Effective Field Theory at the LHC

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CERN

VBScan Training Event
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Outline

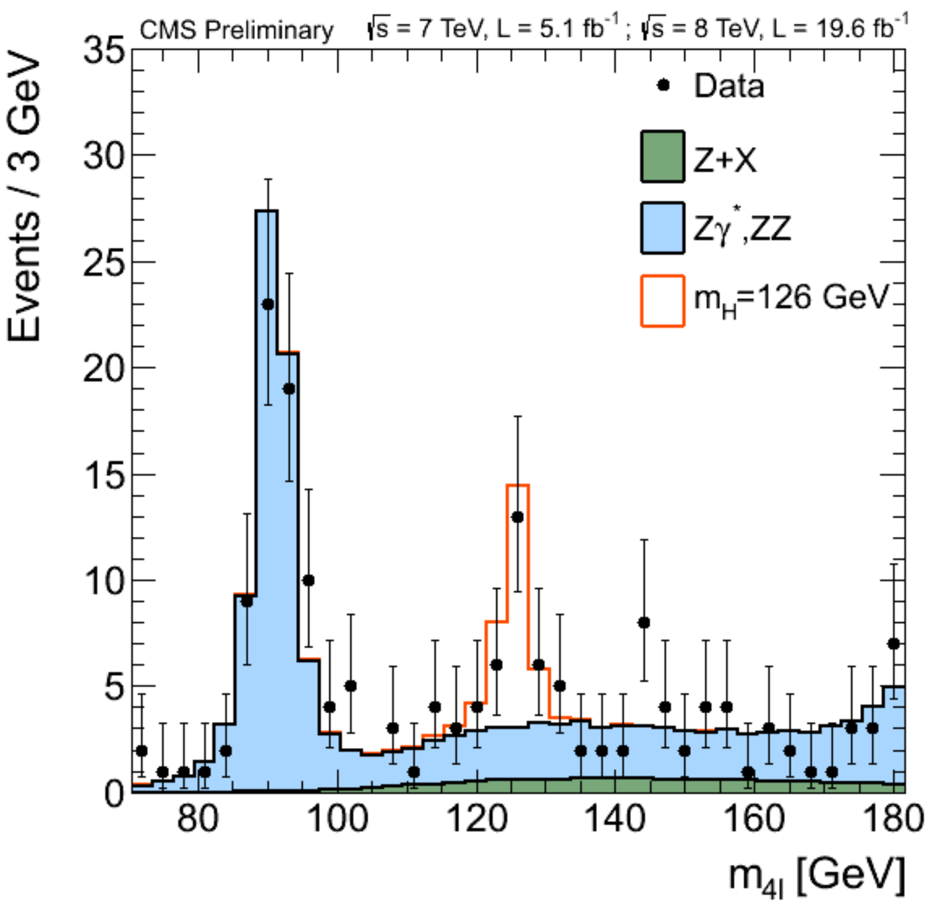
- EFT basics
- Tools and methods
- Physics applications

How to look for new physics?

Model-dependent

SUSY, 2HDM…

New particles

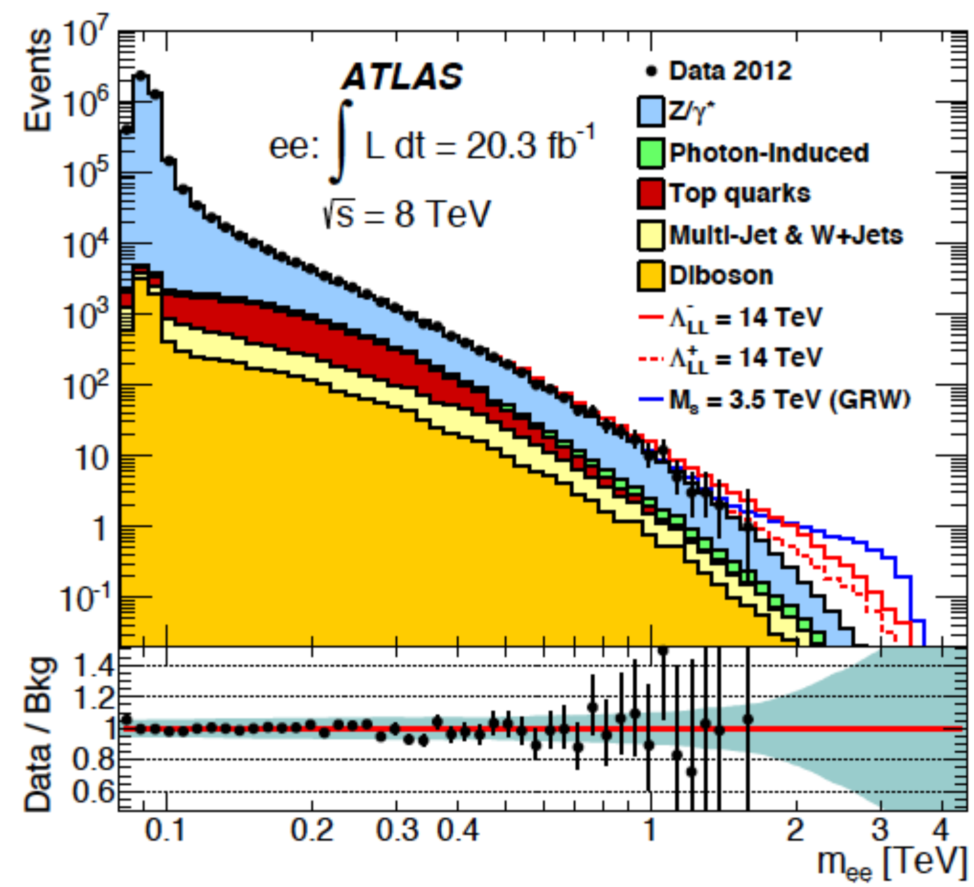


Model-Independent

simplified models,EFT

New Interactions of SM particles

anomalous couplings, EFT



Deviations in tails

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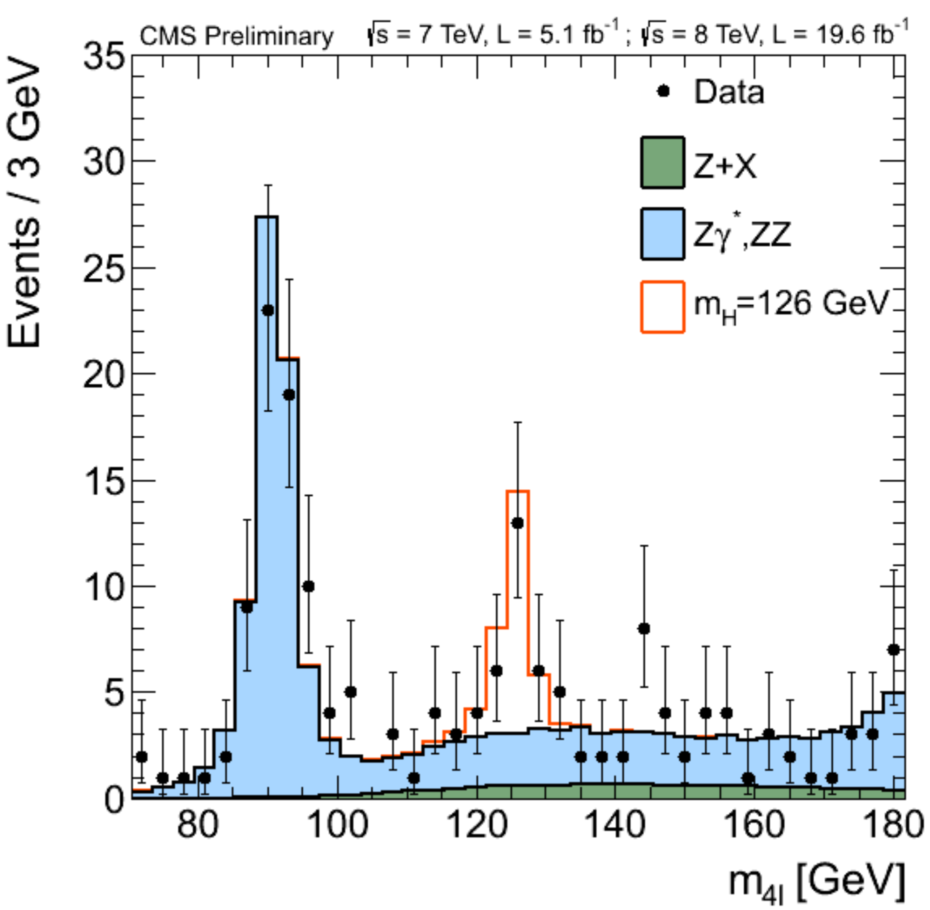
How to look for new physics?

Model-dependent

SUSY, 2HDM…

New particles



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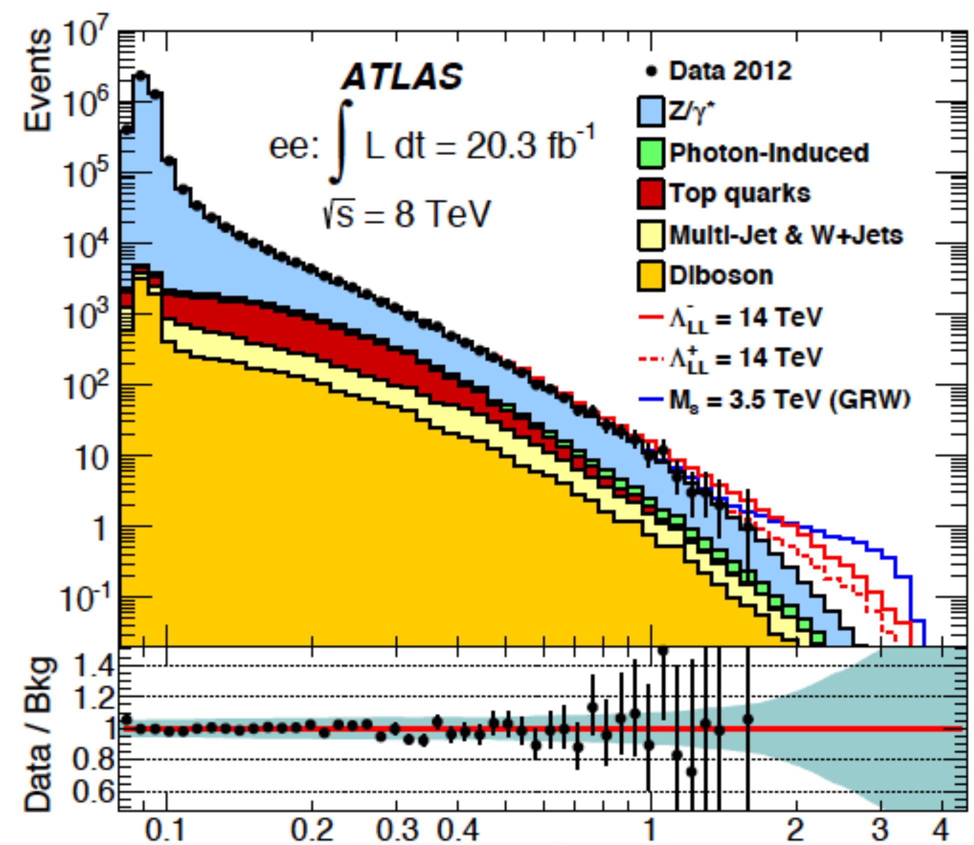

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

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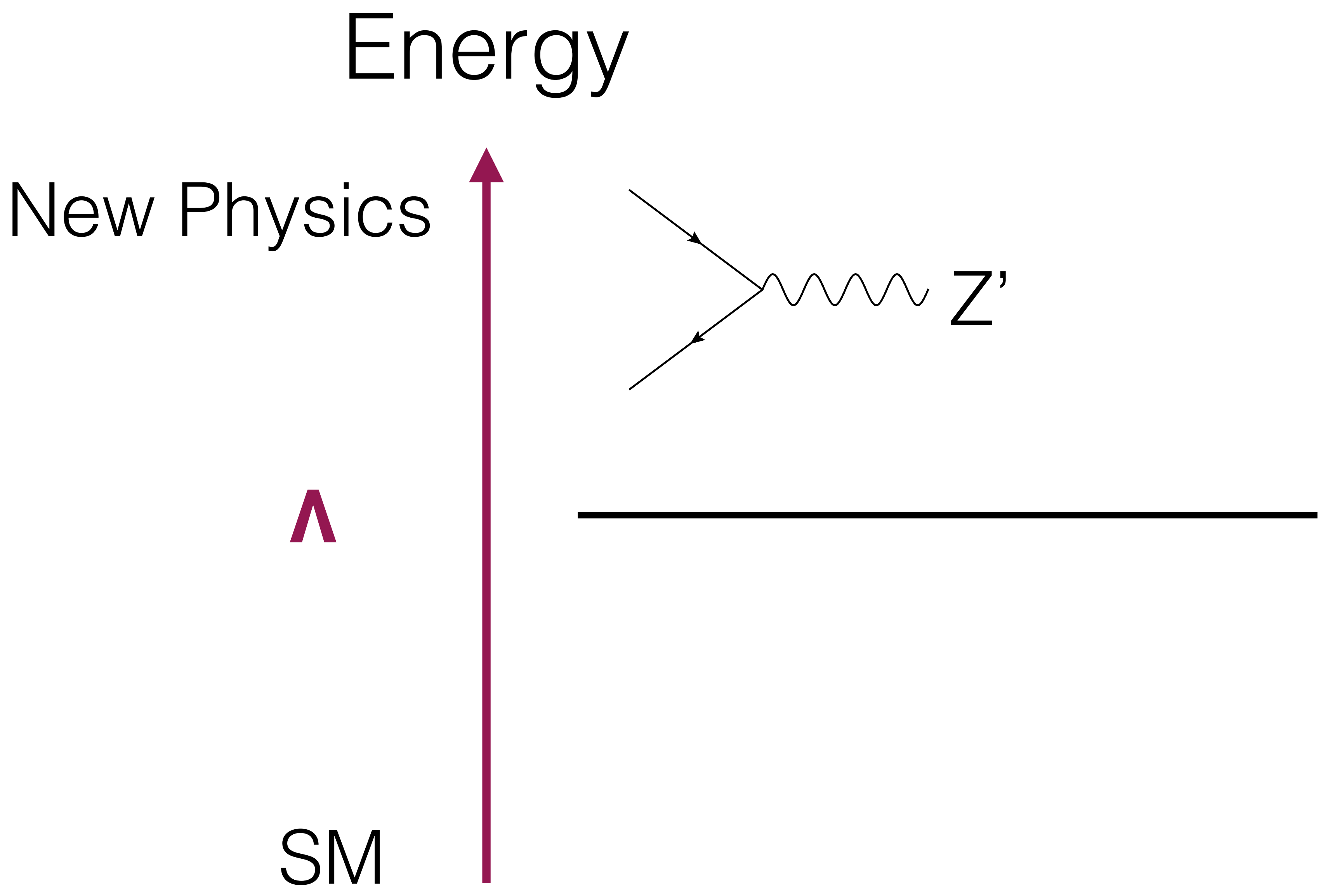
SMEFT: What is it all about?



A Taylor expansion

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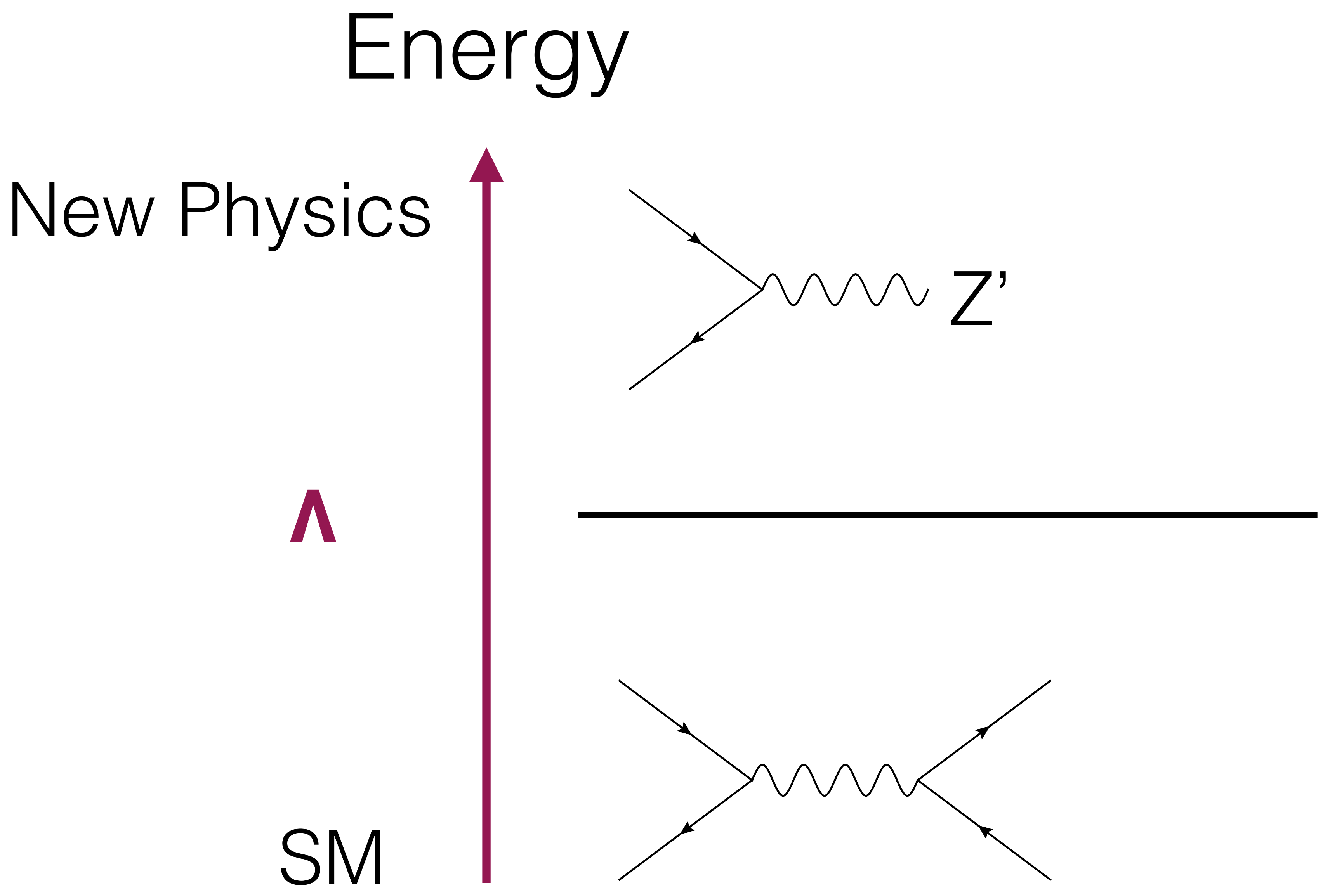

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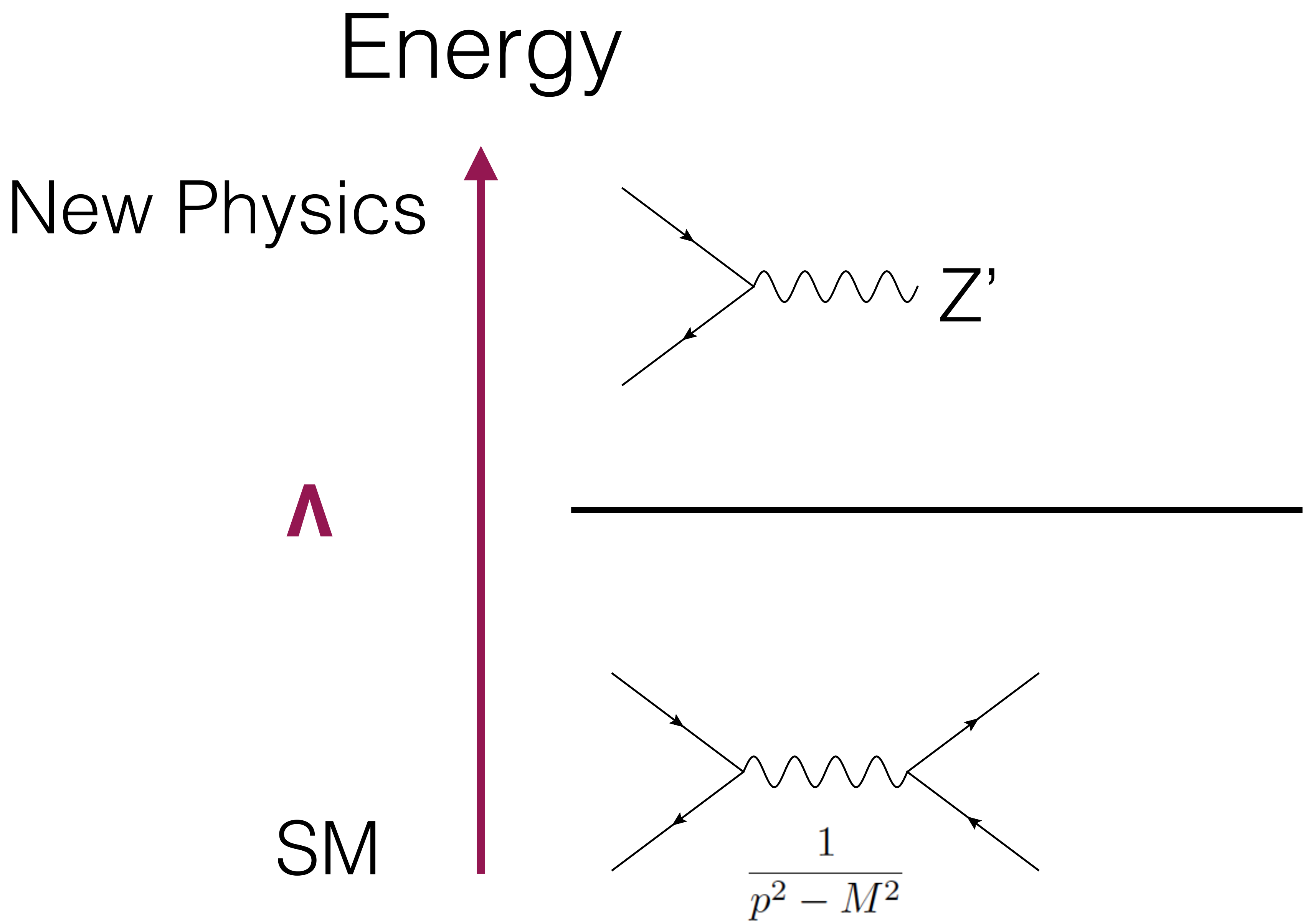

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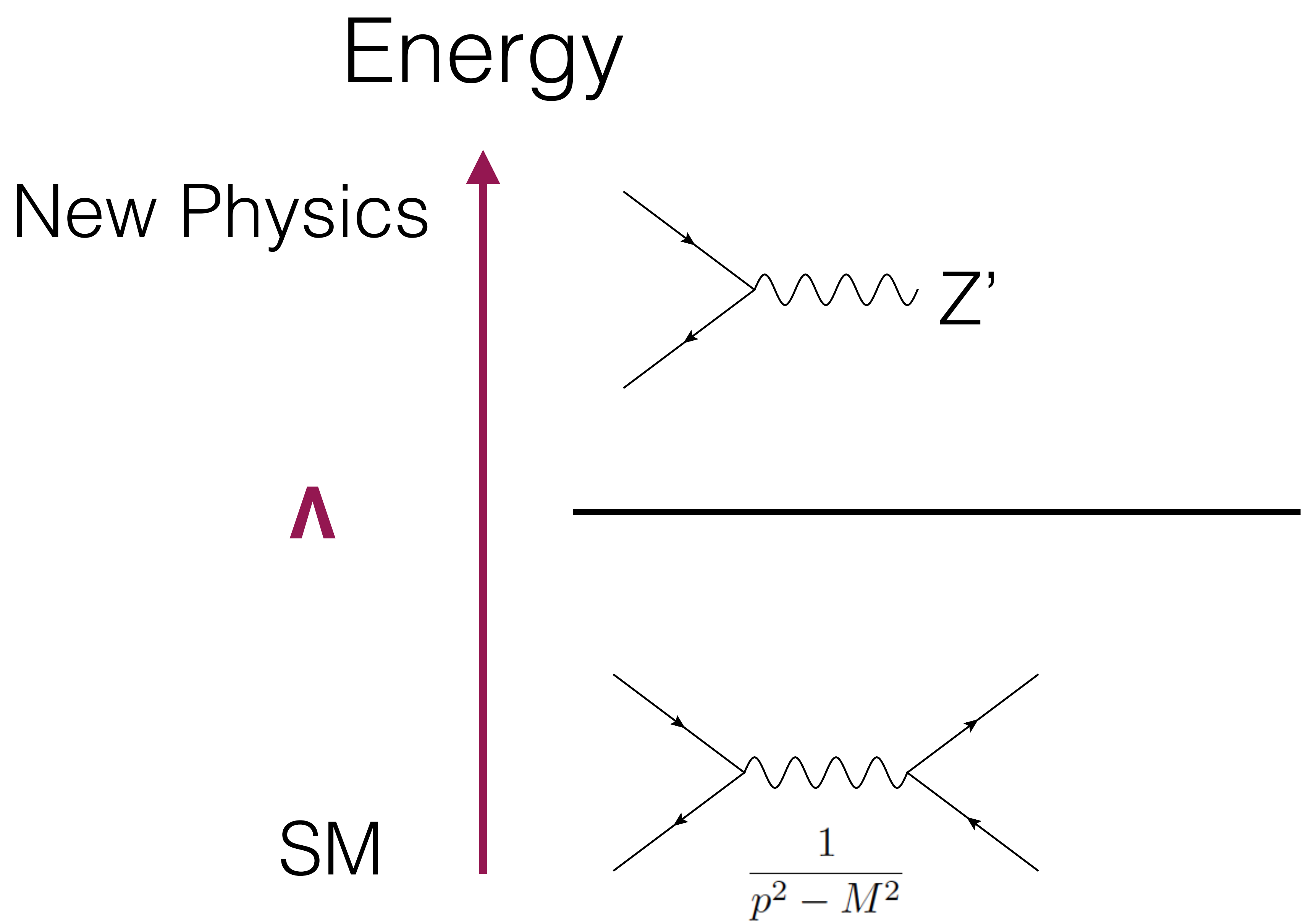
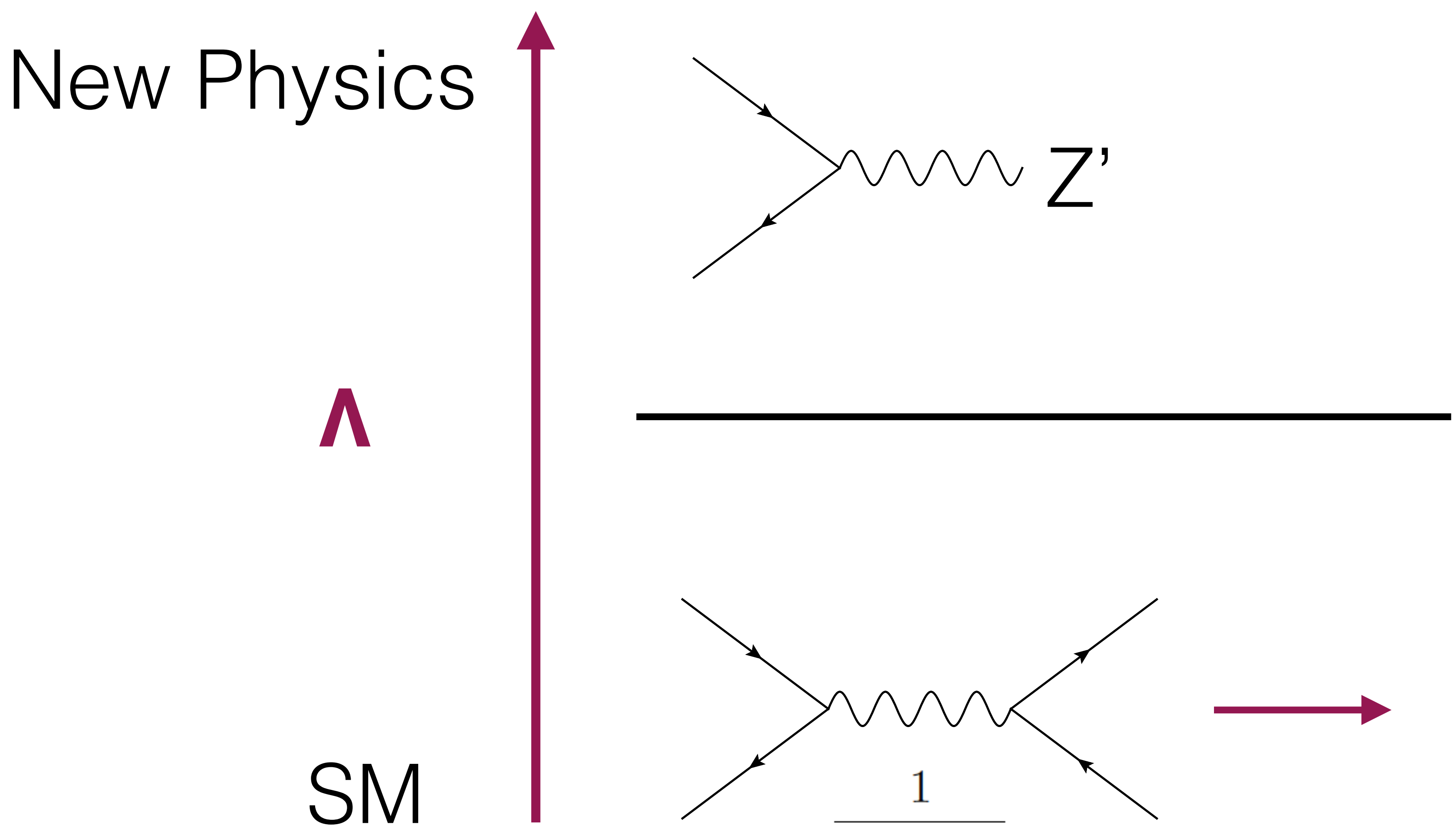


$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$ A Taylor expansion

SMEFT: What is it all about?

Energy



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

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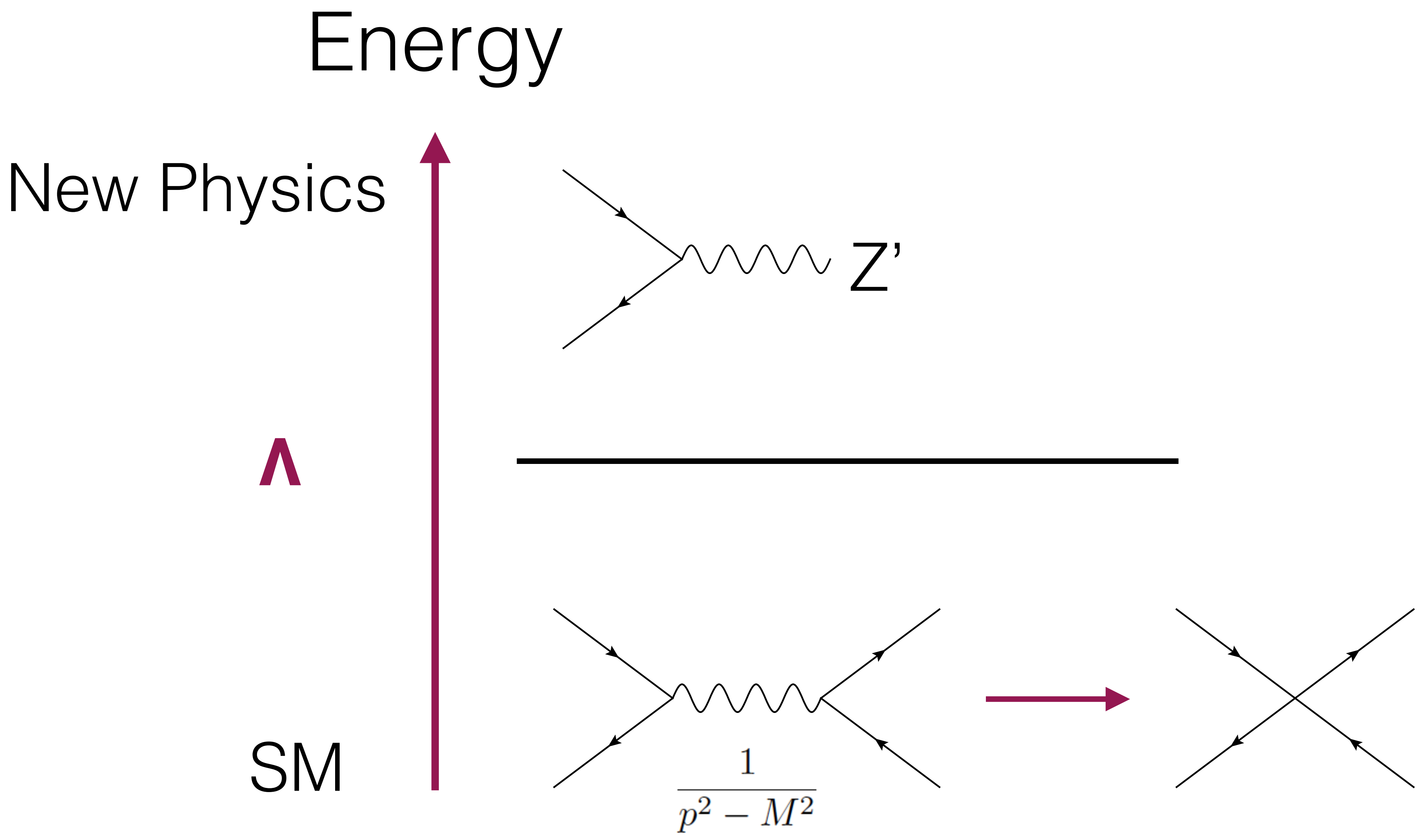

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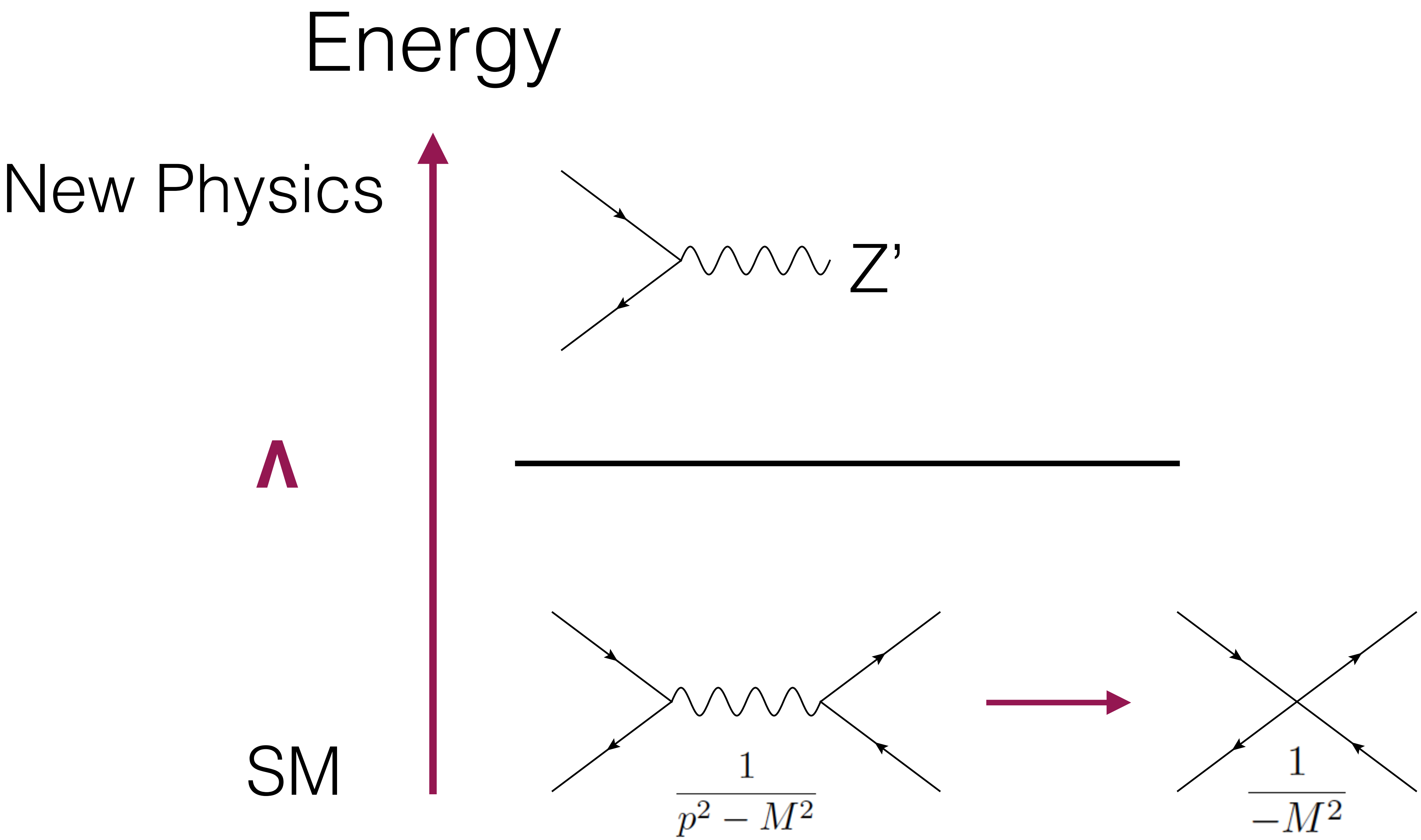

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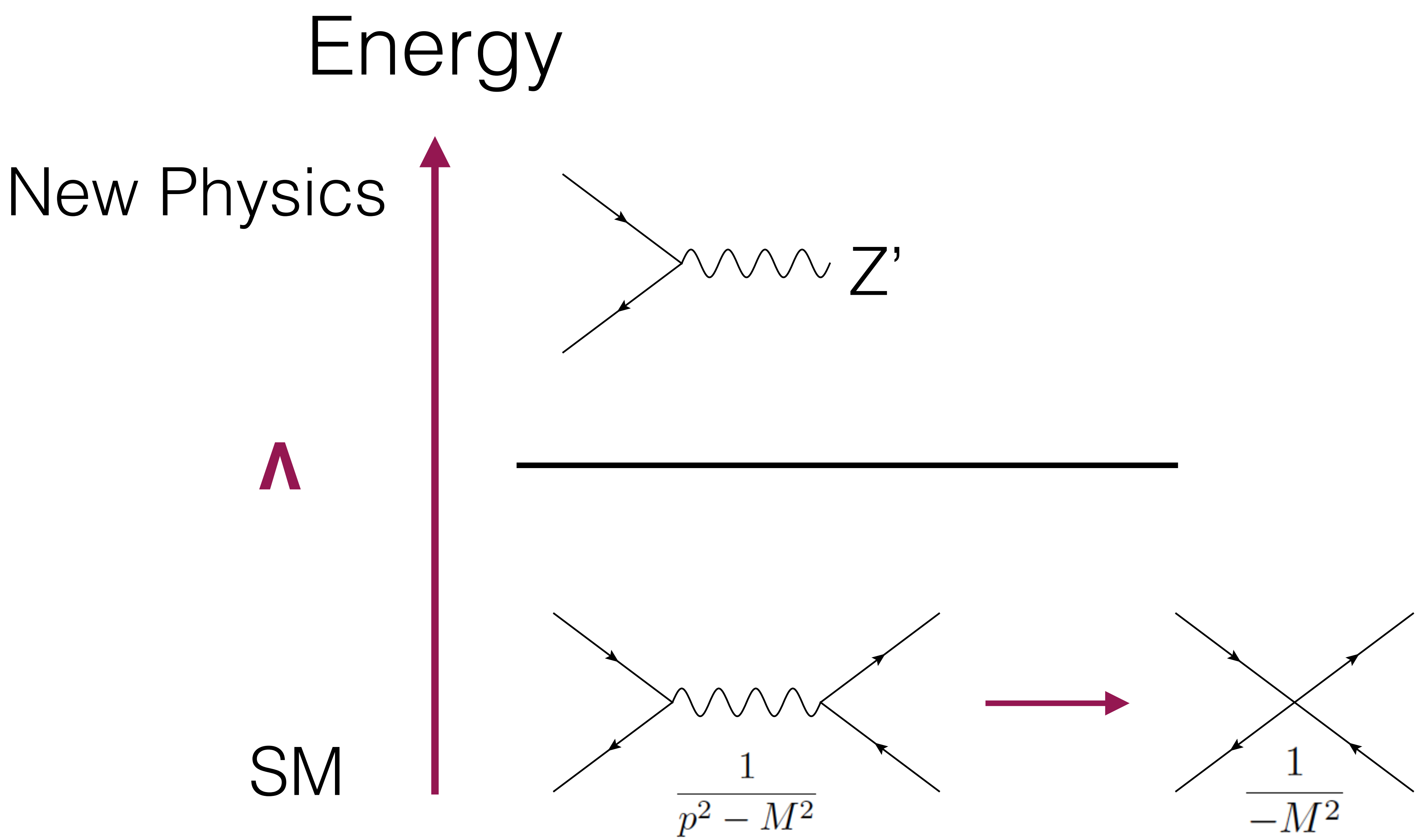

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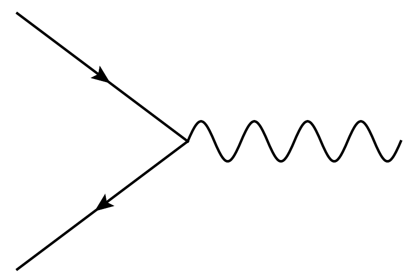
We have integrated out the Z’

SMEFT: What is it all about?

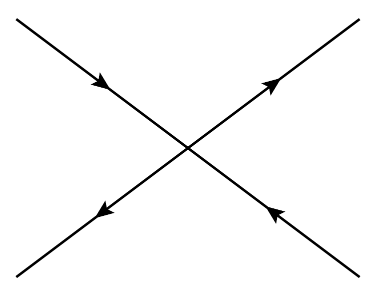
Energy

New Physics



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

Λ=M



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

SM

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

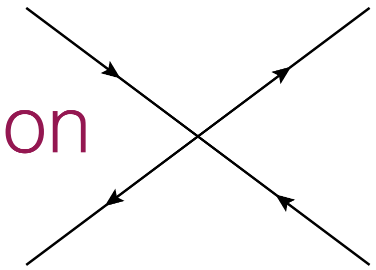
$$\mathcal{L}_{Dim6}(\varphi) = \boxed{\frac{C}{\Lambda^2}}(\bar{f}\gamma^{\mu}f)(\bar{f}\gamma_{\mu}f)$$

c/Λ² can be linked to High Scale physics: Matching and Running

Effective Field Theory for New Physics

Low Energy Effective Theory without the Z'

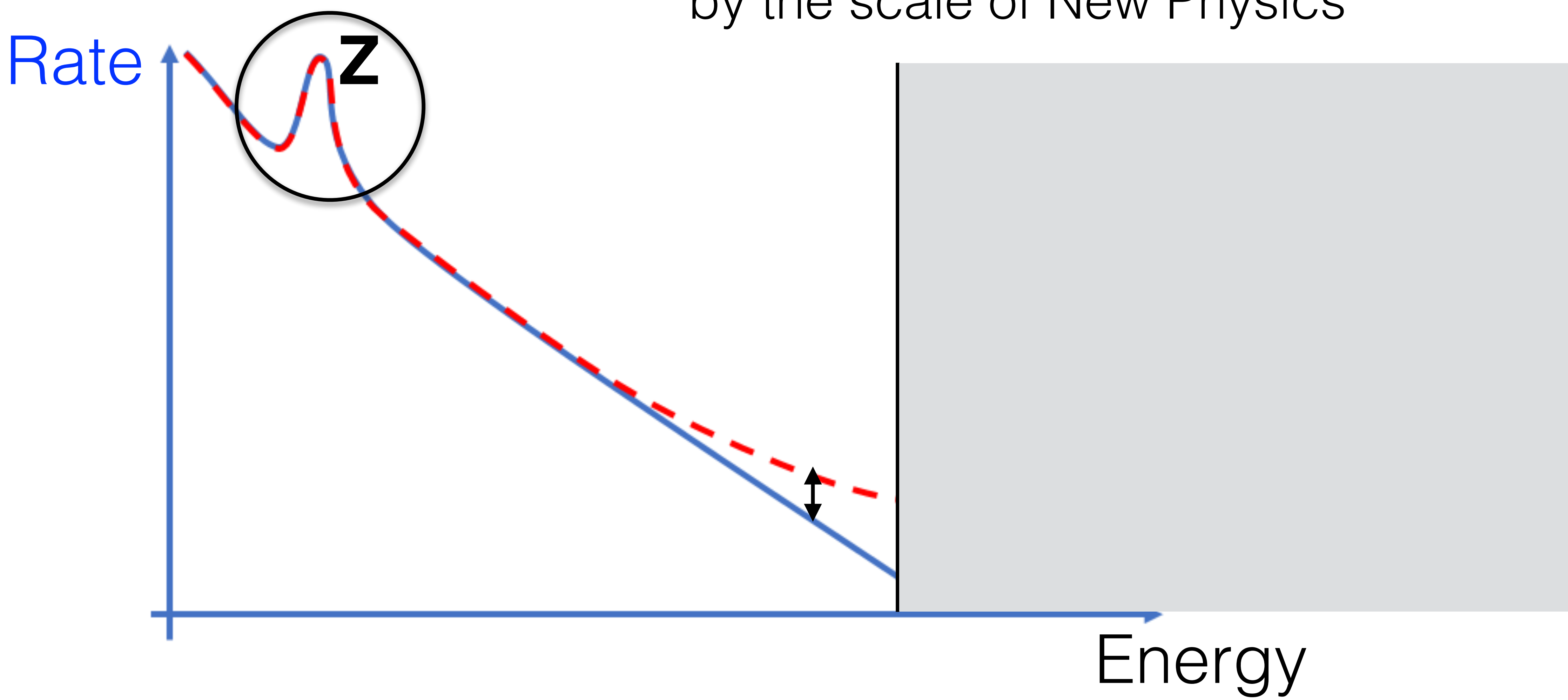
New Interaction



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

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

Modified interactions suppressed by the scale of New Physics

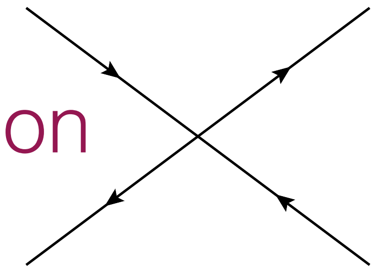


The way to probe New Physics in the absence of light states

Effective Field Theory for New Physics

Low Energy Effective Theory without the Z’

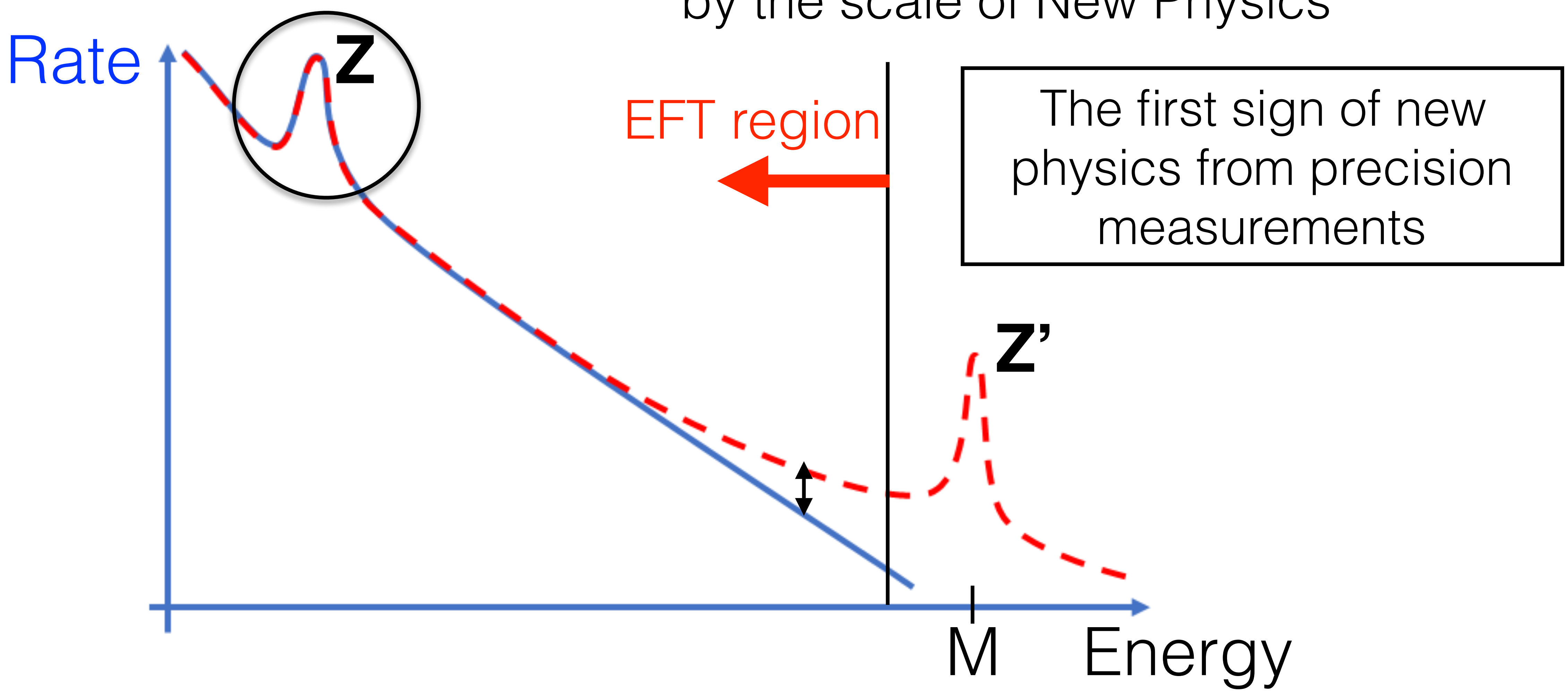
New Interaction



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

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

Modified interactions suppressed by the scale of New Physics

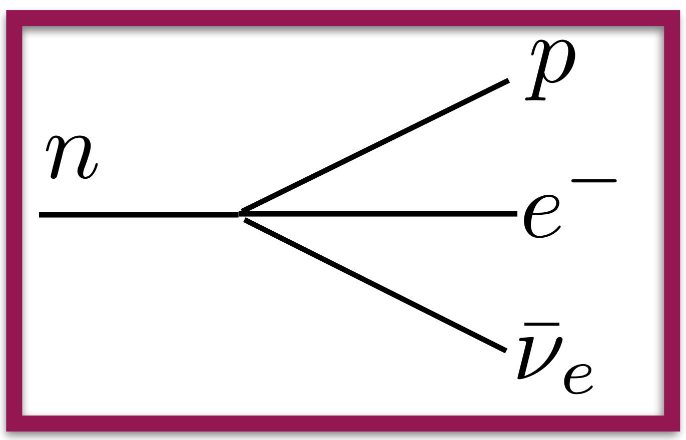


The way to probe New Physics in the absence of light states

Does the effective theory work?

An example of a successful EFT:

$$n \to p + e^- + \bar{\nu}_e$$

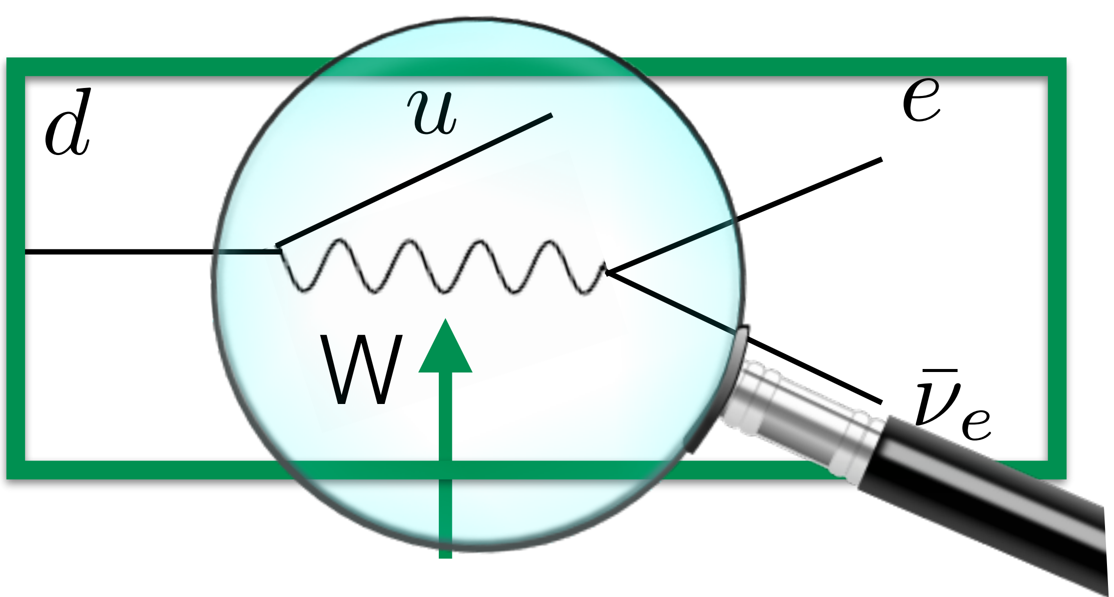


Fermi formulated his theory in the 1930's

It described β-decay data very well

Energy of β-decay: ~MeV

But this is not the full theory: cross-section rising with energy, violating unitarity



1983 Discovery of W-boson at CERN UA1 and UA2

M_W=80 GeV >> Q_β

Energy borrowed from the vacuum
A virtual W-boson exchange

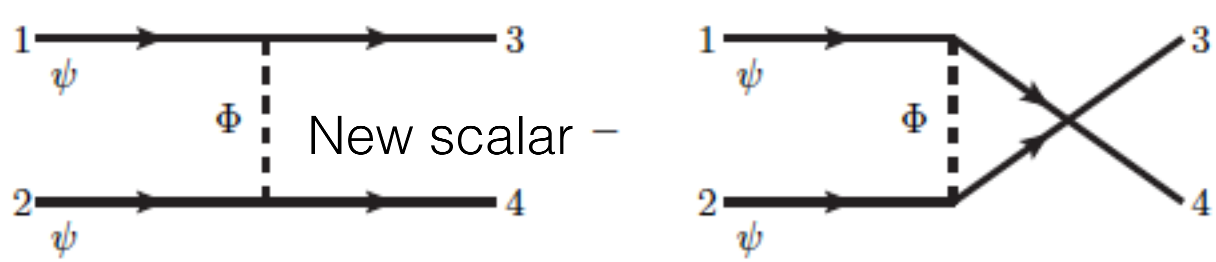
A toy-model example

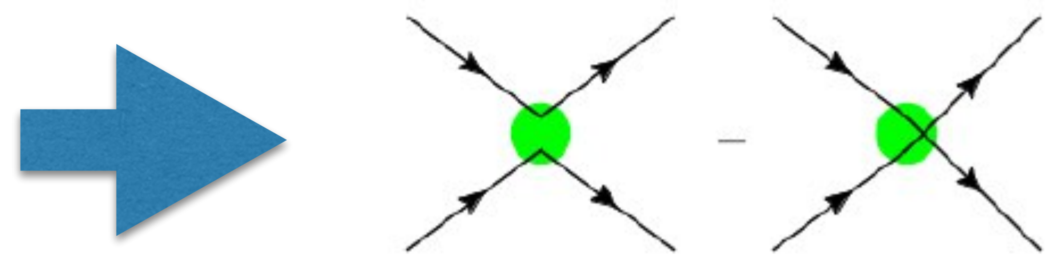
$$\mathcal{L} = i\overline{\psi}\,\partial\!\!\!/\,\psi + \frac{1}{2}(\partial_\mu\Phi)^2 - \frac{M^2}{2}\Phi^2 - \lambda\,\overline{\psi}\psi\Phi$$

Heavy scalar+Massless fermions model

Heavy particle to be integrated out

Yukawa interaction

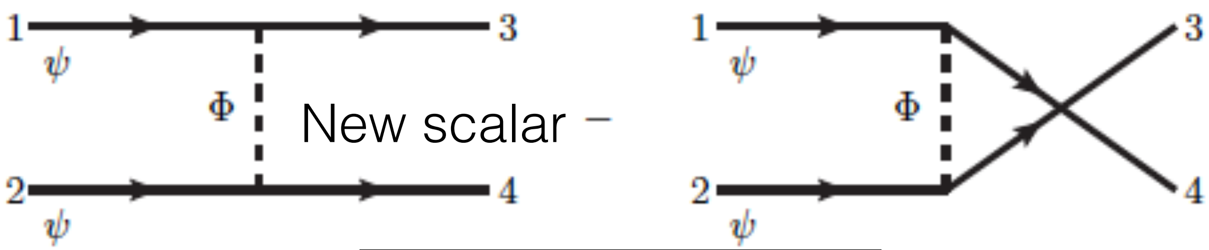




$$\mathcal{L}_{p^0,\lambda^2} = i\overline{\psi}\,\partial\!\!\!/\,\psi + \frac{c}{2}\,\overline{\psi}\psi\,\overline{\psi}\psi$$

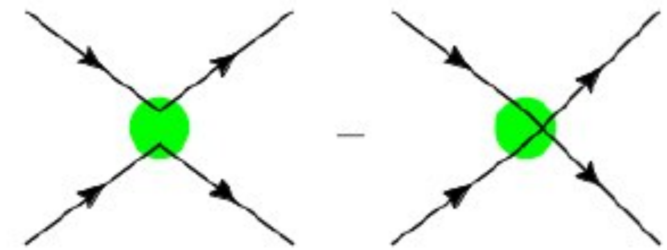
We want to describe the same physics, below scale M

Matching



Full Theory

EFT



$$\mathcal{L}_{p^0,\lambda^2} = i\overline{\psi}\,\partial\!\!\!/\,\psi + \frac{c}{2}\,\overline{\psi}\psi\,\overline{\psi}\psi$$

Matching will allow us to determine c

Writing down the amplitudes:

$$\mathcal{A}_{UV} = \overline{u}(p_3)u(p_1)\overline{u}(p_4)u(p_2)\,(-i\lambda)^2\frac{i}{(p_3-p_1)^2-M^2} - \{3 \leftrightarrow 4\}$$

Expanding the propagator in p^2/M^2:

$$(-i\lambda)^2\frac{i}{(p_3-p_1)^2-M^2} = i\frac{\lambda^2}{M^2}\frac{1}{1-\frac{(p_3-p_1)^2}{M^2}} \approx i\frac{\lambda^2}{M^2}\left(1+\frac{(p_3-p_1)^2}{M^2}+\mathcal{O}(\frac{p^4}{M^4})\right)$$

Reading out c: $\boxed{c = \frac{\lambda^2}{M^2}}$

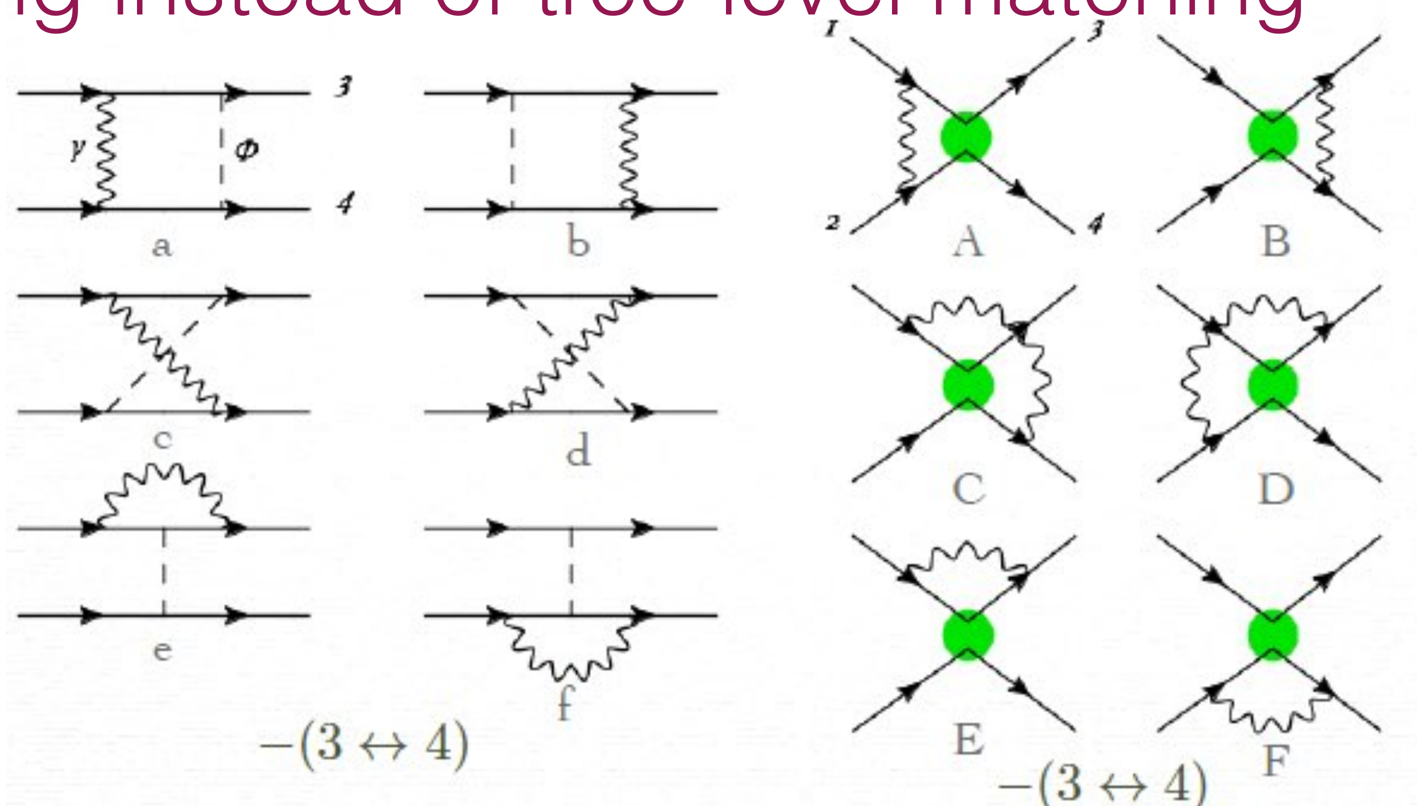
Matching improvements

Higher order terms in the momentum expansion:
→ dimension-8 operators

$$\mathcal{L}_{p^2,\lambda^2} = i\overline{\psi}\,\partial\!\!\!/\,\psi + \frac{\lambda^2}{M^2}\,\frac{1}{2}\,\overline{\psi}\psi\,\overline{\psi}\psi + \boxed{d\,\partial_\mu\overline{\psi}\partial^\mu\psi\,\overline{\psi}\psi} \qquad \boxed{d = -\frac{\lambda^2}{M^4}}$$

EFT expansion systematically improvable by adding higher dimension operators

Higher-order corrections in the QED or QCD couplings:
1-loop matching instead of tree-level matching



Systematically improvable

What we learnt so far

(UV complete model) → EFT: $C_i(\Lambda)$

matching
tree or loop

↓ Running and mixing

RGE: Jenkins et al arXiv: 1308.2627,1310.4838, Alonso et al. 1312.2014

EFT: $C_i(Q)$

What we will learn

(UV complete model) → EFT: $C_i(\Lambda)$

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Tools: FeynRules, MG5_aMC, Pythia etc

Observable → Measurements Constraints

What we will learn

(UV complete model) → EFT: $C_i(\Lambda)$

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Observable → Measurements Constraints

SMEFT@LHC

- Focus on SMEFT:
  - only SM fields
  - respecting SM symmetries ✔
  - valid below scale Λ
- 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 ✔
- Model Independent ✔

SMEFT

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

- 59(2499) 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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

4-fermion operators

EFT bases

Warsaw (arxiv:1008.4884): A well-defined basis
Other bases are equivalent up to dimension-6 terms

How to go from one basis to the others?

Use the Equations of motion $$\frac{\partial \mathcal{L}}{\partial \phi} - \partial_\mu \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi)} = 0$$

E.g.

$$\{\mathcal{O}_{HL}, \mathcal{O}'_{HL}, \mathcal{O}_{WB}\} \to \{\mathcal{O}_W, \mathcal{O}_B, \mathcal{O}_{HB}\}$$

$$\mathcal{O}_B = \mathcal{O}_{HB} + \mathcal{O}_{BB} + \mathcal{O}_{WB}\,,$$
$$\mathcal{O}_W = \mathcal{O}_{HW} + \mathcal{O}_{WW} + \mathcal{O}_{WB}\,,$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{WB} = \frac{gg'}{4}(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_W = g^2 \left[\frac{3}{2}\mathcal{O}_r - \frac{1}{4}\sum_{u,d,e}\mathcal{O}_y - \mathcal{O}_6 + \frac{1}{4}(\mathcal{O}'_{HL} + \mathcal{O}'_{HQ})\right].$$

$$\mathcal{O}_B = g'^2 \left[-\frac{1}{2}\mathcal{O}_T + \frac{1}{2}\sum_F Y_F \mathcal{O}_{HF}\right].$$

with $F = \{L_L, e_R, Q_L, u_R, d_R\}$, Y_F the hypercharge, and

$$\mathcal{O}_{HL} \equiv (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L), \quad \mathcal{O}'_{HL} \equiv (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \sigma^a \gamma^\mu L_L)\,.$$

Biekotter et al., 1406.7320

Bases:

- SILH, G. Giudice et al [hep-ph/0703164].
- Warsaw arXiv:1008.4884
- BSM primaries Gupta, Pomarol, Riva arXiv:1405.0181
- Higgs, LHCHXSWG
- someone's favourite basis

Tools for EFT bases

ROSETTA translation between bases: Falkowski et al. arXiv:1508.05895)

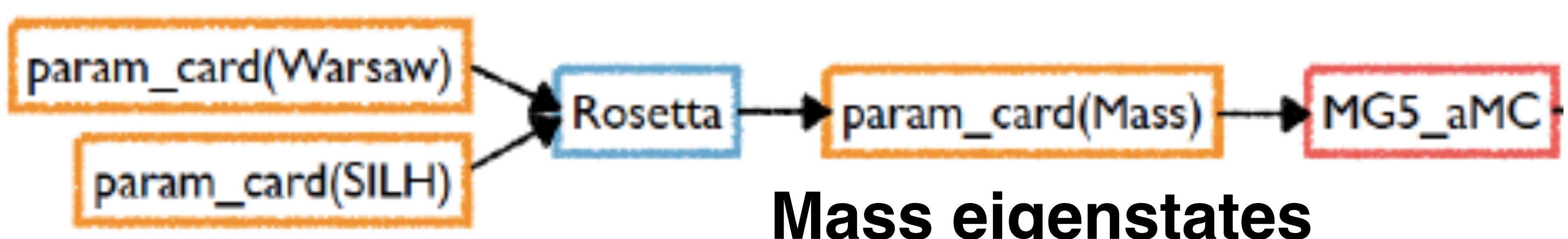
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
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}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

Grzadkowski et al arxiv:1008.4884

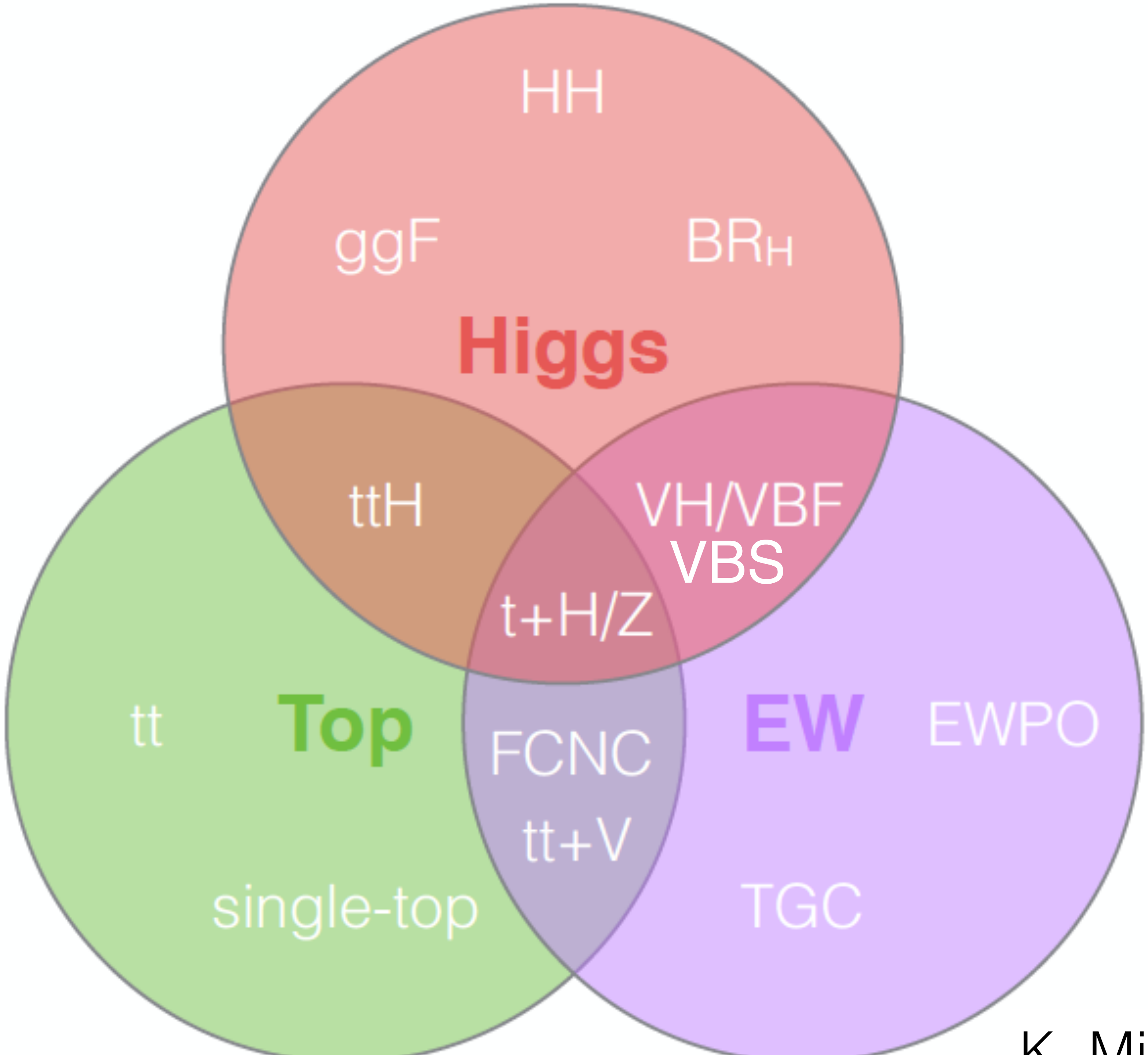
Higgs Physics Only	
$\mathcal{O}_r = \|H\|^2\|D^\mu H\|^2$	1
$\mathcal{O}_{BB} = \frac{g'^2}{4}\|H\|^2 B_{\mu\nu}B^{\mu\nu}$	2
$\mathcal{O}_{WW} = \frac{g^2}{4}\|H\|^2 W_{\mu\nu}^a W^{a\mu\nu}$	2
$\mathcal{O}_{GG} = \frac{g_s^2}{4}\|H\|^2 G_{\mu\nu}^A G^{A\mu\nu}$	2
$\mathcal{O}_{y_u} = y_u\|H\|^2\bar Q_L\widetilde H u_R$	1
$\mathcal{O}_{y_d} = y_d\|H\|^2\bar Q_L H d_R$	1
$\mathcal{O}_{y_e} = y_e\|H\|^2\bar L_L H e_R$	1
$\mathcal{O}_6 = \lambda\|H\|^6$	1

EW and Higgs Physics	
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a\overleftrightarrow{D^\mu}H\right)D^\nu W_{\mu\nu}^a$	2
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\partial^\nu B_{\mu\nu}$	2
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	2
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger\overleftrightarrow{D}_\mu H\right)^2$	1
$\mathcal{O}_{Hu} = (iH^\dagger\overleftrightarrow{D}_\mu H)(\bar u_R\gamma^\mu u_R)$	1
$\mathcal{O}_{Hd} = (iH^\dagger\overleftrightarrow{D}_\mu H)(\bar d_R\gamma^\mu d_R)$	1
$\mathcal{O}_{He} = (iH^\dagger\overleftrightarrow{D}_\mu H)(\bar e_R\gamma^\mu e_R)$	1
$\mathcal{O}_{HQ} = (iH^\dagger\overleftrightarrow{D}_\mu H)(\bar Q_L\gamma^\mu Q_L)$	1
$\mathcal{O}'_{HQ} = (iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)(\bar Q_L\sigma^a\gamma^\mu Q_L)$	1

Biekotter et al., 1406.7320



Physics applications



K. Mimasu

EFT has a global character

SMEFT in Monte Carlos

A well known chain:

Lagrangian → UFO model → MG5_aMC/Sherpa/

your favourite generator

FeynRules

↓

https://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

EFT models publicly available

- SMEFT-sim
- Top-eft
- TGC
- Higgs effective Lagrangian
- Higgs characterisation
- many more

↓

PYTHIA, HERWIG,

your favourite PS

↓

Detector simulation

Delphes,PGS

.

.

.

SMEFT in Monte Carlos

feynrules.irmp.ucl.ac.be

LjubljanaTrainingEvent < VBSCan < TWiki | EffectiveModels – FeynRules

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wiki: EffectiveModels

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Strongly-coupled models and effective field theories

Model	Short Description	Contact	Status
Axion-Like Particles	Effective Theories for a light Axion-Like Particle	I. Brivio	**Available**
Anomalous Gauge Boson Couplings	Model including anomalous couplings among gauge bosons	O.J.P. Eboli, M.C. Gonzalez-Garcia	**Available**
BSM Characterisation	The SM EFT Lagrangian in the mass basis	B. Fuks, K. Mawatari	**Available**
Complete top-quark EFT implementation	A complete top-quark EFT implementation	G. Durieux and C. Zhang	**Available**
Chiral perturbation theory	The effective Lagrangian describing the low-energy interaction of mesons.	C. Degrande	**Available**
EFT mass basis	The SM EFT Lagrangian in the mass basis	B. Fuks, K. Mawatari	**Available**
Effective theory for 4 top production	Dimension-six operators invariant under the SM symmetries affecting 4 top interactions	C.Degrande	**Available**
Effective theory for weak gauge boson production	Dimension-six operators invariant under the SM symmetries affecting triple gauge boson interactions	C.Degrande	**Available**
Effective top-Higgs interactions	Dimension 6 Higgs-top interactions.	E. Salvioni and J. Dror	**Available**
FCNC Higgs interactions	The SM plus higher-dimensional flavor changing Higgs interactions.	S. Krastanov	**Available**
FCNC Top interactions	The SM plus higher-dimensional flavor changing top-quark interactions.	A. Amorim, J. Santiago, N. Castro, R. Santos	**Available**
Four-fermion FCNC	Contact Interaction model with b-s-l-l FCNC terms	Y. Afik and J. Cohen	**Available**
HiggsCharacterisation	The model file for the spin/parity characterisation of a 125 GeV resonance.	F. Demartin, K. Mawatari	**Available**
Higgs Effective Lagrangian	Higgs effective Lagrangian including operators up-to dimension 6.	A. Alloul, B. Fuks and V. Sanz	**Available**
Higgs effective theory	An add-on for the SM implementation containing the dimension 5 gluon fusion operator.	C. Duhr	**Available**
Mimimal Higgsless Model (3-Site Model)	A higgsless model, including new heavy fermions and a Z' and a W' boson.	N. Christensen	**Available**
nTGC Effective theory	dimension-8 operators invariant under the SM symmetries affecting neutral triple gauge boson couplings	C. Degrande	**Available**
Strongly Interacting Light Higgs	A model including higher-dimensional SM operators to describe strongly coupled theories of EWSB.	C. Degrande	**Available**
Technicolor	The Minimal Walking Technicolor Model	M. Järvinen, T. Hapola, E. Del Nobile, C. Pica	**Available**
TFCNC	The SM, plus FCNC top interactions.	M. Buchkremer, G. Cacciapaglia, A. Deandrea, L. Panizzi	**Available**
The SMEFT in the Warsaw basis	Standard Model Effective Field Theory	I. Brivio, Y. Jiang, M. Trott,	**Available**
Top Effective theory	Higher-dimensional operators invariant under the SM symmetries affecting top	C. Degrande	**Available**

EFT in Higgs physics

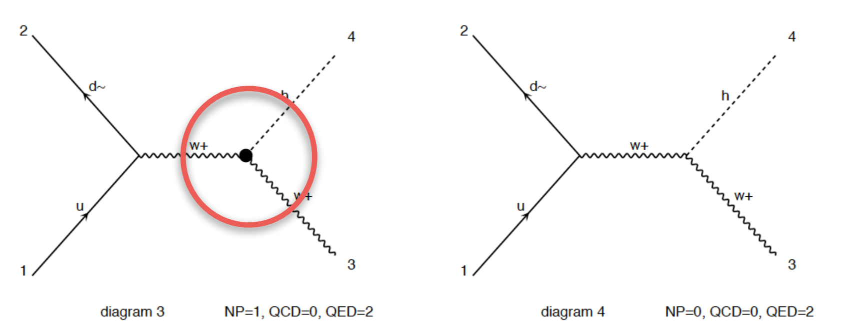
33 CP-even + 6 CP-odd
34 operators relevant for Higgs
Flavor-universal
SILH: hep-ph/0703164, Guildice et al.

arXiv:1310.5150, Alloul, Fuks, Sanz

$$
\begin{aligned}
\mathcal{L}_{\rm SILH} = & \frac{\bar c_H}{2v^2}\partial^\mu\big[\Phi^\dagger\Phi\big]\partial_\mu\big[\Phi^\dagger\Phi\big] + \frac{\bar c_T}{2v^2}\big[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\big]\big[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\big] - \frac{\bar c_6 \lambda}{v^2}\big[\Phi^\dagger\Phi\big]^3 \\
& - \Big[\frac{\bar c_u}{v^2} y_u \Phi^\dagger\Phi\ \Phi^\dagger\cdot \bar Q_L u_R + \frac{\bar c_d}{v^2} y_d \Phi^\dagger\Phi\ \Phi \bar Q_L d_R + \frac{\bar c_l}{v^2} y_\ell\ \Phi^\dagger\Phi\ \Phi \bar L_L e_R + {\rm h.c.}\Big] \\
& + \frac{ig\ \bar c_W}{m_W^2}\big[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi\big] D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar c_B}{2m_W^2}\big[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\big]\partial^\nu B_{\mu\nu} \\
& + \frac{2ig\ \bar c_{HW}}{m_W^2}\big[D^\mu\Phi^\dagger T_{2k} D^\nu \Phi\big] W^k_{\mu\nu} + \frac{ig'\ \bar c_{HB}}{m_W^2}\big[D^\mu\Phi^\dagger D^\nu\Phi\big] B_{\mu\nu} \\
& + \frac{g'^2\ \bar c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar c_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G^{\mu\nu}_a\ ,
\end{aligned}
$$

Public and validated
UFO model

```
MG5_aMC>import model HEL_UFO
MG5_aMC>generate p p > w+ h NP=1
MG5_aMC>output
MG5_aMC>launch
```



feynrules.irmp.ucl.ac.be/wiki/HEL

Higgs effective Lagrangian

Authors

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Veronica Sanz

- University of Sussex
- v.sanz@...

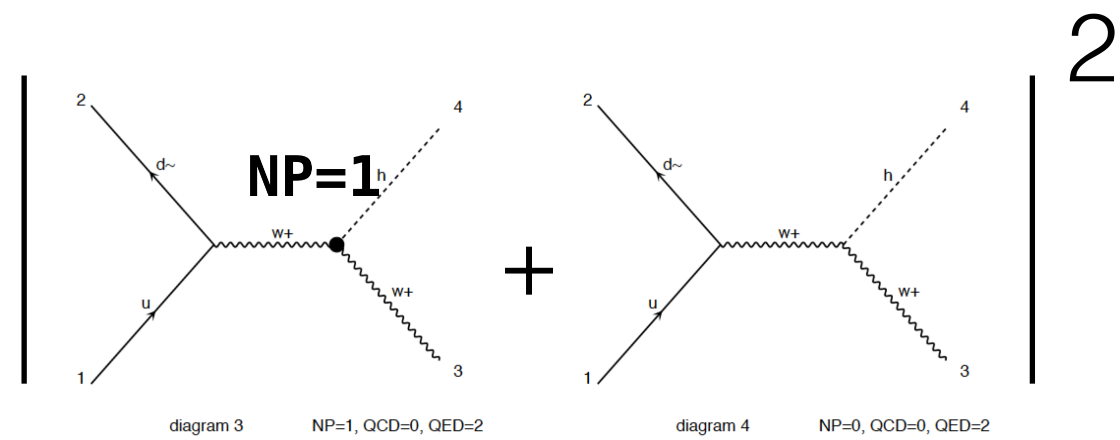
Description of the model & references

The model we have implemented is based on the description given here and on the parametrization adopted here. The Lagrangian consists of an extension of the SM Lagrangian with terms of dimension up to six comprising

E.Vryonidou

Some practical info

```
MG5_aMC>import model HEL_UFO
MG5_aMC>generate p p > w+ h NP=1
MG5_aMC>output
MG5_aMC>launch
```



Allow one EFT insertion

NP=1 Syntax will give you $\sigma = \sigma_{\rm SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i + \boxed{\sum_{i \leq j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}}$.

interference with SM

interference between operators, squared contributions

Formally of dimension-8

```
MG5_aMC>import model HEL_UFO
MG5_aMC>generate p p > w+ h NP^2==1
MG5_aMC>output
MG5_aMC>launch
```

NP^2==1 Syntax will give you $\sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i$

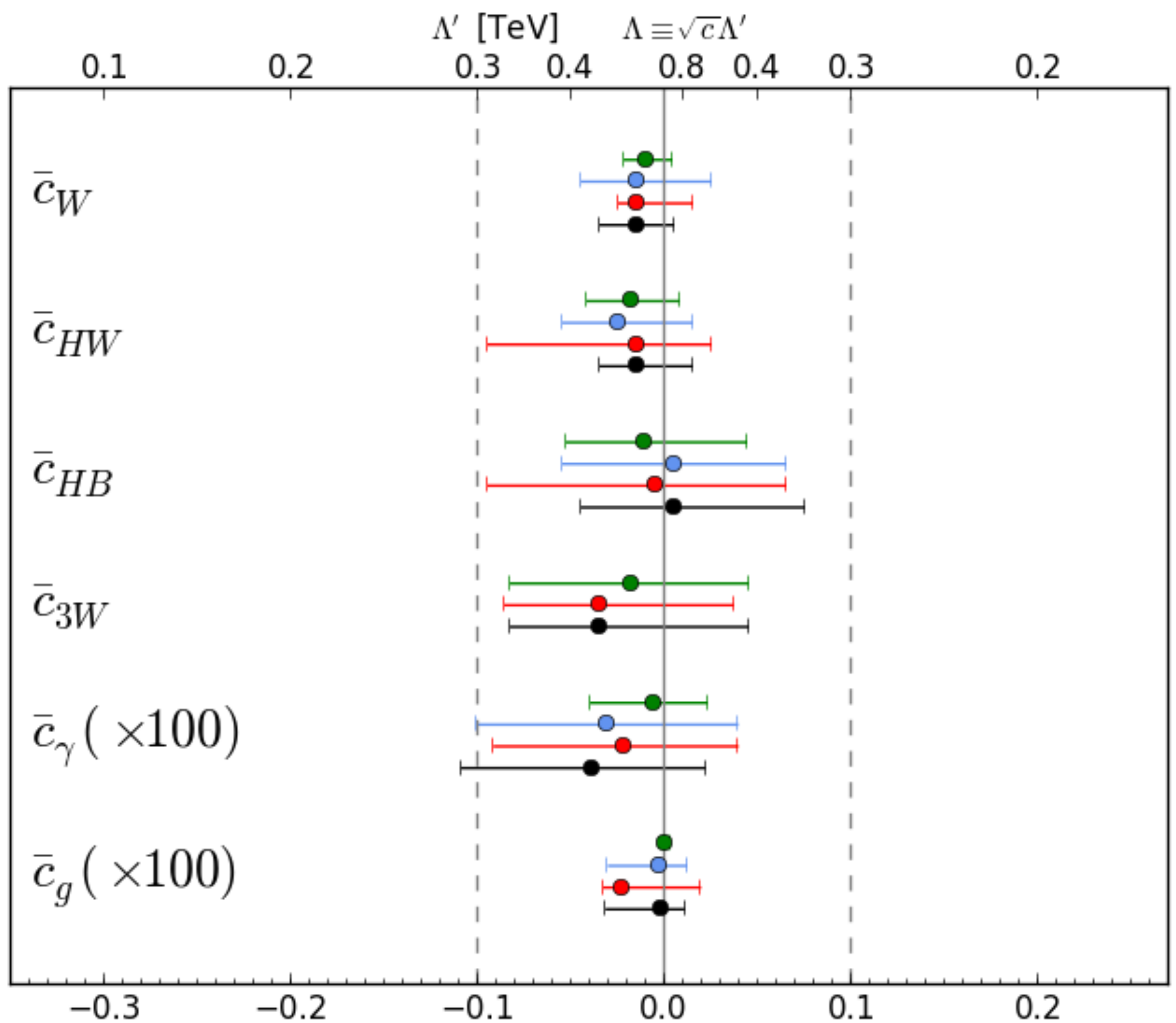
SMEFT predictions: Some considerations

- Theory uncertainties:
  - SM: factorisation and renormalisation scale, PDF uncertainties (obtained automatically in MG5)
  - EFT: as in SM but also EFT scale $c(\mu)$
  - dimension-8 operators
- Simplifying assumptions for operators to consider: flavour, CP violation, FCNC
- $1/\Lambda^2$ 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
- Validity of the EFT expansion: $E<\Lambda$, 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 → Follow a global approach → use as many processes as possible

To keep in mind: connection to flavour, EWPO

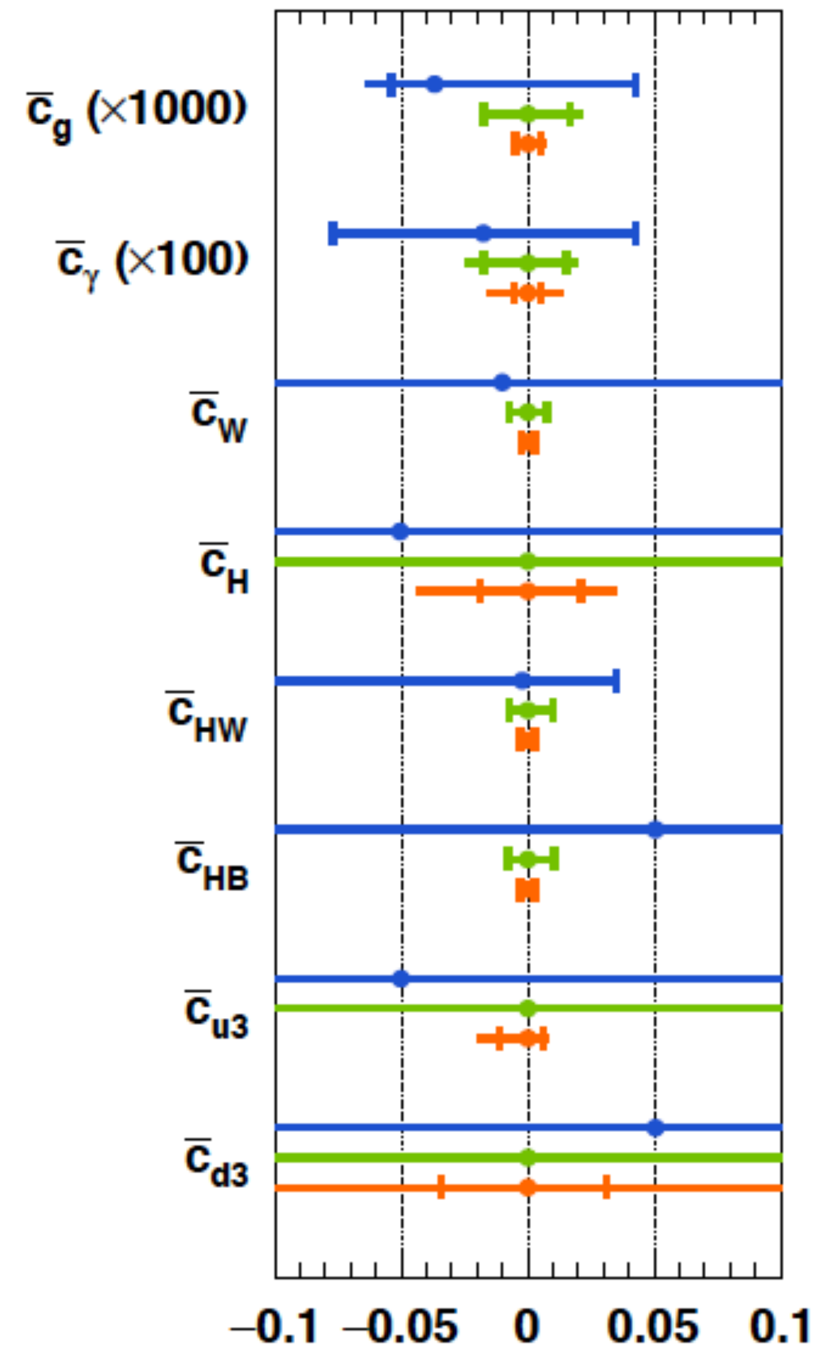
Application: EFT fits in the Higgs sector

Use predictions+measurements:
ggh, VBF, VH, ttH, Higgs decays



Higgs, TGC, combination

1404.3667,1410.7703 Ellis, Sanz, You



Current, 300fb^{-1},3000fb^{-1}

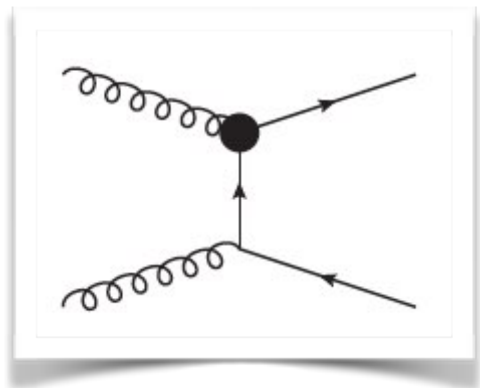
TGC not included

1511.0517 Englert, Kogler, Schulz, Spannowsky

SMEFT in processes with tops

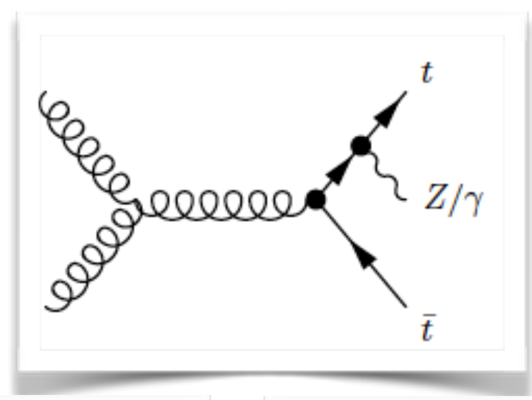
Rich phenomenology:

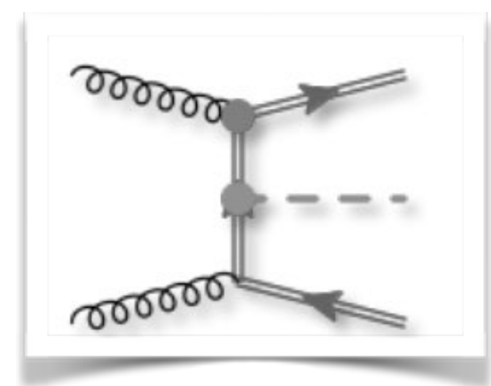
pair production



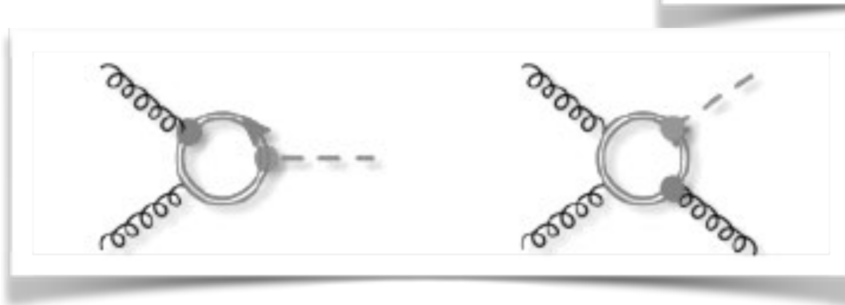
single

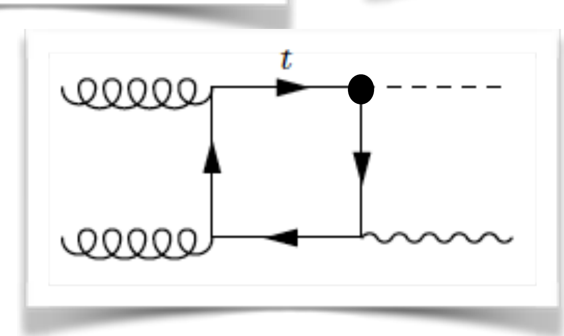
associated production

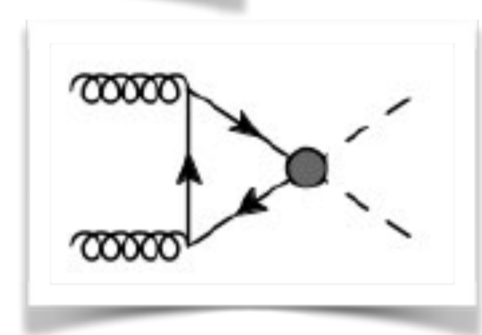




top loops







Top-quark operators and how to look for them

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

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

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

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

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

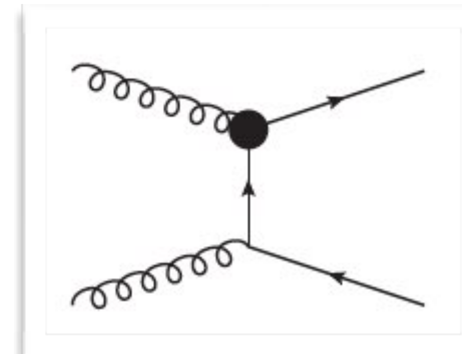
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}\,,$$

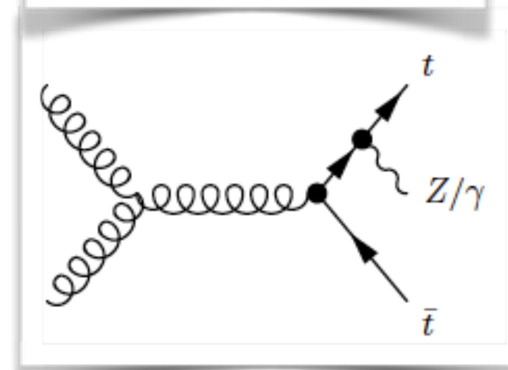
$$O_{t\phi} = y_t^3\left(\phi^\dagger \phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$

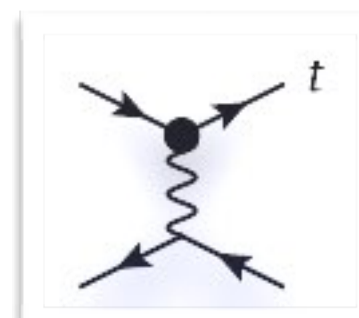
see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

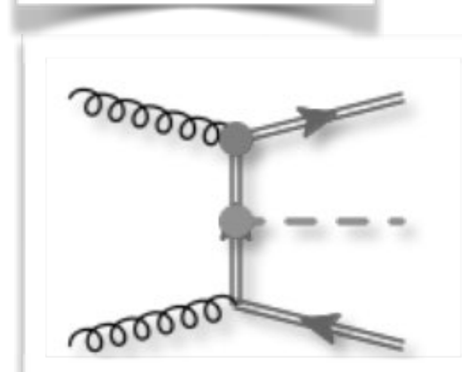
+four-fermion operators

+non-top operators (mixing)









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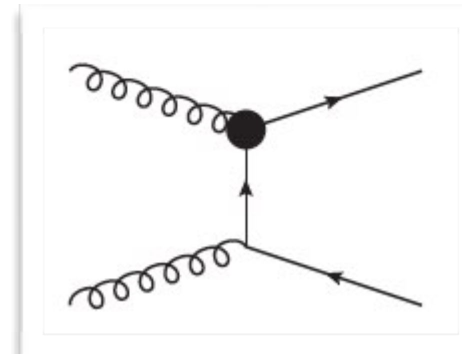

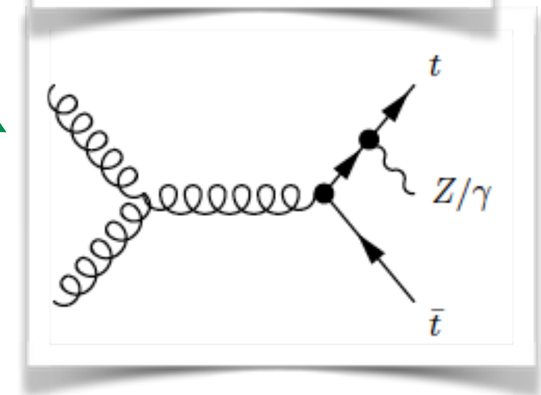

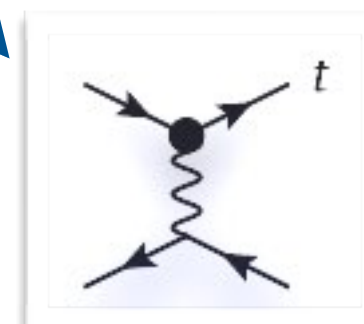

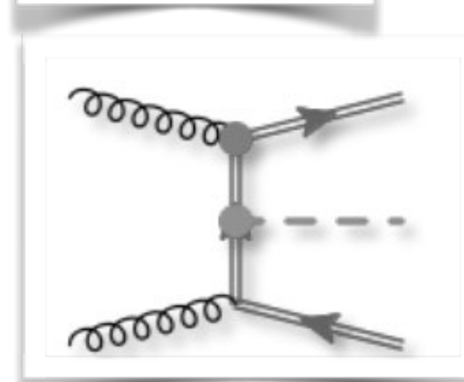

E.Vryonidou

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

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

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

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

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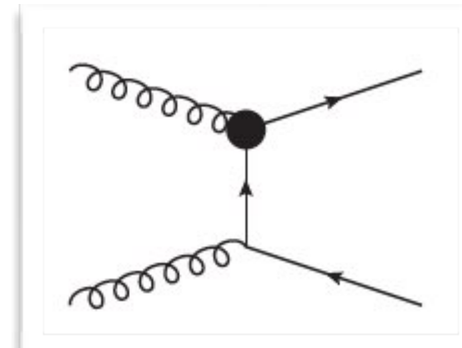

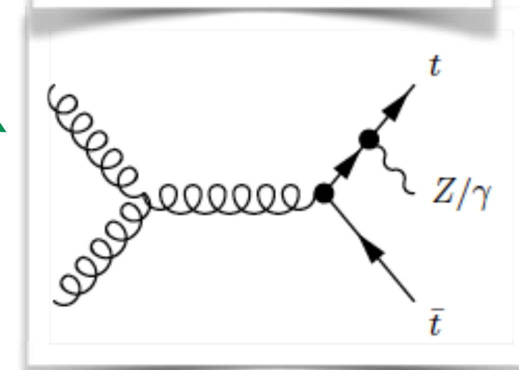

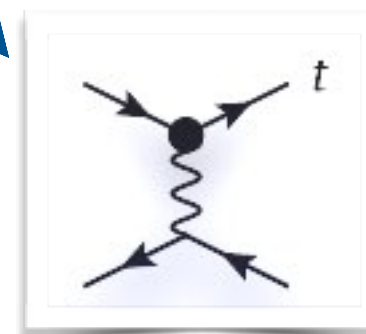

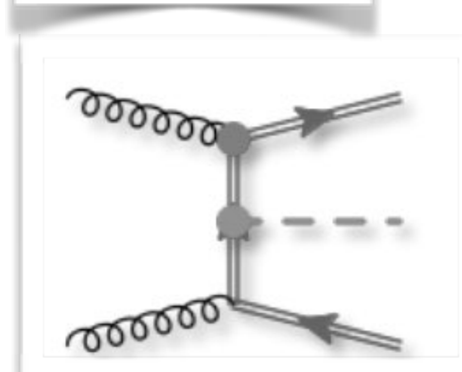

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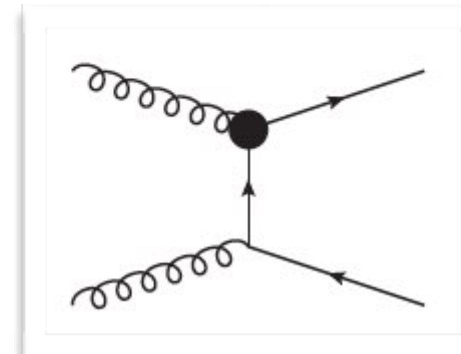

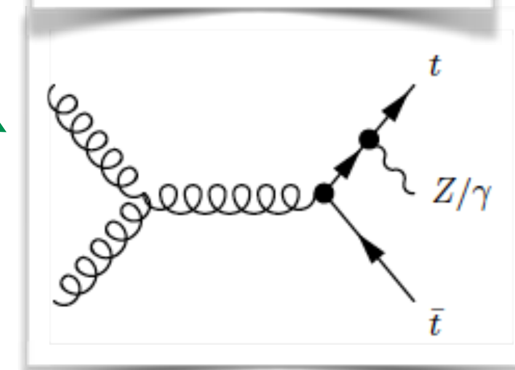

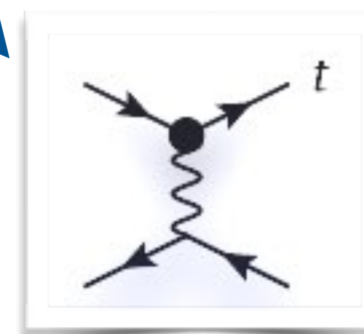

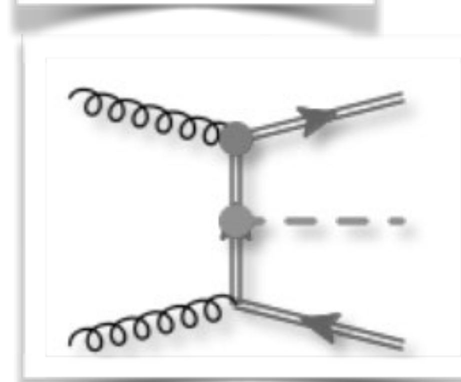

see for example: Aguilar-Saavedra (arXiv:0811.3842)
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+four-fermion operators

+non-top operators (mixing)

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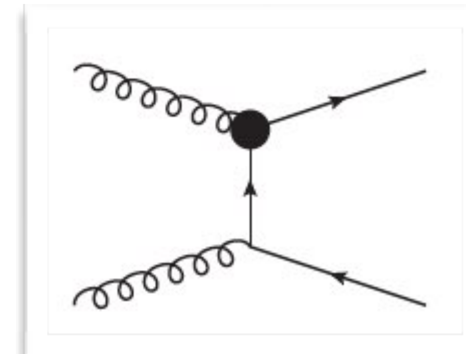

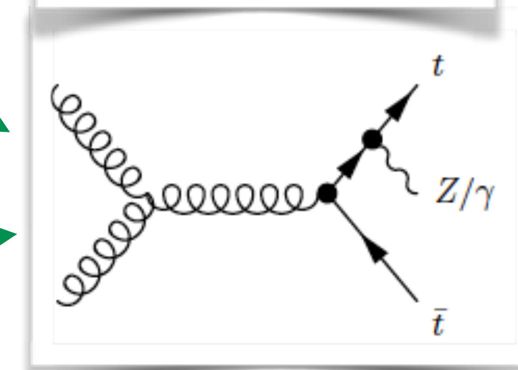

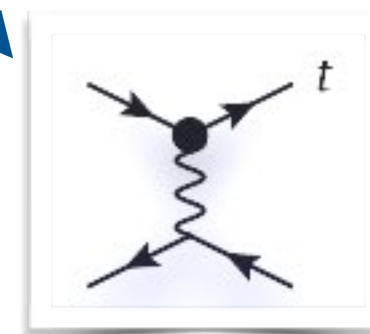

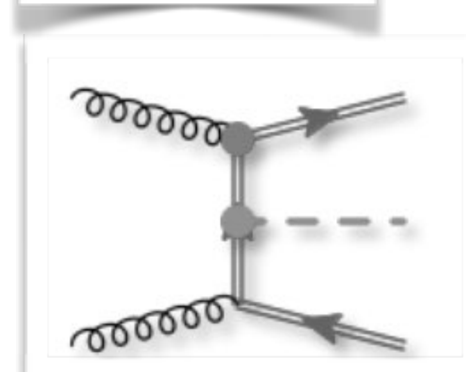

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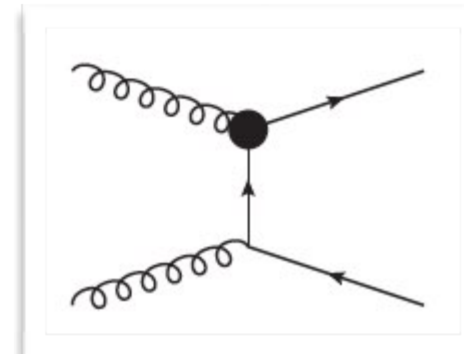

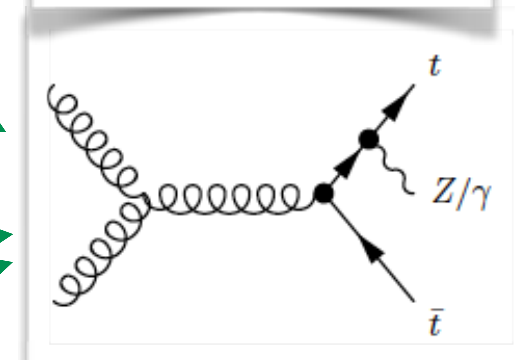

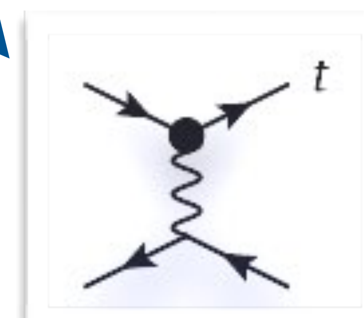

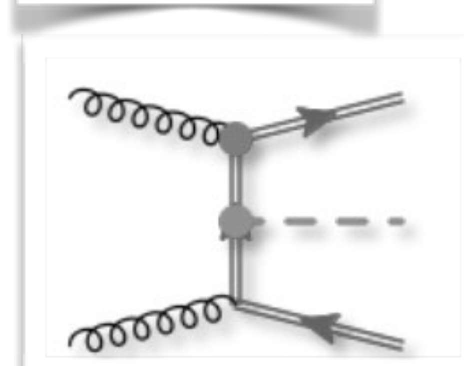

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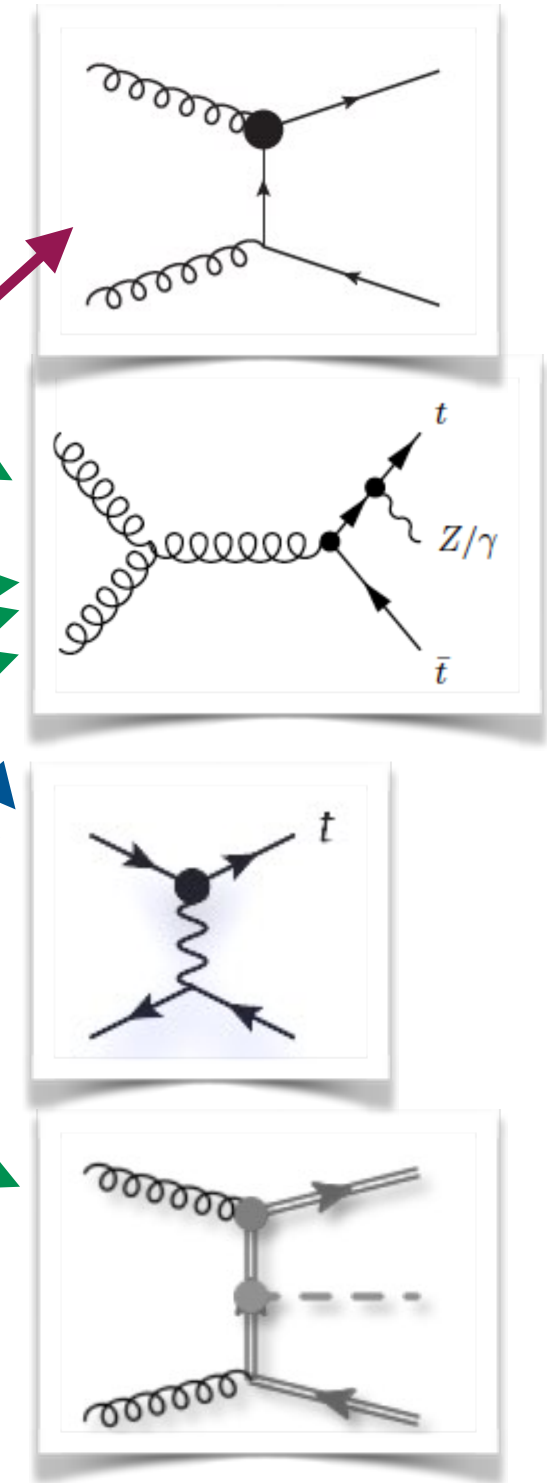

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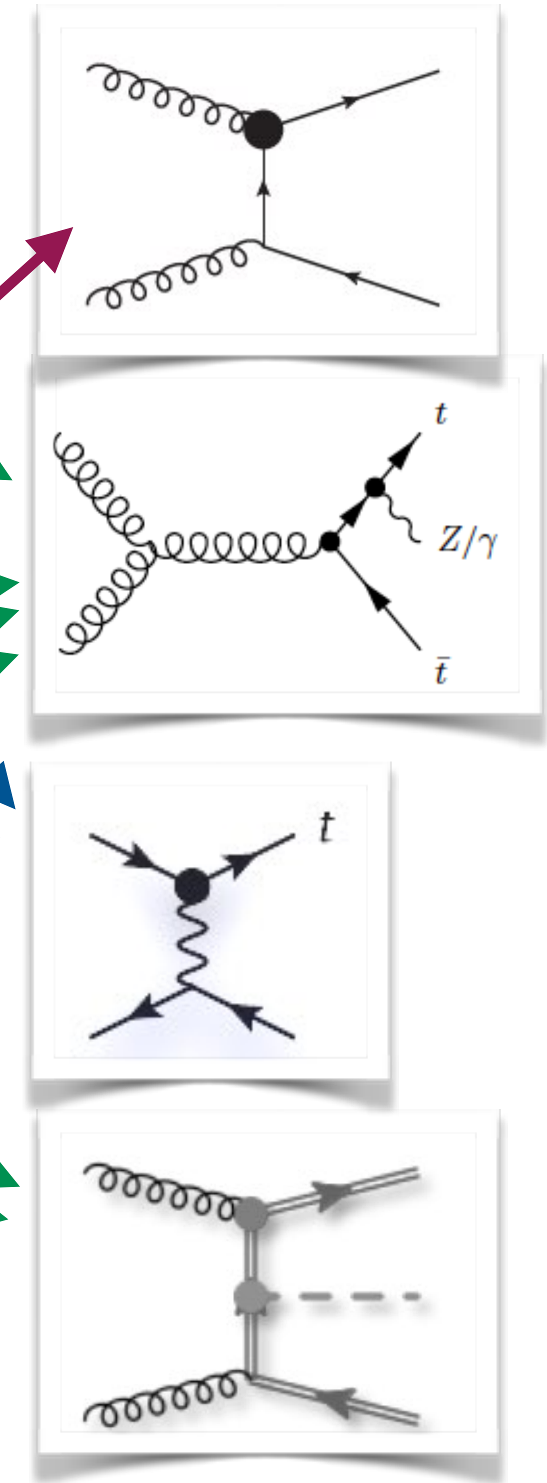

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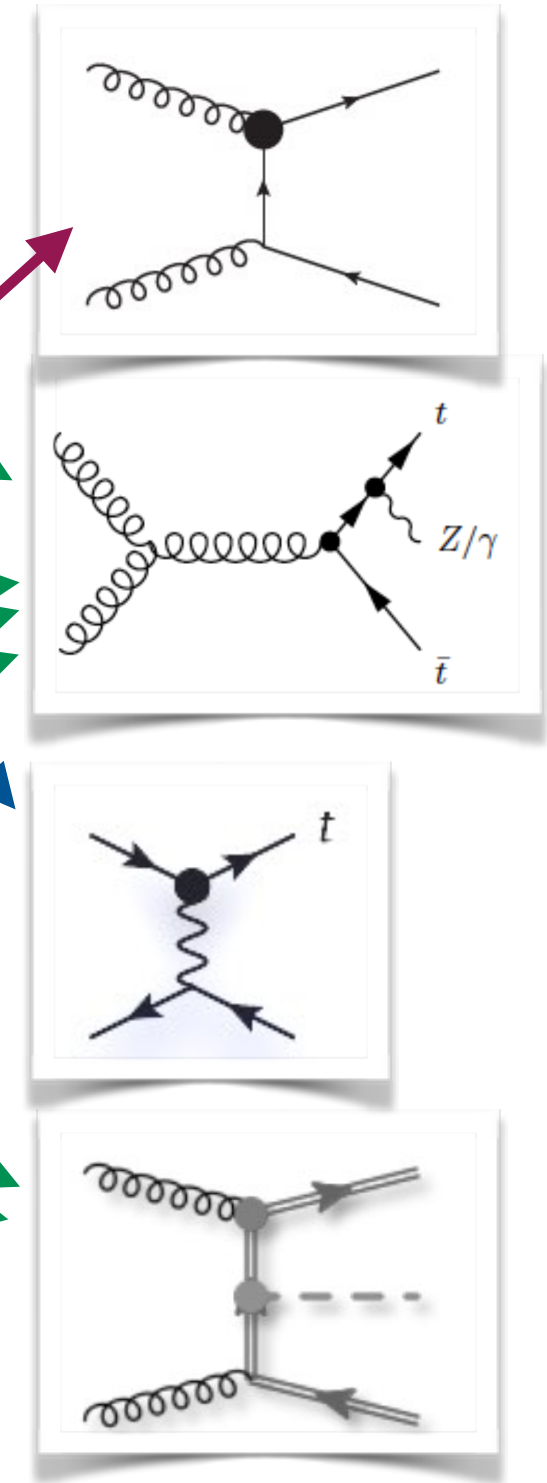

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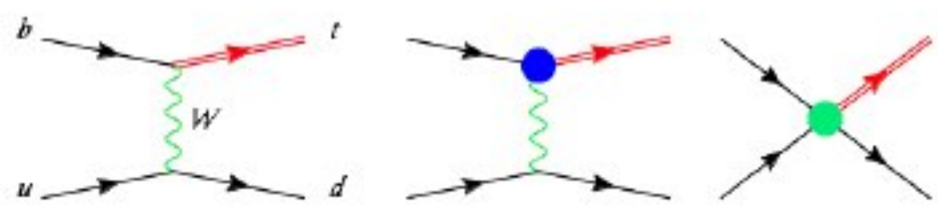
Operators entering various processes: Global approach needed

EFT in top production

Single top production



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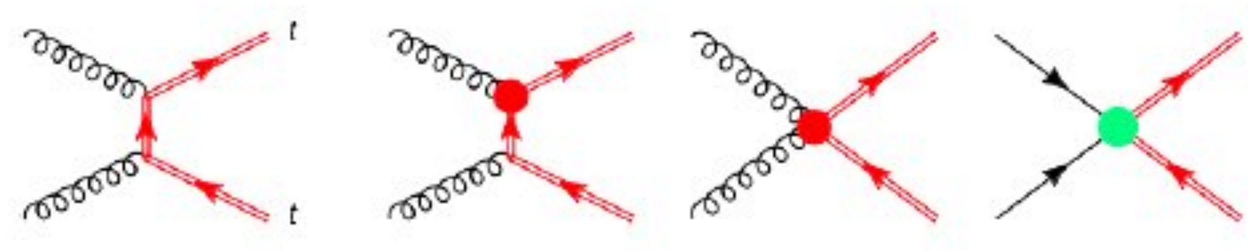
A complete top-quark EFT implementation

Under the umbrella of the LHC TOP WG, common standards and prescriptions were established for the EFT interpretation of top-quark measurements at the LHC. the note at https://arxiv.org/abs/1802.07237. Details concerning the present UFO model implementation are provided in Appendix B.1.

Top pair production



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

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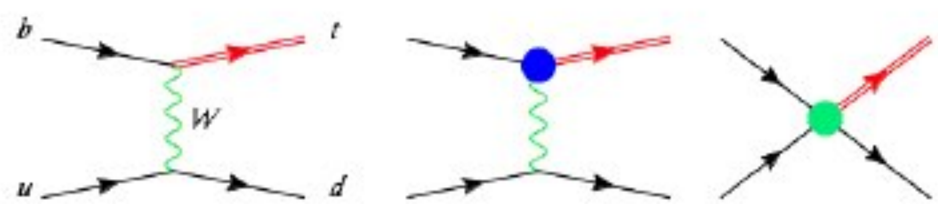

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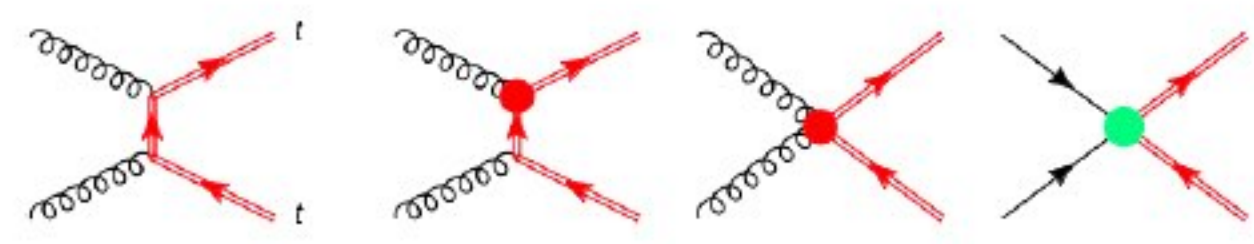

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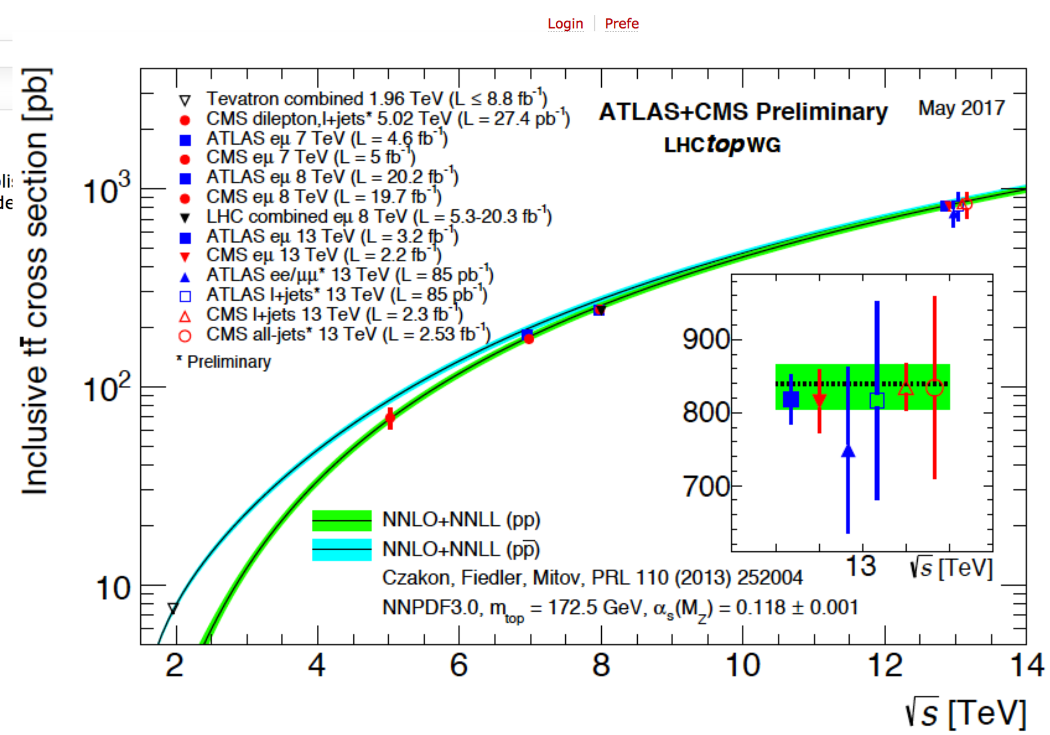

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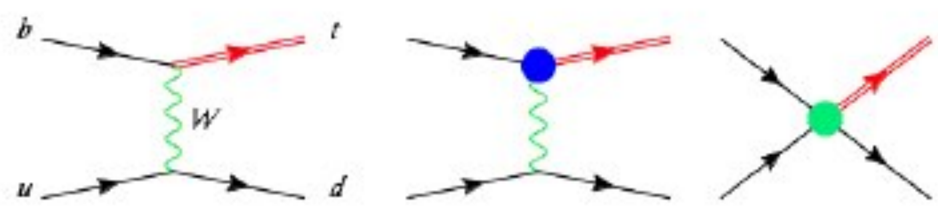

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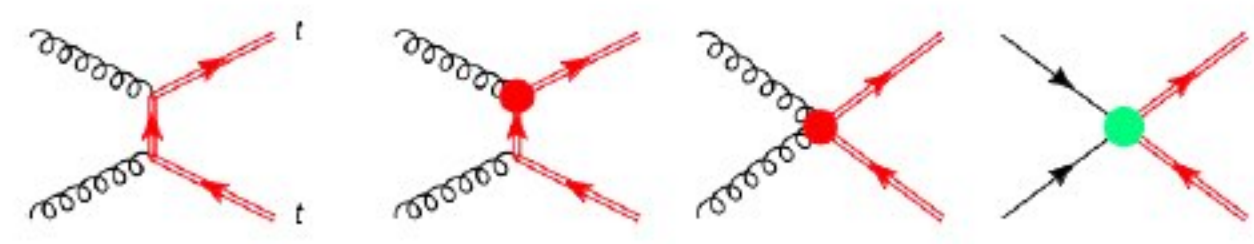

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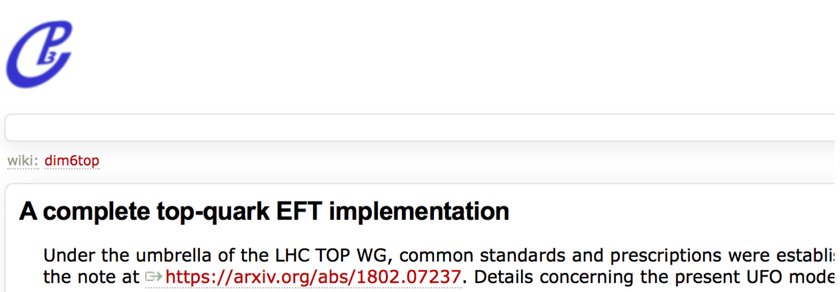
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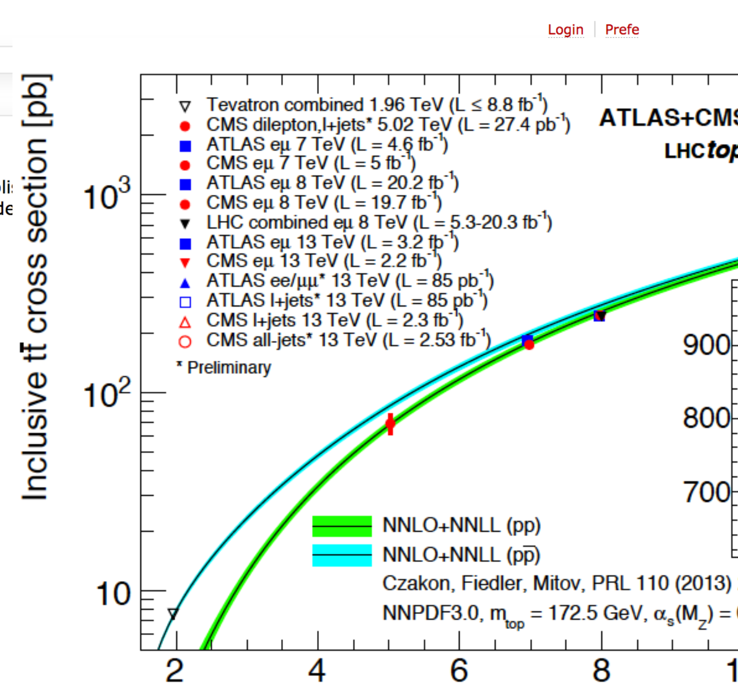
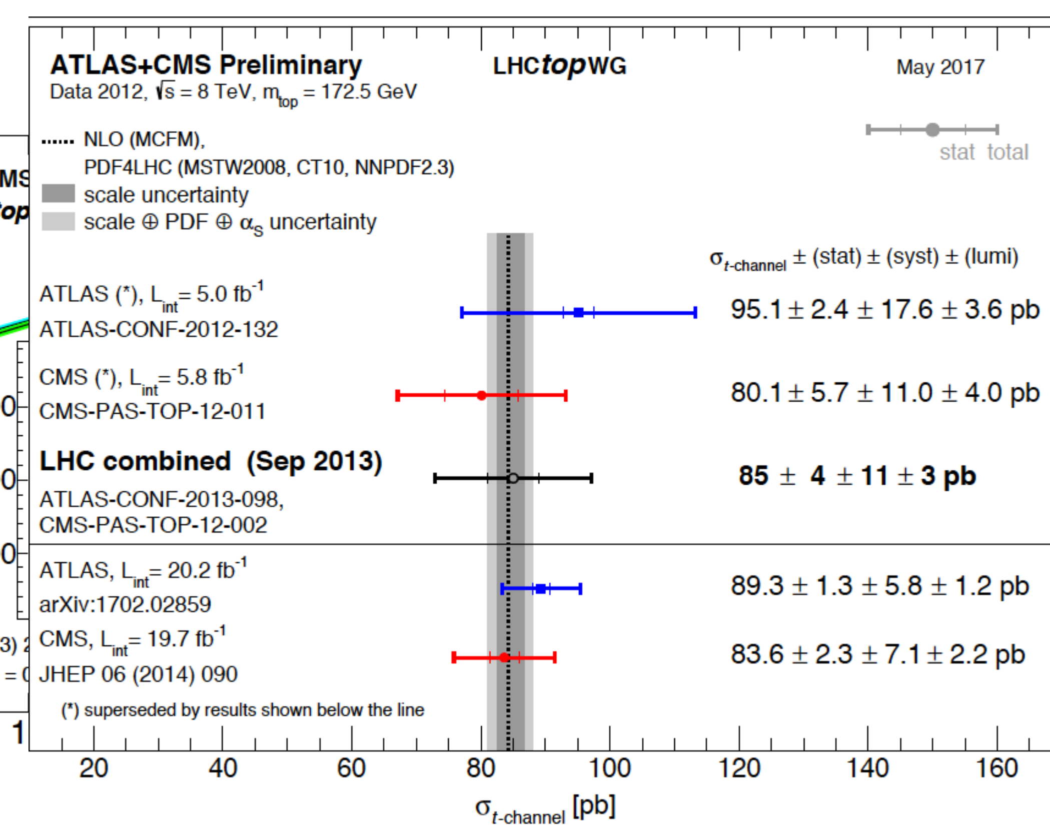




E.Vryonidou

Towards global fits

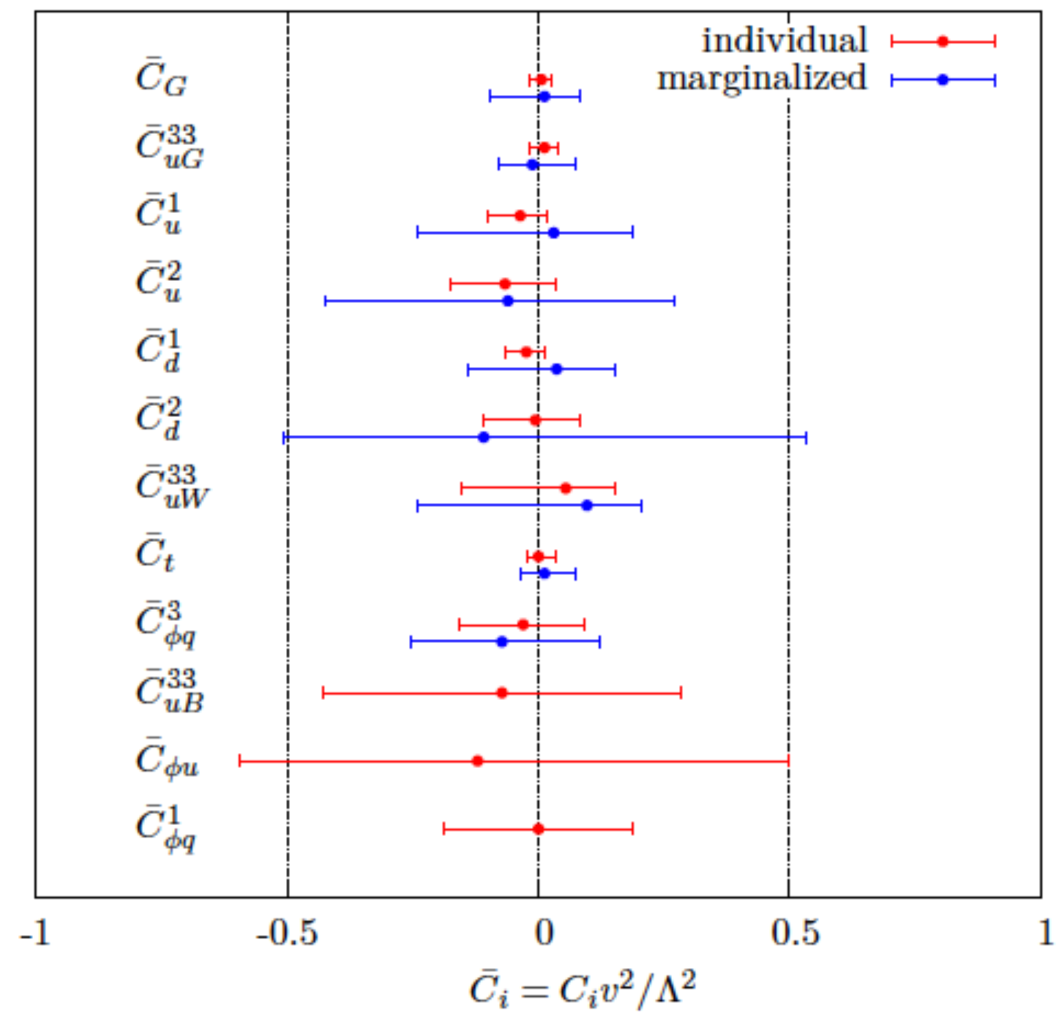
EFT only makes sense if we follow a global approach

First work towards global fits in the top sector:

Buckley et al arxiv:1506.08845 and 1512.03360

(N)NLO SM + LO EFT

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production							
Total cross-sections:				Differential cross-sections:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	1407.0371
ATLAS	7	dilepton	1202.4892	CDF	1.96	$M_{t\bar{t}}$	0903.2850
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
ATLAS	7	lepton w/ b jets	1406.5375	DØ	1.96	$M_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	1401.5785
ATLAS	7	tau+jets	1211.7205				
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	all hadronic	1302.0508	CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
CMS	8	dilepton	1312.7582	DØ	1.96	Γ_{top}	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	Γ_{top}	1201.4156
Single top production				*W*-boson helicity fractions:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.2484
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.4523
CMS	7	t-channel (total)	1406.7844	CMS	7		1308.3879
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.6549
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar{t}\gamma$	1502.00586	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				



Tevatron and LHC data

Cross-sections and distributions

What's next?

Use SMEFT to parametrise and look for deviations from SM predictions

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Use SMEFT to parametrise and look for deviations from SM predictions

→

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

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↓

Use the best SM predictions QCD/EW corrections

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Use SMEFT to parametrise and 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

←

Automated tools for the EFT
Need for precision calculations

How can we improve the EFT predictions?

- SMEFT@NLO in QCD: Adding N's
- MadGraph5_aMC@NLO needs R2+UV counterterms
- NLOCT Degrande (arxiv:1406.3030)
    - Automatic UV and R2 counterterms (under development)
  - Mixing between operators: anomalous dimension matrix (UV counterterms): Jenkins et al arXiv:1308.2627,1310.4838, Alonso et al. 1312.2014
- NLO UFO EFT models:

https://feynrules.irmp.ucl.ac.be/wiki/NLOModels
    - Higgs Characterisation
    - Top FCNC
    - HELatNLO

EFT@NLO examples

Recent progress:

Higgs:

- Higgs characterisation arXiv:1306.6464
  - VBF, VH Maltoni et al arXiv:1311.1829
  - ttH Demartin et al arXiv:1407.5089, tH Demartin et al arXiv:1504.00611
- HELatNLO Degrande et al: arXiv:1609.04833
  - EW Higgs production

Top:

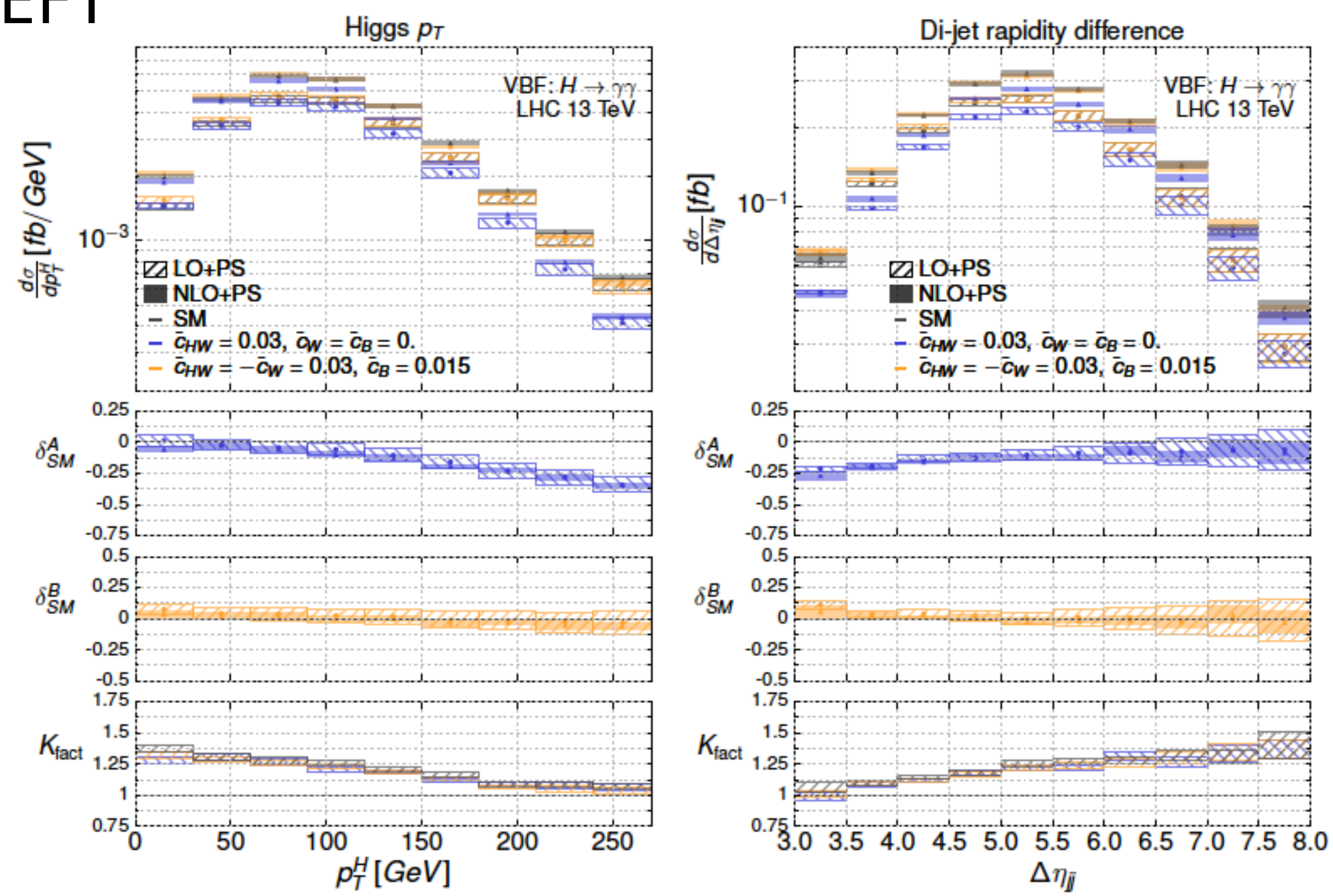
- top pair production: Franzosi and Zhang (arxiv:1503.08841)
- single top production: C. Zhang (arxiv:1601.06163)
- ttZ/γ: Bylund, Maltoni, Tsinikos, EV, Zhang (arXiv:1601.08193)
- ttH: Maltoni, EV, Zhang (arXiv:1607.05330)
- tH/Zj: Degrande, Maltoni, Mimasu, EV, Zhang arXiv:1804.07773

EW Higgs production

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

```
./bin/mg5_aMC
import model HELatNLO
generate p p > h j j $$ w+ w- z a NP=2 QCD=0 [QCD]
output VBFEFT
```

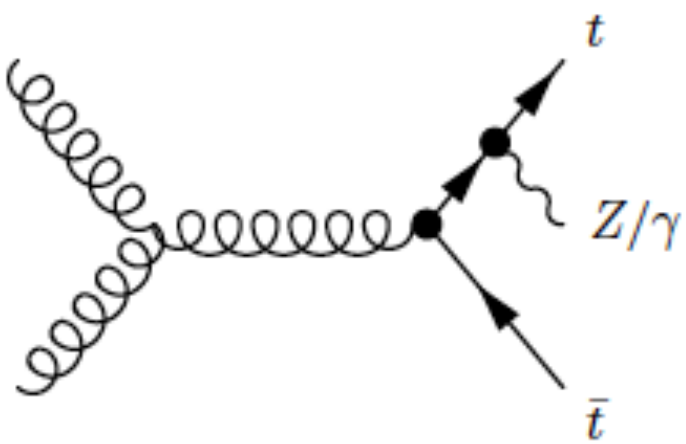
← NLO

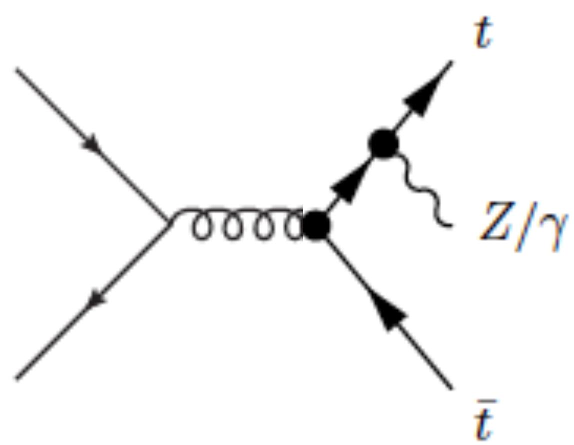


Flexible, process-independent implementation ready for realistic simulations

E.Vryonidou

Top-pair+Z





~900fb at 13 TeV

Relevant operators

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

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

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

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

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

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

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

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

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

$$C^Z_{2,V} = \left(C_{tW}c_W^2 - C_{tB}s_W^2\right)\frac{2m_t m_Z}{\Lambda^2 s_W c_W}$$

$$C^Z_{2,A} = 0$$

Anomalous coupling approach

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

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

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

interference — interference between operators, squared

E.Vryonidou

In practice

Behind the scenes…

operators, squared

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]
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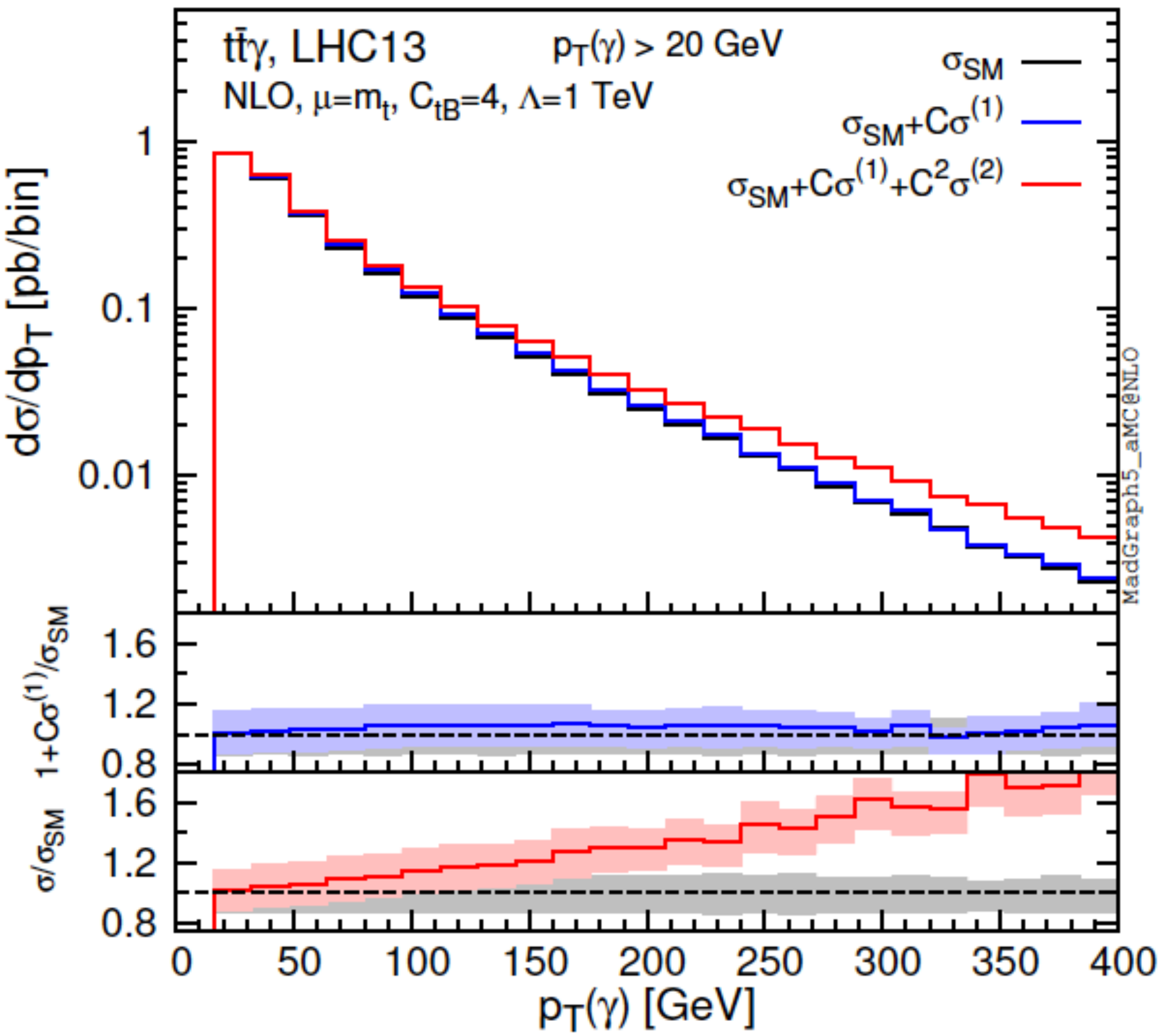
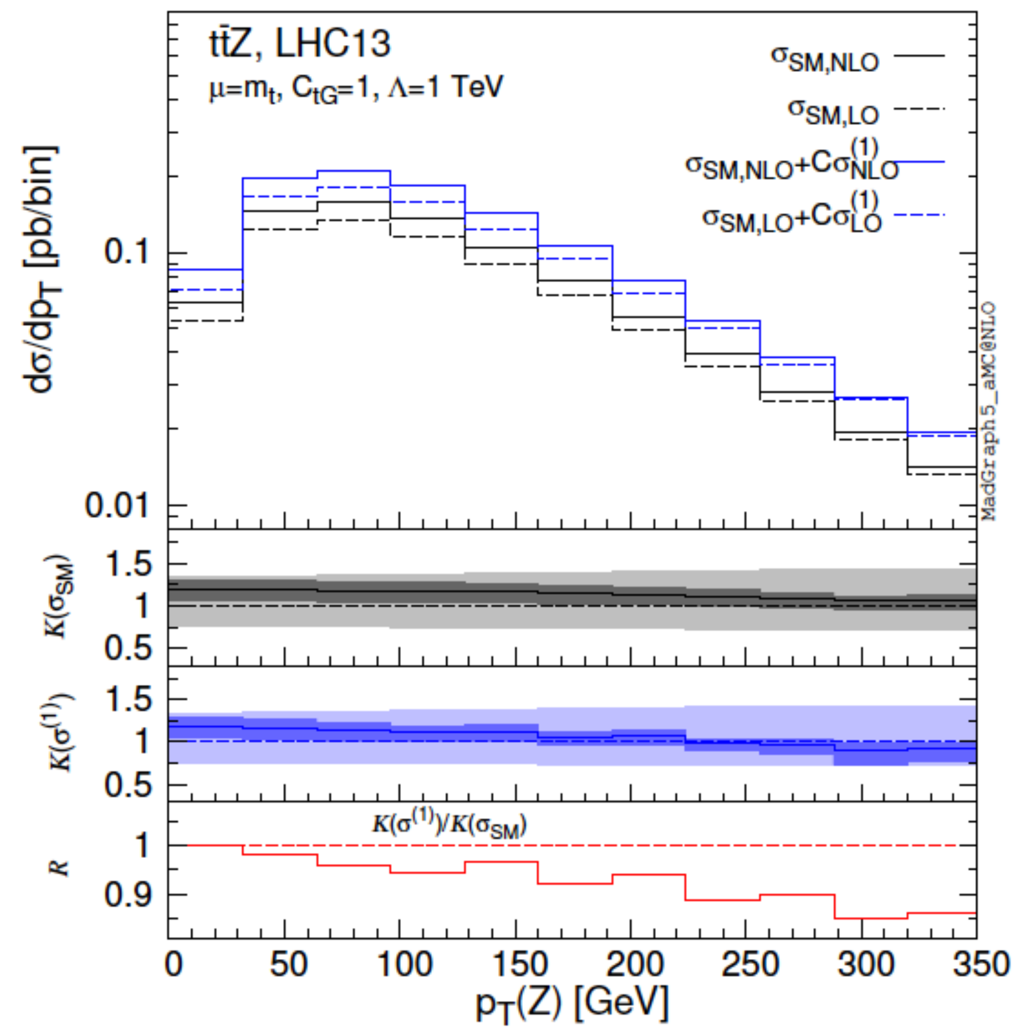
interference — interference between operators, squared

Results for tt+V

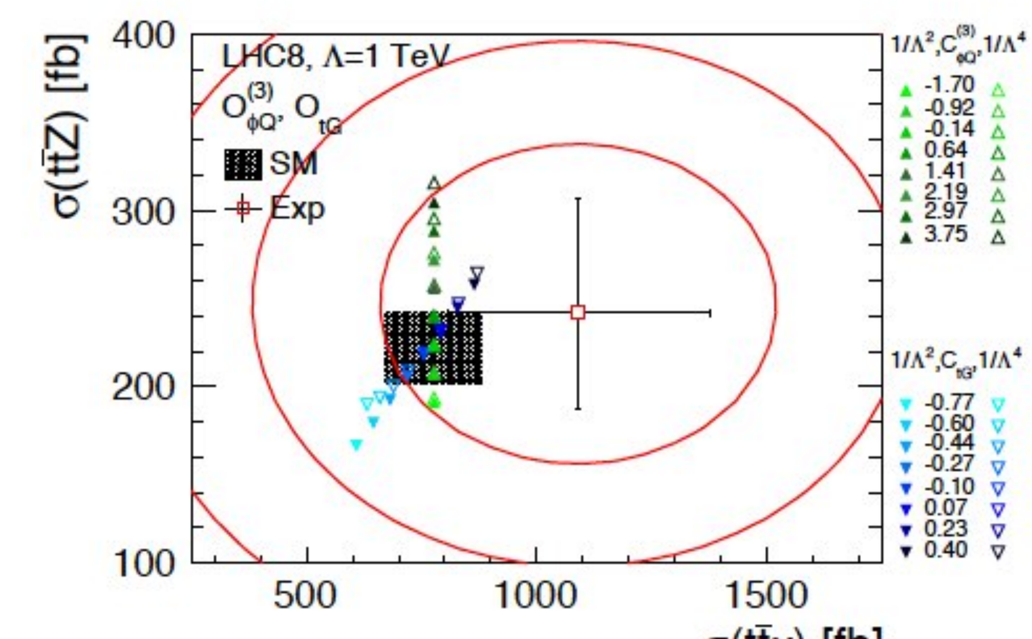




Using SM k-factors is not enough

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

arXiv:1601.08193



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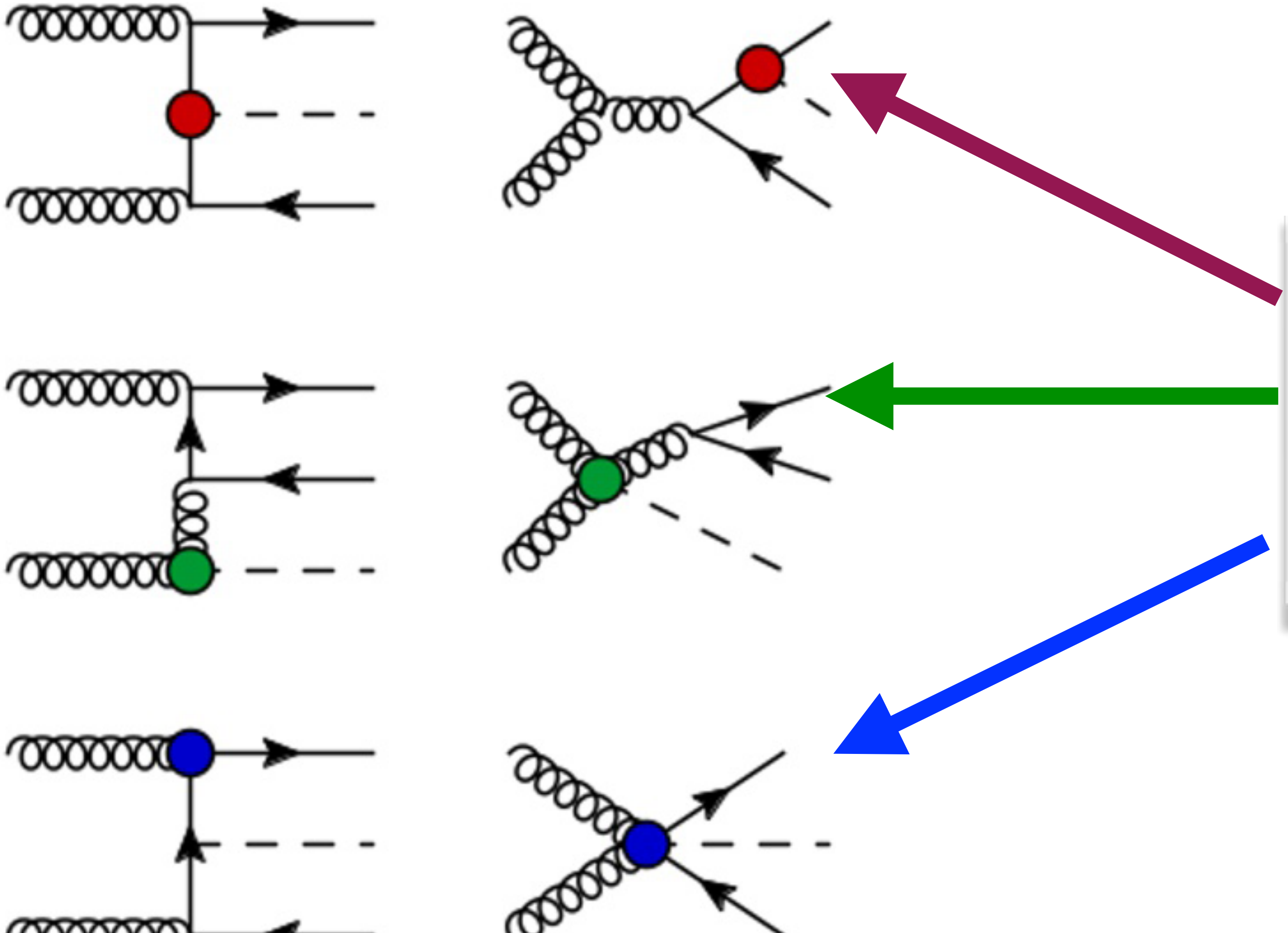
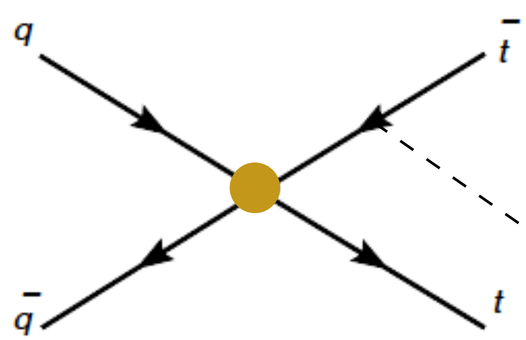
ttH in the EFT



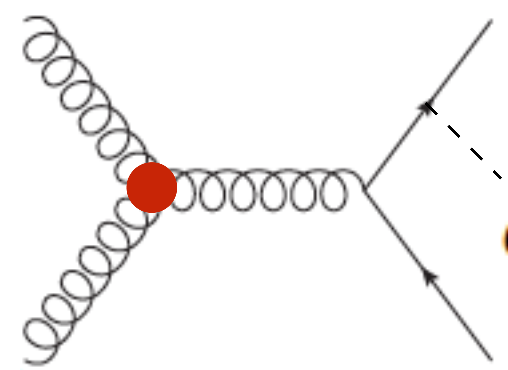
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

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

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



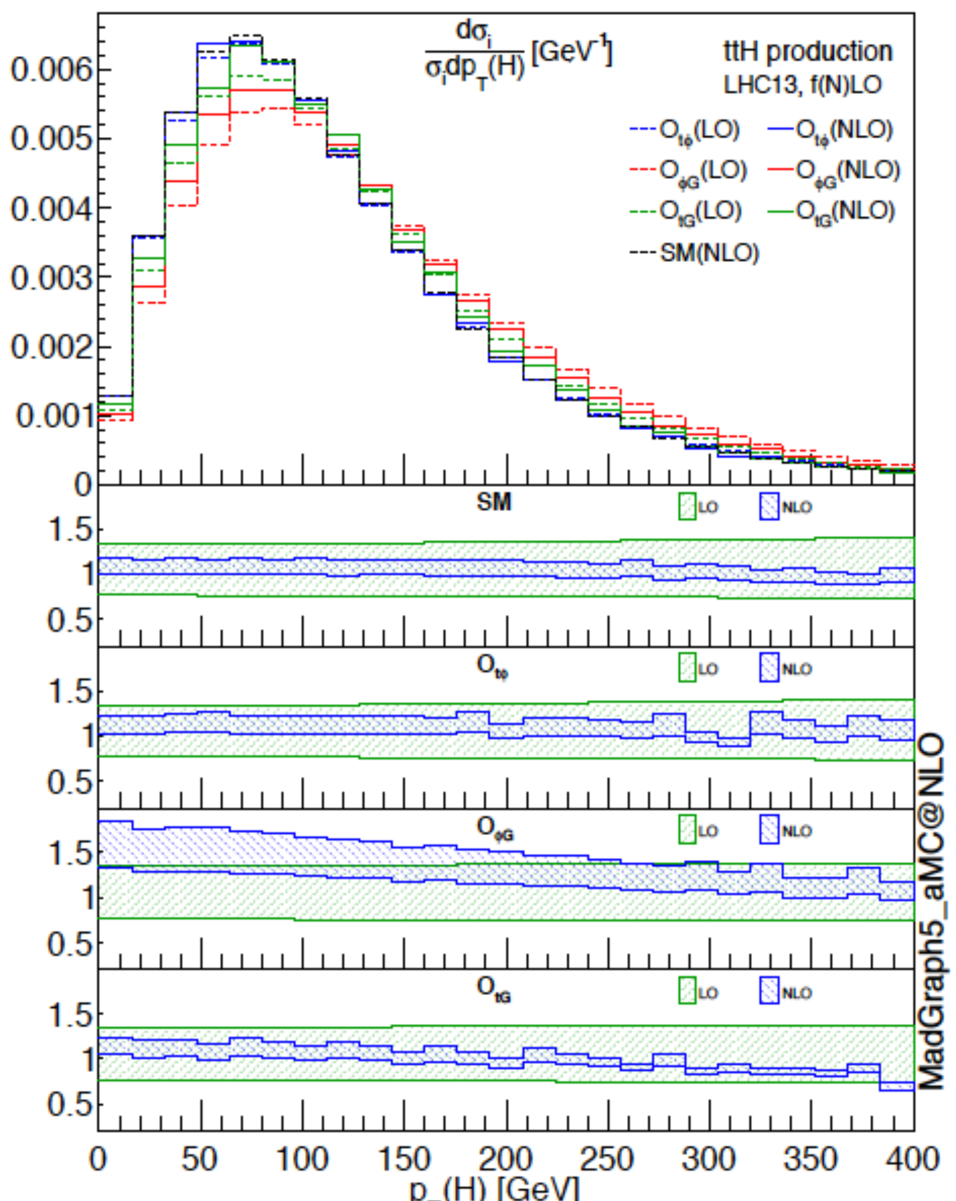
4-fermion operators

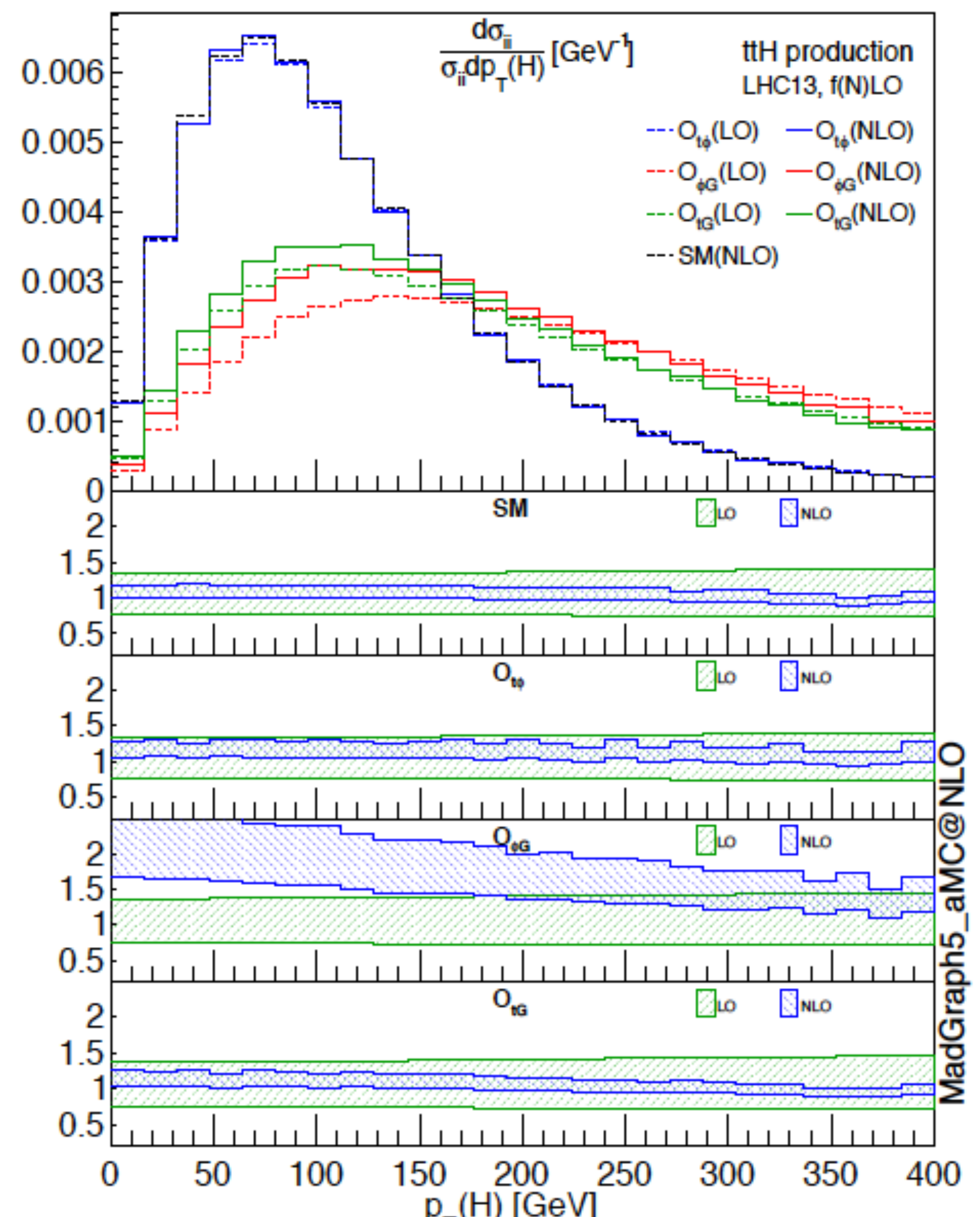


$$O_G = g_s f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$$

Not in this talk, work in progress

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

Towards a complete implementation@NLO

Based on:

- Warsaw basis
- Degrees of freedom for top operators

Current status:

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

Future plans

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

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

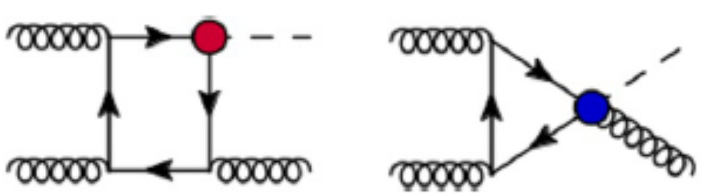
EFT in loop-induced processes

Ingredients:

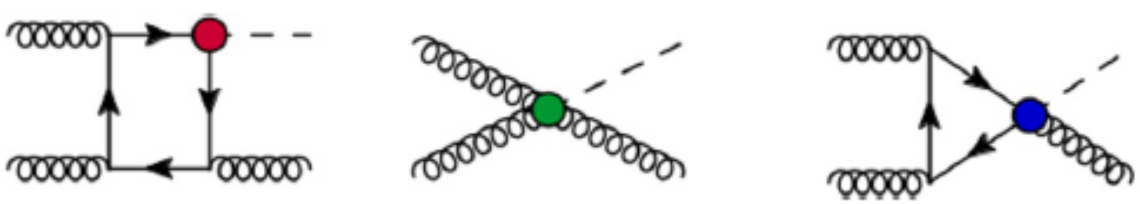
- NLO-ready UFO model as before: UV and R2 counterterms
- Loop-induced event generation

Example:

```
MG5_aMC>import model TEFT_H
MG5_aMC>generate p p > H j EFT=1 [QCD]
MG5_aMC>output
MG5_aMC>launch
```



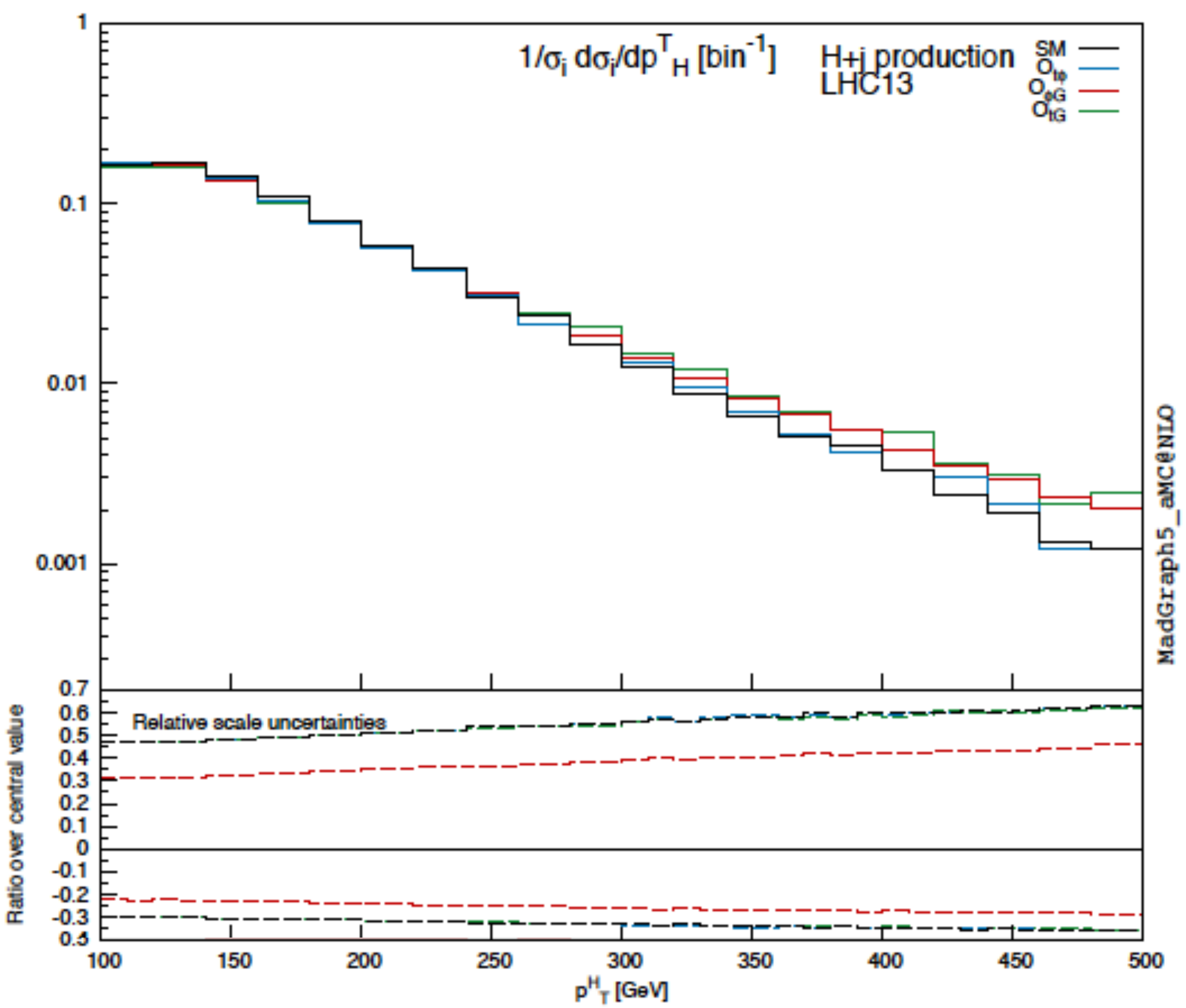
SMEFT in H+j

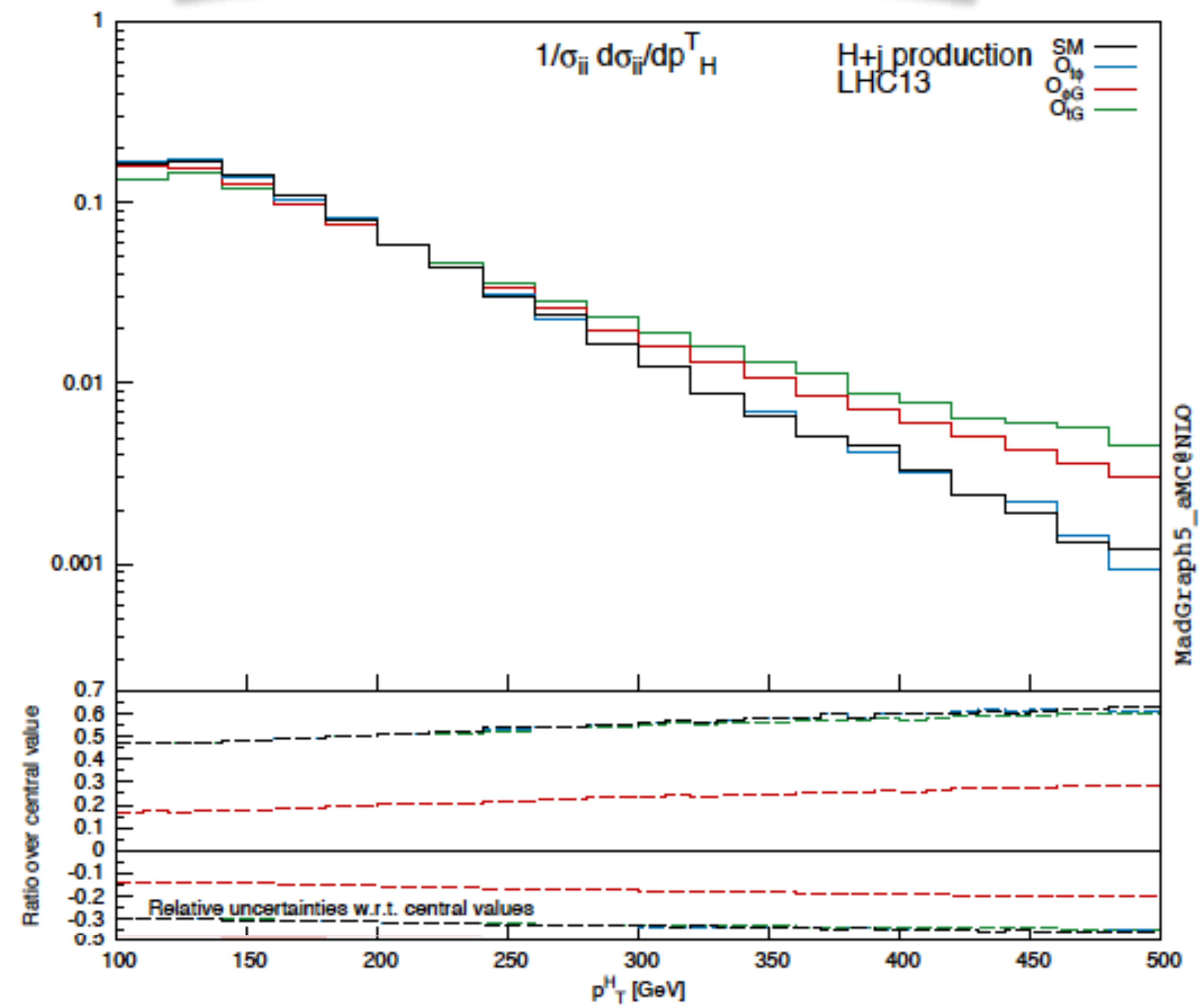


$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}$$

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

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

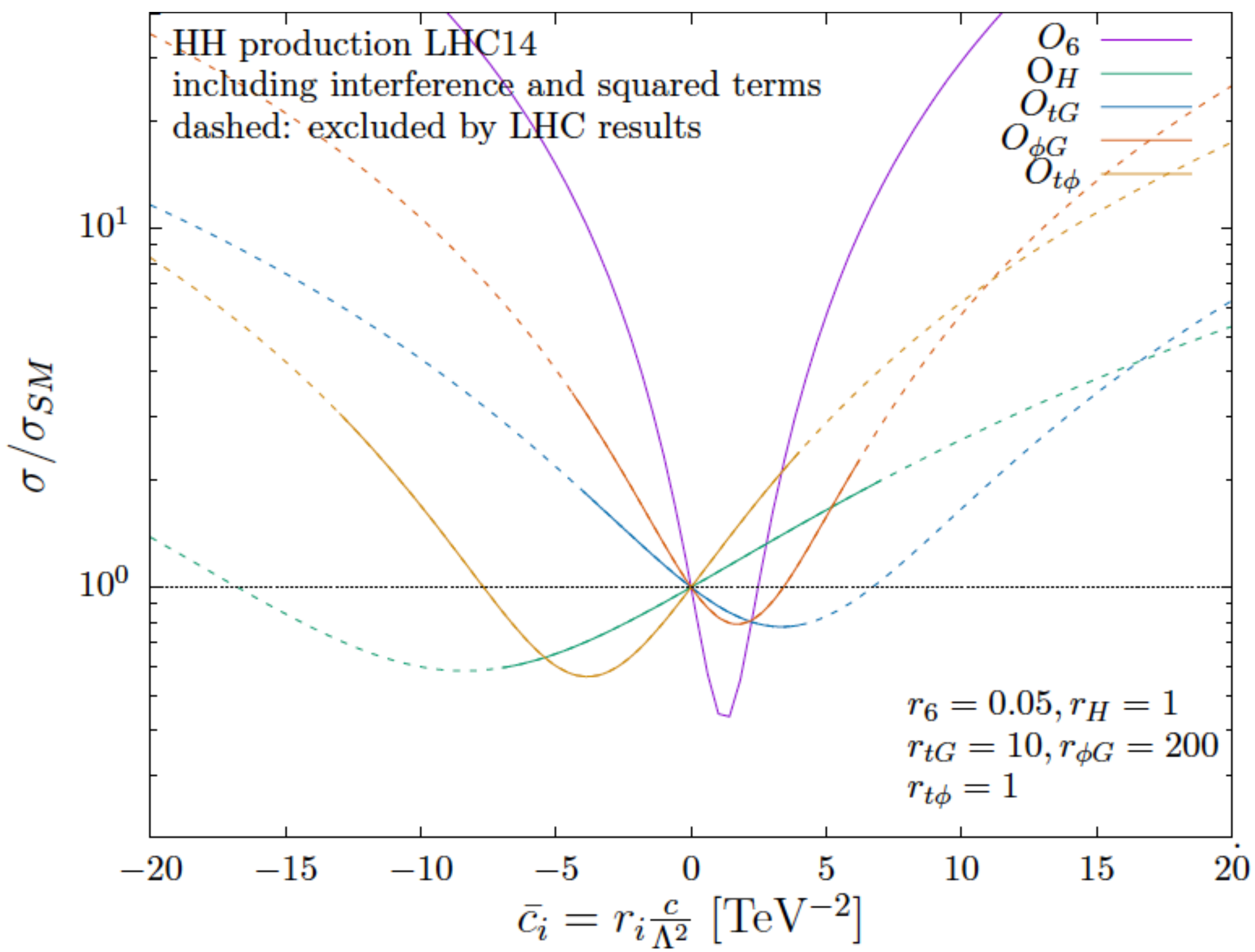


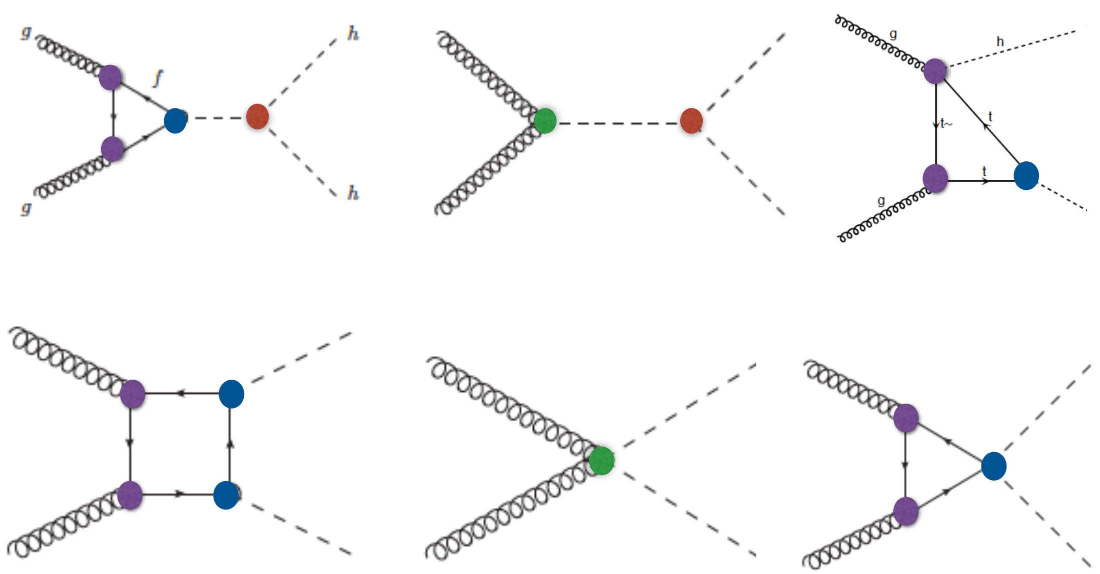


Harder tails from dim-6 operators: Boosted analysis

Maltoni, EV, Zhang: arXiv:1607.05330

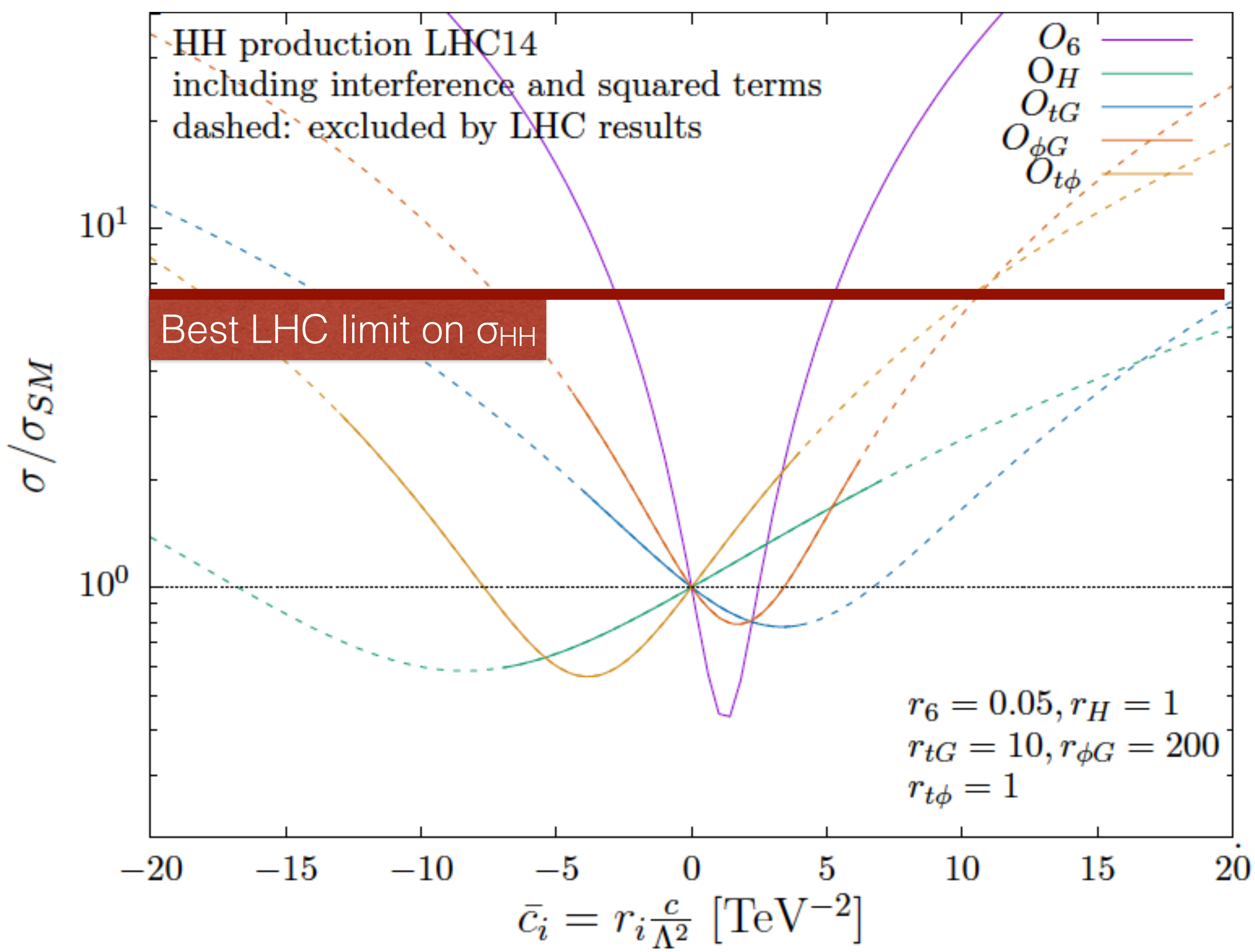
HH in the EFT

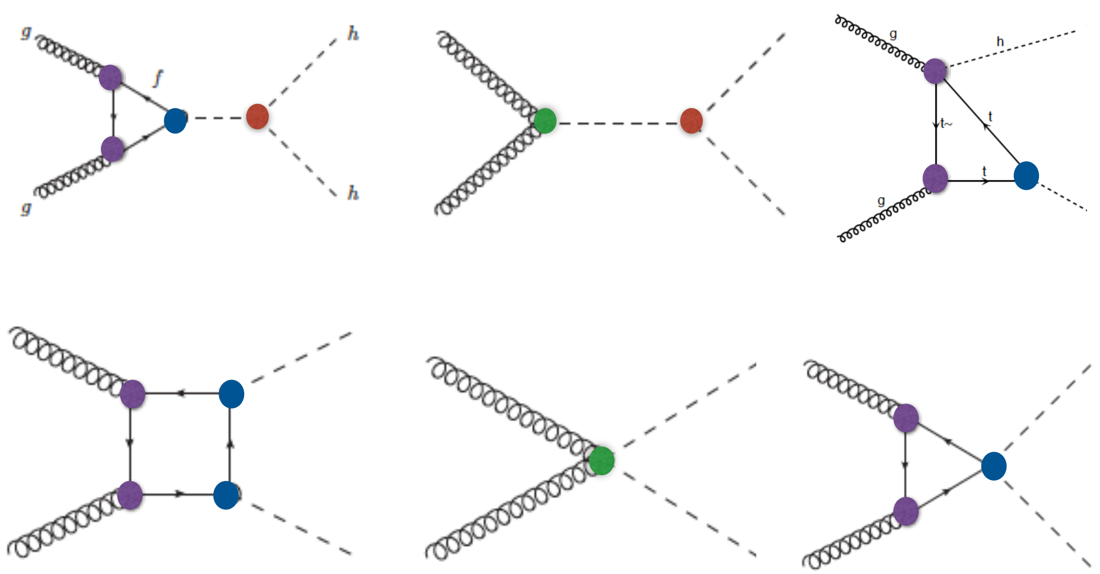




Other couplings enter in the same process:
top Yukawa, ggh(h) coupling, top-gluon interaction

HH in the EFT





Other couplings enter in the same process:
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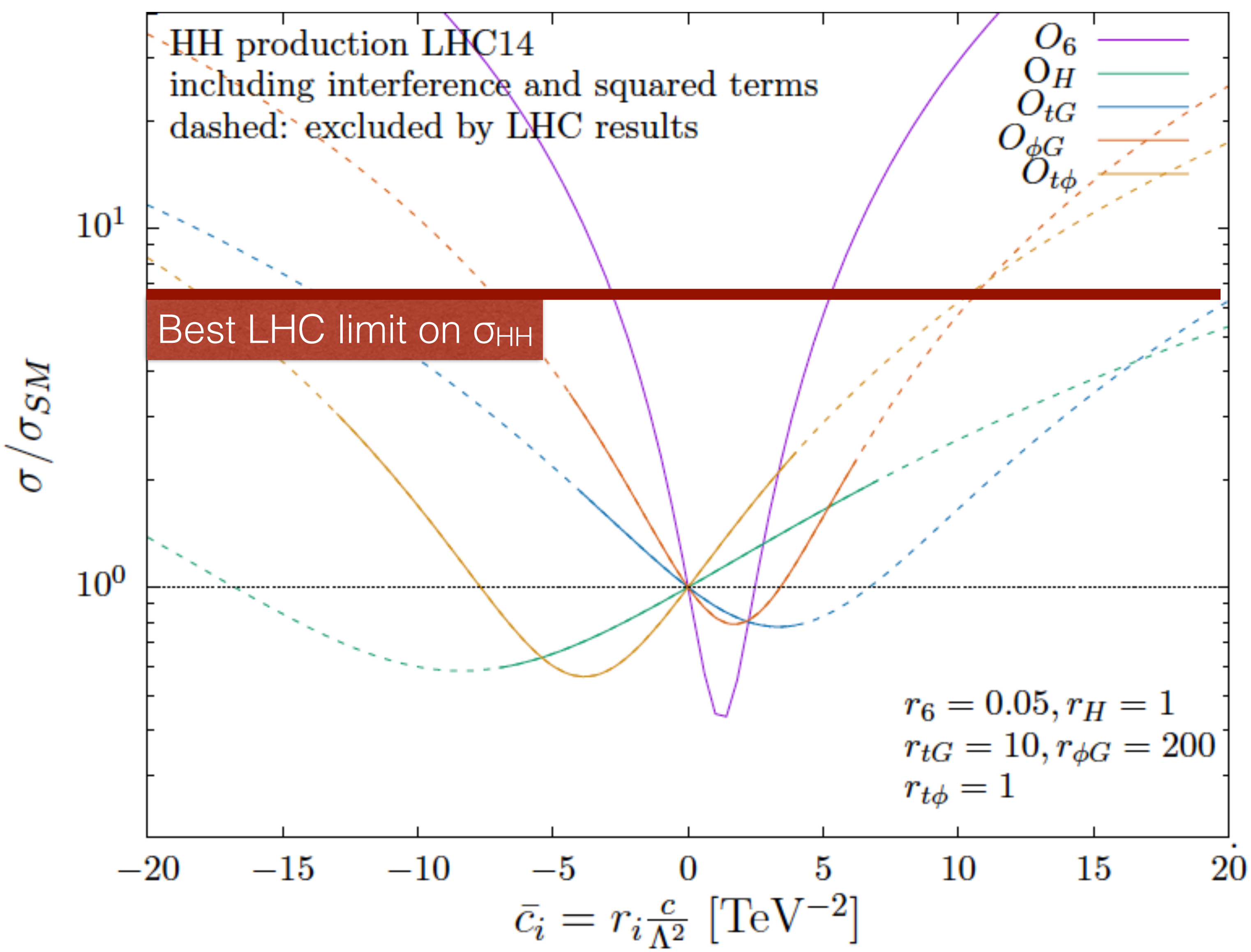
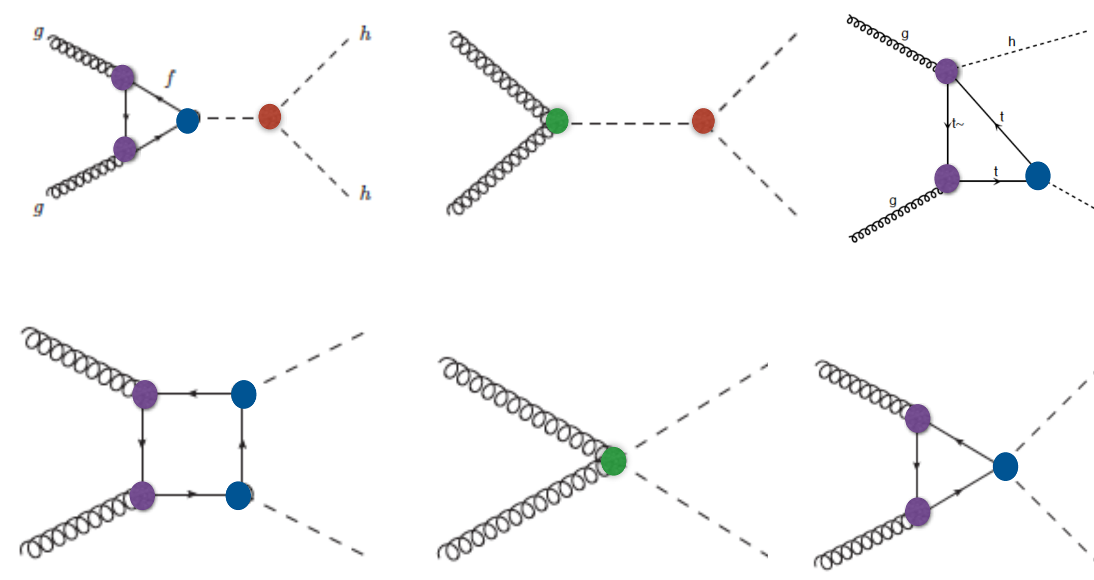
The present
Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained “ignoring” other couplings

HH in the EFT





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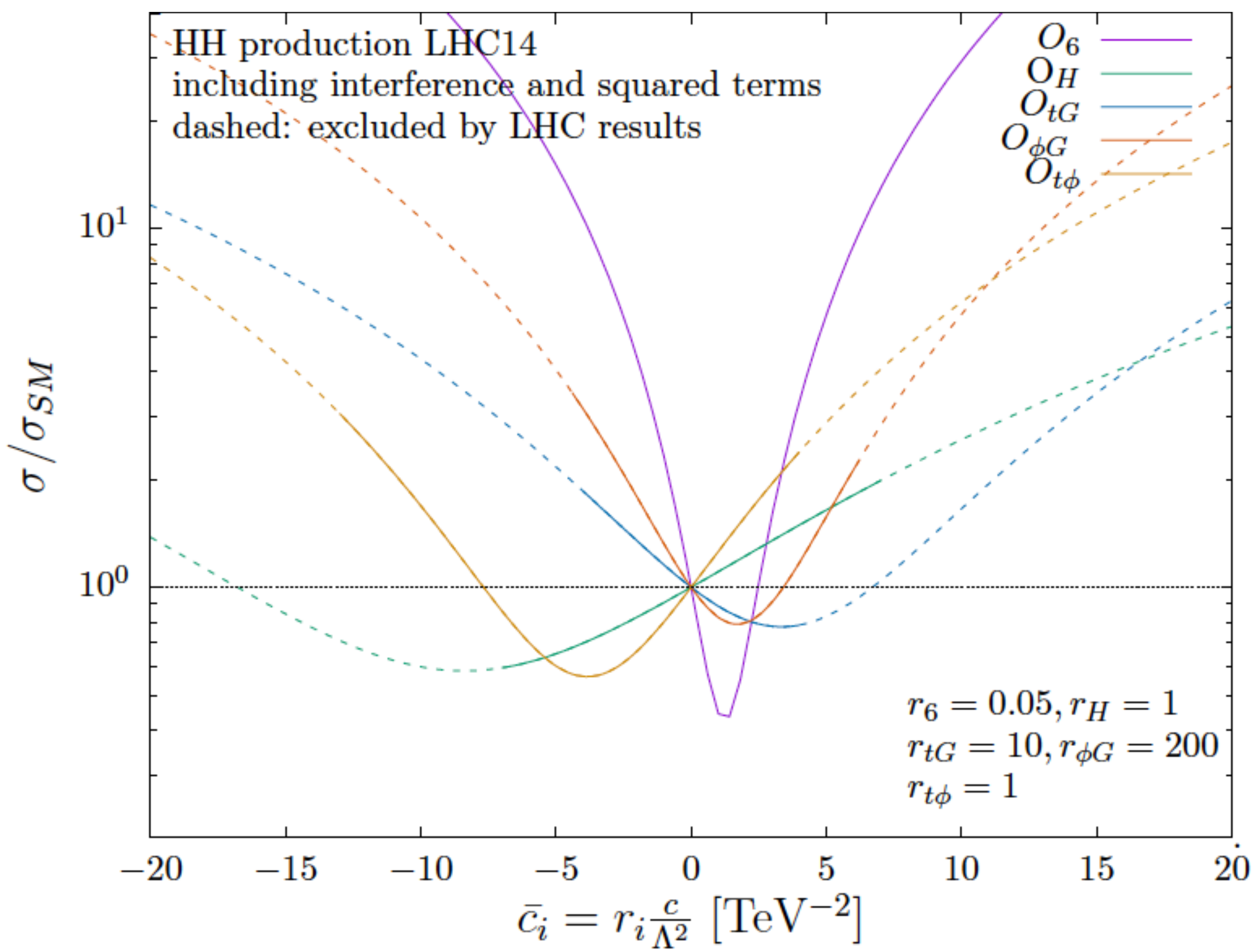
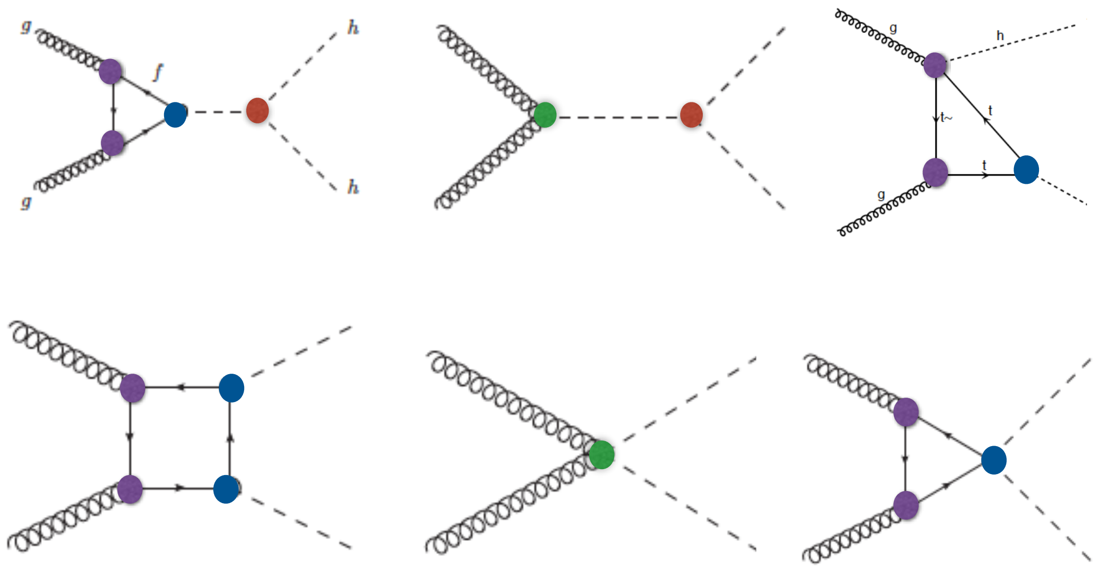
The future
Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM
Differential distributions will also be necessary

HH in the EFT





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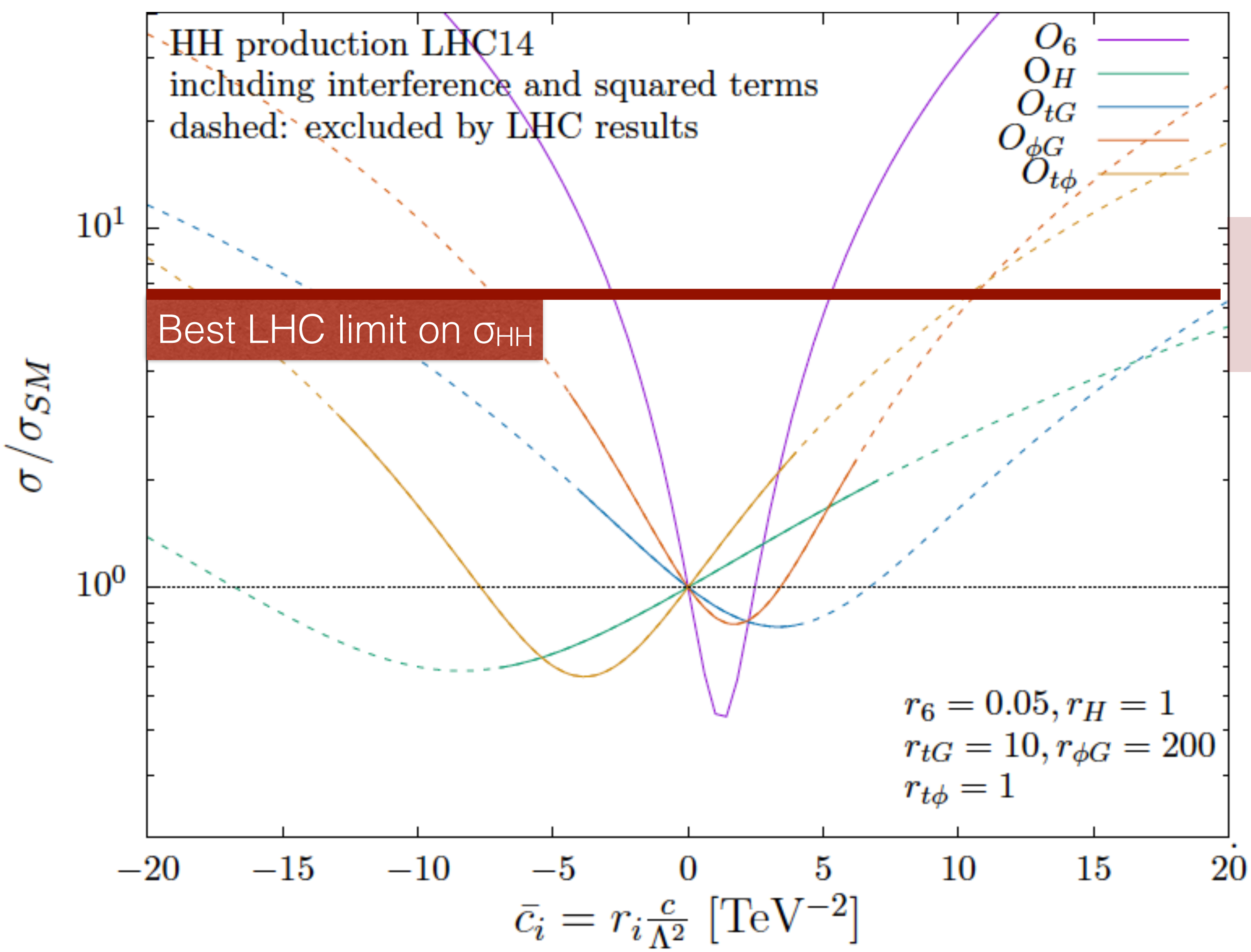

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$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu} \,,$$

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

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

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

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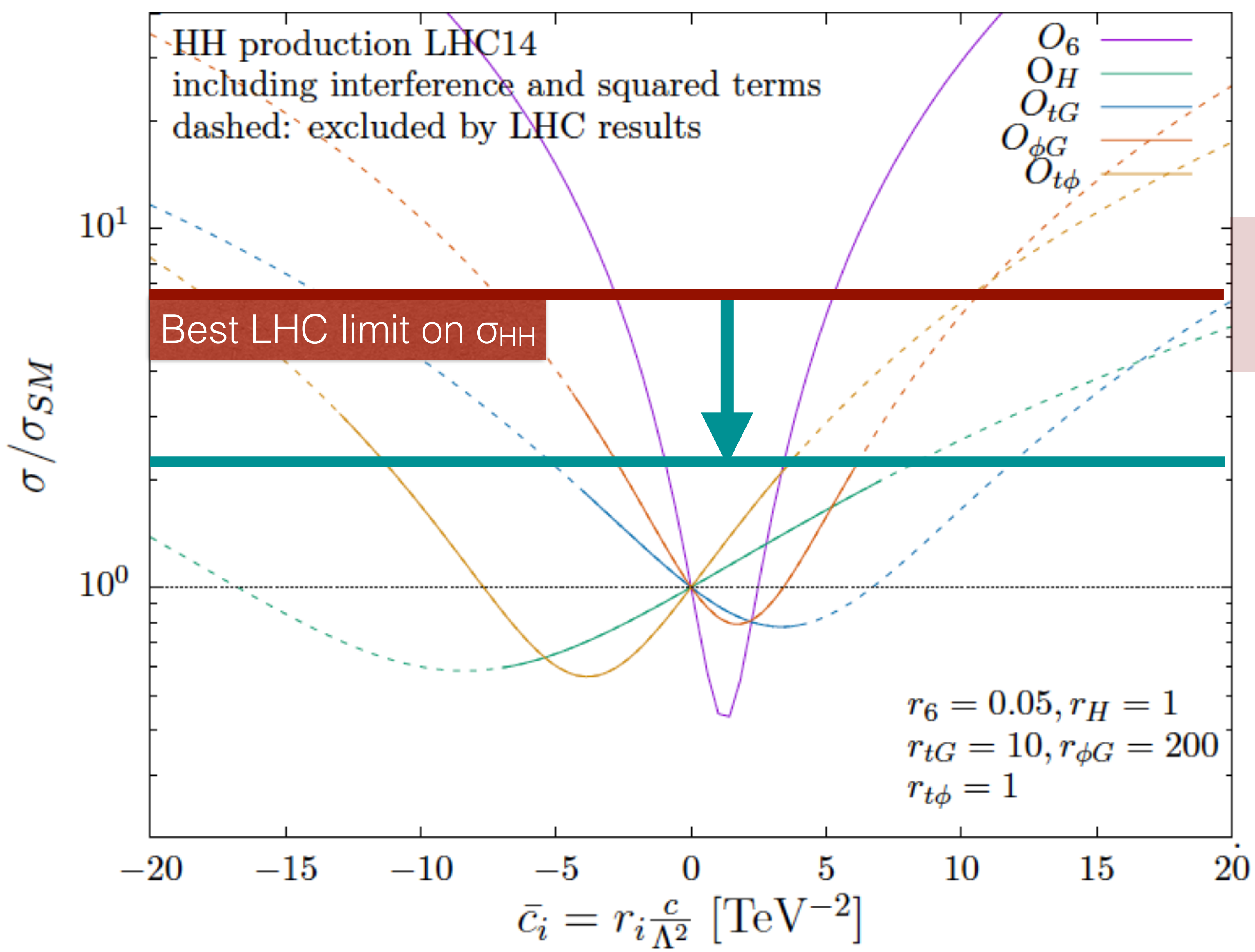
E.Vryonidou

HH in the EFT



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

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

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Other couplings enter in the same process:
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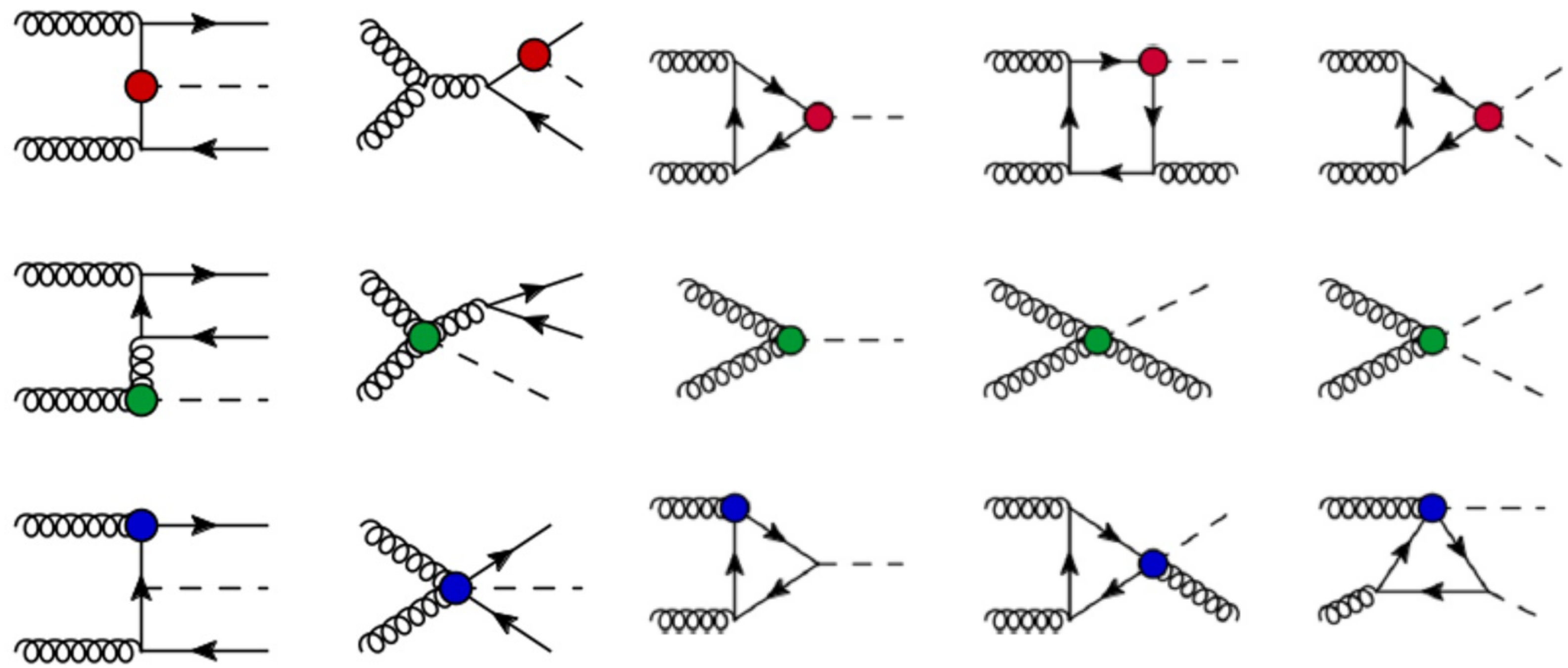
Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM
Differential distributions will also be necessary

E.Vryonidou

Top and Higgs

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



ttH

H, H+j, HH

See also
Degrande et al. arXiv:1205.1065
Grojean et al. arXiv:1312.3317
Azatov et al arXiv:1608.00977
Cirigliano et al arXiv: 1510.00725,1603.03049,1605.04311 (including CP-violation)

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

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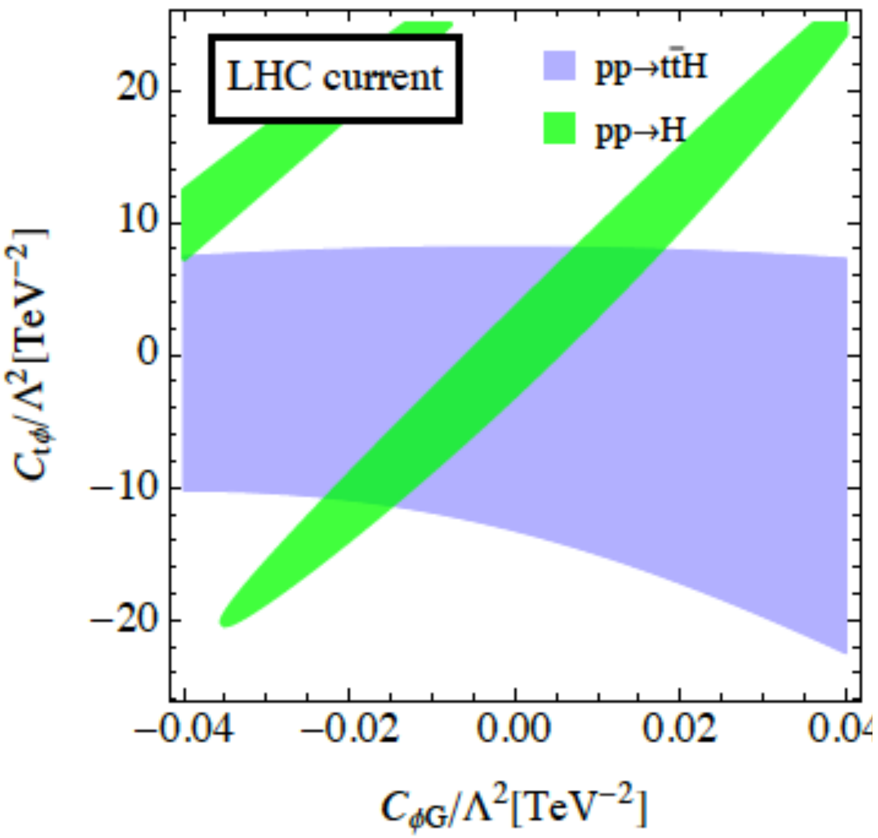
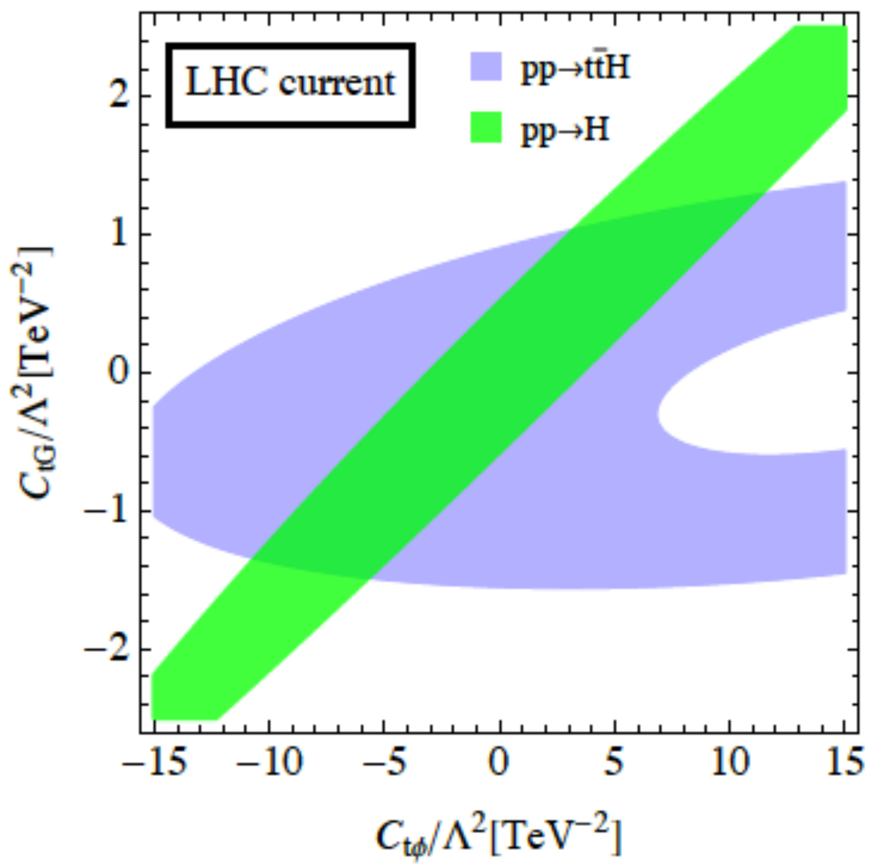
Constraints using two-operator fits



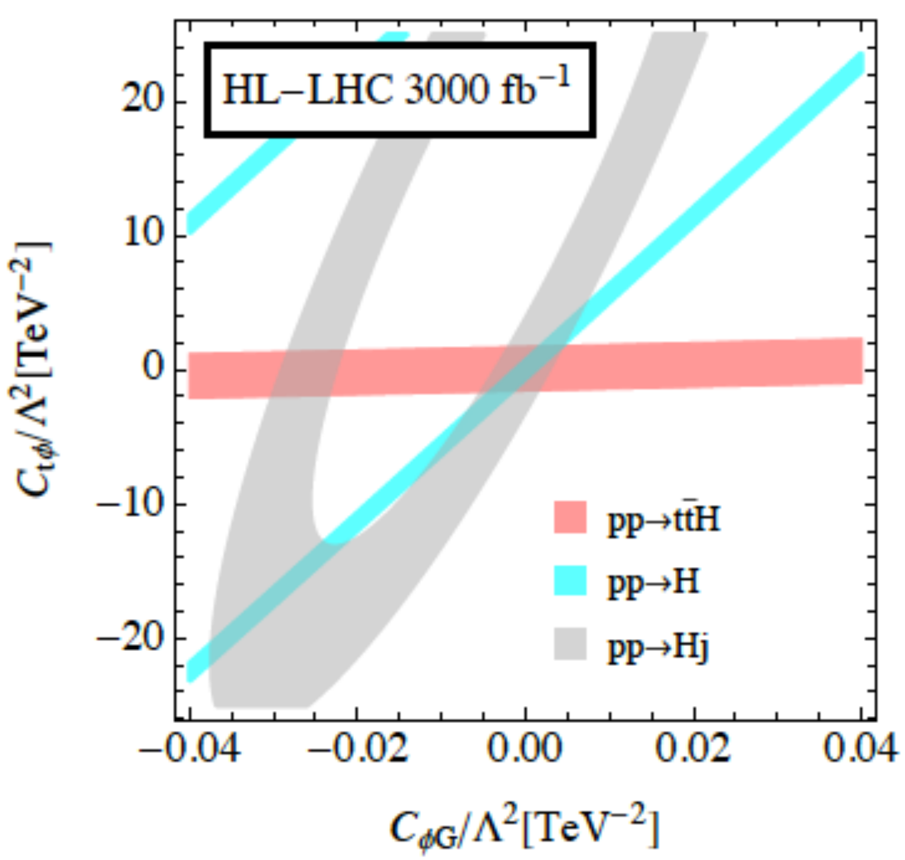


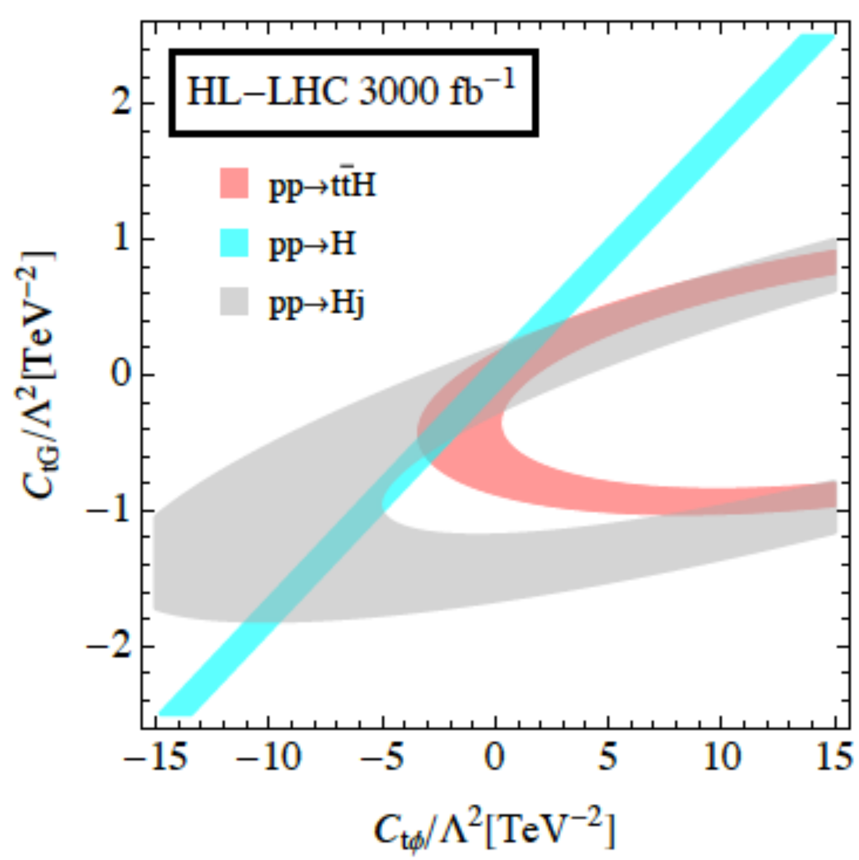
Current limits using LHC measurements

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

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

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





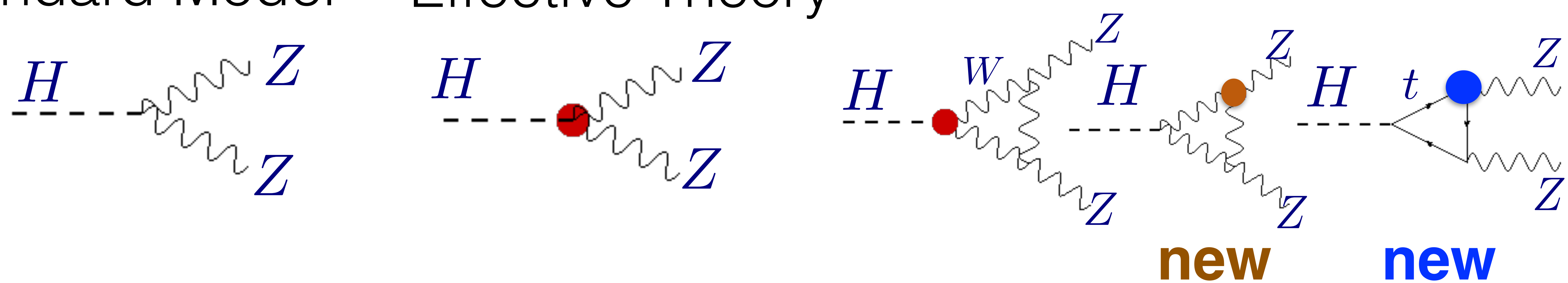
14TeV projection 3000 fb^{-1}

Maltoni, EV, Zhang
arXiv:1607.05330

EW precision in EFT

Leading Order **Higher Order**

Standard Model Effective Theory

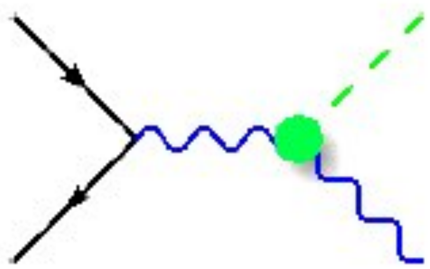
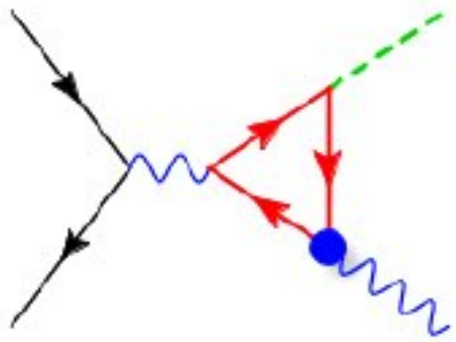


The picture at higher orders is more complicated, the computations are much more challenging:

- New interactions arise for the same initial and final state
- Higher-order corrections can potentially be large

Promoting all effective field theory predictions to higher-order to enhance the discovery potential

Going beyond QCD corrections

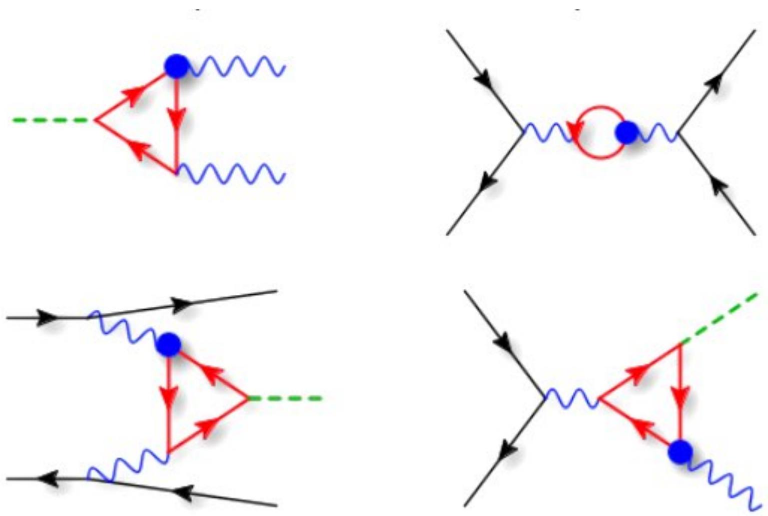
Are we measuring  or  ?

NLO EW in SMEFT may not be small:

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

Weak corrections can be important for unconstrained operators

Towards weak loops in the EFT



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

+

Current constraints

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

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

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

loop-induced

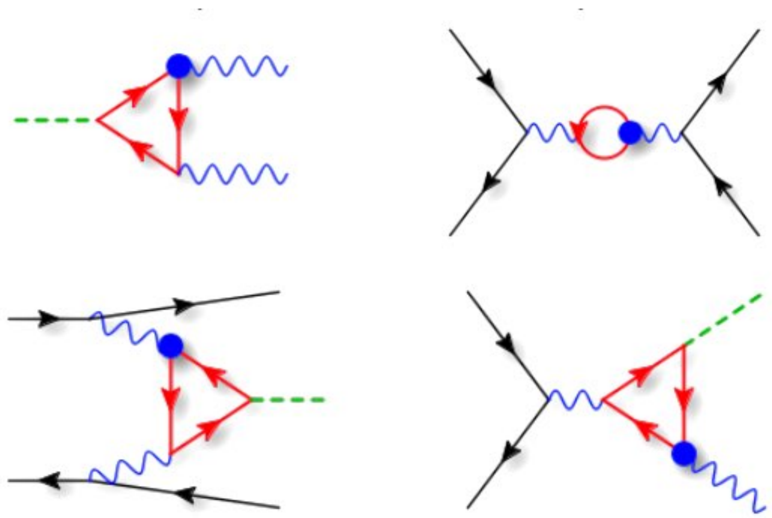
tree-level

E.Vryonidou

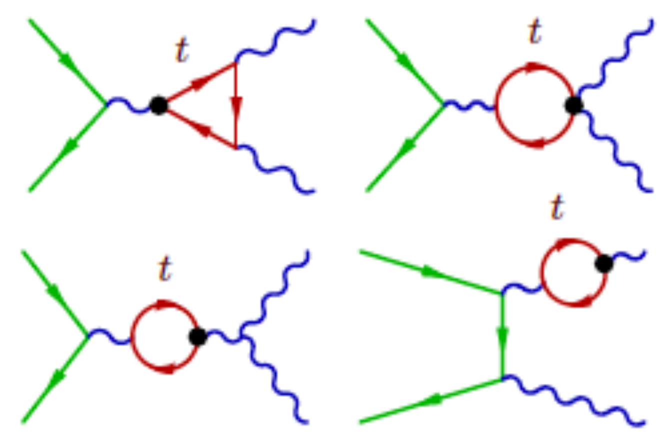
EV, Zhang arXiv:1804.09766

Weak loops in the EFT: Future colliders

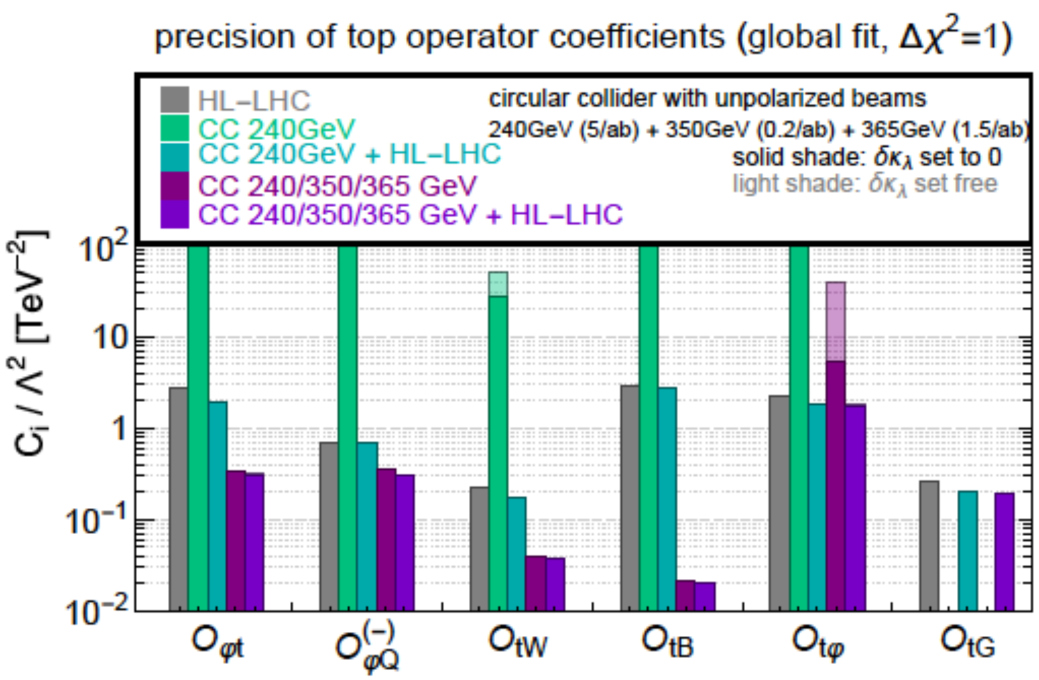
Circular Electron Positron Collider & HL-LHC: Top + Higgs Global Fit

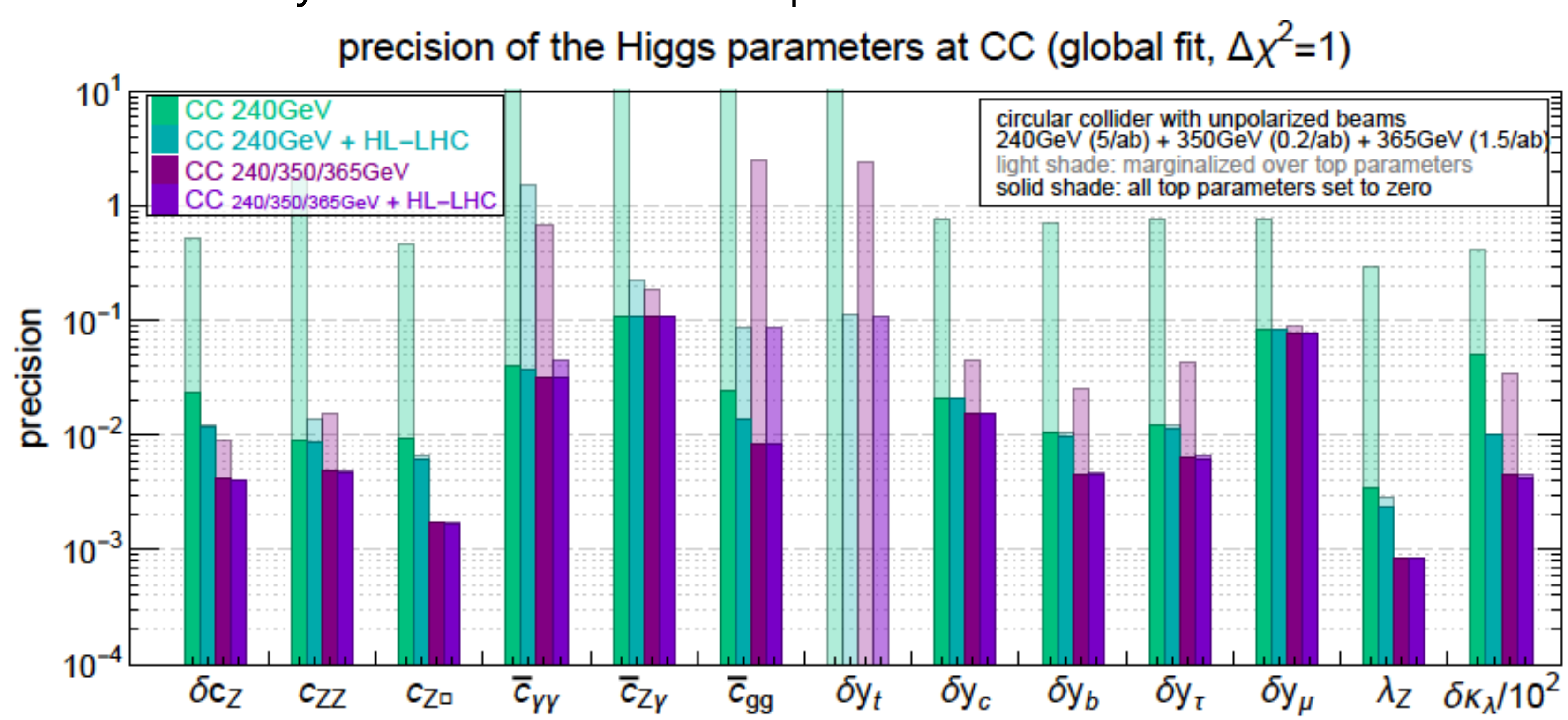


Higgs production and decay



WW production





Durieux, Gu, EV, Zhang arXiv:1809.03520

E.Vryonidou

Summary

- SMEFT is a consistent way to look for new interactions
- SMEFT is a systematically improvable framework
- Tools and automation important to constrain the operators using LHC measurements
- Higher-order corrections needed to match SM precision and experimental accuracy, automation to soon reach the level of SM predictions
- Progress in both Higgs and top-quark processes at NLO in QCD and EW, as well as loop-induced processes

Thank you for your attention