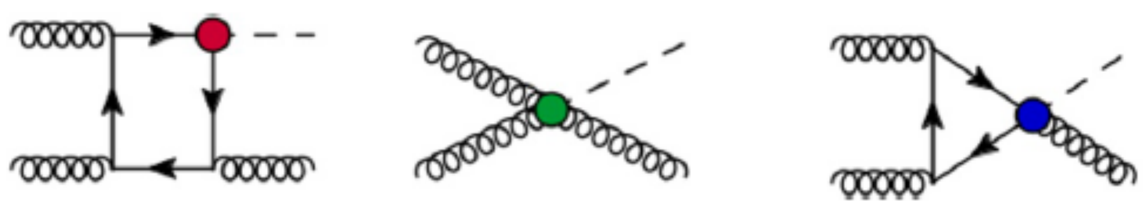


Non-trivial EFT parameter combinations not changing the inclusive cross-section but changing the distributions: **impact of differential measurements**

E.Vryonidou

Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

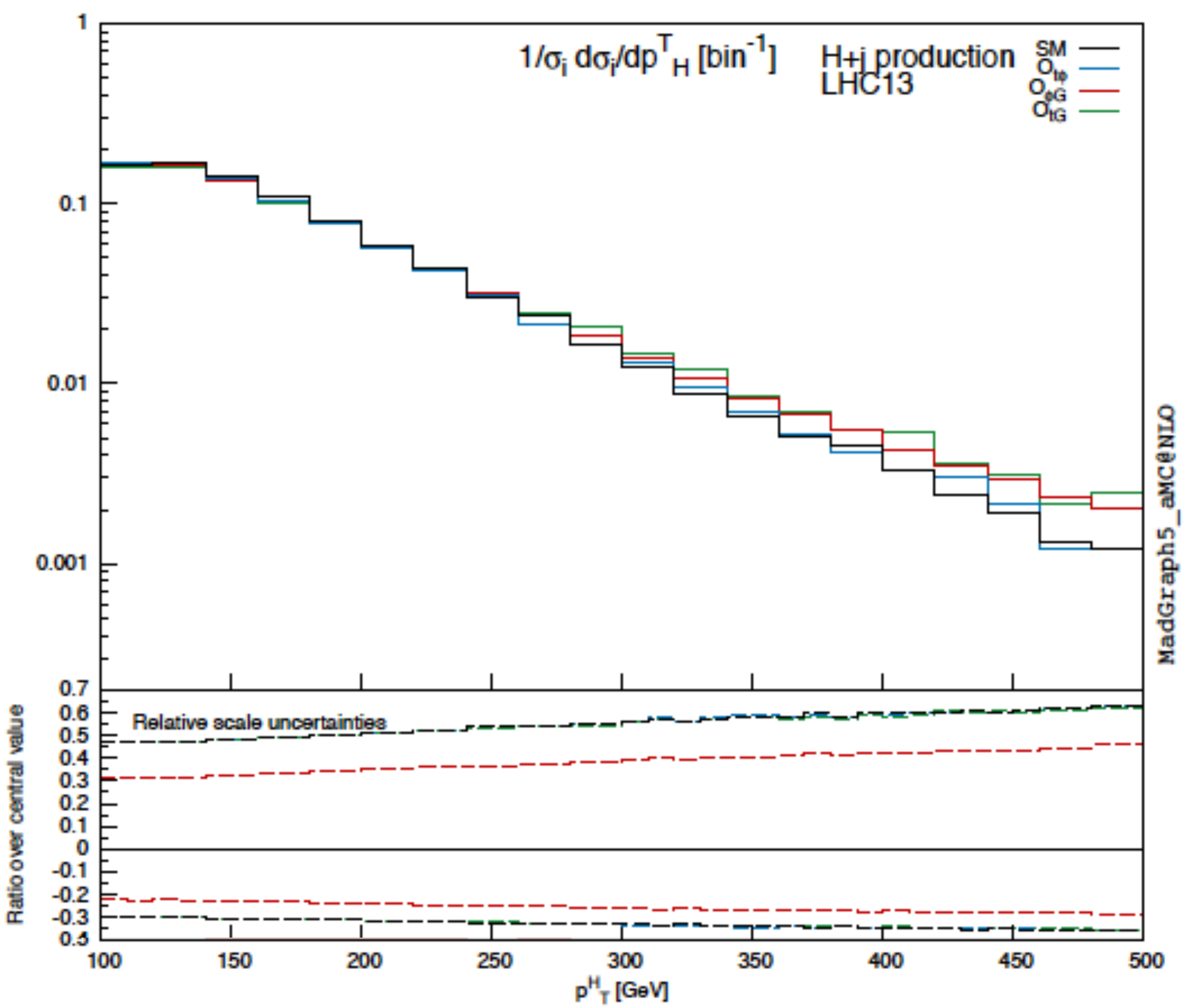
SMEFT in H+j

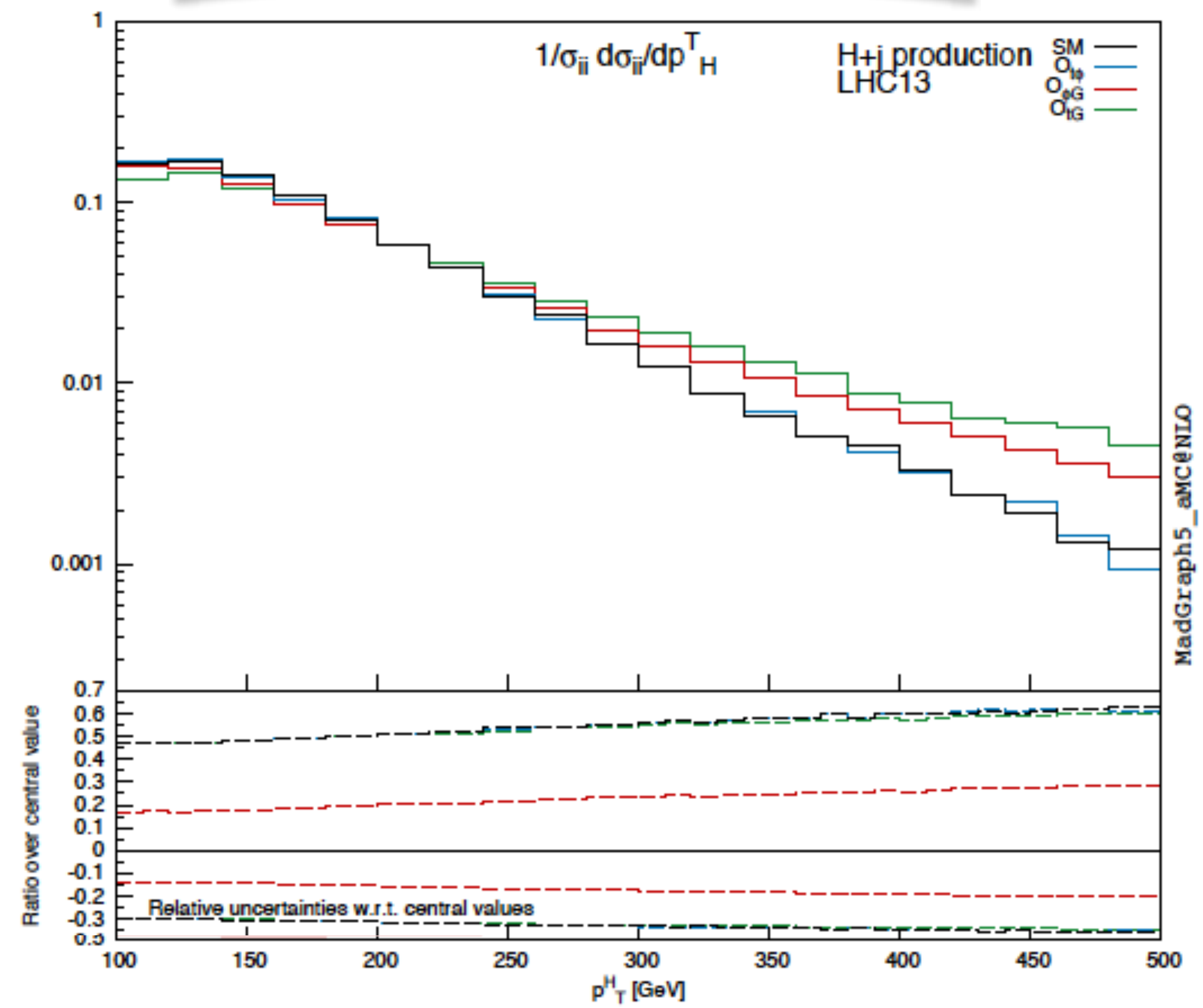


$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right) \left(\bar{Q}t\right) \tilde{\phi}$$

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

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





Harder tails from dim-6 operators: Boosted analysis

Maltoni, EV, Zhang: arXiv:1607.05330

An application: Constraints on the Wilson coefficients

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

Toy χ^2 fit for illustrative purposes using: single H, ttH Run I and Run II results
Impact of the 3 operators also included in Higgs decays

	Individual	Marginalised	C_{tG} fixed
$C_{t\phi}/\Lambda^2$ [TeV^{-2}]	[-3.9,4.0]	[-14,31]	[-12,20]
$C_{\phi G}/\Lambda^2$ [TeV^{-2}]	[-0.0072,-0.0063]	[-0.021,0.054]	[-0.022,0.031]
C_{tG}/Λ^2 [TeV^{-2}]	[-0.68,0.62]	[-1.8,1.6]	

95% c.l.

typically C_{tG}=0 in Higgs analyses

- Individual limit on C_{tG} comparable to the one from top pair production-room to improve with ttH measurement in run II
- Including the chromomagnetic operator leaves much more space to the other two operators

Need for global analysis

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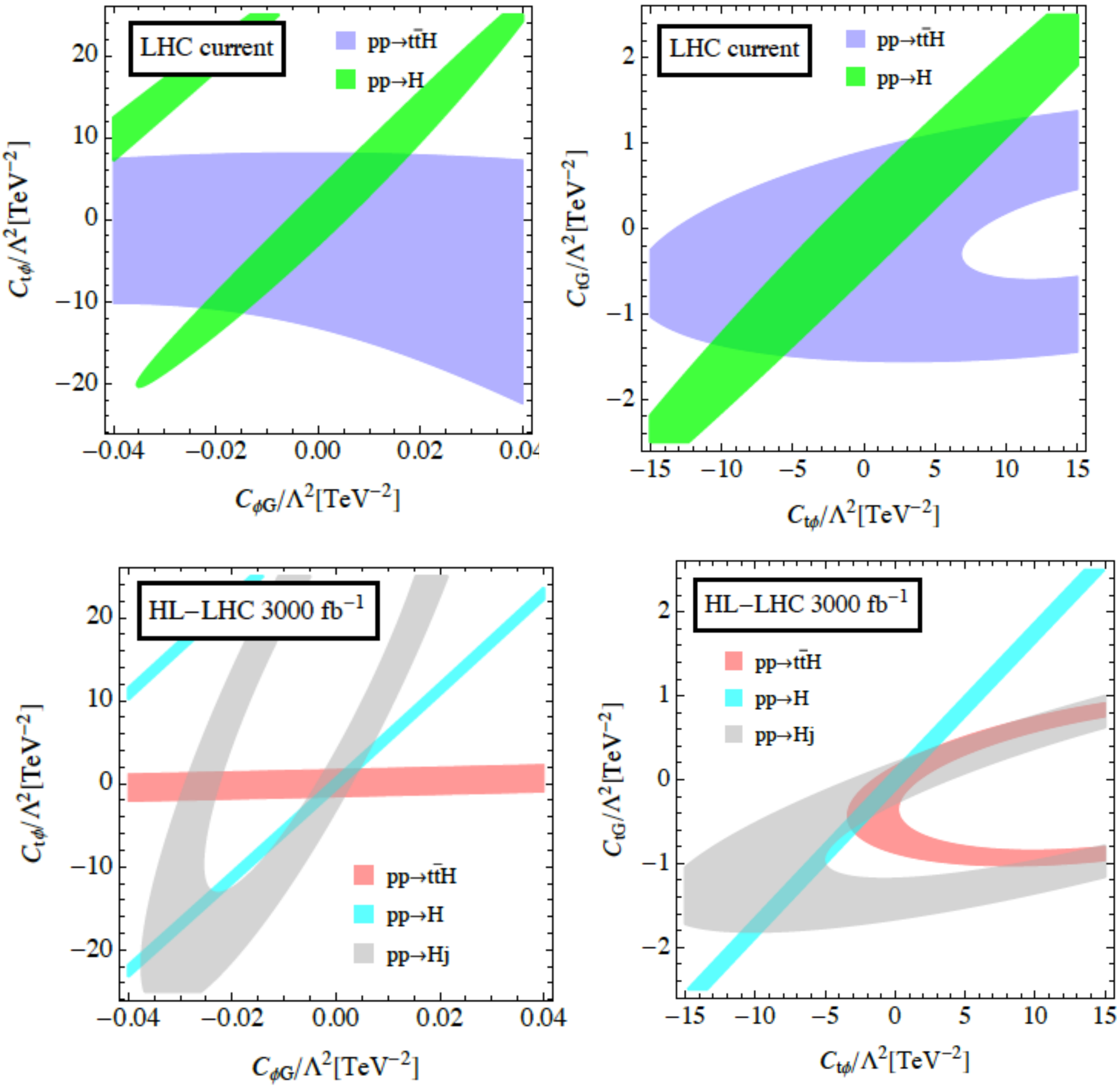
Constraints using two-operator fits



Current limits using LHC measurements

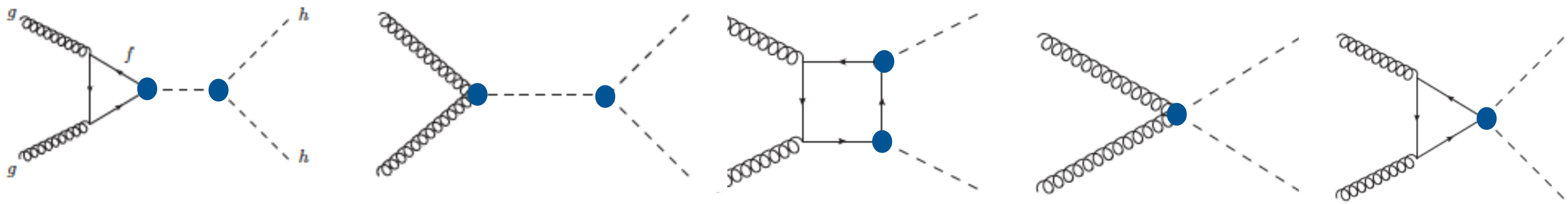
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q}t\right) \tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

14TeV projection 3000 fb^{-1}

Maltoni, EV, Zhang
arXiv:1607.05330

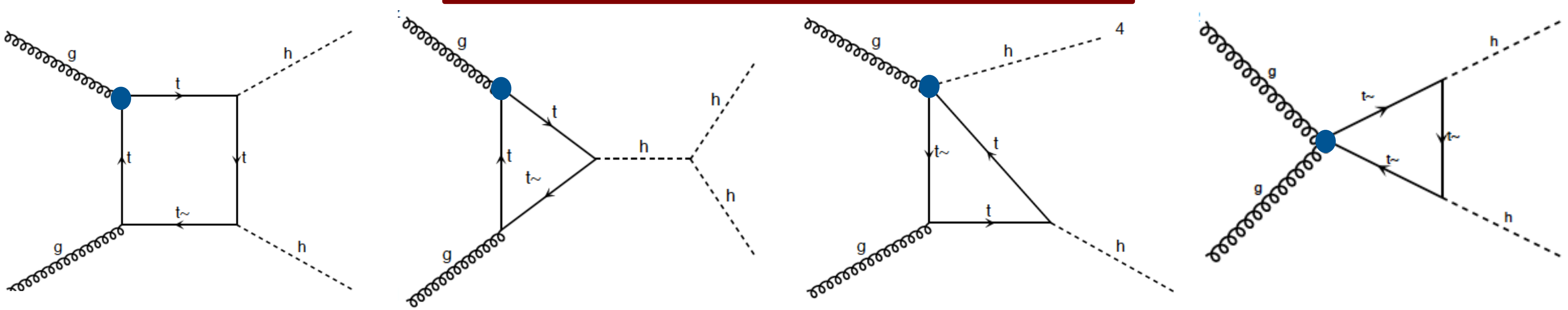
SMEFT in HH

Previously thought of as:



Chromomagnetic operator is also contributing

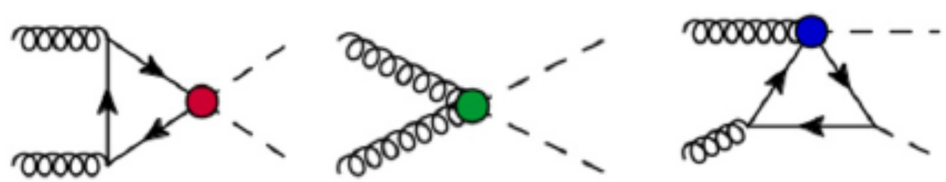
$$\boxed{O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}}$$



Needs to be taken into account in the context of a global EFT analysis for HH

How much does this operator contribute to HH?

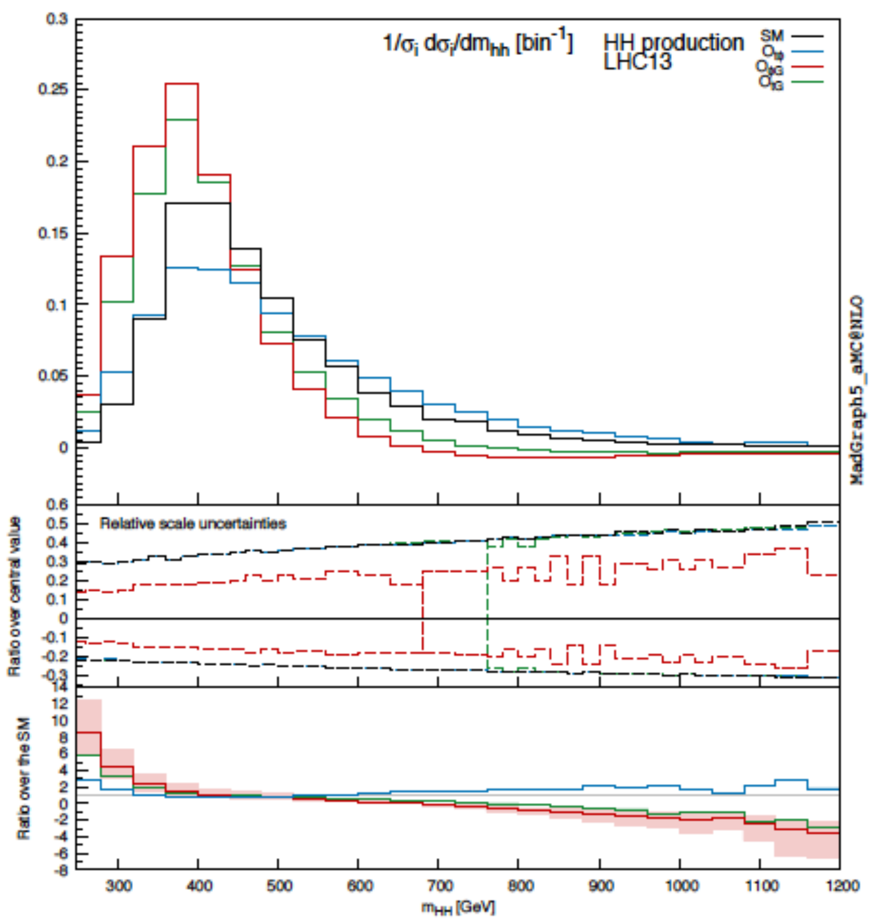
SMEFT in HH

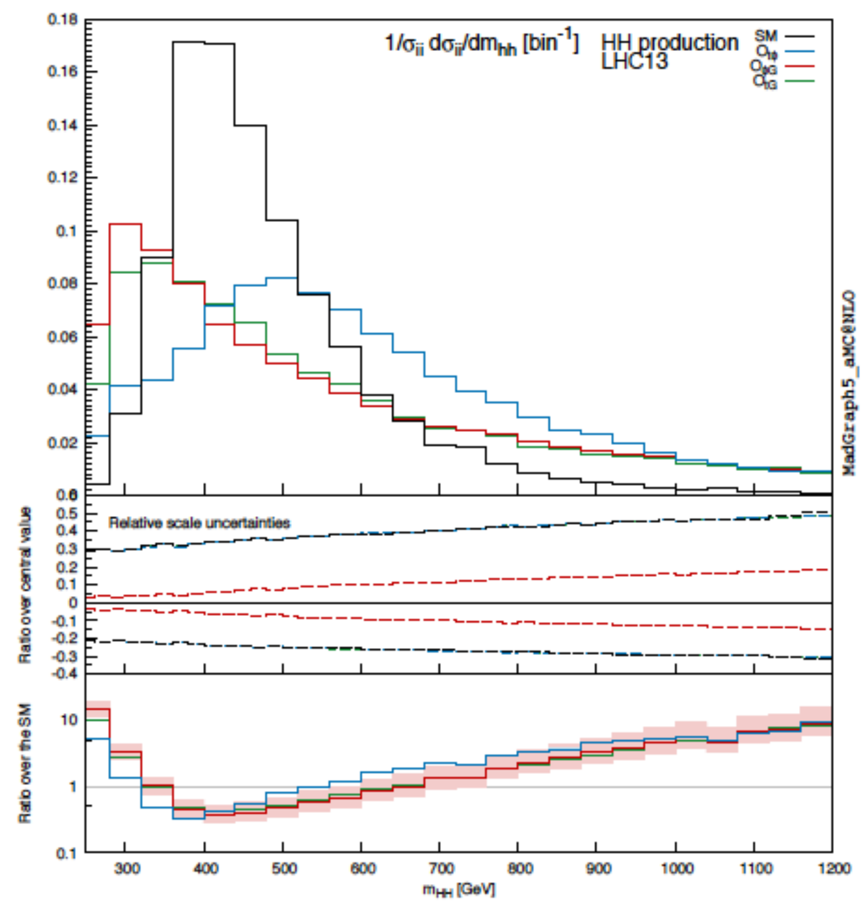


$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q}t\right) \tilde{\phi}$$

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

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





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

Experimental HH analyses with EFT interpretation need to consider:

C_{tG}, $C_{\phi G}$, $C_{t\phi}$, C_H, C_6

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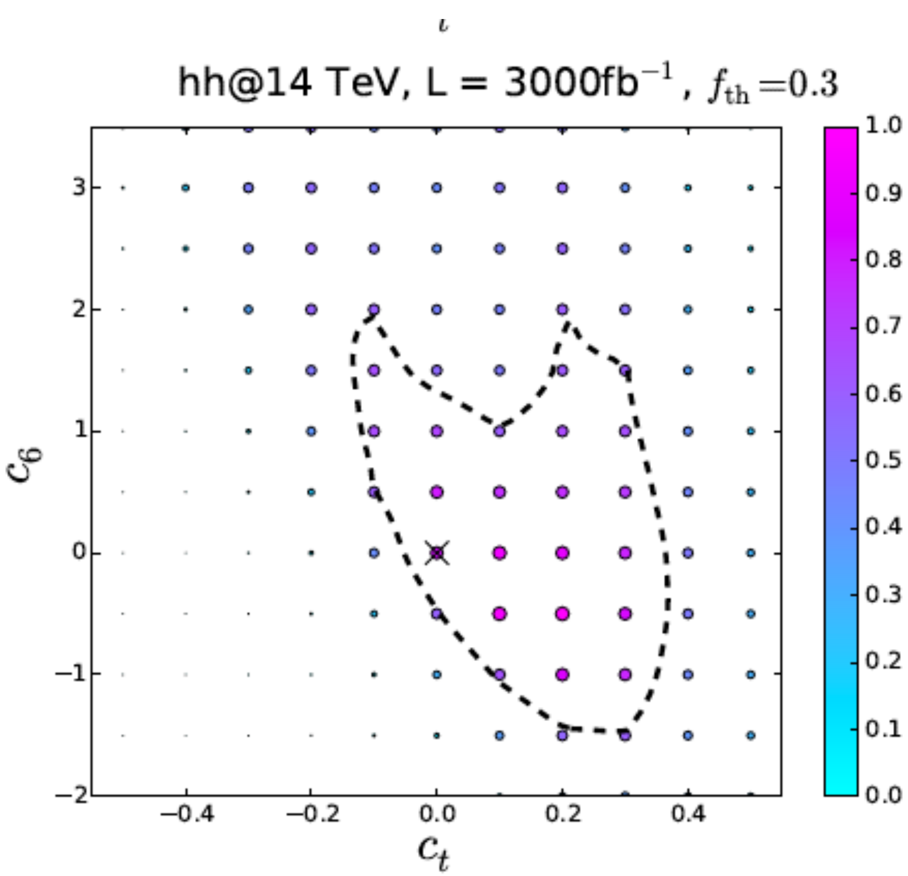
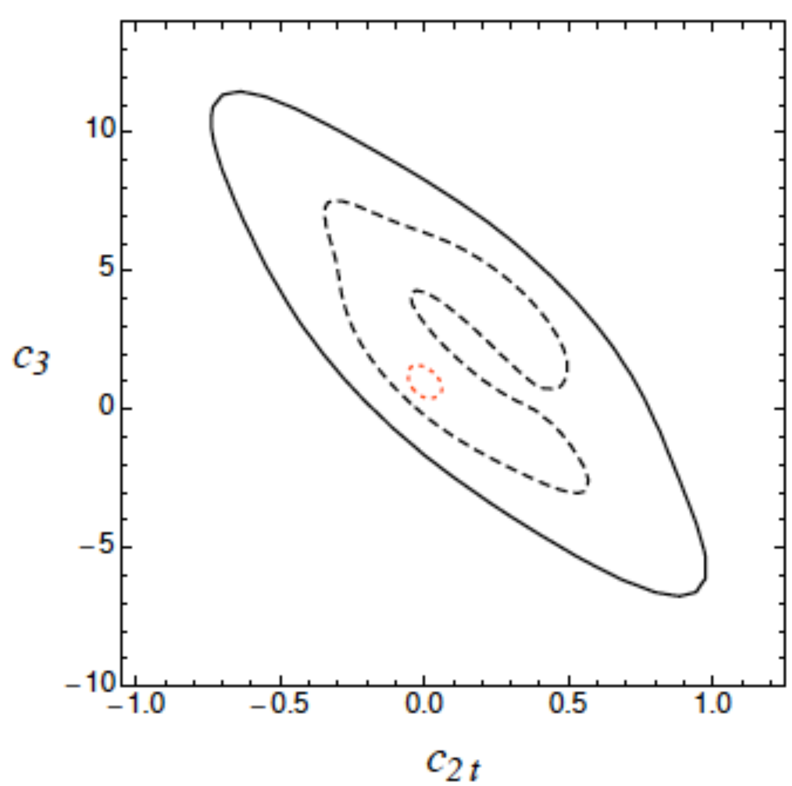
Results of previous HH EFT pheno studies





Prospects for HL-LHC

Goertz et al arxiv:1410.3471
focussing on bbττ

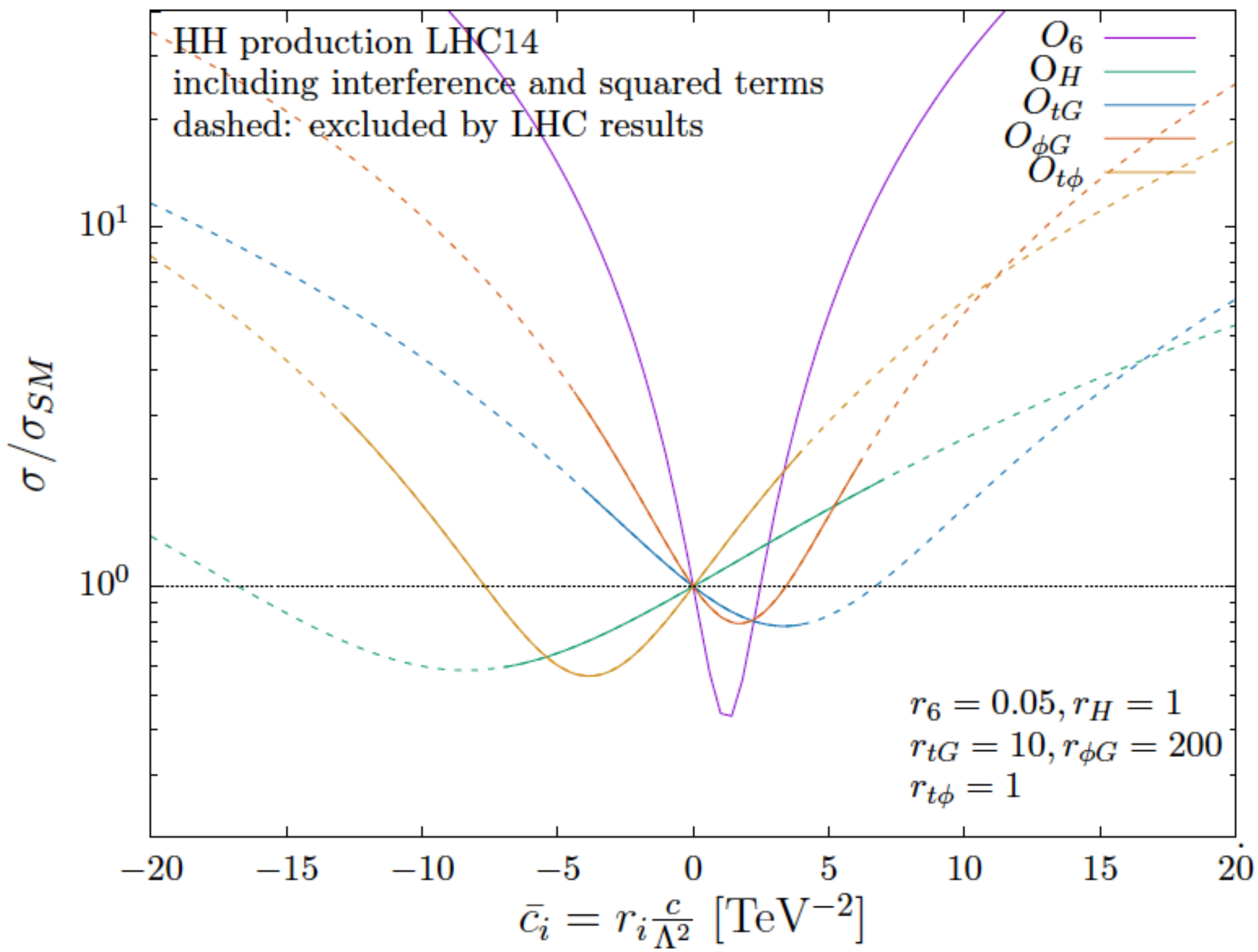
model	$L = 600$ fb^{-1}	$L = 3000$ fb^{-1}
c_6-only	$c_6 \in (-0.5, 0.8)$	$c_6 \in (-0.4, 0.4)$
full	$c_6 \gtrsim -1.3$	$c_6 \gtrsim -1.2$
$c_6 - c_t - c_\tau - c_b$	$c_6 \gtrsim -2.0$	$c_6 \in (-1.8, 2.3)$

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

Prospects for c_6:

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

How will O_{tG} affect the HH EFT analyses?



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

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

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

$$O_6 = -\lambda(\phi^\dagger \phi)^3 \qquad \kappa_\lambda = 1 - c_H \frac{3v^2}{2\Lambda^2} + c_6 \frac{v^2}{\Lambda^2}$$

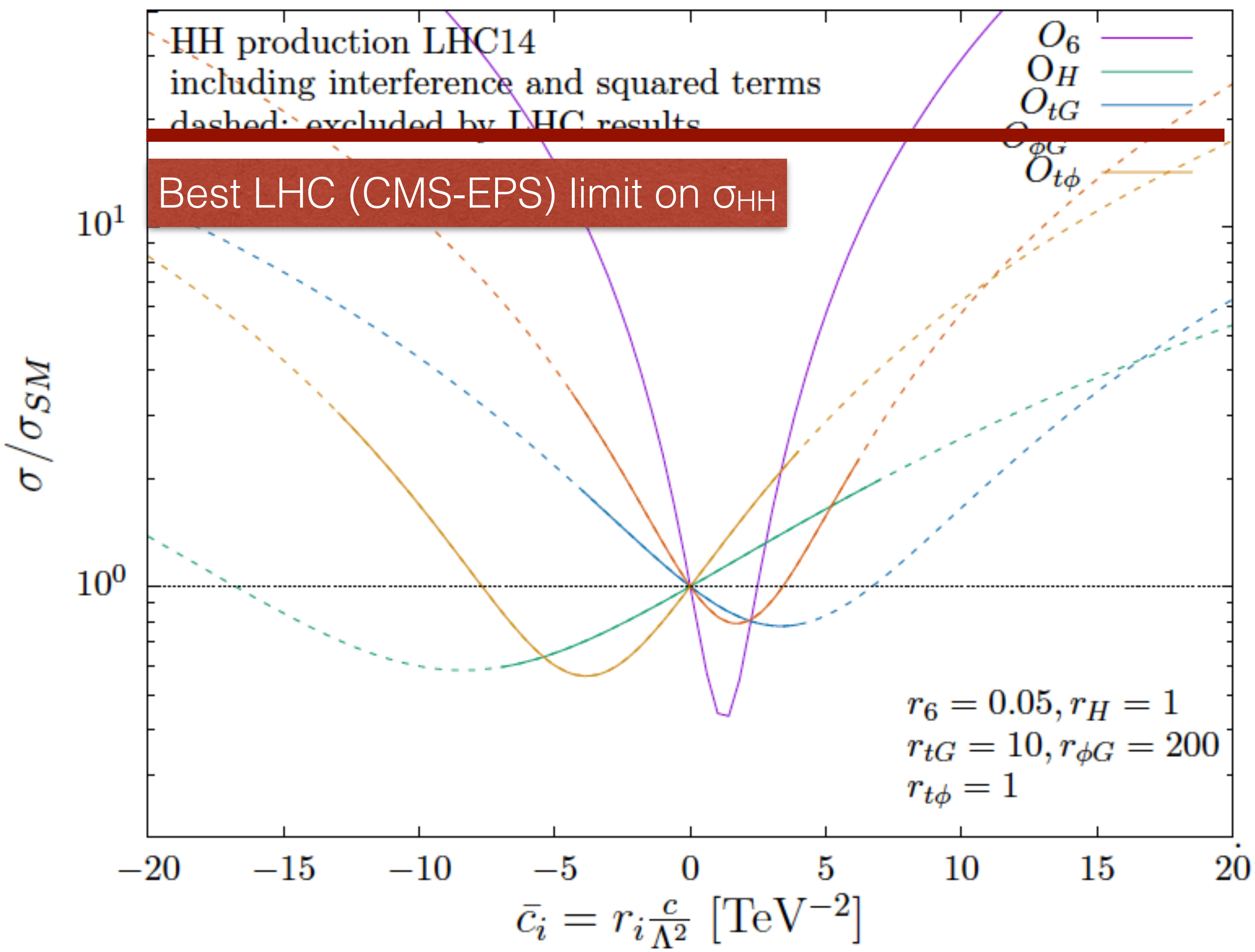
$$O_H = \frac{1}{2}(\partial_\mu(\phi^\dagger \phi))^2$$

5 parameters

- Precise knowledge of other Wilson coefficients will be needed to bound c_6 as the bound gets closer to SM
- Differential distributions will also be necessary

Approximate constraints from single Higgs (e.g. Butter et al arxiv:1604.03105) and top pair production (Franzosi and Zhang arxiv:1503.08841)

How will O_{tG} affect the HH EFT analyses?



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

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5 parameters

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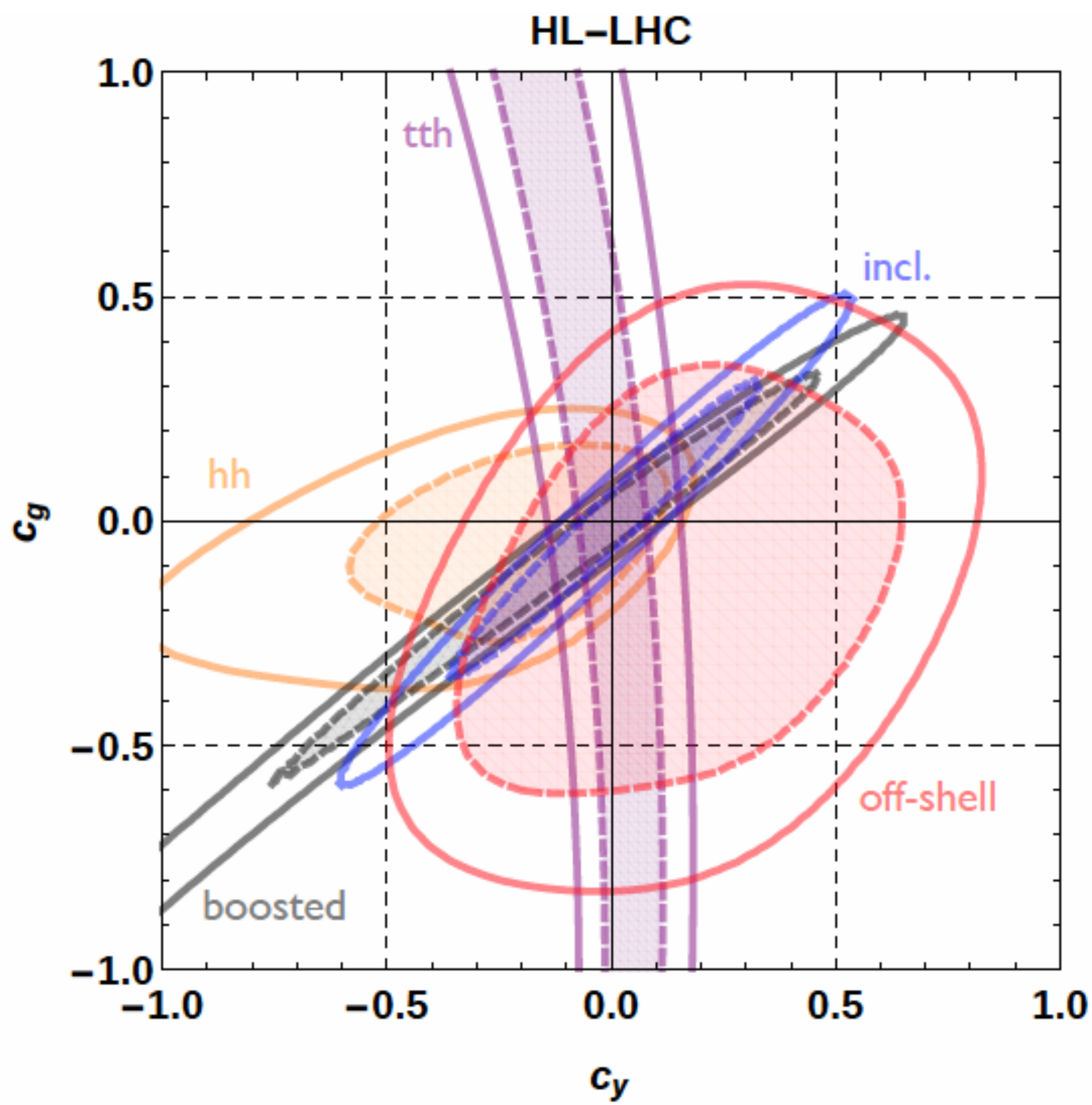
Approximate constraints from single Higgs (e.g. Butter et al arxiv:1604.03105) and top pair production (Franzosi and Zhang arxiv:1503.08841)

How to extract maximal information?

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

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

Combination:
- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs



Azatov et al arXiv:1608.00977

Outlook

- SMEFT a consistent way to look for new interactions
- Higher-order corrections needed to match SM precision and experimental accuracy
- Progress in top-quark processes: pair production, single top, tt+V, tt+H as well as loop-induced processes
- QCD corrections important both for total cross-sections and distributions: SM k-factors are not enough
- Global fits results already available: important to include NLO predictions where available and to combine Higgs and top results to extract maximal information

Thank you for your attention