# EFT interpretations in the Higgs sector at CMS

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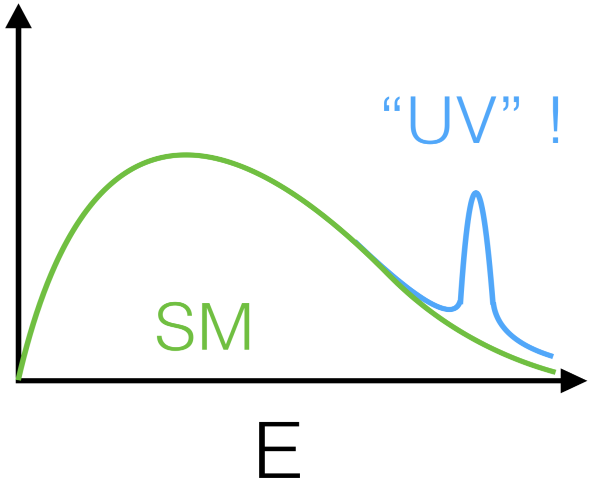
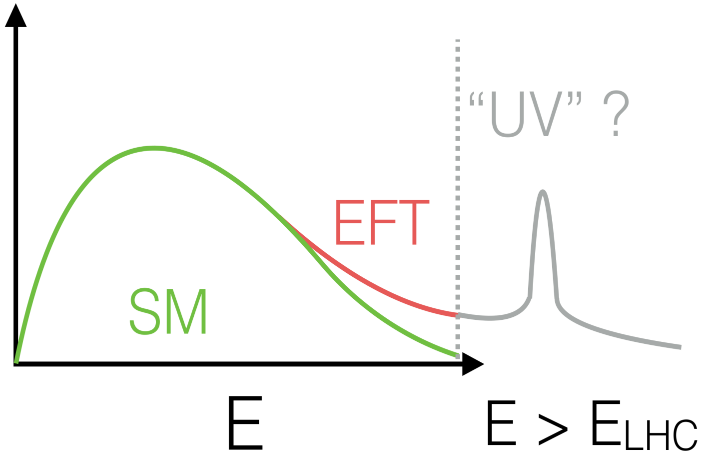
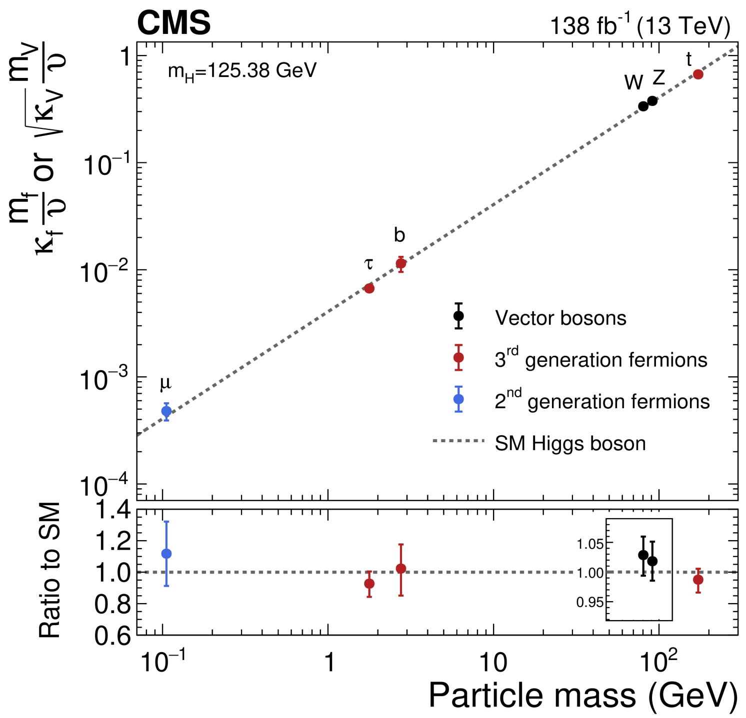
*On behalf of* CMS Collaboration

# Searching for New Physics?




**So far no evidence of New Physics at the LHC**

→ NP at energies reachable by the LHC → **direct** searches for BSM

→ NP at energies **beyond** LHC → **indirect** searches for NP → **EFT** ("model-independent"), ...

**Look for the smallest deviations with the highest available precision!**

# SM Effective Field Theory (SMEFT)

| Operator | Definition | Wilson coefficient | Operator | Definition | Wilson coefficient |
|---|---|---|---|---|---|
| $\mathcal{O}_{Hq}^{(1)}$ | $iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$ | $c_{Hq}^{(1)}$ | $\mathcal{O}_{HWB}$ | $H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$ | $c_{HWB}$ |
| $\mathcal{O}_{Hq}^{(3)}$ | $iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$ | $c_{Hq}^{(3)}$ | $\mathcal{O}_{H\widetilde{W}B}$ | $H^\dagger \sigma^a H W^a_{\mu\nu} \widetilde{B}^{\mu\nu}$ | $c_{H\widetilde{W}B}$ |
| $\mathcal{O}_{Hu}$ | $iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$ | $c_{Hu}$ | $\mathcal{O}_{HW}$ | $(H^\dagger H)\, W^a_{\mu\nu} W^{a\mu\nu}$ | $c_{HW}$ |
| $\mathcal{O}_{Hd}$ | $iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$ | $c_{Hd}$ | $\mathcal{O}_{H\widetilde{W}}$ | $(H^\dagger H)\, W^a_{\mu\nu} \widetilde{W}^{a\mu\nu}$ | $c_{H\widetilde{W}}$ |
| $\mathcal{O}_{HD}$ | $(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$ | $c_{HD}$ | $\mathcal{O}_{HB}$ | $(H^\dagger H)\, B_{\mu\nu} B^{\mu\nu}$ | $c_{HB}$ |
| $\mathcal{O}_{H\Box}$ | $(H^\dagger H)\Box(H^\dagger H)$ | $c_{H\Box}$ | $\mathcal{O}_{H\widetilde{B}}$ | $(H^\dagger H)\, B_{\mu\nu} \widetilde{B}^{\mu\nu}$ | $c_{H\widetilde{B}}$ |

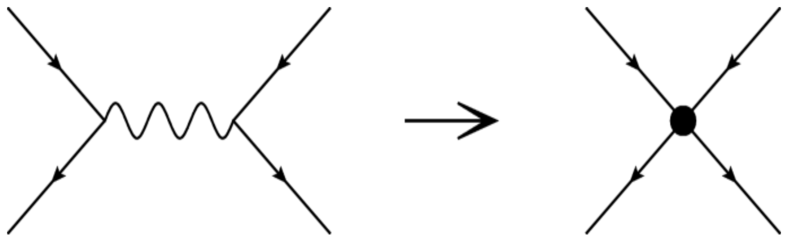
lepton number violation

$$\mathscr{L}_{SMEFT} = \mathscr{L}^4_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \mathcal{O}(8) + \ldots$$

allowed, but neglected ($1/\Lambda^4$)

$$\sigma = |\mathcal{A}_{SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_{SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4}\left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_j^{(6)*}\right)$$

$$\begin{aligned}\mathcal{L}_{SM}^{(4)} &= -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2\varphi^\dagger\varphi - \frac{1}{2}\lambda\left(\varphi^\dagger\varphi\right)^2 \\ &+ i\left(\bar{l}\not{D}l + \bar{e}\not{D}e + \bar{q}\not{D}q + \bar{u}\not{D}u + \bar{d}\not{D}d\right) - \left(\bar{l}\,\Gamma_e e\varphi + \bar{q}\,\Gamma_u u\widetilde{\varphi} + \bar{q}\,\Gamma_d d\varphi + \mathrm{h.c.}\right)\end{aligned}$$



Fermi theory is an example of an EFT

**SMEFT**

→ Theoretically consistent and model-independent approach

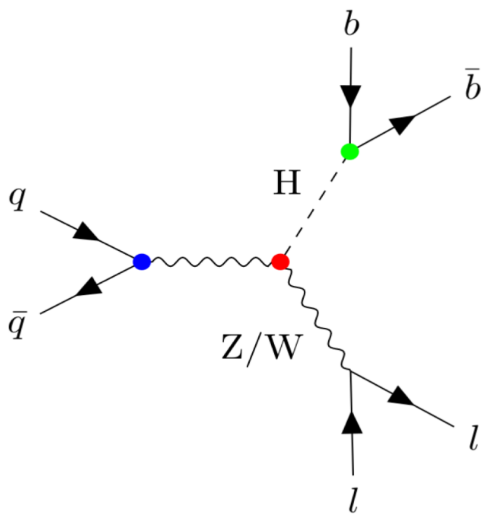
→ Operator expansion typically truncated at dim(6)

→ 2499 operators are possible → reduced to ~100 depending on the assumptions (flavour)

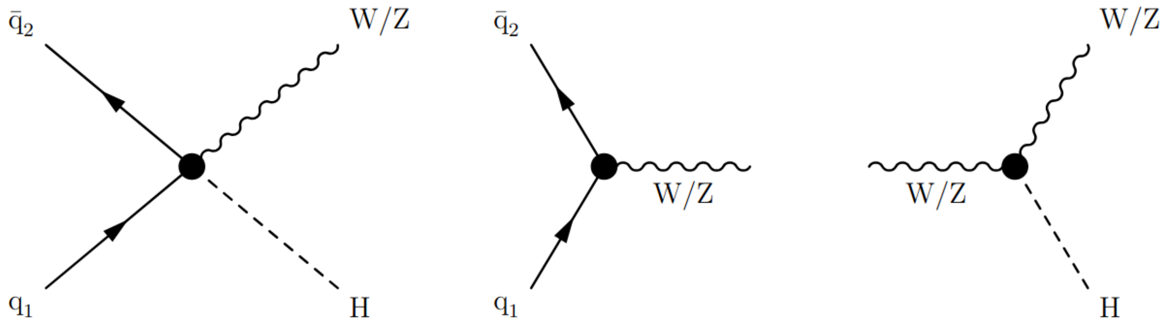
→ Choice of operators depends on the process / an operator is not unique to a process

# VH(bb) EFT

CMS-PAS-HIG-23-016




$Z \to ll$
$Z \to \nu\nu$
$W \to l\nu$



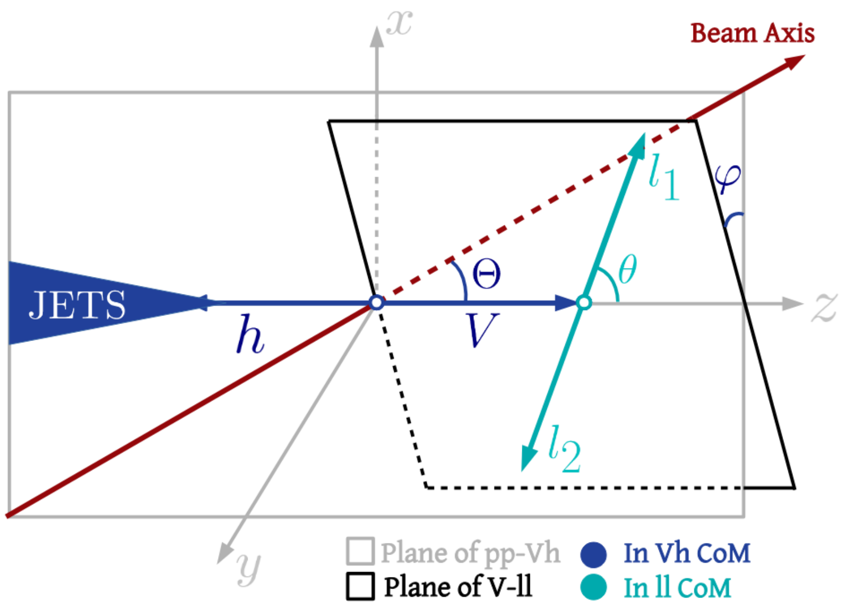

→ EFT effects simulated for the signal

→ Optimal observables

→ Boosted information tree – separation of EFT effects from the SM signal **and** background

→ Measurement in three decay channels (0 or 2 charged leptons (Z) and 1 charged lepton (W)

→ resolved + boosted b quark jets (below and above 250 GeV)



# VH(bb) EFT

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| Operator | Definition | Wilson coefficient | Operator | Definition | Wilson coefficient | |
|---|---|---|---|---|---|---|
| $\mathcal{O}_{\mathrm{Hq}}^{(1)}$ | $i\mathrm{H}^\dagger \overleftrightarrow{D}_\mu \mathrm{H}\bar{\mathrm{q}}_\mathrm{L}\gamma^\mu \mathrm{q}_\mathrm{L}$ | $c_{\mathrm{Hq}}^{(1)}$ | $\mathcal{O}_{\mathrm{HWB}}$ | $\mathrm{H}^\dagger\sigma^a \mathrm{H} \mathrm{W}^a_{\mu\nu}\mathrm{B}^{\mu\nu}$ | $c_{\mathrm{HWB}}$ | CP-even |
| $\mathcal{O}_{\mathrm{Hq}}^{(3)}$ | $i\mathrm{H}^\dagger\sigma^a \overleftrightarrow{D}_\mu \mathrm{H}\bar{\mathrm{q}}_\mathrm{L}\sigma^a\gamma^\mu \mathrm{q}_\mathrm{L}$ | $c_{\mathrm{Hq}}^{(3)}$ | $\mathcal{O}_{\mathrm{H\widetilde{W}B}}$ | $\mathrm{H}^\dagger\sigma^a \mathrm{H} \mathrm{W}^a_{\mu\nu}\widetilde{\mathrm{B}}^{\mu\nu}$ | $c_{\mathrm{H\widetilde{W}B}}$ | CP-odd |
| $\mathcal{O}_{\mathrm{Hu}}$ | $i\mathrm{H}^\dagger \overleftrightarrow{D}_\mu \mathrm{H}\bar{\mathrm{u}}_\mathrm{R}\gamma^\mu \mathrm{u}_\mathrm{R}$ | $c_{\mathrm{Hu}}$ | $\mathcal{O}_{\mathrm{HW}}$ | $(\mathrm{H}^\dagger\mathrm{H})\,\mathrm{W}^a_{\mu\nu}\mathrm{W}^{a\mu\nu}$ | $c_{\mathrm{HW}}$ | |
| $\mathcal{O}_{\mathrm{Hd}}$ | $i\mathrm{H}^\dagger \overleftrightarrow{D}_\mu \mathrm{H}\bar{\mathrm{d}}_\mathrm{R}\gamma^\mu \mathrm{d}_\mathrm{R}$ | $c_{\mathrm{Hd}}$ | $\mathcal{O}_{\mathrm{H\widetilde{W}}}$ | $(\mathrm{H}^\dagger\mathrm{H})\,\mathrm{W}^a_{\mu\nu}\widetilde{\mathrm{W}}^{a\mu\nu}$ | $c_{\mathrm{H\widetilde{W}}}$ | |
| $\mathcal{O}_{\mathrm{HD}}$ | $(\mathrm{H}^\dagger D^\mu \mathrm{H})^*(\mathrm{H}^\dagger D_\mu \mathrm{H})$ | $c_{\mathrm{HD}}$ | $\mathcal{O}_{\mathrm{HB}}$ | $(\mathrm{H}^\dagger\mathrm{H})\,\mathrm{B}_{\mu\nu}\mathrm{B}^{\mu\nu}$ | $c_{\mathrm{HB}}$ | |
| $\mathcal{O}_{\mathrm{H}\Box}$ | $(\mathrm{H}^\dagger\mathrm{H})\Box(\mathrm{H}^\dagger\mathrm{H})$ | $c_{\mathrm{H}\Box}$ | $\mathcal{O}_{\mathrm{H\widetilde{B}}}$ | $(\mathrm{H}^\dagger\mathrm{H})\,\mathrm{B}_{\mu\nu}\widetilde{\mathrm{B}}^{\mu\nu}$ | $c_{\mathrm{H\widetilde{B}}}$ | |

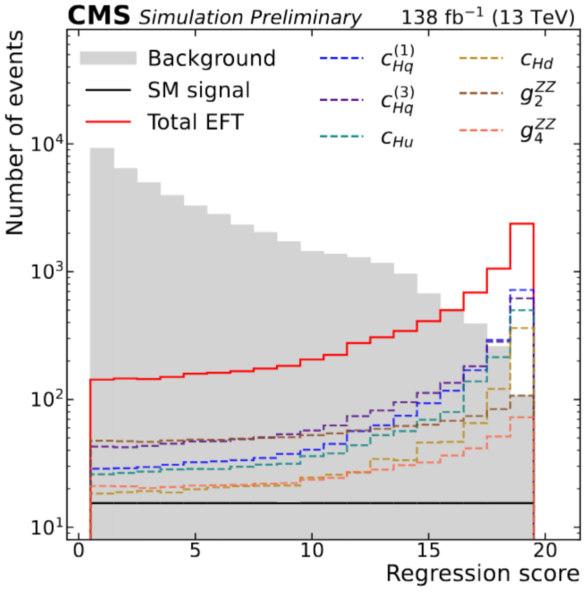
$$g_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 c_{\mathrm{HB}} + c_w^2 c_{\mathrm{HW}} + s_w c_w c_{\mathrm{HWB}}\right)$$
$$g_2^{Z\gamma} = -2\frac{v^2}{\Lambda^2}\left(s_w c_w (c_{\mathrm{HW}} - c_{\mathrm{HB}}) + \frac{1}{2}(s_w^2 - c_w^2) c_{\mathrm{HWB}}\right)$$
$$g_2^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 c_{\mathrm{HB}} + s_w^2 c_{\mathrm{HW}} - s_w c_w c_{\mathrm{HWB}}\right),$$

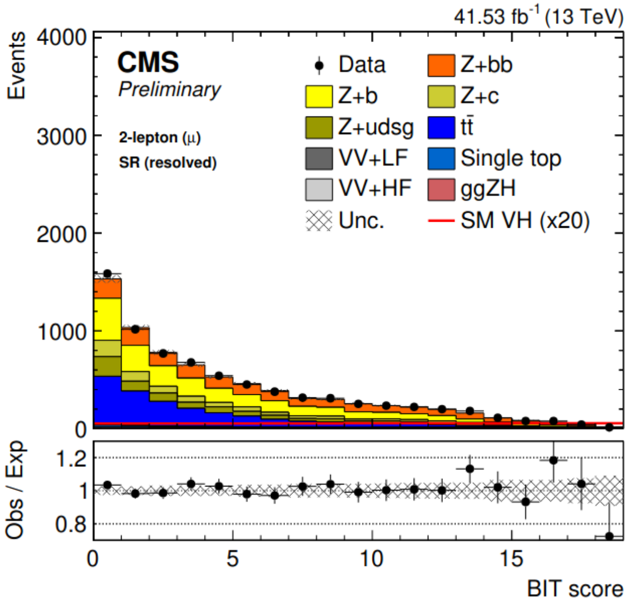
$s_w = \sin\theta_\mathrm{w}$, $c_w = \cos\theta_\mathrm{w}$

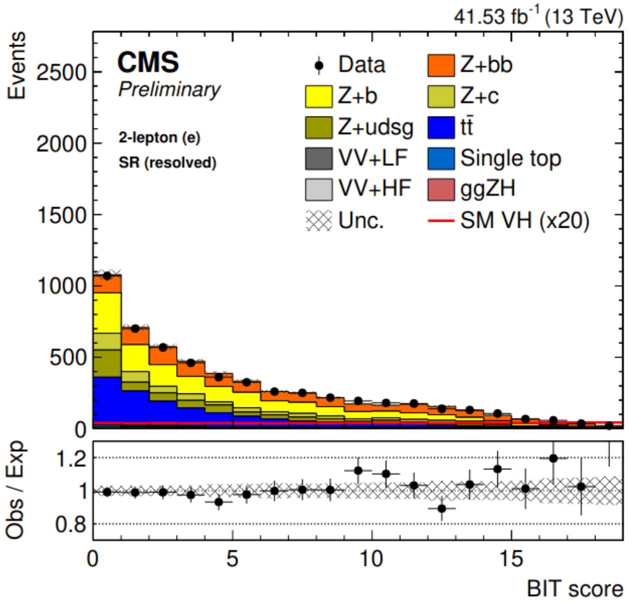
$$g_4^{ZZ} = \tilde{g}_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 c_{\mathrm{H\widetilde{B}}} + c_w^2 c_{\mathrm{H\widetilde{W}}} + s_w c_w c_{\mathrm{H\widetilde{W}B}}\right)$$
$$g_4^{Z\gamma} = \tilde{g}_2^{Z\gamma} = -2\frac{v^2}{\Lambda^2}\left(s_w c_w (c_{\mathrm{H\widetilde{W}}} - c_{\mathrm{H\widetilde{B}}}) + \frac{1}{2}(s_w^2 - c_w^2) c_{\mathrm{H\widetilde{W}B}}\right)$$
$$g_4^{\gamma\gamma} = \tilde{g}_2^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 c_{\mathrm{H\widetilde{B}}} + s_w^2 c_{\mathrm{H\widetilde{W}}} - s_w c_w c_{\mathrm{H\widetilde{W}B}}\right).$$

# VH(bb) EFT

CMS-PAS-HIG-23-016




→ Boosted Information Tree (BIT) templates

→ Optimal at a single point in the Wilson coefficient space → not optimal elsewhere

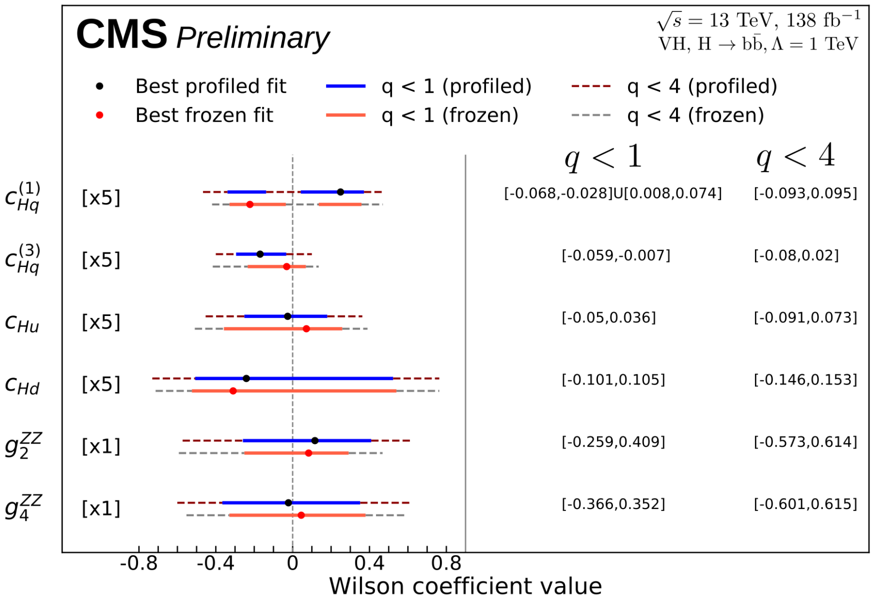
→ Retain as much optimality as possible when profiling all six coefficients

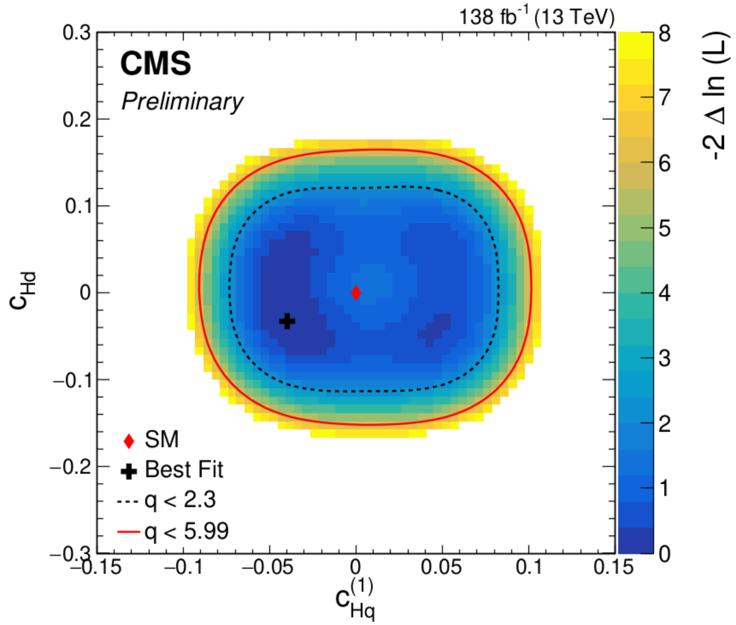
→ Avoid regions in the Wilson coefficient space where anticorrelation among coefficients plays a greater role

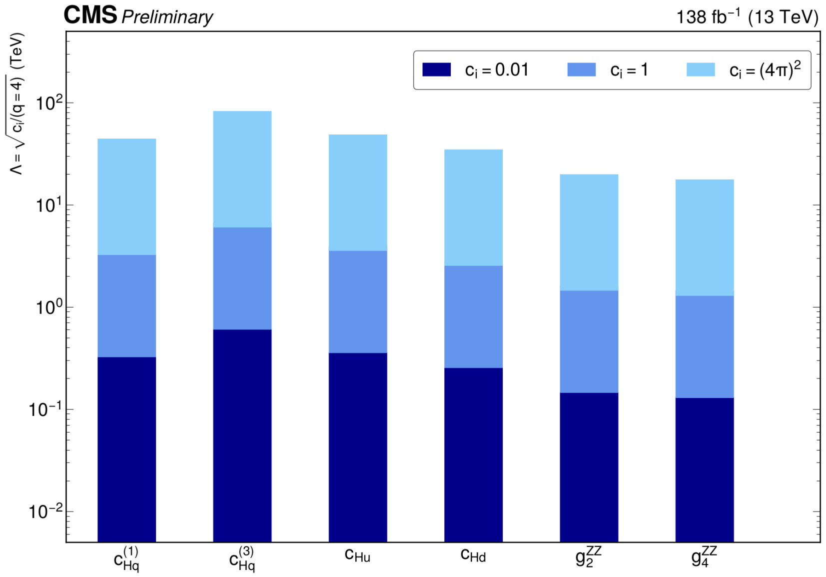
→ Analysis channel / coefficient split for the optimisation → still profiled together

# VH(bb) EFT

CMS-PAS-HIG-23-016




→ Wilson coefficients measured with others frozen at SM and freely floating

→ 2D scans explore correlations between coefficients

→ Limits reported on the cut-off scale for fixed values of Wilson coefficients

→ Results in agreement with SM

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# H→WW anomalous couplings

**ANOMALOUS COUPLINGS**

$$a_1^{WW} = a_1^{ZZ},$$
$$a_2^{WW} = c_w^2 a_2^{ZZ},$$
$$a_3^{WW} = c_w^2 a_3^{ZZ},$$
$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2} = \frac{1}{c_w^2 - s_w^2}\left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} - 2s_w^2 \frac{a_2^{ZZ}}{m_Z^2}\right),$$
$$\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2} = \frac{2s_w c_w}{c_w^2 - s_w^2}\left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} - \frac{a_2^{ZZ}}{m_Z^2}\right),$$

$$A(HV_1V_2) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{\left(\Lambda_1^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

→ Hgg and HVV couplings + CP violation using the different-flavour dilepton final state from H→WW

→ Production via ggH, VBF, and VH

→ Matrix element likelihood method (MELA)

→ Constraints in terms of anomalous couplings as well as SMEFT (Higgs and Warsaw basis)

→ Measuring fractional contributions of the anomalous couplings to the Higgs boson cross section

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \operatorname{sign}\left(\frac{a_i}{a_1}\right)$$

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# H→WW anomalous couplings

**ANOMALOUS COUPLINGS**

$$
\begin{aligned}
a_1^{\mathrm{WW}} &= a_1^{\mathrm{ZZ}}, \\
a_2^{\mathrm{WW}} &= c_{\mathrm{w}}^2 a_2^{\mathrm{ZZ}}, \\
a_3^{\mathrm{WW}} &= c_{\mathrm{w}}^2 a_3^{\mathrm{ZZ}}, \\
\frac{\kappa_1^{\mathrm{WW}}}{(\Lambda_1^{\mathrm{WW}})^2} &= \frac{1}{c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2}\left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} - 2s_{\mathrm{w}}^2 \frac{a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2}\right), \\
\frac{\kappa_2^{\mathrm{Z}\gamma}}{(\Lambda_1^{\mathrm{Z}\gamma})^2} &= \frac{2 s_{\mathrm{w}} c_{\mathrm{w}}}{c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2}\left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} - \frac{a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2}\right),
\end{aligned}
$$

**SMEFT – HIGGS BASIS**

$$
\begin{aligned}
\delta c_{\mathrm{z}} &= \frac{1}{2} a_1^{\mathrm{ZZ}} - 1, \\
c_{\mathrm{zz}} &= -\frac{2 s_{\mathrm{w}}^2 c_{\mathrm{w}}^2}{e^2} a_2^{\mathrm{ZZ}}, \\
\tilde{c}_{\mathrm{zz}} &= -\frac{2 s_{\mathrm{w}}^2 c_{\mathrm{w}}^2}{e^2} a_3^{\mathrm{ZZ}}, \\
c_{\mathrm{z}\Box} &= \frac{m_{\mathrm{Z}}^2 s_{\mathrm{w}}^2}{e^2} \frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2},
\end{aligned}
$$

**SMEFT – WARSAW BASIS**

$$
\begin{aligned}
\delta a_1^{\mathrm{ZZ}} &= \frac{v^2}{\Lambda^2}\left(2 c_{\mathrm{H}\Box} + \frac{6e^2}{s_{\mathrm{w}}^2} c_{\mathrm{HWB}} + \left(\frac{3 c_{\mathrm{w}}^2}{2 s_{\mathrm{w}}^2} - \frac{1}{2}\right) c_{\mathrm{HD}}\right), \\
\kappa_1^{\mathrm{ZZ}} &= \frac{v^2}{\Lambda^2}\left(-\frac{2e^2}{s_{\mathrm{w}}^2} c_{\mathrm{HWB}} + \left(1 - \frac{1}{2 s_{\mathrm{w}}^2}\right) c_{\mathrm{HD}}\right), \\
a_2^{\mathrm{ZZ}} &= -2\frac{v^2}{\Lambda^2}\left(s_{\mathrm{w}}^2 c_{\mathrm{HB}} + c_{\mathrm{w}}^2 c_{\mathrm{HW}} + s_{\mathrm{w}} c_{\mathrm{w}} c_{\mathrm{HWB}}\right), \\
a_3^{\mathrm{ZZ}} &= -2\frac{v^2}{\Lambda^2}\left(s_{\mathrm{w}}^2 c_{\mathrm{H\tilde{B}}} + c_{\mathrm{w}}^2 c_{\mathrm{H\tilde{W}}} + s_{\mathrm{w}} c_{\mathrm{w}} c_{\mathrm{H\tilde{W}B}}\right),
\end{aligned}
$$

→ Hgg and HVV couplings + CP violation using the different-flavour dilepton final state from H→WW

→ Production via ggH, VBF, and VH

→ Matrix element likelihood method (MELA)

→ Constraints in terms of anomalous couplings as well as SMEFT (Higgs and Warsaw basis)

→ Measuring fractional contributions of the anomalous couplings to the Higgs boson cross section

$$
f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \,\mathrm{sign}\left(\frac{a_i}{a_1}\right)
$$

# H→WW anomalous couplings

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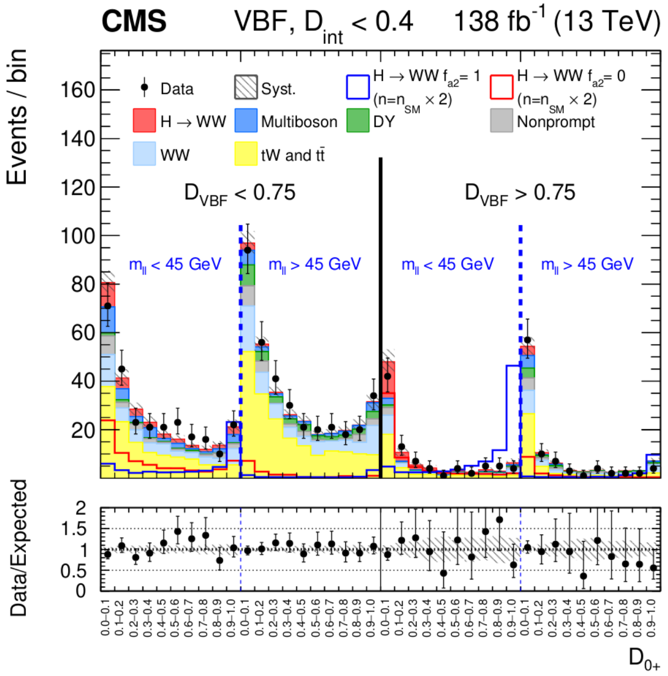


$$\mathcal{D}_{\text{sig}} = \frac{\mathcal{P}_{\text{sig}}(\Omega)}{\mathcal{P}_{\text{sig}}(\Omega) + \mathcal{P}_{\text{bkg}}(\Omega)}$$

$$\mathcal{D}_{\text{BSM}} = \frac{\mathcal{P}_{\text{BSM}}(\Omega)}{\mathcal{P}_{\text{BSM}}(\Omega) + \mathcal{P}_{\text{SM}}(\Omega)}$$

$$\mathcal{D}_{\text{int}} = \frac{\mathcal{P}^{\text{int}}_{\text{SM-BSM}}(\Omega)}{\mathcal{P}_{\text{SM}}(\Omega) + \mathcal{P}_{\text{BSM}}(\Omega)}$$

Observables for HVV coupling:
→ two jets in VBF and VH
→ H→WW decay products

Observables for Hgg coupling:
→ two jets from ggH + 2 jets

Decay vertex discriminant: $m_{ll}$

→ Hgg and HVV couplings + CP violation using the different-flavour dilepton final state from H→WW

→ Production via ggH, VBF, and VH

→ Matrix element likelihood method (MELA)

→ Constraints in terms of anomalous couplings as well as SMEFT (Higgs and Warsaw basis)

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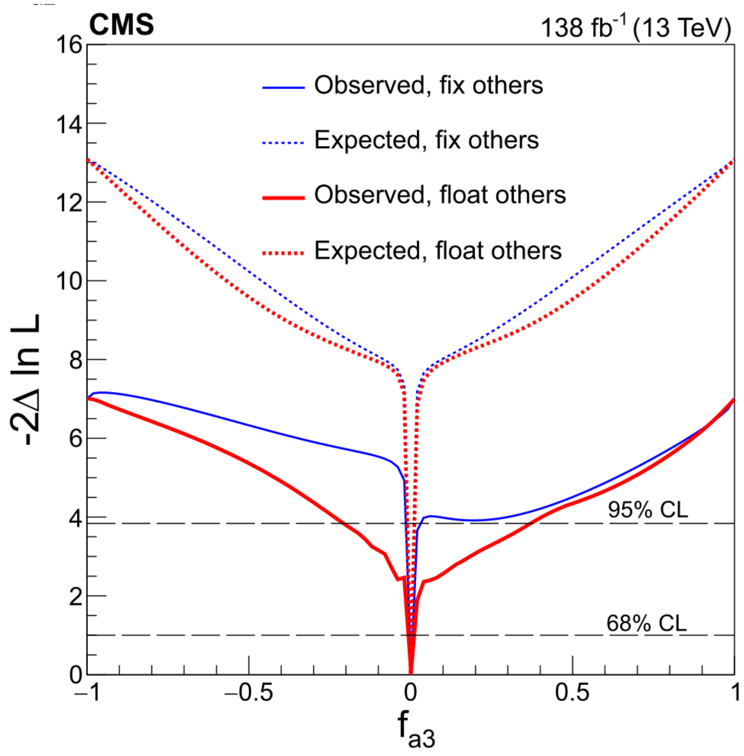
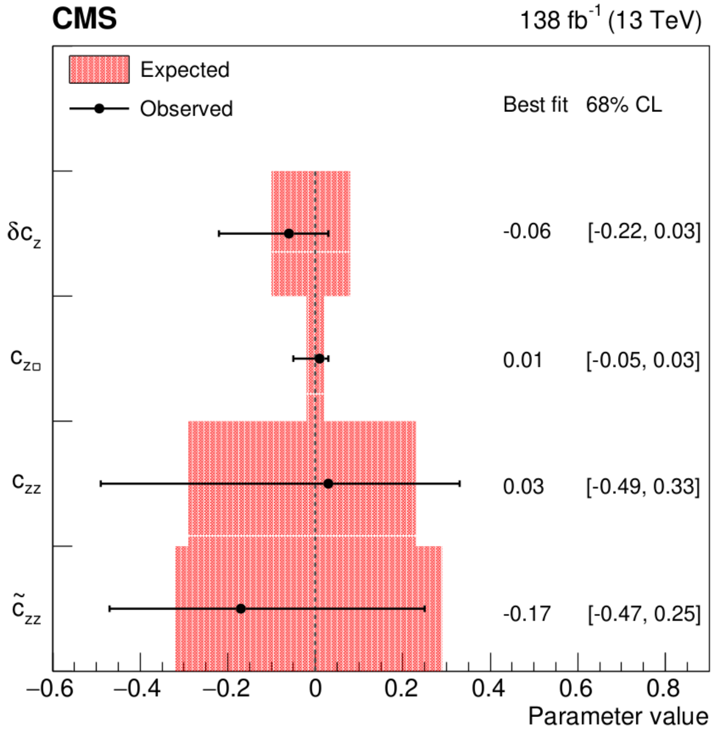
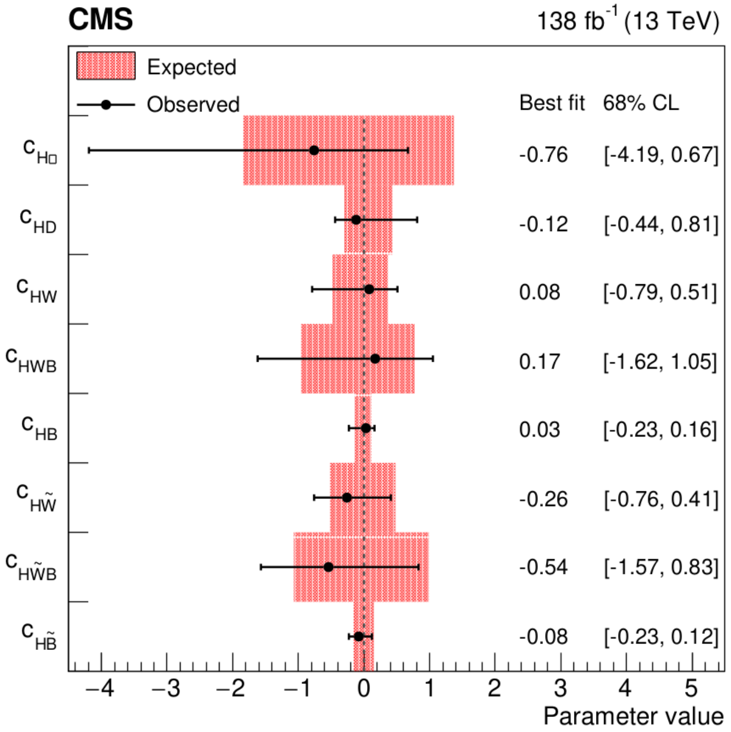
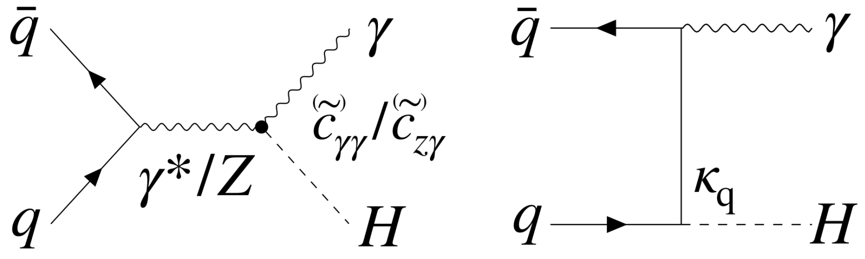


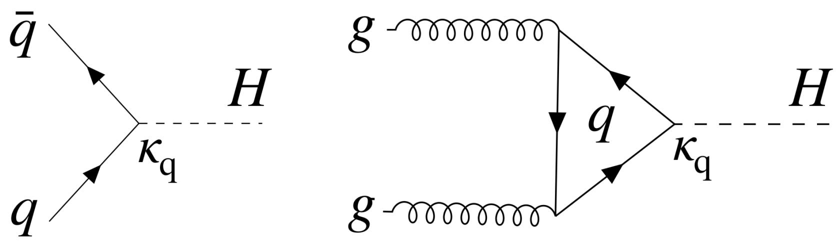



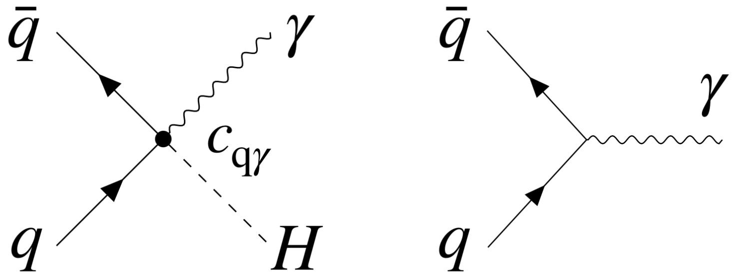



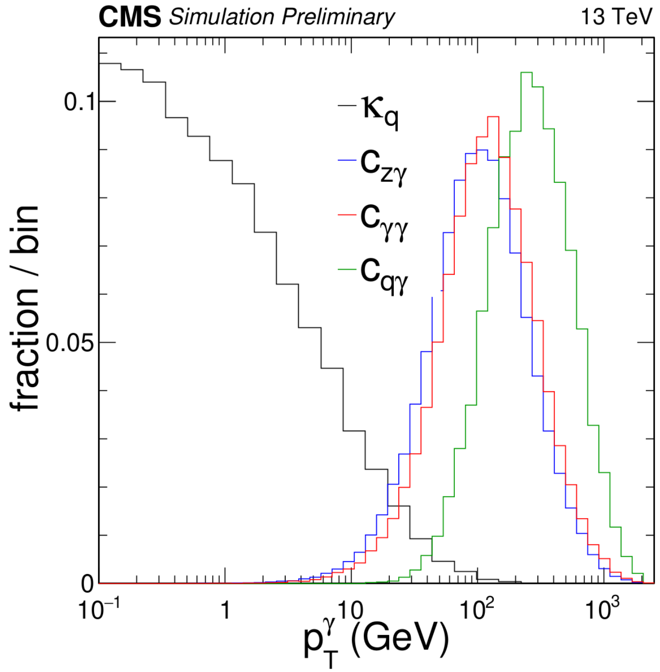

→ 1-D likelihood profiles
→ Correlations between coefficients explored

# H→ZZ→4l and H→bb (Hγγ and HZγ anomalous couplings)



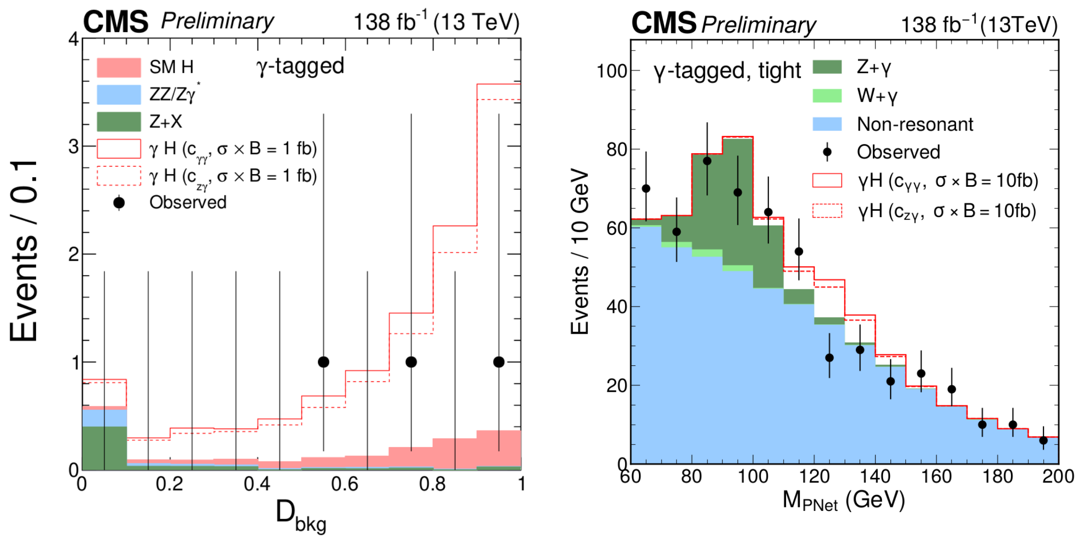

→ Constraint on γH production cross section

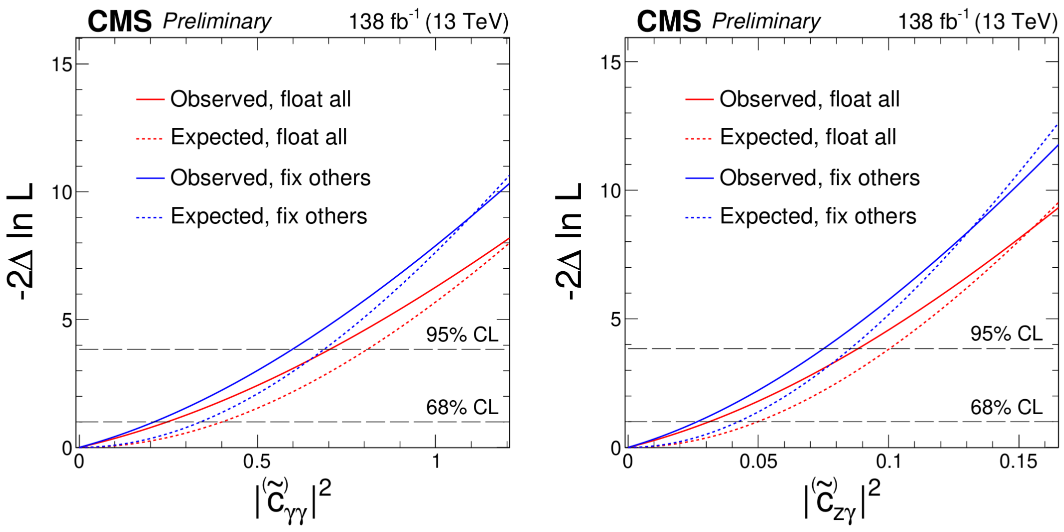
→ H→4l and H→bb final states are used for simultaneous constraints on four anomalous couplings in Hγγ and HZγ

→ Matrix element likelihood method (MELA)

→ Measured potential enhancements in the Yukawa couplings for the bottom and top quarks

# H→ZZ→4l and H→bb (Hγγ and HZγ anomalous couplings)



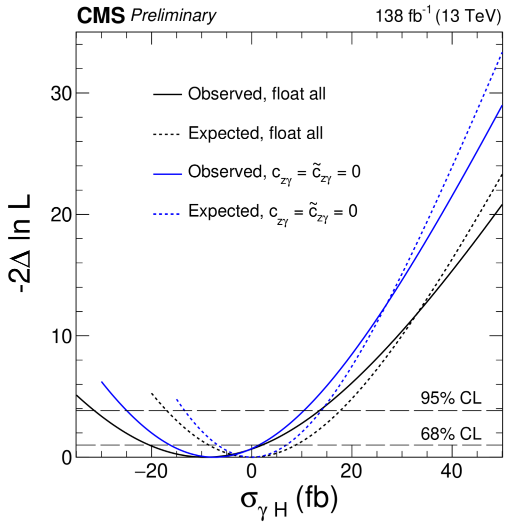




→ Fitted MELA discriminants in H→ZZ→4l
and mass of the Higgs candidate (ParticleNet GNN) in H→bb

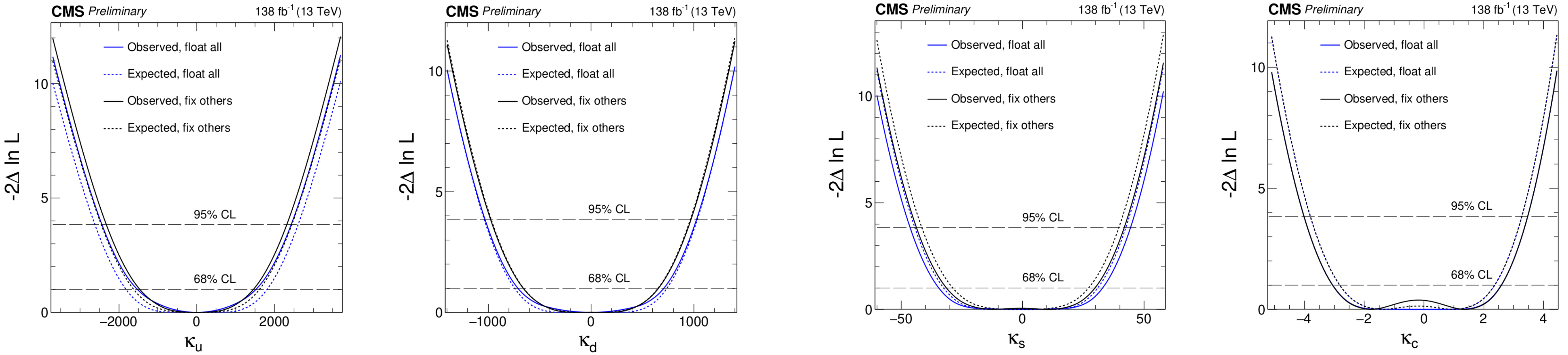
→ Constraints on Wilson coefficients in mass eigenstate basis

→ Constraint on the γH production cross section derived from both channels

→ Consistent with the Standard Model



# H→ZZ→4l and H→bb (Hγγ and HZγ anomalous couplings)




→ Potential enhancements in the Yukawa couplings between light quarks (u,d,s,c) and the Higgs boson
→ Standard model assumption: **$\kappa_b$=1, $\kappa_t$=1** when all are floated simultaneously

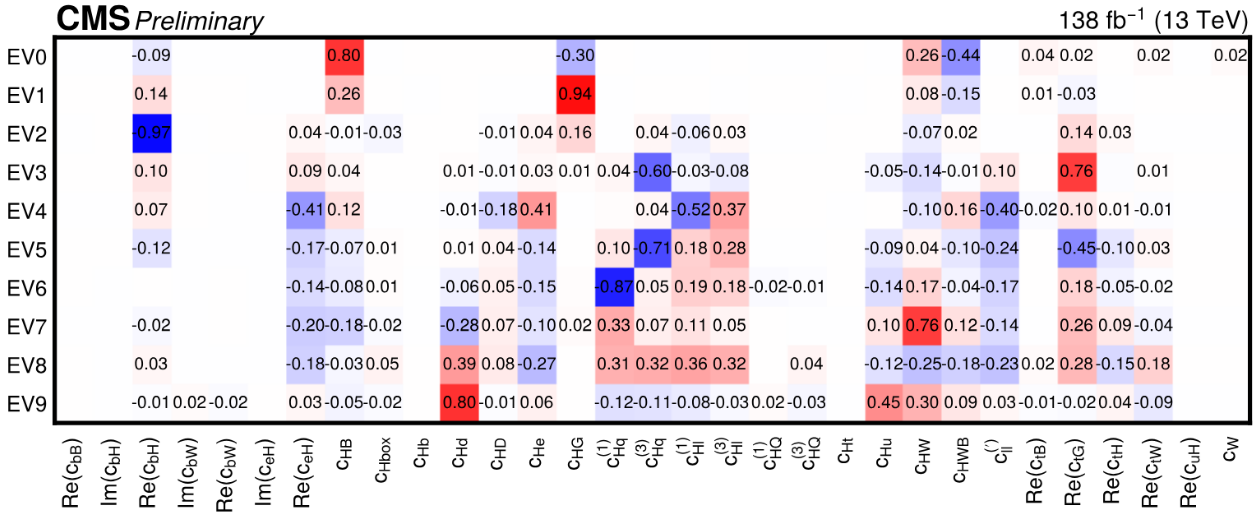
→ Same Yukawa couplings for light quarks as those for the third generation ruled out with CL>95%

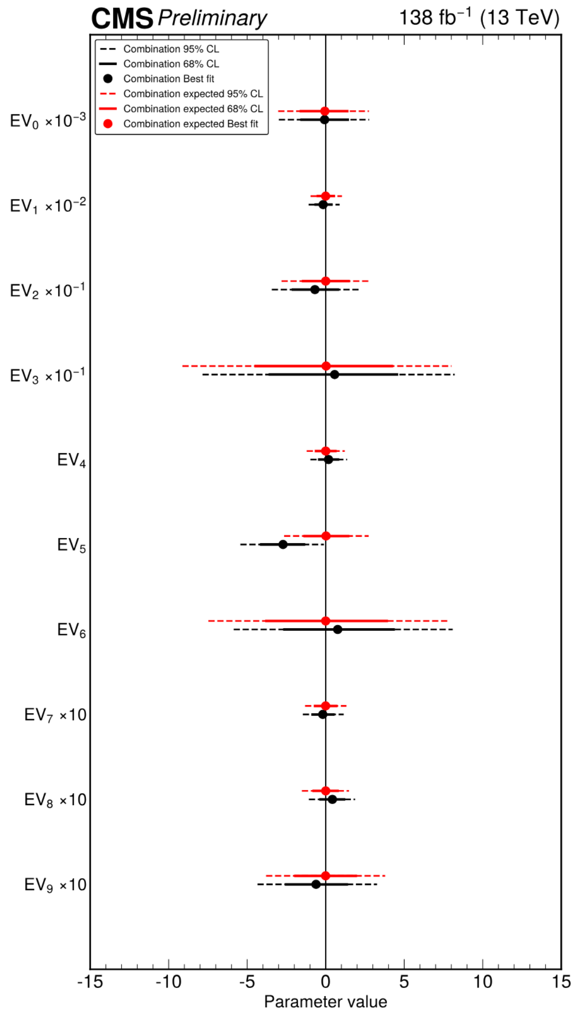
# A peek into the Higgs combination

*(talk by M. Galli)*

→ Principal component analysis – remove flat and unconstrained directions

→ Constraints derived in individual channels lead to global constraints




→ A global combination fit (EW + Higgs + top) with 42 eigenvectors constrained simultaneously (CMS-PAS-SMP-24-003) *(talk by A. Nigamova)*

# Conclusions

**EFT in Higgs at CMS now**

→ SMEFT is a theoretically consistent and model-independent approach

→ Measurements performed in multiple analyses at dim(6)

**VH (H→bb)**
BIT
template optimisation

**H→WW anomalous coupling**
MELA
multiple bases

**Hγγ and HZγ anomalous coupling**
MELA
Yukawa coupling interpretation

→ Individual channels combined in global fits

→ No evidence for deviations from the Standard Model so far

# SMEFT – Warsaw basis

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

→ Multiple operators contribute to the same process

→ Same operator can affect multiple processes

→ Dedicated EFT measurements are needed **AND** their combination

Mass dimension counting:
scalar or vector field: 1
fermion field: 3/2
field strength: 2
derivative: 1

**Measure a catalogue of Wilson coefficients!**

We need to choose a process, identify which operators affect it, and measure them.
→ dedicated EFT measurements
→ e.g. STXS reinterpretation in EFT

# Boosted information tree

With each event having an associated set of weights *w* for a given value of Wilson coefficients *θ*, the differential cross-section for the given parton-level configuration $z_i$ is

$$w(\vec{\theta}, z_i) = \mathcal{L} \frac{\mathrm{d}\sigma_\theta(z)}{\mathrm{d}z}\Big|_{z=z_i} = \mathcal{L}\sigma_\theta p(z_i|\vec{\theta})$$

Parametrisation in terms of Wilson coefficients is propagated to the matrix element (no EFT in the propagator)

$$\mathcal{M} = \mathcal{M}_{\mathsf{SM}} + \sum_i \frac{\theta_i}{\Lambda^2}\mathcal{M}_i$$

The probability distribution function at parton level is then a quadratic function of the Wilson coefficients parametrised by polynomial coefficients *s:*

$$w(\vec{\theta}, z_i) = s_0(z_i) + \sum_i s_{1i}(z_i)\frac{\theta_i}{\Lambda^2} + \sum_j s_{2j}(z_i)\frac{\theta_j^2}{\Lambda^4} + \sum_{j,k} s_{3jk}(z_i)\frac{\theta_j\theta_k}{\Lambda^4}$$

# Boosted information tree

$$L(D|\theta) = \frac{e^{-\mathcal{L}\sigma(\theta)}}{N!} \prod_i \mathcal{L}\sigma(\theta) p(x_i|\theta)$$

**Neyman-Pearson: Largest discrimination power between two simple hypotheses**

$$q_\theta = -\log \frac{L(D|\theta)}{L(D|\theta_0)}$$

$$q_\theta = \mathcal{L}(\sigma(\theta) - \sigma(\theta_0)) - \sum_i \log R(x_i|\theta, \theta_0)$$

Known from simulation

$$R(x|\theta, \theta_0) = \frac{\sigma(\theta) p(x|\theta)}{\sigma(\theta_0) p(x|\theta_0)}$$

$$p(x|\theta) = \int \mathrm{d}z_{\text{det}} \int \mathrm{d}z_{\text{shower}} \int \mathrm{d}z \, \left[p(x, z_{\text{det}}, z_{\text{shower}}, z|\theta)\right]$$

Assumed to not depend on EFT

$$p(x|\theta) = \int \mathrm{d}z \, \left[p(x, z|\theta)\right]$$

**Still untractable**

**But can be sampled**

# Boosted information tree

$$L\left[g(x|\theta)\right] = -\int \mathrm{d}z \frac{\mathrm{d}\sigma(x,z|\theta)}{\mathrm{d}z} \log\left(1 - g(x|\theta)\right) - \int \mathrm{d}z \frac{\mathrm{d}\sigma(x,z|\theta_0)}{\mathrm{d}z} \log g(x|\theta)$$

$$\frac{\delta L}{\delta g} = 0 \implies g(x|\theta) = \frac{1}{1 + R(x|\theta, \theta_0)}$$

Assumption that EFT effects are negligible in showering and detector reconstruction

$$\frac{\frac{\mathrm{d}\sigma(x,z|\theta)}{\mathrm{d}z}}{\frac{\mathrm{d}\sigma(x,z|\theta_0)}{\mathrm{d}z}} \propto \frac{p(x,z|\theta)}{p(x,z|\theta_0)} = \frac{p(z|\theta)}{p(z|\theta_0)} = \boxed{\frac{w(\theta,z)}{w(\theta_0,z)}}$$

Ratio of weights used to simulate EFT effects

# Boosted information tree

Polynomial dependency of EFT effects can be propagated to the LLH ratio

Each BDT is estimating one coefficient function and is trained and optimised independently

$$R(x|\theta,\theta_0) = 1 + \sum_{a} (\theta-\theta_0)_a \frac{\partial_a \left(\sigma(\theta)p(x|\theta)\right)|_{\theta=\theta_0}}{\sigma(\theta_0)p(x|\theta_0)} + \sum_{a,b} \frac{1}{2}(\theta-\theta_0)_a(\theta-\theta_0)_b \frac{\partial_a\partial_b \left(\sigma(\theta)p(x|\theta)\right)|_{\theta=\theta_0}}{\sigma(\theta_0)p(x|\theta_0)}$$

Sum over Wilson coefficients

Goes into the loss function for the training of that EFT component

$$R(x|\theta,\theta_0) = 1 + \sum_{a} (\theta-\theta_0)_a R_a(x) + \sum_{a,b} \frac{1}{2}(\theta-\theta_0)_a(\theta-\theta_0)_b R_{ab}(x)$$

Coefficient functions can be trained independently:
2N + N(N-1)/ 2 trainings for N Wilson coefficients