Effective Field Theory at the LHC

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University of Manchester

EFT school
online, 11/04/21

Outline

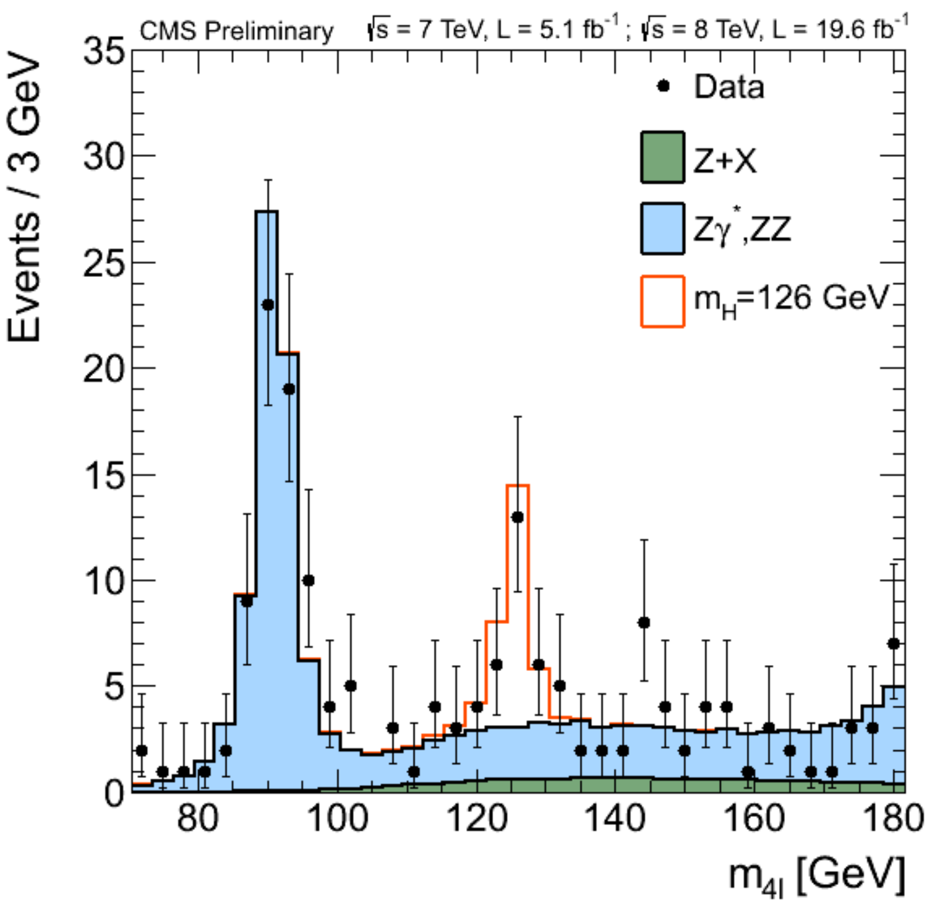
- EFT basics
- LHC physics applications

How to look for new physics?

Model-dependent

SUSY, 2HDM…

New particles

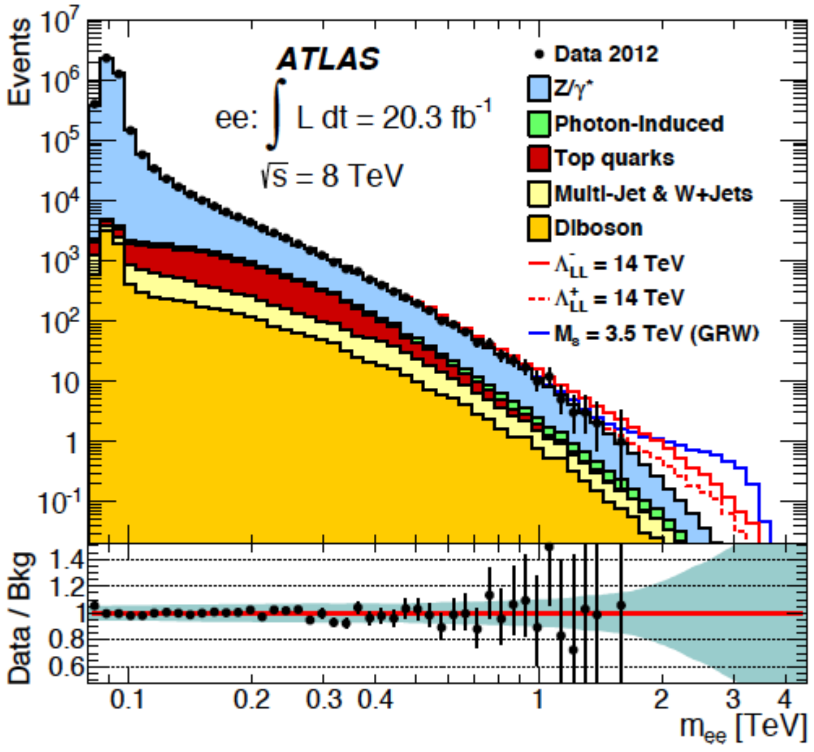


Model-Independent

simplified models,EFT

New Interactions of SM particles

anomalous couplings, EFT



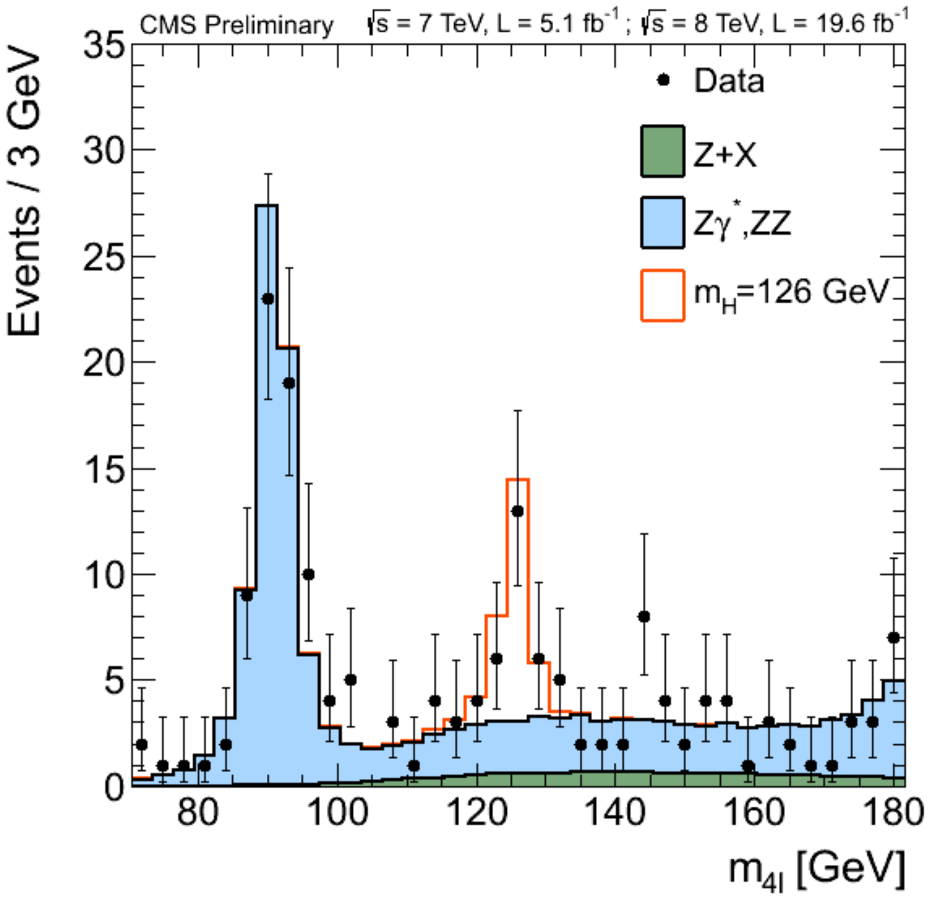
Deviations in tails

How to look for new physics?

Model-dependent

SUSY, 2HDM…

New particles



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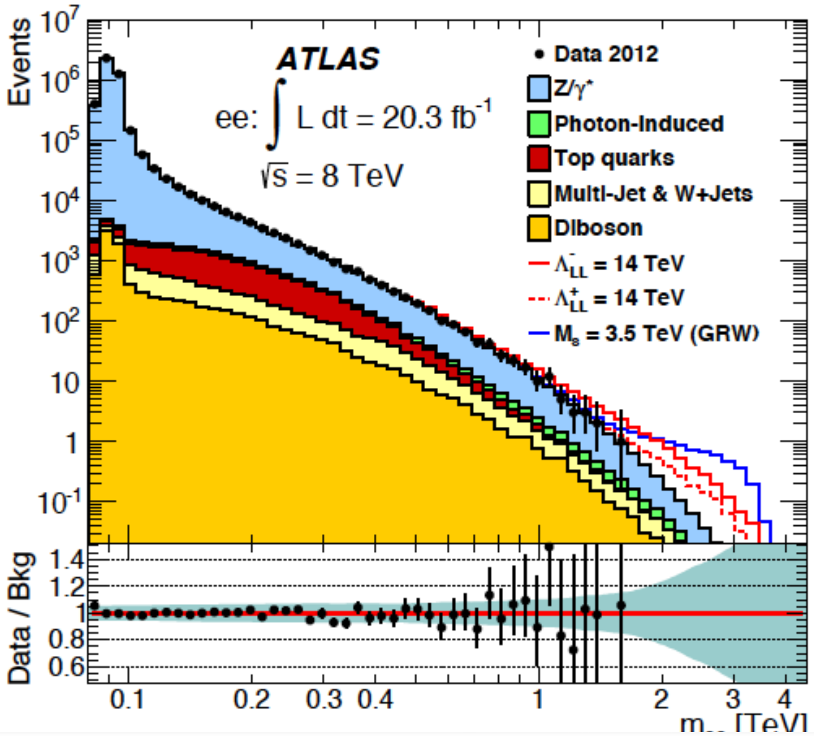
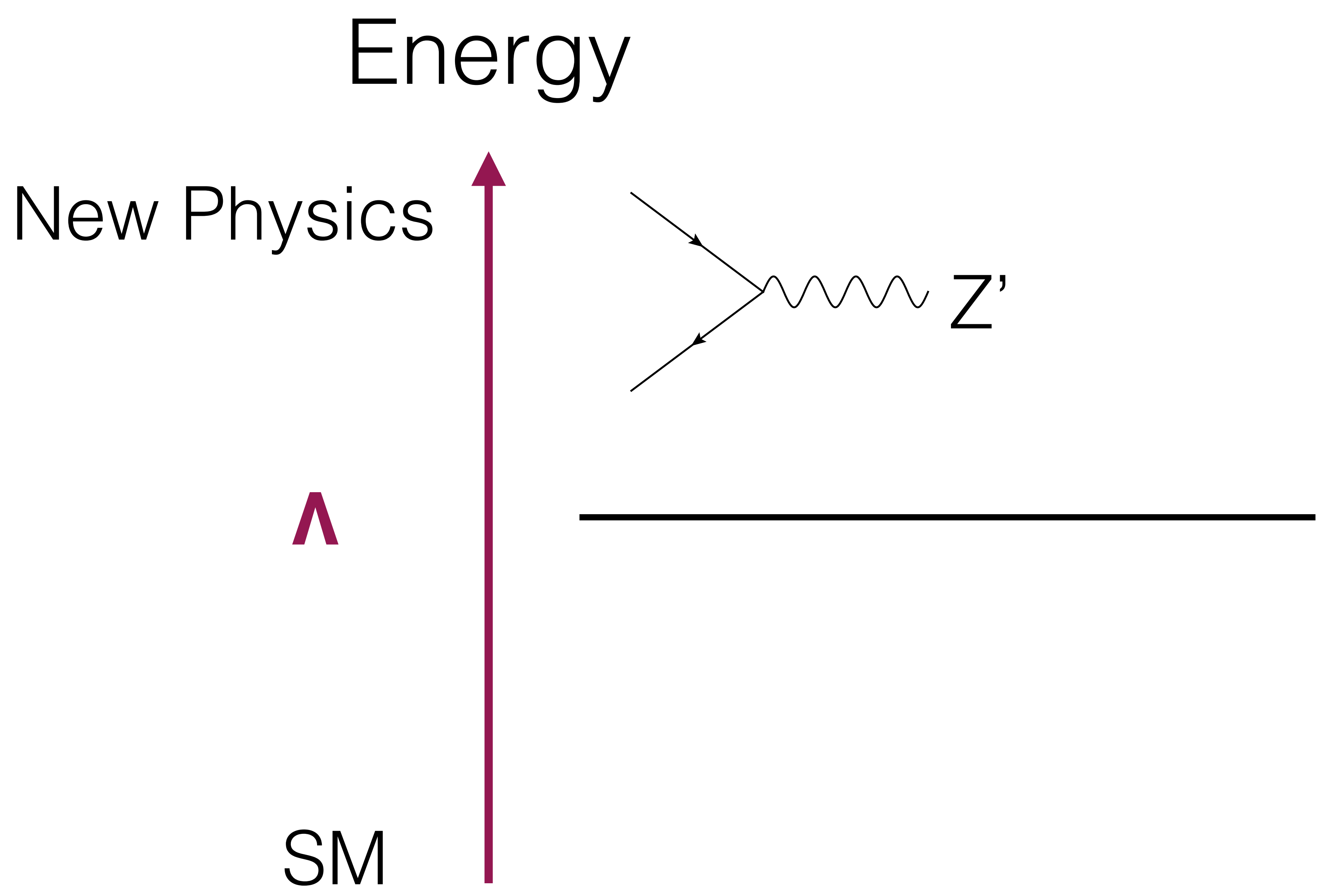


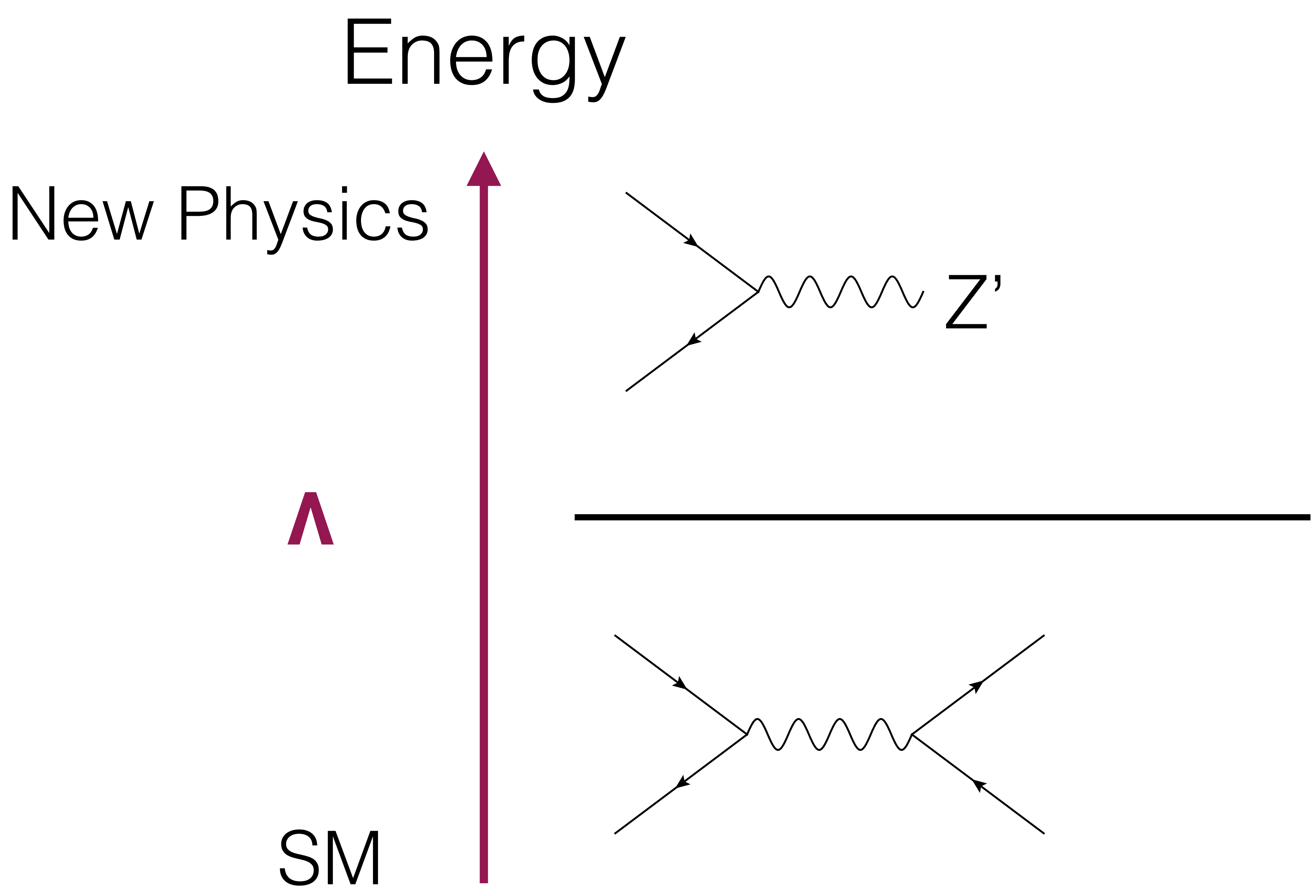
$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

SMEFT: What is it all about?



A Taylor expansion

SMEFT: What is it all about?



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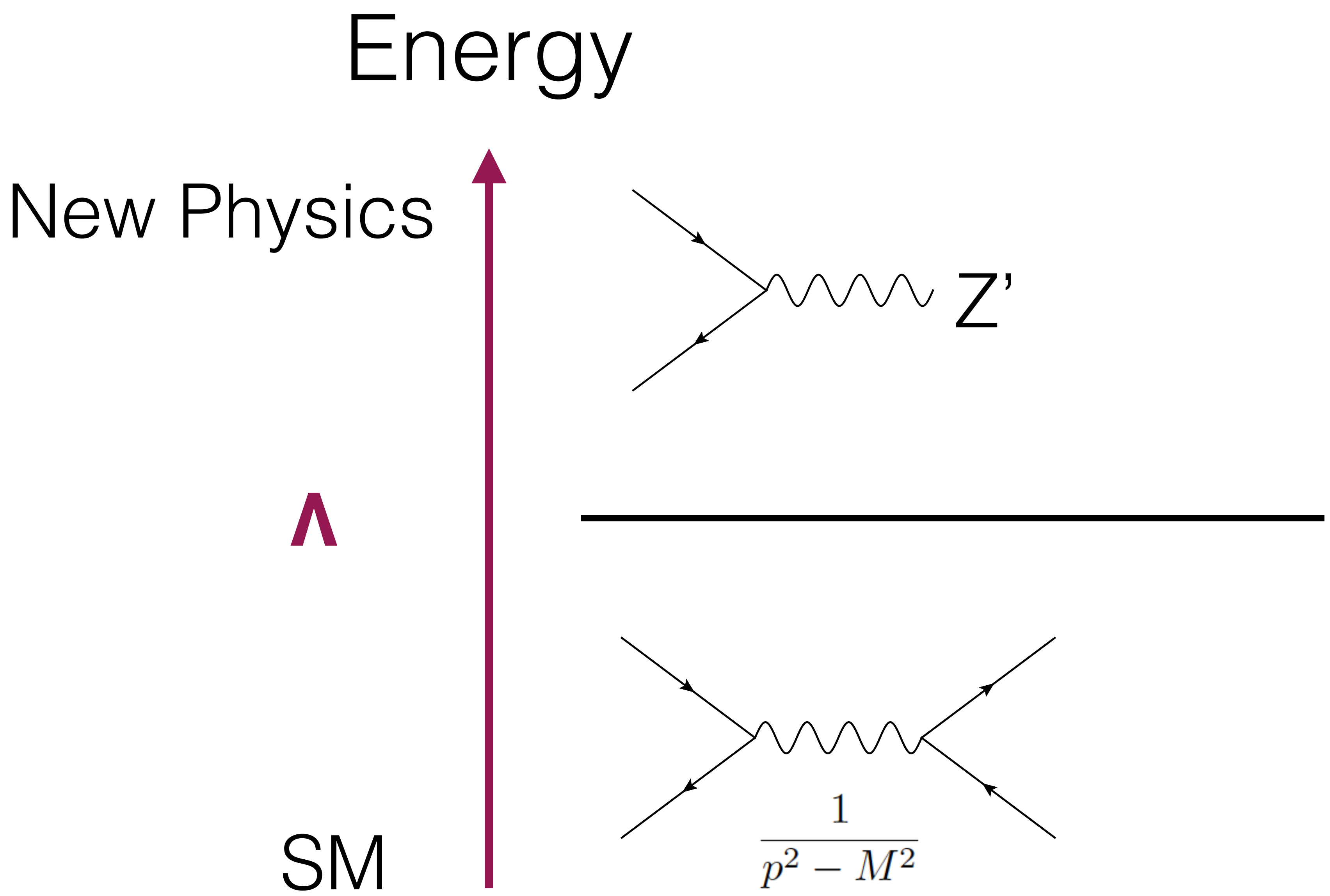

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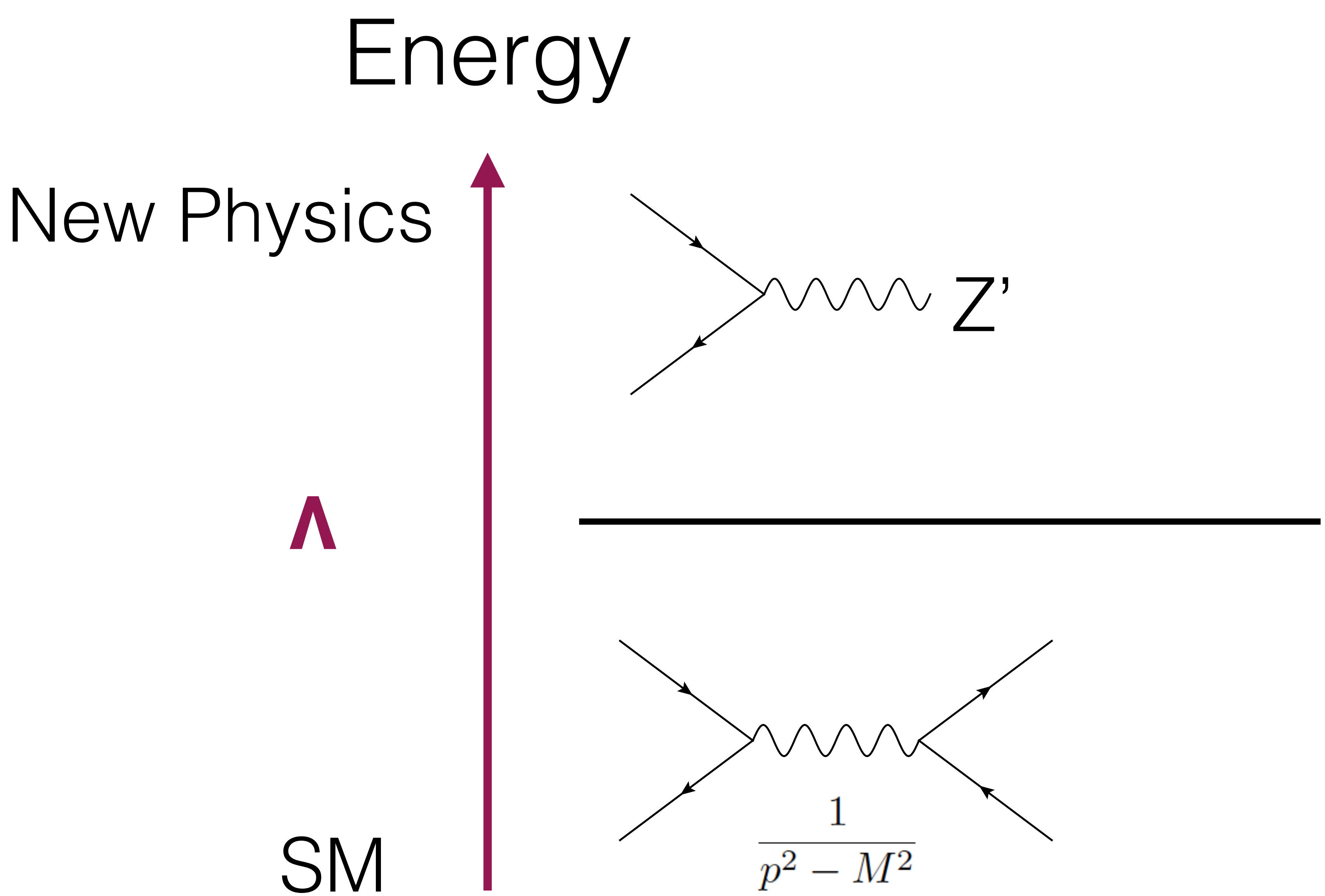

$$\frac{1}{p^2 - M^2}$$

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

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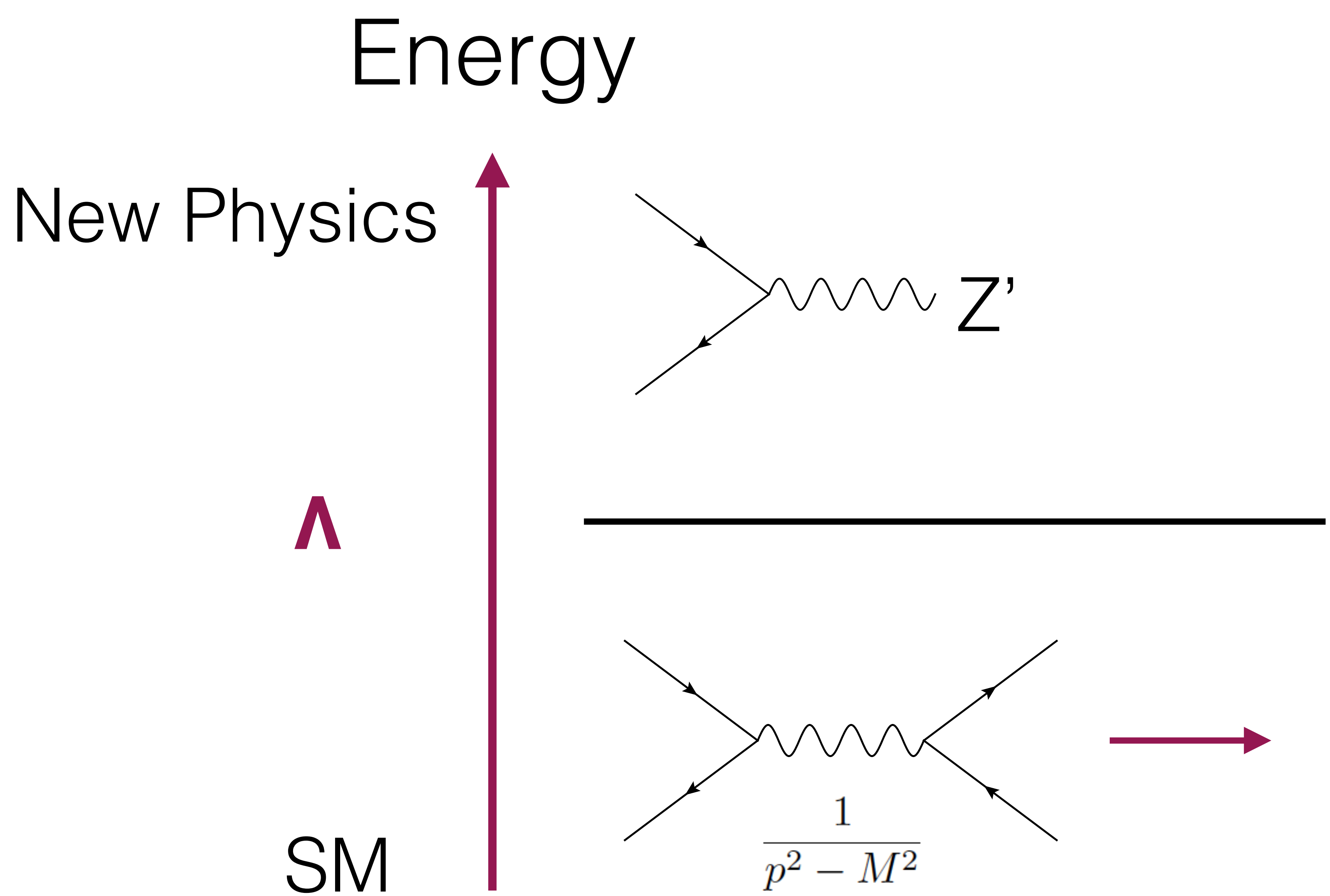

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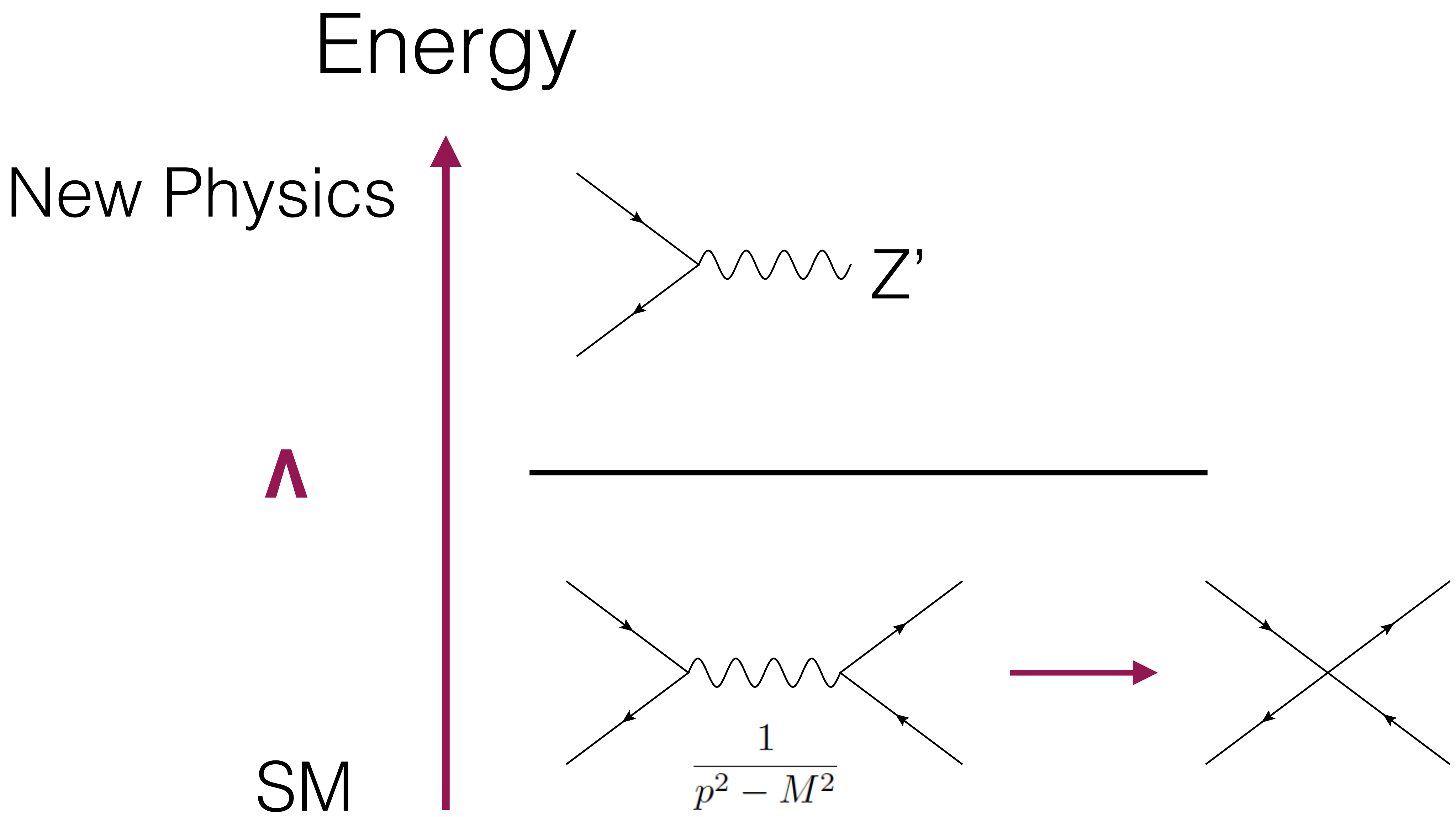

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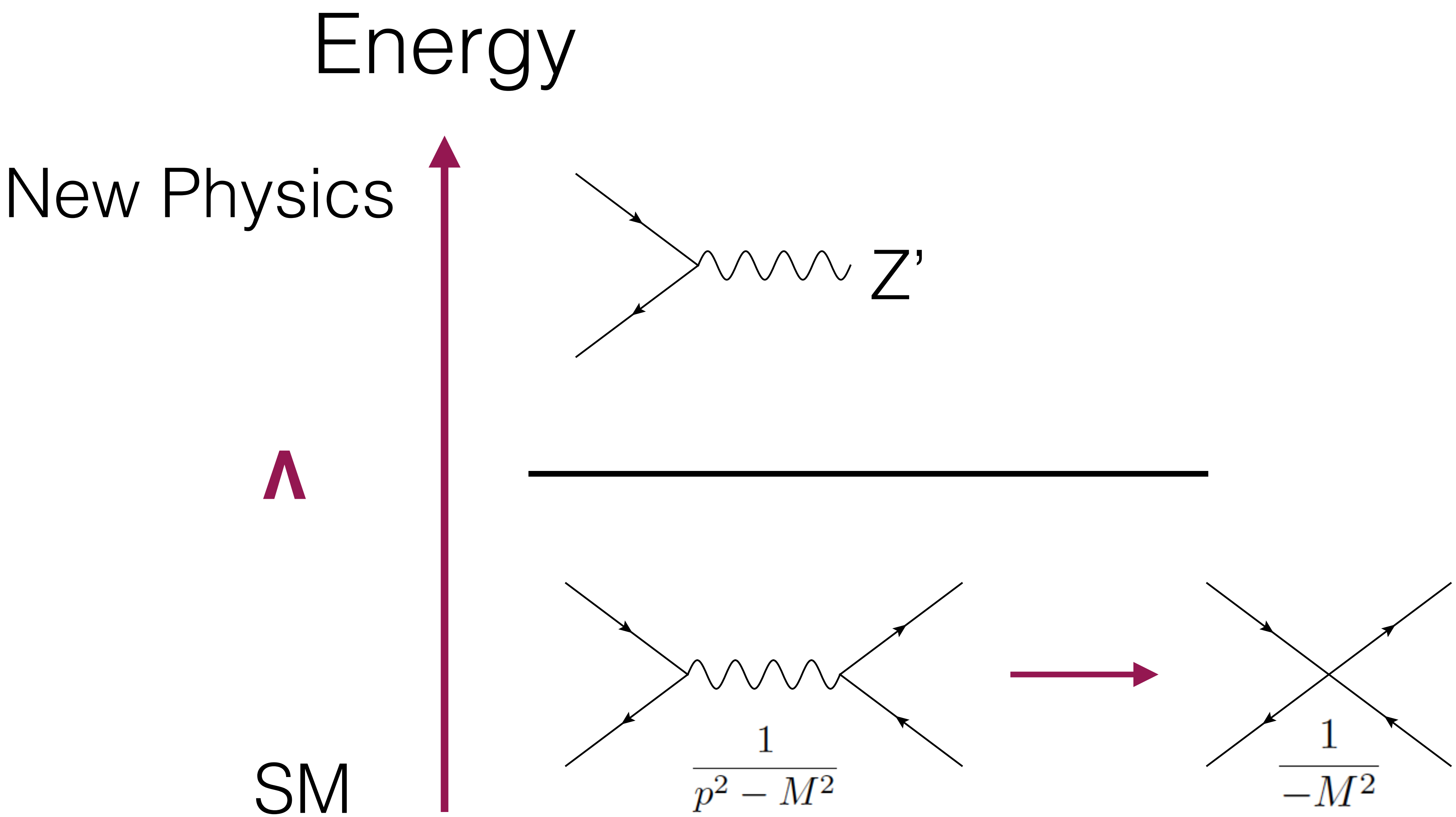

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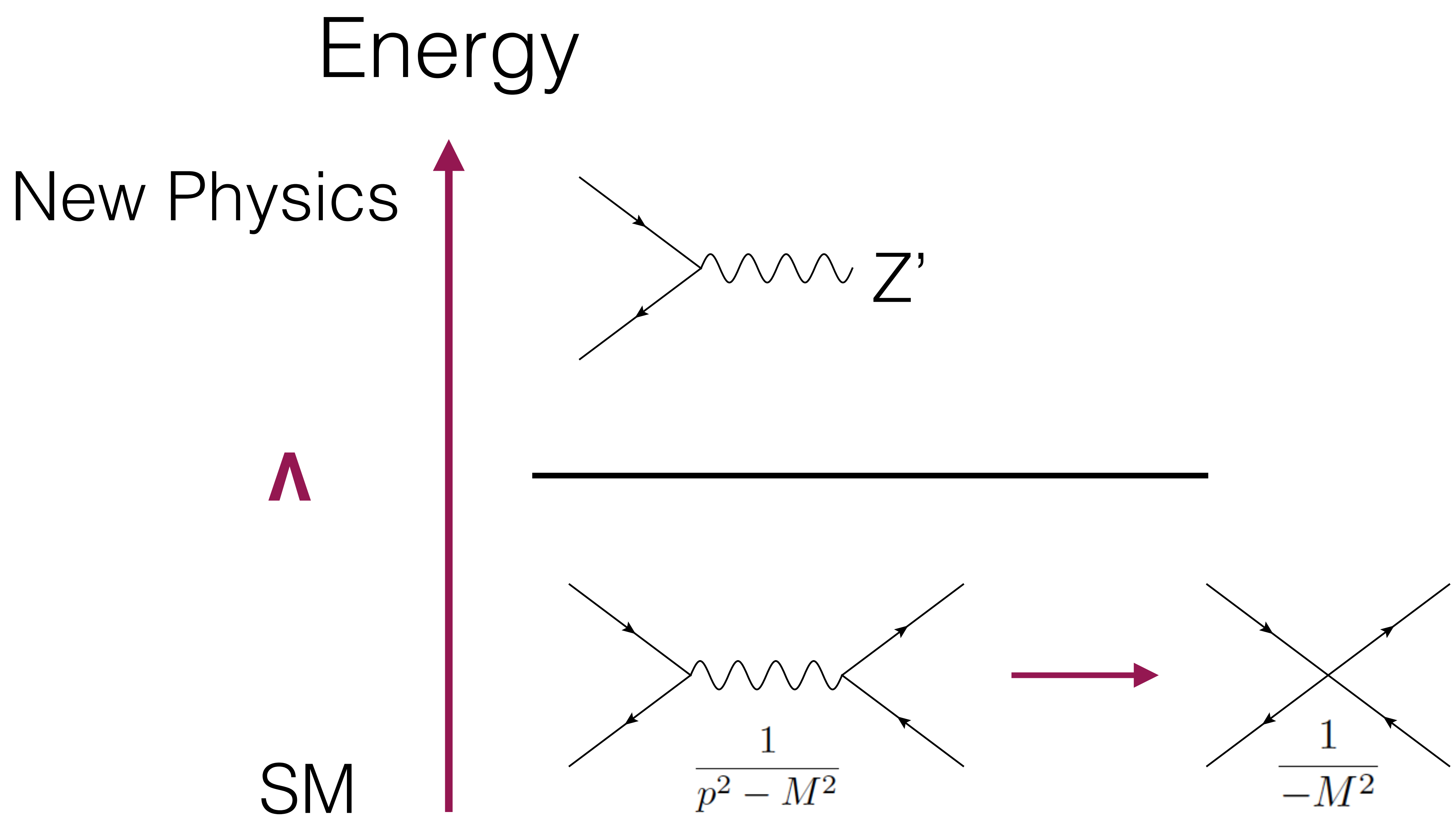


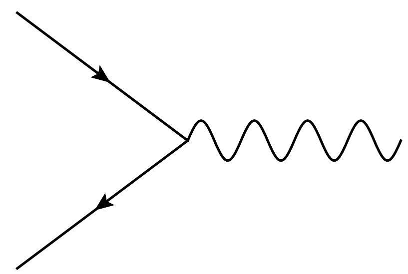
$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$ A Taylor expansion

We have integrated out the Z'

SMEFT: What is it all about?

Energy

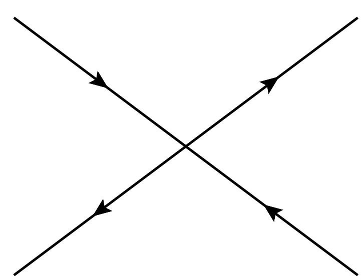
New Physics



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

Λ=M

SM



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

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

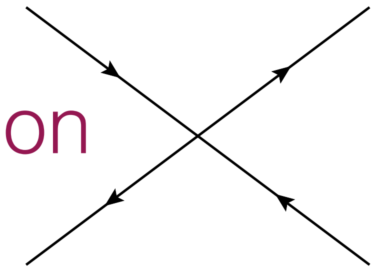
$$\mathcal{L}_{Dim6}(\varphi) = \boxed{\frac{C}{\Lambda^2}}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

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

EFT for New Physics

Low Energy Effective Theory without the Z'

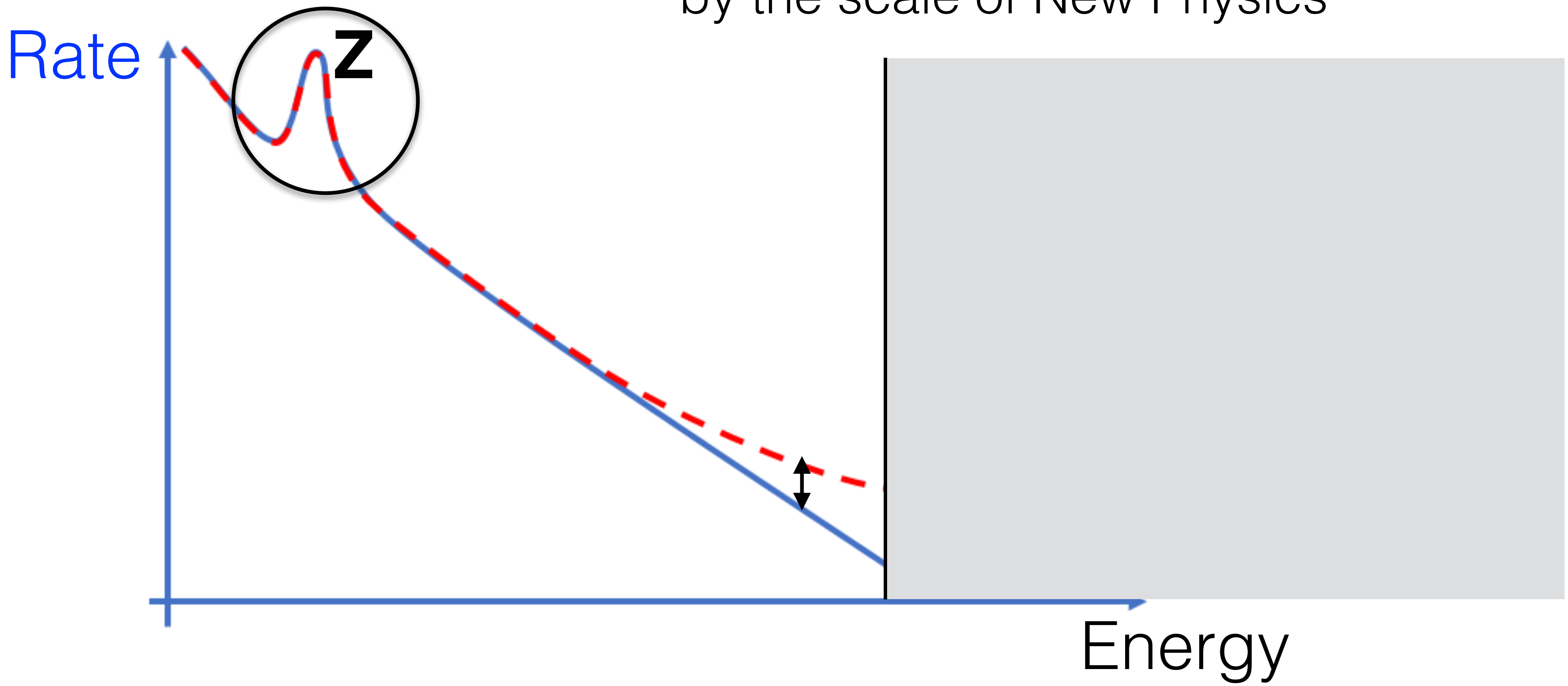
New Interaction



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

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

Modified interactions suppressed by the scale of New Physics

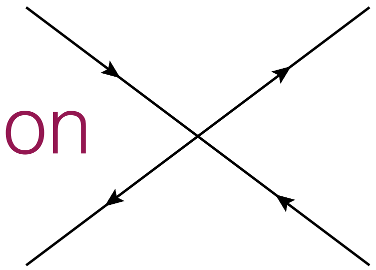


The way to probe New Physics in the absence of light states

EFT for New Physics

Low Energy Effective Theory without the Z'

New Interaction



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

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

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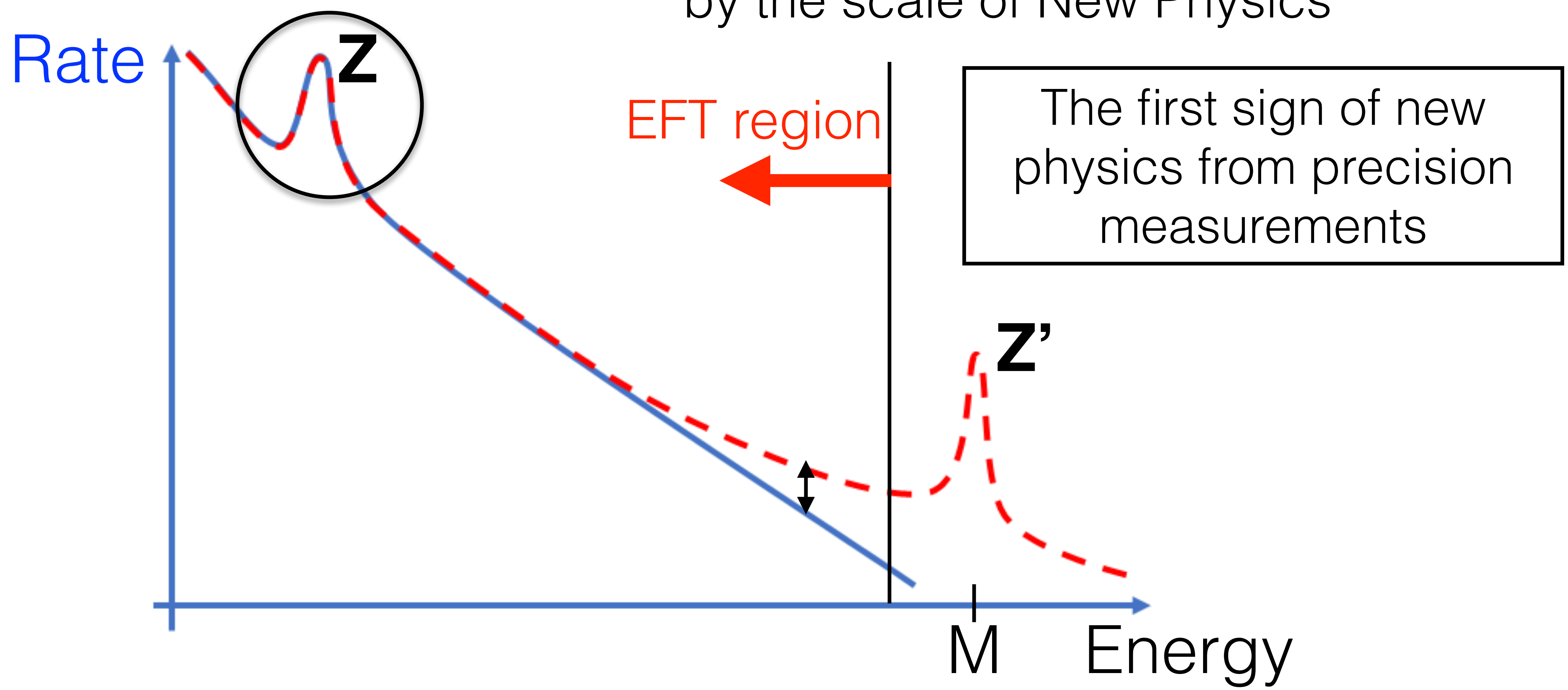
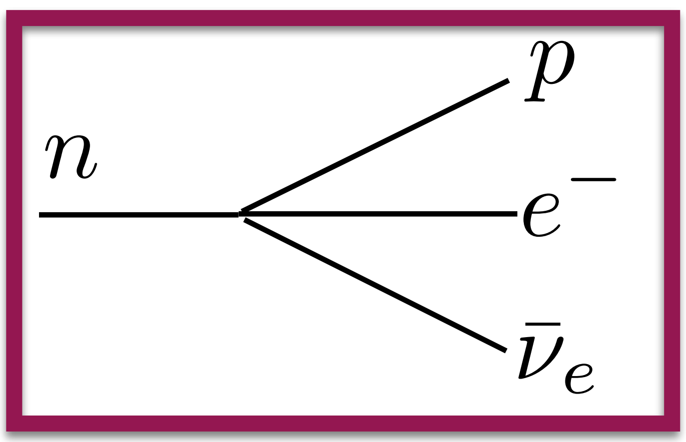


The way to probe New Physics in the absence of light states

Does the effective theory work?

An example of a successful EFT:

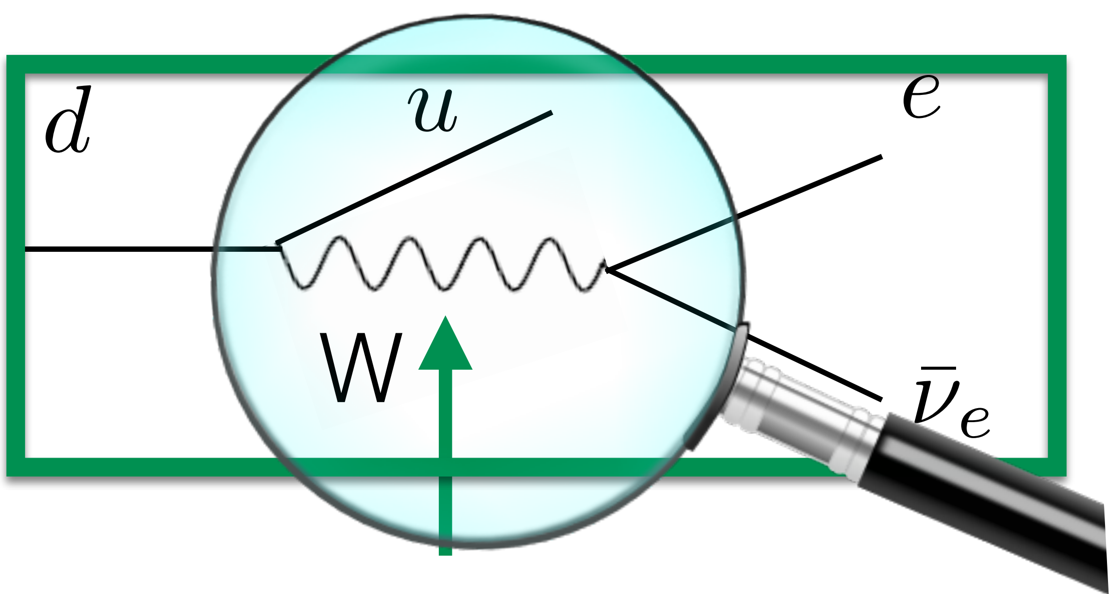
$n \to p + e^- + \bar{\nu}_e$



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

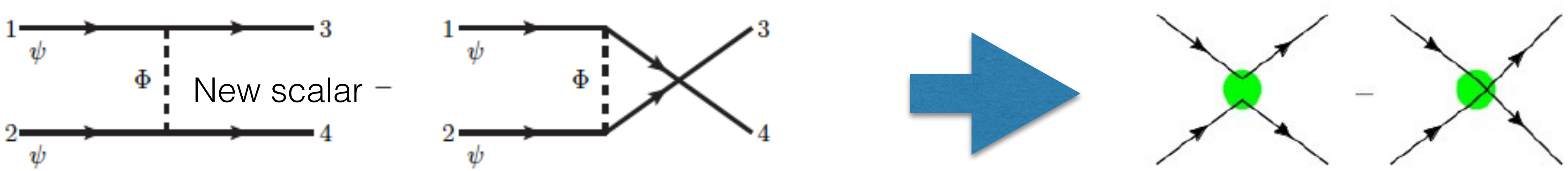
A toy-model example

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

Heavy scalar+Massless fermions model

Heavy particle to be integrated out

Yukawa interaction

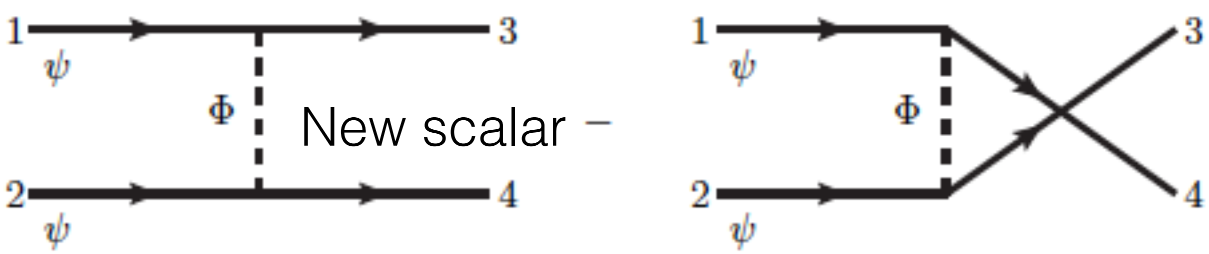


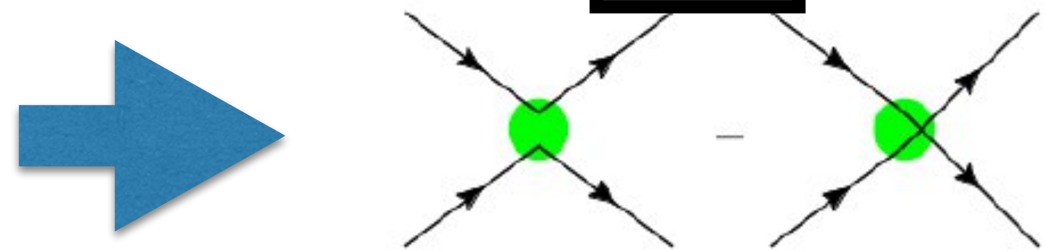
$$\mathcal{L}_{p^0,\lambda^2} = i\bar{\psi}\,\partial\!\!\!/\,\psi + \frac{c}{2}\,\bar{\psi}\psi\,\bar{\psi}\psi$$

We want to describe the same physics, below scale M

Matching

EFT





Full Theory

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

Matching will allow us to determine c

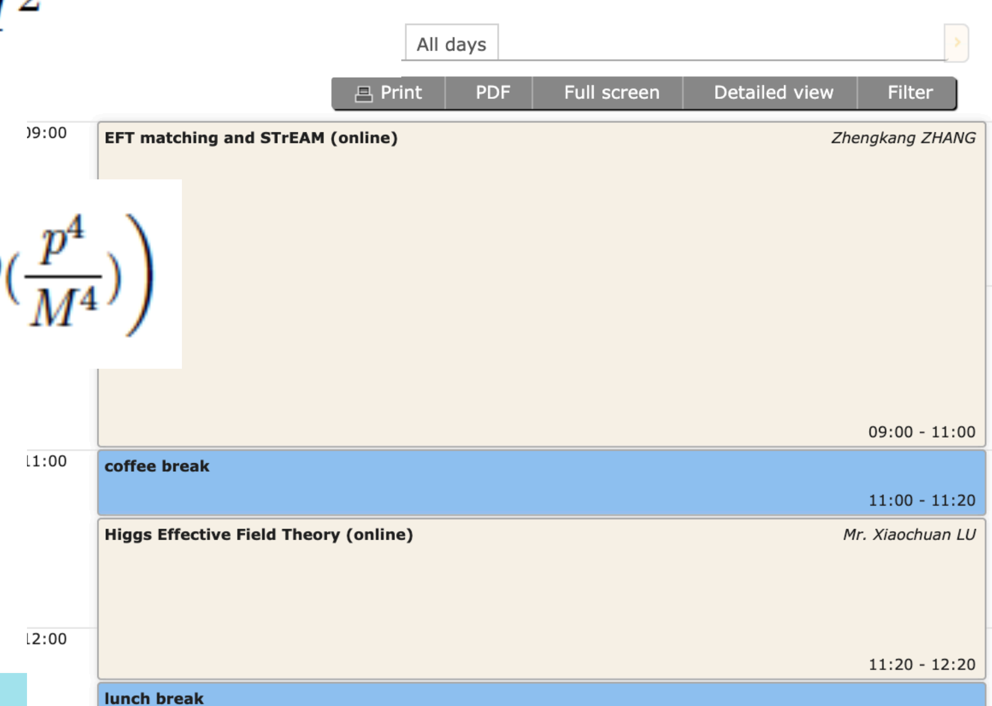
Writing down the amplitudes:

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

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



Matching improvements

We looked at the matching at dimension-6: How can we improve the matching?

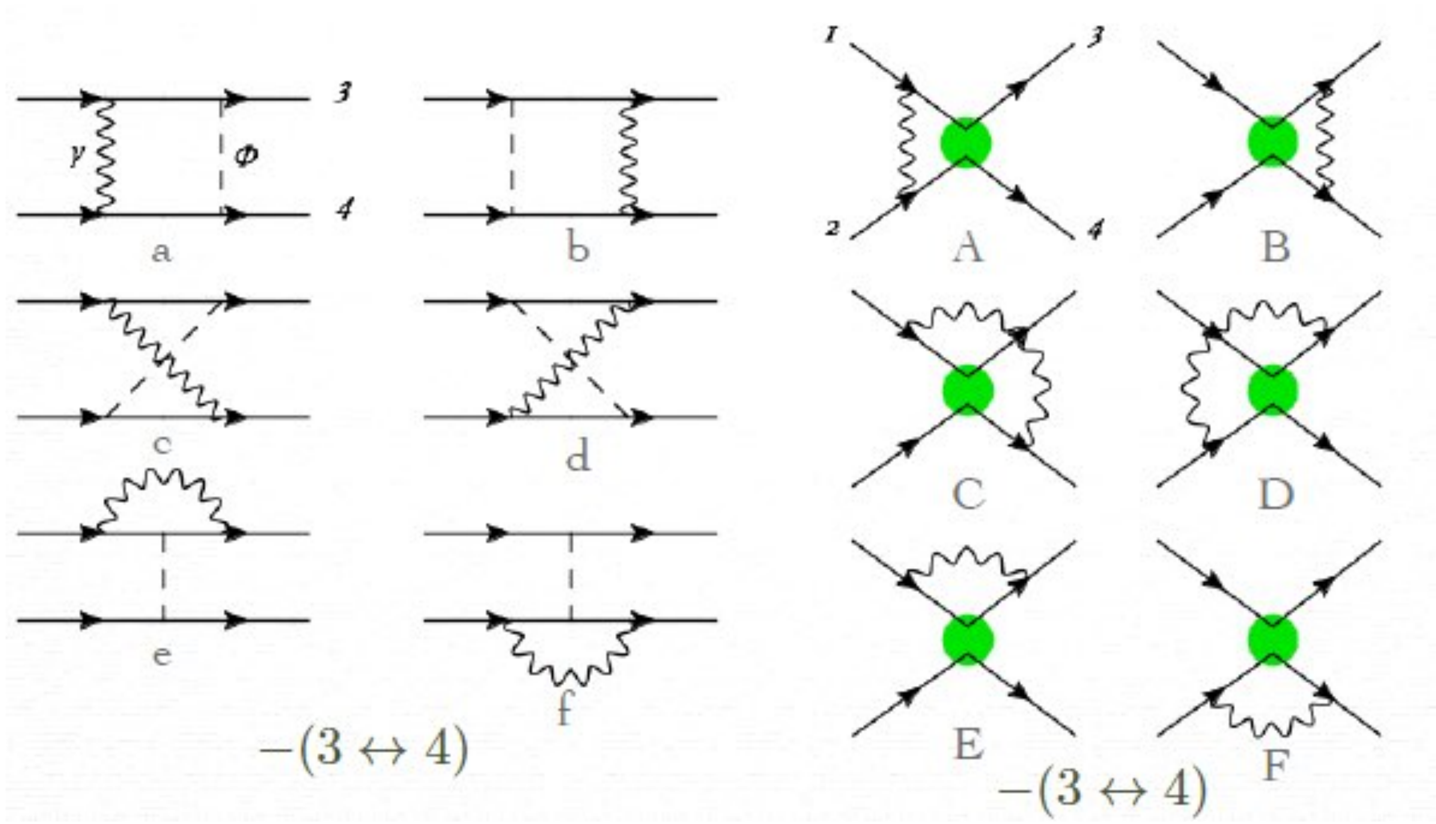
Higher order terms in the momentum expansion:
→ dimension-8 operators

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

EFT expansion systematically improvable by adding higher dimension operators

Matching improvements

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



Systematically improvable

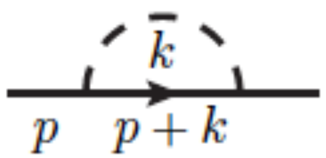
Origin of RG-running

Toy-model example:

$$\mathcal{L}_{p^2,\lambda^2} = i\bar{\psi}\,\not{\partial}\,\psi + \frac{c}{2}\bar{\psi}\psi\,\bar{\psi}\psi + d\,\partial_\mu\bar{\psi}\partial^\mu\psi\,\bar{\psi}\psi + \boxed{\frac{1}{2}(\partial_\mu\varphi)^2 - \frac{m^2}{2}\varphi^2 - \eta\,\bar{\psi}\psi\varphi}$$ Light scalar

Self-energy computation

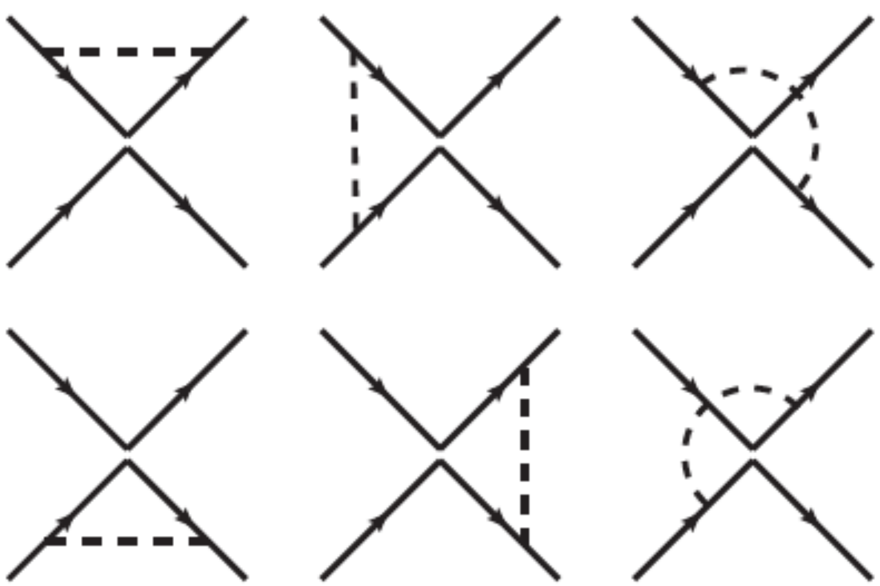
$\psi\psi \to \psi\psi$ $O(\lambda^2\eta^2)$:



$$= (-i\eta)^2\int\frac{d^dk}{(2\pi)^d}\frac{i(\not{k}+\not{p})}{(k+p)^2}\frac{i}{k^2-m^2} = \eta^2\int\frac{d^dl}{(2\pi)^d}\int_0^1 dx\,\frac{\not{l}+(1-x)\not{p}}{[l^2-\Delta^2]^2}$$

$$= \frac{i\eta^2}{(4\pi)^2}\frac{1}{\epsilon}\left(\int_0^1 dx(1-x)\not{p}\right) + \text{finite} = \boxed{\frac{i\eta^2\not{p}}{2(4\pi)^2}\frac{1}{\epsilon}} + \text{finite},$$

Vertex corrections



(a) (b) (c)

a) $-\frac{2ic\eta^2}{(4\pi)^2}\frac{1}{\epsilon} + \text{finite}$

b) $\frac{ic\eta^2}{2(4\pi)^2}\frac{1}{\epsilon}\bar{u}_3\gamma^\mu u_1\,\bar{u}_4\gamma_\mu u_2 + \text{finite}$

c) - $\frac{ic\eta^2}{2(4\pi)^2}\frac{1}{\epsilon}\bar{u}_3\gamma^\mu u_1\,\bar{u}_4\gamma_\mu u_2 + \text{finite}$

cancellation of the divergent pieces

Origin of RG-running

Divergences require CT:
Writing the Lagrangian in terms of bare and renormalised fields and couplings

$$\begin{aligned}\mathcal{L}_{p^0,\lambda^2\eta^2\log} &= i\overline{\psi}_0\,\partial\!\!\!/\,\psi_0 + \frac{c_0}{2}\,\overline{\psi}_0\psi_0\,\overline{\psi}_0\psi_0 = iZ_\psi\overline{\psi}\,\partial\!\!\!/\,\psi + \frac{c}{2}\,Z_c Z_\psi^2\mu^{2\epsilon}\overline{\psi}\psi\,\overline{\psi}\psi \\ &= i\overline{\psi}\,\partial\!\!\!/\,\psi + \mu^{2\epsilon}\frac{c}{2}\,\overline{\psi}\psi\,\overline{\psi}\psi + i(Z_\psi - 1)\overline{\psi}\,\partial\!\!\!/\,\psi + \mu^{2\epsilon}\frac{c}{2}(Z_c Z_\psi^2 - 1)\,\overline{\psi}\psi\,\overline{\psi}\psi\end{aligned}$$

From the loop calculations: $Z_\psi - 1 = -\frac{\eta^2}{2(4\pi)^2}\frac{1}{\epsilon}$ and $c(Z_c Z_\psi^2 - 1) = \frac{2c\eta^2}{(4\pi)^2}\frac{1}{\epsilon}$

$$0 = \mu\frac{d}{d\mu}c_0 = \mu\frac{d}{d\mu}(c\mu^{2\epsilon}Z_c) = \beta_c\mu^{2\epsilon}Z_c + 2\epsilon c\mu^{2\epsilon}Z_c + c\mu^{2\epsilon}\mu\frac{d}{d\mu}Z_c$$

$$\boxed{\mu\frac{dc}{d\mu} = \frac{6\eta^2}{(4\pi)^2}c}$$

Solving the RG equation for c

$$c(m) = c(M) - \frac{6\eta^2}{(4\pi)^2}c\log\left(\frac{M}{m}\right) = \frac{\lambda^2}{M^2}\left[1 - \frac{6\eta^2}{(4\pi)^2}\log\left(\frac{M}{m}\right)\right]$$

c runs with the scale

Origin of RG-running

Divergences require CT:
Writing the Lagrangian in terms of bare and renormalised fields and couplings

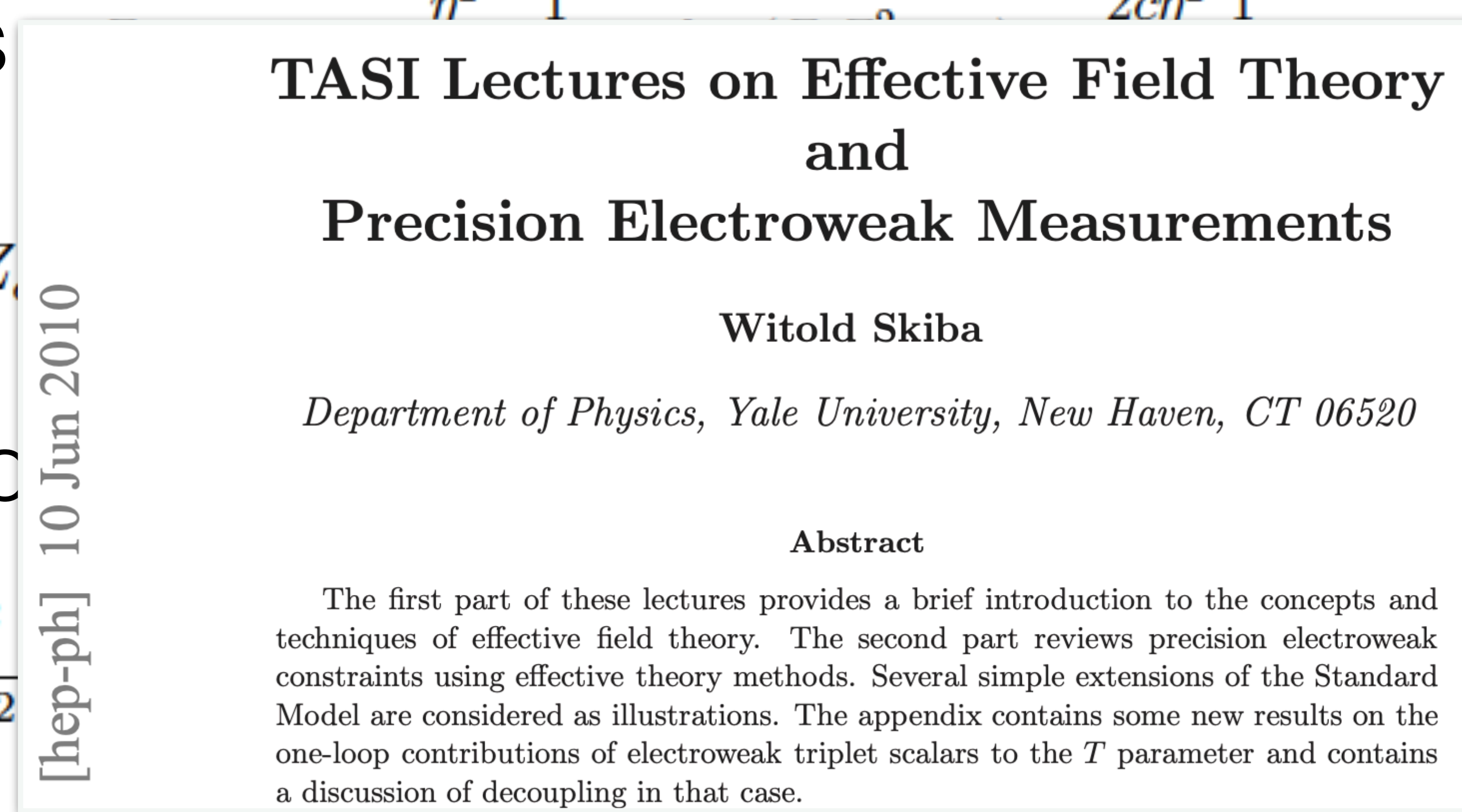
$$\mathcal{L}_{p^0,\lambda^2\eta^2\log} = i\overline{\psi}_0 \,\partial\!\!\!/ \,\psi_0 + \frac{c_0}{2}\,\overline{\psi}_0\psi_0\,\overline{\psi}_0\psi_0 = iZ_\psi\overline{\psi}\,\partial\!\!\!/\,\psi + \frac{c}{2}\,Z_c Z_\psi^2 \mu^{2\epsilon}\overline{\psi}\psi\,\overline{\psi}\psi$$
$$= i\overline{\psi}\,\partial\!\!\!/\,\psi + \mu^{2\epsilon}\frac{c}{2}\,\overline{\psi}\psi\,\overline{\psi}\psi + i(Z_\psi - 1)\overline{\psi}\,\partial\!\!\!/\,\psi + \mu^{2\epsilon}\frac{c}{2}(Z_c Z_\psi^2 - 1)\,\overline{\psi}\psi\,\overline{\psi}\psi$$

From the loop calculations

$$0 = \mu\frac{d}{d\mu}c_0 = \mu\frac{d}{d\mu}(c\mu^{2\epsilon}Z_c) = \beta_c\mu^{2\epsilon}Z_c \ldots$$

Solving the RG equation fo…

$$c(m) = c(M) - \frac{6\eta^2}{(4\pi)^2}c\log\left(\frac{M}{m}\right) = \frac{\lambda^2}{M^2}\ldots$$


TASI Lectures on Effective Field Theory and Precision Electroweak Measurements

Witold Skiba

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[hep-ph] 10 Jun 2010

Abstract

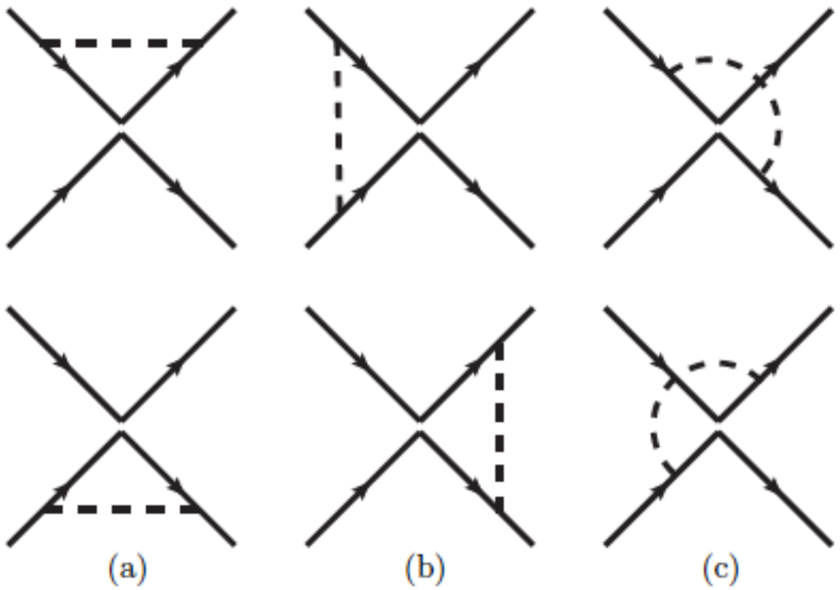
The first part of these lectures provides a brief introduction to the concepts and techniques of effective field theory. The second part reviews precision electroweak constraints using effective theory methods. Several simple extensions of the Standard Model are considered as illustrations. The appendix contains some new results on the one-loop contributions of electroweak triplet scalars to the T parameter and contains a discussion of decoupling in that case.

Origin of RG-mixing

Starting by integrating out a vector field:

$$\mathcal{L}_{p^0,V} = i\bar{\psi}\,\partial\!\!\!/\,\psi + \boxed{\frac{c_V}{2}\,\bar{\psi}\gamma^\mu\psi\,\bar{\psi}\gamma_\mu\psi} + \frac{1}{2}(\partial_\mu\varphi)^2 - \frac{m^2}{2}\varphi^2 - \eta\,\bar{\psi}\psi\varphi$$

RG of c_V



Loop corrections turn one operator into another

→ The operators mix

$$\mu\frac{d}{d\mu}\begin{pmatrix} c_V \\ c_T \end{pmatrix} = \frac{2\eta^2}{(4\pi)^2}\begin{pmatrix} 0 & 6 \\ 1 & 1 \end{pmatrix}\begin{pmatrix} c_V \\ c_T \end{pmatrix}$$

Divergences

$\bar{\psi}\gamma^\mu\psi\,\bar{\psi}\gamma_\mu\psi$ $\quad$ $\boxed{\bar{\psi}\sigma^{\mu\nu}\psi\,\bar{\psi}\sigma_{\mu\nu}\psi}$

A new operator

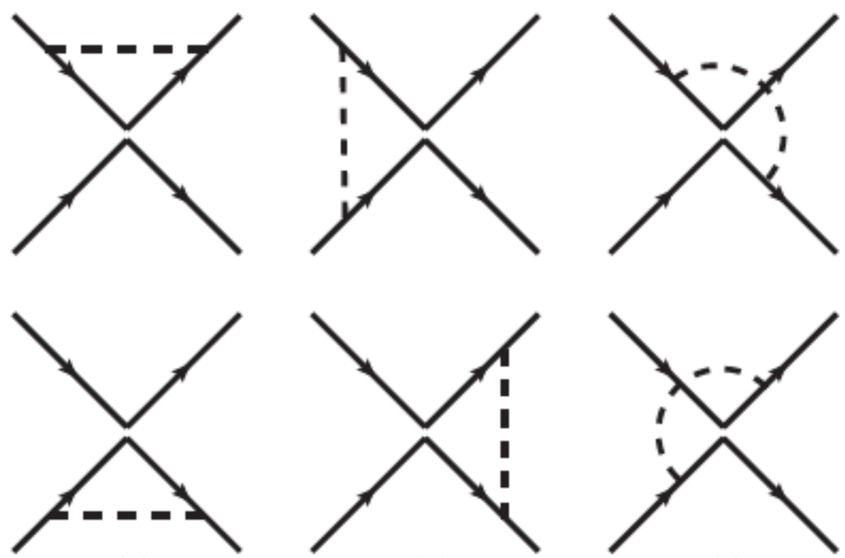
Need to consider: $\dfrac{c_V}{2}\,\bar{\psi}\gamma^\mu\psi\,\bar{\psi}\gamma_\mu\psi + \dfrac{c_T}{2}\,\bar{\psi}\sigma^{\mu\nu}\psi\,\bar{\psi}\sigma_{\mu\nu}\psi$

Origin of RG-mixing

Starting by integrating out a vector field:

$$\mathcal{L}_{p^0,V} = i\overline{\psi}\,\partial\!\!\!/\,\psi + \boxed{\frac{c_V}{2}\,\overline{\psi}\gamma^\mu\psi\,\overline{\psi}\gamma_\mu\psi} + \frac{1}{2}(\partial_\mu\varphi)^2 - \frac{m^2}{2}\varphi^2 - \eta\,\overline{\psi}\psi\varphi$$

RG of c_V



(a) (b) (c)

Divergences

$\overline{\psi}\gamma^\mu\psi\,\overline{\psi}\gamma_\mu\psi$ $\boxed{\overline{\psi}\sigma^{\mu\nu}\psi\,\overline{\psi}\sigma_{\mu\nu}\psi}$

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A new operator

Need to consider: $\frac{c_V}{2}$ –

EFT calculations from amplitude methods — *Alex POMAROL*
科大东区物质科研楼3楼报告厅 and Zoom online — 17:35 - 17:55

Higher order renormalisation in scalar effective field theory — *Jasper ROOSMALE NEPVEU*
科大东区物质科研楼3楼报告厅 and Zoom online — 17:35 - 18:00

Diagrammatic one-loop renormalization within the EChL in the Rxi gauges and applications to scattering and decays — *Roberto MORALES*

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: $C_i(\Lambda)$

matching
tree or loop

↓ Running and mixing
RGE: Jenkins et al
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EFT: $C_i(Q)$

↓ Tools: FeynRules,
MG5_aMC, Pythia etc

Observable → Measurements
Constraints

What we will learn

(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: $C_i(Q)$

Tools: FeynRules,
MG5_aMC, Pythia etc

Measurements
Constraints ← Observable

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

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

Tuesday tutorial

- Complete description ✔
- Model Independent ✔

SMEFT

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

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

4-fermion operators

EOM

$$\mathcal{L}_\varphi = \frac{1}{2}(\partial_\mu\varphi)^2 - \frac{m^2}{2}\varphi^2 - \frac{\eta}{4!}\varphi^4 - c_1\varphi^6 + c_2\varphi^3\partial^2\varphi, \tag{46}$$

where both coefficients c_1 and c_2 are coefficients of operators of dimension 6. We perform a field redefinition $\varphi \to \varphi' + c_2\varphi'^3$ in the Lagrangian in Eq. (46). Field redefinitions do not alter the S matrix as long as $\langle\varphi_1|\varphi'|0\rangle \neq 0$, where $|\varphi_1\rangle$ is a one-particle state created by the field φ. In other words, φ' is an interpolating field for the single-particle state $|\varphi_1\rangle$. This is guaranteed by the LSZ reduction formula which picks out the poles corresponding to the physical external states in the scattering amplitude.

Under the $\varphi \to \varphi' + c_2\varphi'^3$ redefinition

$$\begin{aligned}\mathcal{L}_\varphi \;\to\; & \frac{(\partial_\mu\varphi')^2}{2} - c_2\varphi'^3\partial^2\varphi' - \frac{m^2}{2}\varphi'^2 - c_2m^2\varphi'^4 - \frac{\eta}{4!}\varphi'^4 - \frac{\eta}{3!}c_2\varphi'^6 - c_1\varphi'^6 + c_2\varphi'^3\partial^2\varphi' + \ldots \\ = \; & \frac{(\partial_\mu\varphi')^2}{2} - \frac{m^2}{2}\varphi'^2 - (\frac{\eta}{4!} + c_2m^2)\varphi'^4 - (c_1 + \frac{\eta c_2}{3!})\varphi'^6 + \ldots,\end{aligned} \tag{47}$$

where we omitted terms quadratic in the coefficients $c_{1,2}$. This field redefinition removed the $\varphi^3\partial^2\varphi$ term and converted it into the φ^6 term. Field redefinitions are equivalent to using the lowest oder equations of motions to find redundancies among higher dimensional operators. The equation of motion following from the Lagrangian in Eq. (46) is $\partial^2\varphi = -m^2\varphi - \frac{\eta}{3!}\varphi^3$.

Substituting the derivative part of the $\varphi^3\partial^2\varphi$ operator with the equation of motion gives

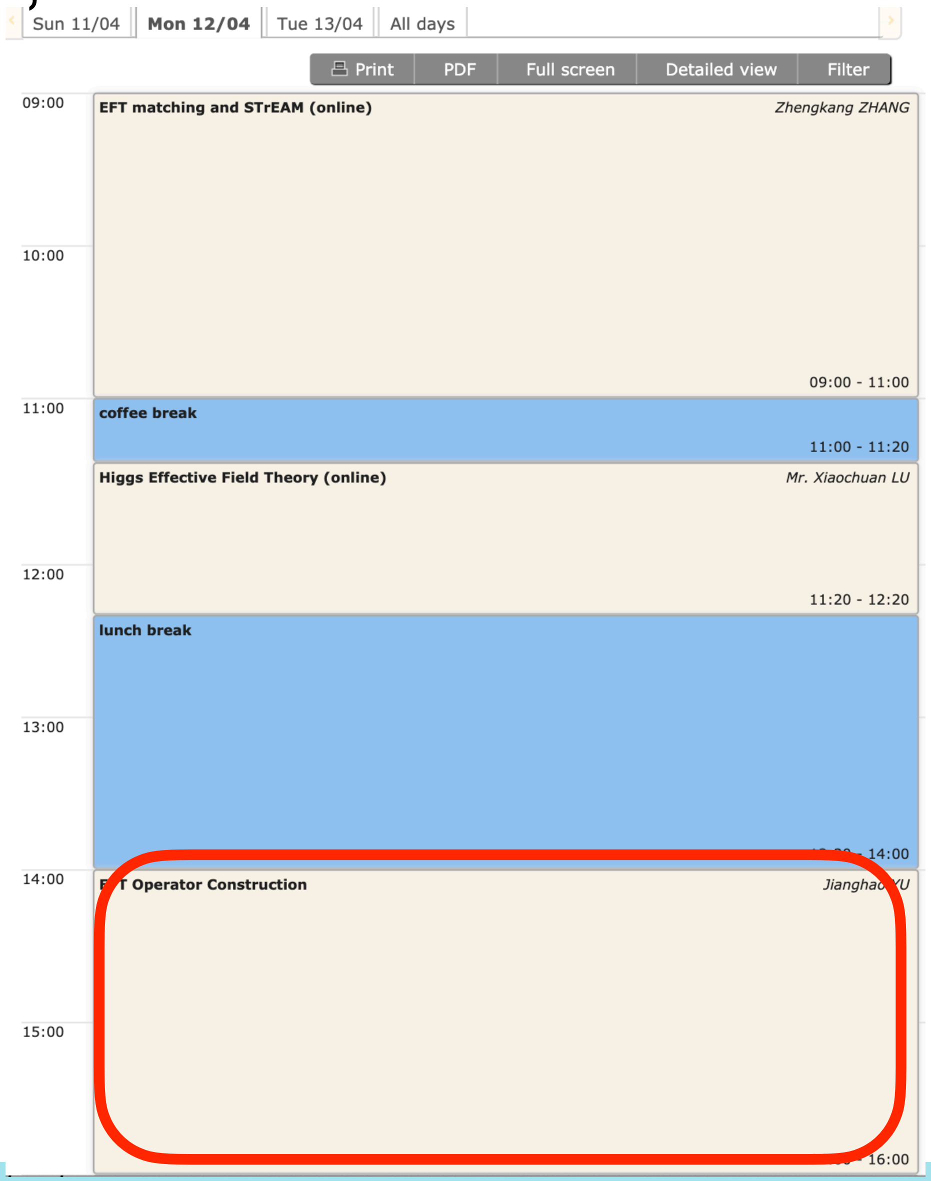
$$\mathcal{L}_{D>4} = -c_1\varphi^6 + c_2\varphi^3\partial^2\varphi \to -c_1\varphi^6 + c_2\varphi^3(-m^2\varphi - \frac{\eta}{3!}\varphi^3) = -(c_1 + \frac{\eta c_2}{3!})\varphi^6 - c_2m^2\varphi^4, \tag{48}$$

EFT bases

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

Bases construction:



EFT bases

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
$\mathcal{O}_{WW} = \frac{g^2}{4} \|H\|^2 W^a_{\mu\nu} W^{a\mu\nu}$	2
$\mathcal{O}_{GG} = \frac{g_s^2}{4} \|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	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	
$\mathcal{O}_W = \frac{ig}{2} \left(H^\dagger \sigma^a \overset{\leftrightarrow}{D^\mu} H \right) D^\nu W^a_{\mu\nu}$	2
$\mathcal{O}_B = \frac{ig'}{2} \left(H^\dagger \overset{\leftrightarrow}{D^\mu} H \right) \partial^\nu B_{\mu\nu}$	2
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	2
$\mathcal{O}_T = \frac{1}{2} \left(H^\dagger \overset{\leftrightarrow}{D}_\mu H \right)^2$	1
$\mathcal{O}_{Hu} = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	1
$\mathcal{O}_{Hd} = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	1
$\mathcal{O}_{He} = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$	1
$\mathcal{O}_{HQ} = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$	1
$\mathcal{O}'_{HQ} = (iH^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	1

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

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

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

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

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

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

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

Biekotter et al., 1406.7320

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	
$\mathcal{O}_r = \lvert H\rvert^2 \lvert D^\mu H\rvert^2$	1
$\mathcal{O}_{BB} = \frac{g'^2}{4}\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	2
$\mathcal{O}_{WW} = \frac{g^2}{4}\lvert H\rvert^2 W_{\mu\nu}^a W^{a\mu\nu}$	2
$\mathcal{O}_{GG} = \frac{g_s^2}{4}\lvert H\rvert^2 G_{\mu\nu}^A G^{A\mu\nu}$	2
$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar Q_L \widetilde H u_R$	1
$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar Q_L H d_R$	1
$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar L_L H e_R$	1
$\mathcal{O}_6 = \lambda \lvert H\rvert^6$	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
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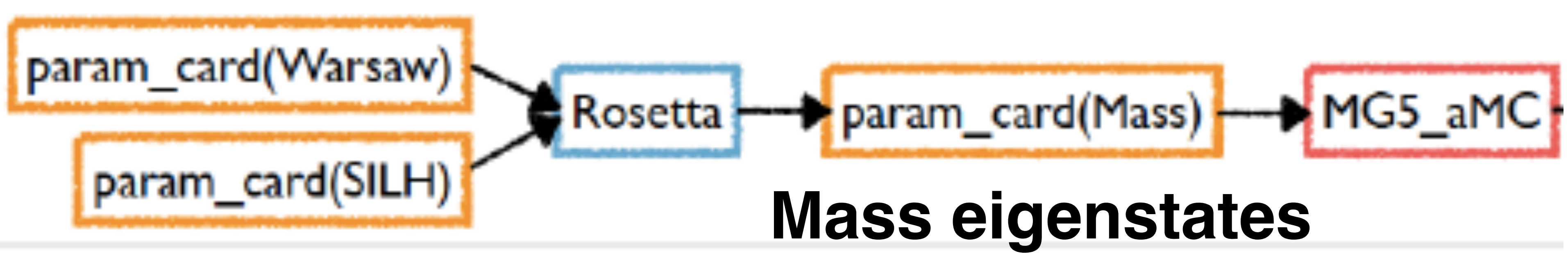
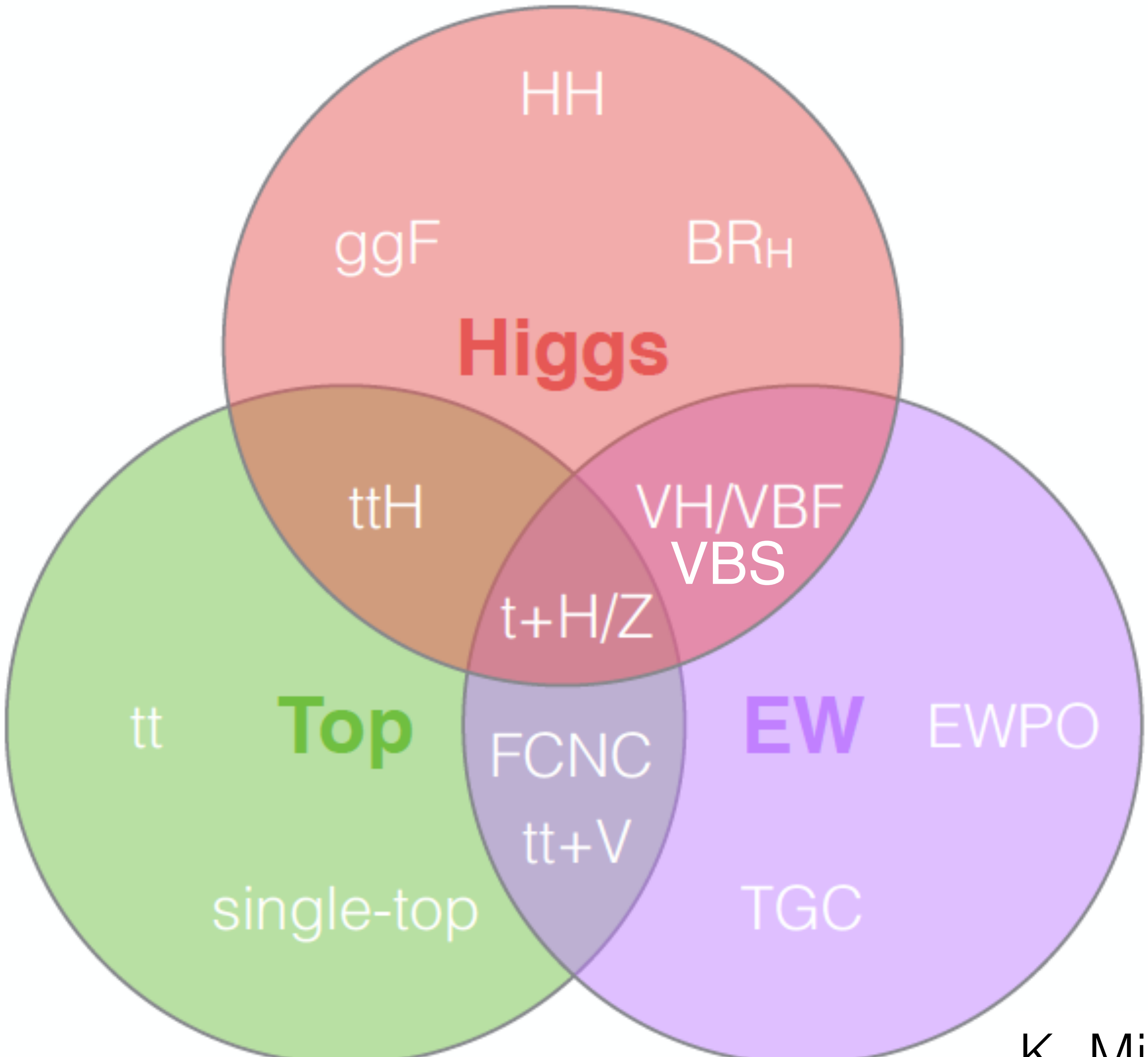
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	1
$\mathcal{O}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar u_R \gamma^\mu u_R)$	1
$\mathcal{O}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar d_R \gamma^\mu d_R)$	1
$\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar e_R \gamma^\mu e_R)$	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
- SMEFTatNLO

Tuesday tutorial

↓

PYTHIA, HERWIG,
your favourite PS

↓

Detector simulation
Delphes,PGS

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SMEFT in Monte Carlos

feynrules.irmp.ucl.ac.be

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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

Outline

- EFT basics
- **LHC physics applications**

Associated top quark production using EFT at CMS	*Brent YATES*	
	科大东区物质科研楼3楼报告厅 and Zoom online	19:40 - 20:10
Putting SMEFT Fits to Work	*Dr. Samuel HOMILLER*	
	科大东区物质科研楼3楼报告厅 and Zoom online	20:10 - 20:35
A_{FB} in the SMEFT: the LHC as a Z-physics laboratory	*Mr. Víctor BRESÓ*	
	科大东区物质科研楼3楼报告厅 and Zoom online	20:35 - 21:00
Reviving the interference: framework and proof-of-principle for the anomalous gluon self-interactions in the SMEFT	*Mr. Matteo MALTONI*	
Break		
	科大东区物质科研楼3楼报告厅 and Zoom online	21:25 - 21:35
Precision from Diboson Processes at FCC-hh	*Philipp ENGLERT*	
	科大东区物质科研楼3楼报告厅 and Zoom online	21:35 - 22:00
All things EFT: SMEFT Practicalities	*Sally DAWSON*	
	科大东区物质科研楼3楼报告厅 and Zoom online	22:00 - 23:00

Recent EFT interpretations in Higgs measurements at ATLAS	*Philipp WINDISCHHOFER*	
	科大东区物质科研楼3楼报告厅 and Zoom online	15:00 - 15:20
Probing Higgs couplings to light quarks via Higgs pair production	*Lina ALASFAR*	
	科大东区物质科研楼3楼报告厅 and Zoom online	15:25 - 15:45
Light quark Yukawas in triboson final states	*Natascia VIGNAROLI*	
	科大东区物质科研楼3楼报告厅 and Zoom online	15:50 - 16:10
The present and future of four top operators	*Javi SERRA*	
	科大东区物质科研楼3楼报告厅 and Zoom online	16:15 - 16:35
Break		
	科大东区物质科研楼3楼报告厅 and Zoom online	16:40 - 17:10
The SMEFT at one-loop	*Eleni VRYONIDOU*	
	科大东区物质科研楼3楼报告厅 and Zoom online	17:10 - 17:30

Examples of operators

Dimension-6 operators of the SMEFT:

	Interaction	Impact
$X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	gauge boson self-coupling	diboson
$H^6 : (\varphi^\dagger \varphi)^3$	Higgs potential, self-coupling	di-Higgs
$\psi^2 H^3 : (\varphi^\dagger \varphi) \; (\bar{q}_i \, u_j \, \tilde{\varphi})$	Higgs-fermion (Yukawa)	ttH, H→bb
$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \, \varphi)(\bar{q}_i \, \gamma^\mu \, q_j)$	gauge-fermion (Z,W)	Z,W prod.
$X^2 H^2 : (\varphi^\dagger \varphi) \; G^a_{\mu\nu} G^{\mu\nu}_a$	gauge-Higgs	ggH, H→VV
$H^4 D^2 : (\varphi^\dagger \, D^\mu \varphi)^* (\varphi^\dagger \, D^\mu \varphi)$	Higgs-Z	m_Z (LEP)
$\psi^2 X H : (\bar{q}_i \, \sigma^{\mu\nu} \, u_j \, \tilde{\varphi}) B_{\mu\nu}$	dipole	ffV, ffVH
$\psi^4 : (\bar{q}_i \, \gamma^\mu \, q_j)(\bar{q}_k \, \gamma_\mu \, q_l)$	four fermion	ffff scattering

SM gauge group singlets

What do these operators do?

1) New Lorentz structures: contact interactions & derivatives

- Explicit source of energy growth

$$\psi^4 : (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l) \qquad X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$$

2) Modification of SM (dim-4) terms

- After electroweak symmetry breaking

$$\langle\varphi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$$

$$\mathcal{O}_6 \to v\mathcal{O}_5,\ v^2\mathcal{O}_4$$

	Modification
$(\varphi^\dagger\varphi)(\bar{q}\,u\,\tilde{\varphi}) \to v^2(\bar{q}\,u\,\tilde{\varphi})$	Yukawa
$(\varphi^\dagger\varphi)^6 \to v^2(\varphi^\dagger\varphi)^4, v^4(\varphi^\dagger\varphi)^2, \ldots$	Higgs potential
$(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{f}\gamma^\mu f) \to v^2 Z^\mu(\bar{f}\gamma^\mu f)$	gauge-fermion
$(\varphi^\dagger\varphi)^2 F^{\mu\nu}F_{\mu\nu} \to v^2 F^{\mu\nu}F_{\mu\nu}$	gauge kinetic

- Shift of **SM-like** interactions
- Spoiling of unitarity cancellations of the SM → energy growth
- SM inputs are extracted by comparing a few measurements to theory

➡ Extraction of SM inputs now **depends on c_i** $\quad (g_1, g_2, v) \to (\alpha, G_F, m_Z)$ or (G_F, m_Z, m_W)

G_F example

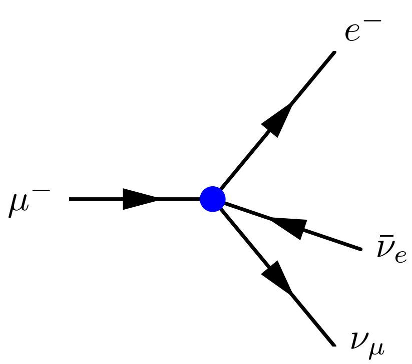
Muon decay data gives: $G_F = 1.17\times10^{-5}$ GeV^{-2} → v = 246 GeV

- EFT contribution: A $[\mathcal{O}_{ll}]^{ijkl} = [\bar{l}^{(i)} \gamma^\mu l^{(j)}] [\bar{l}^{(k)} \gamma_\mu l^{(l)}]$

  B,C $[\mathcal{O}_{\varphi l}^{(3)}]^{ij} = \left[\varphi^\dagger \tau_k \overleftrightarrow{D}_\mu \varphi\right] \left[\bar{l}^{(i)} \tau^k \gamma^\mu l^{(j)}\right], \quad i = 1,2.$
- A contains the O_F up to a Fierz transformation
- B,C shifts W couplings to leptons after EWSB

$$[\mathcal{O}_{ll}]^{1212} = \frac{1}{2} (\bar{e}\, \gamma^\mu (1-\gamma_5)\, \nu_e)\, (\bar{\nu}_\mu\, \gamma_\mu (1-\gamma_5)\, \mu) + \cdots ,$$
$$[\mathcal{O}_{ll}]^{1221} = \frac{1}{4} (\bar{e}\, \gamma^\mu (1-\gamma_5)\, \nu_\mu)\, (\bar{\nu}_e\, \gamma_\mu (1-\gamma_5)\, \mu) + \cdots ,$$
$$[\mathcal{O}_{ll}]^{2112} = \frac{1}{4} (\bar{e}\, \gamma^\mu (1-\gamma_5)\, \nu_\mu)\, (\bar{\nu}_e\, \gamma_\mu (1-\gamma_5)\, \mu) + \cdots ,$$

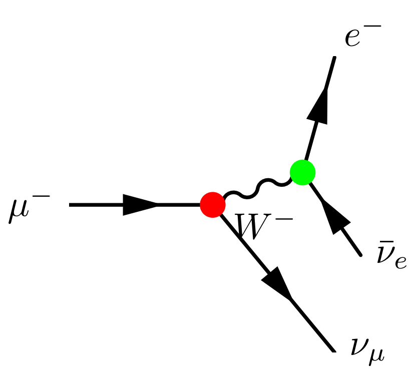
$$-i\frac{g}{\sqrt{2}} \to -i\frac{g}{\sqrt{2}}\left[1 + [C_{\varphi l}^{(3)}]^{ii}\frac{v^2}{\Lambda^2}\right]$$



$$\frac{G_F}{\sqrt{2}} = \frac{1}{2v^2}\left[1 + \frac{v^2}{\Lambda^2}[C_{\varphi l}^{(3)}]^{11}\right]\left[1 + \frac{v^2}{\Lambda^2}[C_{\varphi l}^{(3)}]^{22}\right] - \frac{1}{4}\frac{1}{\Lambda^2}\left(2\,[c_{ll}]^{1212} + [c_{ll}]^{1221} + [c_{ll}]^{2112}\right)$$

$$v_0^2 = \frac{1}{\sqrt{2}G_f}$$

New relation between Higgs vev and Fermi constant



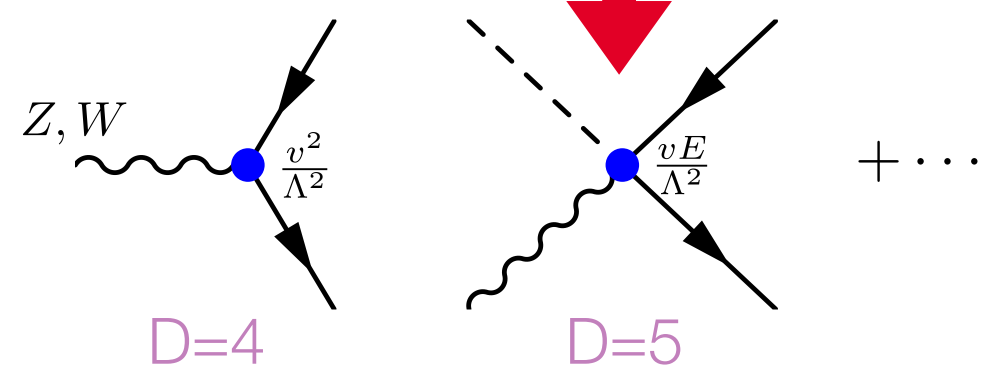
$$v = v_0\left(1 + \left([C_{\varphi l}^{(3)}]^{11} + [C_{\varphi l}^{(3)}]^{22} - [c_{ll}]^{1212} - [c_{ll}]^{1221}\right)\frac{v_0^2}{\Lambda^2}\right)^{\frac{1}{2}}$$

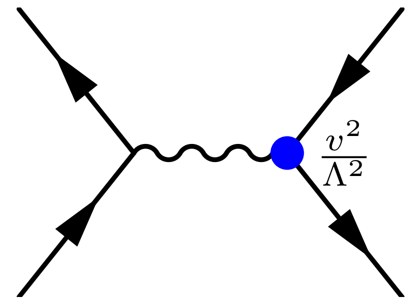
Propagate to all observables that depend on v!
(expanded to order $1/\Lambda^2$)

Current operators

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Contact operator predicted by gauge invariant construction



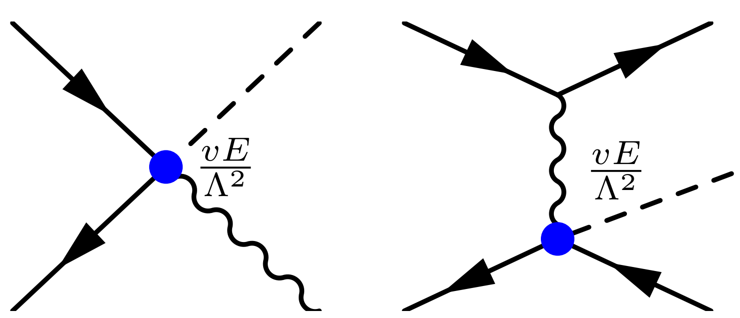


No energy growth w.r.t SM (overall rescaling)

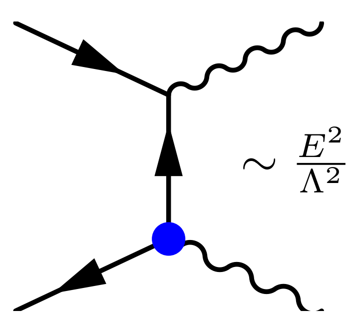
Precision EW on the Z peak (LEP)

Energy growth from non energy growing vertex…?

Unitarity non-cancellation in ff→WW scattering!



EW Higgs production



Diboson production

Diboson at the LHC

- qqZ / qq'W couplings in SM are simply gauge couplings
- To deviate from SM, we need: $\bar{f}\gamma_\mu f \; H^\dagger \overleftrightarrow{D}_\mu H$

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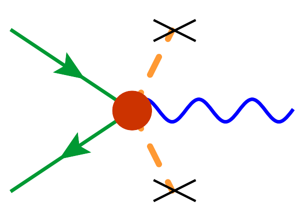
H -> vev



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

W/Z pole measurements
at LEP/SLD/Tevatron

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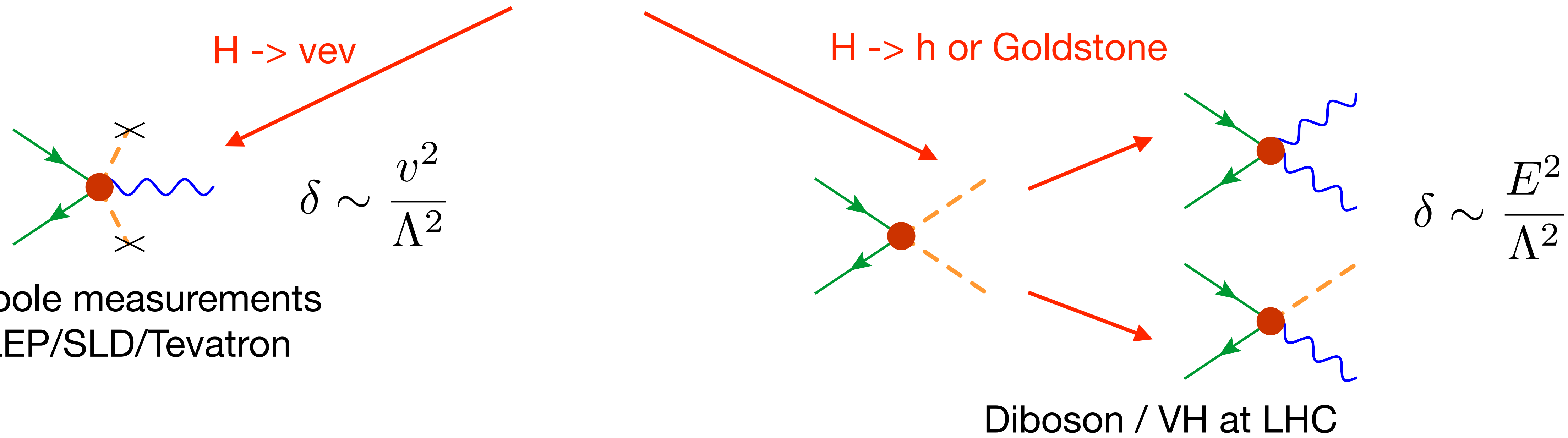


$$\frac{\delta\sigma(\hat{s})}{\sigma_{SM}(\hat{s})} \sim \delta g_i \frac{\hat{s}}{m_Z^2} \,.$$

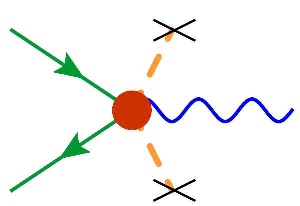
$$30\% \text{ in } \delta\sigma \;\Rightarrow 0.3\% \text{ in couplings}$$

Diboson at the LHC

- qqZ / qq'W couplings in SM are simply gauge couplings
- To deviate from SM, we need: $\bar{f}\gamma_\mu f\, H^\dagger \overleftrightarrow{D}_\mu H$

H -> vev

H -> h or Goldstone



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

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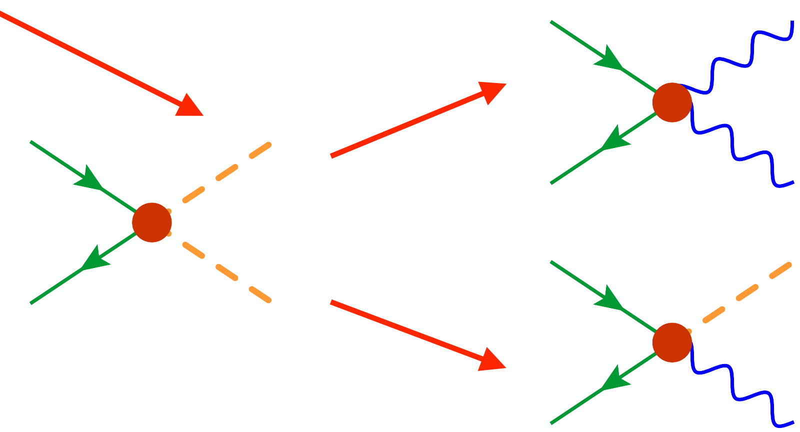

$$\delta \sim \frac{E^2}{\Lambda^2}$$

Diboson / VH at LHC

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

[R. Franceschini et al. 1712.01310]

Warsaw Basis
$\mathcal{O}_L^{(3)} = (\bar{Q}_L\sigma^a\gamma^\mu Q_L)(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_L = (\bar{Q}_L\gamma^\mu Q_L)(iH^\dagger \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_R^u = (\bar{u}_R\gamma^\mu u_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_R^d = (\bar{d}_R\gamma^\mu d_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$

"High energy primaries"

(with the caveat of "interference resurrection", see [G. Panico, F. Riva, A. Wulzer 1708.07823])

Gauge only operators

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
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$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
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$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
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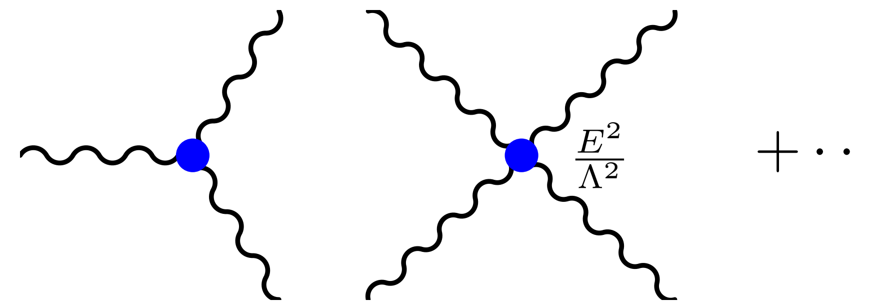
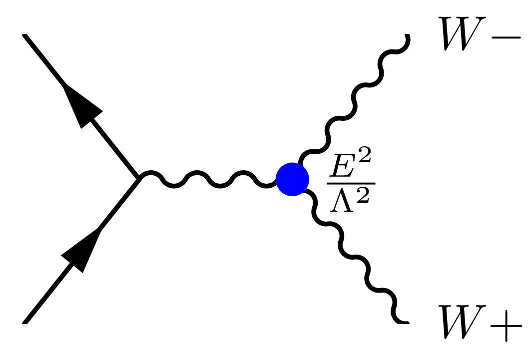
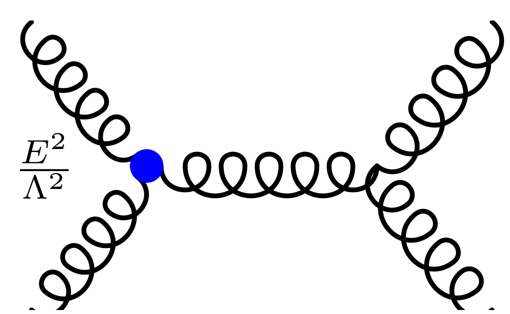
Anomalous triple & quartic gauge couplings





Diboson production LEP/LHC

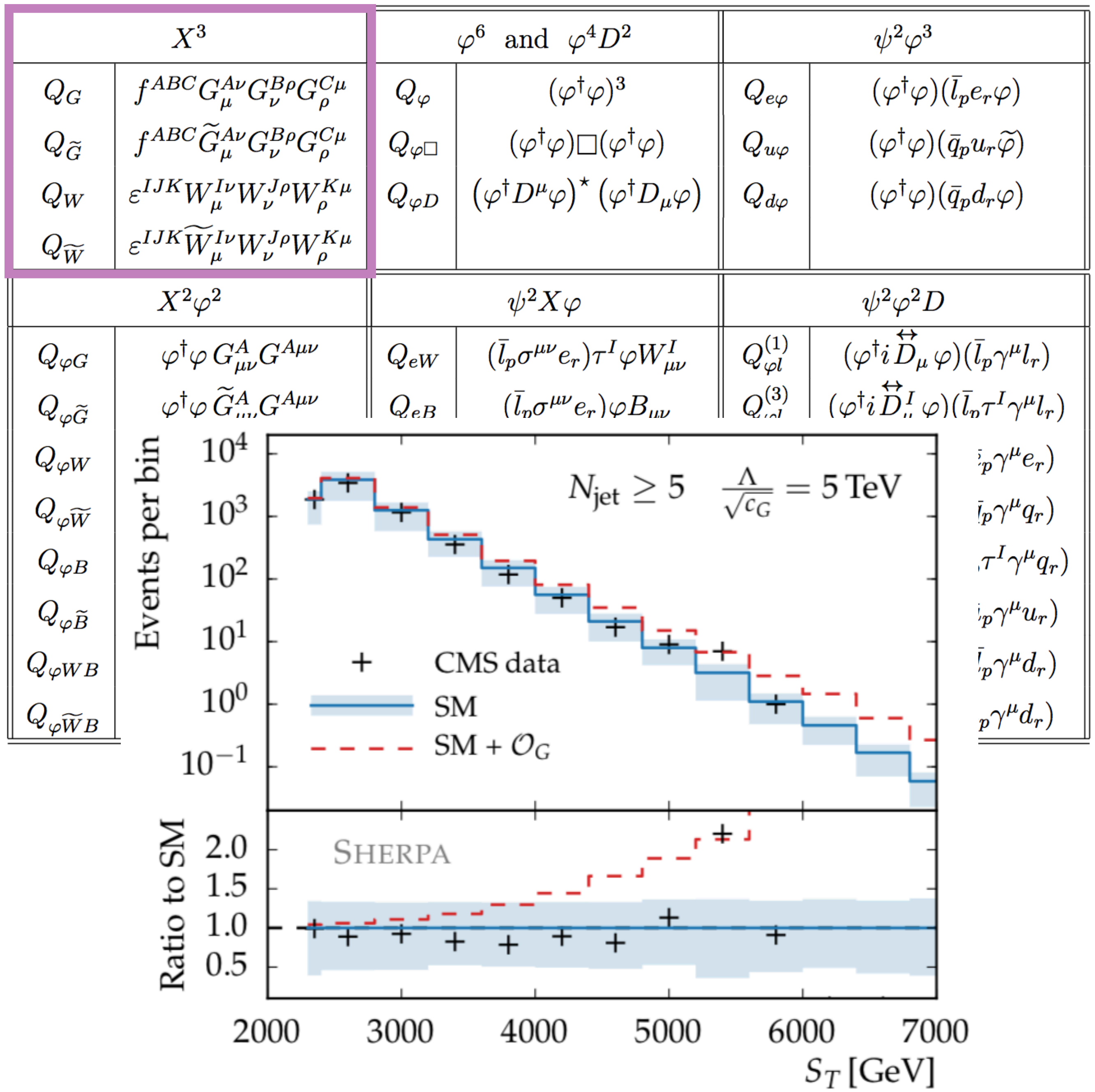
Large energy growth w.r.t SM



Multi-jet production

Operators also have CP violating versions

Gauge only operators



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
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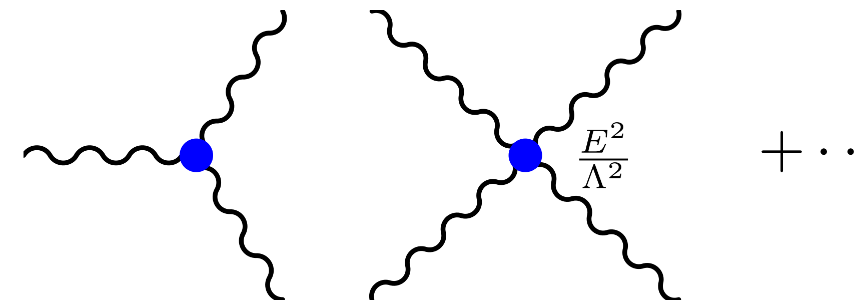
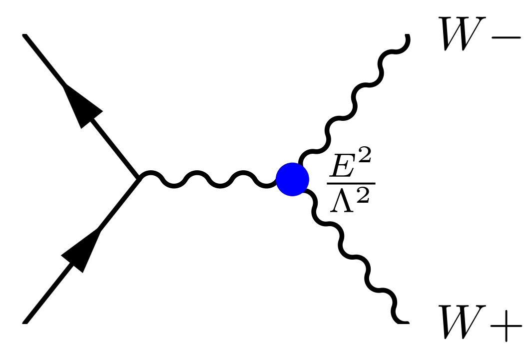
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

[Krauss et al.; PRD 95 (2017) 035024]

Anomalous triple & quartic gauge couplings





Diboson production LEP/LHC

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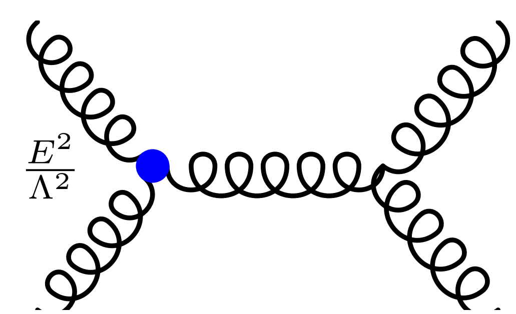

Multi-jet production

Operators also have CP violating versions

Gauge/Higgs operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
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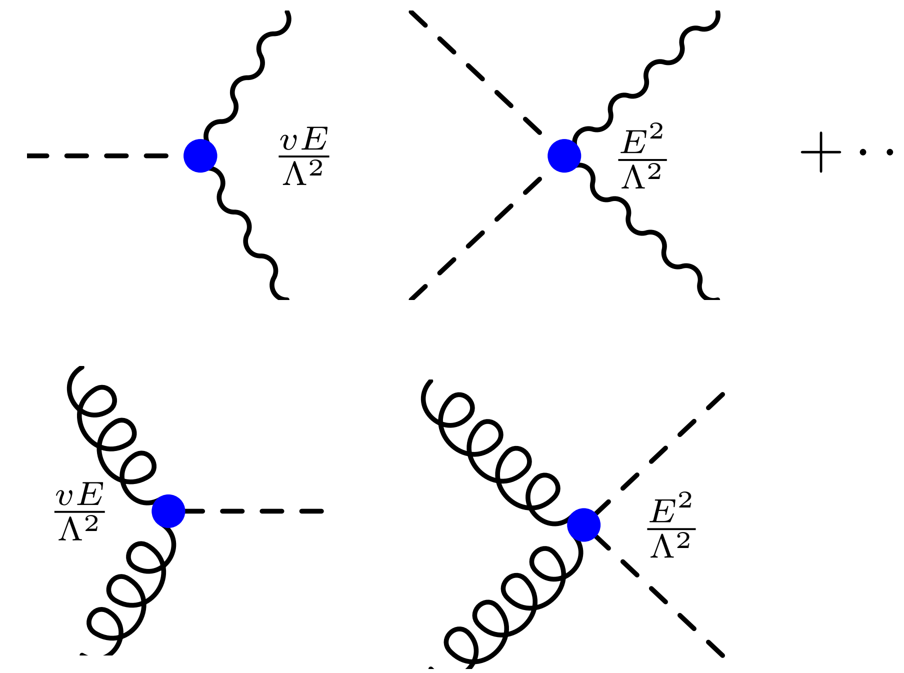
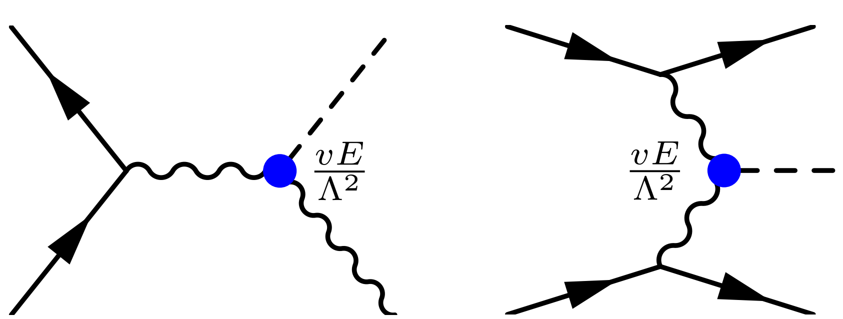
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	T-parameter	
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	S-parameter	[illegible] ν	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$



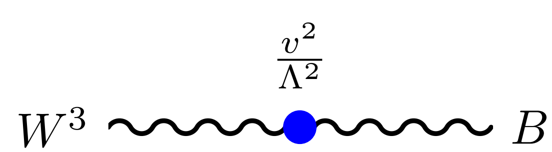
Gluon fusion: Higgs, di-Higgs

[Ellis et al.; JHEP 06 (2018) 146]

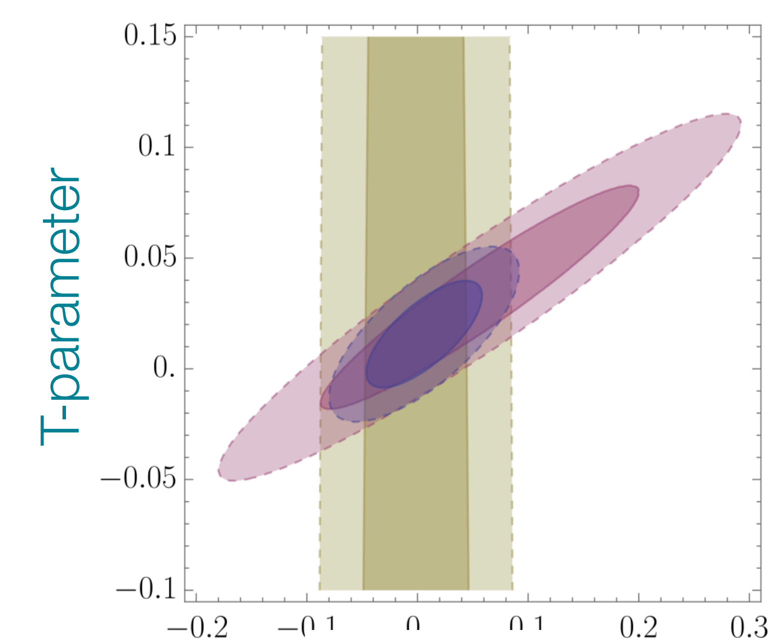


EW Higgs production & decay

kinetic mixing



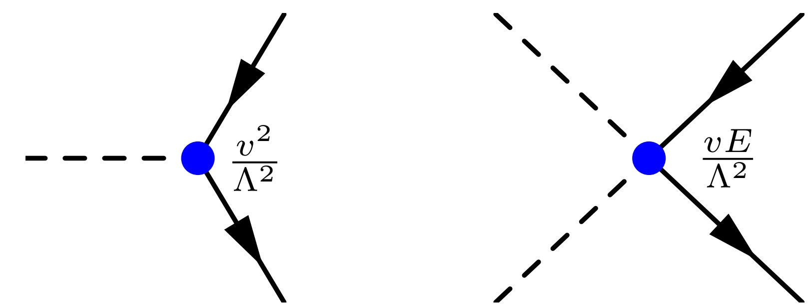
EW precision test



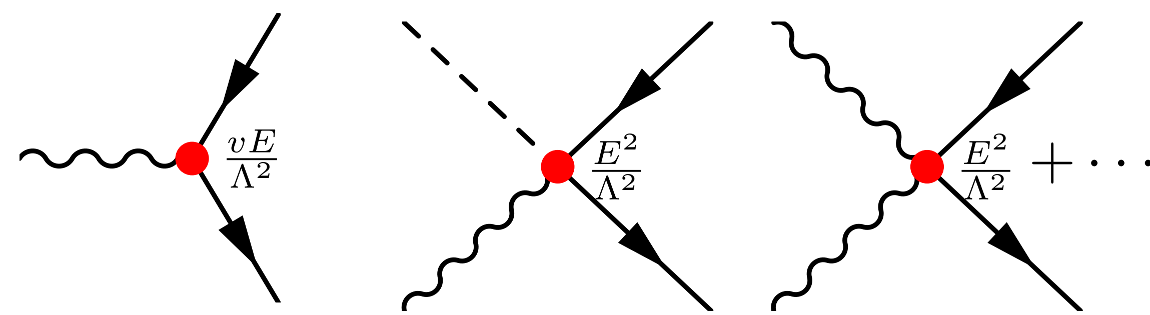
Two fermion operators

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Yukawa operators

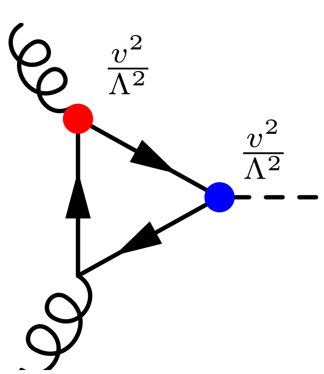


Dipole operators: Z, W, γ, g

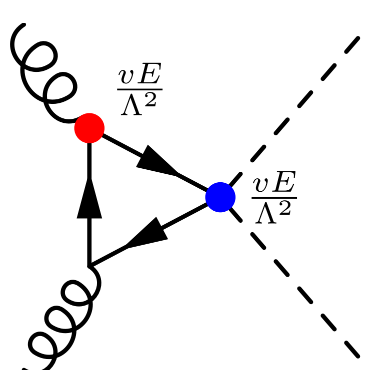


Non-Abelian

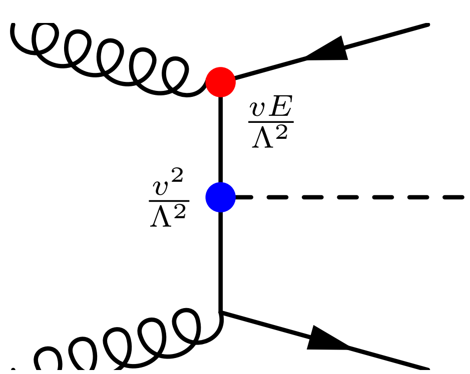
Interplay between Yukawa, dipoles & ggH



ggH

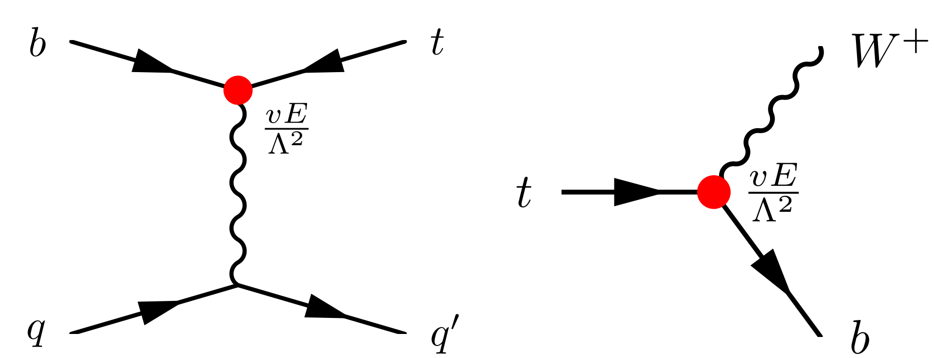


ggHH



ttH

Different energy & helicity structure



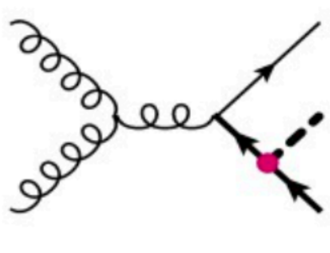
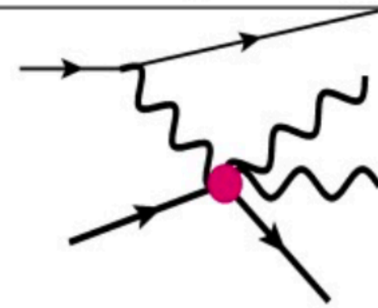
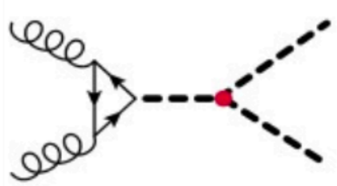
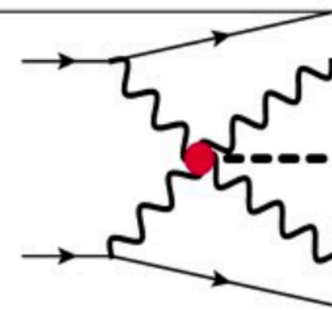
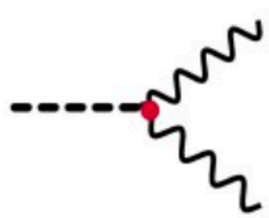
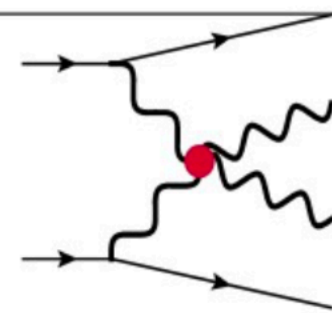
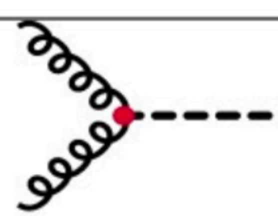
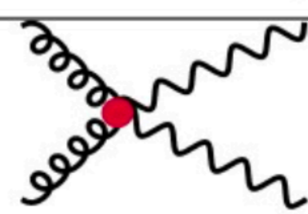
EW top production & decay

Higgs Couplings without the Higgs

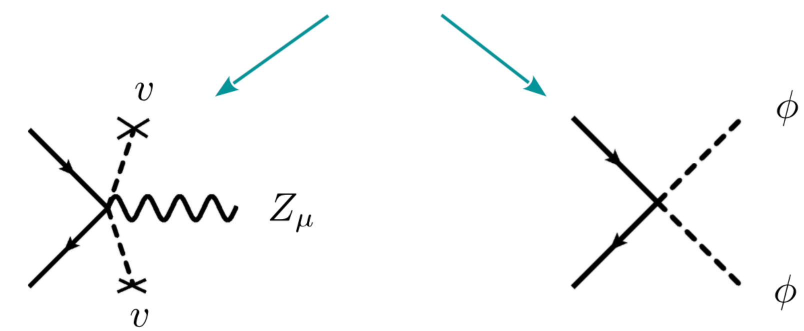
Brian Henning, Davide Lombardo, Marc Riembau, and Francesco Riva
Départment de Physique Théorique, Université de Genève,
24 quai Ernest-Ansermet, 1211 Genève 4, Switzerland

The measurement of Higgs couplings constitute an important part of present Standard Model precision tests at colliders. We show that modifications of Higgs couplings induce energy-growing effects in specific amplitudes involving longitudinally polarized vector bosons, and we initiate a novel program to study these very modifications of Higgs couplings off-shell and at high-energy, rather than on the Higgs resonance. Our analysis suggests that these channels are complementary and, at times, competitive with familiar on-shell measurements; moreover, they offer endless opportunities for refinements and improvements.

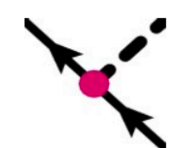
E^2 vs v^2

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

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



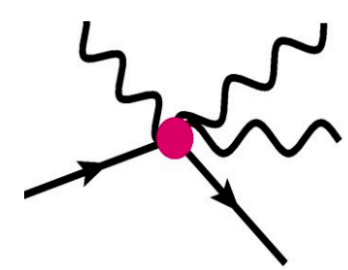
$\delta\mathcal{A} \sim v^2/\Lambda^2$ $\delta\mathcal{A} \sim E^2/\Lambda^2$



$\delta\mathcal{A}/\mathcal{A} \sim v^2/\Lambda^2$

$|H|^2 \bar{f}_L H f_R$

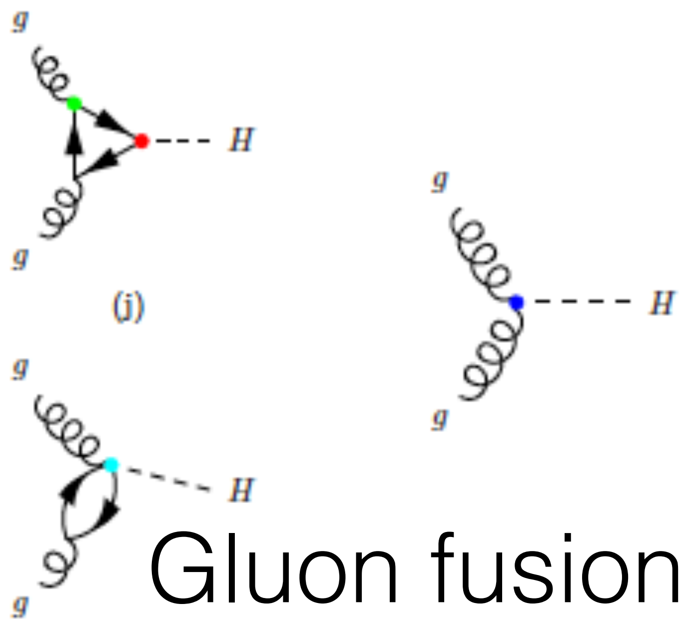
unanchor the Higgs from its vev



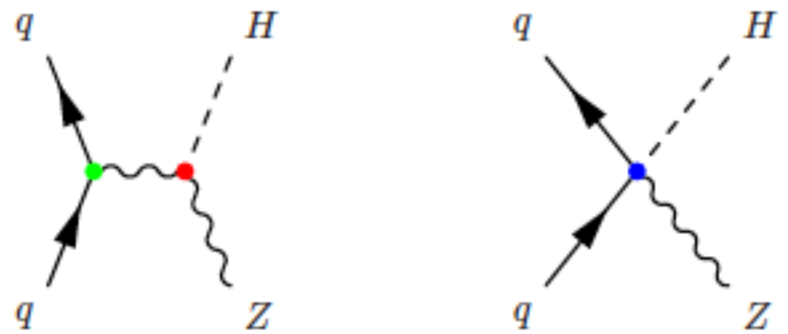
$\delta\mathcal{A}/\mathcal{A} \sim E^2/\Lambda^2$

[Henning, Lombardo, Riembau, Riva 1812.09299]

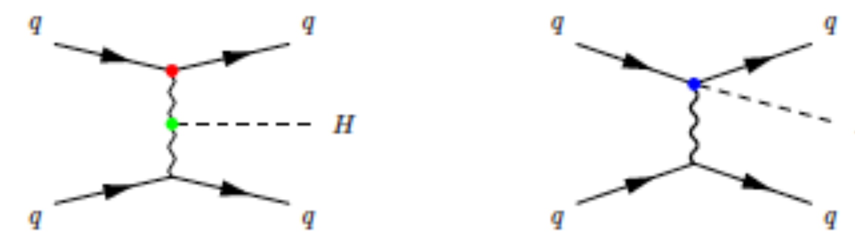
EFT in Higgs physics



Gluon fusion



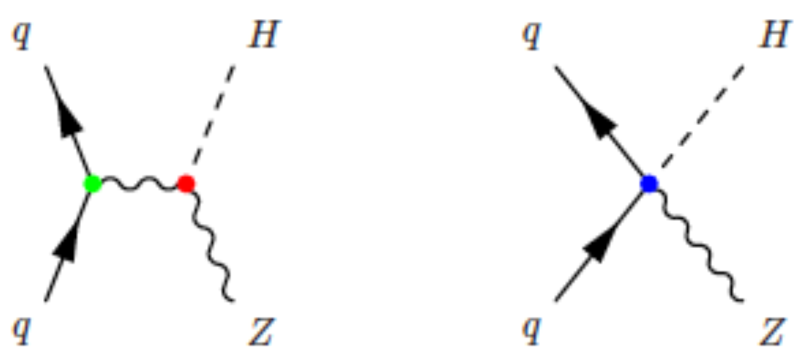
VH



VBF

Tuesday tutorial

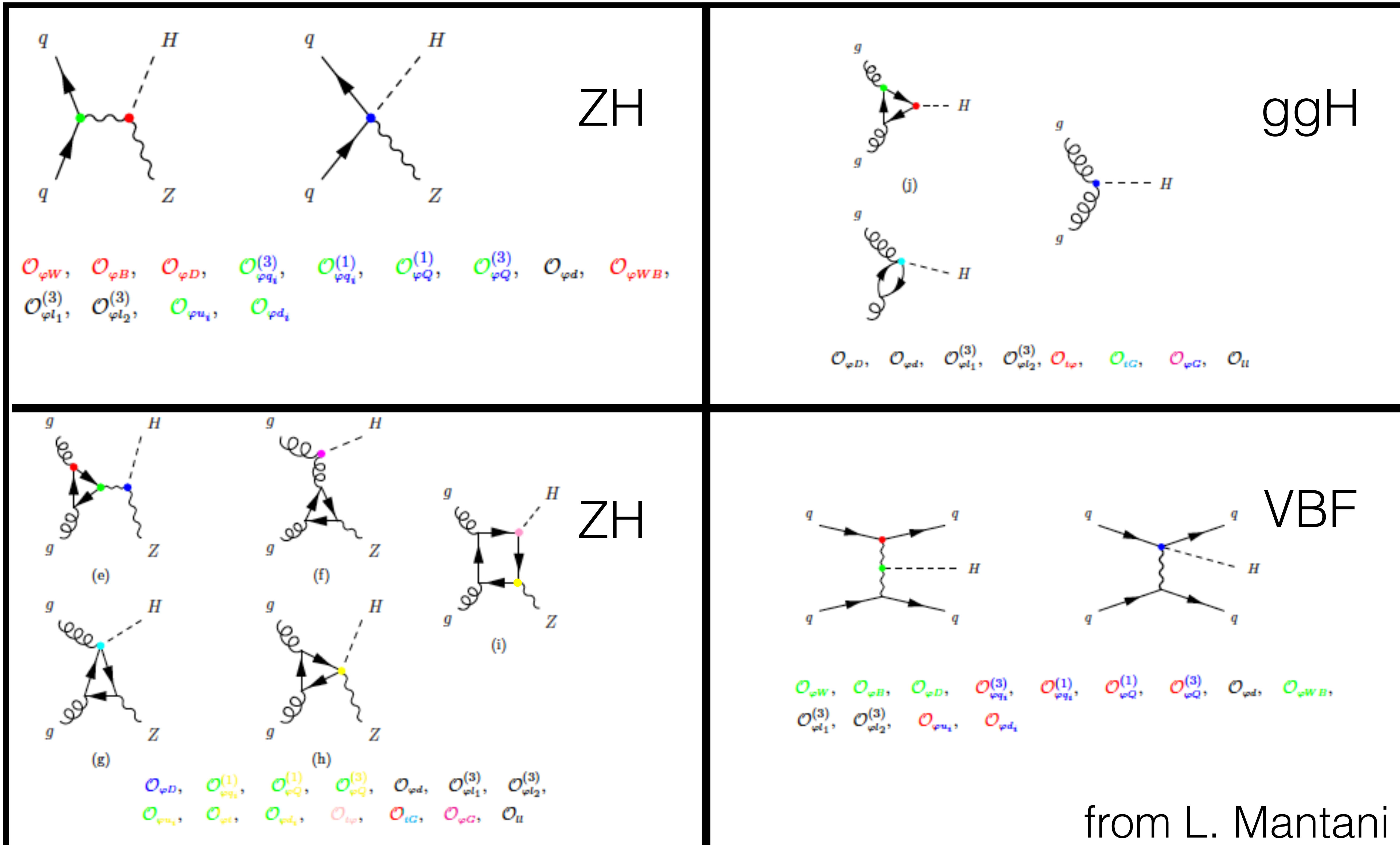
Example: VH



Red/Green: modifying existing vertices
Blue: New vertices
Black: Input parameter

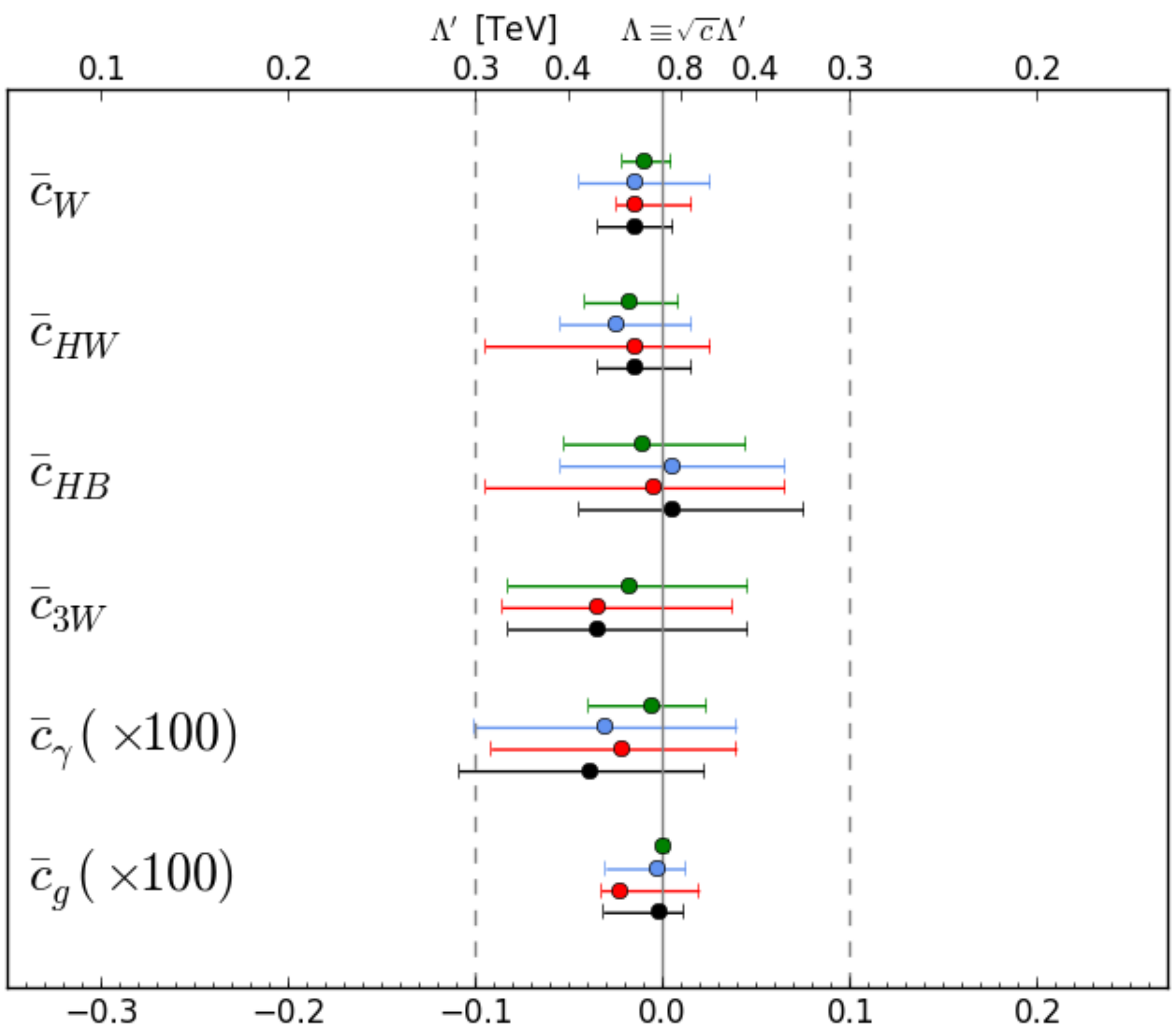
$\mathcal{O}_{\varphi W}$, $\mathcal{O}_{\varphi B}$, $\mathcal{O}_{\varphi D}$, $\mathcal{O}^{(3)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi Q}$, $\mathcal{O}^{(3)}_{\varphi Q}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}_{\varphi WB}$,
$\mathcal{O}^{(3)}_{\varphi l_1}$,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

How do all these operators enter?



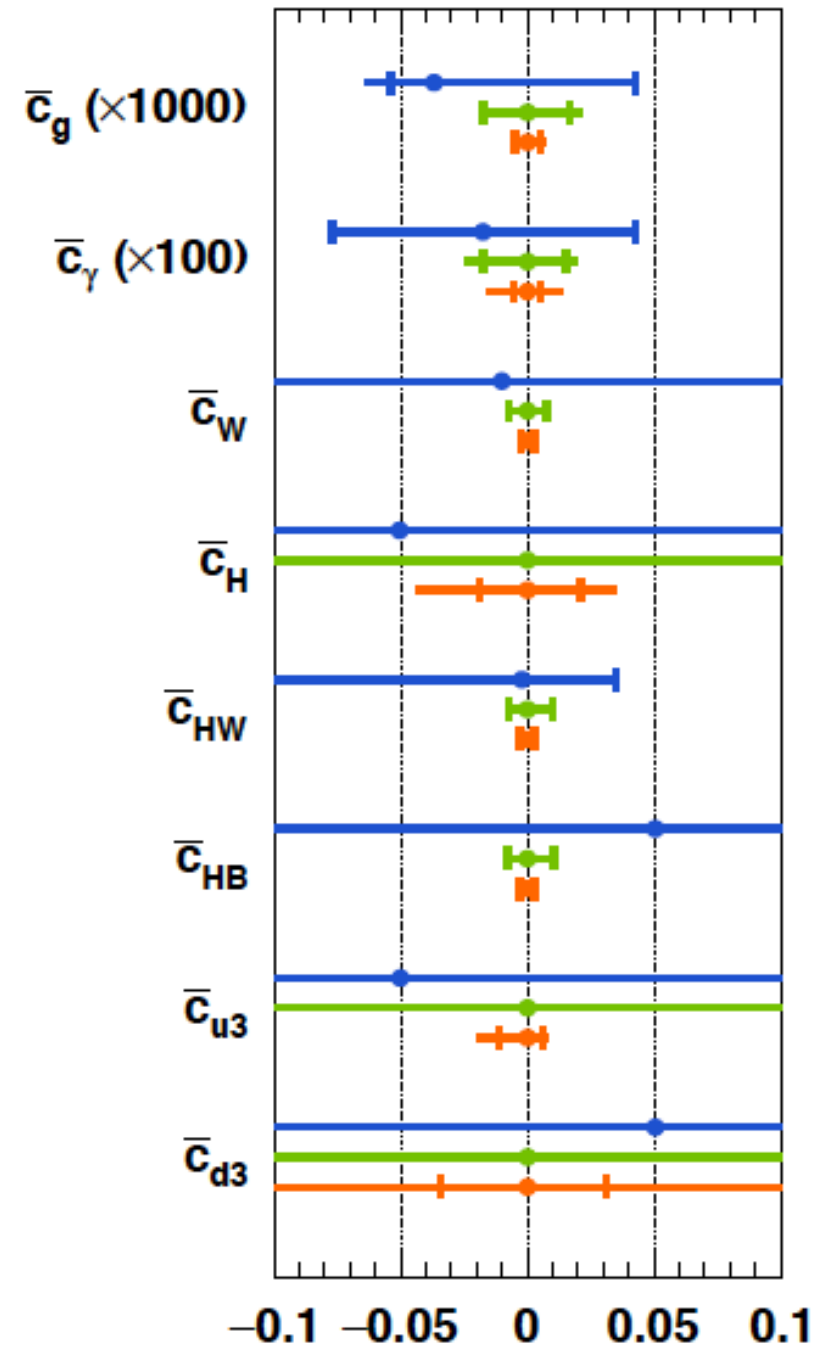
Application: EFT fits in the Higgs sector

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



Higgs, TGC, combination

1404.3667,1410.7703 Ellis, Sanz, You



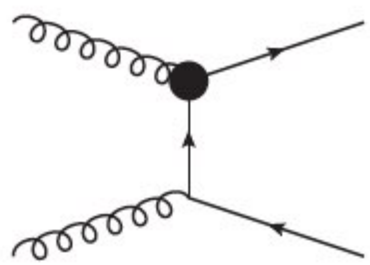
Current, 300fb^{-1},3000fb^{-1}

TGC not included

1511.0517 Englert, Kogler, Schulz, Spannowsky

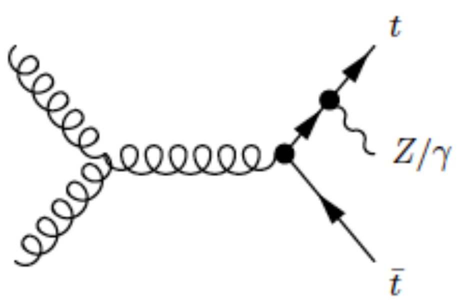
Rich phenomenology:

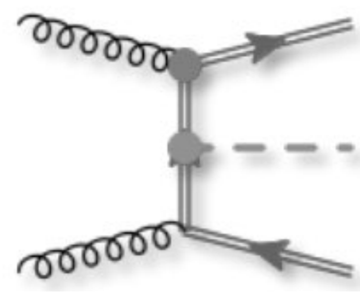
pair production



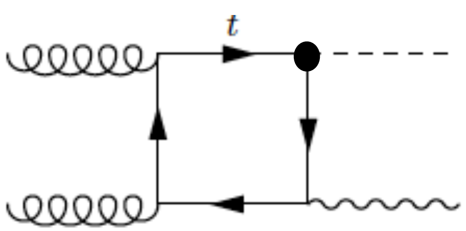
single

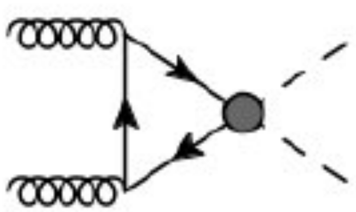
associated production





top loops





Top-quark operators and how to look for them

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

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

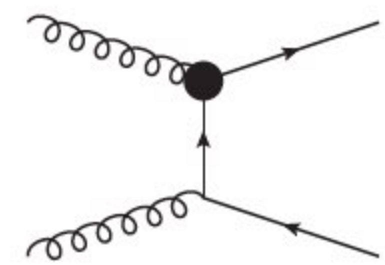
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right) (\bar{t}\gamma^\mu t)$$

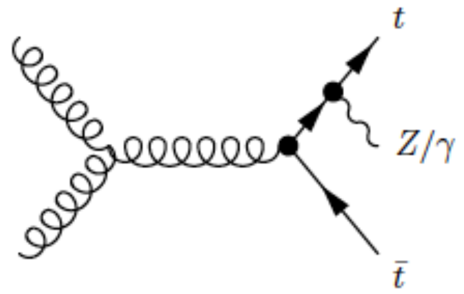
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

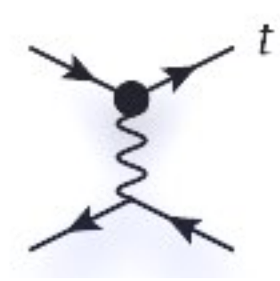
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

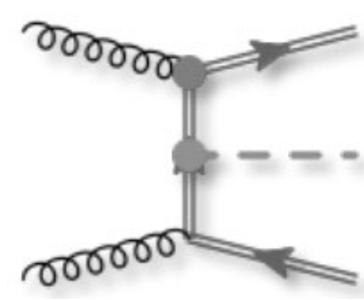
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}\,,$$

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









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

+four-fermion operators
+non-top operators (mixing)

Top-quark operators and how to look for them

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

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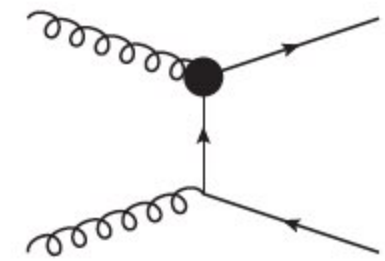
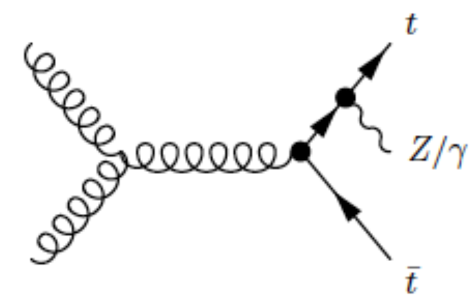
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}\,,$$

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





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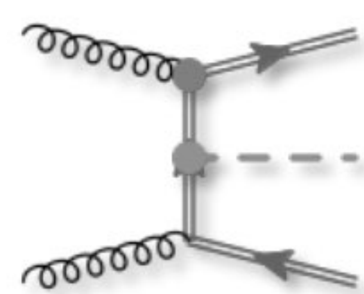

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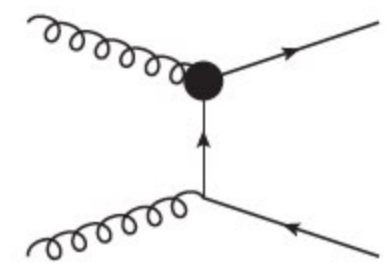

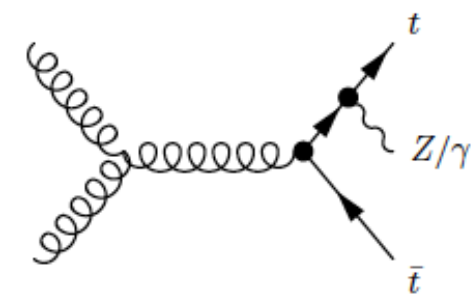

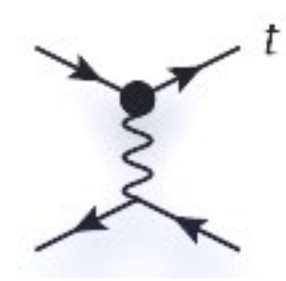

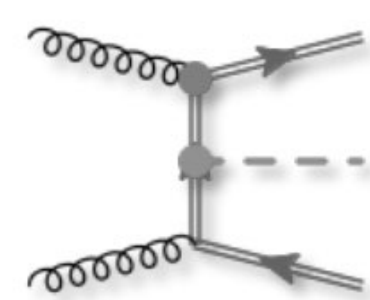

see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

Top-quark operators and how to look for them

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

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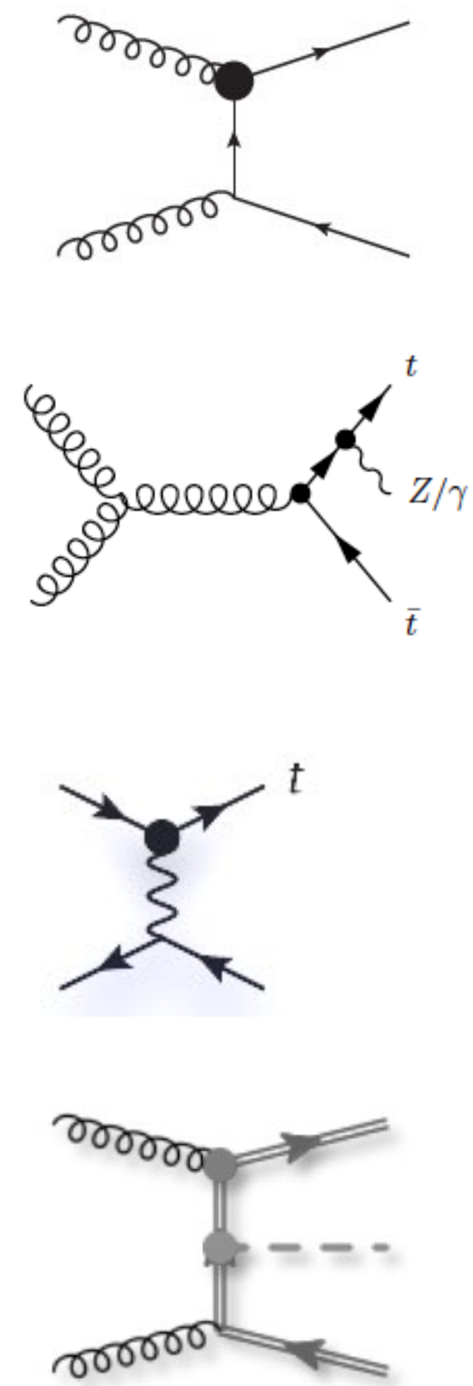

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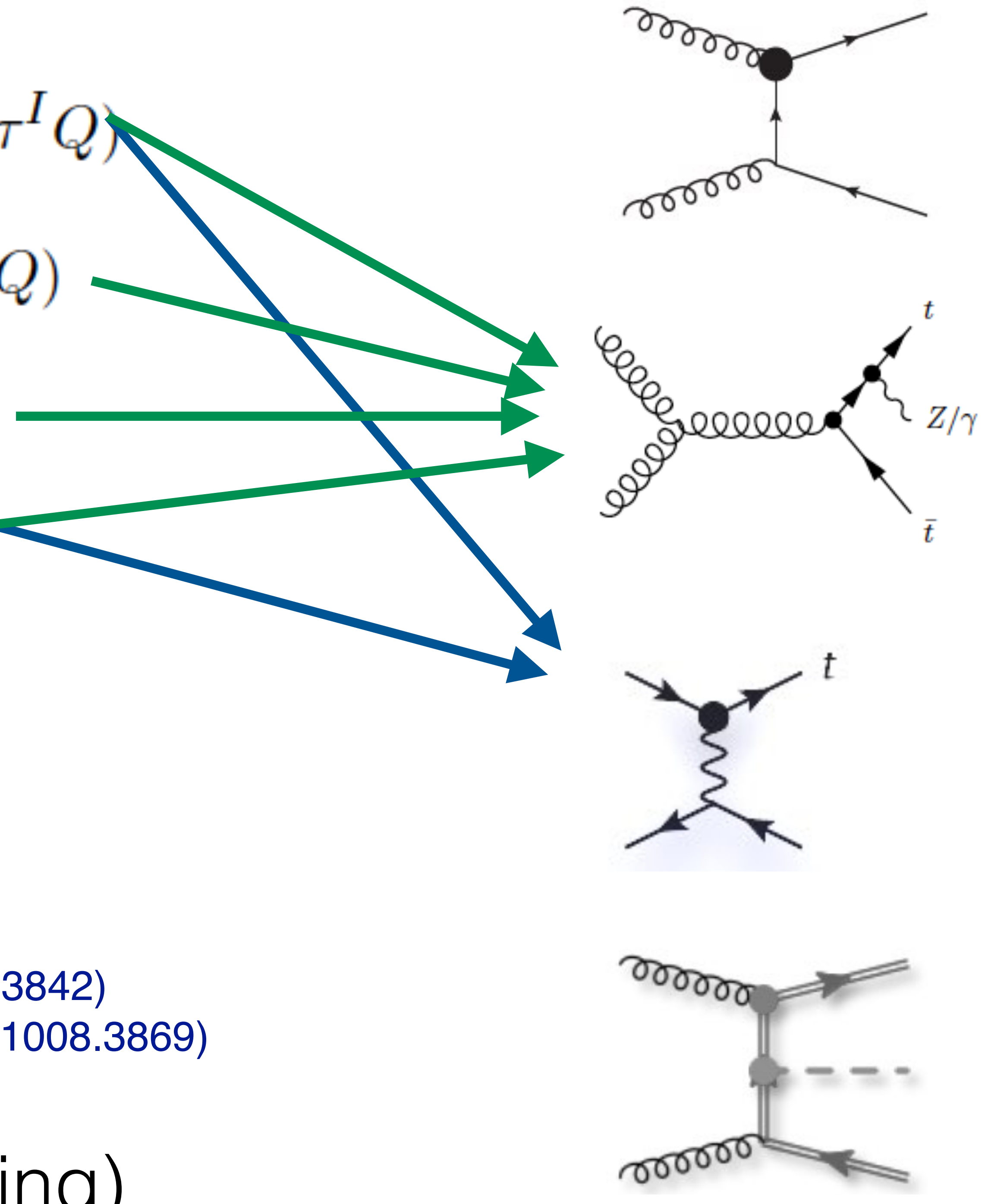

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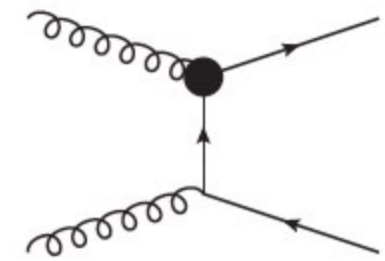

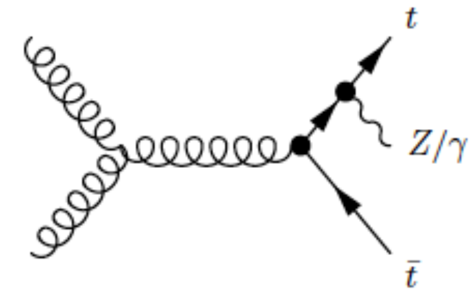

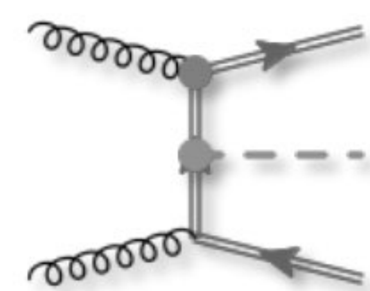

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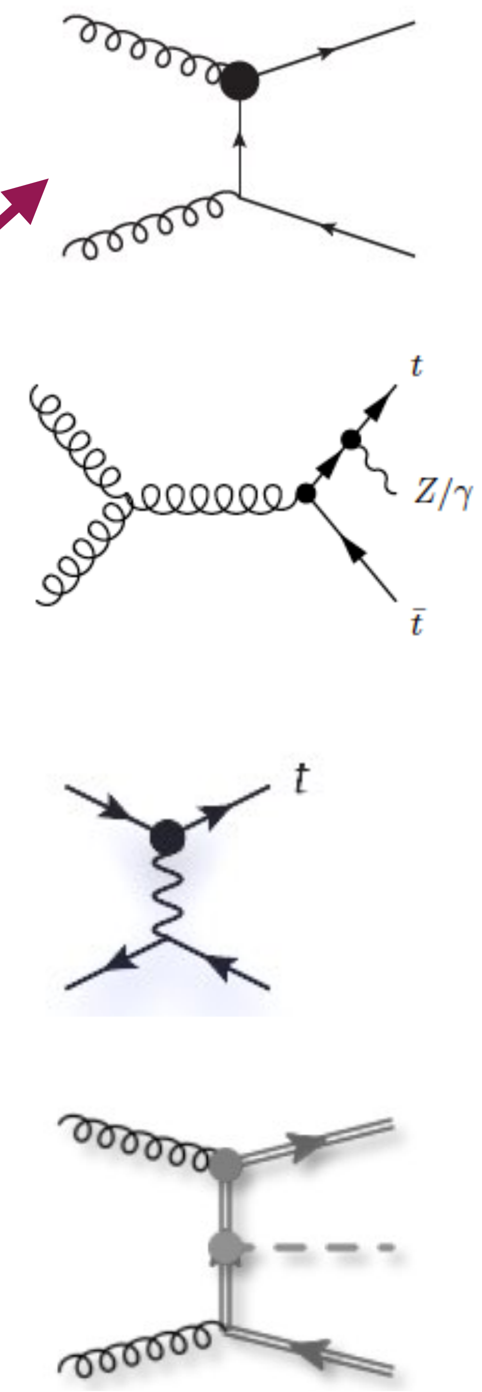

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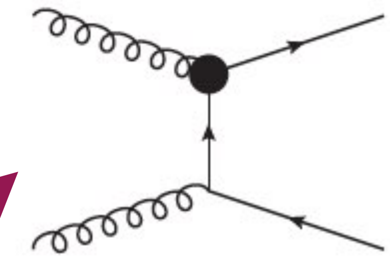

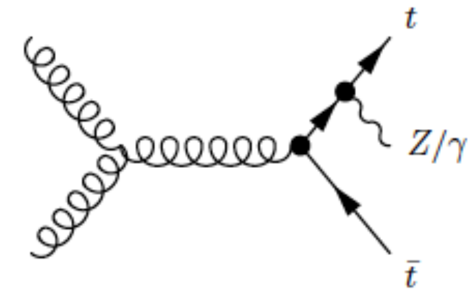

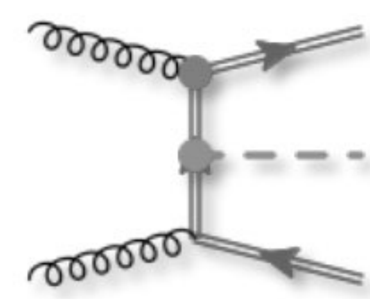

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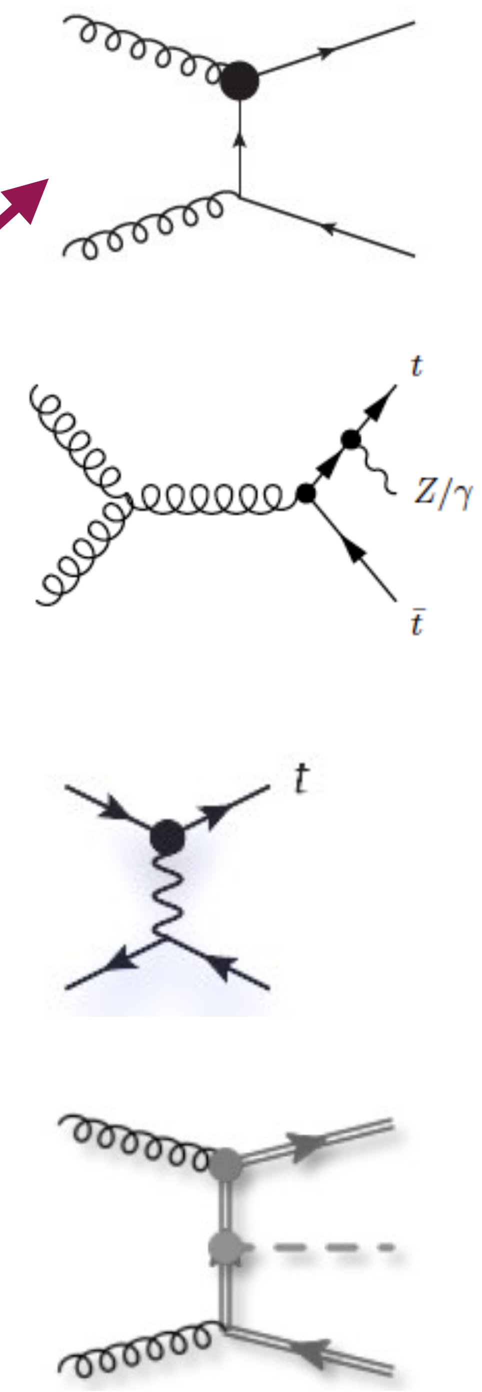

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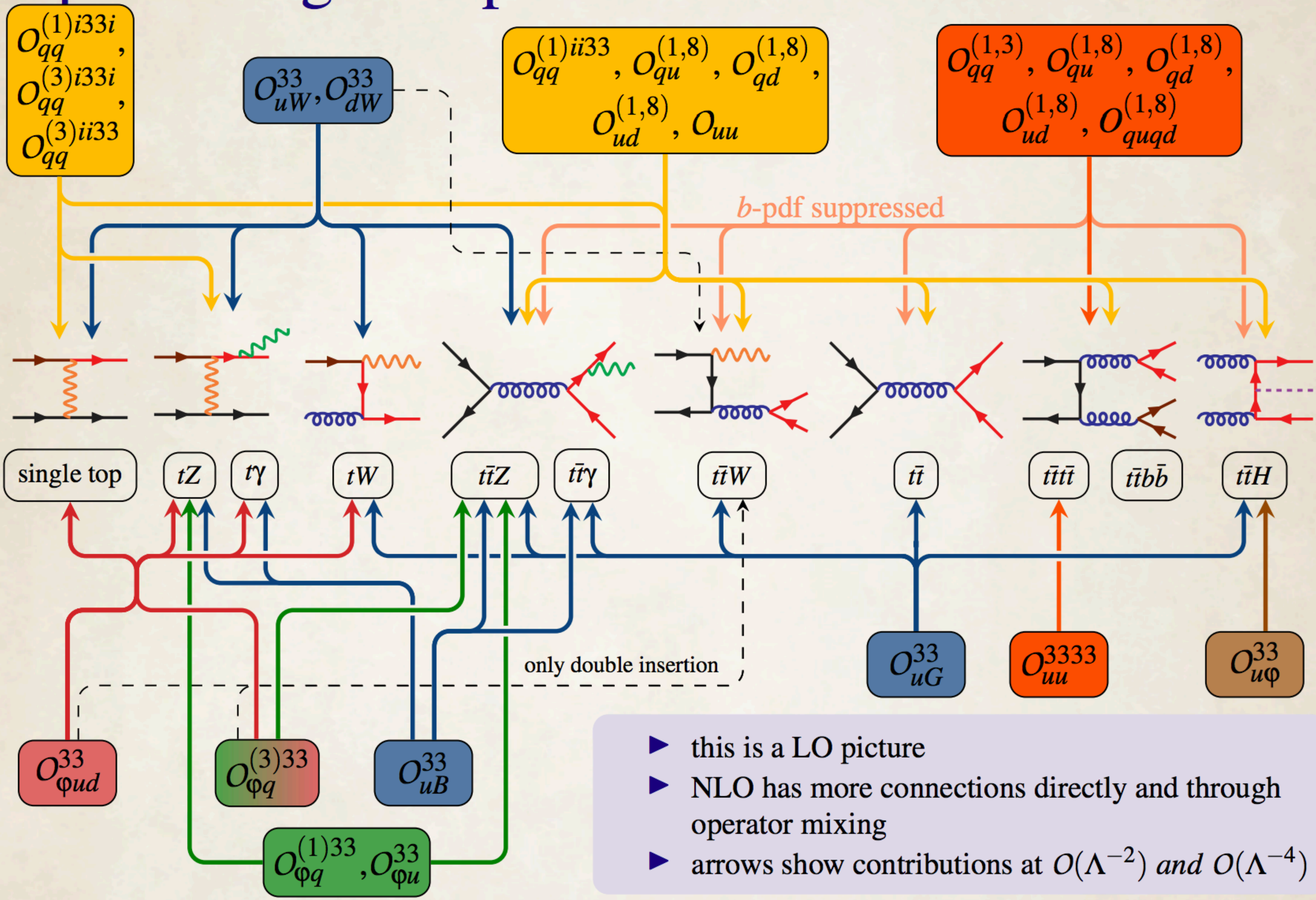
Operators entering various processes: Global approach needed

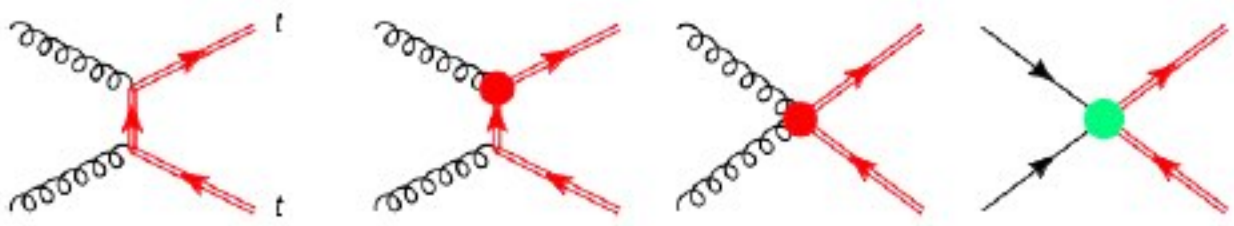
Top EFT: a global picture



- this is a LO picture
- NLO has more connections directly and through operator mixing
- arrows show contributions at $O(\Lambda^{-2})$ *and* $O(\Lambda^{-4})$

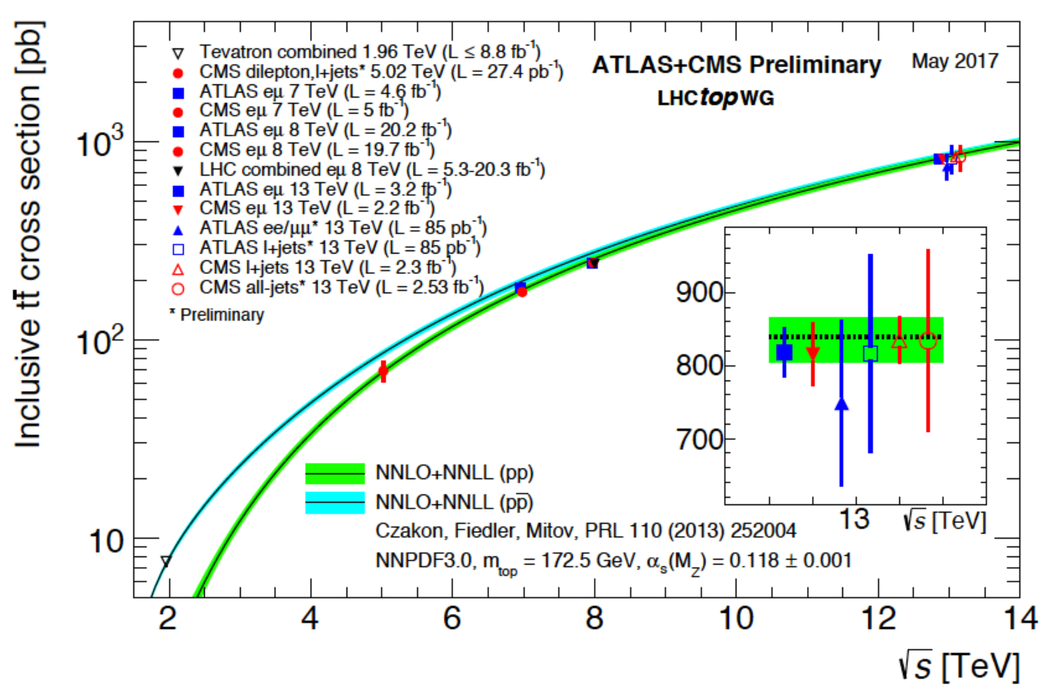
EFT in top production

Top pair production

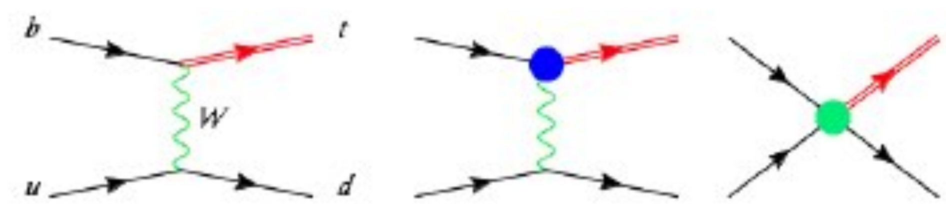


$$O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\,\tilde{\phi}G^T_{\mu\nu}$$

$$O^{(8)}_{ut} = (\bar{u}\gamma_\mu T^A u)(\bar{t}\gamma^\mu T^A t)$$



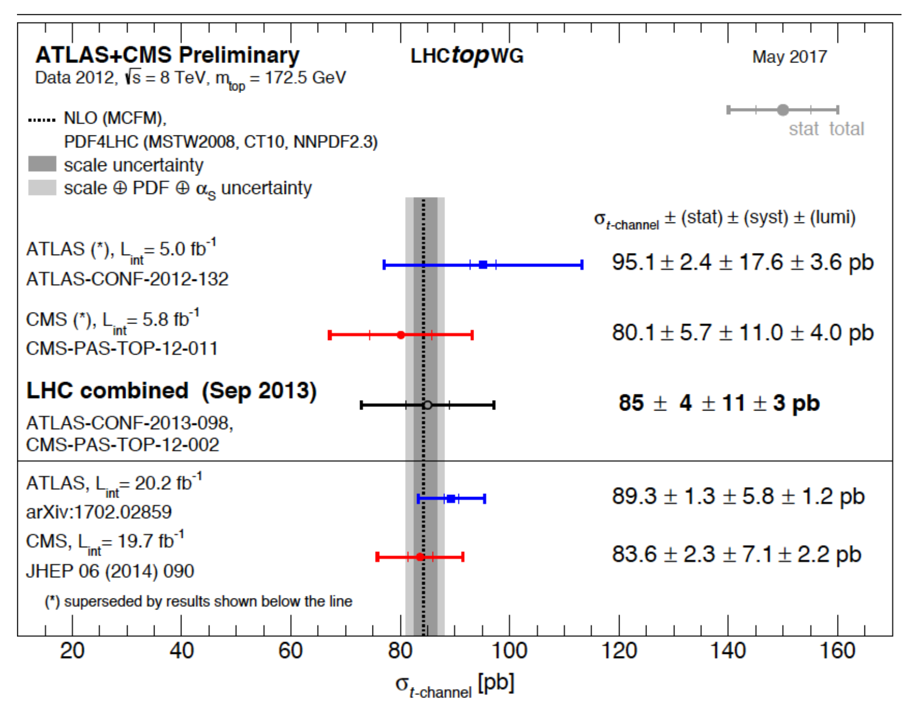
Single top production



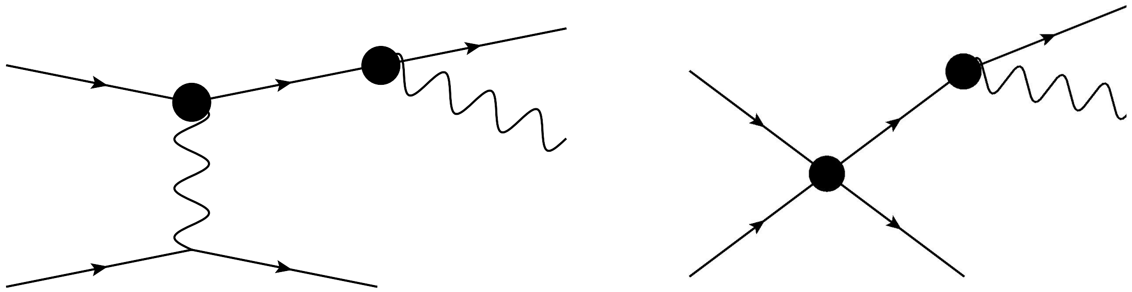
$$O^{(3)}_{\varphi Q} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

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

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



Single top production and decay

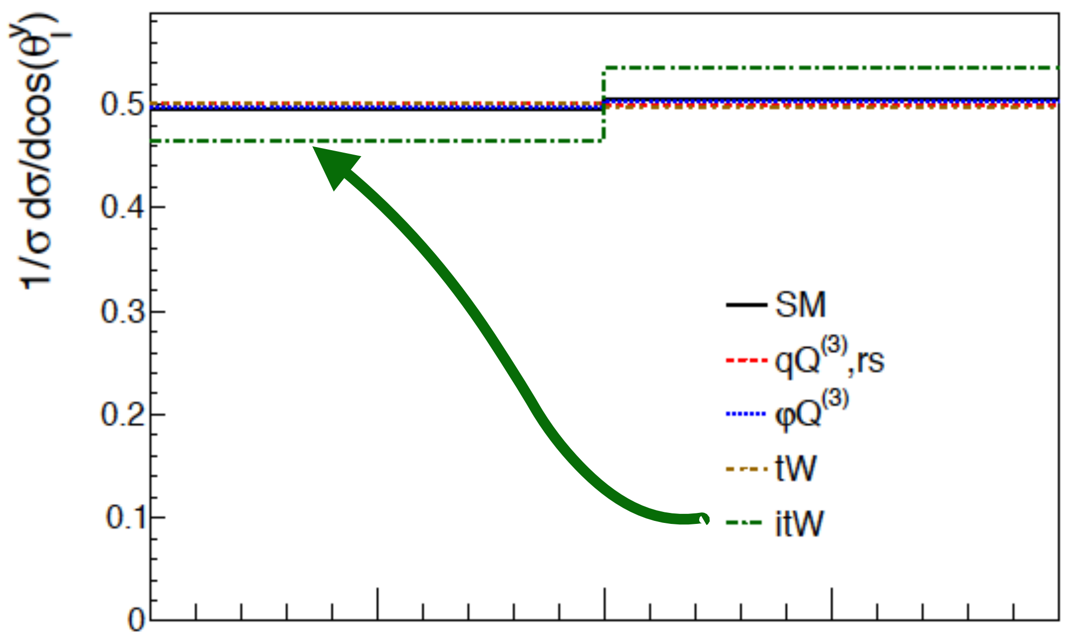


$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

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



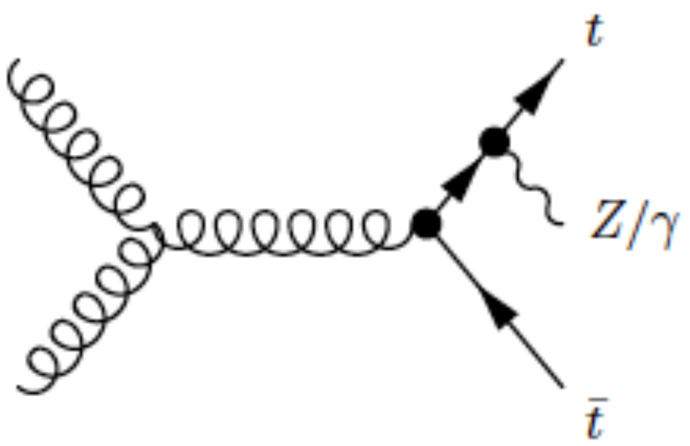
Top polarisation angles

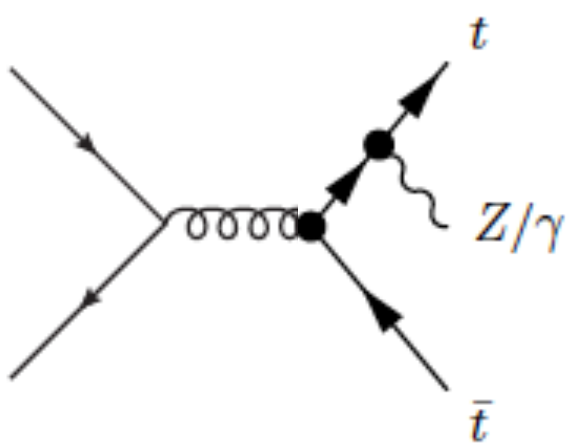
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i^z} = \frac{1}{2}(1 + a_i P\ \cos\theta_i^z)$$

Study including production and decay

de Beurs, Laenen, Vreeswijk, EV arXiv:1807.03576

Top-pair+Z/photon





~900fb at 13 TeV

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

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

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

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

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

Anomalous coupling approach

Relevant operators

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

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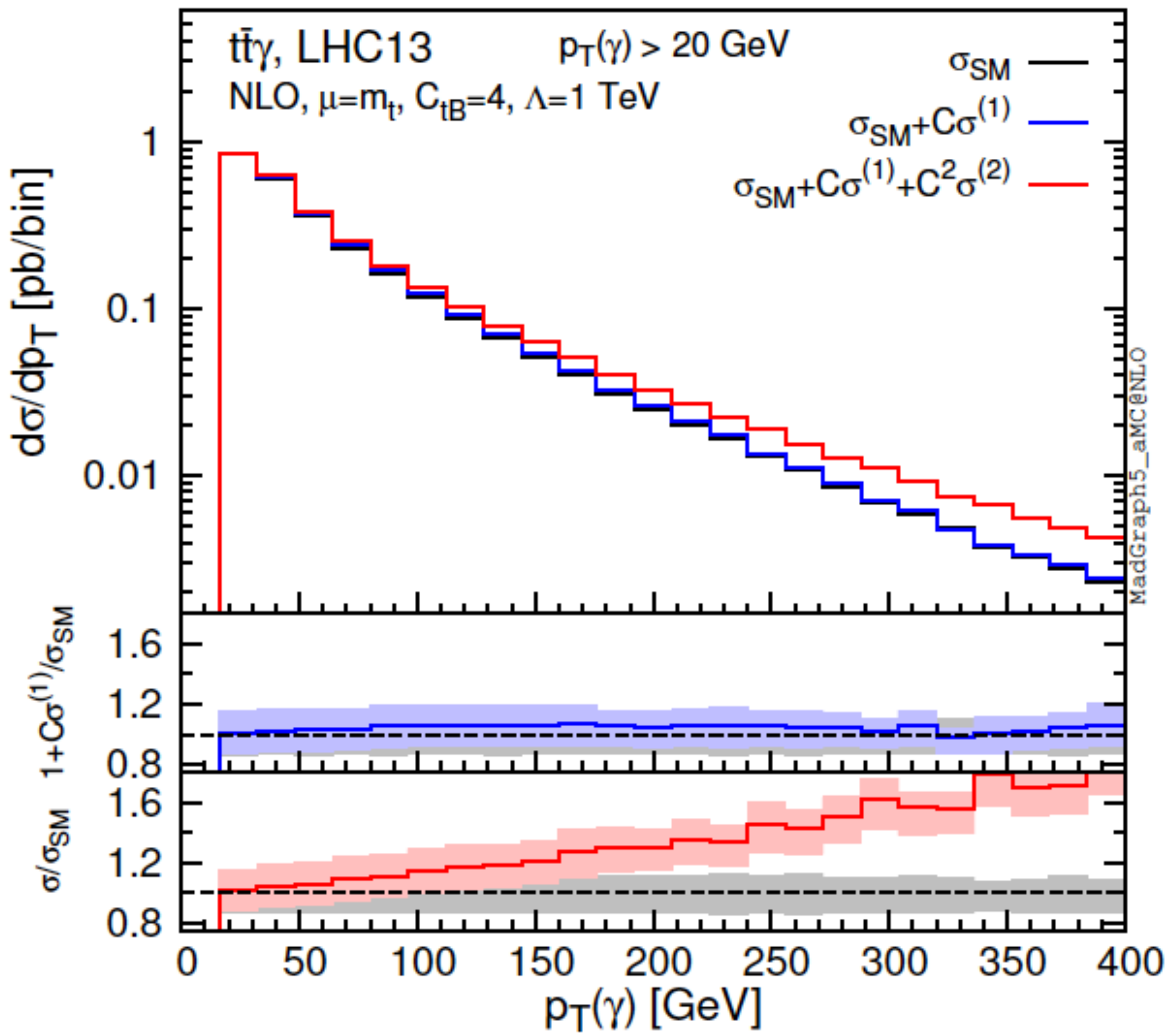
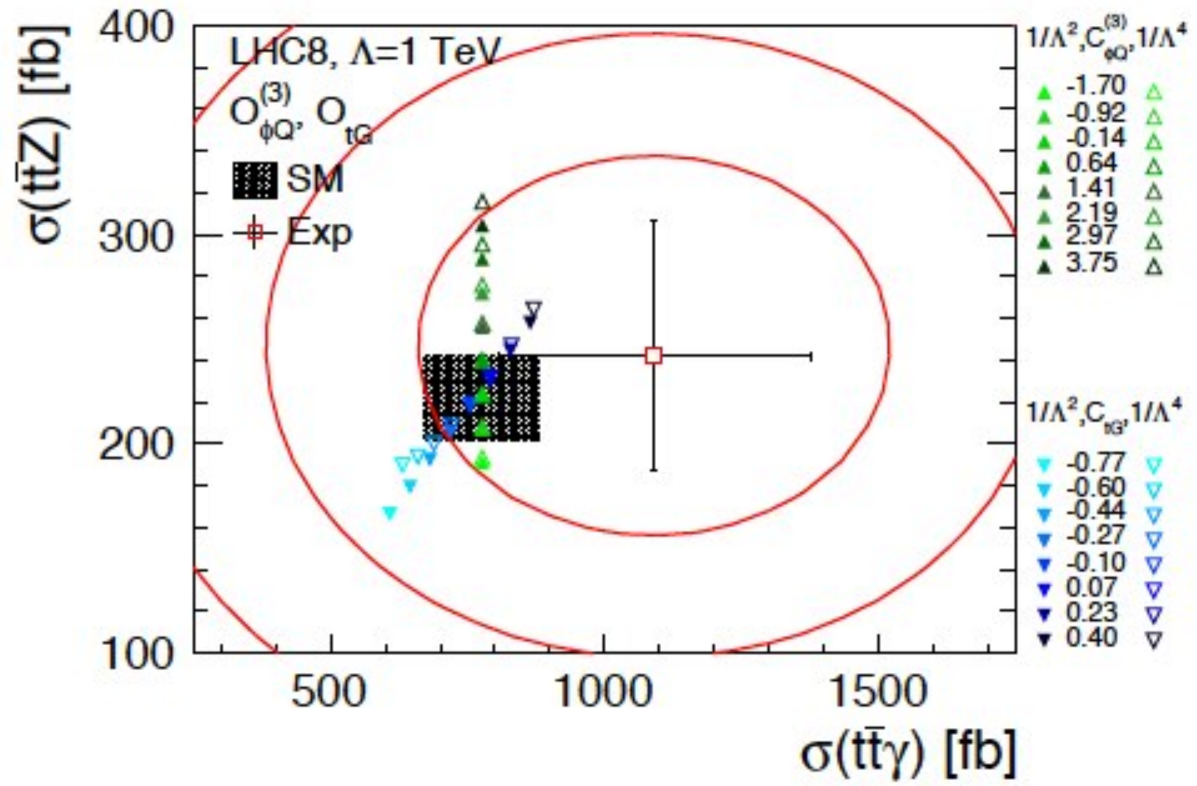
4-fermion operators
Triple gluon operator
(not discussed here)

Results for tt+V



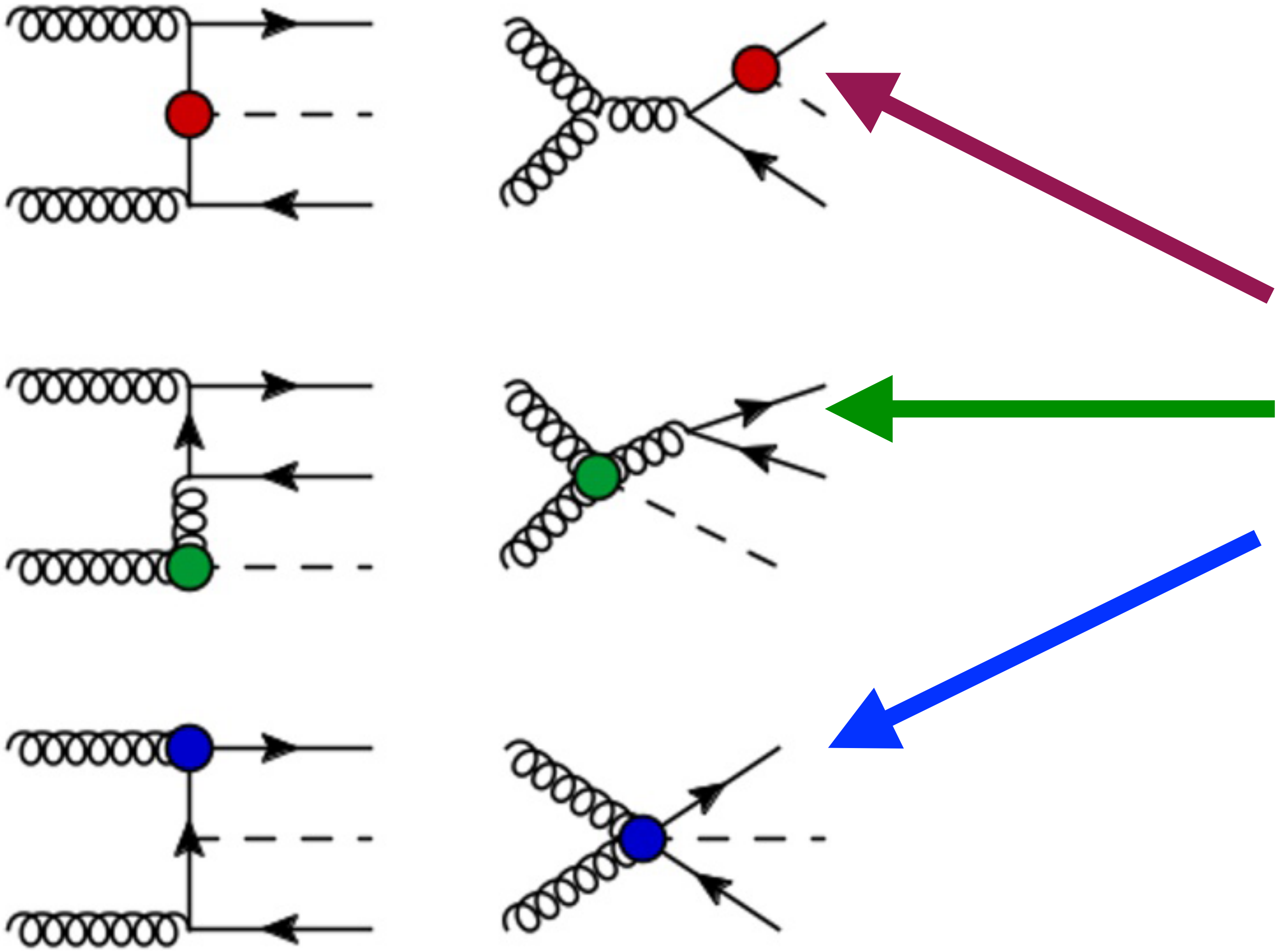


Large contribution at $O(1/\Lambda^4)$ rising with energy

arXiv:1601.08193

	Associated top quark production using EFT at CMS	*Brent YATES*
20:00	*科大东区物质科研楼3楼报告厅 and Zoom online*	*19:40 - 20:10*
	Putting SMEFT Fits to Work	*Dr. Samuel HOMILLER*
	科大东区物质科研楼3楼报告厅 and Zoom online	*20:10 - 20:35*
	A_{FB} in the SMEFT: the LHC as a Z-physics laboratory	*Mr. Víctor BRESÓ*
	科大东区物质科研楼3楼报告厅 and Zoom online	*20:35 - 21:00*
21:00	**Reviving the interference: framework and proof-of-principle for the anomalous gluon self-interactions in the SMEFT**	*Mr. Matteo MALTONI*
	Break	

ttH in the EFT



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

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

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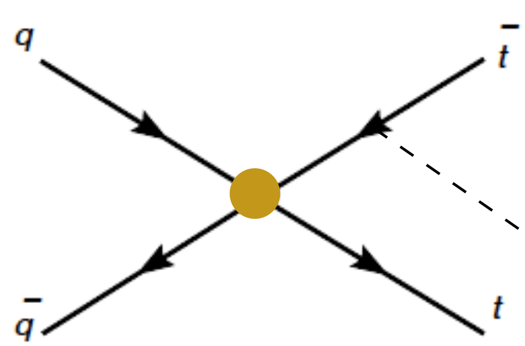
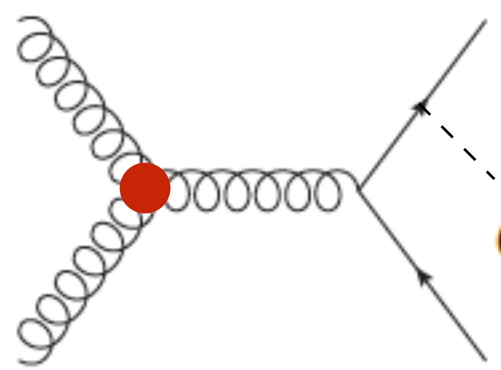
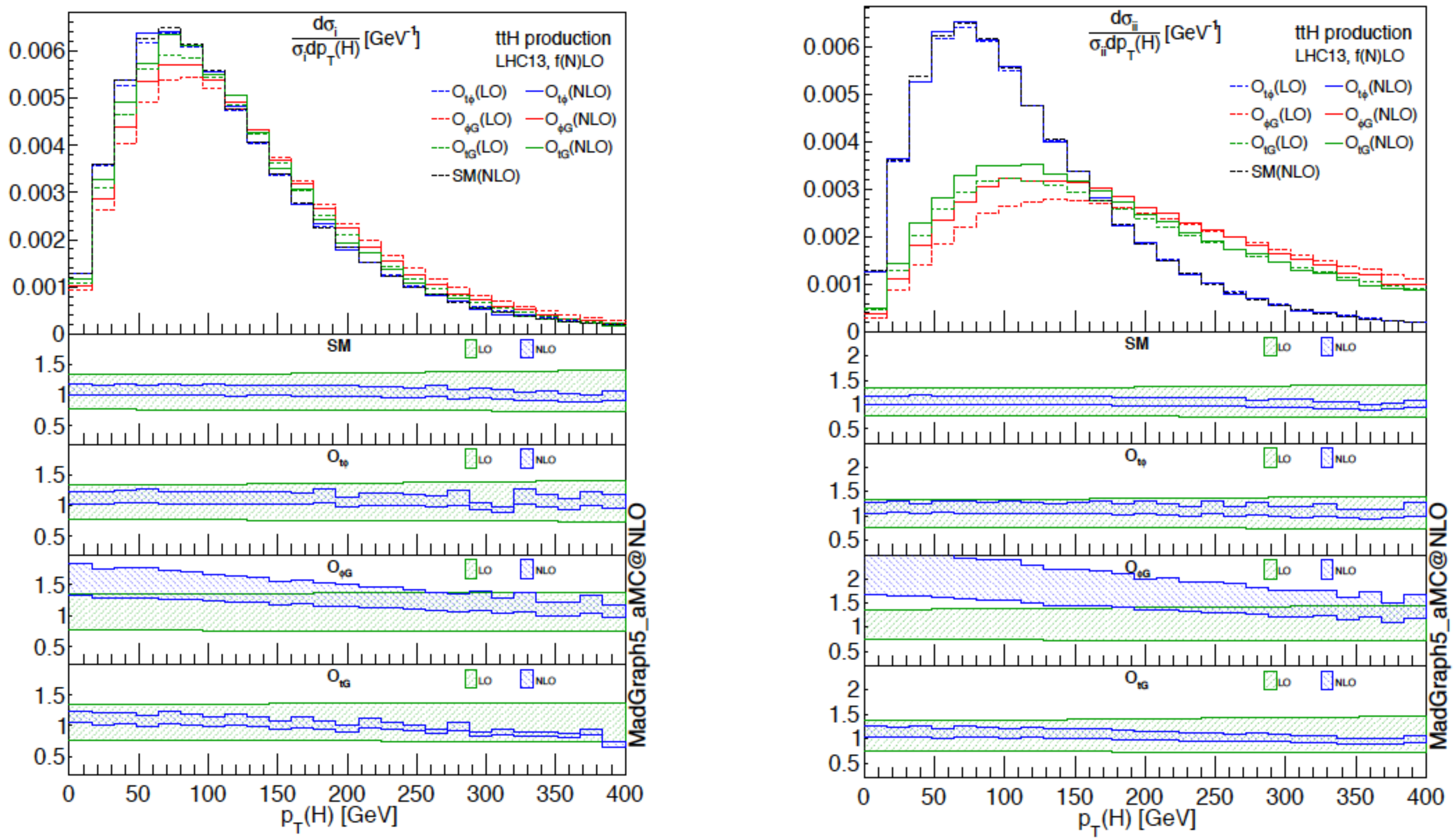


4-fermion operators



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

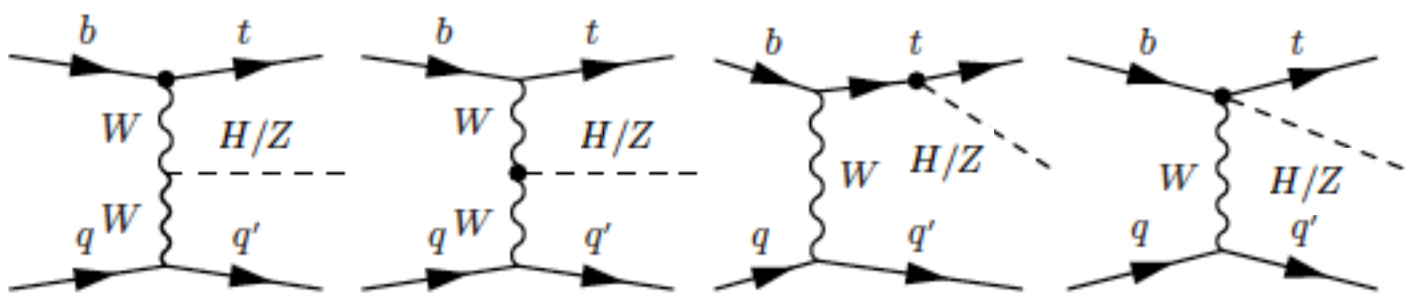
Differential distributions for ttH



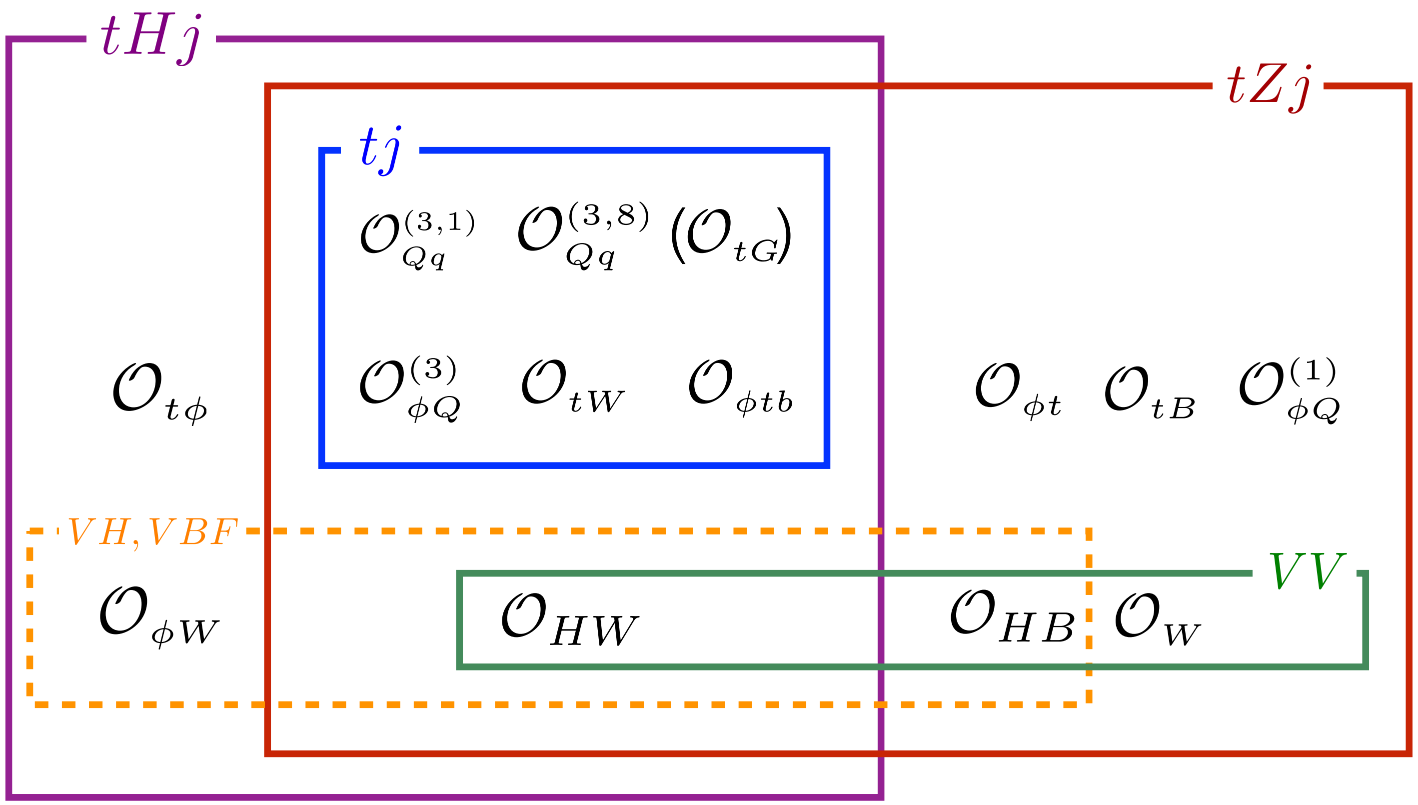
→ Different shapes for different operators for the squared terms

Maltoni, EV, Zhang arXiv:1607.05330

tZj/tHj associated production



Gauge-Higgs
Top couplings
TGC



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

Unique interplay

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

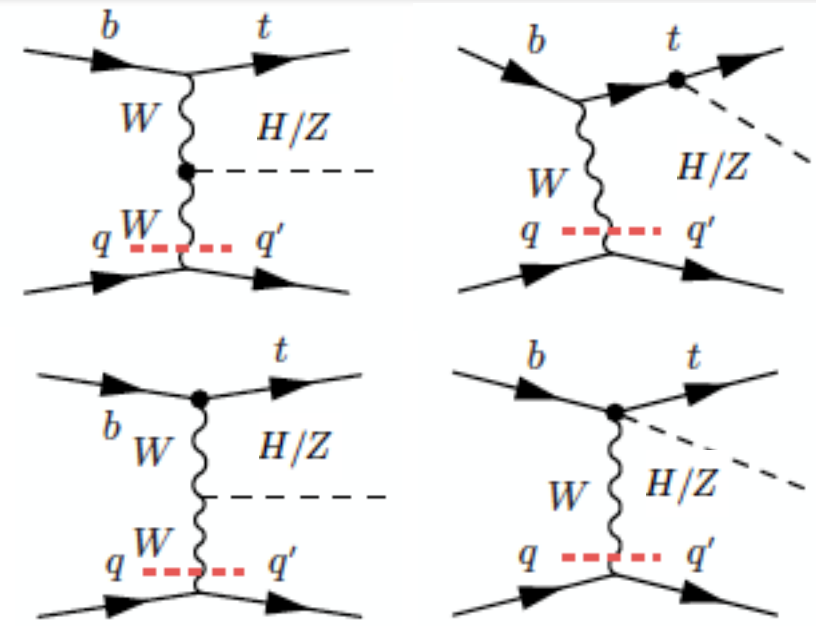
Two-fermion top-quark operators (8): $\mathcal{O}_{\varphi Q}^{(3)}, \mathcal{O}_{\varphi Q}^{(1)}, \mathcal{O}_{\varphi t}, \mathcal{O}_{tW}, \mathcal{O}_{tB}, \mathcal{O}_{tG}, \mathcal{O}_{\varphi tb}, \mathcal{O}_{t\varphi}$

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

Helicity amplitudes for subprocesses

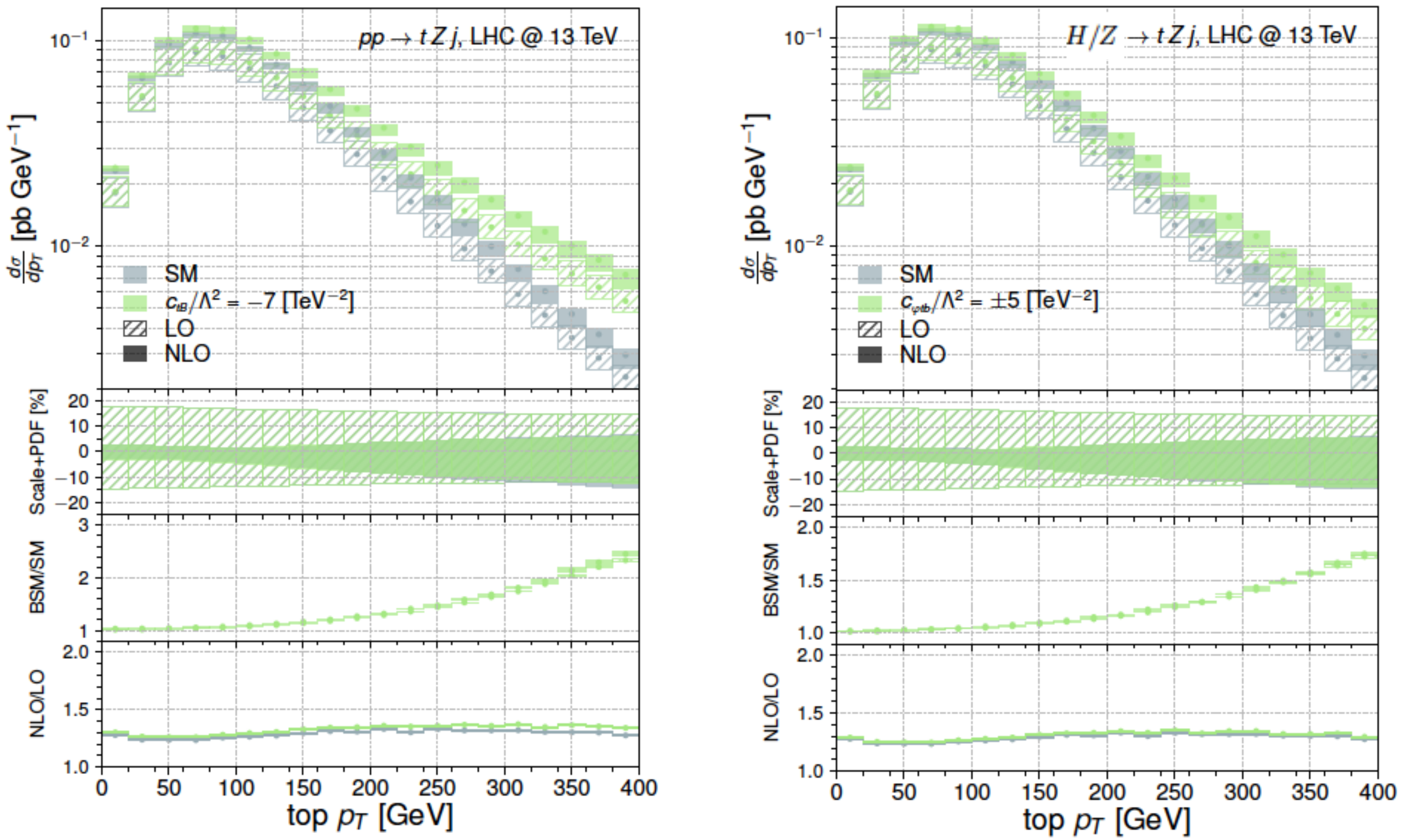
bW → tZ

$\lambda_b, \lambda_W, \lambda_t, \lambda_Z$	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

tZj



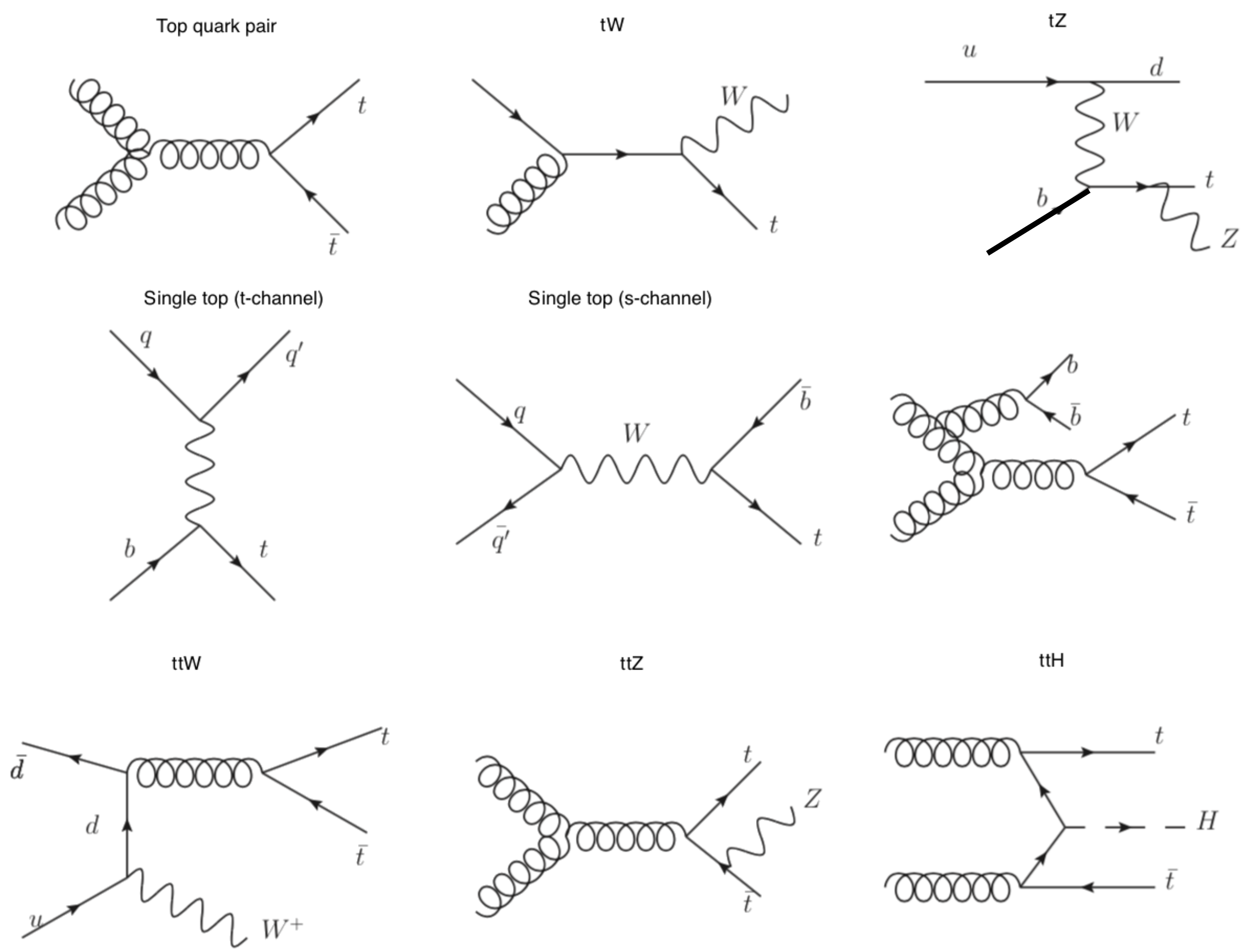
Degrande, Maltoni, Mimasu, EV, Zhang arXiv:1804.07773

Large deviations in the tails, as expected from helicity amplitudes

A first application: A global top fit

Class	Notation	Degree of Freedom	Operator Definition
	OQQ1	c^1_{QQ}	$2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$
	OQQ8	c^8_{QQ}	$8C^{3(3333)}_{qq}$
	OQt1	c^1_{Qt}	$C^{1(3333)}_{qu}$
	OQt8	c^8_{Qt}	$C^{8(3333)}_{qu}$
$QQQQ$	OQb1	c^1_{Qb}	$C^{1(3333)}_{qd}$
	OQb8	c^8_{Qb}	$C^{8(3333)}_{qd}$
	Ott1	c^1_{tt}	$C^{(3333)}_{uu}$
	Otb1	c^1_{tb}	$C^{1(3333)}_{ud}$
	Otb8	c^8_{tb}	$C^{8(3333)}_{ud}$
	OQtQb1	c^1_{QtQb}	$C^{1(3333)}_{quqd}$
	OQtQb8	c^8_{QtQb}	$C^{8(3333)}_{quqd}$
	O81qq	$c^{1,8}_{Qq}$	$C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$
	O11qq	$c^{1,1}_{Qq}$	$C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$
	O83qq	$c^{3,8}_{Qq}$	$C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$
	O13qq	$c^{3,1}_{Qq}$	$C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$
	O8qt	c^8_{tq}	$C^{8(ii33)}_{qu}$
	O1qt	c^1_{tq}	$C^{1(ii33)}_{qu}$
	O8ut	c^8_{tu}	$2C^{(i33i)}_{uu}$
$QQqq$	O1ut	c^1_{tu}	$C^{(ii33)}_{uu} + \frac{1}{3}C^{(i33i)}_{uu}$
	O8qu	c^8_{Qu}	$C^{8(33ii)}_{qu}$
	O1qu	c^1_{Qu}	$C^{1(33ii)}_{qu}$
	O8dt	c^8_{td}	$C^{8(33ii)}_{ud}$
	O1dt	c^1_{td}	$C^{1(33ii)}_{ud}$
	O8qd	c^8_{Qd}	$C^{8(33ii)}_{qd}$
	O1qd	c^1_{Qd}	$C^{1(33ii)}_{qd}$
	OtG	c_{tG}	$\mathrm{Re}\{C^{(33)}_{uG}\}$
	OtW	c_{tW}	$\mathrm{Re}\{C^{(33)}_{uW}\}$
	ObW	c_{bW}	$\mathrm{Re}\{C^{(33)}_{dW}\}$
	OtZ	c_{tZ}	$\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$
$QQ+V,G,\varphi$	Off	$c_{\varphi tb}$	$\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$
	Ofq3	$c^3_{\varphi Q}$	$C^{3(33)}_{\varphi q}$
	OpQM	$c^-_{\varphi Q}$	$C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$
	Opt	$c_{\varphi t}$	$C^{(33)}_{\varphi u}$
	Otp	$c_{t\varphi}$	$\mathrm{Re}\{C^{(33)}_{u\varphi}\}$

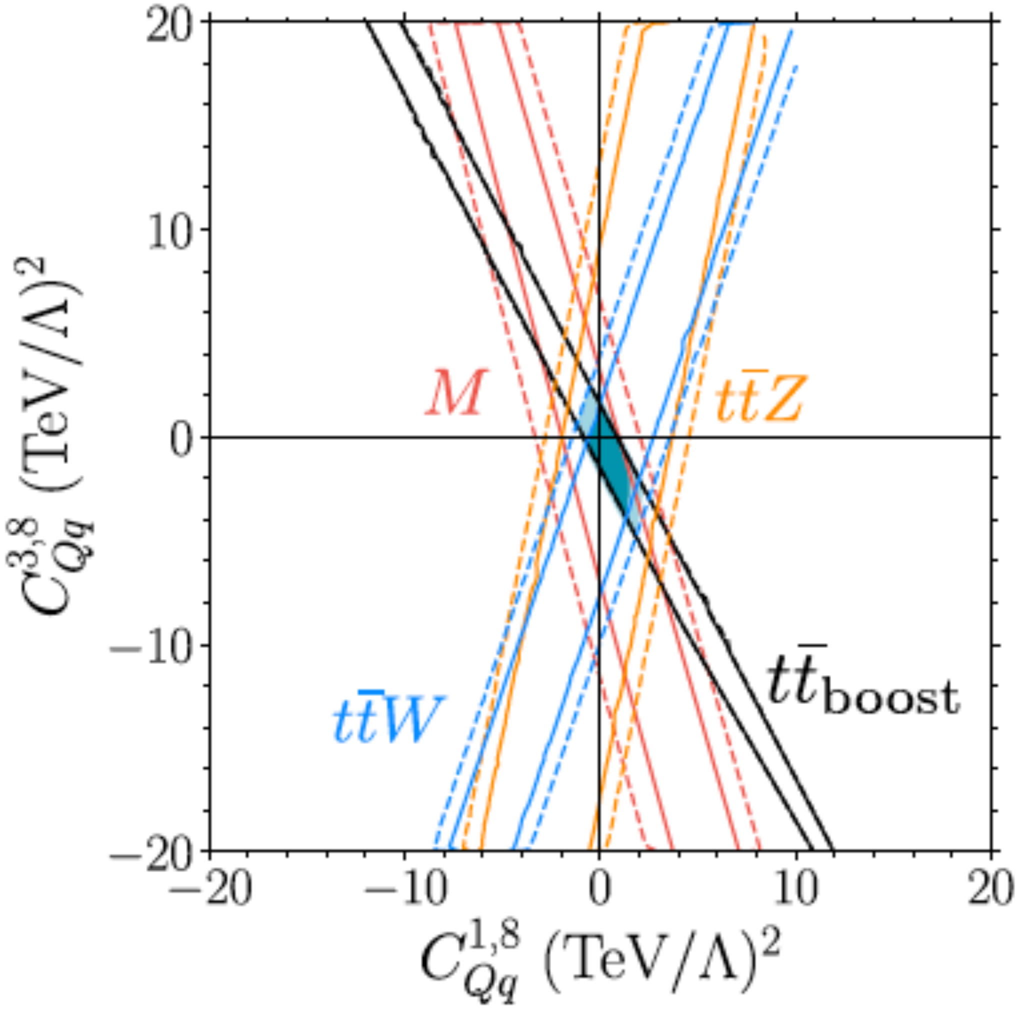
34 d.o.f.
CP-conserving

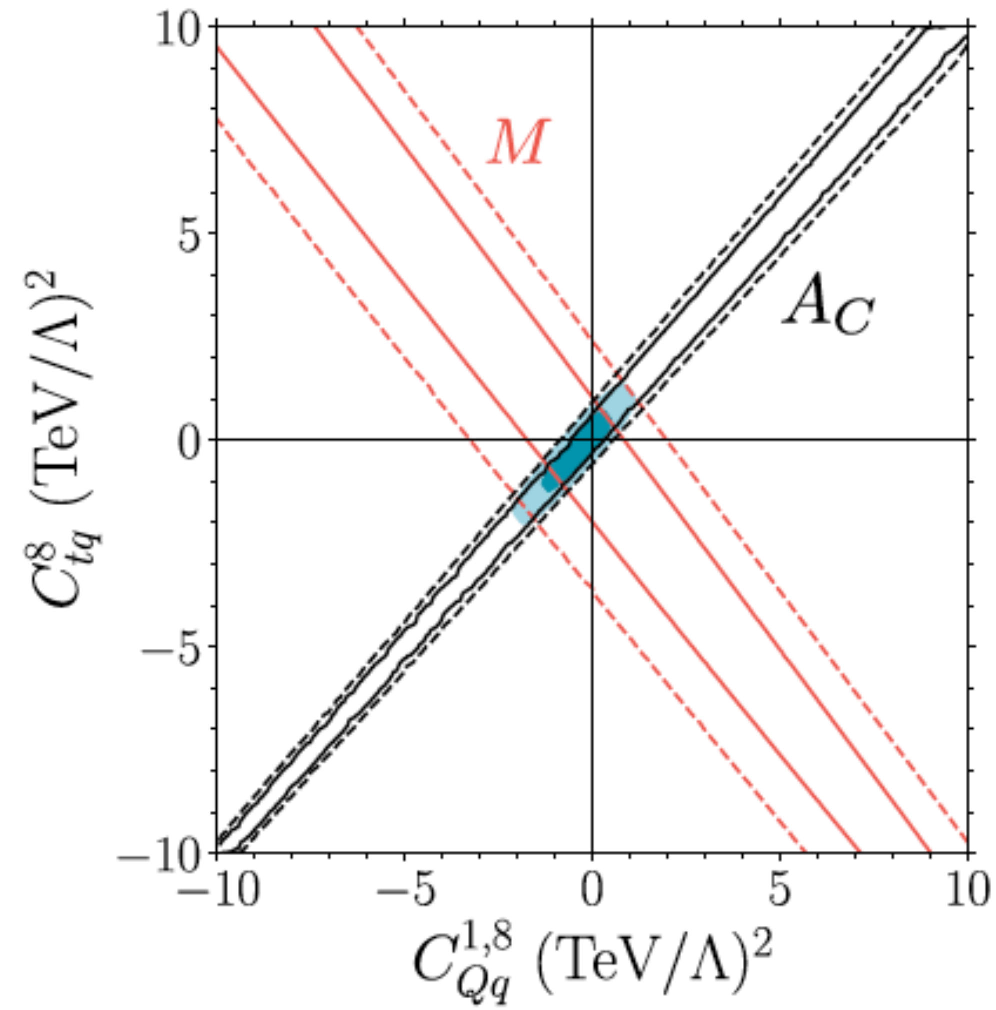


Rich phenomenology

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

The impact of multiple measurements





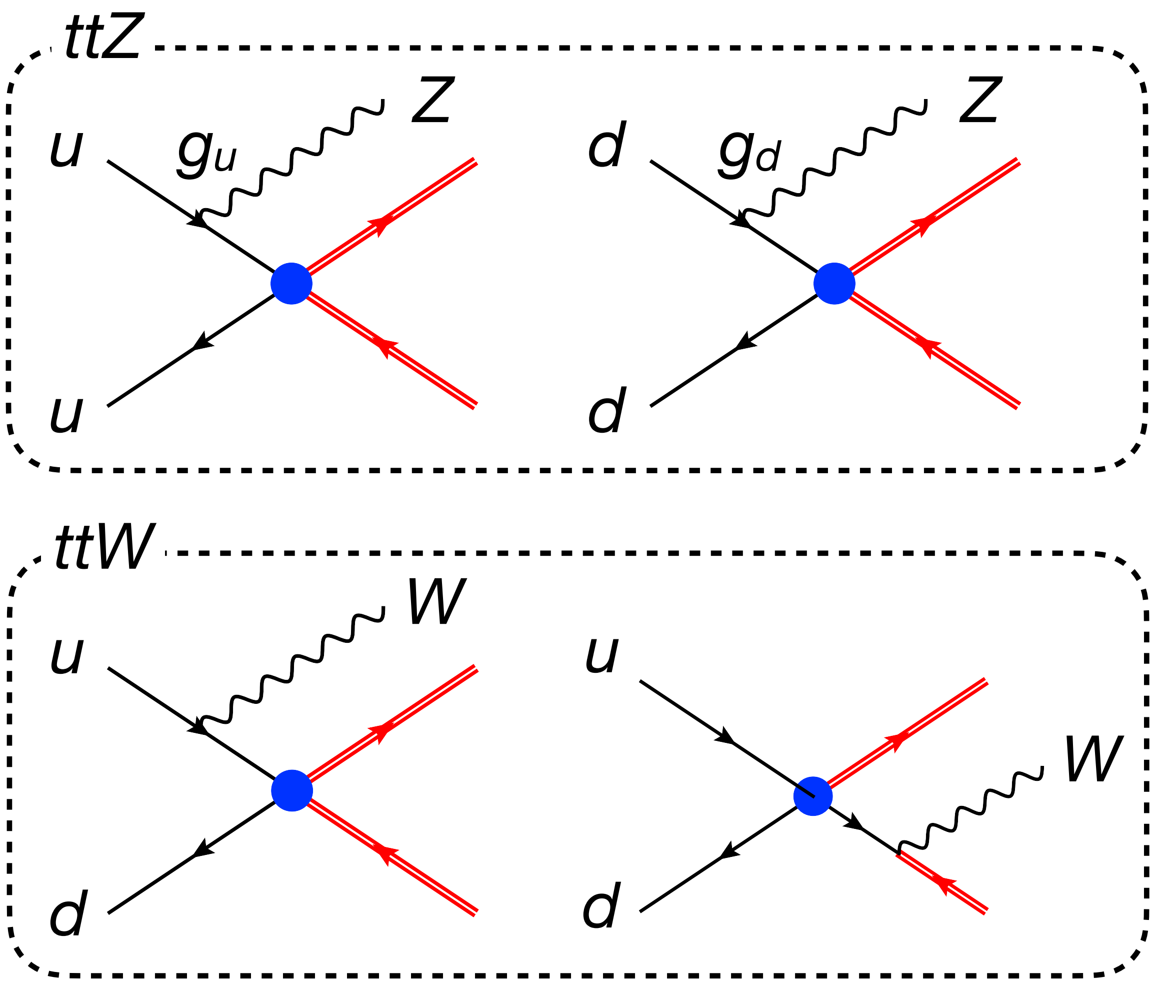
$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$
$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i)$$

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

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

The impact of multiple measurements

- Energy dependence in PDF. $r = \frac{f_u f_{\bar{u}}}{f_d f_{\bar{d}}}$
  - Total xsec: $r\,C^8_{tu} + C^8_{td} \approx 2\,C^8_{tu} + C^8_{td}$.
  - **Ratio depends on energy**. (**D**)
    E.g. boosted top => larger *r*.
- tt + weak boson
  - ttZ: if Z emits from incoming quarks, C_{tu} and C_{td} are roughly weighted by g_{uZ} and g_{dZ} couplings squared.
  - ttW: roughly $C^{1,8}_{Qq}\left(\sigma_{uu} + \sigma_{dd}\right) + C^{3,8}_{Qq}\sigma_{ud}$



Some considerations for a fit

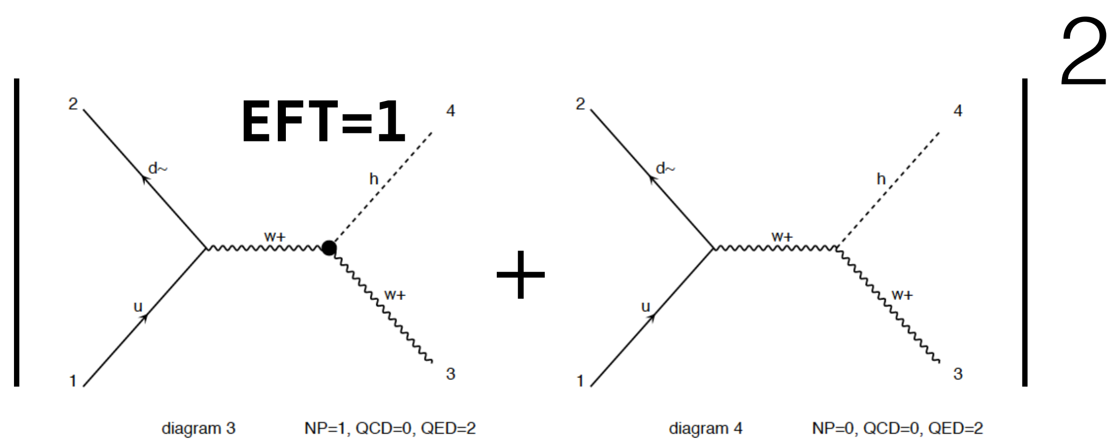
- Validity of the EFT expansion: $E<\Lambda$
  - Ensure results are not dominated by high energy regions
  - Report limits as a function of the max scale probed Contino et al arXiv:1604.06444
- Range of Wilson coefficients:
  - The theory: perturbativity, unitarity, linear or non-linear EFT, UV completion
  - 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

Some practical info



Allow one EFT insertion

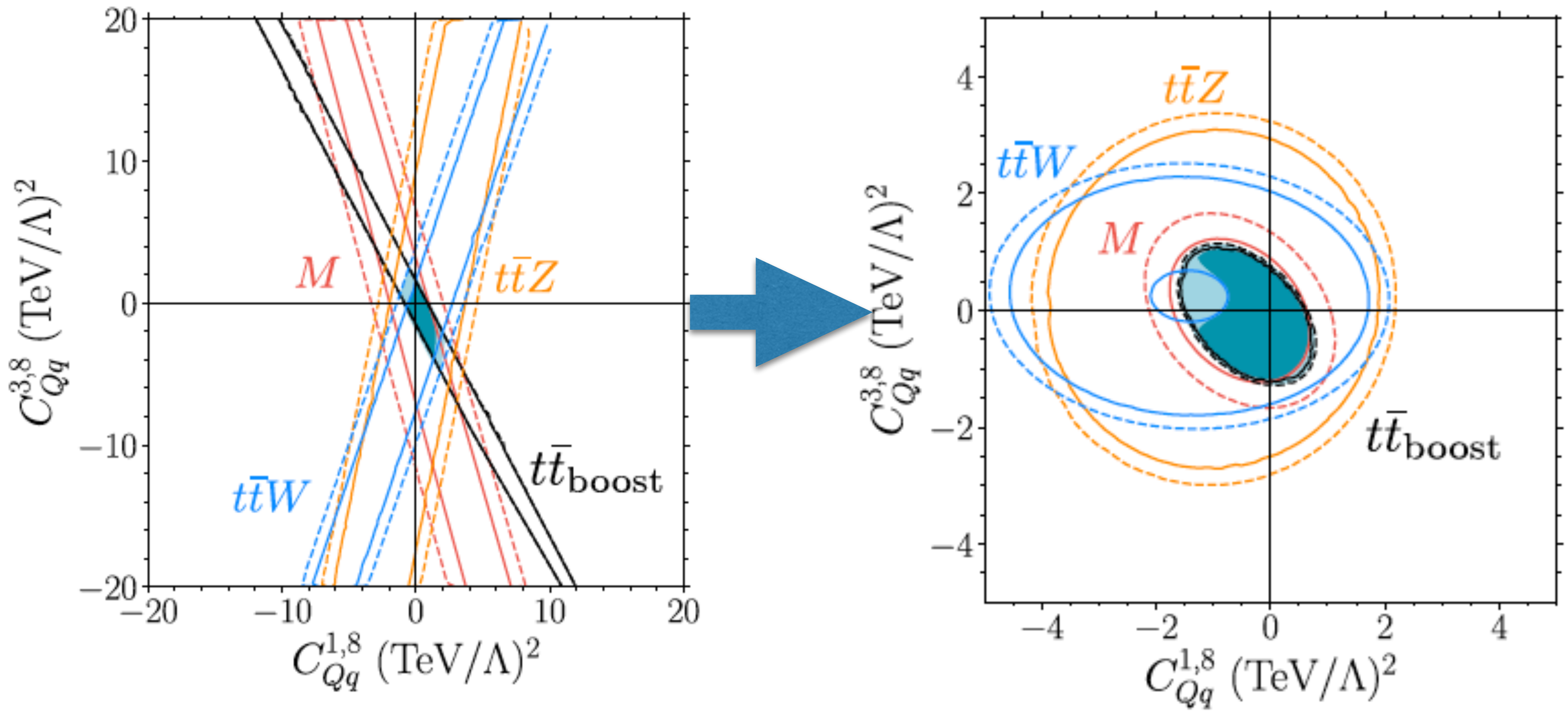
$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1{\rm TeV}^2}{\Lambda^2} C_i \sigma_i + \boxed{\sum_{i \le j} \frac{1{\rm TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}}.$$

interference with SM

interference between operators, squared contributions

Formally of dimension-8

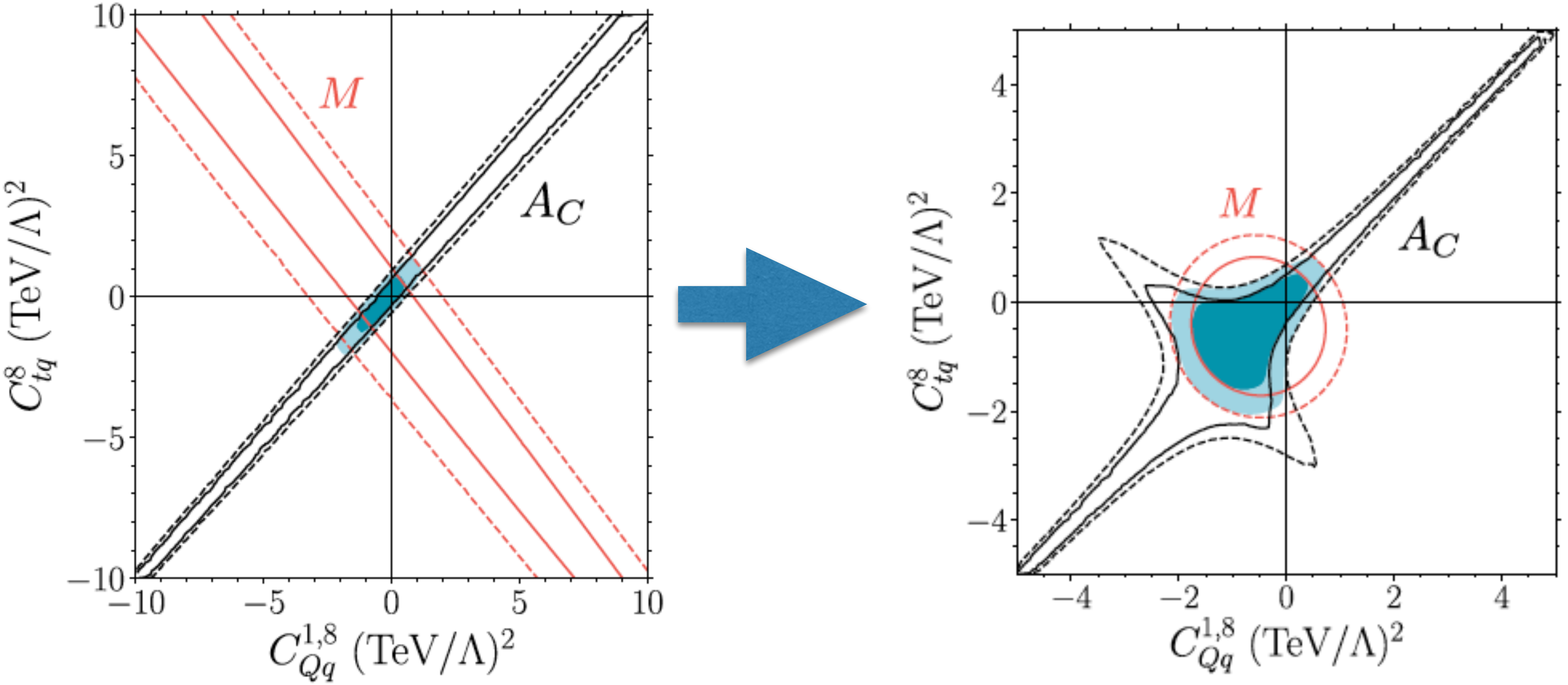
Impact of quadratic terms in top production



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

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

Theory

(N)NLO QCD for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions
Parton-level

Global SMEFT fit of the top-quark sector

Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Methodology

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added

Output

Global fit Setup

Theory

(N)NLO QCD for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions
Parton-level

Global S
of the top-q

Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Methodology

ATLAS overview 科大东区物质科研楼3楼报告厅 and Zoom online	*Lailin XU*	14:45 - 15:15
Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory 科大东区物质科研楼3楼报告厅 and Zoom online	*Maeve MADIGAN*	15:15 - 15:40
SMEFiT results 科大东区物质科研楼3楼报告厅 and Zoom online	*Luca MANTANI*	15:40 - 16:05
Break 科大东区物质科研楼3楼报告厅 and Zoom online		16:05 - 16:25
SMEFT analysis of vector boson scattering and diboson data from the LHC Run II 科大东区物质科研楼3楼报告厅 and Zoom online	*Giacomo MAGNI*	16:25 - 16:50
Parton distributions in the SMEFT from high-energy Drell-Yan tails 科大东区物质科研楼3楼报告厅 and Zoom online	*Cameron VOISEY*	16:50 - 17:15
A fully differential SMEFT analysis of the golden channel using the method of moments	*Elena VENTURINI*	
Parametrized classifiers for optimal EFT sensitivity 科大东区物质科研楼3楼报告厅 and Zoom online	*Alfredo GLIOTI*	17:40 - 18:05

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

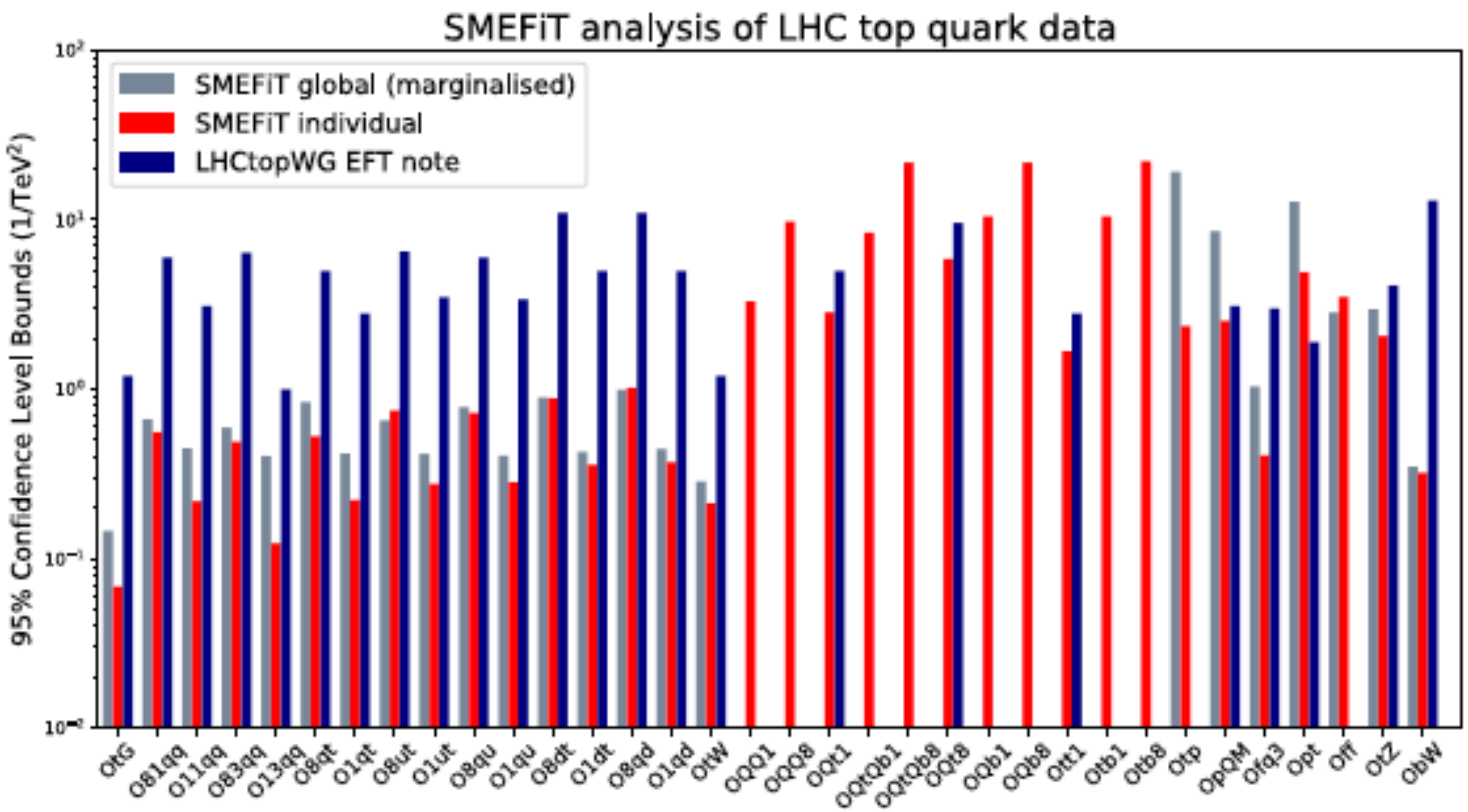
Theoretical predictions

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)

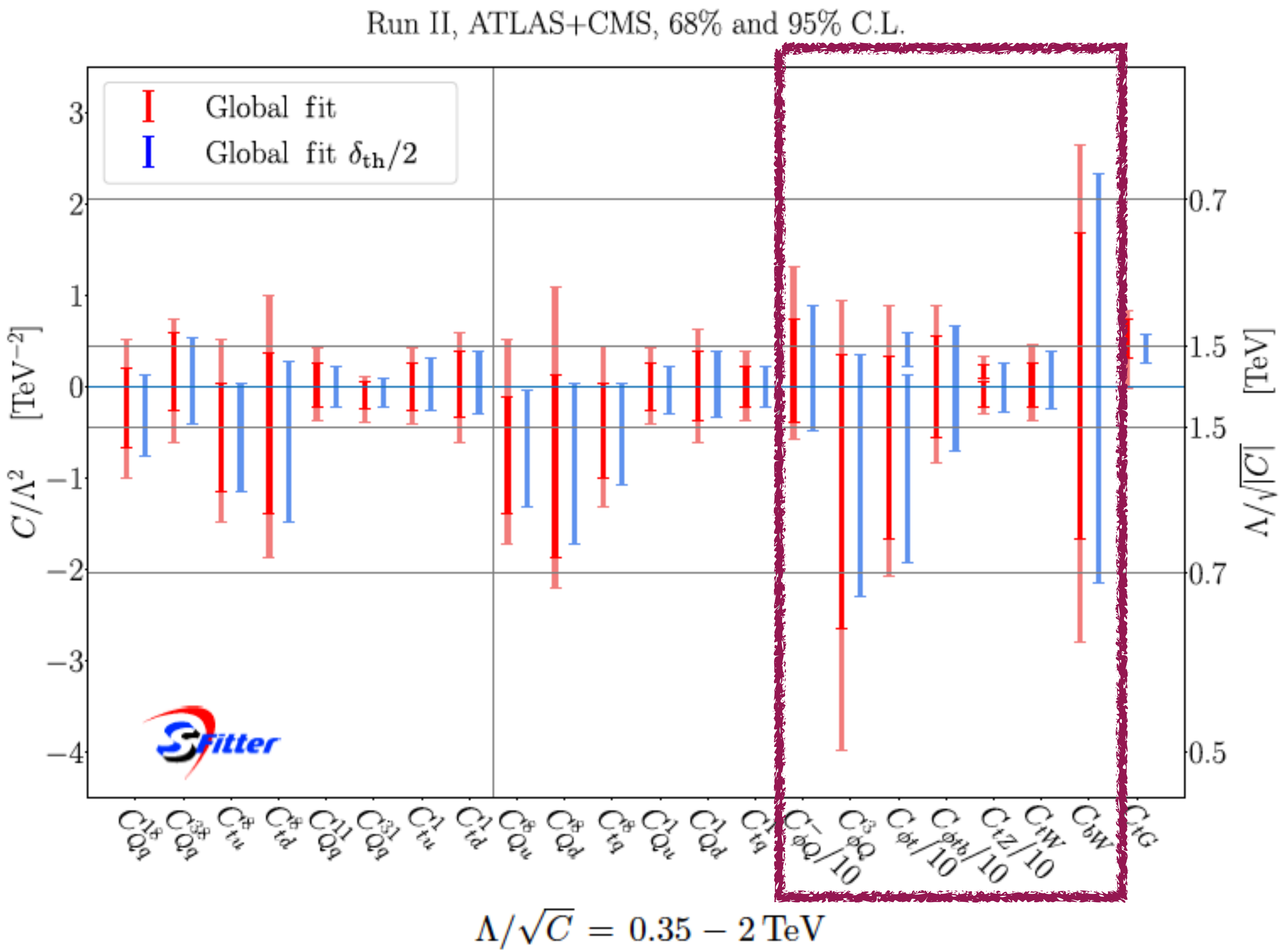


First limits reported for some operators

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)



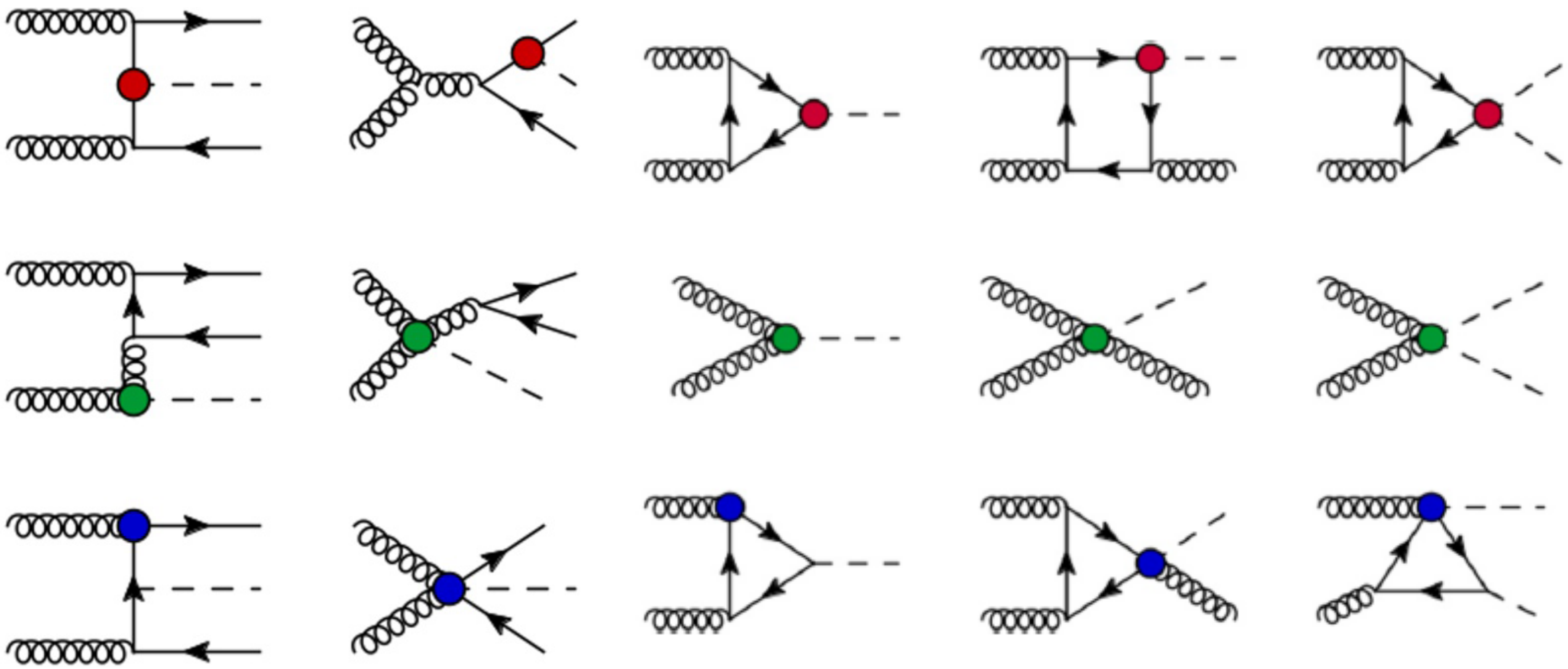
Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606 (SFitter analysis)

Connection to Higgs physics

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

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

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



ttH

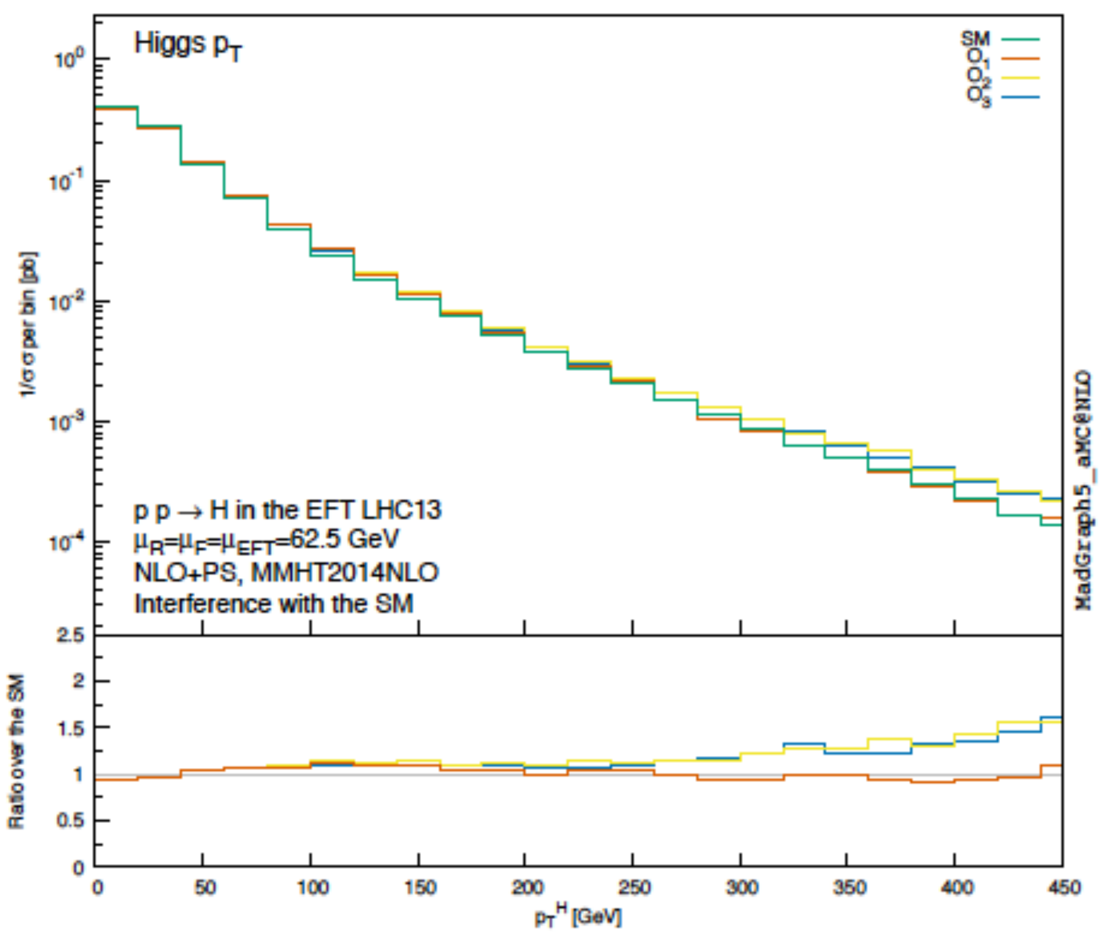
H, H+j, HH

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

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

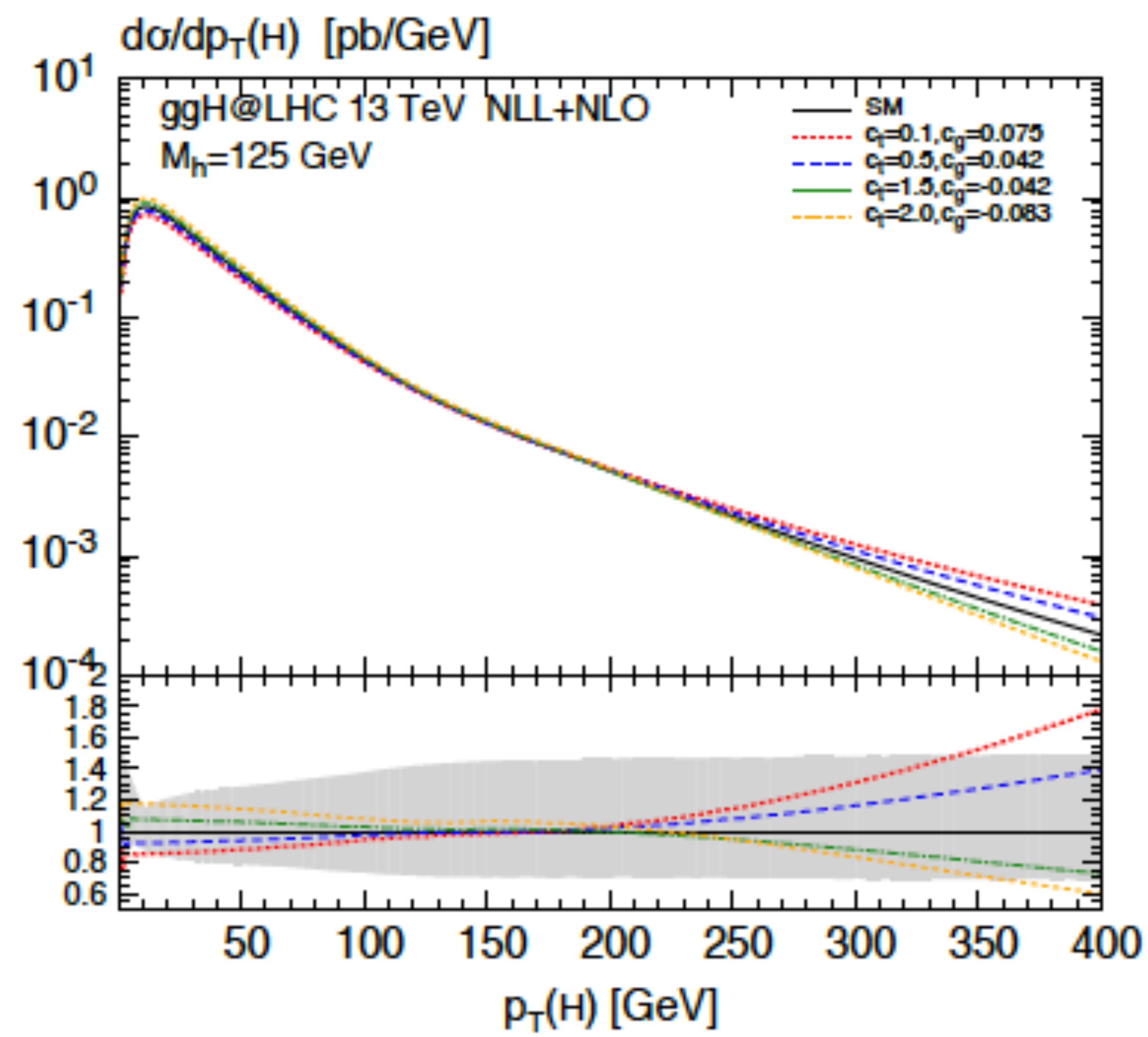
Maltoni, EV, Zhang: arXiv:1607.05330

SMEFT in Higgs production



Higgs p_T

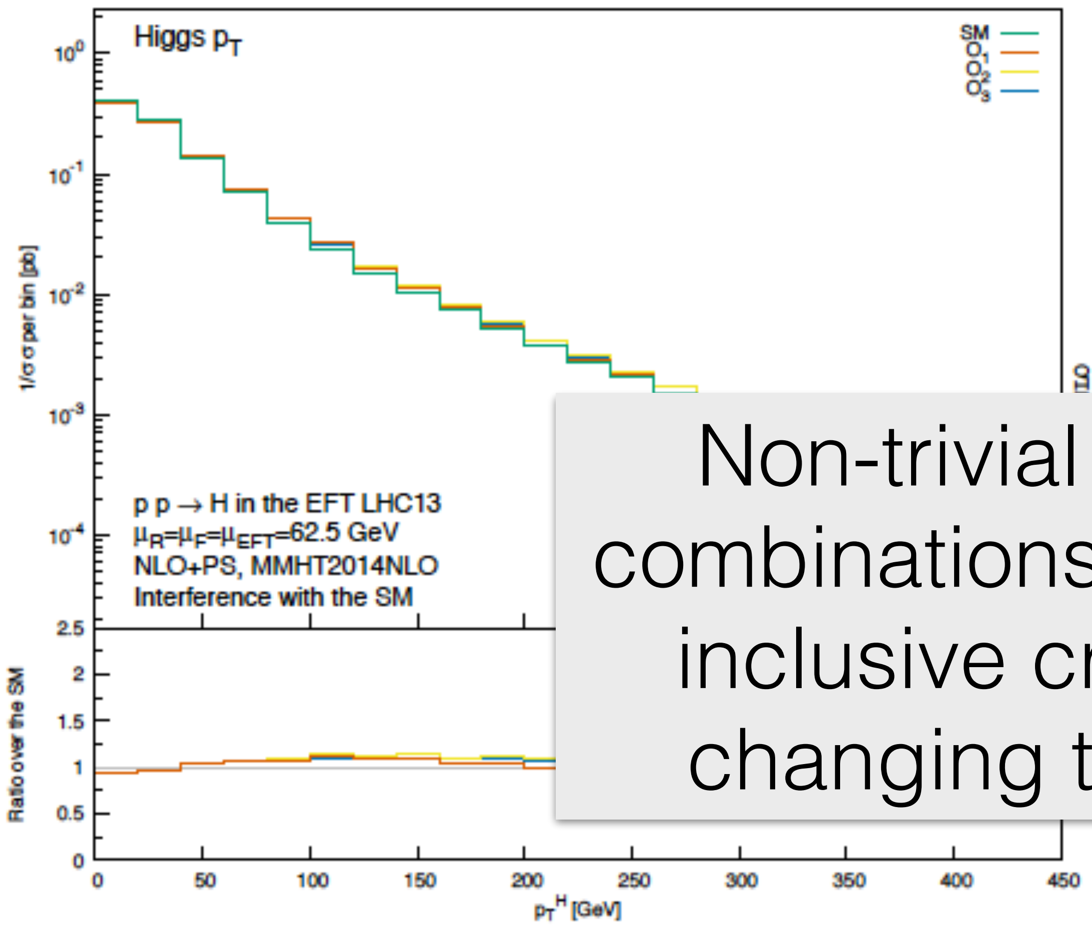
Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

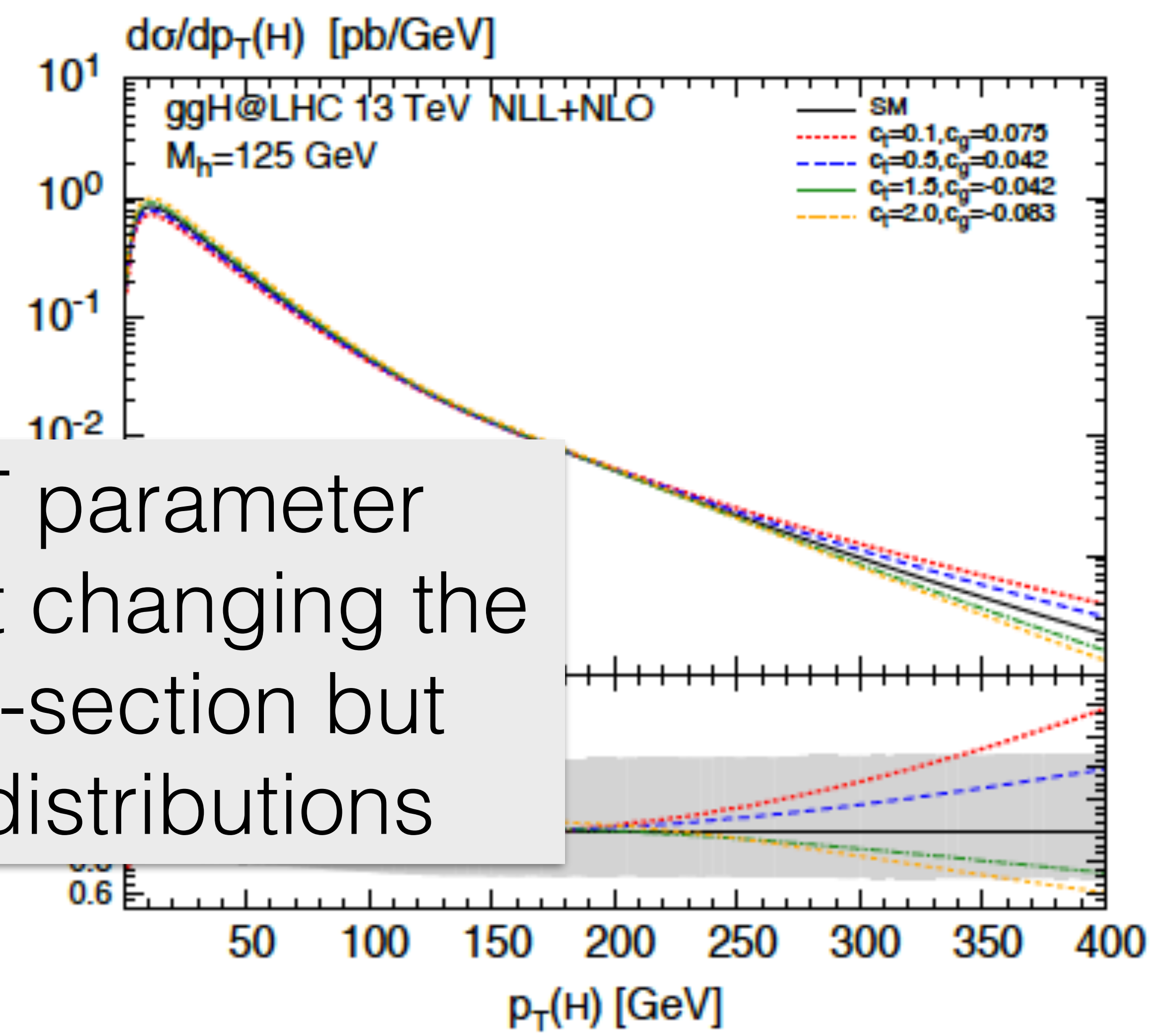


Higgs p_T

Grazzini et al 1612.00283

SMEFT in Higgs production





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

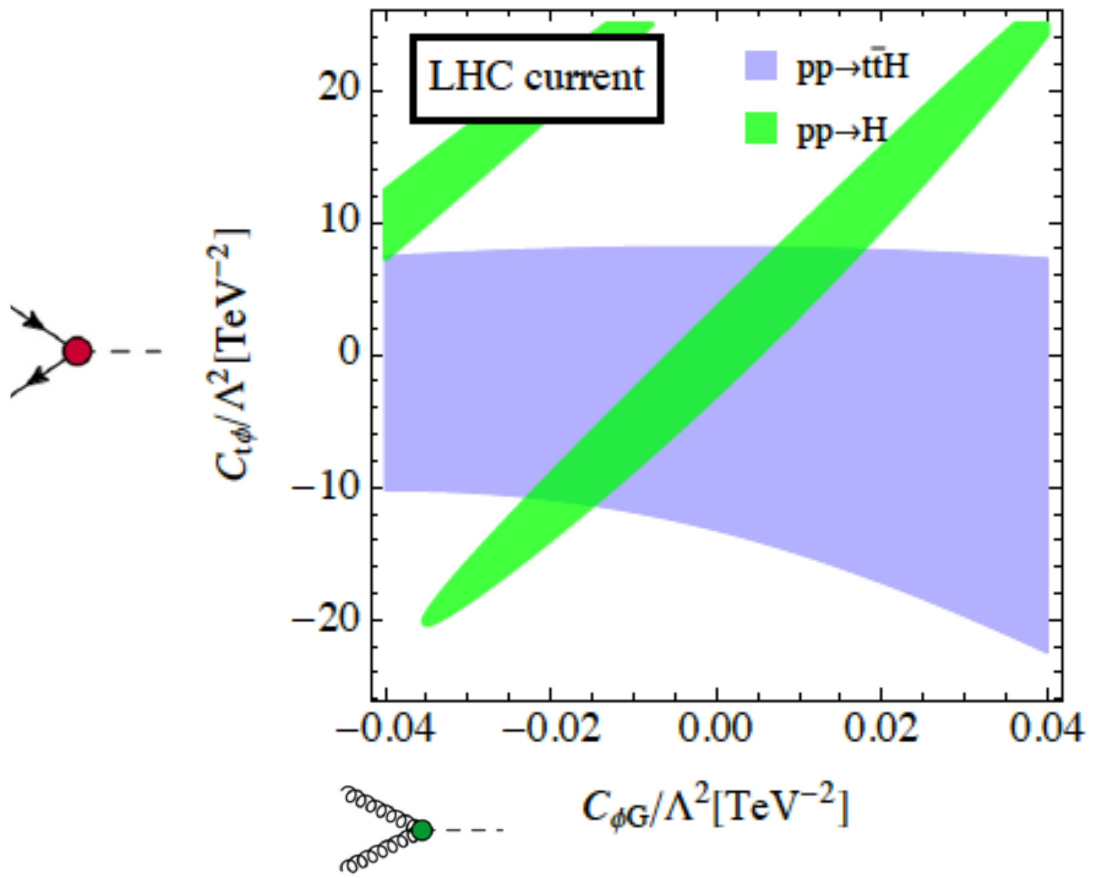
Higgs p_T

Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

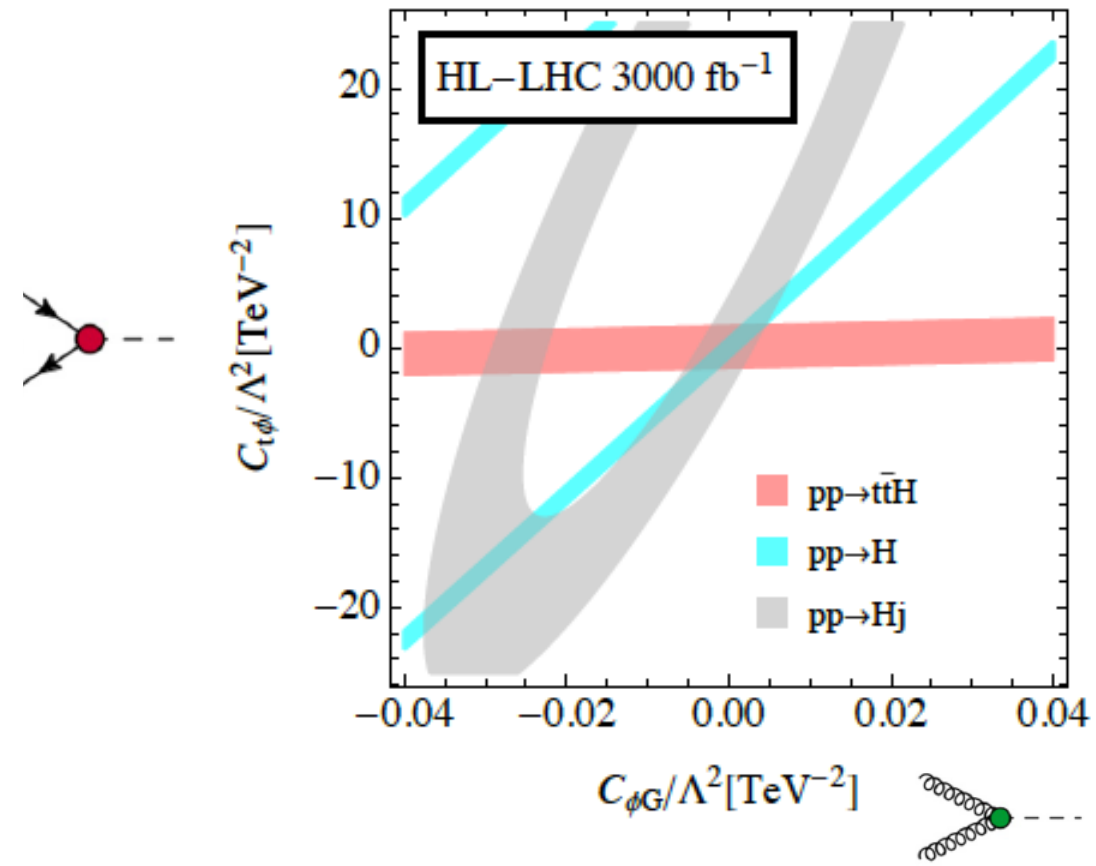
Higgs p_T

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

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

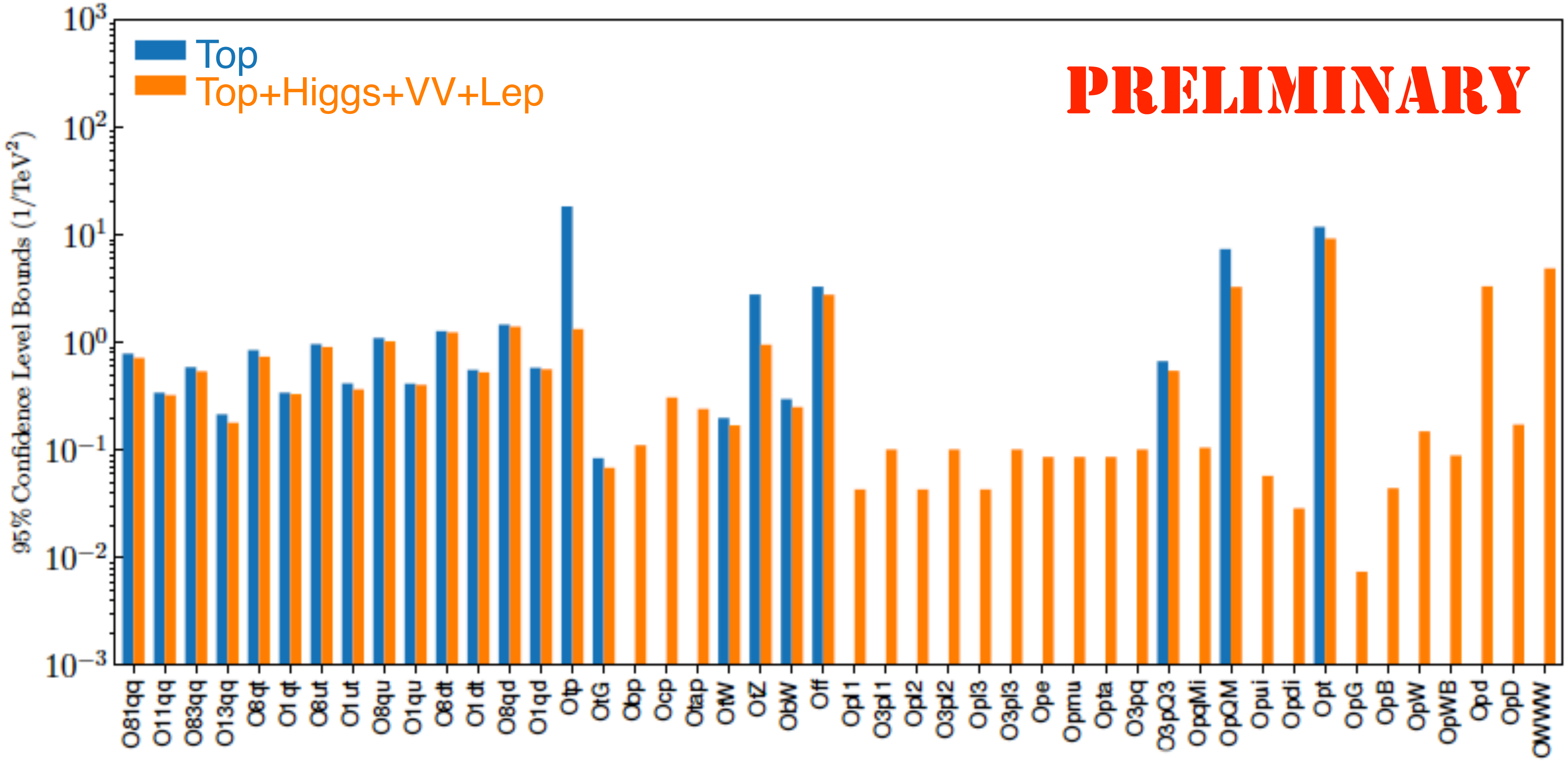
Bosonic					
$\mathcal{O}_{\phi G}$	OpG	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)G_A^{\mu\nu}\,G^A_{\mu\nu}$	$\mathcal{O}_{\phi B}$	OpB	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)B^{\mu\nu}\,B_{\mu\nu}$
$\mathcal{O}_{\phi W}$	OpW	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)W_I^{\mu\nu}\,W^I_{\mu\nu}$	$\mathcal{O}_{\phi WB}$	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

Towards a global Higgs & Top fit



New operators

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

Impact of various datasets

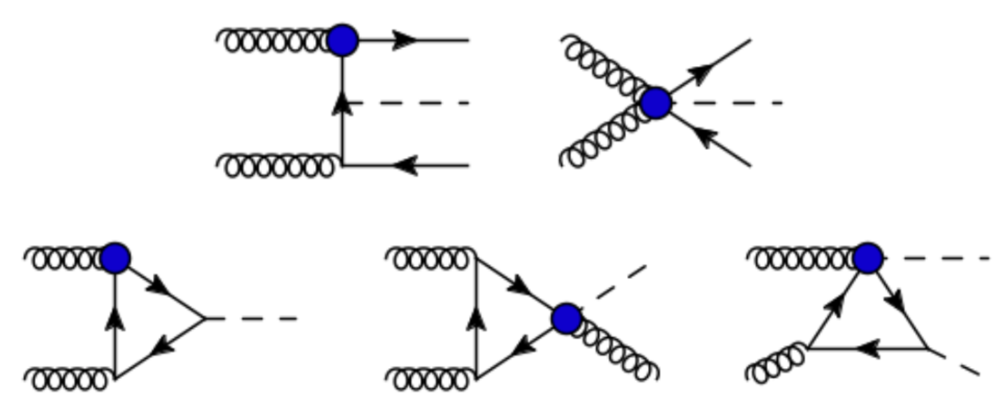
PRELIMINARY

Class	Coefficient	Processes											
		Mtt	Ytt(Mtt)	Whel	ttZ_tot	ttZ_pTZ	ttW_tot	t_tot	Yt	tttt	ttbb	tZ	tW
2FB	ctp	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)
	ctG	45.0(46.8)	13.3(13.6)	0.0(0.0)	0.3(0.3)	0.3(0.4)	0.1(0.1)	×(×)	×(×)	0.1(0.1)	0.2(0.2)	×(×)	×(×)
	cbp	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)
	ccp	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)
	ctap	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)	×(×)
	ctW	×(×)	×(×)	7.5(0.5)	0.0(0.0)	×(×)	0.0(-0.0)	0.2(0.0)	0.7(0.0)	×(×)	×(×)	0.0(0.0)	0.1(0.0)
	ctZ	×(×)	×(×)	×(×)	0.0(0.0)	0.0(0.0)	×(×)	×(×)	×(×)	×(×)	×(×)	0.0(-0.0)	×(×)
	c3pQ3	×(×)	×(×)	×(0.0)	0.0(0.0)	0.0(-0.0)	0.0(-0.0)	2.9(1.5)	89.0(44.8)	×(×)	×(×)	3.8(1.9)	2.1(1.1)
	cpQM	×(×)	×(×)	×(×)	26.2(0.2)	28.1(0.2)	×(×)	×(×)	×(×)	×(×)	×(×)	1.6(0.0)	×(×)
	cpt	×(×)	×(×)	×(×)	34.7(0.1)	44.7(0.1)	×(×)	×(×)	×(×)	×(×)	×(×)	0.4(0.0)	×(×)

Higgs

Class	Coefficient	Processes					
		Hrun1	Hrun2	Hdiff	WW	WZ	LEP_WW
2FB	ctp	15.3(18.2)	65.8(81.8)	19.0(0.0)	×(×)	×(×)	×(×)
	ctG	6.4(6.0)	27.7(25.9)	6.6(6.6)	×(×)	×(×)	×(×)
	cbp	20.6(21.2)	79.4(78.8)	×(×)	×(×)	×(×)	×(×)
	ccp	21.0(12.4)	79.0(87.6)	×(×)	×(×)	×(×)	×(×)
	ctap	38.6(37.0)	61.4(63.0)	×(×)	×(×)	×(×)	×(×)
	ctW	15.7(17.0)	75.8(82.4)	×(×)	×(×)	×(×)	×(×)
	ctZ	17.1(17.2)	82.8(82.8)	×(×)	×(×)	×(×)	×(×)
	c3pQ3	0.2(7.9)	1.2(41.7)	0.8(1.2)	×(×)	×(×)	×(×)
	cpQM	4.8(17.2)	23.0(78.6)	16.3(3.9)	×(×)	×(×)	×(×)
	cpt	2.5(20.0)	12.2(79.8)	5.5(0.0)	×(×)	×(×)	×(×)

OtG enters: ttH, H, Hj, HH,…



Ethier, Maltoni, Mantani, Nocera, Rojo, EV and Zhang in preparation
See also Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779 for a recent global fit

What's next?

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

Aspects of EFT predictions

* Higher Orders in $1/\Lambda^4$
  * squared dim-6 contributions
  * double insertions of dim-6
  * dim-8 contributions
* Higher Orders in QCD and EW
  * EFT is a QFT, renormalisable order-by-order in $1/\Lambda^2$

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

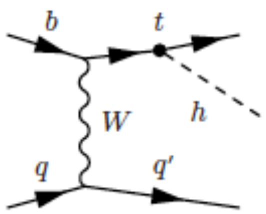
Why bother with higher orders?

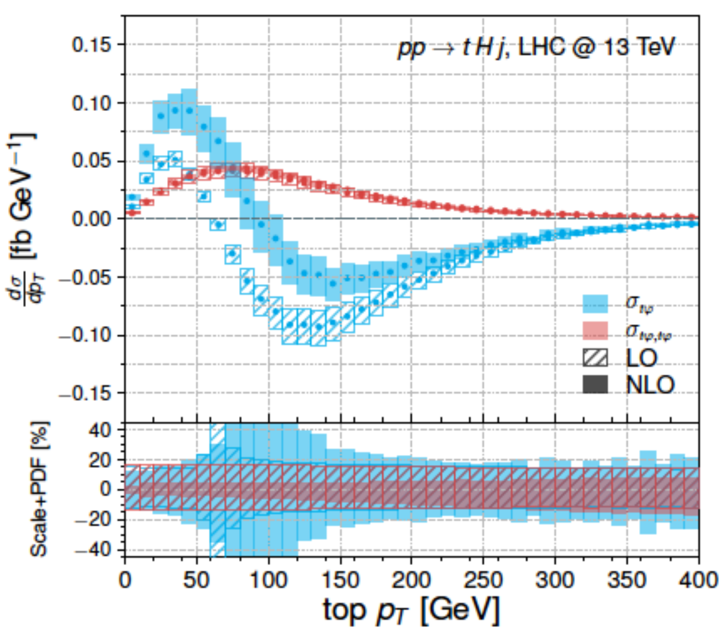
Higher orders in SMEFT bring:

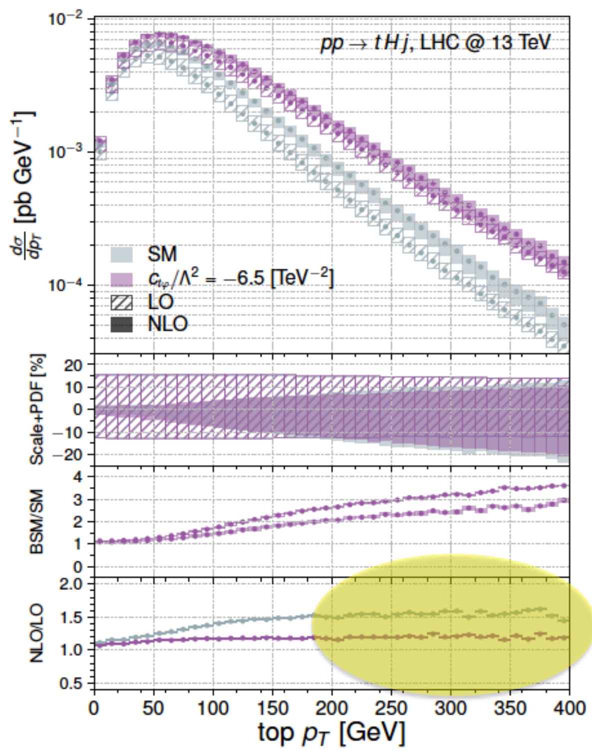
* Accuracy
* Precision
* Improved sensitivity
  * Accurate knowledge of the deviations (distribution shapes, correlations between observables, etc.) can be the key to disentangle them from the SM.
  * Loop-induced new sensitivity: operators entering at one-loop

Accuracy and precision

tHj







Different shapes at NLO

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

ttH

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

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

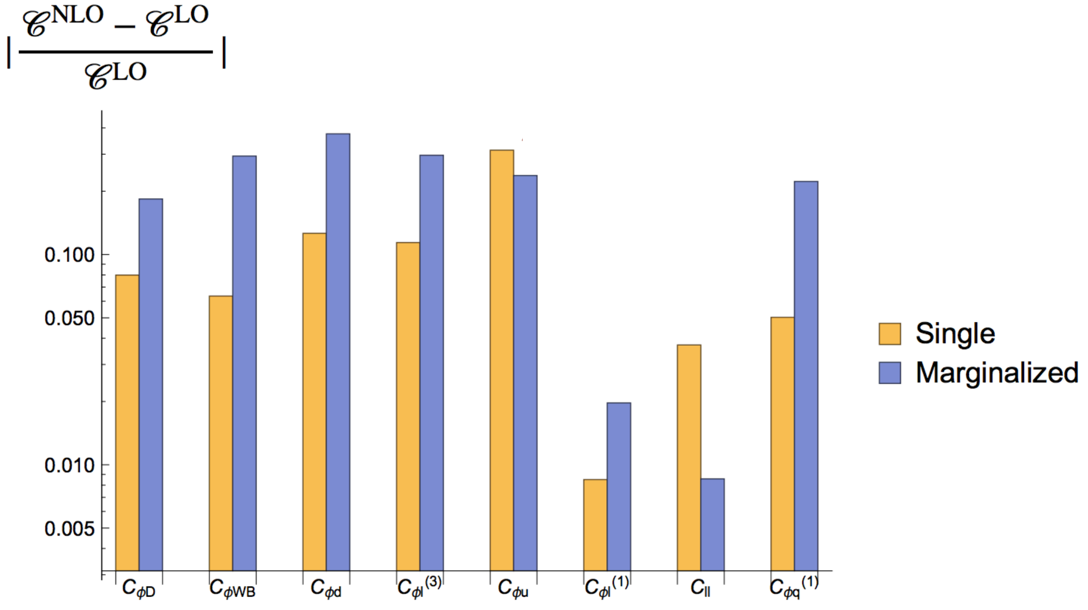
Different K-factors for different operators, different from the SM

Maltoni, EV, Zhang arXiv:1607.05330

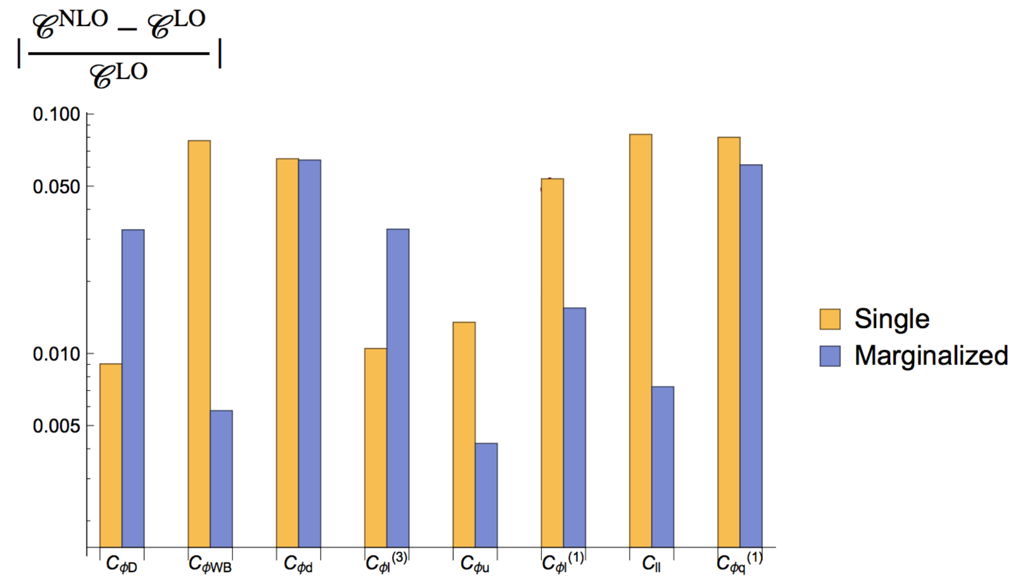
Accuracy and precision

Impact of NLO corrections on W, Z pole observables:

LEP



ILC GigaZ [arXiv:1908.11299]



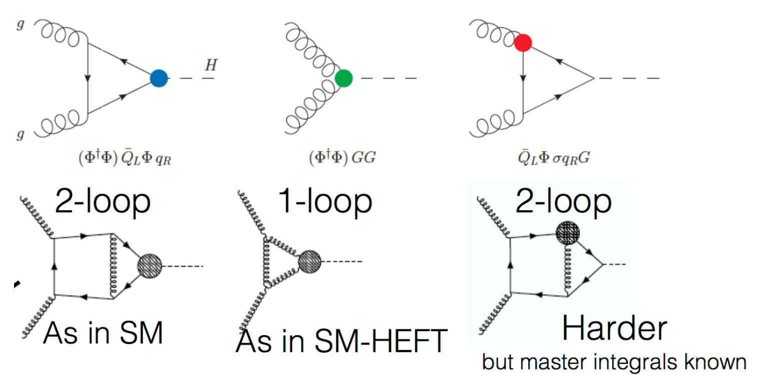
Dawson and Giardino arXiv:1909.02000 & Giardino@HEFT2020

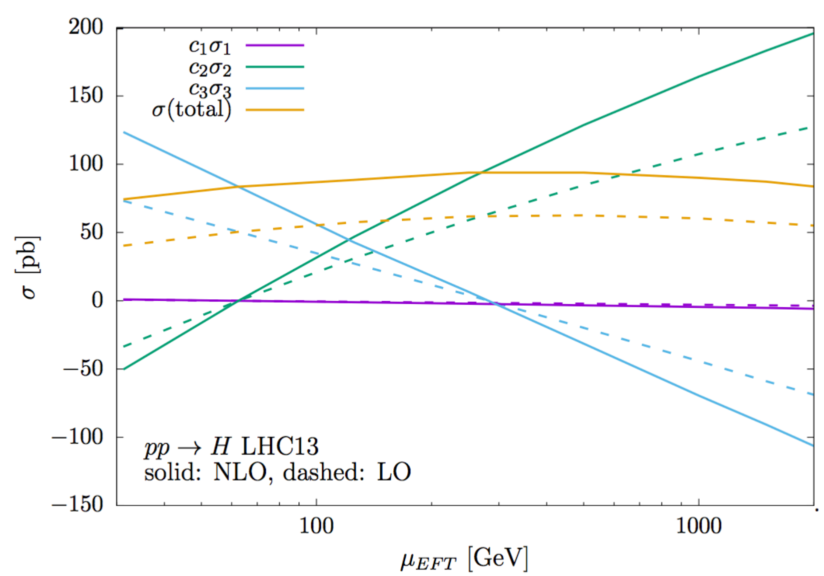
Even EW corrections lead to ~20% difference

Accuracy and precision

Scale Uncertainties:

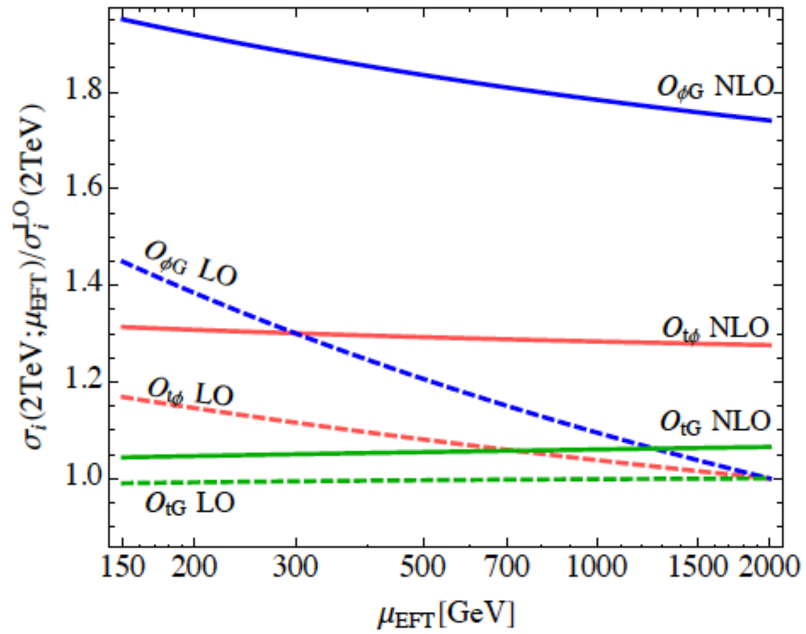
ggH





Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

ttH



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

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

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

Maltoni, EV, Zhang arXiv:1607.05330

Improved sensitivity

4-heavy operators in top pair production

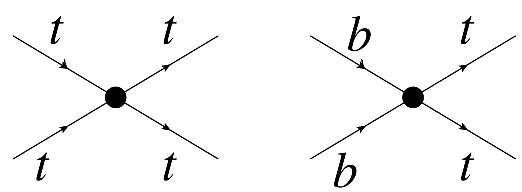
$\mathcal{O}^8_{QQ} = (\bar{Q}\gamma^\mu T^A Q)(\bar{Q}\gamma_\mu T^A Q)$

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

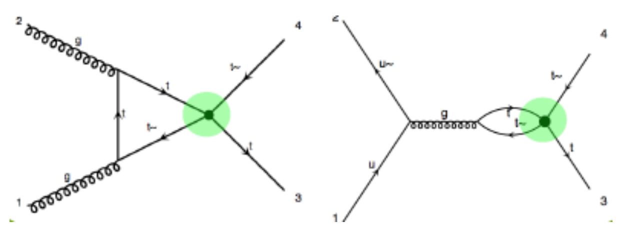
$\mathcal{O}^8_{Qt} = (\bar{Q}\gamma^\mu T^A Q)(\bar{t}\gamma_\mu T^A t)$

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

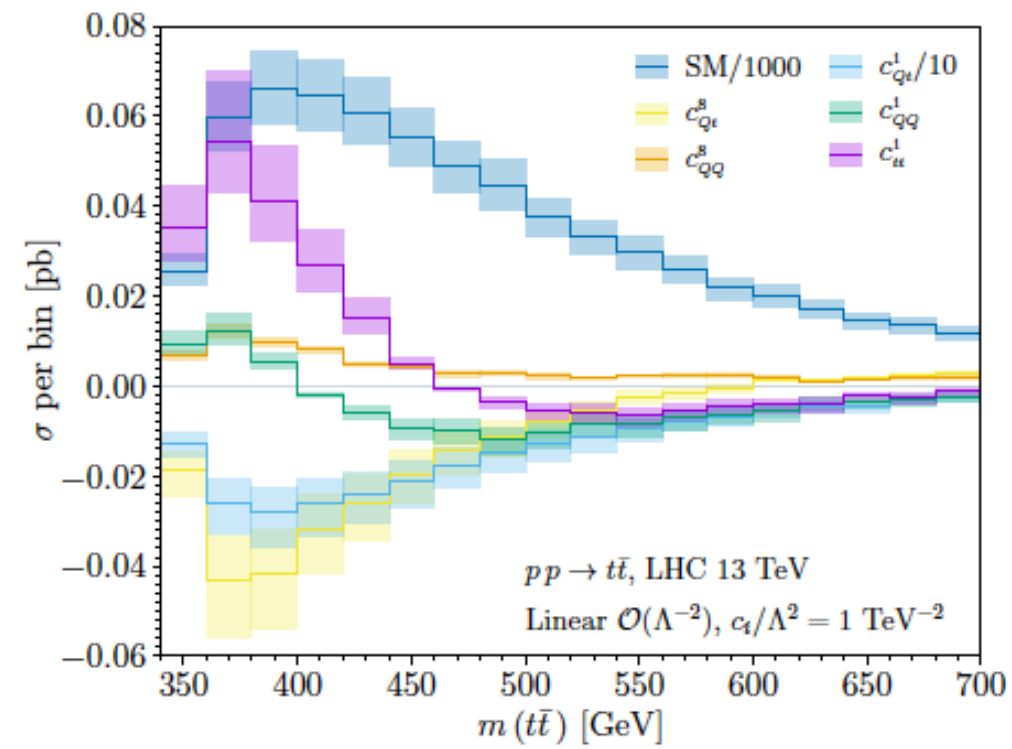
$\mathcal{O}^1_{tt} = (\bar{t}\gamma^\mu t)(\bar{t}\gamma_\mu t)$



At NLO:



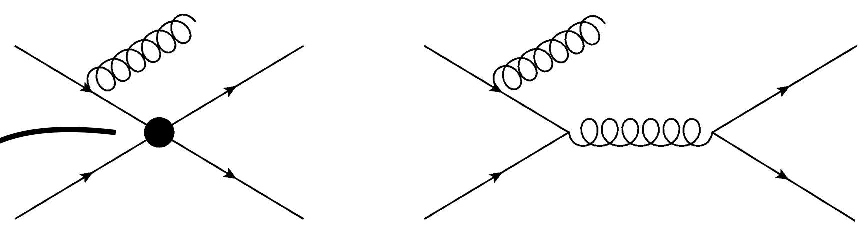
c^8_{QQ} c^8_{Qt}	$0.0586^{+27\%}_{-25\%}$ $0.0583^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$ $-0.107(6)^{+40\%}_{-33\%}$		$0.00628^{+13\%}_{-16\%}$ $0.00619^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$ $0.0118^{+8\%}_{-5\%}$
c^1_{QQ} c^1_{Qt}	$[-0.11^{+15\%}_{-18\%}]$ $[-0.068^{+16\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$ $-2.51^{+29\%}_{-21\%}$	$[-0.12^{+7\%}_{-5\%}]$ $[-0.12^{+3\%}_{-6\%}]$	$0.0282^{+13\%}_{-16\%}$ $0.0283^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$ $0.066^{+5\%}_{-6\%}$
c^1_{tt}	×	$0.215^{+23\%}_{-18\%}$		×	×



Complimentary information to ttbb and 4top production

Improved sensitivity

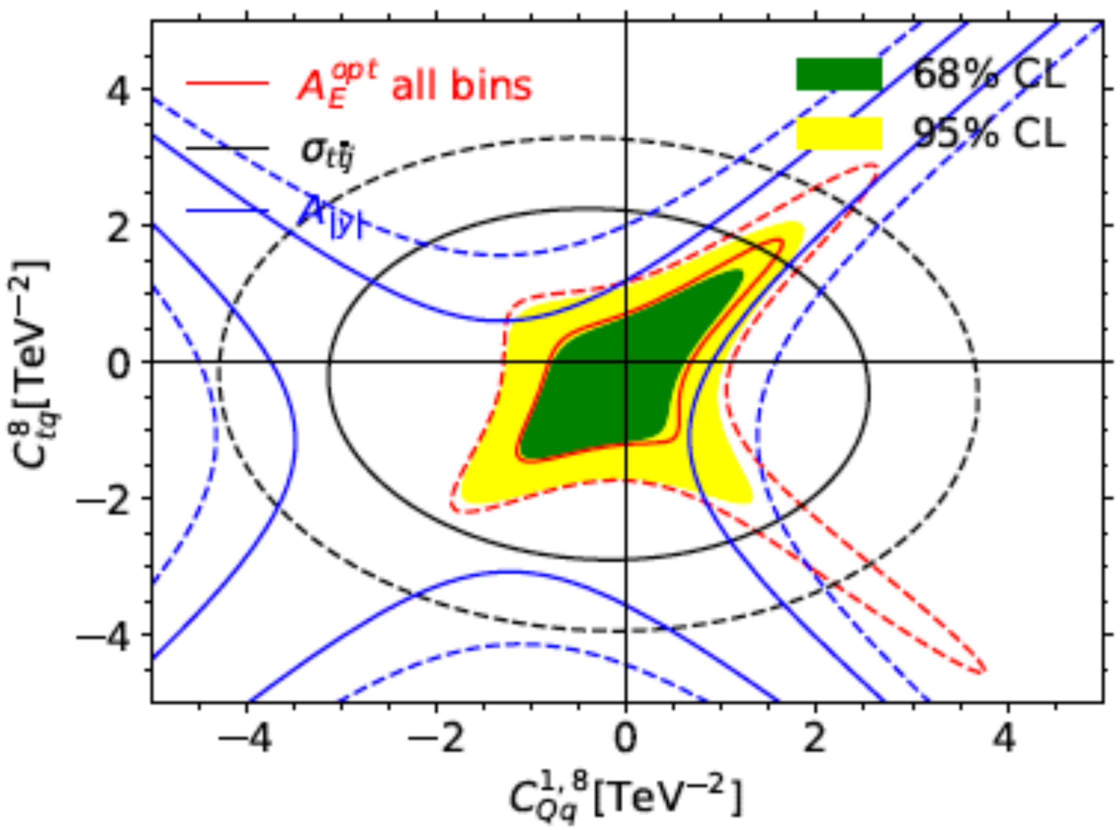
New observables to break degeneracies



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

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

Different top chiralities



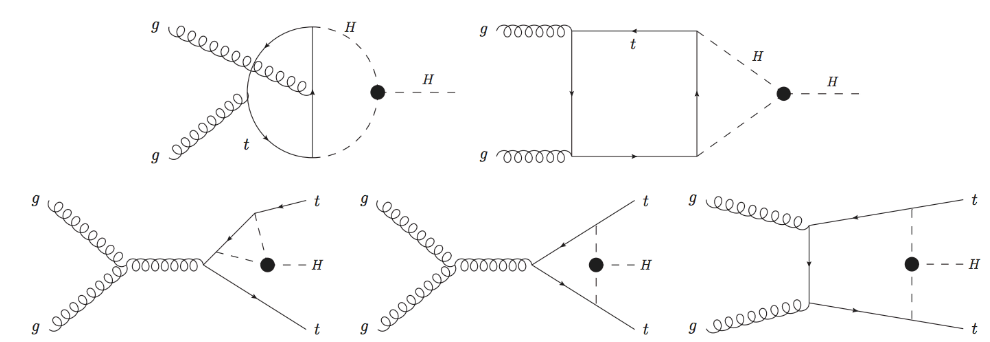
An asymmetry observable

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

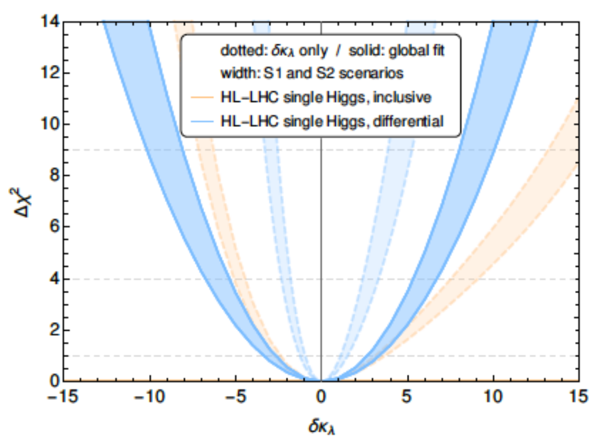
Basan, Berta, Masetti, EV, Westhoff arXiv:2001.07225

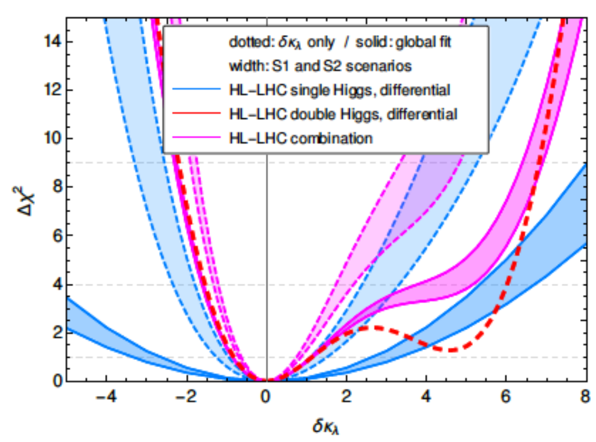
Loop-induced sensitivity (1)

- Sensitivity through 1-loop EW corrections to single Higgs production.
- A new opportunity to extract information, beyond the typical probe of HH production.

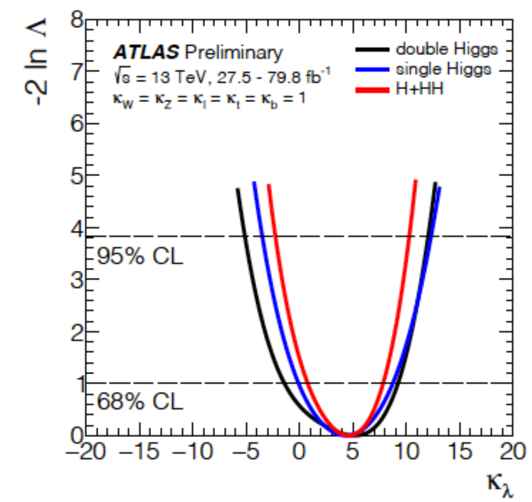


Degrassi et al. arXiv:1607.04251, Gorbahn, Haisch 1607.03773, Bizon et al 1610.05771, Maltoni et al 1709.08649



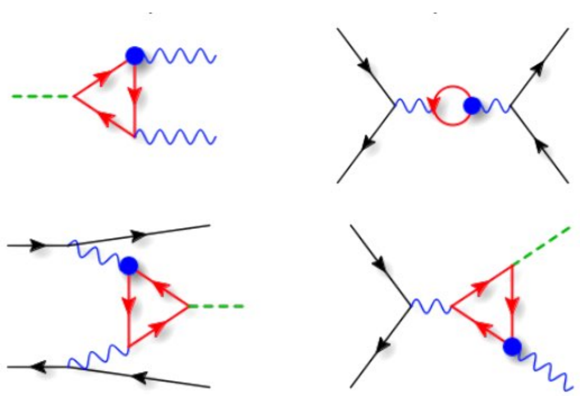


Di Vita et al. arXiv:1704.01953 and HH white paper



ATLAS-CONF-2019-049

Loop-induced sensitivity (2)



+

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

\+ **Relatively loose constraints from top LHC measurements (tZ, ttZ, tj, …)**

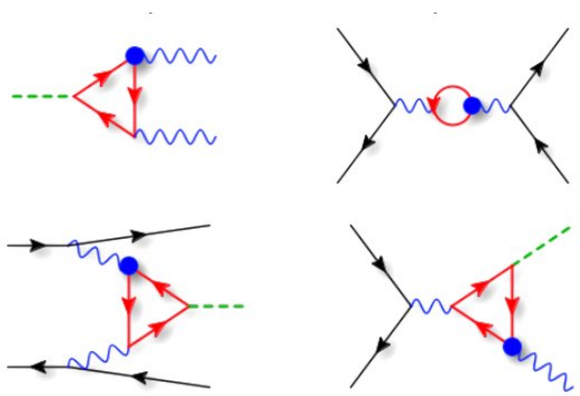
	$\gamma\gamma$	γZ	bb	WW*	ZZ*
gg	(-100%,1980%)	(-88%,200%)	(-40%,48%)	(-40%,47%)	(-40%,46%)
VBF	(-100%,1880%)	(-88%,170%)	(-6.1%,5.3%)	(-6.8%,6.7%)	(-8.8%,9.2%)
WH	(-100%,1880%)	(-88%,170%)	(-5.5%,4.2%)	(-6.1%,5.6%)	(-7.8%,7.9%)
ZH	(-100%,1880%)	(-87%,170%)	(-6.5%,5.9%)	(-7.1%,7.1%)	(-9.4%,9.9%)

loop-induced ($\gamma\gamma$, γZ columns) — tree-level (ZZ* column, VBF/WH/ZH)

EV, Zhang
arXiv:1804.09766

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

Loop-induced sensitivity (2)



+

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

+ **Relatively loose constraints from top LHC measurements (tZ, ttZ, tj, …)**

→

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

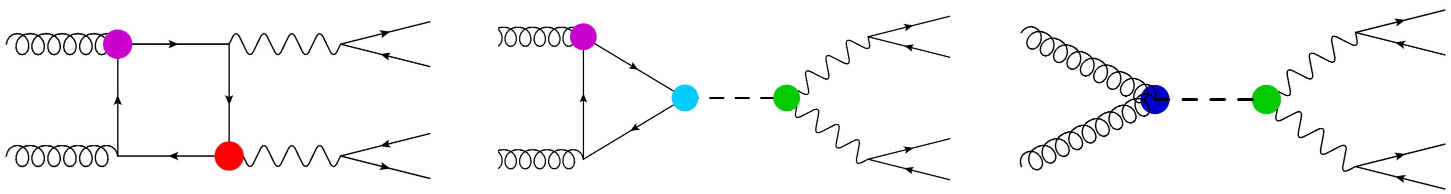
loop-induced tree-level

EV, Zhang
arXiv:1804.09766

Or… maybe one should use Higgs measurements to bound top couplings?

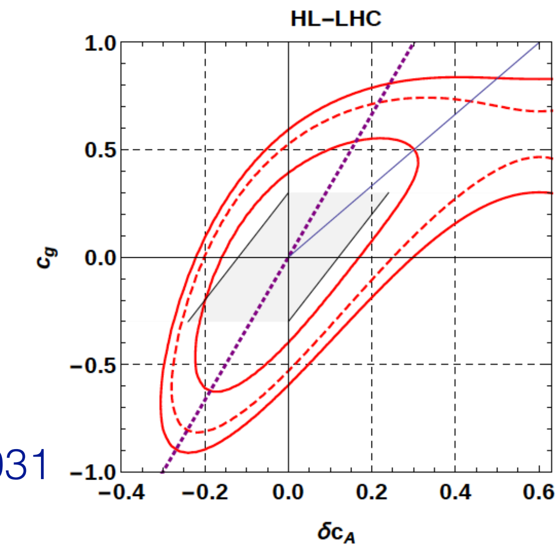
More loop-induced sensitivities

Diboson (off-shell Higgs) sensitivity to top couplings



Azatov, Grojean, Paul, Salvioni arXiv:1608.00977

See also: Englert, Soreq, Spannowsky arXiv:1410.5440 and Cao et al 2004.02031



4-parameter fit:

c_t, c_g, c_V, c_A

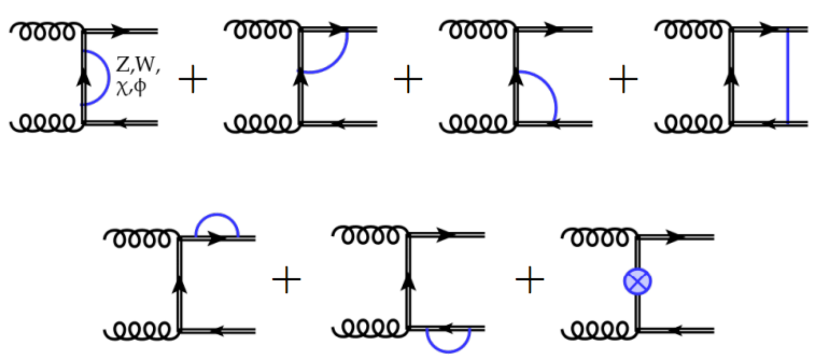
Constraint from gg to ZH
Englert et al arXiv:1603.0530

Constraints on ttZ couplings
competitive with ttZ process

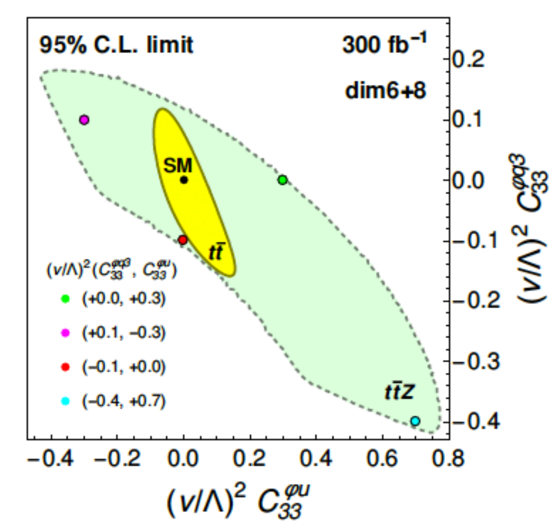
Azatov, Grojean, Paul, Salvioni arXiv:1608.00977

Top pair production sensitivity to EW top couplings

EW corrections:



Martini and Schulze arXiv:1911.11244



Global Higgs-top fit

Higgs data

Run I & 2 signal strengths (CMS+ATLAS):

* gluon fusion
* VH
* VBF
* ttH
* H decays

Differential distributions & STXS

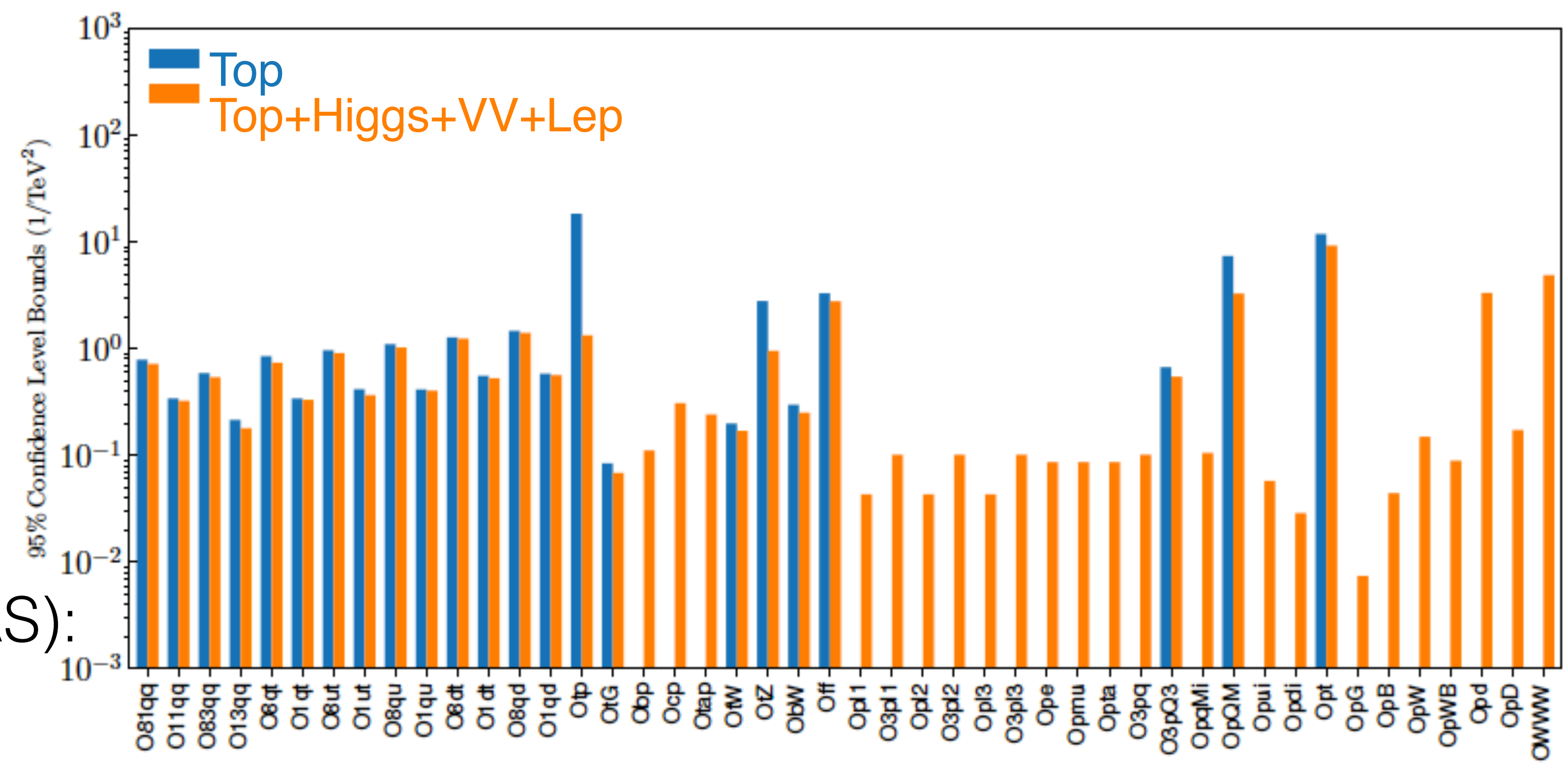
Top data

Run I & 2 results (CMS+ATLAS):

* pair production
* tt+V, tttt, ttbb
* single top
* tZj
* W helicity fractions

Cross-sections & Differential distributions

PRELIMINARY



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

Global Higgs-top fit

PRELIMINARY

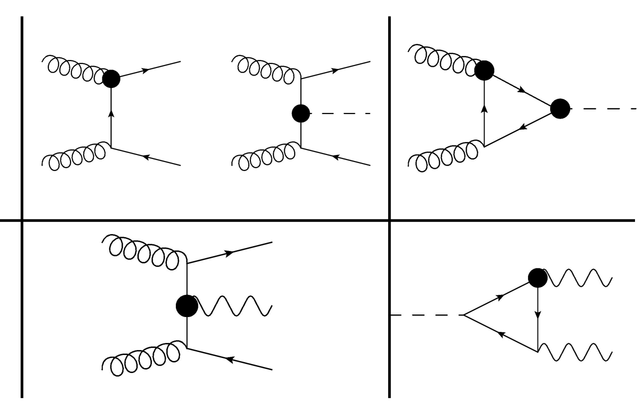
		Processes					
Class	Coefficient	Hrun1	Hrun2	Hdiff	WW	WZ	LEP_WW
2FB	ctp	15.3(18.2)	65.8(81.8)	19.0(0.0)	×(×)	×(×)	×(×)
	ctG	6.4(6.0)	27.7(25.9)	6.6(6.6)	×(×)	×(×)	×(×)
	cbp	20.6(21.2)	79.4(78.8)	×(×)	×(×)	×(×)	×(×)
	ccp	21.0(12.4)	79.0(87.6)	×(×)	×(×)	×(×)	×(×)
	ctap	38.6(37.0)	61.4(63.0)	×(×)	×(×)	×(×)	×(×)
	ctW	15.7(17.0)	75.8(82.4)	×(×)	×(×)	×(×)	×(×)
	ctZ	17.1(17.2)	82.8(82.8)	×(×)	×(×)	×(×)	×(×)
	c3pQ3	0.2(7.9)	1.2(41.7)	0.8(1.2)	×(×)	×(×)	×(×)
	cpQM	4.8(17.2)	23.0(78.6)	16.3(3.9)	×(×)	×(×)	×(×)
	cpt	2.5(20.0)	12.2(79.8)	5.5(0.0)	×(×)	×(×)	×(×)

Top Yukawa

ttV couplings

Tree Loop

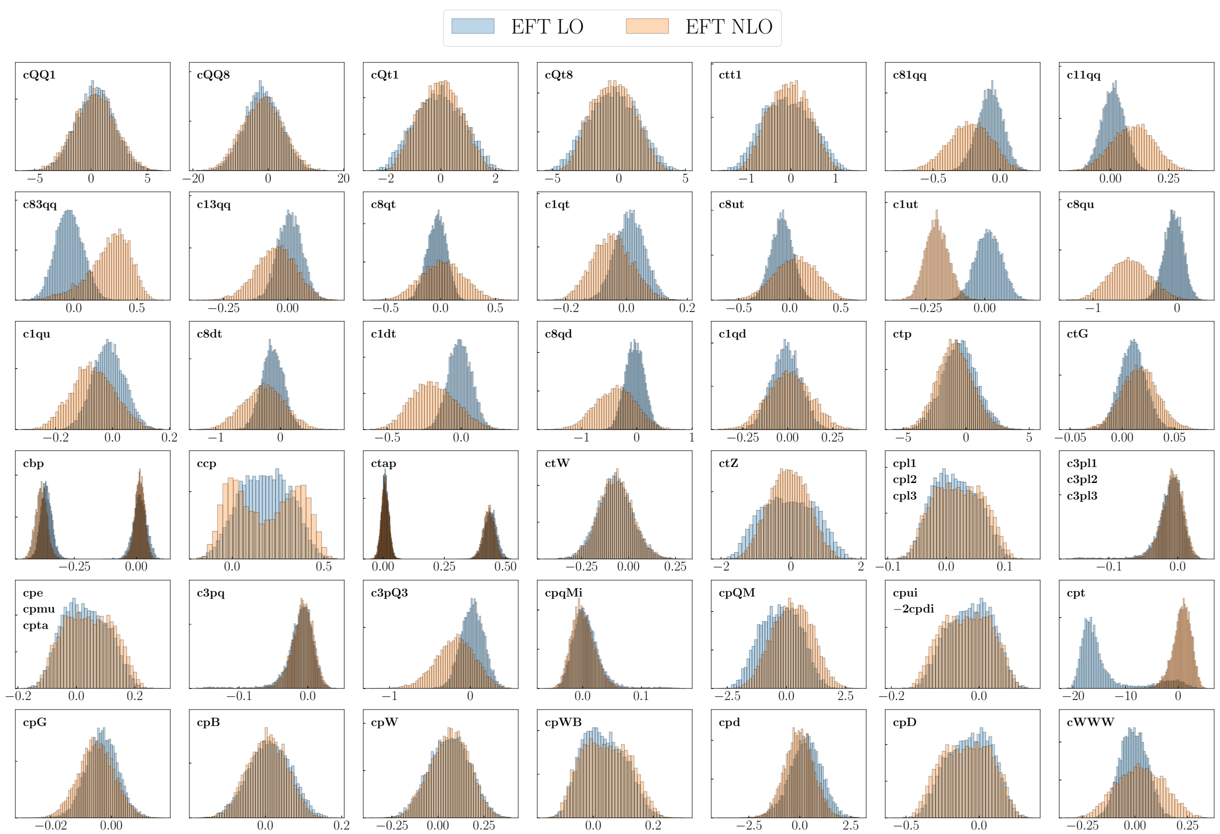
Chromo dipole

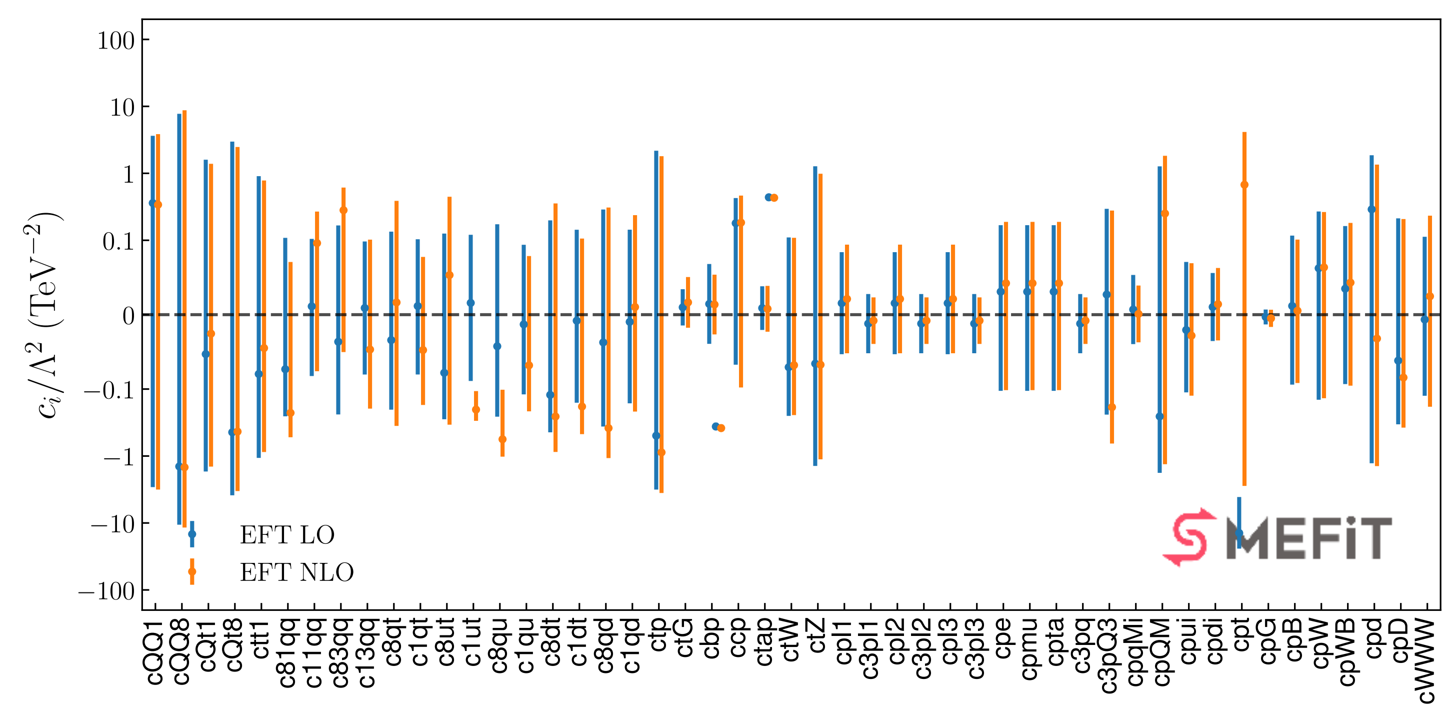


Ethier, Maltoni, Mantani, Nocera, Rojo, EV and Zhang in preparation

Impact of NLO predictions in global fits

Marginalised constraints





Posterior distributions

Significant impact of NLO for some operators

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]
```

What's in the box?

Warsaw basis operators

Flavour assumption:

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

Includes Higgs, top, gauge boson interactions

Conventions matching dim6top (LHC Top WG)

CP & Flavour conserving

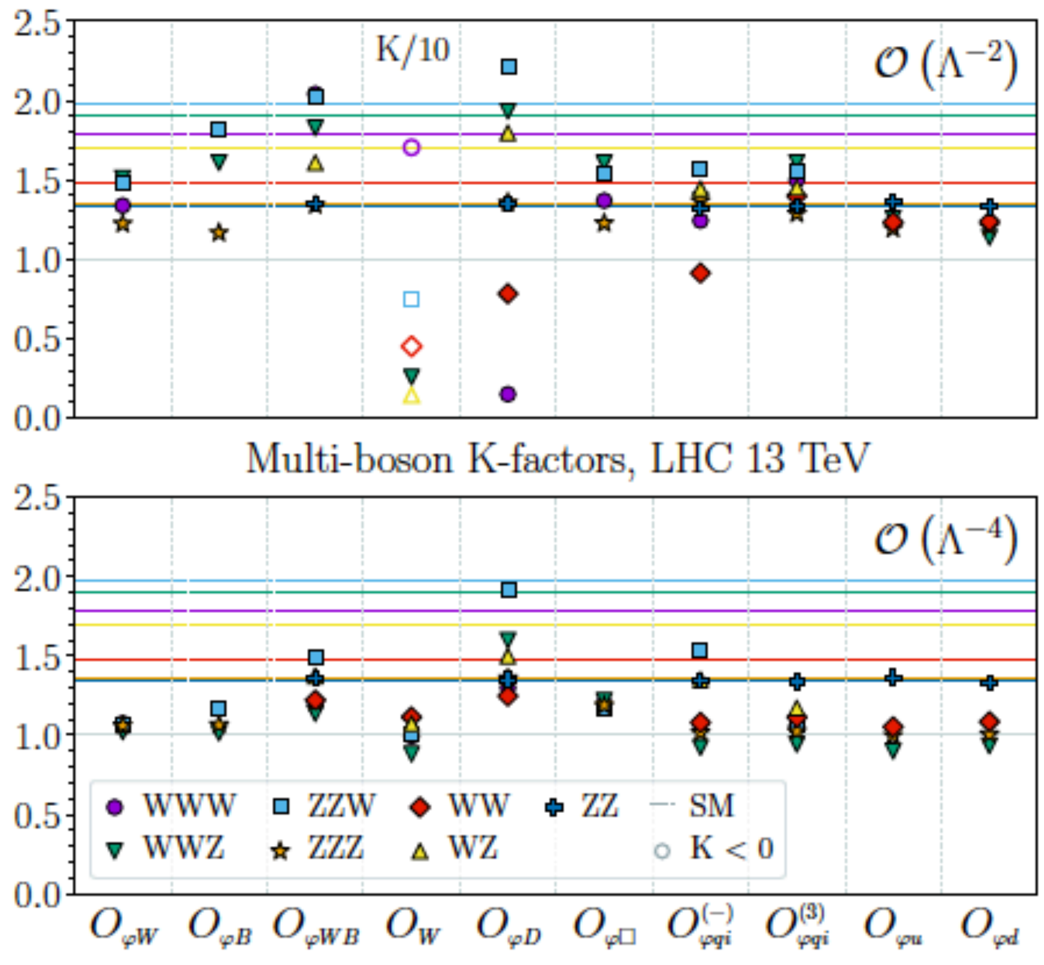
→ Including 4-fermion operators ★

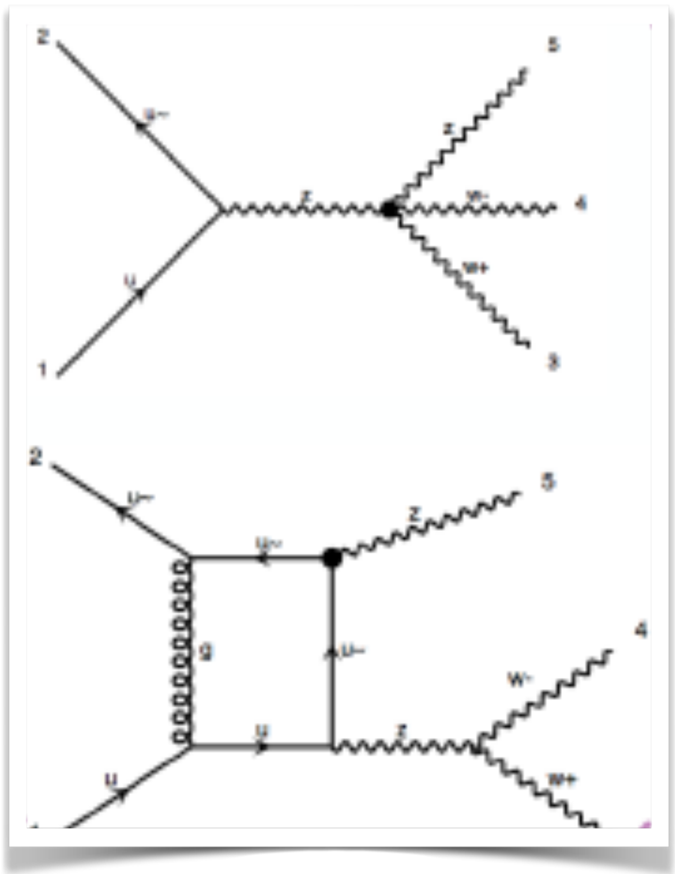
And many more on the website…

Applications at NLO

NEW

Triboson production





First computation of VVV@NLO in the SMEFT

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

Summary

- EFT is a theoretically 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
- Higher-order effects relevant in global fits

Thank you for your attention