Anomalous Higgs boson couplings and CP properties at CMS

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On behalf on the CMS Collaboration

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Why is the Higgs boson so light?

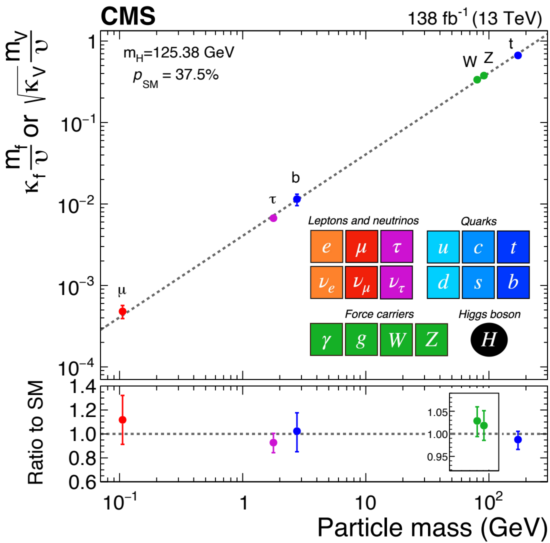
BSM ideas to solve the Hierarchy problem :

- A new symmetry protects the higgs mass : **SUSY**
- Higgs is a bound state of new strong interaction : **Composite Higgs**

Can significantly alter Higgs phenomenology

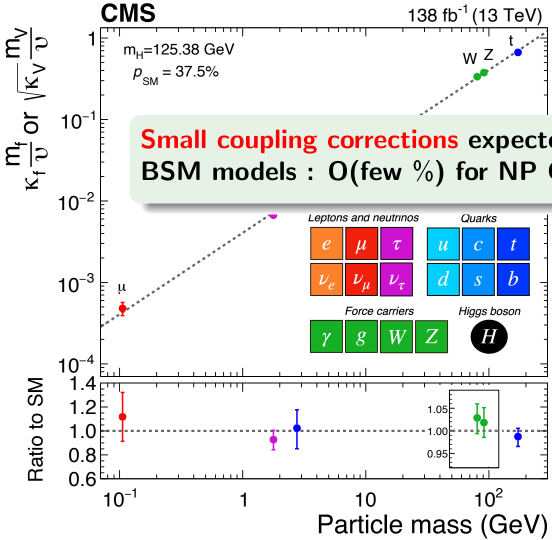
Nature 607(2022)60

SM picture observed so far



Nature 607(2022)60

SM picture observed so far



Small coupling corrections expected for many BSM models : O(few %) for NP @ 1TeV

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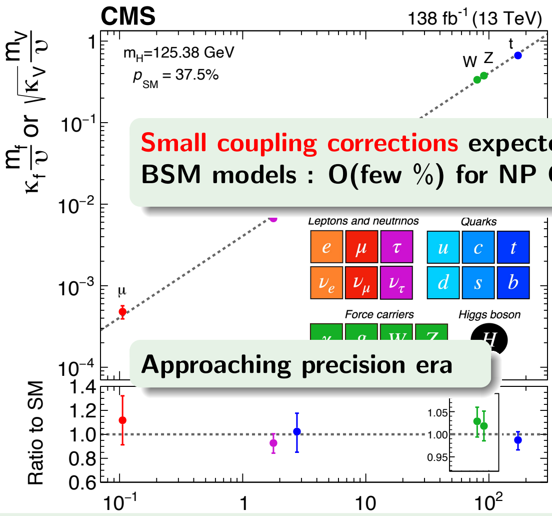
SM picture observed so far



Small coupling corrections expected for many BSM models : O(few %) for NP @ 1TeV

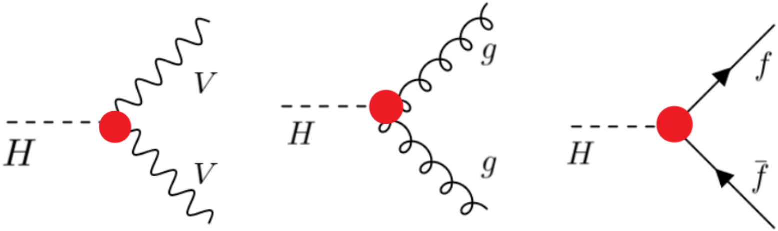
Approaching precision era

κ: Simple coupling modifier based on inclusive measurements

→ Deeper study of coupling structure is possible...

Anomalous couplings (AC) approach

Framework for general study of the **Higgs coupling structure**



For a given **vertex**, consider **scattering amplitude** with multiple contributions (**tree-level**, **loops/BSM**)

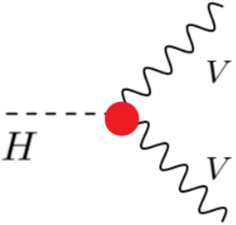
Exploit **full event kinematics** to constrain contributions

(**production + decay vertex**)

Higgs to Electroweak vector bosons

HVV scattering amplitude :

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$



HVV couplings :

a_1 : **SM tree level coupling**

k/Λ^2 : **CP-Even AC**

a_2 : **CP-Even AC**

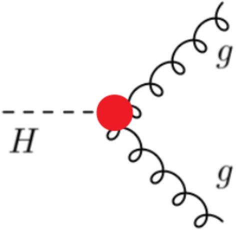
a_3 : **CP-Odd AC**

→ Target **VBF, VH** production + **HWW/HZZ** decay

Higgs to gluons

Hgg scattering amplitude :

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$



Hgg couplings :

a_2 **: SM loop**

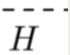
a_3 **: CP-Odd AC**

→ Target **ggH + 2 Jets** process (VBF-like events)

Higgs to gluons

Hgg scattering amplitude :

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$



Convenient to measure fractional contribution of AC (a_i) to σ :

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

Signal model includes signal strength μ and f_{ai}

Equivalent to SM EFT

Assuming **SU(2)xU(1)** relationship between a_i^{WW} and a_i^{ZZ}

$$\delta c_z = \frac{1}{2} a_1^{ZZ} - 1,$$

$$c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_2^{ZZ},$$

$$\tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_3^{ZZ},$$

$$c_{z\Box} = \frac{m_Z^2 s_w^2}{e^2} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2},$$

EFT couplings (Higgs basis) map directly to **amplitude couplings**

Dedicated observables

built using **Machine learning (ML)** techniques

and/or **ME based discriminants (MELA)**

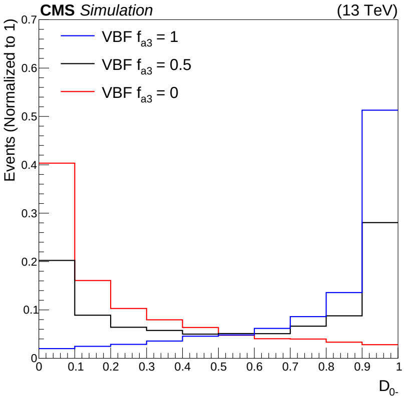
With MELA can target :

Production mode (D_{VBF})

Pure AC contribution
$\propto a_i^2$
(D_{0+}, D_{0-})

Interference AC contribution
$\propto a_i$
(D_{Int}, D_{CP})

$$D_{BSM} = \frac{\mathcal{P}_{BSM}(\Omega)}{\mathcal{P}_{BSM}(\Omega)+\mathcal{P}_{SM}(\Omega)}.$$

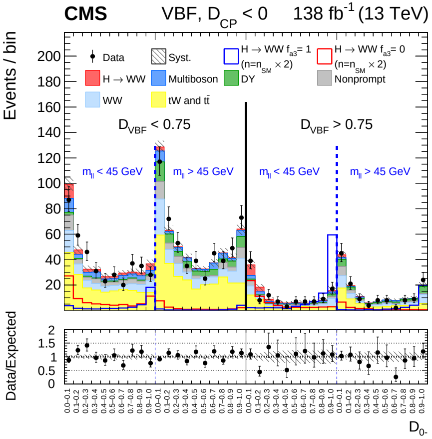


HVV AC

arXiv:2403.00657
Accepted by EPJC

HVV studies in **HWW, HZZ** and **H$\tau\tau$** decay channels

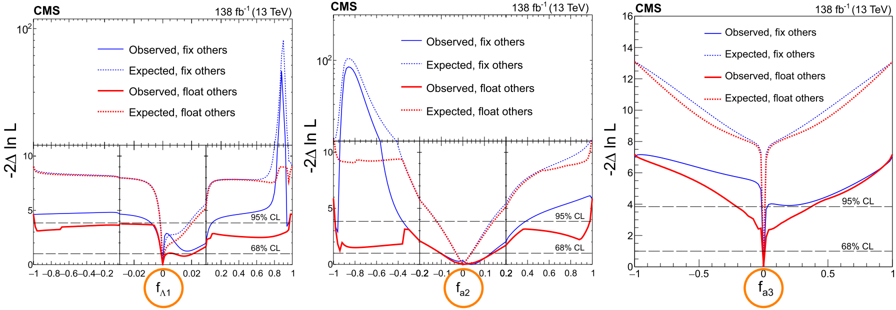
Example discriminant from **VBF HWW** using **MELA**:



HVV f_{ai} scans in HWW channel

Assume **SU(2)xU(1)** relationship between a_i^{WW} and a_i^{ZZ}

3 f_{ai} analyzed simultaneously



f_{ai}∼ 0 consistent with SM Higgs boson

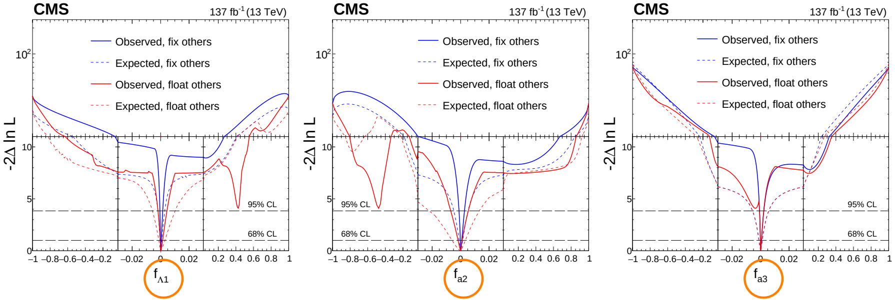
(**per mille level constraints**)

Phys.Rev.D 104,052004(2021)

HVV f_{ai} scans in HZZ channel

Assume **SU(2)xU(1)** relationship between a_i^{WW} and a_i^{ZZ}

3 f_{ai} **analyzed simultaneously**



$f_{ai} \sim 0$ **with constraints at the** $10^{-3} - 10^{-4}$ **level**

What about constraints in terms of **EFT couplings?**

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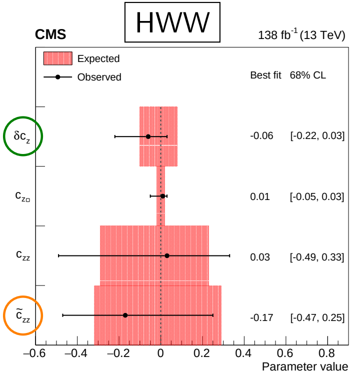
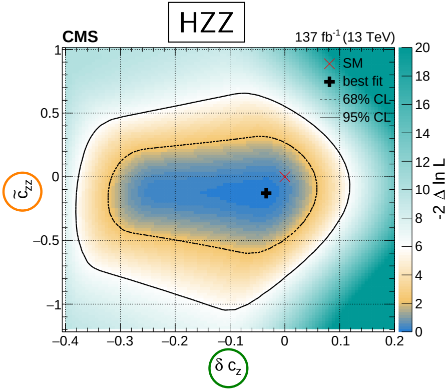
Higgs basis EFT couplings

4 couplings **analyzed simultaneously**





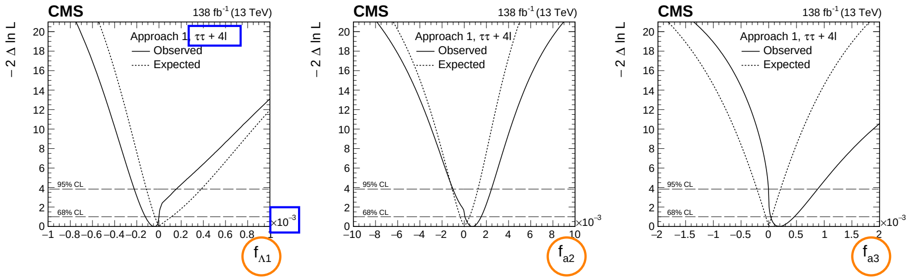
Some of the tightest constraints on these couplings to date

HVV f_{ai} scans in H$\tau\tau$ channel

Target **VBF** production (assuming $a_i^{WW} = a_i^{ZZ}$)

f_{ai} **analyzed independently**

Combination with HZZ channel



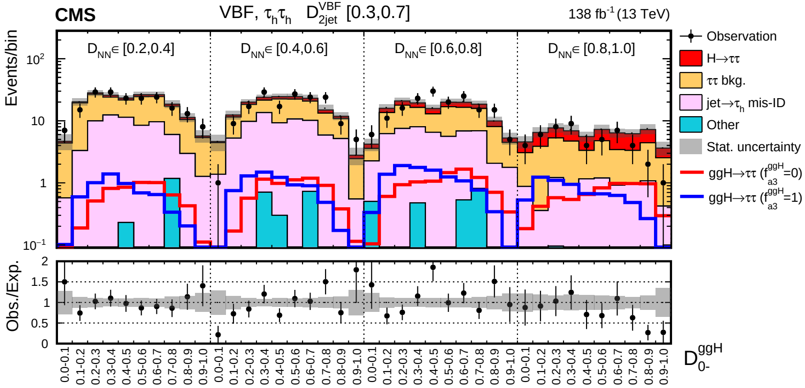
$f_{ai} \sim 0$ **with constraints at the** $10^{-3} - 10^{-4}$ **level**

Hgg AC

Phys.Rev.D 108(2023)032013

Hgg studies in **HWW, HZZ** and **H$\tau\tau$** decay channels

Example discriminant from **ggH + 2 jets H$\tau\tau$** :
Neural Networks (separate H$\tau\tau$ from bkg)
+ **MELA** (target a_i)

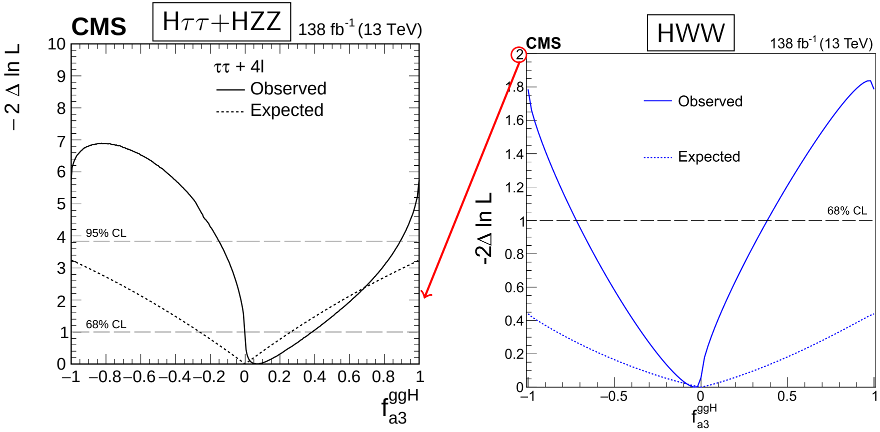


Phys.Rev.D 108(2023)032013

arXiv:2403.00657
Accepted by EPJC

Hgg f_{ai} scans

f_{a3}^{ggH} scanned with **HVV** f_{a3} for VBF also left floating

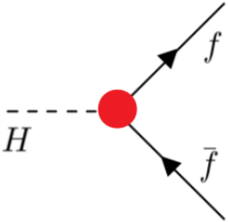


Most stringent limits on CP violation in ggH to date

Higgs yukawa couplings

Hff scattering amplitude :

$$\mathcal{A}(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_\mathrm{f}\left(\kappa_\mathrm{f} + \mathrm{i}\widetilde{\kappa}_\mathrm{f}\gamma_5\right)\psi_\mathrm{f}.$$



Hff yukawa modifiers :

κ_f **: CP-Even (SM)**

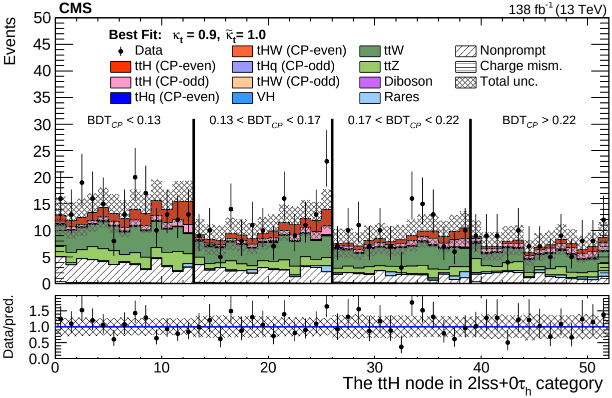
$\tilde{\kappa_f}$ **: CP-Odd**

→ Target **ttH/tH** production and **H**$\tau\tau$ decay

Higgs top yukawa

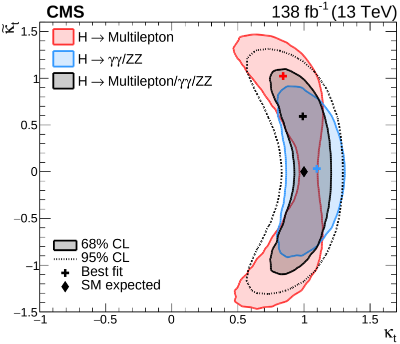
ttH/tH studies in **HWW, H$\tau\tau$, HZZ, H$\gamma\gamma$** and **Hbb** decay channels

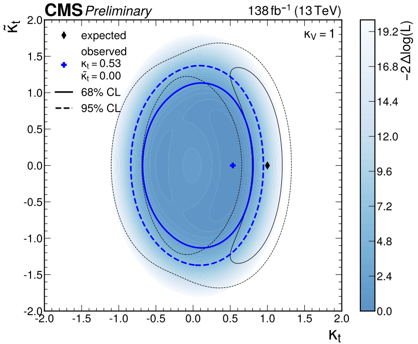
Example from **ttH Multilepton (HWW/H$\tau\tau$)** :
Neural Networks (separate ttH from bkg)
+ **BDT** (target CP)



Higgs top yukawa

ttH/tH results in **Multilepton+HZZ+H$\gamma\gamma$** and **Hbb** channels

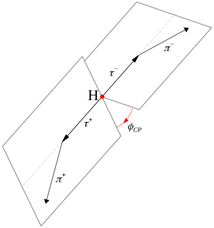




Pure CP-Odd coupling excluded at 3.7 σ

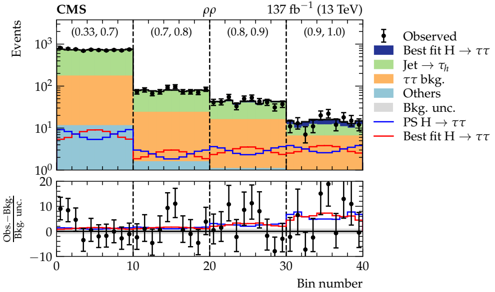
Constraint on **Fractional CP-Odd contribution**: $|f_{CP}^{Htt}| < 0.55$

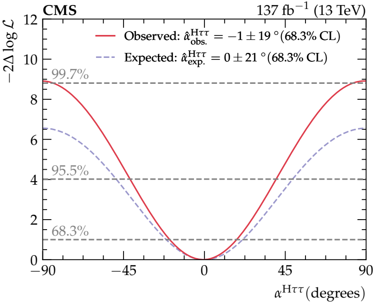
Higgs τ yukawa



$H\tau\tau$ decay : study angle ϕ_{CP} between τ decay planes
$+$ MVA discriminants to separate signal from background

Measure **mixing angle $\alpha^{H\tau\tau}$** between $\tilde{\kappa_\tau}, \kappa_\tau$ [$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$]
$\alpha^{H\tau\tau} = 0(90)^\circ$ corresponds to CP-Even(CP-Odd) state





Pure CP-Odd coupling excluded at 3 σ

Conclusions

Measurement of Higgs boson coupling structure a crucial test of SM

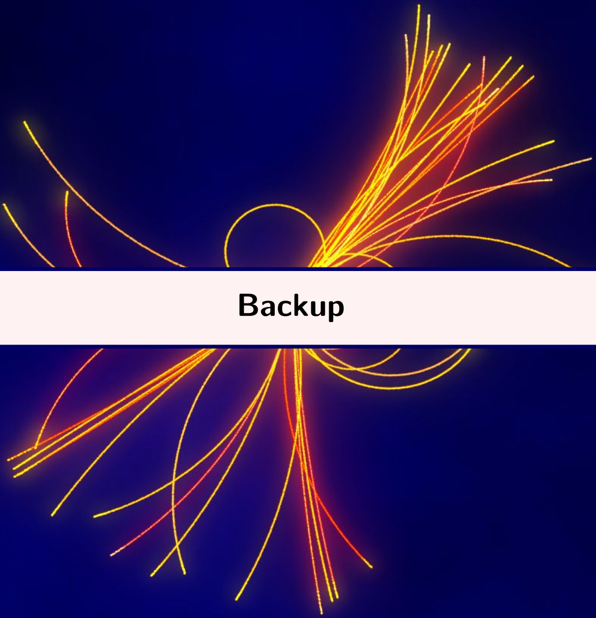
Recent dedicated studies in multiple channels with full Run 2 data presented

Covering Higgs to electroweak vector bosons, gluons and fermion couplings

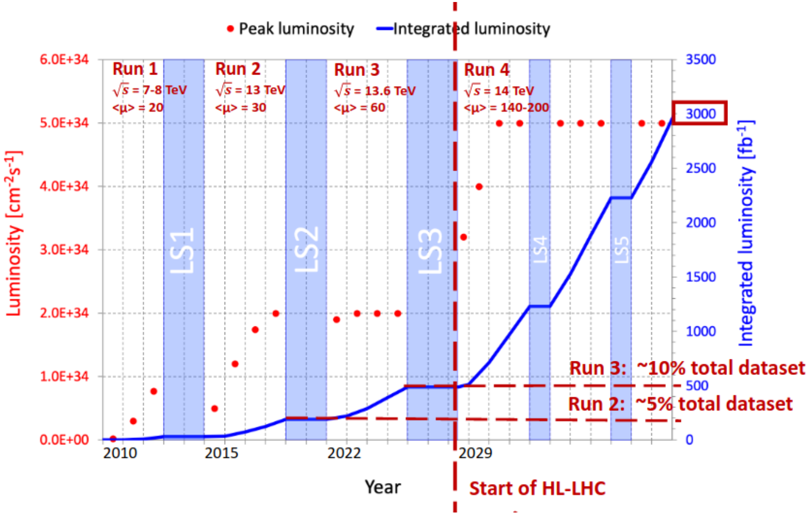
To date measurements consistent with SM Higgs boson

Many of these analyses are statistically limited
$\rightarrow$ A lot to gain in the future so watch this space

Backup



Currently statistically limited



→ A lot to gain in the future..

SU(2) x U(1) and Higgs basis relationships

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

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

ttH Multilepton categorizaion strategy