SMEFT and searches for new physics

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KCL TPPC Seminar

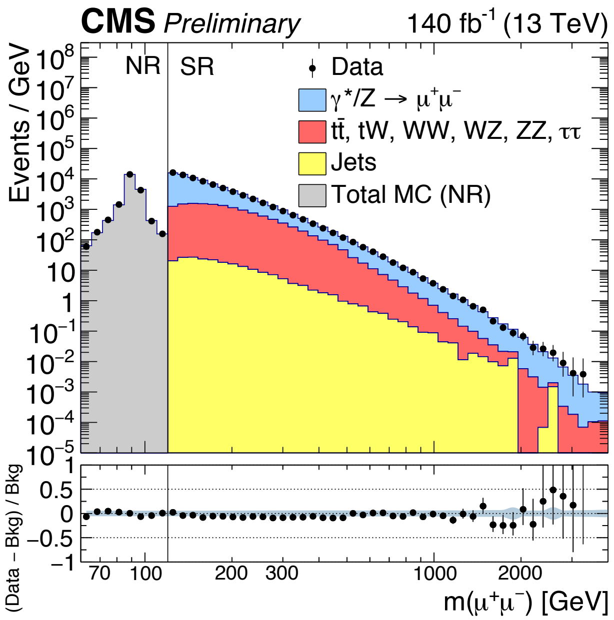
14th October 2020

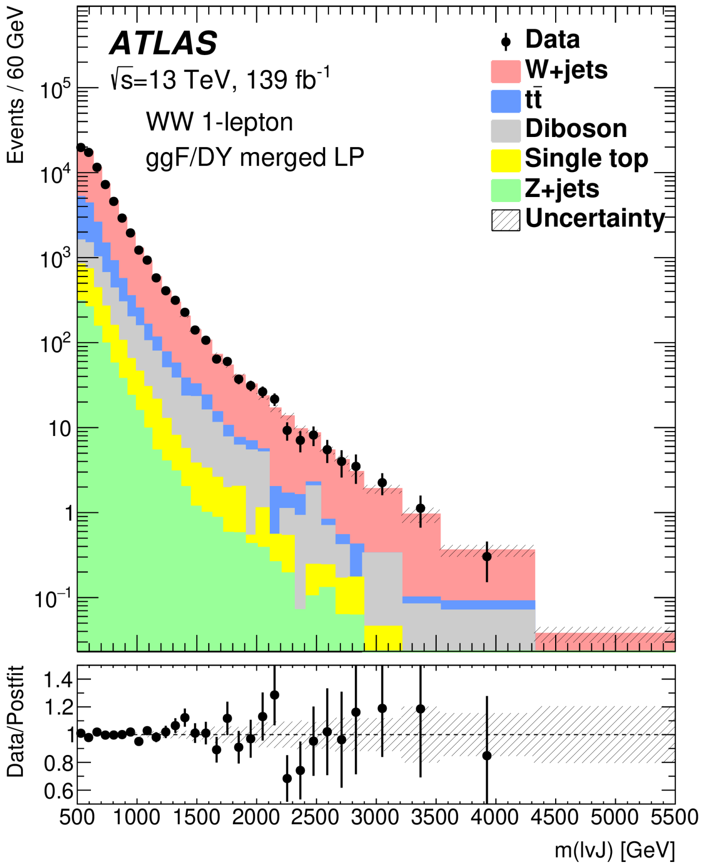
Where are we?

10 years since the start of LHC run 1

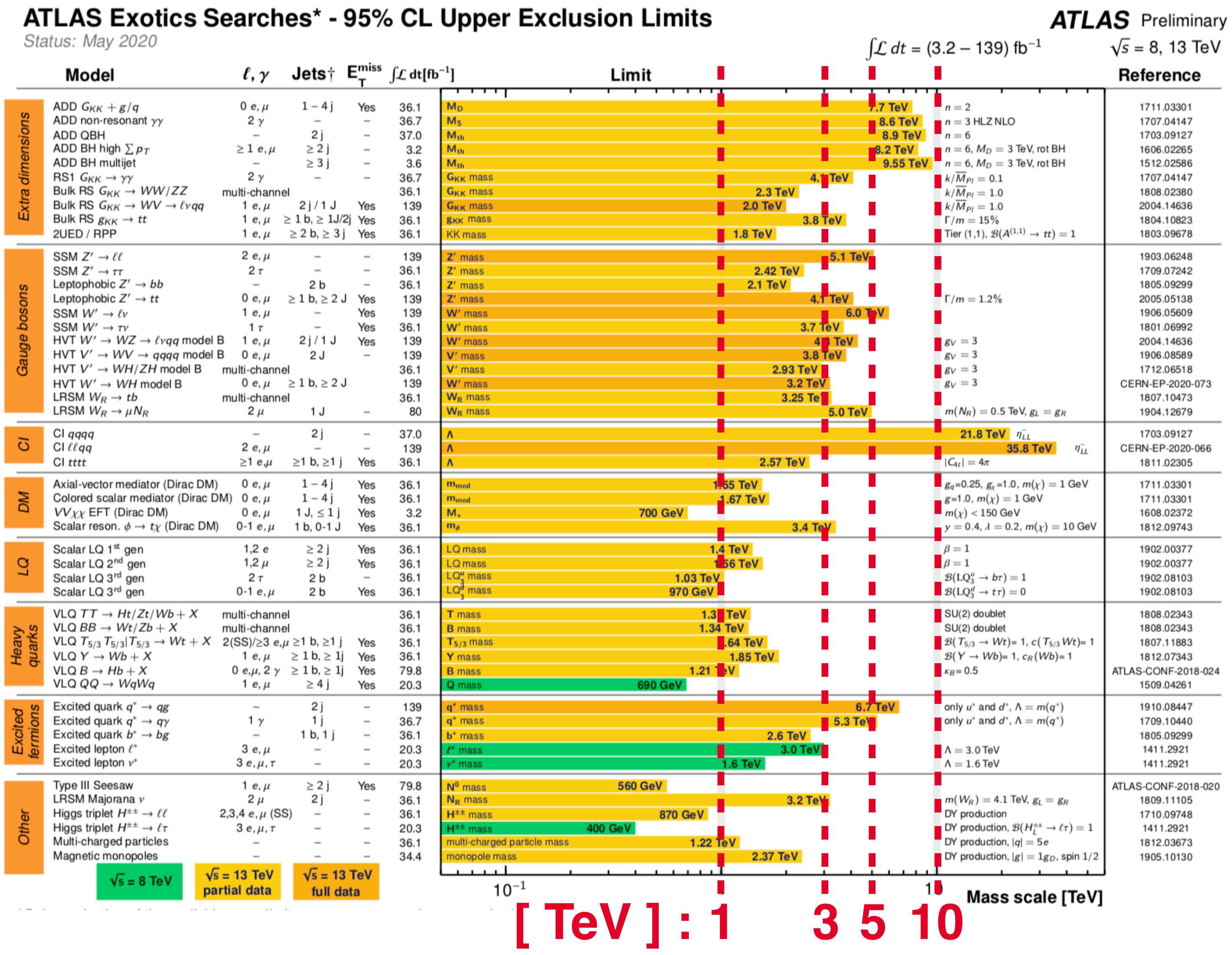
- No clear sign of TeV scale new physics
- Direct searches have saturated the energy frontier

[CMS-PAS-EXO-19-019]





[CERN-EP-2020-049]



[TeV] : 1 3 5 10

What do we know?

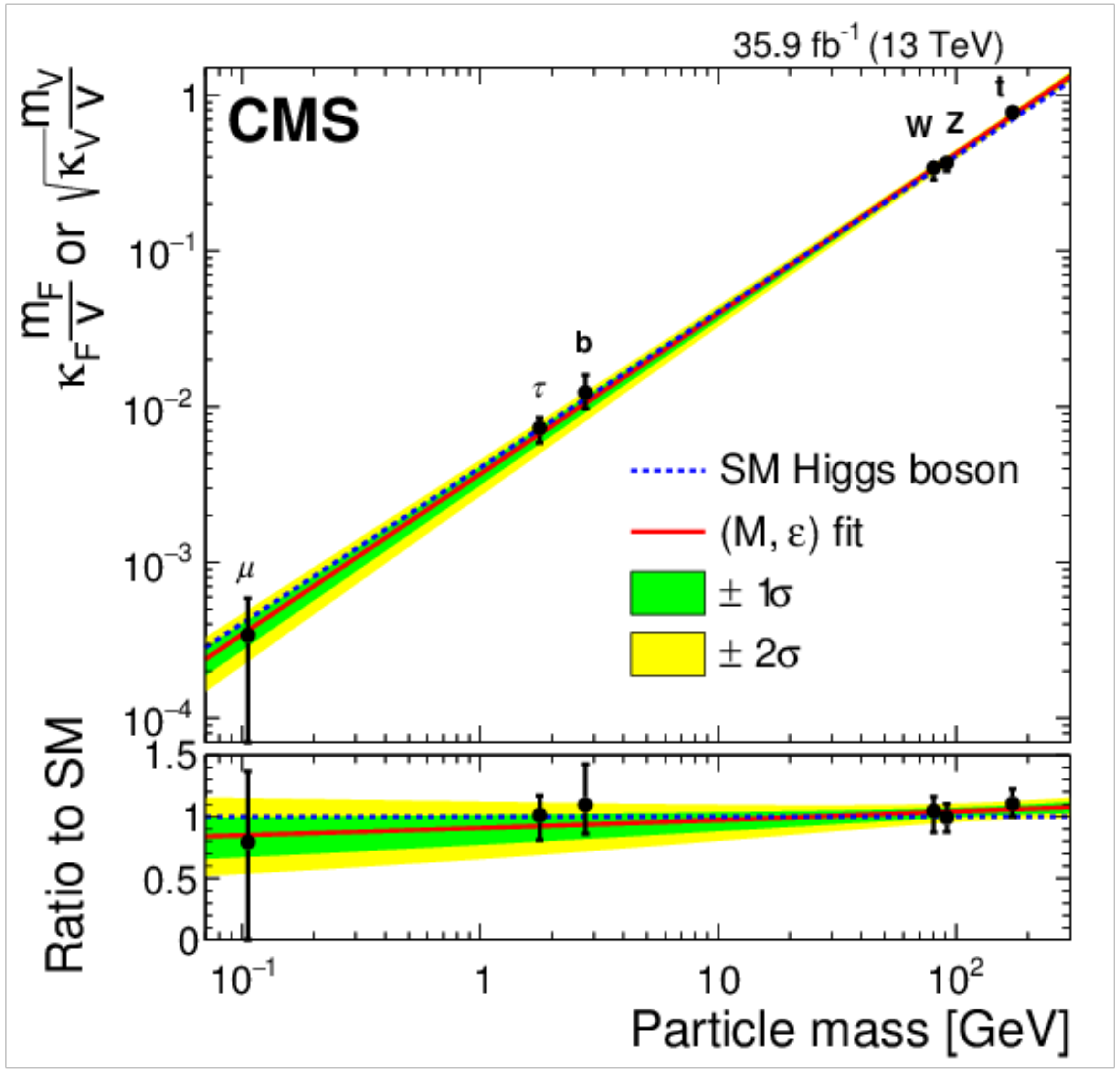
BSM states are either too…

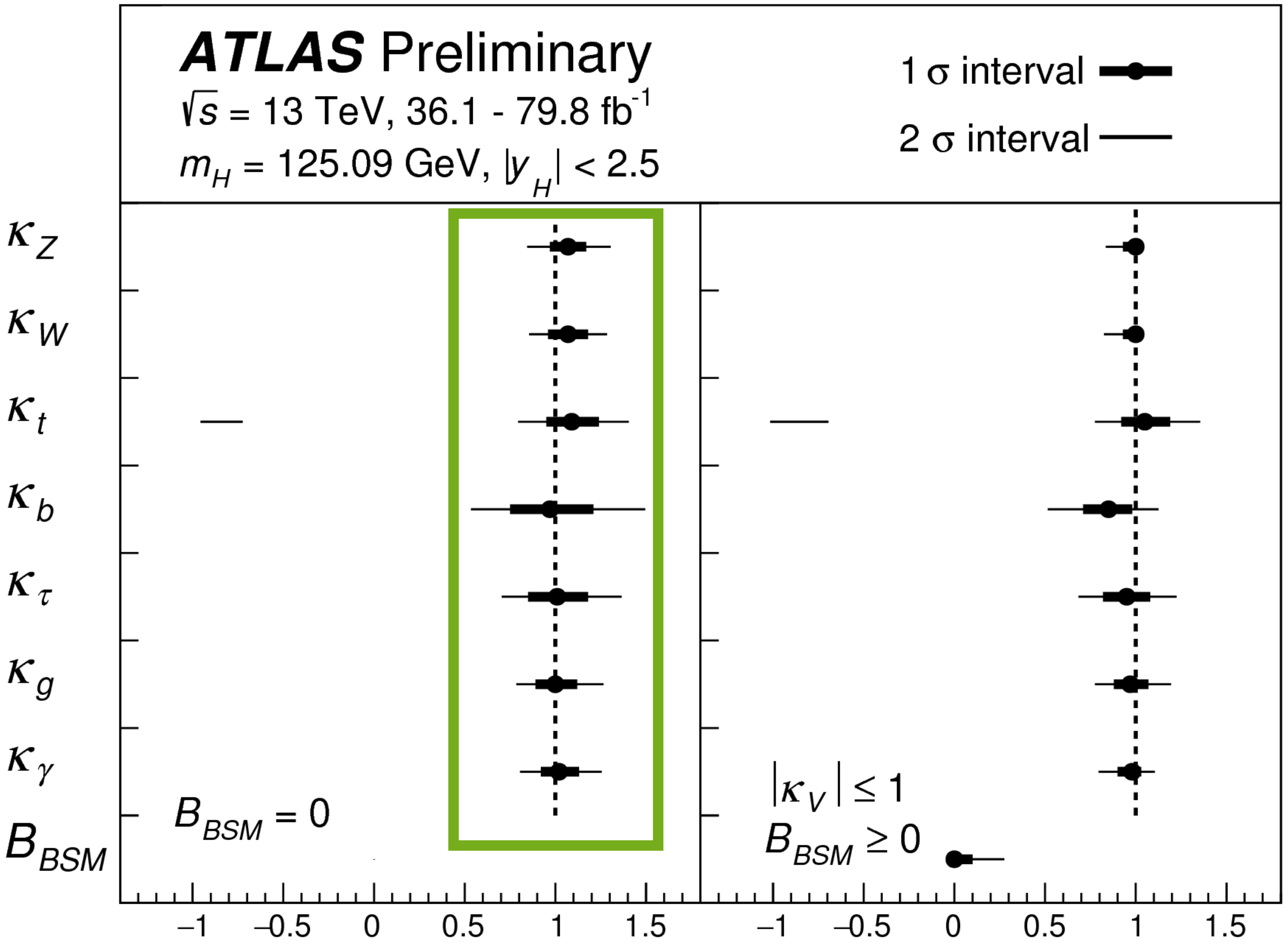
Weakly coupled *rate limited*	Room for improvement with increasing luminosity Still 20x more data to come
Exotic *we aren't looking in the right place*	Limited by our creativity Work for theorists & experimentalists to motivate & enable searches for new signatures
Heavy *kinematically out of reach*	Worst-case scenario from direct search point of view Complemented by indirect searches

A lot more than pre-2010

We have found a scalar that couples to mass

- It behaves ***quite a bit*** like the SM Higgs





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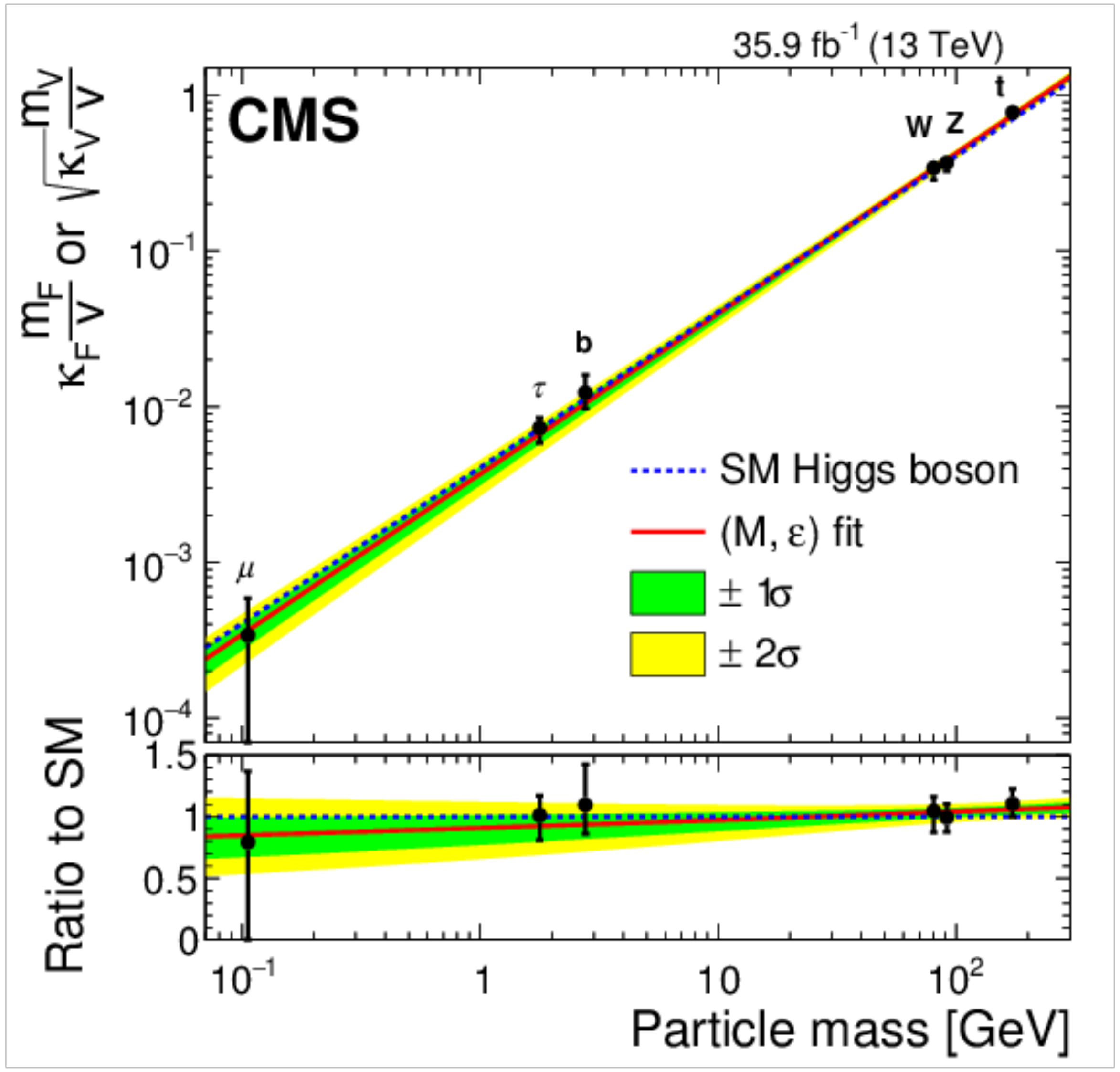

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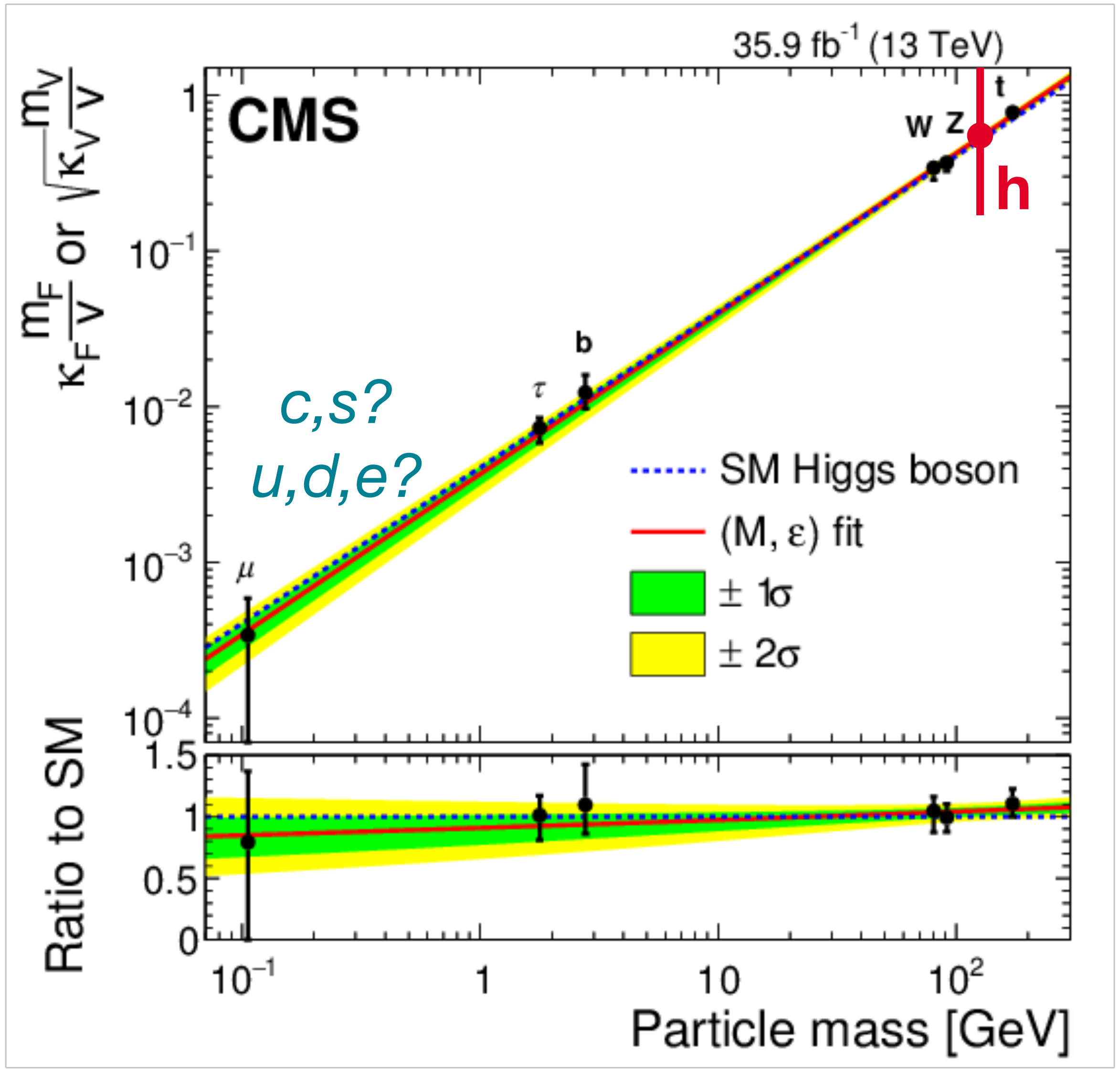

At least *one* missing ingredient…

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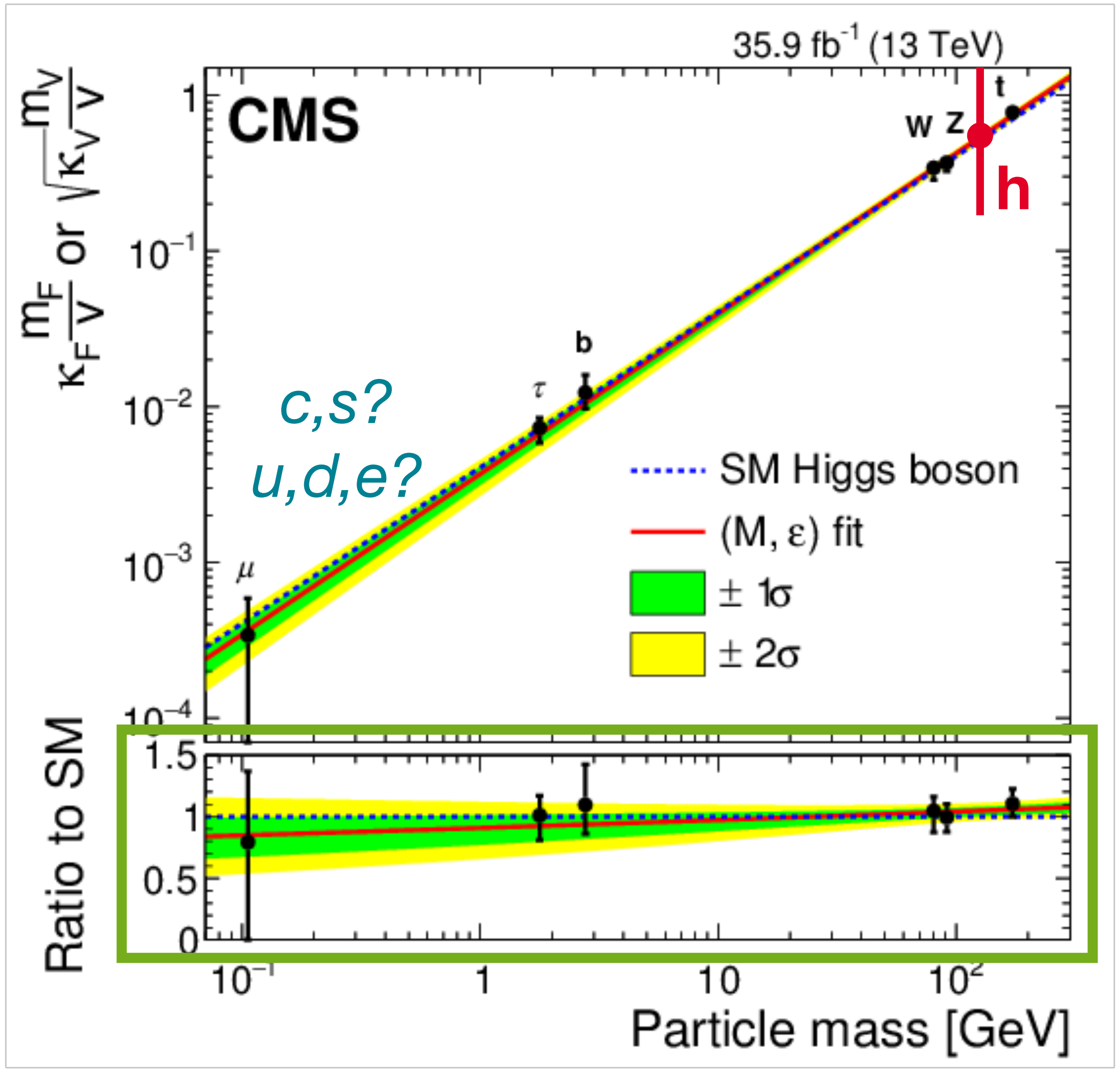

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Still some way to go to pin down precise interactions

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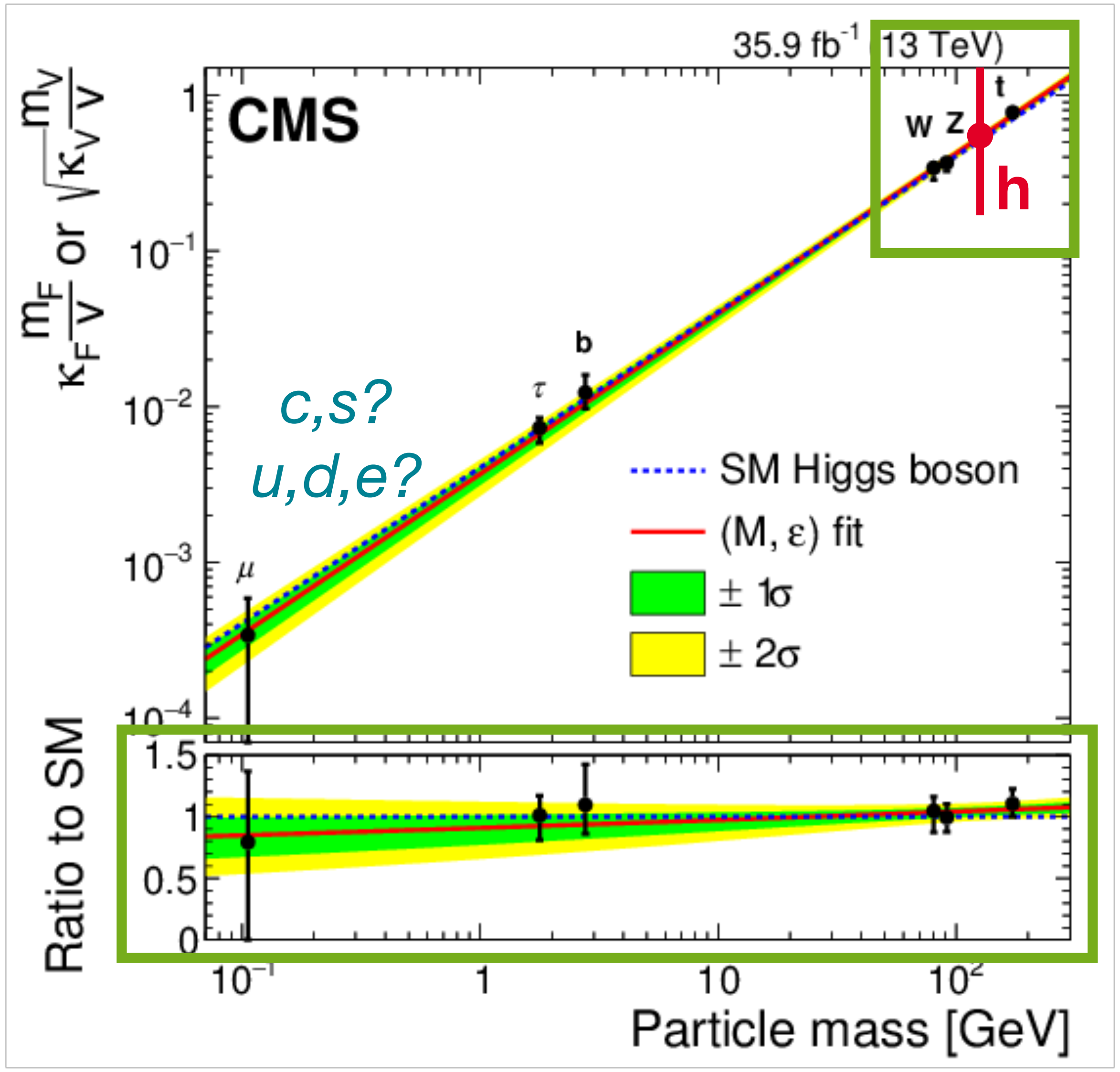
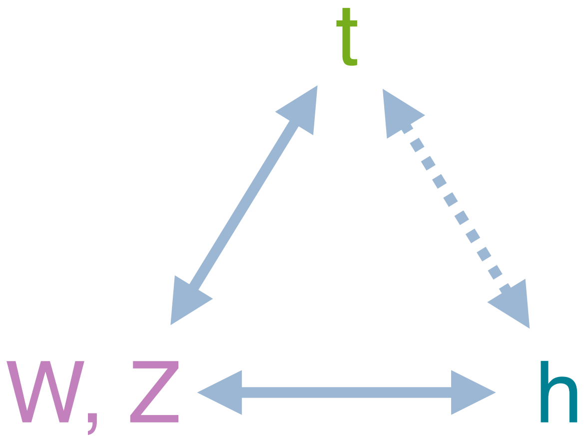


At least *one* missing ingredient…

Still some way to go to pin down precise interactions

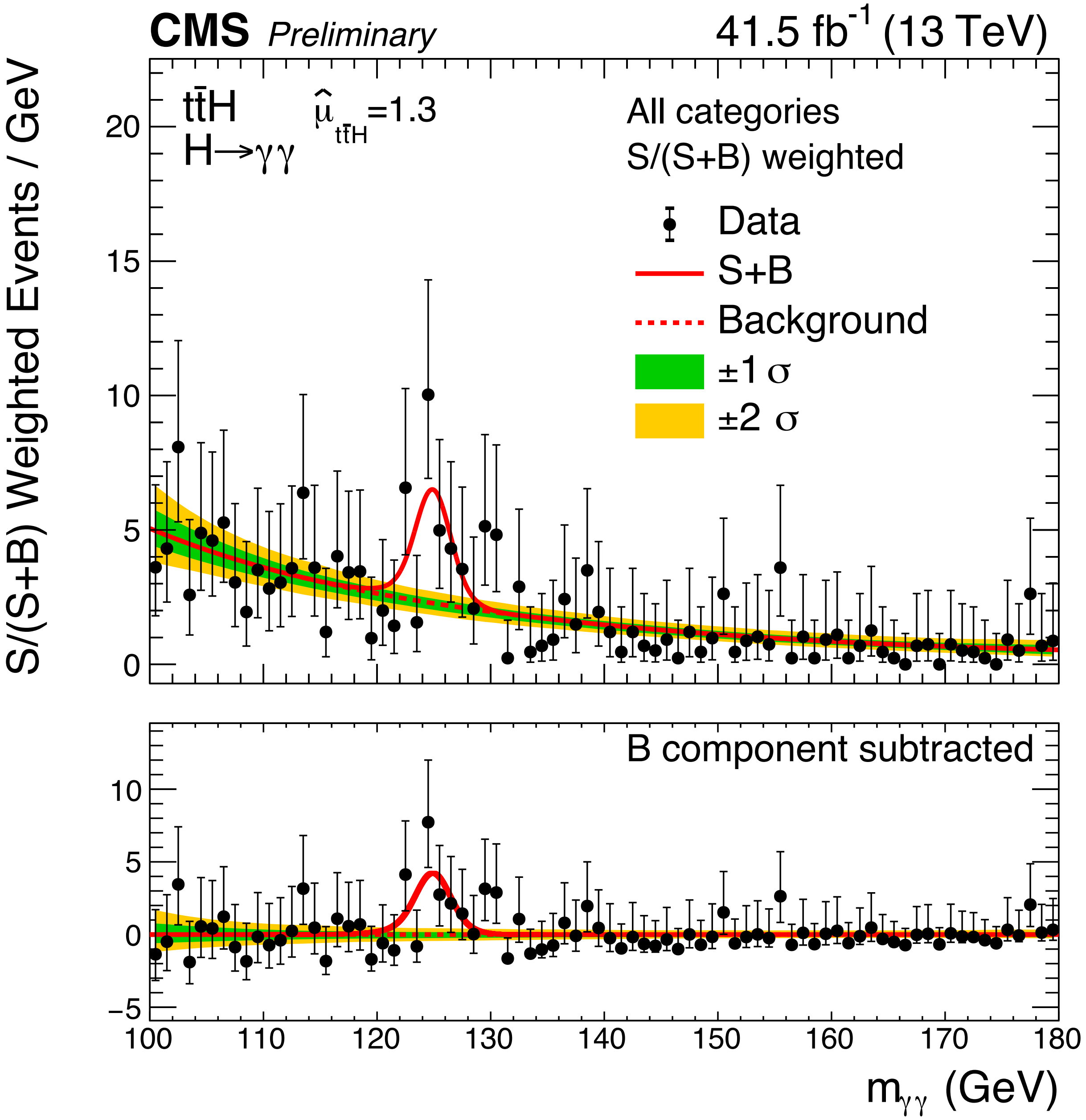
The priority mission of the LHC is to characterise the EWSB sector



Recent headlines

[CMS; PRL 120 (2018) 231801] & [ATLAS; PLB 784 (2018) 173]

It couples to the top



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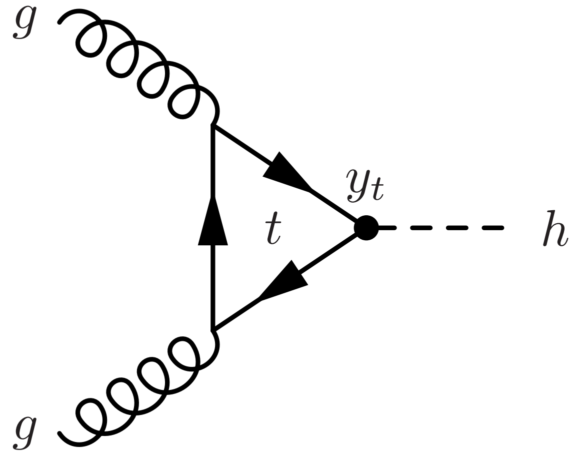
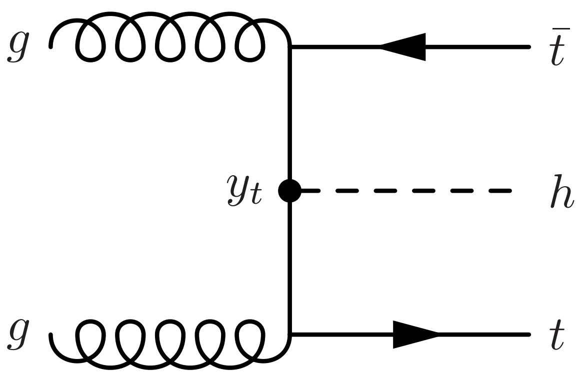
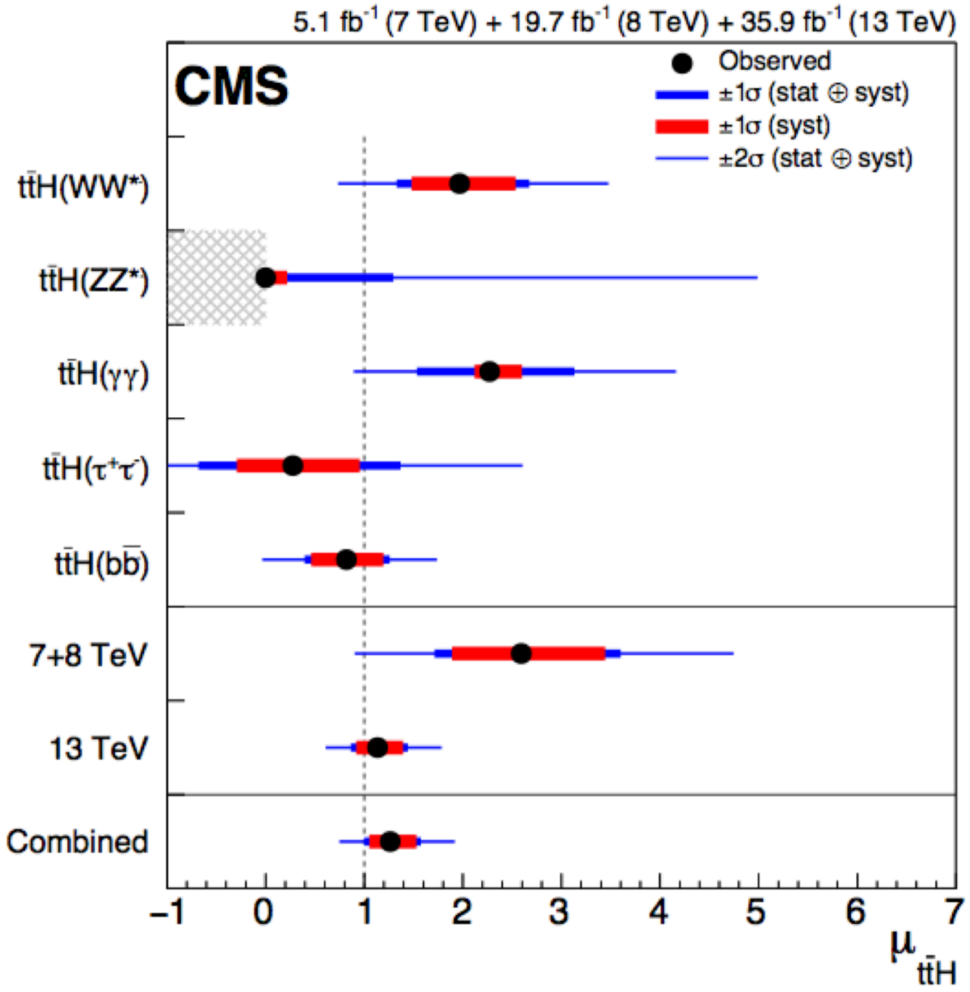
It couples to the top

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







Consistent with SM ~ 100% errors

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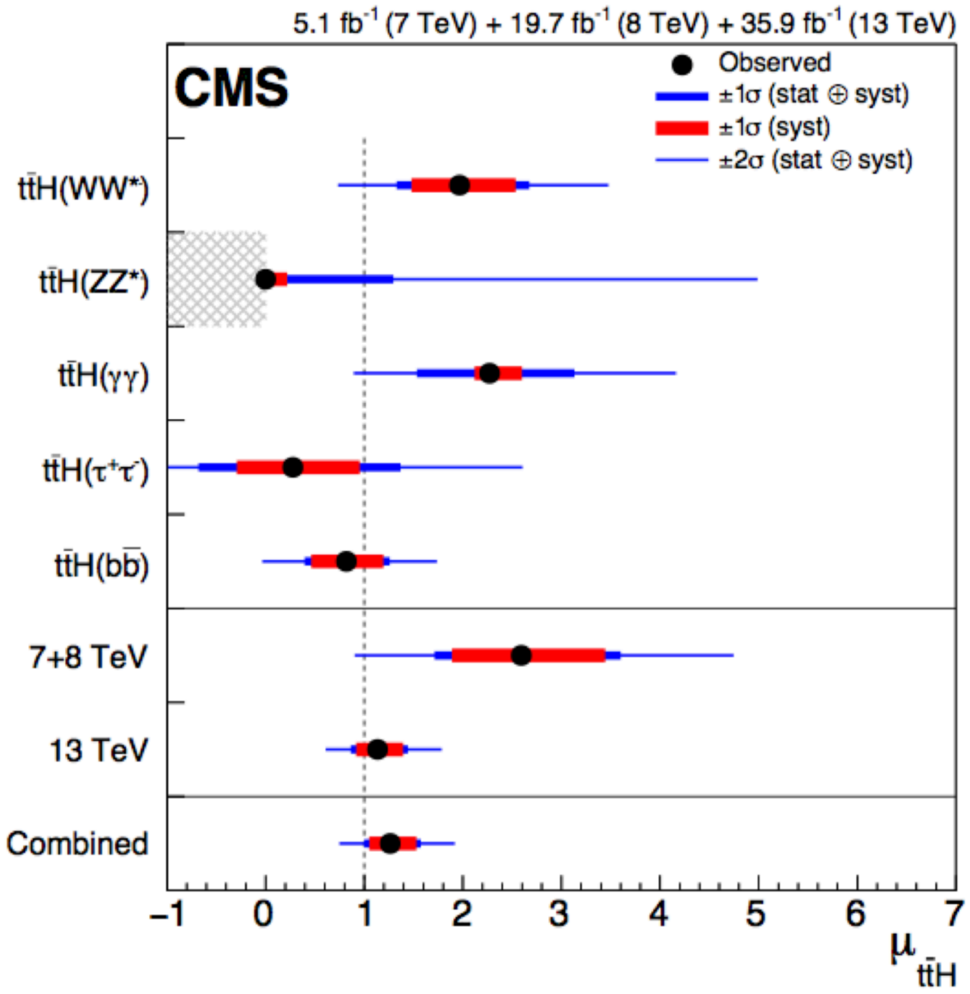

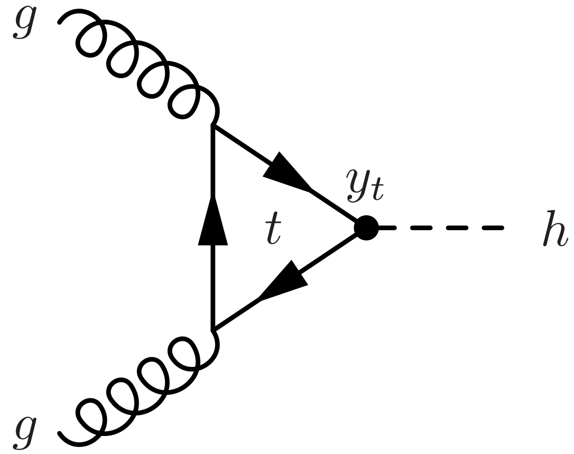

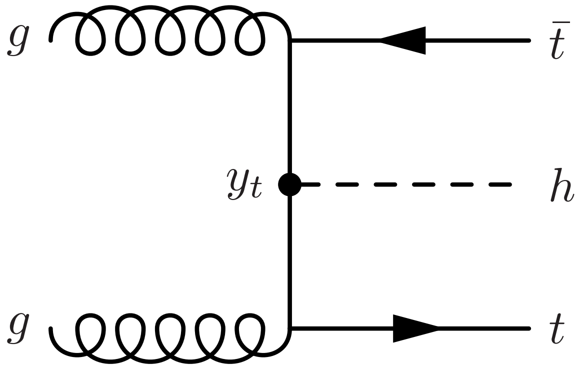

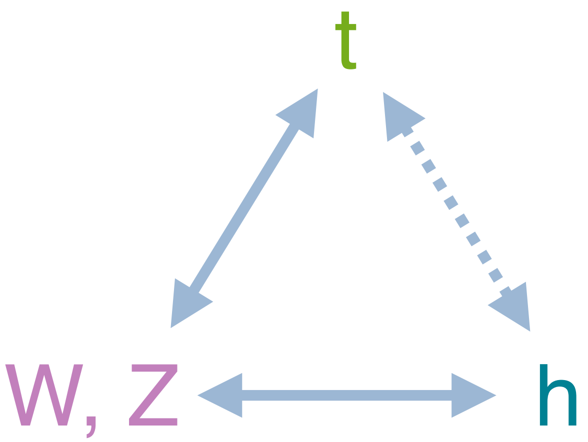
t

W, Z

h

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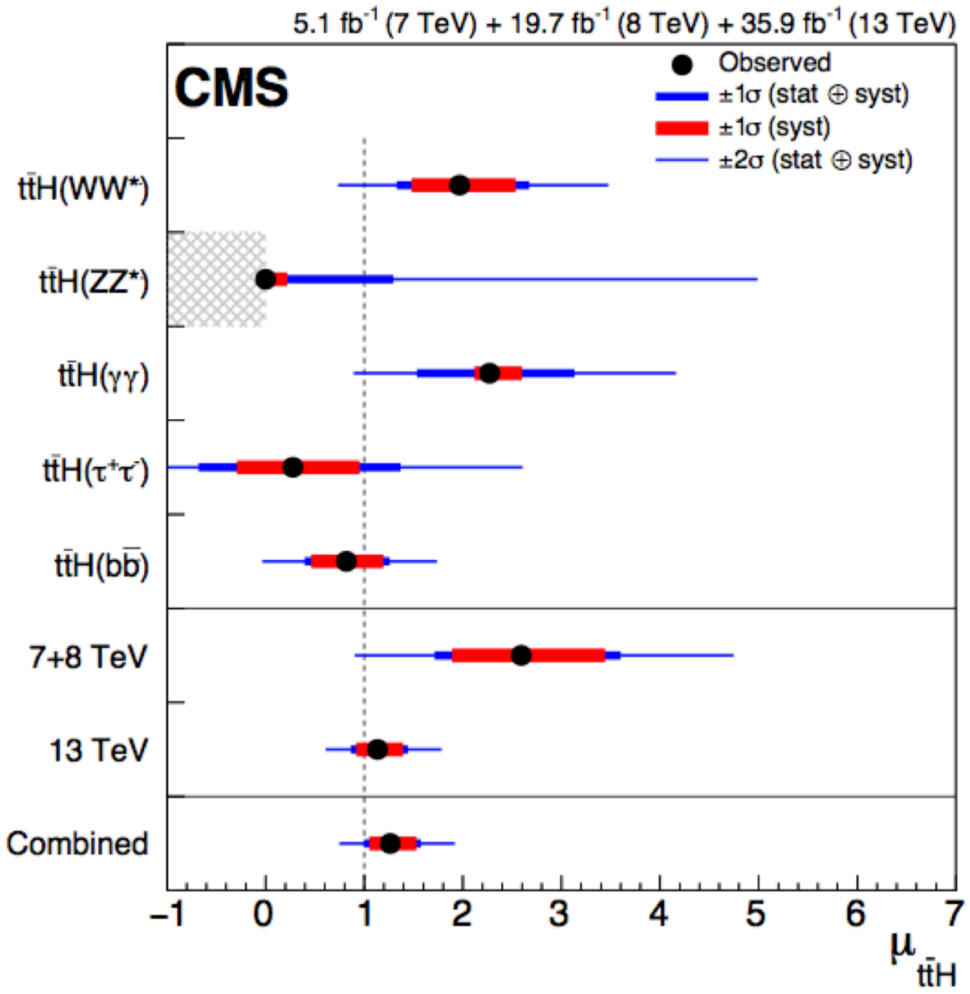
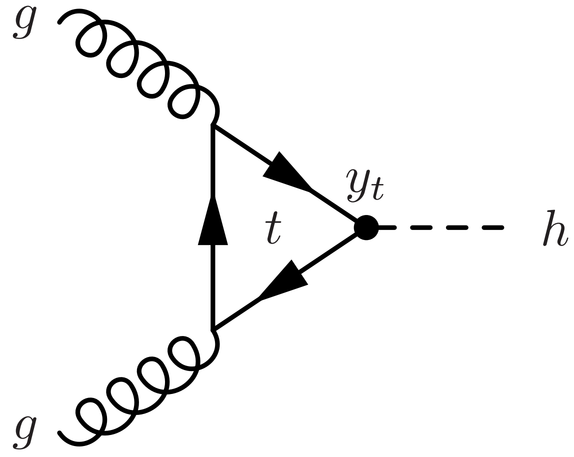
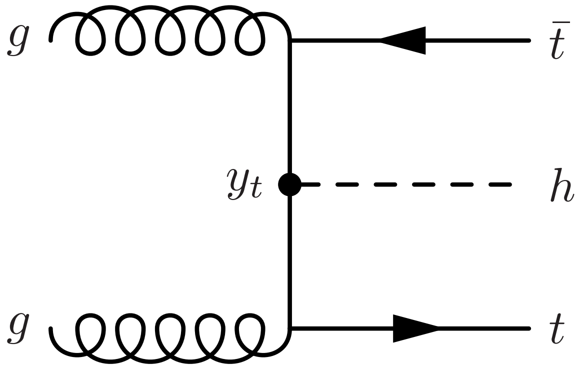
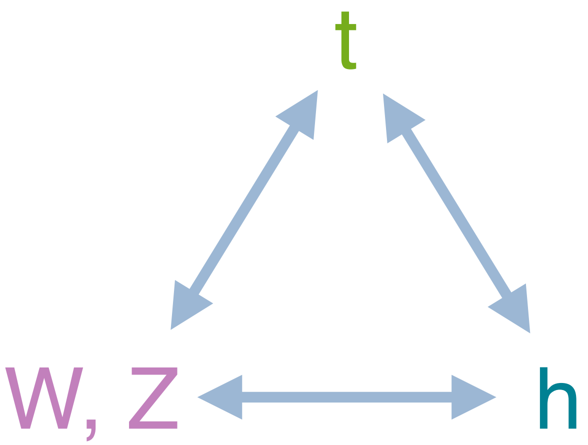






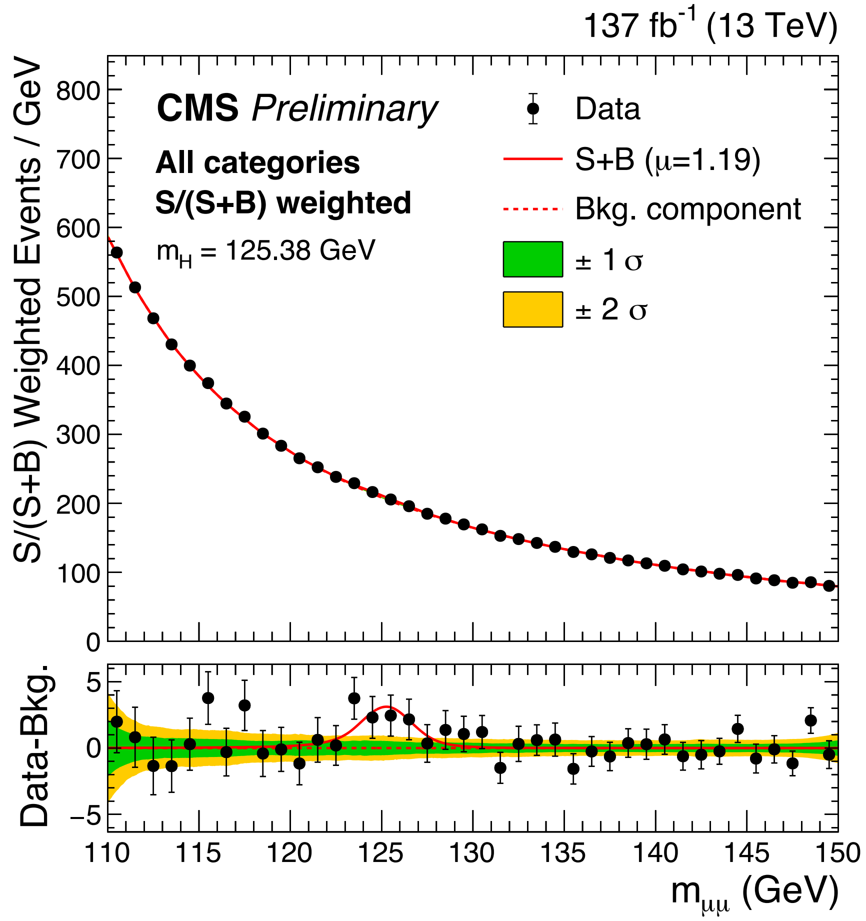


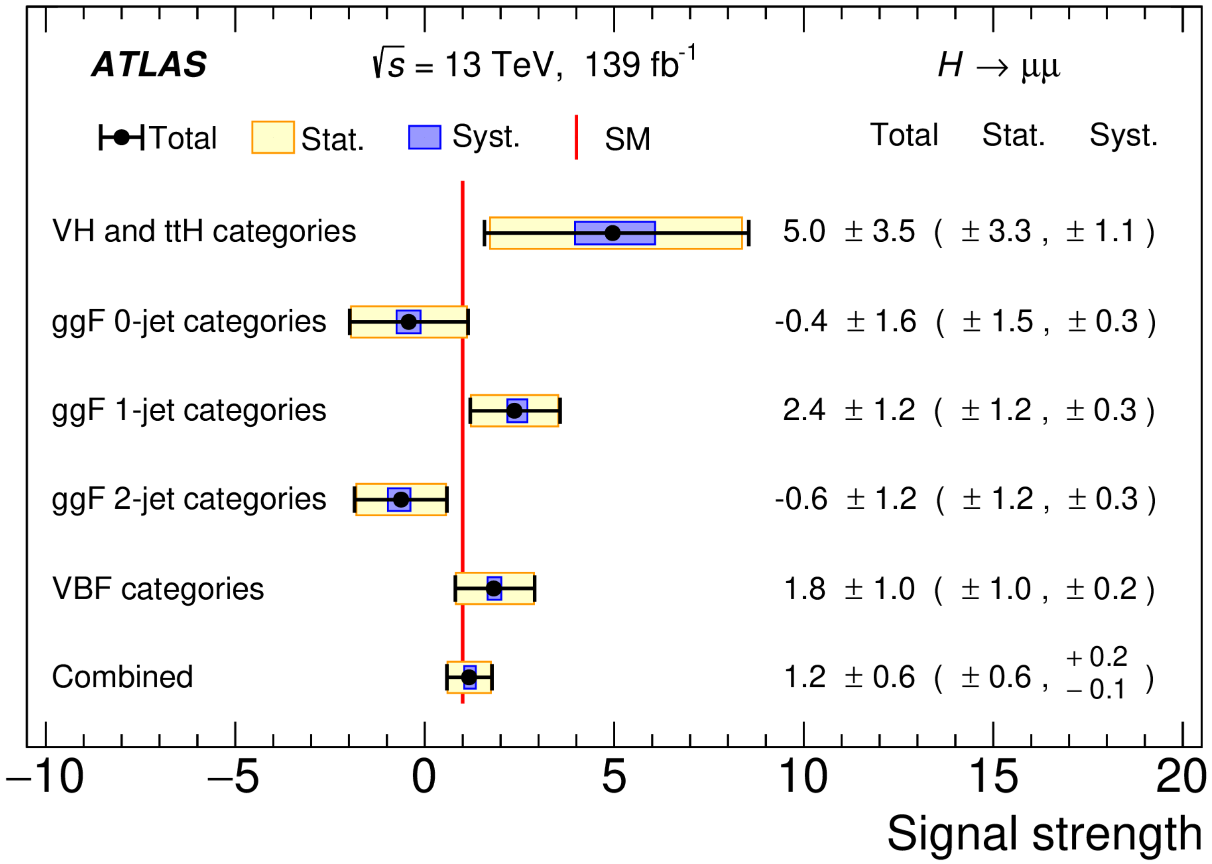
Recent headlines

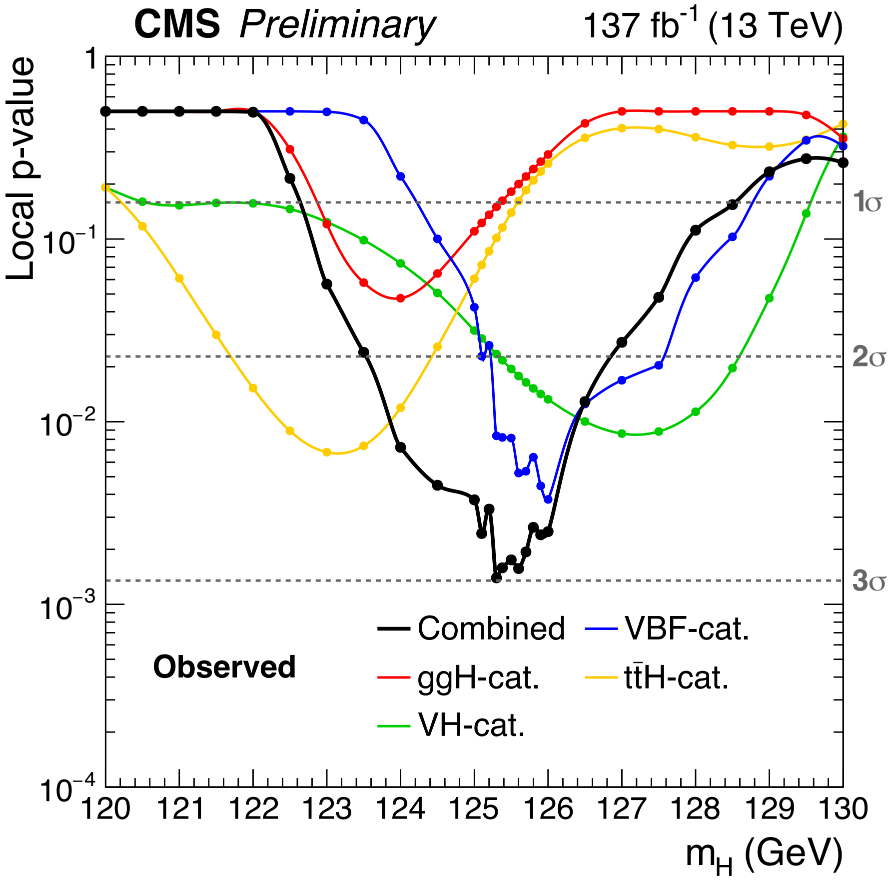
[CERN-EP-2020-117] & [CMS-PAS-HIG-19-006]

It couples to the muon

- First evidence for 2nd generation coupling
- Combination of channels > 3σ
- The LHC is probing EWSB interactions across m_t/m_μ ~ 3 orders of magnitude



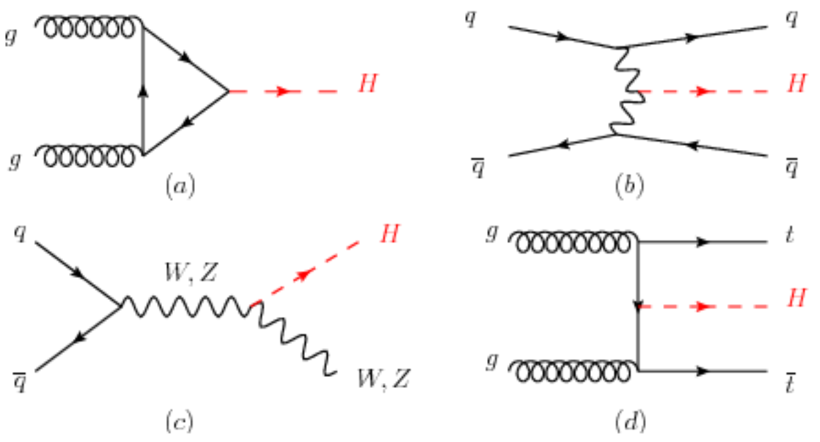




The LHC explorer

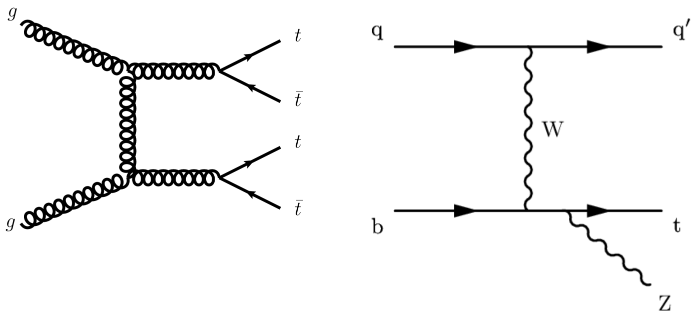
Many new processes observed at the LHC for the first time

Main Higgs production modes



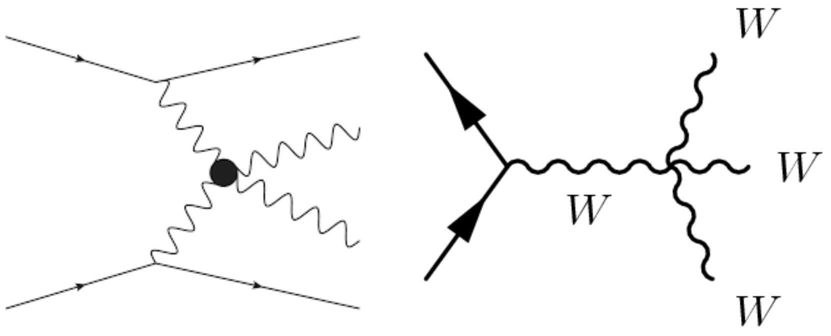
ggF, VH, VBF, ttH

Rare top production



tttt, ttbb *ttV, tW, tZ*

Weak boson scattering



VBS, VVV

Each of them provides a new window, through which to

- Improve our understanding of the SM interactions
- Search for new physics via new interactions

The indirect way

“…the direct method may be used…but indirect methods will be needed in order to secure victory.”

“…there are not more than two methods of attack – the direct and the indirect; …Who can exhaust the possibilities of their combination?”

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"…there are not more than two methods of attack – the direct and the indirect; …Who can exhaust the possibilities of their combination?"

— Sun Tzu, *The Art of War*

The SM is broken

We understand the (low energy) symmetry & matter content

SU(3)$_C$ x SU(2)$_L$ x U(1)$_Y$

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

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**

The indirect way

Direct searches are not the *only* way

LHC's #1 objective (Higgs discovery) has been achieved

Thanks to the efforts of th. and exp. colleagues, the LHC can be used as a precision machine

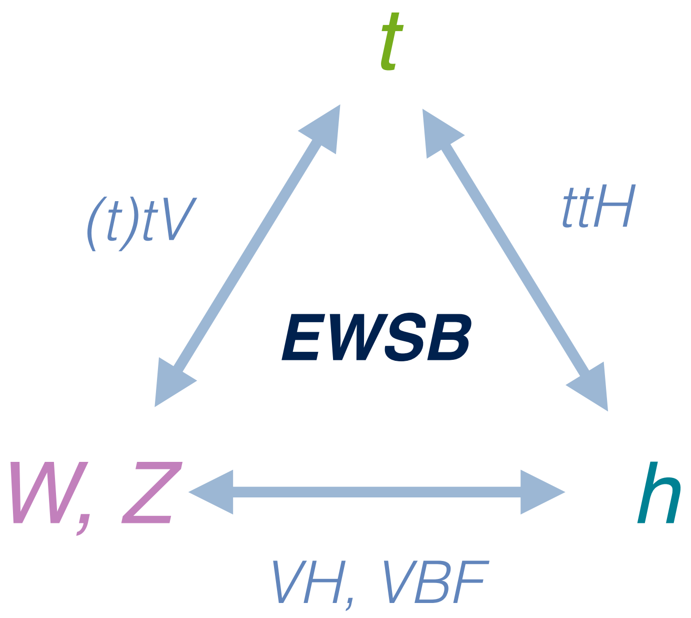
We are in the midst of a huge programme of precision measurements of SM interactions up to the TeV scale

Big question: Origin of the Electroweak scale

Where to look: Interactions among the key players

Higgs, EW gauge bosons, top quark,…

Pinning down EWSB



LHC legacy = precise set of measurements of the interactions that govern EWSB

Independent of the outcome of direct NP searches

Gauge/Higgs: test all components of Higgs field

$$\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix} -iG^{+} \\ v+h+iG^{0} \end{pmatrix} \qquad \begin{array}{c} \partial_\mu G^{+} \leftrightarrow W_\mu^{+} \\ \partial_\mu G^{0} \leftrightarrow Z_\mu \end{array}$$

- Connects gauge and Goldstone boson interactions
- Equivalence of longitudinal modes at high energy

The top is special yet relatively poorly measured

- Being most strongly coupled to the Higgs has strong BSM implications
- The LHC is a top factory

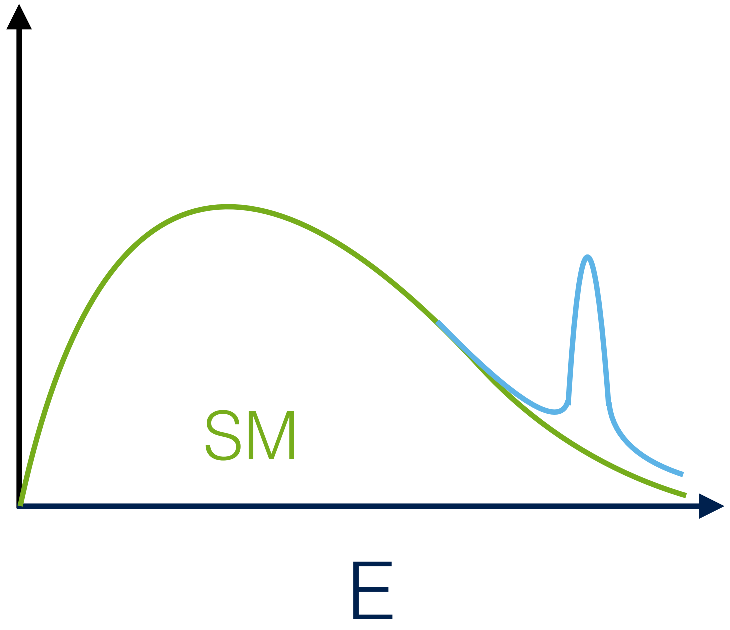
Marrying energy & precision

Paradigm shift at the energy frontier for BSM searches

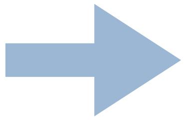
Direct (bump hunts)

Indirect (measuring tails)

⇒ New physics is heavy



Heavy new physics
Precision measurements
High energy



Standard Model Effective Field Theory (SMEFT)

A parameter space for BSM interactions between SM particles

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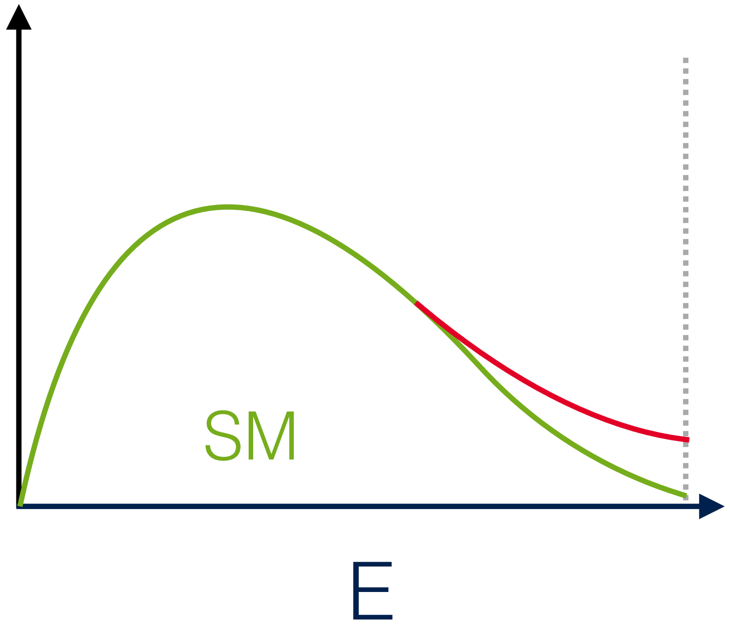

Heavy new physics
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→

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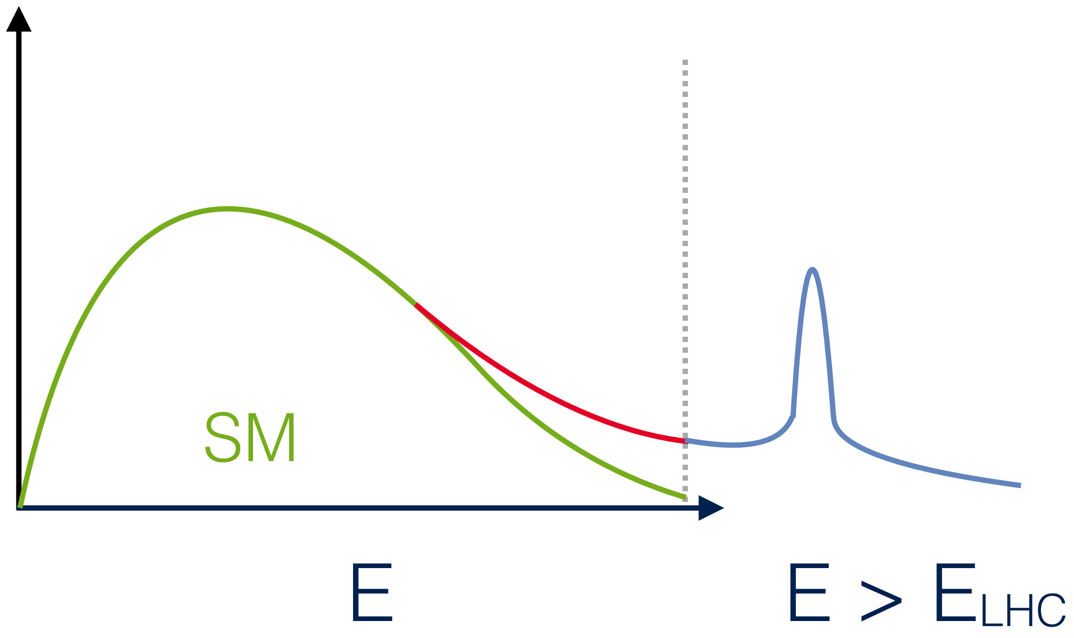

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EFT

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

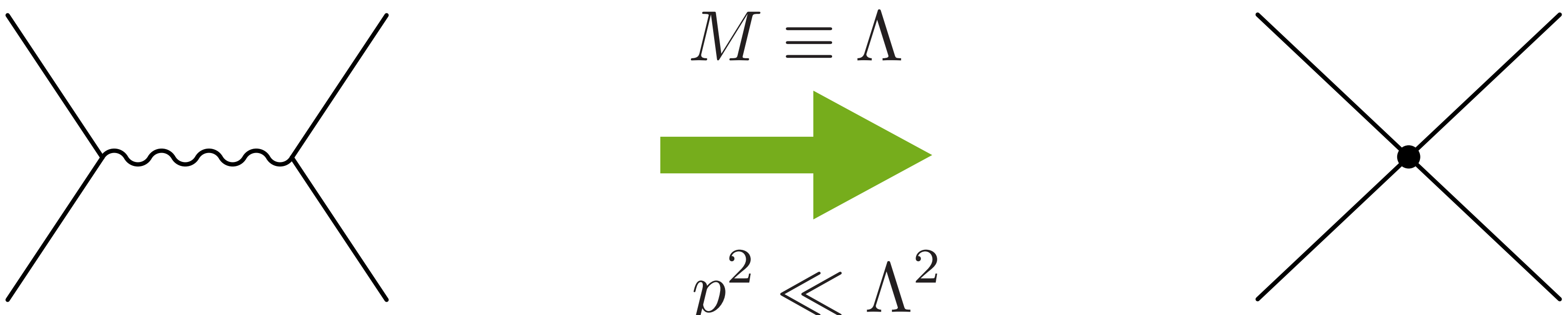
Widely used calculation technique

Simplify problems that have a *separation of scales*

Electroweak scale ~ 100 GeV ⟷ New physics scale, M ≳ TeV

At energies E ≪ M, e.g., E_{LHC}

- Keep only the relevant degrees of freedom, $m_i < E$
- Integrate out heavy states → operator expansion in mass dimension



$$M \equiv \Lambda$$

$$p^2 \ll \Lambda^2$$

cf. Fermi Theory

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

D=6 $$\boxed{-\frac{g^2}{\Lambda^2}\Big[1}+\frac{p^2}{\Lambda^2}+\frac{p^4}{\Lambda^4}+\cdots\Big]$$

SMEFT: SM v2.0

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

We have access to a low energy effective description

- SM: all relevant & marginal (D ≤ 4) operators
- \+ EFT: tower of irrelevant (D > 4) operators

SM gauge symmetry & linear EWSB

SU(3)$_c$ x SU(2)$_L$ x U(1)$_Y$

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

More than ‘just’ a parametrisation of ignorance

- **Unlike** ‘Anomalous Couplings’
- Finite energy range < Λ (NP)
- Renormalisable QFT (order-by-order)
- Well-defined matching procedure

aTGC y_f

λ_h ffV

$$X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$$

$$H^6 : (\varphi^\dagger \varphi)^3$$

$$\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{q}_i \, u_j \, \tilde{\varphi})$$

$$\psi^2 H^2 D : (\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{q}_i \, \gamma^\mu \, q_j)$$

$$X^2 H^2 : (\varphi^\dagger \varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a$$

$$H^4 D^2 : (\varphi^\dagger \, D^\mu \varphi)^* (\varphi^\dagger \, D^\mu \varphi)$$

$$\psi^2 X H : (\bar{q}_i \, \sigma^{\mu\nu} \, u_j \, \tilde{\varphi}) B_{\mu\nu}$$

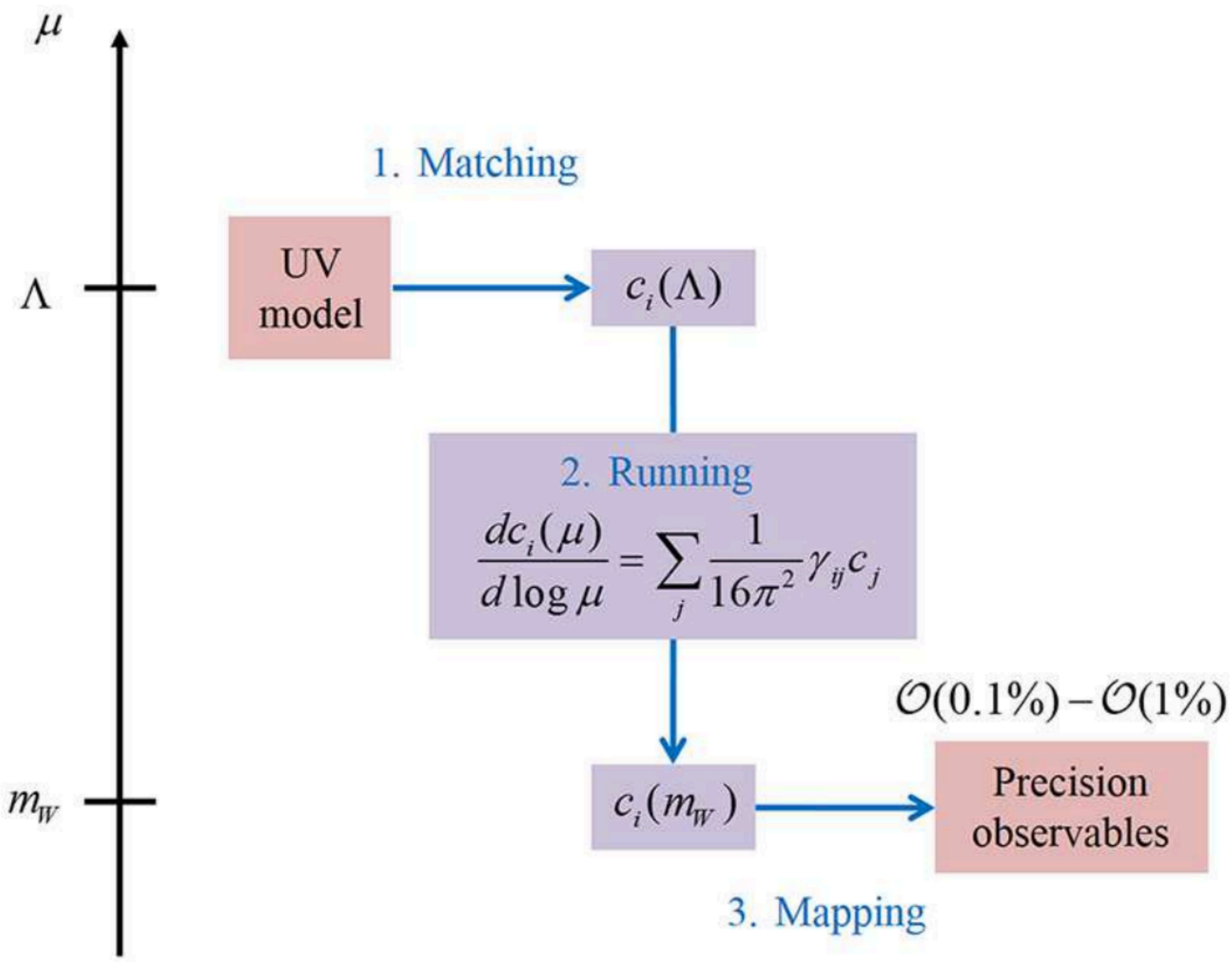
$$\psi^4 : (\bar{q}_i \, \gamma^\mu \, q_j)(\bar{q}_k \, \gamma_\mu \, q_l)$$

ggh(h) δM_Z

‘dipole’   4F

SMEFT: SM v2.0

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



SMEFT is an economical way to test many BSM scenarios

UV matching quasi-automated

- Complete tree-level dictionary

[de Blas et al.; JHEP 03 (2018) 109]

- Universal 1-loop effective action

[Henning, Lu & Murayama; JHEP 01 (2016) 023]

[Drozd et al.; JHEP 03 (2016) 180]

RGE are known

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

Map coefficients to the data once and for all

D=6 operators

'Warsaw' basis

[Grzadkowski et al.; JHEP 1010 (2010) 085]

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

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

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

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

Degrees of freedom 76: flavor universal 2499: flavor general

Measure the couplings of the SM at dimension-6 (and beyond)

D=6 operators

'Warsaw' basis

[Grzadkowski et al.; JHEP 1010 (2010) 085]

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

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

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
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$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
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Degrees of freedom 76: flavor universal 2499: flavor general

Measure the couplings of the SM at dimension-6 (and beyond)

↓

Extend the reach of our colliders to NP beyond nominal energy

Strategy

Strategy

Basis

Warsaw, SILH, HISZ, Higgs Basis

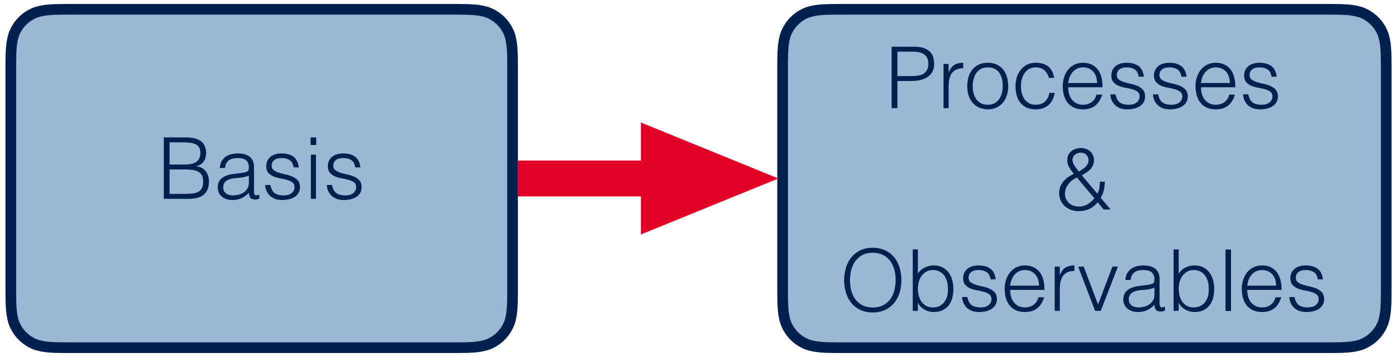
Flavor assumptions

Universal, diagonal, 3rd gen, general?

Symmetries

CP, Baryon/Lepton number?

Strategy



Basis

Processes
&
Observables

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

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

High-level

asymmetries

optimal observables

NN-output

Strategy

Basis

Processes & Observables

Sensitivity

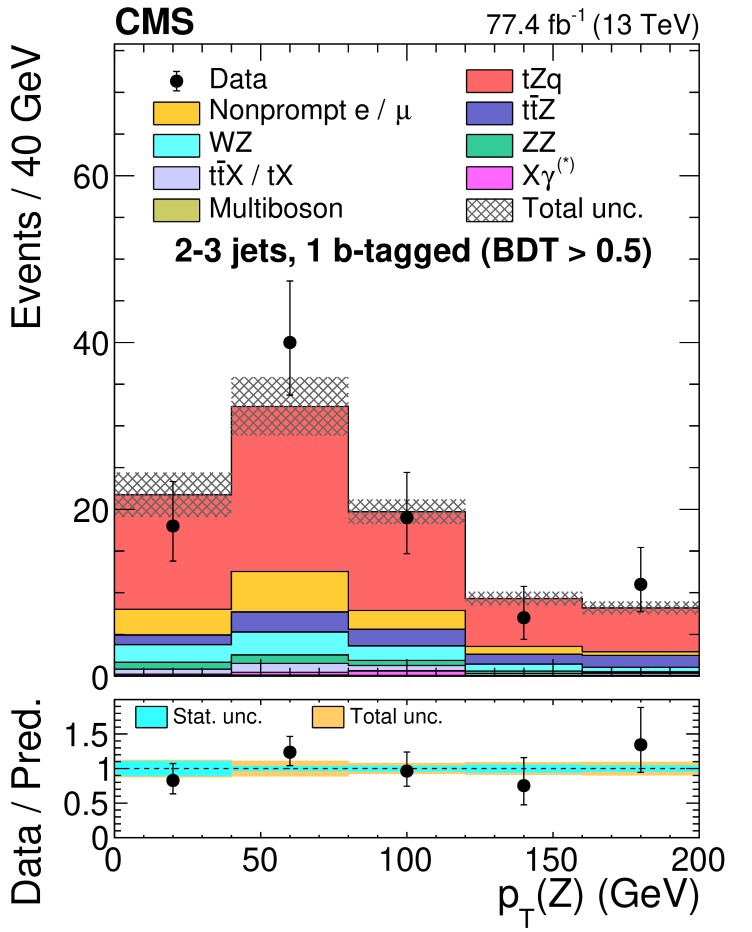
Determine dependence on Wilson coefficients

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

Precise Monte Carlo tools

Strategy

Basis → Processes & Observables → Sensitivity → Measurement



[CMS.; PRL 122 (2019) 132003]

Fiducial volume

Not sensitive to deviations outside acceptance (model dependent)

Extract limits

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

Strategy

Basis

Processes & Observables

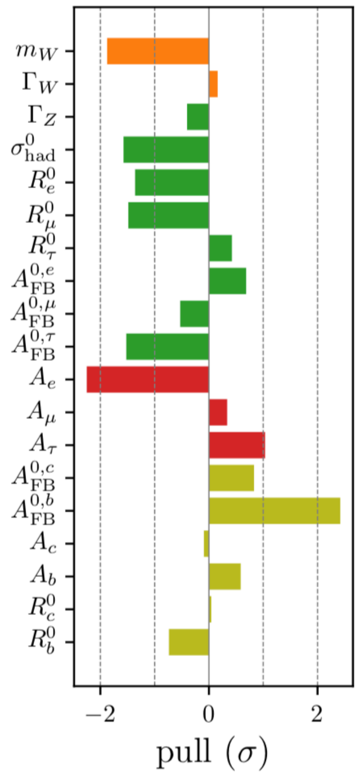
Sensitivity

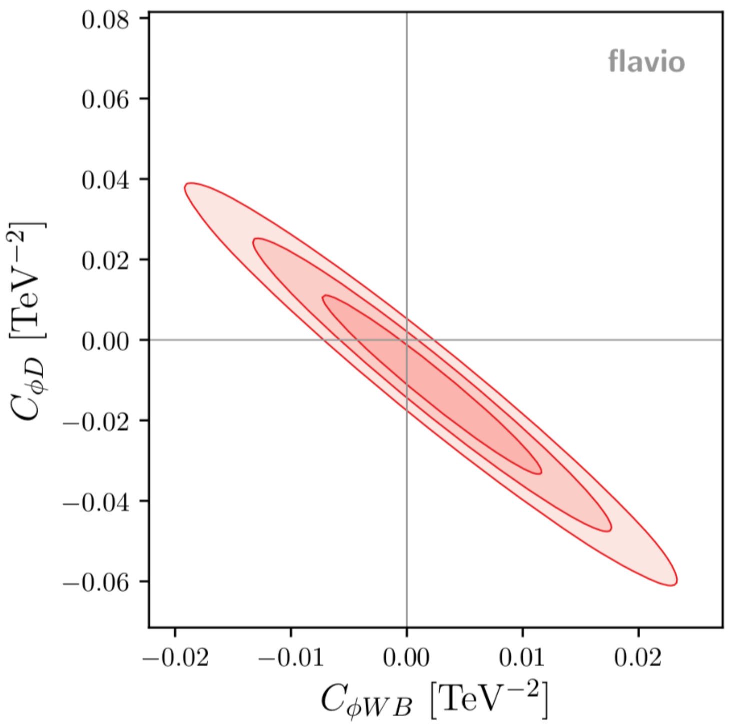
Measurement

Global fit

$$\{\mathcal{O}_i, \mathcal{O}_j, \ldots, \mathcal{O}_n\} \rightarrow \mathcal{L}\left(c_i, c_j, \ldots, c_n, \vec{\theta} \,\middle|\, \vec{\mathcal{O}}\right)$$

[Aebischer et al.; EPJC 79 (2019) 6, 509]

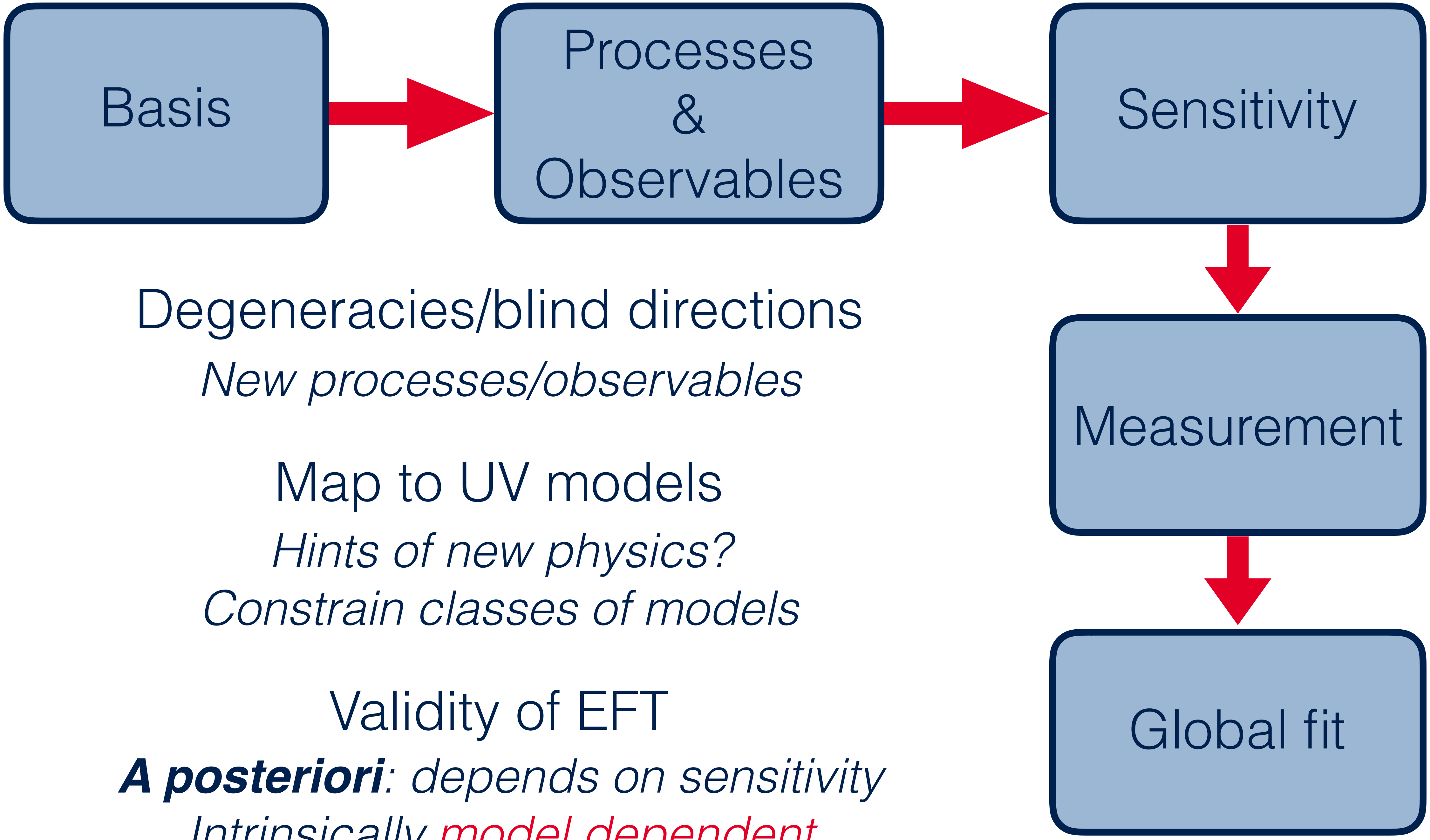




Observations/ Limits

Individual
Marginalised
Pulls,…

Strategy



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

SMEFT is…

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

Model independent

- Underlying assumptions

Heavy new physics: $M > E_{exp}$
SM field content & gauge symmetries
Linear EWSB: Higgs = doublet

Systematically improvable

- Double expansion *higher dim.* $\frac{E^2}{\Lambda^2}$ *&* $\{g_S,\, g,\, g'\}$ *more loops*

Global

- Model independence: we don't know what operators NP will generate
- Patterns & correlations among observables are key
- Ultimate goal: complete likelihood for SMEFT confronted with HEP data

EWPO, Higgs, multiboson, top, DY, flavor,…

Established part of LHC programme

Precision interpretations

Want to improve…

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

Precision interpretations

Want to improve…

$$\boxed{\Delta o_n} = o_n^{\mathrm{EXP}} - o_n^{\mathrm{SM}} = \sum_i \frac{a^{(6)}_{n,i}(\mu)\, c^{(6)}_i(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Precision interpretations

Want to improve…

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

Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Sensitivity

Experiment:
Best measurements & understanding of uncertainties and correlations

Theory:
Best available predictions for observables (NLO, NNLO, N3LO,…)

Precision interpretations

Want to improve…

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

Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Sensitivity

Experiment:
Best measurements & understanding of uncertainties and correlations

Theory:
Best available predictions for observables (NLO, NNLO, N3LO,…)

Interpretation

Relies on accurate knowledge of the size & correlation among a_i

Determining $c_i^{(6)}$ requires most precise available SMEFT predictions

Why higher orders

Higher orders (loops) in SMEFT improve…

Accuracy (better central value)

- No deviation: better representation of new physics reach
- Yes deviation: better pinpointing of new physics origin

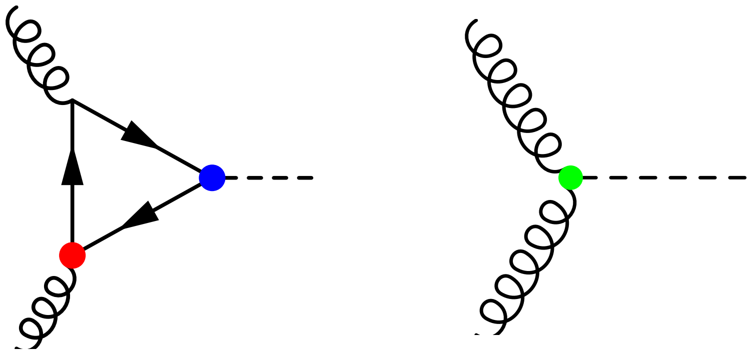
Precision (better error bars)

- Control over scale uncertainty (must include running & mixing)

Sensitivity

- Knowledge of the patterns & correlations
- Differential predictions - key for, *e.g.*, multivariate & ME based analyses
- New loop-induced sensitivity

LHC Higgs production



Loop-induced process in the SM

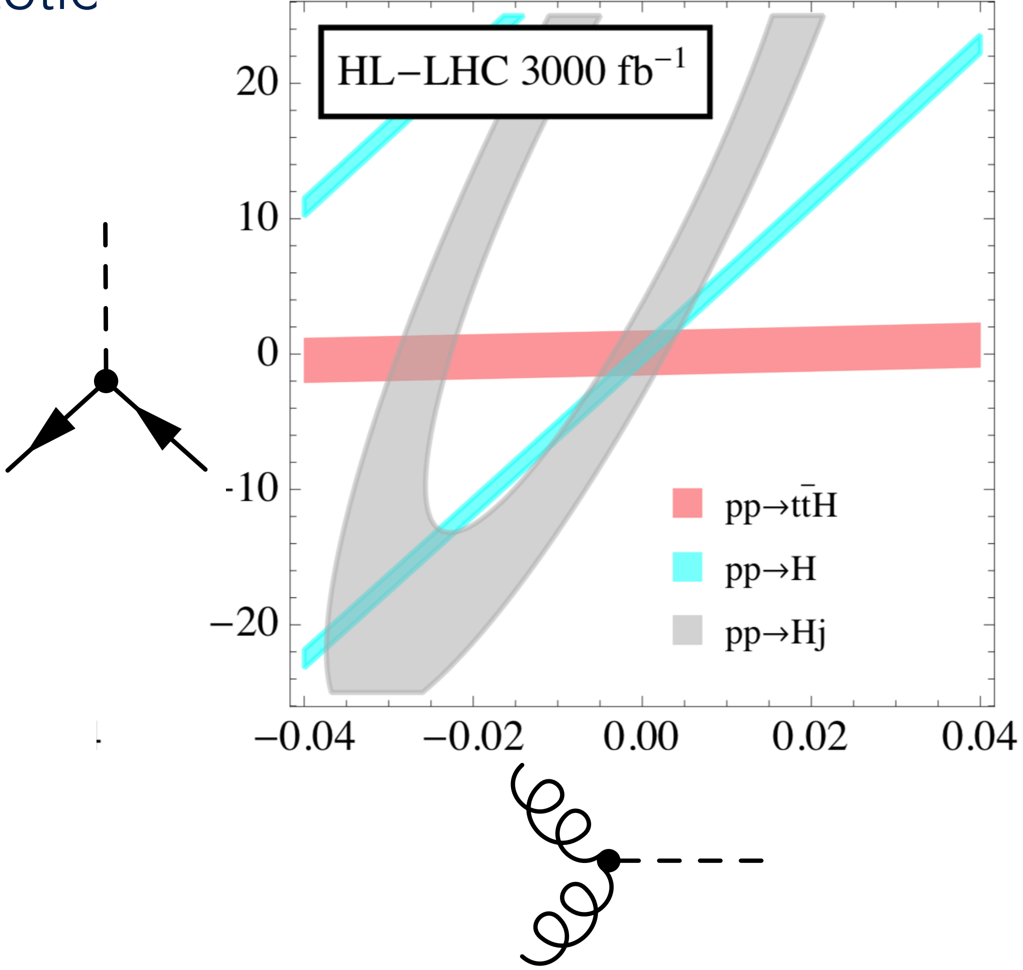
SMEFT

- Tree-level ggH contact interaction (heavy fermion)
- Modified top-Higgs or top-gluon (dipole) interactio

We have measured gg→h precisely

- Degeneracy: can't say for sure that, e.g., heavy new fermions are excluded
- Importance of ttH (and tt) measurements
- Global approach is essential
- Loop sensitivity can be important

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



Precision calculations

NLO computations for SMEFT: active field

- Many results & analyses have appeared in the last few years
- Non-universal K-factors in EFT space → new information at NLO

K≡NLO/LO

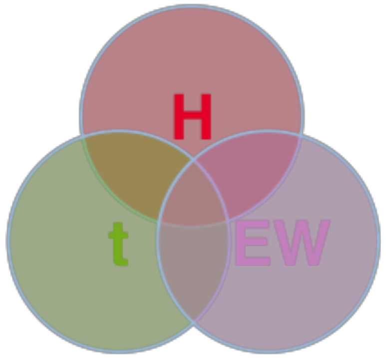
- Experimental interest in including one-loop for SMEFT analyses/interpretations

Many processes x many operators

- NLO generally complicates picture
- Automated tools are essential

SMEFT@NLO

[Degrande et al.; arXiv:2008.11743]
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO



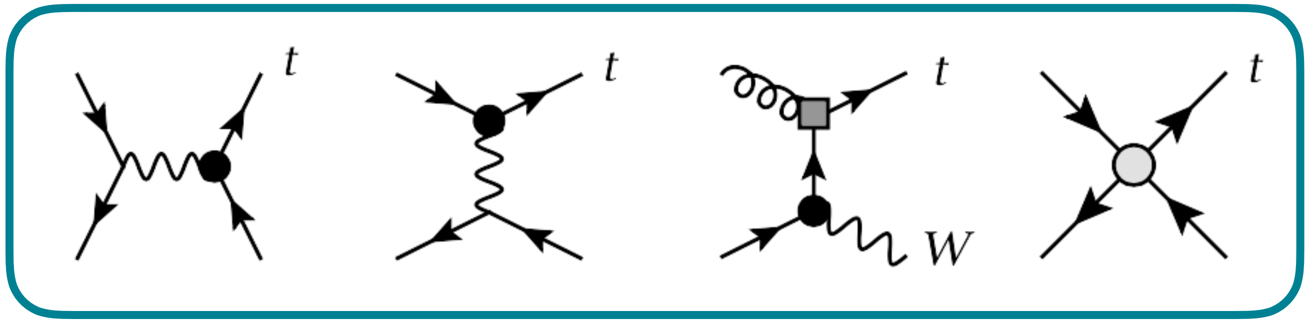
- Process independent SMEFT implementation: top-specific flavor limit
- Suitable for LO/NLO computations of EW/Higgs/Top processes
- Milestone in delivering required precision for LHC lifetime

Selected results

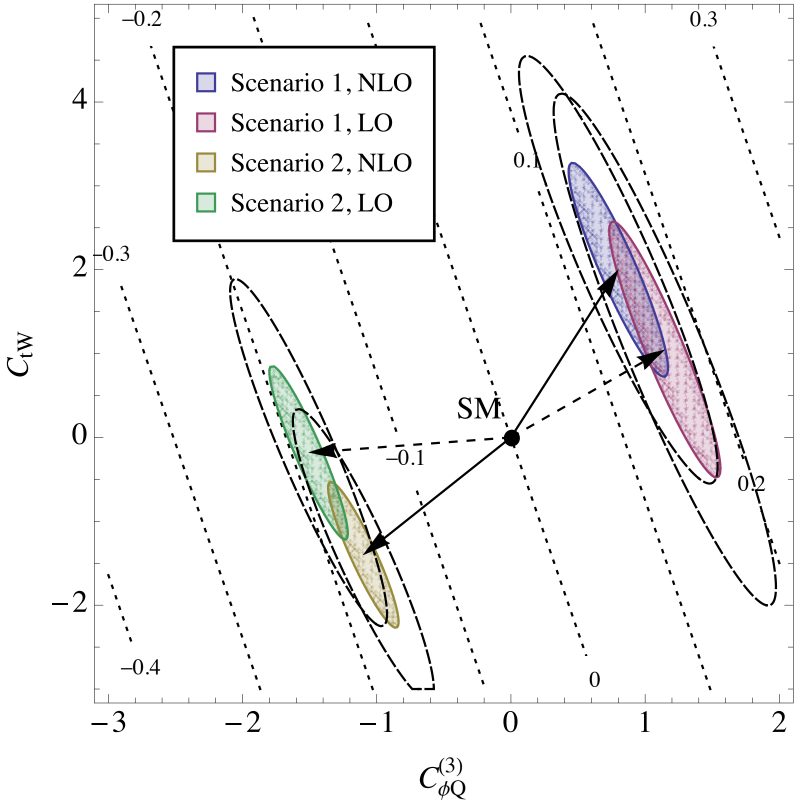
Some from previous works, superseded by SMEFT@NLO
A few, simple new results presented in 2008.11743

t-channel single top

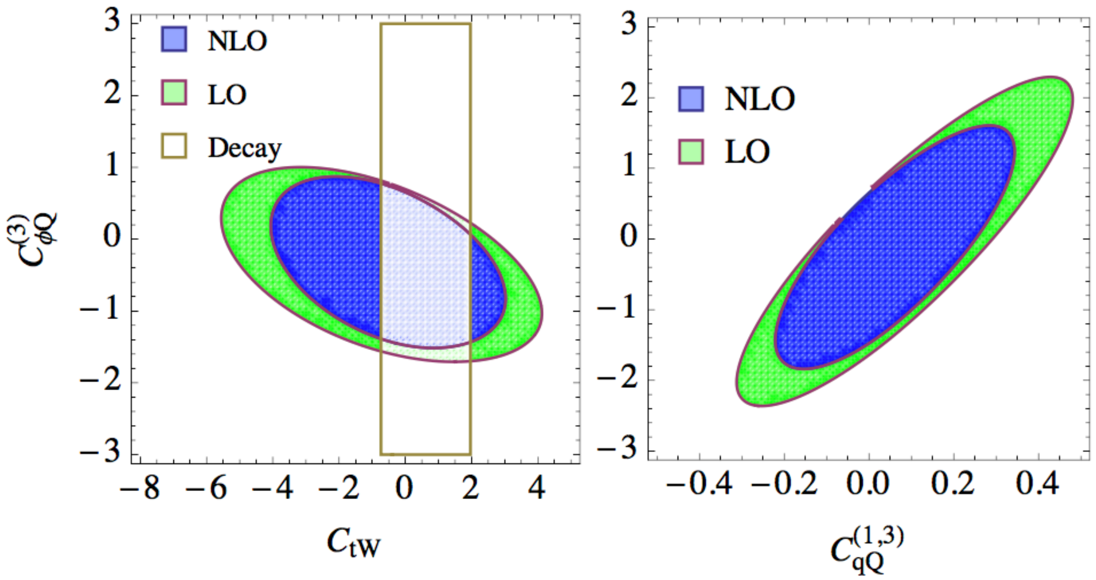
[Zhang; PRL 116 (2016) 162002]



Fit with a (hypothetical) deviation



Fit without deviation

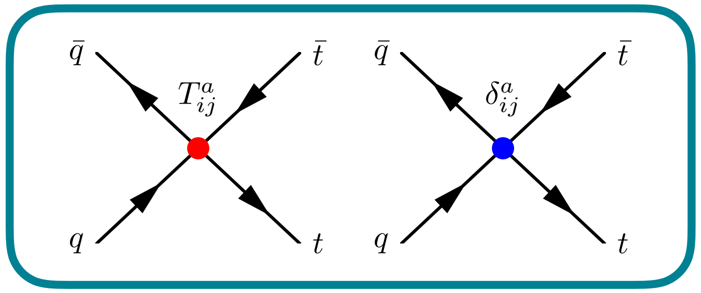


LHC 13 TeV, SM = 744 pb, K-factor = 1.46

[SMEFT@NLO; arXiv:2008.11743]

Top pair production

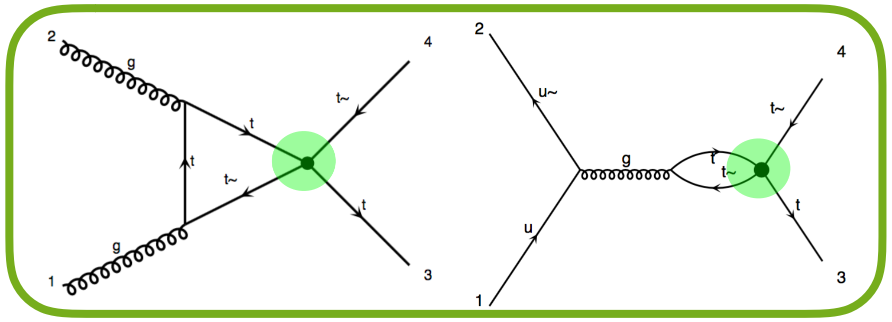
Color octet and singlet 4F operators



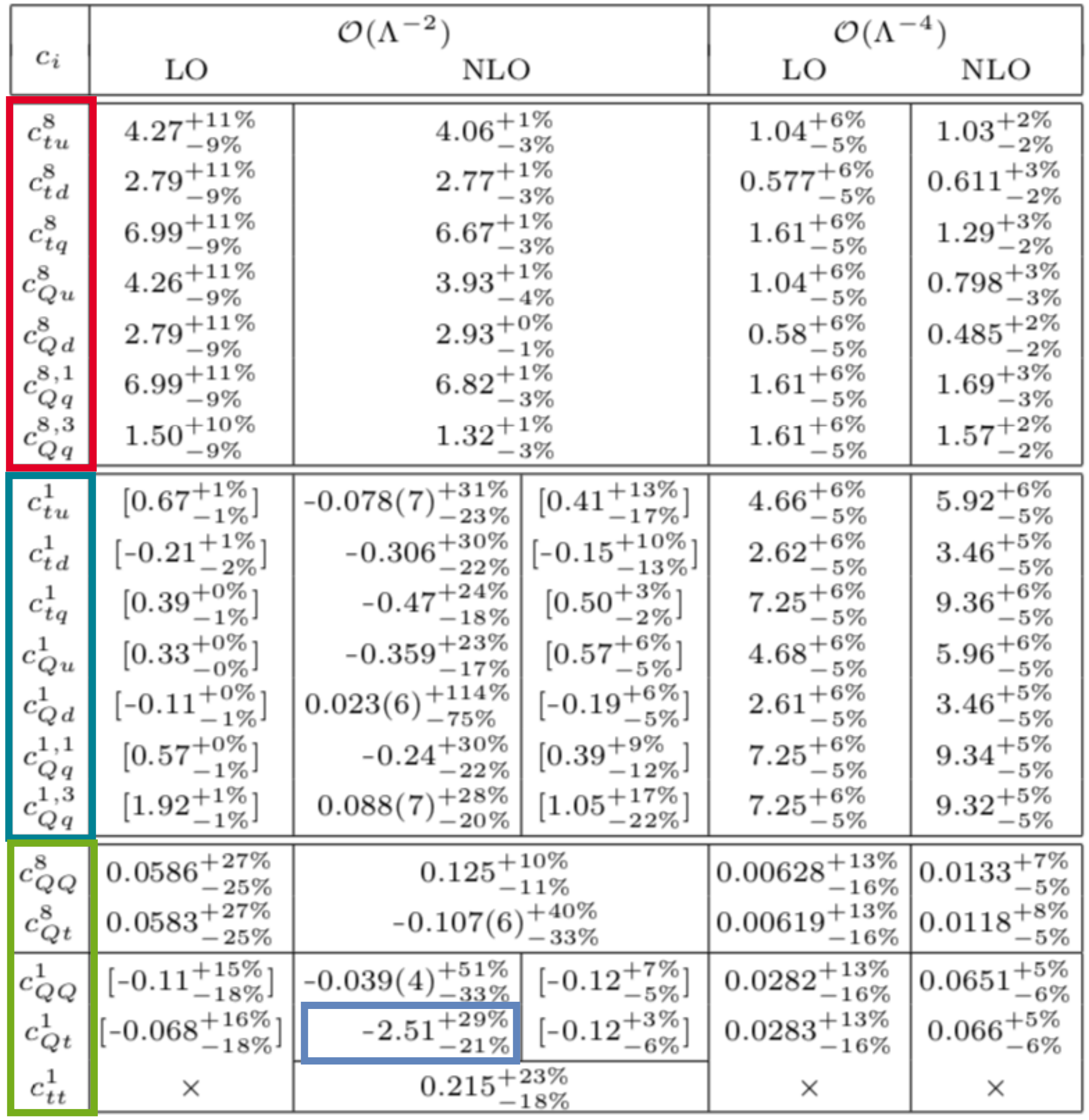
dominant operators in tt
NLO corrections can break degeneracies

interference with QCD ttbar at NLO
[x] interference with EW ttbar

4-top operators: loop-induced sensitivity



4-top interference in ttbar: one large contribution
pattern of cancellations at differential level
competition between phase space & gg, bb



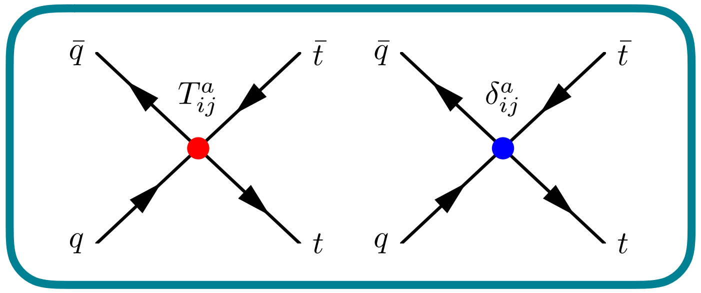
c_i	$\mathcal{O}(\Lambda^{-2})$			$\mathcal{O}(\Lambda^{-4})$	
	LO	NLO		LO	NLO
c^8_{tu}	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$		$1.04^{+6\%}_{-5\%}$	$1.03^{+2\%}_{-2\%}$
c^8_{td}	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$		$0.577^{+6\%}_{-5\%}$	$0.611^{+3\%}_{-2\%}$
c^8_{tq}	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.29^{+3\%}_{-2\%}$
c^8_{Qu}	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$		$1.04^{+6\%}_{-5\%}$	$0.798^{+3\%}_{-3\%}$
c^8_{Qd}	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$		$0.58^{+6\%}_{-5\%}$	$0.485^{+2\%}_{-2\%}$
$c^{8,1}_{Qq}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.69^{+3\%}_{-3\%}$
$c^{8,3}_{Qq}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.57^{+2\%}_{-2\%}$
c^1_{tu}	$[0.67^{+1\%}_{-1\%}]$	$-0.078(7)^{+31\%}_{-23\%}$	$[0.41^{+13\%}_{-17\%}]$	$4.66^{+6\%}_{-5\%}$	$5.92^{+6\%}_{-5\%}$
c^1_{td}	$[-0.21^{+1\%}_{-2\%}]$	$-0.306^{+30\%}_{-22\%}$	$[-0.15^{+10\%}_{-13\%}]$	$2.62^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
c^1_{tq}	$[0.39^{+0\%}_{-1\%}]$	$-0.47^{+24\%}_{-18\%}$	$[0.50^{+3\%}_{-2\%}]$	$7.25^{+6\%}_{-5\%}$	$9.36^{+6\%}_{-5\%}$
c^1_{Qu}	$[0.33^{+0\%}_{-0\%}]$	$-0.359^{+23\%}_{-17\%}$	$[0.57^{+6\%}_{-5\%}]$	$4.68^{+6\%}_{-5\%}$	$5.96^{+6\%}_{-5\%}$
c^1_{Qd}	$[-0.11^{+0\%}_{-1\%}]$	$0.023(6)^{+114\%}_{-75\%}$	$[-0.19^{+6\%}_{-5\%}]$	$2.61^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
$c^{1,1}_{Qq}$	$[0.57^{+0\%}_{-1\%}]$	$-0.24^{+30\%}_{-22\%}$	$[0.39^{+9\%}_{-12\%}]$	$7.25^{+6\%}_{-5\%}$	$9.34^{+5\%}_{-5\%}$
$c^{1,3}_{Qq}$	$[1.92^{+1\%}_{-1\%}]$	$0.088(7)^{+28\%}_{-20\%}$	$[1.05^{+17\%}_{-22\%}]$	$7.25^{+6\%}_{-5\%}$	$9.32^{+5\%}_{-5\%}$
c^8_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^8_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c^1_{QQ}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c^1_{Qt}	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c^1_{tt}	×	$0.215^{+23\%}_{-18\%}$		×	×

LHC 13 TeV, SM = 744 pb, K-factor = 1.46

[SMEFT@NLO; arXiv:2008.11743]

Top pair production

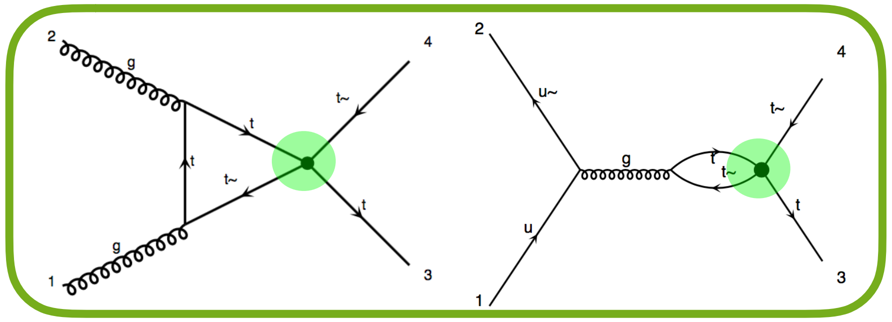
Color octet and singlet 4F operators



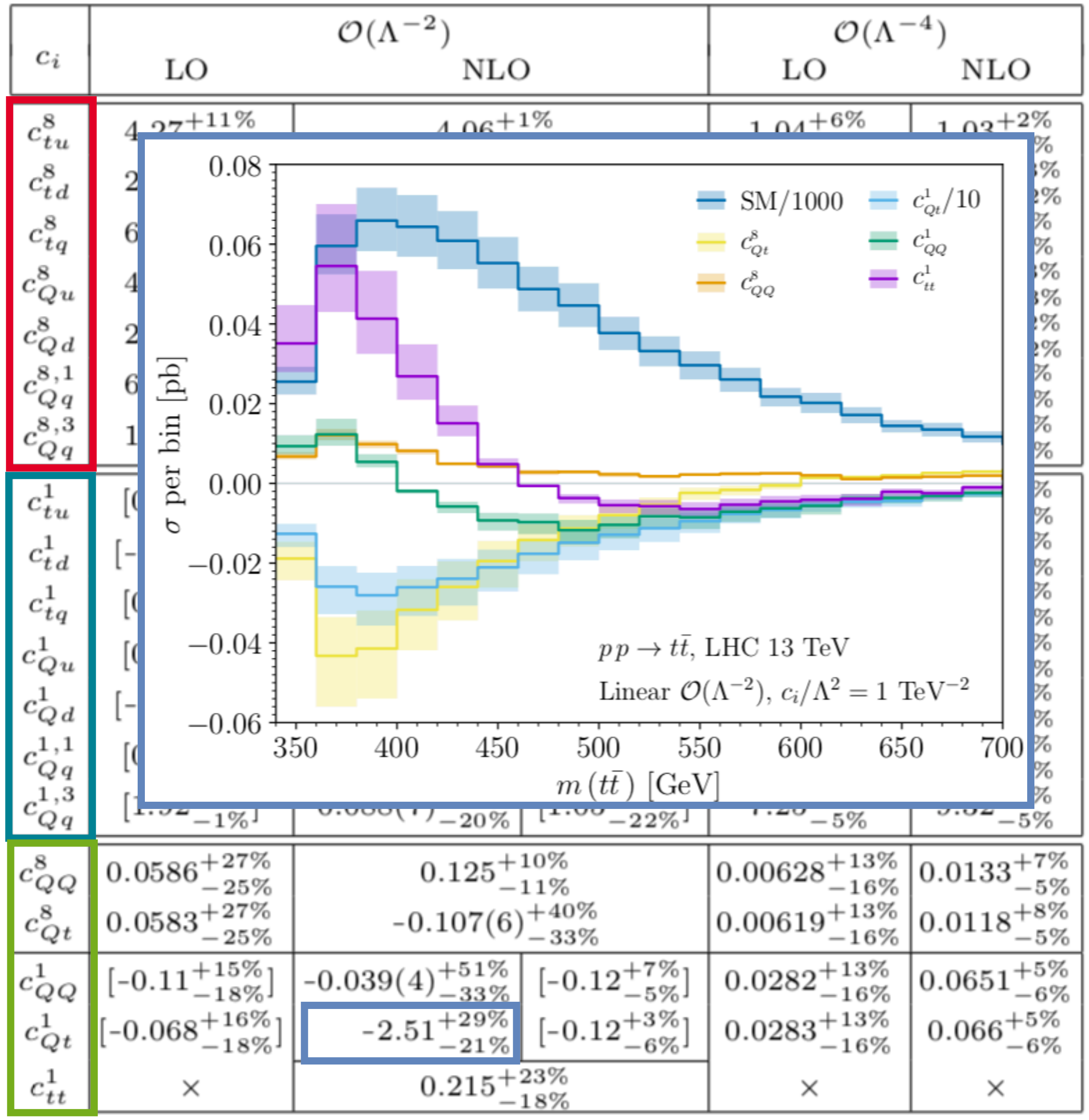
dominant operators in tt
NLO corrections can break degeneracies

interference with QCD ttbar at NLO
[x] interference with EW ttbar

4-top operators: loop-induced sensitivity



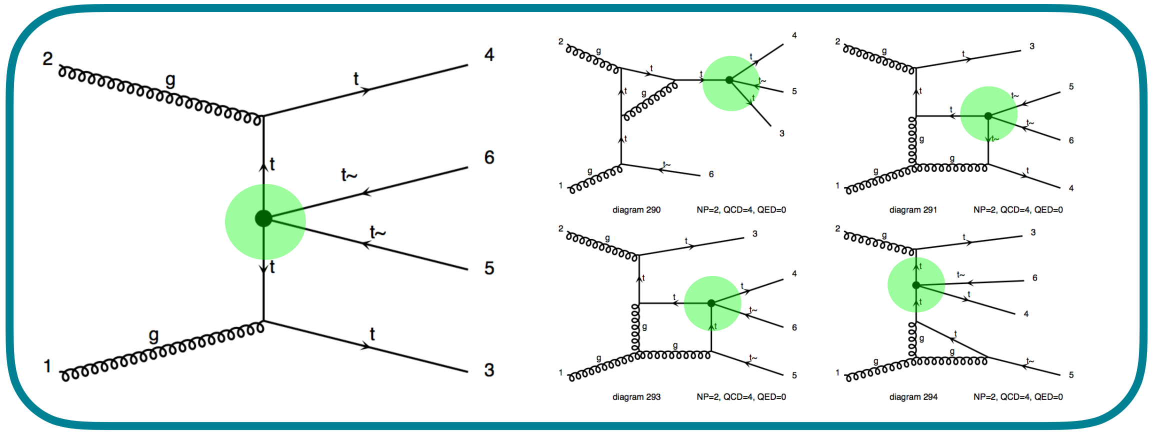
4-top interference in ttbar: one large contribution
pattern of cancellations at differential level
competition between phase space & gg, bb



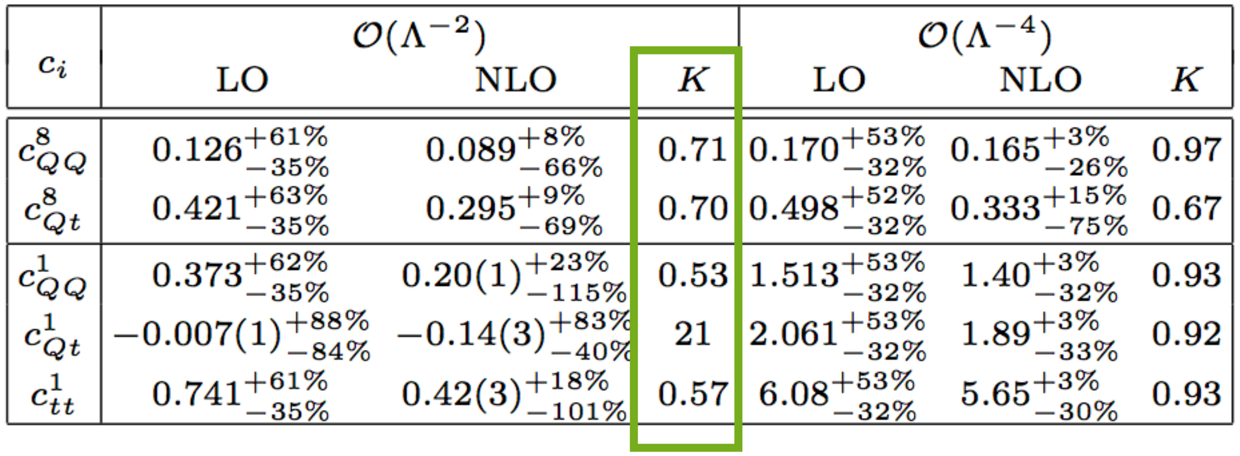
c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO		$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO
c^8_{tu}					
c^8_{td}					
c^8_{tq}					
c^8_{Qu}					
c^8_{Qd}					
$c^{8,1}_{Qq}$					
$c^{8,3}_{Qq}$					
c^1_{tu}					
c^1_{td}					
c^1_{tq}					
c^1_{Qu}					
c^1_{Qd}					
$c^{1,1}_{Qq}$					
$c^{1,3}_{Qq}$					
c^8_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^8_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c^1_{QQ}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c^1_{Qt}	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c^1_{tt}	×	$0.215^{+23\%}_{-18\%}$		×	×

LHC 13 TeV, SM = 13.9 fb, K-factor = 1.37 *[SMEFT@NLO; arXiv:2008.11743]*

Four top production



All K-factors very different from SM



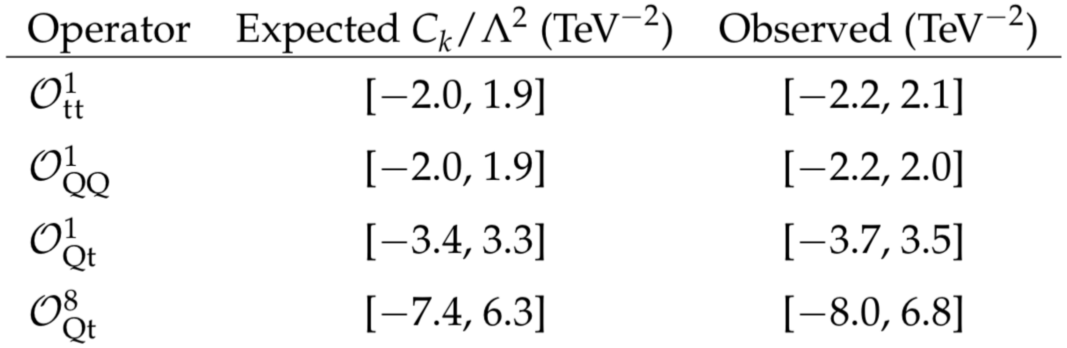
c_i	$\mathcal{O}(\Lambda^{-2})$ LO	NLO	K	$\mathcal{O}(\Lambda^{-4})$ LO	NLO	K
c^8_{QQ}	$0.126^{+61\%}_{-35\%}$	$0.089^{+8\%}_{-66\%}$	0.71	$0.170^{+53\%}_{-32\%}$	$0.165^{+3\%}_{-26\%}$	0.97
c^8_{Qt}	$0.421^{+63\%}_{-35\%}$	$0.295^{+9\%}_{-69\%}$	0.70	$0.498^{+52\%}_{-32\%}$	$0.333^{+15\%}_{-75\%}$	0.67
c^1_{QQ}	$0.373^{+62\%}_{-35\%}$	$0.20(1)^{+23\%}_{-115\%}$	0.53	$1.513^{+53\%}_{-32\%}$	$1.40^{+3\%}_{-32\%}$	0.93
c^1_{Qt}	$-0.007(1)^{+88\%}_{-84\%}$	$-0.14(3)^{+83\%}_{-40\%}$	21	$2.061^{+53\%}_{-32\%}$	$1.89^{+3\%}_{-33\%}$	0.92
c^1_{tt}	$0.741^{+61\%}_{-35\%}$	$0.42(3)^{+18\%}_{-101\%}$	0.57	$6.08^{+53\%}_{-32\%}$	$5.65^{+3\%}_{-30\%}$	0.93

Interference K-factors mainly « 1

Quadratic < 1

Recent 4.3(2.6) sigma evidence reported by ATLAS(CMS)

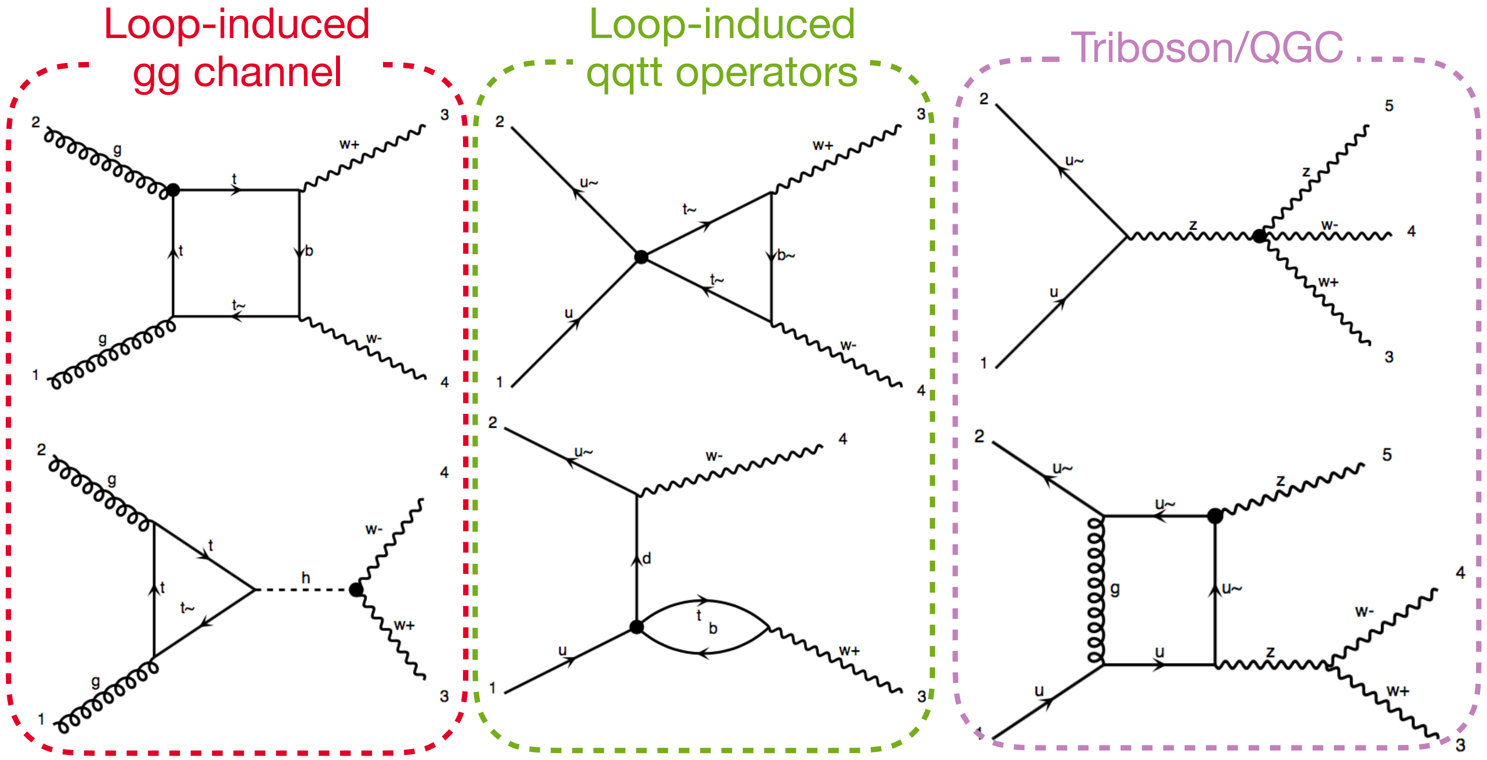
- Actually an *excess*, μ ~ 2 *[ATLAS-CONF-2020-013] [CMS; EPJC 80 (2020) 2, 75]*
- Current limits on 4-top operators ~ |C| < 2-5 (Λ/1 TeV)^2 *[CMS; JHEP 11 (2019) 082]*
- Dominated by EFT^2 quadratic term
- Room for complementarity from loop-induced top pair effects



Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	[−2.0, 1.9]	[−2.2, 2.1]
$\mathcal{O}^1_{QQ}$	[−2.0, 1.9]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−3.4, 3.3]	[−3.7, 3.5]
$\mathcal{O}^8_{Qt}$	[−7.4, 6.3]	[−8.0, 6.8]

Multiboson *[SMEFT@NLO; arXiv:2008.11743]*

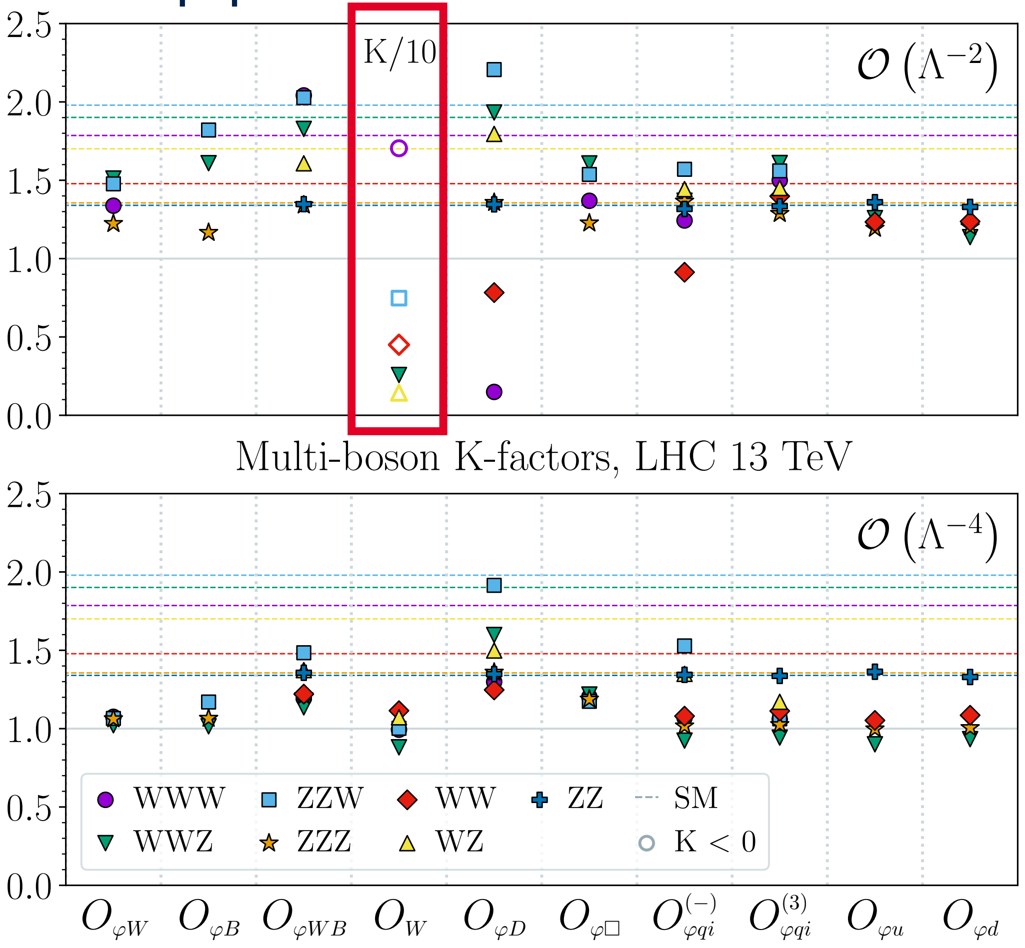
WW/WZ/ZZ/WWW/WWZ/ZZW/ZZZ


Loop-induced gg channel

Loop-induced qqtt operators

Triboson/QGC

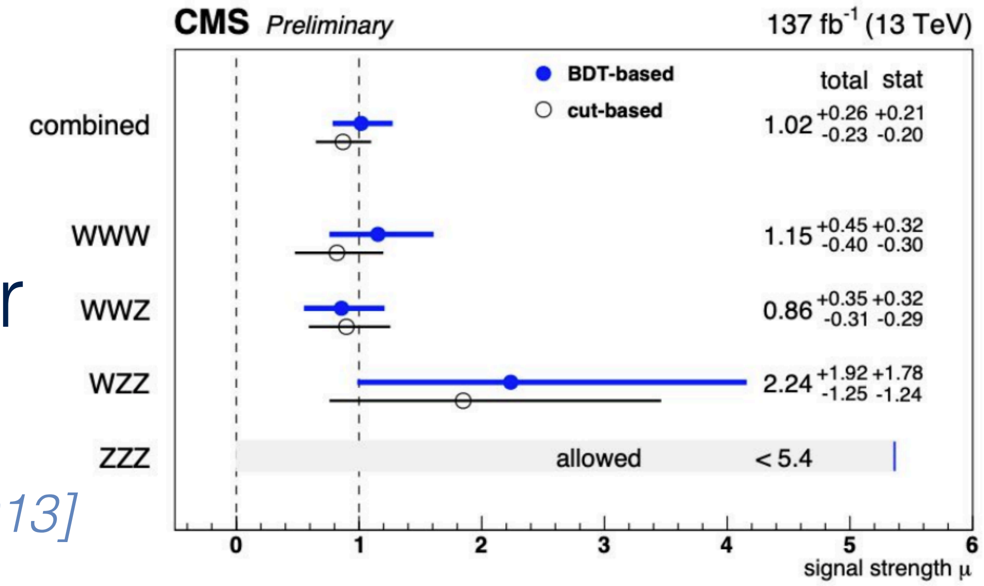
qq-initiated K-factors



Non-universal NLO corrections, different from SM

Large, negative K-factors for triple gauge operator, c_W
Non-interference/cancellation at LO broken at NLO

[CMS; arXiv:2006.11191]

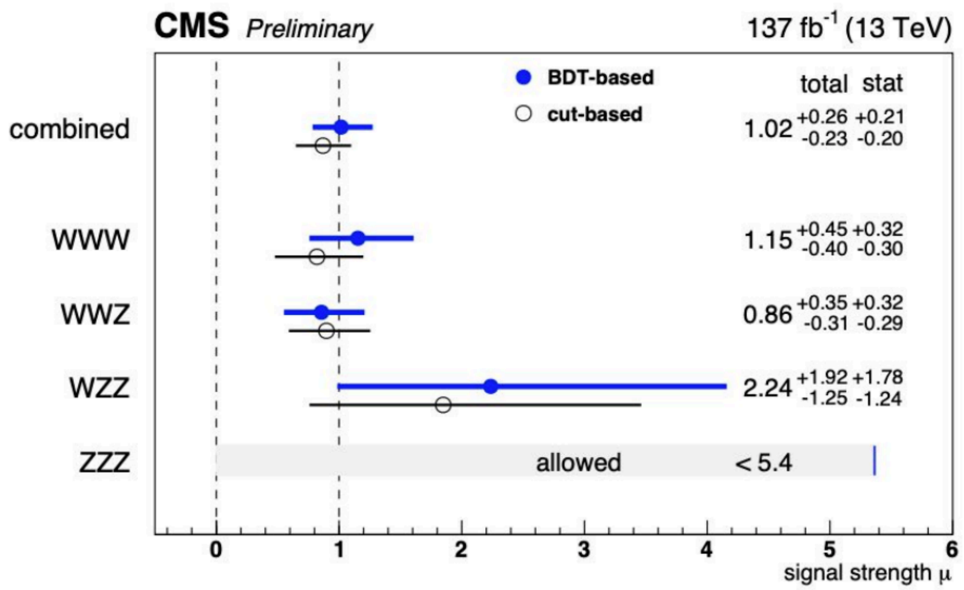


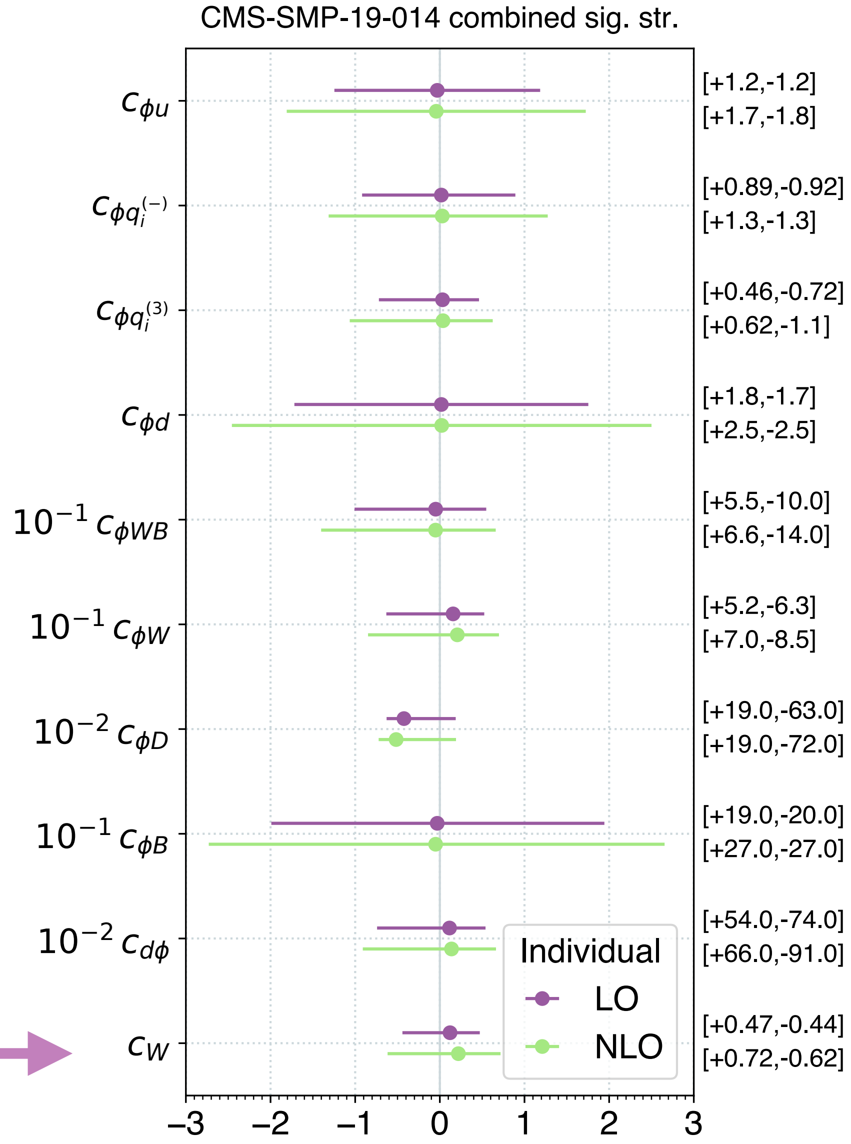
First triboson observation by CMS this year

- Also strong evidence from ATLAS
- New window into SMEFT? *[ATLAS; PLB 798 (2019) 134913]*

New constraints from triboson

[CMS; arXiv:2006.11191]





$$\epsilon_{IJK} W^{I}_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$$

Triple gauge coupling:
Better than the best constraint from differential diboson analyses!

[CMS; JHEP 12 (2019) 062]

aTGC	Expected limit	Observed limit
c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]
c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]
c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]

- More info differentially?

Putting it all together

Model independence means global fits

- Don't know *a priori* which operators NP will generate

Ultimate goal: complete likelihood for general SMEFT

- Start small.. realistic subsets of measurements/operators (exploit symmetries)

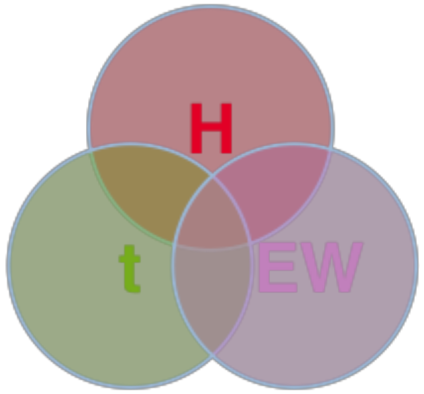
Long Shutdown 2 is an opportune time to take stock

- Legacy papers coming out with full Run II dataset
- SMEFT fit is a fantastic benchmarking & data preservation exercise
- The tools are available & the data is there

Several groups/analyses on various datasets

EWPO, Higgs, multiboson, top, DY, flavor,…

Putting it all together



Conspicuous split between top & Higgs/EW sector fits

Higgs/EW

Z pole (LEP)
W mass (LEP+LHC)
Diboson
Higgs couplings

[Ellis, Murphy, Sanz & You; JHEP 06 (2018)146]
[Falkowski & Straub.; JHEP 04 (2020) 066]
[Dawson, Homiller & Lane; PRD 102 (2020) 055012]
…

top

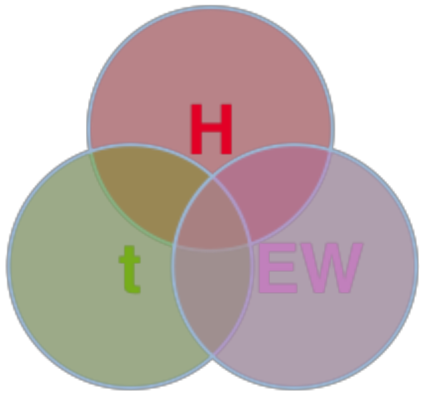
top pair
single top
ttV, tW, tZ

[Buckley et al.; JHEP 04 (2016) 015]
[Hartland et al.; JHEP 04 (2019) 100]
[Brivio et al.; JHEP 04 (2020) 131]

Do they talk beyond gg→ h?

Work in progess

[Ellis, Madigan, KM, Sanz, You; in preparation]



First combined fit to Higgs/EW/top data

Higgs/EW
Z pole (LEP)
W mass (LEP+LHC)
Diboson
Higgs couplings
top
top pair
single top
ttV, tW, tZ

~300 observables

Linear SMEFT contributions

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

Leading order predictions

- Loops in gg → h using SMEFT@NLO

χ^2 Likelihood analysis

- Assumes Gaussian PDF for observables
- Experimental & SM theory errors

Improve & update *[Ellis, Murphy, Sanz & You; JHEP 06 (2018)146]* *+ top data*

Degrees of freedom

Dictated by symmetries and data sensitivity

- B, L & CP conservation
- Flavor symmetry to control operators with fermions

aTGC $X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$

Yukawa $\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{q}_i\, u_j\, \tilde{\varphi})$

ffV, ffVh $\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$

$X^2 H^2 : (\varphi^\dagger \varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a$ VVh

$H^4 D^2 : (\varphi^\dagger\, D^\mu \varphi)^* (\varphi^\dagger\, D^\mu \varphi)$ δM_Z

$\psi^2 X H : (\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu}$ ‘dipole’

$\psi^4 : (\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$ top 4F

Operators enter directly & indirectly by shifting SM inputs

Baseline scenarios:

- Flavour universal (20 ops) $U(3)_L$ x $U(3)_e$ x $U(3)_Q$ x $U(3)_u$ x $U(3)_d$
- Top specific (34 ops) $U(3)_L$ x $U(3)_e$ x $U(2)_Q$ x $U(2)_u$ x $U(3)_d$
- Independent coefficients for 3 generation Q_L & t_R

Top sector

ttbar data doesn't agree with SM

Impact of EWPO & asymmetries

2 fermion operators:

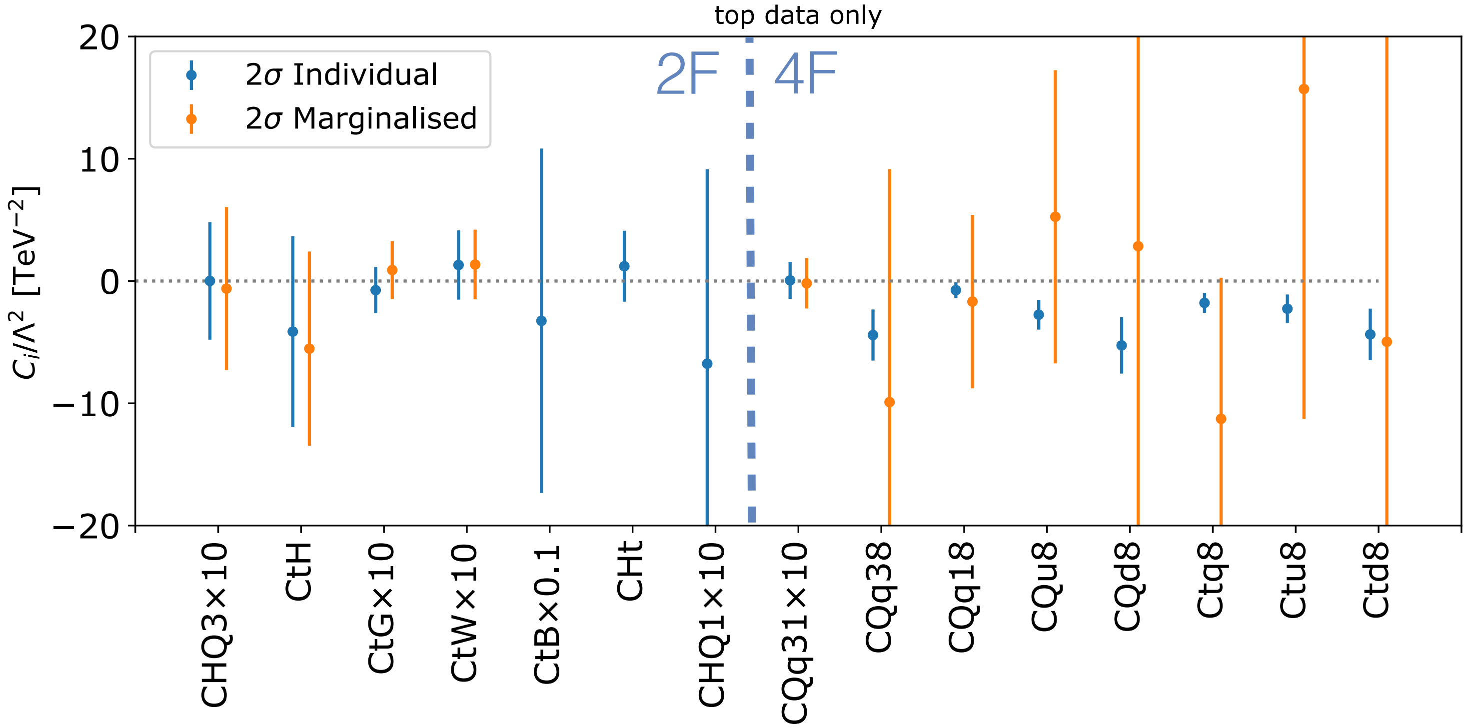
- EWPO closes 3 unconstrained directions related to ttZ & bbZ couplings

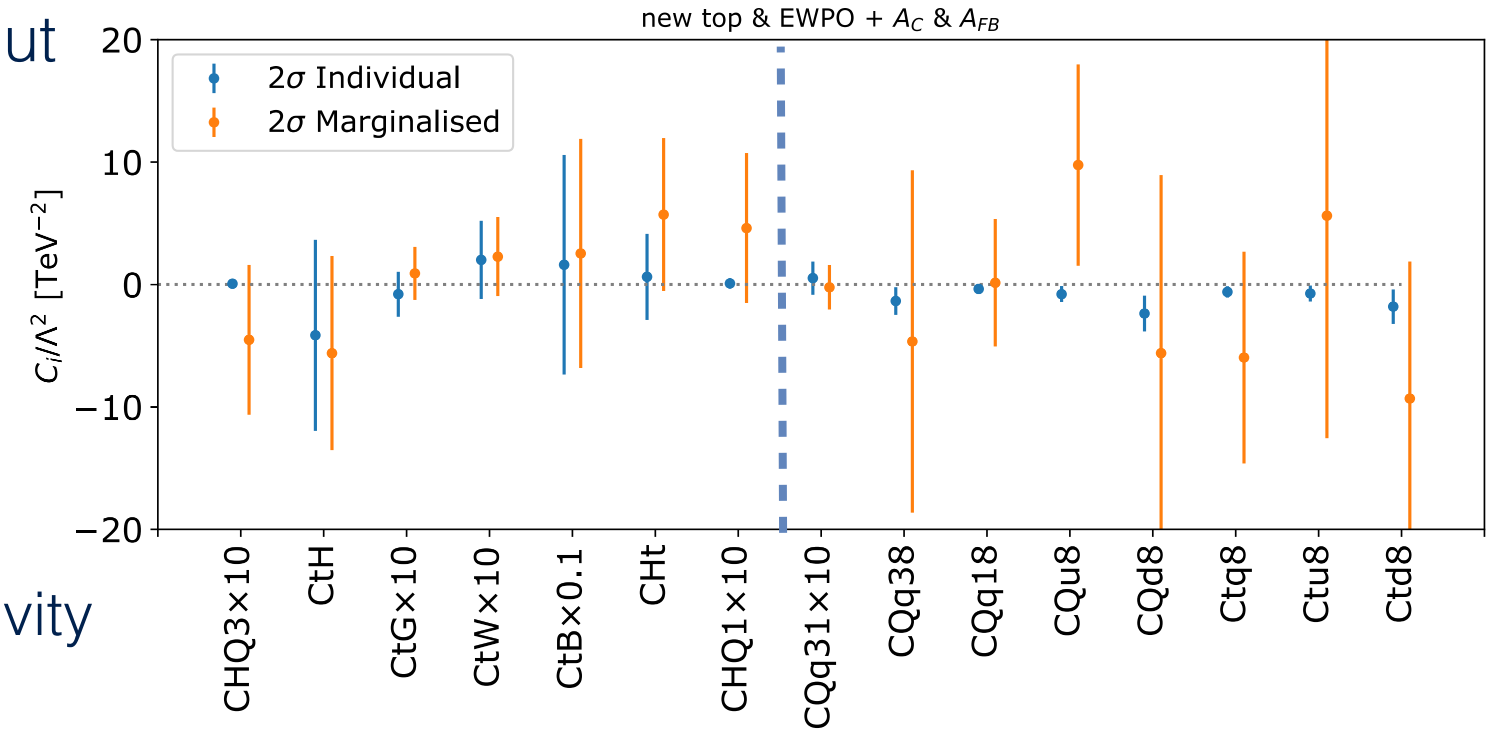
4 fermion operators:

- Individually tightly constrained but huge impact of marginalisation

  Degeneracy: only specific linear combinations well constrained

- Charge & forward backward asymmetry measurements significantly improve global sensitivity





STXS impact

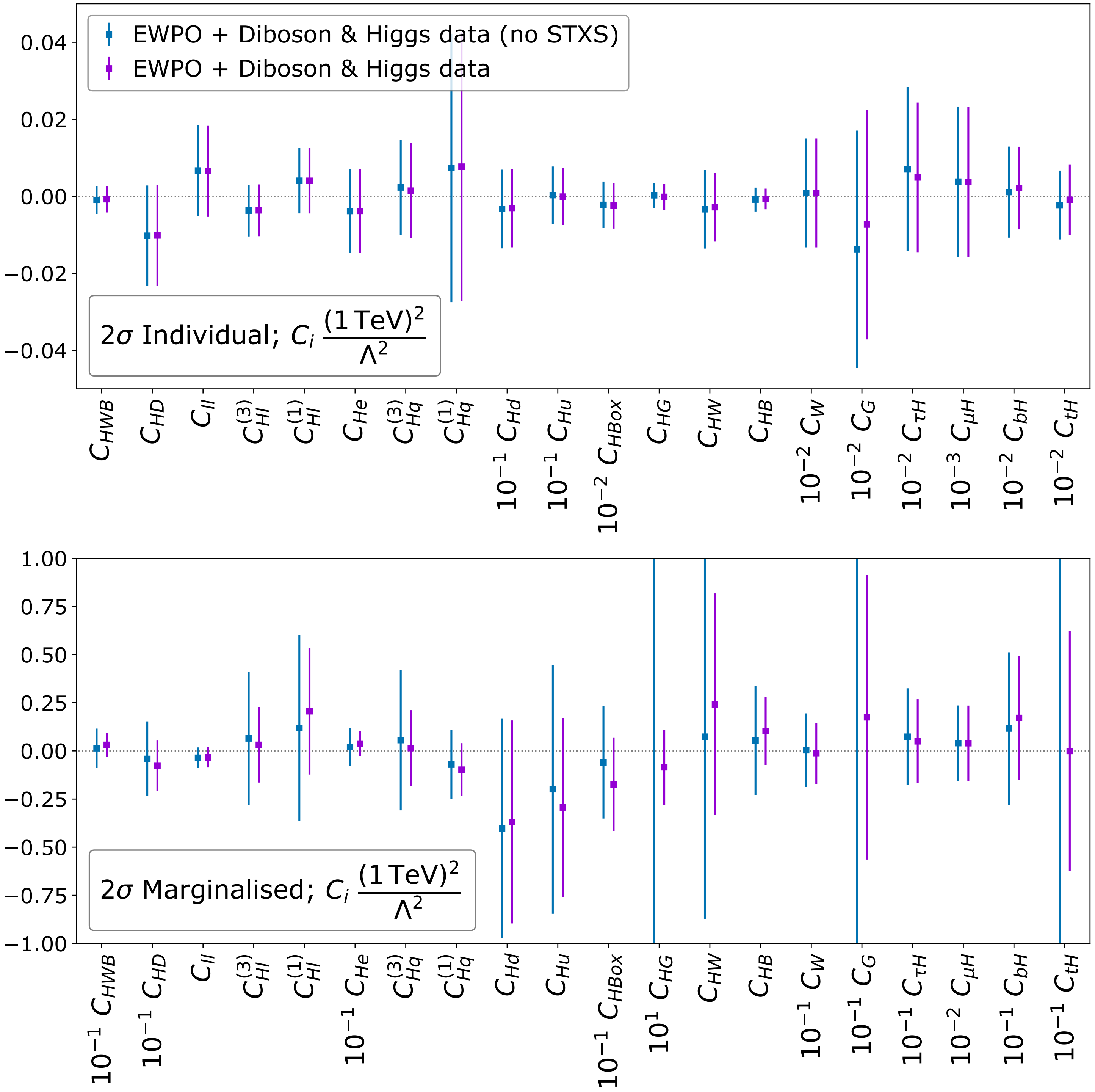
'Simplified template cross section' measurements

- Evolution of signal strength measurements (E=m_h)
- Start to include differential information (high energy bins)

  higgs + jets, high p_T VH,..

- Significant impact on marginalised constraints
- Close blind directions

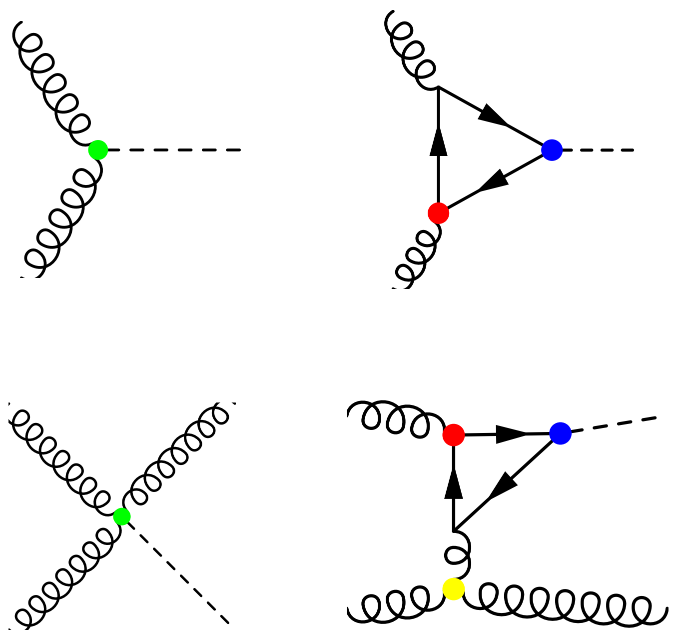
{hVV, hgg, htt} couplings

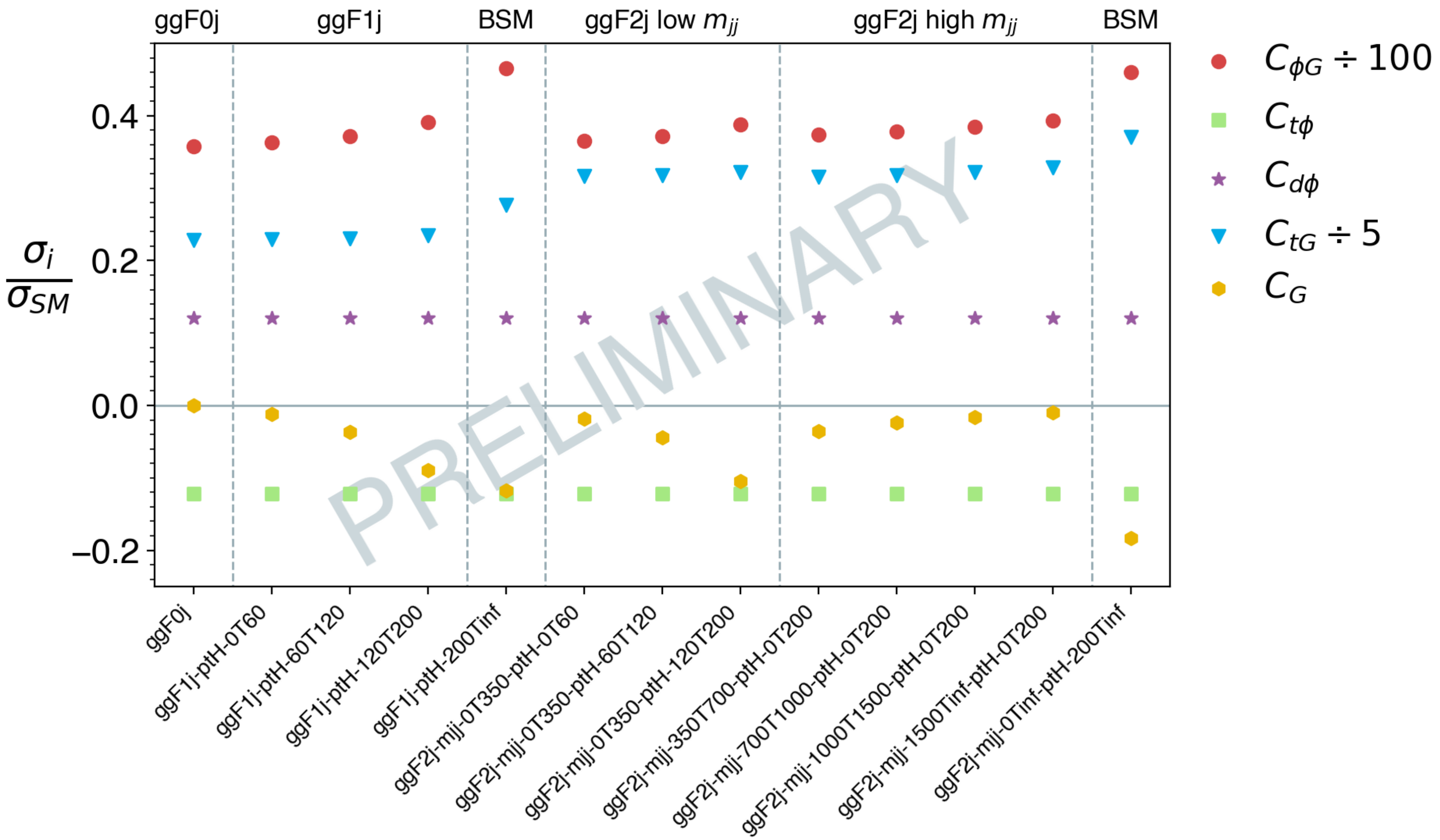


STXS impact

STXS for ggF: one-loop is LO for the SM

- Tree-EFT x loop-SM and loop-EFT x loop-SM interference terms
- Heavy top limit OK for 0-jet, breaks down for high-p_T





STXS impact

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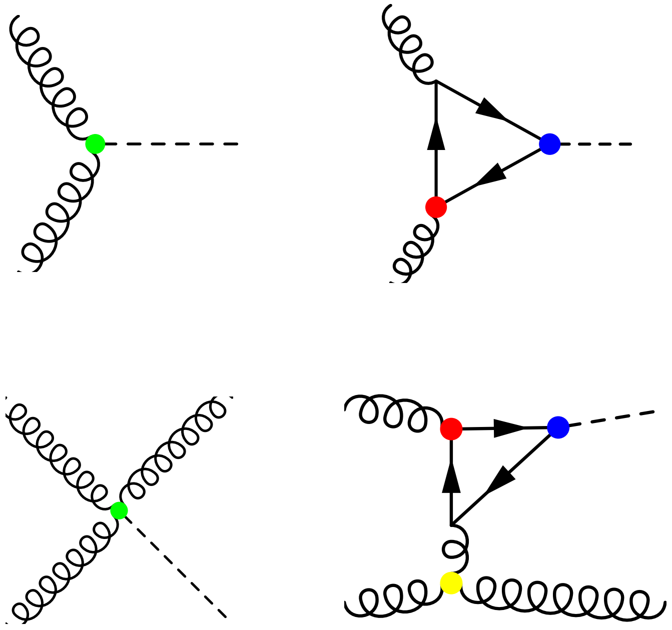

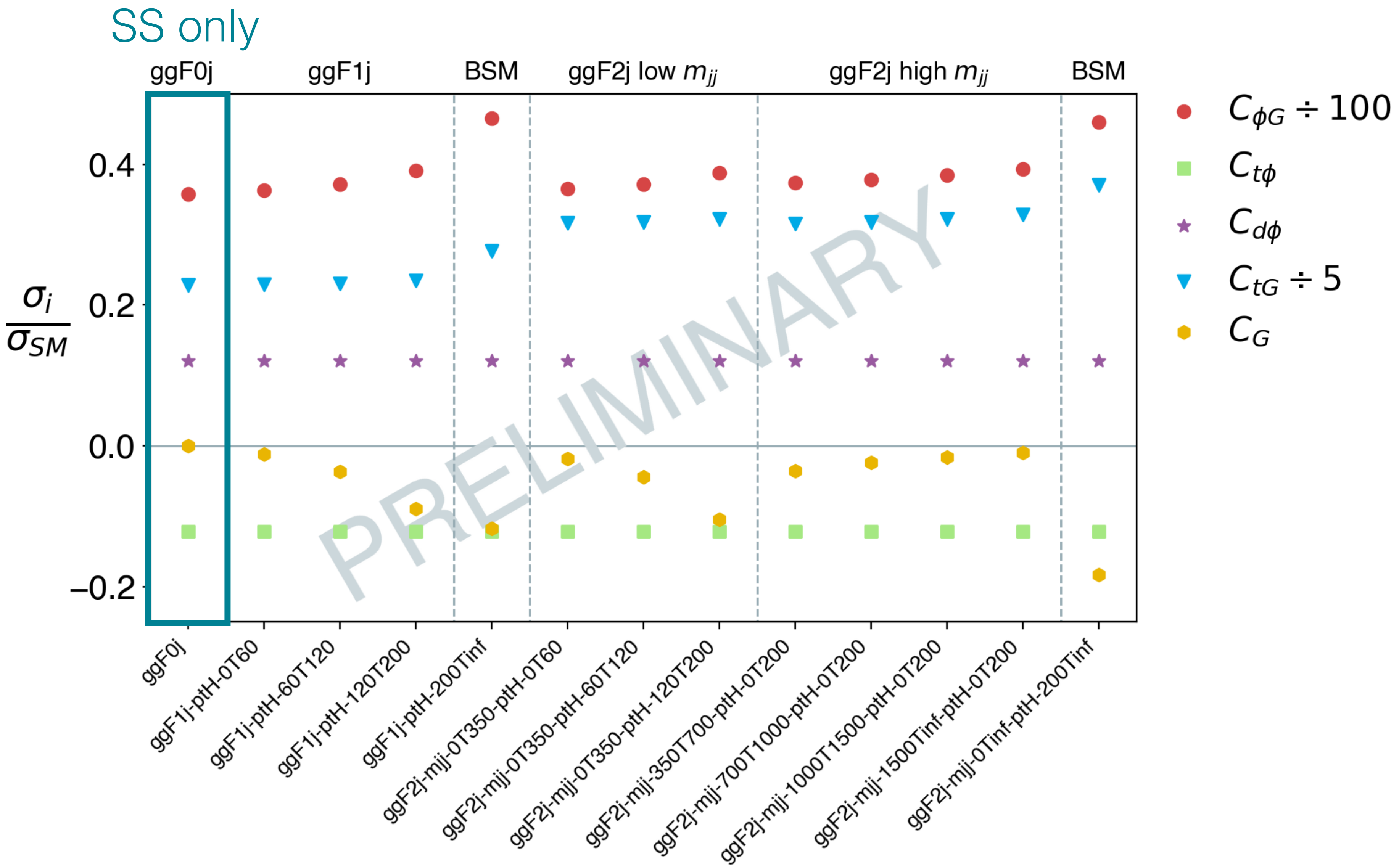

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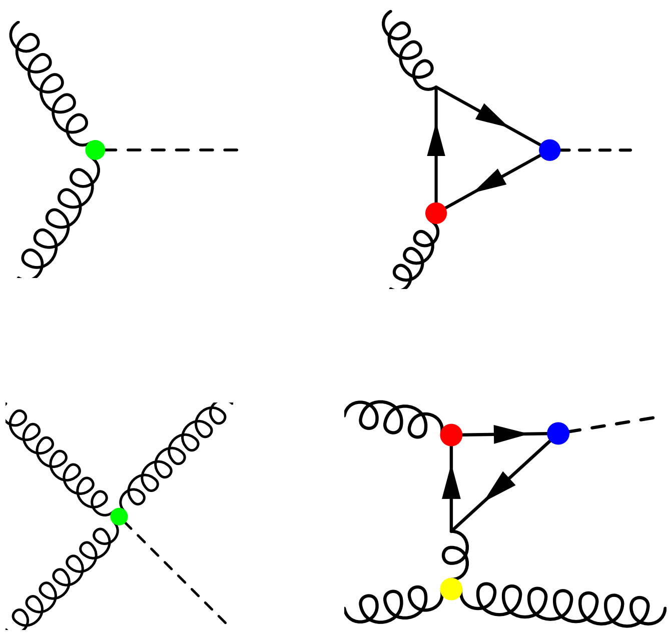
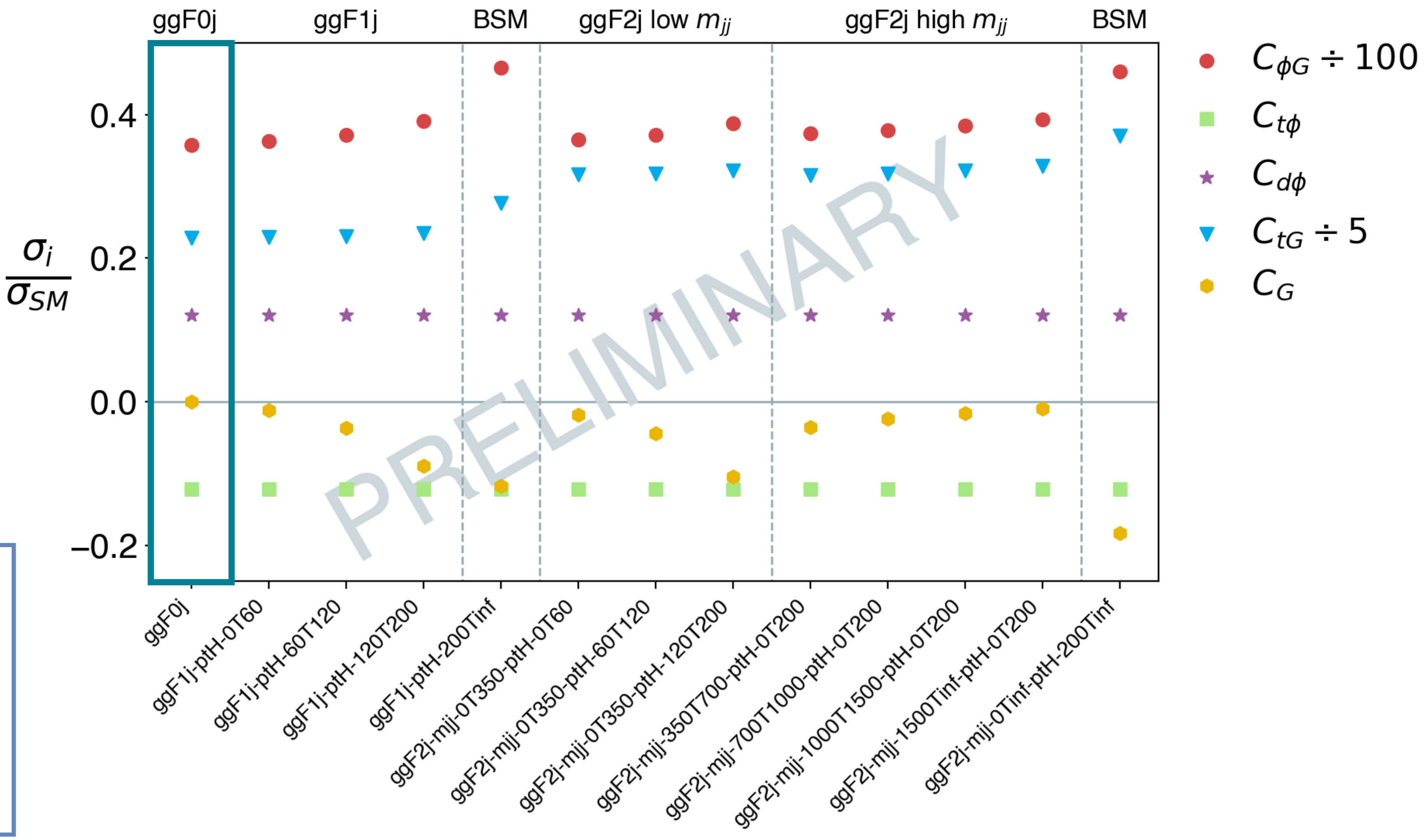


Bottom line:
Different bins have different relative sensitivity (energy dependence) to the coefficients

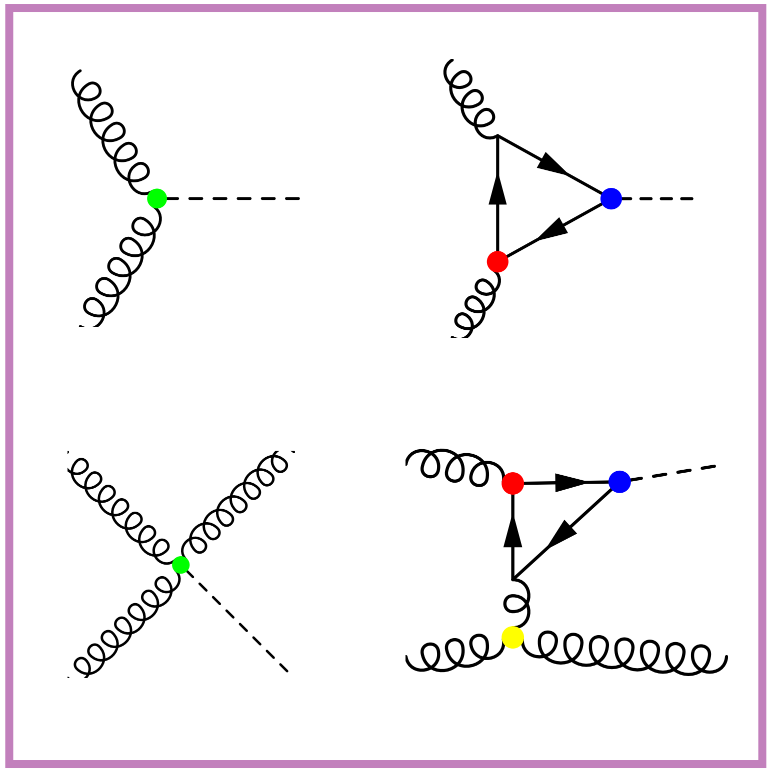
SS only

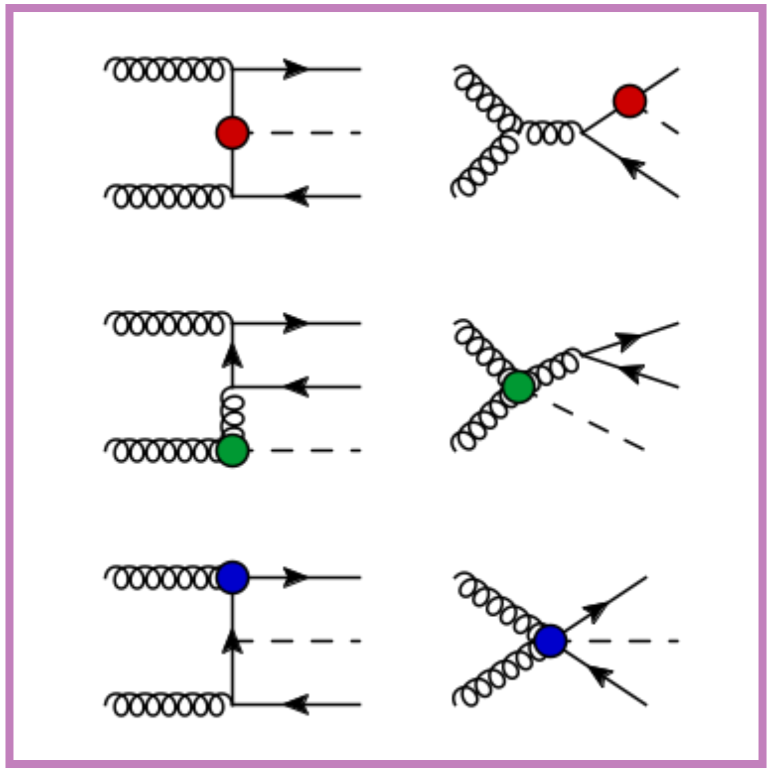


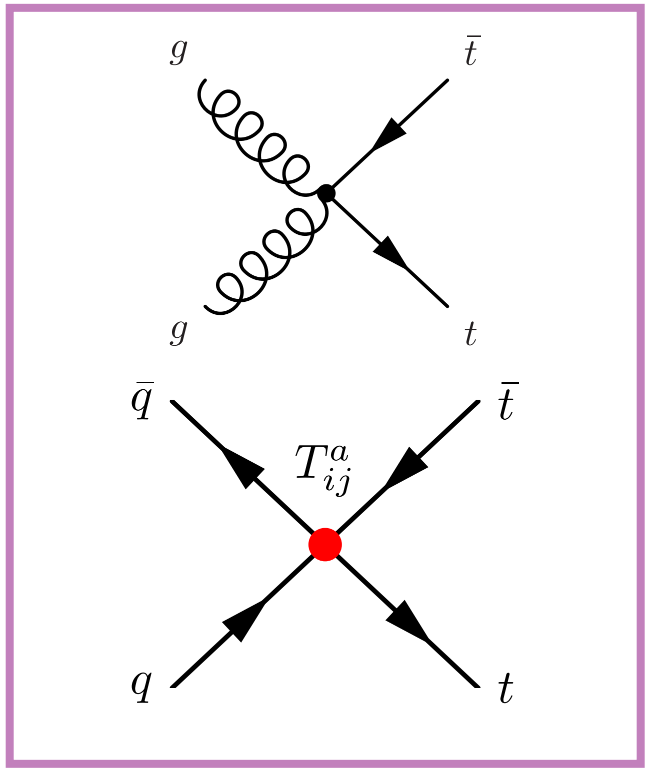
Top-Higgs interplay

Combination of ggF, ttH & top pair is crucial

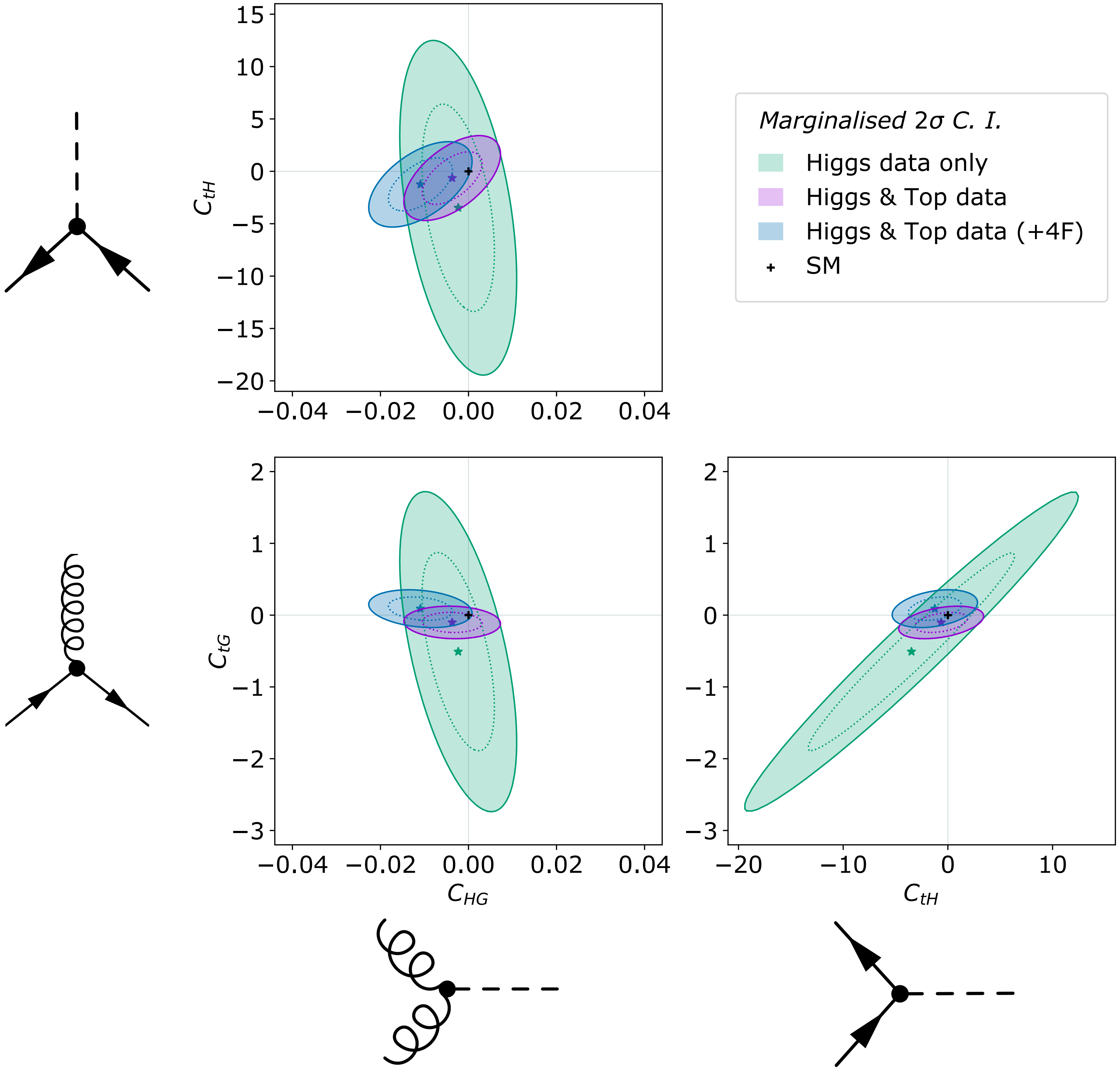
- **ggF** constrains a linear combination of ggH and top Yukawa operators
- **ttH** & **STXS** close the subspace
- Top dipole operator can also contribute but is constrained by **top pair**
- Large number of qqtt operators may affect/dilute sensitivity







Top-Higgs interplay



Higgs only

Subset of operators that gives a closed fit to Higgs data

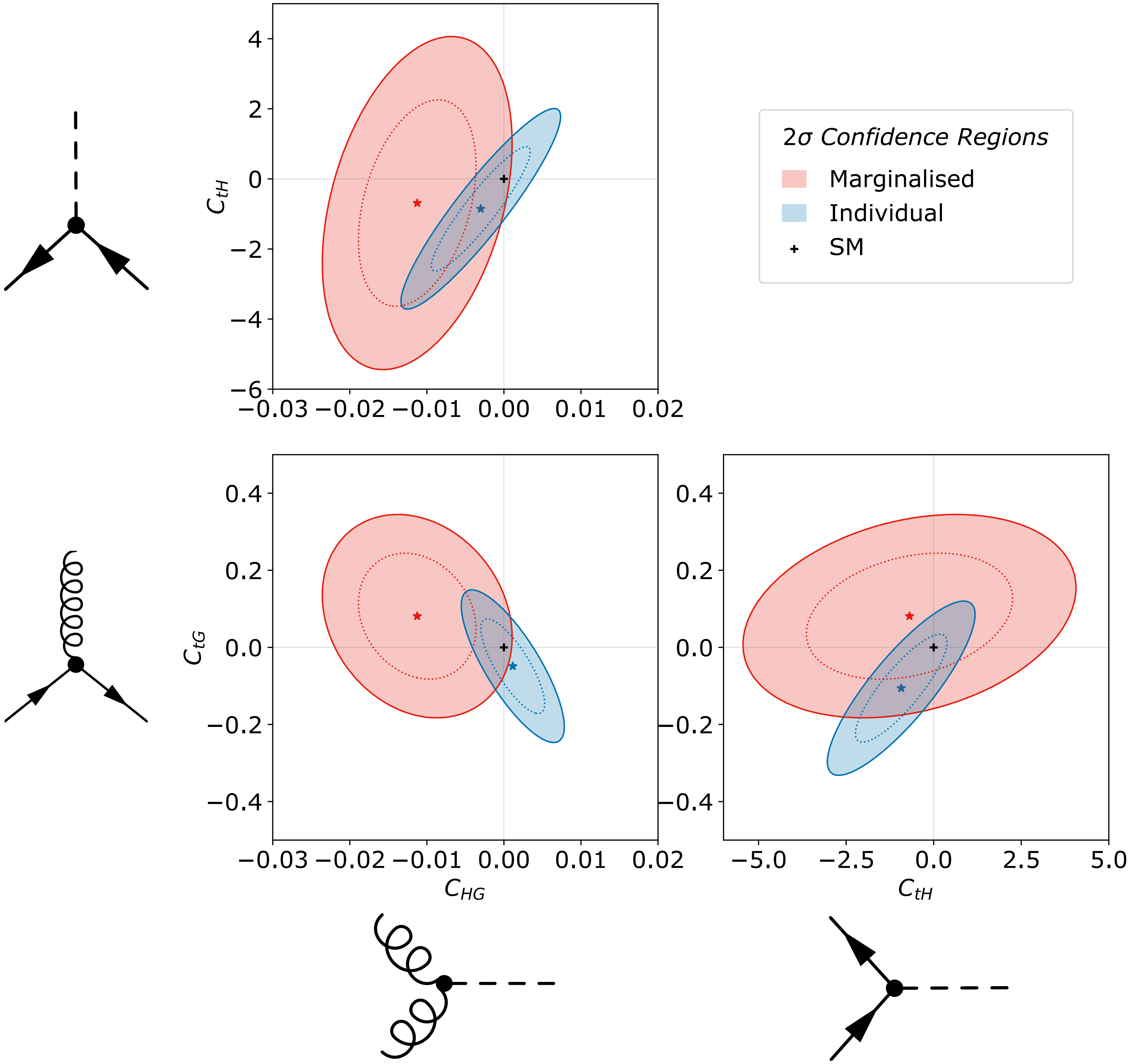
Higgs & top

Combining top data significantly constrains ctG direction & ctH by correlation

+ 4 Fermion

Adding 7 new 4F degrees of freedom does not significantly degrade the sensitivity, as previously expected

Top-Higgs interplay



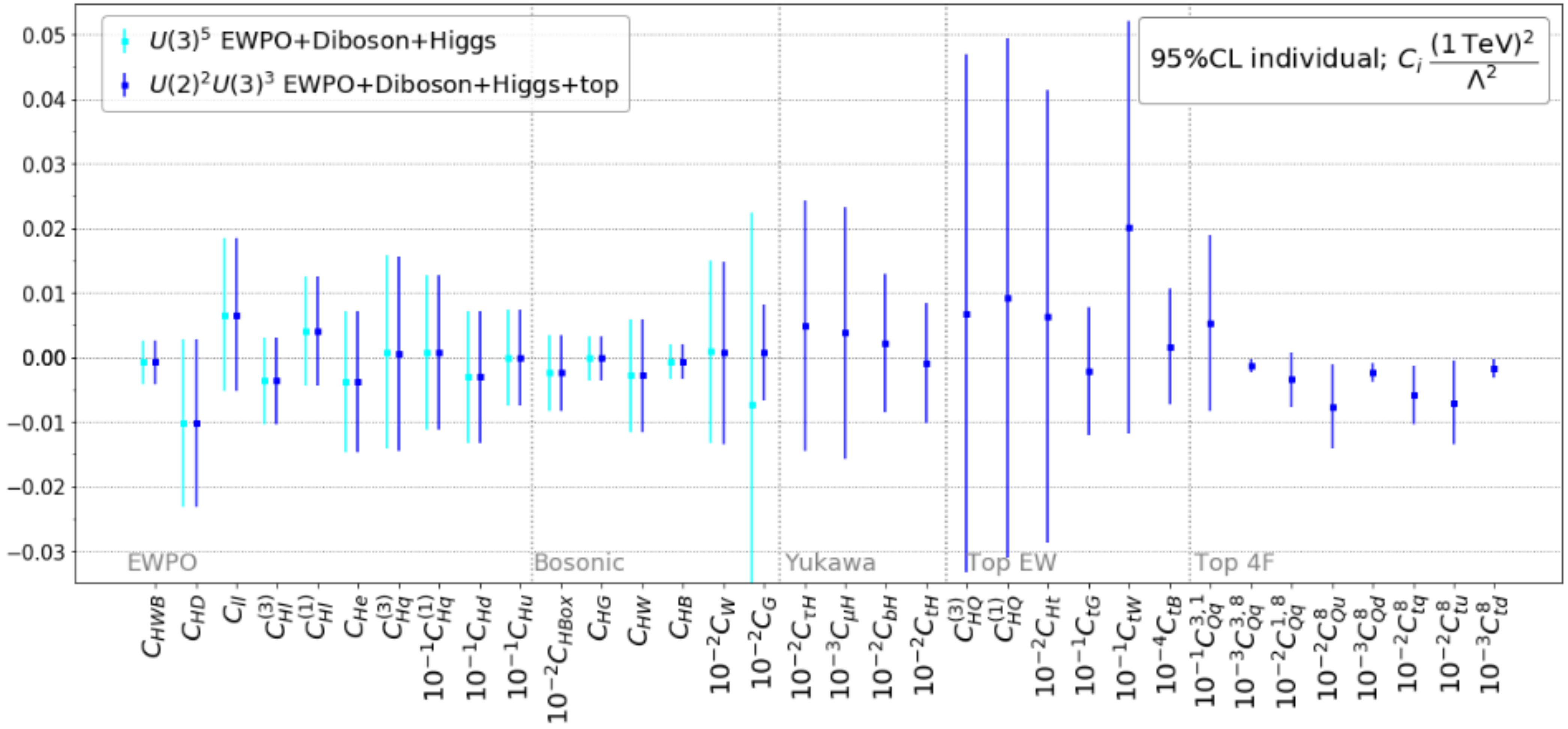
Full fit to the top-specific flavor scenario (34 operators)

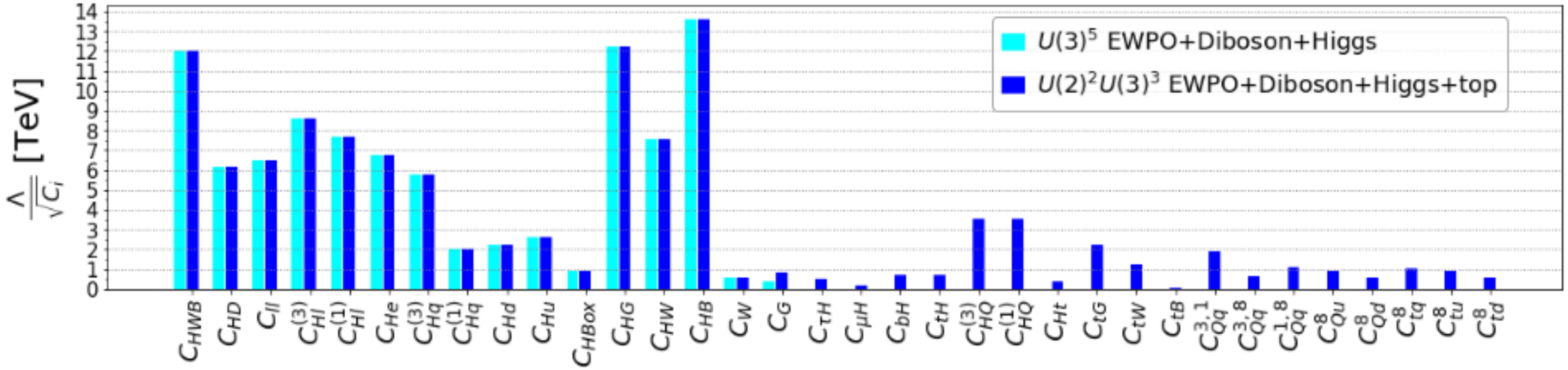
Significant marginalisation effects

Consistent with SM within 2σ

Individual bounds

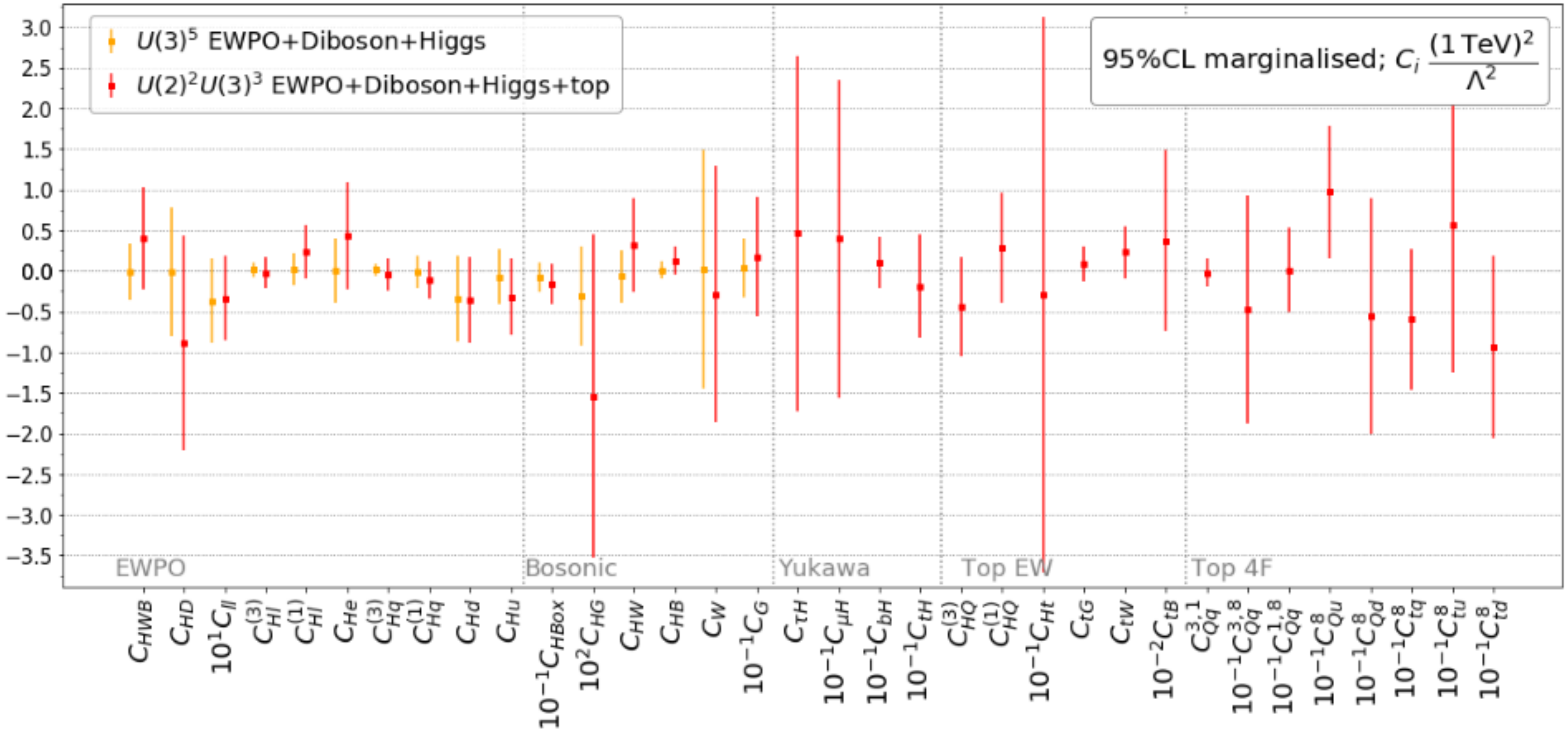
All other coeffs=0

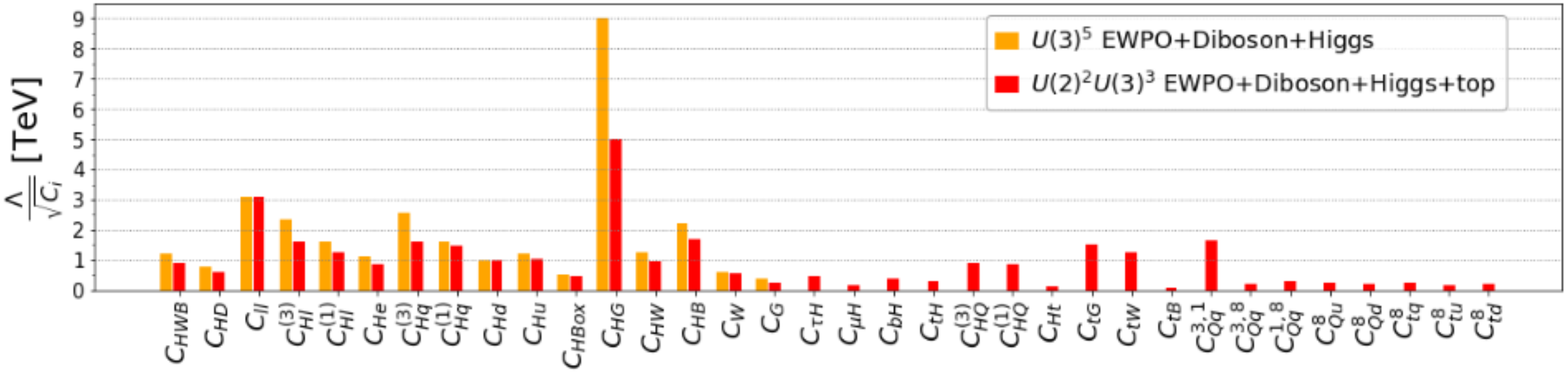




Marginalised bounds

All other coeffs profiled

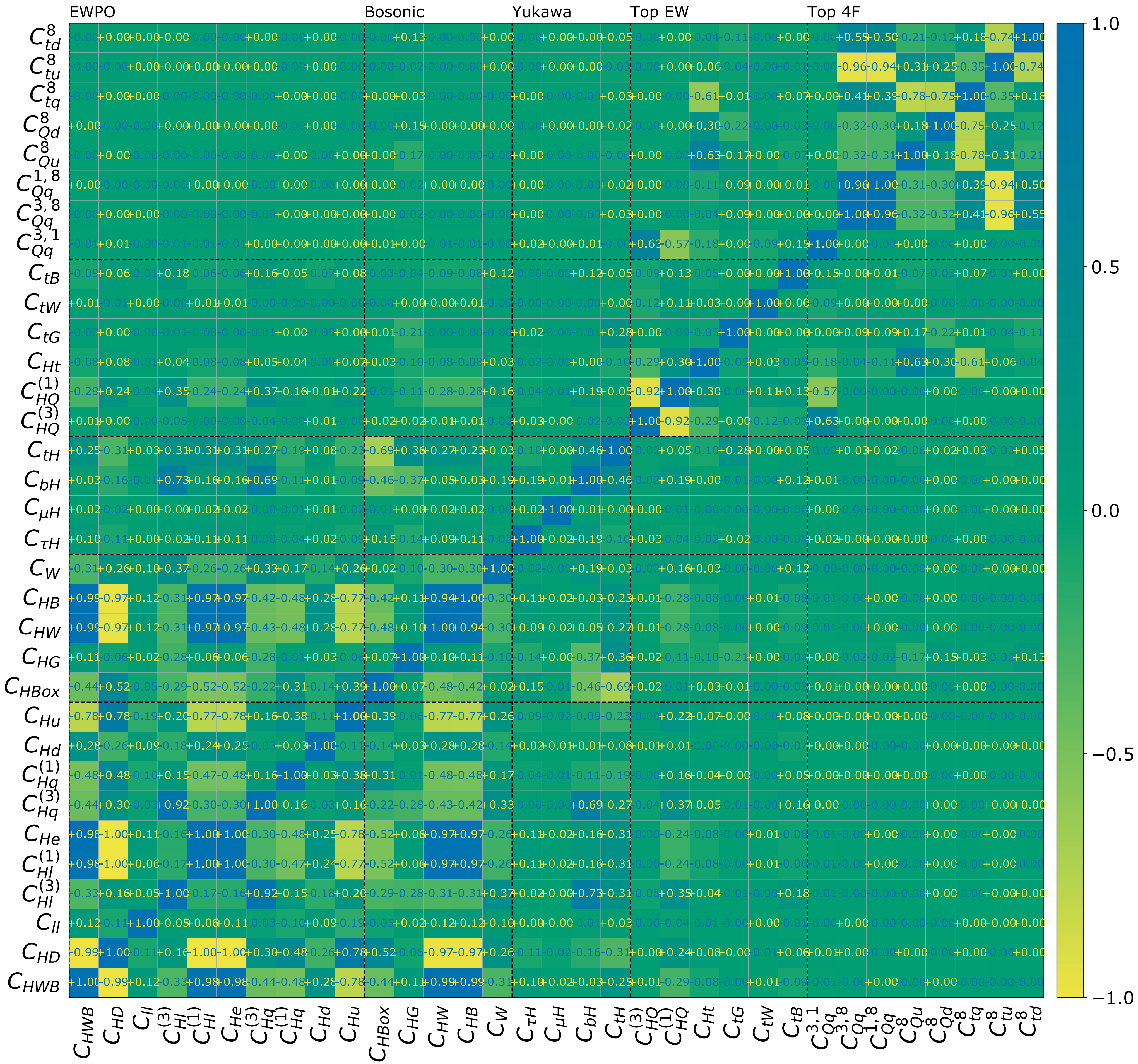




Correlation Matrix

Block diagonal: How sectors talk among themselves

Block off-diagonal: How sectors talk to eachother



Eigensystem

Benefits of linearised fit

- Full likelihood information is contained in intervals & correlation matrix, **U**
- Fisher information matrix **F=U^{-1}** represents constraining power of data

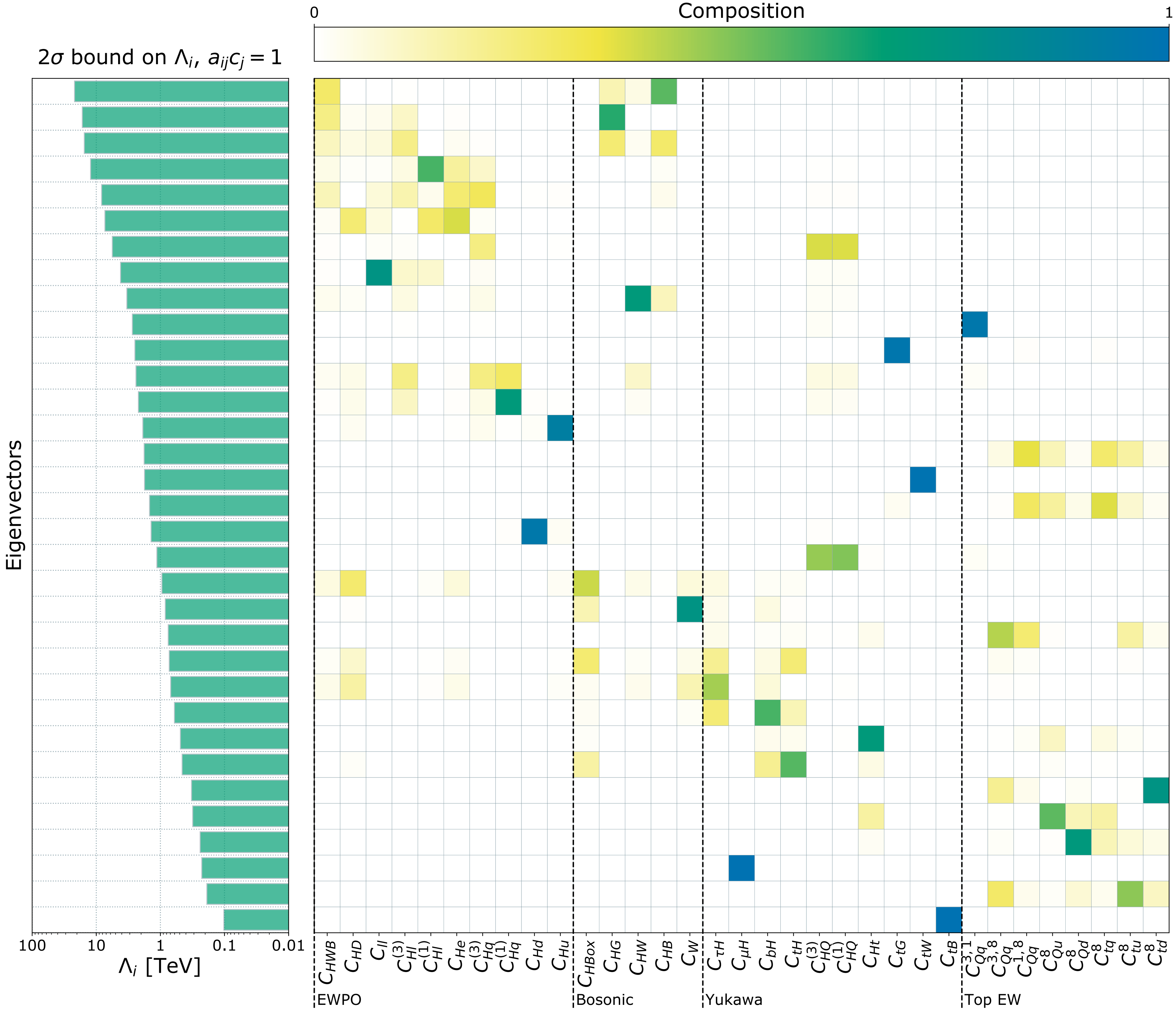
$$
\begin{aligned}
\chi^2(\boldsymbol{c}) &= (\boldsymbol{y} - \boldsymbol{\mu}(\boldsymbol{c}))^\top \cdot \widetilde{\boldsymbol{V}} \cdot (\boldsymbol{y} - \boldsymbol{\mu}(\boldsymbol{c})) \\
&= \chi_{SM} - 2\,\boldsymbol{c}^\top \cdot \boldsymbol{\omega}^\top + \boldsymbol{c}^\top \cdot \boldsymbol{F} \cdot \boldsymbol{c} \\
&= \chi^2_{\text{min.}} + (\boldsymbol{c} - \hat{\boldsymbol{c}})^\top \cdot \boldsymbol{F} \cdot (\boldsymbol{c} - \hat{\boldsymbol{c}})
\end{aligned}
$$

$$
\boldsymbol{\mu}(\boldsymbol{c}) = \boldsymbol{\mu}^{SM} + \boldsymbol{H} \cdot \boldsymbol{c}
$$

- Break down how the data affect each direction in parameter space
- Diagonalise the system, get eigenvectors & associated bounds
- Eigenvectors: individual bounds = marginalised bounds

Eigensystem

Sensitivities between 100 GeV & 10 TeV



Relative constraining power (%)

EWPO	LEP WW	Run 1, μ_H	Run 2, μ_H	STXS	LHC WW	$t\bar{t}$	single top	$t\bar{t}V$
6.61	×	15.03	28.47	49.89	×	×	×	×
38.15	0.02	13.02	26.16	22.61	0.03	×	×	×
55.61	0.05	7.65	16.32	20.31	0.06	×	×	×
99.38	0.08	0.08	0.17	0.28	×	×	×	×
97.71	0.76	0.13	0.40	0.65	0.31	×	0.03	×
99.68	0.17	0.02	0.07	0.06	×	×	×	×
95.88	1.16	0.26	0.48	1.83	0.19	×	0.19	×
74.97	23.36	0.12	0.61	0.58	0.29	×	0.05	×
1.32	0.48	6.57	85.09	6.23	0.14	×	0.17	×
0.09	0.02	0.04	0.37	0.49	0.02	×	98.93	0.03
×	×	1.25	16.14	6.95	×	68.25	0.03	7.38
21.31	1.03	4.65	16.67	52.66	1.45	0.06	2.13	0.04
76.43	4.47	0.98	3.23	10.96	2.73	0.01	1.14	0.05
70.21	11.84	1.43	2.30	11.23	2.52	0.08	0.39	×
×	×	×	×	×	×	99.02	×	0.97
0.11	0.01	×	0.01	0.06	×	86.68	13.11	×
×	×	0.02	×	0.15	×	95.75	0.07	4.00
90.30	5.83	0.22	0.35	1.50	0.95	0.05	0.80	×
0.75	0.02	0.25	0.82	0.83	0.04	3.65	73.41	20.24
2.65	8.37	26.75	43.85	10.89	4.83	1.35	0.30	1.01
2.80	66.60	5.23	11.93	4.20	8.10	0.87	0.24	0.03
0.08	0.01	1.14	3.94	2.66	×	7.34	6.35	78.47
0.82	4.02	10.29	37.17	26.96	0.87	15.38	0.17	4.33
1.15	13.32	18.08	31.96	26.79	4.44	0.14	1.82	2.31
0.15	1.69	14.54	36.93	39.91	1.81	2.50	1.69	0.76
0.13	0.08	1.52	3.99	3.21	0.36	6.96	14.49	69.25
1.94	0.70	15.90	41.26	27.43	0.54	7.08	1.56	3.59
×	×	×	×	0.03	×	97.26	0.02	2.68
×	0.01	0.02	0.03	0.11	0.01	96.49	1.02	2.30
×	×	×	×	0.04	×	99.63	0.24	0.08
×	×	22.37	77.54	0.08	×	×	×	×
×	×	×	×	×	×	99.89	0.04	0.06
0.33	0.81	0.19	0.58	1.61	0.18	0.69	95.13	0.47

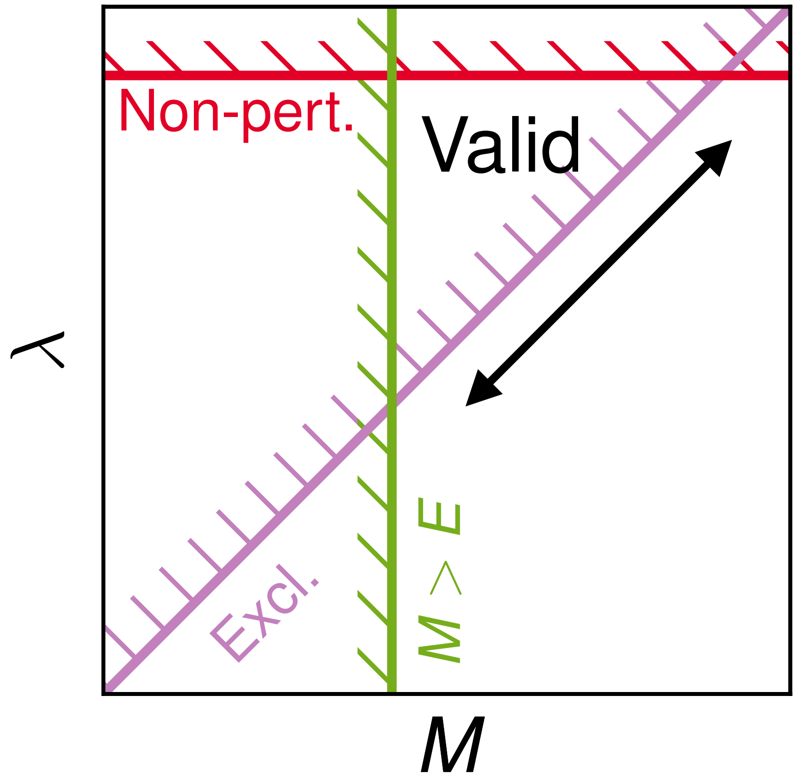
BSM implications

SMEFT-UV connection is model dependent by construction

- Implications on heavy new physics & validity of EFT is ***a posteriori***
- Depends on sensitivity & energy scale probed by data
- Bottom-up philosophy: new physics scale unknown

arbitrary dimensionful parameter $$\frac{c_S}{\Lambda^2} = \frac{\lambda^2}{M^2}$$ *coupling/mass scale of new physics*

constraint: c/Λ² < X



Difficult to address in a general way

- Today we are probing TeV scale new physics
- Hierarchies in sensitivity EWPO > Higgs > top (EW)
- Moderate-to-strong coupling scenarios most safe
- Generic NP in loops looks challenging for the LHC
- Concrete models should be better constrained
- Less underlying parameters

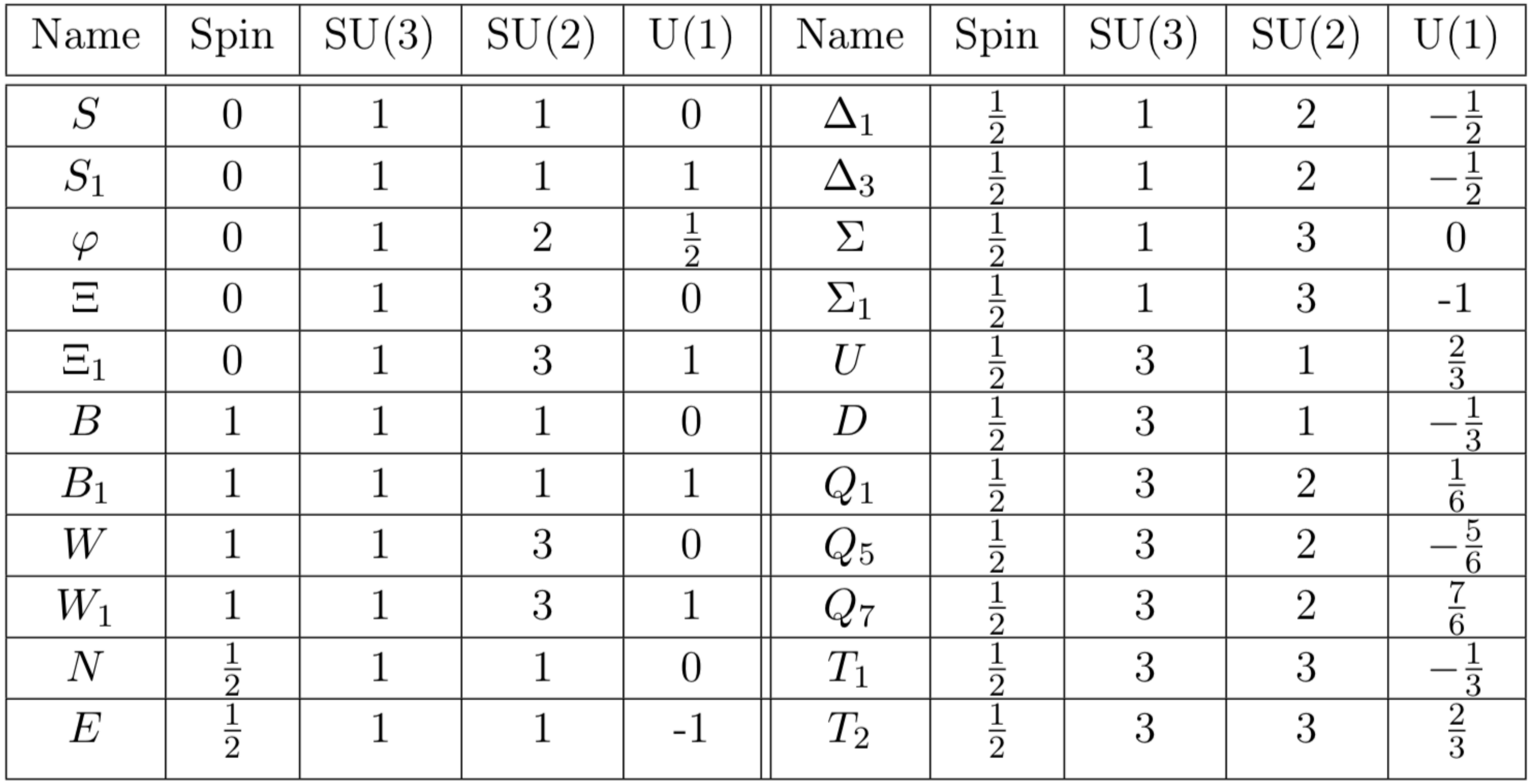
BSM implications

Fit results allow us to test compatibility of any BSM model

- Provided it obeys the basic rule M > E

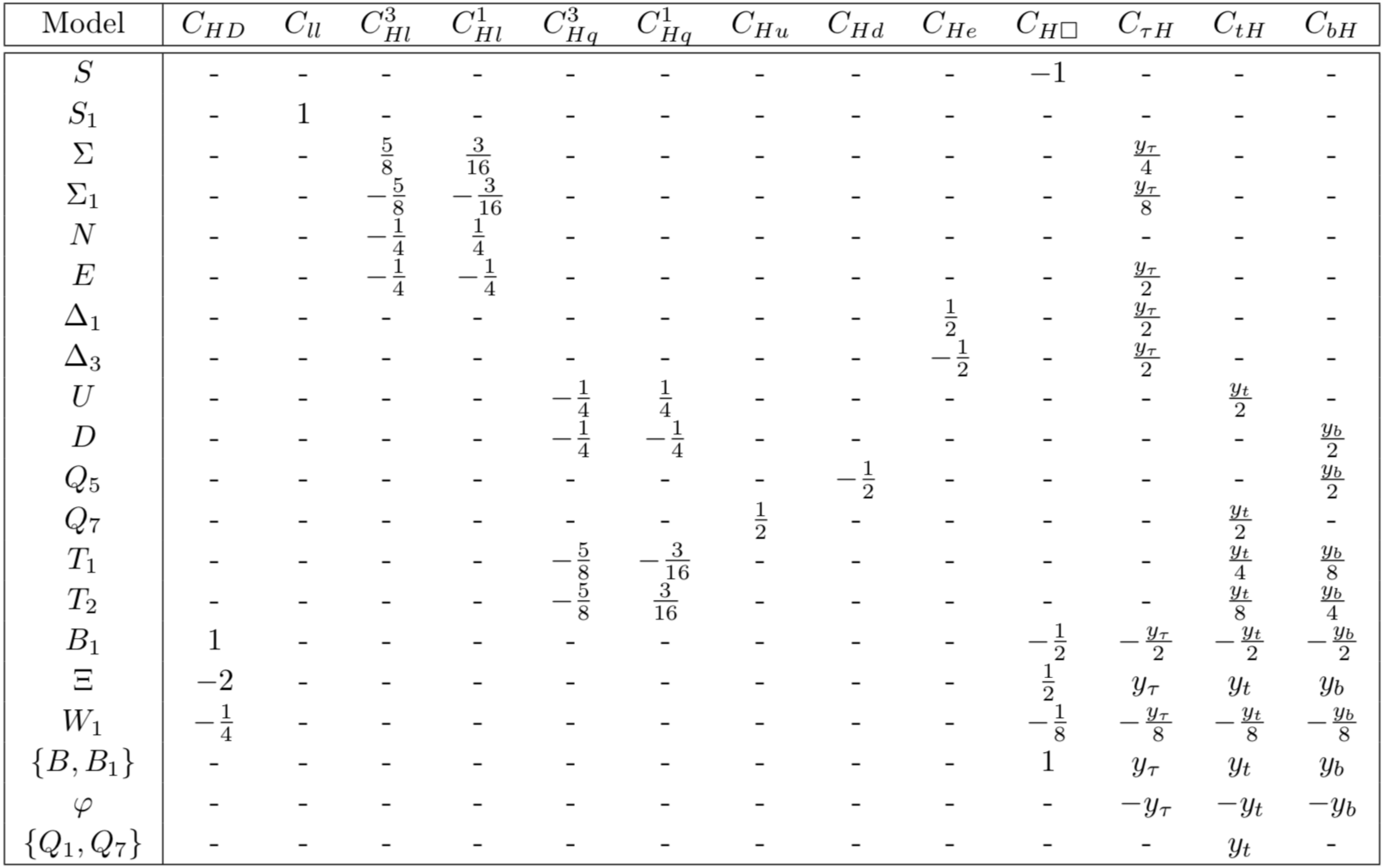
We use the complete tree-level dictionary *[de Blas et al.; JHEP 03 (2018) 109]*

- Tree-level matching for all one-particle extensions of the SM



Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	1	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
W_1	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$

BSM implications

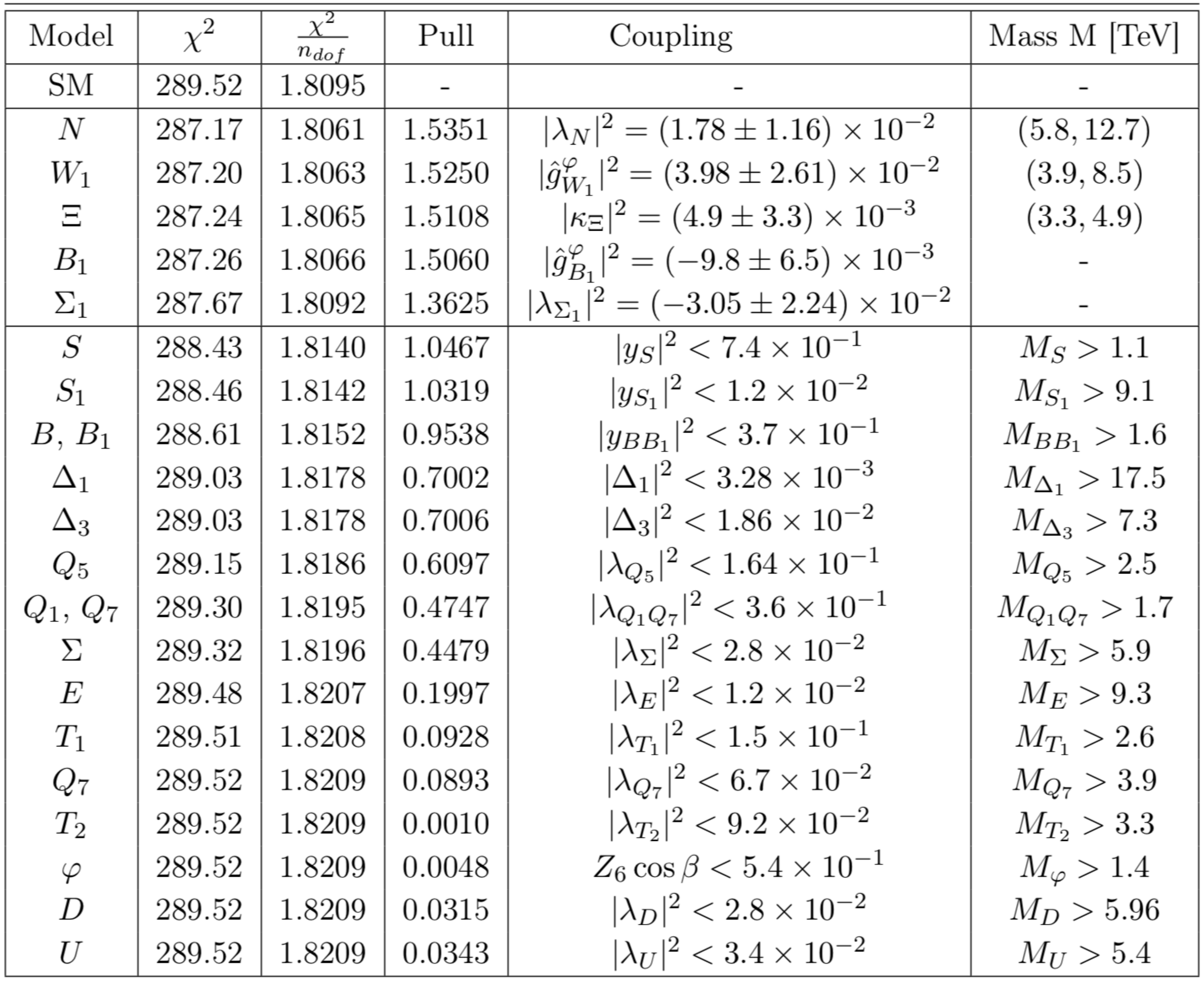


Model	C_{HD}	C_{ll}	C_{Hl}^3	C_{Hl}^1	C_{Hq}^3	C_{Hq}^1	C_{Hu}	C_{Hd}	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S	-	-	-	-	-	-	-	-	-	-1	-	-	-
S_1	-	1	-	-	-	-	-	-	-	-	-	-	-
Σ	-	-	$\frac{5}{8}$	$\frac{3}{16}$	-	-	-	-	-	-	$\frac{y_\tau}{4}$	-	-
Σ_1	-	-	$-\frac{5}{8}$	$-\frac{3}{16}$	-	-	-	-	-	-	$\frac{y_\tau}{8}$	-	-
N	-	-	$-\frac{1}{4}$	$\frac{1}{4}$	-	-	-	-	-	-	-	-	-
E	-	-	$-\frac{1}{4}$	$-\frac{1}{4}$	-	-	-	-	-	-	$\frac{y_\tau}{2}$	-	-
Δ_1	-	-	-	-	-	-	-	-	$\frac{1}{2}$	-	$\frac{y_\tau}{2}$	-	-
Δ_3	-	-	-	-	-	-	-	-	$-\frac{1}{2}$	-	$\frac{y_\tau}{2}$	-	-
U	-	-	-	-	$-\frac{1}{4}$	$\frac{1}{4}$	-	-	-	-	-	$\frac{y_t}{2}$	-
D	-	-	-	-	$-\frac{1}{4}$	$-\frac{1}{4}$	-	-	-	-	-	-	$\frac{y_b}{2}$
Q_5	-	-	-	-	-	-	-	$-\frac{1}{2}$	-	-	-	-	$\frac{y_b}{2}$
Q_7	-	-	-	-	-	-	$\frac{1}{2}$	-	-	-	-	$\frac{y_t}{2}$	-
T_1	-	-	-	-	$-\frac{5}{8}$	$-\frac{3}{16}$	-	-	-	-	-	$\frac{y_t}{4}$	$\frac{y_b}{8}$
T_2	-	-	-	-	$-\frac{5}{8}$	$\frac{3}{16}$	-	-	-	-	-	$\frac{y_t}{8}$	$\frac{y_b}{4}$
B_1	1	-	-	-	-	-	-	-	-	$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2	-	-	-	-	-	-	-	-	$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$	-	-	-	-	-	-	-	-	$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
$\{B, B_1\}$	-	-	-	-	-	-	-	-	-	1	y_τ	y_t	y_b
φ	-	-	-	-	-	-	-	-	-	-	$-y_\tau$	$-y_t$	$-y_b$
$\{Q_1, Q_7\}$	-	-	-	-	-	-	-	-	-	-	-	y_t	-

8) 109]

One parameter models

Coupling for Λ = 1 TeV or mass for coupling =1



Model	χ^2	$\frac{\chi^2}{n_{dof}}$	Pull	Coupling	Mass M [TeV]
SM	289.52	1.8095	-	-	-
N	287.17	1.8061	1.5351	$\|\lambda_N\|^2 = (1.78 \pm 1.16) \times 10^{-2}$	$(5.8, 12.7)$
W_1	287.20	1.8063	1.5250	$\|\hat{g}^{\varphi}_{W_1}\|^2 = (3.98 \pm 2.61) \times 10^{-2}$	$(3.9, 8.5)$
Ξ	287.24	1.8065	1.5108	$\|\kappa_{\Xi}\|^2 = (4.9 \pm 3.3) \times 10^{-3}$	$(3.3, 4.9)$
B_1	287.26	1.8066	1.5060	$\|\hat{g}^{\varphi}_{B_1}\|^2 = (-9.8 \pm 6.5) \times 10^{-3}$	-
Σ_1	287.67	1.8092	1.3625	$\|\lambda_{\Sigma_1}\|^2 = (-3.05 \pm 2.24) \times 10^{-2}$	-
S	288.43	1.8140	1.0467	$\|y_S\|^2 < 7.4 \times 10^{-1}$	$M_S > 1.1$
S_1	288.46	1.8142	1.0319	$\|y_{S_1}\|^2 < 1.2 \times 10^{-2}$	$M_{S_1} > 9.1$
$B,\ B_1$	288.61	1.8152	0.9538	$\|y_{BB_1}\|^2 < 3.7 \times 10^{-1}$	$M_{BB_1} > 1.6$
Δ_1	289.03	1.8178	0.7002	$\|\Delta_1\|^2 < 3.28 \times 10^{-3}$	$M_{\Delta_1} > 17.5$
Δ_3	289.03	1.8178	0.7006	$\|\Delta_3\|^2 < 1.86 \times 10^{-2}$	$M_{\Delta_3} > 7.3$
Q_5	289.15	1.8186	0.6097	$\|\lambda_{Q_5}\|^2 < 1.64 \times 10^{-1}$	$M_{Q_5} > 2.5$
$Q_1,\ Q_7$	289.30	1.8195	0.4747	$\|\lambda_{Q_1 Q_7}\|^2 < 3.6 \times 10^{-1}$	$M_{Q_1 Q_7} > 1.7$
Σ	289.32	1.8196	0.4479	$\|\lambda_{\Sigma}\|^2 < 2.8 \times 10^{-2}$	$M_{\Sigma} > 5.9$
E	289.48	1.8207	0.1997	$\|\lambda_E\|^2 < 1.2 \times 10^{-2}$	$M_E > 9.3$
T_1	289.51	1.8208	0.0928	$\|\lambda_{T_1}\|^2 < 1.5 \times 10^{-1}$	$M_{T_1} > 2.6$
Q_7	289.52	1.8209	0.0893	$\|\lambda_{Q_7}\|^2 < 6.7 \times 10^{-2}$	$M_{Q_7} > 3.9$
T_2	289.52	1.8209	0.0010	$\|\lambda_{T_2}\|^2 < 9.2 \times 10^{-2}$	$M_{T_2} > 3.3$
φ	289.52	1.8209	0.0048	$Z_6 \cos\beta < 5.4 \times 10^{-1}$	$M_{\varphi} > 1.4$
D	289.52	1.8209	0.0315	$\|\lambda_D\|^2 < 2.8 \times 10^{-2}$	$M_D > 5.96$
U	289.52	1.8209	0.0343	$\|\lambda_U\|^2 < 3.4 \times 10^{-2}$	$M_U > 5.4$

- Better fit than SM
- Worse fit than SM

1 parameter fit can bound very high scales, depending on the operators generated.

Two parameter models

Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
Ξ_1	0	1	3	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
B	1	1	1	0	W	1	1	3	0

Real scalar SU(2) triplet, Y=1: $(\kappa_\Xi)_r \phi^\dagger \Xi^a_r \sigma^a \phi + (\lambda_\Xi)_{rs} \left(\Xi^a_r \Xi^a_s\right) \left(\phi^\dagger \phi\right)$

Vector-like quark doublet (top partner): $(\lambda^u_{Q_1})_{ri} \bar{Q}_{1Lr} \tilde{\phi} u_{Ri} + (\lambda^d_{Q_1})_{ri} \bar{Q}_{1Lr} \phi d_{Ri}$

Vector singlet: $(g^\phi_{\mathcal{B}})_r \mathcal{B}^\mu_r \phi^\dagger i D_\mu \phi + \text{h.c.}$

Vector SU(2) triplet: $\frac{1}{2}(g^\phi_{\mathcal{W}})_r \mathcal{W}^{\mu a}_r \phi^\dagger \sigma^a i D_\mu \phi + \text{h.c.}$

Higgs coupling only

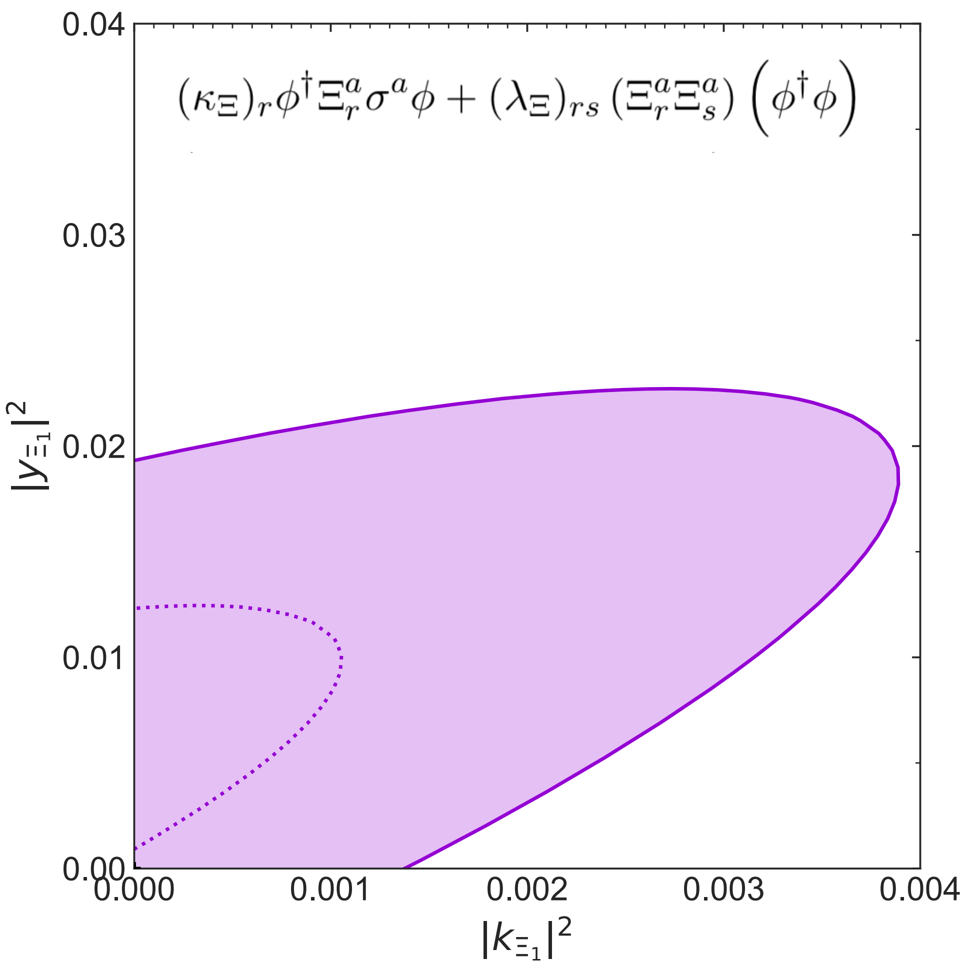
EWPO *hVV + Yukawa*

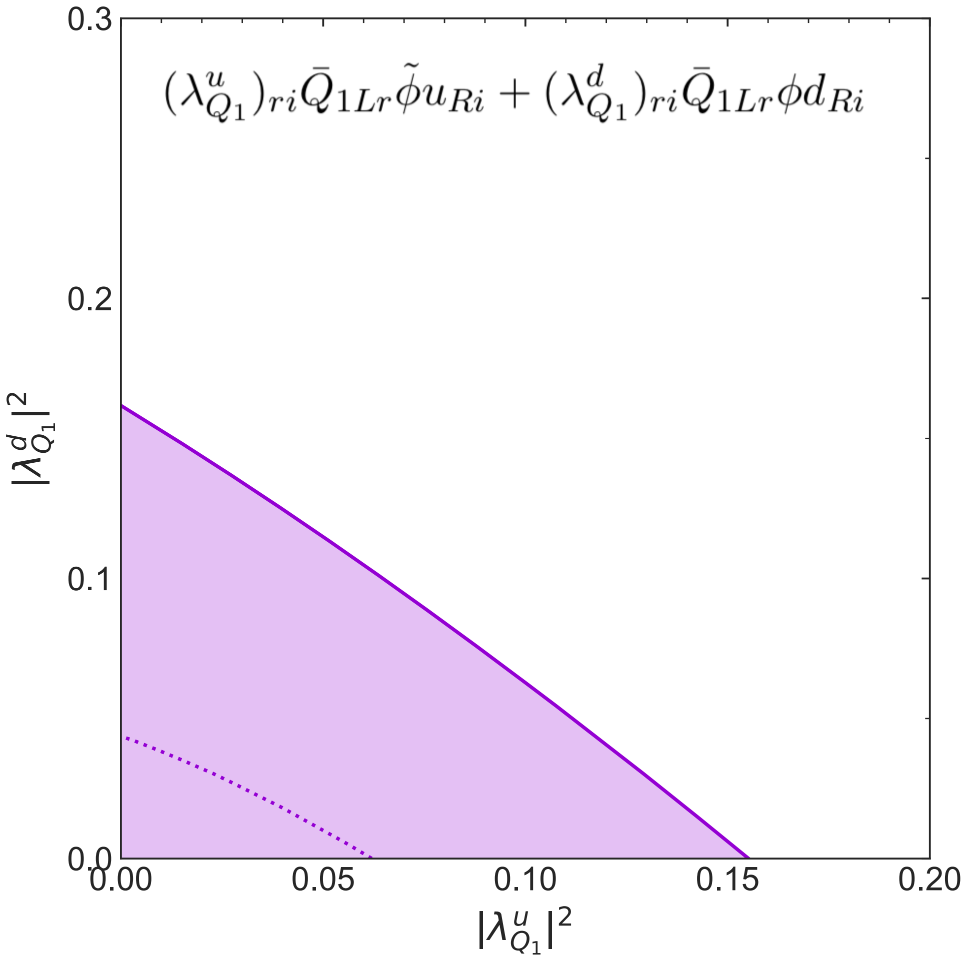
Model	C_{HD}	C_{ll}	C_{Hu}	C_{Hd}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
Ξ_1	$4a$	b	0	0	$2a$	$2ay_\tau$	$2ay_t$	$2ay_b$
Q_1	0	0	$-\frac{1}{2}a$	$\frac{1}{2}b$	0	0	$\frac{1}{2}ay_t$	$\frac{1}{2}by_b$
B	$-2a^2$	0	0	0	$-\frac{1}{2}(a^2-b^2)$	$-aby_\tau$	$-aby_t$	$-aby_b$
W	$\frac{1}{2}b^2$	0	0	0	$-\frac{1}{8}(3a^2+b^2)$	$-\frac{1}{4}y_\tau(a+b)^2$	$-\frac{1}{4}y_t(a+b)^2$	$-\frac{1}{4}y_b(a+b)^2$

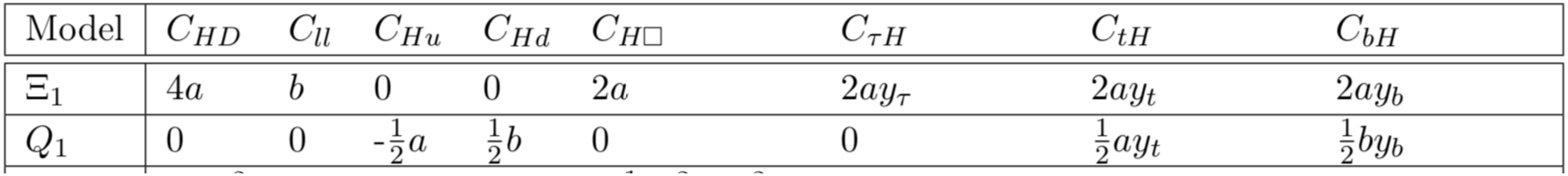
Two parameter models

Scalar triplet & Vector-like Quark doublet (universal)

- Mass = 1 TeV, mostly EWPO when universal





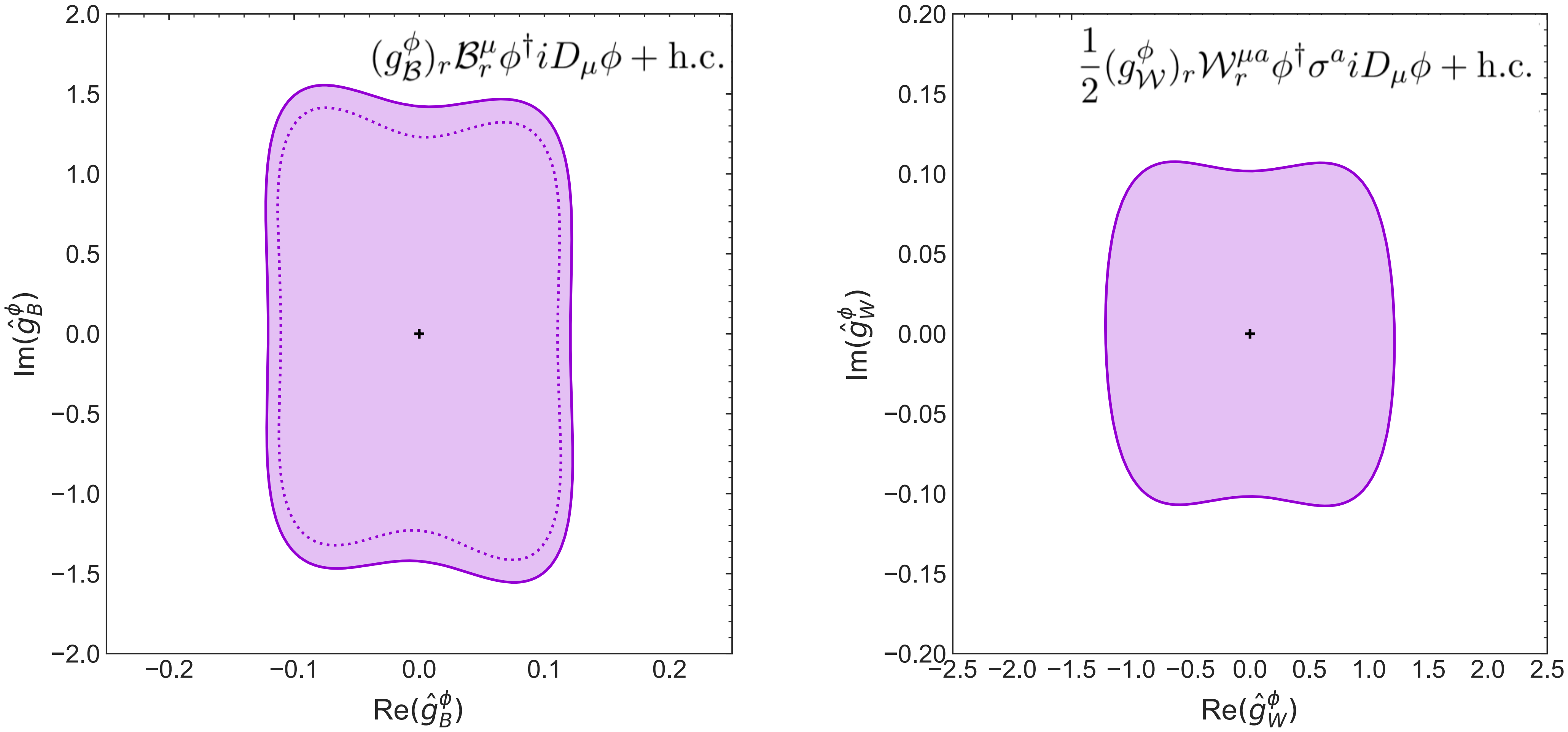


Model	C_{HD}	C_{ll}	C_{Hu}	C_{Hd}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
Ξ_1	$4a$	b	0	0	$2a$	$2ay_\tau$	$2ay_t$	$2ay_b$
Q_1	0	0	$-\frac{1}{2}a$	$\frac{1}{2}b$	0	0	$\frac{1}{2}ay_t$	$\frac{1}{2}by_b$

Two parameter models

Vector singlet and triplet coupled to the Higgs

- Mass = 1 TeV, EWPO + Higgs couplings



Model	C_{HD}	C_{ll}	C_{Hu}	C_{Hd}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
B	$-2a^2$	0	0	0	$-\frac{1}{2}(a^2-b^2)$	$-aby_{\tau}$	$-aby_t$	$-aby_b$
W	$\frac{1}{2}b^2$	0	0	0	$-\frac{1}{8}(3a^2+b^2)$	$-\frac{1}{4}y_{\tau}(a+b)^2$	$-\frac{1}{4}y_t(a+b)^2$	$-\frac{1}{4}y_b(a+b)^2$

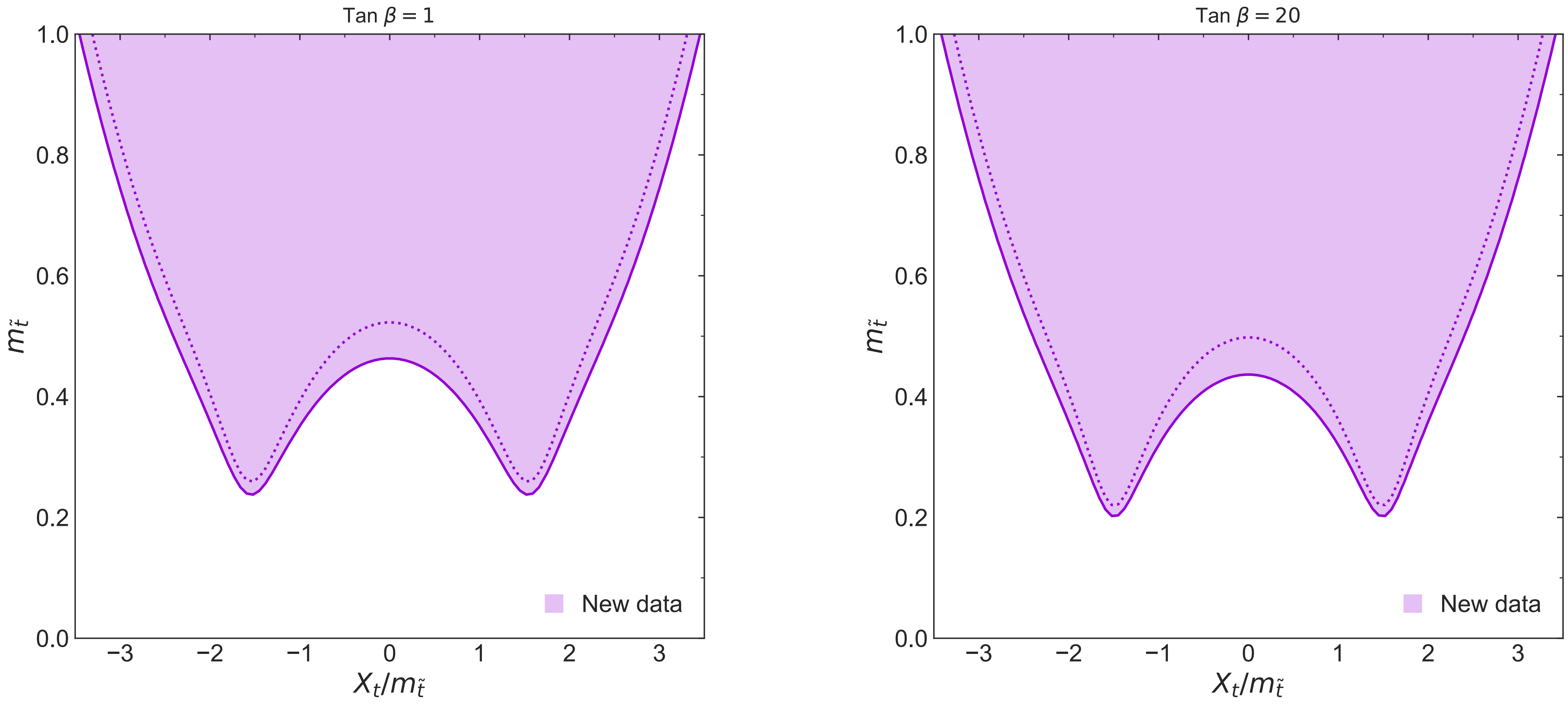
Two parameter models

MSSM stops using Universal One-Loop Effective Action

$$\mathcal{L}_{\mathrm{MSSM}} \supset \Phi^\dagger \left(-D^2 - M^2 - U\right)\Phi \qquad M^2 = \begin{pmatrix} m^2_{\tilde{Q}_3} & 0 \\ 0 & m^2_{\tilde{t}_R} \end{pmatrix}$$

$$U = \begin{pmatrix} \left(y_t^2 s_\beta^2 + \frac{1}{2}g^2 c_\beta^2\right)\tilde{H}\tilde{H}^\dagger + \frac{1}{2}g^2 s_\beta^2 H H^\dagger - \frac{1}{2}\left(g'^2 Y_Q c_{2\beta} + \frac{1}{2}g^2\right)|H|^2 & y_t s_\beta X_t \tilde{H} \\ y_t s_\beta X_t \tilde{H}^\dagger & \left(y_t^2 s_\beta^2 - \frac{1}{2}g'^2 Y_{t_r} c_{2\beta}\right)|H|^2 \end{pmatrix}$$

- Constraint dominated by ggF operator



Next steps for BSM via EFT

Target more realistic, multi-particle models

- Connected to solving real problems with the SM

Quantify validity of the EFT expansion

- How well does the EFT approximate the underlying model?

  Given the sensitivity that we obtain

- Are higher dimension (> 6) operators important?

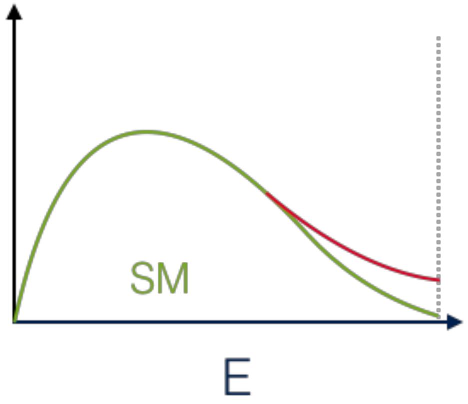
  Is (dim-8 x SM) comparable to (dim-6)^2?

- Can some of the mass range be probed by direct searches?
- How strongly coupled must it be to retain EFT validity?

Need to develop a systematic approach to these questions

- Quantify the indirect reach of the LHC to real models via EFT

Energy growth



Higher dimensional operators mean energy growth

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.

Outlines a systematically improvable process for improving our understanding of the D>4 parameters of the SM

Slightly complicated by interference structure w/ A_{SM}

- Cross sections contain terms up to order $1/\Lambda^4$
- Different energy growth/symmetries can mix the hierarchy in EFT expansion
- Dim-8 operators generally not studied

High energy & multiplicity

How can we improve with increasing statistics?

- Target energy growth (energy helps accuracy)

more differential
higher multiplicity

Dim-6 operators don't guarantee energy growth

Operator contribution to a given process:

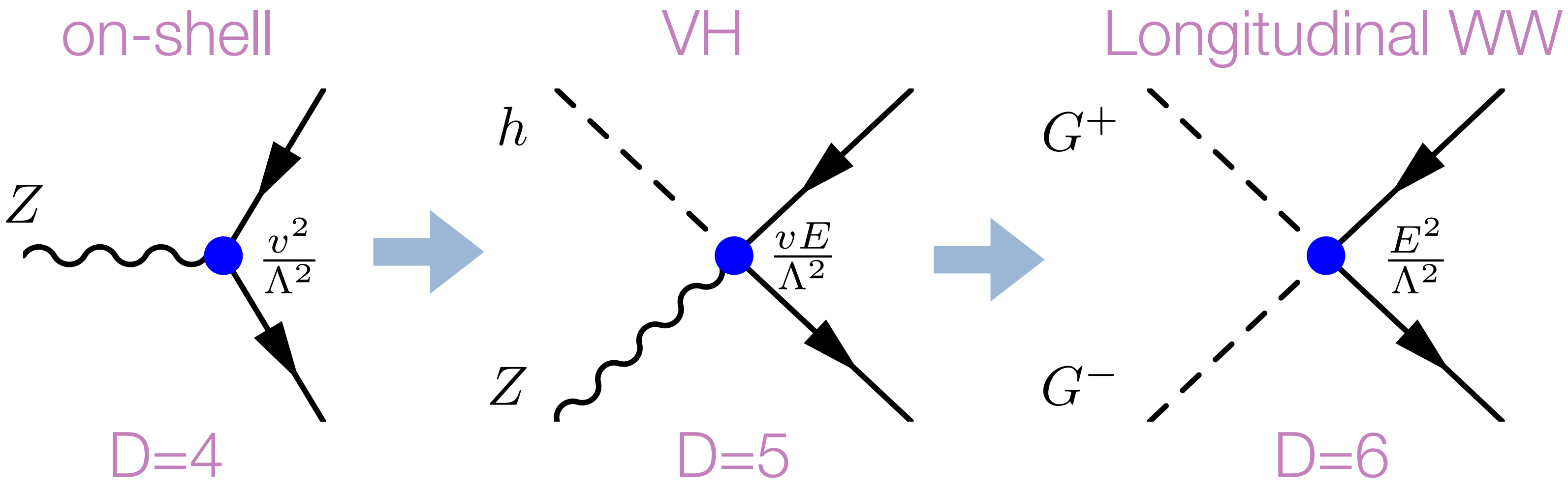
(a) **May not** grow maximally with energy (E^2)

(b) 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

$$(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{f}_i \gamma^\mu f_j)$$



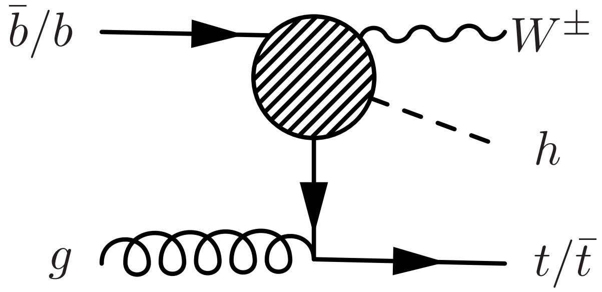
SM
interference

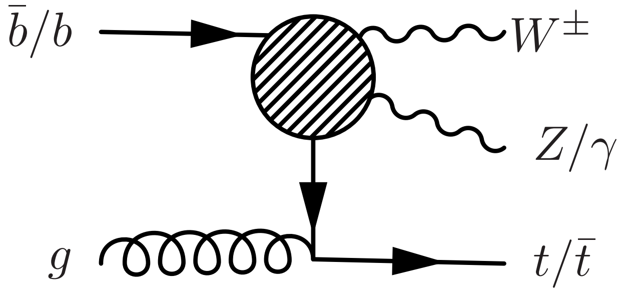
High energy & multiplicity

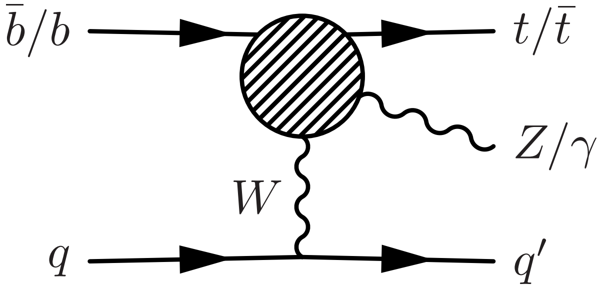
[Maltoni, Mantani, KM; JHEP 10 (2019) 004]

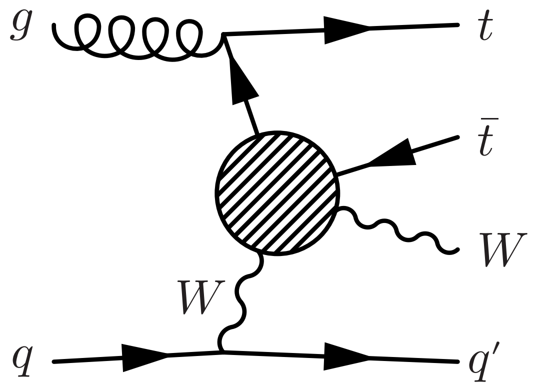
Top-EW couplings: rare top production

- Processes that embed high-energy EW top scattering





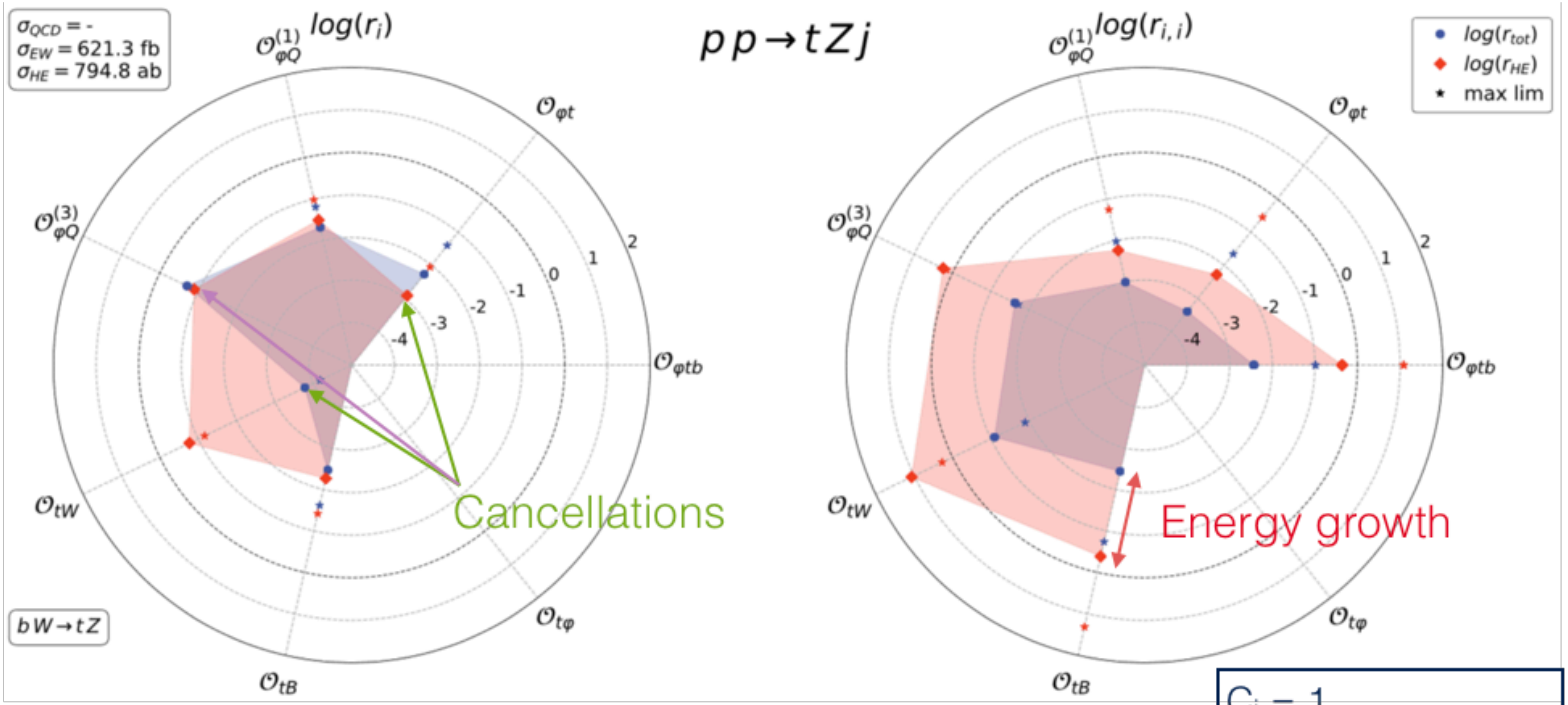




High energy & multiplicity

[Maltoni, Mantani, KM; JHEP 10 (2019) 004]

Top-EW couplings: rare top production



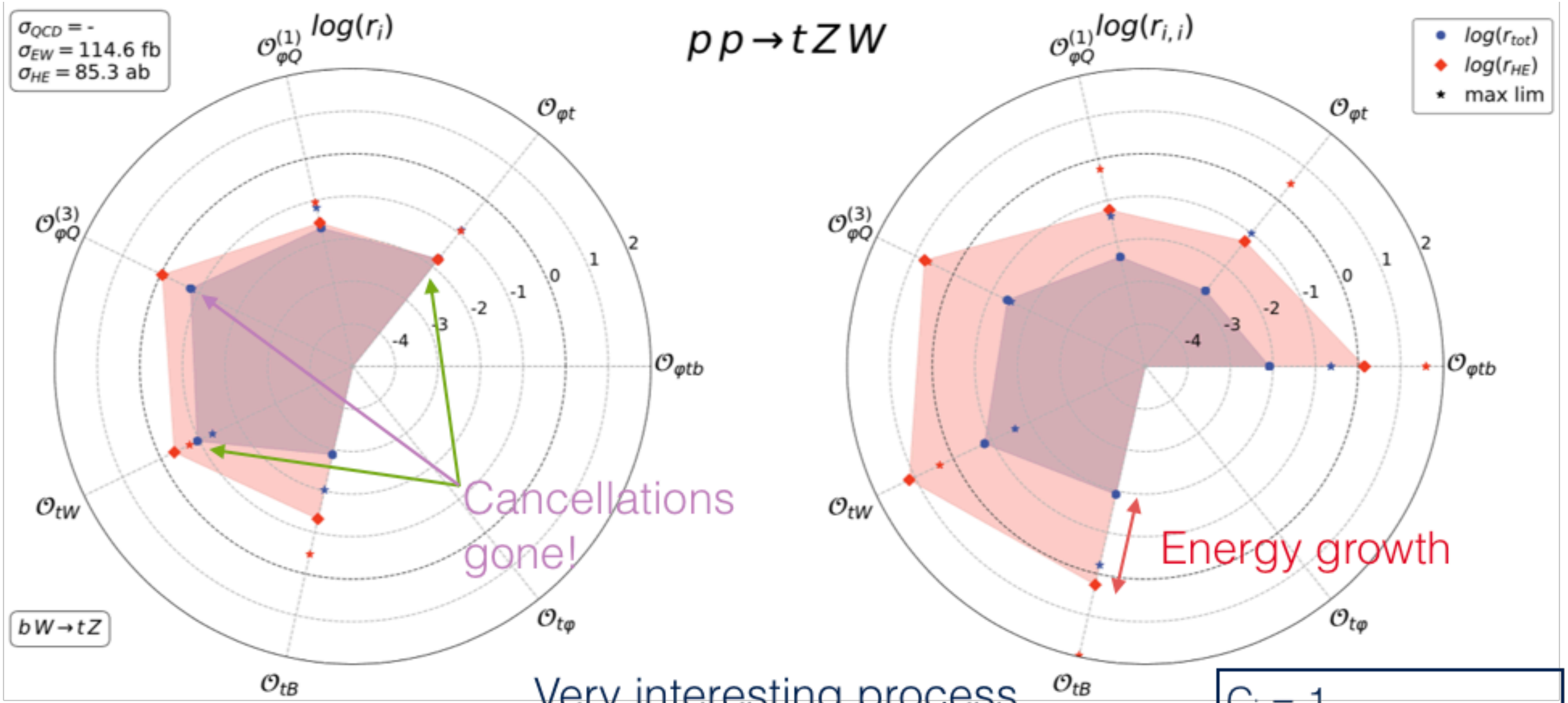
C_i = 1
Inclusive
p_T (Z)> 500 GeV

Expected growth from 2→2 absent!

High energy & multiplicity

[Maltoni, Mantani, KM; JHEP 10 (2019) 004]

Top-EW couplings: rare top production



Cancellations gone!

Energy growth

Expected growth is there!

Very interesting process that should be measured at the LHC

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

High energy & multiplicity

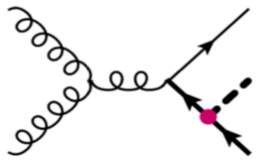
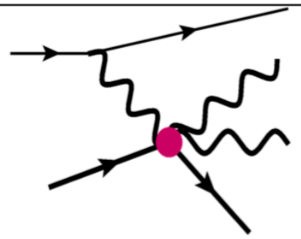
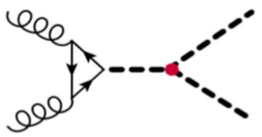
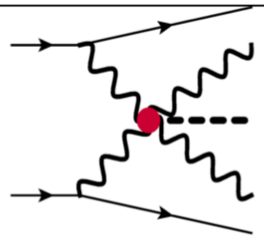
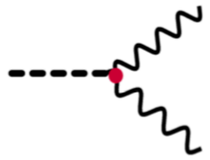
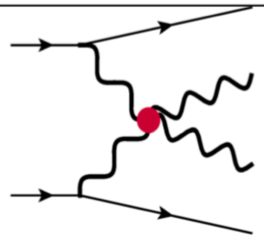
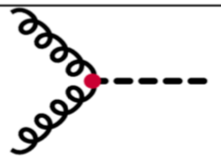
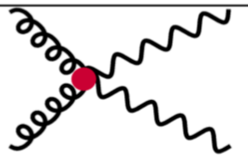
[Henning et al.; PRL 123 (2019), no.18 181801]

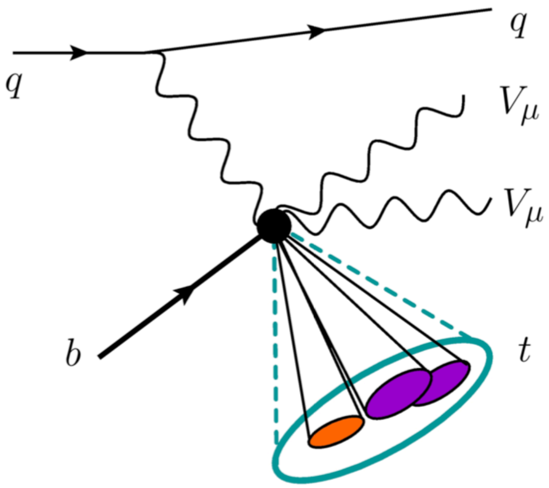
Higgs couplings… without the Higgs

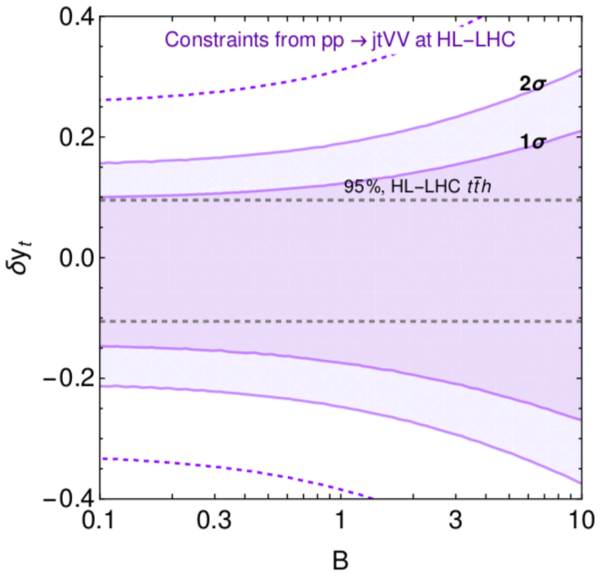
$$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_6 = |H|^6$$

- Operators that affect Higgs signal strengths contain

$$|H|^2 = \frac{1}{2}\left(v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2\right)$$

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





Modified EWSB sector interactions

Energy growth in high-multiplicity final states of Higgs, top & longitudinal gauge bosons

Promising avenue for the future

Conclusions

SMEFT is truly well established in the HEP community

- On the path to measuring the SM parameters up to dimension-6
- Extend the reach of the LHC beyond nominal energy
- Multi-TeV scale within reach, next step: more realistic models

Much work to do towards the global SMEFT likelihood

- Precision tools available & will be used in next generation of ananlyses

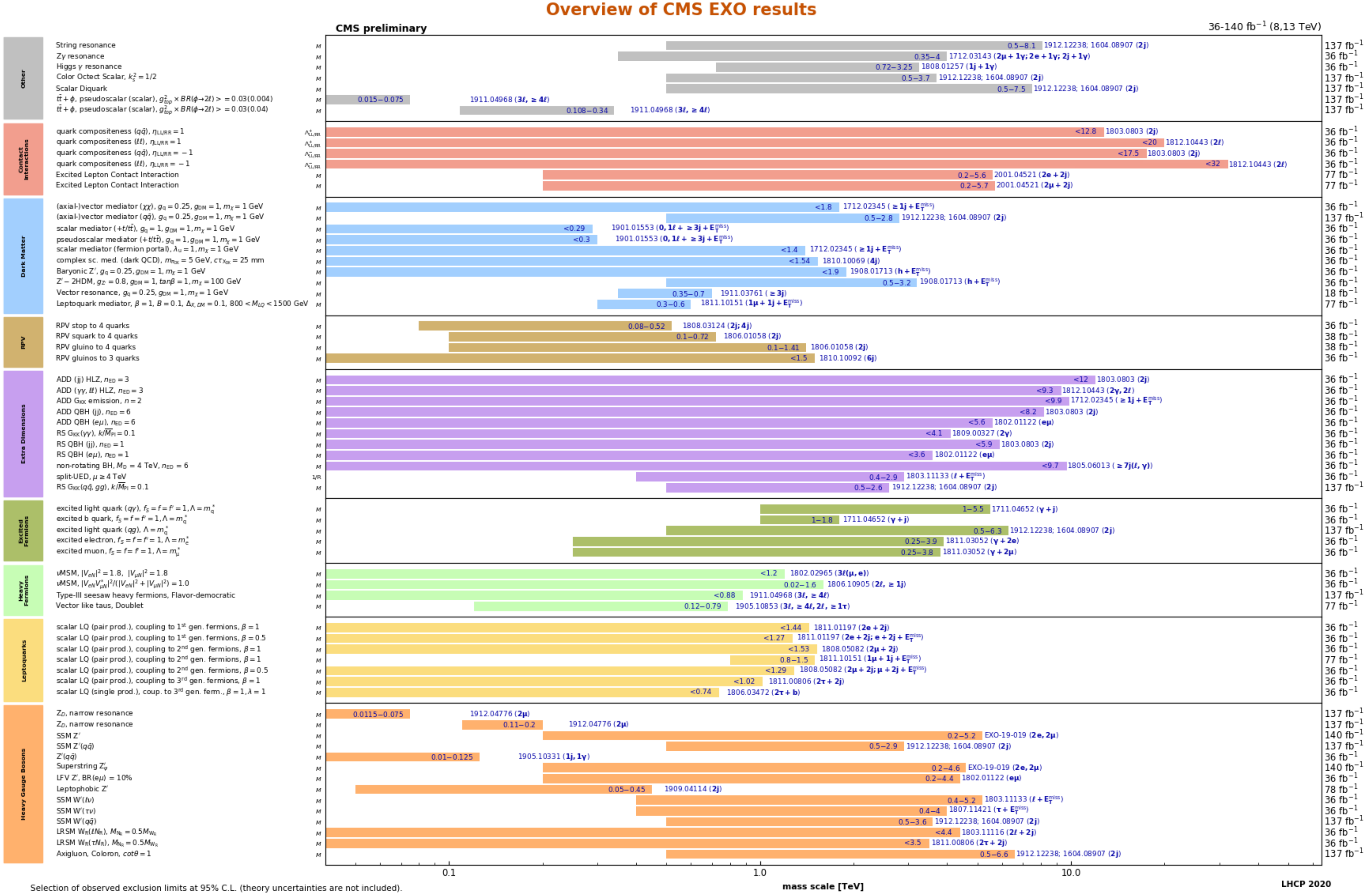
Presented some results of an ongoing top/EW/Higgs fit

- Interesting interplay between Higgs production & top data
- EW precision measurements help to constrain top quark operators
- Map to simplified models can yield multi-TeV sensitivity
- Will publish code & data for fit/plots (python)

High energy & multiplicity lays a roadmap for the future

Thank you

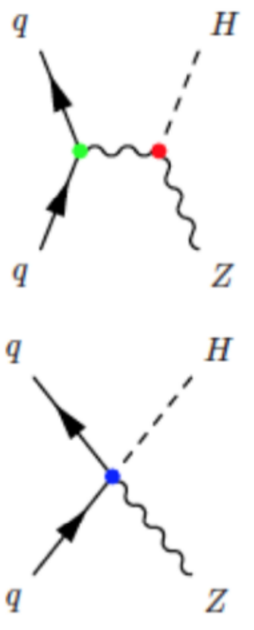
CMS exotic summary

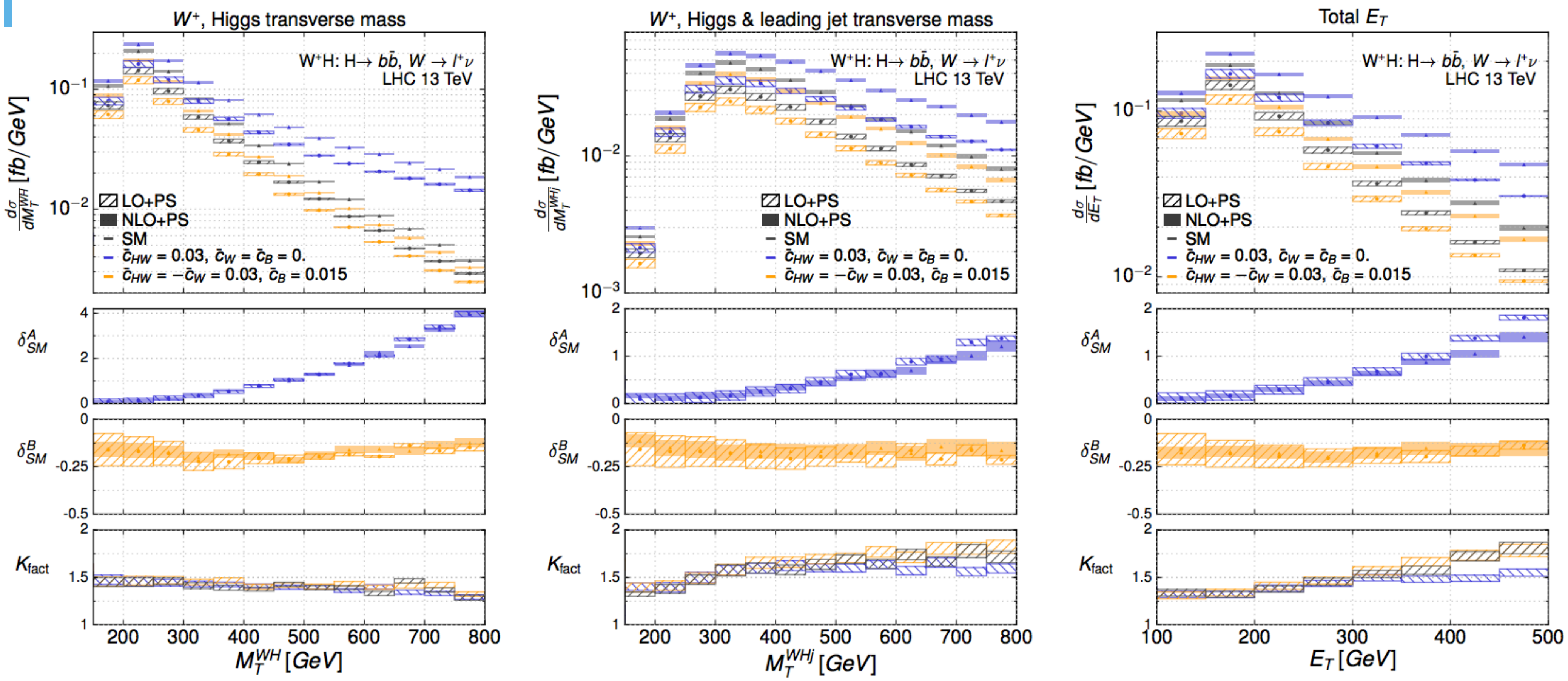


pp → VH

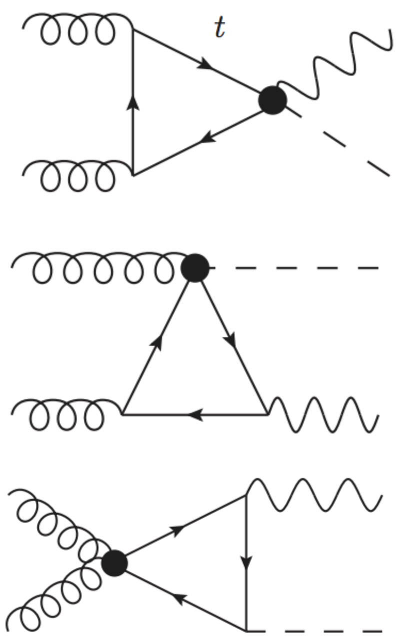
[Degrande, et al.; EPJC 77 (2017) 4, 262]

Quark-initiated



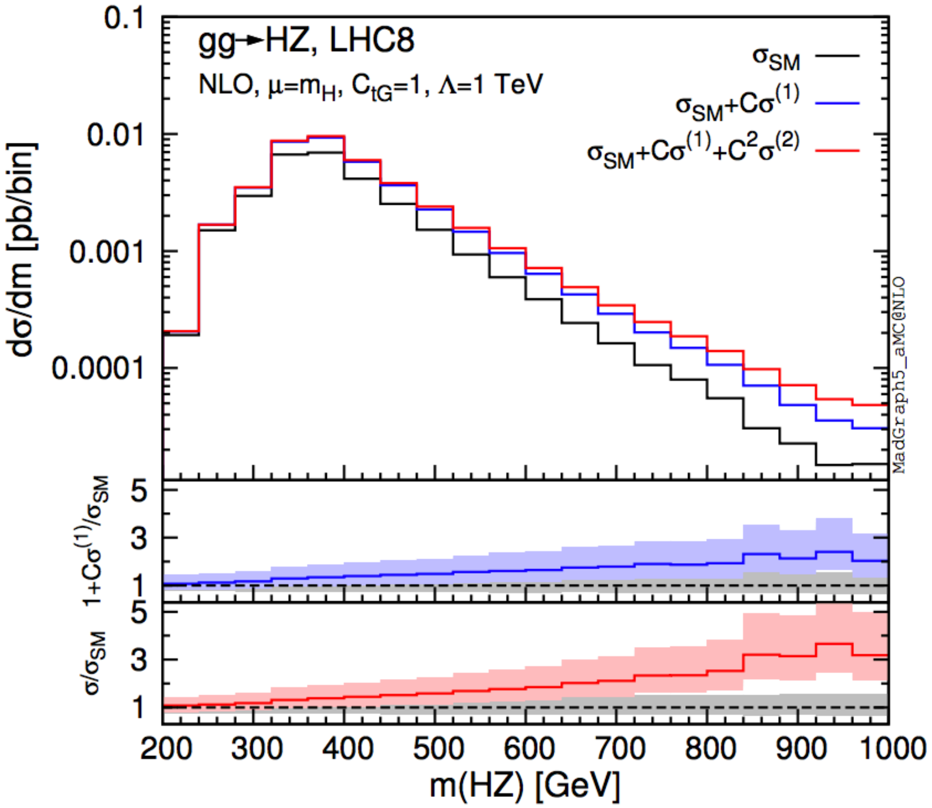


gg, loop-induced



[Bylund et al.; JHEP 1605 (2016) 052]

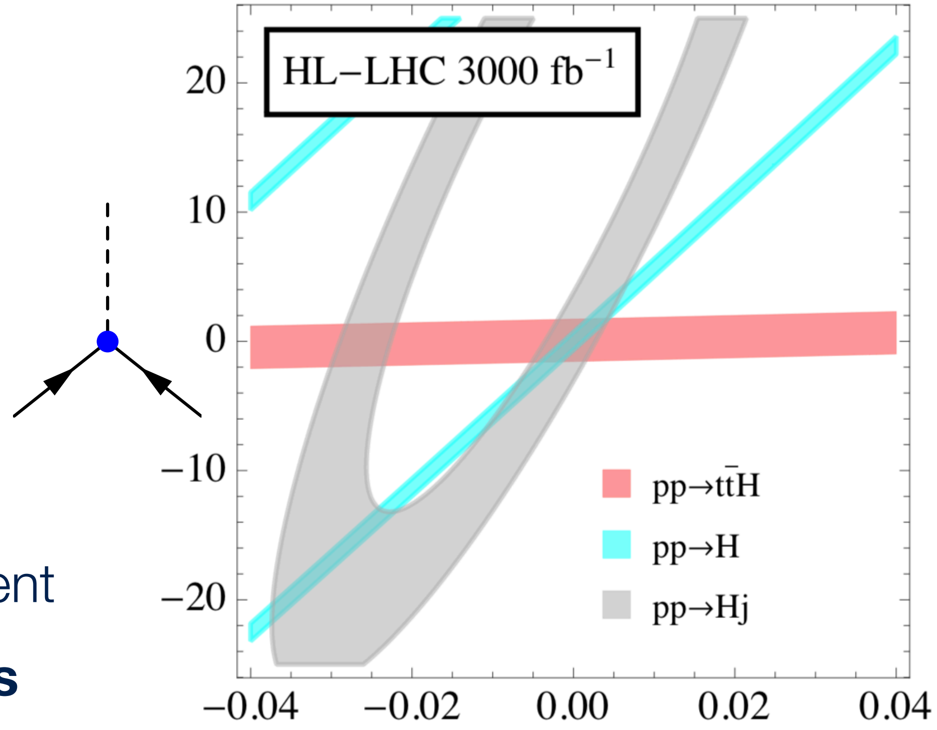
[fb]	SM		$\mathcal{O}_{tG}$	$\mathcal{O}^{(1)}_{\phi Q}$
8TeV	$29.15^{+40.0\%}_{-26.6\%}$	$\sigma_i^{(1)}$	$10.37^{+41.3\%}_{-27.2\%}$	$1.719^{+42.5\%}_{-27.6\%}$
		$\sigma_i^{(2)}$	$1.621^{+45.1\%}_{-28.7\%}$	$0.0469^{+46.5\%}_{-29.2\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.356^{+0.9\%}_{-0.8\%}$	$0.0590^{+1.8\%}_{-1.4\%}$
		$\sigma_i^{(2)}/\sigma_i^{(1)}$	$0.156^{+2.6\%}_{-2.0\%}$	$0.0273^{+2.8\%}_{-2.3\%}$
13TeV	$93.6^{+34.3\%}_{-23.8\%}$	$\sigma_i^{(1)}$	$34.6^{+35.2\%}_{-24.5\%}$	$5.91^{+36.4\%}_{-24.9\%}$
		$\sigma_i^{(2)}$	$6.09^{+39.2\%}_{-26.1\%}$	$0.182^{+40.2\%}_{-26.6\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.370^{+0.7\%}_{-0.9\%}$	$0.0631^{+1.6\%}_{-1.5\%}$
		$\sigma_i^{(2)}/\sigma_i^{(1)}$	$0.176^{+2.9\%}_{-2.1\%}$	$0.0309^{+2.8\%}_{-2.2\%}$



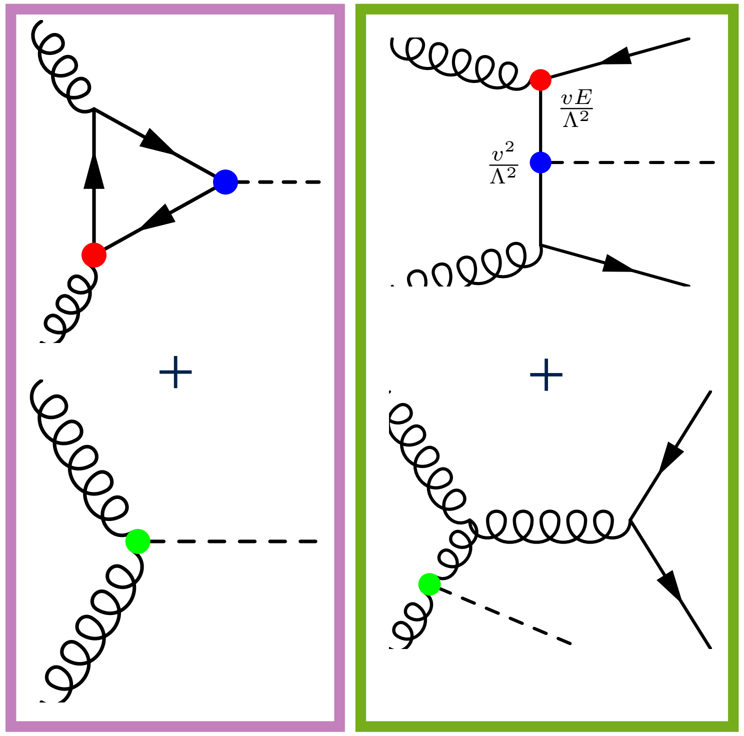
SMEFT

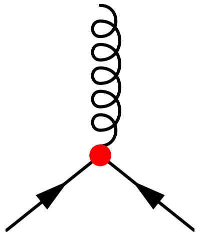
[Maltoni, Vryonidou & Zhang; JHEP 10 (2016) 123]
[Azatov, Grojean, Paul & Salvioni; JHEP 09 (2016) 123]

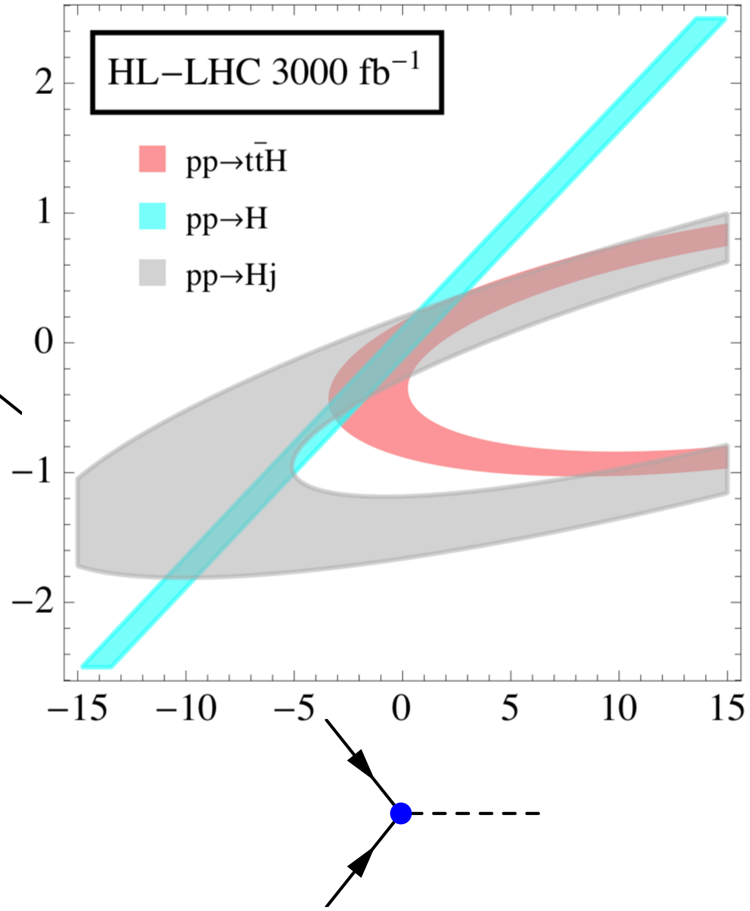
Direct ttH measurement breaks **degeneracy** among y_t, ggH and dipole in gg-fusion

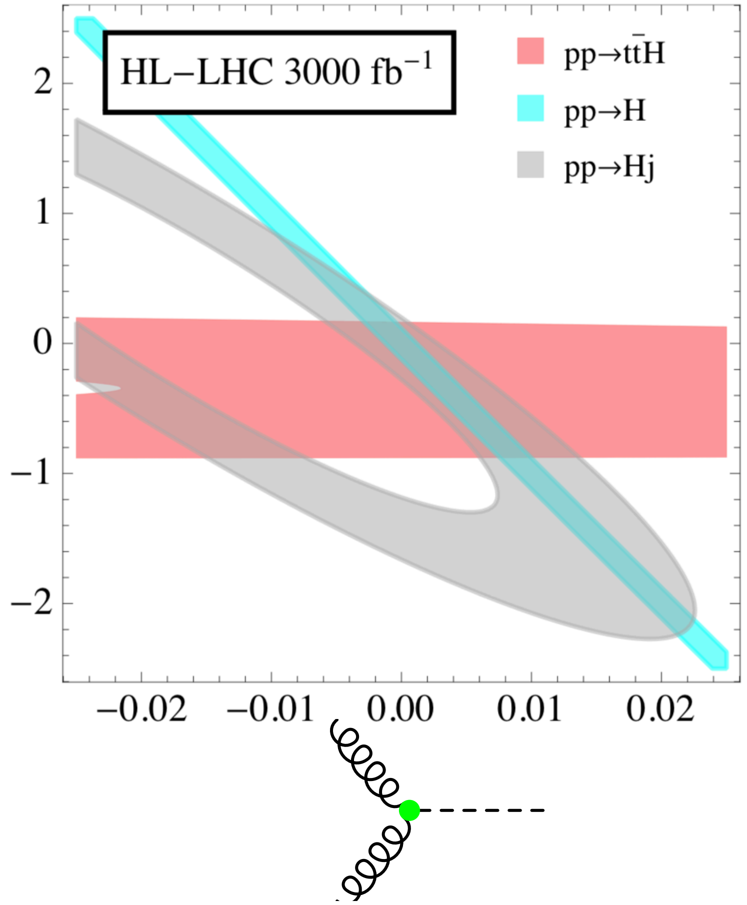


Single measurement
=
Blind directions









Pin down heavy coloured particles in the loop

Higher orders in Λ

[Li et al.; 2005.00008] & [Murphy; arXiv: 2005.00059]

EFTs are systematically improvable in 1/Λ

- Dimension-6 is the LO for baryon/lepton number conserving operators

Important to think about possible dim-8 effects

- Theoretical uncertainties / validity of the EFT expansion
- Some measurements are dominated by quadratic dim-6 effects ($1/\Lambda^4$)
- Small/no interference due to symmetry, helicity selection, color structure,…

Operator counting known to arbitrary dimensions

2, 84, 30, $\boxed{993}$, 560, 15456, 11962, 261485, . . .: higher dimension operators in the SM EFT

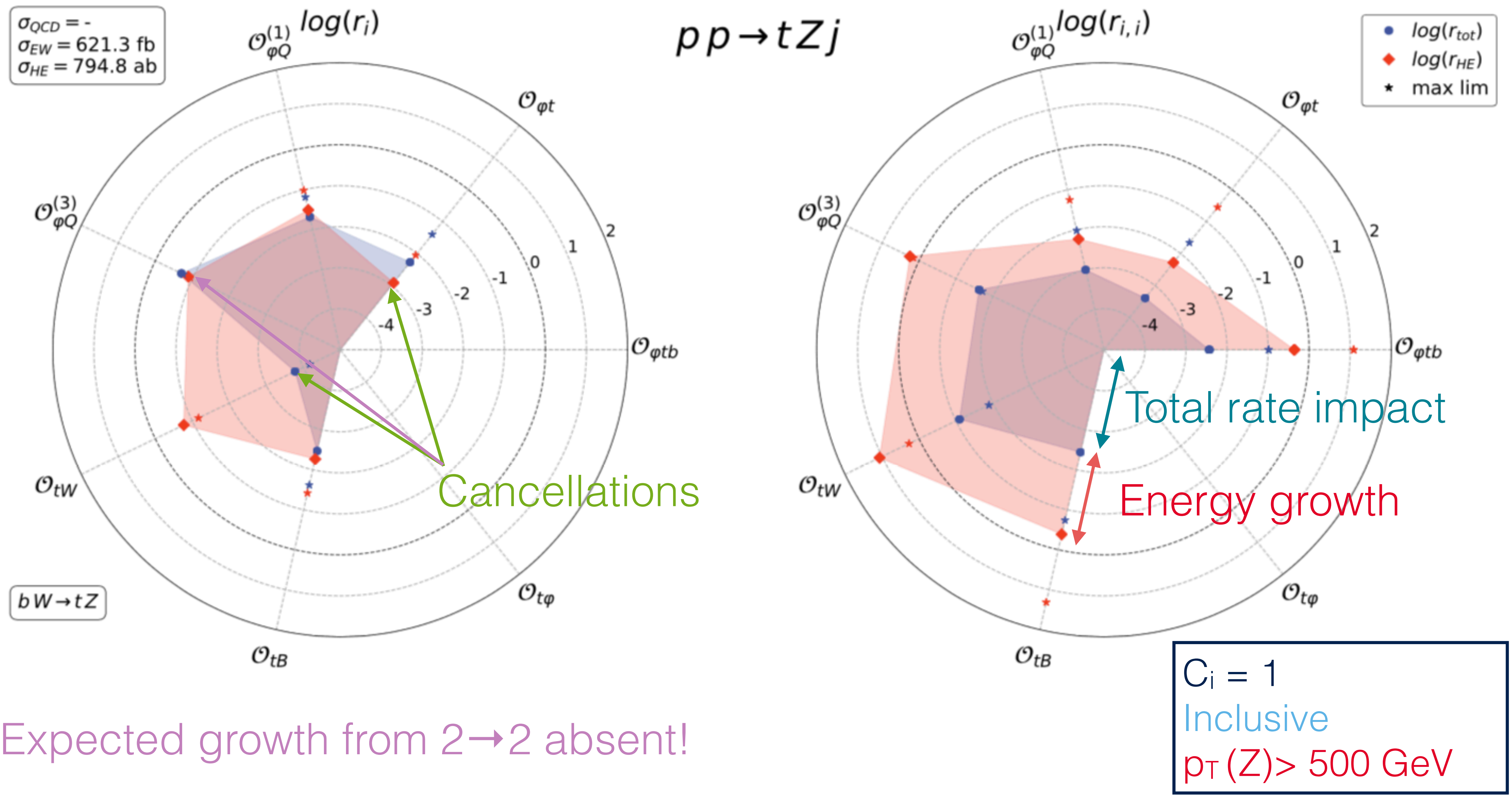
[Henning et al.; JHEP 08 (2017) 016]
[Lehman & Martin; JHEP 02 (2016) 081]

New result: complete dimension 8 basis written down

- 44807 operators encoded in 1029 Lagrangian terms
- Paves the way for more exploratory studies of importance & unique pheno

First-principles positivity constraints applicable (e.g. VBS)

tZj total & high energy xs



interference/SM

square/SM

Cancellations

Total rate impact

Energy growth

C_i = 1

Inclusive

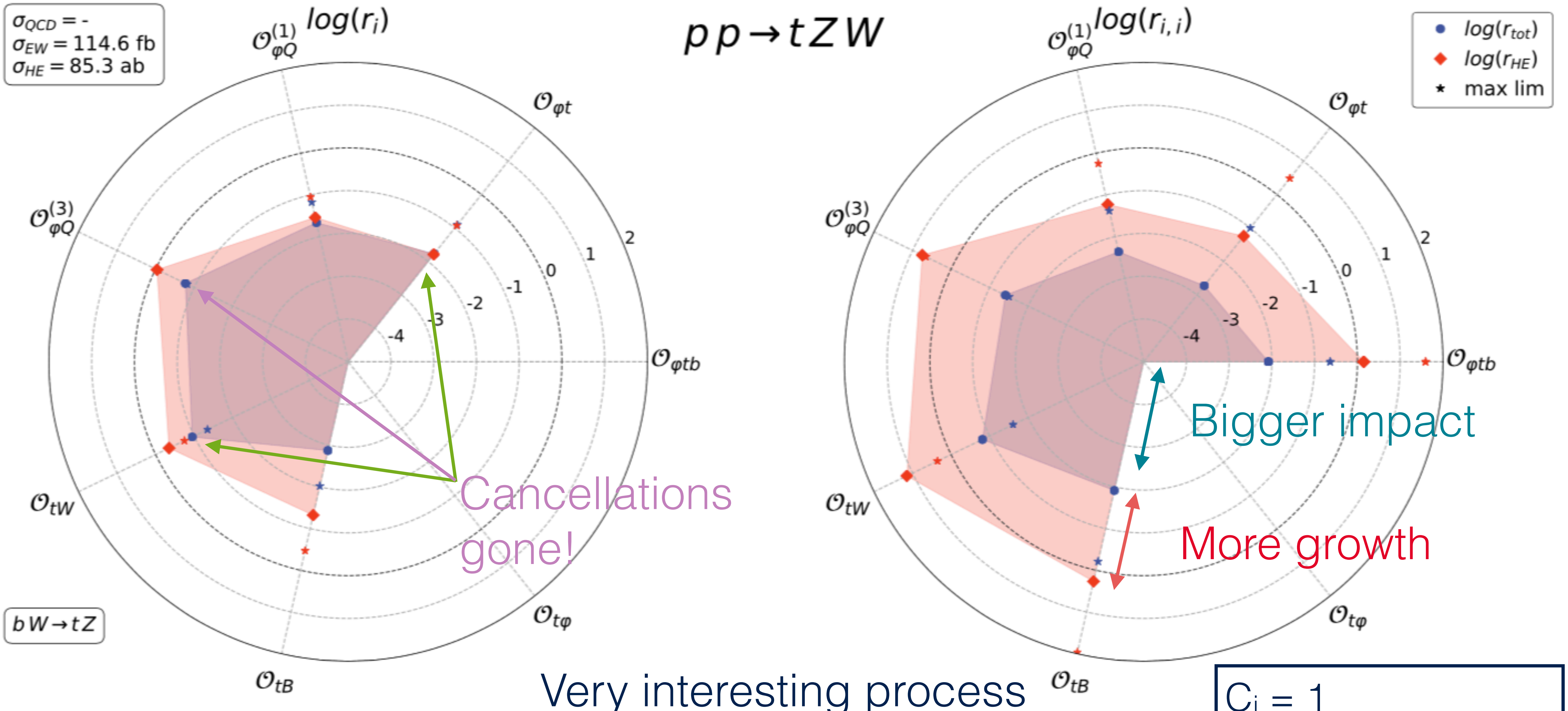
p_T (Z)> 500 GeV

Expected growth from 2→2 absent!

tZW total & high energy xs

interference/SM

square/SM



Cancellations gone!

Bigger impact

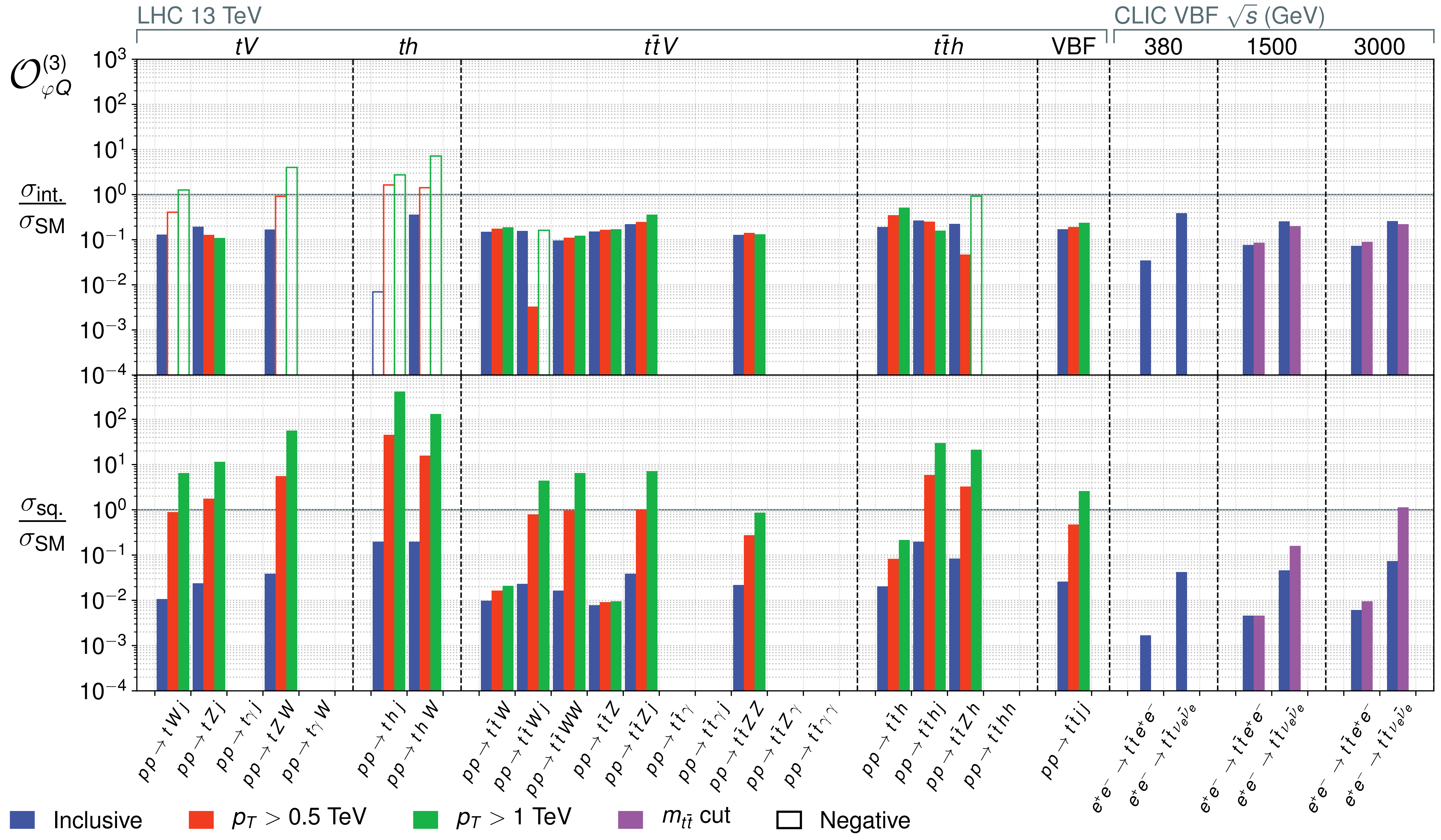
More growth

Expected growth is there!

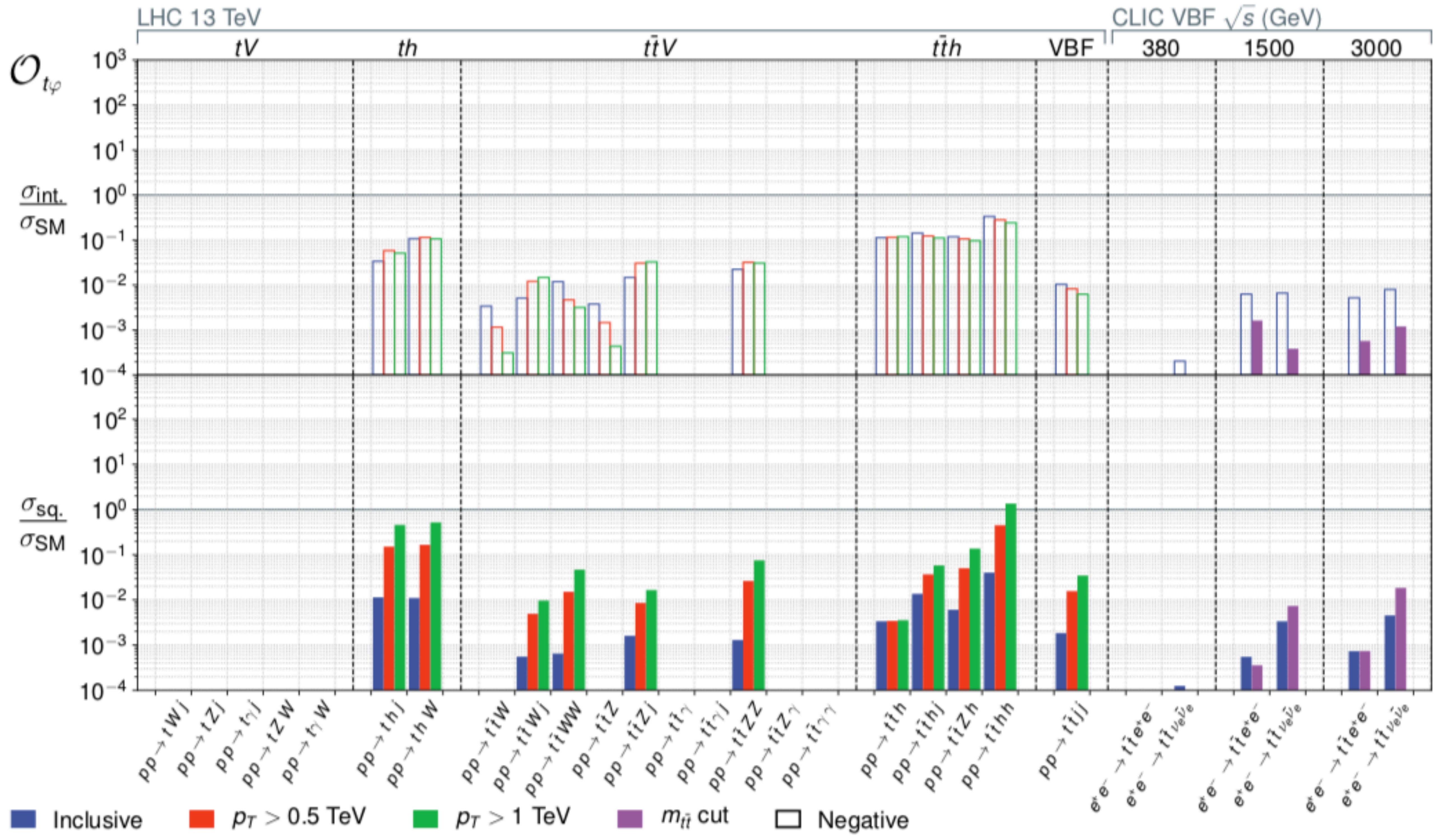
Very interesting process that should be measured at the LHC/FCC

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

Charged current operator



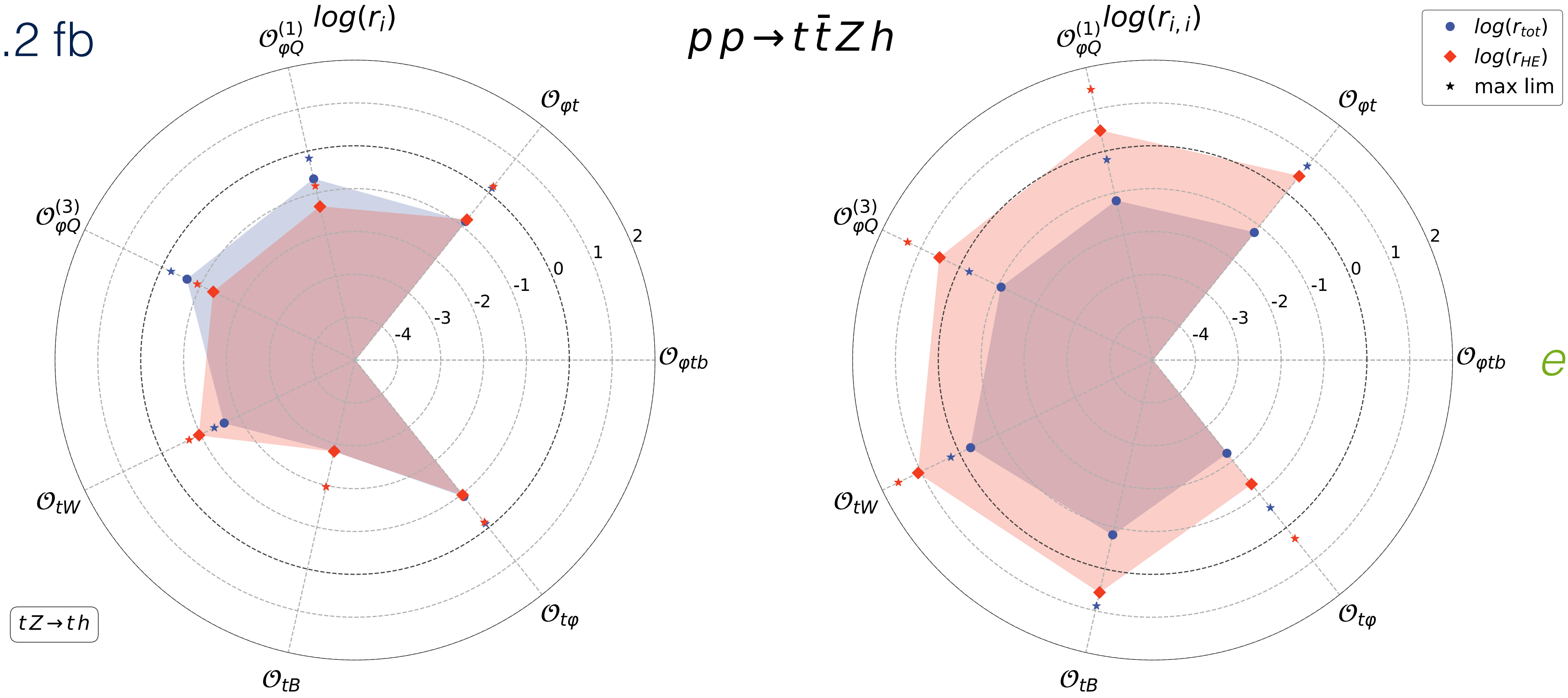
Yukawa operator



ttZh: LHC vs FCC-hh

High energy: $p_T(Z,h) > 500$ GeV

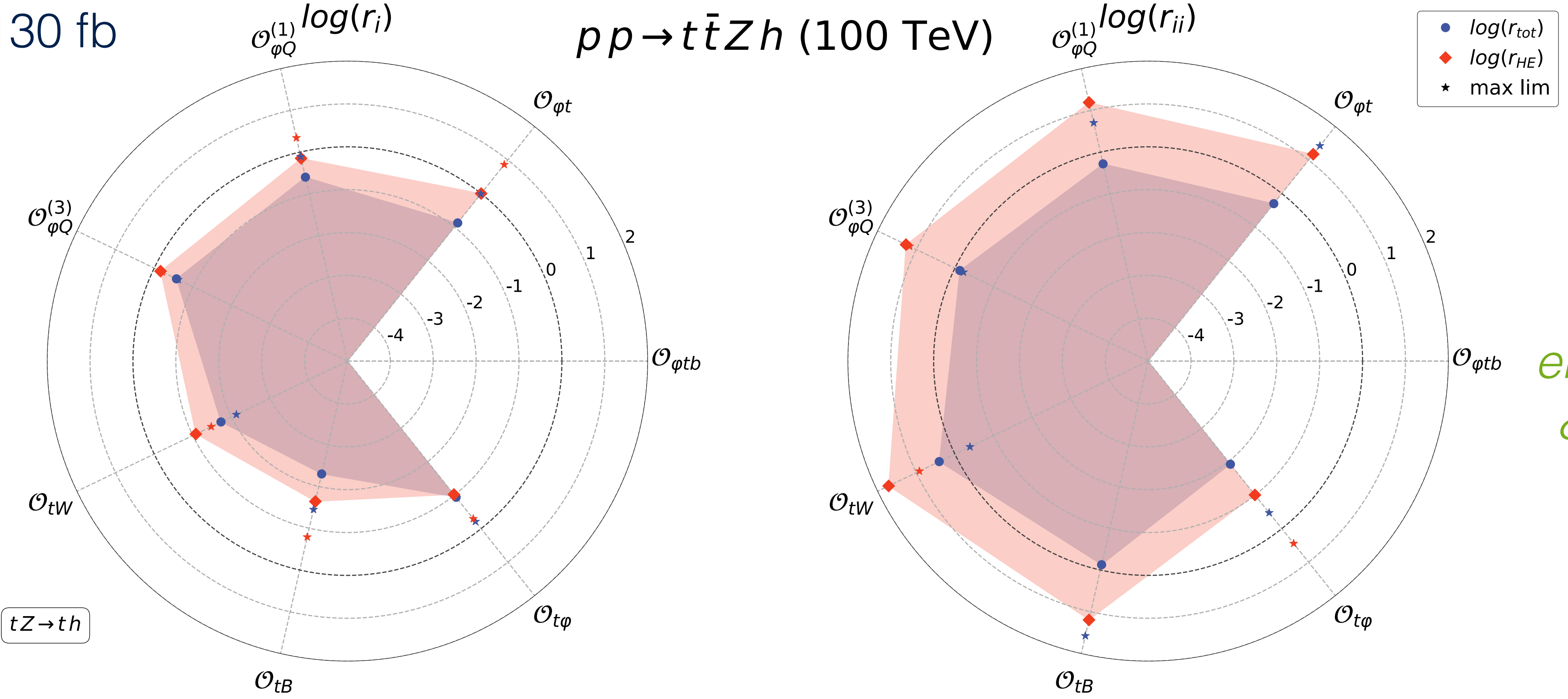
σ_{13} = 1.2 fb



Interference: phase space cancellations

Quadratic: energy growth & O(1-10)

σ_{100} = 130 fb



Interference: energy growth & O(1) effects

Quadratic: energy growth & O(10-100)