# Effective Field Theories with applications to collider Phenomenology

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NExT PhD Workshop, 24th August 2026

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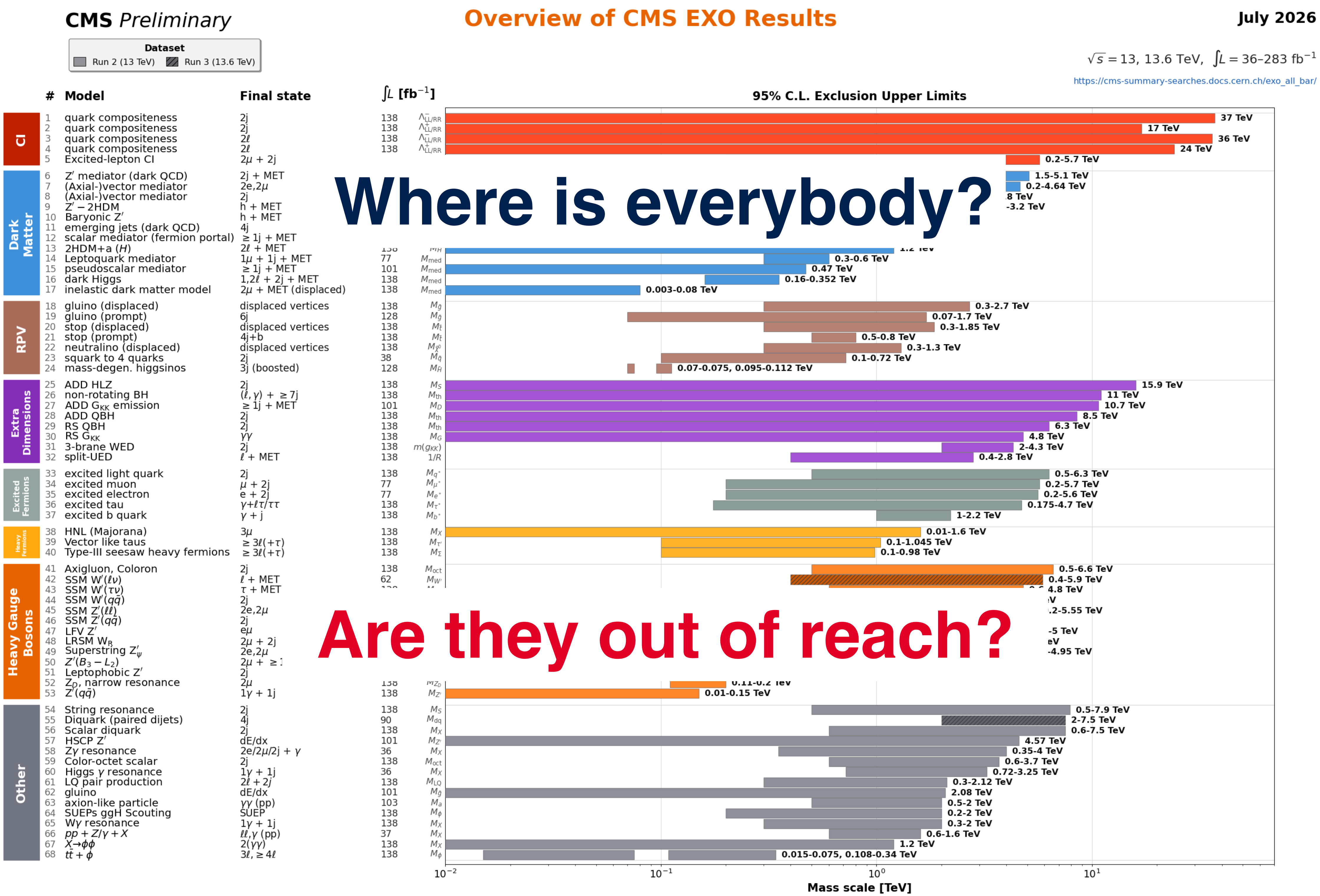
# The best motivation for EFT




**Where is everybody?**

**Are they out of reach?**

# Back to reality

The standard model is a great candidate for an EFT

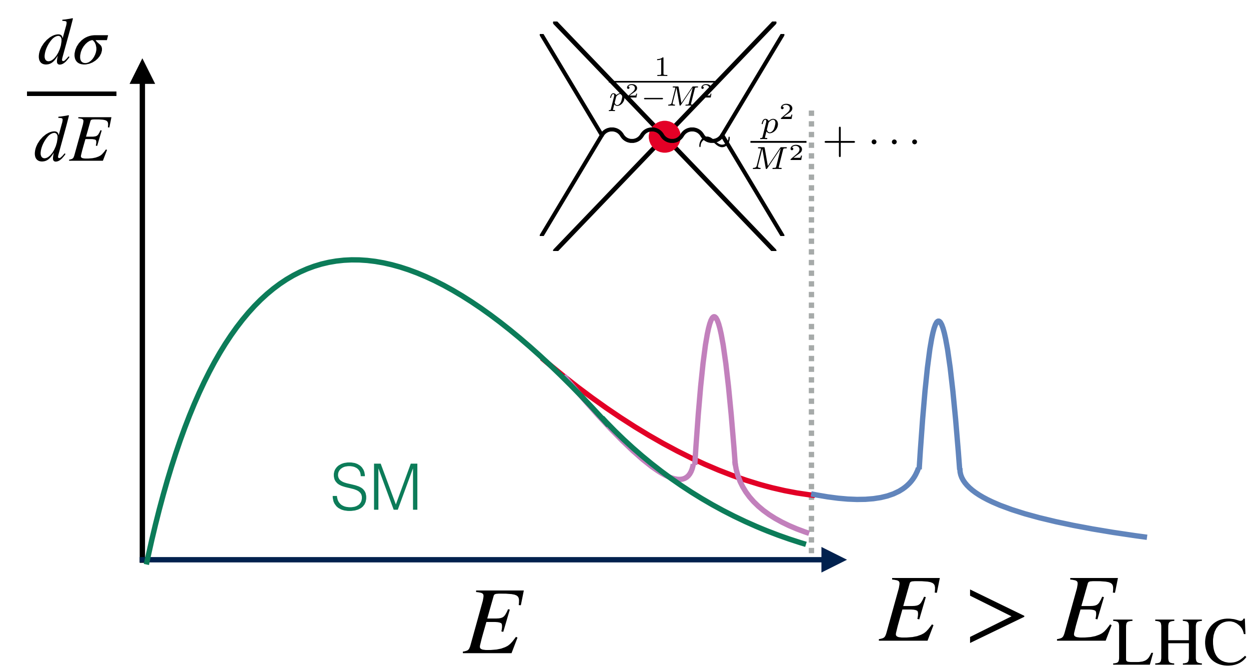
- A well understood low energy theory around the weak scale, $v$
- Low energy degrees of freedom: $\{Q_i, L_i, u_i, d_i, e_i, g, \gamma, W^\pm, Z, h\}$
- LHC data indicates a scale separation from possible new physics

Paradigm shift at the energy frontier for BSM searches

**2010s:** direct

**2020s:** Indirect

$\Rightarrow$ New physics is heavy

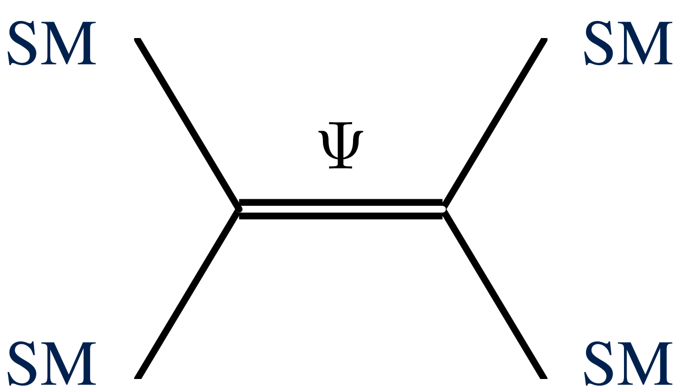



Heavy new physics
Precision measurements
High energy

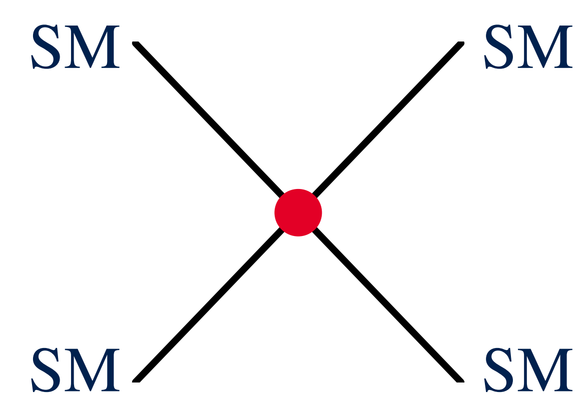
$\Longrightarrow$ **Standard Model Effective Field Theory (SMEFT)**

# EFT expansion

$$\mathcal{A}^n_{\rm BSM}(E,M) \sim E^{4-n}\left(a_0 + a_1\frac{E}{M} + a_2\frac{E^2}{M^2} + \cdots\right), \quad E \ll M$$




$$\frac{g^2}{p^2 - M^2} \approx -\frac{g^2}{M^2}\left[1 + \frac{p^2}{M^2} + \frac{p^4}{M^4} + \cdots\right]$$




$$\mathscr{L} \sim g\Psi\left(\phi^\dagger\phi\right) \approx \frac{g^2}{M^2}(\phi^\dagger\phi)^2 + \frac{g^2}{M^4}\phi^\dagger\phi\,\partial^\mu\phi^\dagger\partial_\mu\phi + \frac{g^2}{M^6}\partial^\mu\phi^\dagger\partial_\mu\phi\partial^\nu\phi^\dagger\partial_\nu\phi + \cdots$$

$s = p^2 < M^2$ : EFT validity criterion

$g$ not too large : Perturbative UV completion

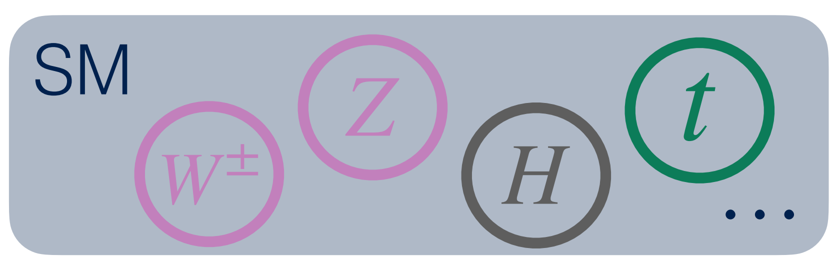
# SMEFT: SM v2.0

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{i,D} \frac{c_i^{(D)} \mathcal{O}_i^{(D)}}{\Lambda^{D-4}}$$

*BSM particle masses* $M$ ⇔ *Generic new physics scale* $\Lambda$

*Taylor expansion of* $\mathscr{A}_{BSM}$ ⇔ *Tower of operators* $\mathcal{O}_i^{(D)}$

$\mathcal{O}_i^{(D)} \supset$




*Low energy (SM) fields & symmetries*

*Model parameters* $\left\{g^i_{\mathrm{BSM}}, M_k\right\}$ ⇔ *Wilson coefficients* $\dfrac{c_j^{(D)}}{\Lambda^{D-4}}\left(g^i_{\mathrm{BSM}}, M_k\right)$

*measure* $g_i$ *: new physics model parameters*

"Matching"

*measure* $c_i$ *: coupling strengths of new BSM interactions*

# SMEFT

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

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

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

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

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

59 independent operators (+ 5 B-violating)

# 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]

# 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

$$\langle\varphi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix} \qquad \mathcal{O}_6 \to v\mathcal{O}_5,\; v^2\mathcal{O}_4$$

| | | 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 $c_i$**

# Example: $G_F$ shift

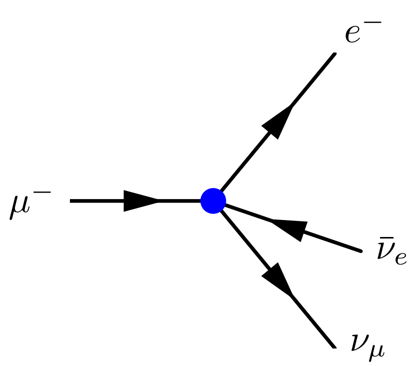
## Muon decay data gives: $G_F$ = 1.17x10$^{-5}$ GeV$^{-2}$ → v = 246 GeV

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

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

- A contains the $O_F$ up to a Fierz transformation $\quad [\mathcal{O}_{ll}]^{1221} = \frac{1}{4} (\bar{e}\, \gamma^\mu (1-\gamma_5)\, \nu_\mu)\, (\bar{\nu}_e\, \gamma_\mu (1-\gamma_5)\, \mu) + \cdots,$
- B,C shifts W couplings to leptons after EWSB $\quad [\mathcal{O}_{ll}]^{2112} = \frac{1}{4} (\bar{e}\, \gamma^\mu (1-\gamma_5)\, \nu_\mu)\, (\bar{\nu}_e\, \gamma_\mu (1-\gamma_5)\, \mu) + \cdots,$

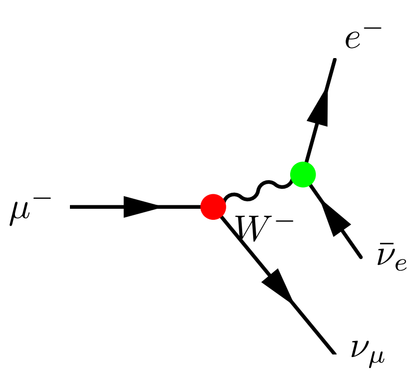
$$-i\frac{g}{\sqrt{2}} \to -i\frac{g}{\sqrt{2}}\left[1 + [C^{(3)}_{\varphi l}]^{ii}\, \frac{v^2}{\Lambda^2}\right]$$




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

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

New relation between Higgs vev and Fermi constant




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

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 for LHC

flavor structure,
CP conservation,
...

## Generic contribution from SMEFT is an expansion in $\Lambda^2$

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

single operator insertion

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

## 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

Basis $\rightarrow$ Processes & Observables $\rightarrow$ Sensitivity $\rightarrow$ Measurement $\rightarrow$ 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*

# SMEFT likelihood

$$\Delta o_n = o_n^{EXP} - o_n^{SM} = \sum_i a_{n,i}^{(6)}(\mu)\frac{c_i^{(6)}(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

***Model A***

***Model B***

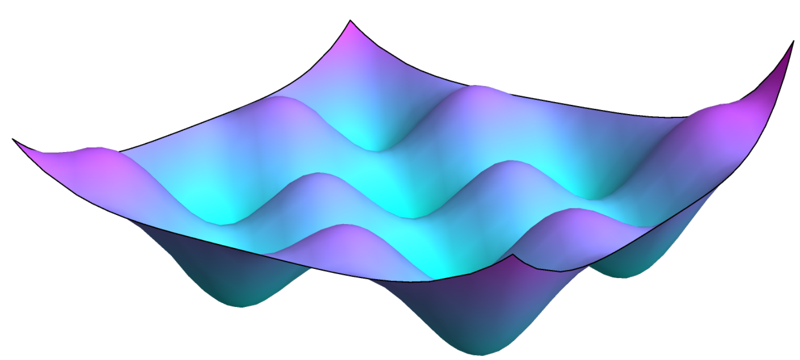
***Model C***

$U(3)^5$ $U(2)^5$

$U(3)^3 \times U(2)^2$

$$\mathscr{L}(c_i\,|\,\vec{o})$$

SMEFT likelihood



$\mathscr{L}(g_A)$ $\mathscr{L}(g_B)$

$\mathscr{L}(g_C)$

$c_i$ **bounds**

- Individual
- Marginalised
- Flat directions

# Flavour symmetry

Consider SM fermion kinetic terms: $\mathscr{L}_{\text{kin.}} = \sum_{\psi=q,u,d,\ell,e}^{i=1,2,3} \bar{\psi}_i \gamma^\mu D_\mu \psi_i$

- Each term is invariant under a $U(3)_\psi$ flavor rotation

$$\psi_i \to U^\psi_{ij}\, \psi_j$$

*all generations equivalent*

- Massless SM has a large global flavor symmetry:

$$G_f = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e \Rightarrow U(3)^5$$

- Yukawa interactions break the flavor symmetry $G_f$

$$\mathscr{L}_{\text{Yuk.}} = y_u^{ij}\, \tilde{\phi}\, \bar{q}_i u_j + y_d^{ij}\, \phi\, \bar{q}_i d_j + y_e^{ij}\, \phi\, \bar{\ell}_i e_j + \text{h.c.}$$

*involve two different $G_f$ representations*

$$G_f \to U(1)^5 = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_Y$$

New physics can have arbitrary flavor structure

- Flavour symmetry assumptions often used to control number of parameters

# Flavour symmetry in SMEFT

Large number of SMEFT coefficients come from flavor indices

$$c_{ijkl}\,\bar{\psi}_i\psi_j\bar{\psi}_k\psi_l \qquad c_{ij}\,|\phi|^3\,\bar{\psi}_i\psi_j \qquad c_{ij}\,(\phi\overleftrightarrow{D}^\mu\phi)(\bar{\psi}_i\gamma_\mu\psi_j) \qquad c_{ij}\,\phi(\bar{\psi}_i\sigma_{\mu\nu}\psi_j)F^{\mu\nu}$$

Assume UV theory respects particular flavor symmetry

- $U(3)^5$: single coefficients for each operator a.k.a. *universal theory*
- $U(2)_\psi$: common coefficient for 1st & 2nd generation, independent for 3rd
- $U(2)_q \times U(2)_u \times U(3)^3$: singles out top quark
- Minimal flavor violation: same flavour breaking as the SM $(y_\psi^{ij})$

  *[D'Ambrosio et al.; Nucl. Phys. B 645 (2002) 155]*

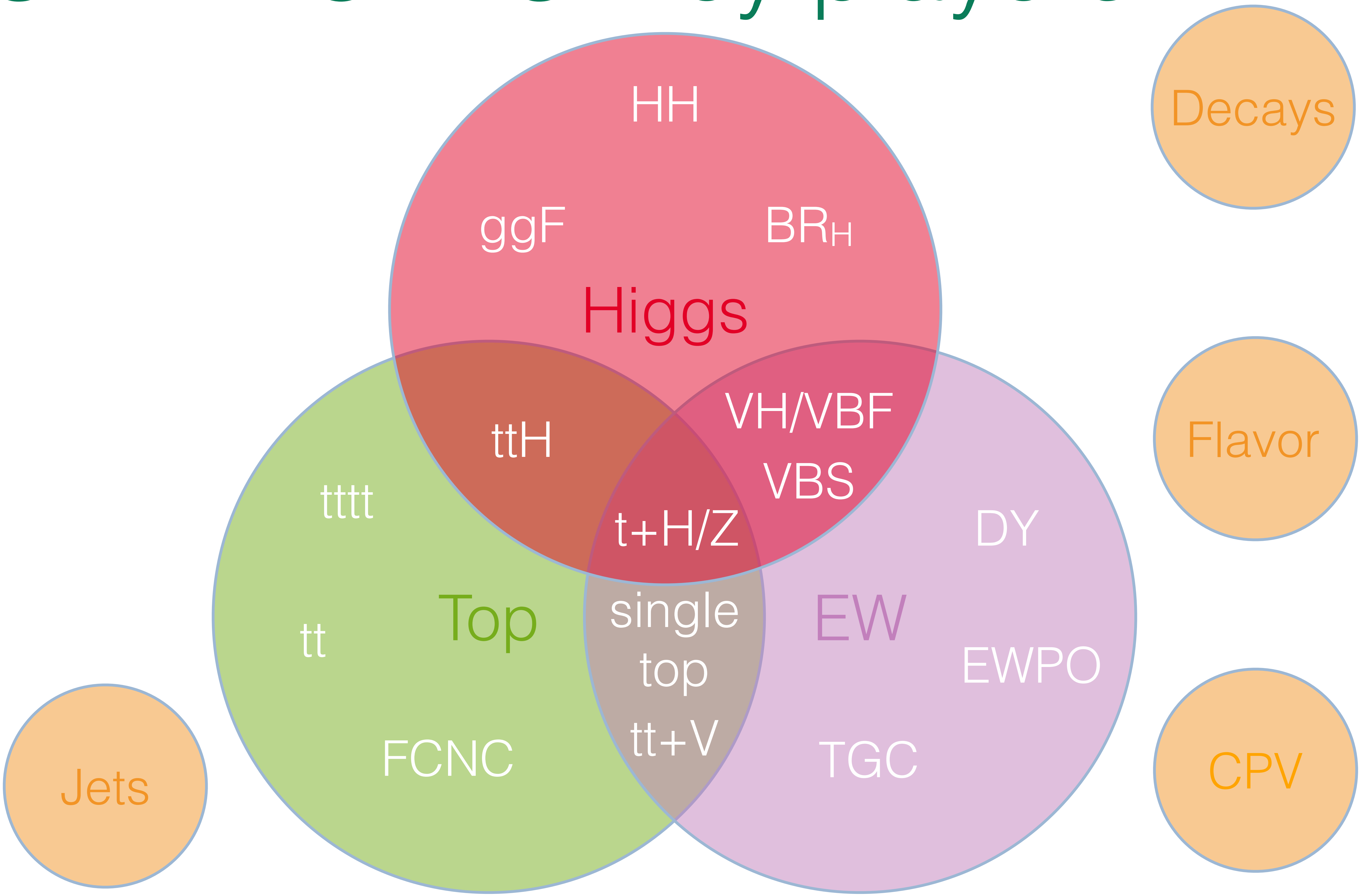
Coefficients $c_{ijkl}$ will respect that symmetry at the matching scale

SM breaks $U(3)^5 \to U(1)^5$

- Flavour symmetries not preserved by RG evolution (weak loops)

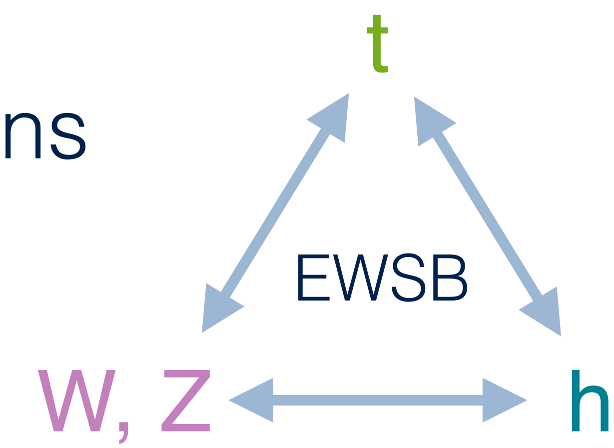
# Part 3
# Application:
# SMEFT in the EW sector

# SMEFT@LHC: key players



# EWSB sector at the LHC

Main players: top, Higgs & EW gauge bosons




**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

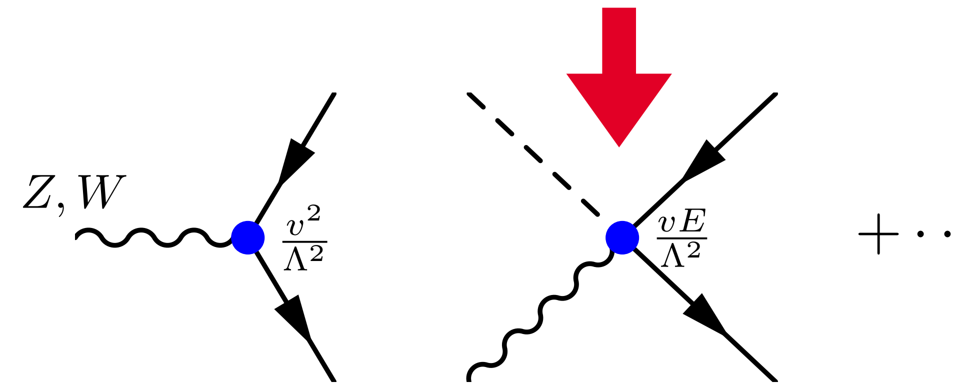
Delicate ‘balance’ conserves **unitarity** & **renormalisability**

SMEFT contributions break this balance

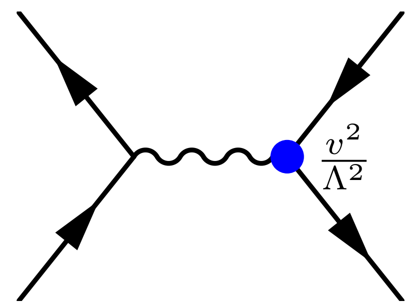
# Current operators

Contact operator predicted by gauge invariant construction

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

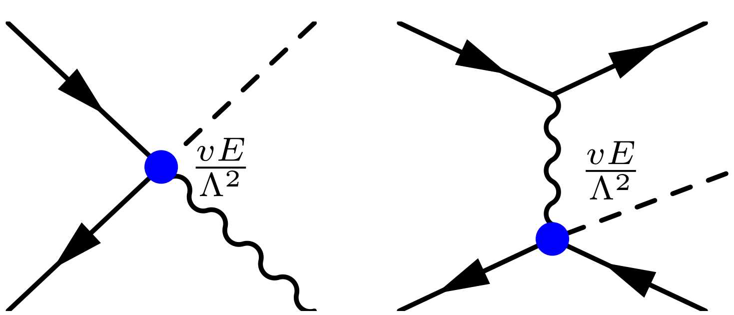



D=4 D=5

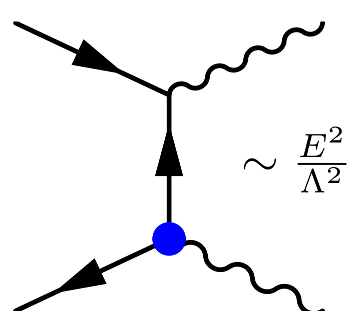



No energy growth w.r.t SM (overall rescaling)

Precision EW on the Z peak (LEP)




EW Higgs production



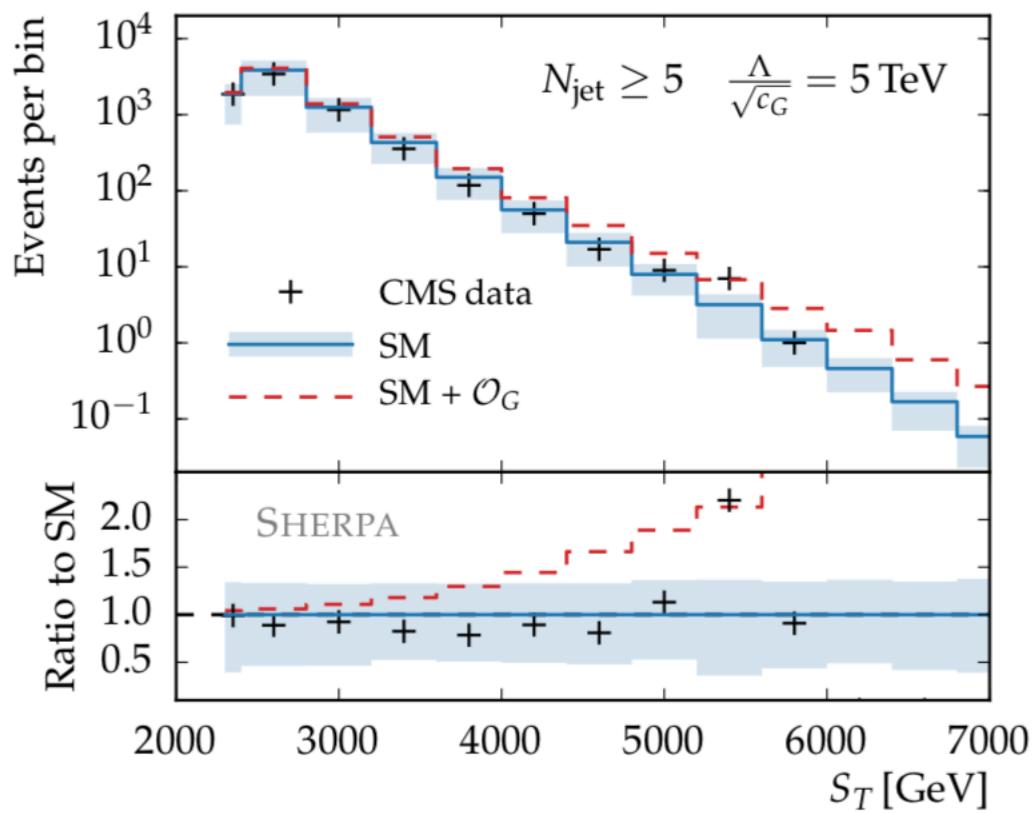

Diboson production

Energy growth from non energy growing vertex…?

Unitarity non-cancellation in ff→WW scattering!

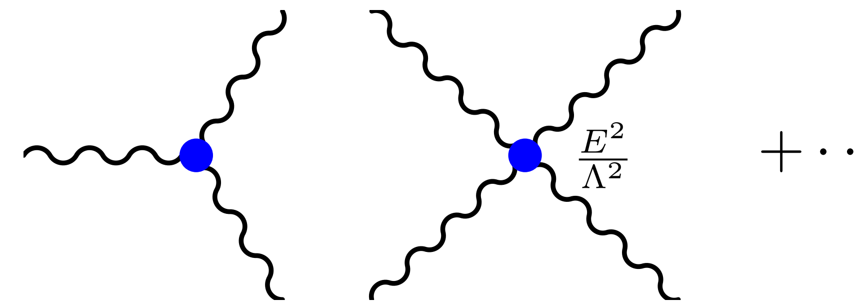
# Gauge only

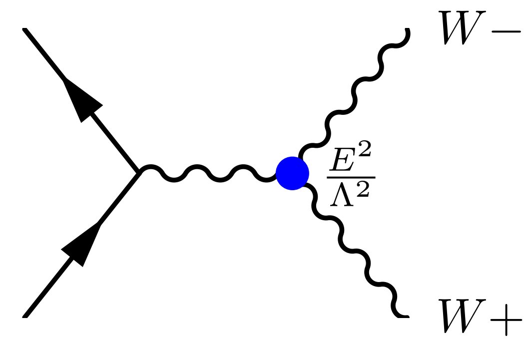
| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |
| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | | | | | $_p\gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | | | | | $_p\gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | | | | | $\tau^I\gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | | | | | $_p\gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | | | | | $_p\gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde W B}$ | | | | | $_p\gamma^\mu d_r)$ |




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

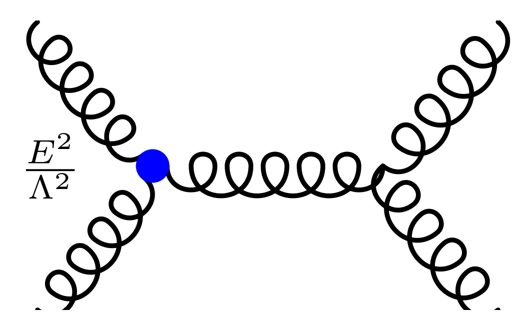
Anomalous triple & quartic gauge couplings




Diboson production LEP/LHC

Large energy growth w.r.t SM




Multi-jet production

Operators have CP violating versions

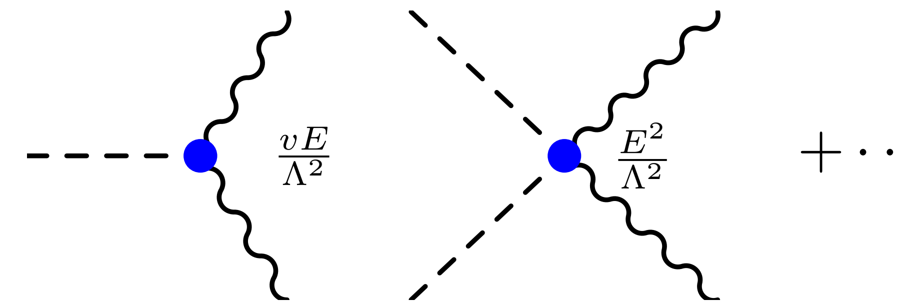
# Gauge/Higgs

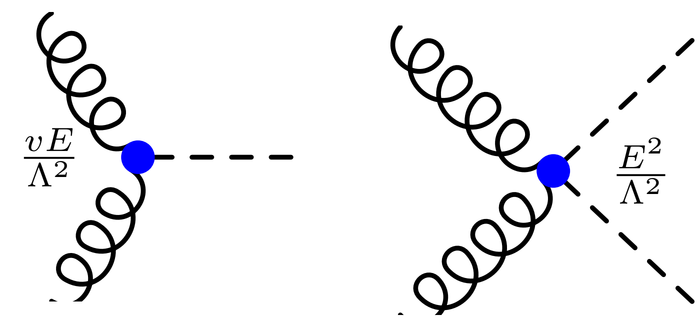
+ CP violating versions

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

T-parameter

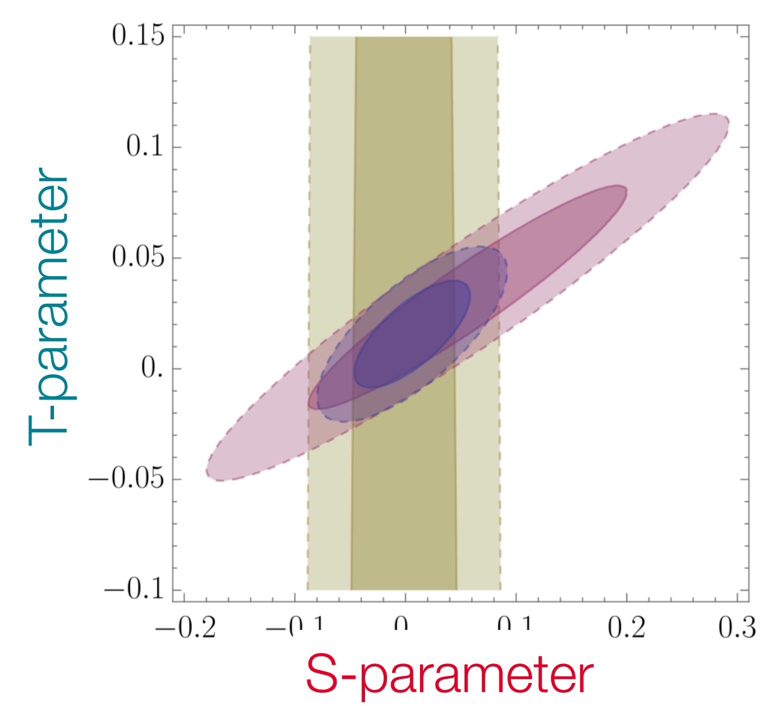
S-parameter

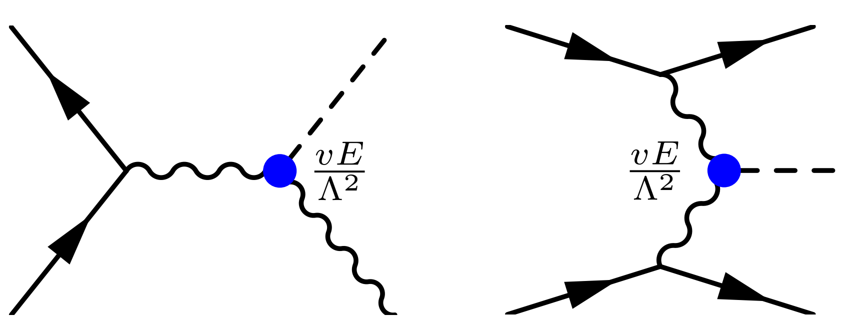



Gluon fusion: Higgs, di-Higgs

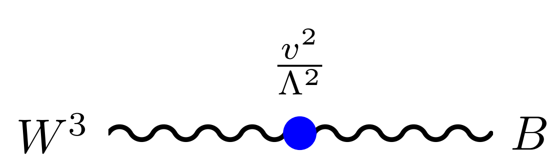
[Ellis et al.; JHEP 06 (2018) 146]




EW Higgs production & decay

kinetic mixing

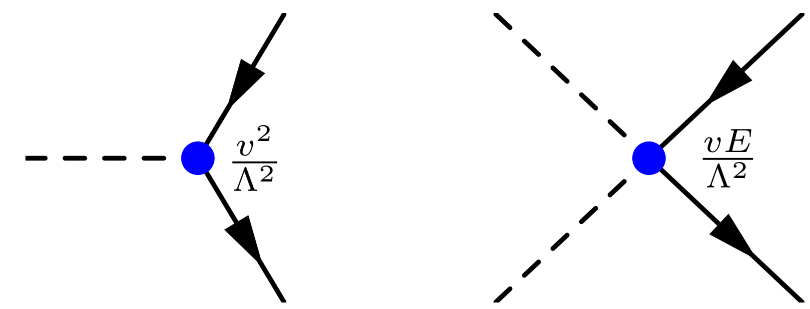



EW precision test

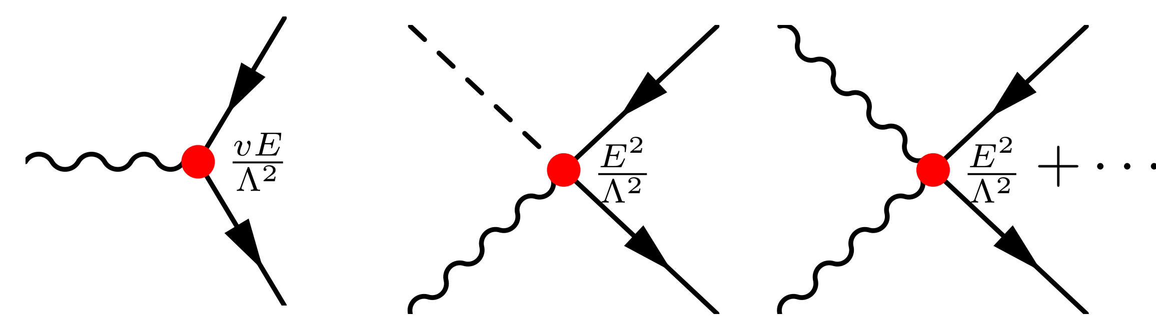
# Two fermions

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

Yukawa operators

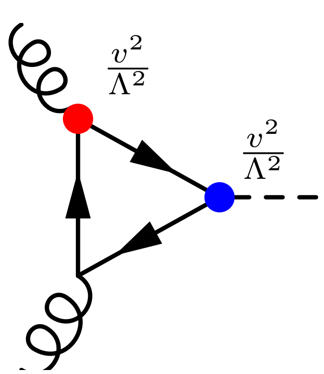



Dipole operators: $Z, W, \gamma, g$

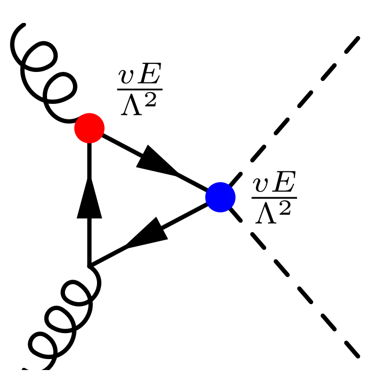



Non-Abelian

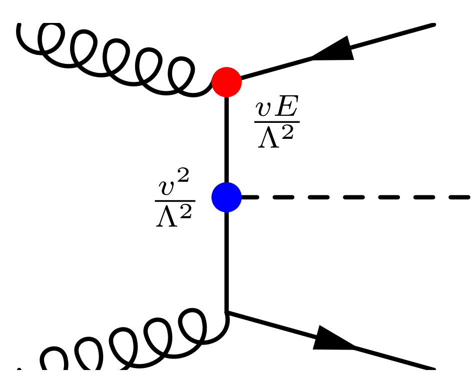
Interplay between Yukawa, dipoles & ggH




ggH

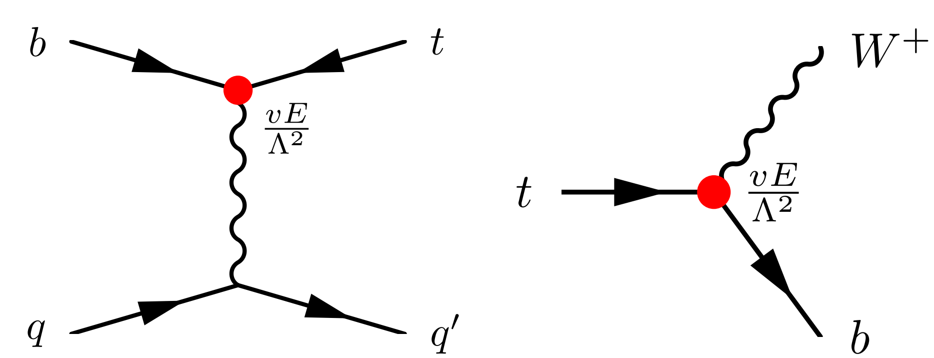



ggHH




ttH

Different energy & helicity structure



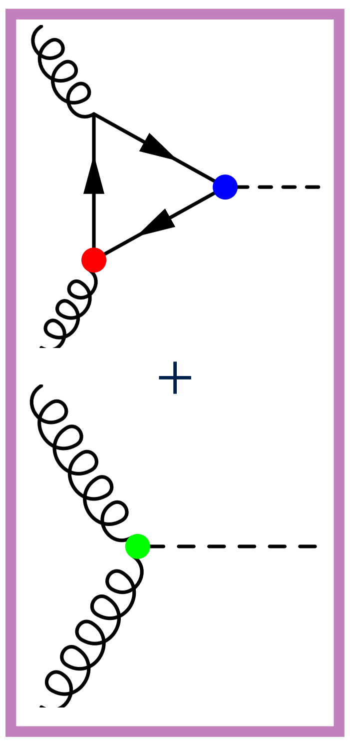

EW top production & decay

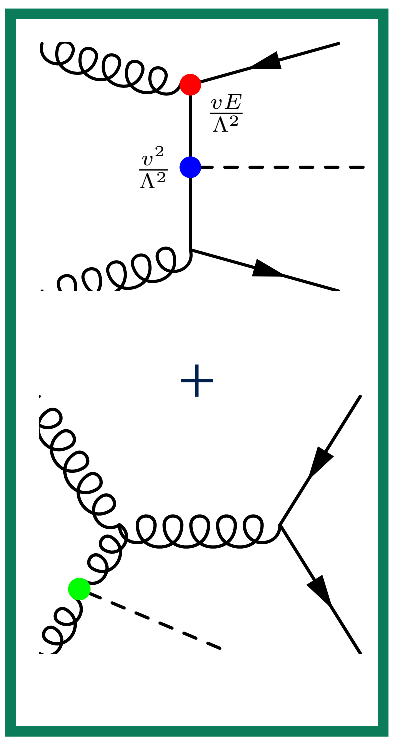
# Global approach

## Global approach essential

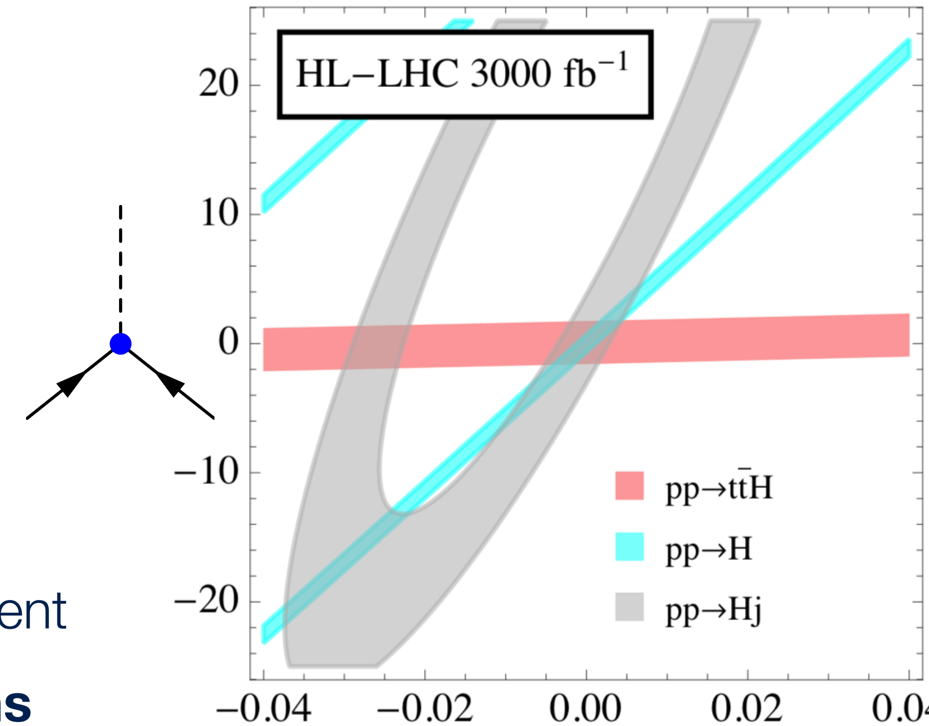
- e.g. direct ttH measurement breaks **degeneracy** among $y_t$, ggH and dipole in gg-fusion

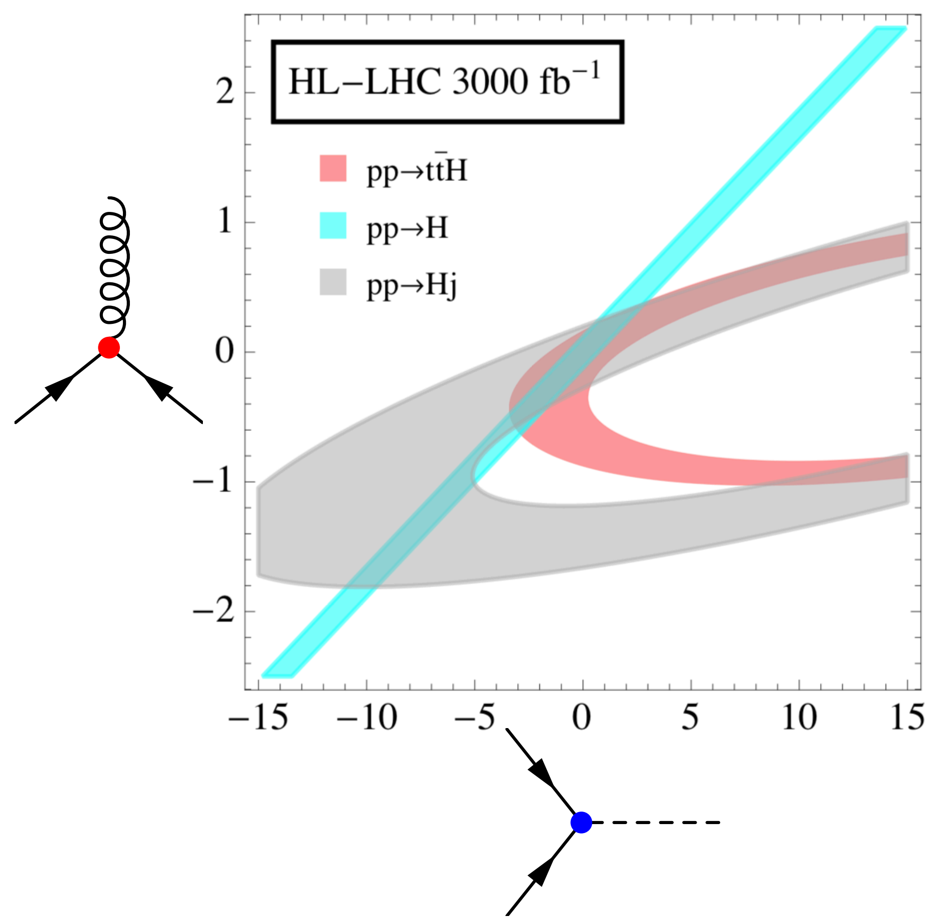
*[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]*

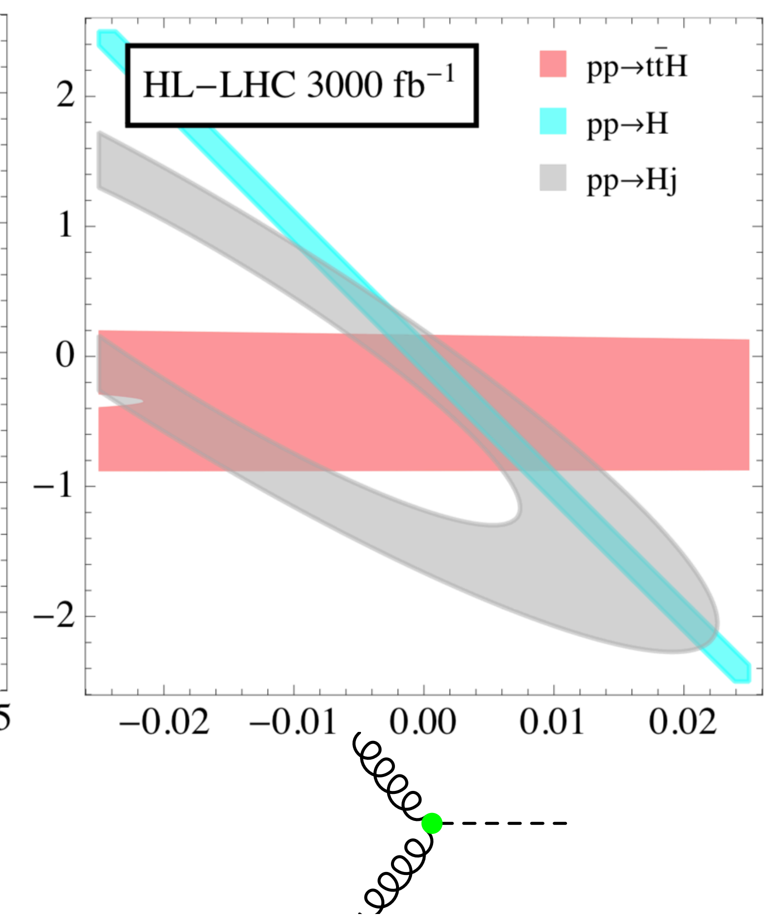



Single measurement
=
**Blind directions**



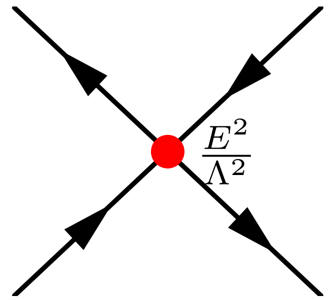

Pin down heavy coloured particles in the loop

# Four fermions

| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-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 ttH, ttZ, ttW, Zjj,… and 'pollute'/complicate fits

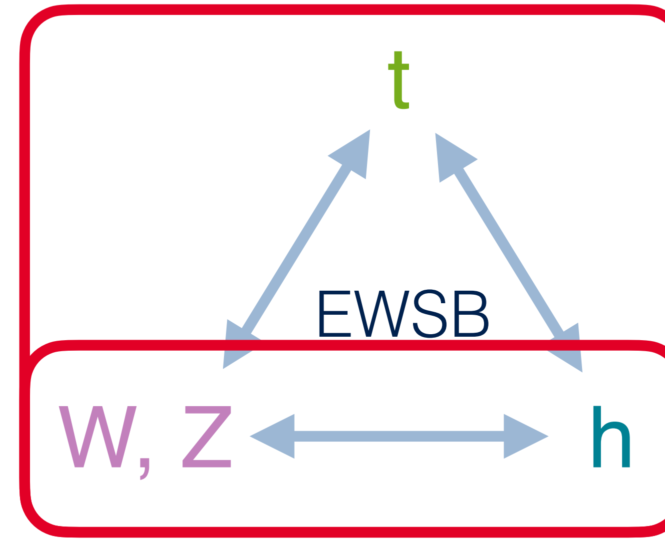
# SMEFT for EWSB sector

Bosonic operators ...es
cover deviations i... or

Including the top ... yond
universal flavor as...

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

| $X^2\varphi^2$ | |
|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$ |
| $Q_{\varphi\widetilde{G}}$ | $\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$ |
| $Q_{\varphi\widetilde{W}}$ | $\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ |
| $Q_{\varphi\widetilde{B}}$ | $\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$ |
| $Q_{\varphi\widetilde{W}B}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$ |




Exploit *approxima*... symmetry (broken by Yukawas)

universal $U(3)_L$ x ... $)_Q$ x $U(3)_u$ x $U(3)_d$

top $U(3)_L$ x $U(3)_e$ x $U(2)_Q$ x $U(2)_u$ x $U(3)_d$

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

Single out independent operators for modified top/EW interactions

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

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

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

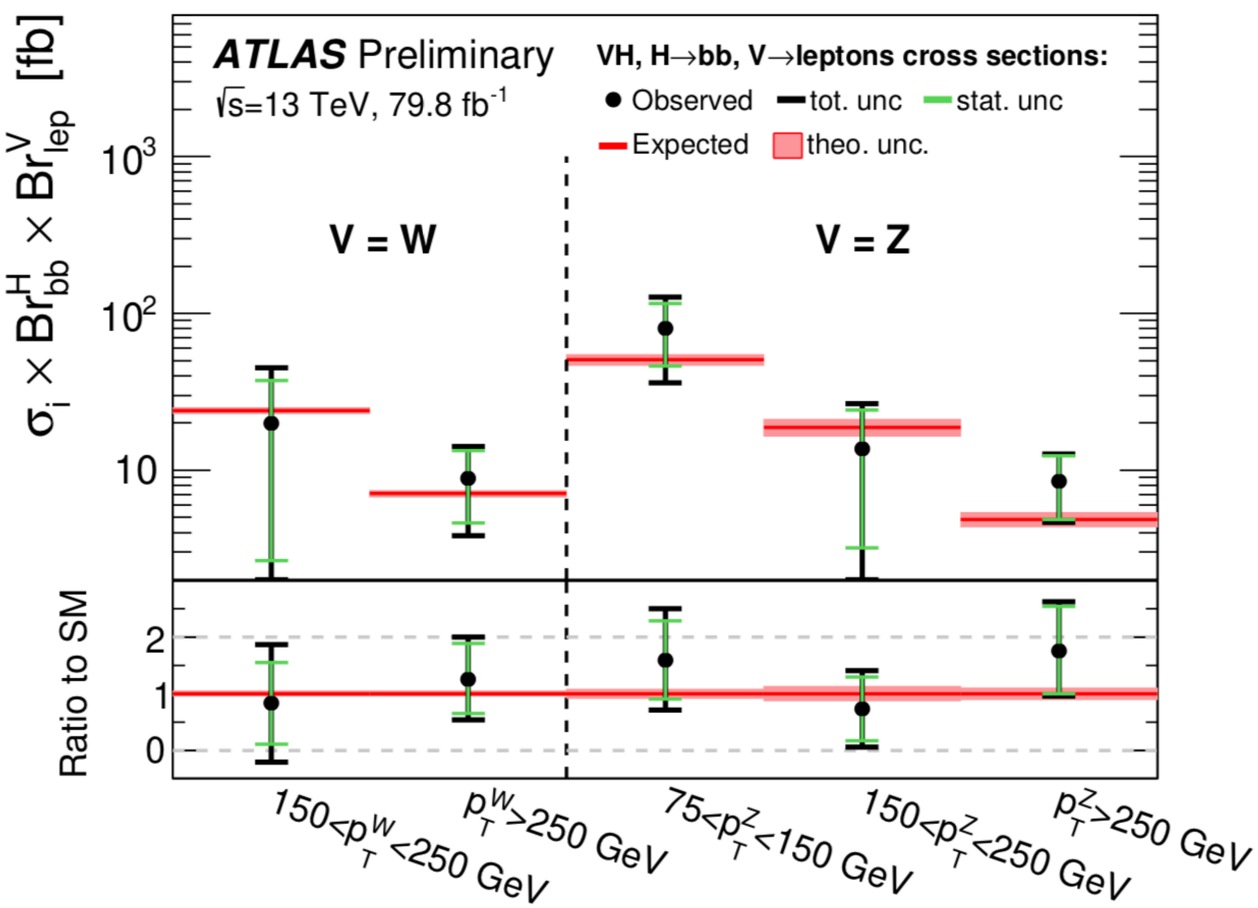
$$\psi^4 : (\bar{Q}\,\gamma^\mu\, Q)(\bar{q}\,\gamma_\mu\, q),\ (\bar{Q}\,\gamma^\mu\, Q)(\bar{Q}\,\gamma_\mu\, Q), \ldots$$

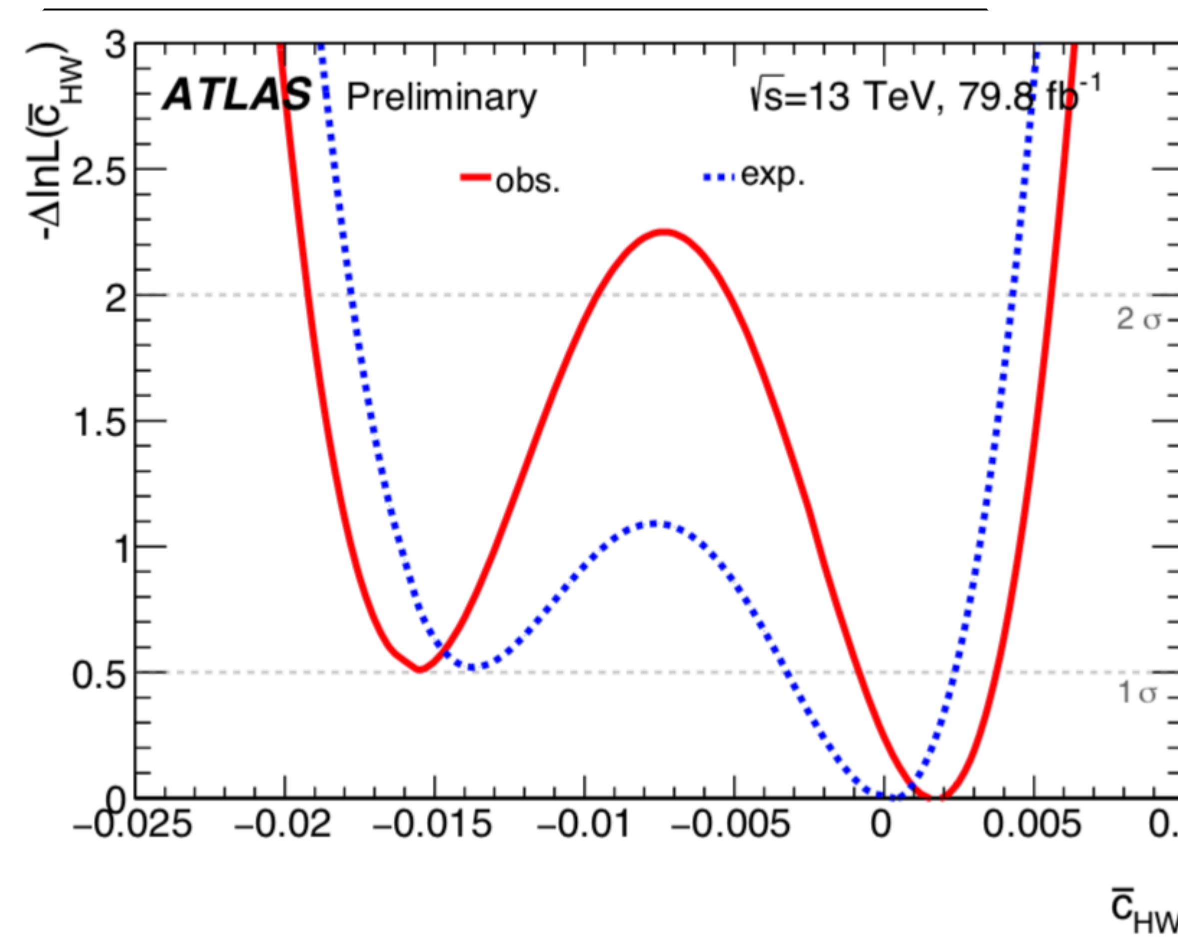
Top quark interactions not so well known: LHC is the first precision top machine

# Applications: LHC

Increasing number of EFT interpretations in LHC analyses

CMS *Preliminary* 77.5 fb$^{-1}$ (13TeV) CMS *Preliminary* 77.5 fb$^{-1}$ (13TeV)



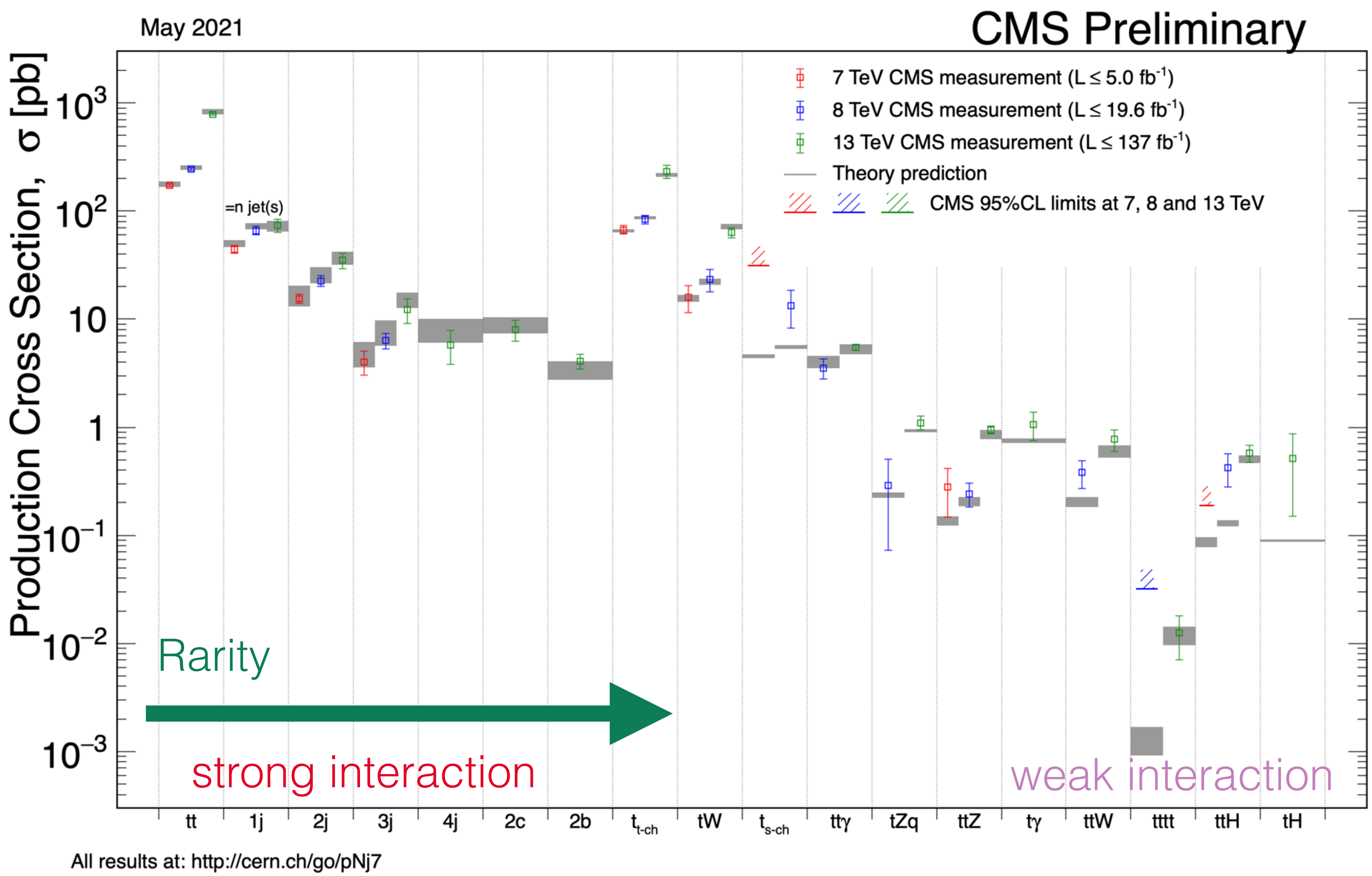




VH STXS *[ATLAS-CONF-2018-053]* $C_{tG} / \Lambda^2$ [TeV$^{-2}$]

*-18-006]*

Limited to small subsets of operator space

# LHC top measurements




$t\bar{t}$ : $10^9$

$tj, tW, tb$ : $10^8$

$t\bar{t} + Z/W/\gamma$ : $10^7$

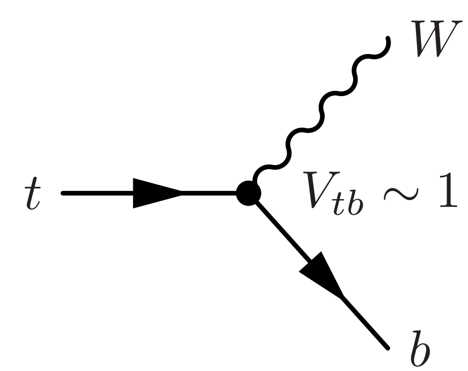
$t\bar{t}H$ : $10^6$

$t\bar{t}t\bar{t}$ : $10^4$

$\mathscr{L}^{\text{int.}} \sim 3\,\text{ab}^{-1}$

## Decays before hadronising

- Spin/helicity information preserved

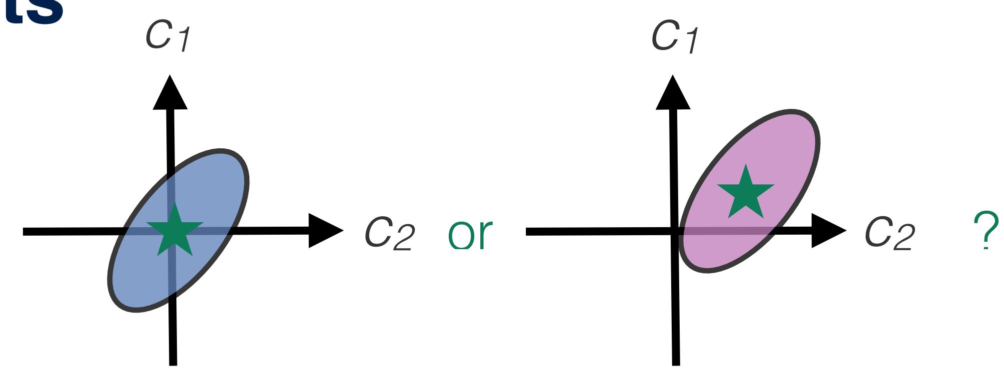



$$\frac{1}{\Gamma_t}\frac{d\Gamma_{t_\pm}}{d\cos\theta_\ell} \propto (1 \pm \cos\theta_\ell)$$

# The importance of top data

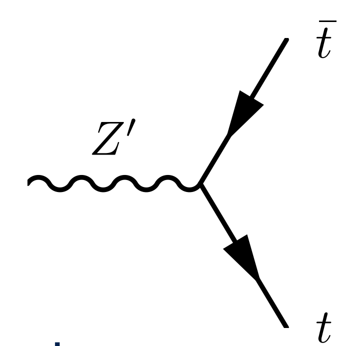
**Likelihood ⇔ Fit to the Wilson coefficients**

- Search for deviations from the SM: $\frac{C_i}{\Lambda^2} = 0$
- Find hints for heavy new physics
- LHC top data has a vital role in this programme



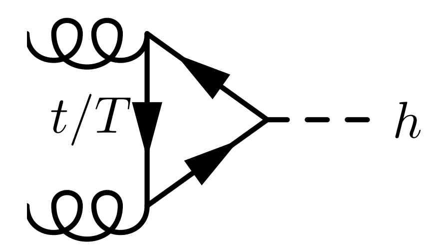

## By itself: individual bounds; top data alone

- Determine top quark properties/interactions
- Probe heavy new physics that couples preferentially to tops




## Globally: marginalised; top, Higgs, diboson, LEP, … data

- Influence determination of other couplings in EW sector,…
- Probe more realistic models connected to the EWSB puzzle



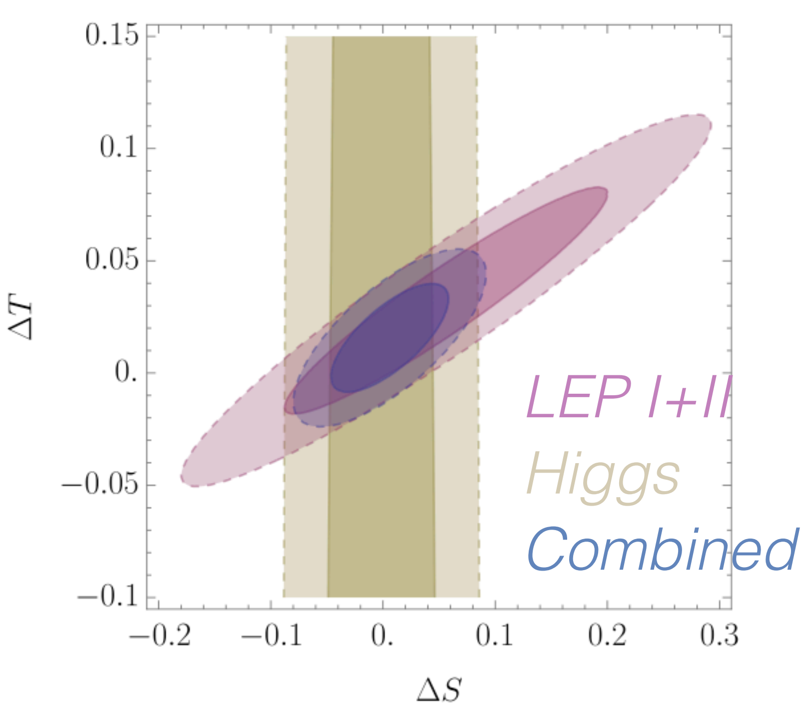
# Status in a nutshell

Global new physics searches via high precision/energy

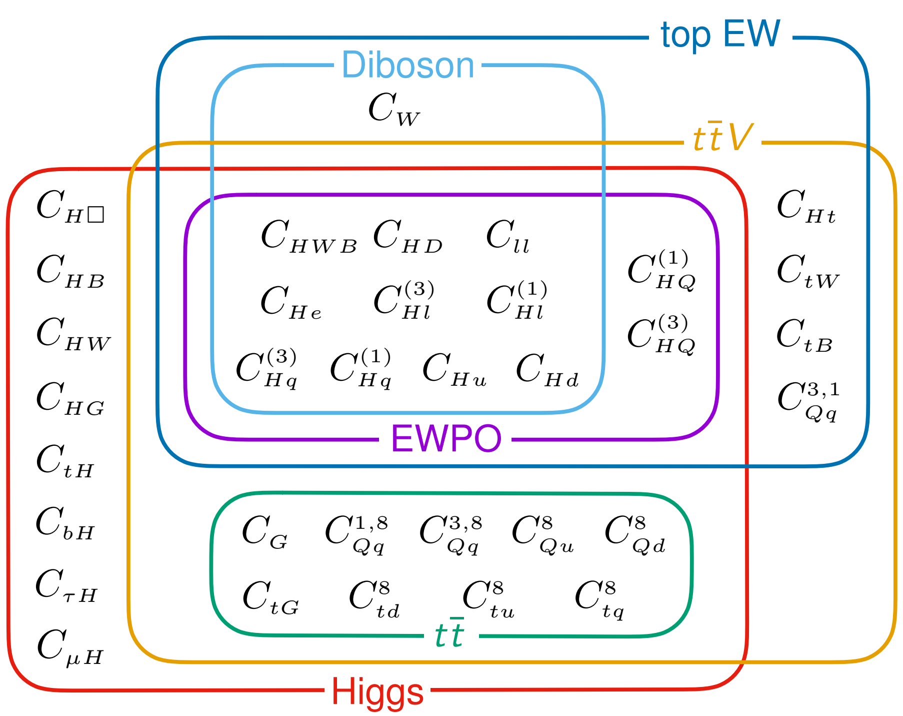
- Z & W-pole data: handle on the EW gauge sector
- LHC: thriving Higgs & top programmes
- Probing gauge interactions at high energy (VV, VBS, VVV, …)

**How much cross-talk? Where does being global matter?**

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



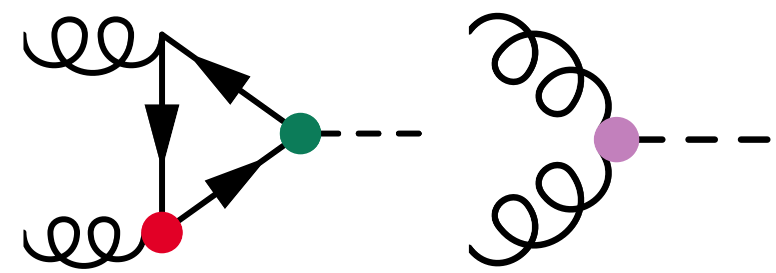

**The frontier:**
**Top data**
**Flavor physics**

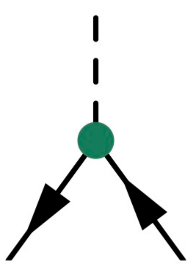


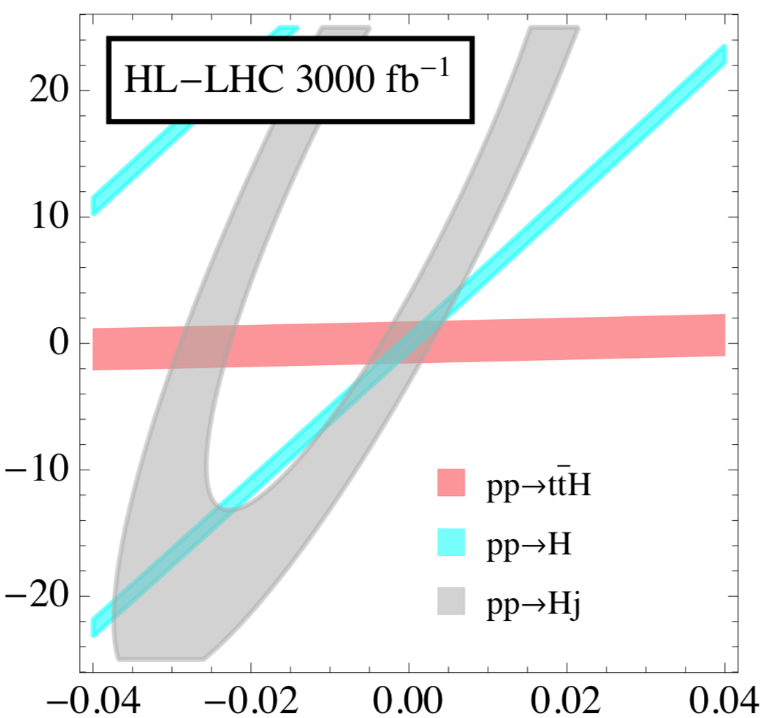
# Top-Higgs interplay

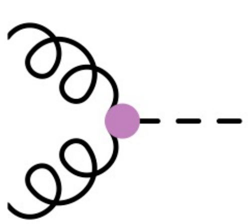
## Top data indirectly improves Higgs coupling measurements

- $gg \to h$ has 3 relevant new interactions
- Yukawa, dipole & contact term
- Degeneracy in coefficient/theory space







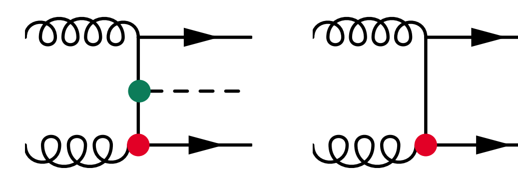



*[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]*

**ggF is well measured, yet…**

**Cannot rule out heavy particles in the loop**

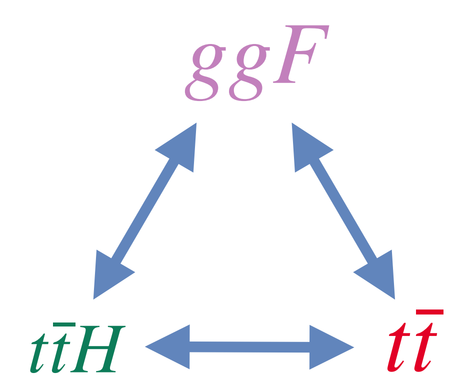
## $t\bar{t}$ and $t\bar{t}h$ data can help



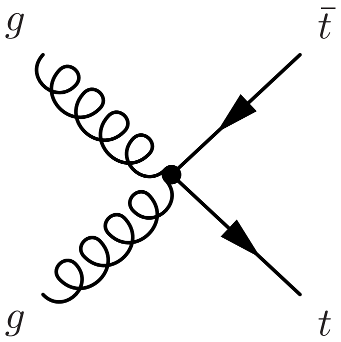
- Constrain dipole & Yukawa

## What about 4 fermion ops.?

- Do they limit ultimate sensitivity?

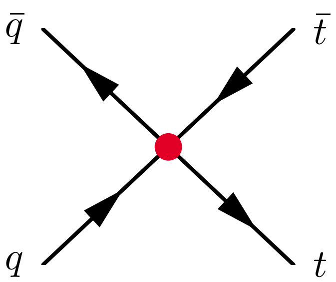


# The role of top data




✓ $t\bar{t}$ cross section measurements constrain $C_{tG}$

- Indirectly improve bounds on $C_{HG}$ and $C_{tH}$




⚠ Several other new interactions can affect $t\bar{t}$

- Notably $q\bar{q}t\bar{t}$ operators, of which there are many (14)
- Also enter in $t\bar{t}h/Z/W/\gamma$
- To what extent do these limit ultimate NP sensitivity in top/Higgs sector?

Can only be addressed in combined fit

- Beyond tree-level (at least for ggF)

[Degrande et al.; PRD 103 (2021) 9, 096024]
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

- Identify other cross-talk (non-trivial correlations)
- Crystallisation of knowledge gained after LHC Run 2/3
- Broaden range of applicability to UV models where the top is special

# The fit

`fitmaker` https://gitlab.com/kenmimasu/fitrepo

**Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory**

John Ellis,[a,b,c] Maeve Madigan,[d] Ken Mimasu,[a] Veronica Sanz[e,f] and Tevong You[b,d,g]

[JHEP 04 (2021) 279]

## Global SMEFT interpretation of 4 categories of data

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

14 • Electroweak Precision Observables (EWPO): Z-pole & W-mass

118 • LEP2 & LHC diboson production: differential WW, WZ, Zjj

72 • Higgs measurements: signal strengths & STXS

137 • Top data: single-top, ttbar & asymmetries, ttV, tZ, tW

Big thanks to authors of SMEFiT analysis [JHEP 04 (2019) 100] for sharing some of their top predictions

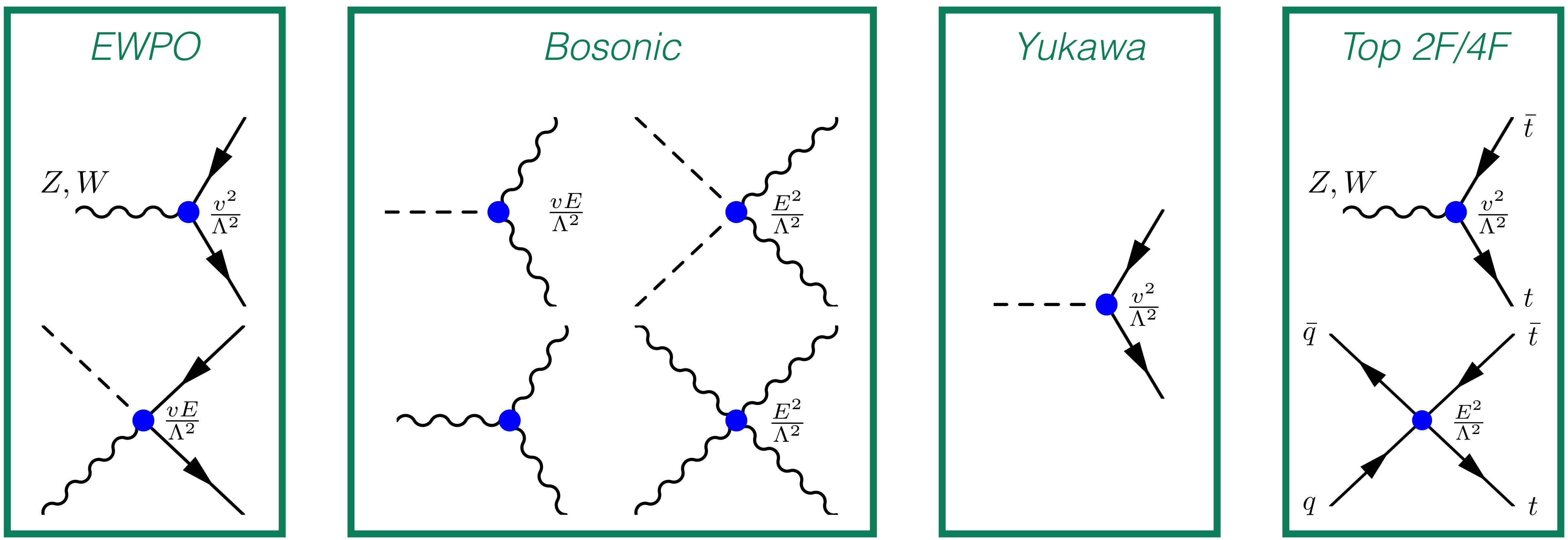
## 341 measurements across categories

- Chosen to be statistically independent & maximise reach
- Correlations included when publicly available (mostly are)

Linear EFT approximation: $$\mu_X \equiv \frac{X}{X_{SM}} = 1 + \sum_i a_i^X \frac{C_i}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

# Degrees of freedom

| Flavor scenario | | | |
|---|---|---|---|
| Universal | EWPO: | $\mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$ | |
| | Bosonic: | $\mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$ | |
| | Yukawa: | $\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,,$ | 20 |
| ‘Top specific’ | Top 2F: | $\mathcal{O}_{HQ}^{(3)}\,,\ \mathcal{O}_{HQ}^{(1)}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,$ | |
| | Top 4F: | $\mathcal{O}_{Qq}^{3,1}\,,\ \mathcal{O}_{Qq}^{3,8}\,,\ \mathcal{O}_{Qq}^{1,8}\,,\ \mathcal{O}_{Qu}^{8}\,,\ \mathcal{O}_{Qd}^{8}\,,\ \mathcal{O}_{tQ}^{8}\,,\ \mathcal{O}_{tu}^{8}\,,\ \mathcal{O}_{td}^{8}\,.$ | +14 |



# Degrees of freedom

| ***Flavor scenario*** | | |
|---|---|---|
| *Universal* | EWPO: | $\mathcal{O}_{HWB}\,, \mathcal{O}_{HD}\,, \mathcal{O}_{ll}\,, \mathcal{O}_{Hl}^{(3)}\,, \mathcal{O}_{Hl}^{(1)}\,, \mathcal{O}_{He}\,, \mathcal{O}_{Hq}^{(3)}\,, \mathcal{O}_{Hq}^{(1)}\,, \mathcal{O}_{Hd}\,, \mathcal{O}_{Hu}\,;$ |
| | Bosonic: | $\mathcal{O}_{H\Box}\,, \mathcal{O}_{HG}\,, \mathcal{O}_{HW}\,, \mathcal{O}_{HB}\,, \mathcal{O}_{W}\,, \mathcal{O}_{G}\,,$ |
| | Yukawa: | $\mathcal{O}_{\tau H}\,, \mathcal{O}_{\mu H}\,, \mathcal{O}_{bH}\,, \mathcal{O}_{tH}\,,$ 20 |
| *'Top specific'* | Top 2F: | $\mathcal{O}_{HQ}^{(3)}\,, \mathcal{O}_{HQ}^{(1)}\,, \mathcal{O}_{Ht}\,, \mathcal{O}_{tG}\,, \mathcal{O}_{tW}\,, \mathcal{O}_{tB}\,,$ |
| | Top 4F: | $\mathcal{O}_{Qq}^{3,1}\,, \mathcal{O}_{Qq}^{3,8}\,, \mathcal{O}_{Qq}^{1,8}\,, \mathcal{O}_{Qu}^{8}\,, \mathcal{O}_{Qd}^{8}\,, \mathcal{O}_{tQ}^{8}\,, \mathcal{O}_{tu}^{8}\,, \mathcal{O}_{td}^{8}\,.$ +14 |

In total: 20(34) d.o.f. for the two flavor scenarios

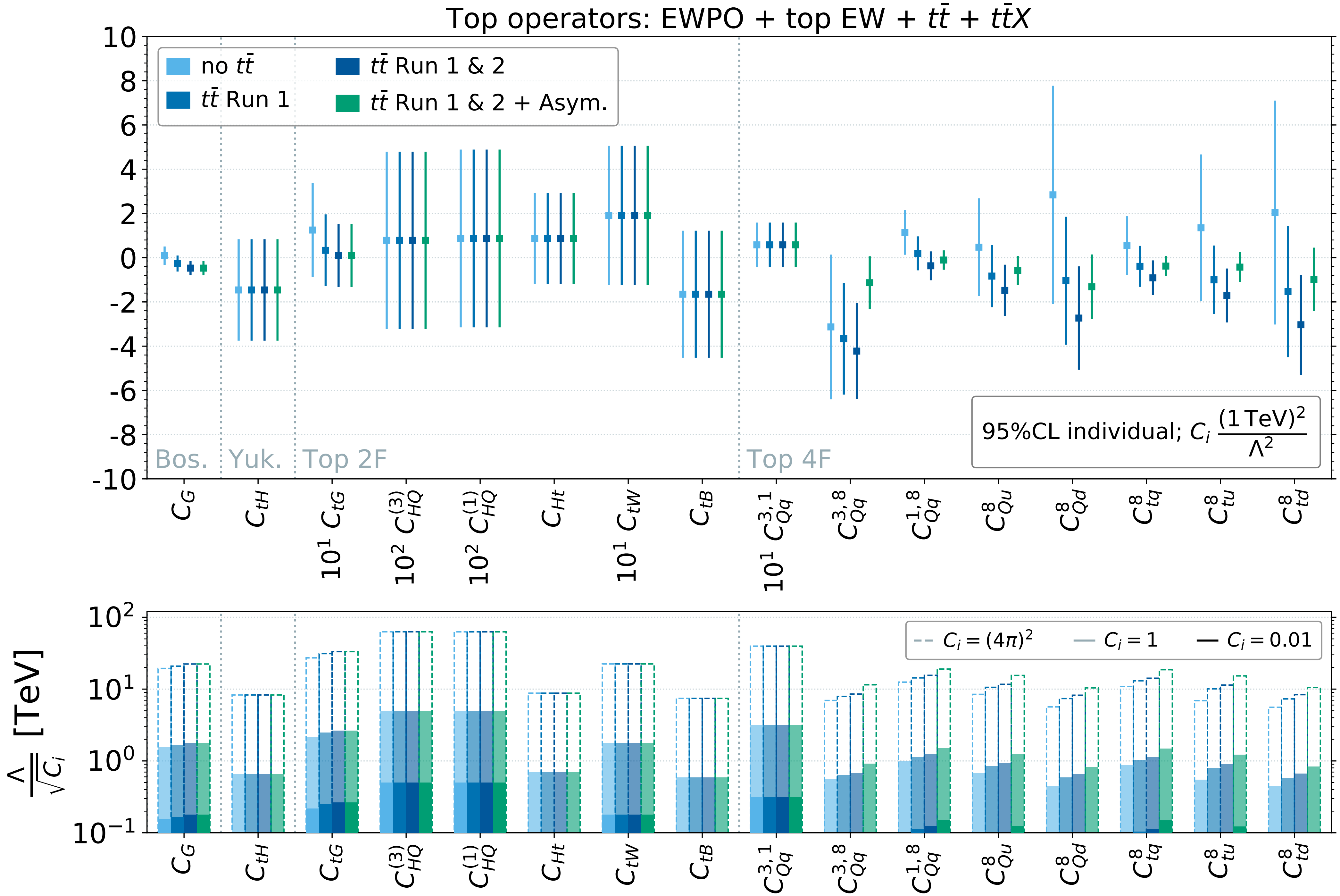
*Dim6top conventions: [Aguilar-Saavedra et al.; arXiv:1802.07237]*

Dictated by flavor symmetry & sensitivity of dataset

Linear EFT fit: precludes sensitivity to some ops

- Those that cannot interfere due to helicity/symmetries
- e.g. neutral colour-singlet top 4F operators: $(\bar{q}\gamma^\mu q)(\bar{t}\gamma^\mu t)$ (x 6)
- Four-heavy quark operators in 4top & ttbb (quadratic dominated)

# Top-only: top + EWPO individual

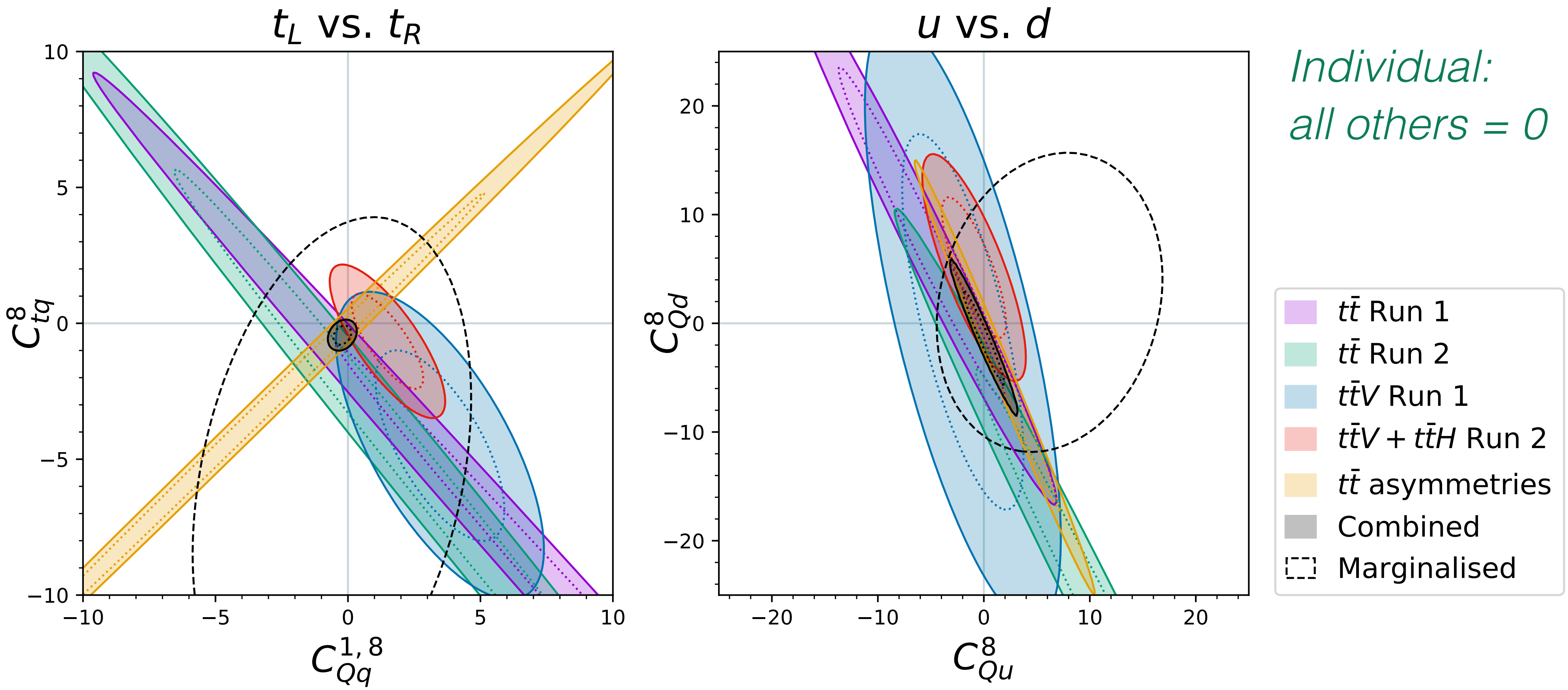



- Some tension in $t\bar{t}$ data
- Asymmetries help to improve agreement

See also dedicated top fits: SMEFiT [Hartland et al.; JHEP 04 (2019) 100]
SFitter [Brivio et al.; JHEP 02 (2020) 131]

# Top-only: breakdown

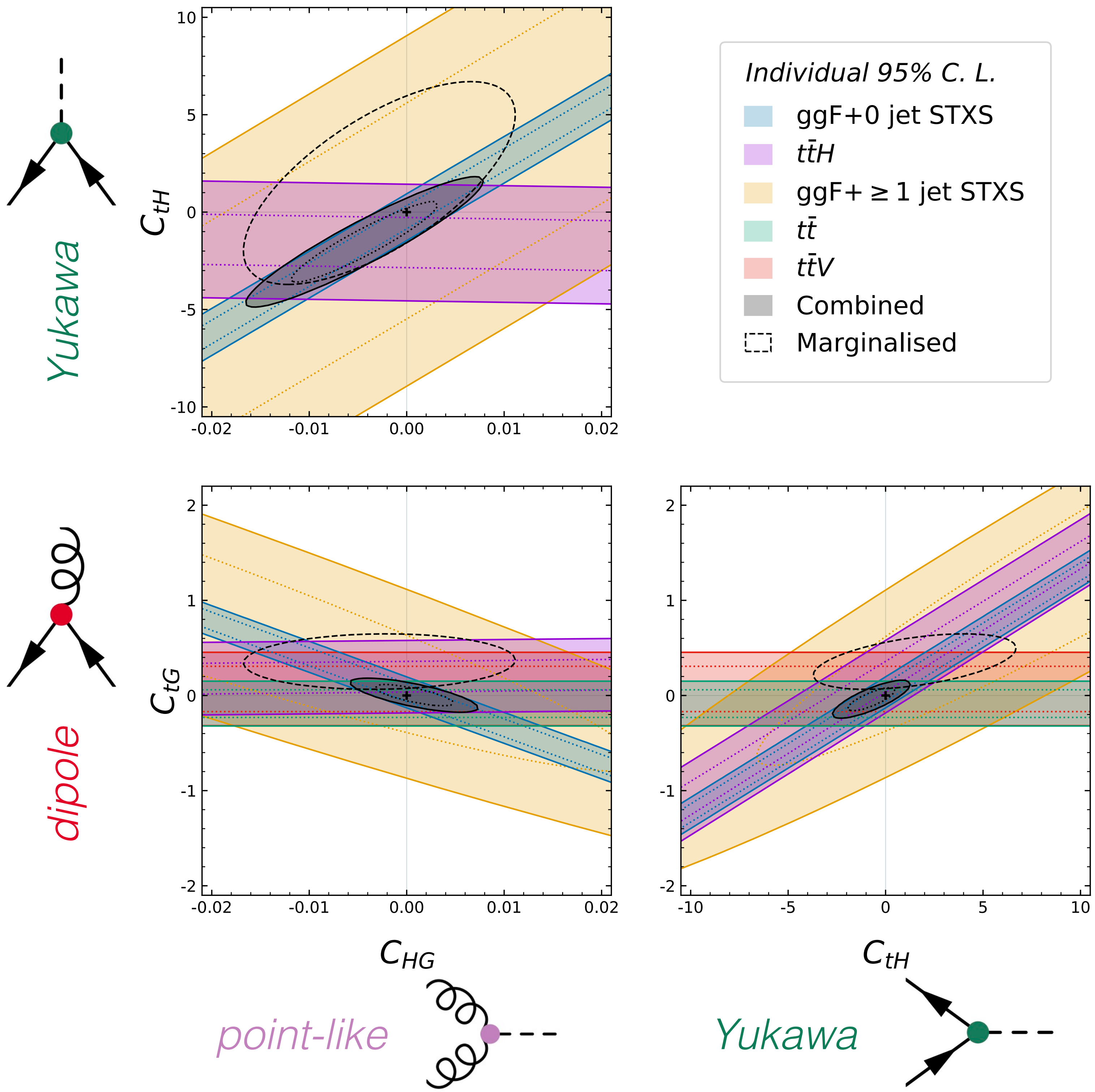
4F ($\bar{t}t\bar{q}q$) operators




Individual: all others = 0

- $t\bar{t}$ asymmetries constrain orthogonal direction to cross section
- Large marginalisation effects: many similar operators
- $t\bar{t}V$ & $t\bar{t}H$ help to close the space
- Marginalised linear sensitivity: $C_{4F}\left[\frac{1\,\mathrm{TeV}^2}{\Lambda^2}\right] \sim (5-15)$ significant $\frac{1}{\Lambda^4}$ effects

# Top-Higgs interplay

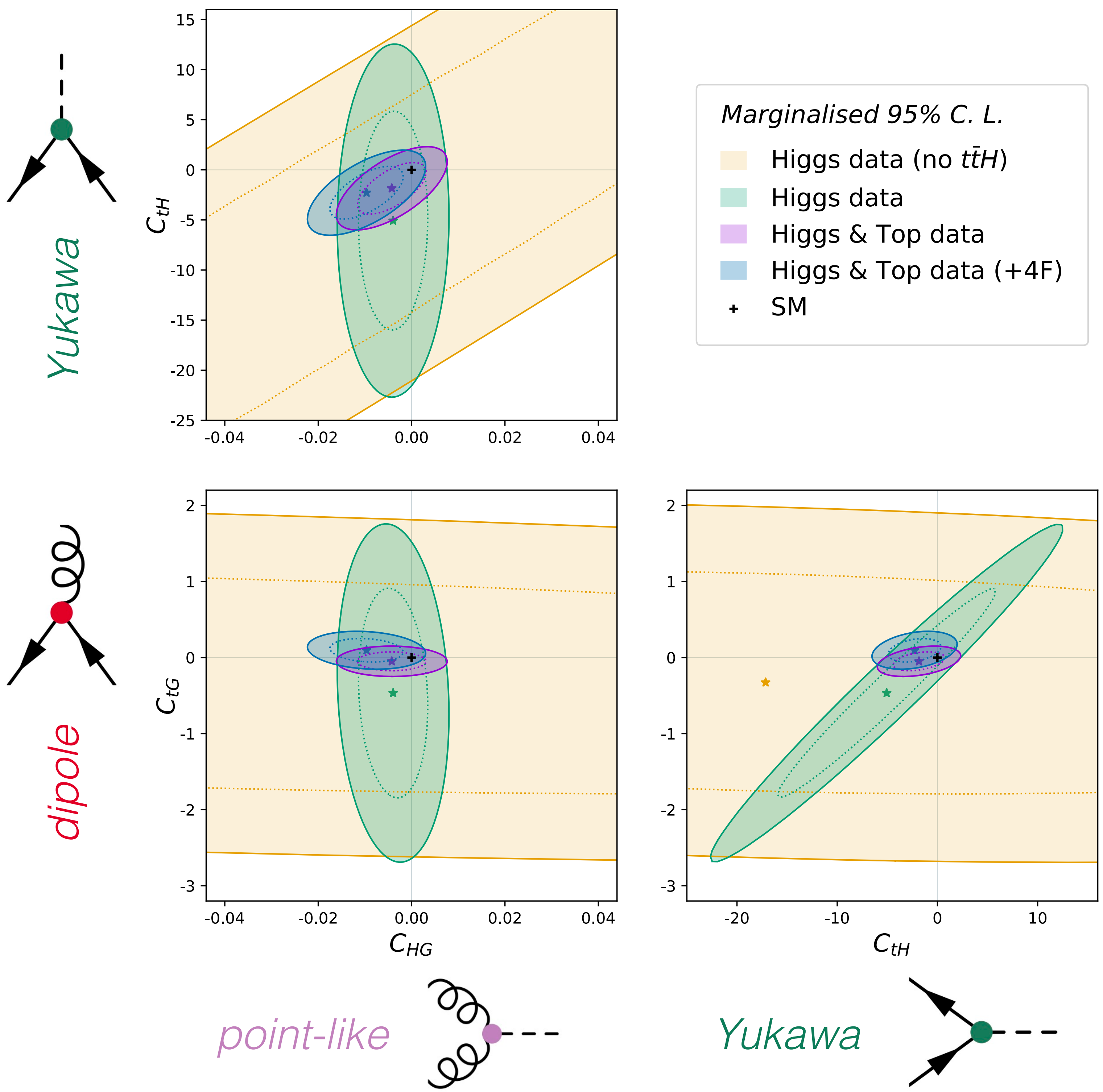



## 2D individual constraints

- All others set to 0
- $ggF/t\bar{t}H$ complementarity for $(C_{HG}, C_{tH})$
- H+jets STXS & $t\bar{t}V$ not yet competitive
- Strong impact of $t\bar{t}$ evident for $C_{tG}$
- Tension with SM $\sim 2\sigma$
- Significant correlations remain
- Large marginalisation effects

**What is the concrete impact of 4F?**

# Top-Higgs interplay




Fit: Higgs SS & STXS $\mathcal{O}(\Lambda^{-2})$

8 Higgs operators + $C_{tG}$

- Marginalised confidence regions
- Significant impact of $t\bar{t}H$ & $t\bar{t}(V)$

Now add in $t\bar{t}$ 4F operators

$$+\ C^{3,8}_{Qq}, C^{1,8}_{Qq}, C^{8}_{Qu}, C^{8}_{Qd}, C^{8}_{tq}, C^{8}_{tu}, C^{8}_{td}$$

- Relatively mild impact
- Preferred $t\bar{t}$ phase space is different

$C_{tG}$ : low $m_{t\bar{t}}$

$4F$ : high $m_{t\bar{t}}$

- Able to constrain them independently

**Top data is crucial!**

# 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!

Science and Technology Facilities Council

University of Southampton

# 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 & tt$\gamma$ |
| *[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

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

## eHDECAY for BR

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

## HAWK

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

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

## VBFNLO

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

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

## VH via POWHEG-BOX/MCFM

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

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

## HELatNLO

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

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

## Dilepton & EW Higgs in POWHEG-BOX

- Larger set of operators considered

# Going forward

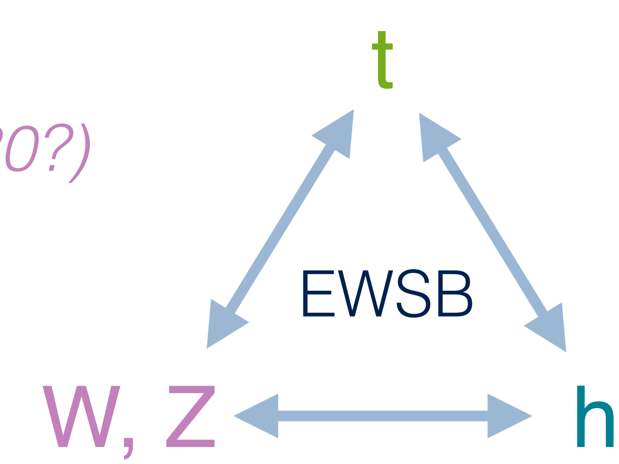
So far, global analyses consider top & Higgs/EW in isolation

Many rare top/EW processes are within LHC reach

t$\gamma$j *(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

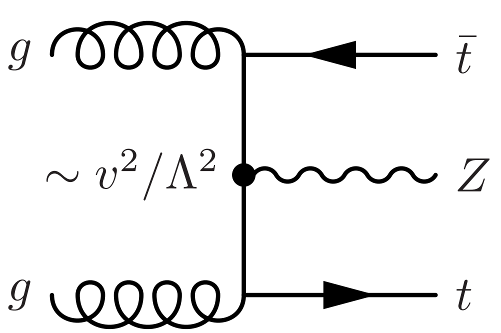
- Identify new processes e.g. ttbb
- Maximise energy growing effects

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

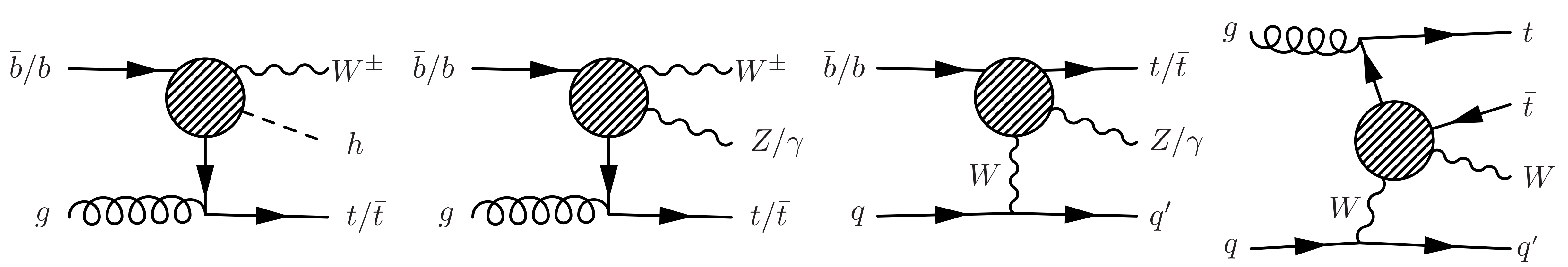
# High-energy EW tops

## 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

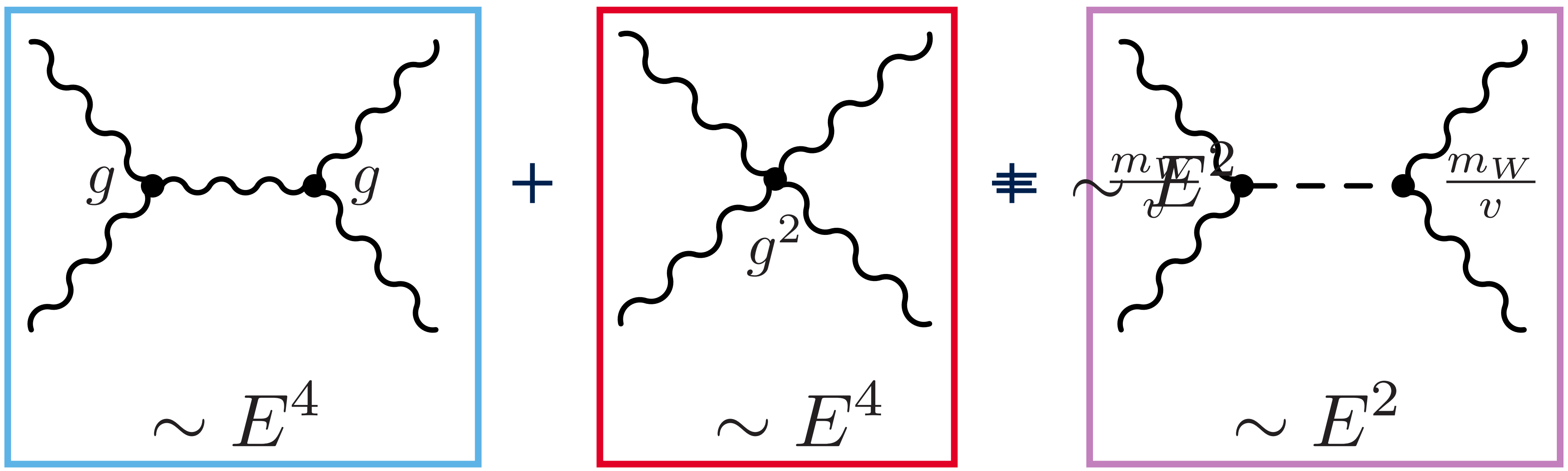
- Probe mixed top/EW/Higgs interactions
- Unitarity violating behaviour (energy growth) ∝ $vE$, $E^2$

Analogous to $V_L$ scattering

# Scattering unitarity

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

$\mathcal{A} =$




$= \boxed{\sim E^0}$

triple-gauge — quartic — EWSB

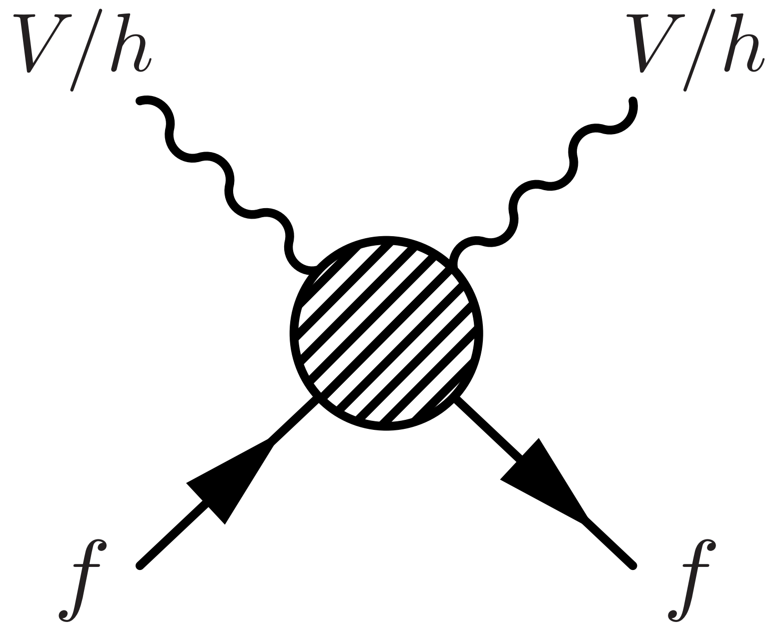
Diboson (TGC) — VBS (TGC, QGC) — EW Higgs prod./decay

## 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*

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

*'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:

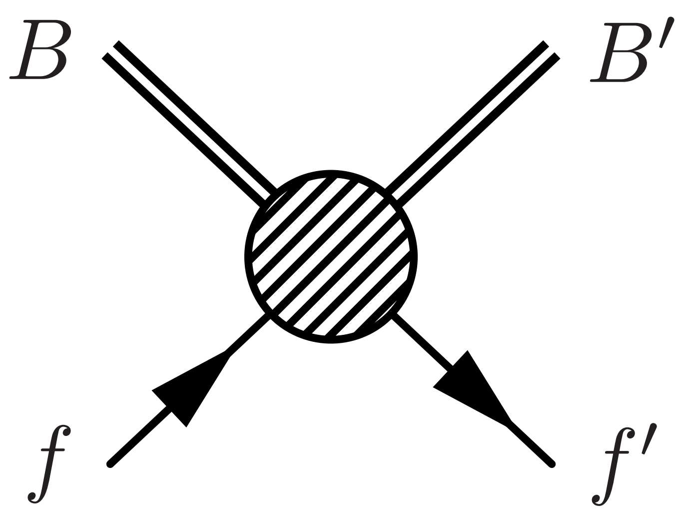
- **May not** grow maximally with energy ($E^2$)
- Have **suppressed** interference w/ SM

*[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 | $b\,W \to t\,(Z/\gamma)$ | $t\,W \to t\,W$<br>$t\,(Z/\gamma) \to t\,(Z/\gamma)$ |
| w/ Higgs | $b\,W \to t\,h$ | $t\,(Z/\gamma) \to t\,h$<br>$t\,h \to t\,h$ |

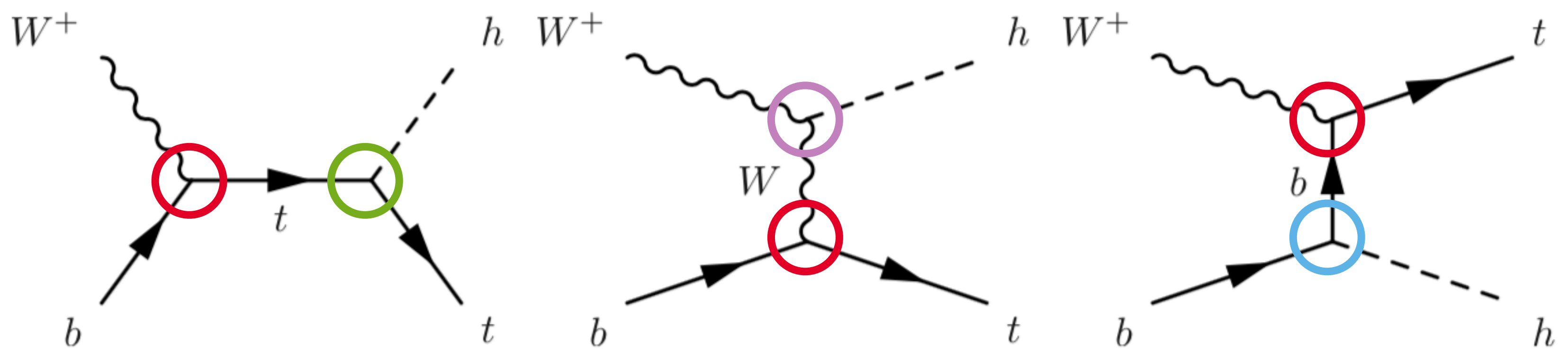
Considered 10, 2 → 2 scattering amplitudes with ≥ one top

- 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

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

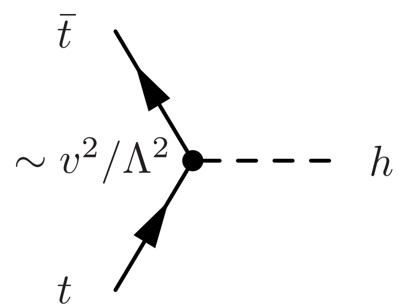
- Fixing couplings to SM values sends it to $E^{-1}$

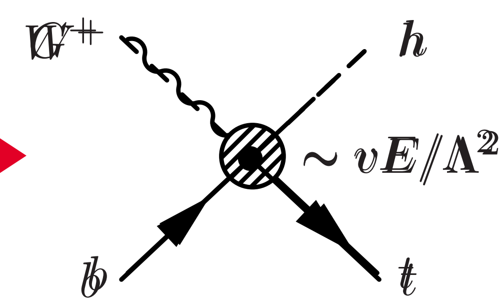
# bW⁺ → tH in SMEFT

## One source of energy growth from modified SM interactions

- Yukawa operator: disconnects kinematical mass from coupling to Higgs

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



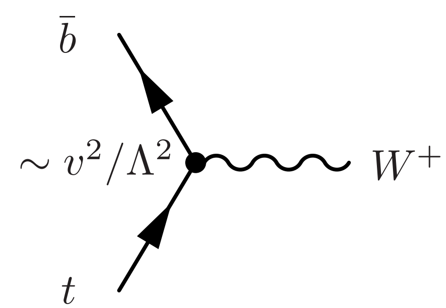



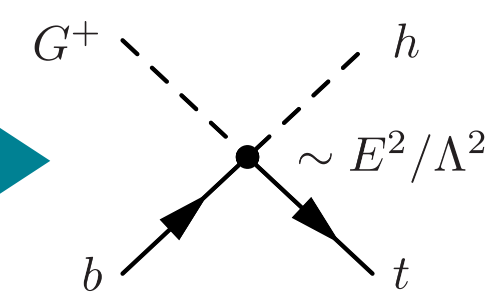

$$\boxed{h\, G^+\, \bar{t}_L\, b_R}$$

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

## Max growth from dim-6 contact-terms

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



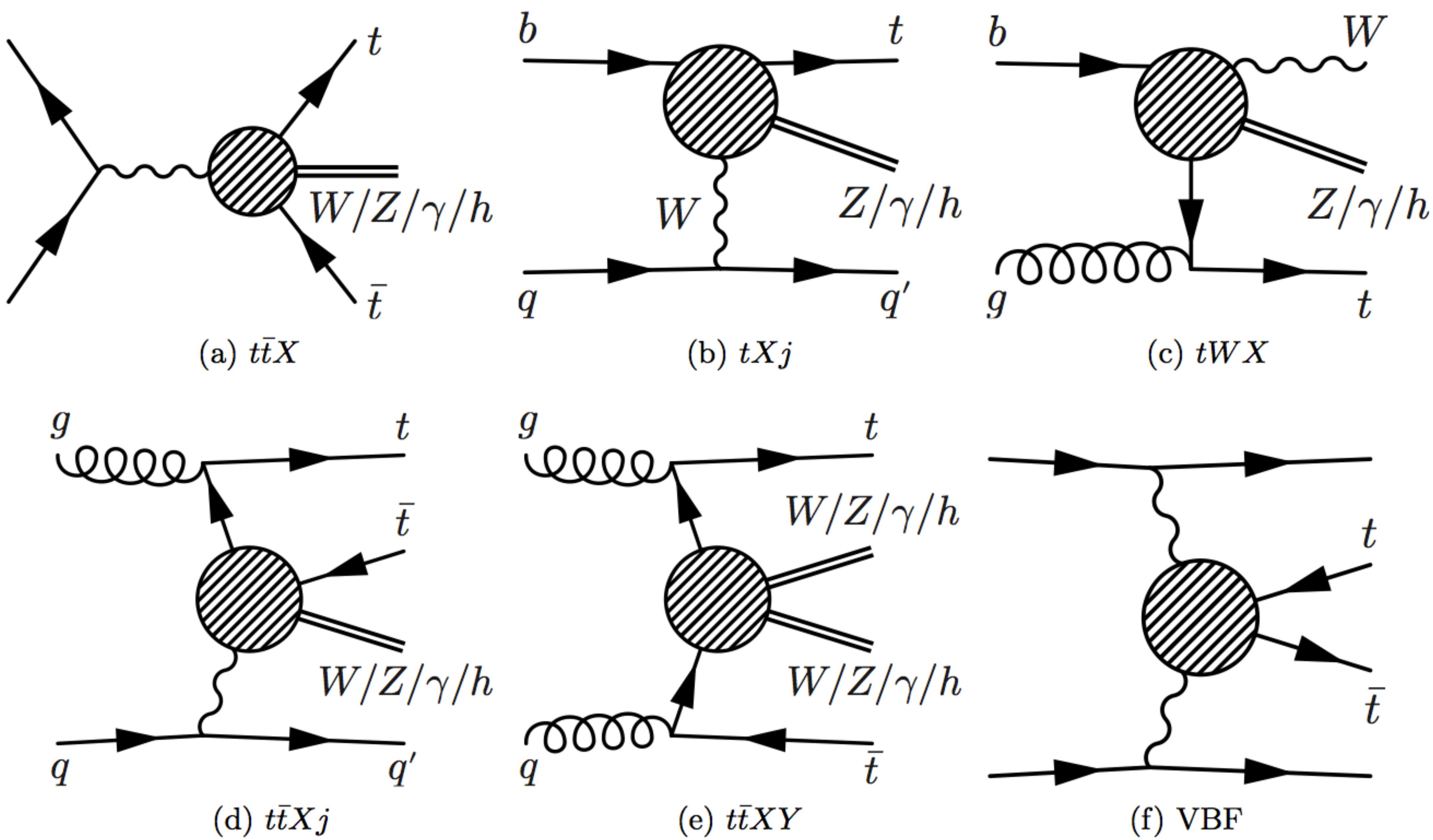




$$\boxed{h\, \partial_\mu G^+\, \bar{t}\, \gamma^\mu b}$$

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

# Embedding the amplitudes

## Collider processes: rare top production



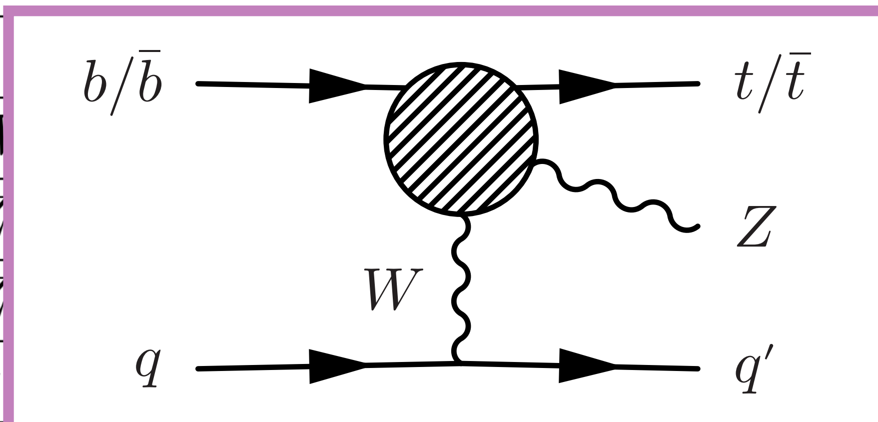

(a) $t\bar{t}X$ (b) $tXj$ (c) $tWX$

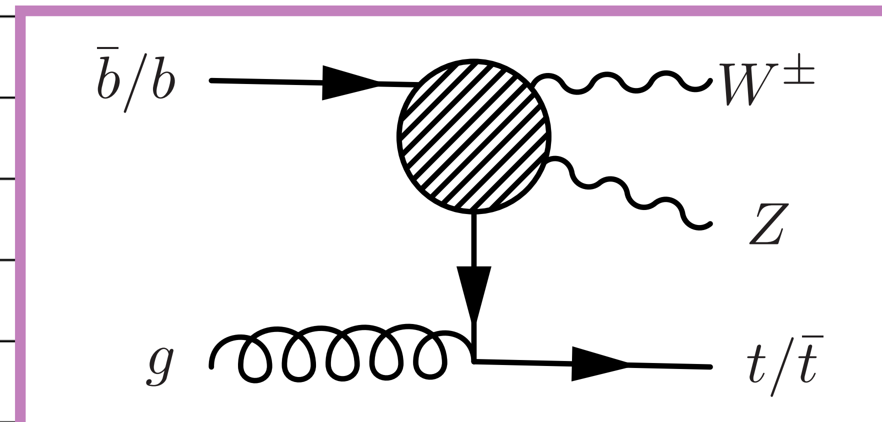
(d) $t\bar{t}Xj$ (e) $t\bar{t}XY$ (f) VBF

# Embedding the amplitudes

## Collection of ‘sensitivity’ studies, general discussion

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



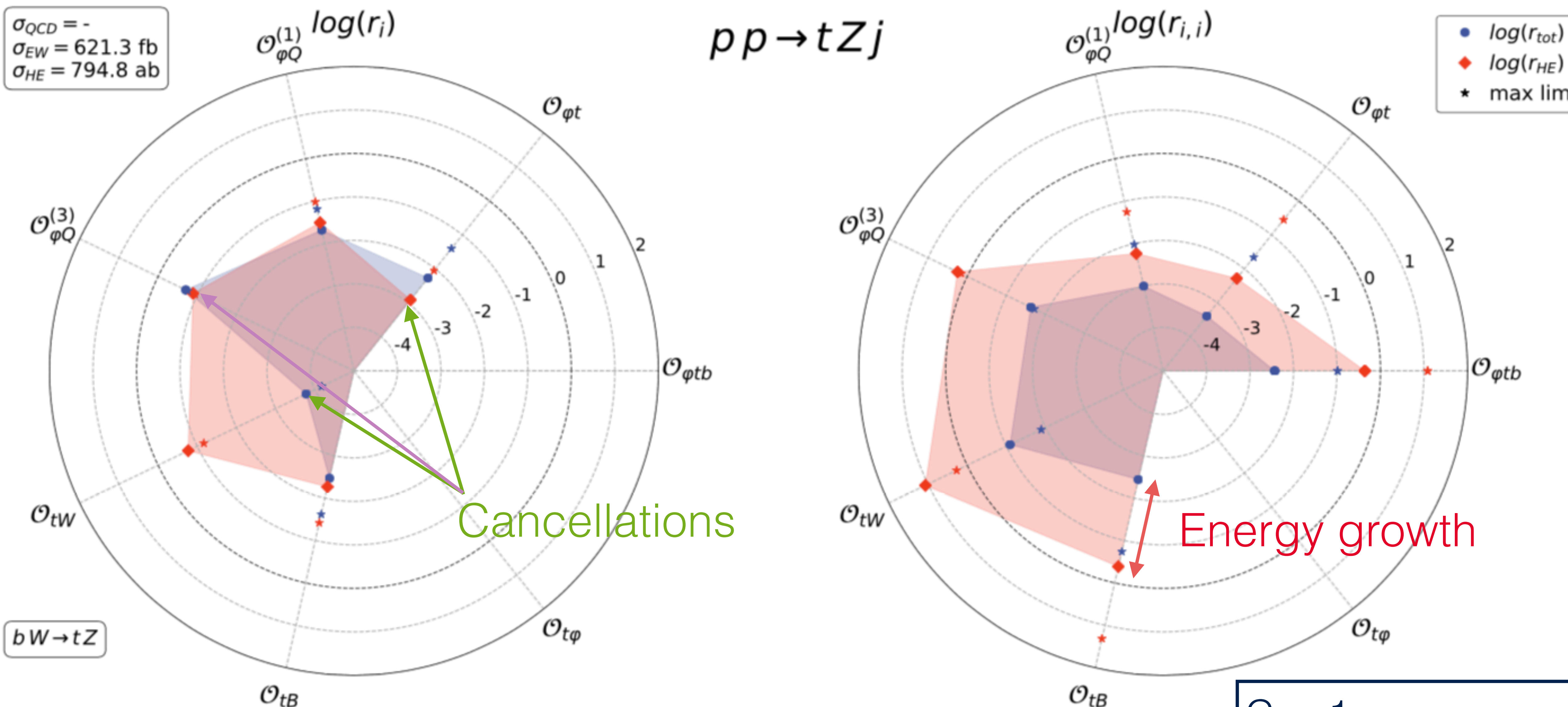

| | $BF$ |
|---|---|
| $tW$ | ✓ |
| $tZ$ | ✓ |
| $tZ$ | ✓ |
| $t\gamma$ | ✓ |

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

# tZj total & high energy xs

interference/SM

square/SM




$C_i$ = 1
Inclusive
$p_T$ (Z)> 500 GeV

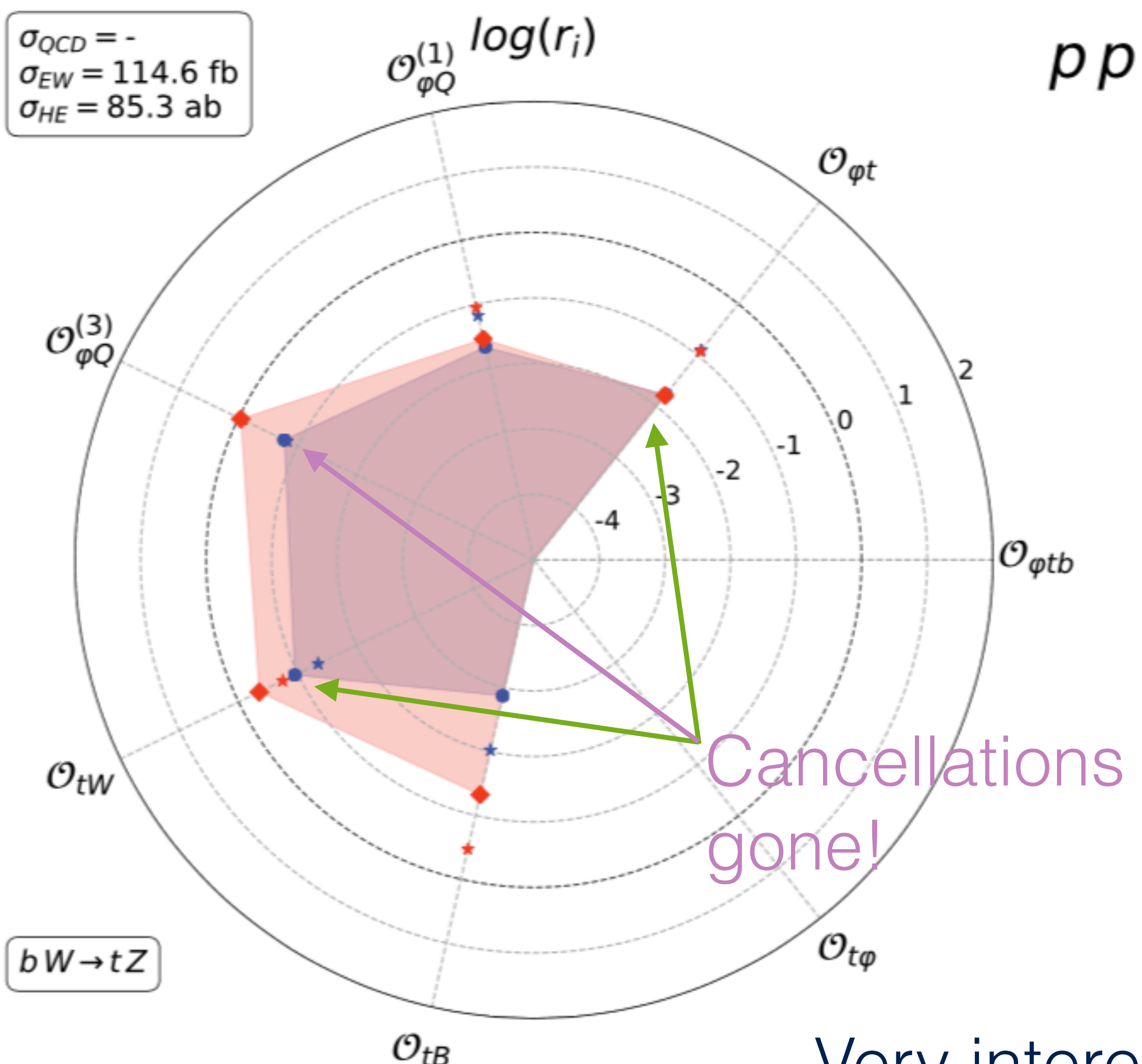
Expected growth from 2→2 absent!

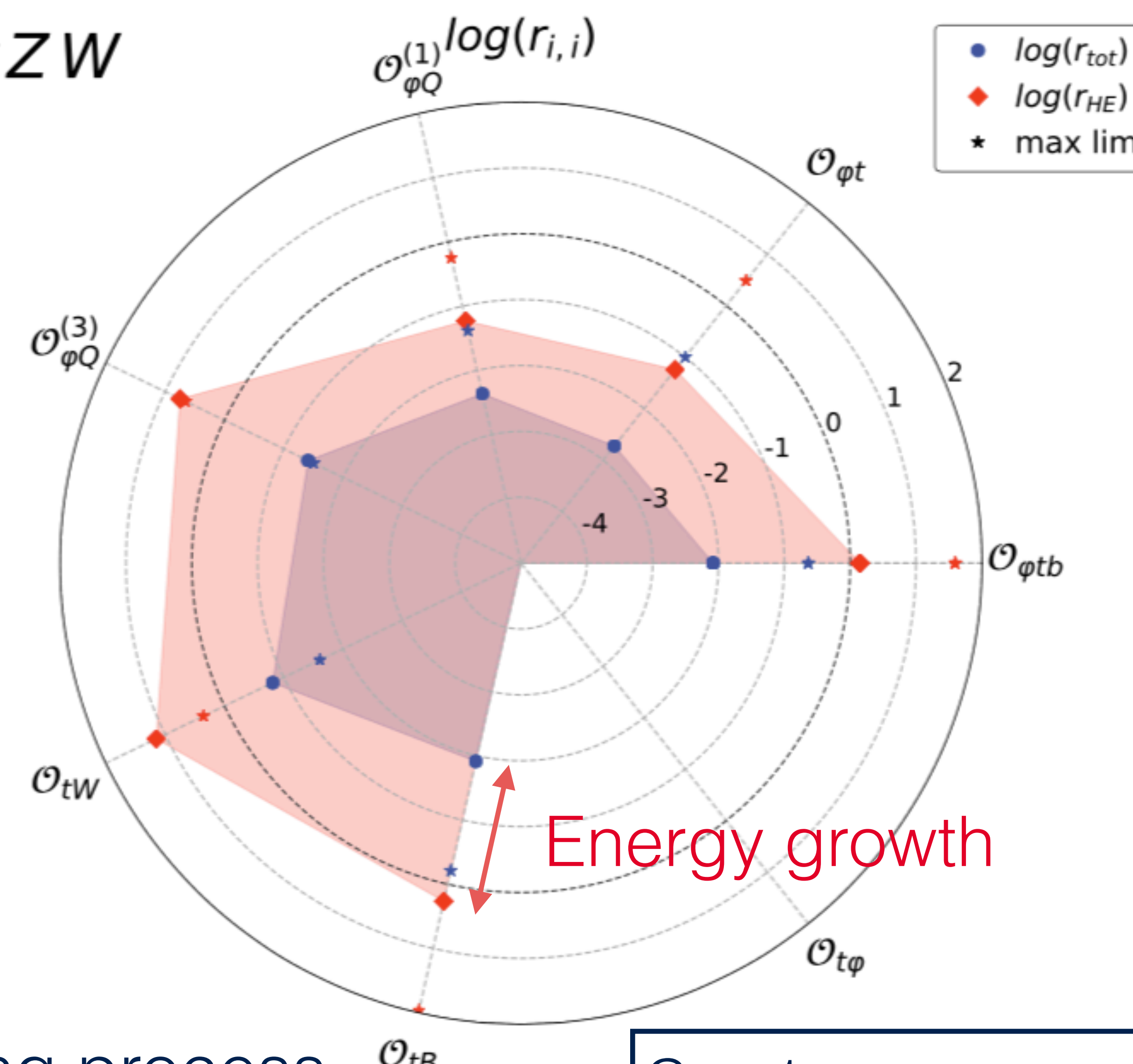
# tZW total & high energy xs

interference/SM

square/SM

$pp \rightarrow tZW$




Expected growth is there!

Very interesting process that should be measured at the LHC

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