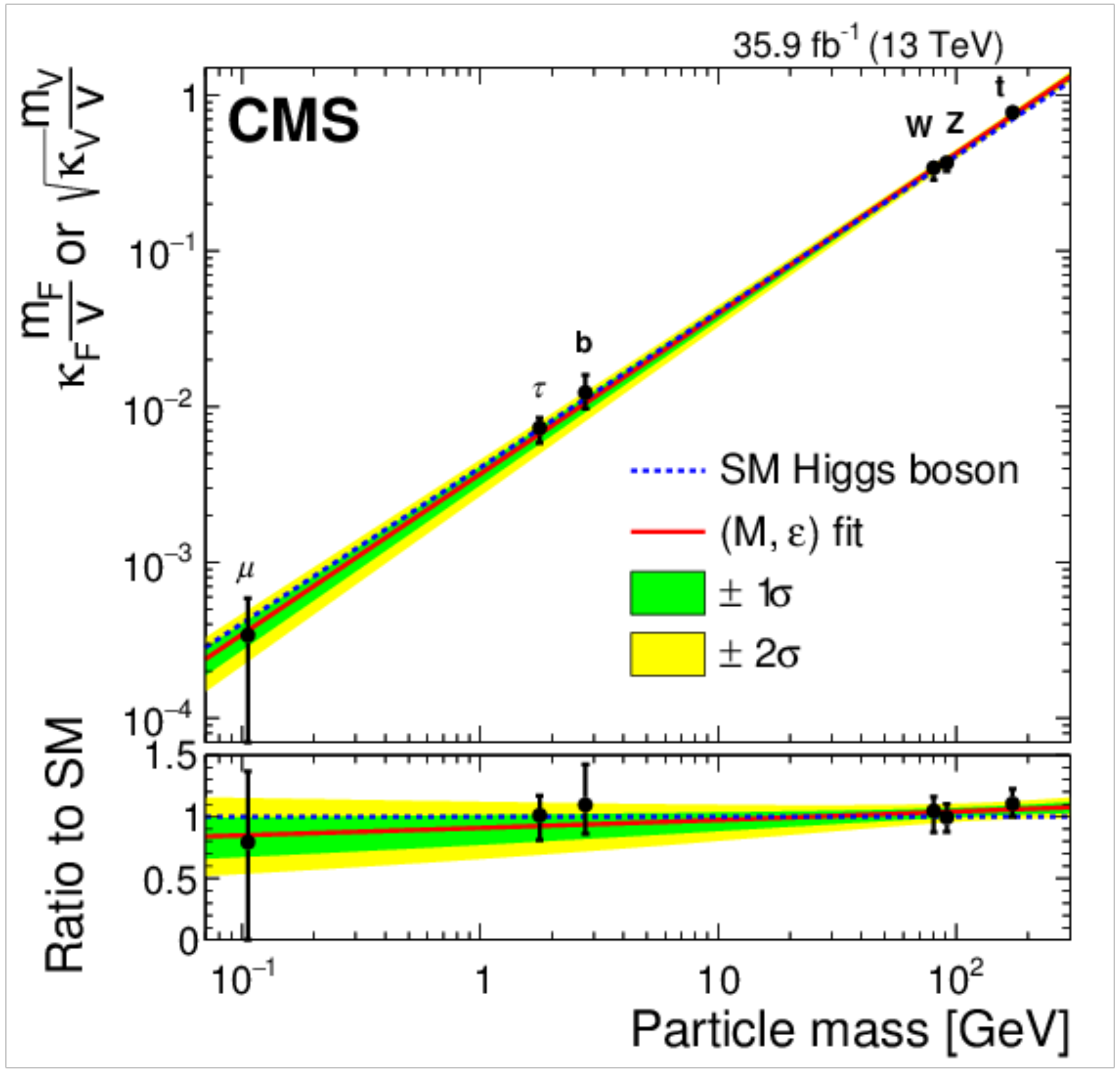
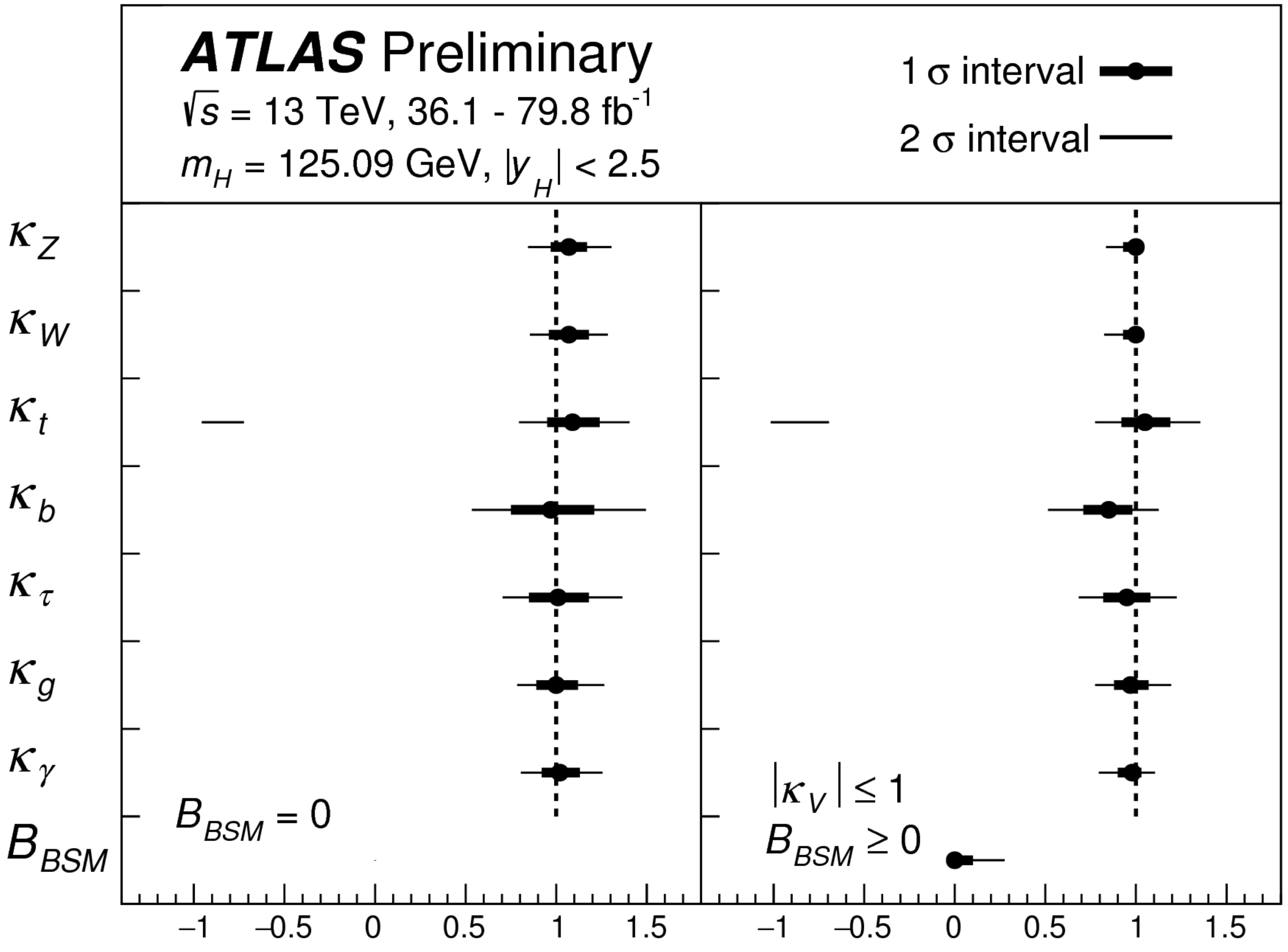
Part 2
The standard model as an EFT

The SM success story

We have found a scalar that couples to mass





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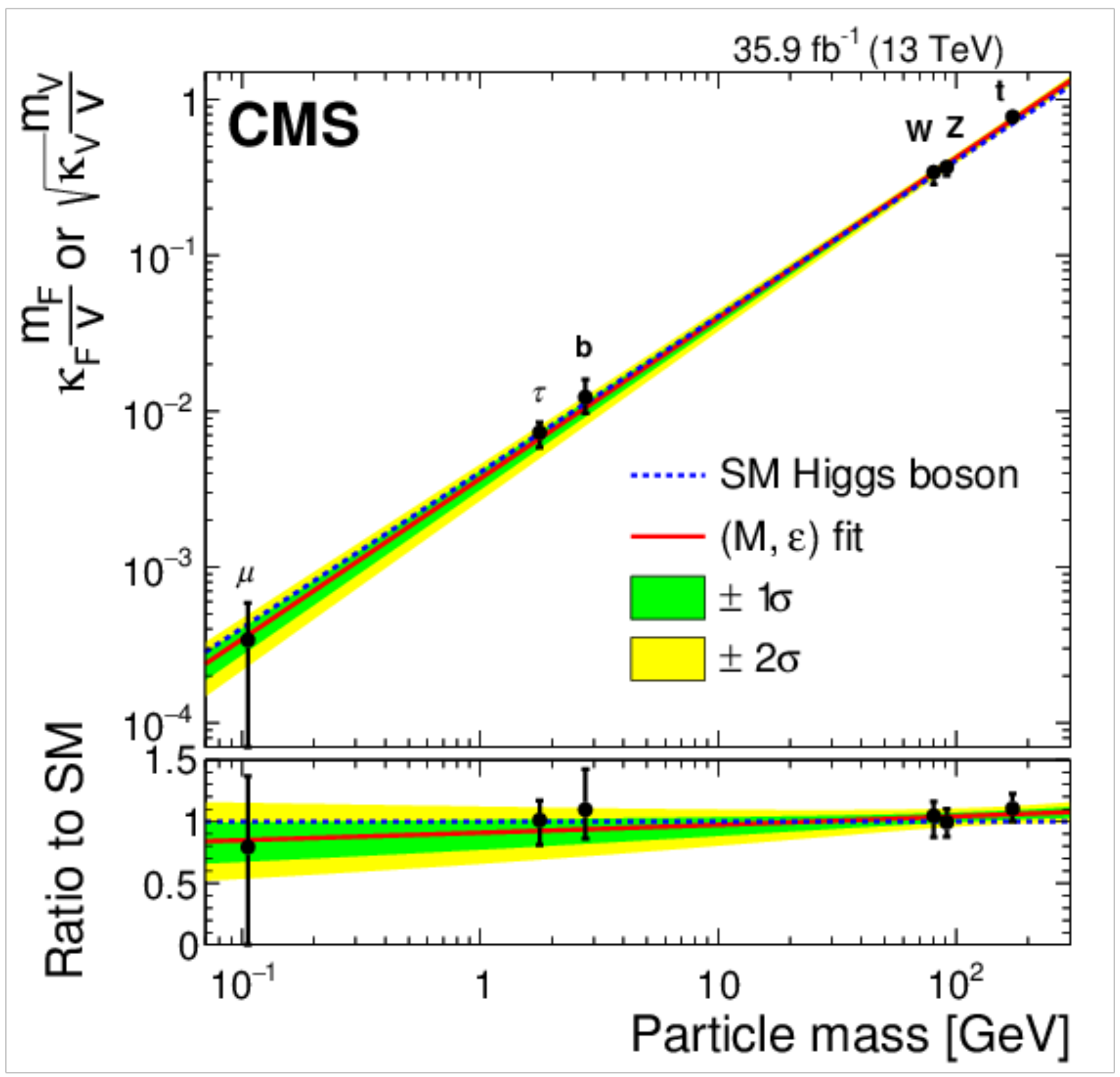

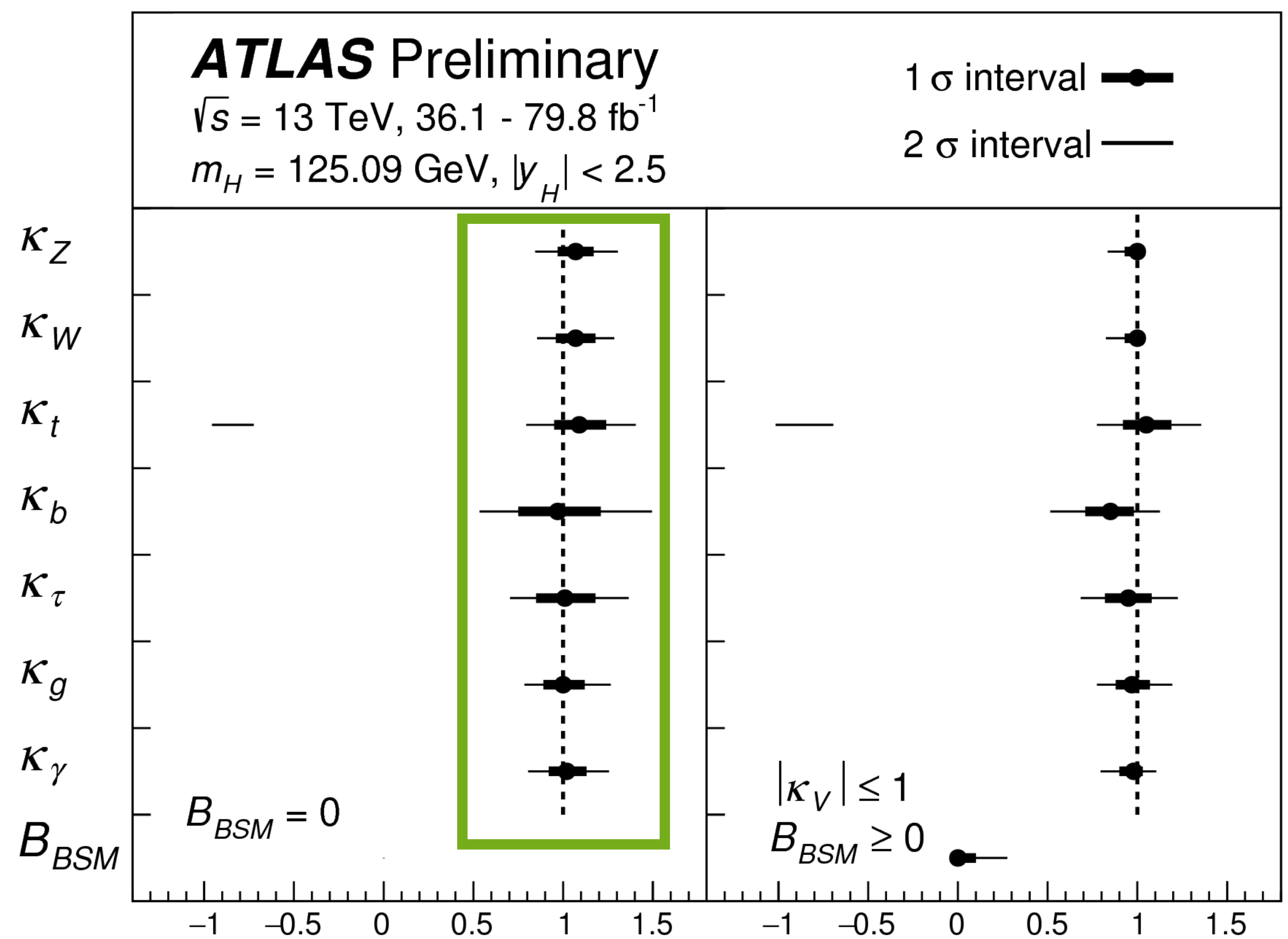

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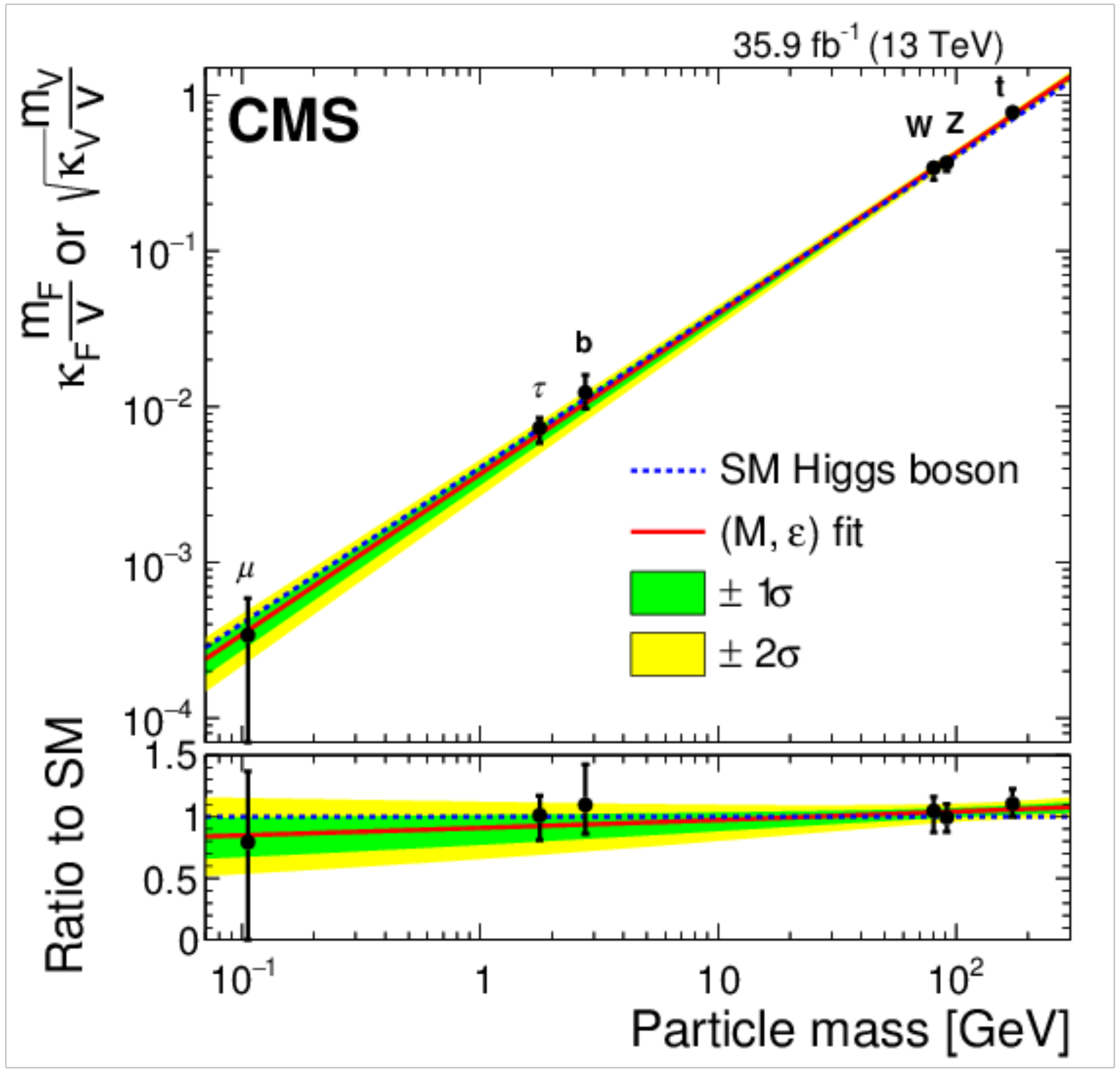

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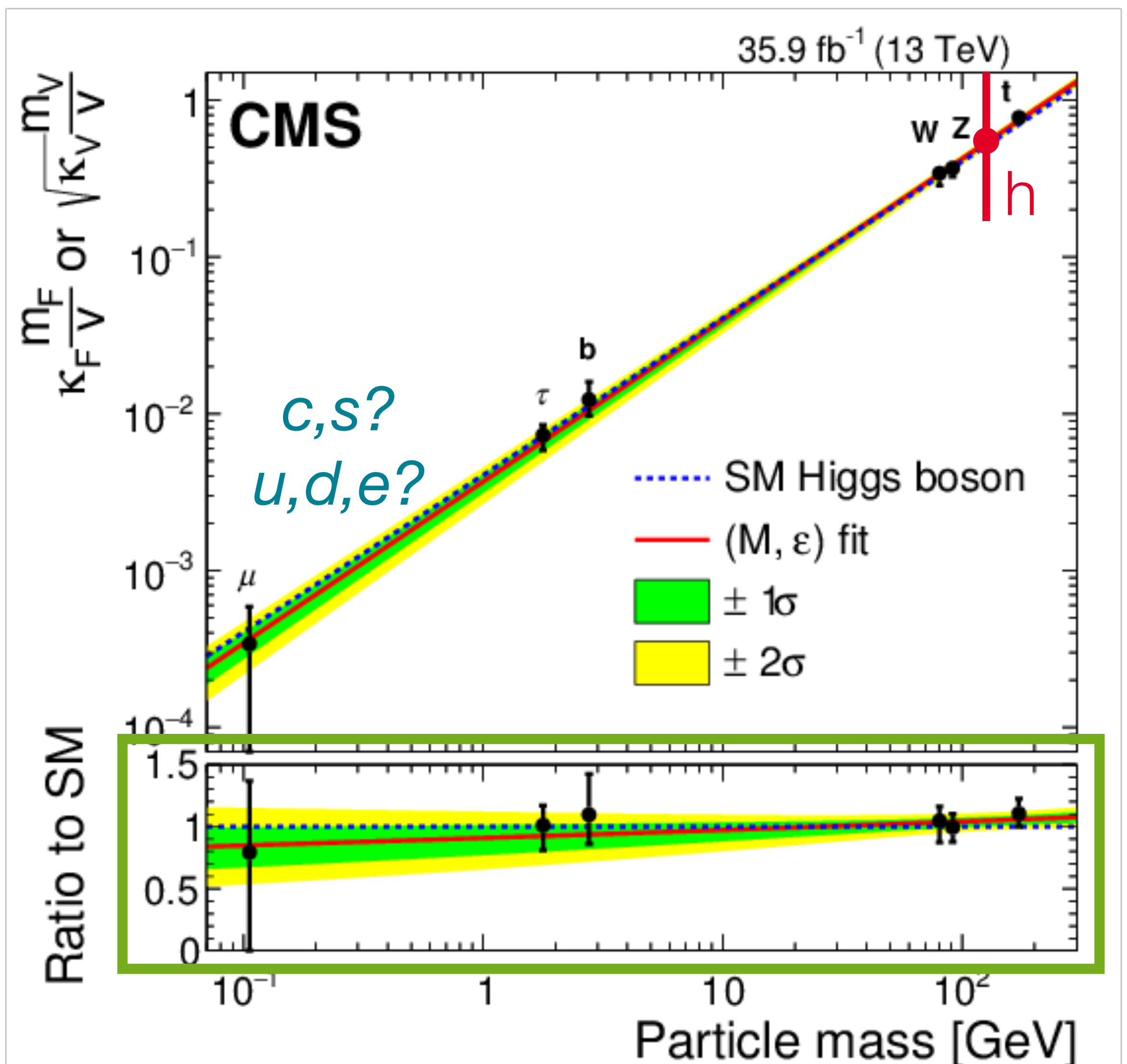


At least *one* missing ingredient…

Still some way to go to pin down precise interactions

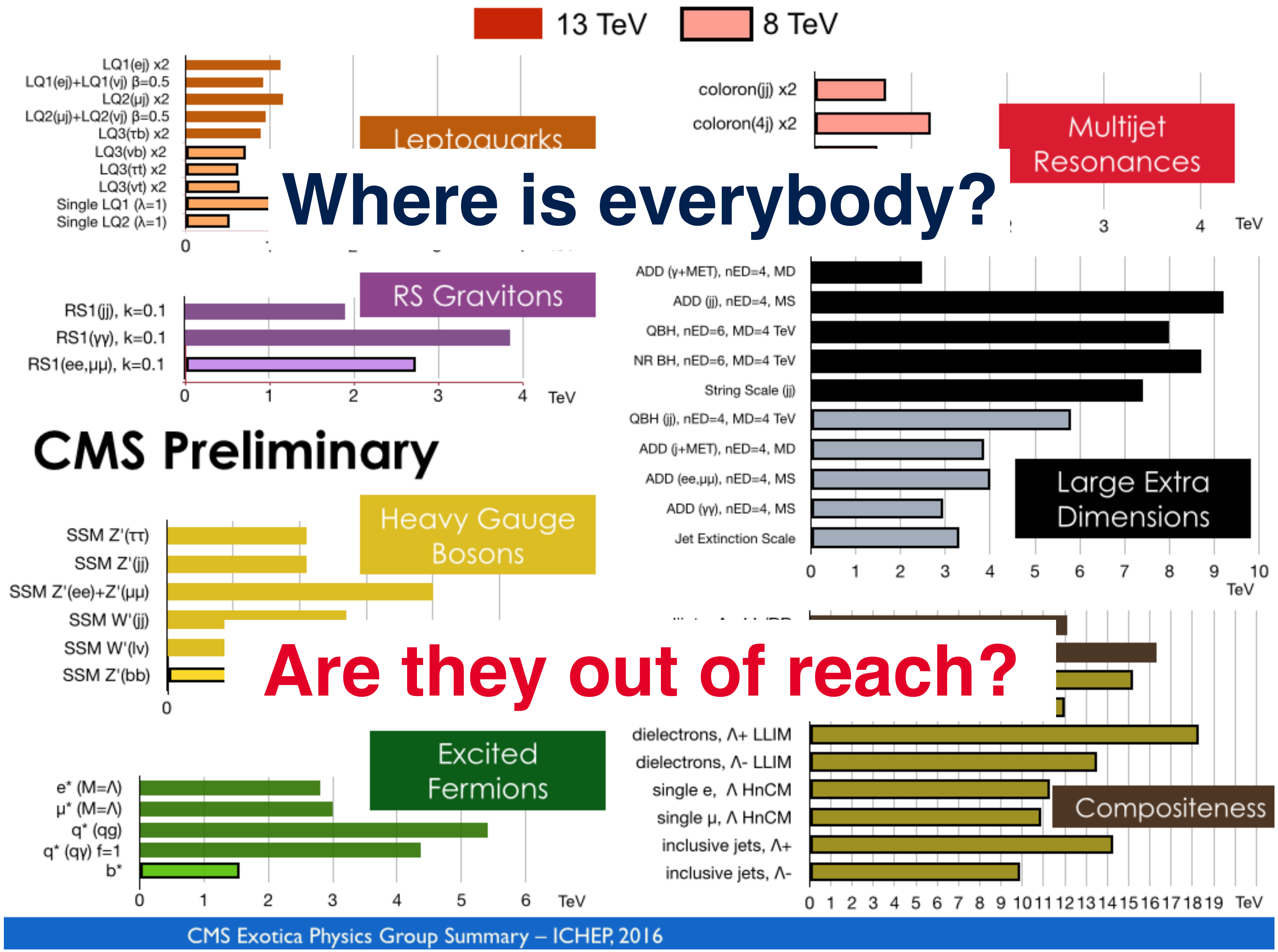
So far, all HEP data is broadly consistent with SM expectations

The LHC mission continues…

Precision measurements

New physics searches

The best motivation for EFT



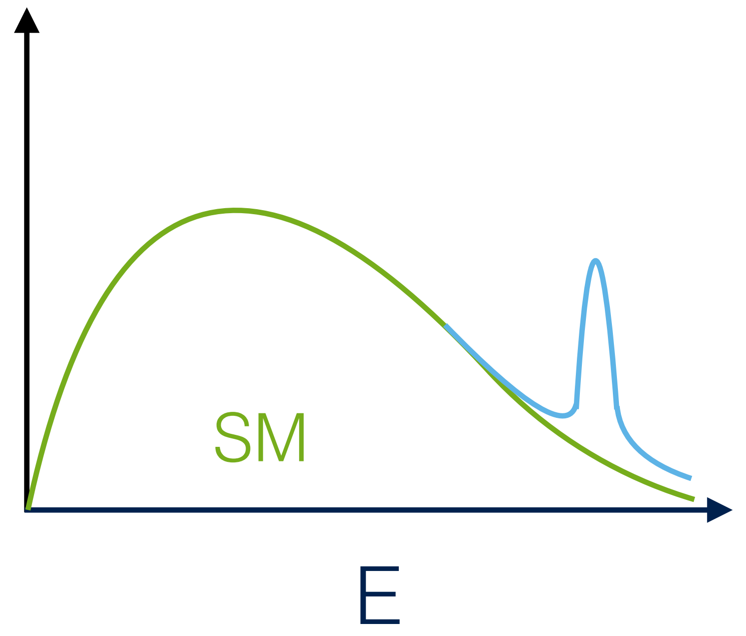
Back to reality

The standard model is a great candidate for EFT

- A well understood low energy theory around the weak scale, *v*
- Low energy degrees of freedom: $\{Q_i, L_i, u_i, d_i, e_i, g, \gamma, W^\pm, Z, h\}$
- LHC data indicates a gap to the new physics mass scale

Paradigm shift at the energy frontier for BSM searches

Direct (bump hunts)



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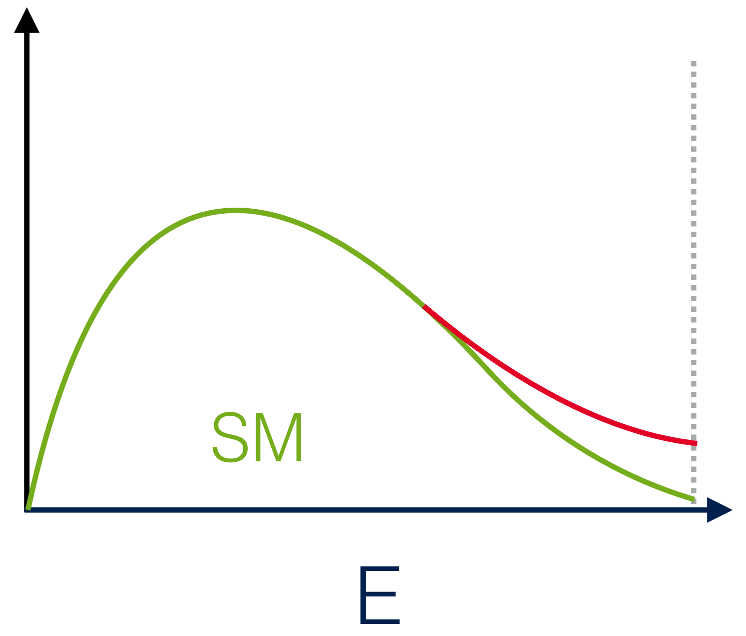
Paradigm shift at the energy frontier for BSM searches

Direct (bump hunts)

Indirect (scouting tails)



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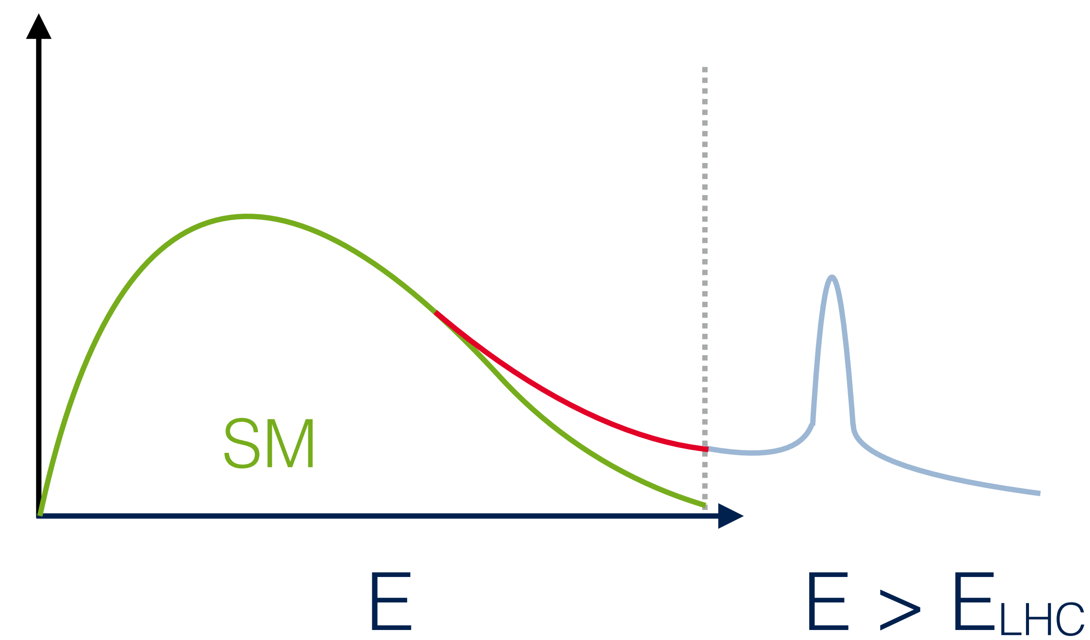
Paradigm shift at the energy frontier for BSM searches

Direct (bump hunts)

Indirect (scouting tails)

$\Rightarrow$ New physics is **heavy**



Precision measurements + Heavy new physics

Standard Model Effective Field Theory (SMEFT)

SMEFT

Operator expansion: $\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$ → more fields derivatives

SM gauge symmetry & linear EWSB

- Higgs is an SU(2) **doublet**
- Operators are $SU(3)_C \times SU(2)_L \times U(1)_Y$ **singlets**

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\varphi = \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} : \mathbf{2}_{\frac{1}{2}}$$

Parameter space for new interactions between SM particles

- With all nice features of EFT (gauge symmetry, matching, improvability,…)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

At dimension-5, only one operator

- Lepton number violating Weinberg operator (neutrino masses) $(\bar{L}^c \cdot H)(L \cdot H)$

Dimension-6 is the lowest non-trivial order

Operator classes

Dimension-6 operators of the SMEFT:

Operator	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

[Buchmuller & Wyler; Nucl. Phys. B 268 (1986) 621]
[Grzadkowski et al.; JHEP 10 (2010) 085]

D=6 basis

'Warsaw' basis

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

59 independent operators

real parameters (degrees of freedom)

76: flavor universal — All fermion generations have the same coefficient

2499: flavor general — Independent coefficient for all flavor combinations

Number for Dimension 8 (835, 36971) known (up to D=15!)

[Henning et al.; JHEP 08 (2017) 016]

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$X^2\varphi^2$					
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$ …				
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$ …				
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					… $[(q_s^{\gamma j})^T C l_t^k]$
					… $[(u_s^\gamma)^T C e_t]$
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Warsaw [Grzadkowski et al.; JHEP 10 (2010) 085]

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$Q_{\varphi \widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\ldots}$				
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\ldots}$				
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				$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
				$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
				$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
				$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
				$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
				$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
				$[(q_s^{\gamma j})^T C l_t^k]$
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Rosetta: an operator basis translator for SMEFT
[Falkowski et al.; EPJC 75 (2015) 12, 583]
https://rosetta.hepforge.org

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SMEFT: SM v2.0

The SMEFT Wilson coefficients are **theory input parameters**

- In addition & analogous to SM input parameters $\{\alpha_S, \alpha_{EW}, G_F, m_Z, m_H, m_{f_i}\}$

LHC precision programme

↓

Measure the parameters of the
SM at dimension-6 (and beyond) $\{c_i\}$

↓

Extend the energy reach of our colliders to NP beyond E_{CM}

In order to do this, we must understand the impact of SMEFT interactions on scattering amplitudes in the low energy model (SM)

Impact of SMEFT

A) New Lorentz structures: contact interactions & derivatives

- Explicit source of energy growth

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

B) 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 → more energy growth
- SM inputs are extracted by comparing a few measurements to theory

➡ Extraction of SM inputs now **depends on c_i**

G_F example

Muon decay data gives: G_F = 1.17x10^{-5} GeV^{-2} → v = 246 GeV

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

  B,C $[\mathcal{O}^{(3)}_{\varphi l}]^{ij} = \left[\varphi^\dagger \tau_k \overleftrightarrow{D}_\mu \varphi\right] \left[\bar{l}^{(i)}\, \tau^k \gamma^\mu\, l^{(j)}\right], \quad i = 1, 2.$

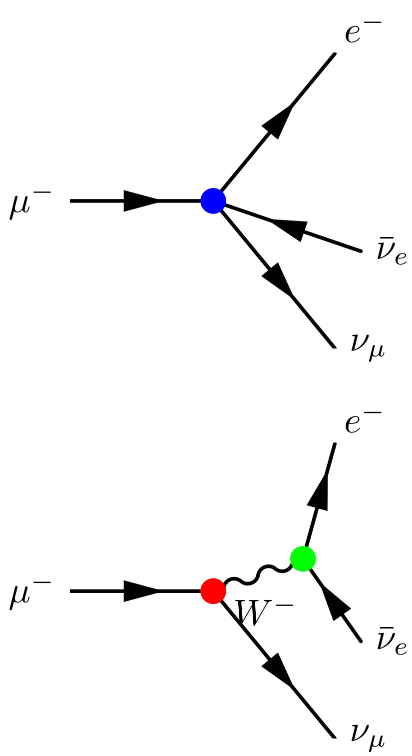
- A contains the O_F up to a Fierz transformation
- B,C shifts W couplings to leptons after EWSB

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

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

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

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



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

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

New relation between Higgs vev and Fermi constant

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

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

Computing observables

Pick a SMEFT basis and appropriate symmetries

- Control the number of parameters (2499 is a bit tough)
- Work out the Feynman rules (e.g. using FeynRules)
- Calculate Matrix element of scattering processes e.g. pp→ X

flavor structure,
CP conservation,
...

Generic contribution from SMEFT is an expansion in Λ^2

$$\mathcal{A} = \mathcal{A}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{A}^i \longrightarrow \sigma = \sigma_{SM} + \sum_i \frac{c_i}{\Lambda^2}\sigma^i_{(\text{int.})} + \sum_{i,j}\frac{c_i c_j}{\Lambda^4}\sigma^{ij}_{(\text{sq.})}$$

single operator insertion

$|\mathcal{A}_{SM}|^2$ $\quad 2\text{Re}[\mathcal{A}^*_{SM}\mathcal{A}_{EFT}]$ $\quad |\mathcal{A}_{EFT}|^2$

Leading contribution from interference

- Quadratic EFT term is formally higher order, although basis independent
- Subleading unless interference forbidden/suppressed (symmetries/helicity)
- Importance with respect to dim-8 operators is model dependent

SMEFT roadmap

SMEFT roadmap

Basis

Warsaw, SILH, HISZ, Higgs Basis

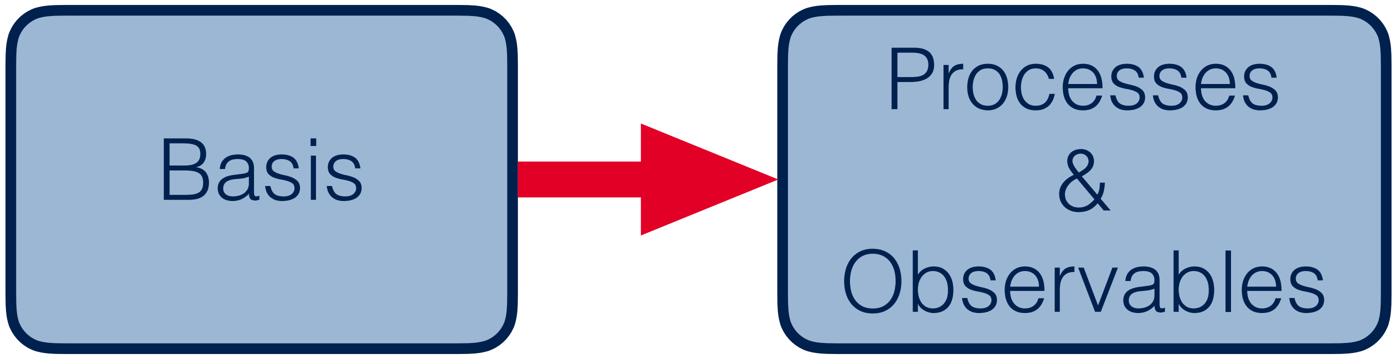
Flavor assumptions

Universal, diagonal, 3rd gen, general?

Symmetries

CP, Baryon/Lepton number?

SMEFT roadmap



Rate measurements $\sigma_{\text{tot.}}\,, \quad \mu = \frac{\sigma}{\sigma_{\text{SM}}}$

Differential $\frac{d\sigma}{dM_{\text{XX}}}$ *energy, angular*

asymmetries

High-level *optimal observables*

NN-output

SMEFT roadmap

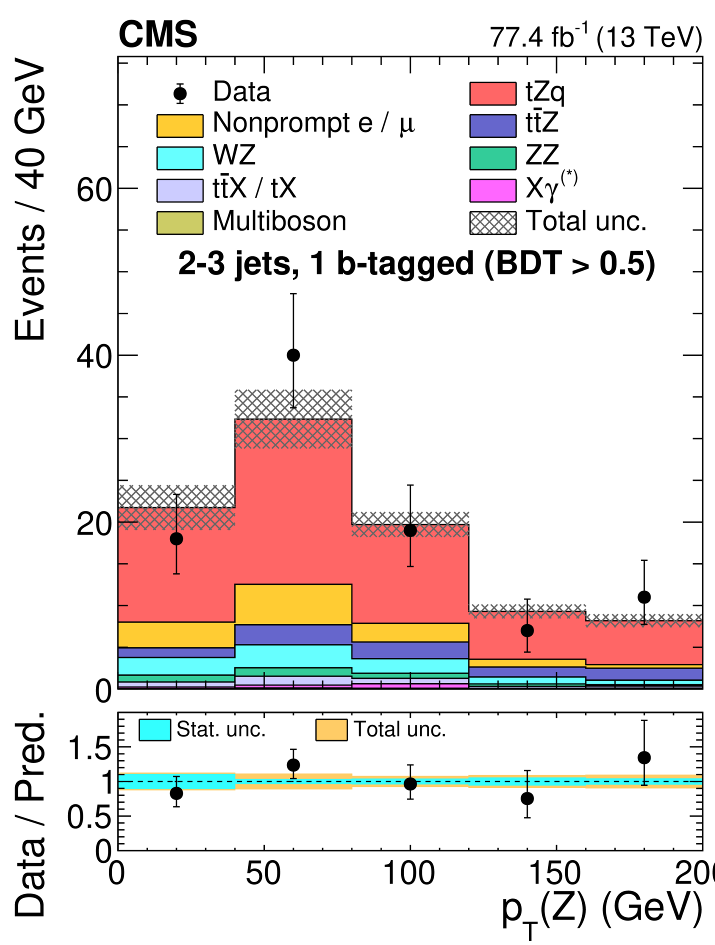
Determine dependence on
Wilson coefficients

$$\mathcal{O} = \mathcal{O}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}^i_{\mathrm{int}} + \sum_{i,j} \frac{c_i\, c_j}{\Lambda^4} \mathcal{O}^{ij}_{\mathrm{sq}}$$

Precise Monte Carlo tools

SMEFT roadmap

Basis → Processes & Observables → Sensitivity → Measurement



[CMS.; PRL 122 (2019) 132003]

Fiducial volume

Not sensitive to deviations outside acceptance (model dependent)

Extract limits

$$c_i \subset [a, b] \;\; \left[\mathrm{TeV}^{-2}\right]$$

SMEFT roadmap

Basis → Processes & Observables → Sensitivity → Measurement → Global fit

Degeneracies/blind directions

New processes/observables

Map to UV models

Hints of new physics?

Constrain classes of models

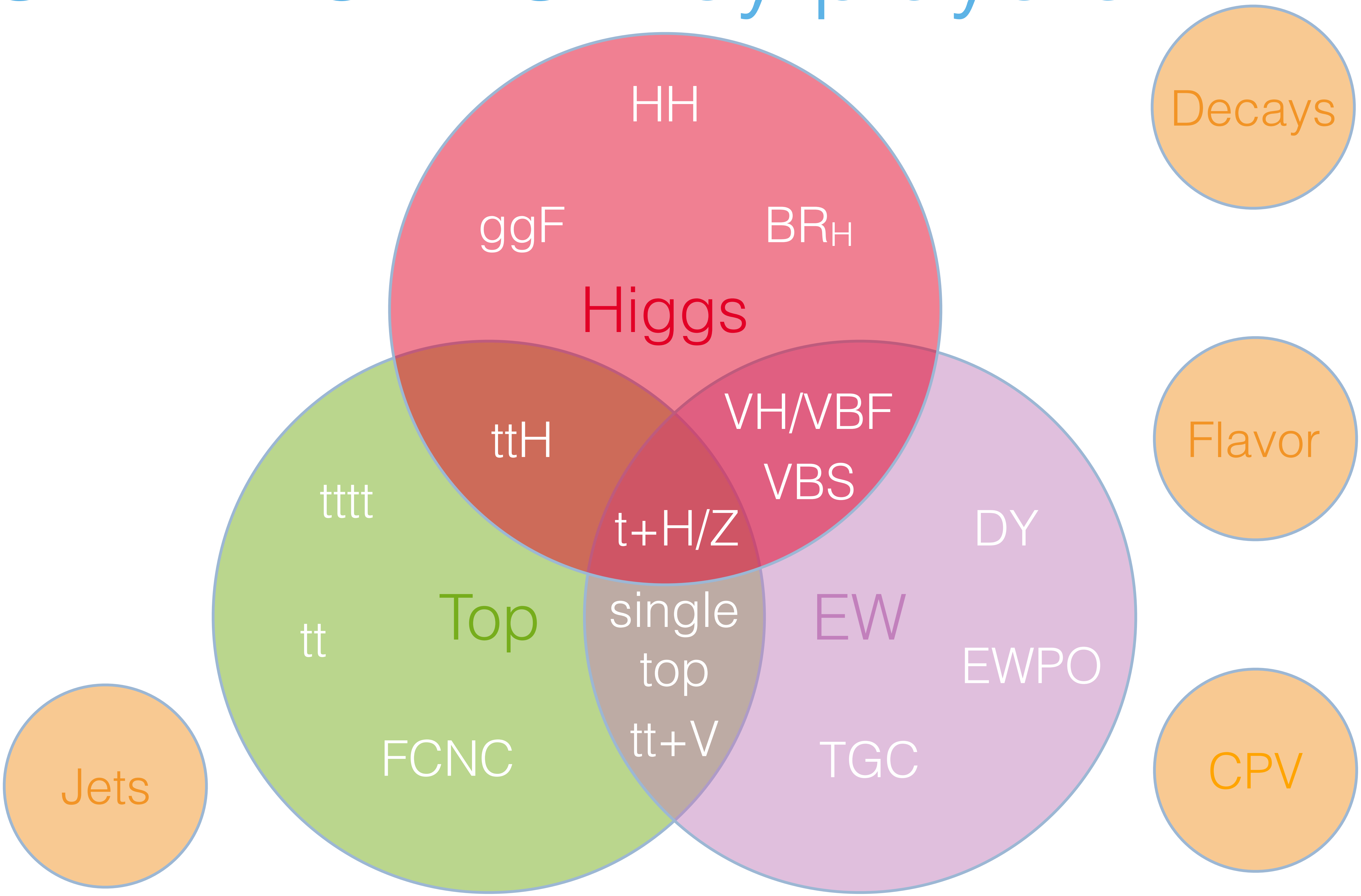
Validity of EFT

***A posteriori**: depends on sensitivity*

Intrinsically model dependent

Part 3
Application:
SMEFT in the EW sector

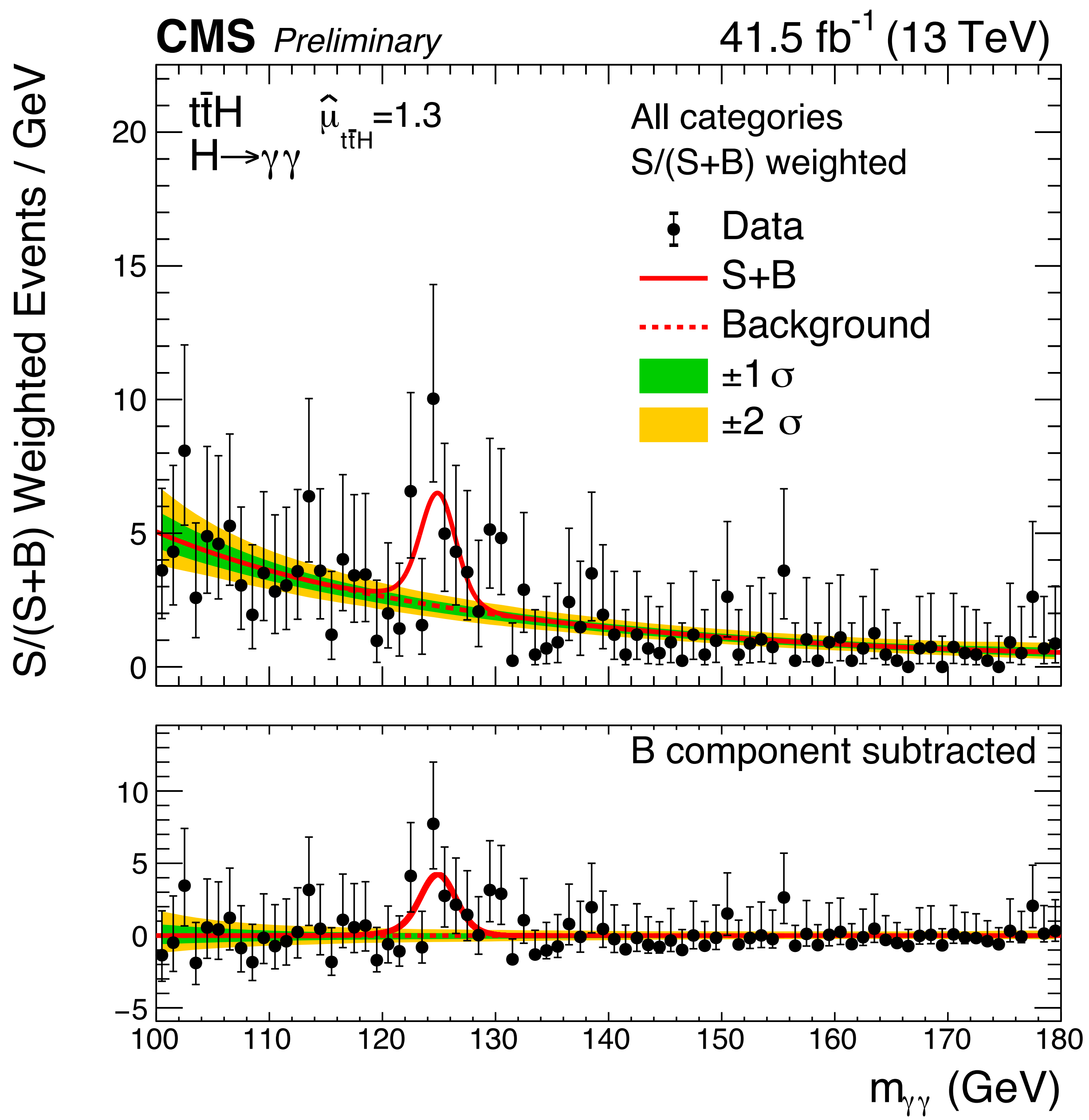
SMEFT@LHC: key players



Big news of the year

Big news of the year

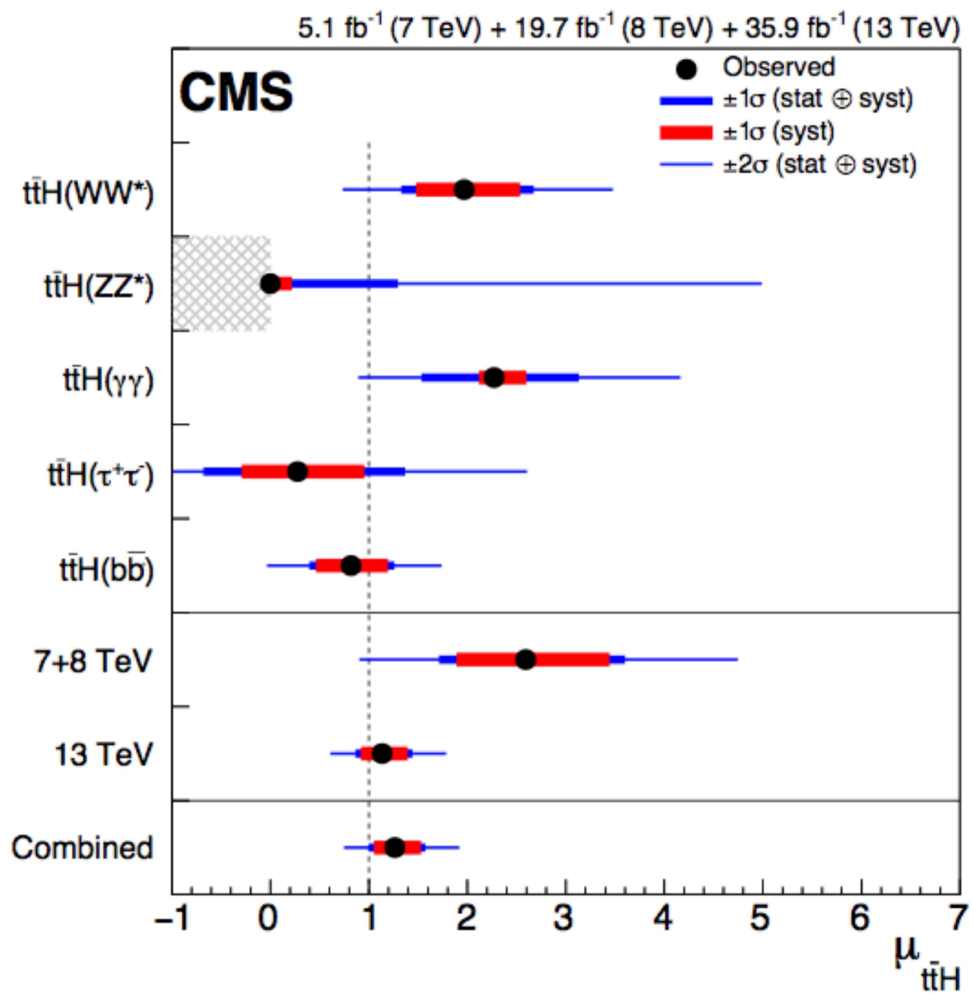
The top couples to the Higgs!

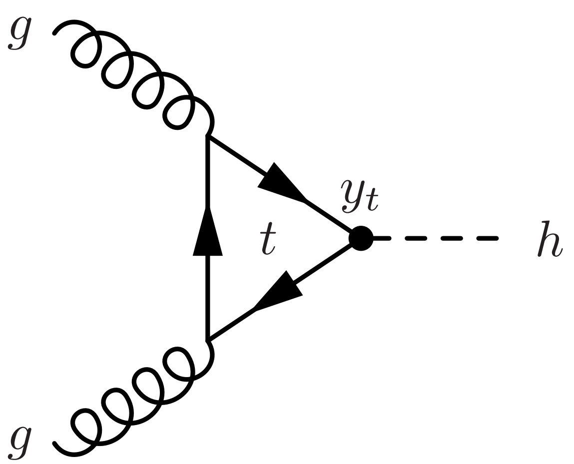


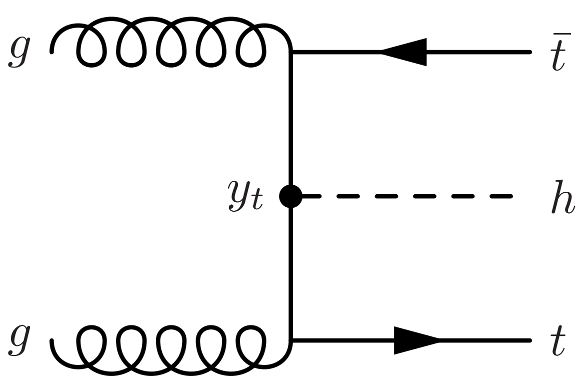
Big news of the year

The top couples to the Higgs!

- *Indirect* evidence from gluon fusion production
- **Direct** determination of the top quark Yukawa interaction via ttH observation at > 5σ







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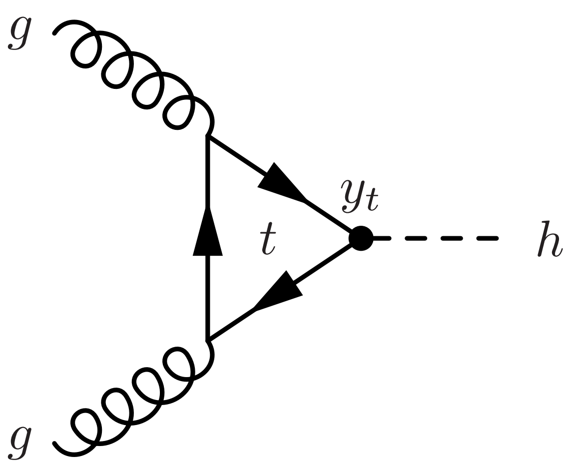

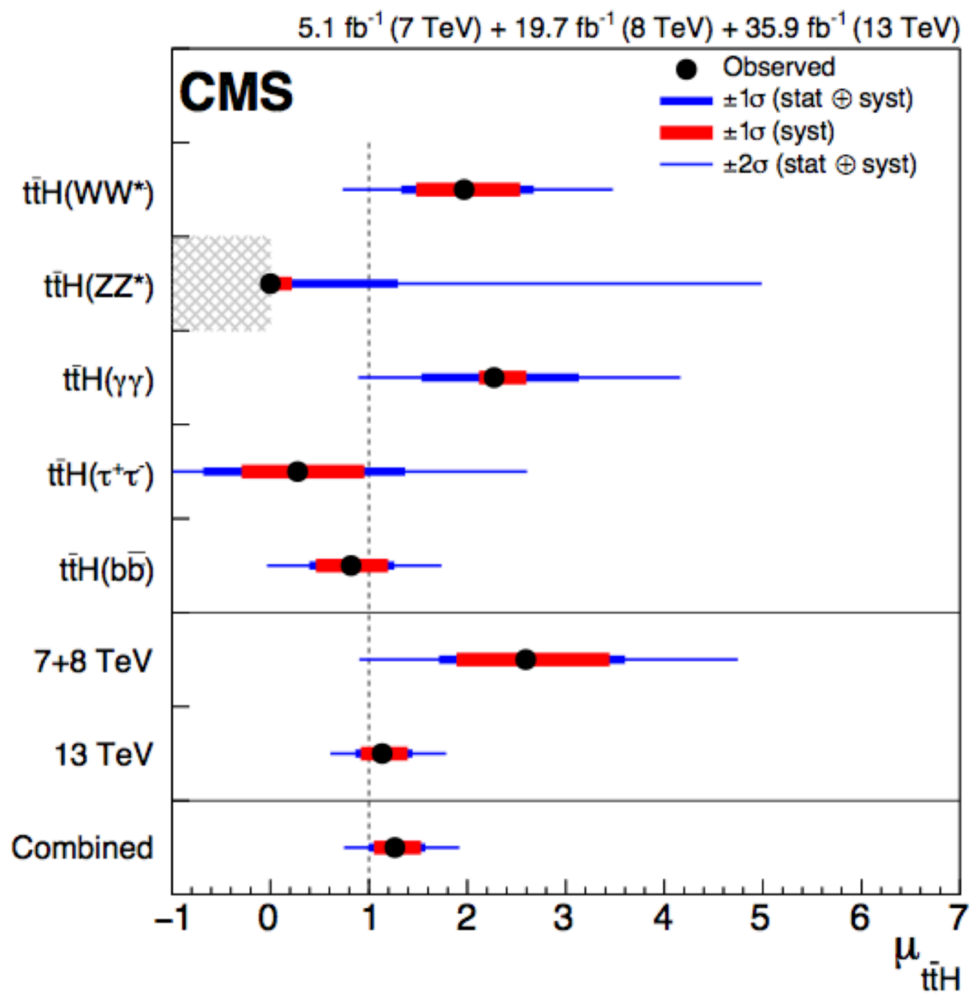

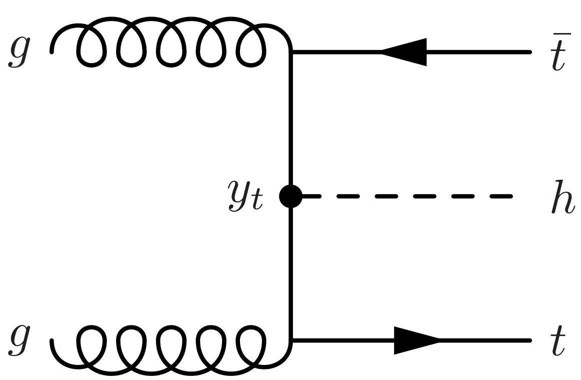

Consistent with SM ~ 100% errors

Big news of the year

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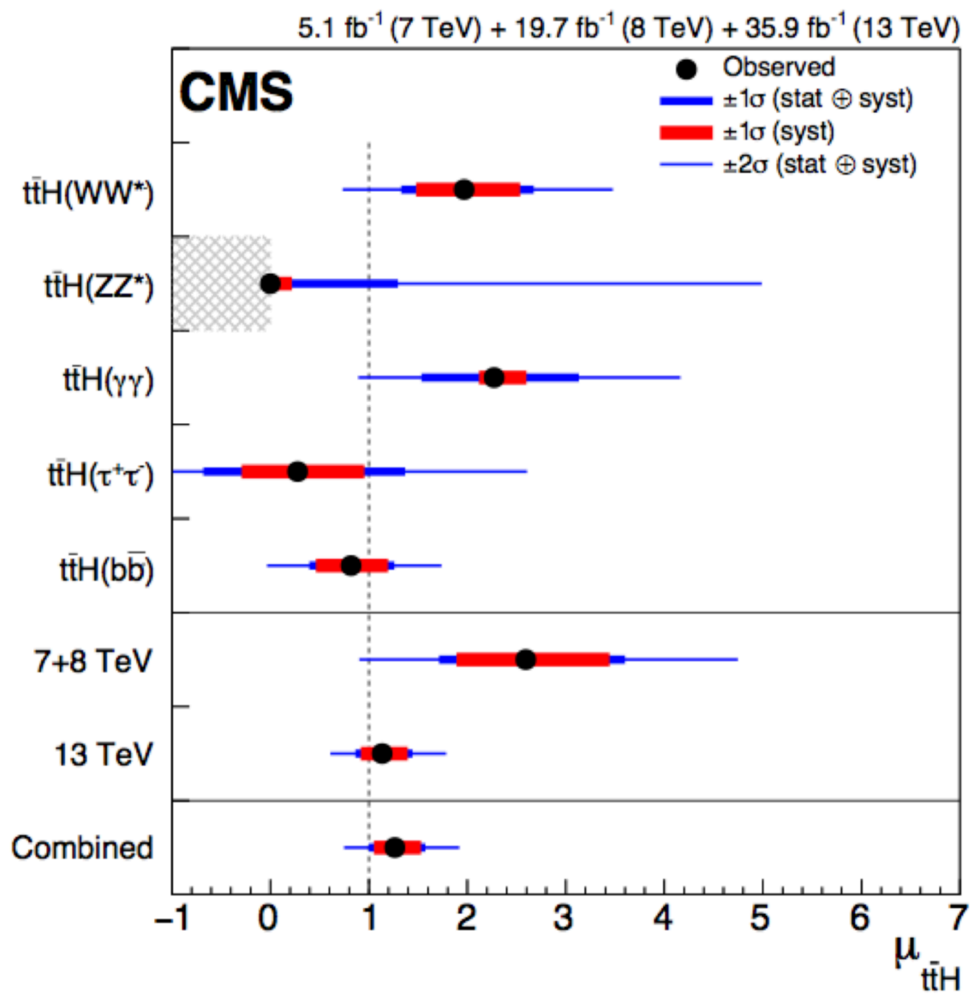

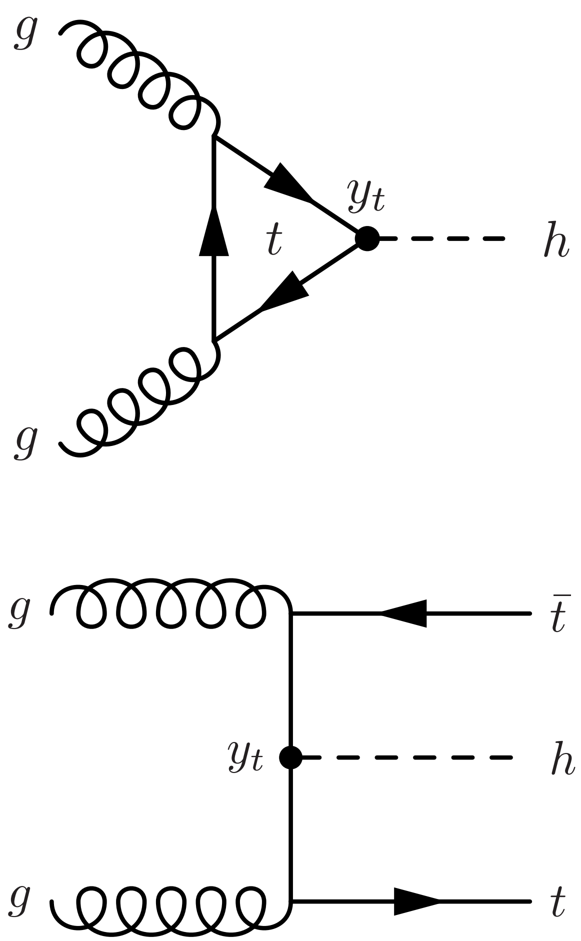

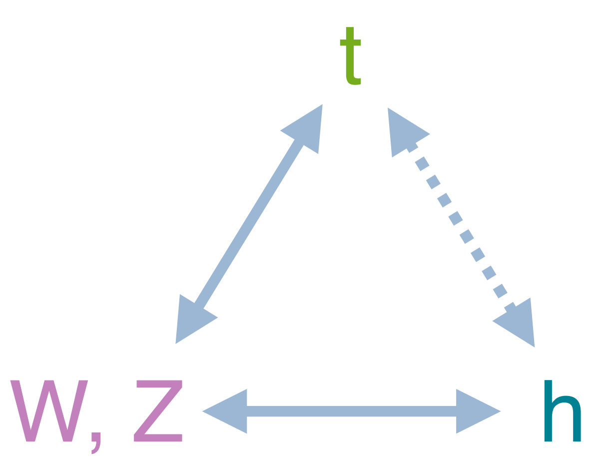

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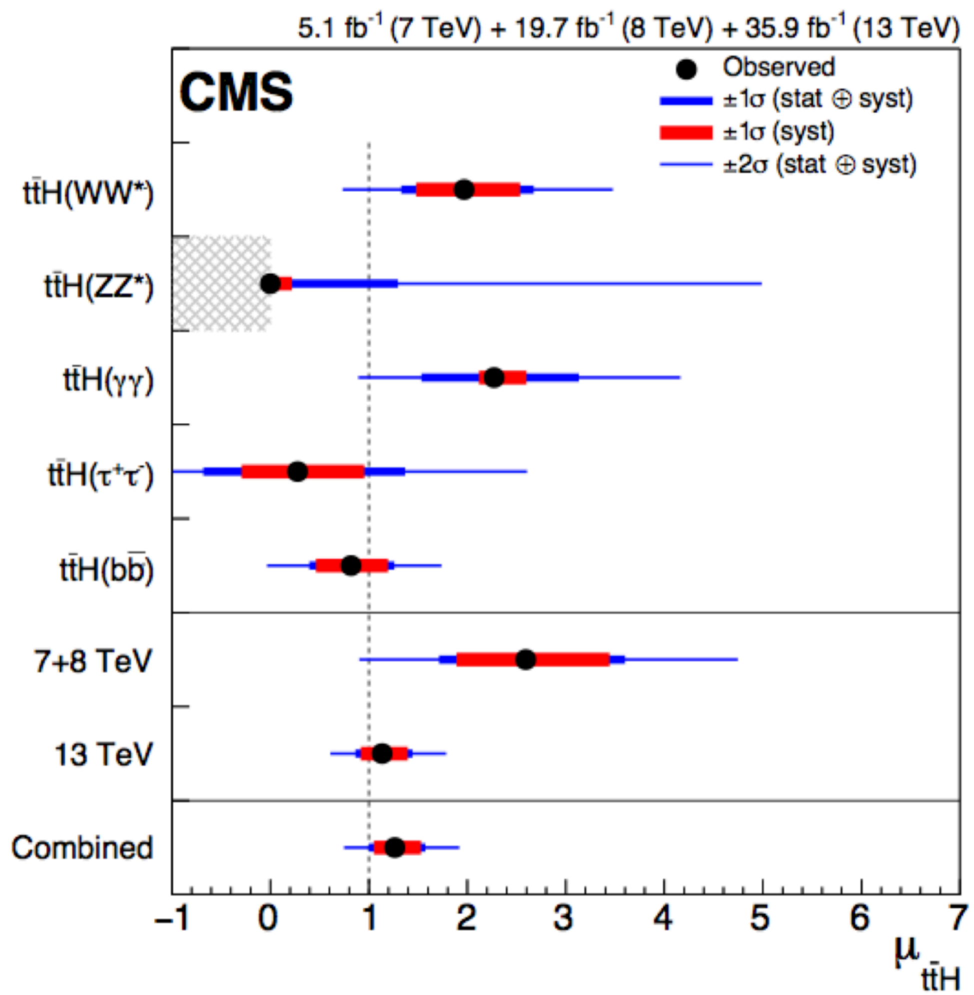
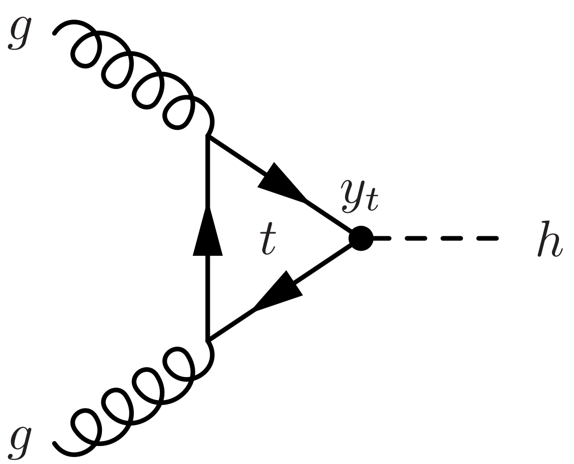
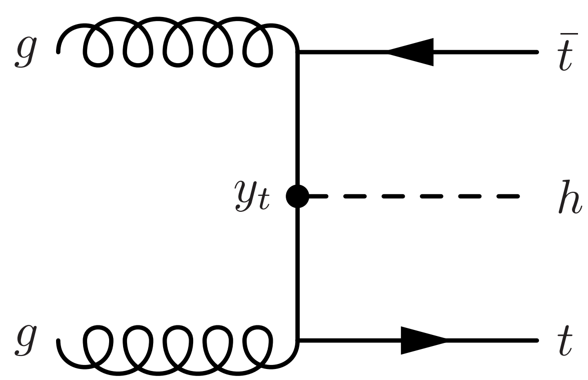
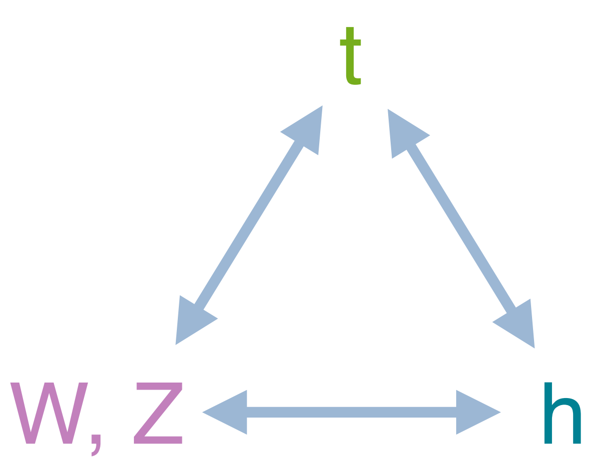
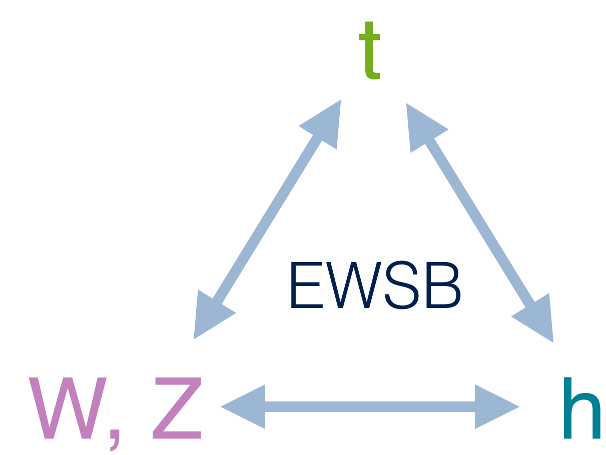








EWSB sector at the LHC



All players are in the game

LHC legacy = precise measurements of the interactions that govern EWSB

SM is a spontaneously broken, gauge-Yukawa theory

- Offers a parametrisation, lacks dynamical origin for the weak scale

Symmetry ↔ Constraints/Relations

$$y_f\,\bar{F}_L f_R\,\varphi \qquad (D^\mu\varphi)^\dagger\,(D_\mu\varphi)$$

Mass ↔ Higgs coupling

$$\frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu} \qquad i\bar{F}\not{D}F$$

Self-interactions ↔ Gauge currents

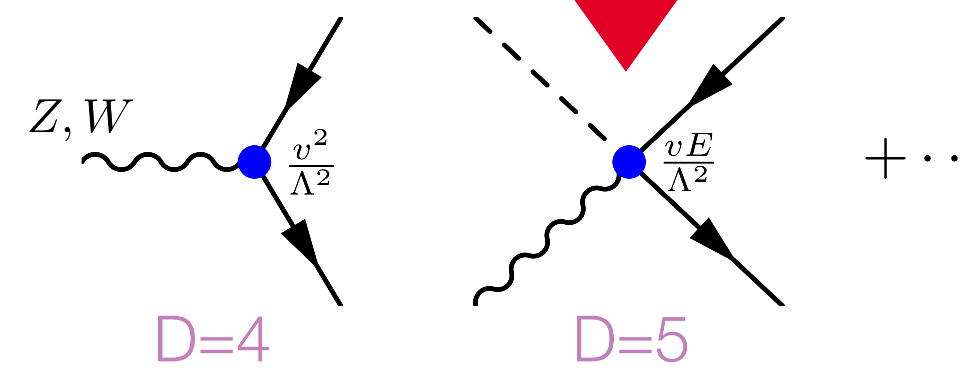
Delicate ‘balance’ conserves **unitarity** & **renormalisability**

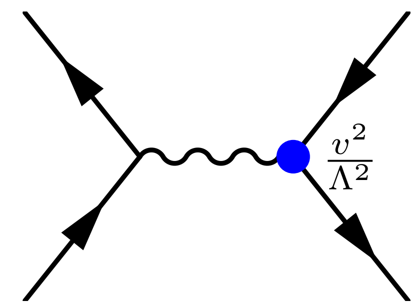
SMEFT contributions break this balance

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

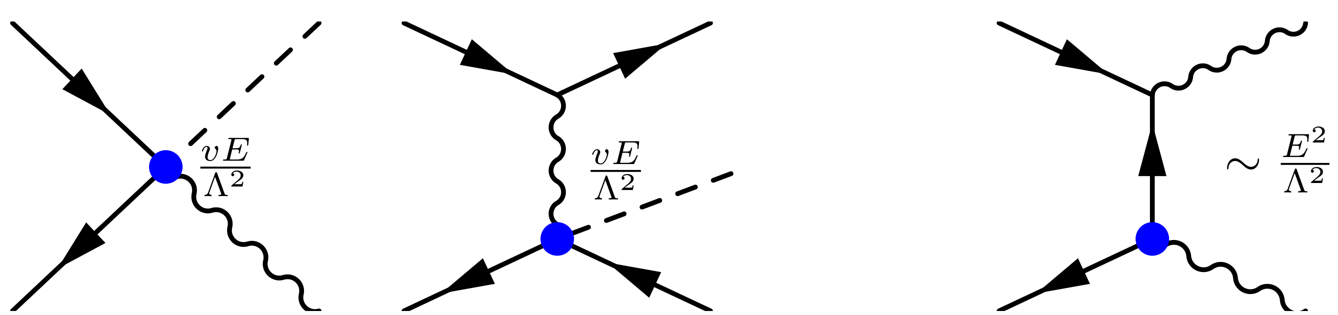
Contact operator predicted by gauge invariant construction





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

Precision EW on the Z peak (LEP)



EW Higgs production

Diboson production

Energy growth from non energy growing vertex…?

Unitarity non-cancellation in ff→WW scattering!

Gauge only

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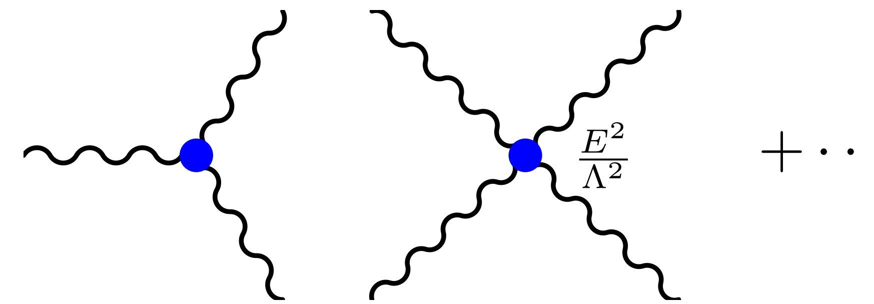
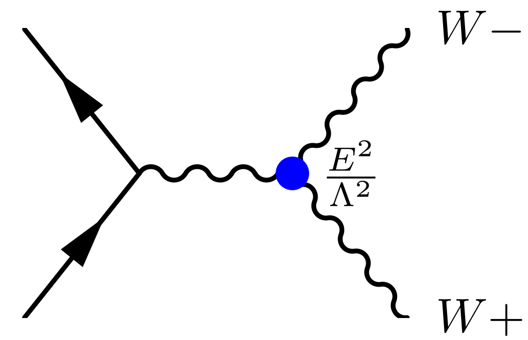
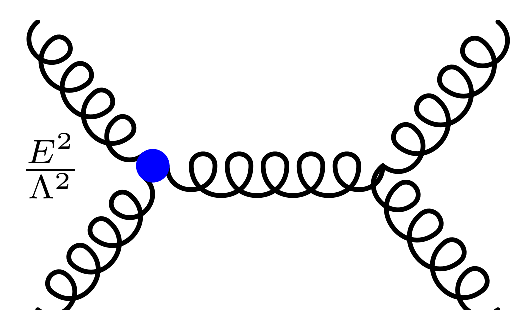
Anomalous triple & quartic gauge couplings





Diboson production LEP/LHC

Large energy growth w.r.t SM



Multi-jet production

Operators have CP violating versions

Gauge only

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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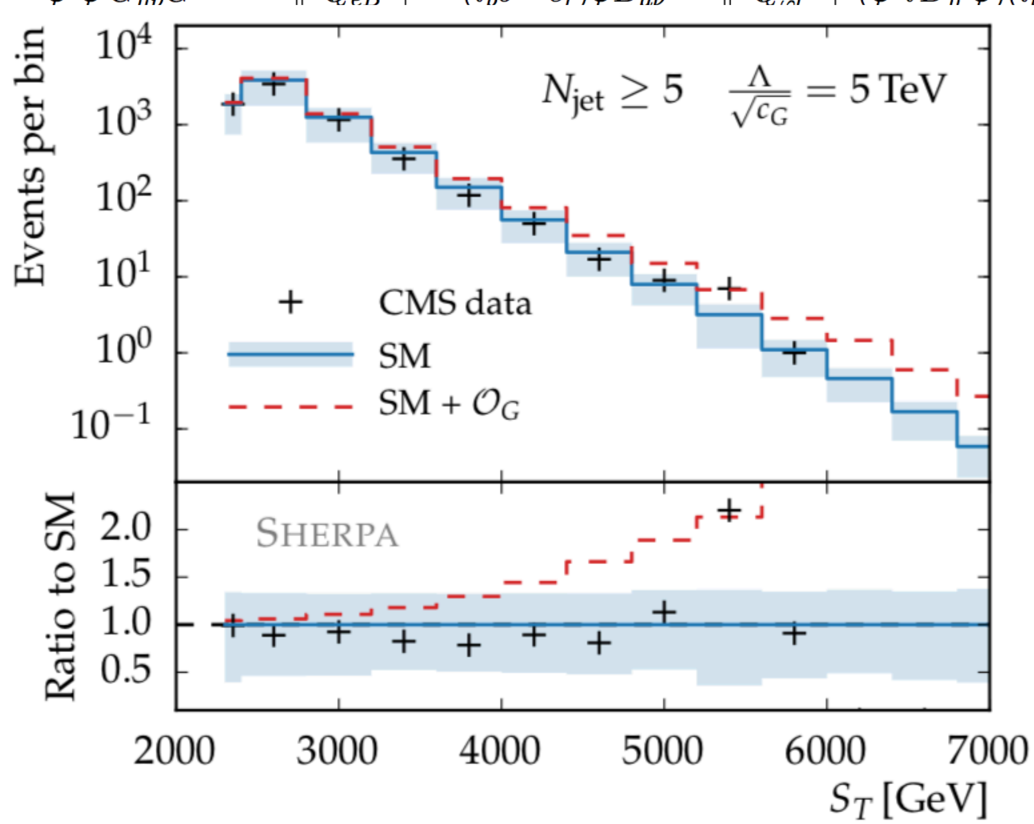
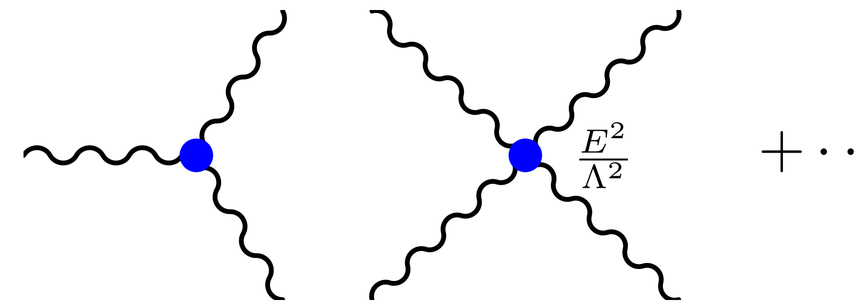
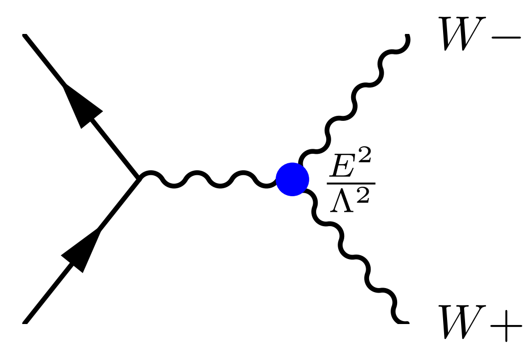
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$					$_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$					$_p\gamma^\mu q_r)$
$Q_{\varphi B}$					$\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$					$_p\gamma^\mu u_r)$
$Q_{\varphi WB}$					$_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$					$_p\gamma^\mu d_r)$



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

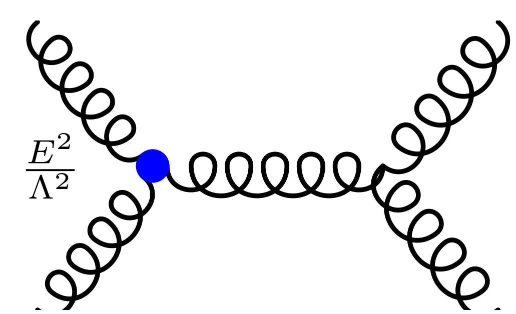
Anomalous triple & quartic gauge couplings





Diboson production LEP/LHC

Large energy growth w.r.t SM



Multi-jet production

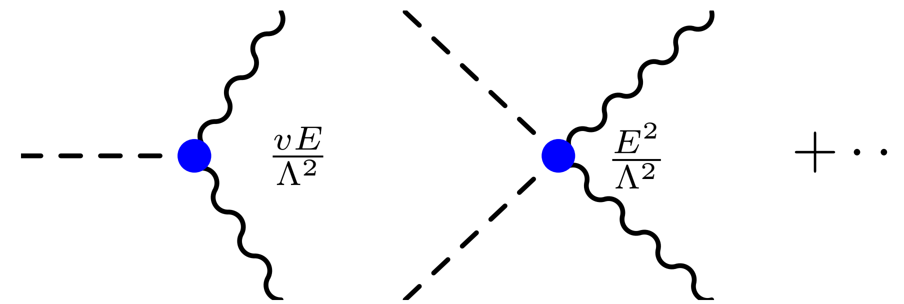
Operators have CP violating versions

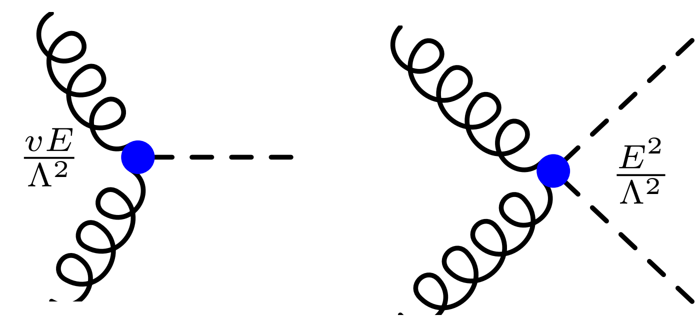
Gauge/Higgs

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	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]	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

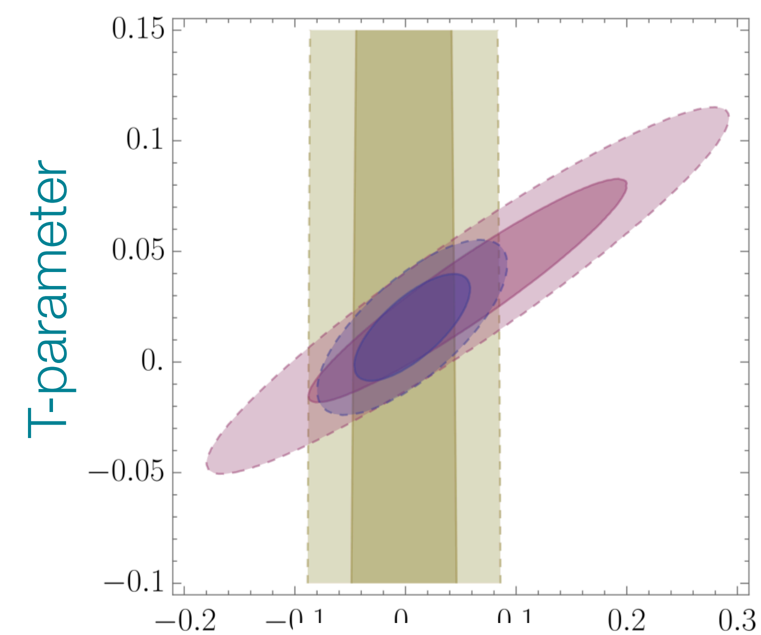
CP violating versions

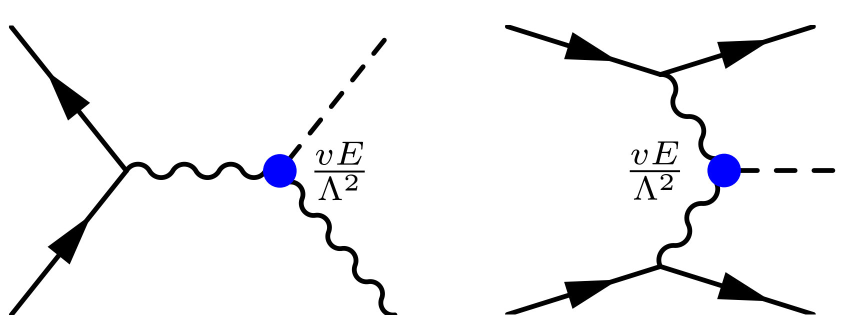




Gluon fusion: Higgs, di-Higgs

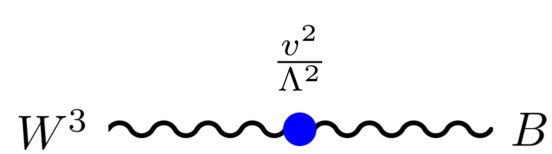
[Ellis et al.; JHEP 06 (2018) 146]





EW Higgs production & decay

kinetic mixing

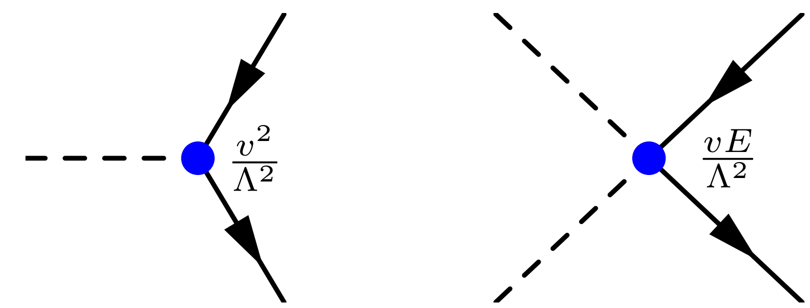


EW precision test

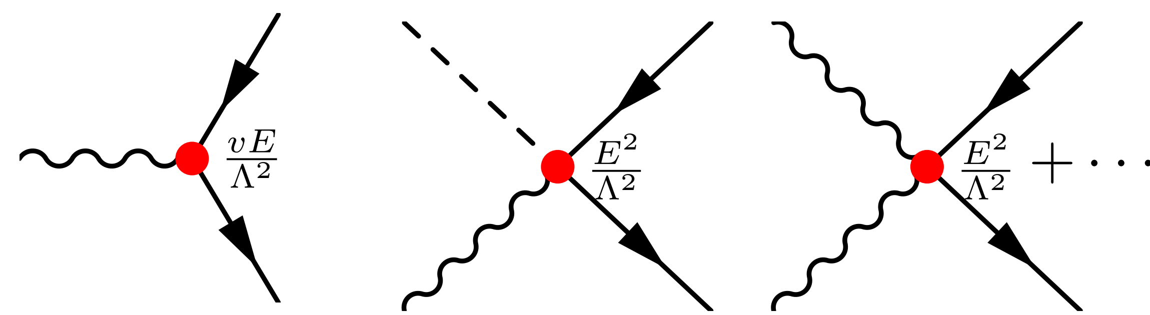
Two fermions

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

Yukawa operators

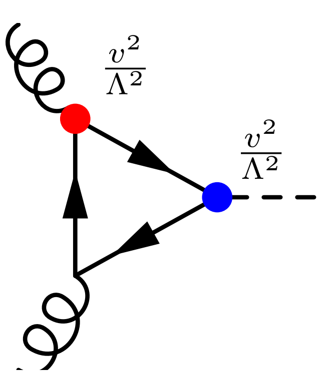


Dipole operators: Z, W, γ, g

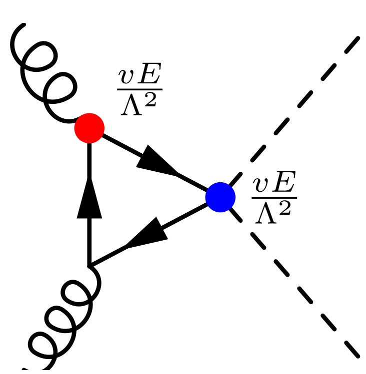


Non-Abelian

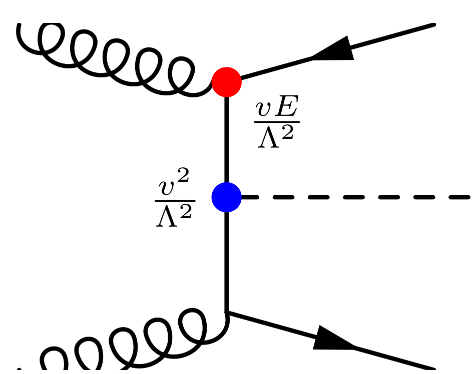
Interplay between Yukawa, dipoles & ggH



ggH

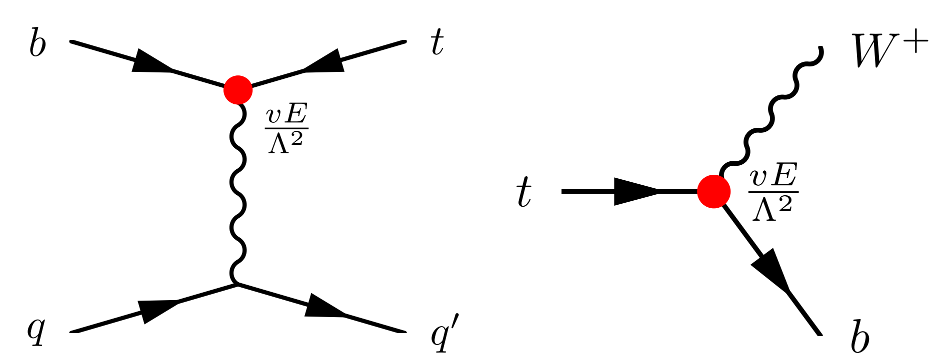


ggHH



ttH

Different energy & helicity structure



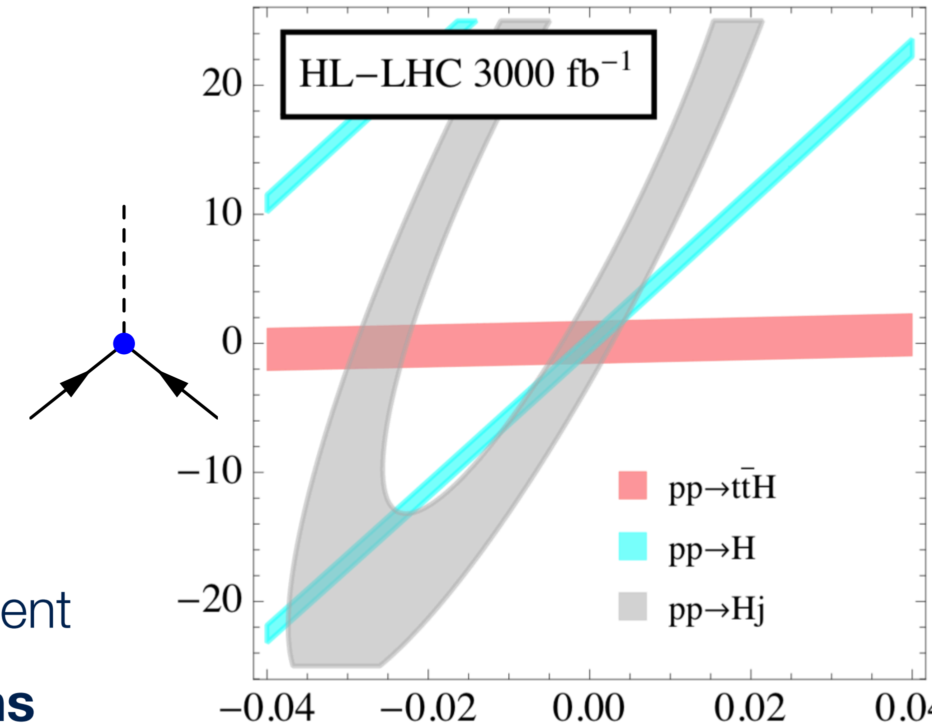
EW top production & decay

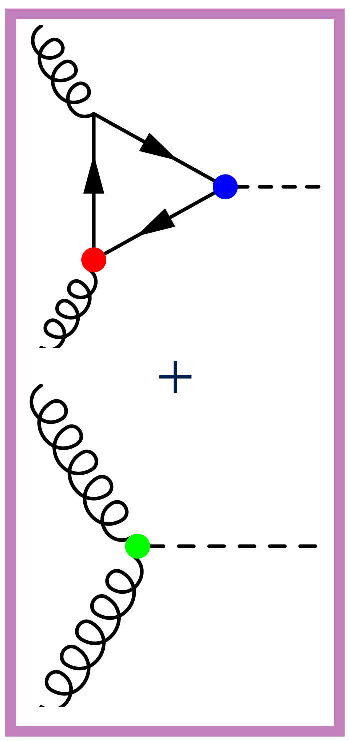
Global approach

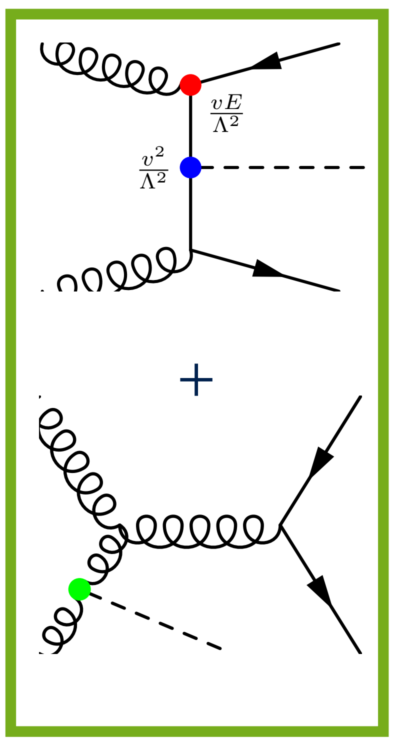
Global approach essential

- e.g. direct ttH measurement breaks **degeneracy** among y_t, ggH and dipole in gg-fusion

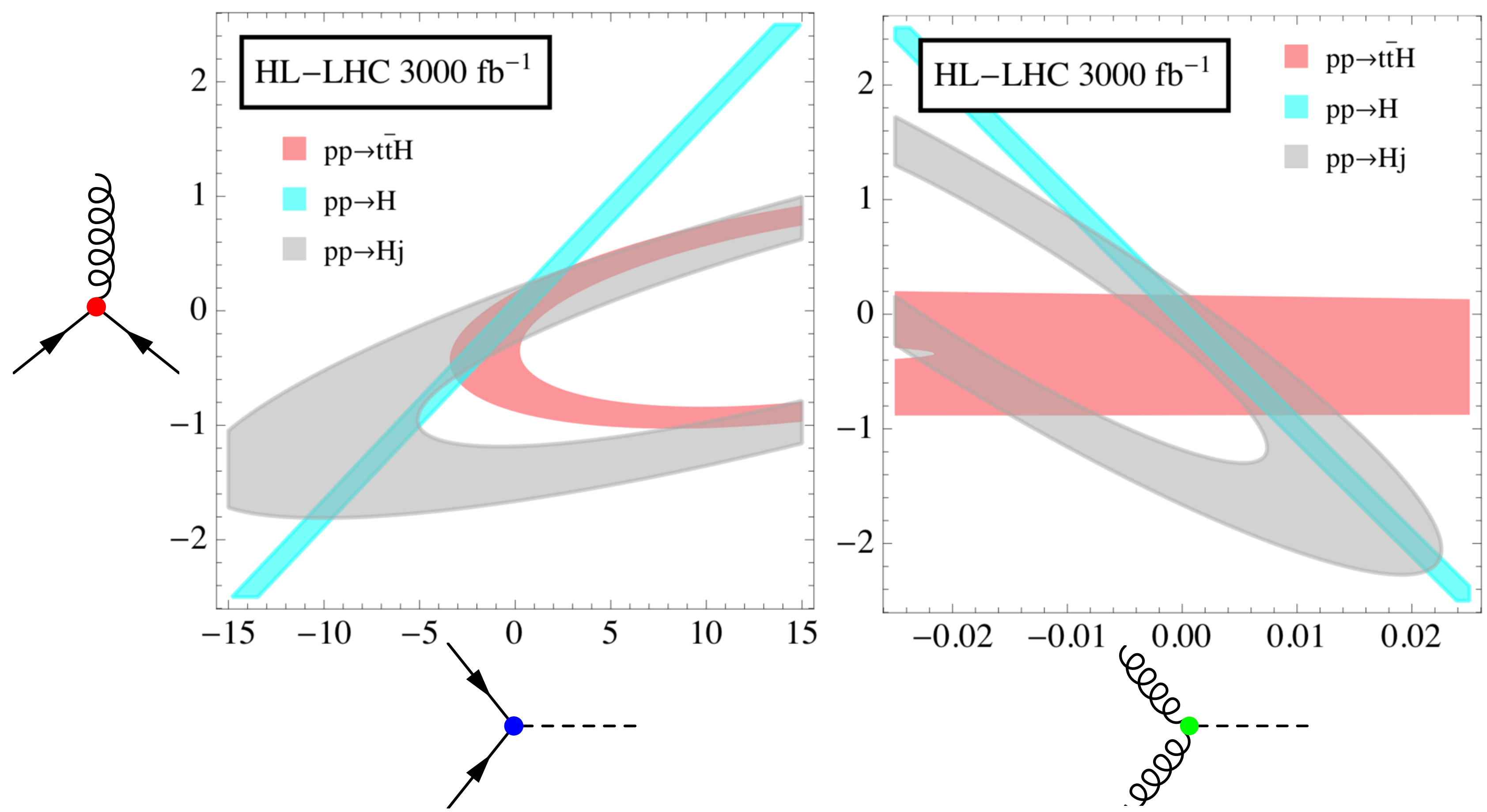
[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]







Single measurement
=
Blind directions



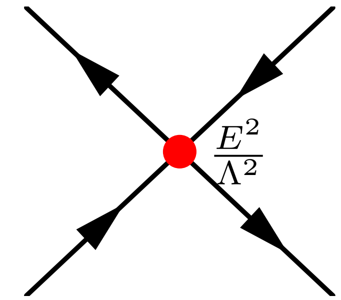
Pin down heavy coloured particles in the loop

Four fermions

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Pandora's box of SMEFT



Many structures allowed:

Lorentz scalar/vector currents

SU(2) singlet/triplet

SU(3) singlet/octet

They appear **everywhere…**

We can limit their number by assuming *flavor universality*

For the LHC, the interesting set involves at least one qq current

Four light quarks (qqqq) → dijet production (strong constraints)

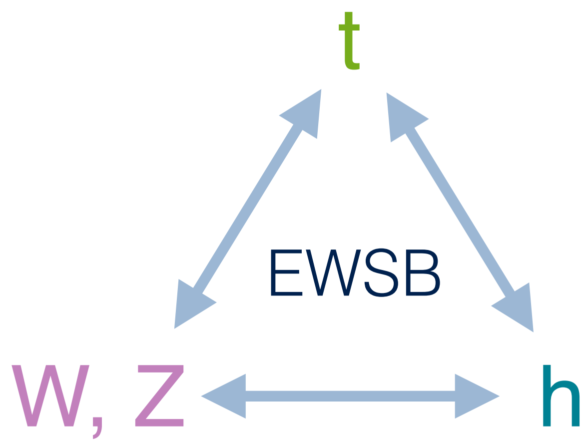
Two light-two lepton (qqll) → Drell Yan (strong constraints)

Two light-two heavy (qqQQ) → tt invariant mass, single top (quite strong constraints)

Four heavy (QQQQ) → 4 top, ttbb (relatively unconstrained)

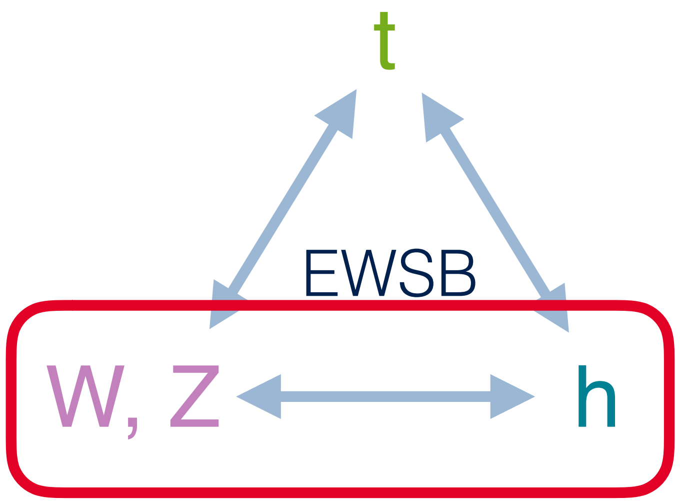
Also contribute to higher point (ttH, ttZ, ttW, Zjj,…) and 'pollute'/complicate fits

SMEFT for EWSB sector



SMEFT for EWSB sector

Bosonic operators of flavor universal bases cover deviations in the gauge/Higgs sector

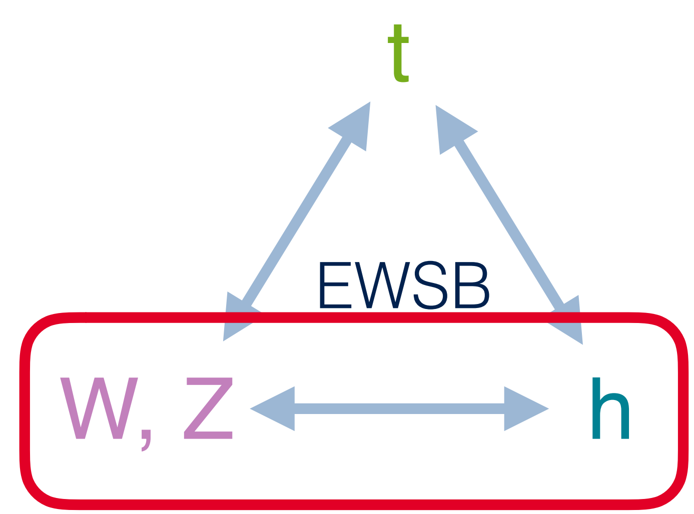


SMEFT for EWSB sector

Bosonic operators ... es
cover deviations ir ... or

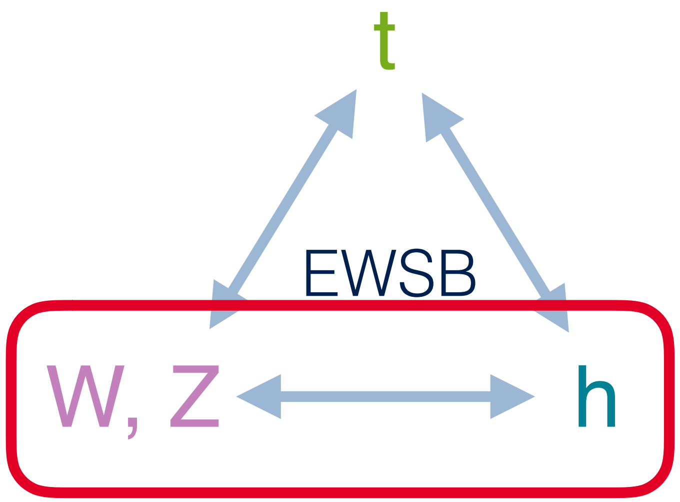
X^3		φ^6 and $\varphi^4 D^2$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu}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

$X^2\varphi^2$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

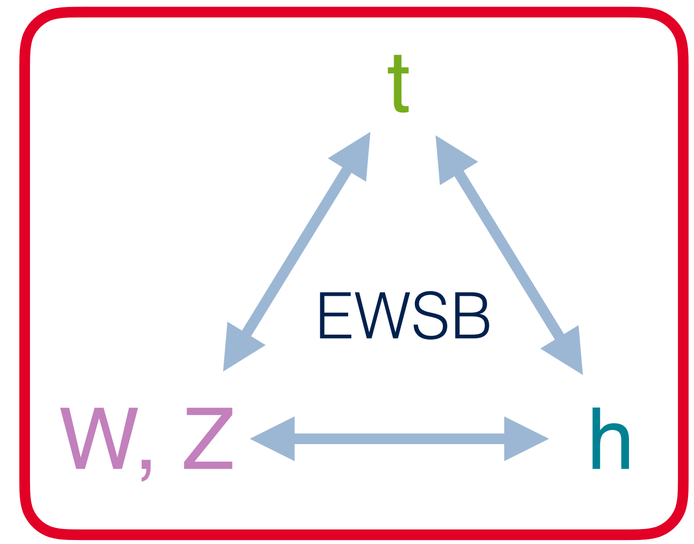


SMEFT for EWSB sector

Bosonic operators of flavor universal bases cover deviations in the gauge/Higgs sector



SMEFT for EWSB sector



Bosonic operators of flavor universal bases cover deviations in the gauge/Higgs sector

Including the top → going beyond universal flavor assumption

Exploit *approximate* SM flavor symmetry (broken by Yukawas)

universal	$U(3)_L \times U(3)_e \times U(3)_Q \times U(3)_u \times U(3)_d$
top	$U(3)_L \times U(3)_e \times U(2)_Q \times U(2)_u \times U(3)_d$

cf. Minimal flavor violation [D'Ambrosio et al.; Nucl. Phys. B645 (2002) 155]

Single out independent operators for modified top/EW interactions

$$\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{Q}\, t\, \tilde{\varphi})$$

$$\psi^2 X H : (\bar{Q}\, \sigma^{\mu\nu}\, t\, \tilde{\varphi}) B_{\mu\nu}\ [W^I_{\mu\nu},\, G^a_{\mu\nu}]$$

$$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\, \gamma^\mu\, Q)\ [(\bar{Q}\, \gamma^\mu \tau^I\, Q),\, (\bar{t}\, \gamma^\mu\, t), ...]$$

$$\psi^4 : (\bar{Q}\, \gamma^\mu\, Q)(\bar{q}\, \gamma_\mu\, q),\, (\bar{Q}\, \gamma^\mu\, Q)(\bar{Q}\, \gamma_\mu\, Q), ...$$

Top quark interactions not so well known: LHC is the first precision top machine

MC tools for SMEFT

SMEFT programme requires MC tools for precise predictions

Several implementations exist, mostly FeynRules/UFO

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

At LO:

- HEL, SMEFTsim, dim6top…
- Higgs Characterisation, BSMC, HiggsPO

[Alloul et al.; JHEP 1404 (2014) 110]
[Brivio et al.; JHEP 1712 (2017) 070]
[Aguilar Saavedra et al.; arXiv:1802.07237]
[Artoisenet et al.; JHEP 1311 (2013) 043]
[Falkowski et al.; EPJC 75 (2015) 12, 583]
[Greljo et al,; EPJC 77 (2017) 12, 838]

NLO precision can be important

- Reduce scale uncertainties, get better predictions for normalisations/shapes
- Operator sensitivity can arise at one-loop

Useful if relatively **weakly constrained** directions contribute to **precisely measured** observables

This is the state-of-the-art

- Currently NLOQCD is available
- Will provide required precision in SMEFT analyses for the LHC lifetime

Beyond LO

Going beyond: **SMEFT@NLO**

[Degrande, Durieux, Maltoni, KM, Vryonidou, Zhang; in preparation]

- NLO QCD (FeynRules//NLOCT/UFO) *http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO*
- Full EWSB sector (top/Higgs/EW)

Based on:

[Zhang; PRL 116 (2016) 162002]	single-top
[Bylund, Maltoni, Tsinikos, Vryonidou, Zhang; JHEP 1605 (2016) 052]	ttZ & ttγ
[Maltoni, Vryonidou, Zhang; JHEP 1610 (2016) 123]	ttH, ggH, H+j
[Degrande, Fuks, Mawatari, KM, Sanz; EPJC 77 (2017) 4, 262]	VH & VBF
[Degrande, Maltoni, KM, Zhang, Vryonidou; JHEP 1810 (2018) 005]	tZq & tHq

Advantage: **process independent**

- NLO QCD for any desired process
- 4 fermion operators forthcoming

The full (2499 x 2499) anomalous dimension matrix known

- RG-improved predictions possible
- Running from matching scale to e.g. LHC
- EFT scale uncertainties

[Alonso, Jenkins, Manohar & Trott; JHEP 1310 (2013) 087, JHEP 1401 (2014) 035 & JHEP 1404 (2014) 159*]*

Other tools

[Spira; arXiv:hep-ph/9510347]
[Harlander, Liebler & Mantler; arXiv:1605.03190]
[Dawson, Dittmaier & Spira; Phys. Rev. D58:115012]
[Goertz et al.; JHEP 1504 (2015) 167]

Single & double Higgs

- HiGlu, SusHi, HPAIR, HiggsPair

eHDECAY for BR

[Contino et al.; Comp. Phys. Comm. 185 (2014) 3412-3423]
https://www.itp.kit.edu/~maggie/eHDECAY/

HAWK

[Denner et al.; JHEP 1203 (2012) 075]
http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk

- VBF and VH @ NLO in QCD & EW for SM + 2 anomalous couplings

VBFNLO

[Baglio et al.; arXiv:1404.3940]
https://www.itp.kit.edu/vbfnlo

- General (FO) tool for Higgs/weak boson production @ NLO in QCD

VH via POWHEG-BOX/MCFM

[KM, Sanz & Williams.; JHEP 1608 (2016) 039]
http://powhegbox.mib.infn.it

- NLO QCD + PS event generation for Higgs/EW operators (SILH)

HELatNLO

[Degrande, et al.; EPJC 77 (2017) 4, 262]
http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO

- FeynRules/NLOCT/UFO implementation of Higgs/EW operators
- VH, VBF & any other process of interest (CPV operators also on the way)

Dilepton & EW Higgs in POWHEG-BOX

[Alioli et al.; JHEP 08 (2018) 205]
http://powhegbox.mib.infn.it

- Larger set of operators considered

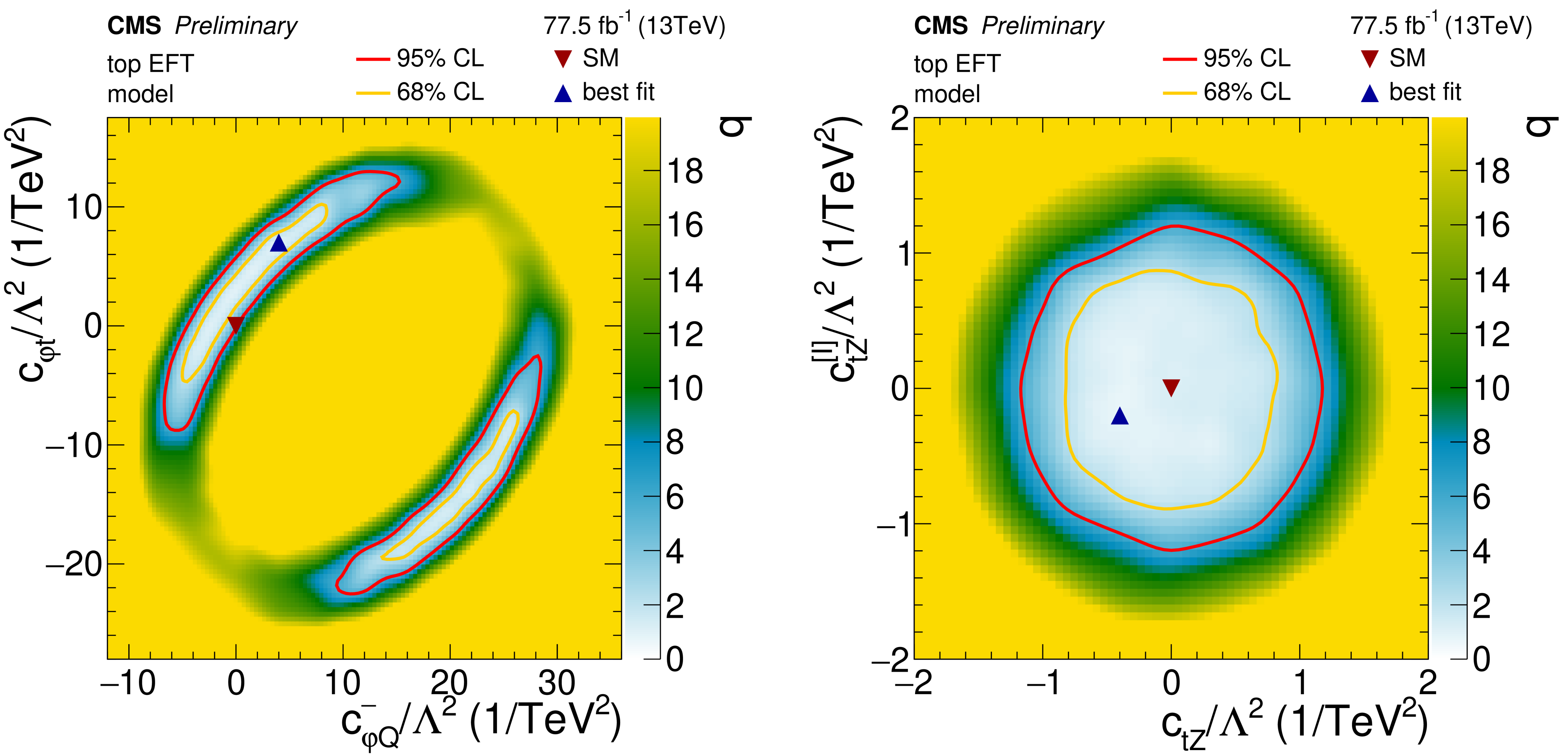
Applications: LHC

Applications: LHC

Increasing number of EFT interpretations in LHC analyses

Applications: LHC

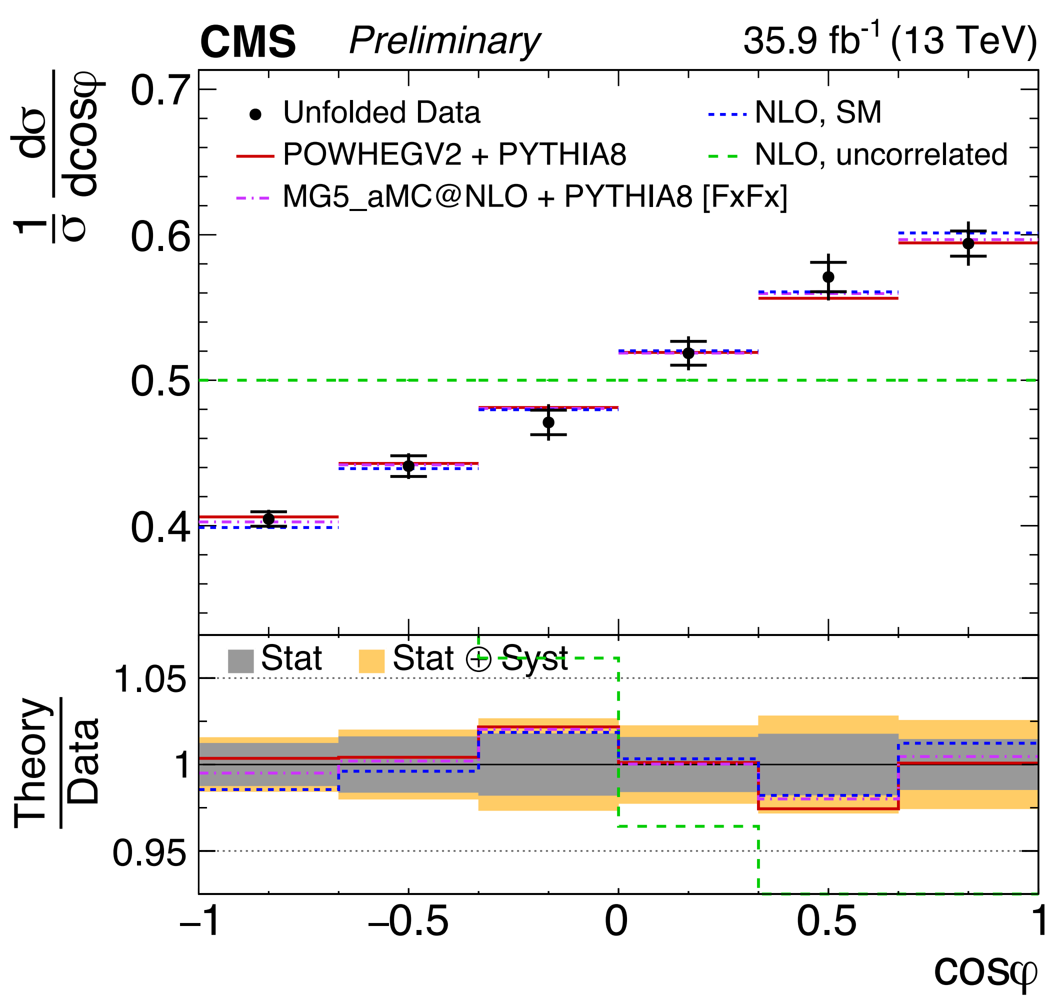
Increasing number of EFT interpretations in LHC analyses

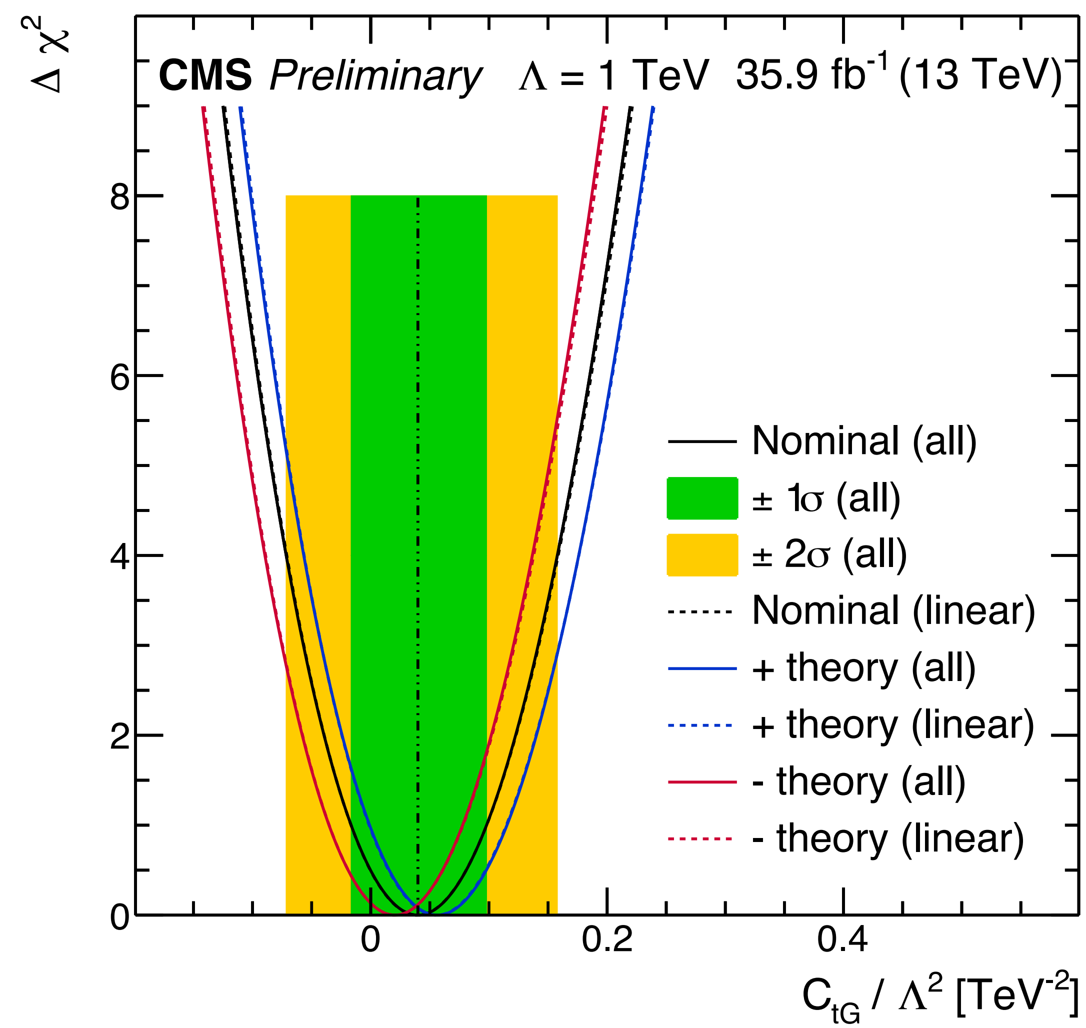


ttZ differential [CMS-PAS-TOP-18-009]

Applications: LHC

Increasing number of EFT interpretations in LHC analyses

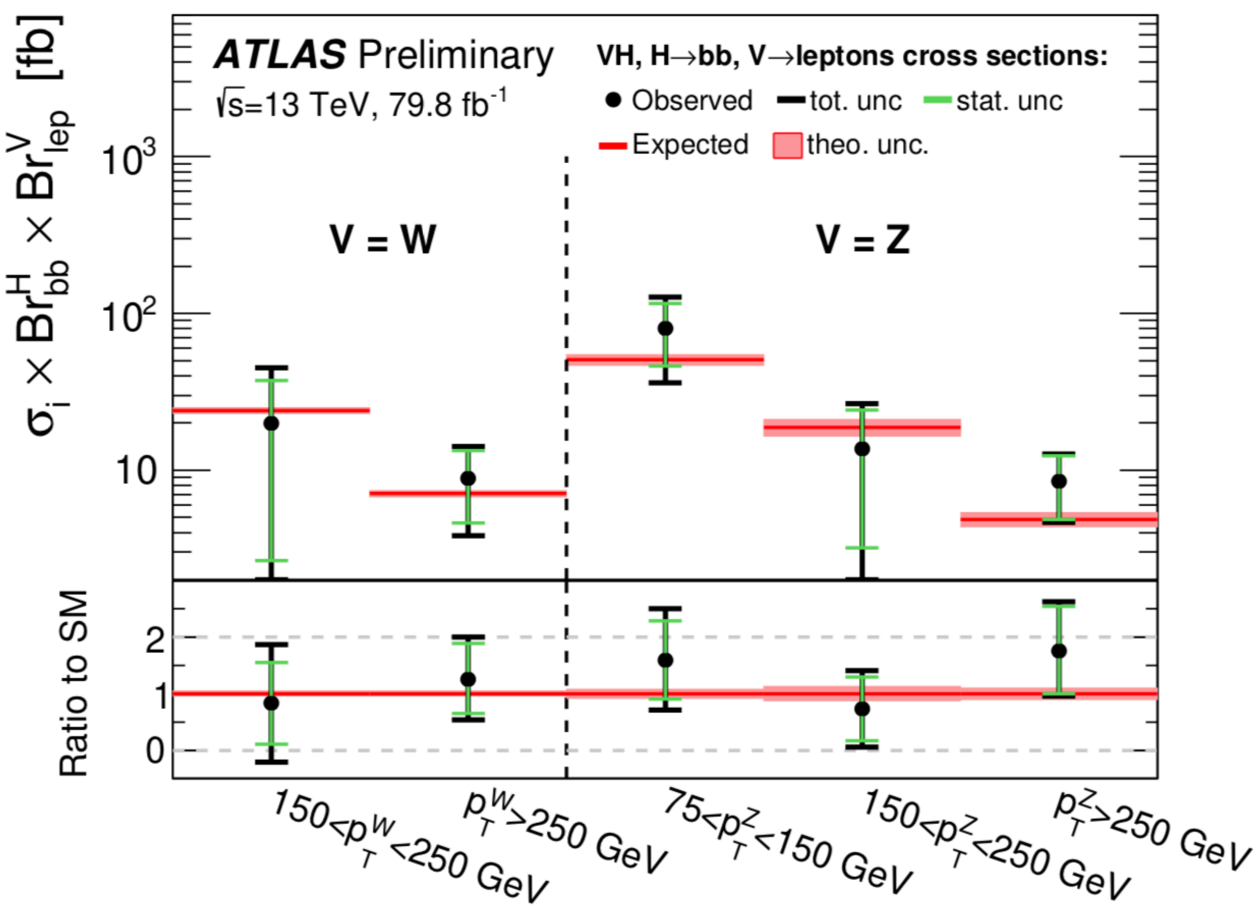


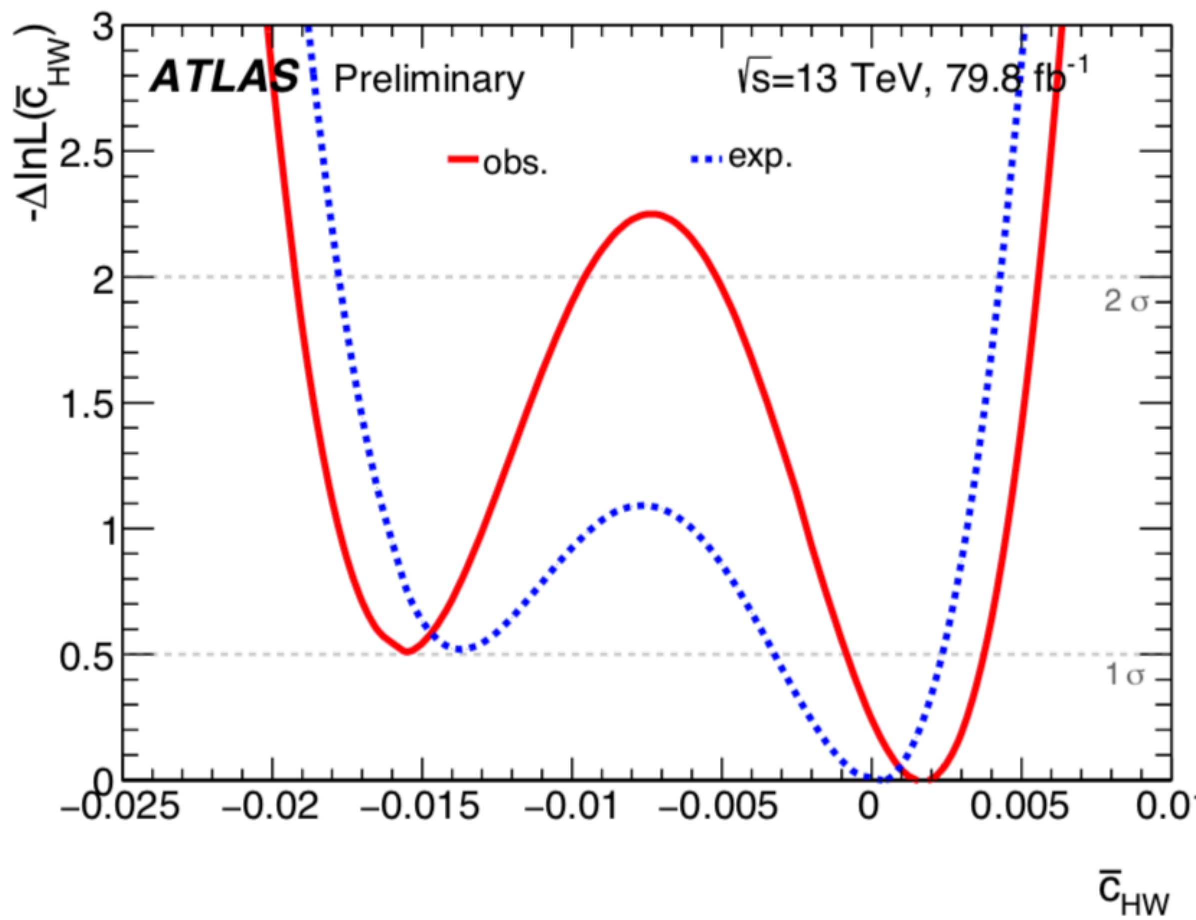


tt polarisation/spin corr. *[CMS-PAS-TOP-18-006]*

Applications: LHC

Increasing number of EFT interpretations in LHC analyses

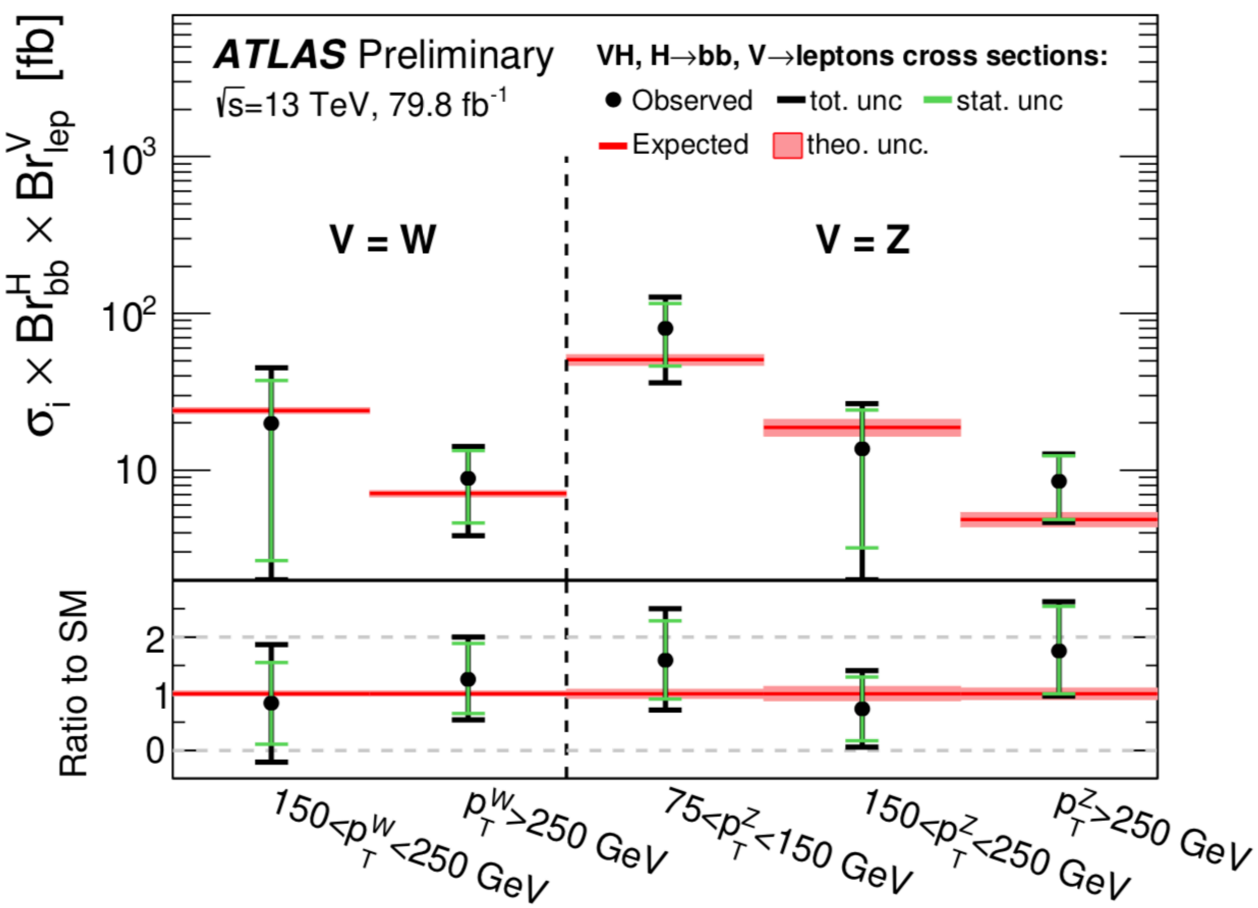


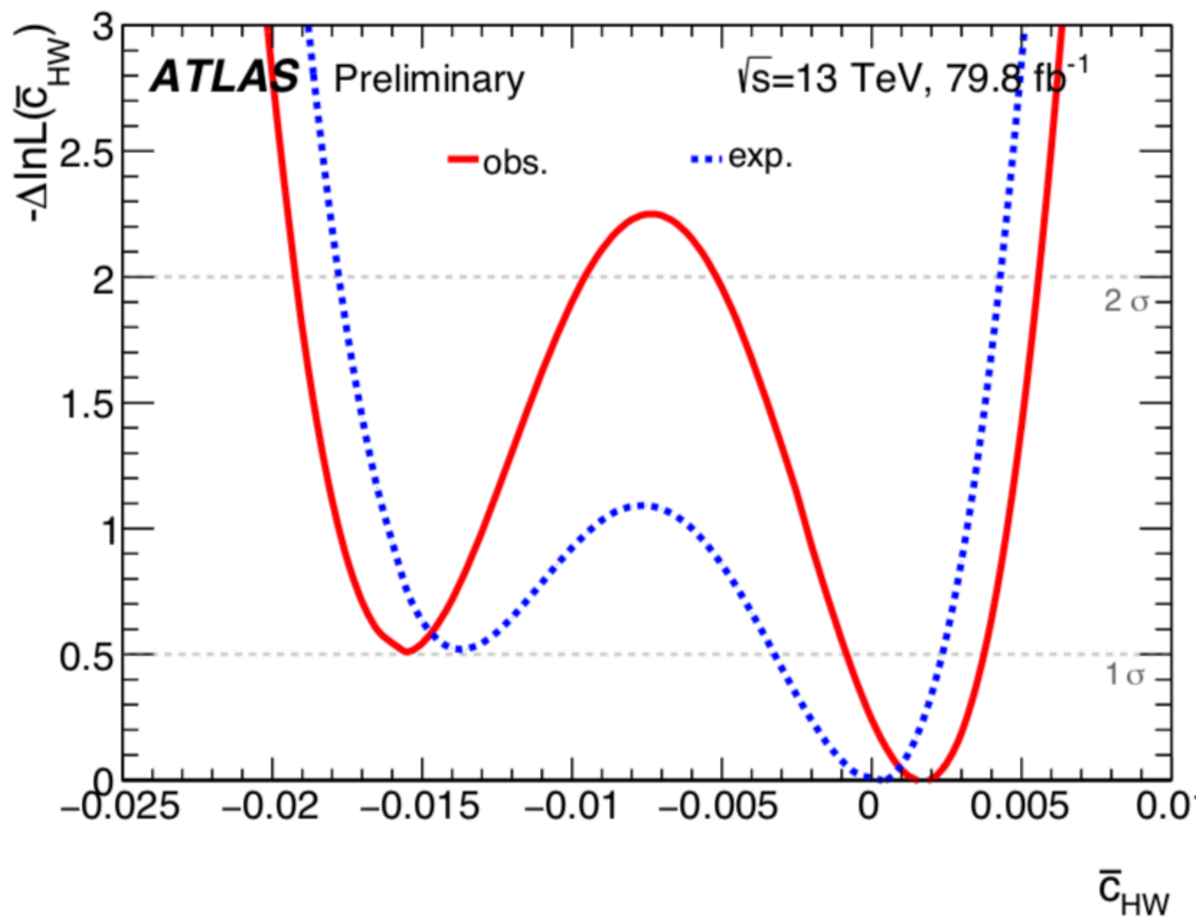


VH STXS *[ATLAS-CONF-2018-053]*

Applications: LHC

Increasing number of EFT interpretations in LHC analyses

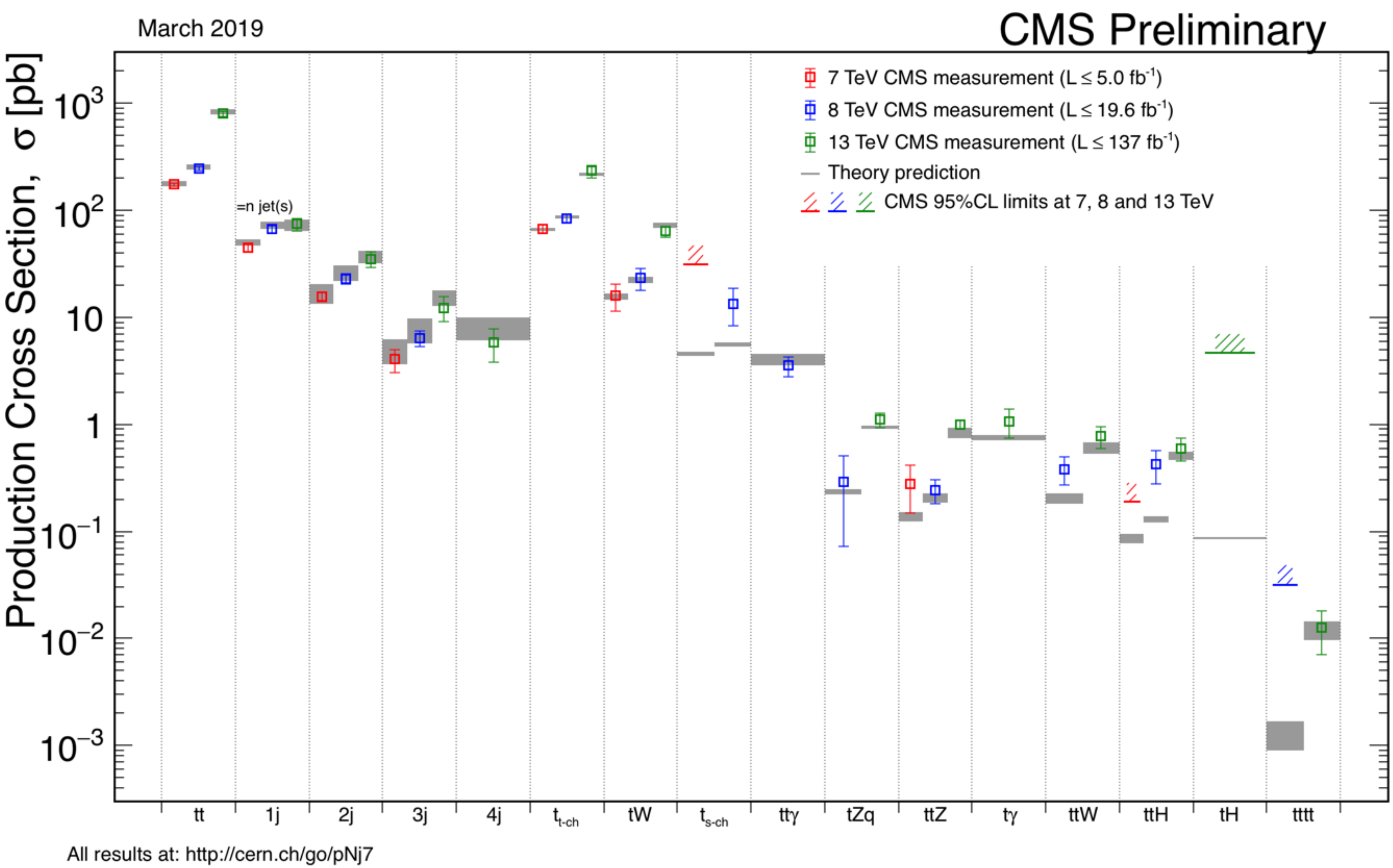




VH STXS *[ATLAS-CONF-2018-053]*

Limited to small subsets of operator space

LHC top measurements



Application: SMEFiT

State-of-the-art top EFT fit

[Hartland et al.; JHEP 1904 (2019)100]

- (N)NLO QCD predictions for SM
- Mostly NLO QCD for SMEFT
- 34 Wilson coefficients

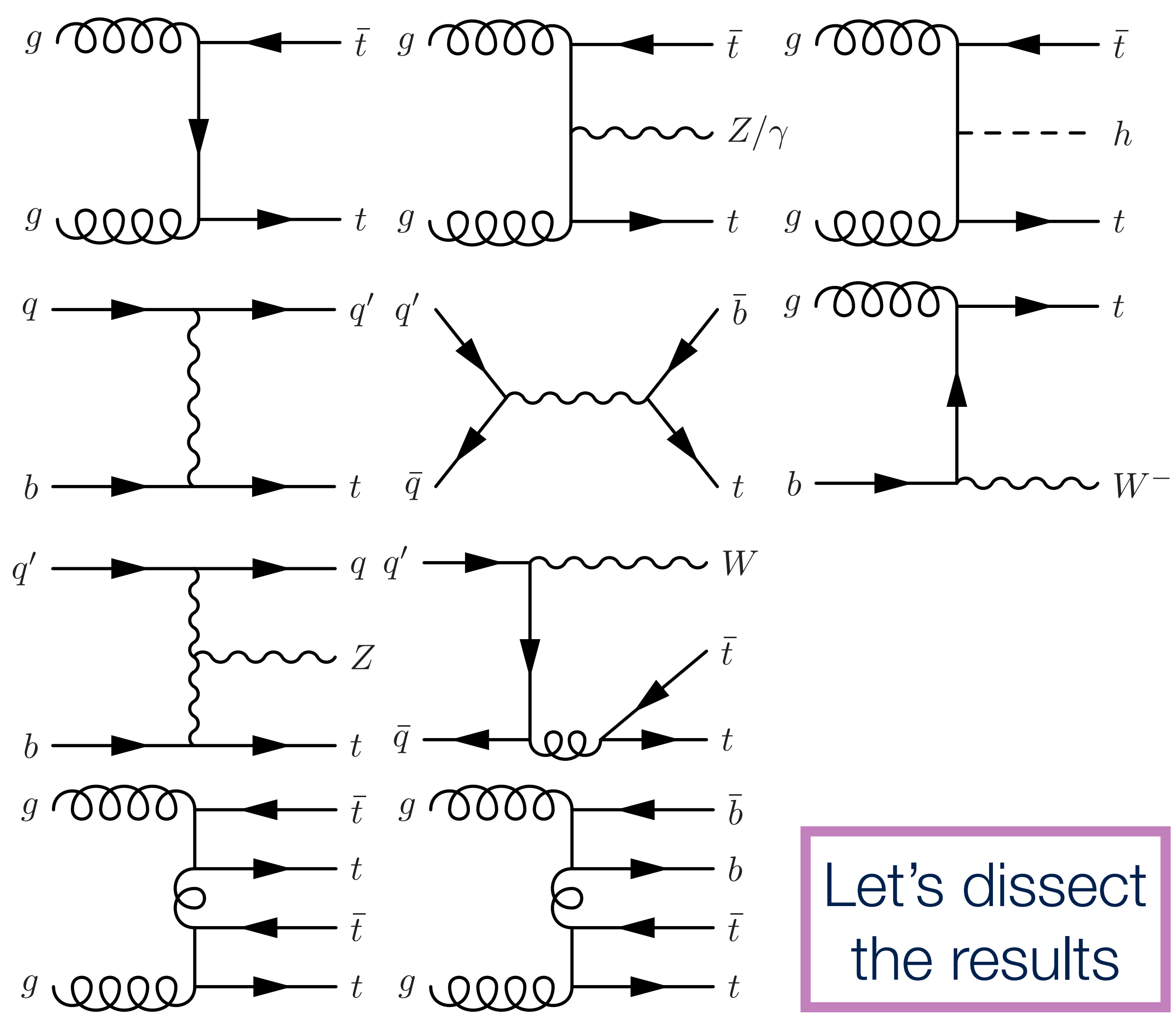
4F

c^{1}_{QQ}	$c^{1,8}_{Qq}$
c^{8}_{QQ}	$c^{1,1}_{Qq}$
c^{1}_{Qt}	$c^{3,8}_{Qq}$
c^{8}_{Qt}	$c^{3,1}_{Qq}$
c^{1}_{Qb}	c^{8}_{tq}
c^{8}_{Qb}	c^{1}_{tq}
c^{1}_{tt}	c^{8}_{tu}
c^{1}_{tb}	c^{1}_{tu}
c^{8}_{tb}	c^{8}_{Qu}
c^{1}_{QtQb}	c^{1}_{Qu}
c^{8}_{QtQb}	c^{8}_{td}
	c^{1}_{td}
	c^{8}_{Qd}
	c^{1}_{Qd}

2F

c_{tG}
c_{tW}
c_{bW}
c_{tZ}
$c_{\varphi tb}$
$c^{3}_{\varphi Q}$
$c^{-}_{\varphi Q}$
$c_{\varphi t}$
$c_{t\varphi}$

- > 100 7,8,13 TeV LHC measurements
- > 10 production processes



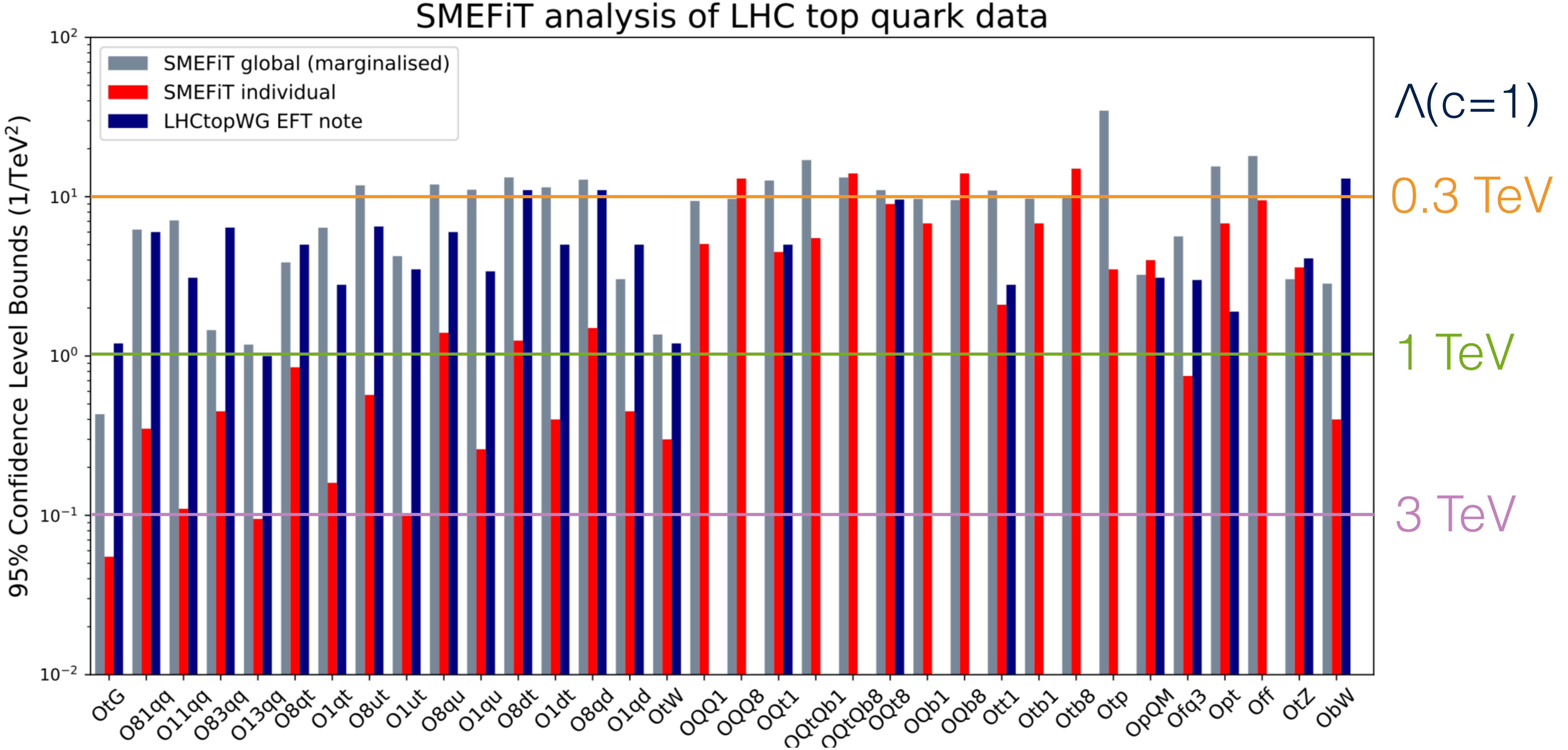
Let's dissect the results

SMEFiT results

Individual: all other c's=0 Marginalised: all other c's allowed to vary

"New physics scale"

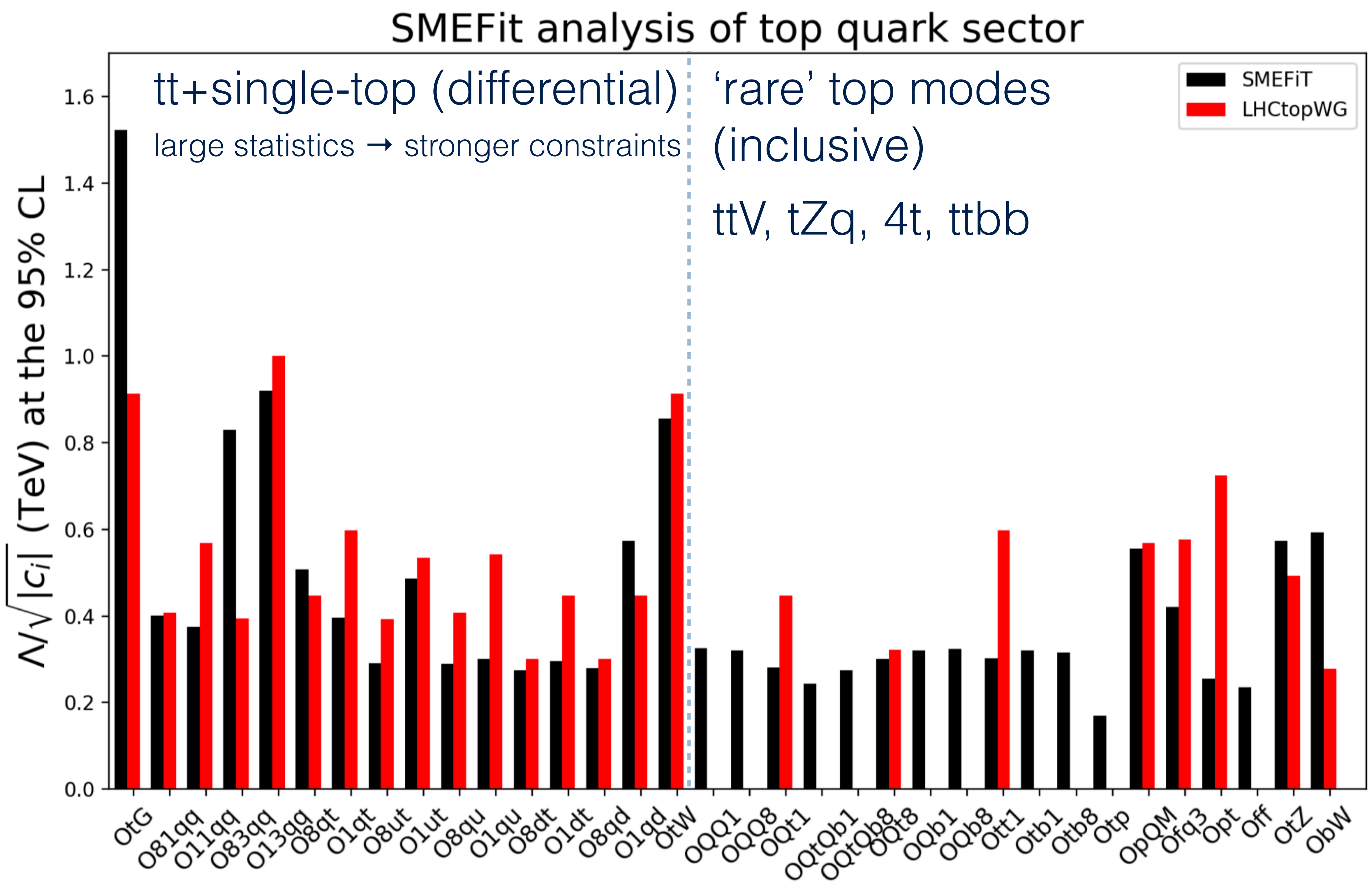
$$\frac{c_i}{\Lambda^2} = a_i \rightarrow \Lambda = \sqrt{\frac{c_i}{a}}$$



Energy reach

Some scales as low as few 100's of GeV

LHC measurements easily at this scale!



Validity in question…

Still much further to go

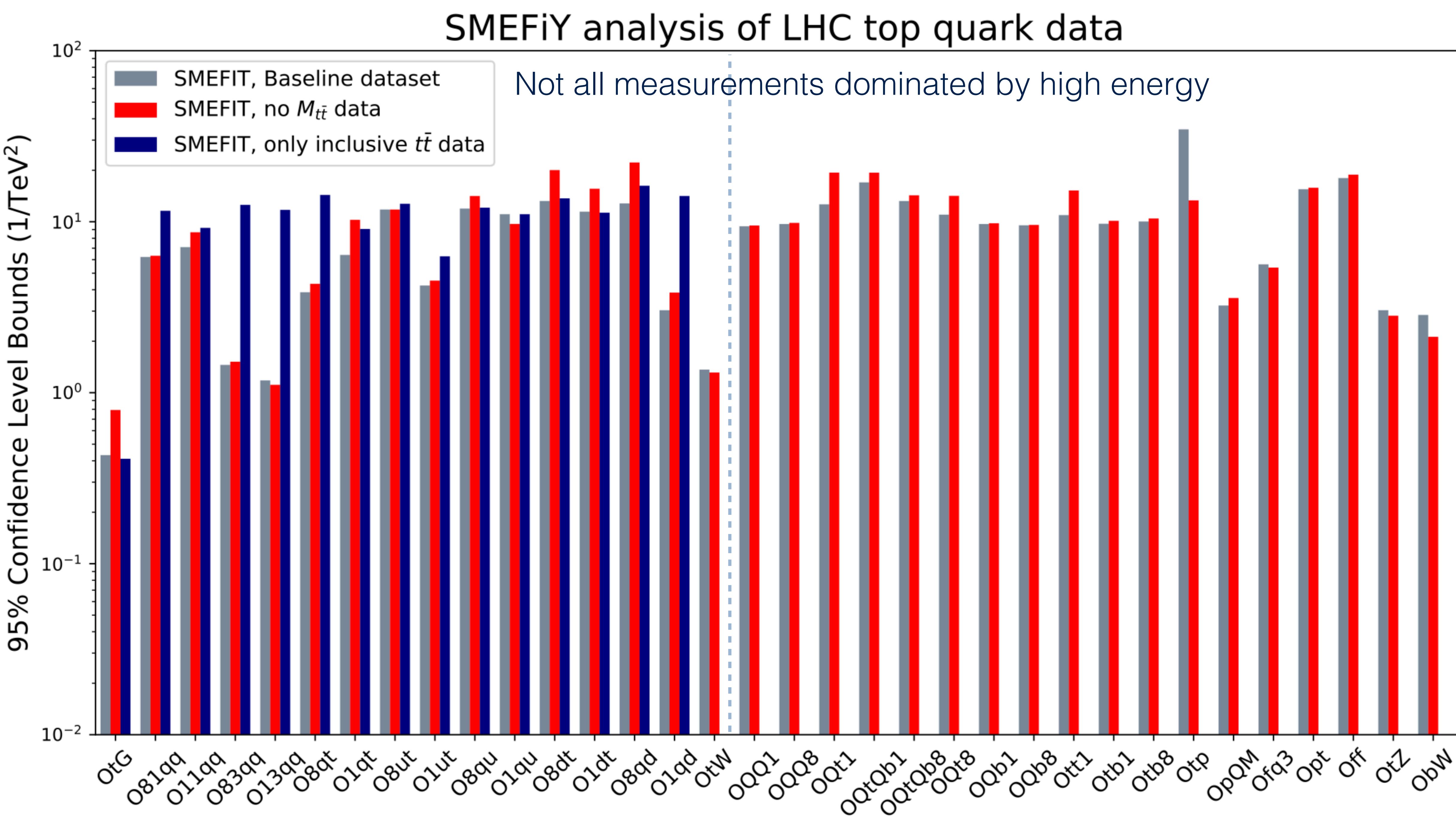
$\lesssim$ 100 fb^{-1}

↓

3000 fb^{-1}

Validity

Check impact of high energy by removing differential M_{tt} data

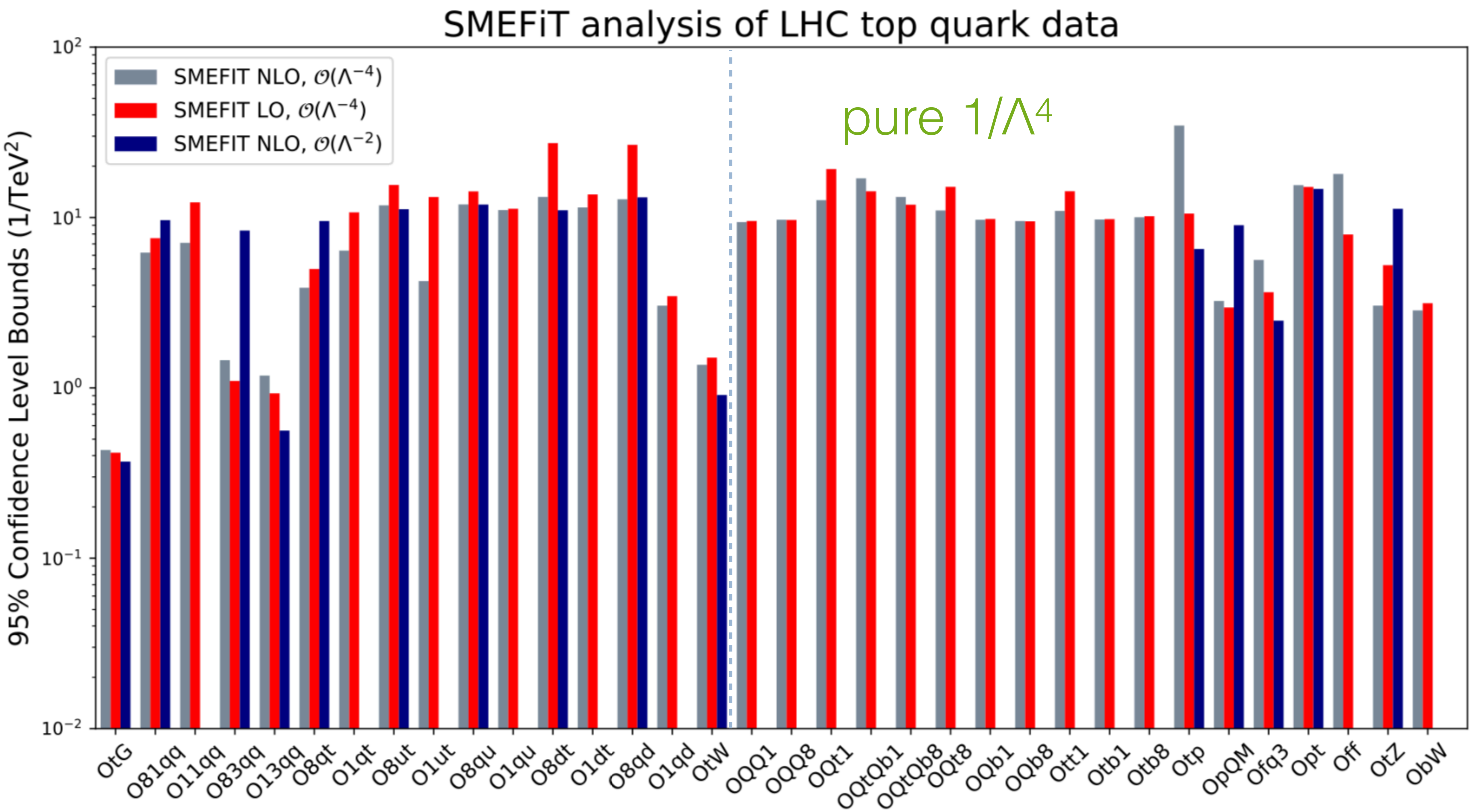


Higher orders

$$\mathcal{O} = \mathcal{O}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}^i_{\rm int} + \sum_{i,j} \frac{c_i\, c_j}{\Lambda^4}\mathcal{O}^{ij}_{\rm sq}$$

Impact of NLO and $1/\Lambda^4$

LO vs NLO $1/\Lambda^2$ vs $1/\Lambda^4$



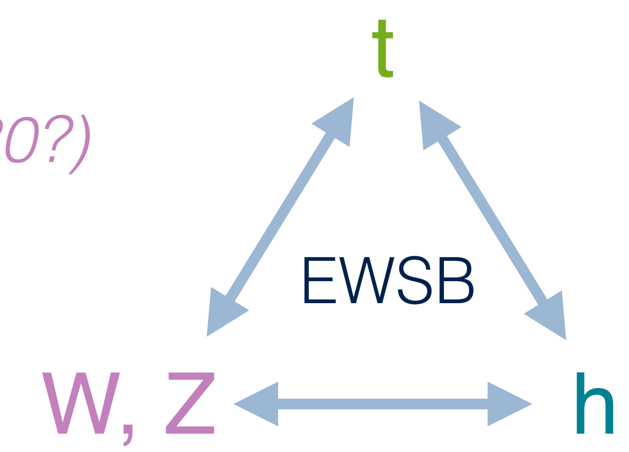
Going forward

So far, global analyses consider top & Higgs/EW in isolation

Many rare top/EW processes are within LHC reach

tγj *(2018)*, tZj *(2018)*, ttZ *(2019)*,
tZW *(2020?)*, 4t *(2021?)*, ttWj *(2021?)*, tHj *(~2030?)*

at the heart of EWSB



Timely moment to consider them together

- Make statements about models that address the origin of the weak scale
- Exploit new NLO QCD technology for SMEFT

Thorough programme of sensitivity studies

- Identify new processes e.g. ttbb
- Maximise energy growing effects

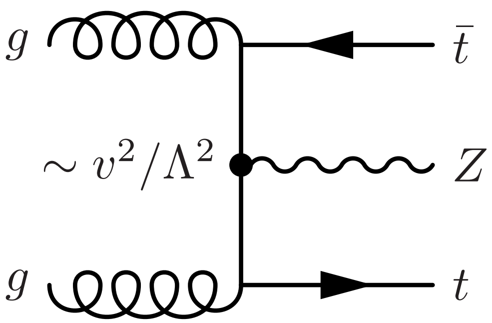
[D'Hondt, Mariotti, KM, Moortgat & Zhang; JHEP 1811 (2018) 131]

[Mantani, Maltoni & KM; arXiv:1904.05637]
[Dror et al.; JHEP 01 (2016) 071]

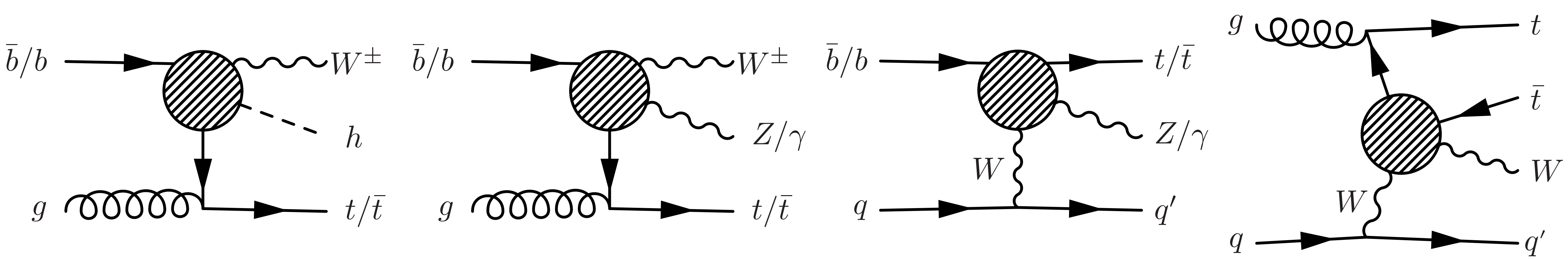
High-energy EW tops

Can we do better? Many EW processes considered so far:

- **Do not** grow maximally with energy (E^2)
- Have **suppressed** SM interference
- Are not at the heart of EWSB



This is the heart of EWSB!



Embed top/EW 2→2 scattering amplitudes

- Probe mixed top/EW/Higgs interactions
- Unitarity violating behaviour (energy growth) ∝ vE, E^2

Analogous to V_L scattering

Scattering unitarity

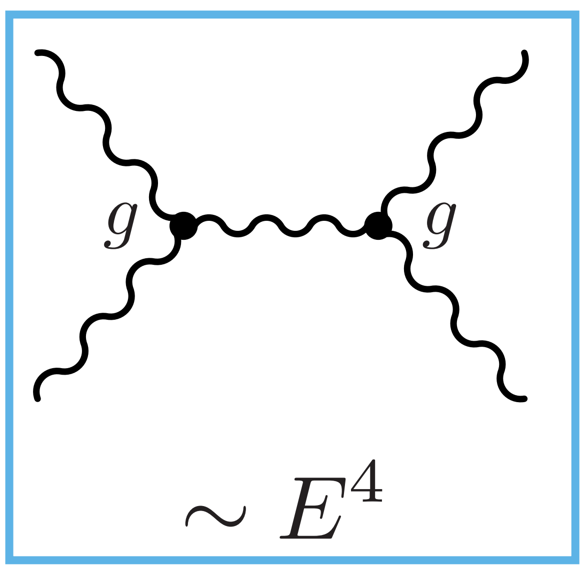
Scattering unitarity

$W_L\, W_L \rightarrow W_L\, W_L$: Unitarity ‘cancellations’ in the SM

Scattering unitarity

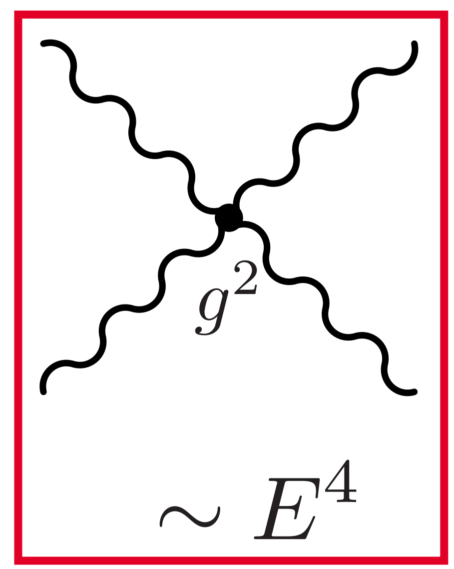
$W_L\, W_L \rightarrow W_L\, W_L$: Unitarity 'cancellations' in the SM

$\mathcal{A} =$



triple-gauge

$+$

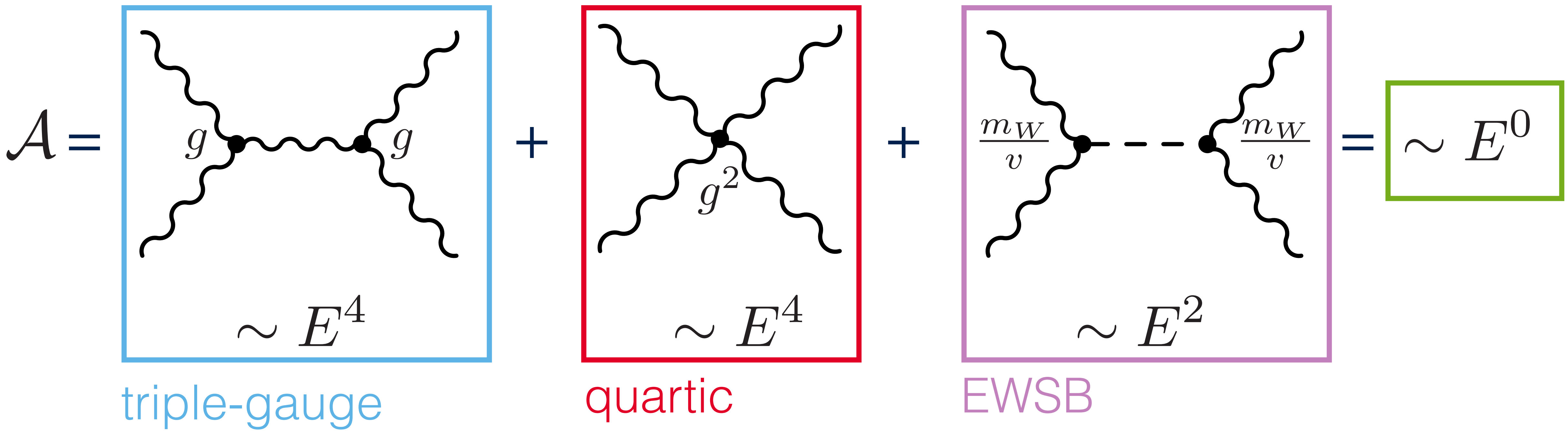


quartic

$= \sim E^2$

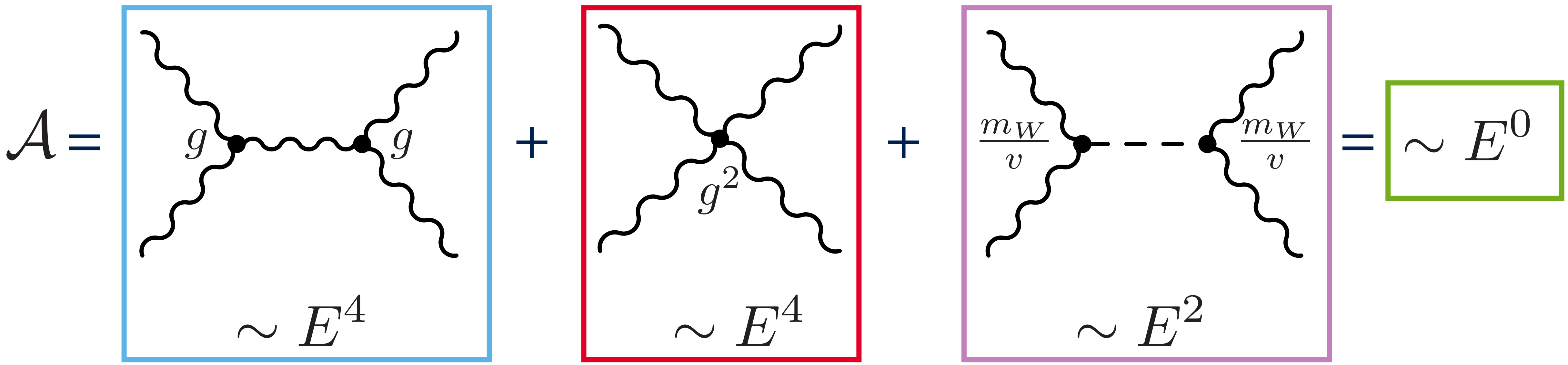
Scattering unitarity

$W_L W_L \rightarrow W_L W_L$: Unitarity ‘cancellations’ in the SM



Scattering unitarity

$W_L W_L \rightarrow W_L W_L$: Unitarity ‘cancellations’ in the SM



triple-gauge | quartic | EWSB

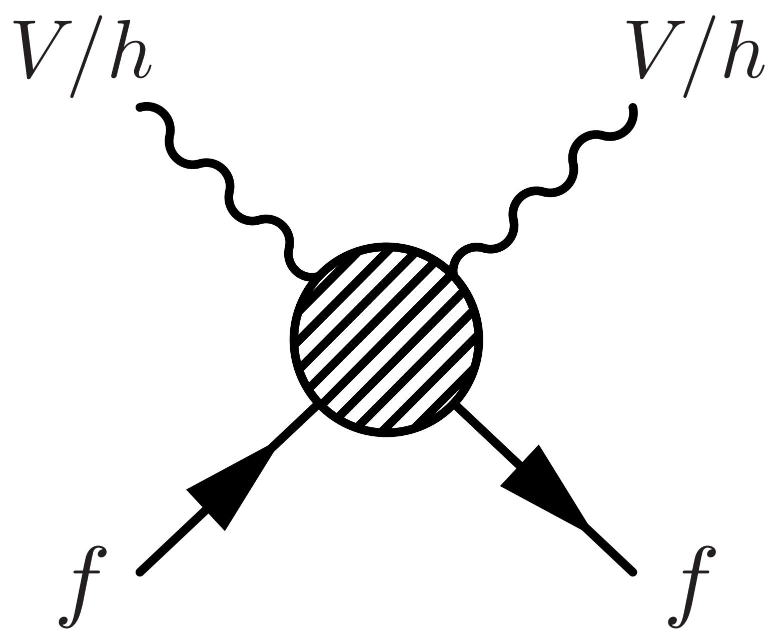
Diboson (TGC) | VBS (TGC, QGC) | EW Higgs prod./decay

Deviations from SM interactions → energy growth

- Cancellations are a feature of gauge invariance & EWSB mechanism
- E-growth: theory has limited validity range → heavy new physics

Tops and unitarity

Analogous behaviour in scatterings involving fermions



$$\mathcal{A} \sim E^2 \to E^0$$ gauge interactions

$$\mathcal{A} \sim m_f E \to E^{-1}$$ EWSB mechanism

High-energy limit with finite mass effects

- Top quark scattering sector especially rich

Limited validity range

Heavy new physics

→ SM Effective Field Theory

Energy growth in SMEFT

Dim-6

$$\mathcal{A} \sim \mathcal{A}_{SM}\left(1 + c_i\frac{v^2}{\Lambda^2} + c_j\frac{v\,E}{\Lambda^2} + c_k\frac{E^2}{\Lambda^2}\right)$$

'Energy helps accuracy'
[Farina et al.; PLB 772 (2017) 210-215]

Rate measurements will become systematics dominated

Increasingly high-energy measurements scale with lumi.

However, inserting an SMEFT operator into an amplitude does not guarantee energy growth…

Operator contribution to a given process:

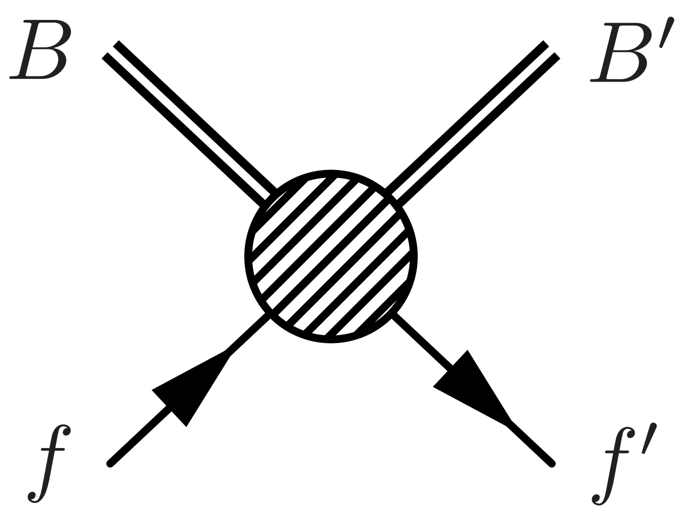
- **May not** grow maximally with energy (E^2)
- Have **suppressed** interference w/ SM

[Azatov et al.; PRD 95 (2017) no. 6, 065014]

There will always be some scattering amplitude that displays maximal (E^2) growth w.r.t the SM

Find and exploit them!

Our study



	Single-top	Two-top ($t\bar{t}$)
w/o Higgs	$b\,W \to t\,(Z/\gamma)$	$t\,W \to t\,W$ $t\,(Z/\gamma) \to t\,(Z/\gamma)$
w/ Higgs	$b\,W \to t\,h$	$t\,(Z/\gamma) \to t\,h$ $t\,h \to t\,h$

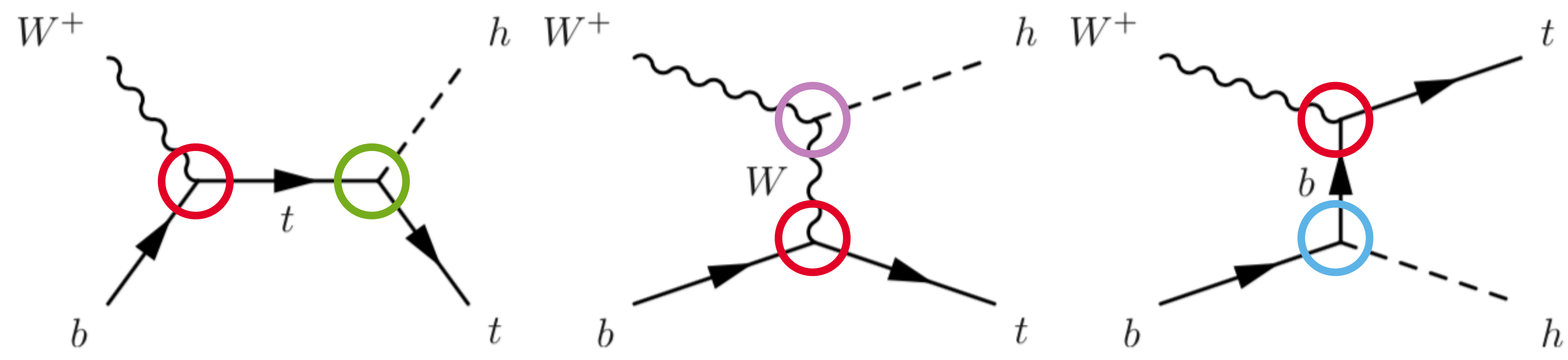
Considered 10, 2 → 2 scattering amplitudes with ≥ one top

- High energy limit: **$s \sim |t| \gg v^2$**
- Max. unitary energy dependence: E^0
- Study unitarity cancellations/energy growth in SMEFT vs. anomalous couplings
- Do they interfere in an energy-growing way with the SM?
- How can we access them through collider processes?

Interesting processes: 'rare' EW top production

tZj, tWj, tHj, tZW, tHW, ttWj, VBF-tt,…

Example: bW⁺ → tH



In the SM, fully left handed, longitudinal W configuration ~ E^0

Anomalous interactions:

- tbW vertex: present in all diagrams → overall rescaling ~ E^0
- bbH vertex: ∝ mb → 0
- HWW & ttH interactions: participate in a unitarity cancellation ~ v E

$$\mathcal{A}(b_L, W_L, t_R) \propto \sqrt{-t}(2m_W^2 g_{th} - g_{Wh} m_t)$$

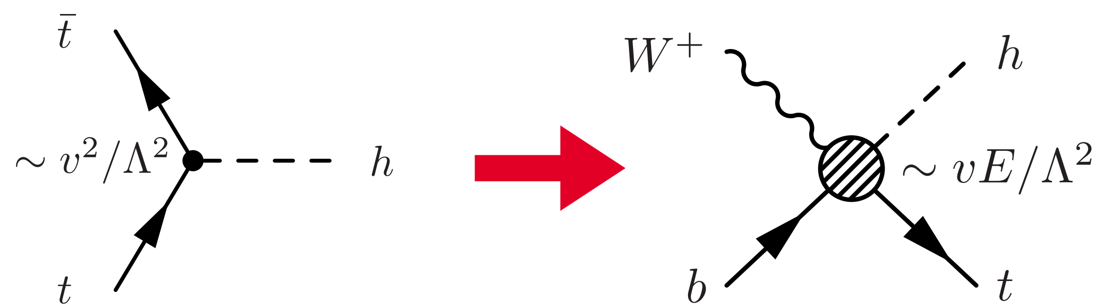
- Fixing couplings to SM values sends it to E^{-1}

bW+ → tH in SMEFT

One source of energy growth from modified SM interactions

- Yukawa operator: disconnects kinematical mass from coupling to Higgs

$$\mathcal{O}_{t\varphi} = (\varphi^\dagger\varphi)^2(\bar{Q}\,t\,\tilde{\varphi})$$



bW+→ tH in SMEFT

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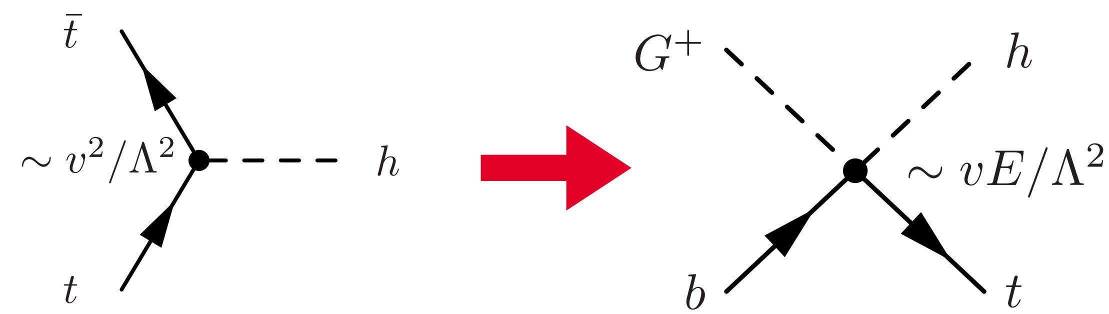
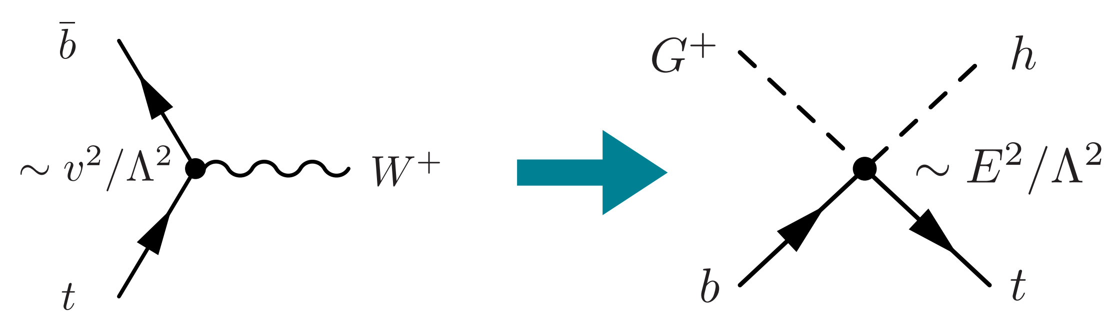


$$h\,G^+\,\bar{t}_L\,b_R$$

- 'Unitarity cancellation' **OR** dim-5 contact-interaction w/ charged Goldstone

Max growth from dim-6 contact-terms

$$\mathcal{O}^{(3)}_{\varphi Q} = i(\varphi^\dagger \overleftrightarrow{D}_\mu\,\tau^I\varphi)(\bar{Q}\,\gamma^\mu\,\tau_I\,Q)$$
$$\mathcal{O}_{\varphi tb} = i(\tilde{\varphi}\,D_\mu\varphi)(\bar{t}\,\gamma^\mu\,b) + \text{h.c.}$$

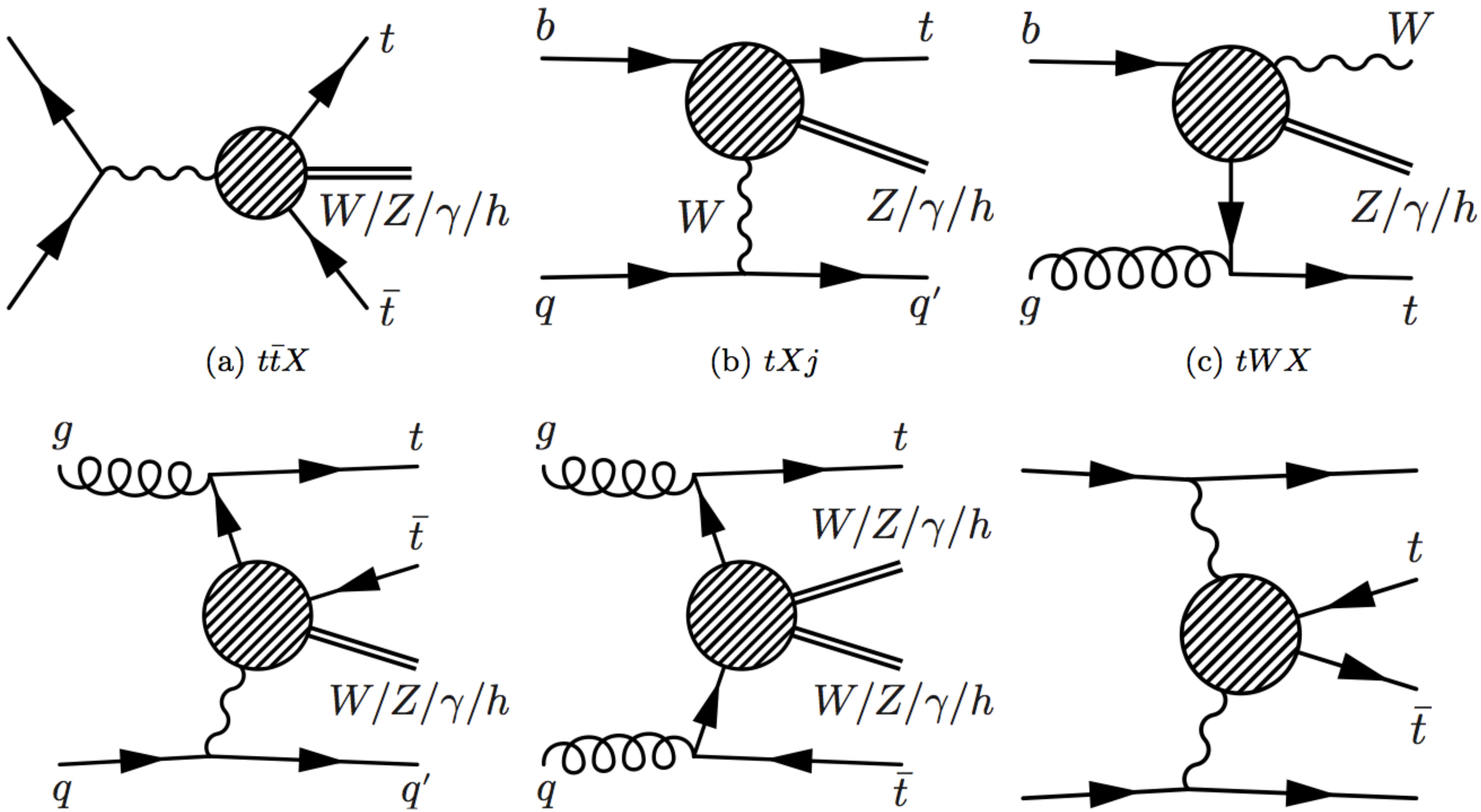


$$h\,\partial_\mu G^+\,\bar{t}\,\gamma^\mu b$$

- No anomalous coupling analogues *(recall Wtb vertex only rescales)*
- Prediction from gauge invariant dim-6 operators

Embedding the amplitudes

Collider processes: rare top production



(a) $t\bar{t}X$ (b) tXj (c) tWX (d) $t\bar{t}Xj$ (e) $t\bar{t}XY$ (f) VBF

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

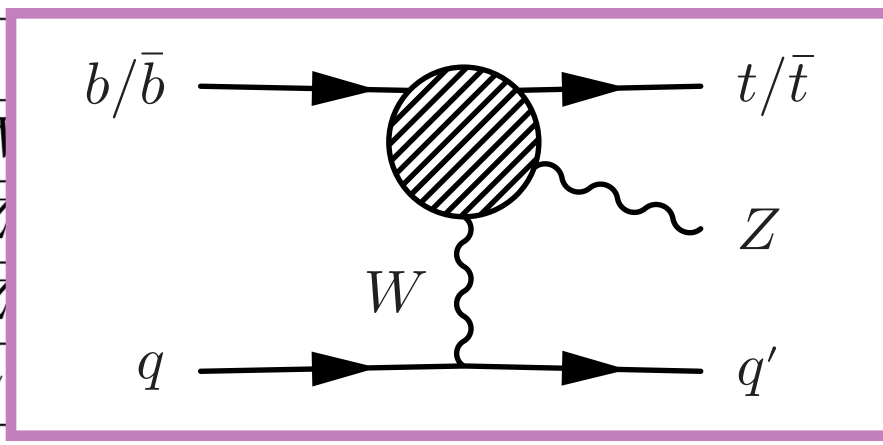
	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

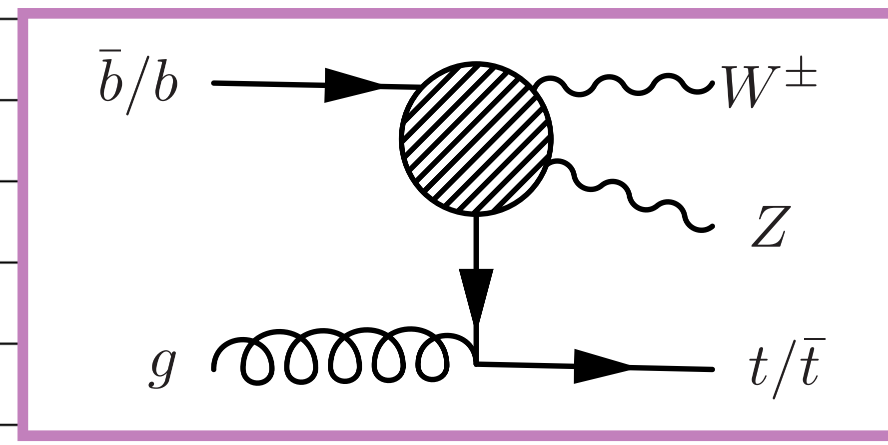
Embedding the amplitudes

Collection of ‘sensitivity’ studies, general discussion

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

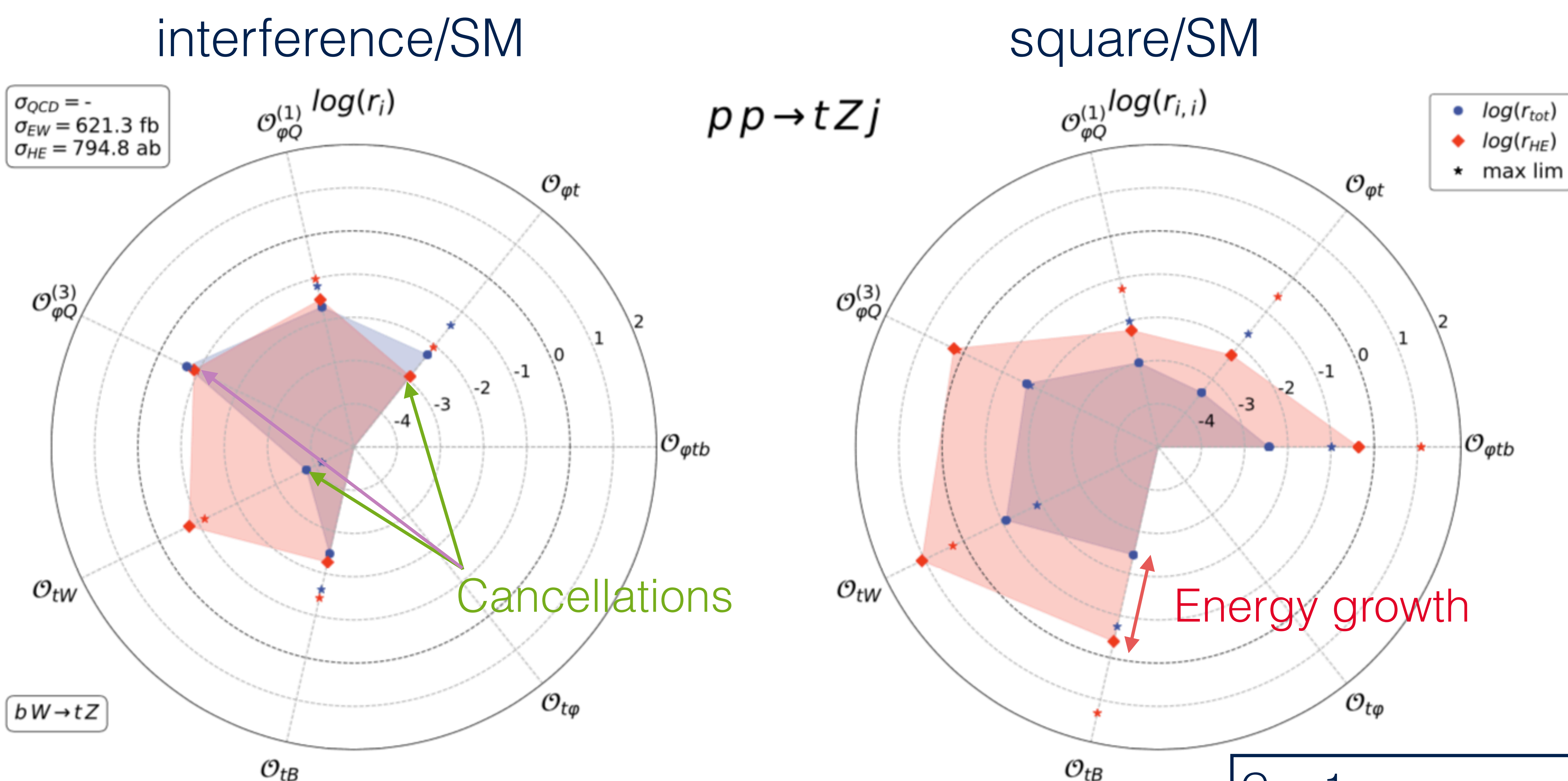
	BF
tW	✓
tZ	✓
tZ	✓
$t\gamma$	✓





	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

tZj total & high energy xs



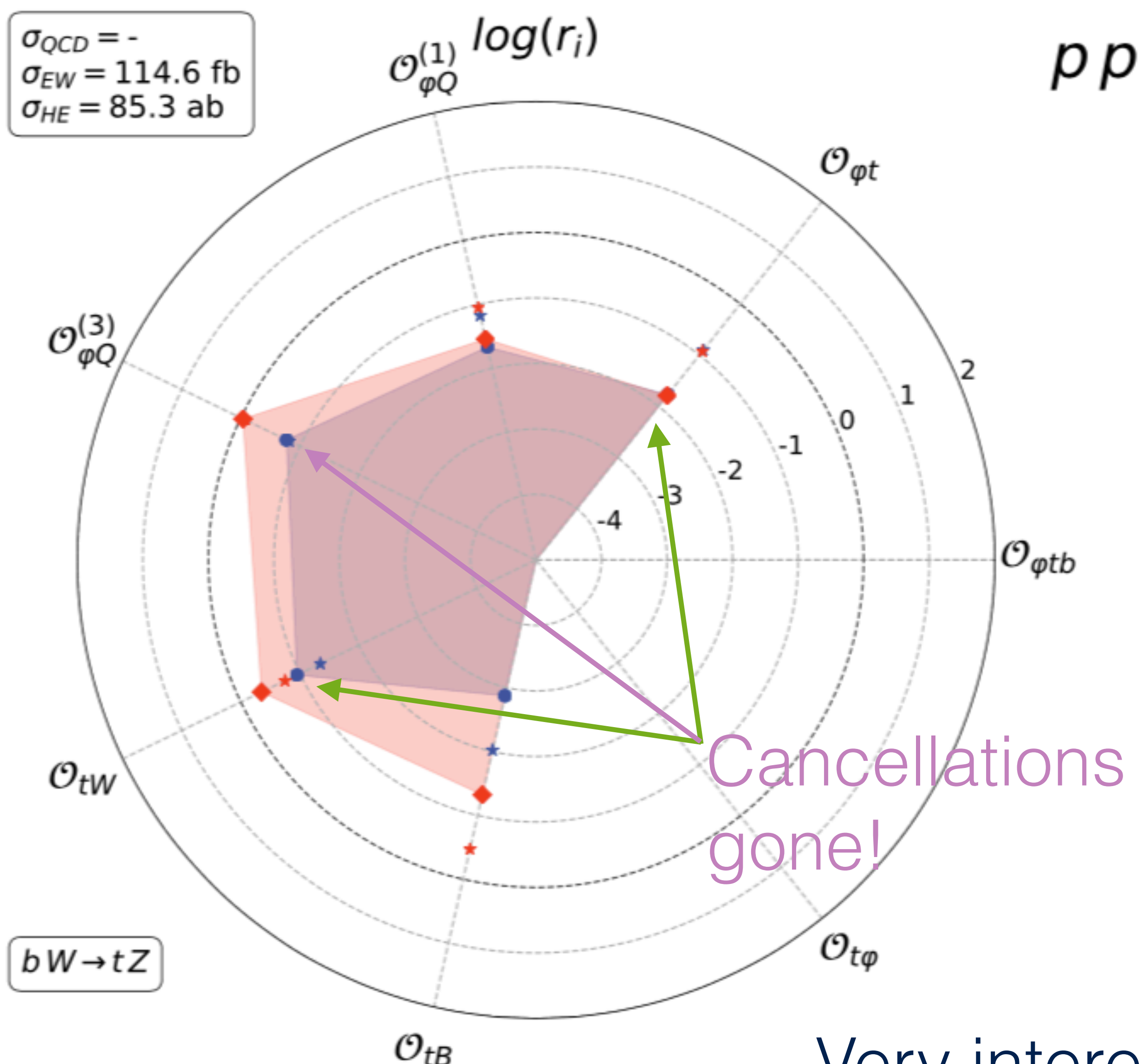
C_i = 1
Inclusive
p_T (Z)> 500 GeV

Expected growth from 2→2 absent!

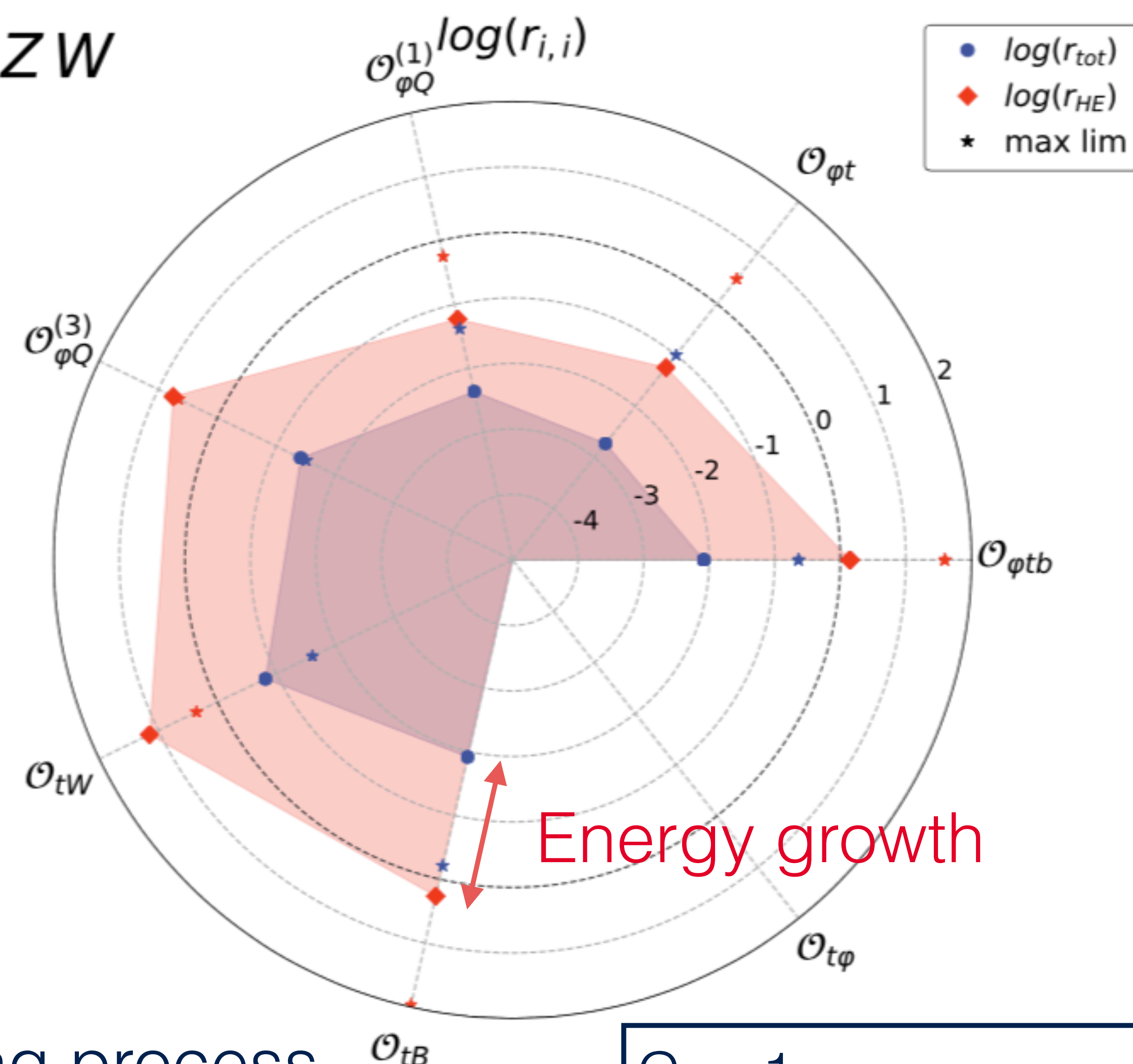
tZW total & high energy xs

interference/SM

square/SM



$p\,p \rightarrow t\,Z\,W$



Expected growth is there!

Very interesting process that should be measured at the LHC

C_i = 1
Inclusive
p_T (W,Z)> 500 GeV

Conclusions

EFTs are a powerful tool for new physics searches complementary to the direct approach

SMEFT is a thriving field in the LHC era

Opportune time to study EWSB sector in full

- Healthy, ongoing dialogue between theory and experiment
- Precision MC tools available
- Global top/Higgs/EW fit on the way!
- New insight into the origin of EWSB

Roadmap for the future

- High energy EW-top quark production
- Increasingly rare processes that exploit energy growth

Thank you!