Anomalous couplings and off-shell Higgs measurements at CMS

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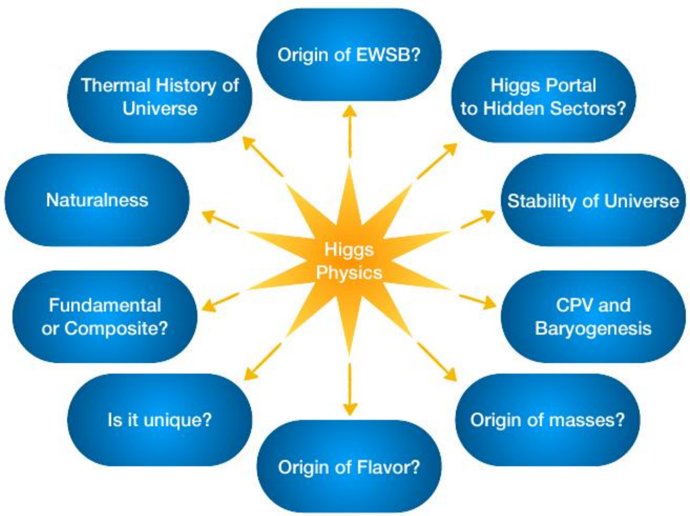
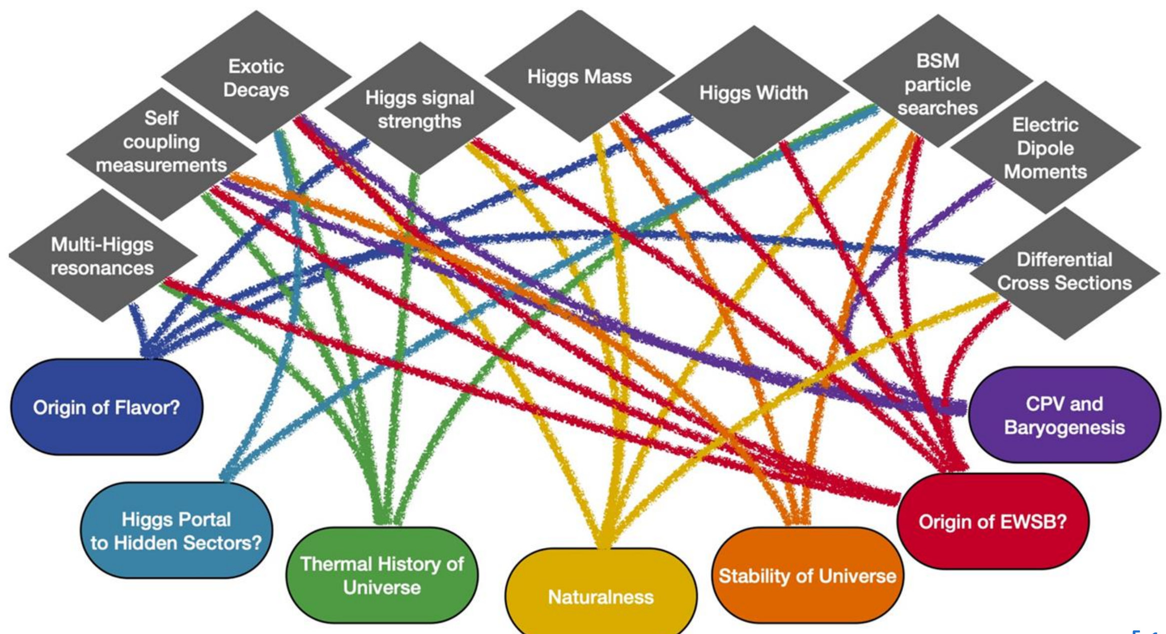
December 20 2024

Introduction

- **Higgs Boson**: a key piece of the SM and a portal to BSM physics at the LHC
- Higgs couplings to SM particles are well predicted from mass measurements
- **Any deviations** in Higgs couplings implies **new physics** that couples to the Higgs boson
- **Main topics of this talk**:
  - *Theory behind CMS anomalous coupling measurements (beyond kappa framework)*
  - *Results and methodology for experimental constraints*





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Interpreting Deviations

$$\delta\eta_{SM} \sim c_\eta \frac{v^2}{M^2}$$

$\delta\eta_{SM}$ $\sim 1\%$ / $\sim .1\%$

Size of Higgs Coupling deviations?

- **Tree level origin** $\sim \frac{v^2}{M^2}$
  - **SM Neutral** e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2 s}}{2M^2}\right)\frac{v^2}{M^2}$
    - $M \lesssim 1.7\,\mathrm{TeV}$
    - $M \lesssim 5.5\,\mathrm{TeV}$
  - **SM Charged** e.g. 2HDM $\sim \left(\frac{\lambda_6^2 v^2}{M^2}\right)\frac{v^2}{M^2}$
    - $M \lesssim 0.8\,\mathrm{TeV}$
    - $M \lesssim 1.4\,\mathrm{TeV}$
- **Loop level** $\sim \frac{1}{(4\pi)^2}\frac{v^2}{M^2}$
  - **SM Neutral** e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2 s^2}}{48\pi^2}\right)\frac{v^2}{M^2}$
    - $M \lesssim 0.1\,\mathrm{TeV}$
    - $M \lesssim 0.4\,\mathrm{TeV}$
  - **SM Charged w/ SM loop** e.g. stops in SUSY $\sim \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}}^2}$
    - $M \lesssim 0.9\,\mathrm{TeV}$
    - $M \lesssim 2.8\,\mathrm{TeV}$

Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

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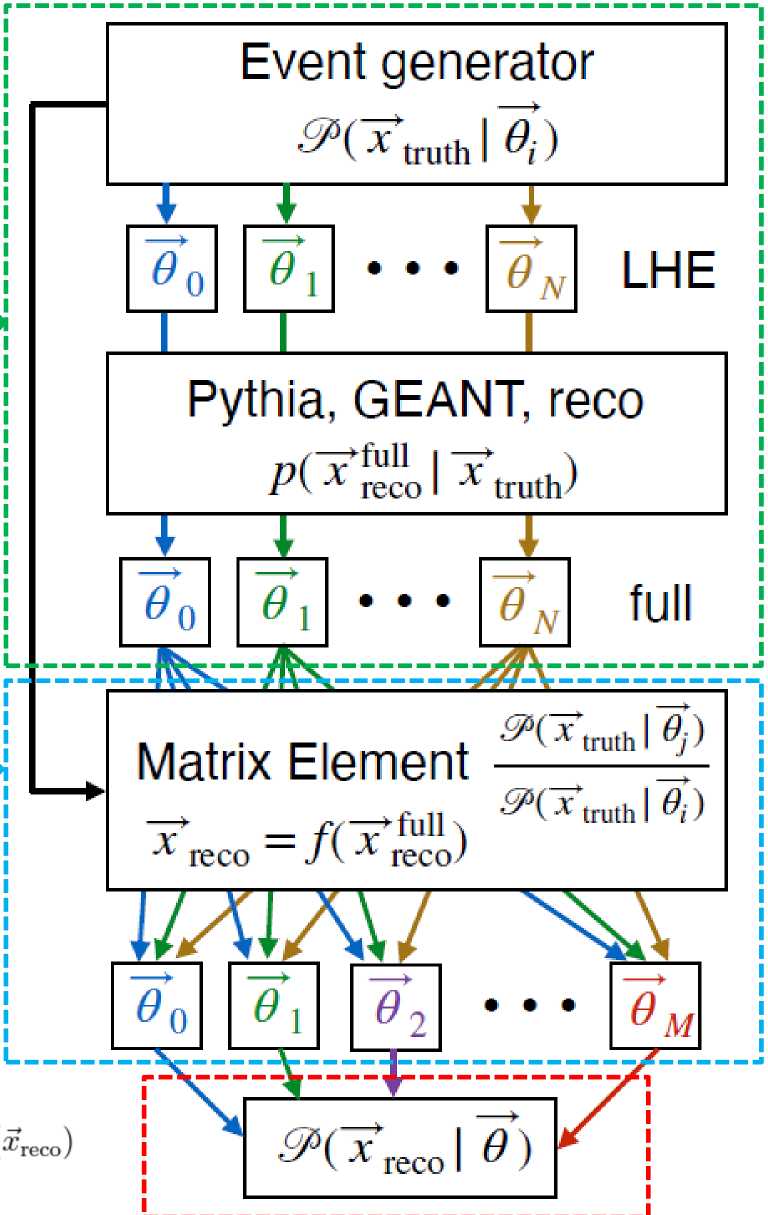
General Concepts

- “Dedicated” analysis on CMS consists of three main features:

- Full detector simulation of anomalous couplings

- Optimized observables for each targeted coupling
- Matrix Element based reweighting for reshaping of pdf



Construct PDF in following way

$$\mathcal{P}(\vec{x}_{\text{reco}}|\vec{\theta}) \propto \mathcal{P}_0(\vec{x}_{\text{reco}}) + \sum_{1\le k\le K}\left(\frac{2\theta_k}{\theta_0}\right)\mathcal{P}_{0k}(\vec{x}_{\text{reco}}) + \sum_{1\le k\le K}\left(\frac{\theta_k}{\theta_0}\right)^2\mathcal{P}_k(\vec{x}_{\text{reco}}) + \sum_{1\le i<j\le K}\left(\frac{2\theta_i\theta_j}{\theta_0^2}\right)\mathcal{P}_{ij}(\vec{x}_{\text{reco}})$$

Amplitude Formalism

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

- SM Tree Level (+Kinetic Terms), CP-Even Dim-6, CP-Odd Dim-6

- Measure **effective fractional cross sections**
  - Many systematics cancel

Ex: $f_{a2} = 0.5 \rightarrow \frac{1}{2}$ measured $H \rightarrow ZZ$ cross-section from anomalous coupling a_2^{ZZ}

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

- **Note**: a_i can be related to Wilson coefficients in SMEFT Lagrangian (Ex. below)

$$\begin{aligned}
\mathcal{L}_{\mathrm{hvv}} = \quad & \frac{h}{v}\Big[M_Z^2 \left(1+\delta c_z\right) Z_\mu Z^\mu + \frac{M_Z^2}{v^2} c_{zz} Z_{\mu\nu} Z^{\mu\nu} + \frac{e^2}{s_w^2} c_{z\Box} Z_\mu \partial_\nu Z^{\mu\nu} + \frac{M_Z^2}{v^2} \tilde{c}_{zz} Z^{\mu\nu} \tilde{Z}_{\mu\nu} \\
& + 2 M_W^2 \left(1+\delta c_w\right) W_\mu^+ W^{-\mu} + 2\frac{M_W^2}{v^2} c_{ww} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{e^2}{s_w^2} c_{w\Box} \left(W_\mu^- \partial_\nu W^{+\mu\nu} + \mathrm{h.c.}\right) \\
& + \frac{e^2}{2 s_w^2} \tilde{c}_{ww} W^{+\mu\nu} \tilde{W}_{\mu\nu}^- + \frac{e^2}{2 s_w c_w} c_{z\gamma} Z_{\mu\nu} A^{\mu\nu} + \frac{e^2}{2 s_w c_w} \tilde{c}_{z\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu} + \frac{e^2}{s_w c_w} c_{\gamma\Box} Z_\mu \partial_\nu A^{\mu\nu} \\
& + c_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} A^{\mu\nu} + \tilde{c}_{\gamma\gamma} \frac{e^2}{4} A^{\mu\nu} \tilde{A}_{\mu\nu} + c_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a G^{a\mu\nu} + \tilde{c}_{gg} \frac{g_s^2}{4} G^{a\mu\nu} \tilde{G}_{\mu\nu}^a \Big],
\end{aligned}$$

SMEFT Relations: Amplitude Formalism

- f_{ai} can be interpreted in different ways
  - Search for single anomalous contribution

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- f_{ai} can be interpreted in different ways
  - Search for single anomalous contribution
  - $SU(2) \times U(1)$ (SMEFT) Approach

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

SMEFT Relations: Amplitude Formalism

- f_{ai} can be interpreted in different ways
  - Search for single anomalous contribution
  - $SU(2) \times U(1)$ (SMEFT) Approach
  - Custodial Symmetry?

$$\boxed{a_1^{\mathrm{WW}} = a_1^{\mathrm{ZZ}}} + \frac{\Delta m_{\mathrm{W}}}{m_{\mathrm{W}}},$$

$$a_2^{\mathrm{WW}} = c_{\mathrm{w}}^2 a_2^{\mathrm{ZZ}} + s_{\mathrm{w}}^2 a_2^{\gamma\gamma} + 2 s_{\mathrm{w}} c_{\mathrm{w}} a_2^{\mathrm{Z}\gamma},$$

$$a_3^{\mathrm{WW}} = c_{\mathrm{w}}^2 a_3^{\mathrm{ZZ}} + s_{\mathrm{w}}^2 a_3^{\gamma\gamma} + 2 s_{\mathrm{w}} c_{\mathrm{w}} a_3^{\mathrm{Z}\gamma},$$

$$\frac{\kappa_1^{\mathrm{WW}}}{(\Lambda_1^{\mathrm{WW}})^2}(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) = \frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + 2 s_{\mathrm{w}}^2 \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2} + 2 \frac{s_{\mathrm{w}}}{c_{\mathrm{w}}}(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) \frac{a_2^{\mathrm{Z}\gamma}}{m_{\mathrm{Z}}^2},$$

$$\frac{\kappa_2^{\mathrm{Z}\gamma}}{(\Lambda_1^{\mathrm{Z}\gamma})^2}(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) = 2 s_{\mathrm{w}} c_{\mathrm{w}} \left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2} \right) + 2 (c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) \frac{a_2^{\mathrm{Z}\gamma}}{m_{\mathrm{Z}}^2}$$

SMEFT Relations: Amplitude Formalism

- f_{ai} can be interpreted in different ways
  - Search for single anomalous contribution
  - $SU(2) \times U(1)$ (SMEFT) Approach
  - Custodial Symmetry?
  - Already constrained to be small?

$$\boxed{a_1^{\mathrm{WW}} = a_1^{\mathrm{ZZ}}} + \frac{\Delta m_{\mathrm{W}}}{m_{\mathrm{W}}},$$

$$a_2^{\mathrm{WW}} = c_{\mathrm{w}}^2 a_2^{\mathrm{ZZ}} + s_{\mathrm{w}}^2 \cancel{a_2^{\gamma\gamma}} + 2 s_{\mathrm{w}} c_{\mathrm{w}} \cancel{a_2^{\mathrm{Z}\gamma}},$$

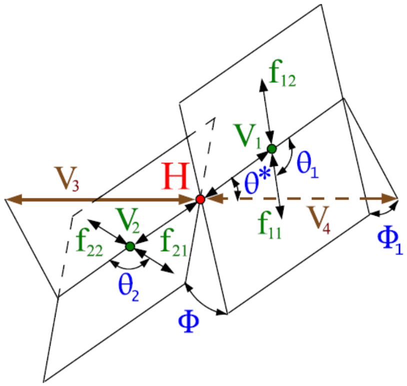
$$a_3^{\mathrm{WW}} = c_{\mathrm{w}}^2 a_3^{\mathrm{ZZ}} + s_{\mathrm{w}}^2 \cancel{a_3^{\gamma\gamma}} + 2 s_{\mathrm{w}} c_{\mathrm{w}} \cancel{a_3^{\mathrm{Z}\gamma}},$$

$$\frac{\kappa_1^{\mathrm{WW}}}{(\Lambda_1^{\mathrm{WW}})^2}(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) = \frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + 2 s_{\mathrm{w}}^2 \frac{\cancel{a_2^{\gamma\gamma}} - a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2} + 2 \frac{s_{\mathrm{w}}}{c_{\mathrm{w}}}(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) \frac{\cancel{a_2^{\mathrm{Z}\gamma}}}{m_{\mathrm{Z}}^2},$$

$$\frac{\kappa_2^{\mathrm{Z}\gamma}}{(\Lambda_1^{\mathrm{Z}\gamma})^2}(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) = 2 s_{\mathrm{w}} c_{\mathrm{w}} \left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + \frac{\cancel{a_2^{\gamma\gamma}} - a_2^{\mathrm{ZZ}}}{m_{\mathrm{Z}}^2} \right) + 2(c_{\mathrm{w}}^2 - s_{\mathrm{w}}^2) \frac{\cancel{a_2^{\mathrm{Z}\gamma}}}{m_{\mathrm{Z}}^2}$$

Optimal Observables

- In many CMS Anomalous Coupling Analysis, Matrix Element Based Discriminants are used as observables (Calculated using MELA)
- Nelson Pearson Lemma guarantees that discriminants are most optimal



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

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

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

3 Matrix Element based observables
- D_{sig}: SM Signal vs Bkg
- D_{BSM}: Dim-6 ^2 vs SM
- D_{int}: Dim-6 x SM

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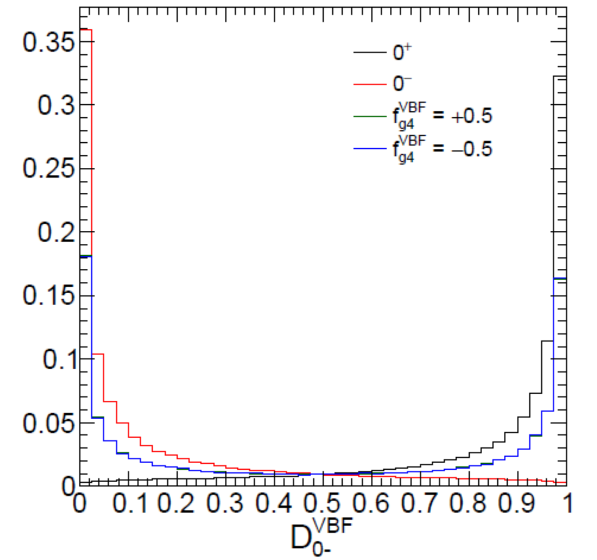
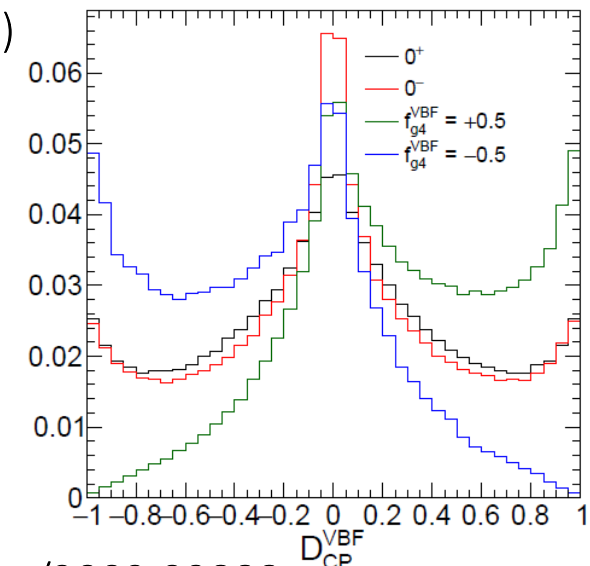
D_{BSM} for $f_{a3}(D_{0-})$



D_{int} for $f_{a3}(D_{CP})$



[11]

https://arxiv.org/abs/2002.09888

On-Shell Results

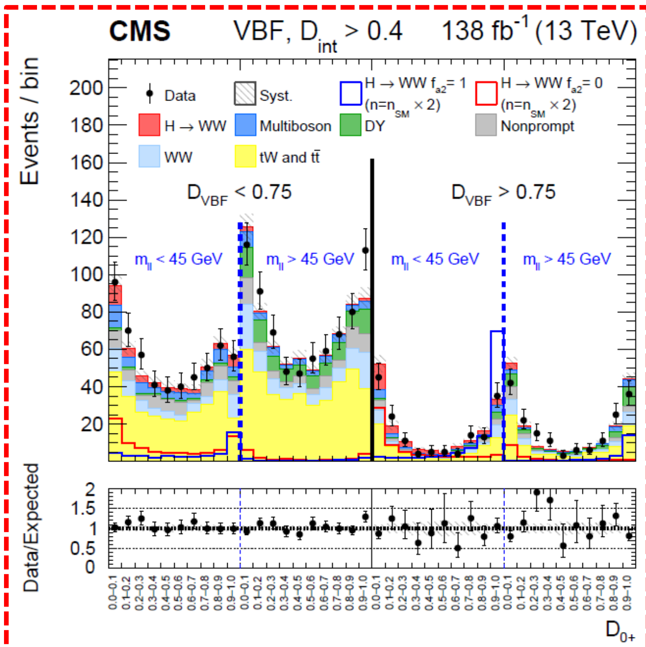
Anomalous Couplings in $H \rightarrow WW$ on CMS

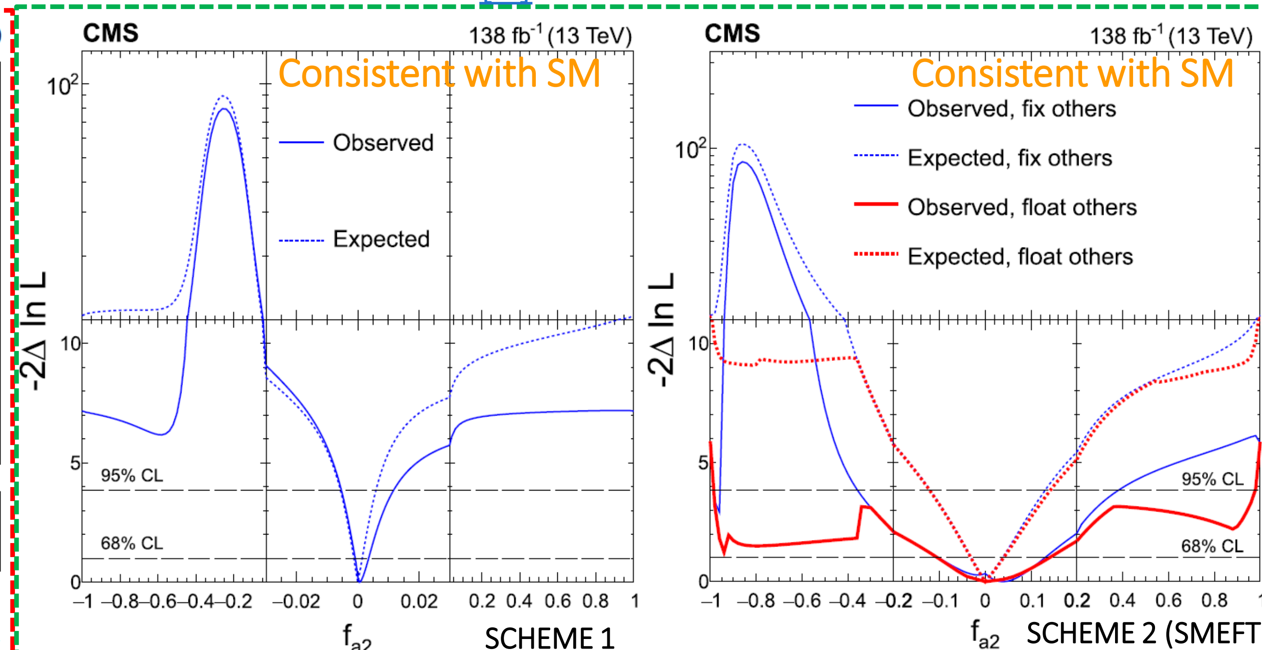
- Constrain Anomalous HVV couplings in $H \rightarrow WW$
- All $H \rightarrow WW$ candidates use common selection
  - FS and m_{ll} cuts orthogonal to $2l2\nu$ analysis
- Candidates further categorized by production mode
- Ex: Observables for f_{a2} (Scheme 2)
  - m_{ll}, D_{VBF}, D_{0+}
- **First constraints** on f_{ai} in $H \rightarrow WW$ channel (Run-2)
- All results consistent with the SM
- Ready for combination with other channels!

Variable	Selection
Number of leptons	2 ($e\mu$ of opposite charge)
$p_T^{\ell 1}$	>25 GeV
$p_T^{\ell 2}$	>13 GeV (10 GeV for 2016 data)
$m_{\ell\ell}$	12–76.2 GeV or >106.2 GeV
$p_T^{\ell\ell}$	>30 GeV
p_T^{miss}	>20 GeV
$m_T^{\ell 2}$	>30 GeV
m_T^H	60–125 GeV
N_{jet} (b jets)	0

Variable	ggH	VBF	Resolved VH	Boosted VH
N_{jet} (V jets)	0	0	0	>0
N_{jet} (AK4 jets)	0 & 1	2	2	—
m_{jj}	—	>120 GeV	60–120 GeV	—

[7]

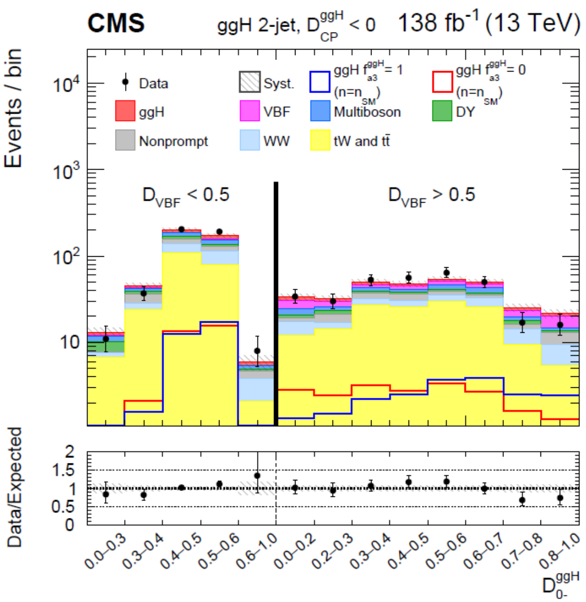


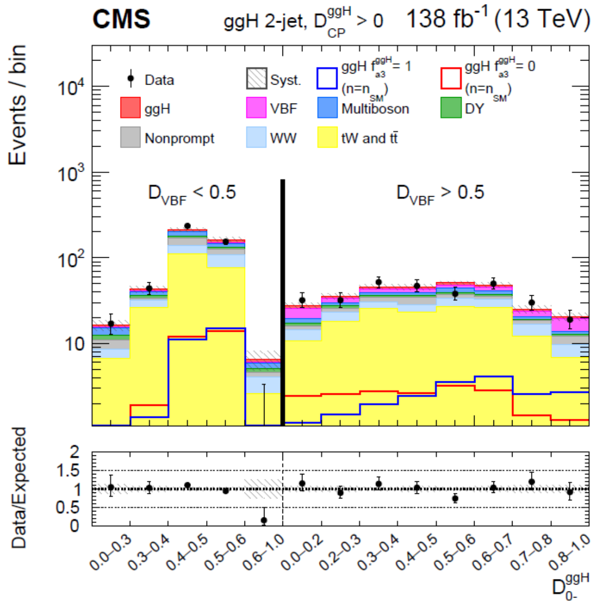


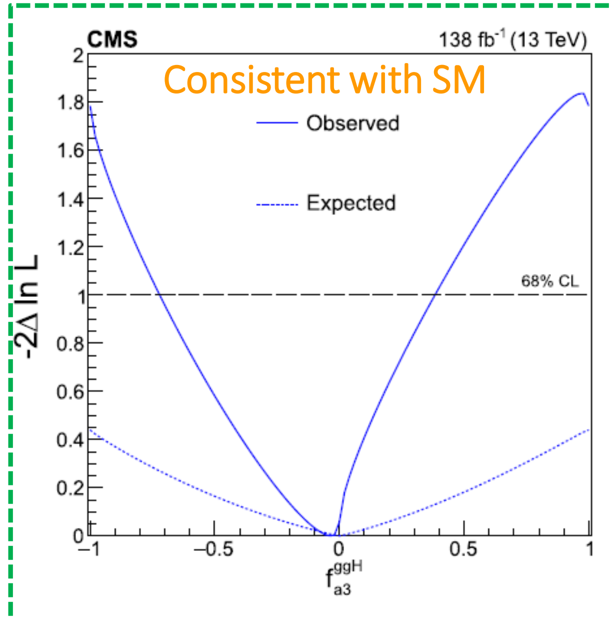
Anomalous Couplings in $H \to WW$ on CMS

- Constraints on anomalous Higgs-gluon couplings
- Same Selection as before
- New Categorization (2-jet ggH vs others)
    - Further Split
        - VBF-like (D_{VBF}>0.5)
        - $sign\left(\frac{g_4^{gg}}{g_2^{gg}}\right)$

Variable	ggH	2-jet ggH
N_{jet} (AK4 jets)	0 & 1	2
m_{jj}	—	>120 GeV
$m_{\ell\ell}$	—	<55 GeV





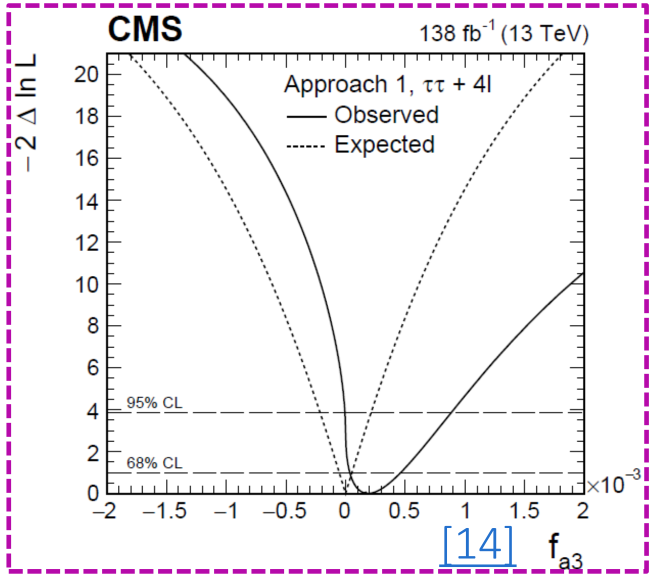


$$f_{a3}^{ggH} = \frac{|a_3^{gg}|^2\sigma_3^{gg}}{|a_2^{gg}|^2\sigma_2^{gg} + |a_3^{gg}|^2\sigma_3^{gg}} \operatorname{sign}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

- **First constraint on CP structure** of gluon vertex in $H \to WW$
- Constraints looser than $H \to \tau\tau$ but tighter than $H \to 4l$ [7]

Anomalous Couplings Combination $H \to ZZ, \gamma\gamma, \tau\tau$

- Constraints on anomalous HVV couplings using the ZZ + ττ final states
- Will not go in detail about selection etc. in interest of time
- **$H \to \tau\tau$ constrains anomalous HVV couplings in EW production**
- **$H \to ZZ$ constrains anomalous couplings in decay and production**



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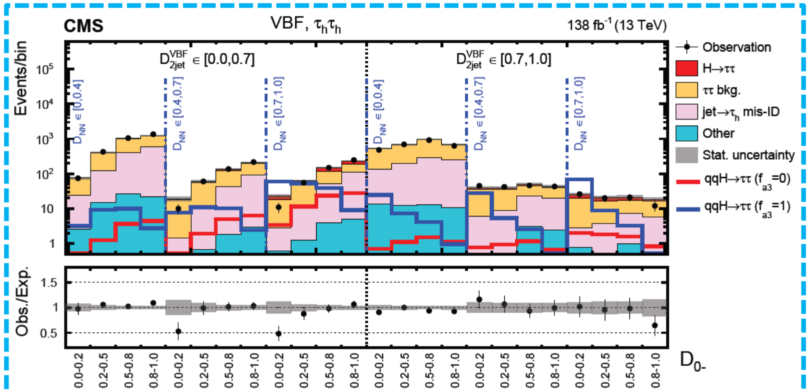
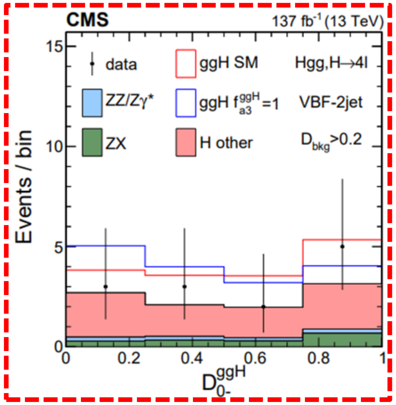
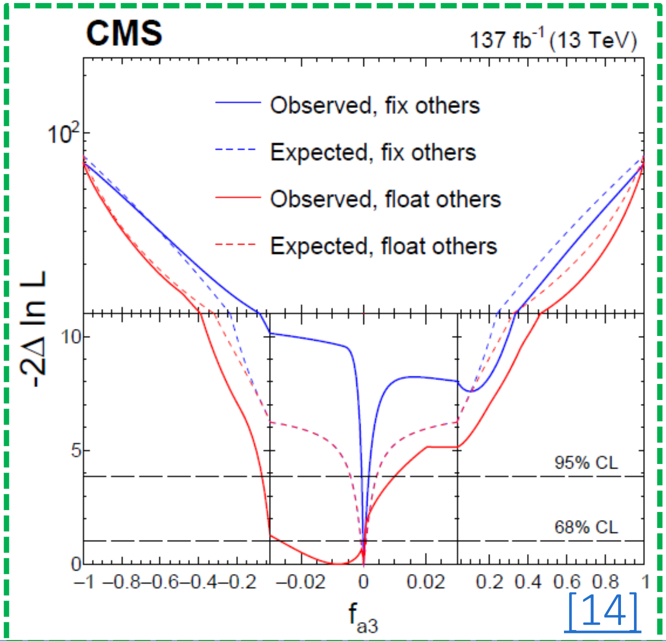




- Combined results do not enforce SMEFT relations or float other f_{ai}
- HZZ only enforces SMEFT relations and floats all anomalous couplings



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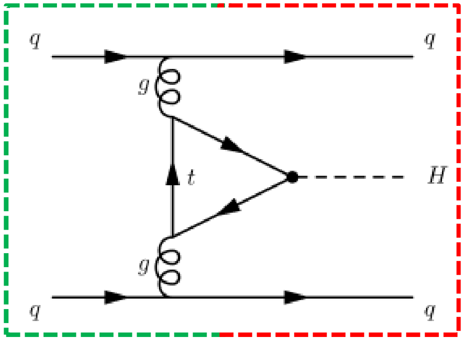
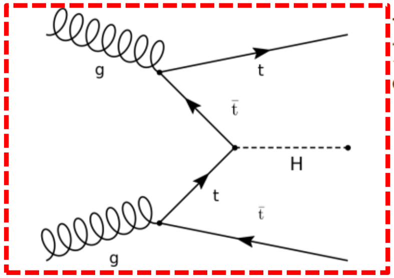
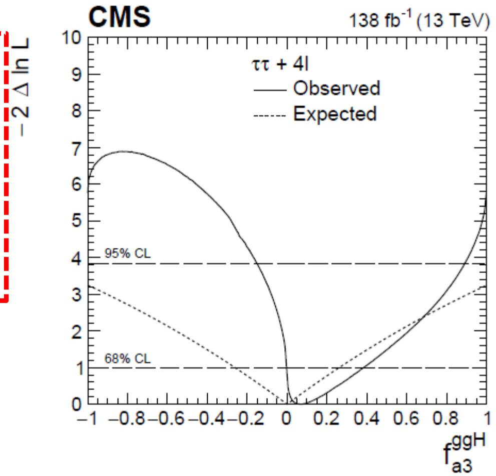
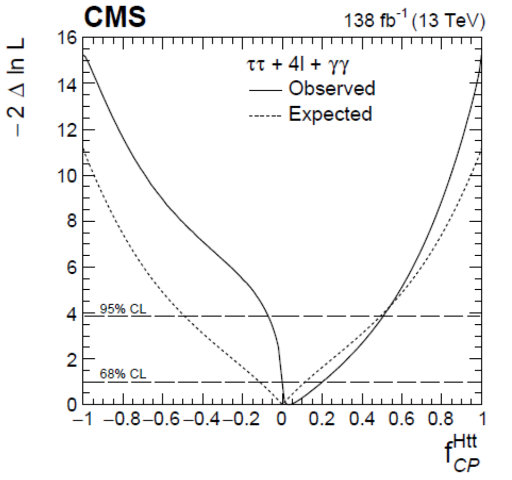
Anomalous Couplings Combination $H \rightarrow ZZ, \gamma\gamma, \tau\tau$

- Constraints on anomalous Hff and Hgg couplings using the ZZ + ττ+ γγ final states
- $H \rightarrow \tau\tau, H \rightarrow ZZ$ jet correlations in ggF constrain anomalous coupling
- $H \rightarrow \gamma\gamma$ constrains anomalous couplings from ttH



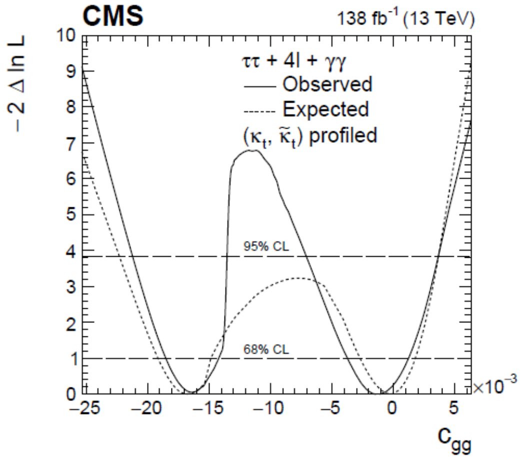


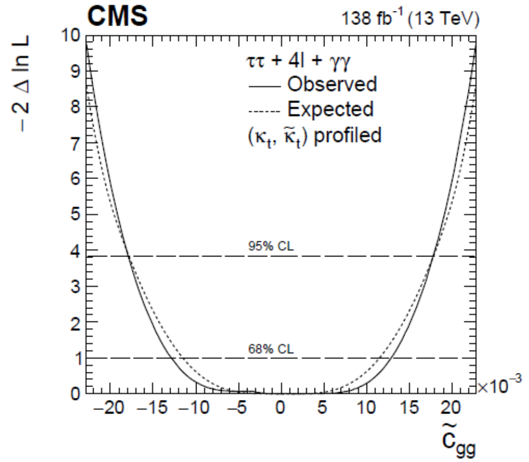




Diagrams Proportional to

$$\kappa_t,\ \tilde{\kappa}_t,\ c_{gg},\ \tilde{c}_{gg}$$

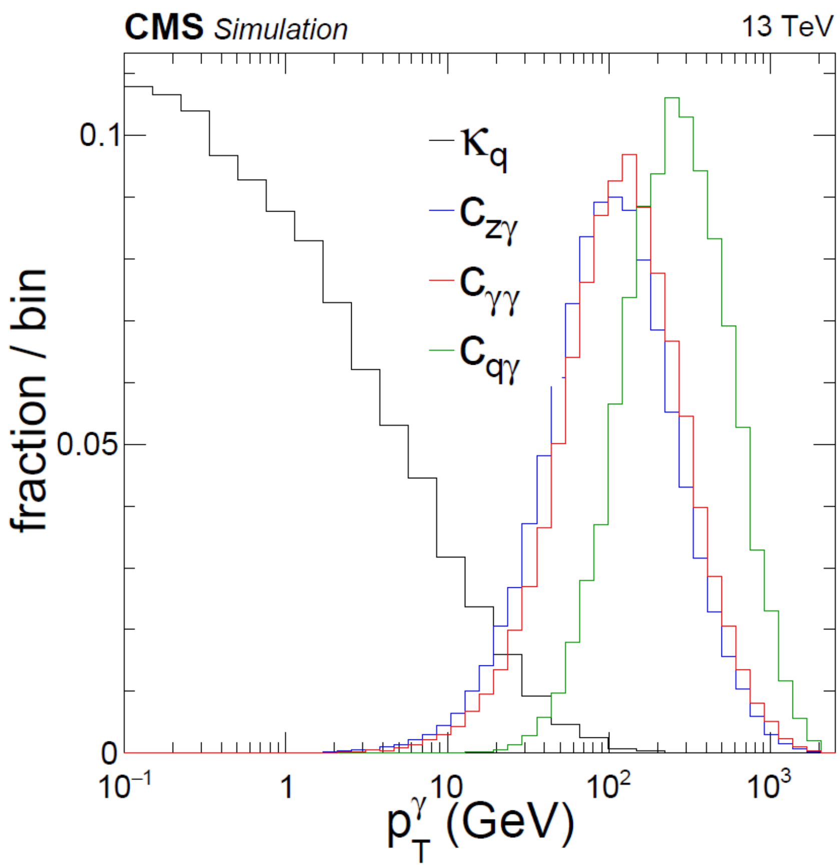




$$\mathcal{A}(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\tilde{\kappa}_f\gamma_5\right)\psi_f$$

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\mathrm{sign}(\tilde{\kappa}_t/\kappa_t).$$

γH Production at the LHC



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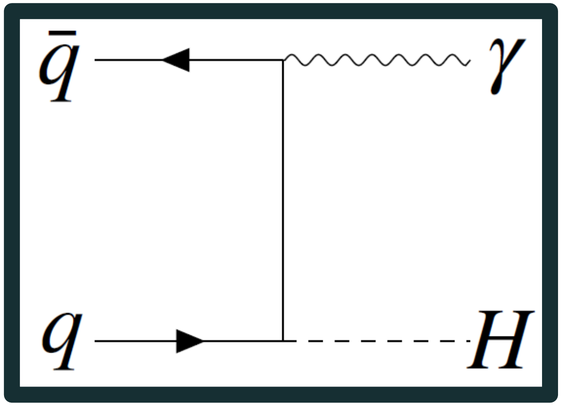
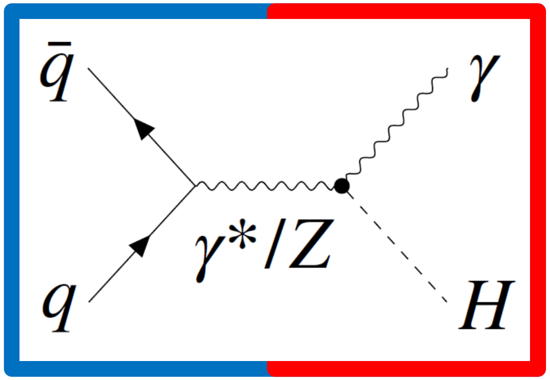


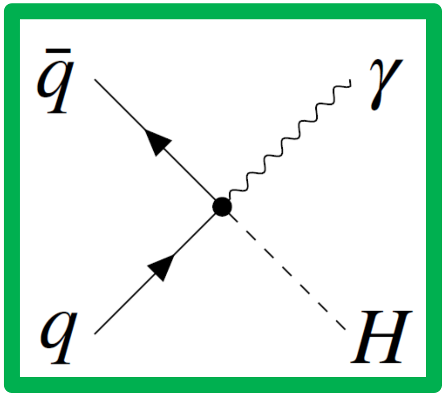
SM-Tree Level

Extremely small cross section



Dim-6 EFT VH-like

Target of γH XS Analysis!



Dim-6 EFT 4-Point

Well constrained by precision EW data

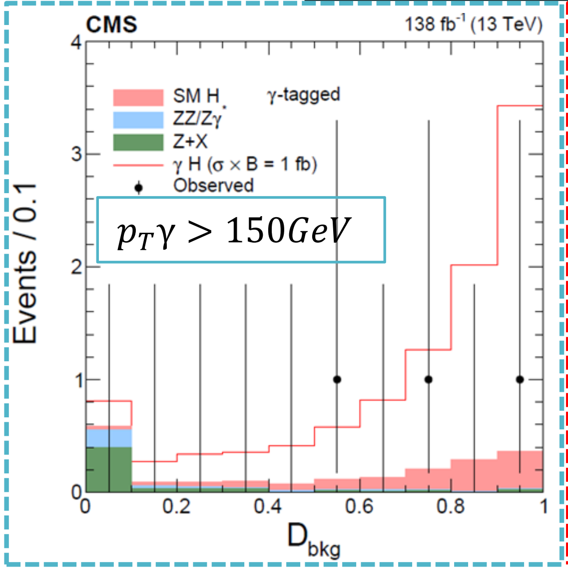
- Non-Zero Wilson coefficients greatly enhance high p_T region
- **Signal**: Higgs with associated high p_T photon

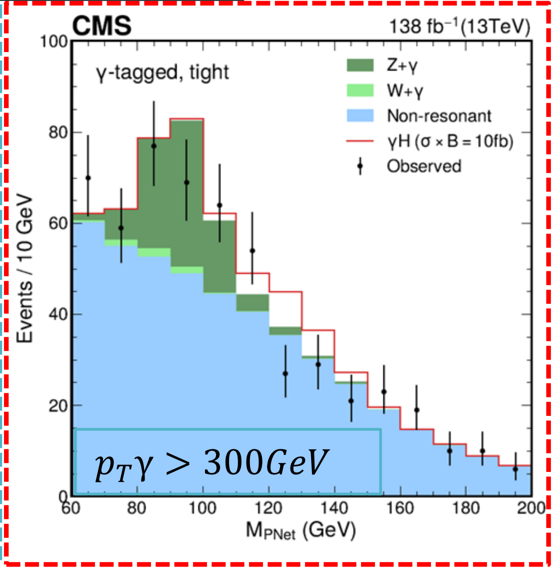
γH Production on CMS

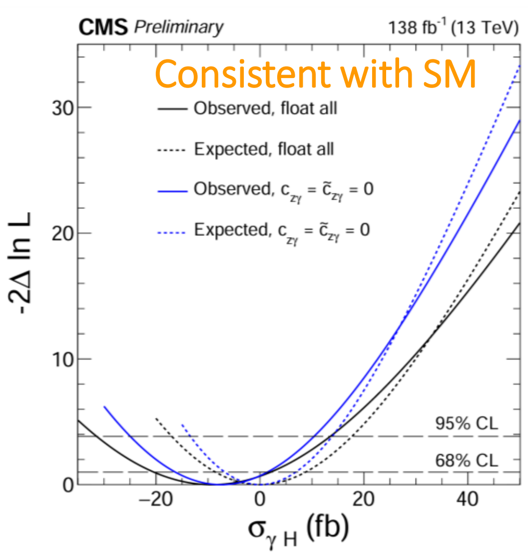
- Combined channels
- $H \to b\bar{b} + \mathrm{H} \to 4l$
- Observables
- Hbb (MParticle Net)
- HZZ (ME based Discriminant)

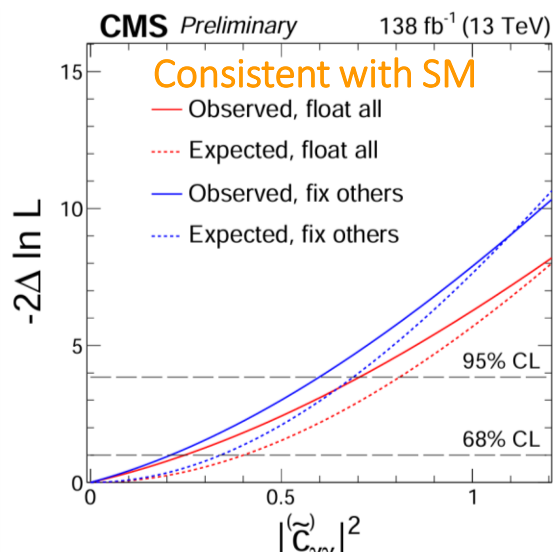
- Results consistent with SM

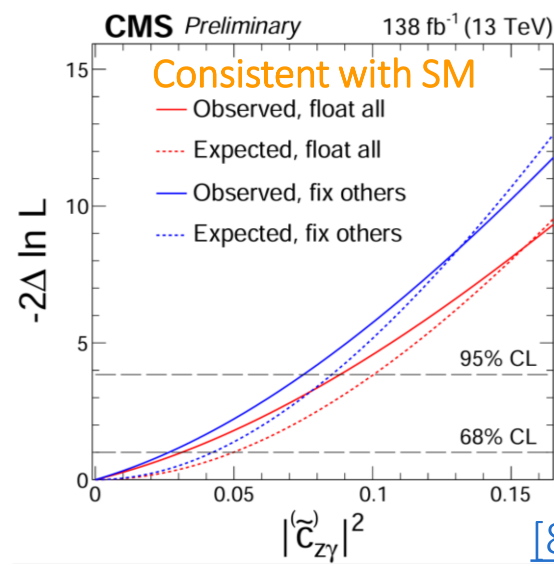
Signal regions for each channel











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Off-Shell Higgs

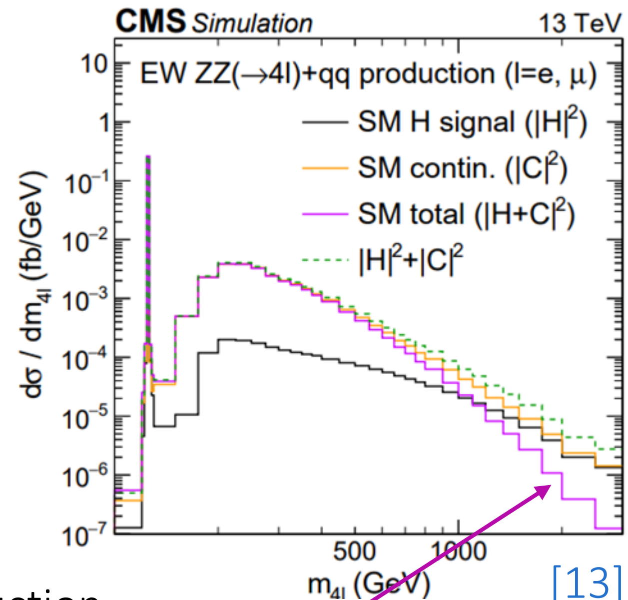
Concepts

- Higgs cross section proportional to couplings and width

$$\frac{d\sigma(i \to H \to f)}{ds} \propto \frac{\left(\sum \alpha_{jk}^{(i)} a_j a_k\right)\left(\sum \alpha_{lm}^{(f)} a_l a_m\right)}{(s - M_H^2)^2 + \cancel{M_H^2 \Gamma_{\text{tot}}^2}}$$

Neglect width in off-shell region (s-M_H^2)>>Γ_{tot}

$$\boxed{\frac{\sigma_{on-shell}}{\sigma_{off-shell}} \propto \frac{1}{\Gamma_{tot}}}$$



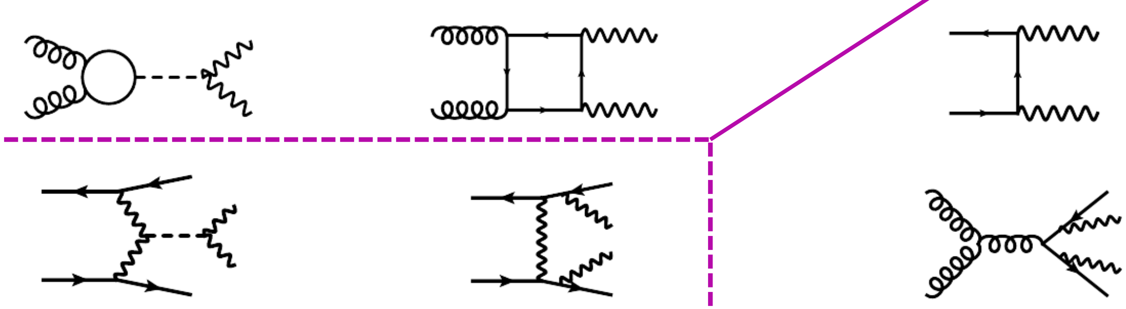
[13]

- Interference in high mass region → evidence for H* production

Relevant processes: (a) Signal (b) Interfering background (c) Non-interfering background

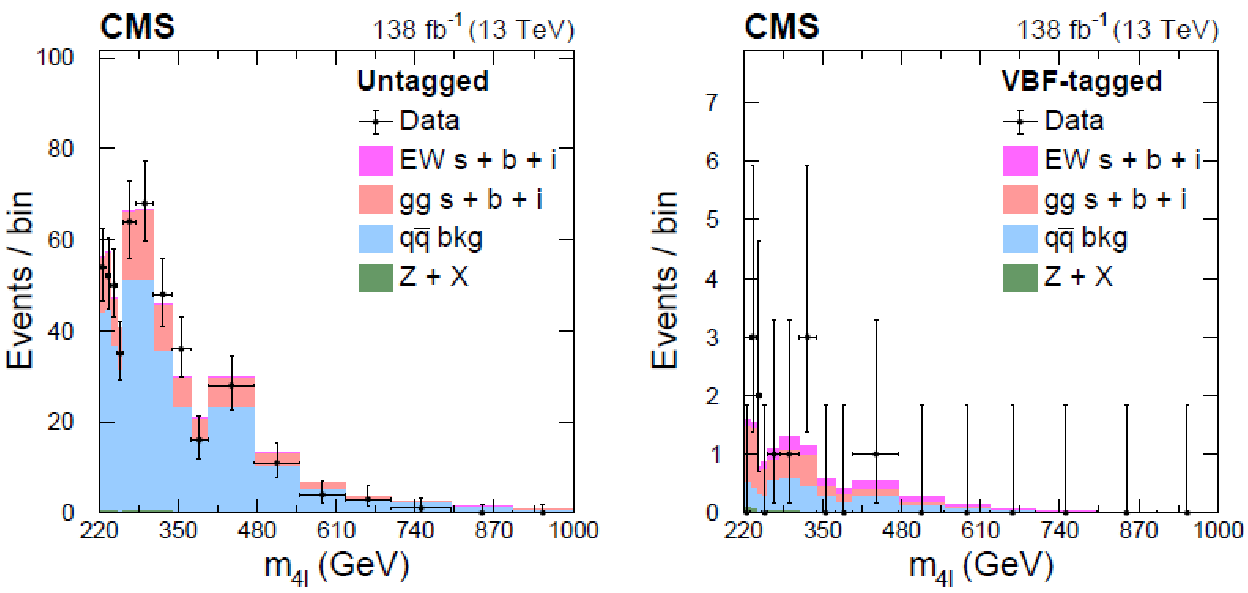
Gluon fusion

Vector boson fusion



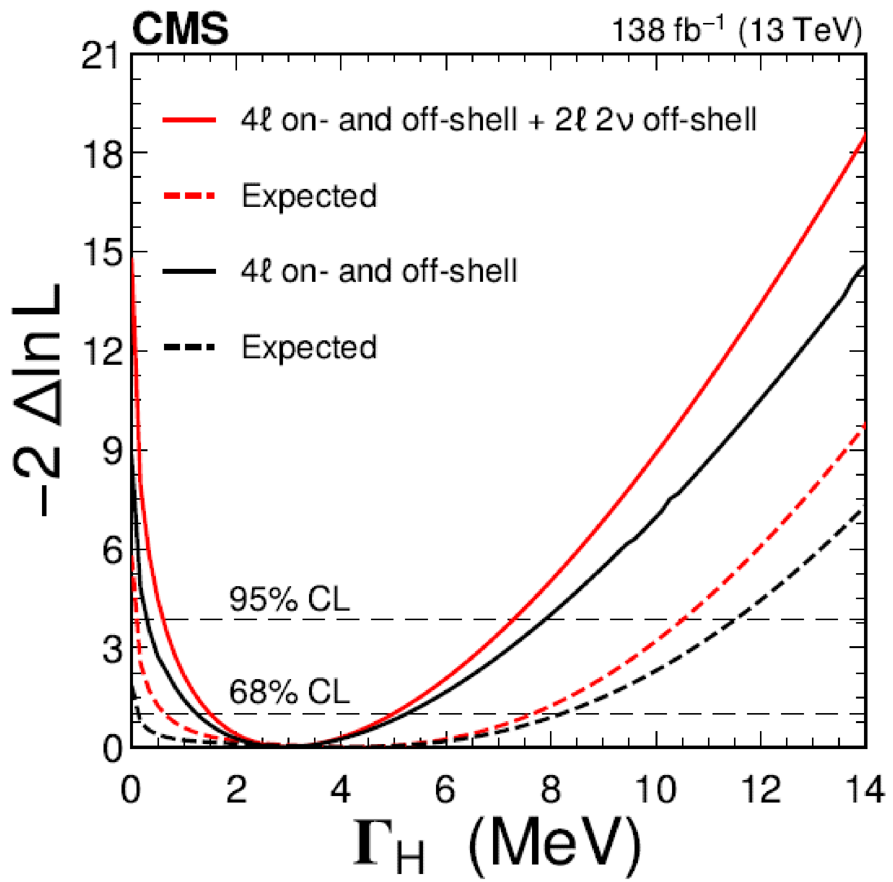
Recent Off-shell result from CMS

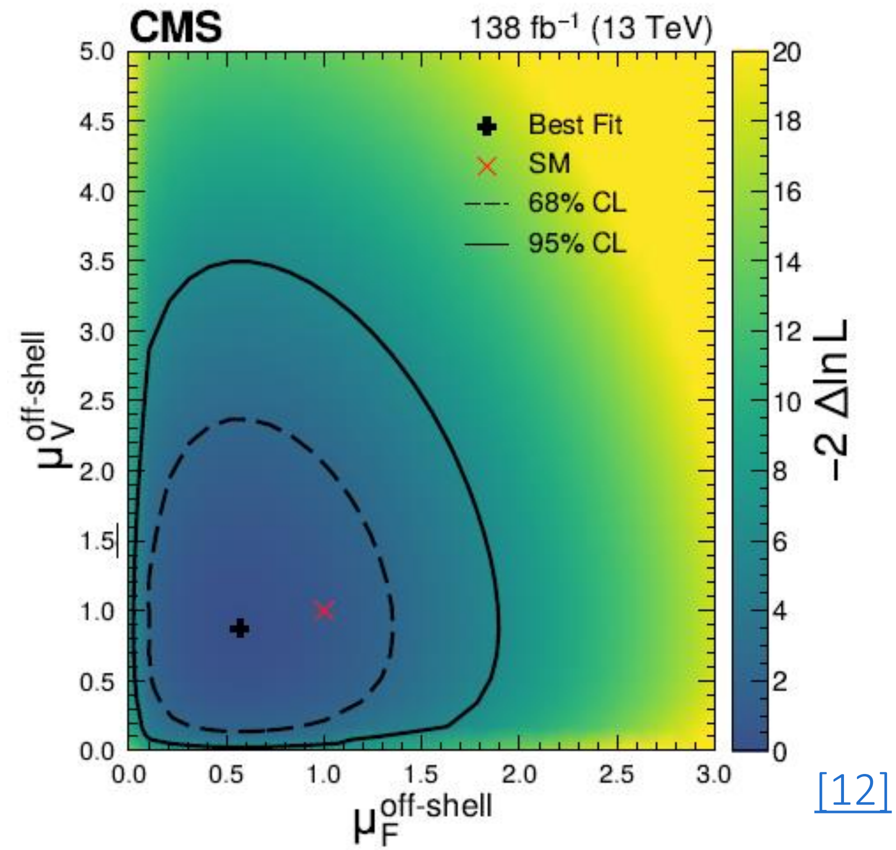
Category	VBF-tagged	VH-tagged	Untagged
Selection	$\mathcal{D}_{\text{2jet}}^{\text{VBF}} > 0.5$	$\mathcal{D}_{\text{2jet}}^{\text{ZH}}$ or $\mathcal{D}_{\text{2jet}}^{\text{WH}} > 0.5$	Rest of the events
Observables	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VBF+dec}}, \mathcal{D}_{\text{bsi}}^{\text{VBF+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{VH+dec}}, \mathcal{D}_{\text{bsi}}^{\text{VH+dec}}$	$m_{4\ell}, \mathcal{D}_{\text{bkg}}^{\text{kin}}, \mathcal{D}_{\text{bsi}}^{\text{gg+dec}}$



[12]

$$\mathcal{P}_{jk}(\vec{x};\vec{\xi}_{jk},\vec{\zeta}) = \frac{\mu_j\Gamma_{\text{H}}}{\Gamma_0}\mathcal{P}_{jk}^{\text{sig}}(\vec{x};\vec{\xi}_{jk}) + \sqrt{\frac{\mu_j\Gamma_{\text{H}}}{\Gamma_0}}\mathcal{P}_{jk}^{\text{int}}(\vec{x};\vec{\xi}_{jk}) + \mu_j\mathcal{P}_{jk}^{\text{cross}}(\vec{x};\vec{\xi}_{jk}) + \mathcal{P}_{jk}^{\text{bkg}}(\vec{x};\vec{\xi}_{jk})$$



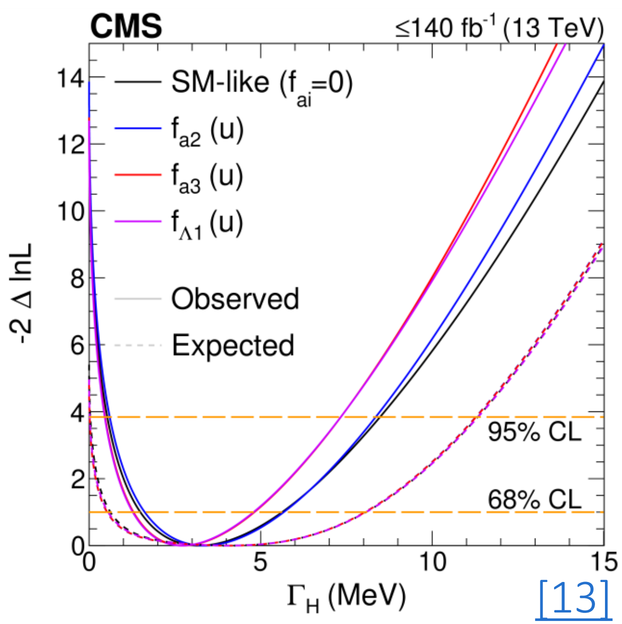


[12]

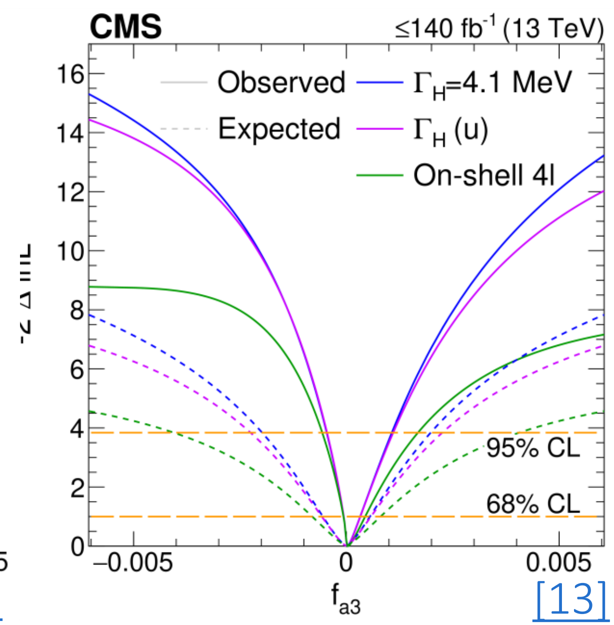
Channel	Observed Γ_H (MeV)	Expected Γ_H (MeV)
4ℓ on- and off-shell + $2\ell 2\nu$ off-shell	$3.0^{+2.0}_{-1.5}$ [0.6, 7.3]	4.1 ± 3.5 [0.1, 10.5]

Anomalous Couplings in Off-shell H

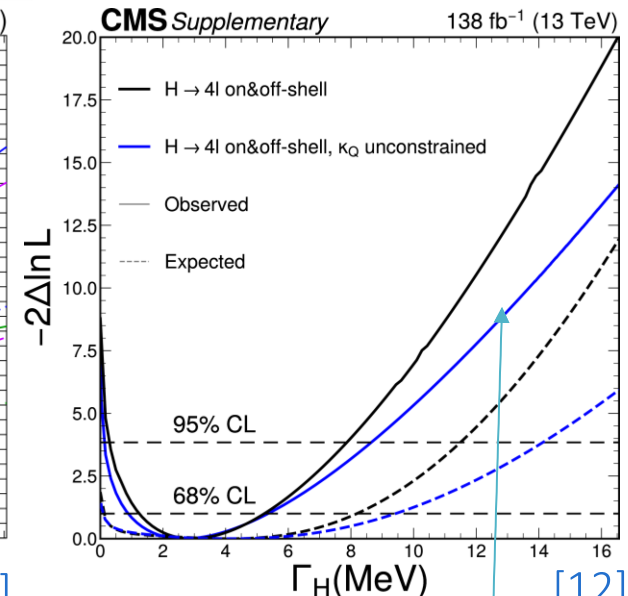
- Applied to CMS data using H*→ $4l/2l2\nu$
- *First step towards full EFT anomalous coupling fit using on-shell/off-shell*



[13]



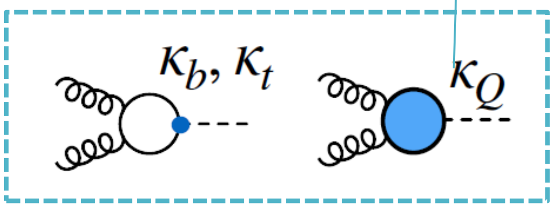
[13]



[12]

•Demonstrates that the width is stable to various HVV EFT/anomalous couplings operators

Off-shell information combined with on-shell improves constraints



Conclusion

- Rich program of anomalous coupling measurements at CMS
- “Dedicated” analysis important to push precision on Higgs couplings
- New production modes can play a key role!
- Presented newest off-shell result and H->WW
- New combinations with Run-3 , off-shell and other decay channels is expected to improve constraints
- Expect to see more exciting results in the future!

References

[1] The Case for Precision Higgs Physics arxiv:2209.07510

[2] The Custodial Symmetry arxiv:0302058

[3] A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery arxiv:2207.00092

[4] A portrait of the Higgs boson by the CMS experiment ten years after the discovery https://arxiv.org/abs/2207.00043

[7] Constraints on anomalous Higgs boson couplings from its production and decay using the WW channel in proton-proton collisions at sqrt{s} = 13TeV arxiv:2403.00657

[8] Search for gammaH production in pp collisions at sqrt{s} = 13TeV and constraints on the Yukawa couplings of light quarks to the Higgs boson using data from the CMS detector cds:2911152

[10] Yellow Report 3 arxiv:1307.1347

[11] New features in the JHU generator framework: constraining Higgs boson properties from on-shell and off-shell production arxiv.:2002.09888

[12] Measurement of the Higgs boson mass and width using the four-lepton final state in proton-proton collisions at sqrt{s} = 13TeV https://arxiv.org/abs/2409.13663

[13] Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production arxiv:2202.06923

[14] Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the ττ final state arxiv:2205.05120

Backup

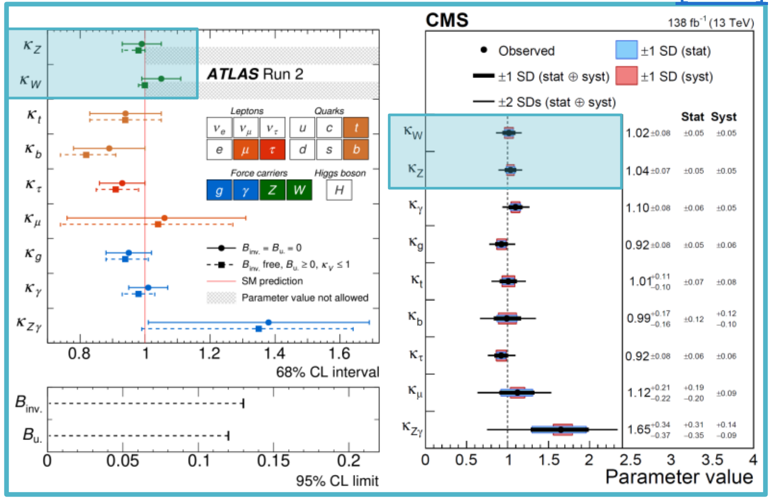
Relative Sign κ_w/κ_z at the LHC

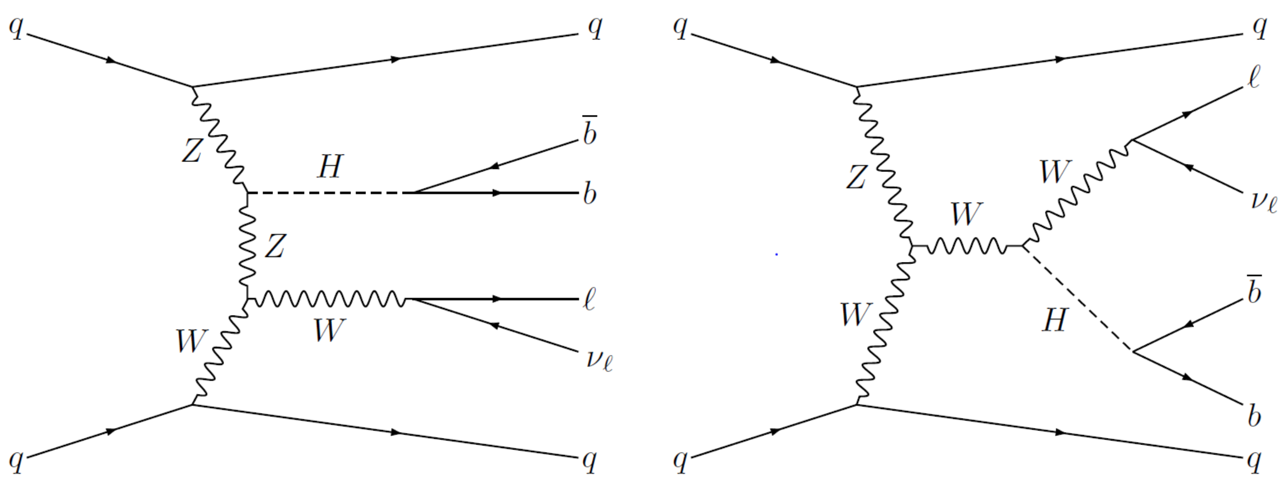
[3-4]

- Target $\lambda_{WZ} = \kappa_w/\kappa_z$
- If EW gauge symmetry broken by Higgs doublet [2]

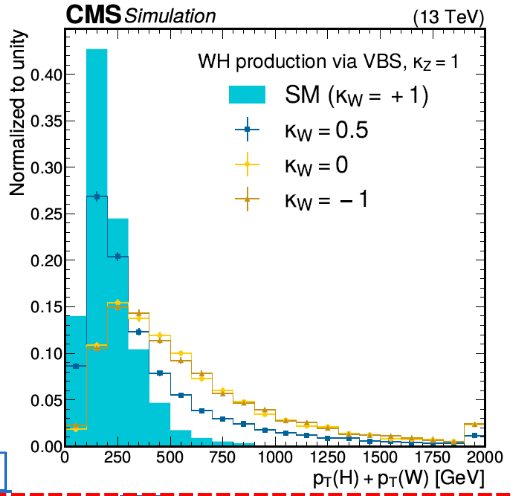
Custodial Symmetry → $\rho \equiv \dfrac{M_W^2}{M_Z^2 \cos^2\theta} = 1$

- Therefore $\lambda_{WZ} \neq 1$ clear signal for BSM physics
- Run-2 combinations sensitive to κ_w^2, κ_z^2 and assumed positive. However: $|\lambda_{WZ}|$ consistent with 1





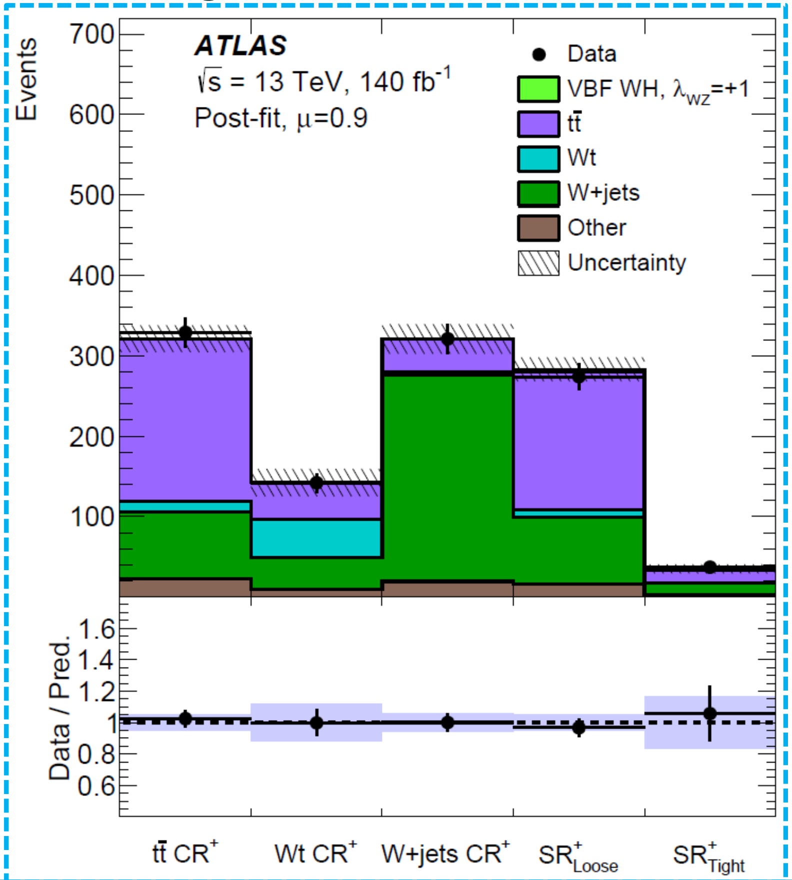
[6]

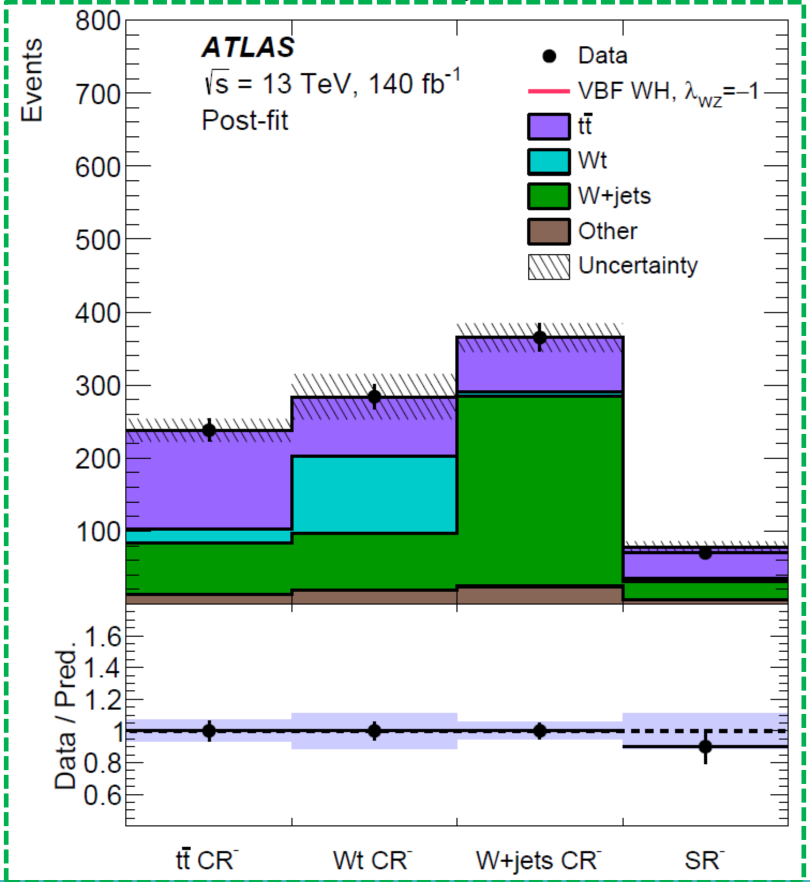


- Amplitude of $qq \to qqW(\to l\nu)H(\to b\bar{b})$ proportional to $(\kappa_w\kappa_z)$ at tree-level with enhancement at high p_T for negative λ_{WZ} [5-6]

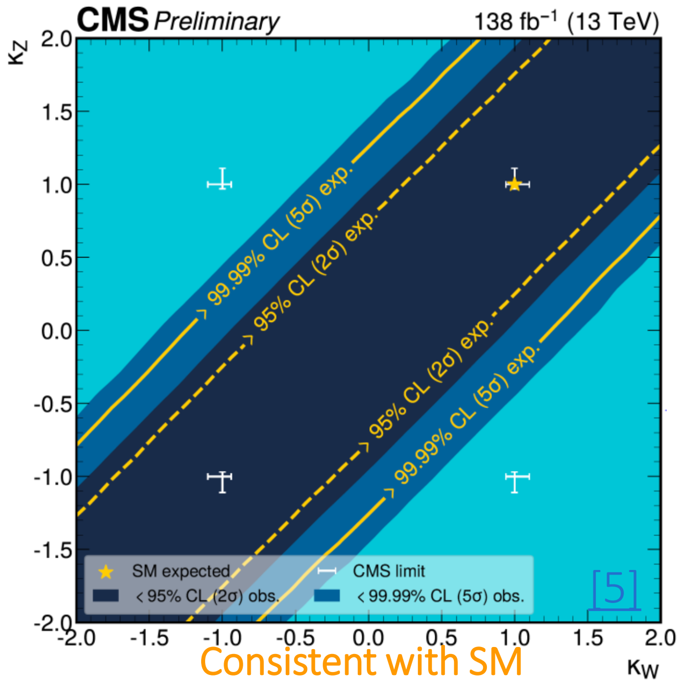
Relative Sign κ_w/κ_z on ATLAS [5]

- Two different analysis tuned for each scenario (similar selection):
  - SM: $sign(\lambda_{WZ}) = 1$
    - **Observable:** Yield in Signal Region (2 orthogonal SR used)
  - BSM: $sign(\lambda_{WZ})$ unconstrainted
    - **Observable:** Yield in signal region
  - All backgrounds in SR: **normalized with respect to best fit in control region**



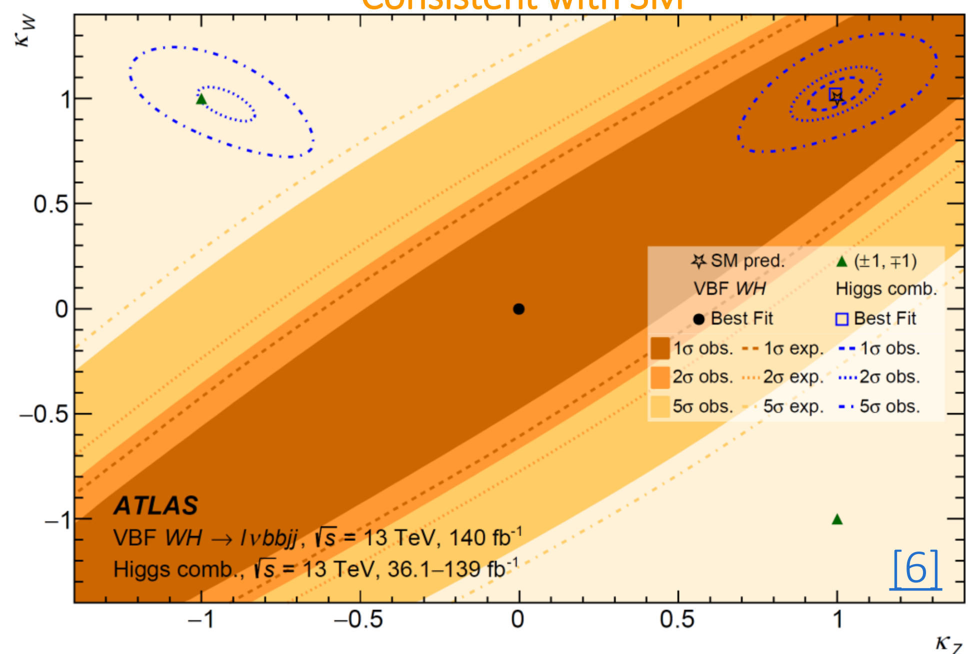


Relative Sign κ_w/κ_z Comparison



Consistent with SM

Consistent with SM



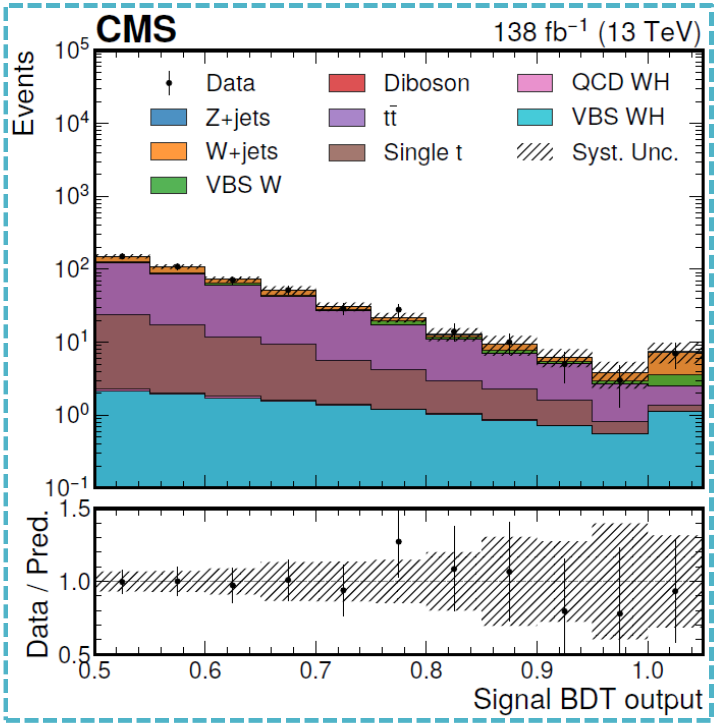
- Observed (Expected) 95% CL on SM-like VBF WH
  - $\sigma_{qqW(\to l\nu)H(\to b\bar{b})}$< 14.3(9.0) x $\sigma^{SM}_{qqW(\to l\nu)H(\to b\bar{b})}$
- $\lambda_{WZ} = -1$ excluded with significance > 5σ

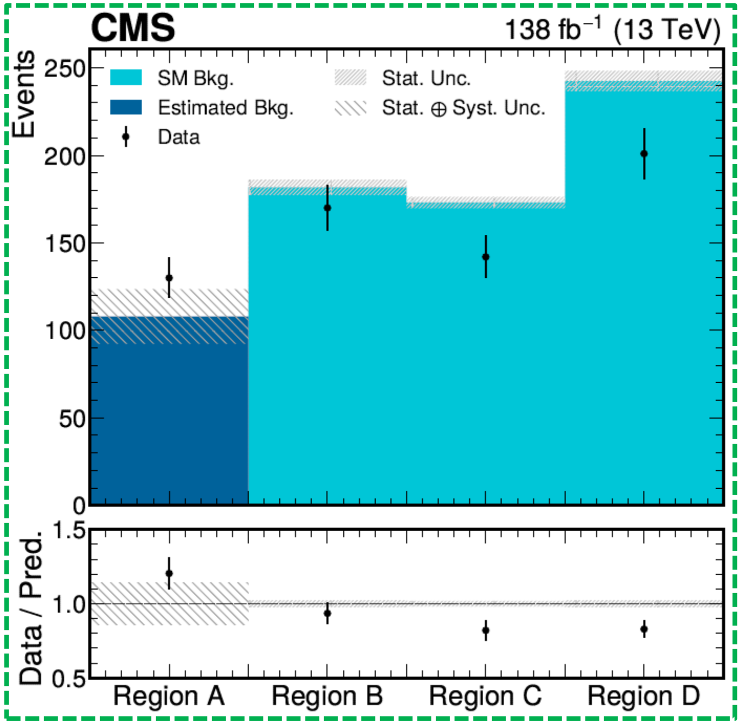
- Observed (Expected) 95% CL on SM-like VBF WH
  - $\sigma_{qqW(\to l\nu)H(\to b\bar{b})}$< 9.0(8.7) x $\sigma^{SM}_{qqW(\to l\nu)H(\to b\bar{b})}$
- $\lambda_{WZ} = -1$ excluded with significance > 5σ

Both measurements consistent with each other and the SM

Relative Sign κ_W/κ_Z at CMS [6]

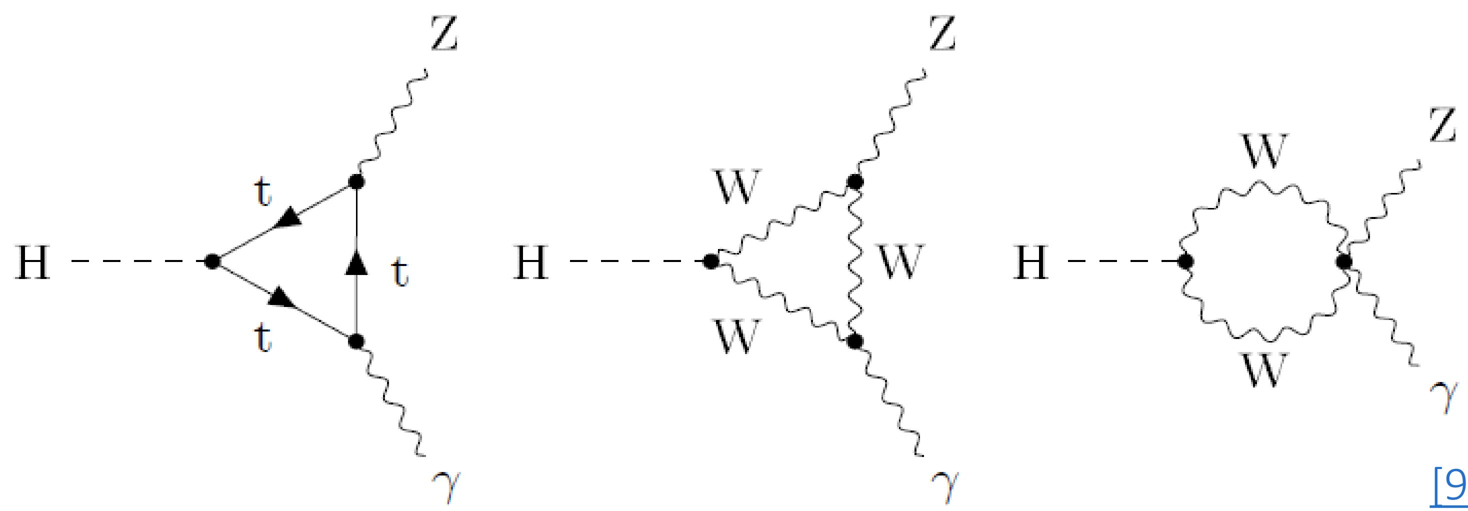
- Two different analysis tuned for each scenario (similar selection):
  - SM: $sign(\lambda_{WZ}) = 1$
    - **Observable:** BDT score (SM VBS WH vs Bkg)
  - BSM: λ_{WZ} unconstrained
    - **Observable:** Yield in signal region
      - Background estimated from orthogonal regions





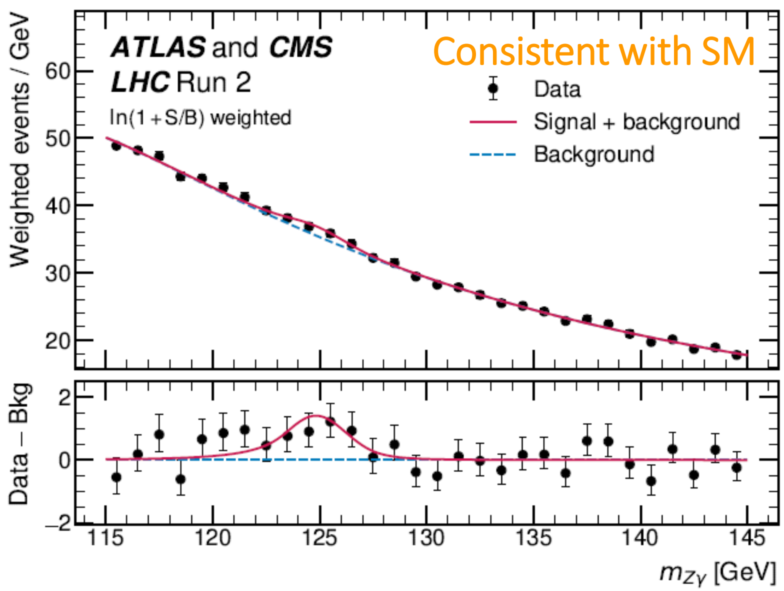
Evidence for $H \rightarrow Z\gamma$ at the LHC

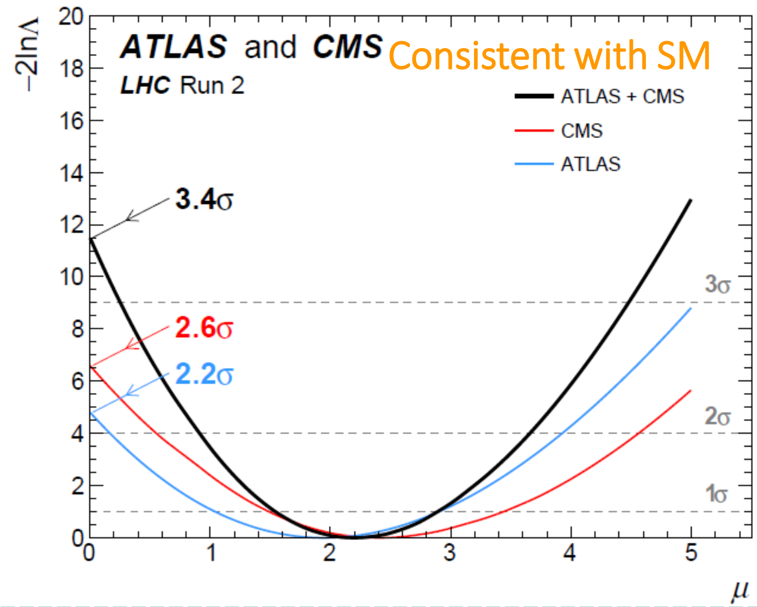
- Leading order $H \rightarrow Z\gamma$ single loop in SM
- **Rarest** H decay to vector bosons $\Gamma^{SM}_{H\rightarrow Z\gamma}$~0.0015%
  - *Only observable in $Z \rightarrow ll$*
- Enhancement of $H \rightarrow Z\gamma$ signal of BSM physics
  - *Higgs is Composite,Singlet, pseudo Nambu–Goldstone?*
  - *Heavy,charged BSM particles in the loop?*



[9]

Evidence for $H \to Z\gamma$ at the LHC





[9]

- Evidence for $H \to Z\gamma$ at **3.4σ** with signal strength $\mu = 2.2 \pm 0.7$
- Interpret signal strength in terms of coupling strength modifier

Assuming SM H production

$$\mu = \frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa^2_{(Z\gamma)}(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_{(Z\gamma)} \end{cases}$$

No BSM

$$\kappa^2_{(Z\gamma)}(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma^{ij}_{Z\gamma}(m_H)}{\sum_{i,j} \Gamma^{ij}_{Z\gamma}(m_H)}$$

$$\kappa^2_{(Z\gamma)}$$

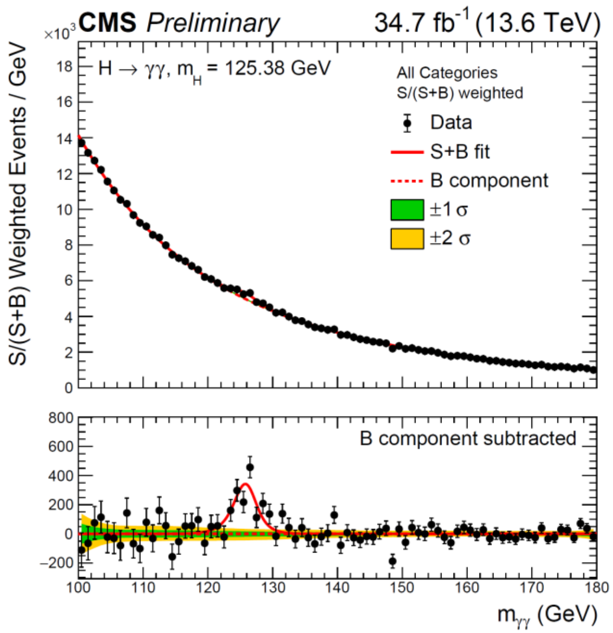
Or model BSM particles in loop with new effective coupling
Ex: κ_q

[10]

$H \rightarrow ZZ + H \rightarrow \gamma\gamma$ Run-3 CMS

- CMS recently published their first Run-3 cross section measurements of $\boldsymbol{H \rightarrow ZZ}$ and $\boldsymbol{H \rightarrow \gamma\gamma}$ (13.6 TeV)

- Analysis Strategy: Fit to $\boldsymbol{m_{\gamma\gamma}}$ or $\boldsymbol{m_{4l}}$
- Results: Fiducial cross section (assumes SM BR and Selection Efficiency)



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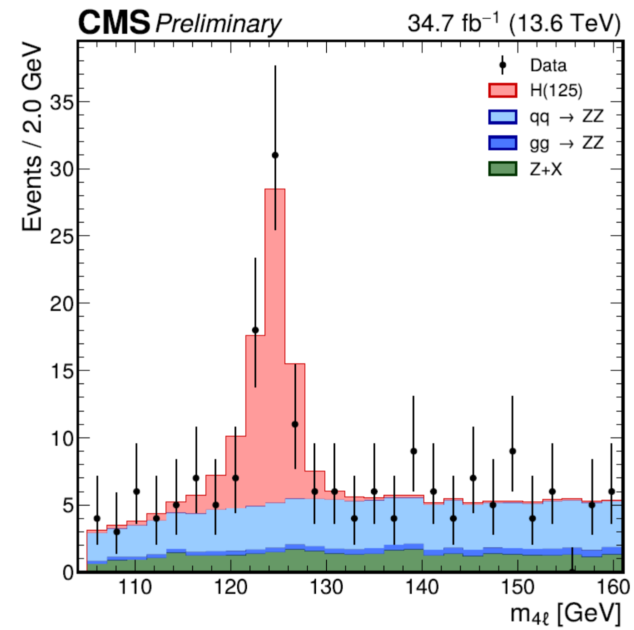


[13]

$$\sigma_{\text{fid}} = 78 \pm 11(\text{stat.})^{+6}_{-5}(\text{syst.})\ \text{fb}$$

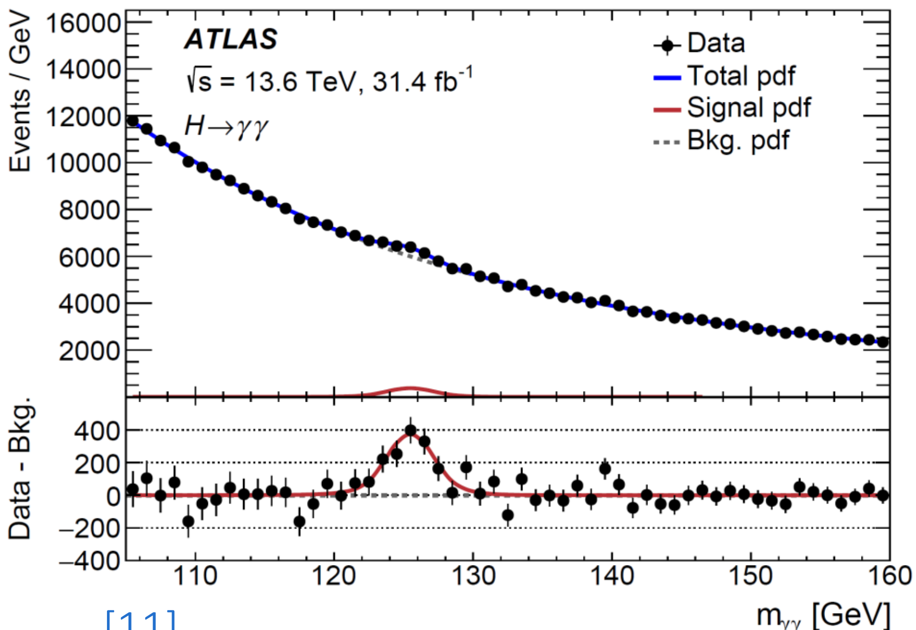
$$\sigma_{\text{fid}} = 2.94^{+0.53}_{-0.49}(\text{stat.})^{+0.29}_{-0.22}(\text{syst.})\ \text{fb}$$

67.8 ± 3.8 fb   Consistent with SM $3.09^{+0.27}_{-0.24}$ fb

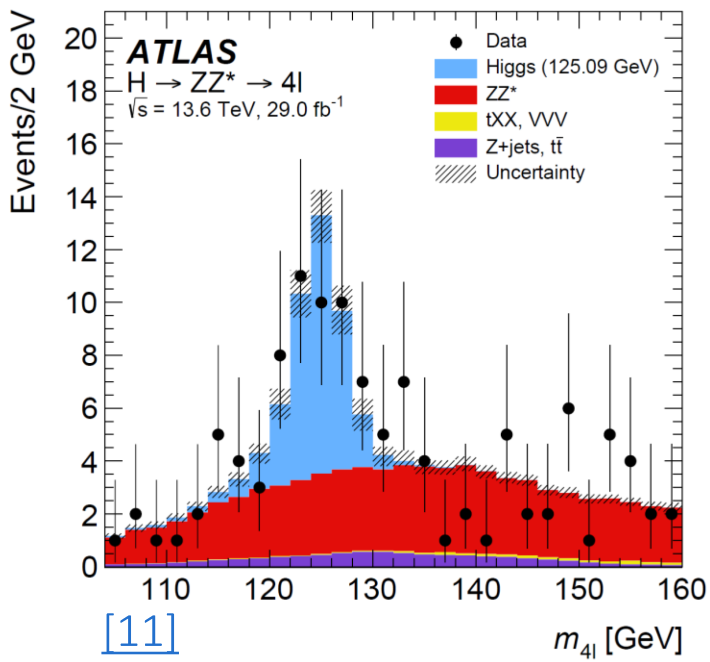
$H \rightarrow ZZ + H \rightarrow \gamma\gamma$ Run-3 ATLAS

- ATLAS published the first Run-3 cross section measurements of $\boldsymbol{H \rightarrow ZZ}$ and $\boldsymbol{H \rightarrow \gamma\gamma}$ (13.6 TeV)

- Analysis Strategy: Fit to $\boldsymbol{m_{\gamma\gamma}}$ or $\boldsymbol{m_{4l}}$
- Results: Fiducial cross section (assumes SM BR and Selection Efficiency)



[11]



[11]

$$\sigma_{\text{fid},\gamma\gamma} = 76^{+14}_{-13}\ \text{fb}$$

Consistent with SM 67.6 ± 3.7 fb

$$\sigma_{\text{fid},4\ell} = 2.80 \pm 0.74\ \text{fb}$$

Consistent with SM 3.67 ± 0.19 fb