Precision in EFT studies for top and Higgs physics

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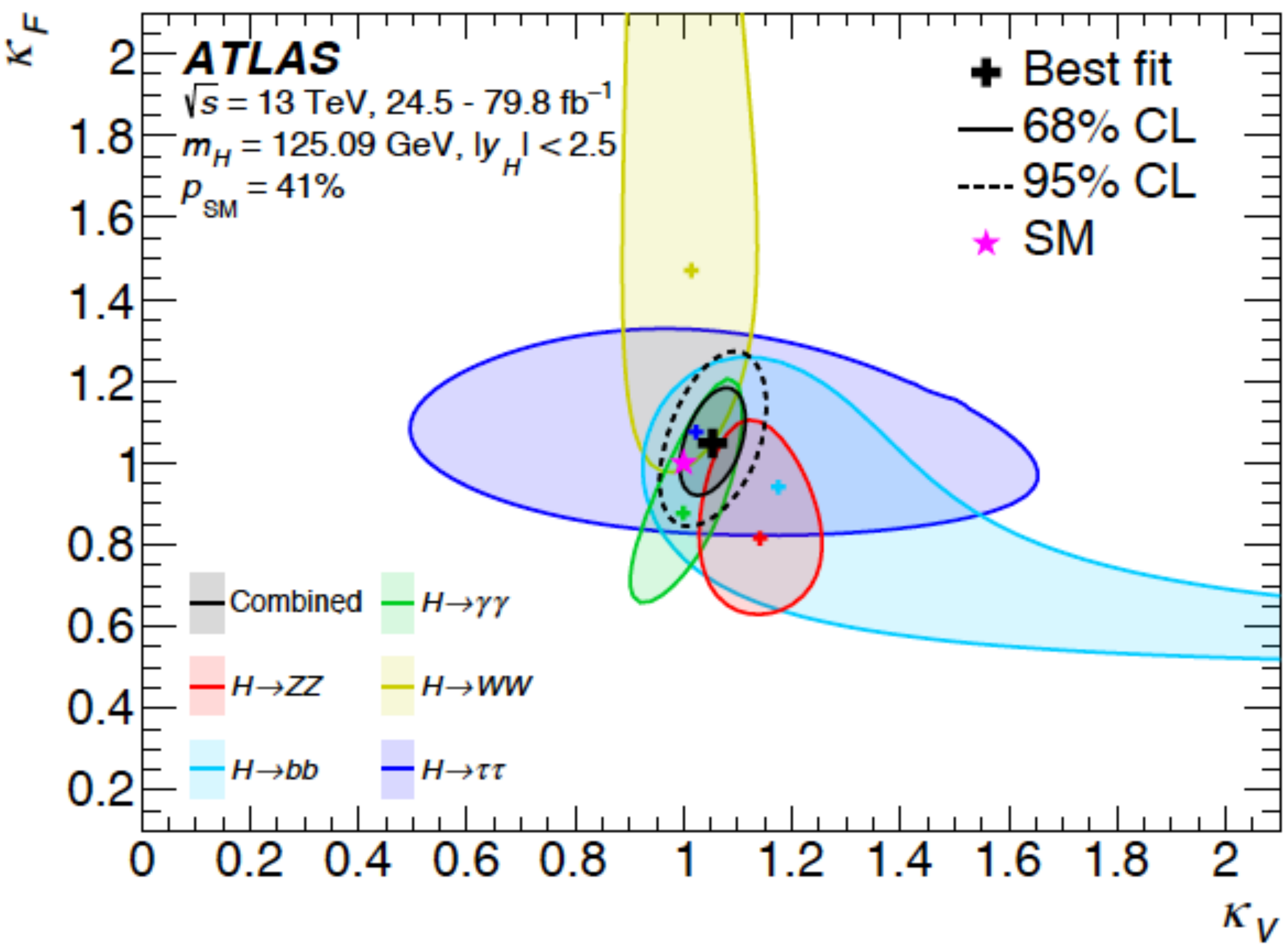
Manchester Bohr Seminar
30/10/20

Outline

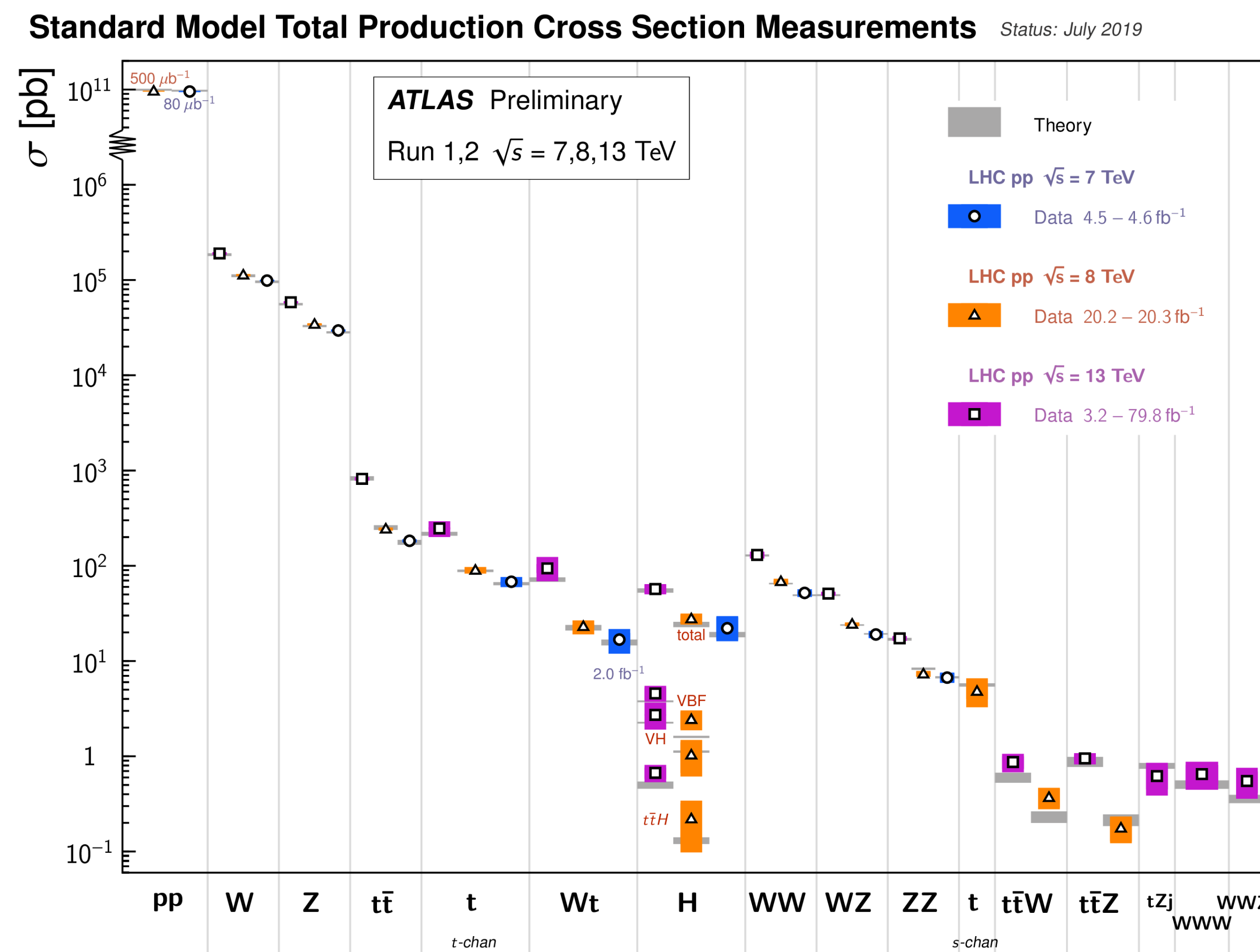
- Introduction to the EFT
- EFT for the LHC
    - Precision calculations in the EFT
- EFT in the top-Higgs sector
    - Global fits in the top sector
    - Towards global fits for top-Higgs

LHC: the story so far

Higgs discovery



Rediscovering the SM



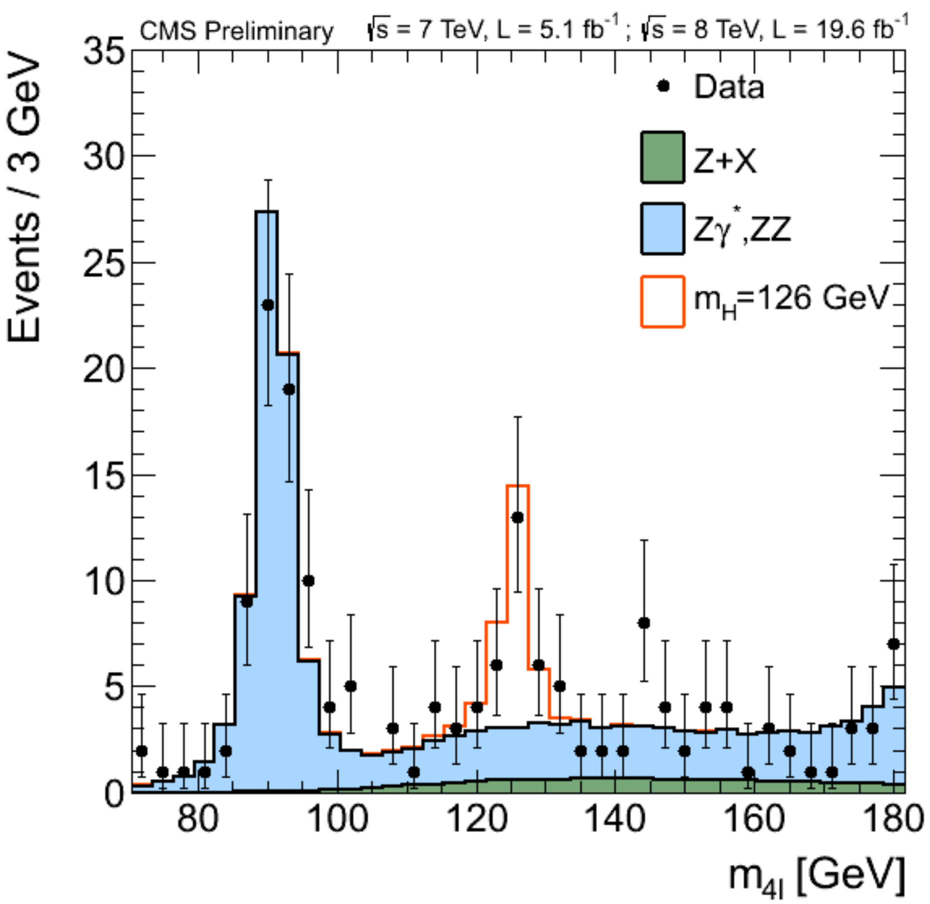
Good agreement with the SM predictions

How to look for new physics?

Model-dependent

SUSY, 2HDM…

New particles



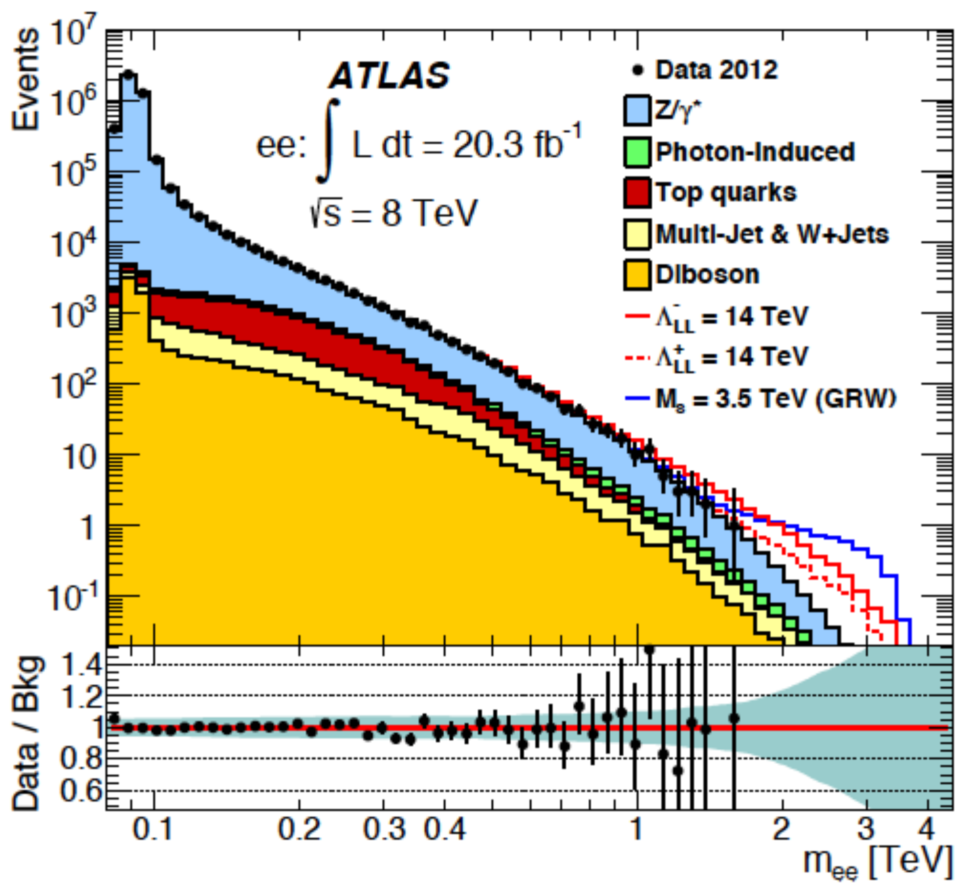
Resonance peaks

Model-Independent

simplified models, EFT

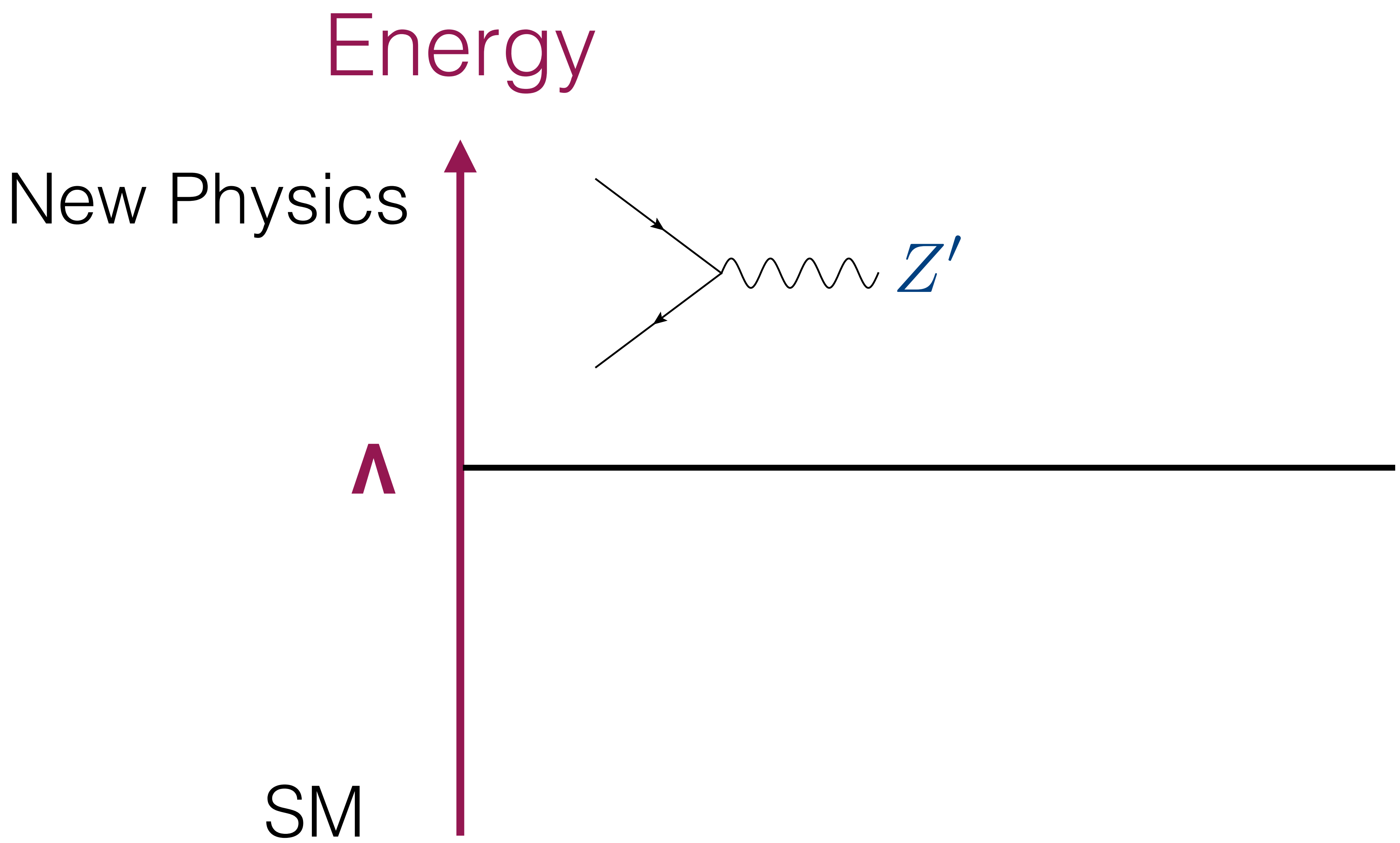
New Interactions of SM particles

anomalous couplings, EFT



Deviations in tails

SMEFT: What is it all about?



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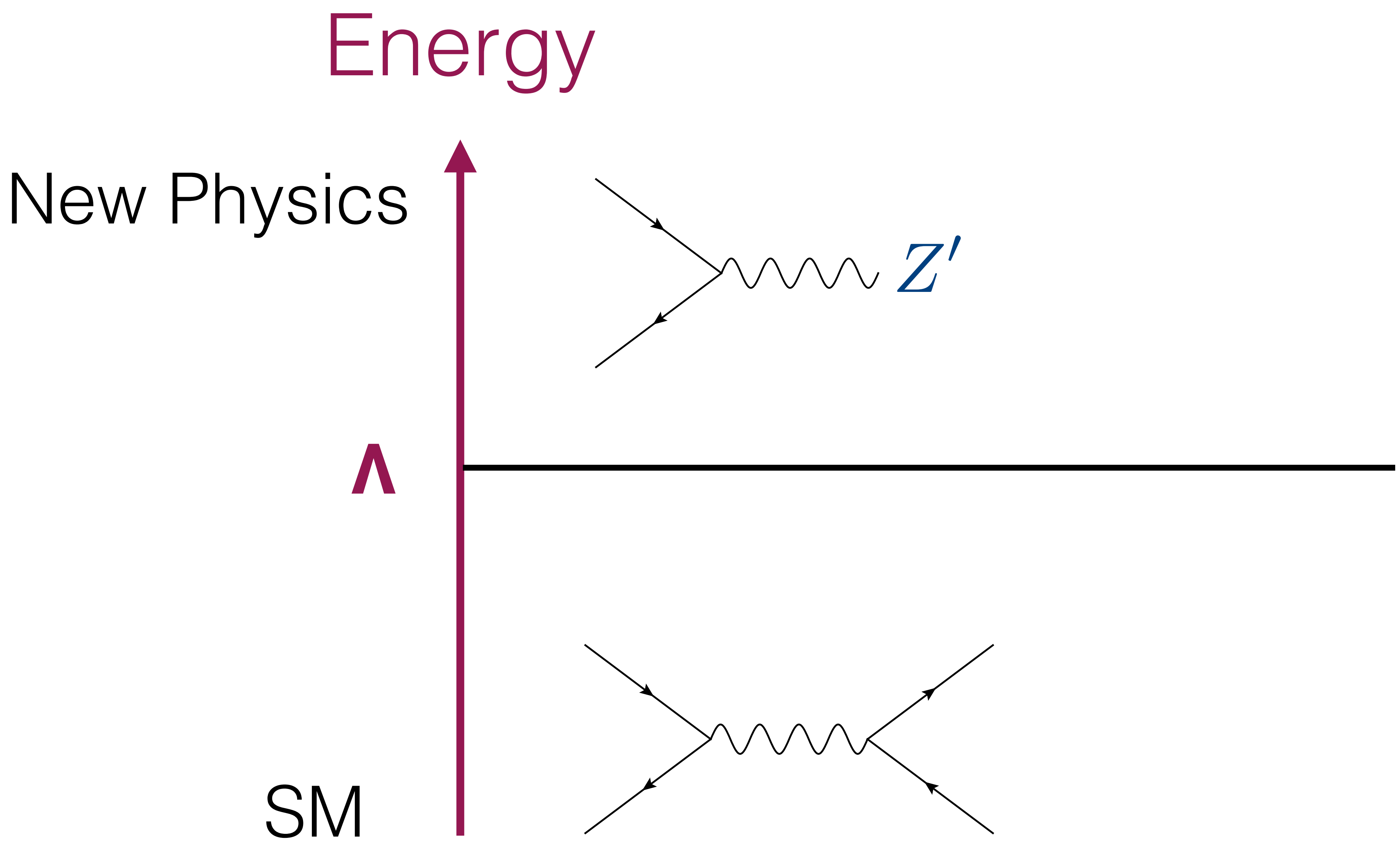

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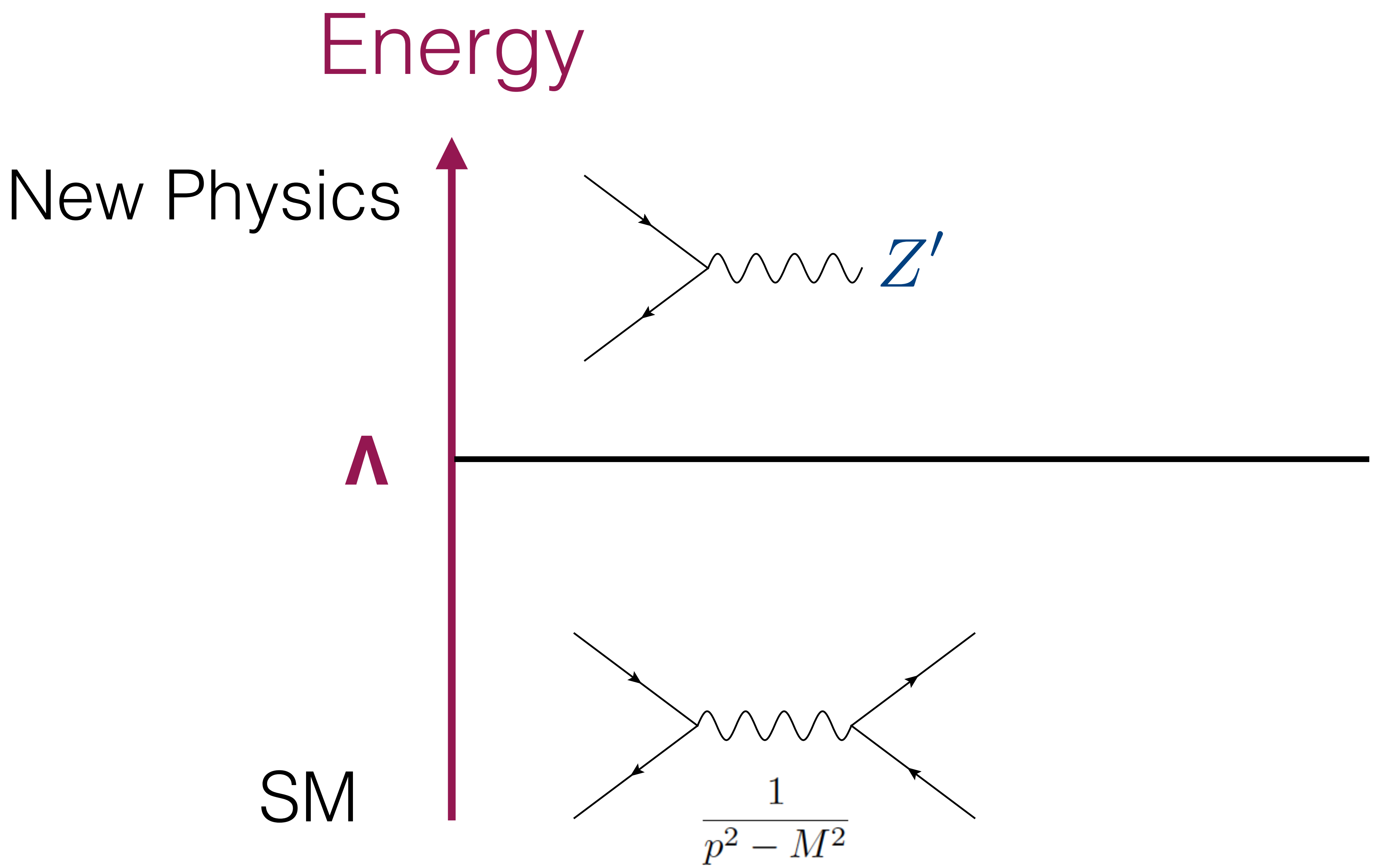

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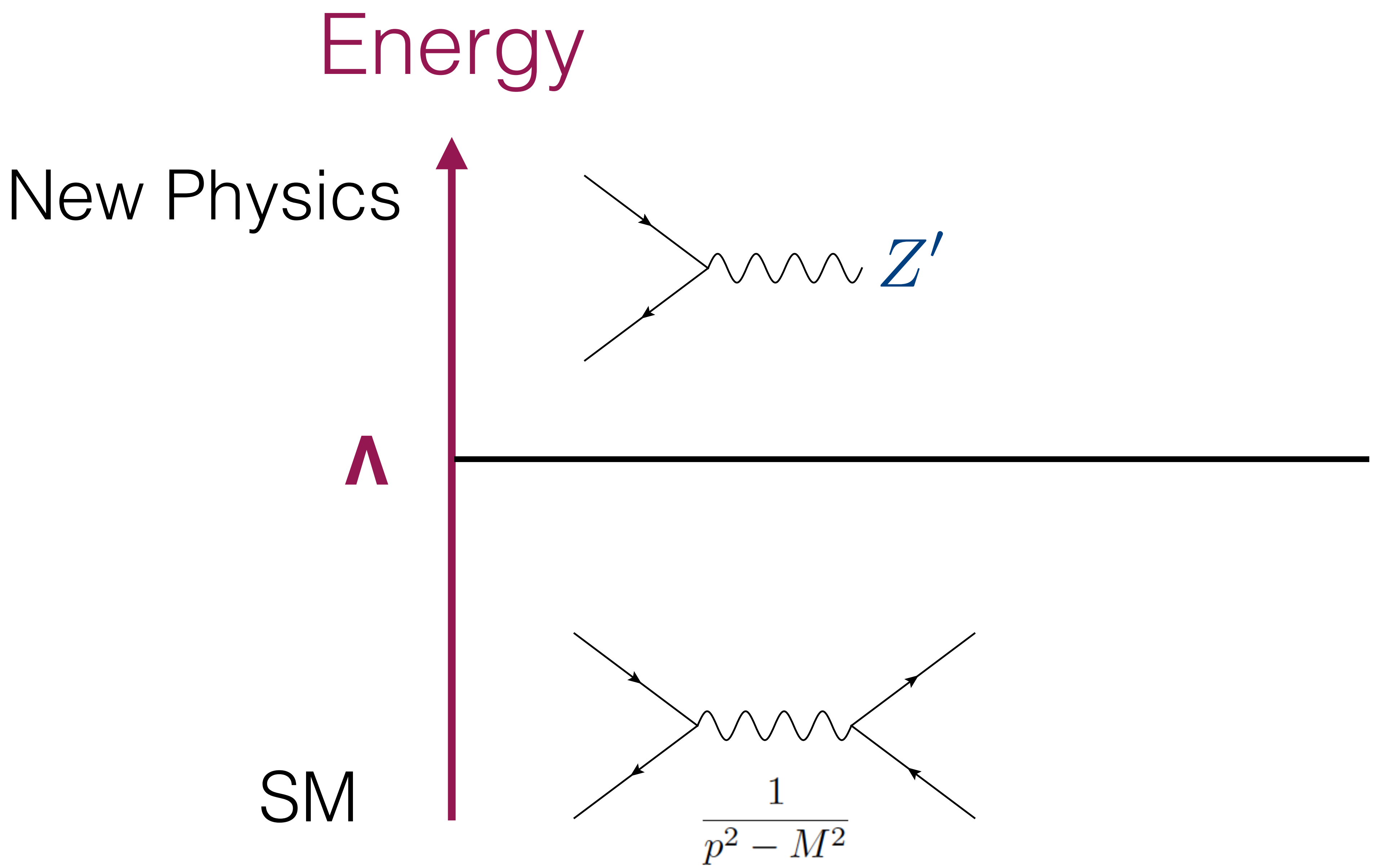

$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

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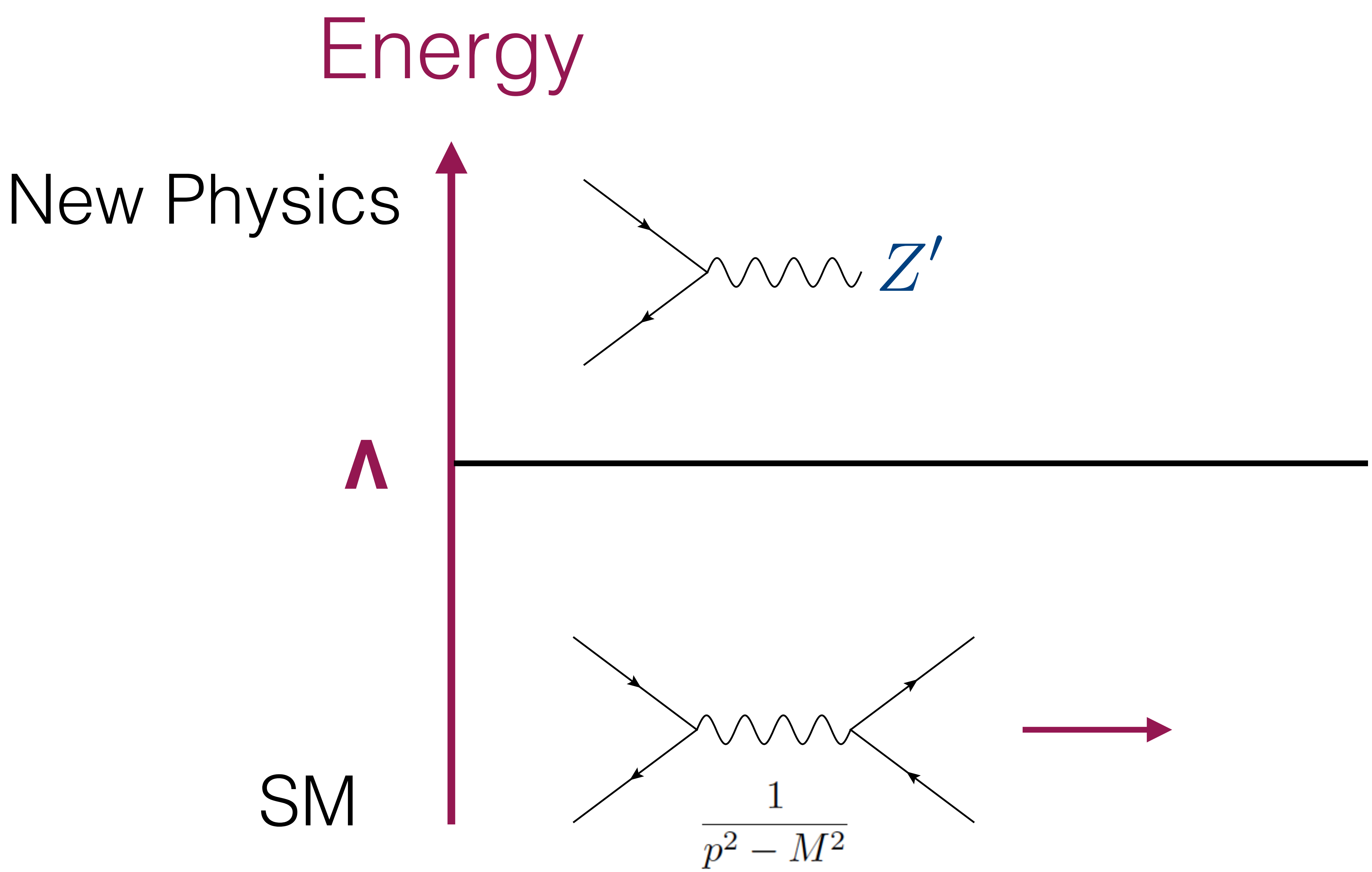

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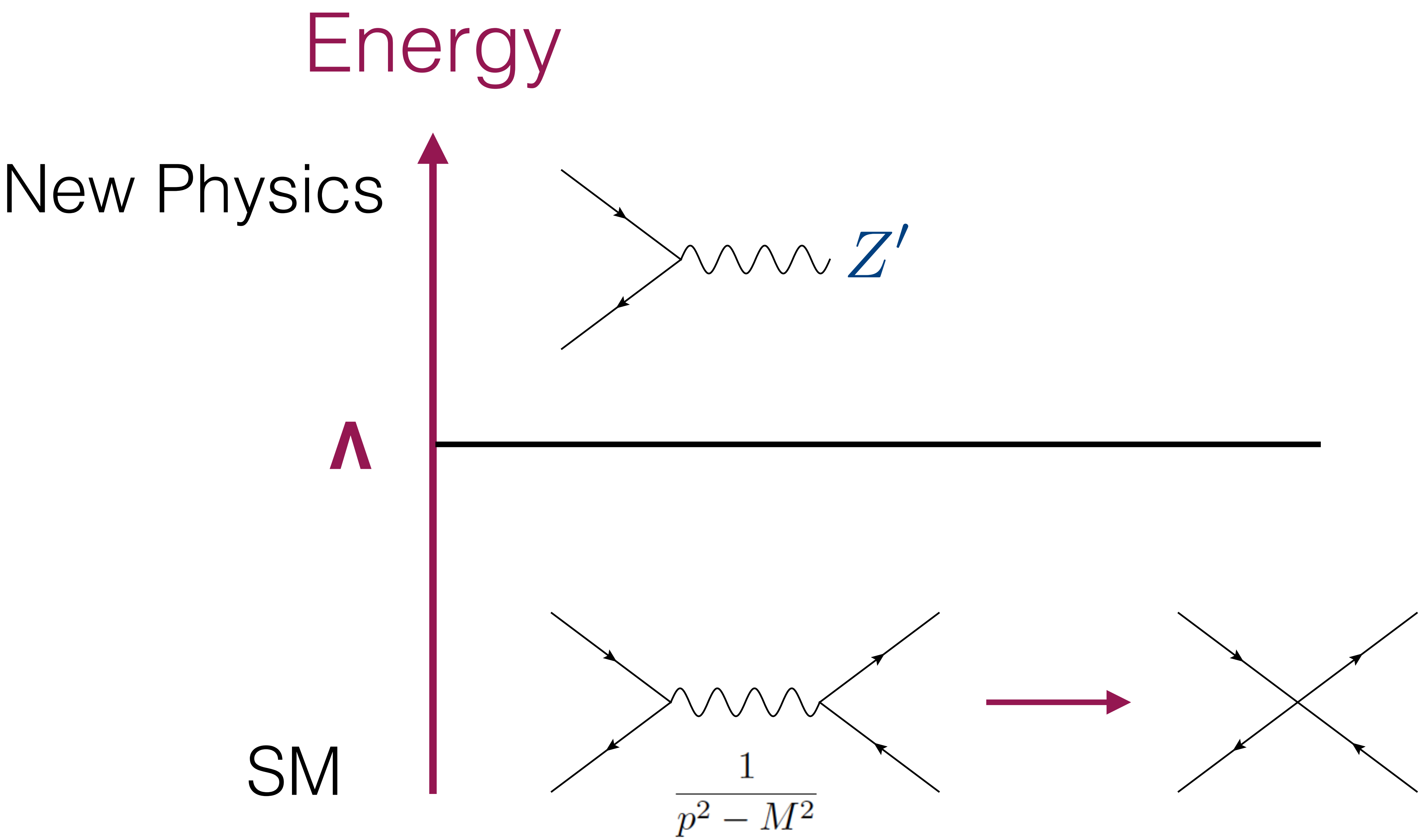

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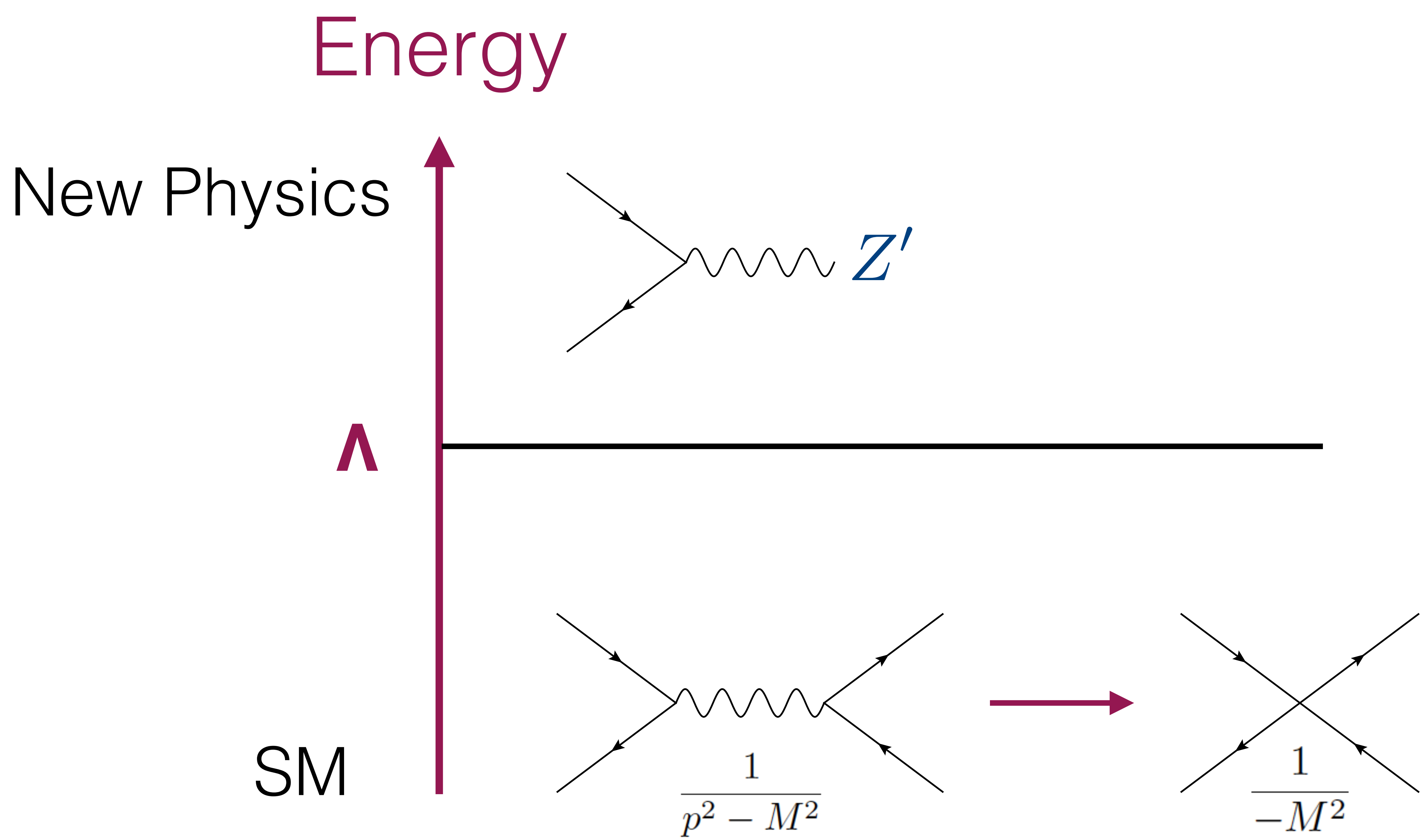

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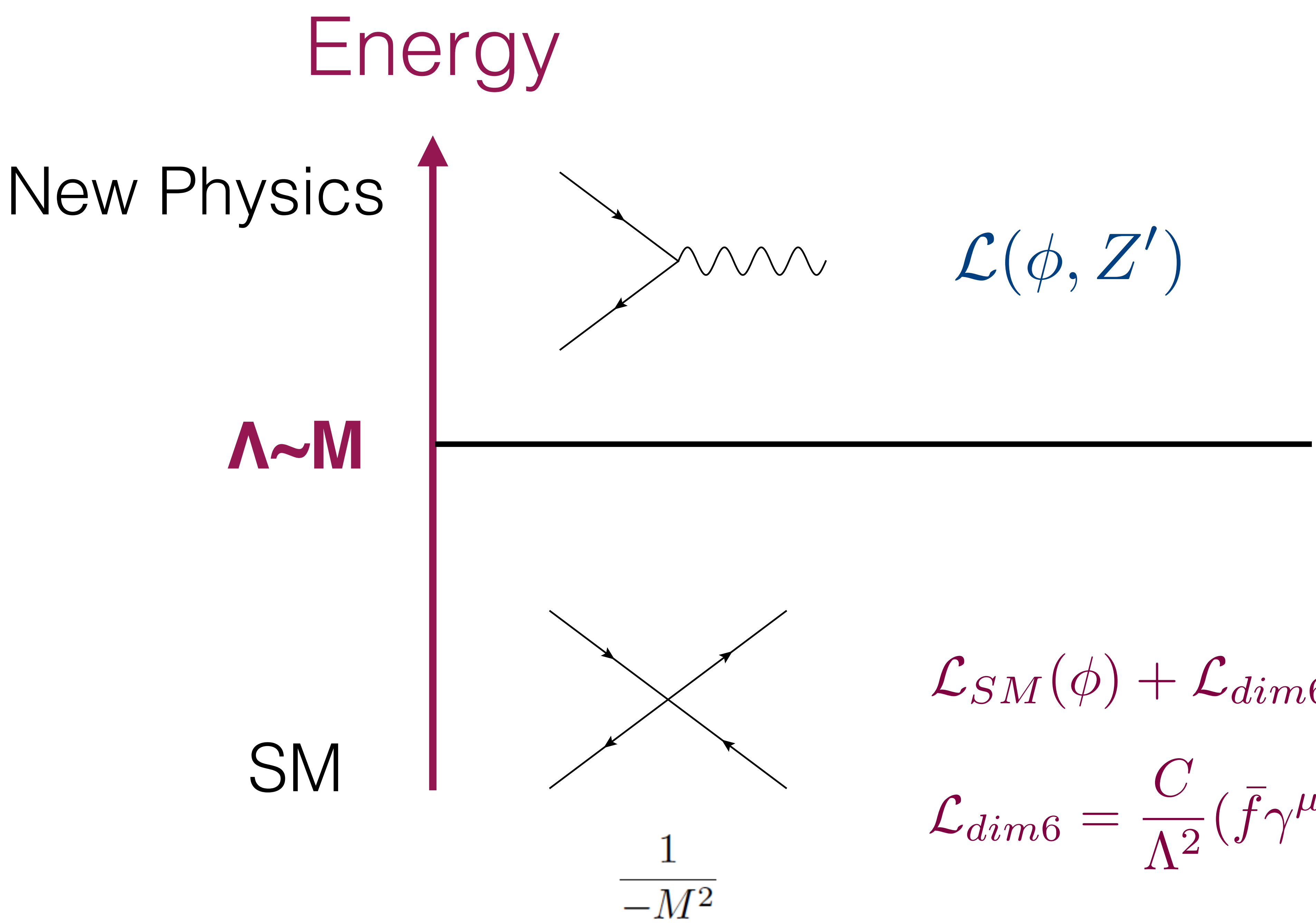

$$\mathcal{L}(\phi, Z')$$

$$\mathcal{L}_{SM}(\phi) + \mathcal{L}_{dim6}(\phi) + \ldots$$

$$\mathcal{L}_{dim6} = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

SMEFT basics

New Interactions of SM particles

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

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

Grzadkowski et al arXiv:1008.4884

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

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

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

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EFT for top quark interactions

SMEFT vs Anomalous couplings

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

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

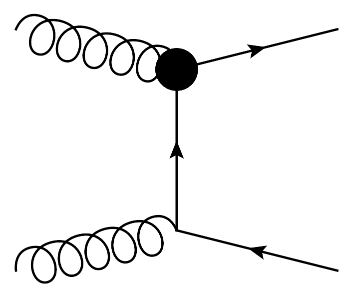
- SMEFT:
  - Gauge invariant ✔
  - Higher-order corrections: renormalisable order by order in 1/Λ ✔

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

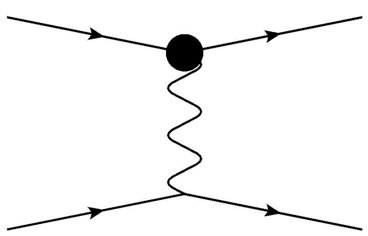
  - Complete description-respecting SM symmetries ✔
  - Model Independent ✔

Rich phenomenology:

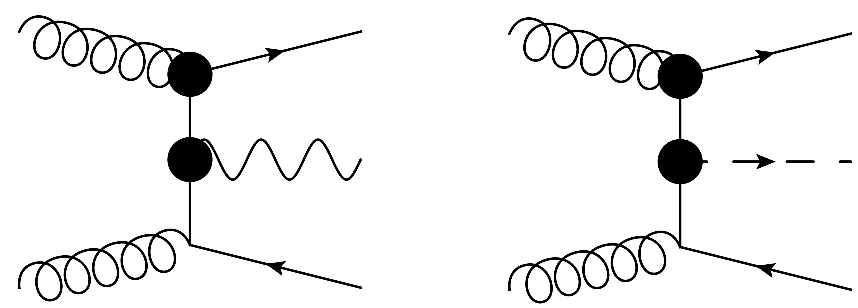
pair production



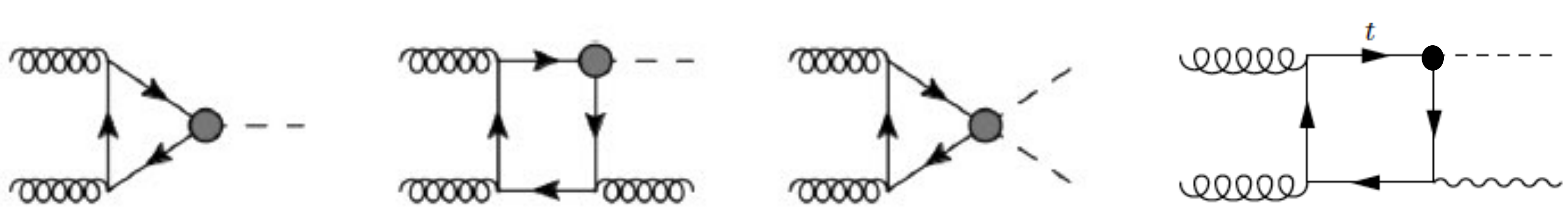
single



associated production



top loops



→ **connection to Higgs physics**

Top-quark operators & how to look for them

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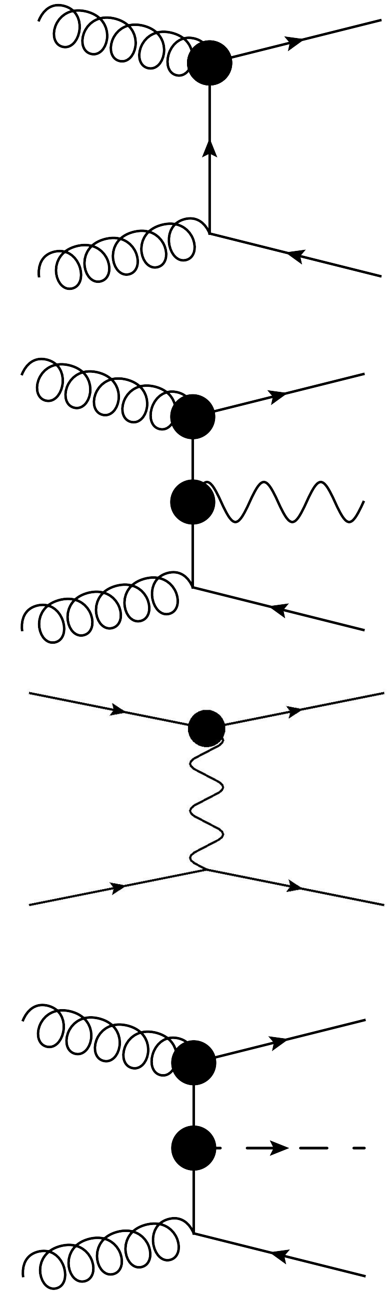

see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

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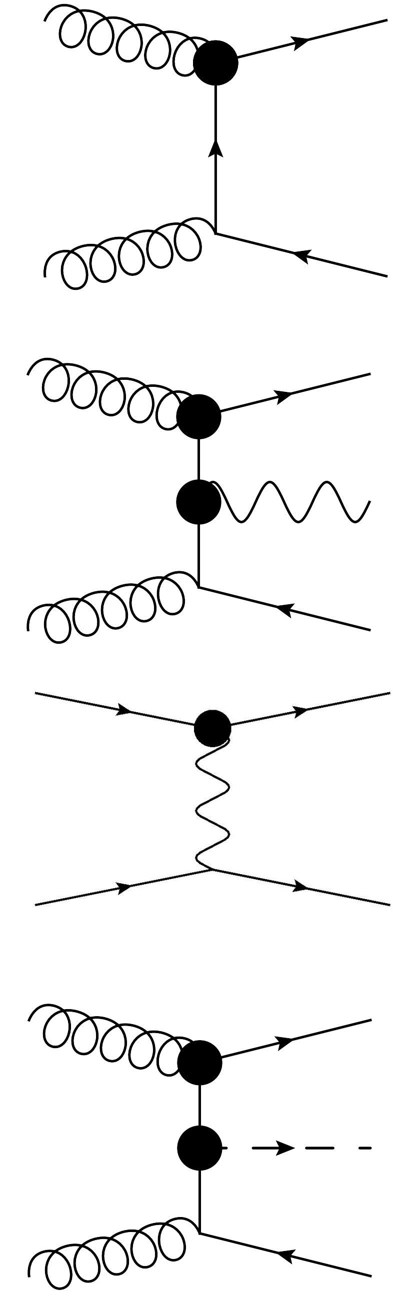

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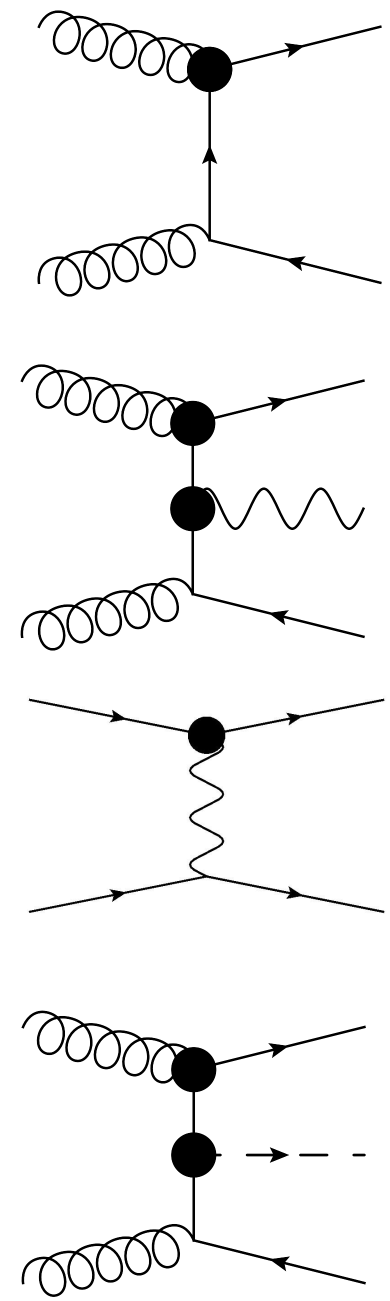

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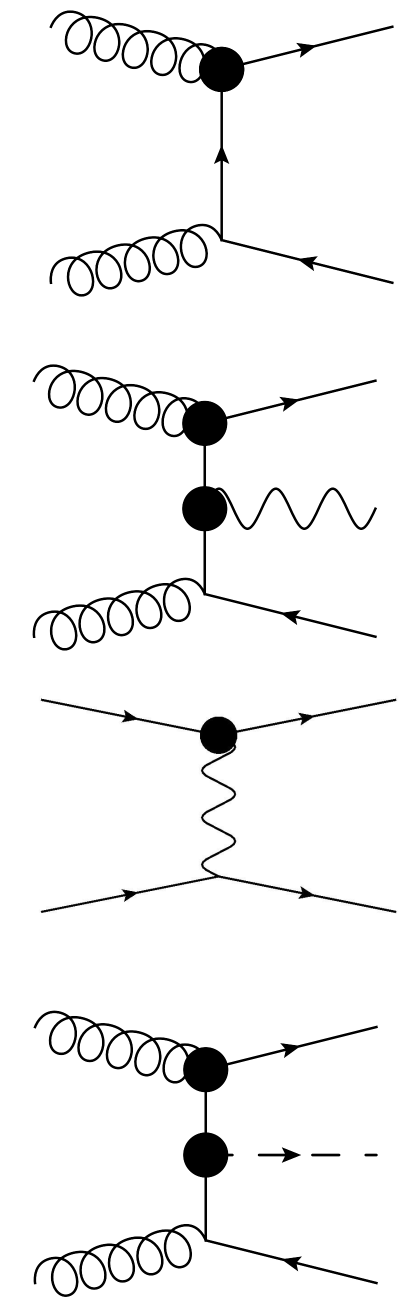

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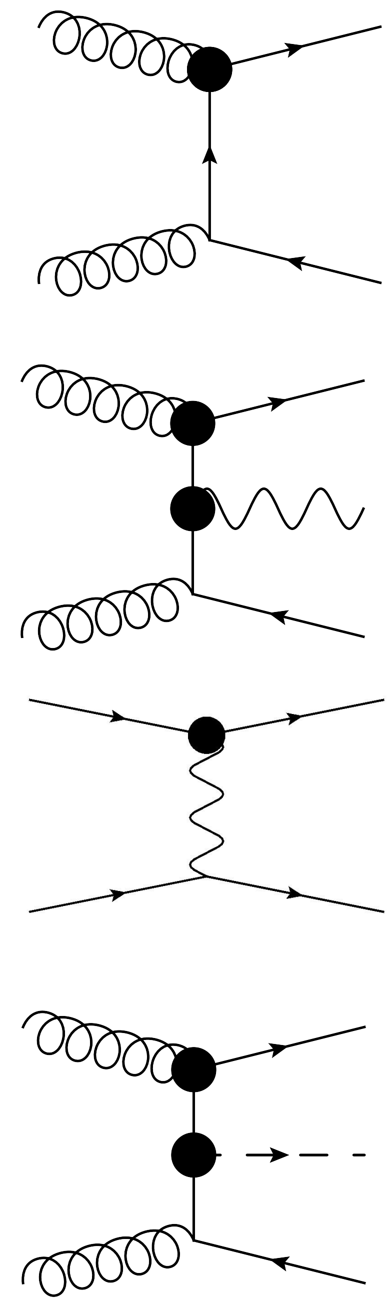

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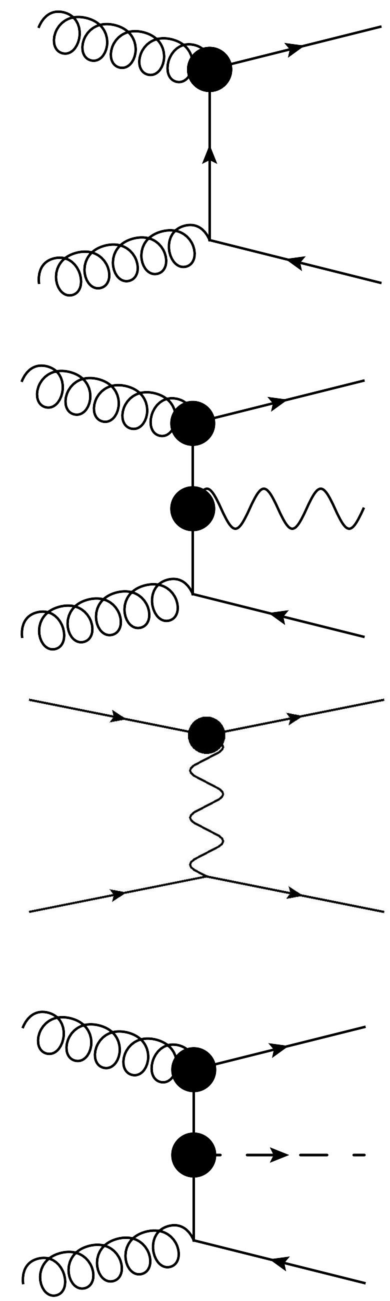
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

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

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

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



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

+four-fermion operators

+non-top operators (mixing)

Top-quark operators & 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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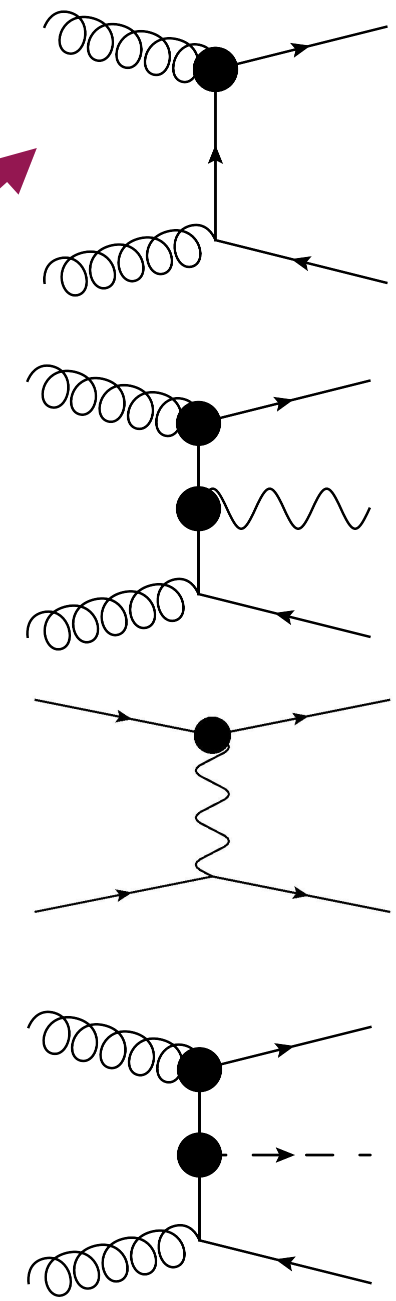

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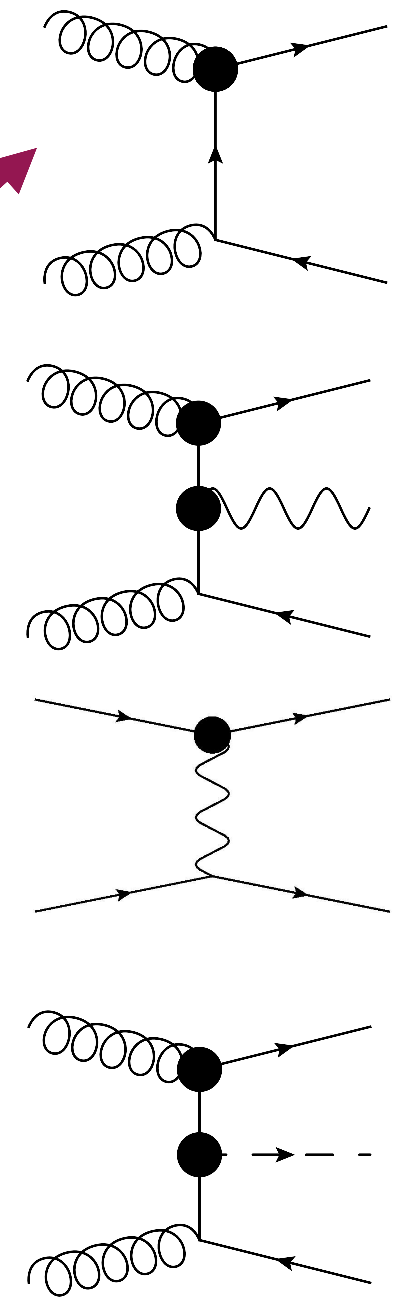

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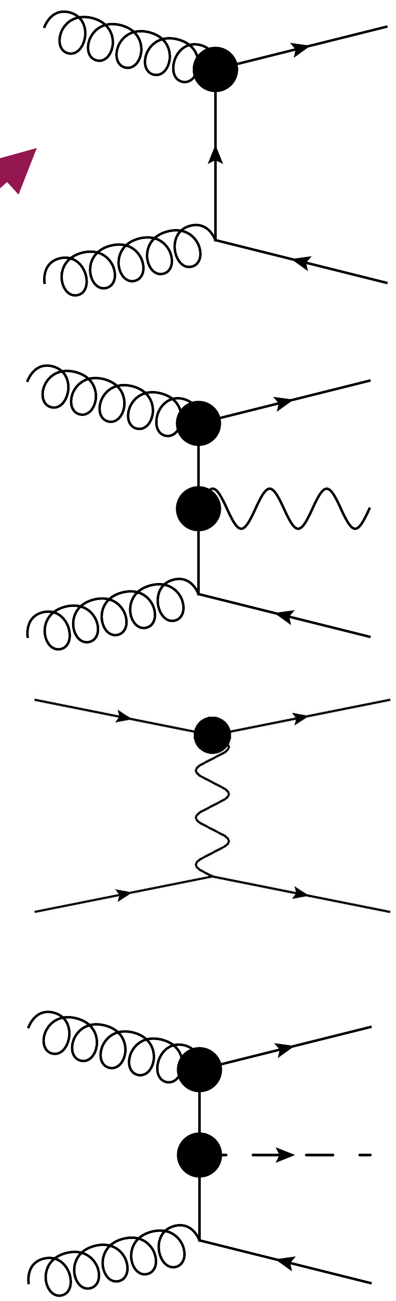

see for example: Aguilar-Saavedra (arXiv:0811.3842)
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+four-fermion operators

+non-top operators (mixing)

Operators entering various processes: Global approach needed

What's the path?

Use SMEFT to look for deviations from SM predictions

=

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

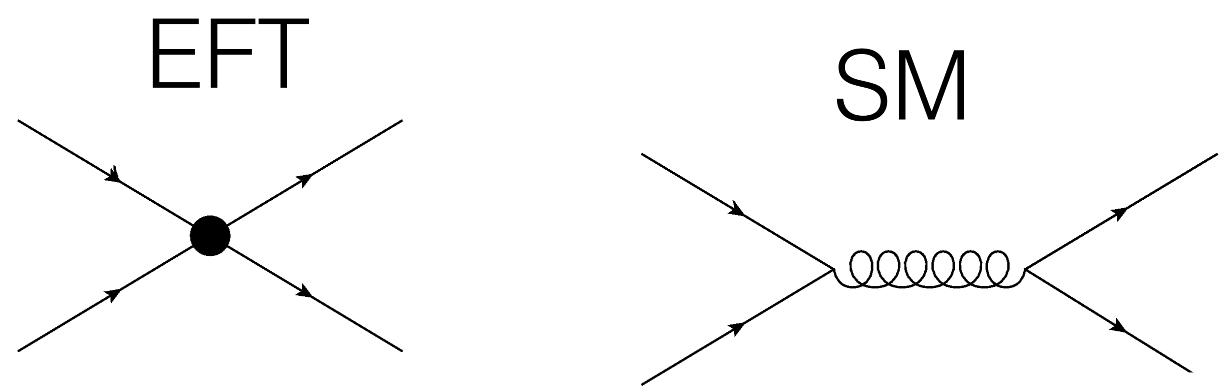
+

Use the best SM predictions
QCD/EW corrections

+

Use precise SMEFT predictions to maximise sensitivity

EFT in top pair production



4-fermion operators

$$O^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i) \qquad O^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i)$$

$$O^{3,8}_{Qq} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i) \qquad O^{3,1}_{Qq} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i)$$

$$O^{8}_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i) \qquad O^{1}_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i)$$

$$O^{8}_{td} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i) \qquad O^{1}_{td} = (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)\ ;$$

$$O^{8}_{Qu} = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i\gamma_\mu T^A u_i) \qquad O^{1}_{Qu} = (\bar{Q}\gamma^\mu Q)(\bar{u}_i\gamma_\mu u_i)$$

$$O^{8}_{Qd} = (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i\gamma_\mu T^A d_i) \qquad O^{1}_{Qd} = (\bar{Q}\gamma^\mu Q)(\bar{d}_i\gamma_\mu d_i)$$

$$O^{8}_{tq} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t) \qquad O^{1}_{tq} = (\bar{q}_i\gamma^\mu q_i)(\bar{t}\gamma_\mu t)\ ;$$

Octets Singlets

Different chiralities and colour structures

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^1_{tu}	$[0.67^{+1\%}_{-1\%}]$	$-0.078(7)^{+31\%}_{-23\%}$	$[0.41^{+13\%}_{-17\%}]$	$4.66^{+6\%}_{-5\%}$	$5.92^{+6\%}_{-5\%}$
c^1_{td}	$[-0.21^{+1\%}_{-2\%}]$	$-0.306^{+30\%}_{-22\%}$	$[-0.15^{+10\%}_{-13\%}]$	$2.62^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
c^1_{tq}	$[0.39^{+0\%}_{-1\%}]$	$-0.47^{+24\%}_{-18\%}$	$[0.50^{+3\%}_{-2\%}]$	$7.25^{+6\%}_{-5\%}$	$9.36^{+6\%}_{-5\%}$
c^1_{Qu}	$[0.33^{+0\%}_{-0\%}]$	$-0.359^{+23\%}_{-17\%}$	$[0.57^{+6\%}_{-5\%}]$	$4.68^{+6\%}_{-5\%}$	$5.96^{+6\%}_{-5\%}$
c^1_{Qd}	$[-0.11^{+0\%}_{-1\%}]$	$0.023(6)^{+114\%}_{-75\%}$	$[-0.19^{+6\%}_{-5\%}]$	$2.61^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
$c^{1,1}_{Qq}$	$[0.57^{+0\%}_{-1\%}]$	$-0.24^{+30\%}_{-22\%}$	$[0.39^{+9\%}_{-12\%}]$	$7.25^{+6\%}_{-5\%}$	$9.34^{+5\%}_{-5\%}$
$c^{1,3}_{Qq}$	$[1.92^{+1\%}_{-1\%}]$	$0.088(7)^{+28\%}_{-20\%}$	$[1.05^{+17\%}_{-22\%}]$	$7.25^{+6\%}_{-5\%}$	$9.32^{+5\%}_{-5\%}$

Interesting interference patterns

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

EFT in top pair production

4-heavy operators in top pair production

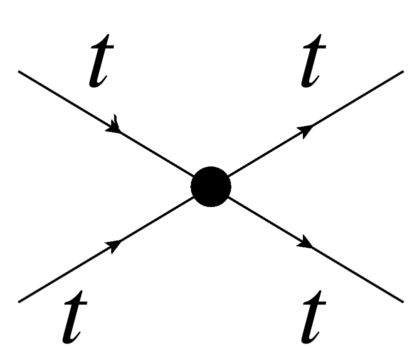
$$\mathcal{O}^{8}_{QQ} = (\bar{Q}\gamma^{\mu}T^{A}Q)(\bar{Q}\gamma_{\mu}T^{A}Q)$$

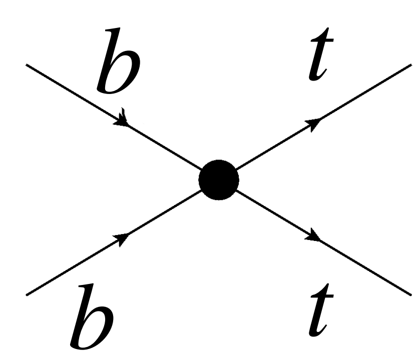
$$\mathcal{O}^{1}_{QQ} = (\bar{Q}\gamma^{\mu}Q)(\bar{Q}\gamma_{\mu}Q)$$

$$\mathcal{O}^{8}_{Qt} = (\bar{Q}\gamma^{\mu}T^{A}Q)(\bar{t}\gamma_{\mu}T^{A}t)$$

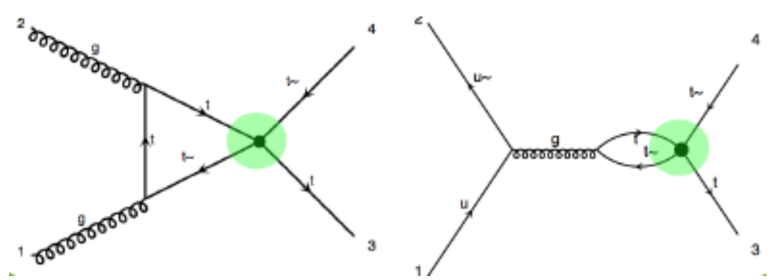
$$\mathcal{O}^{1}_{Qt} = (\bar{Q}\gamma^{\mu}Q)(\bar{t}\gamma_{\mu}t)$$

$$\mathcal{O}^{1}_{tt} = (\bar{t}\gamma^{\mu}t)(\bar{t}\gamma_{\mu}t)$$

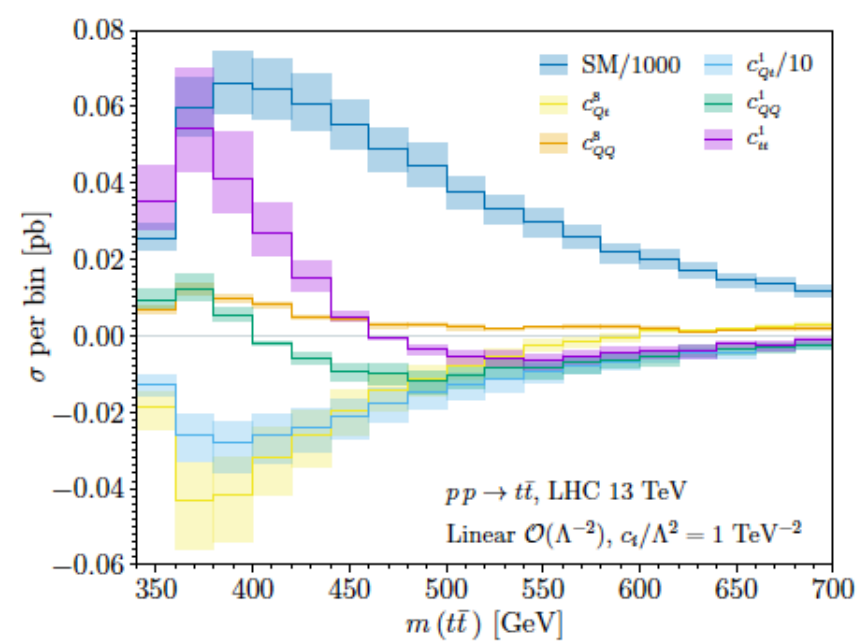




At NLO:



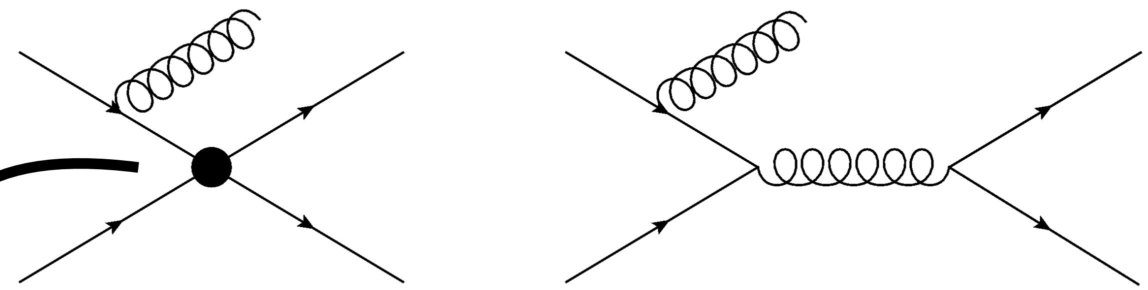
c^{8}_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^{8}_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c^{1}_{QQ}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
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}	×	$0.215^{+23\%}_{-18\%}$		×	×



Complimentary information to ttbb and 4top production

New observables in $t\bar{t}$

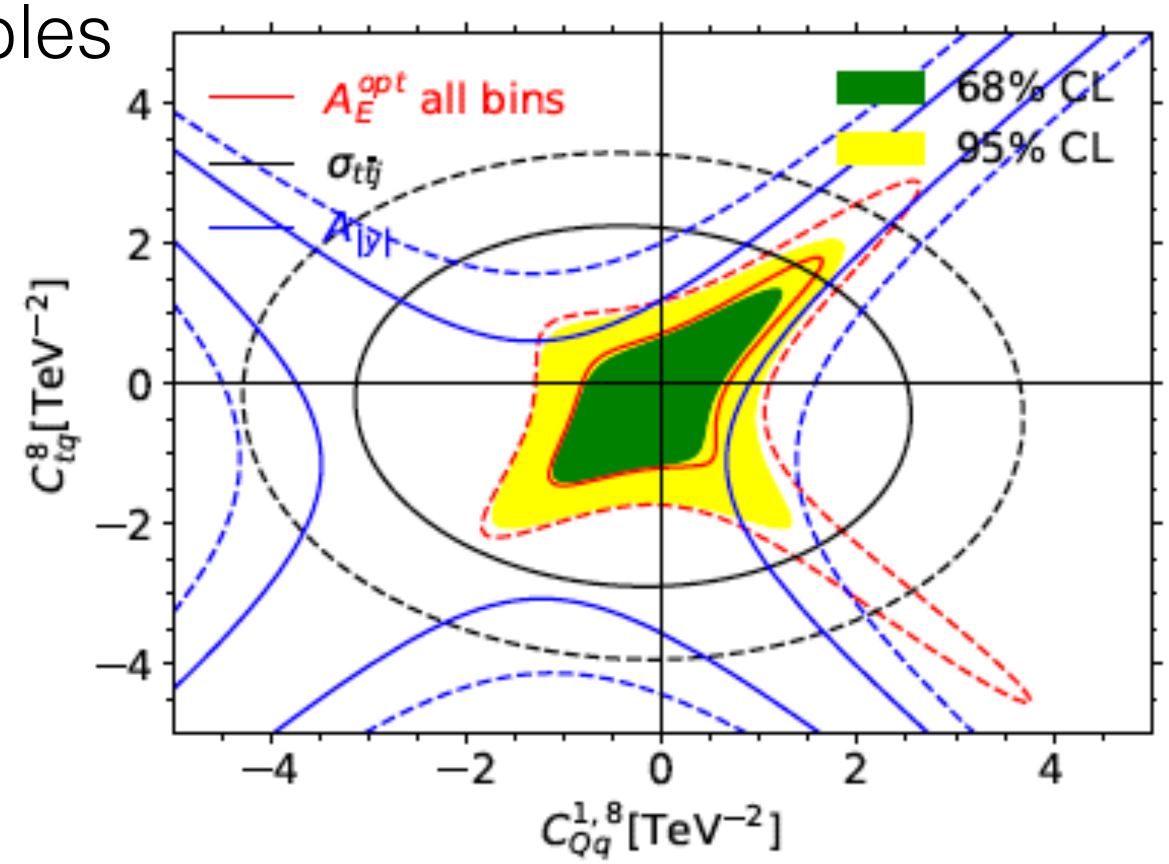
LHC can probe more sensitive observables



$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$

$$O_{tq}^{8} = (\bar{t}\gamma_\mu T^A t)(\bar{q}_i \gamma^\mu T^A q_i)$$

Different top chiralities

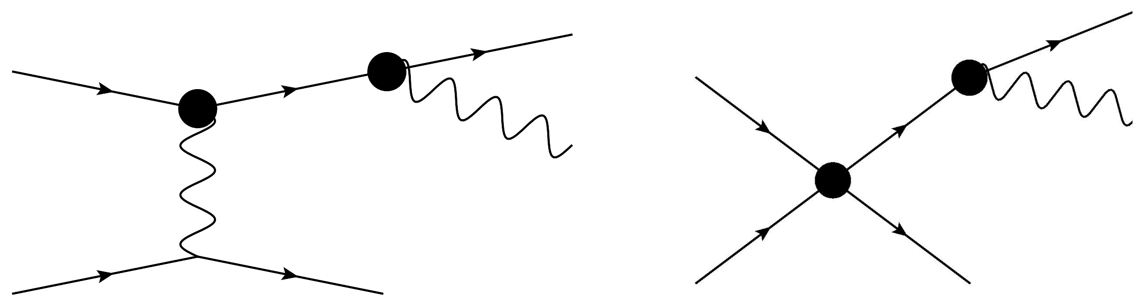


Basan, Berta, Masetti, EV, Westhoff arXiv:2001.07225

An asymmetry observable

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}$$

Single top production and decay

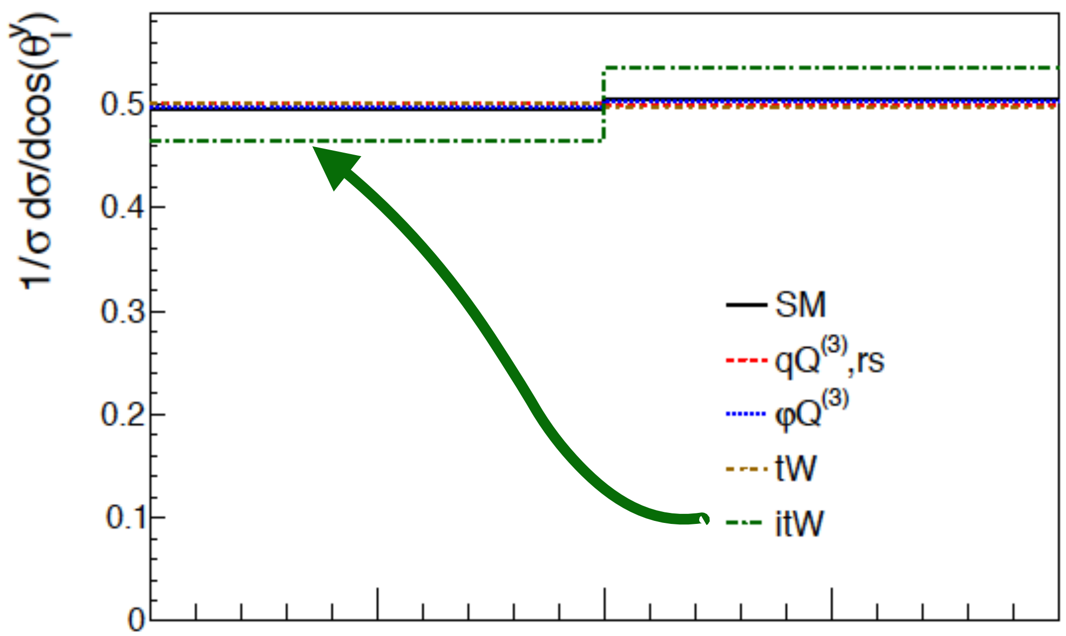


$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

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

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

Identify the optimal observables and provide precise and reliable predictions:



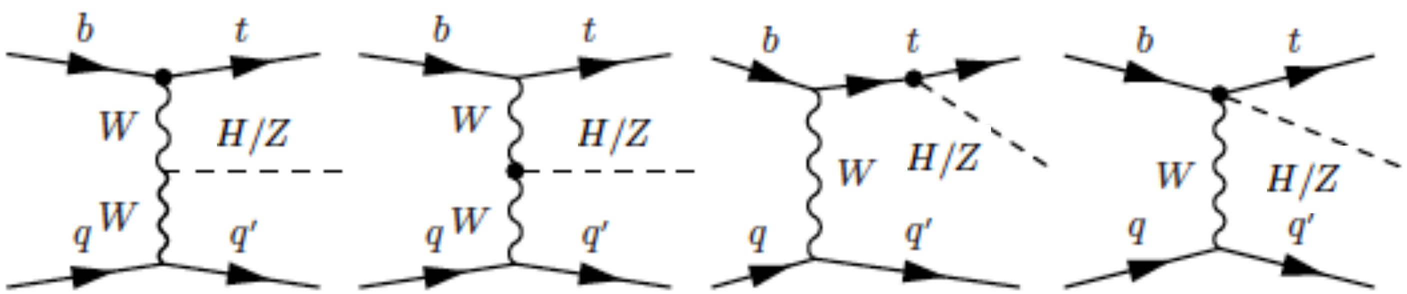
Top polarisation angles

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

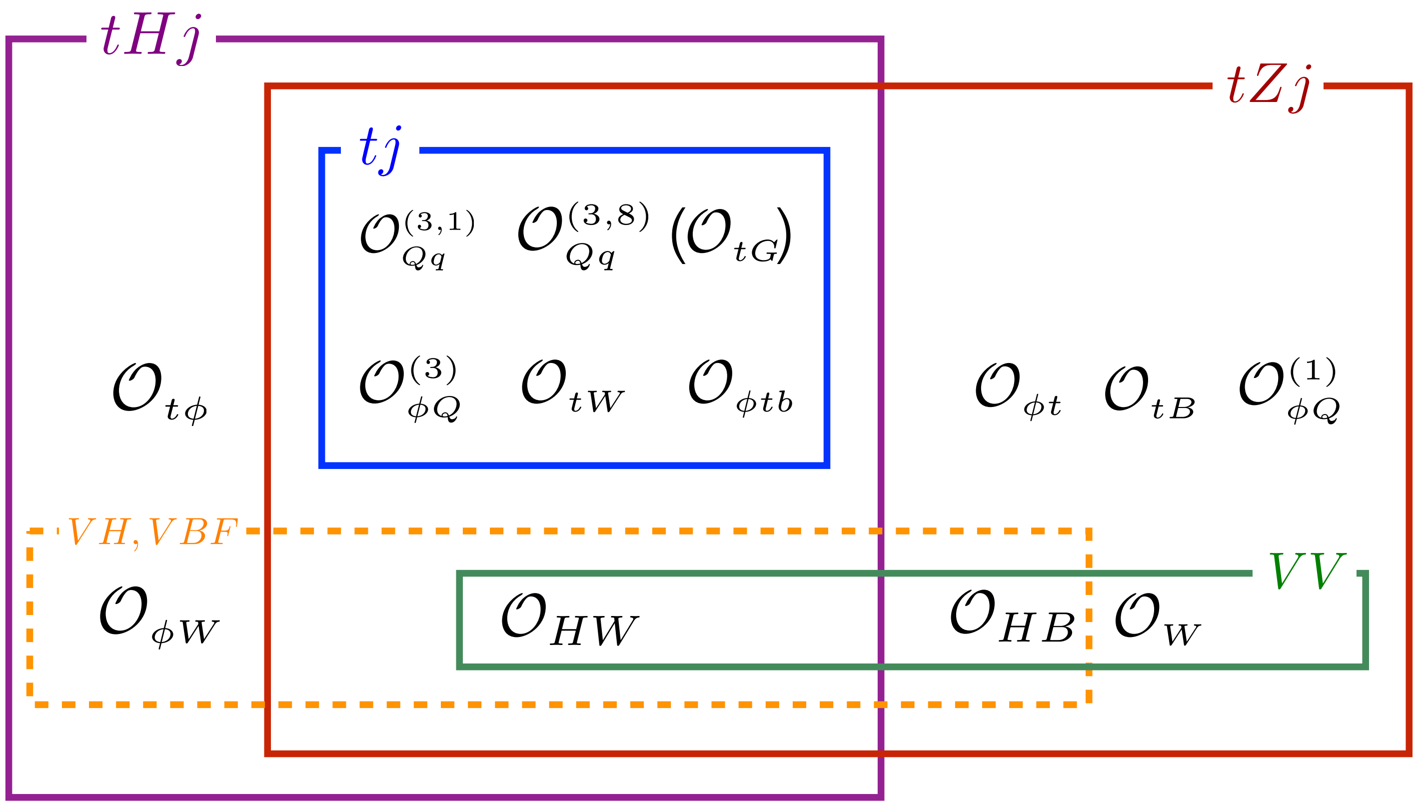
NLO study including production and decay

de Beurs, Laenen, Vreeswijk, EV arXiv:1807.03576

tZj/tHj associated production



Gauge-Higgs
Top couplings
TGC



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

Unique interplay

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

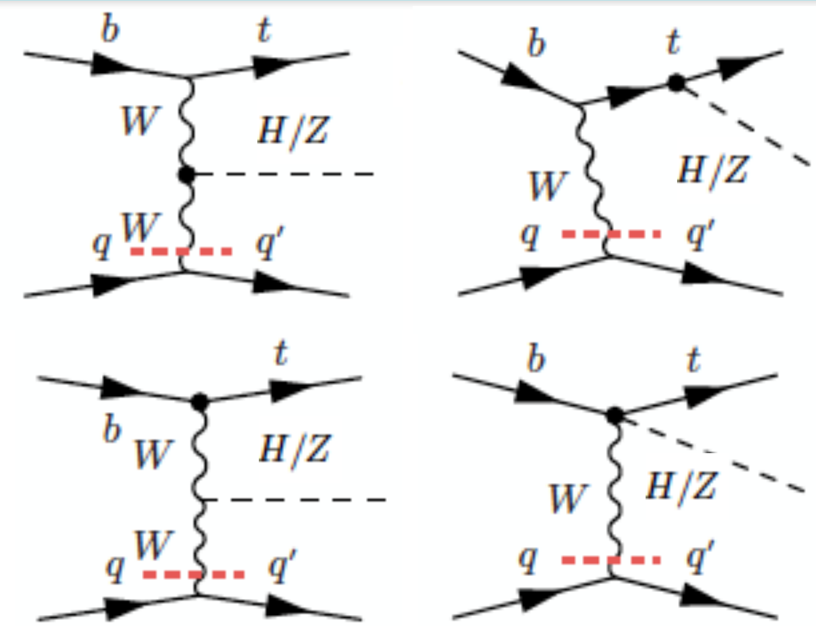
Two-fermion top-quark operators (8): $\mathcal{O}^{(3)}_{\varphi Q}, \mathcal{O}^{(1)}_{\varphi Q}, \mathcal{O}_{\varphi t}, \mathcal{O}_{tW}, \mathcal{O}_{tB}, \mathcal{O}_{tG}, \mathcal{O}_{\varphi tb}, \mathcal{O}_{t\varphi}$

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

Helicity amplitudes for subprocesses

bW → tZ

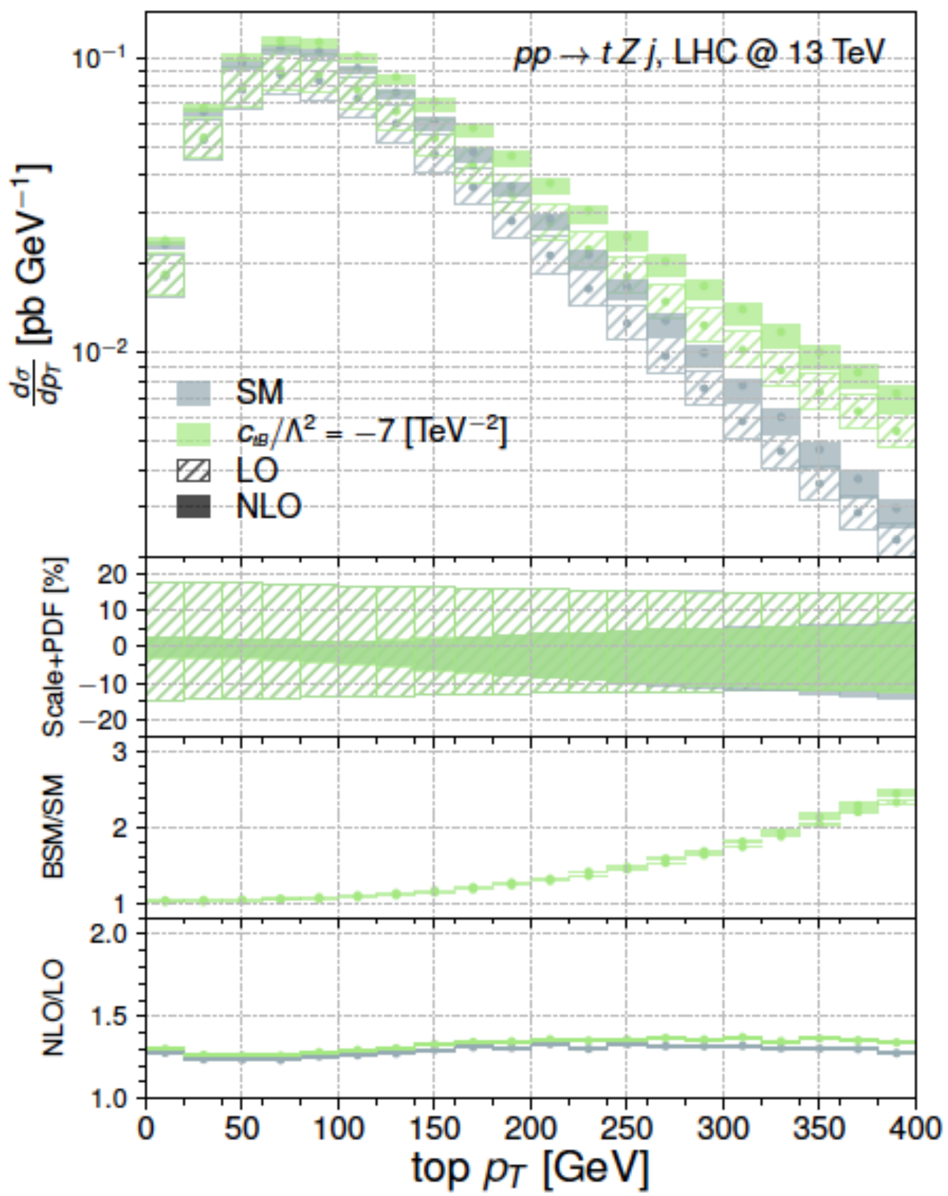
$\lambda_b, \lambda_W, \lambda_t, \lambda_Z$	SM	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$
$-,0,-,0$	s^0	$\sqrt{s(s+t)}$	–	–	–	s^0	s^0	$\sqrt{s(s+t)}$	s^0
$-,0,+,0$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

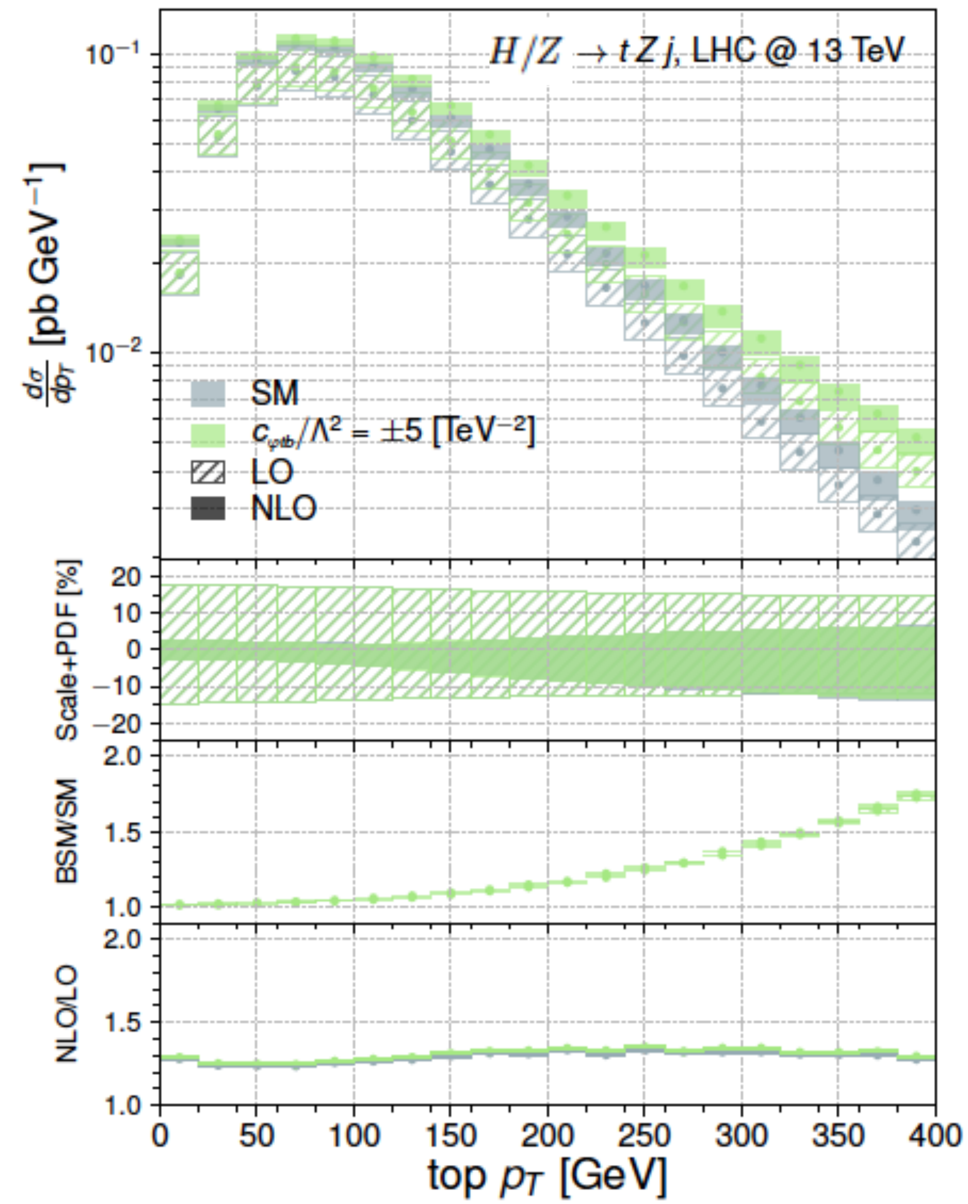


Amplitudes growing with energy as SM cancellations get spoiled ➡ Large deviations
Differential distributions

Differential results

tZj



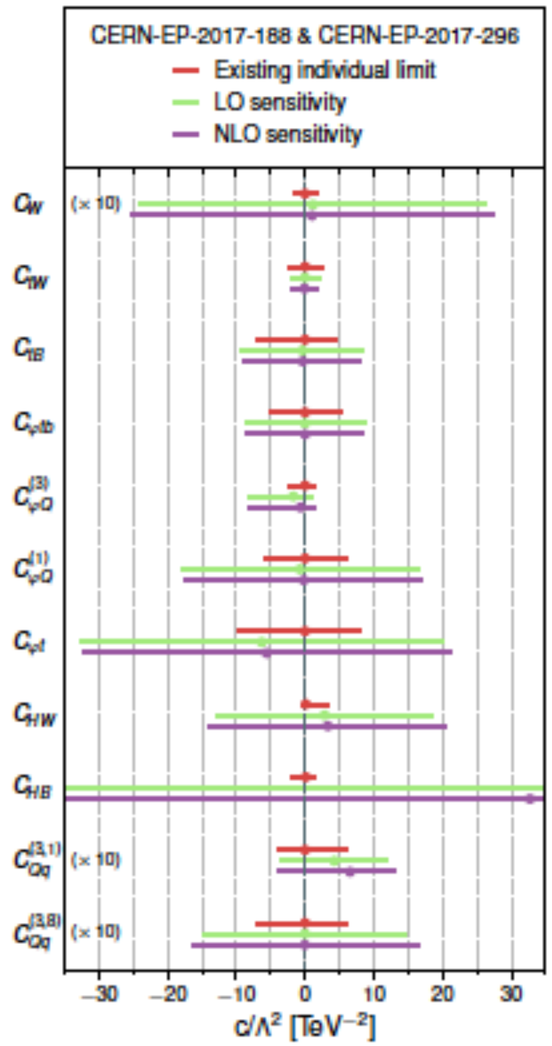


Degrande, Maltoni, Mimasu, EV, Zhang arXiv:1804.07773

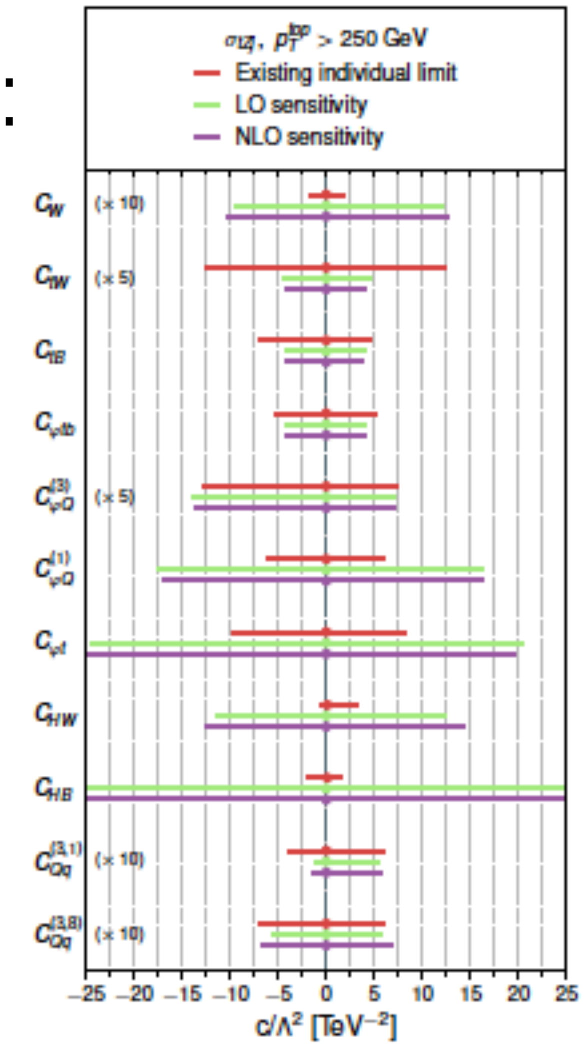
Large deviations in the tails, as expected from helicity amplitudes

Current and future sensitivity

Current:



Future:



Degrande, Maltoni, Mimasu, EV, Zhang arXiv:1804.07773

tZj observation:
CMS; arXiv:1812.05900
ATLAS; arXiv: 2002.07546

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

Rare processes can play a role in a global fit

How to compute these results?

SMEFT@NLO

Automated one-loop computations in the SMEFT

Céline Degrande,[1,*] Gauthier Durieux,[2,†] Fabio Maltoni,[1,3,‡]
Ken Mimasu,[1,§] Eleni Vryonidou,[4,¶] and Cen Zhang[5,6,**]

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.

Standard Model Effective Theory at One-Loop in QCD

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang, arXiv:2008.11743

The implementation is based on the Warsaw basis of dimension-six SMEFT operators, after canonical normalization. Electroweak input parameters are taken to be G_F, M_Z, M_W. The CKM matrix is approximated as a unit matrix, and a $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_l \times U(1)_e)^3$ flavor symmetry is enforced. It forbids all fermion masses and Yukawa couplings except that only of the top quark. The model therefore implements the five-flavor scheme for PDFs.

A new coupling order, `NP=2`, is assigned to SMEFT interactions. The cutoff scale `Lambda` takes a default value of 1 TeV^{-2} and can be modified along with the Wilson coefficients in the `param_card`. Operators definitions, normalisations and coefficient names in the UFO model are specified in definitions.pdf. The notations and normalizations of top-quark operator coefficients comply with the LHC TOP WG standards of 1802.07237. Note however that the flavor symmetry enforced here is slightly more restrictive than the baseline assumption there (see the dim6top page for more information). This model has been validated at tree level against the `dim6top` implementation (see 1906.12310 and the comparison details).

Current implementation

UFO model: SMEFTatNLO_v1.0.tar.gz

- 2020/08/24 - v1.0: Official release including notably four-quark operators at NLO.

Support

Please direct any questions to smeftatnlo-dev**[at]**cern**[dot]**ch.

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

What can the code do?

Multi-boson production

quark-initiated

```
> p p > W+ W-     QED=2 QCD=0 NP=2 [QCD]
> p p > W+ Z      QED=2 QCD=0 NP=2 [QCD]
> p p > Z  Z      QED=2 QCD=0 NP=2 [QCD]
```

loop-induced

```
> g g > W+ W-     QED=2 QCD=2 NP=2 [QCD]
> g g > Z  Z      QED=2 QCD=2 NP=2 [QCD]
> g g > W+ W- Z   QED=3 QCD=2 NP=2 [QCD]
> g g > Z  Z  Z   QED=3 QCD=2 NP=2 [QCD]
```

loop-induced

```
> g g > H          QED=1 QCD=2 NP=2 [QCD]
> g g > H H        QED=2 QCD=2 NP=2 [QCD]
> g g > H H H      QED=3 QCD=2 NP=2 [QCD]
> g g > H j        QED=1 QCD=3 NP=2 [QCD]
```

Top quark production

```
> e+ e- > t t~           QED=2 QCD=0 NP=2 [QCD]
> p p > t t~             QED=0 QCD=2 NP=2 [QCD]
> p p > t t~ h           QED=1 QCD=2 NP=2 [QCD]
> p p > t t~ Z           QED=1 QCD=2 NP=2 [QCD]
> p p > t t~ W+          QED=1 QCD=2 NP=2 [QCD]
> p p > t W-      $$ t~  QED=1 QCD=1 NP=2 [QCD]
> p p > t W- j    $$ t~  QED=1 QCD=2 NP=2 [QCD]
> p p > t j       $$ W-  QED=2 QCD=0 NP=2 [QCD]
> p p > t h j     $$ W-  QED=3 QCD=0 NP=2 [QCD]
> p p > t Z j     $$ W-  QED=3 QCD=0 NP=2 [QCD]
> p p > t a j     $$ W-  QED=3 QCD=0 NP=2 [QCD]
```

→ Including 4-fermion operators ★

What's in the box?

Warsaw basis operators

Flavour assumption:

$$U(2)_q \times U(2)_u \times U(2)_d \times [U(1)_l \times U(1)_e]^3$$

Includes Higgs, top, gauge boson interactions

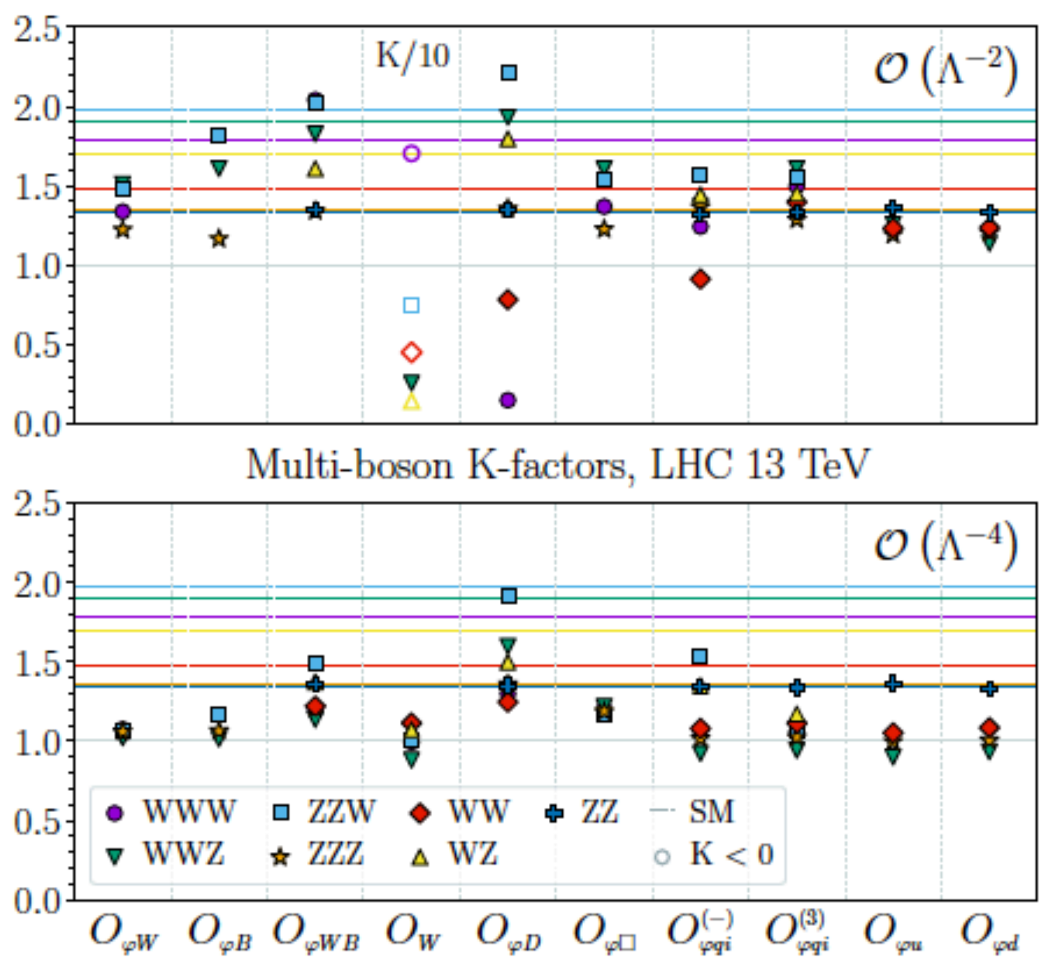
Conventions matching dim6top (LHC Top WG)

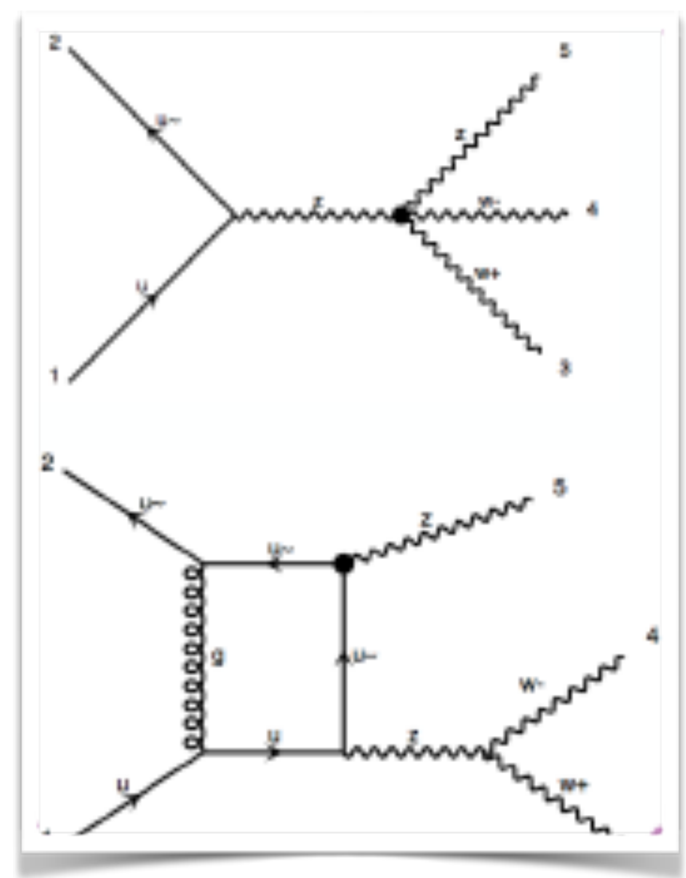
CP & Flavour conserving

And many more on the website…

NEW

Triboson production





First computation of VVV@NLO in the SMEFT

c.f. first observation by CMS: arXiv:2006.11191

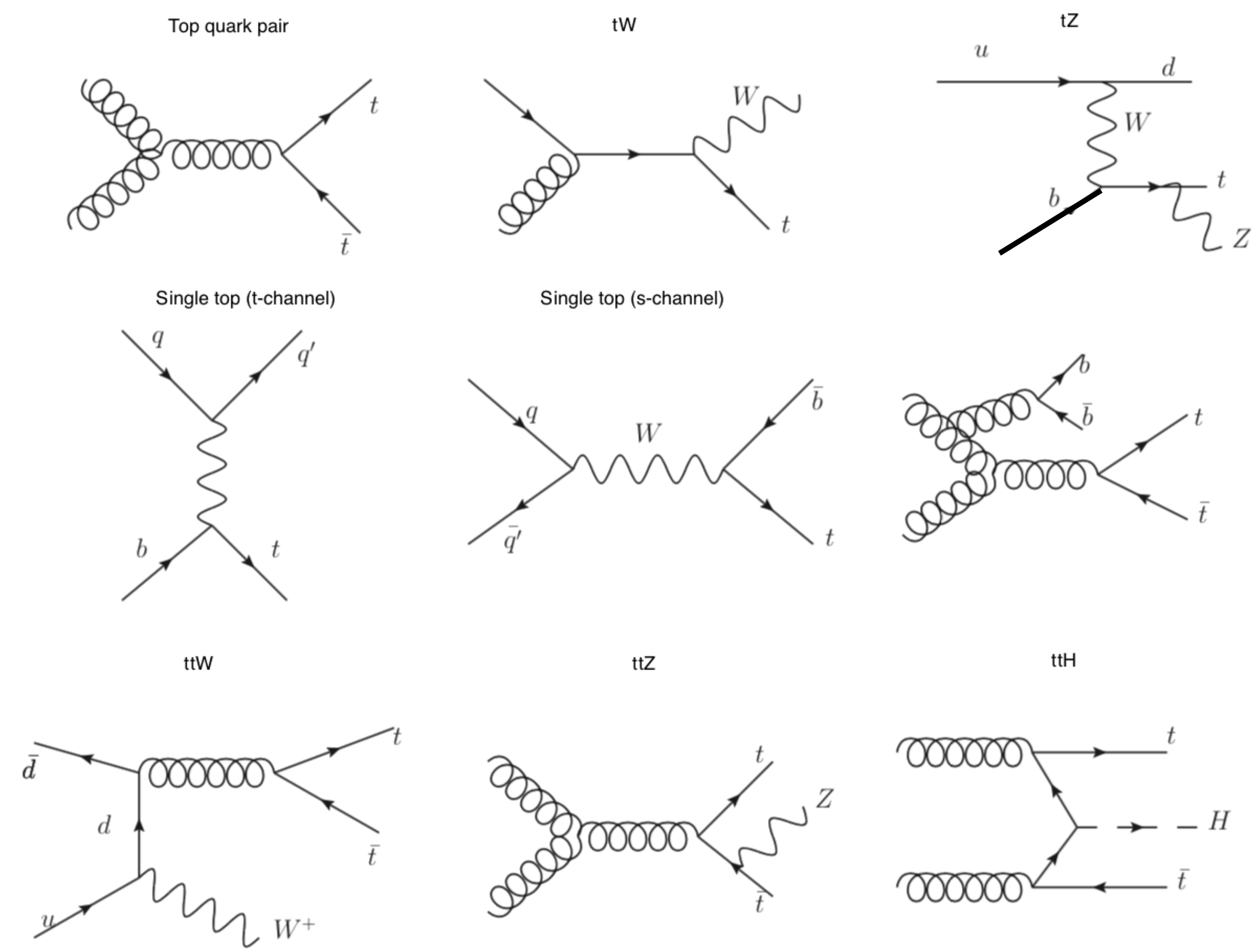
Outline

- Introduction to the EFT
- EFT for the LHC
  - Precision calculations in the EFT
- EFT in the top-Higgs sector
  - Global fits in the top sector
  - Towards global fits for top-Higgs

A first application: A global top fit@NLO

Class	Notation	Degree of Freedom	Operator Definition
$QQQQ$	0QQ1	c^1_{QQ}	$2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$
	0QQ8	c^8_{QQ}	$8C^{3(3333)}_{qq}$
	0Qt1	c^1_{Qt}	$C^{1(3333)}_{qu}$
	0Qt8	c^8_{Qt}	$C^{8(3333)}_{qu}$
	0Qb1	c^1_{Qb}	$C^{1(3333)}_{qd}$
	0Qb8	c^8_{Qb}	$C^{8(3333)}_{qd}$
	0tt1	c^1_{tt}	$C^{(3333)}_{uu}$
	0tb1	c^1_{tb}	$C^{1(3333)}_{ud}$
	0tb8	c^8_{tb}	$C^{8(3333)}_{ud}$
	0QtQb1	c^1_{QtQb}	$C^{1(3333)}_{quqd}$
	0QtQb8	c^8_{QtQb}	$C^{8(3333)}_{quqd}$
$QQqq$	081qq	$c^{1,8}_{Qq}$	$C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$
	011qq	$c^{1,1}_{Qq}$	$C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$
	083qq	$c^{3,8}_{Qq}$	$C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$
	013qq	$c^{3,1}_{Qq}$	$C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$
	08qt	c^8_{tq}	$C^{8(ii33)}_{qu}$
	01qt	c^1_{tq}	$C^{1(ii33)}_{qu}$
	08ut	c^8_{tu}	$2C^{(i33i)}_{uu}$
	01ut	c^1_{tu}	$C^{(ii33)}_{uu} + \frac{1}{3}C^{(i33i)}_{uu}$
	08qu	c^8_{Qu}	$C^{8(33ii)}_{qu}$
	01qu	c^1_{Qu}	$C^{1(33ii)}_{qu}$
	08dt	c^8_{td}	$C^{8(33ii)}_{ud}$
	01dt	c^1_{td}	$C^{1(33ii)}_{ud}$
	08qd	c^8_{Qd}	$C^{8(33ii)}_{qd}$
	01qd	c^1_{Qd}	$C^{1(33ii)}_{qd}$
$QQ+V,G,\varphi$	0tG	c_{tG}	$\mathrm{Re}\{C^{(33)}_{uG}\}$
	0tW	c_{tW}	$\mathrm{Re}\{C^{(33)}_{uW}\}$
	0bW	c_{bW}	$\mathrm{Re}\{C^{(33)}_{dW}\}$
	0tZ	c_{tZ}	$\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$
	0ff	$c_{\varphi tb}$	$\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$
	0fq3	$c^3_{\varphi Q}$	$C^{3(33)}_{\varphi q}$
	0pQM	$c^-_{\varphi Q}$	$C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$
	0pt	$c_{\varphi t}$	$C^{(33)}_{\varphi u}$
	0tp	$c_{t\varphi}$	$\mathrm{Re}\{C^{(33)}_{u\varphi}\}$

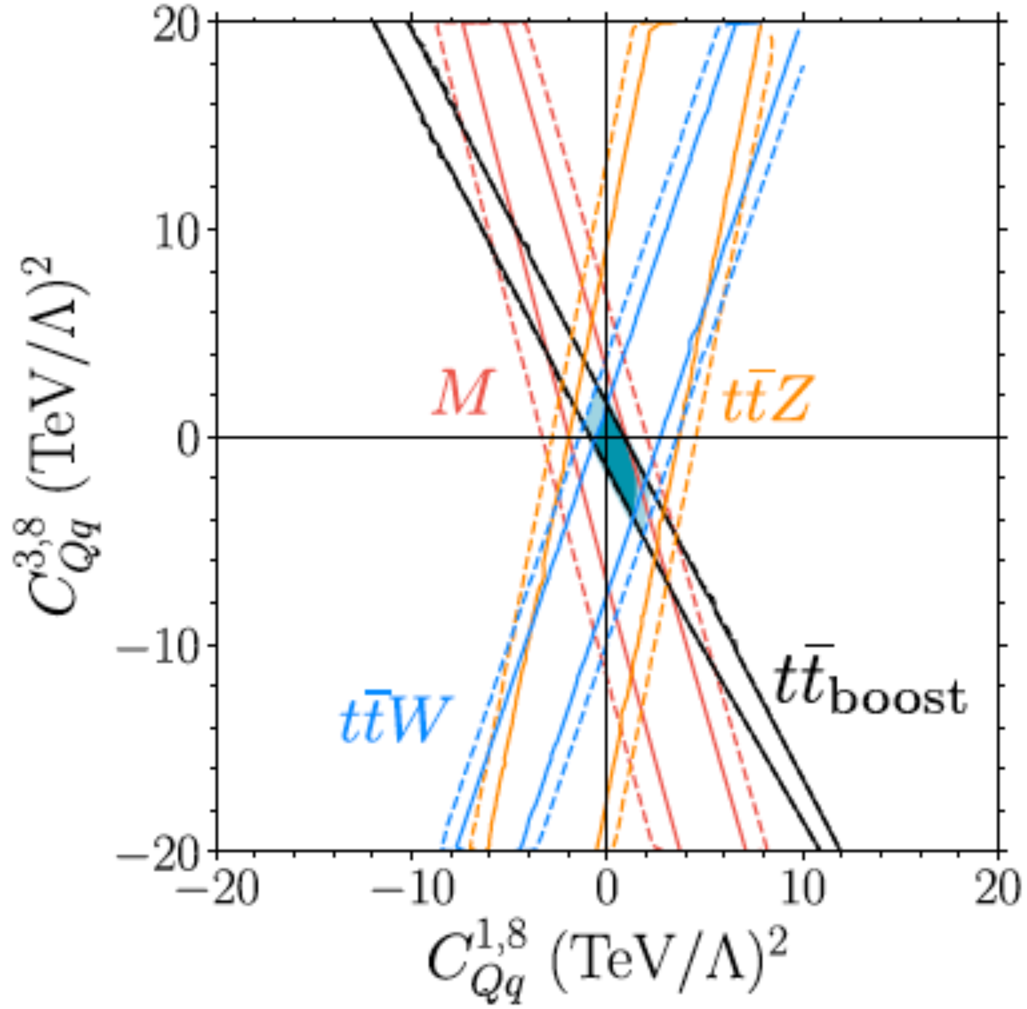
34 d.o.f.
CP-conserving

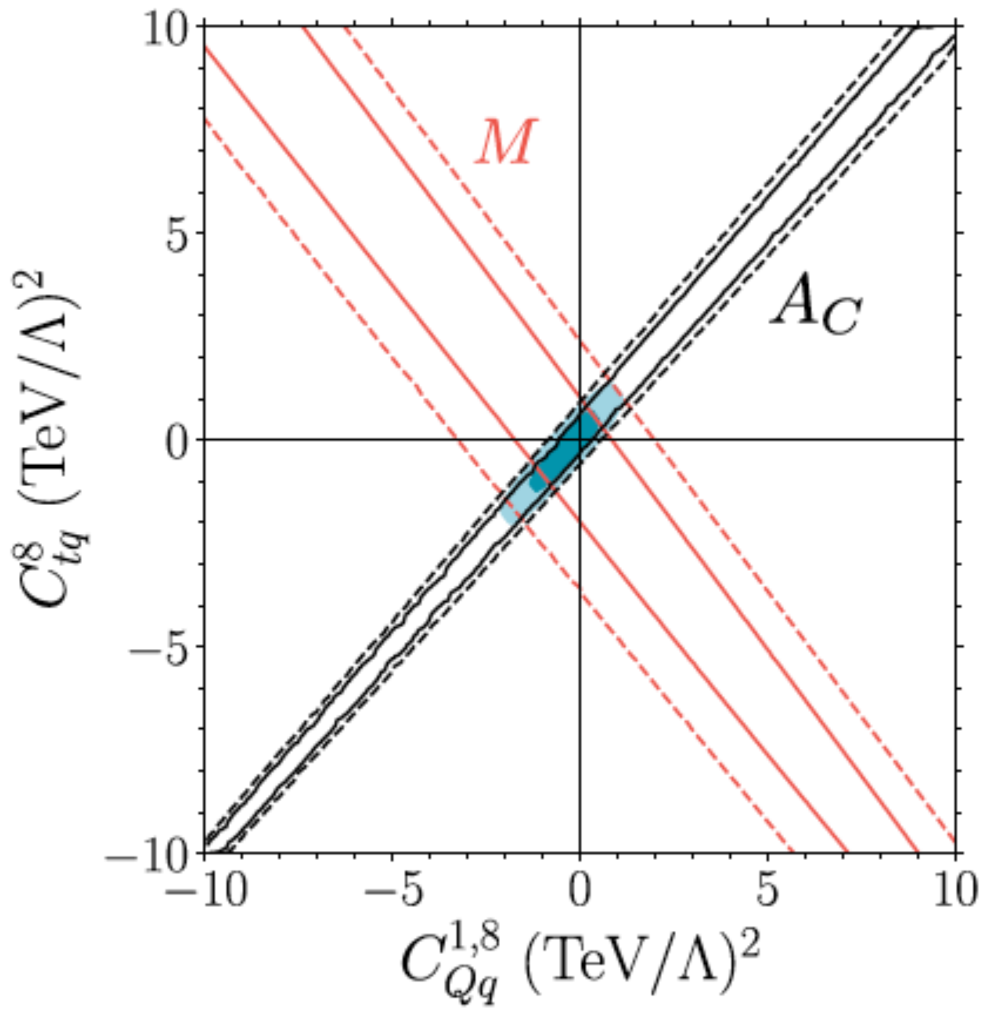


Rich phenomenology

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

The impact of multiple measurements





$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$
$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i)$$

$$O_{tq}^{8} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$$
$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

Some considerations for a fit

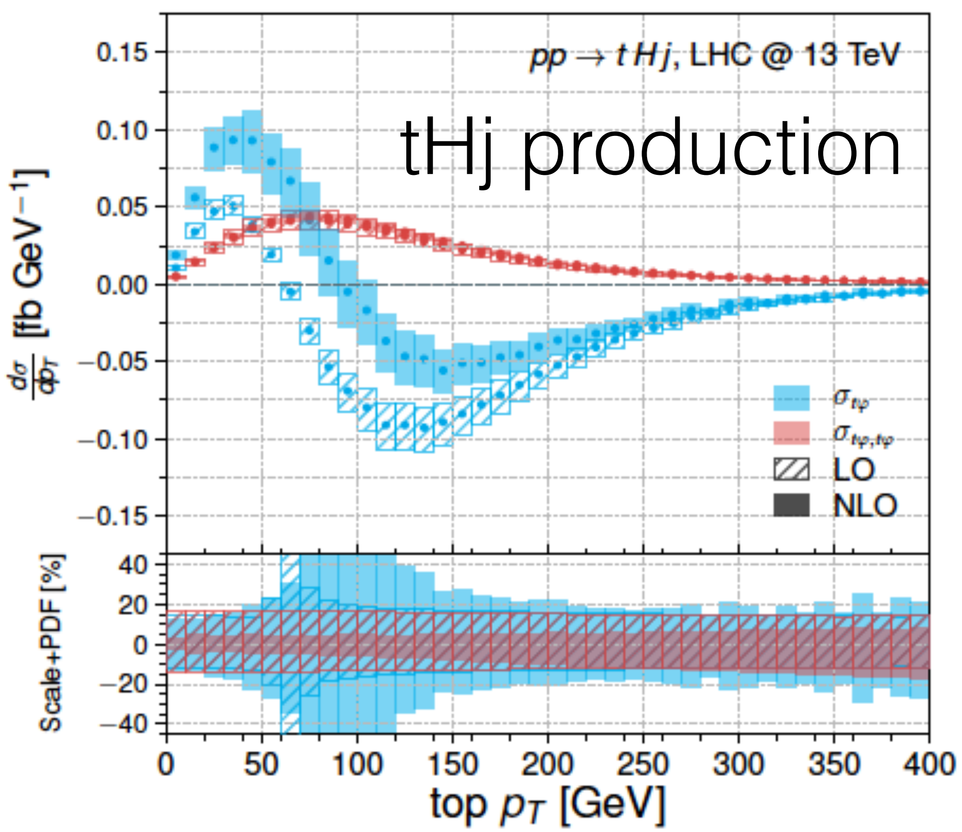
- Validity of the EFT expansion: $E<\Lambda$
  - Ensure results are not dominated by high energy regions
  - Report limits as a function of the max scale probed Contino et al arXiv:1604.06444
- Range of Wilson coefficients:
  - The theory: perturbativity, unitarity, linear or non-linear EFT, UV completion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

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

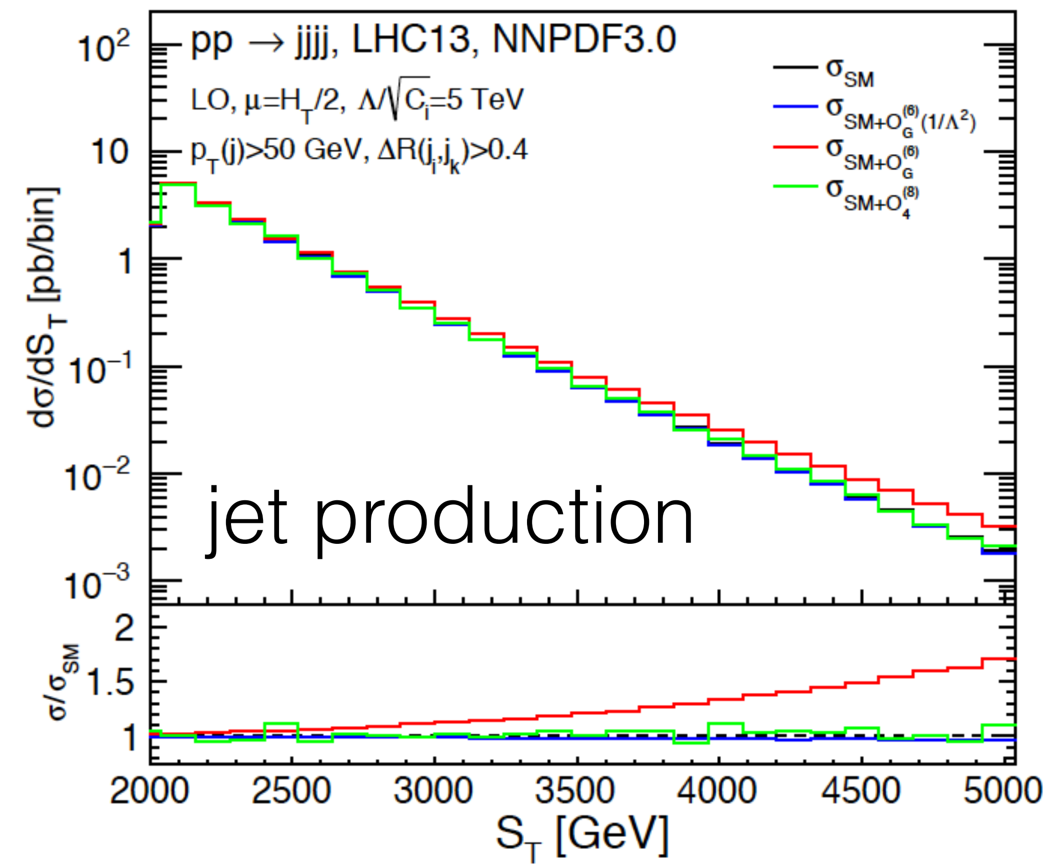
$$C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

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

1)



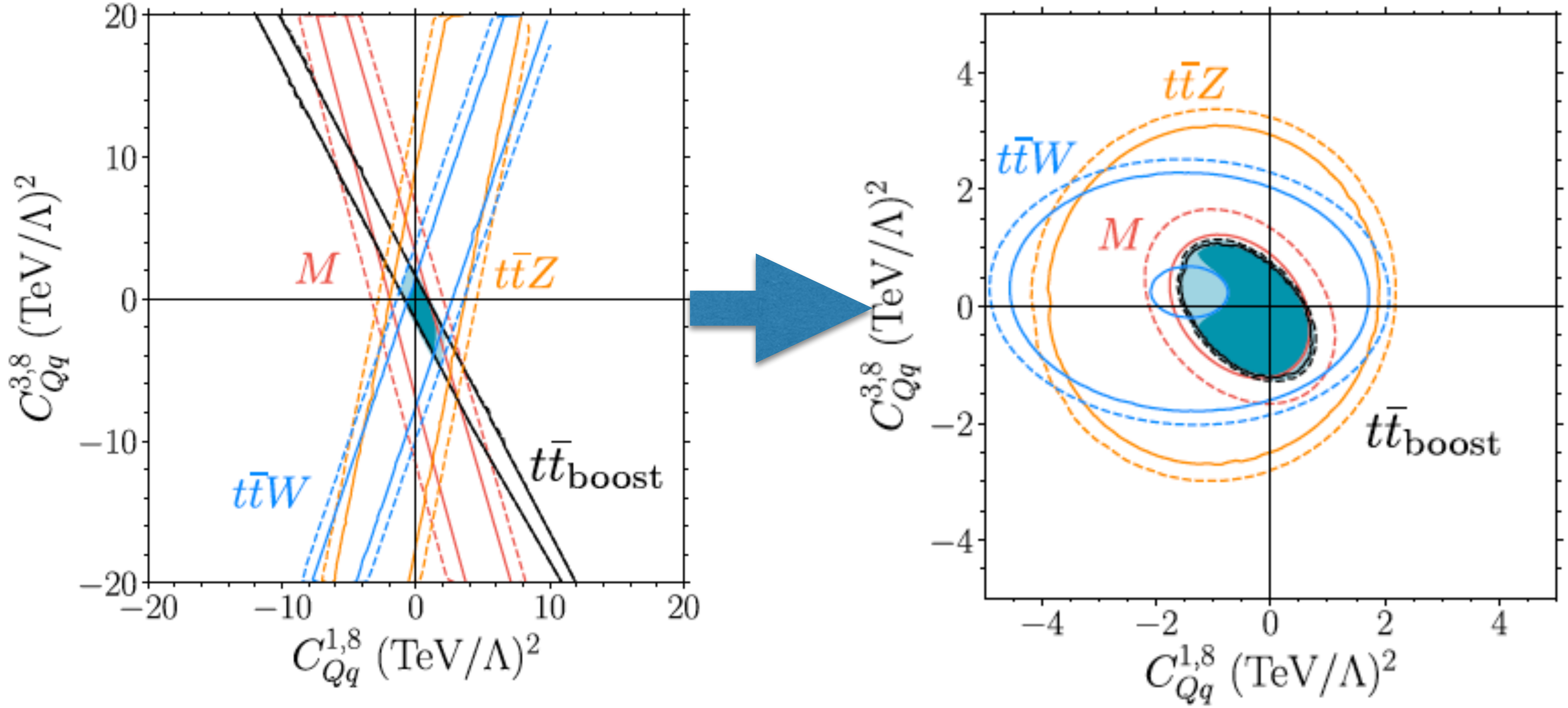
2)



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

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

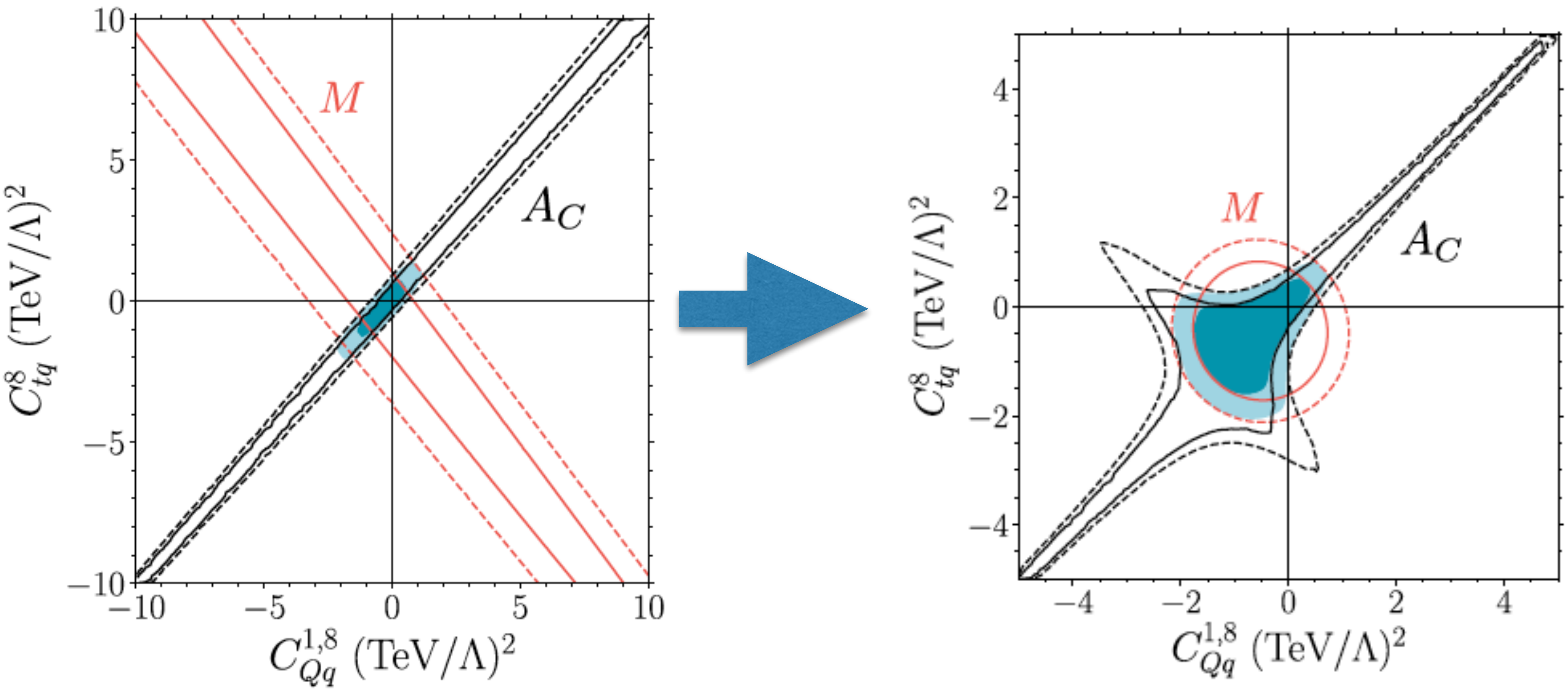
Impact of quadratic terms in top production



$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$
$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i)$$

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

Impact of quadratic terms in top production

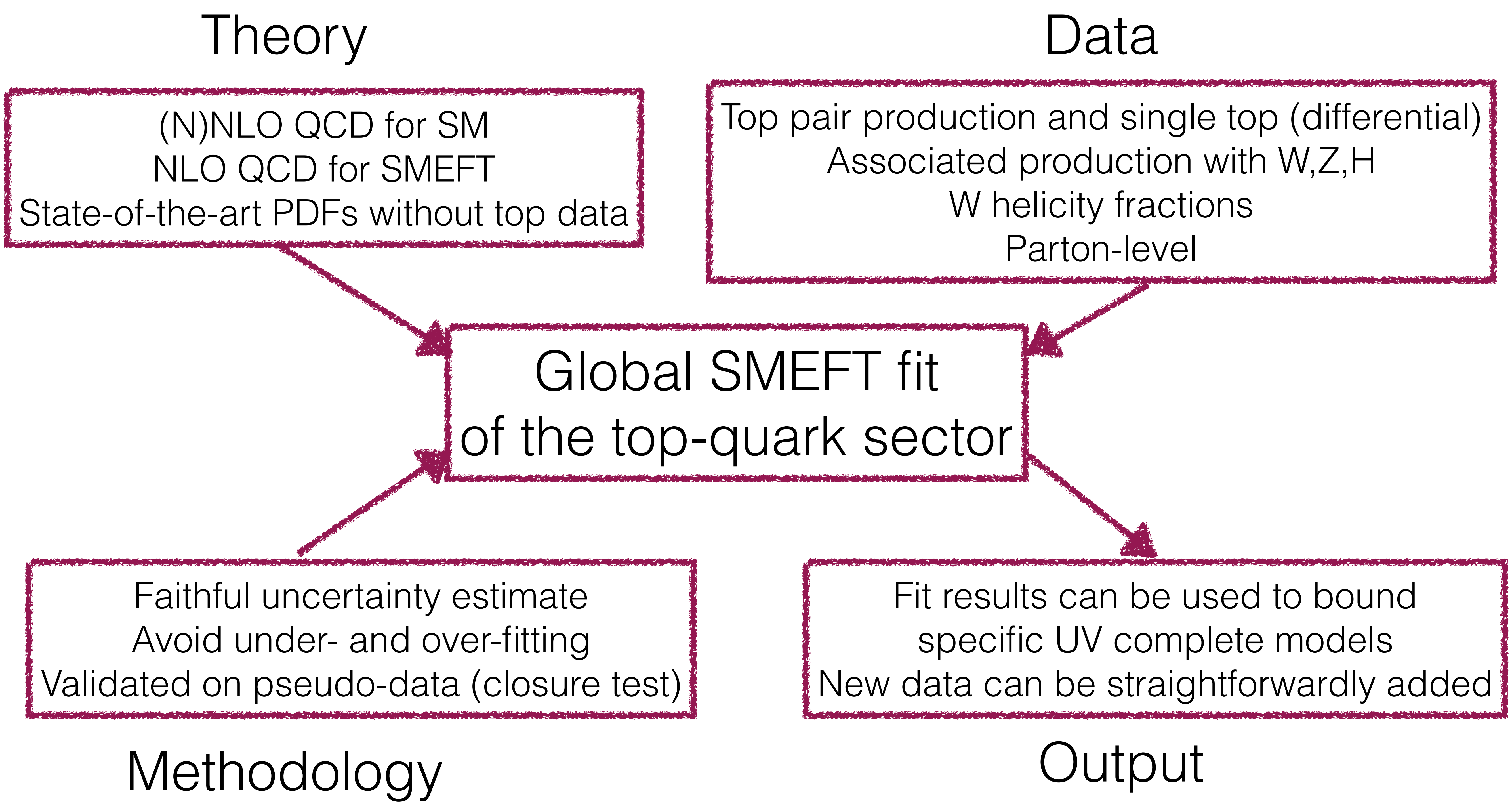


$$O_{tq}^{8} = (\bar{q}_i \gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$$

$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

Global fit Setup



Observables and theory predictions

Data

Top-pair production
W-helicities

4 tops, ttbb, top-pair associated production

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

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

One distribution from each dataset, to avoid double counting

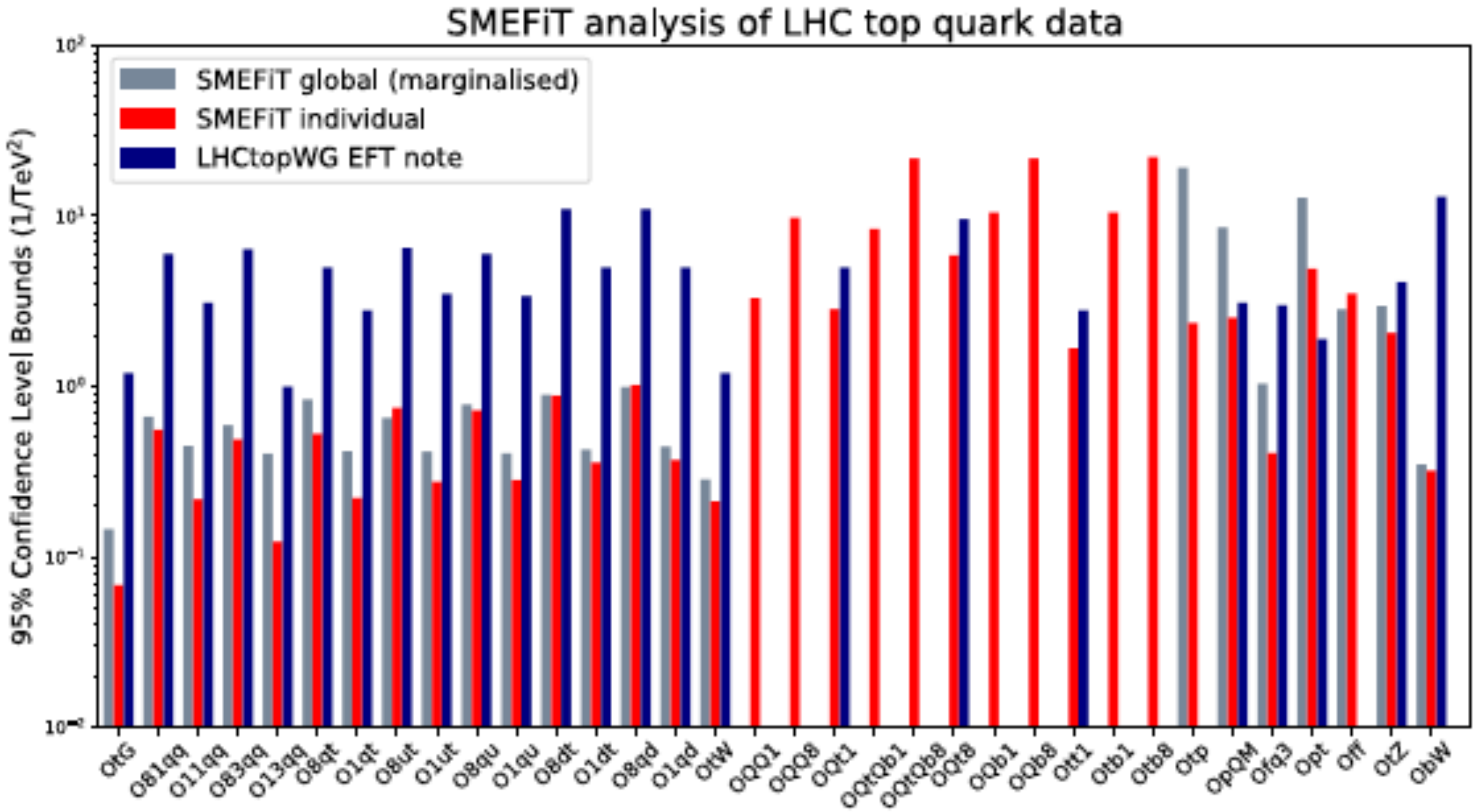
Theoretical predictions

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

Baseline fit includes:

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

Global top fit results (1)

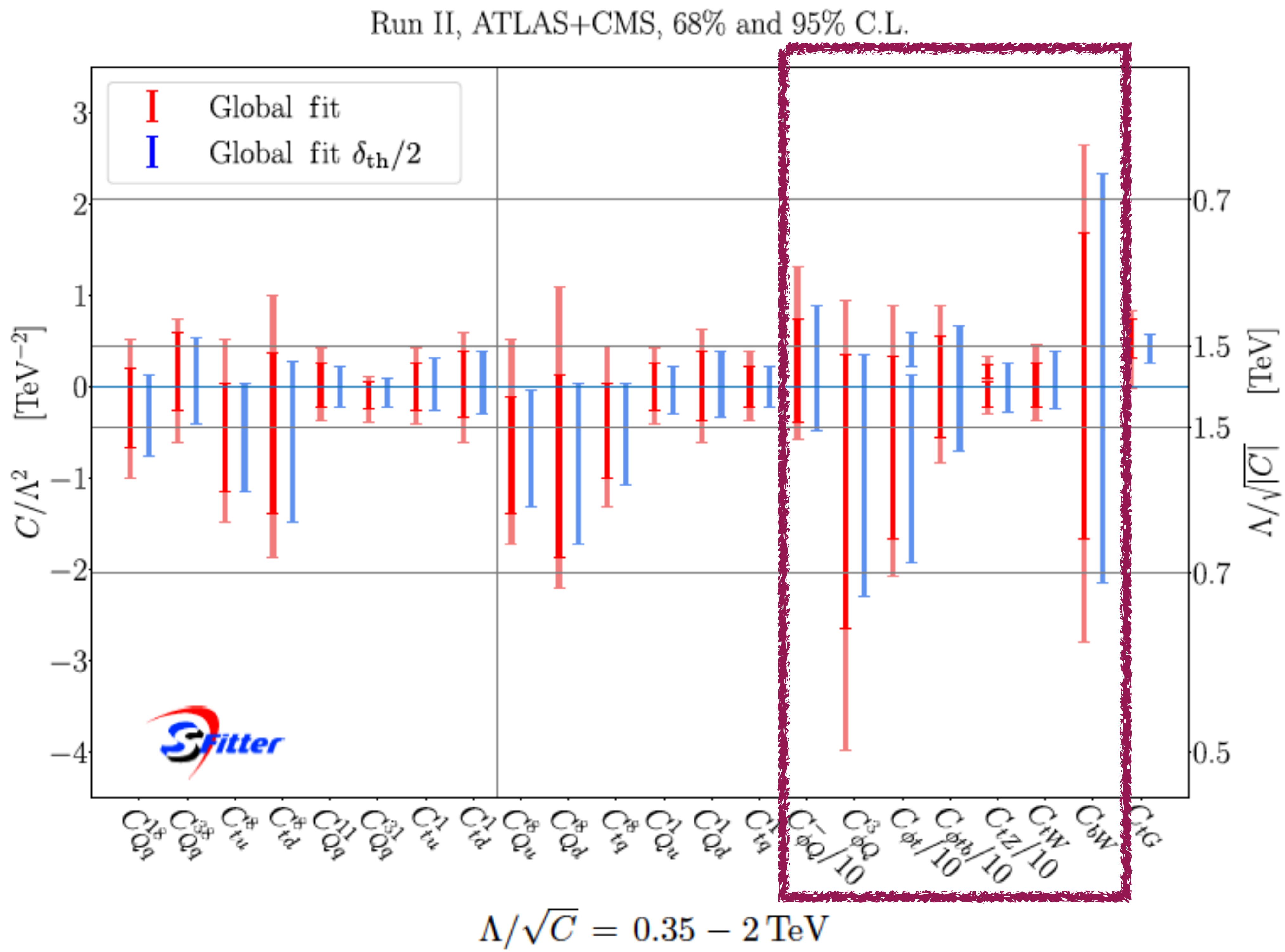


First limits reported for some operators

Improvement for some operators: e.g. O_{tG}, O^{83}_{qq}, O_{bW}

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

Global top fit results (2)



Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606 (SFitter analysis)

Outline

- Introduction to the EFT
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  - Towards global fits for top-Higgs

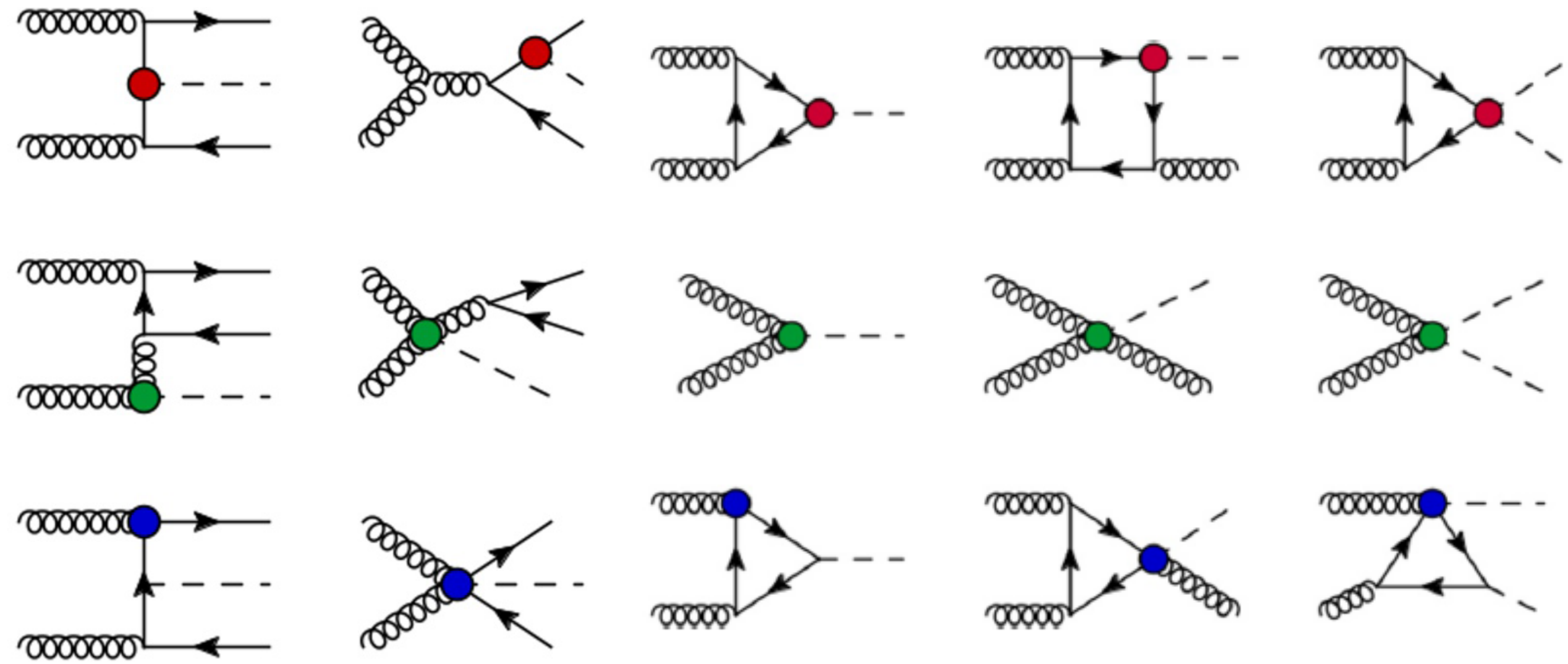
The top-Higgs interface

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

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

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

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



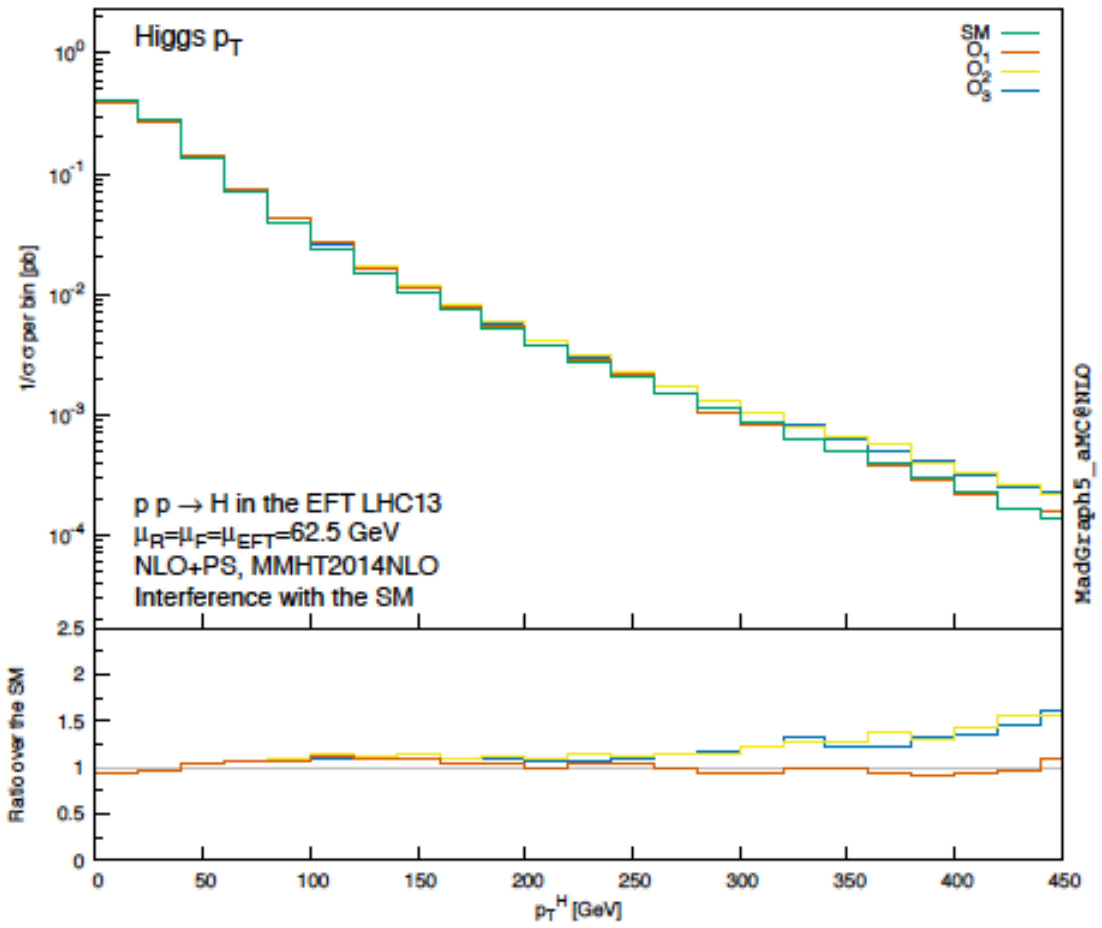
ttH

H, H+j, HH

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

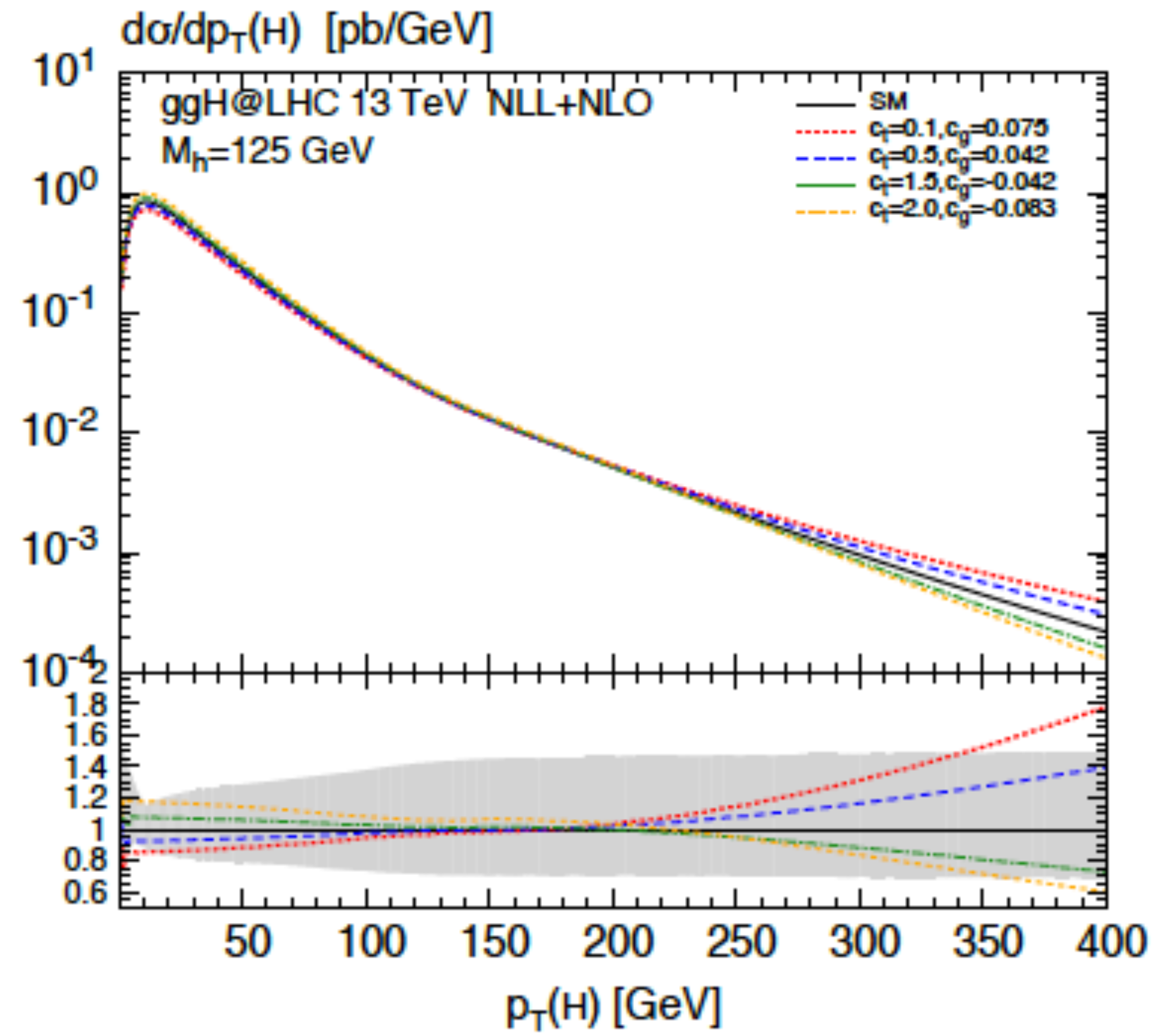
Maltoni, EV, Zhang: arXiv:1607.05330

SMEFT in Higgs production



Higgs p_T

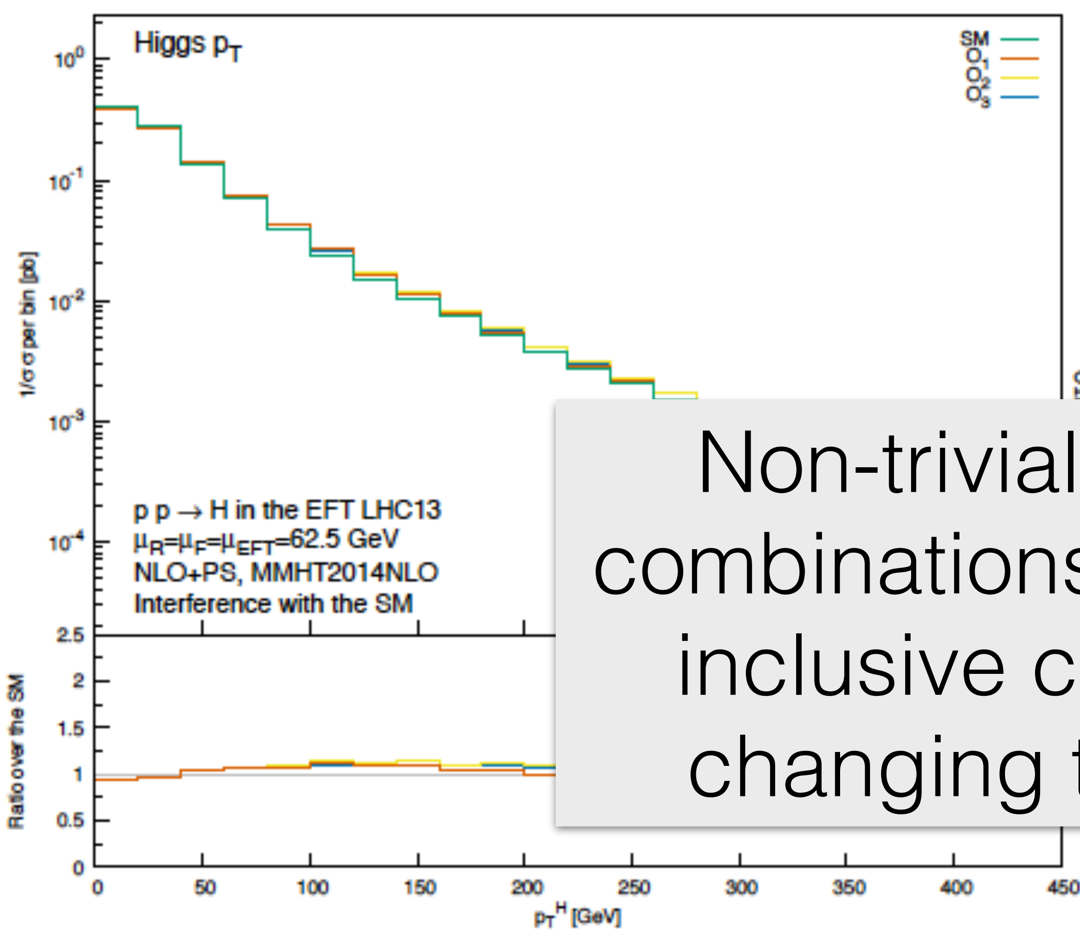
Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

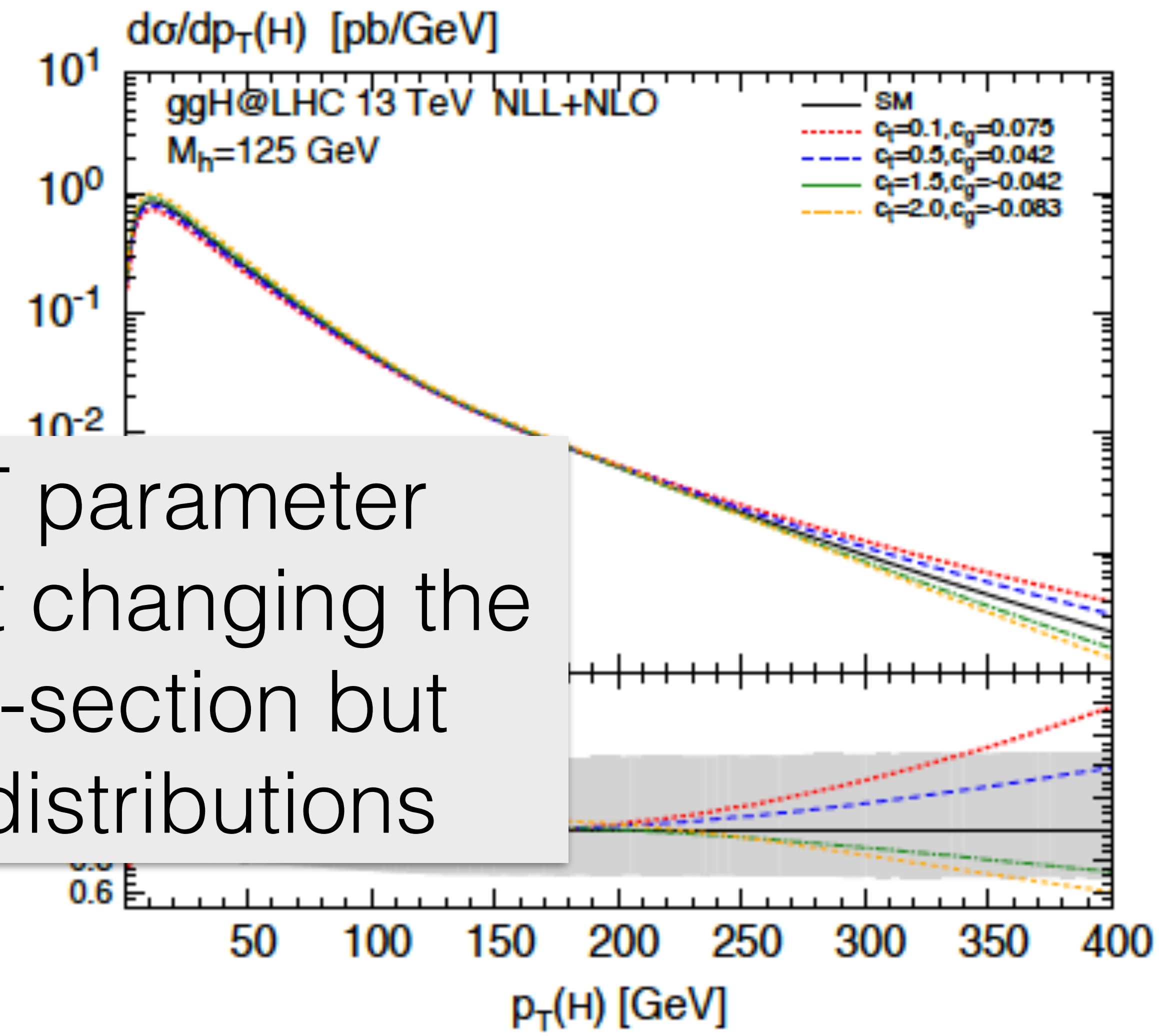


Higgs p_T

Grazzini et al 1612.00283

SMEFT in Higgs production





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

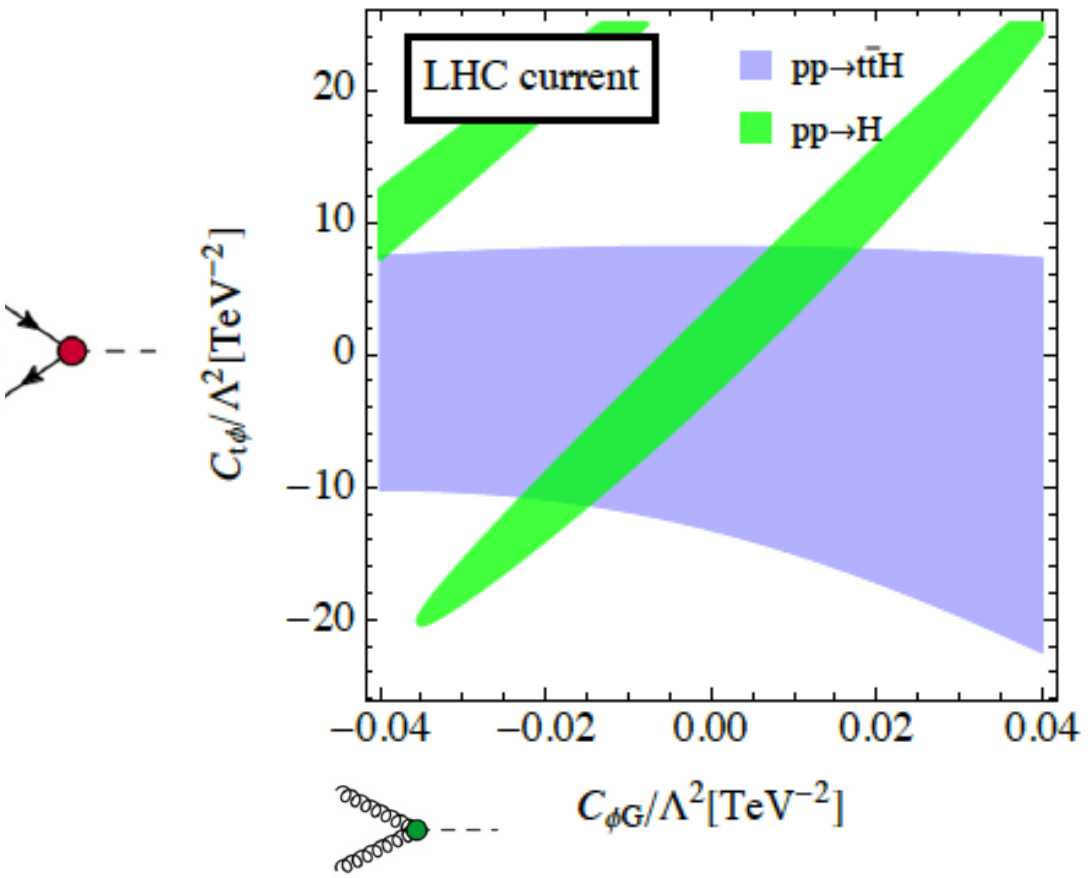
Higgs p_T

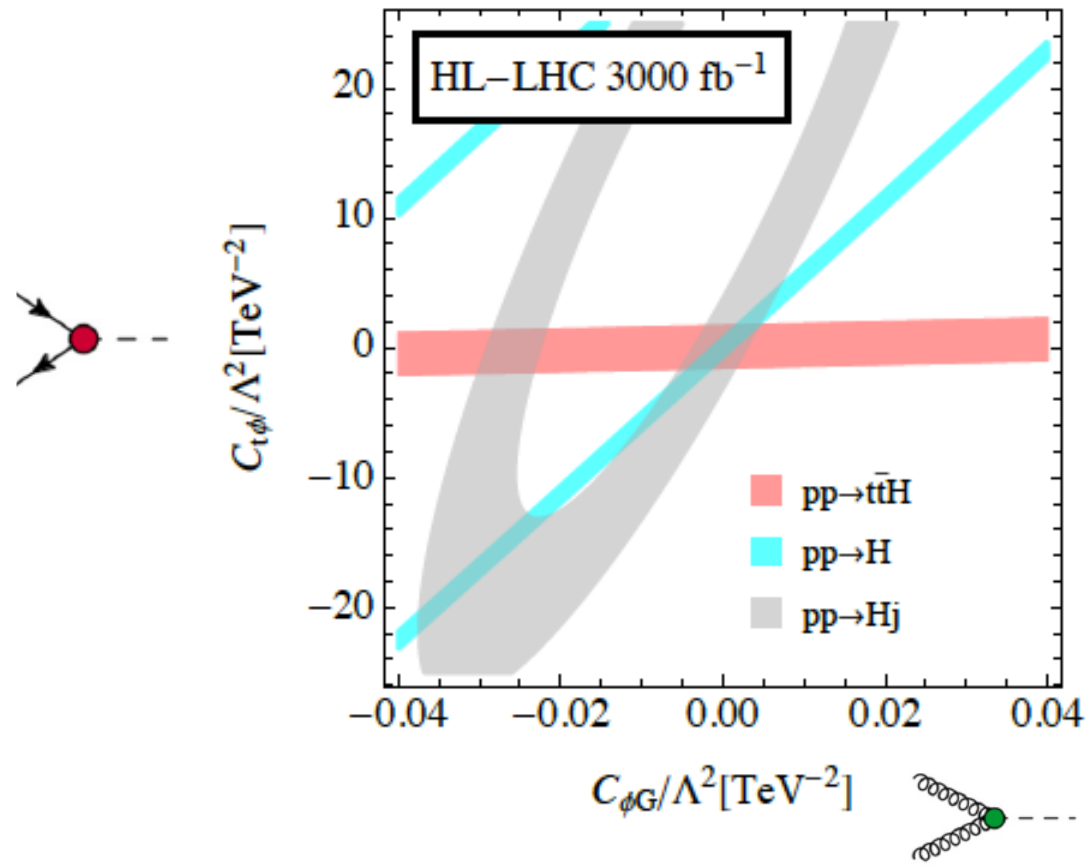
Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

Higgs p_T

Grazzini et al 1612.00283

Present and future prospects





Current limits using LHC Run I measurements

14TeV projection 3000 fb^{-1}

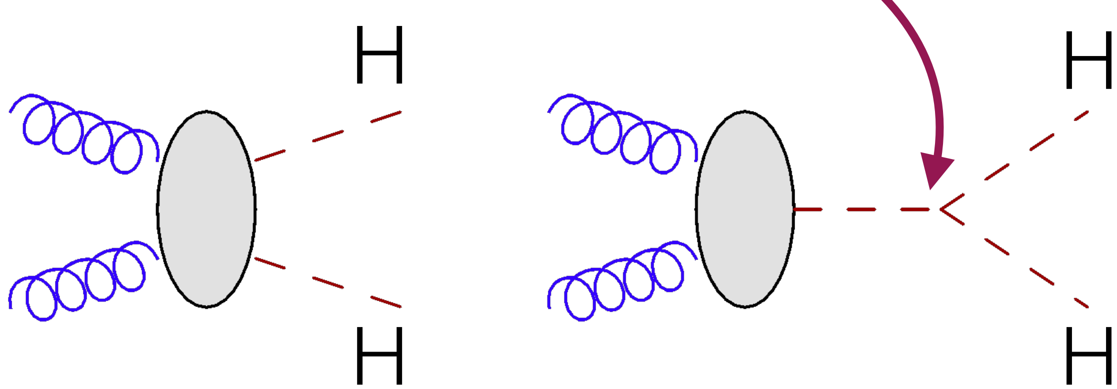
Maltoni, EV, Zhang arXiv:1607.05330

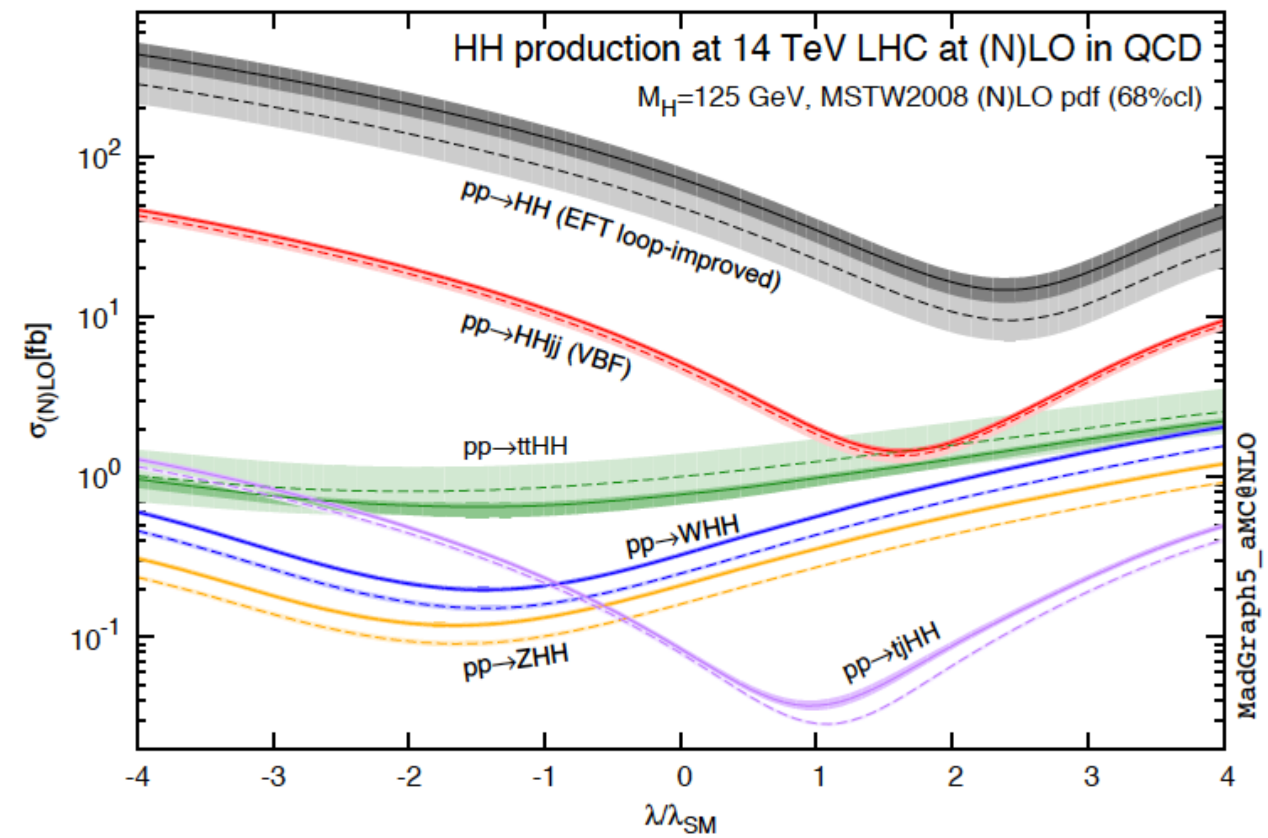
Double Higgs production

The Higgs potential

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

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

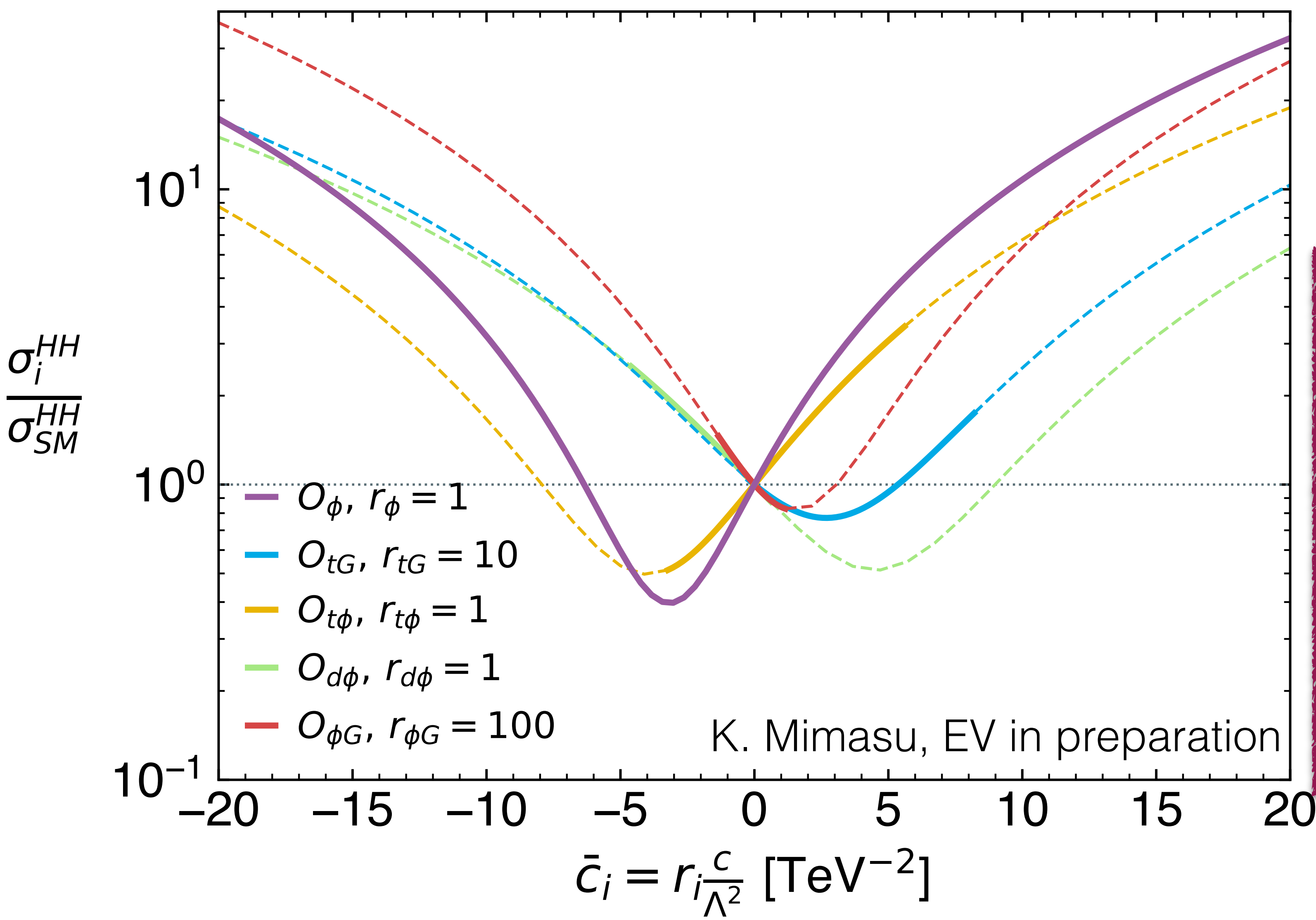




Phys.Lett. B732 (2014) 142-149

A challenging process at the LHC

HH in the EFT

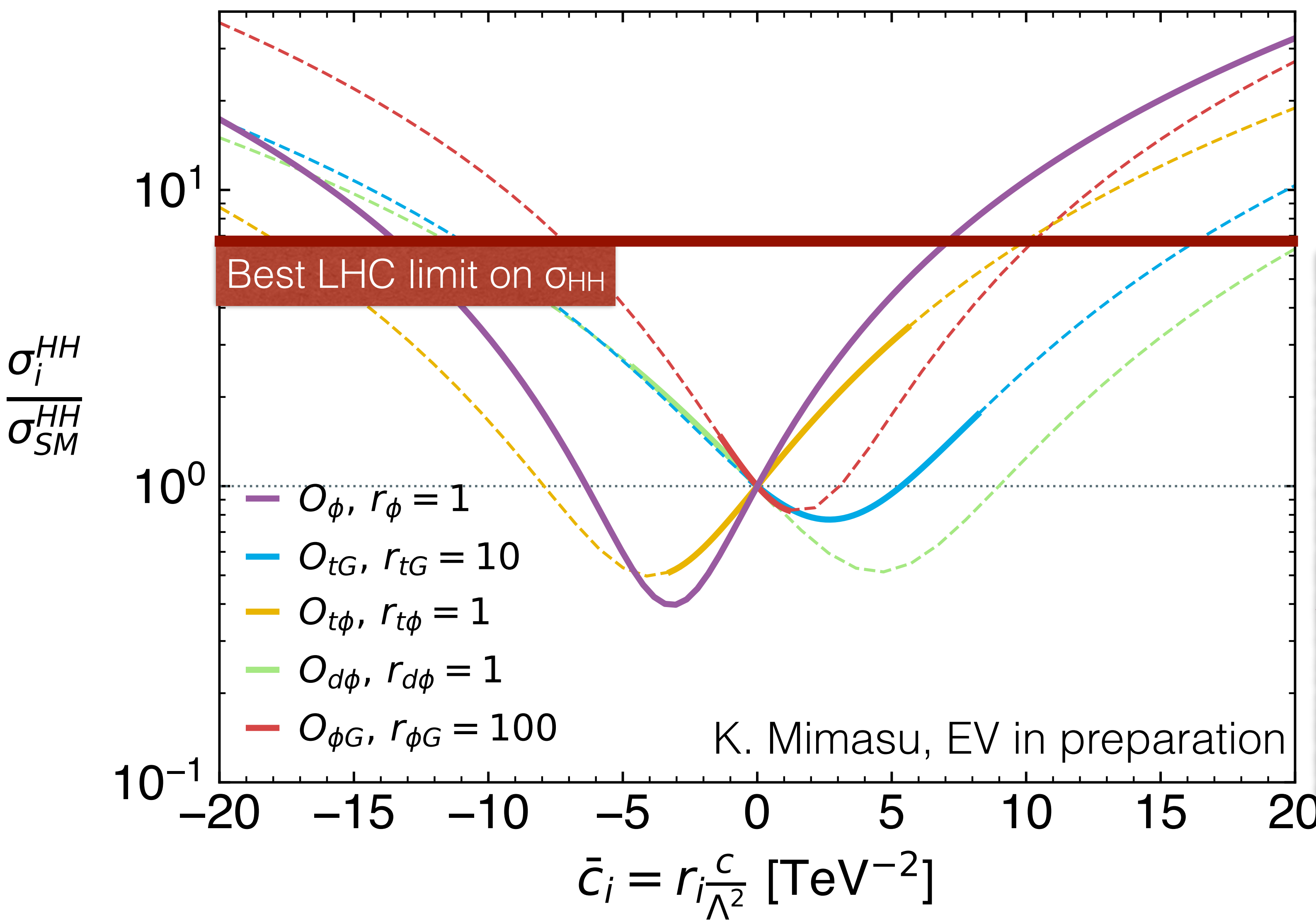


$\mathcal{O}_\varphi$	**cp**	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$

Constrained from other processes:

$\mathcal{O}_{t\varphi}$	**ctp**	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{tG}$	**ctG**	$ig_s\,(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi d}$	**cdp**	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi G}$	**cpG**	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)G^{\mu\nu}_A\,G^A_{\mu\nu}$

HH in the EFT



$\mathcal{O}_\varphi$ **cp** $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$

Constrained from other processes:

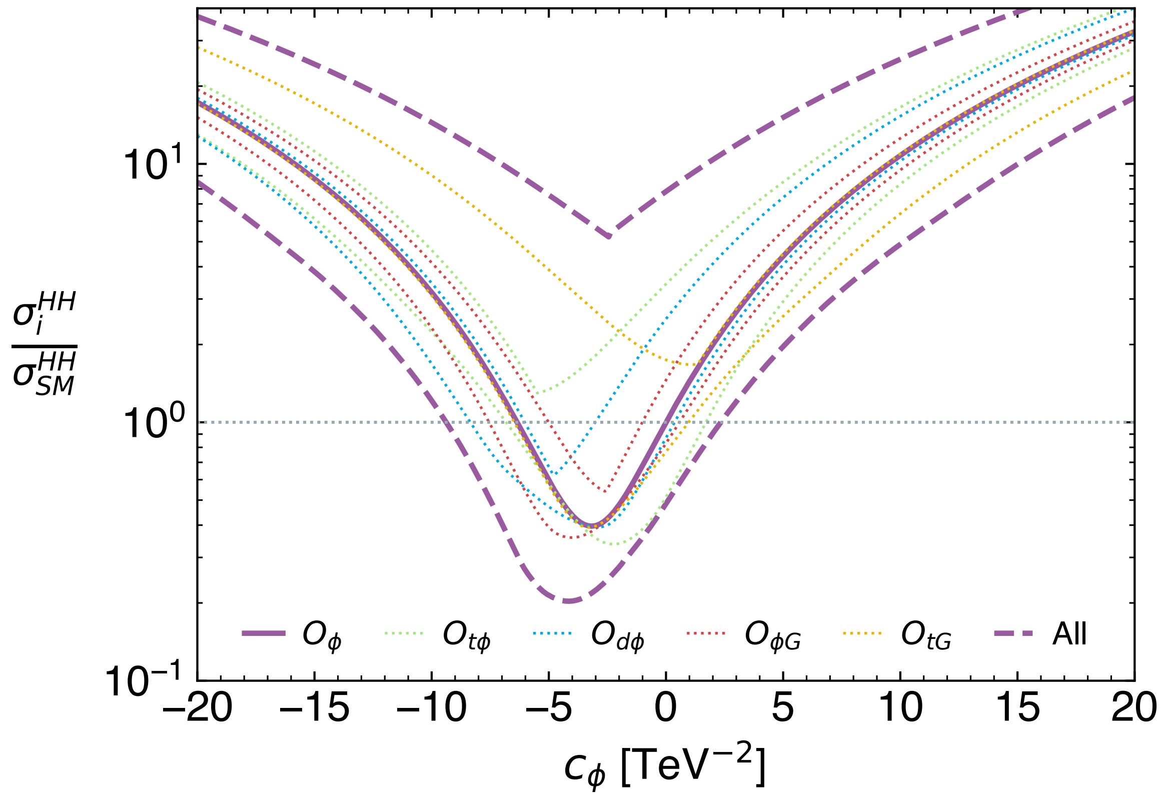
$\mathcal{O}_{t\varphi}$ **ctp** $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$

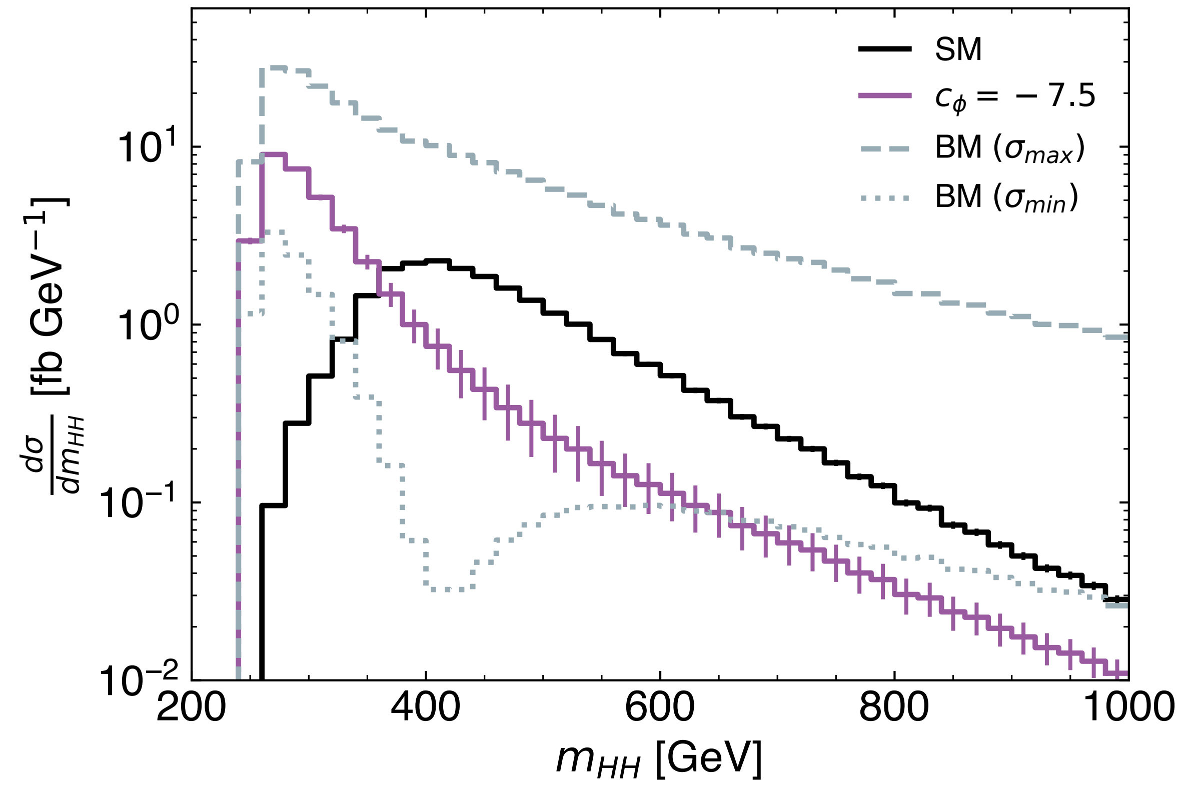
$\mathcal{O}_{tG}$ **ctG** $ig_s\left(\bar{Q}\tau^{\mu\nu}T_A\,t\right)\tilde{\varphi}\,G^A_{\mu\nu} + \text{h.c.}$

$\mathcal{O}_{\varphi d}$ **cdp** $\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$

$\mathcal{O}_{\varphi G}$ **cpG** $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)G_A^{\mu\nu}\,G^A_{\mu\nu}$

Differential distributions in HH

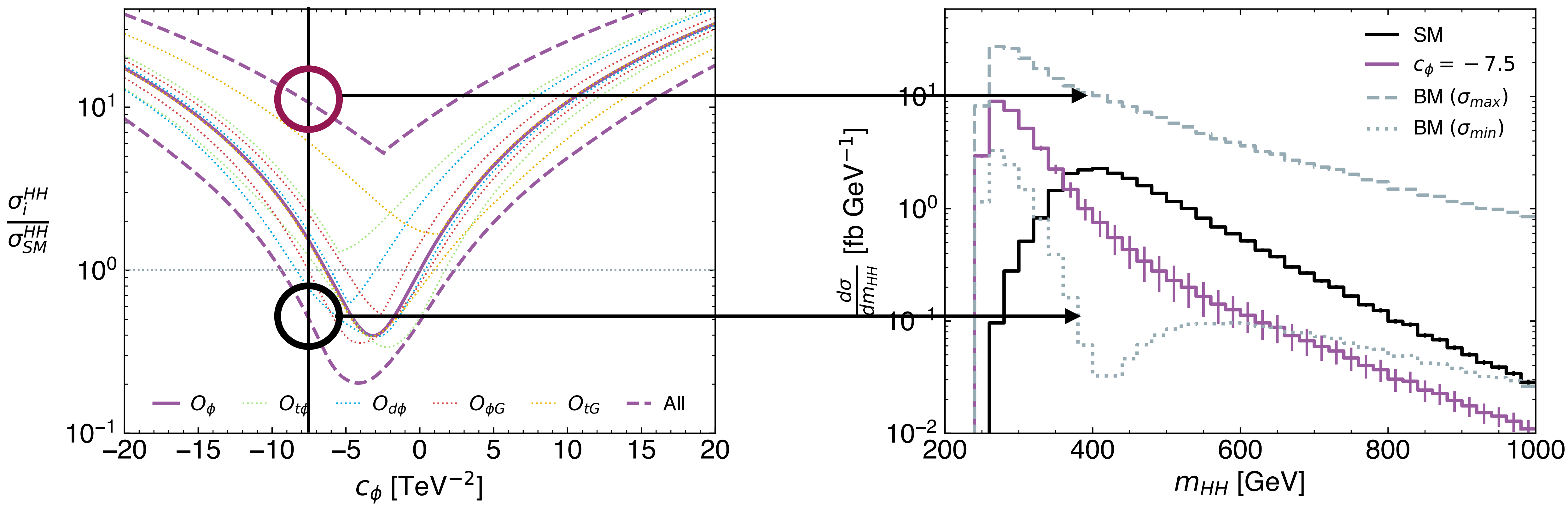




Variation of other parameters gives a large range of cross-sections for given trilinear coupling

Large deviation in the differential shapes

K. Mimasu, EV in preparation



Variation of other parameters gives a large range of cross-sections for given trilinear coupling

Large deviation in the differential shapes

K. Mimasu, EV in preparation

Adding Higgs data to a global fit

New data

Run I & 2 signal strengths (CMS+ATLAS):
gluon fusion
VH
VBF
ttH
H decays

New predictions

NLO QCD for all production
Full decay width computation
Including corrections to V widths

New operators

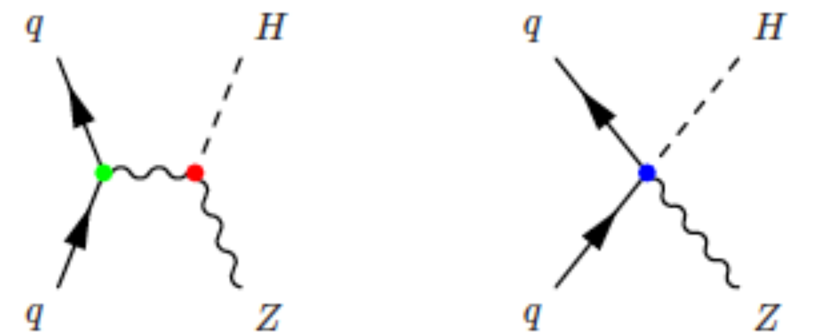
Bosonic					
$\mathcal{O}_{\phi G}$	OpG	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right) G_A^{\mu\nu}\, G^A_{\mu\nu}$	$\mathcal{O}_{\phi B}$	OpB	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$
$\mathcal{O}_{\phi W}$	OpW	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}_{\phi WB}$	OpWB	$(\phi^\dagger\tau_I\phi)\, B^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{\phi d}$	Opd	$\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$	$\mathcal{O}_{\phi D}$	OpD	$(\phi^\dagger D^\mu\phi)^\dagger(\phi^\dagger D_\mu\phi)$

2 Fermions					
$\mathcal{O}_{t\varphi}$	Otp	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, t\, \tilde{\phi} + \text{h.c.}$	$\mathcal{O}_{tG}$	OtG	$igs\,(\bar{Q}\tau^{\mu\nu}\, T_A\, t)\, \tilde{\phi}\, G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{b\varphi}$	Obp	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, b\, \phi + \text{h.c.}$	$\mathcal{O}_{c\varphi}$	Ocp	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, c\, \phi + \text{h.c.}$
$\mathcal{O}_{\tau\varphi}$	Otap	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, \tau\, \tilde{\phi} + \text{h.c.}$	$\mathcal{O}_{tW}$	OtW	$i(\bar{Q}\tau^{\mu\nu}\, \tau_I\, t)\, \tilde{\phi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tB}$	-	$i(\bar{Q}\tau^{\mu\nu}\, t)\, \tilde{\phi}\, B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{tZ}$	OtZ	$-\sin\theta_W \mathcal{O}_{tB} + \cos\theta_W \mathcal{O}_{tW}$
$\mathcal{O}^{(1)}_{\varphi l_1}$	Opl1	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{l}_1\, \gamma^\mu\, l_1)$	$\mathcal{O}^{(3)}_{\varphi l_1}$	O3pl1	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{l}_1\, \gamma^\mu\, \tau^I l_1)$
$\mathcal{O}^{(1)}_{\varphi l_2}$	Opl2	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{l}_2\, \gamma^\mu\, l_2)$	$\mathcal{O}^{(3)}_{\varphi l_2}$	O3pl2	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{l}_2\, \gamma^\mu\, \tau^I l_2)$
$\mathcal{O}^{(1)}_{\varphi l_3}$	Opl3	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{l}_3\, \gamma^\mu\, l_3)$	$\mathcal{O}^{(3)}_{\varphi l_3}$	O3pl3	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{l}_3\, \gamma^\mu\, \tau^I l_3)$
$\mathcal{O}_{\varphi e}$	Ope	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{e}\, \gamma^\mu\, e)$	$\mathcal{O}_{\varphi\mu}$	Opmu	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{\mu}\, \gamma^\mu\, \mu)$
$\mathcal{O}_{\varphi\tau}$	Opta	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{\tau}\, \gamma^\mu\, \tau)$			
$\mathcal{O}^{(1)}_{\varphi q_i}$	-	$\sum_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{q}_i\, \gamma^\mu\, q_i)$	$\mathcal{O}^{(3)}_{\varphi q_i}$	O3pq	$\sum_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{q}_i\, \gamma^\mu\, \tau^I q_i)$
$\mathcal{O}^{(1)}_{\varphi Q}$	-	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{Q}\, \gamma^\mu\, Q)$	$\mathcal{O}^{(3)}_{\varphi Q}$	O3pQ3	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{Q}\, \gamma^\mu\, \tau^I Q)$
$\mathcal{O}^{(-)}_{\varphi q_i}$	OpqMi	$\mathcal{O}^{(1)}_{\varphi q_i} - \mathcal{O}^{(3)}_{\varphi q_i}$	$\mathcal{O}^{(-)}_{\varphi Q}$	OpQM	$\mathcal{O}^{(1)}_{\varphi Q} - \mathcal{O}^{(3)}_{\varphi Q}$
$\mathcal{O}_{\varphi u_i}$	Opui	$\sum_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{u}_i\, \gamma^\mu\, u_i)$	$\mathcal{O}_{\varphi d_i}$	Opdi	$\sum_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{d}_i\, \gamma^\mu\, d_i)$
$\mathcal{O}_{\phi t}$	Opt	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{t}\, \gamma^\mu\, t)$			
$\mathcal{O}_{ll}$	Oll	$(l\gamma_\mu l)(l\gamma^\mu l)$			

24 new d.o.f.s

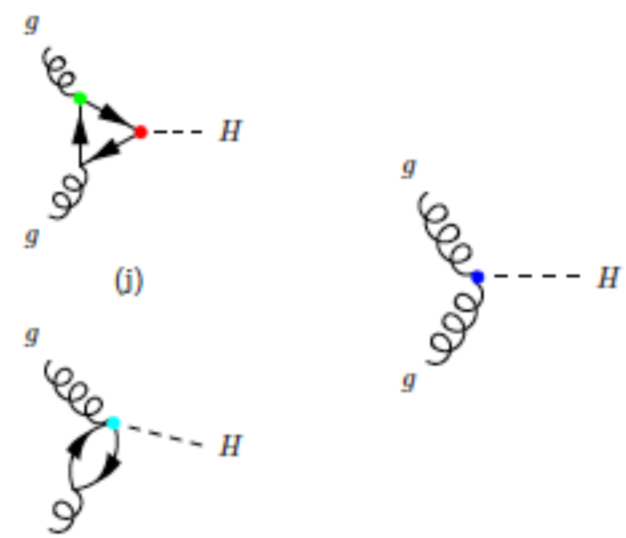
Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang in preparation

How do all these operators enter?



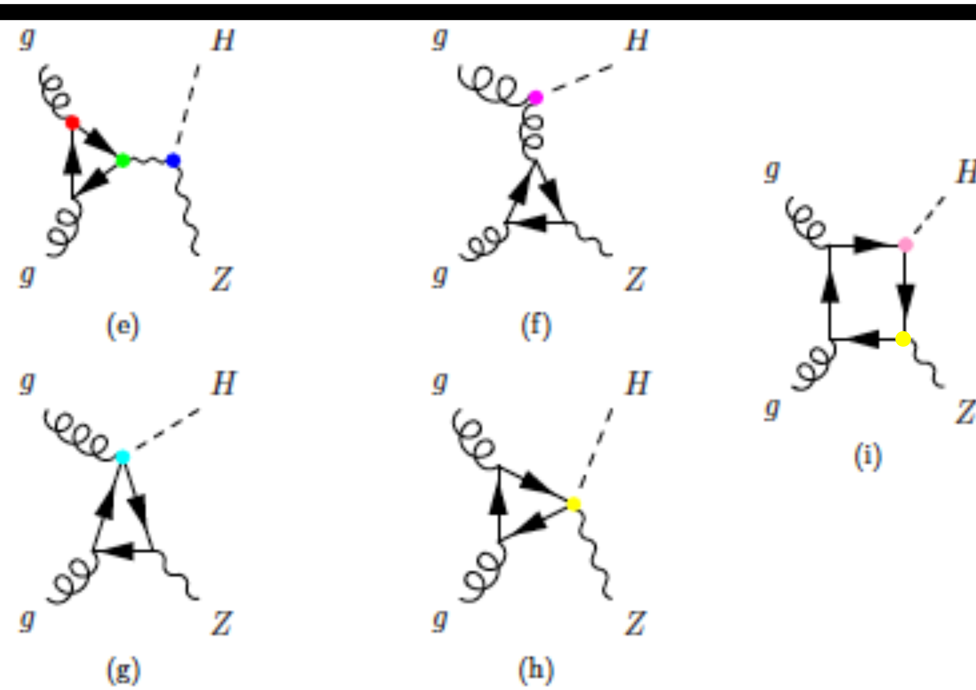
ZH

$\mathcal{O}_{\varphi W}$, $\mathcal{O}_{\varphi B}$, $\mathcal{O}_{\varphi D}$, $\mathcal{O}^{(3)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi Q}$, $\mathcal{O}^{(3)}_{\varphi Q}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}_{\varphi WB}$,
$\mathcal{O}^{(3)}_{\varphi l_1}$, $\mathcal{O}^{(3)}_{\varphi l_2}$, $\mathcal{O}_{\varphi u_i}$, $\mathcal{O}_{\varphi d_i}$



ggH

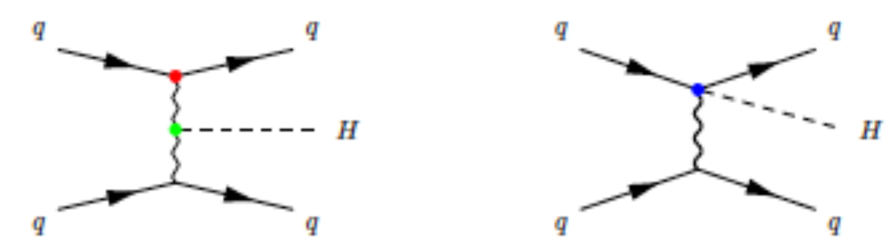
$\mathcal{O}_{\varphi D}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}^{(3)}_{\varphi l_1}$, $\mathcal{O}^{(3)}_{\varphi l_2}$, $\mathcal{O}_{t\varphi}$, $\mathcal{O}_{tG}$, $\mathcal{O}_{\varphi G}$, $\mathcal{O}_{ll}$



ZH

$\mathcal{O}_{\varphi D}$, $\mathcal{O}^{(1)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi Q}$, $\mathcal{O}^{(3)}_{\varphi Q}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}^{(3)}_{\varphi l_1}$, $\mathcal{O}^{(3)}_{\varphi l_2}$,
$\mathcal{O}_{\varphi u_i}$, $\mathcal{O}_{\varphi t}$, $\mathcal{O}_{\varphi d_i}$, $\mathcal{O}_{t\varphi}$, $\mathcal{O}_{tG}$, $\mathcal{O}_{\varphi G}$, $\mathcal{O}_{ll}$

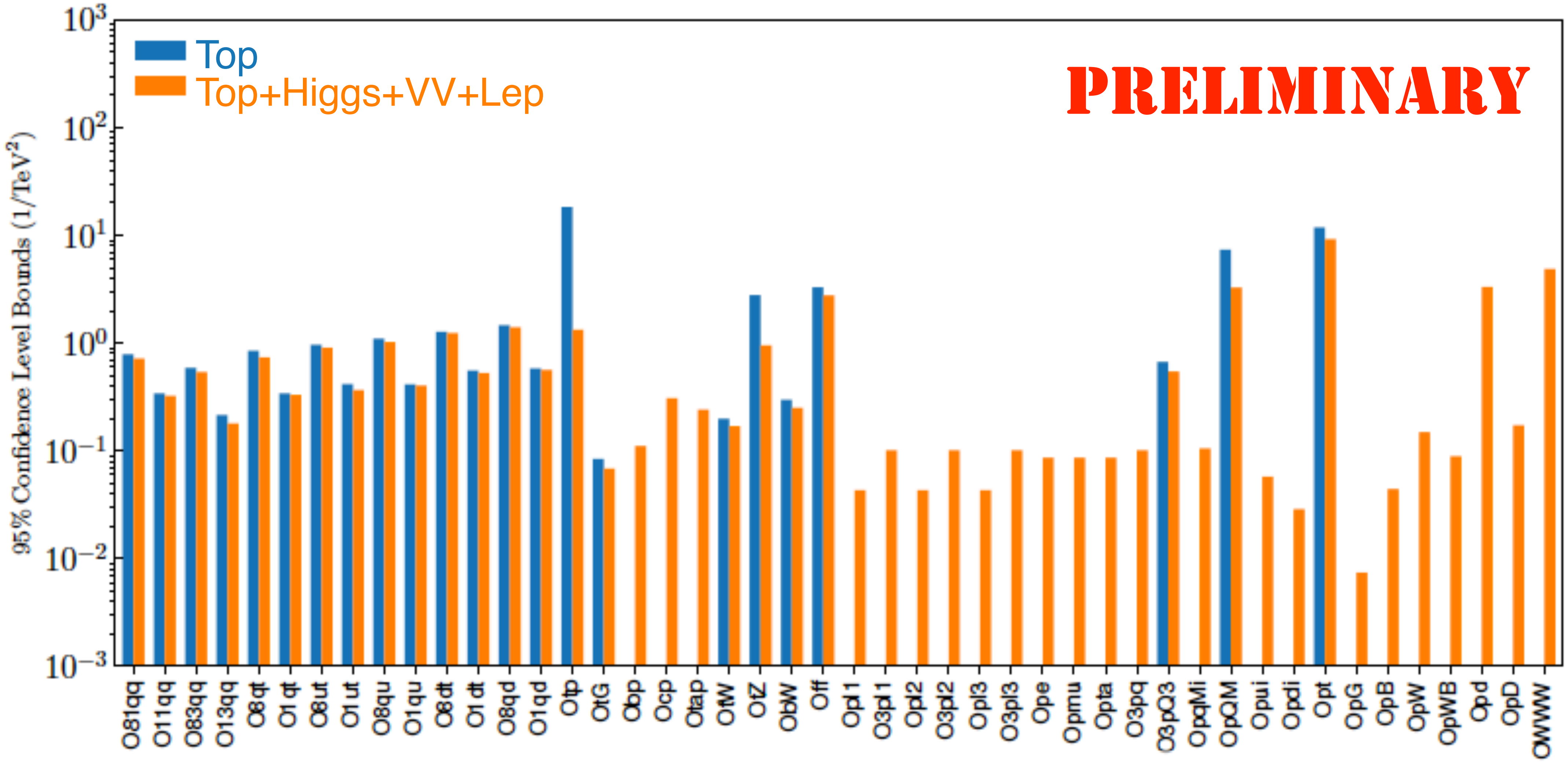
VBF



$\mathcal{O}_{\varphi W}$, $\mathcal{O}_{\varphi B}$, $\mathcal{O}_{\varphi D}$, $\mathcal{O}^{(3)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi Q}$, $\mathcal{O}^{(3)}_{\varphi Q}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}_{\varphi WB}$,
$\mathcal{O}^{(3)}_{\varphi l_1}$, $\mathcal{O}^{(3)}_{\varphi l_2}$, $\mathcal{O}_{\varphi u_i}$, $\mathcal{O}_{\varphi d_i}$

from L. Mantani

Towards a global Higgs & Top fit



New operators

Ethier, Maltoni, Mantani, Nocera, Rojo, EV and Zhang in preparation

Impact of various datasets

PRELIMINARY

		Processes							
Class	Coefficient	tt	ttV	t	tV	Hrun1	Hrun2	Hdiff	VV
2L2H	O81qq	81.7(96.0)	16.4(2.4)	×(×)	×(×)	0.1(-0.0)	1.7(0.8)	0.1(0.7)	×(×)
	O11qq	100.0(98.8)	0.0(0.5)	×(×)	×(×)	×(0.0)	0.0(0.6)	×(0.2)	×(×)
	O83qq	48.3(46.2)	25.9(50.6)	23.9(2.6)	0.0(0.3)	0.1(-0.0)	1.7(0.2)	0.1(0.1)	×(×)
	O13qq	0.4(13.8)	0.0(1.2)	96.5(82.7)	3.1(2.1)	×(-0.1)	0.0(0.1)	×(0.2)	×(×)
	O8qt	56.1(47.0)	38.9(31.4)	×(×)	×(×)	0.3(0.2)	4.5(12.2)	0.2(9.2)	×(×)
	O1qt	100.0(94.6)	0.0(3.3)	×(×)	×(×)	×(0.0)	0.0(1.7)	×(0.4)	×(×)
	O8ut	97.7(97.9)	0.4(0.3)	×(×)	×(×)	0.1(0.0)	1.7(0.8)	0.1(0.9)	×(×)
	O1ut	100.0(98.3)	0.0(0.3)	×(×)	×(×)	×(0.0)	0.0(1.1)	×(0.3)	×(×)
	O8qu	88.8(80.1)	3.6(5.2)	×(×)	×(×)	0.4(0.1)	6.8(8.3)	0.4(6.2)	×(×)
	O1qu	100.0(97.9)	0.0(0.7)	×(×)	×(×)	×(0.0)	0.0(1.1)	×(0.3)	×(×)
	O8dt	95.0(97.9)	1.4(0.7)	×(×)	×(×)	0.2(0.0)	3.3(0.9)	0.2(0.5)	×(×)
	O1dt	100.0(98.9)	0.0(0.2)	×(×)	×(×)	×(0.0)	0.0(0.7)	×(0.2)	×(×)
	O8qd	94.3(69.0)	2.6(9.5)	×(×)	×(×)	0.1(0.3)	2.8(12.6)	0.1(8.6)	×(×)
	O1qd	100.0(97.6)	0.0(1.0)	×(×)	×(×)	×(0.0)	0.0(1.2)	×(0.2)	×(×)
2FB	Otp	×(×)	×(×)	×(×)	×(×)	13.7(18.6)	46.2(67.9)	40.1(13.4)	×(×)
	OtG	61.1(23.2)	0.2(0.1)	×(×)	×(×)	5.9(10.4)	17.5(29.5)	15.2(36.8)	×(×)
	Obp	×(×)	×(×)	×(×)	×(×)	26.6(26.8)	73.4(73.2)	×(×)	×(×)
	Ocp	×(×)	×(×)	×(×)	×(×)	26.8(26.3)	73.2(73.7)	×(×)	×(×)
	Otap	×(×)	×(×)	×(×)	×(×)	39.1(38.5)	60.9(61.5)	×(×)	×(×)
	OtW	9.1(0.4)	0.0(0.0)	0.4(0.0)	0.2(0.0)	18.9(20.8)	71.5(78.7)	×(×)	×(×)
	OtZ	×(×)	0.0(0.0)	×(×)	0.0(0.0)	21.0(21.0)	79.0(79.0)	×(×)	×(×)
	O3pQ3	×(0.0)	0.0(0.0)	80.0(4.7)	14.3(0.8)	1.2(18.2)	4.5(76.1)	0.0(0.1)	×(×)
	OpQM	×(×)	41.8(0.0)	×(×)	0.6(0.0)	11.9(20.0)	45.7(79.9)	0.0(0.0)	×(×)
	Opt	×(×)	64.5(0.0)	×(×)	0.2(0.0)	7.4(21.0)	27.9(79.0)	0.0(0.0)	×(×)
B	OpG	×(×)	×(×)	×(×)	×(×)	15.3(15.5)	42.9(42.3)	41.8(42.2)	×(×)
	OpB	×(×)	×(×)	×(×)	×(×)	21.0(21.0)	79.0(79.0)	0.0(0.0)	×(×)
	OpW	×(×)	×(×)	×(×)	×(×)	21.0(21.1)	78.9(78.9)	0.0(0.0)	×(×)
	Opd	×(×)	×(×)	×(×)	×(×)	25.4(27.4)	67.2(72.6)	7.4(0.0)	×(×)
	OWWW	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	100.0(100.0)
	OpWB	×(×)	×(×)	×(×)	×(×)	21.1(21.1)	78.8(78.8)	0.1(0.1)	0.0(0.0)
	OpD	×(×)	×(×)	×(×)	×(×)	21.1(21.1)	78.8(78.8)	0.1(0.1)	0.0(0.0)

4F mostly top

Top Yukawa
Top Chromomagnetic

ttV couplings
impacted by Higgs

Unique interplay
Lots to learn with more measurements coming in

Ethier, Maltoni, Mantani, Nocera, Rojo, EV and Zhang in preparation

Outlook

- SMEFT is a consistent way to look for new interactions
- Higher-order corrections needed to match SM precision and experimental accuracy
- Progress towards full Monte Carlo automation of NLO QCD corrections

- First global fits results already available: important to include NLO predictions where available and to combine as many processes as possible to extract maximal information

Thank you for your attention