6th RED LHC workshop

Measurement of Higgs couplings to WW

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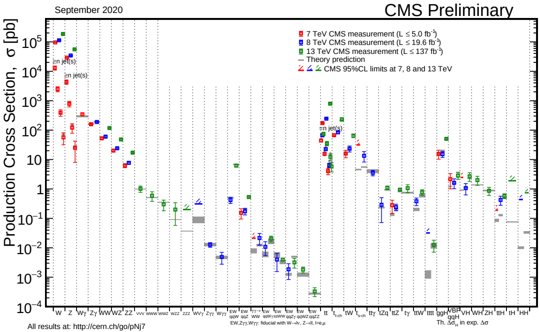
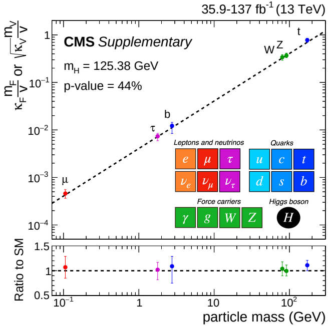
Triumph of the SM at the LHC

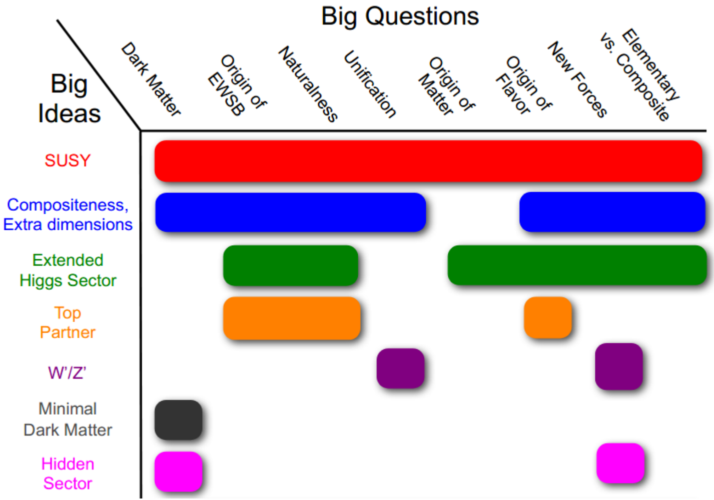




Predictions and measurements agree over **many orders of magnitude**

Established **SM picture of EWSB**

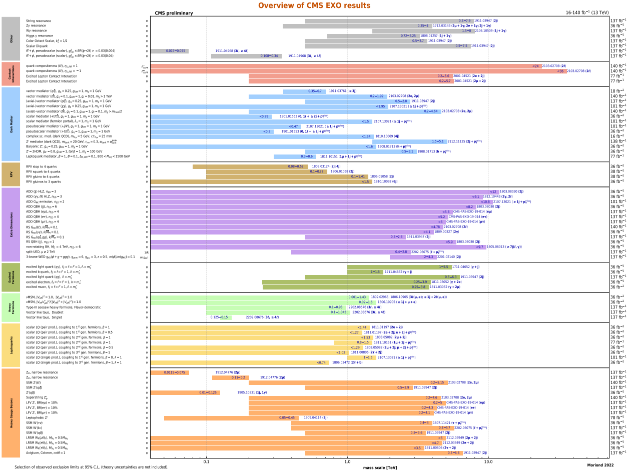
Big questions remain



Big ideas for what lies beyond the SM

→ Generally predict **new particles at the TeV scale**

Direct searches at LHC find no new particles



Suggests **energy gap** between SM and New Physics (NP)

Energy scale hierarchy motivates use of **Effective Field Theory (EFT)**

A SM EFT

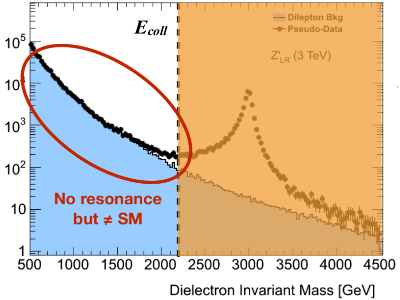
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \bar{c}_i^{(6)} O_i^{(6)}.$$

Effects of heavy **NP mapped onto** $\mathcal{O}_i^6$

c_i specify the strength of the new interactions

EFT only **valid at** $E < \Lambda$

Deformations in SM described by $\mathcal{O}_i^6$ effective interaction

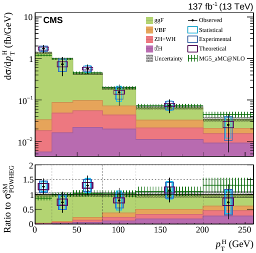


So how are HVV related EFT couplings measured?

Dedicated (detector-level) measurements :

Use **dedicated discriminants** and **full simulation** of Signal PDFs

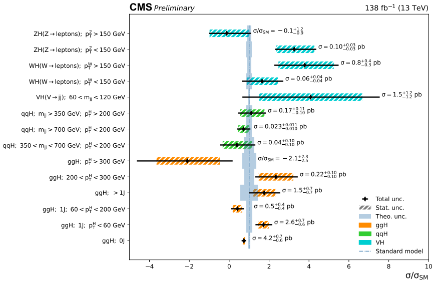
"Anomalous coupling" approach



Interpretations of other measurements :

2 types : Differential fiducial σ and simplified template σ (STXS)

Signal **parameterised in gen-level** fiducial bins



Focus on dedicated HVV coupling measurement!

HVV anomalous coupling parameterisation

General Lorentz invariant form of **HVV** $(V = W, Z, \gamma)$ **scattering amplitude :**

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

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In particular for V=W,Z :

a_1 **SM**

a_2, k_1, $k_2^{Z\gamma}$ **: CP-Even Anomalous couplings**

a_3 **: CP-Odd Anomalous coupling**

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Can consider SU(2)xU(1) symmetry → Equivalent to SM EFT

Higgs basis EFT : Expressed in terms of mass eigenstates (after EWSB)

Considering SU(2)xU(1) symmetry

SU(2)xU(1) enforces relations between ZZ,WW,$\gamma\gamma$ and Zγ couplings :

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

Assume $a^{\gamma\gamma}$ and $a^{Z\gamma}$ constrained by H$\rightarrow \gamma\gamma$ and H$\rightarrow$Zγ measurements

4 independent HVV couplings : a_1, a_2, a_3, k_1

EFT interpretation

Amplitude couplings map directly to **EFT couplings :**

$$\delta c_z = \frac{1}{2} a_1 - 1 \,,$$
$$c_{z\Box} = \frac{m_Z^2 s_w^2}{e^2} \frac{\kappa_1}{(\Lambda_1)^2} \,,$$
$$c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_2 \,,$$
$$\tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_3 \,.$$

Full detector simulation of corresponding HVV states

For **1 HVV vertex** $\sigma \propto |a_1 \mathcal{M}_1 + a_2 \mathcal{M}_2 + a_3 \mathcal{M}_3 + k_1 \mathcal{M}_{k1}|^2$

Many interference terms!

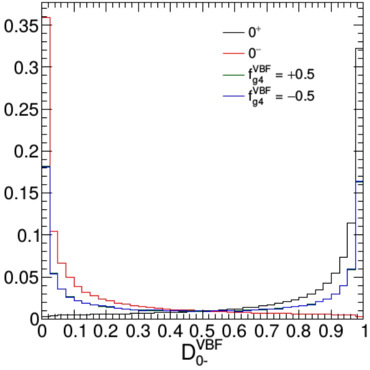
Use **reweighting** rather than simulate all required terms

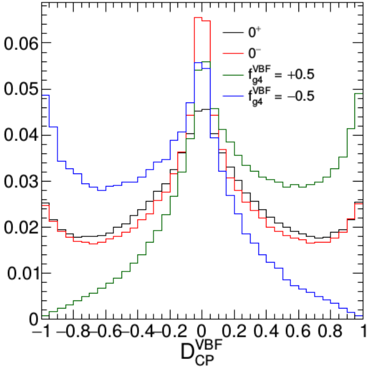
Dedicated Observables

Exploit full production (VBF,VH) and decay info with **ME based discriminants**

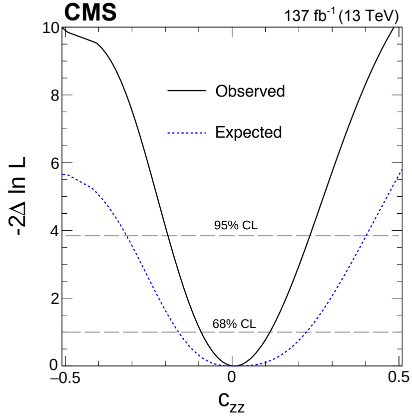
Can target **production mode**, **Higgs coupling** and **interference**

For example to study a_3 in VBF (HZZ) :





Scans of Higgs basis EFT couplings (HZZ)



All couplings floating in fit to data

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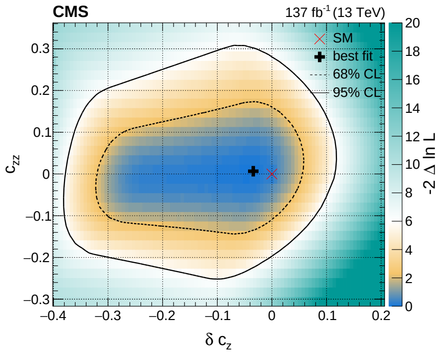

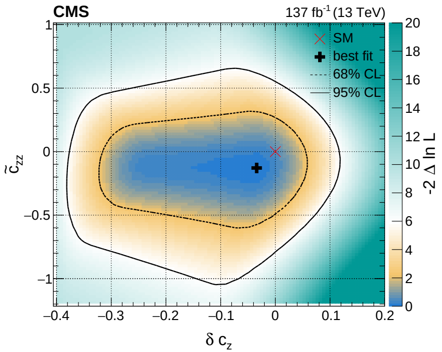

Dedicated HWW analysis in mature state → Combination with HZZ

Rotate to warsaw basis → In principle could include in **global EFT fits**

SUMMARY

- Given apparent energy gap between SM and new physics an EFT approach is well motivated at the LHC
- Dedicated (detector-level) analysis to constrain HVV (V=W/Z) couplings in SM EFT framework
- HZZ results available with HWW to follow soon (+ combination)
- Potential to include in global EFT fits