Discovery through effective field theory interpretations at the LHC

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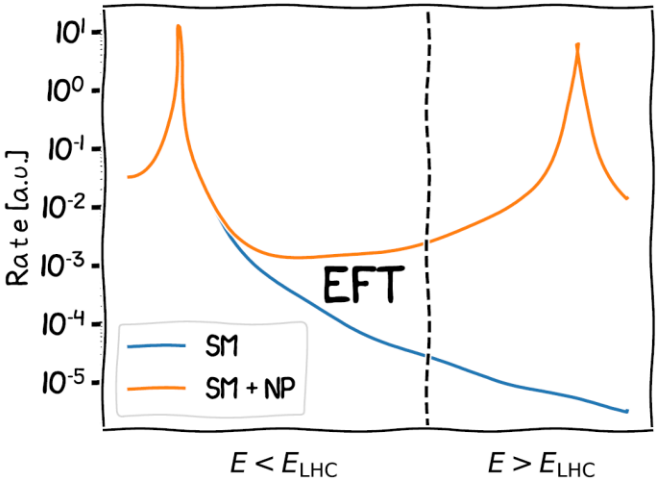
27th June 2025

IC Seminar

Introduction

- At the LHC, we probe energies (q^2) up to $O(\mathrm{TeV})$ scale
- If the mass of a new particle (Λ) is $\gg q^2$, we will not be able to discover it directly (mass bump)
- But at lower energies, indirect (off-shell) effects may still be measurable
  → alternative and complementary way (possibly the only way!) to find NP
- Indirect effects can be approximated by the SM effective field theory (SMEFT):



$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{4} + \sum_{i,d} \frac{C_i^d}{\Lambda^{d-4}} Q_i^d$$

Wilson coefficients (WC) encode the size of new contributions

Operators encode the type of new physics

d = dimension
i iterates over all possible operators

- All possible operators* up to a particular order are considered → model-independent approach
- Expect the new contributions to manifest as small deviations in SM measurements
  → measure Wilson coefficients by reinterpreting SM measurements
- A non-zero measurement of a Wilson coefficient → indication of new physics 🎉
- In this talk, will focus on details relevant to LHC and Higgs physics

Outline

1. The theory behind effective field theories – an experimentalist's perspective
    1. Low energy approximation of the weak interaction – Fermi theory
    2. What are higher-dimensional operators?
    3. What new physics can they lead to?

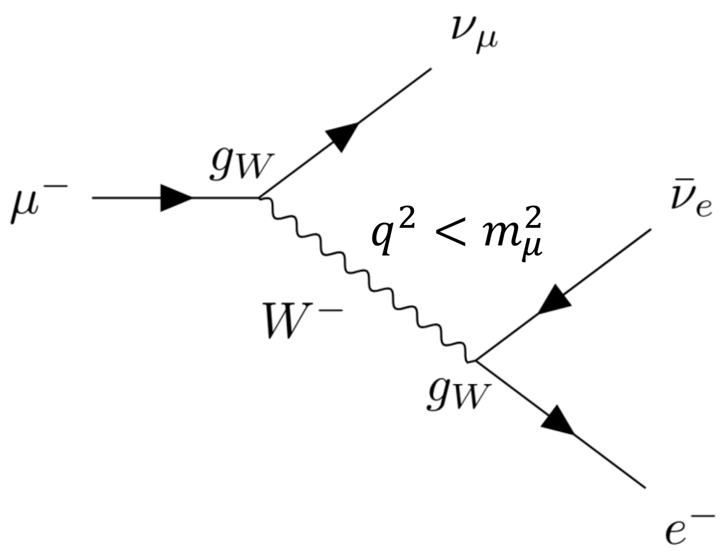
2. Recent measurements and SMEFT interpretations from CMS
    1. Combination of STXS Higgs boson measurements
    2. First steps towards a global fit: Higgs, EW, top, multi-jet
    3. Differential fiducial measurements

3. What are the challenges/open questions?
    1. Acceptance corrections
    2. EFT expansion cut-off
    3. More…

4. Outlook towards a global EFT fit with the High-Luminosity LHC

Muon decay & Fermi's interaction

- Muon decay: $\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$, is a weak process involving the exchange of a W boson
- But the decay is described well by Fermi theory which does not contain the W boson, how?



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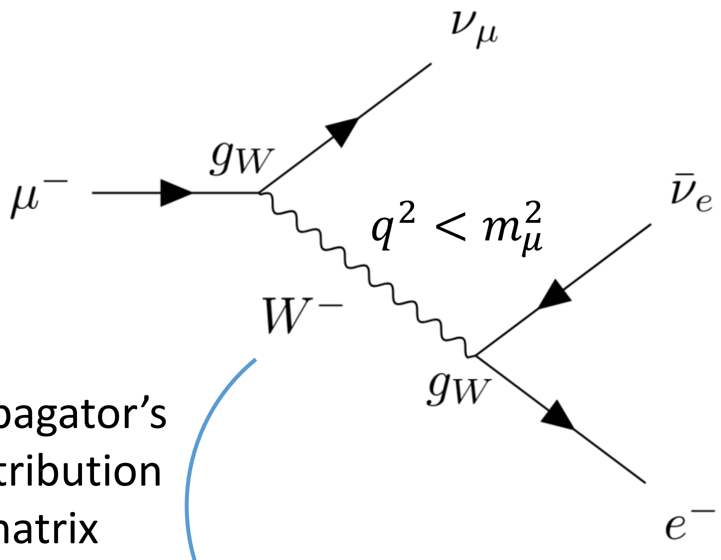

Propagator's contribution to matrix element

$$M = -i \frac{g_{\mu\nu} - \frac{q_\mu q_\nu}{m_W^2}}{q^2 - m_W^2 + i m_W \Gamma_W} \times \cdots$$

$m_\mu = 106 \text{ MeV},\ m_W = 80.4 \text{ GeV},\ \Gamma_W = 2.1 \text{ GeV}$

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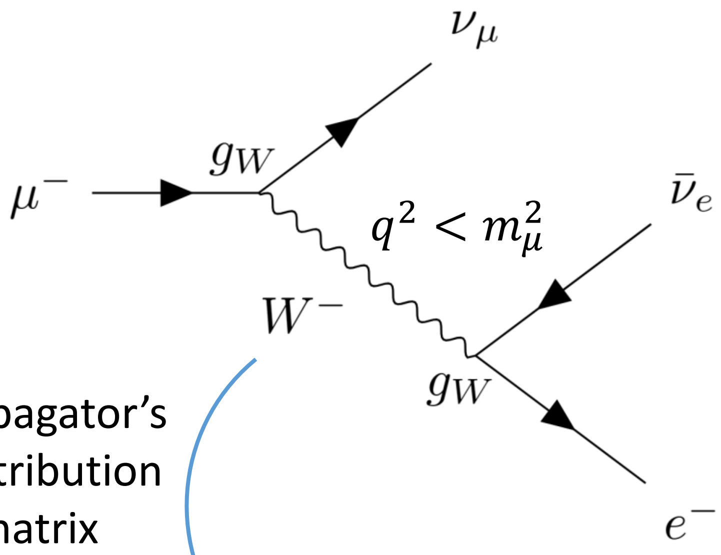

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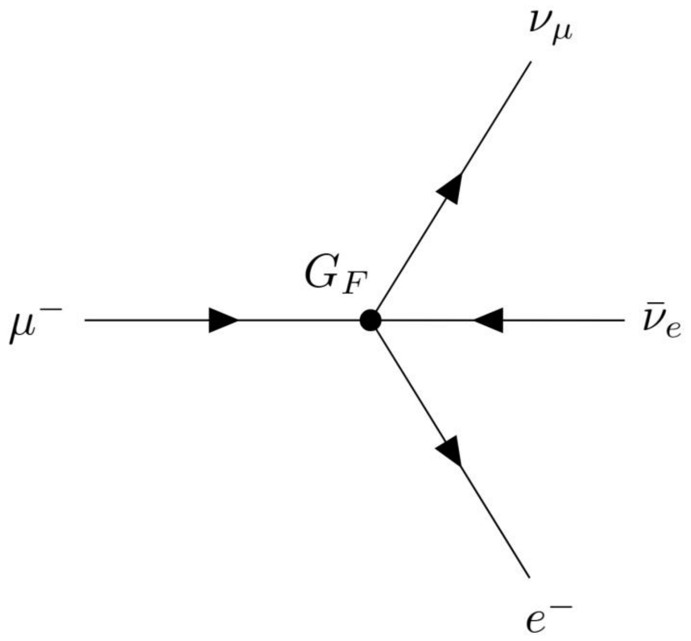

Now we have a four-point vertex that has a coupling, G_F

$$G_F = \frac{1}{4\sqrt{2}} \frac{g_W^2}{m_W^2}$$

Combines the g_W from each 3-point vertex and the $1/m_W^2$ from the propagator

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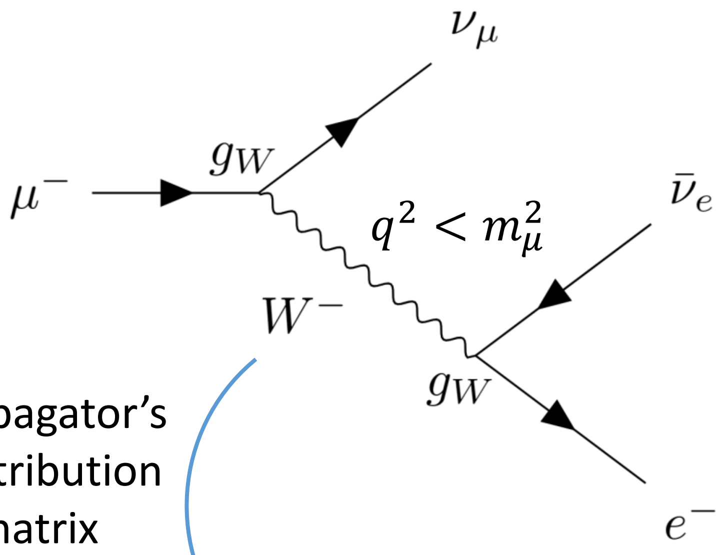

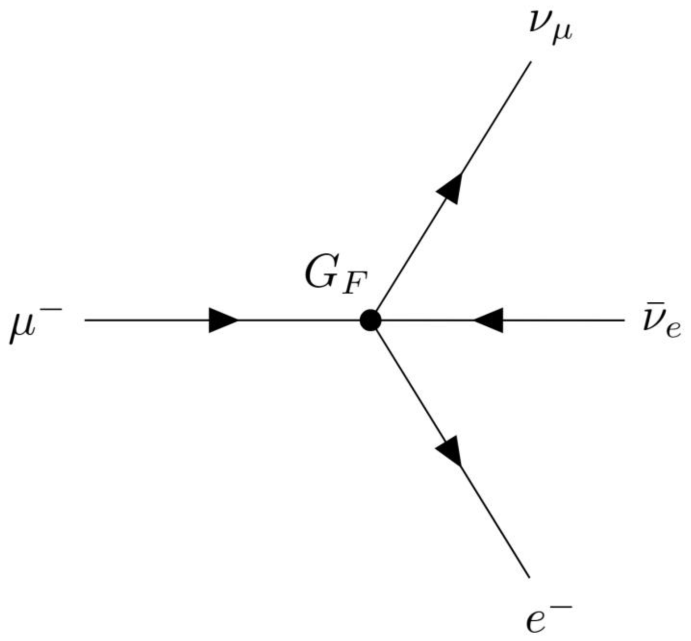

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In EFTs, we measure relationships between the NP coupling and mass

The Lagrangian perspective

$$\mathcal{L}_{SM} = \sum_{f\in\{e,\mu\}} \bar{l}_L^f i\gamma^\mu D_\mu l_L^f + \cdots$$

$$D_\mu = \partial_\mu + ig_W W_\mu^a T^a + \cdots$$

$$l_L^e = \begin{pmatrix} \nu_e \\ e_L \end{pmatrix} \qquad l_L^\mu = \begin{pmatrix} \nu_\mu \\ \mu_L \end{pmatrix}$$

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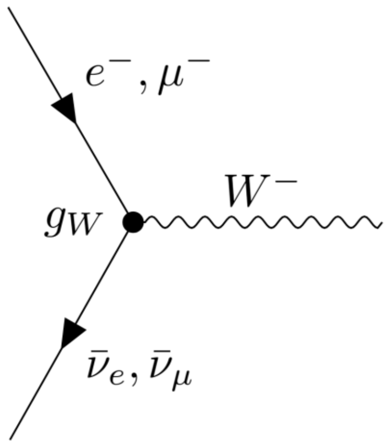
$$\xrightarrow[\text{In physical basis}]{\text{EWSB}}$$

$$\mathcal{L}_{SM} = \frac{i}{\sqrt{2}} \gamma^\alpha \overbrace{g_W}^{\text{Coupling strength}} \left(\underbrace{\bar{e}_L W_\alpha^- \nu_e} + \underbrace{\bar{\mu}_L W_\alpha^- \nu_\mu} \right) + \cdots$$

3-point interactions



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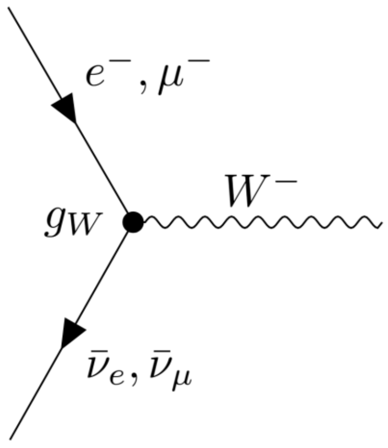
$$D(\text{fermion}) = 3/2, \qquad D(\text{boson}) = 1$$

$$\rightarrow D\left(e_L W_\mu^a \bar{\nu}_e\right) = \frac{3}{2} + \frac{3}{2} + 1 = 4$$



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$\xrightarrow{\text{EWSB}}$ In physical basis

Coupling strength

$$\mathcal{L}_{SM} = \frac{i}{\sqrt{2}}\gamma^\alpha \overbrace{g_W}^{\text{Coupling strength}} \big(\underbrace{\bar{e}_L W_\alpha^- \nu_e}_{} + \underbrace{\bar{\mu}_L W_\alpha^- \nu_\mu}_{}\big) + \cdots$$

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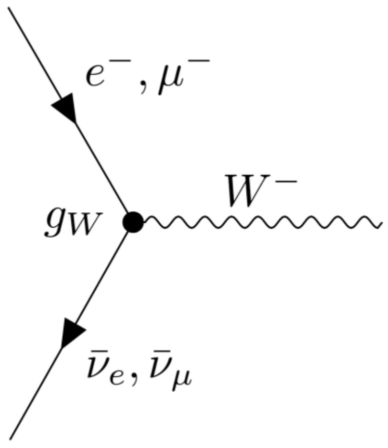

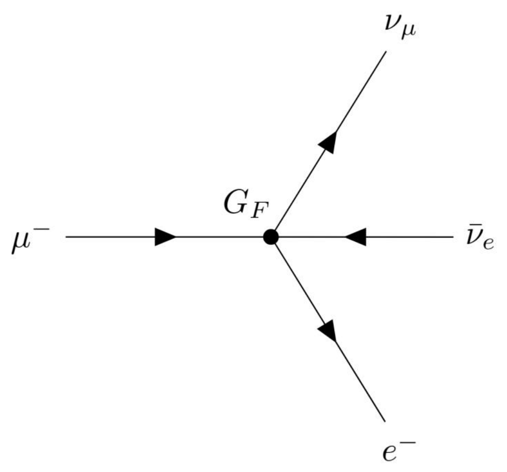

$$\mathcal{L}_{Fermi} \propto G_F(\bar{e}_L\gamma_\alpha\nu_e)\underbrace{(\bar{\mu}_L\gamma^\alpha\nu_\mu)}_{}$$

4-point interaction

$$G_F = \frac{1}{4\sqrt{2}}\frac{g_W^2}{m_W^2} \qquad D(\mathcal{L}_{Fermi}) = 4 \times \frac{3}{2} = 6$$

Two 3-point interactions
→ single 4-point interaction

Effect of W^- boson absorbed into G_F

Results in a dimension-6 operator

Extending not reducing

- In Fermi theory, we **reduced** to the SM to a low-energy approximation

$$\mathcal{L}_{SM} = \frac{i}{\sqrt{2}}\gamma^{\alpha} g_W \left(\bar{e}_L W_\alpha^- \nu_e + \bar{\mu}_L W_\alpha^- \nu_\mu\right) + \cdots \longrightarrow \mathcal{L}_{Fermi} \propto G_F(\bar{e}_L \gamma_\alpha \nu_e)(\bar{\mu}_L \gamma^\alpha \nu_\mu)$$

- To discover new physics, we want to **extend** the SM with higher dimension operators

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^4 + \sum\nolimits_{i,d} \frac{C_i^d}{\Lambda^{d-4}} O_i^d \quad \text{for example,} \quad Q_{Hq}^3 = \left(H^\dagger i \overleftrightarrow{D}_\mu^i H\right)(\bar{q}\sigma_i \gamma^\mu q) \qquad q = \binom{u}{d}$$

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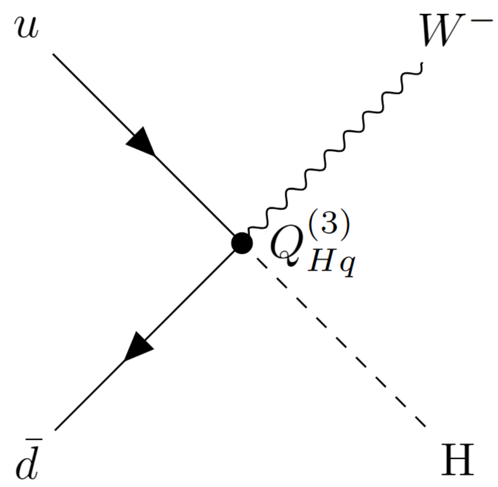


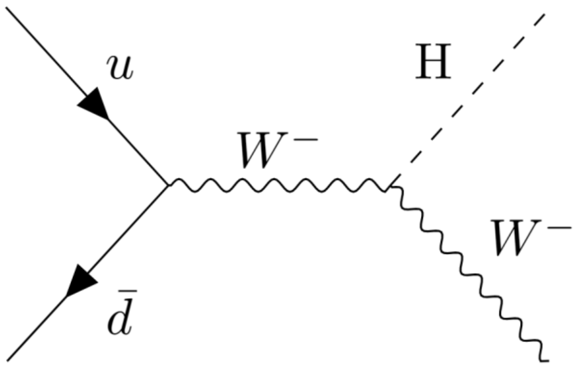
$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$ EWSB | Expanding

$$\downarrow$$

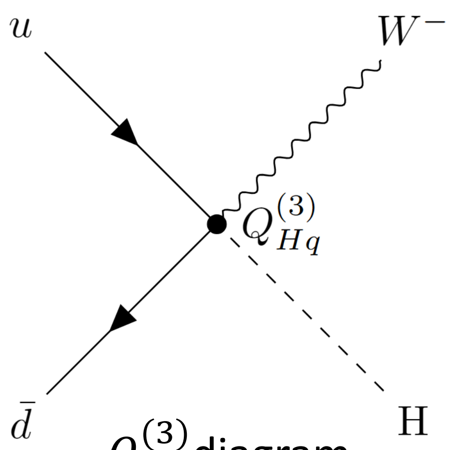
$$\underbrace{Q_{Hq}^3 \sim hW_\mu^- \bar{u}\gamma^\mu d}_{\text{a } udW^-h \text{ vertex}} + \cdots$$

How might we measure $C_{HQ}^{(3)}$?

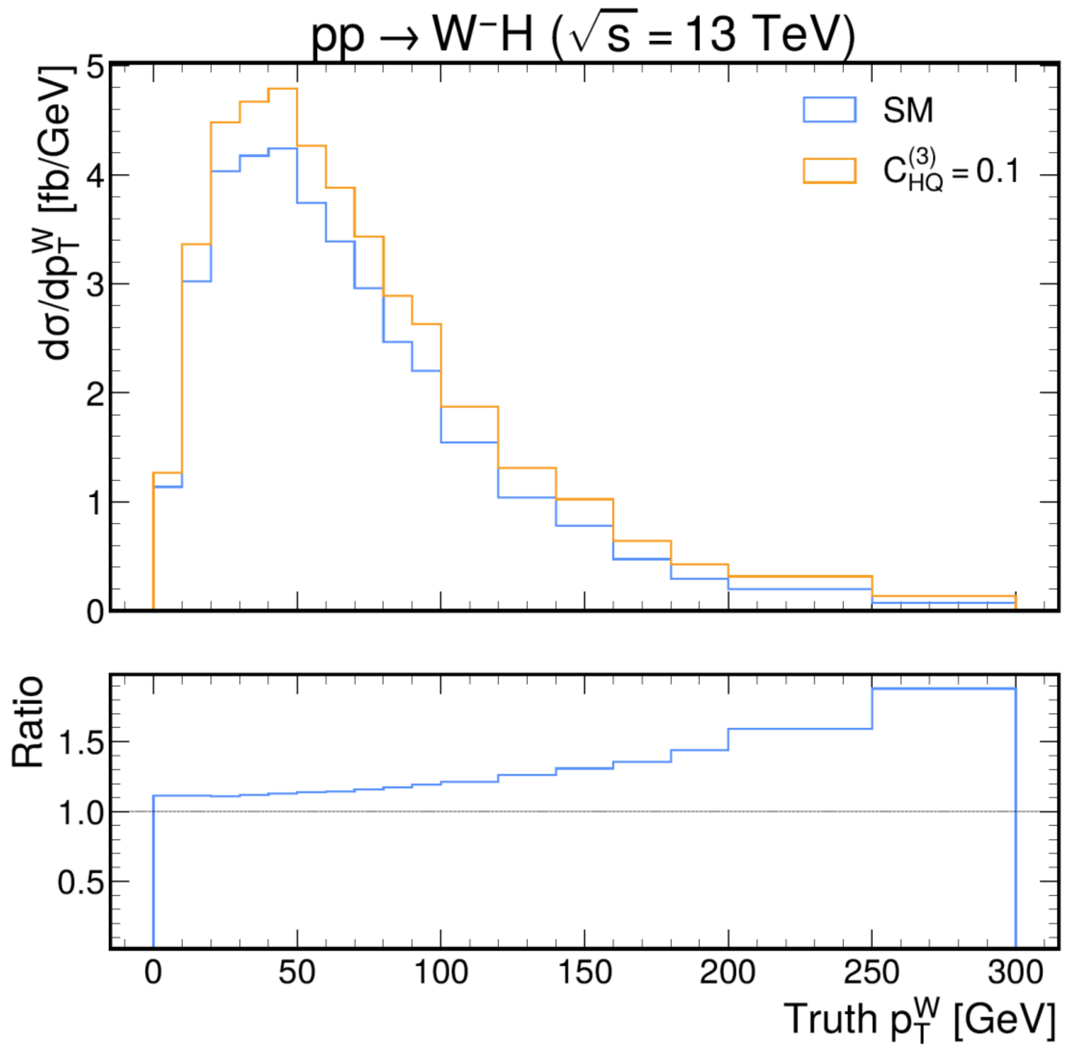
- Let's look at $pp \rightarrow W^- H$ production



SM diagram



$Q_{Hq}^{(3)}$ diagram



- Positive value of $C_{Hq}^{(3)}$ leads to an enhancement of $W^- H$ production
- Greater enhancement at higher p_T^W
  - Should measure $pp \rightarrow W^- H$ in bins of p_T^W to extract most information
  - Will see this with real measurements later!

Generalizing

- We don't know what the NP will be → consider as many types as we can
- Consider all operators made up of SM fields & invariant under SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^4 + \frac{1}{\Lambda}\sum_i C_i^5 Q_i^5 + \frac{1}{\Lambda^2}\sum_i C_i^6 Q_i^6 + O\left(\frac{1}{\Lambda^3}\right)$$

Expansion is valid when

$q^2 \ll \Lambda$ and $\frac{C_i^d}{\Lambda^d} < O(1)$

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→ Consider only dimension-6 operators

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Suppressed by higher orders of $\frac{1}{\Lambda}$

*There are cases where dimension-7 and above are important & where you may be interested in dimension-5… but not the focus of this talk

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$\mathcal{L}_6^{(1)} - X^3$		$\mathcal{L}_6^{(6)} - \psi^2 XH$		$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_G	$f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\sigma^i H W^i_{\mu\nu}$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{\widetilde{G}}$	$f^{abc} \widetilde{G}_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_W	$\varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^a u_r)\widetilde{H}\, G^a_{\mu\nu}$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk} \widetilde{W}_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\sigma^i \widetilde{H}\, W^i_{\mu\nu}$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{L}_6^{(2)} - H^6$		Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
Q_H	$(H^\dagger H)^3$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^a d_r) H\, G^a_{\mu\nu}$	$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{L}_6^{(3)} - H^4 D^2$		Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\sigma^i H\, W^i_{\mu\nu}$	$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^a u_r)(\bar{d}_s \gamma^\mu T^a d_t)$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$		
Q_{HD}	$\left(D^\mu H^\dagger H\right)\left(H^\dagger D_\mu H\right)$				
$\mathcal{L}_6^{(4)} - X^2 H^2$		$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$		$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
Q_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^{a\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^{a\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p \sigma^i \gamma^\mu l_r)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^{i\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^{i\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{u}_s \gamma^\mu T^a u_t)$
Q_{HWB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B^{\mu\nu}$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B^{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{d}_s \gamma^\mu T^a d_t)$
$\mathcal{L}_6^{(5)} - \psi^2 H^3$		$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$		$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$	$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$	$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \sigma^i q_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^a u_r)\varepsilon_{jk}(\bar{q}_s^k T^a d_t)$
		$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

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- There are 59 dimension-6 independent operators
  - Some operators carry flavour indices → more than 59 Wilson coefficients
  - Counting real and imaginary parts separately → 2599 free parameters in $\mathcal{L}_6$
  - We cannot measure 2599 parameters… we must make some choices/assumptions

$$\mathcal{L}_6 = \frac{1}{\Lambda^2}\sum_i \sum_{p,r} C_{i,pr} Q_{i,pr} + \cdots$$

Flavour assumptions

- The most restrictive flavour assumption is $U(3)^5$
  - Assumes NP scales couplings to each flavour of lepton or quark equally

$$\mathcal{L}_6 = \frac{1}{\Lambda^2}\sum_i \sum_{p,r} C_{i,pr} Q_{i,pr} + \cdots \xrightarrow[\text{assumption}]{\text{flavour}} \mathcal{L}_6 = \frac{1}{\Lambda^2}\sum_i \sum_{p,r} C_i X_{i,pr} Q_{i,pr} + \cdots$$

Single WC per operator

Depends on type of operator to ensure equal scaling

$C_{Hl}^{(3)}$ $C_{Hq}^{(3)}$ $\cancel{C_{H\tau}^{(3)}}$

C_{Hu} C_{Hd}

→ 85 free parameters

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Single WC per operator

Depends on type of operator to ensure equal scaling

$\rightarrow$ 85 free parameters

- Such an assumption makes sense for measurements where you can not separate flavour
  - e.g. light quark production at the LHC
  - e.g. the statistics are too low to individually measure $W^-(\rightarrow e\nu_e)H$ from $W^-\ (\rightarrow \mu\nu_\tau)H$

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  - e.g. light quark production at the LHC
  - e.g. the statistics are too low to individually measure $W^-(\rightarrow e\nu_e)H$ from $W^-(\rightarrow \mu\nu_\tau)H$
- You should adjust flavour assumption to match measurement capabilities
- The topU3l assumption is like $U(3)^5$ but treats first two generations of quark differently to third

First two generations	Third generation
(q, u, d)	(Q, t, b)
e.g. $C_{Hq}^{(3)}$	e.g. $C_{HQ}^{(3)}$

At the LHC, we make dedicated b and t measurements
$\rightarrow$ we should disentangle them

$\rightarrow$ 120 free parameters

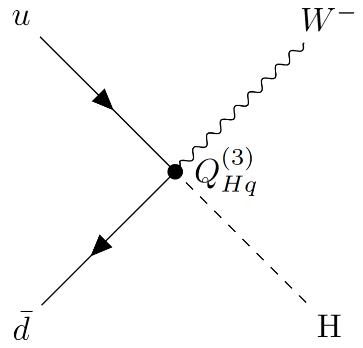
Recap

- At the LHC, we probe energies up to $O(\mathrm{TeV})$ scale
- If the mass of a new particle (Λ) is $\gg q^2$ we will not detect it directly (mass bump)
- In the $q^2 \ll \Lambda$ regime, approximations of NP contributions introduces higher-dimension operators
- We choose to consider all possible under certain reasonable assumptions (e.g. flavour assumption)

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^4 + + \frac{1}{\Lambda^2} \sum_i C_i^6 Q_i^6$$

$$Q_{Hq}^3 = \left(H^\dagger i \overleftrightarrow{D}_\mu^i H\right) \left(\bar{q}_p \sigma_i \gamma^\mu q_r\right)$$

$$Q_{Hq}^3 \sim h W_\mu^- \bar{u} \gamma^\mu d + \cdots$$

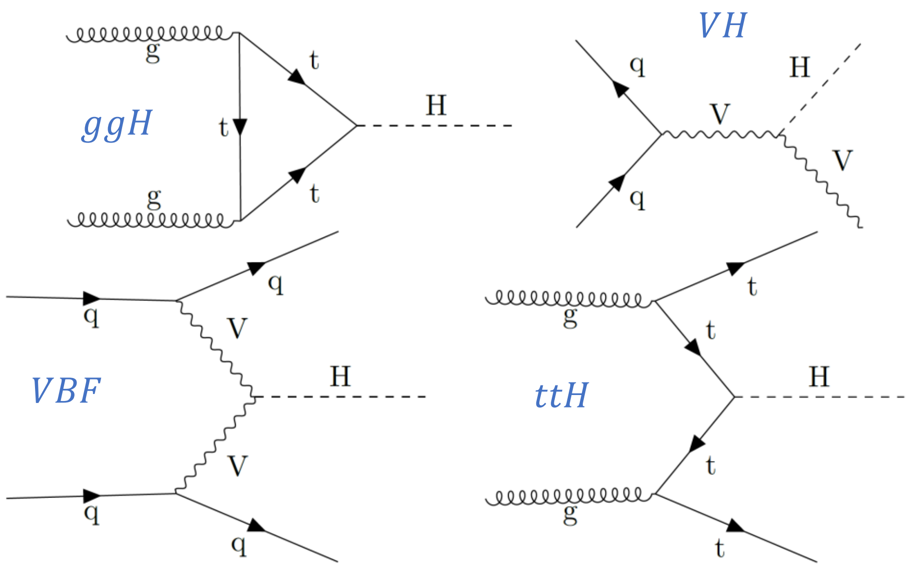


Flavour assumption	Free parameters
$U(3)^5$	85
topU3l	120

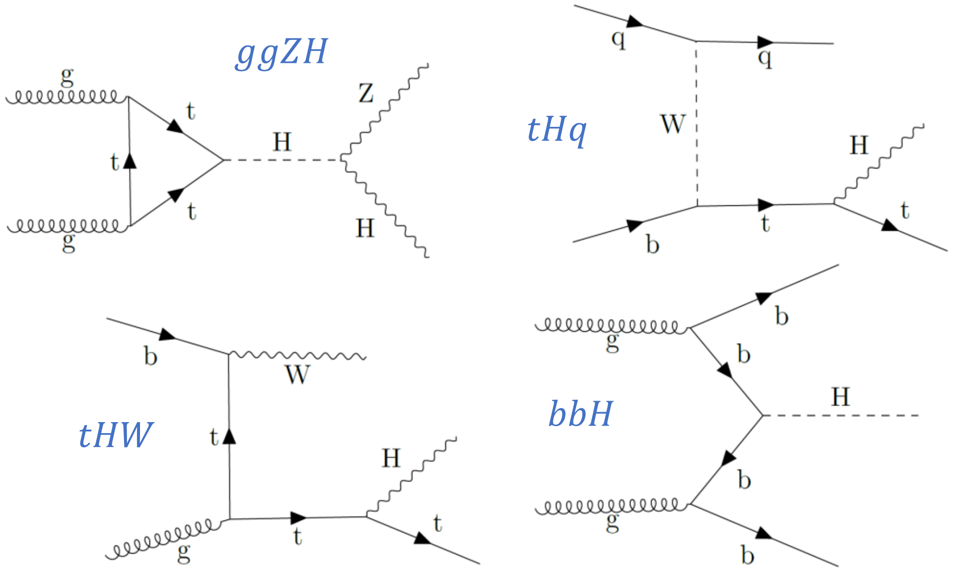
- As model-independent as we can be provided the measurements we use/have
- To constrain C_i, we should measure related processes, preferably differentially
- Non-zero value of C_i → new physics!

Combination of Higgs measurements at CMS

- Is there any NP lurking in the Run2 (138^{-1}) Higgs dataset at CMS?
- There is a lot to measure…



Dominant production modes



Subdominant production modes

- Recent CMS result ([CMS-PAS-HIG-21-018]) combines 11 analyses… an exhaustive list of production and decay mode pairings

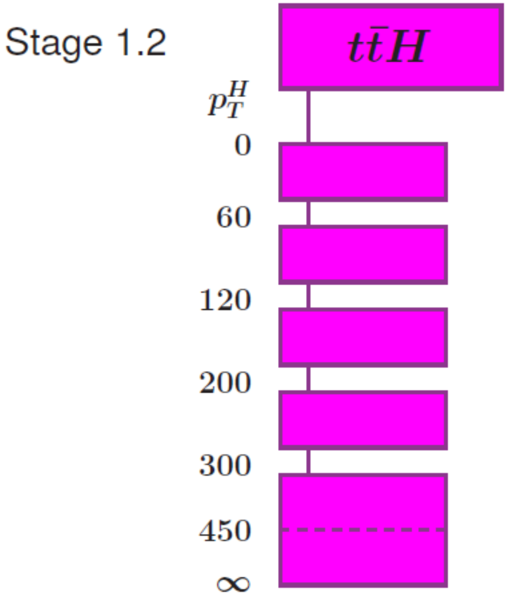
Prod mode	σ [pb]
ggH	48.6
VBF	3.78
WH	1.37
ZH	0.761
ttH	0.507
bbH	0.528
$ggZH$	0.123
tHq	0.07
tHW	0.503

Decay mode	BR (%)
bb	58.2
WW	21.4
gg	8.19
$\tau\tau$	6.27
cc	2.89
ZZ	2.62
$\gamma\gamma$	0.227
Other	0.194

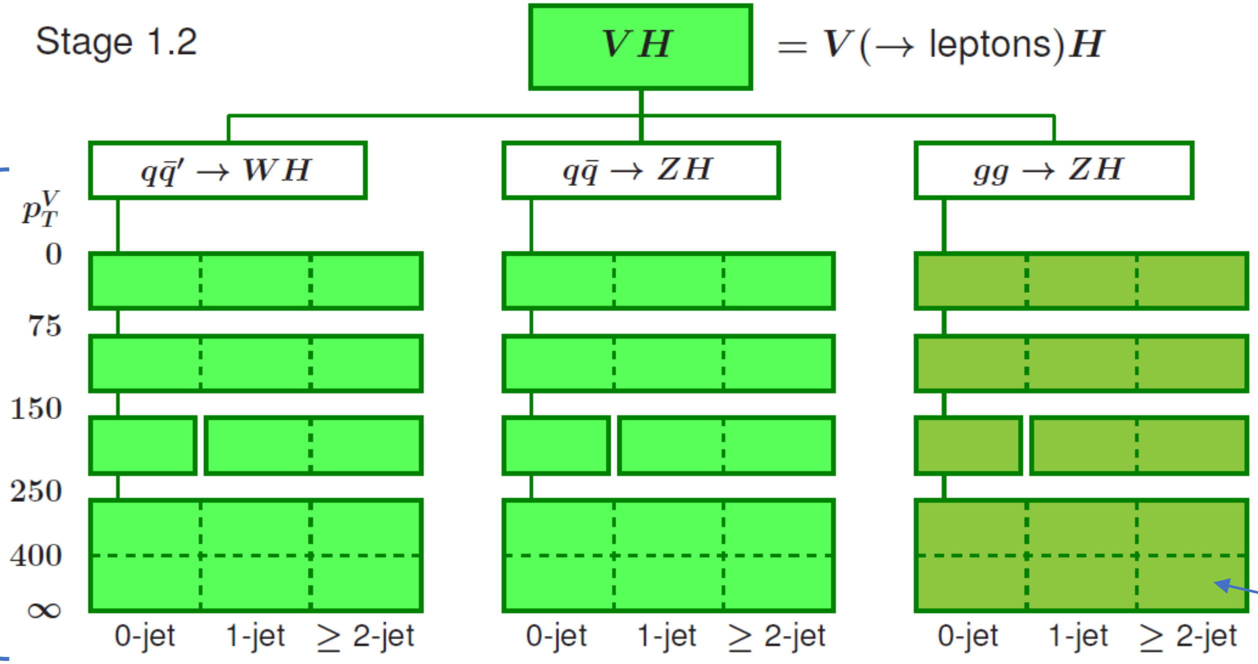
The Simplified Template Cross Sections (STXS)

- How do we combine these analyses sensibly? We coordinate…
- Most of the input analyses measure the STXS
  - Suggested binning scheme for each production mode
  - Split by variables like p_T^H, p_T^V, N_{jet} to increase sensitivity to NP

Useful for differentiating NP couplings to top quarks vs other generations (topU3l)



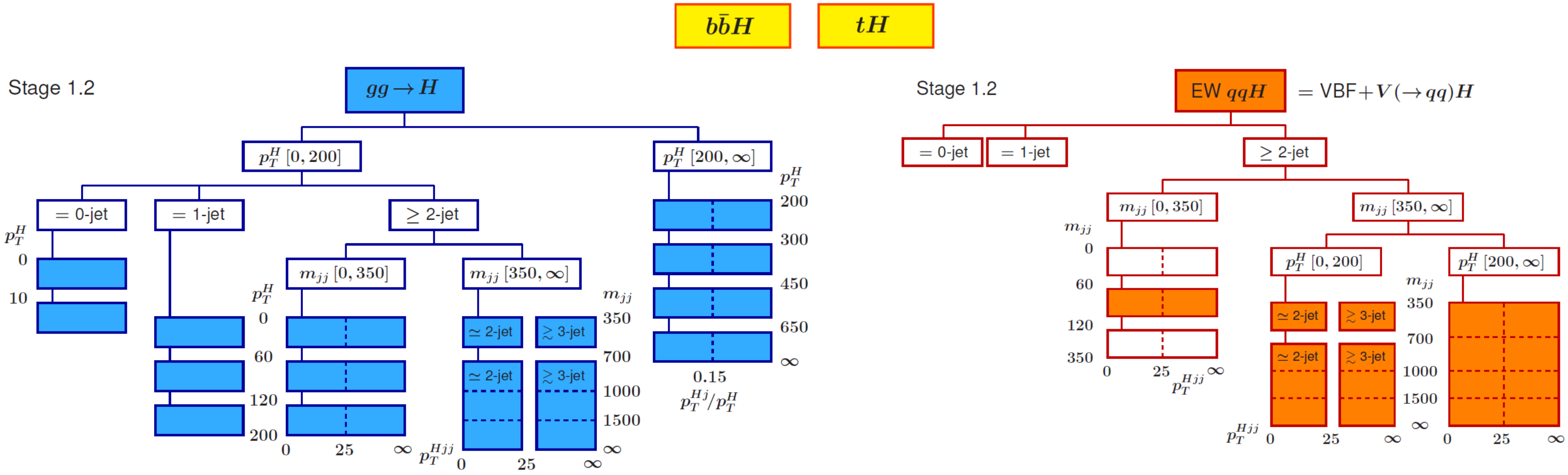
Useful for $C_{Hq}^{(3)}$



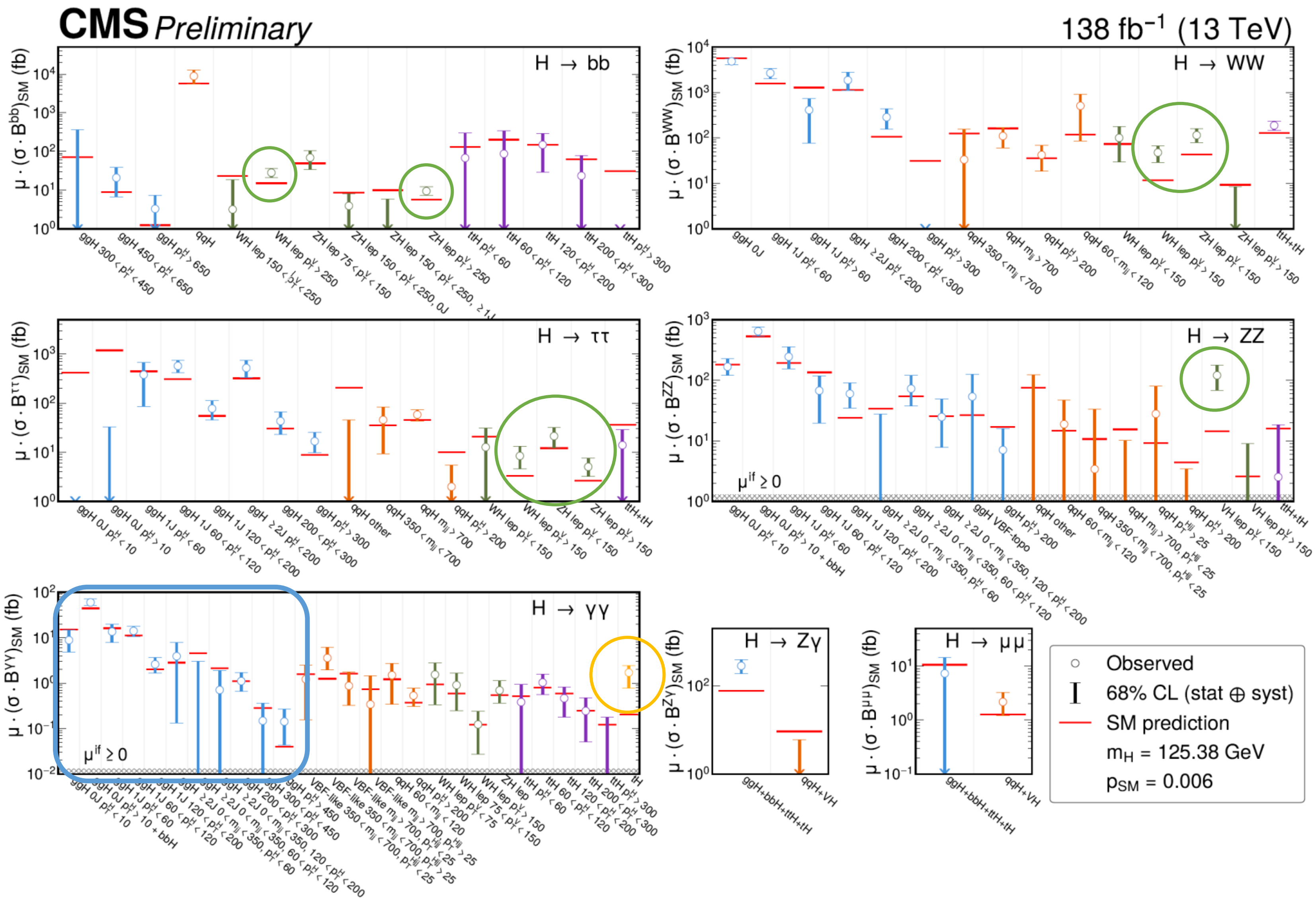
Every bin corresponds to a cross section measurement

The Simplified Template Cross Sections (STXS)

- Every input decay channel will measure as many bins as they can
- Merge bins where necessary – dashed lines suggest merging points



STXS results



Consistent deviations in the VH leptonic bins

Great sensitivity to ggH in $H \to \gamma\gamma$ (important later)

tH excess in $H \to \gamma\gamma$ decay channel

Overall poor agreement with the SM with a p-value = 0.006

How does this look from an EFT perspective…?

Interpreting the STXS in the SMEFT

- Let's parameterize our measurements in terms of the Wilson coefficients, C_i
- In an analysis which targets decay mode, j, the expected signal events in category, c, is:

$$N_{jc}(C_i) = \sum_i \sigma_i(C_i) \times BR_j(C_i) \times A_{ijc}(C_i)$$

STXS bin i

BR for decay mode j

Acceptance = fraction of events from bin i and decay channel j that land in category c

- For now, let's assume that A_{ijc} is independent of the WC's, we will return to this later…
- If we consider only a single insertion of an EFT vertex in our Feynman diagrams:

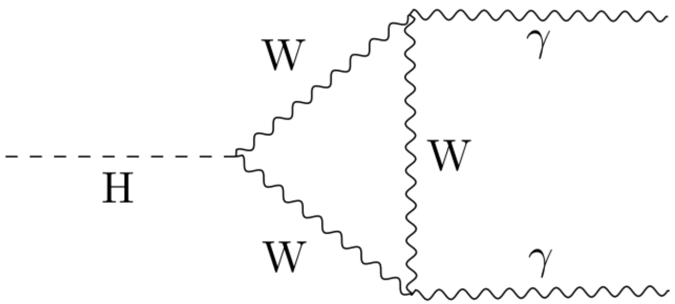
$$\frac{\sigma_i}{\sigma^{SM}} = 1 + \frac{1}{\Lambda^2}\sum_i A_i C_i + \frac{1}{\Lambda^4}\sum_{ij} B_{ij} C_i Cj \quad \text{and} \quad \frac{\Gamma}{\Gamma^{SM}} = 1 + \frac{1}{\Lambda^2}\sum_i A_i C_i + \frac{1}{\Lambda^4}\sum_{ij} B_{ij} C_i Cj$$

Scaling equations

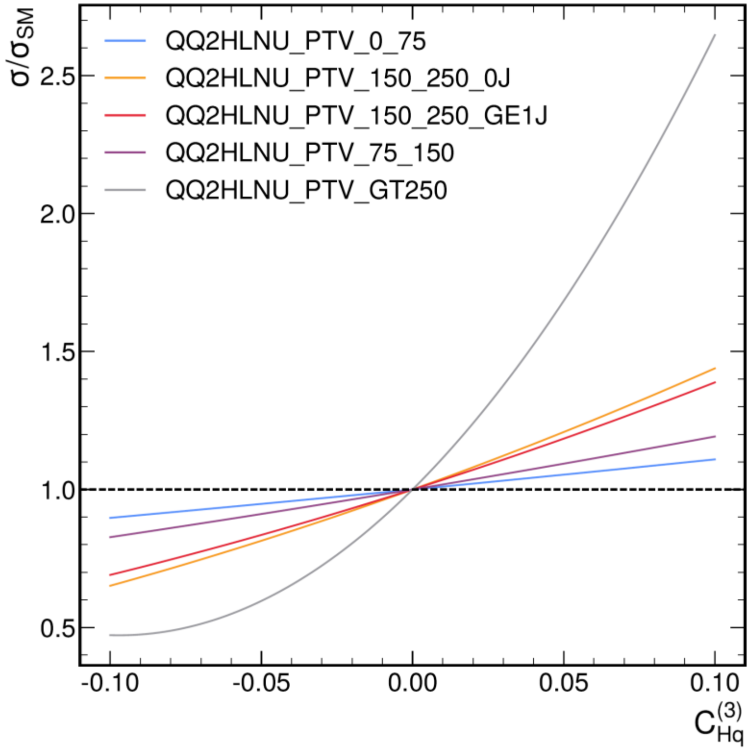
- Derive a scaling equation per STXS bin + per decay mode → complete parameterization

How to determine A_i and B_{ij}?

- Option 1: analytical derivations
  - Possible for some decay modes – is what we do for $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$
  - Includes NLO EW + EFT effects (not possible with MC tools)



- Option 2: Monte-Carlo methods
  - Use event generators (MadGraph) to sample σ or Γ at different values of C_i and infer A_i and B_j terms
  - For N WC's, need $2N + N(N-1)/2$ samples
  - To reduce computation time, we reweight SM events instead of regenerating events for every sample
    - Except for special cases
  - Mixture of models used in the generators
    - Mostly LO calculations
    - Loop-level in QCD calculations for ggH and $ggZH$



Linear-only or up to quadratic?

- Linear terms are suppressed by $\frac{1}{\Lambda^2}$, and quadratic terms by $\frac{1}{\Lambda^4}$

$$\frac{\sigma_i}{\sigma^{SM}} = 1 + \frac{1}{\Lambda^2}\sum_i A_i C_i + \frac{1}{\Lambda^4}\sum_{ij} B_{ij} C_i Cj$$

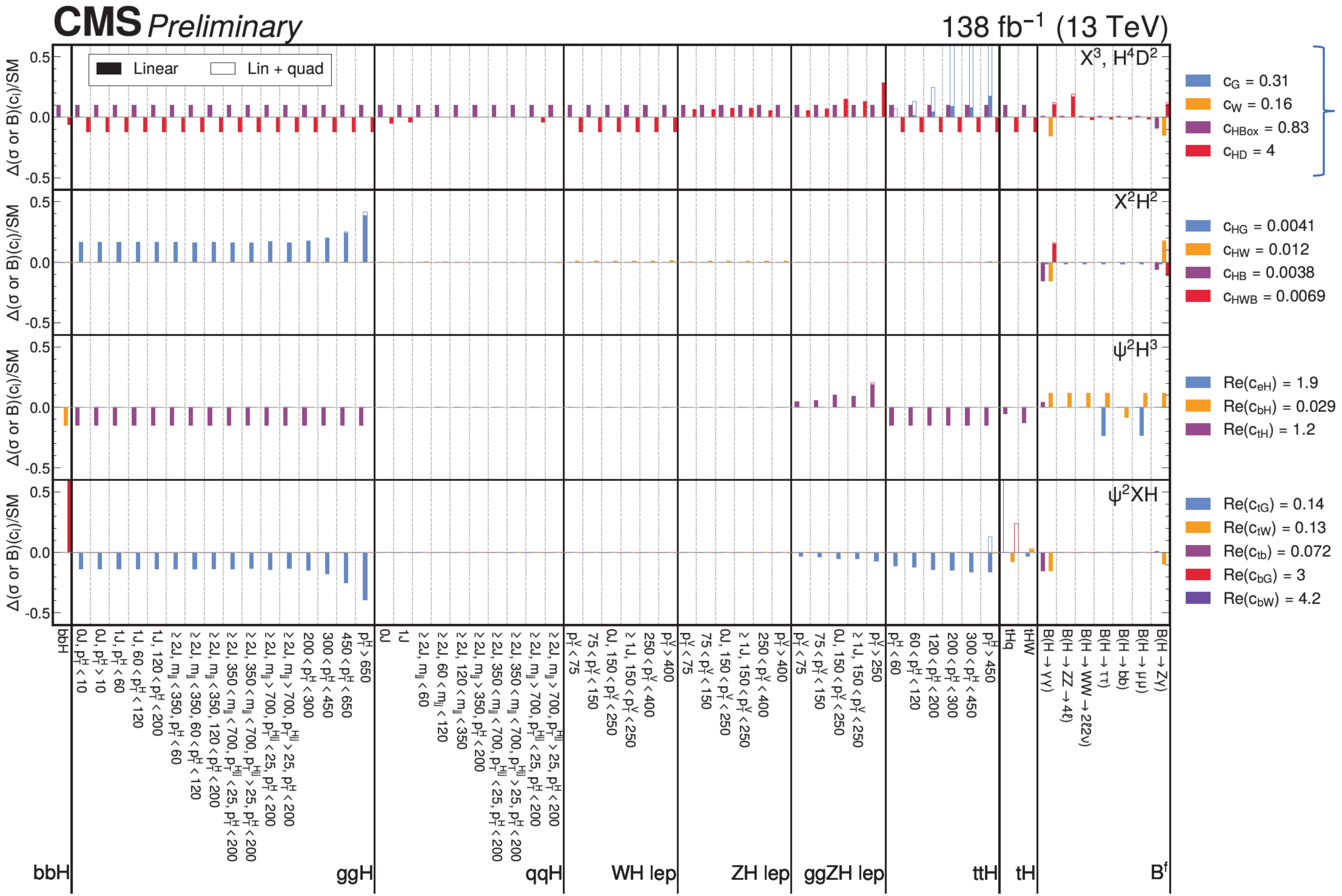
- If we considered dimension-8 operators as well for a moment, we would get

$$\frac{\sigma_i}{\sigma^{SM}} = 1 + \frac{1}{\Lambda^2}\sum_i A_i^6 C_i^6 + \underbrace{\frac{1}{\Lambda^4}\sum_{ij} B_{ij}^6 C_i^6 C_j^6 + \frac{1}{\Lambda^4}\sum_i A_i^8 C_i^8}_{} + \frac{1}{\Lambda^8}\sum_{ij} B_{ij}^8 C_i^8 C_j^8$$

Quadratic terms from dimension-6 are the same order ($1/\Lambda^4$) as the linear from dimension-8!

- This is an inconsistent cut-off in the expansion of $\frac{1}{\Lambda}$
- Using only the linear terms (up to $1/\Lambda^2$) may lead to more conservative but more valid results
- We tend to look at both results for comparison, keeping this all this in mind

STXS parameterization (1)

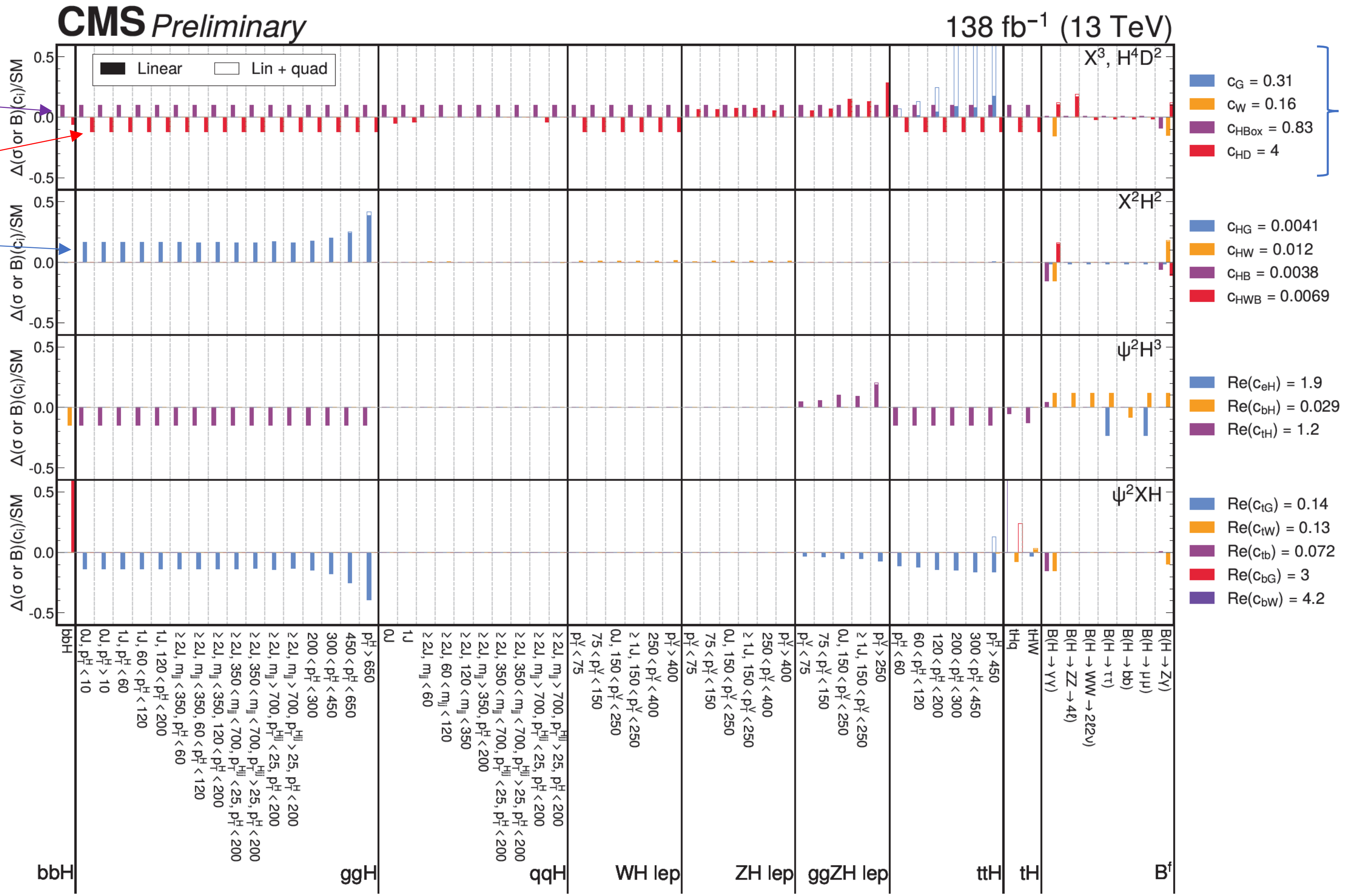


WC set to their expected 95% CL interval value

STXS parameterization (1)

Some WC lead to global flat scalings

Others affect particular production modes



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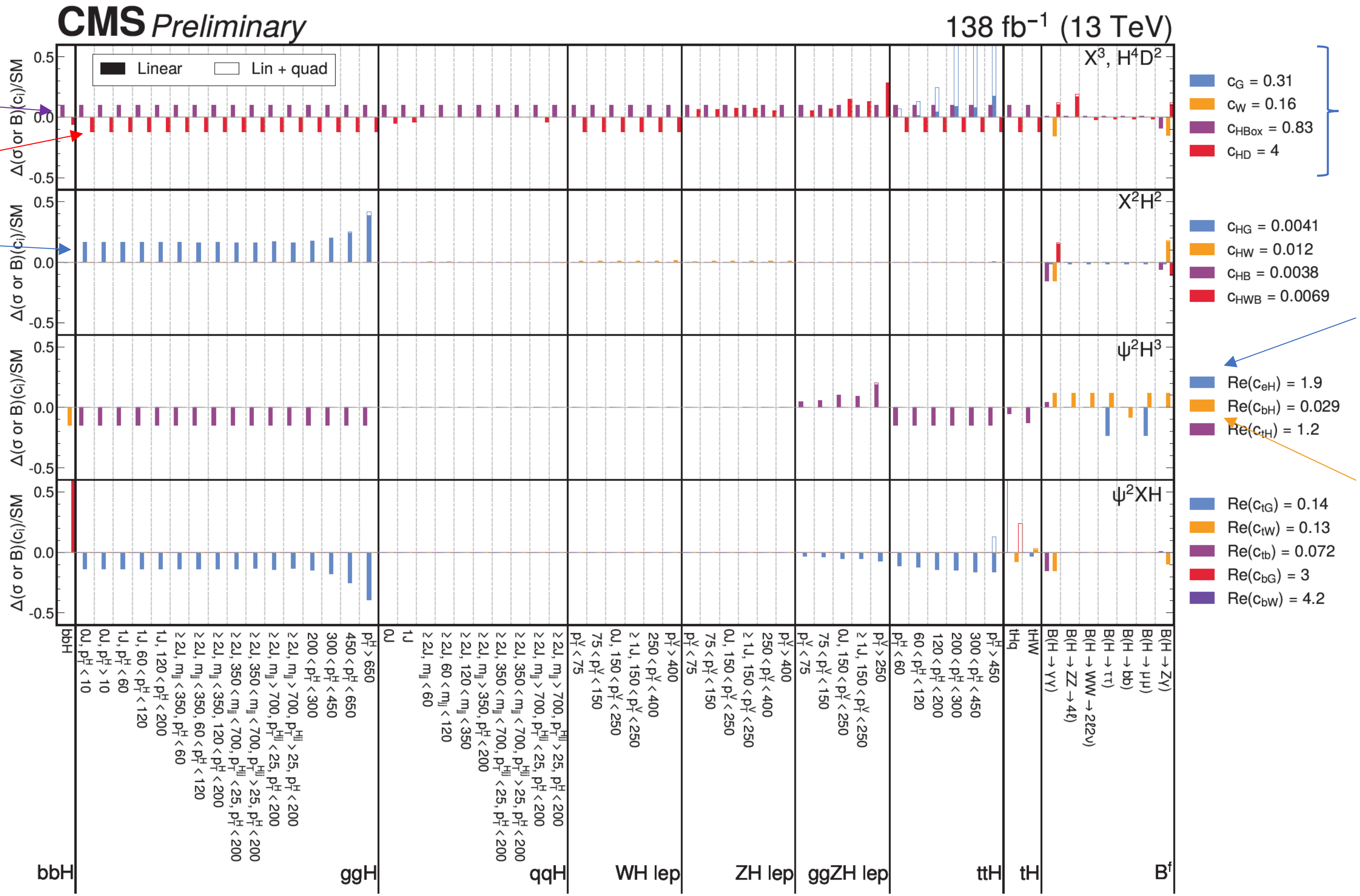


WC set to their expected 95% CL interval value

C_{eH} rescales the leptonic Yukawa terms → affects only $H \to \tau\tau$ and $H \to \mu\mu$

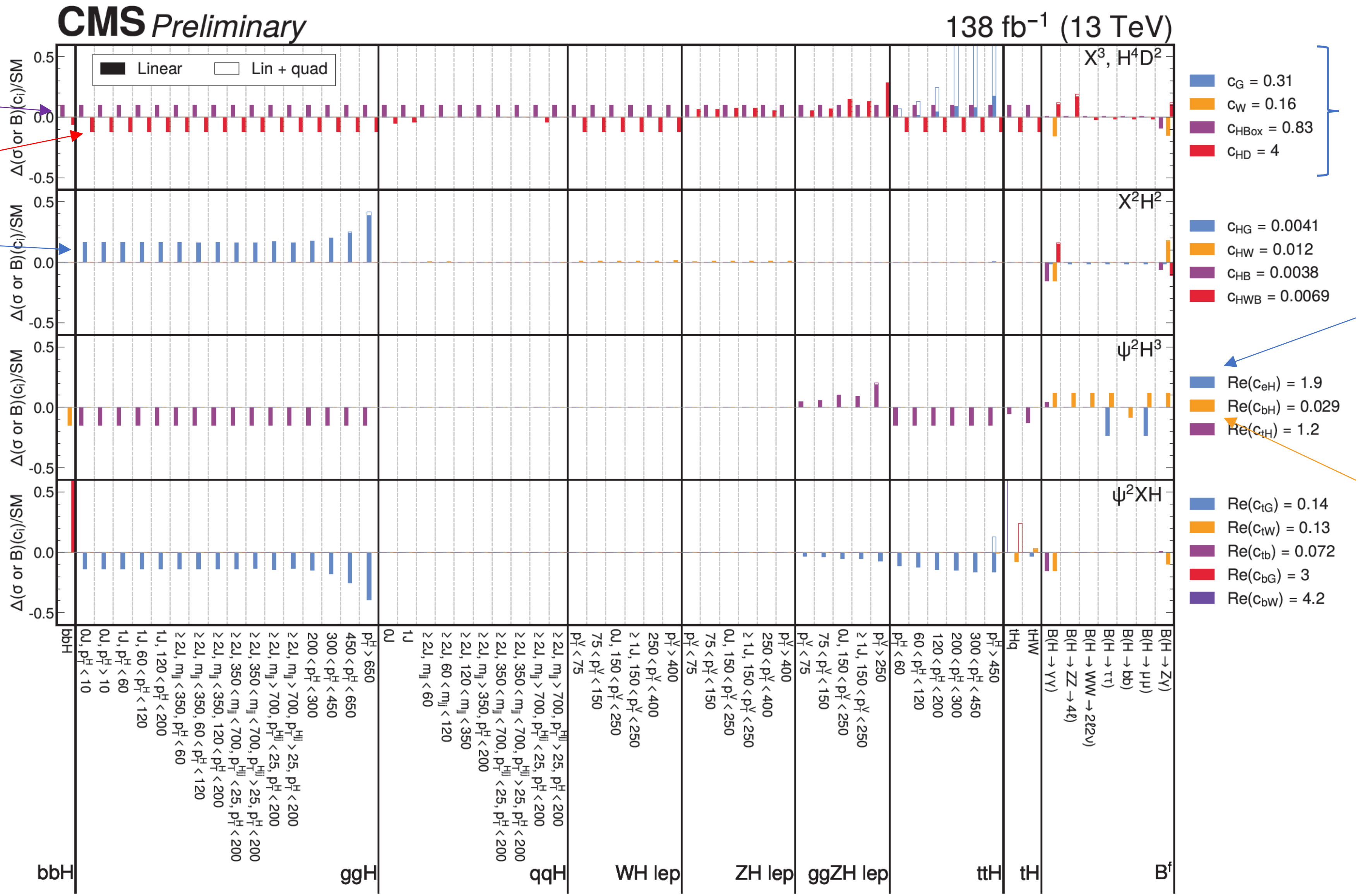
C_{bH} rescales the hbb Yukawa term → affects all BR's through the Higgs total width

STXS parameterization (1)

Some WC lead to global flat scalings

Others affect particular production modes

Linear mostly dominates with some exceptions



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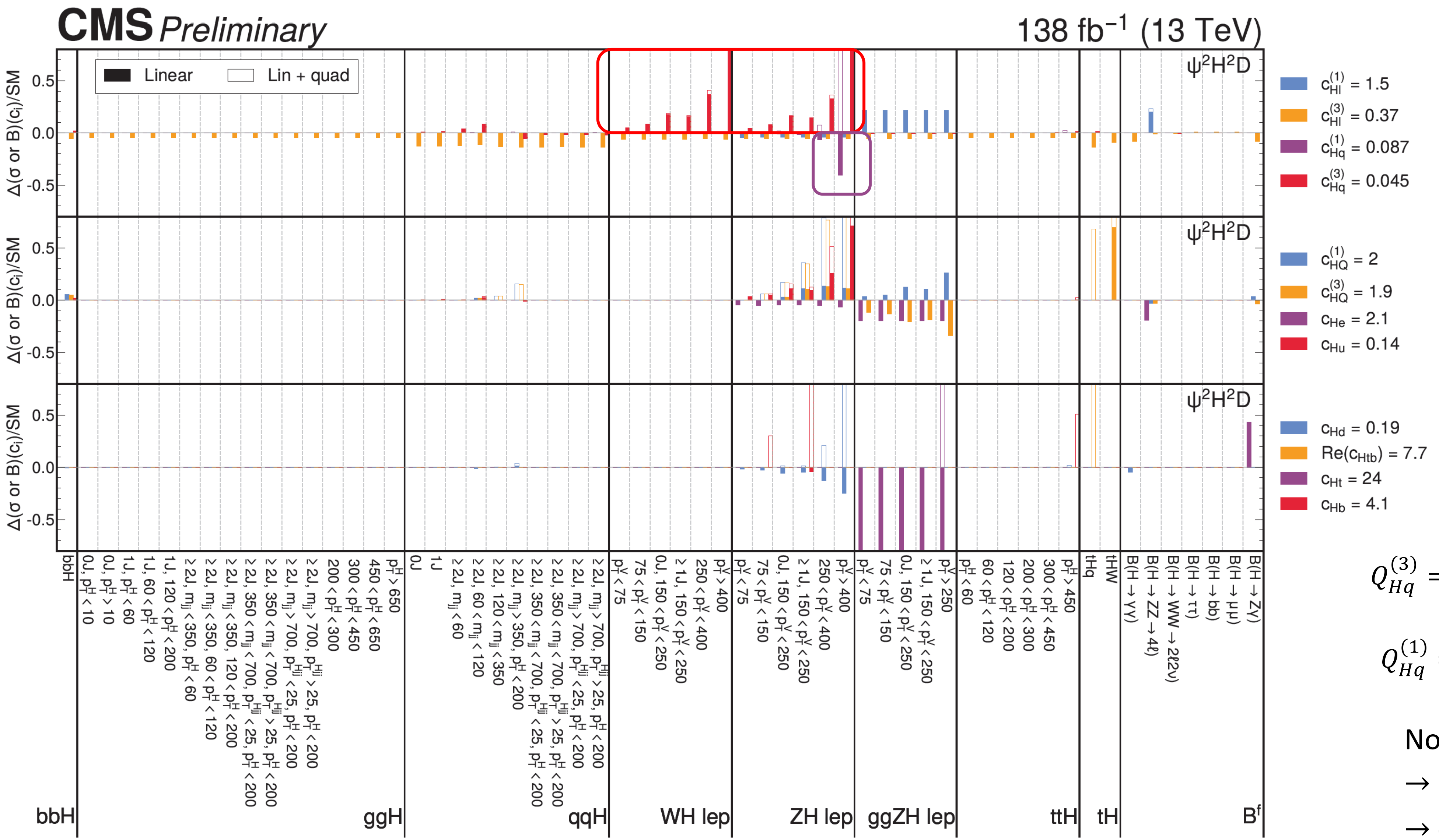
STXS parameterization (2)



$C_{Hq}^{(3)}$ showing the same p_T^V dependence seen before

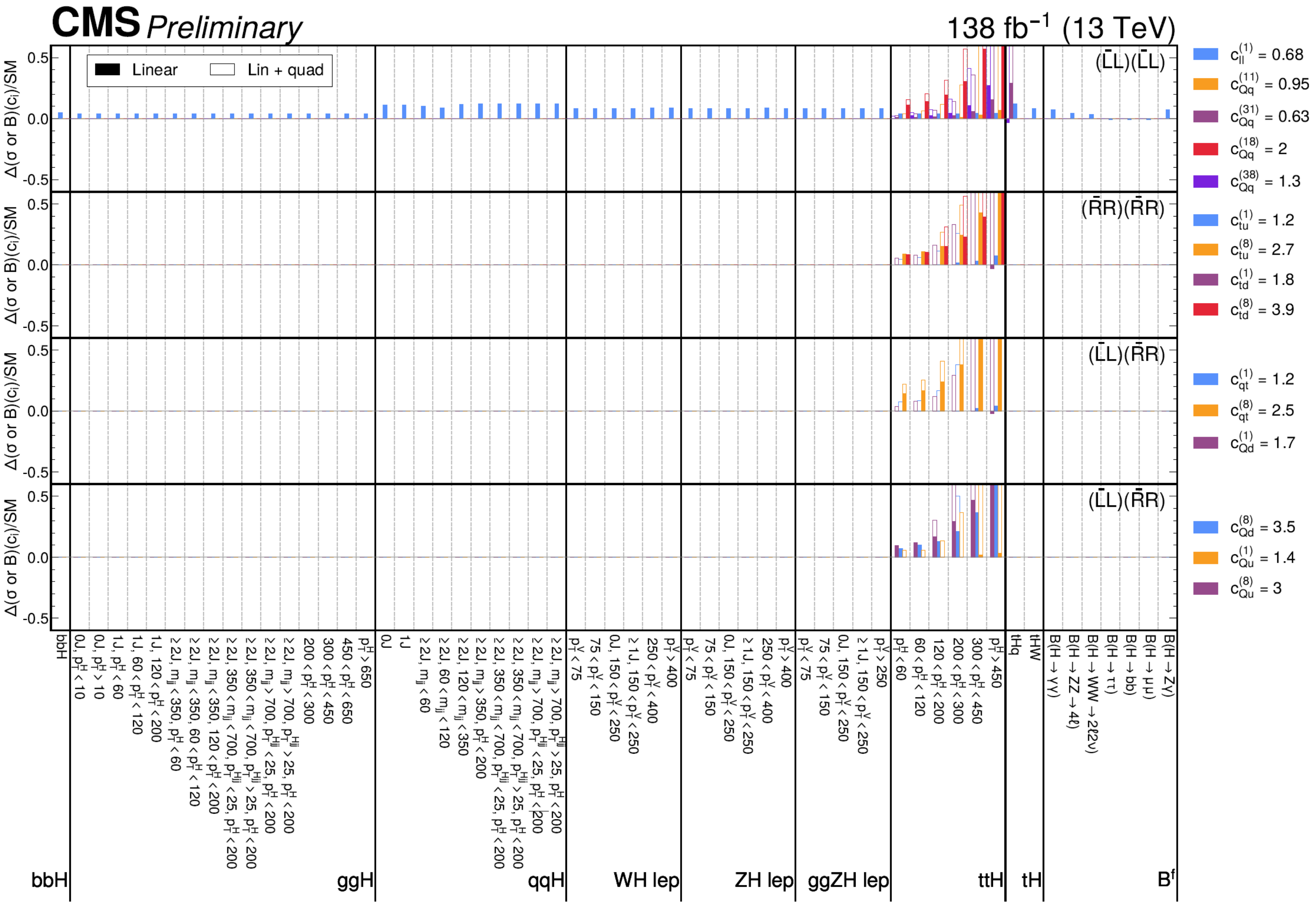
$C_{Hq}^{(1)}$ shows similar dependence

$$Q_{Hq}^{(3)} = \left(H^\dagger i \overleftrightarrow{D}_\mu^i H\right)(\bar{q}_p \sigma_i \gamma^\mu q_r)$$

$$Q_{Hq}^{(1)} = \left(H^\dagger i \overleftrightarrow{D}_\mu^i H\right)(\bar{q}_p \gamma^\mu q_r)$$

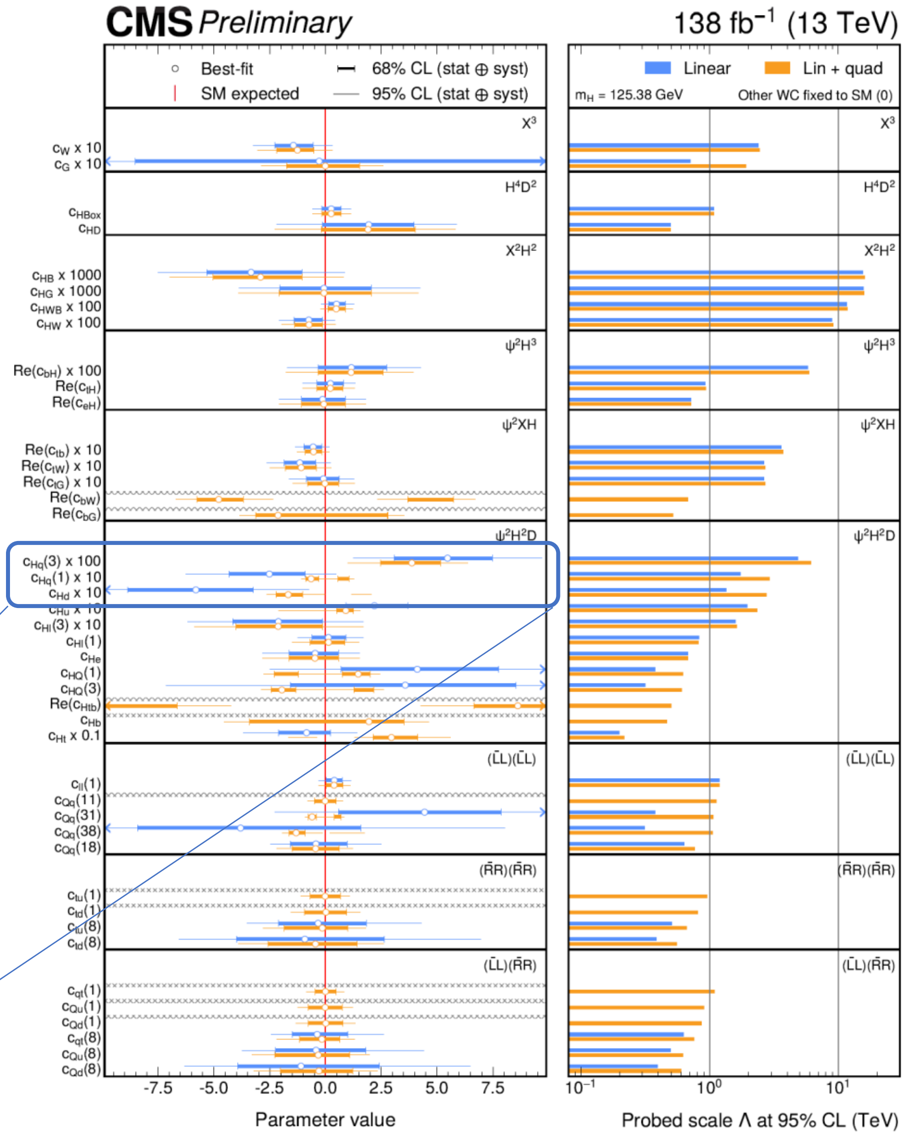
No Pauli matrix in $Q_{Hq}^{(1)}$
→ no mixing u and d
→ only ZH for $Q_{Hq}^{(1)}$

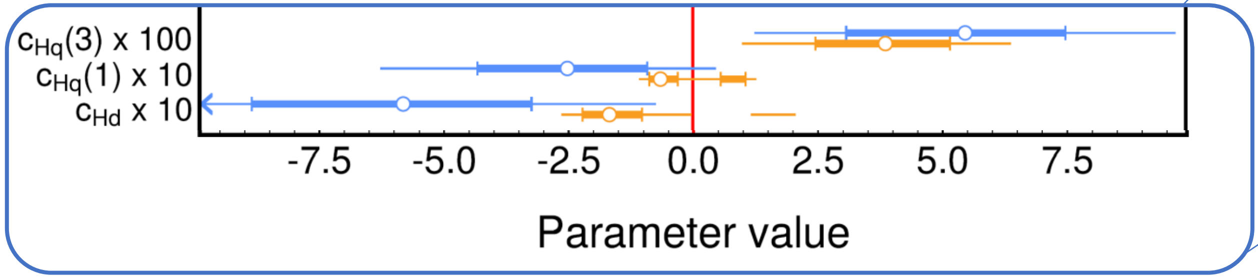
STXS parameterization (3)



Results in nominal basis

- Take $\Lambda = 1$ TeV (can rescale afterwards if wanted)
- Firstly, we fit C_i, assuming all other $C_{j\neq i} = 0$
  - Sensitive to very specific types of NP
  - Simple interpretation
- Sensitive to 43 Wilson Coefficients
- Most discrepant result is $C_{Hq}^{(3)}$ with a p-value of 0.01
  - Originating from VH discrepancies
  - Smaller tension in related $C_{Hq}^{(1)}$
- Assuming $C_i = 1$, the tightest constraint corresponds to excluding $\Lambda < 15$ TeV

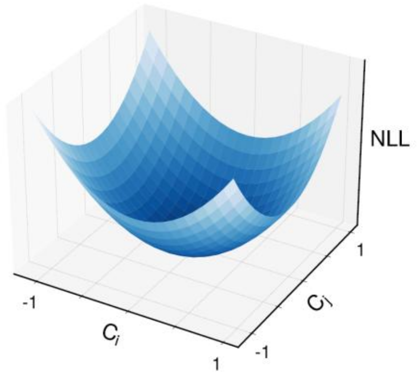




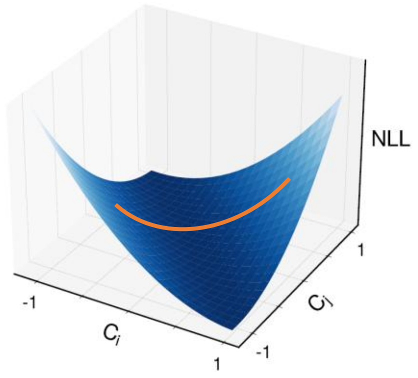
Degenerate effects

- A BSM theory usually leads to several non-zero WC's, let's try to constraint them simultaneously…
  - Fit one WC but leave the rest to float

Good curvature is all directions
→ simultaneous constraint for both WCs



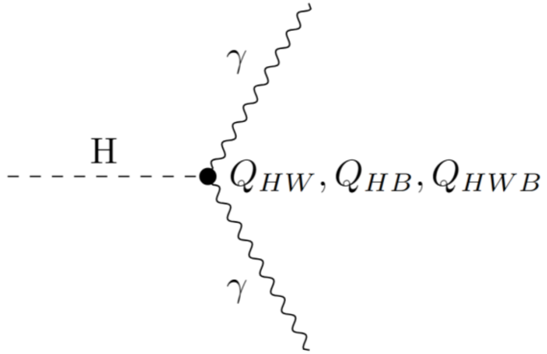
What we want



~What we usually get

A flat (degenerate) direction in the likelihood
→ no constraint for either WC
Only a particular combination $(C_i + C_j)$ has a constraint

- Why does this happen?
  - Some WC's have similar (degenerate) effects on our measurements, e.g. $H \to \gamma\gamma$
  - Cannot easily tell whether a deviation in $H \to \gamma\gamma$ is due to Q_{HW}, Q_{HB} or Q_{HWB}



→ need to derive a rotated basis for our 43 WCs

Deriving a rotated basis

Find the Hessian (matrix of second derivates of NLL)

$$H_{SMEFT}$$

Use eigenvector decomposition to write as

$$H_{SMEFT} = R^T \Lambda R$$

R = rotation matrix
Λ = diagonal matrix
$1/\sqrt{\lambda_i}$ = estimated 68% CL intervals

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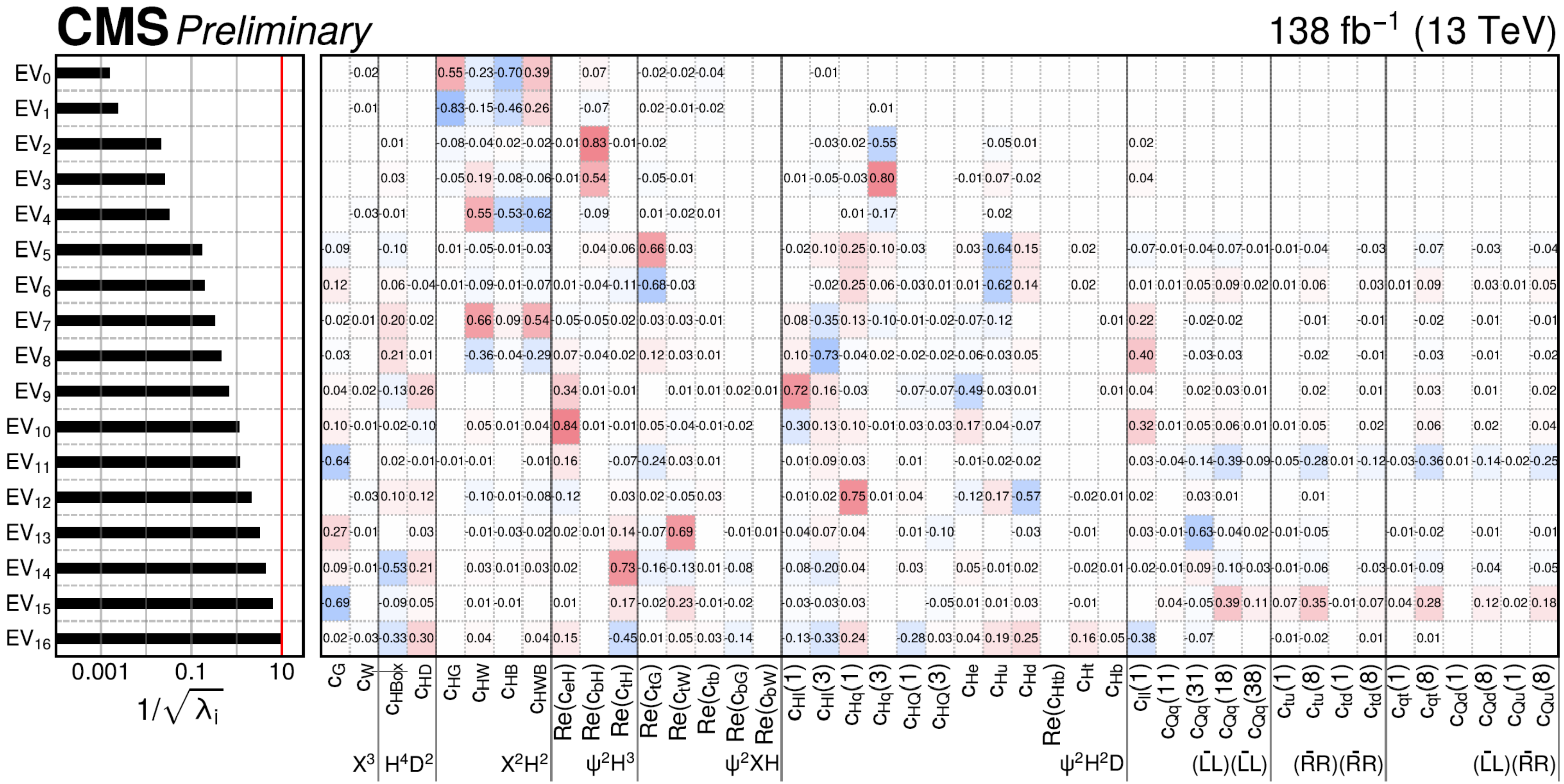
$$EV_0 = \underbrace{0.55C_{HG}}_{ggH \text{ production}} \underbrace{- 0.23C_{HW} - 0.70C_{HB} + 0.39C_{HWB}}_{H \rightarrow \gamma\gamma}$$

This combination of production and decay mode is our most sensitive measurement of the Higgs



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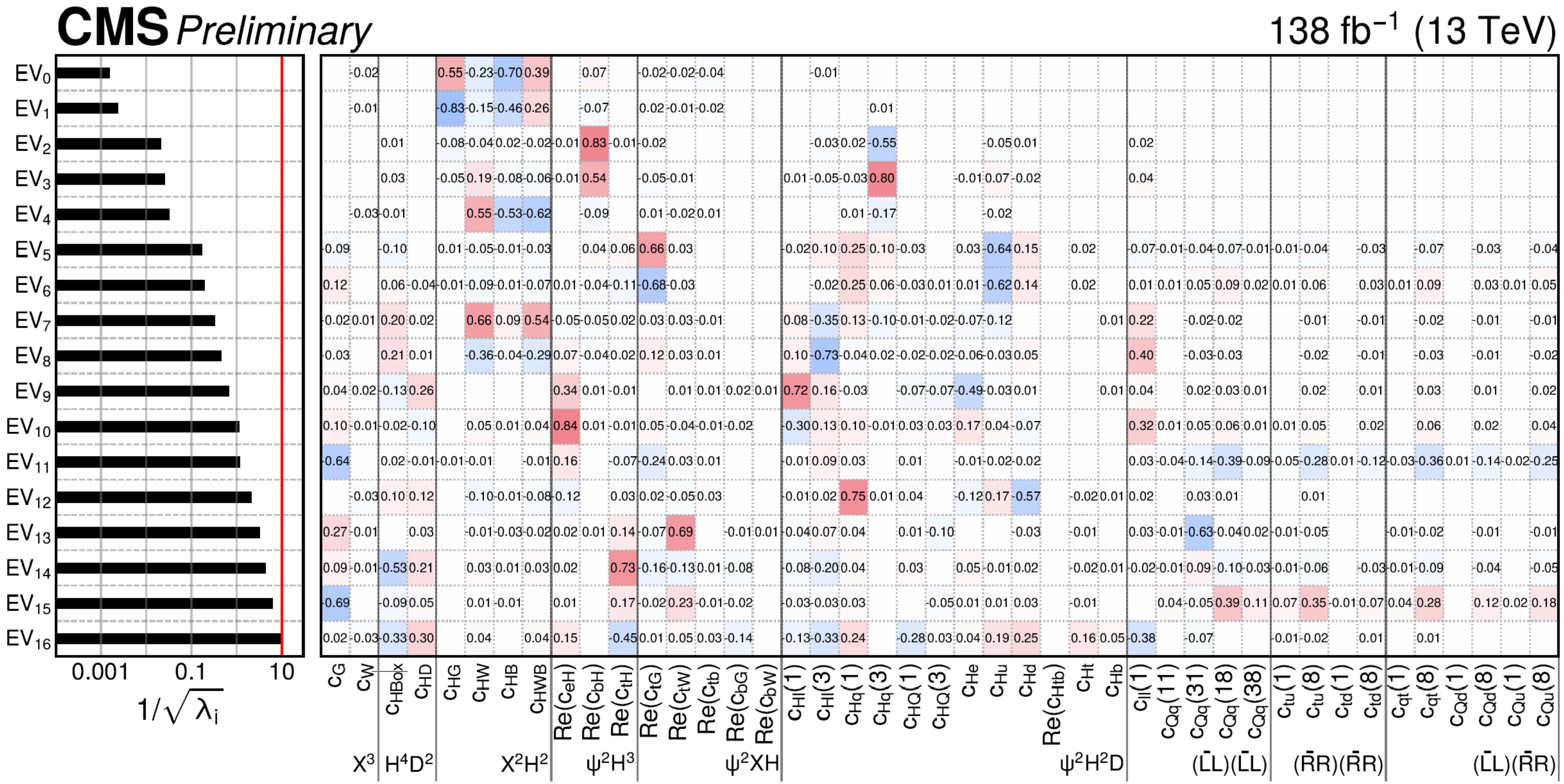

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We used linear-only, otherwise $H_{SMEFT} = H_{SMEFT}(C_i)$
→ rotation matrix is C_i dependent

$$EV_0 = \underbrace{0.55C_{HG}}_{ggH\text{ production}} \underbrace{- 0.23C_{HW} - 0.70C_{HB} + 0.39C_{HWB}}_{H \to \gamma\gamma}$$

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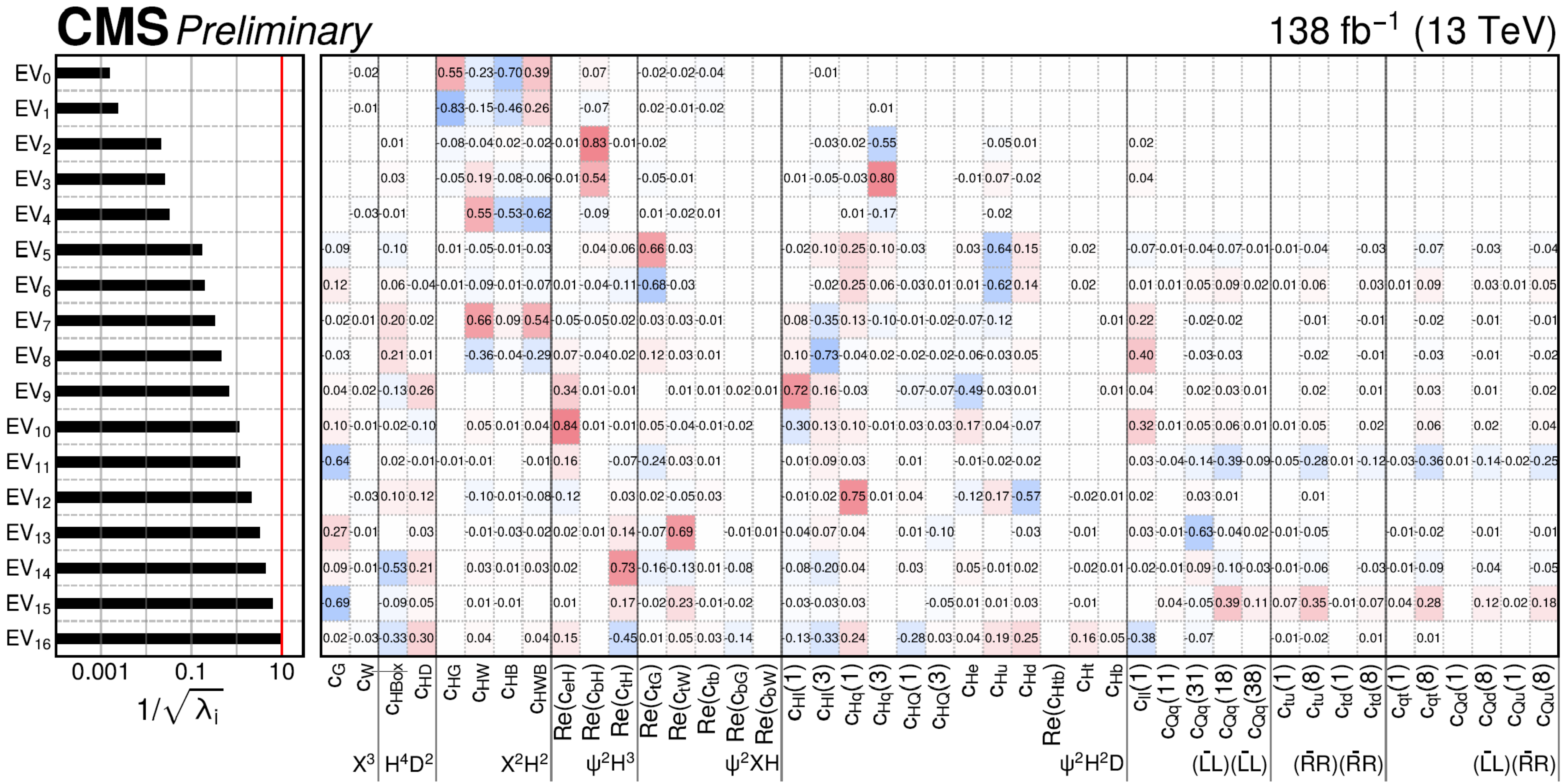
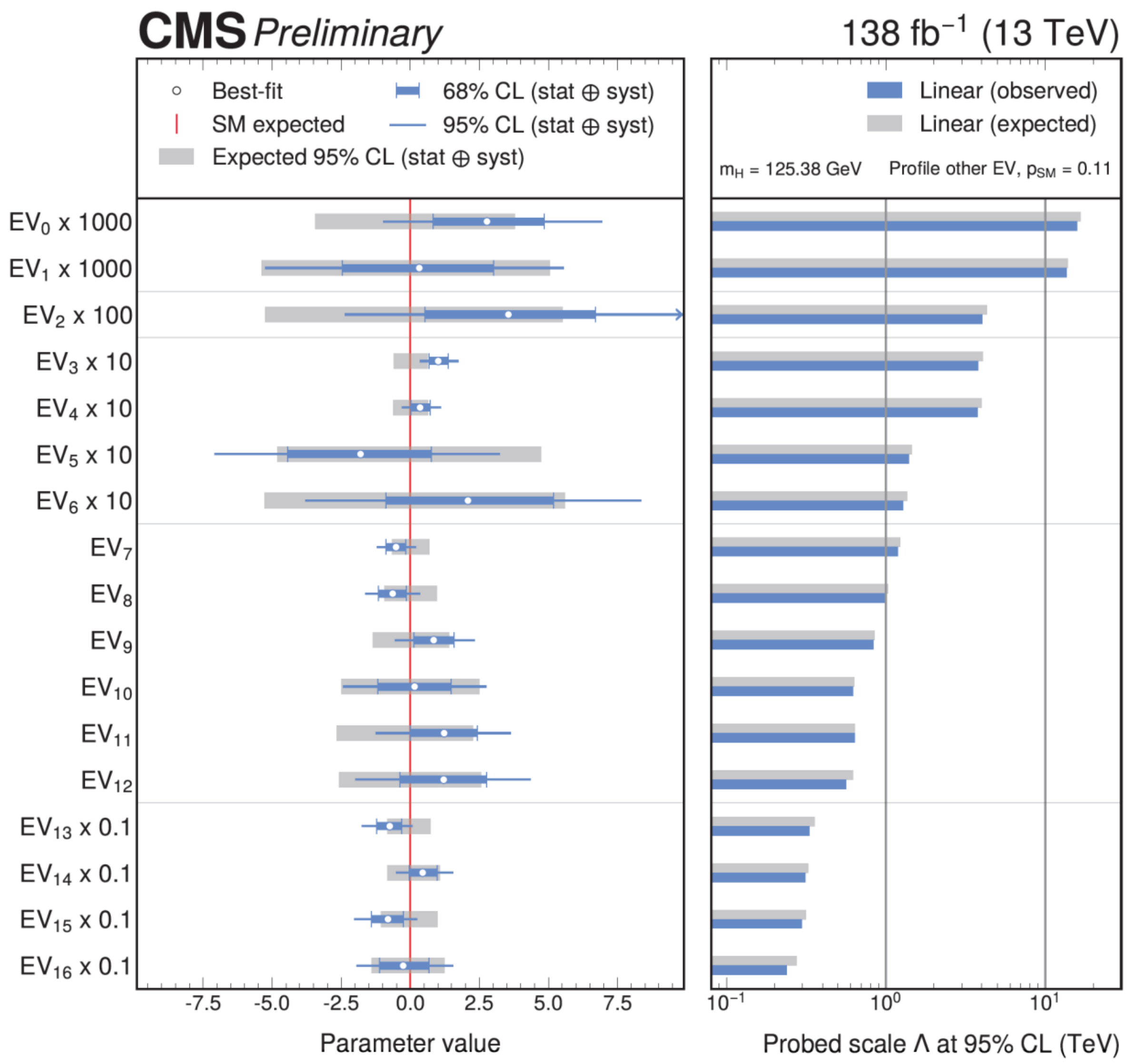


Results in rotated basis

- Mostly consistent with the SM, overall p-value = 0.11
- Discrepancy in $EV_3 = 0.80C_{Hq}^{(3)} + 0.54Re(C_{bH})$ as now expected
- At $EV = 1$, we probe energy scales up to 11 TeV

- Using STXS measurements of the Higgs boson, we can constrain 17 different “directions” of NP with different strength
- Some hints of deviation → focus on in future
- Not enough to claim any discovery
- Can we look in other/more “directions”?



Global fits

- Combine four sectors: Higgs boson, electroweak vector boson, top quark, multi-jet (QCD)

CMS-SMP-24-003

Only one Higgs analysis

Wide variety of others

Analysis	Type of measurement	Observables used	Experimental likelihood
$H \to \gamma\gamma$	Differential cross sections	STXS bins [54]	✓
$W\gamma$	Fiducial differential cross sections	$p_T^{\gamma} \times \lvert\phi_f\rvert$ [33]	✓
$Z \to \nu\nu$	Fiducial differential cross sections	p_T^{Z}	✓
WW	Fiducial differential cross sections	$m_{\ell\ell}$	✓
$t\bar{t}$	Fiducial differential cross sections	$m_{t\bar{t}}$	×
$t(\bar{t})X$	Direct EFT	Yields in regions of interest	✓
Inclusive jet	Fiducial differential cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$	×
EWPO	Pseudo-observables	Γ_Z, σ^0_{had}, R_ℓ, R_c, R_b, $A^{0,\ell}_{FB}$, $A^{0,c}_{FB}$, $A^{0,b}_{FB}$ [36]	×

EWPO: LEP and SLC

Expect to be less sensitive for Higgs-specific couplings but sensitive to more WC's overall

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EWPO	Pseudo-observables	Γ_Z, σ^0_{had}, R_ℓ, R_c, R_b, $A_{FB}^{0,\ell}$, $A_{FB}^{0,c}$, $A_{FB}^{0,b}$ [36]	×

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CMS-SMP-24-003

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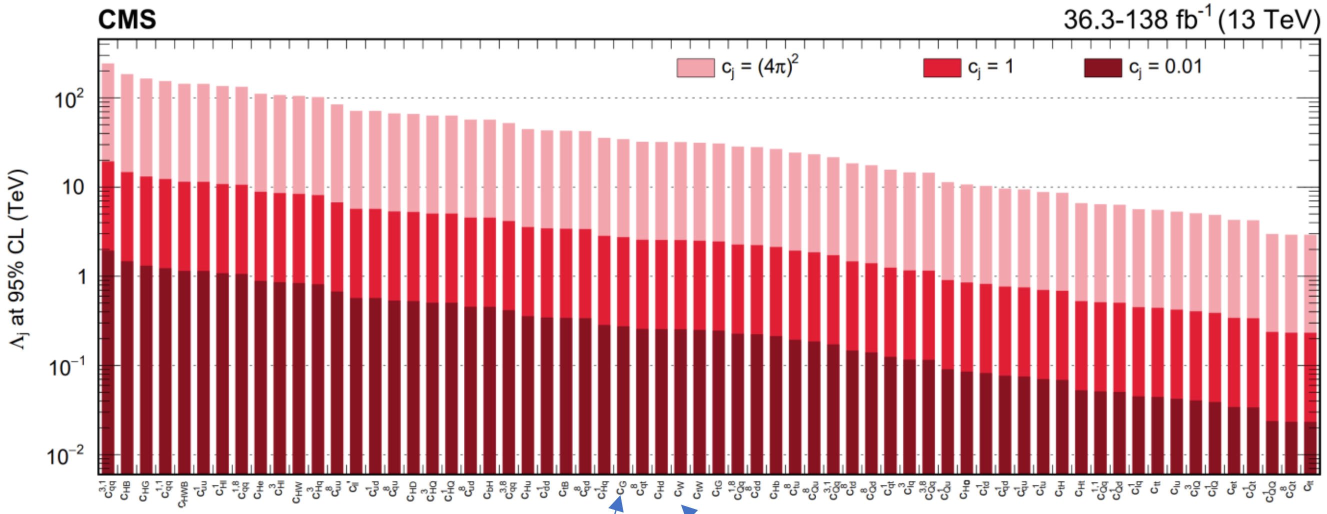


$$Q_G = f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\nu}$$

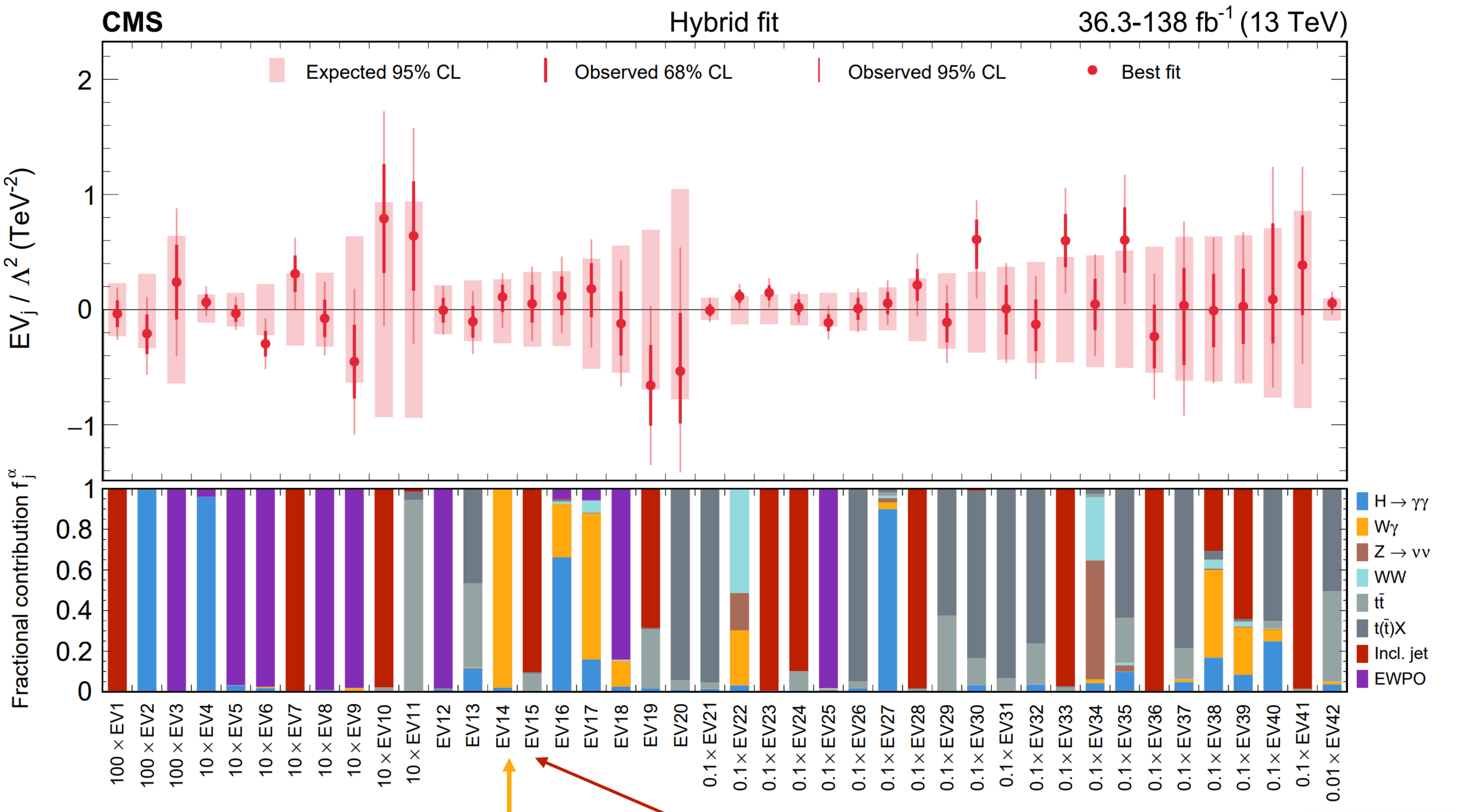
$$Q_W = \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\nu}$$

Individual constraints on 64 WCs!
(43 for Higgs combination)

Fit	Expected 95% CL interval size on C_{HG}
Higgs comb.	± 0.004
Global	± 0.006

Using ~most sensitive channel ($H \rightarrow \gamma\gamma$)
→ not huge difference in sensitivity

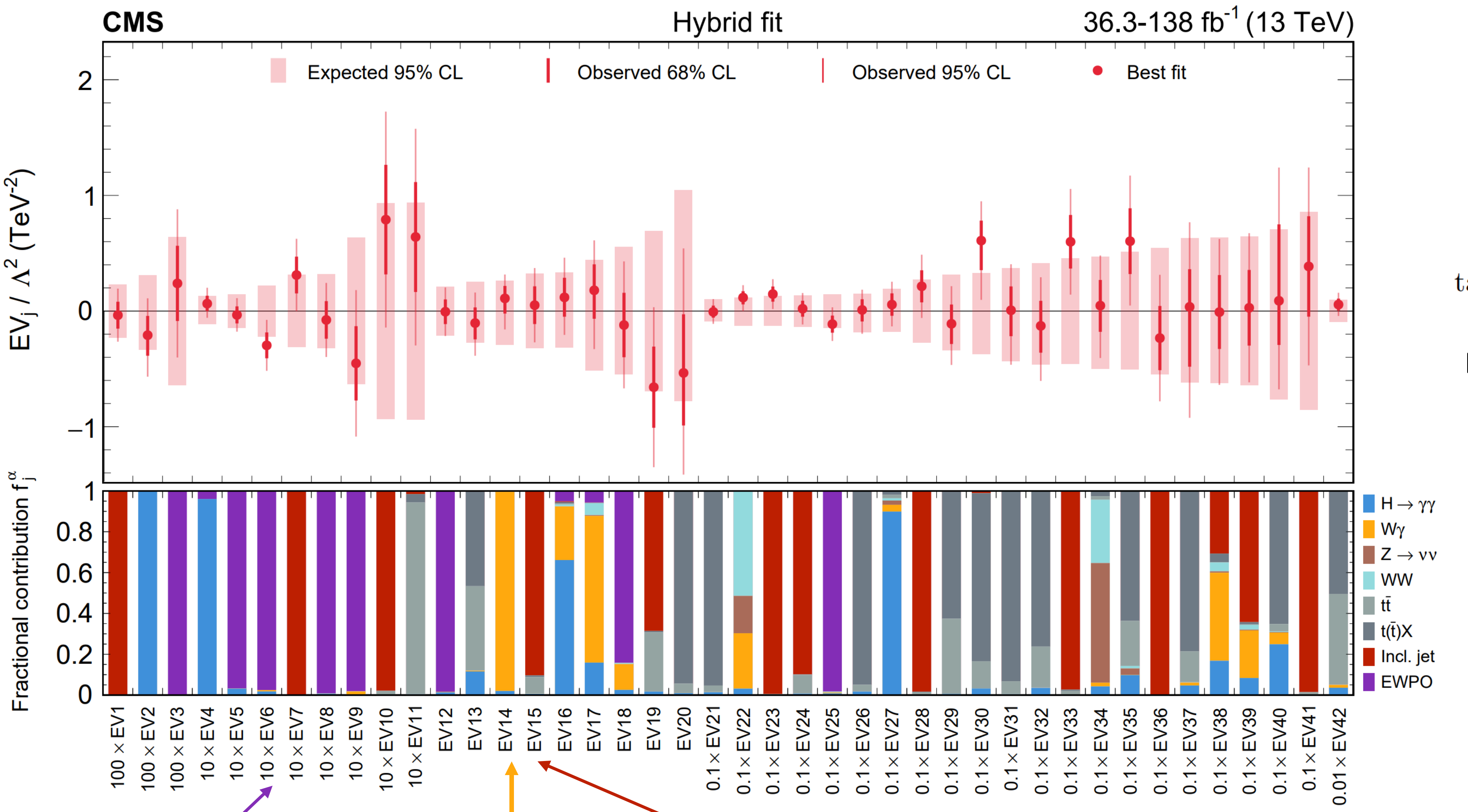
Global fits – simultaneous constraints



$EV_{14} = -C_W$ $\quad$ $EV_{15} = -0.7C_G + \cdots$

Constrain 42 directions simultaneously!

Global fits – simultaneous constraints



$EV_6 = 0.5C_{HWB} + 0.6C_{HD}$ $EV_{14} = -C_W$ $EV_{15} = -0.7C_G + \cdots$

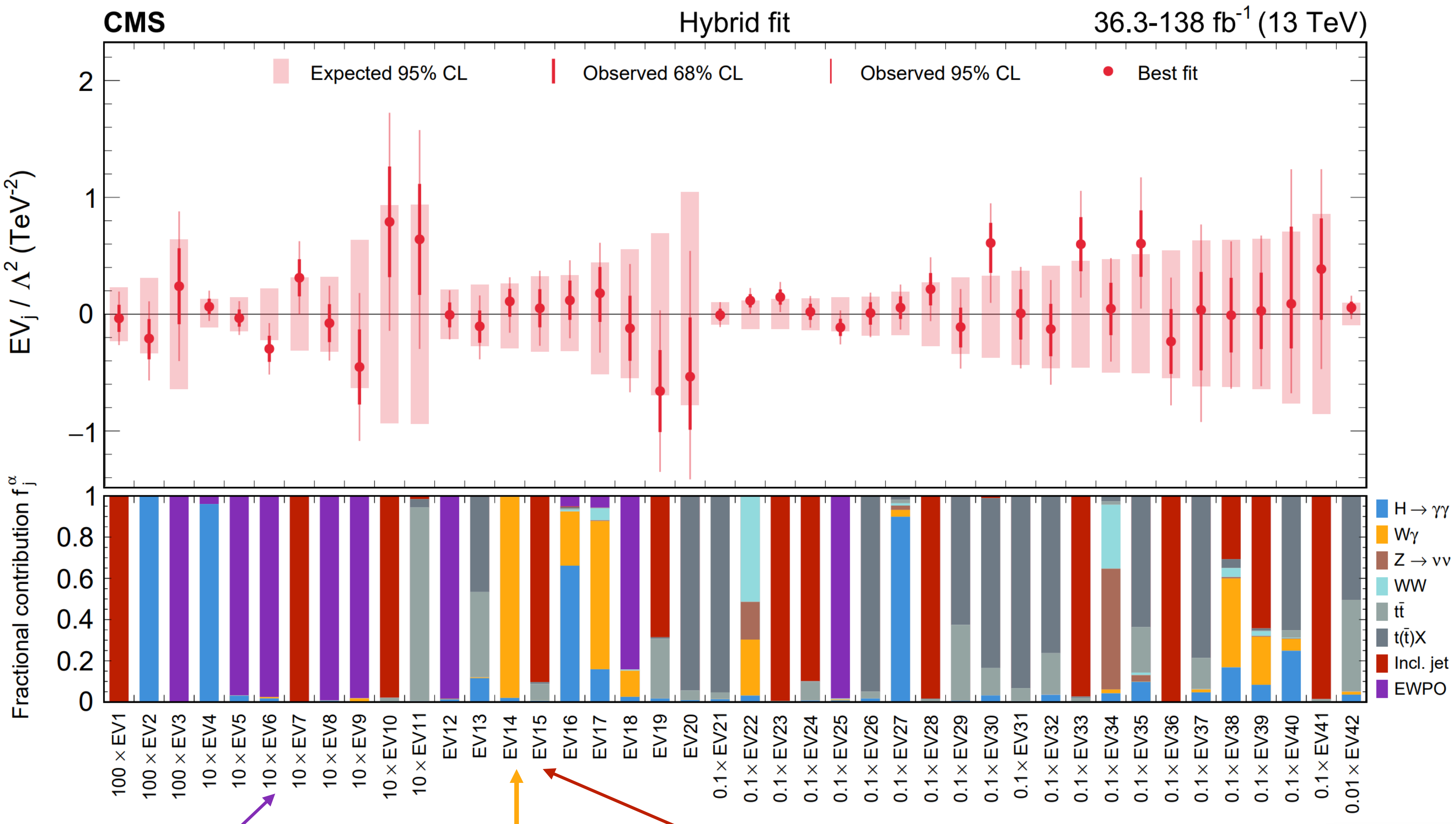
Constrain 42 directions simultaneously!

C_{HWB} affects EWPO via

$$\tan\theta = \frac{g_1}{g_W} + \frac{1}{2}\bar{C}_{HWB}\left(1 - \frac{g_1^2}{g_W^2}\right)$$

EWPO measurements should break a degeneracy

Global fits – simultaneous constraints



$EV_6 = 0.5C_{HWB} + 0.6C_{HD}$ $\quad EV_{14} = -C_W$ $\quad EV_{15} = -0.7C_G + \cdots$

Constrain 42 directions simultaneously!

C_{HWB} affects EWPO via

$$\tan\theta = \frac{g_1}{g_W} + \frac{1}{2}\bar{C}_{HWB}\left(1 - \frac{g_1^2}{g_W^2}\right)$$

EWPO measurements should break a degeneracy

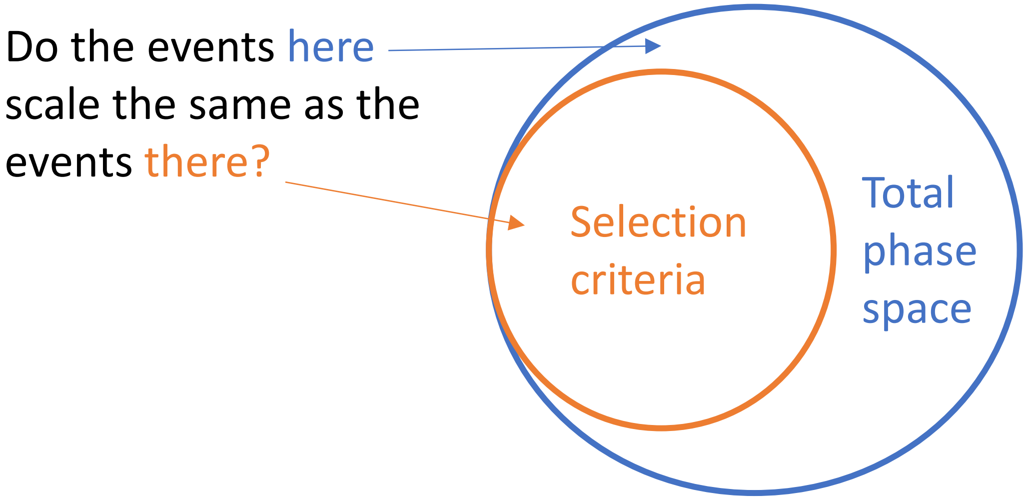
Moving in the right direction…
If we combine even more measurements → greater sensitivity and even wider reaching

But is difficult…
Let's talk about some challenges

Challenges: acceptance corrections

- Is A_{ijc} really independent of C_i?

$$N_{jc}(C_i) = \sum_i \sigma_i(C_i) \times BR_j(C_i) \times A_{ijc}(C_i)$$



Challenges: acceptance corrections

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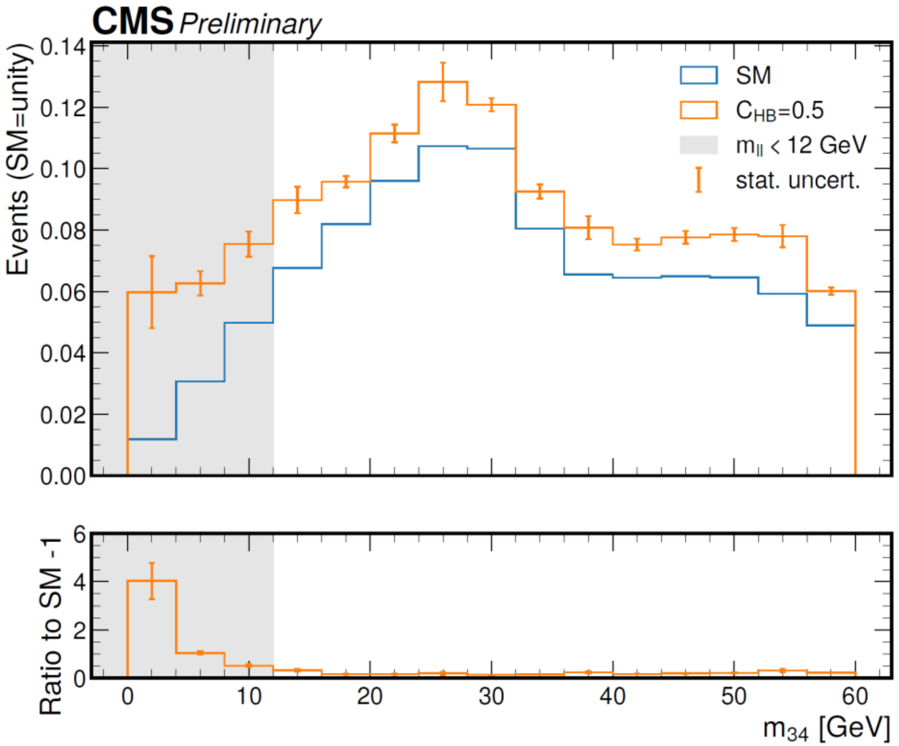
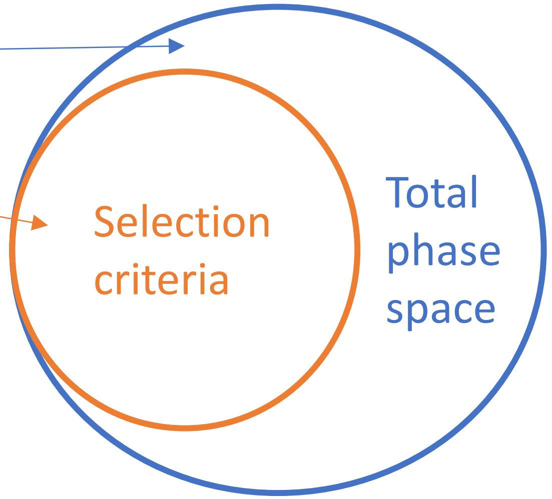
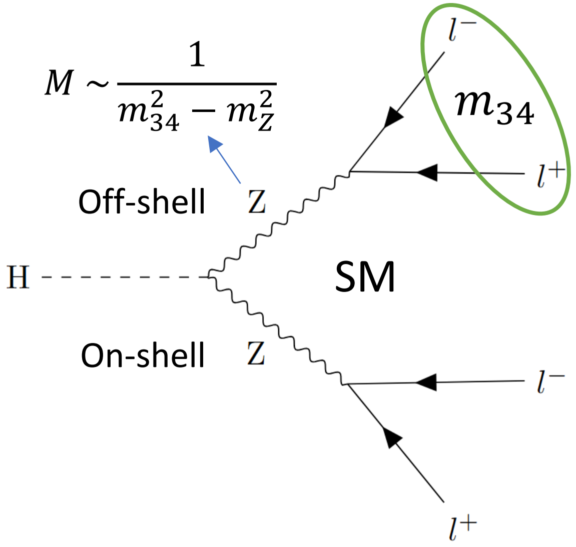
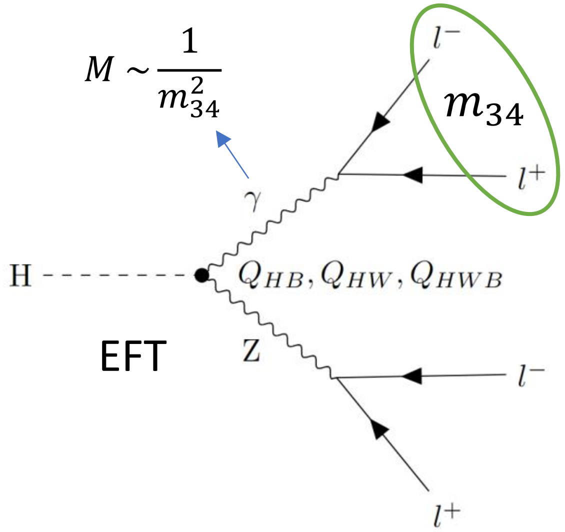


Do the events here scale the same as the events there?



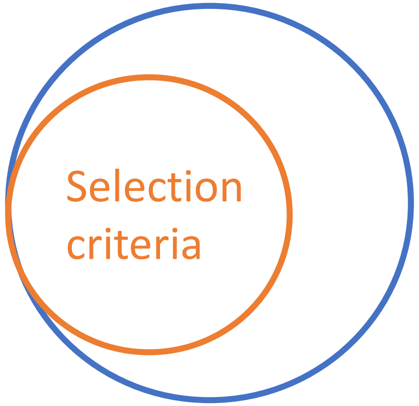


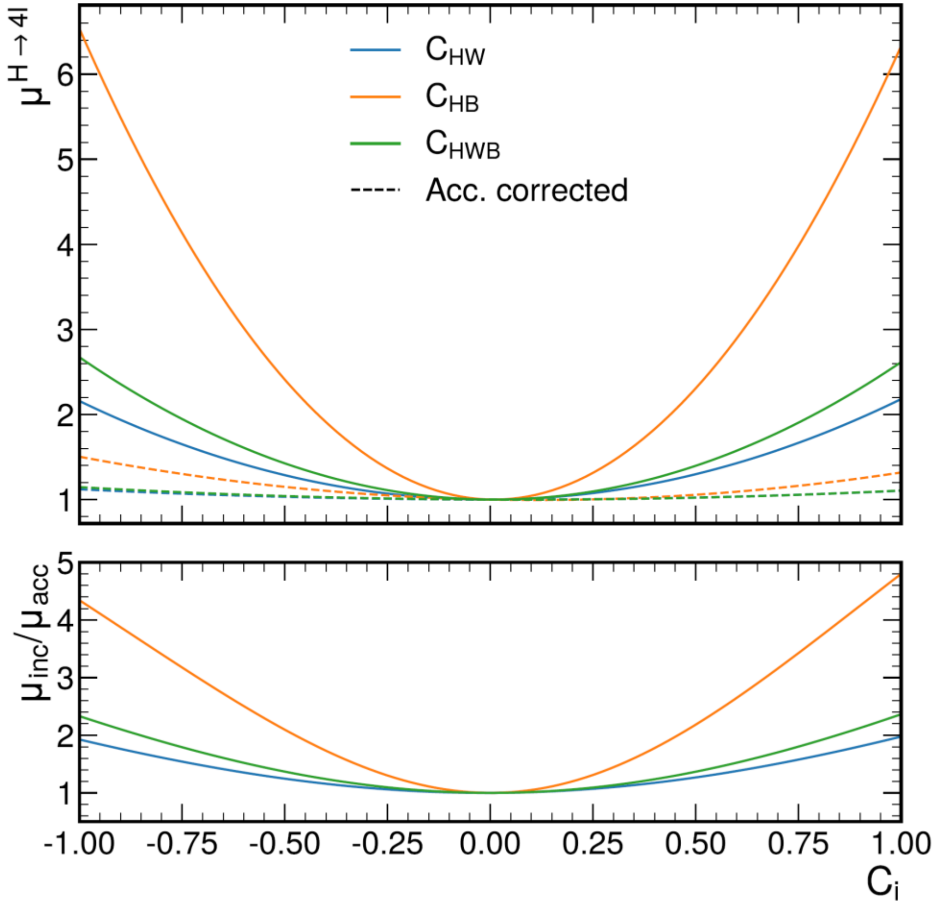


In $H \to 4l$ analysis, we require $m_{34} > 12$ GeV but EFT very dependent on m_{34}
$\to A_{ijc}(C_i) \neq A_{ijc}$!

Accounting for acceptance corrections

- We need to derive $\Gamma_i(C_i)/\Gamma_{SM}$ using events inside selection criteria phase space

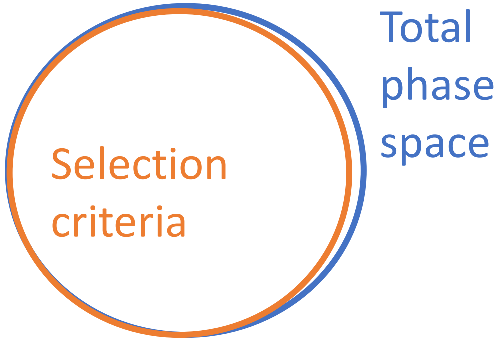




- Required the use of newly-developed reweighting techniques using the same MC samples and selection used by the original analyses
  - More time-consuming but clearly necessary for $H \rightarrow 4l$
- Is challenging to check for every analysis in a combination
  - Either we put in the effort or pick analyses where we know acceptance corrections ought to be small…

Differential fiducial measurements

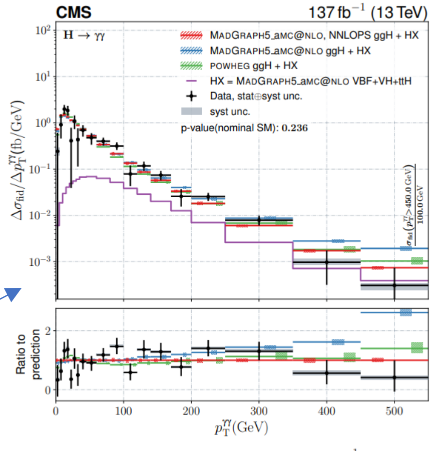
- Fiducial measurements: where you try to match up definition of cross sections to selection criteria as closely as possible



HIG-19-016

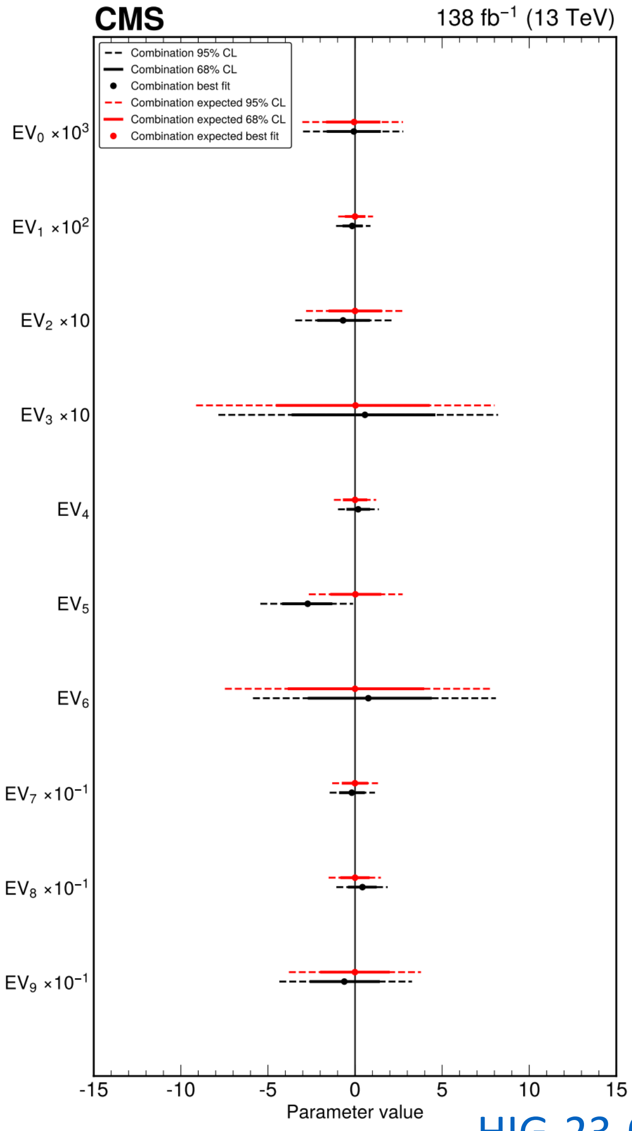
Observable	Selection
$p_T^{\gamma_1}/m_{\gamma\gamma}$	$>1/3$
$p_T^{\gamma_2}/m_{\gamma\gamma}$	$>1/4$
$\mathcal{I}_{\text{gen}}^{\gamma}$	$<10\,\text{GeV}$
$\lvert\eta^{\gamma}\rvert$	<2.5

Fiducial phase space for $H \to \gamma\gamma$
&
measure p_T^H bins



- Selection is often simpler, e.g. less/no machine learning involved
  - Less sensitive but more model-independent (less worries about acceptance)
- How does the analogous combination of fiducial Higgs boson measurements perform?
  - Fewer eigenvectors constrained: 10 instead of 17

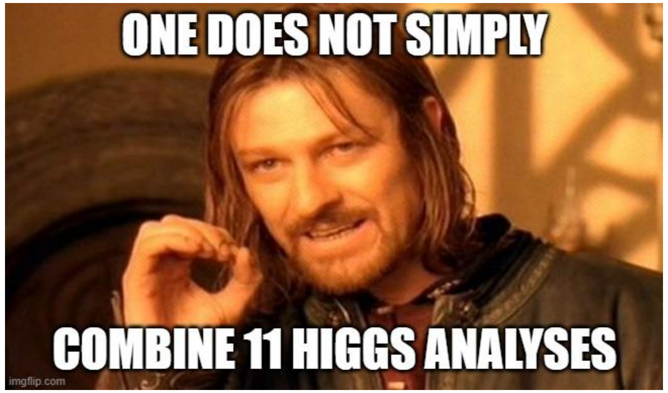
  → Compromise between trustworthiness and sensitivity



HIG-23-013

What else?

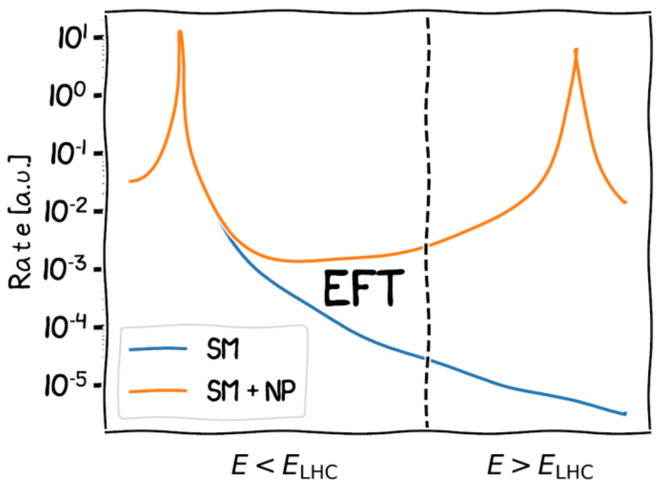
- Combining likelihoods is not an easy job, the Higgs combination alone was a mammoth effort:
  - 1+ years with a team of about 10 people
  - Minimizing the likelihood takes $O(week)$
- Automatic and general EFT predictions do not exist at dimension-8
- Tools for dimension-6 predictions are not all complete either
  - LO tools are fairly complete
  - But NLO (in QCD) tools lack good choices of flavour assumptions, assume CP conservation, no accounting for how EFT affects a particle's width
- What about proton distribution functions (PDFs)?
  - PDFs are extracted from data but assuming SM physics
  - What if some EFT effects are being absorbed into the PDFs?
  - Would we get different constraints on WCs if we did a simultaneous fit?
- EFT in backgrounds
  - In the Higgs combination, we only considered EFT effects in signal but if background also affected → possibly invalidates results

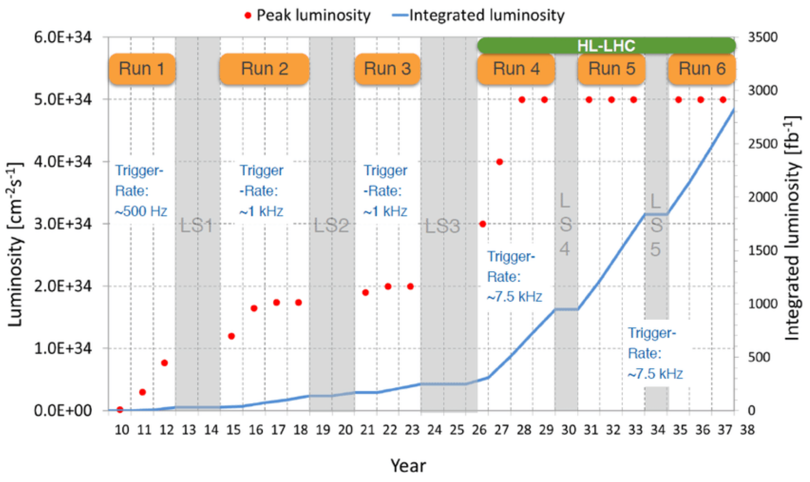


Outlook

- In the absence of direct signatures, EFTs may be our best shot at finding at finding new physics
- EFTs provide a minimally-model dependent approach and are synergistic with combination across sectors
- Results shown here use up to 138 fb^{-1} – the High-Luminosity LHC will bring 3000fb^{-1}!
  - Fantastic opportunity for precision physics and unprecedented SMEFT constraints… but there is a lot of work to do
- Must think ahead about which measurements to perform and interpret, i.e. STXS vs differential fiducial
  - Get good balance between model-independence and sensitivity
- Continue to develop EFT prediction and statistical inference tools
  → more accurate predictions and faster fits
- Already made good progress over the last 5 years, I reckon we've got a good shot in the next 15-20

🤞 for a discovery!





Cumulative integrated luminosity during HL-LHC
*subject to change