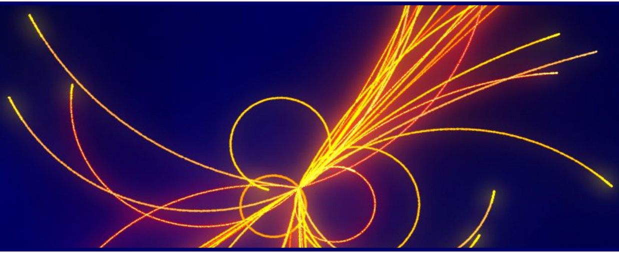
Constraints on anomalous Higgs boson couplings in the HWW channel at CMS



Dermot Moran (CIEMAT)

8th Red LHC 2024 workshop
28-30 May 2024 (UCM)

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Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

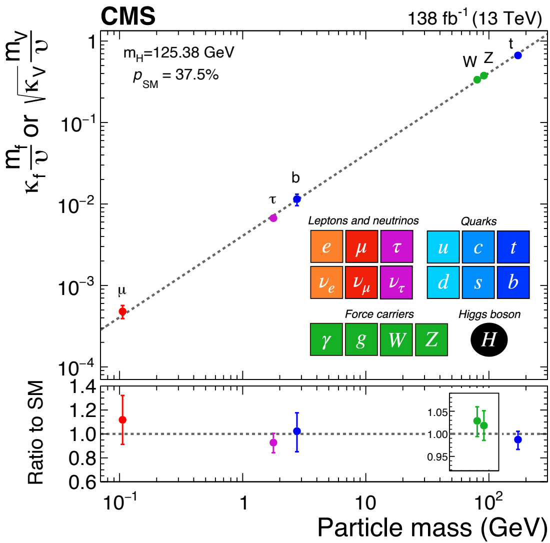
Why is the Higgs boson so light?

BSM ideas to solve the Hierarchy problem :

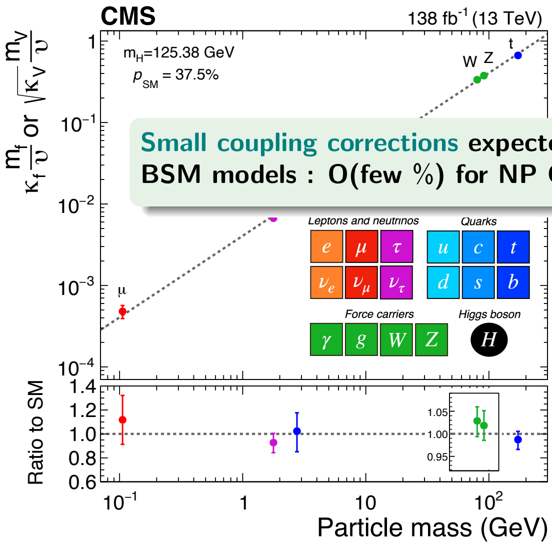
- A new symmetry protects the higgs mass : **SUSY**
- Higgs is a bound state of new strong interaction : **Composite Higgs**

Can significantly alter Higgs phenomenology

SM picture observed so far

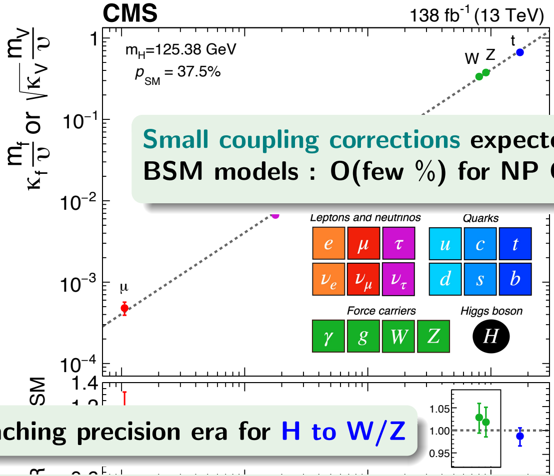


SM picture observed so far



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

SM picture observed so far



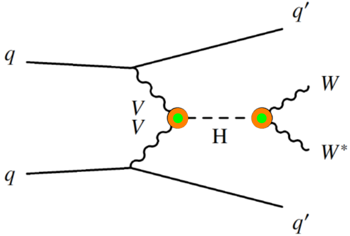
Small coupling corrections expected for many BSM models : O(few %) for NP @ 1TeV

Approaching precision era for H to W/Z

κ_V: Simple coupling modifier based on inclusive measurements
$\rightarrow$ Deeper study of coupling structure is possible...

Anomalous couplings (AC) approach

Ideal framework for **general study of the HVV coupling structure**



→ Consider **tree-level**, **loops/BSM** contributions to HVV

→ Exploit **full event kinematics** (production + decay information)

Will discuss **Run 2 study** of **HVV coupling structure** in **HWW channel**

HIG-22-008 (Accepted for publication by EPJC)
arXiv:2403.00657

HVV anomalous coupling parametrization

HVV scattering amplitude (General Lorentz invariant form) :

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

Higgs to EWK vector boson couplings :

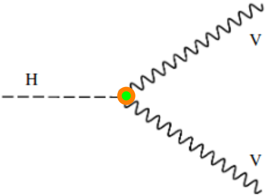
HWW, **HZZ**
H$\gamma\gamma$, **HZ**γ

$\rightarrow$ Assume **H**$\gamma\gamma$, **HZ**γ constrained from **direct decay measurements**

$\rightarrow$ **SU(2) x U(1)** sets relationship between **HWW** and **HZZ**

HVV anomalous coupling parametrization

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



4 independent HVV couplings :

a_1 **: SM tree level coupling**

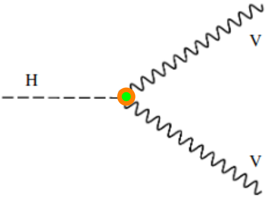
k_1/Λ^2 **: CP-Even AC**

a_2 **: CP-Even AC**

a_3 **: CP-Odd AC**

HVV anomalous coupling parametrization

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



4 independent HVV couplings :

a_1 **: SM tree level coupling**

k_1/Λ^2 **: CP-Even AC**

a_2 **: CP-Even AC**

a_3 **: CP-Odd AC**

$\rightarrow$ **Convenient to measure fractional contribution of AC to** σ **:**

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

Signal model contains signal strength μ **+ 3** f_{ai}

Equivalent to SM EFT

$$\mathcal{L}_{\rm hvv} = \frac{h}{v}\Big[M_Z^2\left(1+\delta c_z\right)Z_\mu Z^\mu + \frac{M_Z^2}{v^2}c_{zz}Z_{\mu\nu}Z^{\mu\nu} + \frac{e^2}{s_w^2}c_{z\Box}Z_\mu\partial_\nu Z^{\mu\nu} + \frac{M_Z^2}{v^2}\tilde{c}_{zz}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

$$+2M_W^2\left(1+\delta c_w\right)W_\mu^+W^{-\mu} + 2\frac{M_W^2}{v^2}c_{ww}W_{\mu\nu}^+W^{-\mu\nu} + \frac{e^2}{s_w^2}c_{w\Box}\left(W_\mu^-\partial_\nu W^{+\mu\nu} + \mathrm{h.c.}\right)$$

$$+\frac{e^2}{2s_w^2}\tilde{c}_{ww}W^{+\mu\nu}\tilde{W}_{\mu\nu}^- + \frac{e^2}{2s_wc_w}c_{z\gamma}Z_{\mu\nu}A^{\mu\nu} + \frac{e^2}{2s_wc_w}\tilde{c}_{z\gamma}Z_{\mu\nu}\tilde{A}^{\mu\nu} + \frac{e^2}{s_wc_w}c_{\gamma\Box}Z_\mu\partial_\nu A^{\mu\nu}$$

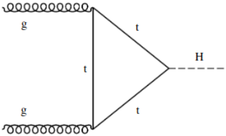
$$+c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A^{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A^{\mu\nu}\tilde{A}_{\mu\nu} + c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^aG^{a\mu\nu} + \tilde{c}_{gg}\frac{g_s^2}{4}G^{a\mu\nu}\tilde{G}_{\mu\nu}^a\Big],$$

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

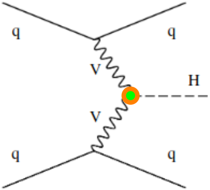
Interpretation in terms of EFT couplings also considered.

HVV Analysis strategy

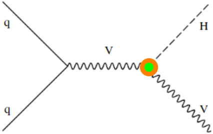
Production : | **Categories :** | **Decay :**



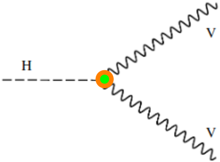
0- & 1-jet ggF



2-jet VBF



2-jet &
boosted VH



$\mathbf{H} \rightarrow WW \rightarrow \mu e + p_T^{miss}$

Dramatic reduction of background

Dedicated Observables

Exploit kinematics of 2 associated jets with **MELA based discriminants**

At production vertex can target :

$\rightarrow$ **Production mode**

D_{VBF}

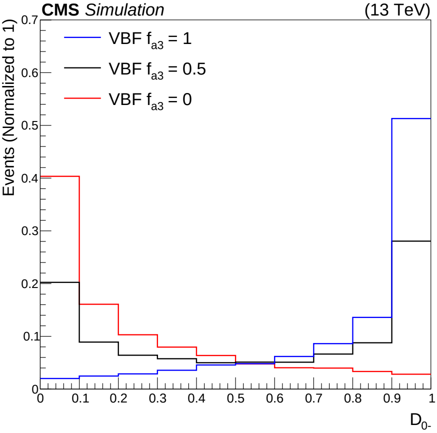
$\rightarrow$ **For each AC, the pure coupling contribution ($\propto a^2$) :**

D_{0+}, D_{0-}

+ the interference contribution ($\propto a$) :

D_{Int}, D_{CP}

Example : D_{0-} discriminates a_1 and a_3

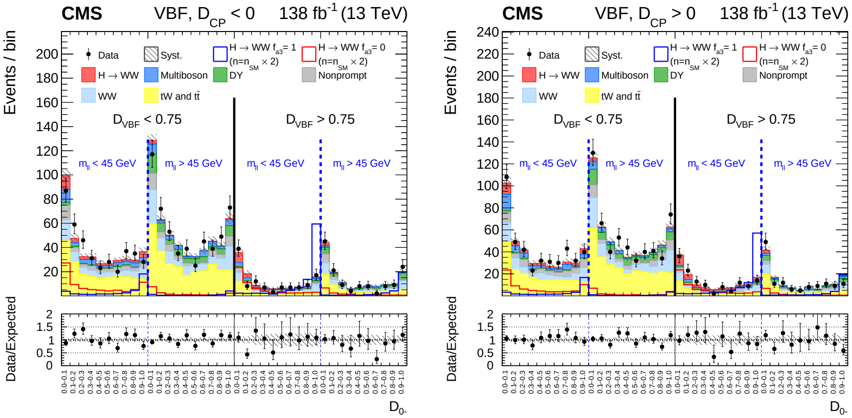


For AC sensitivity at decay vertex : m_{ll}, m_T

Kinematic Discriminants (KDs)

KDs combine **multiple observables**

Example : VBF(a_3) KD using D_{CP} and $[D_{VBF}, m_{ll}, D_{0-}]$



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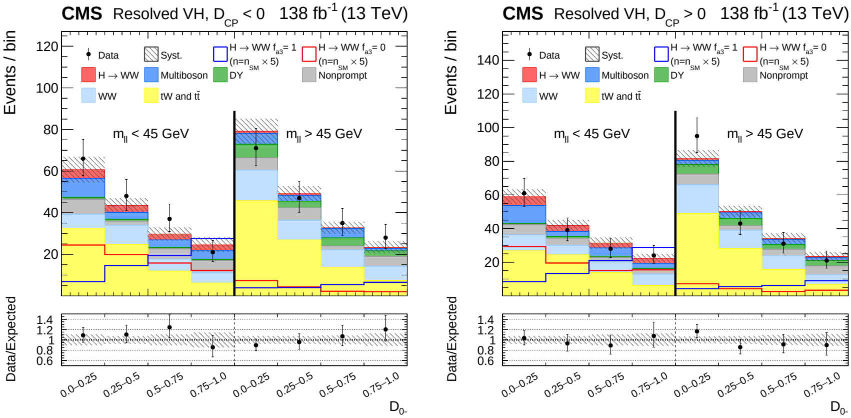

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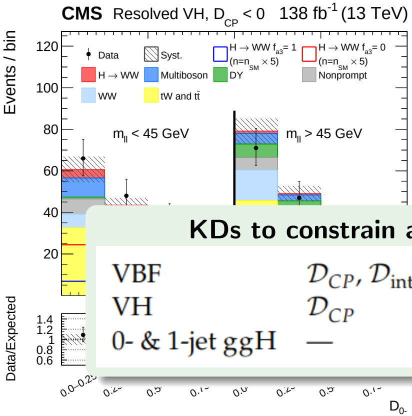
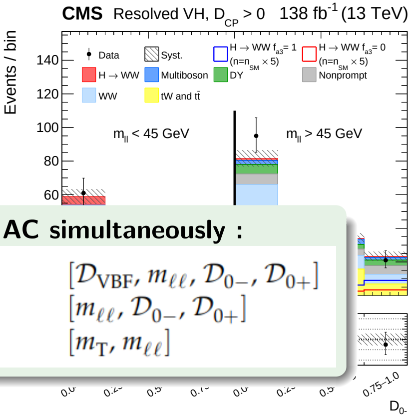


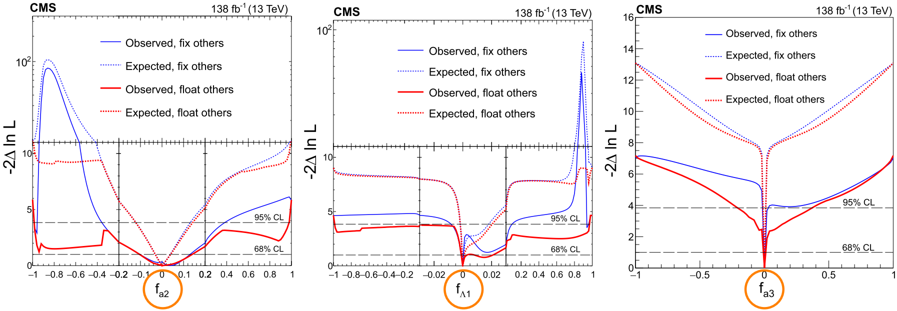


KDs to constrain all AC simultaneously :

VBF	$\mathcal{D}_{CP}, \mathcal{D}_{\text{int}}$	$[\mathcal{D}_{\text{VBF}}, m_{\ell\ell}, \mathcal{D}_{0-}, \mathcal{D}_{0+}]$
VH	$\mathcal{D}_{CP}$	$[m_{\ell\ell}, \mathcal{D}_{0-}, \mathcal{D}_{0+}]$
0- & 1-jet ggH	—	$[m_{\text{T}}, m_{\ell\ell}]$

f_{ai} likelihood scans

signal strength μ + f_{ai} floated simultaneously

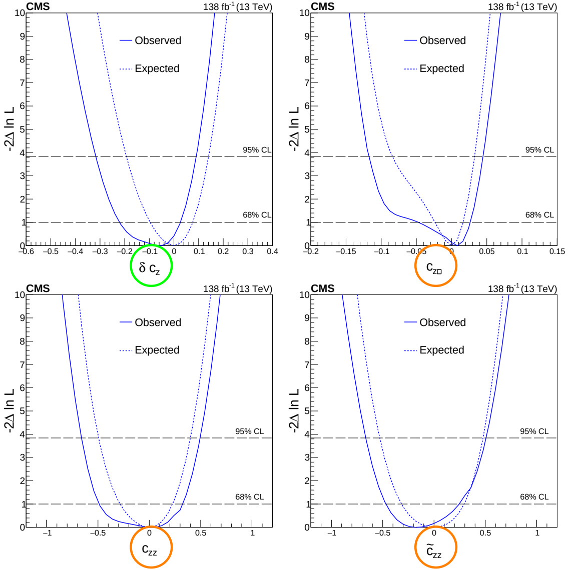


Signal strength $\mu \sim 0.9 \pm 20\%$

$f_{ai} \sim 0$ consistent with SM Higgs boson

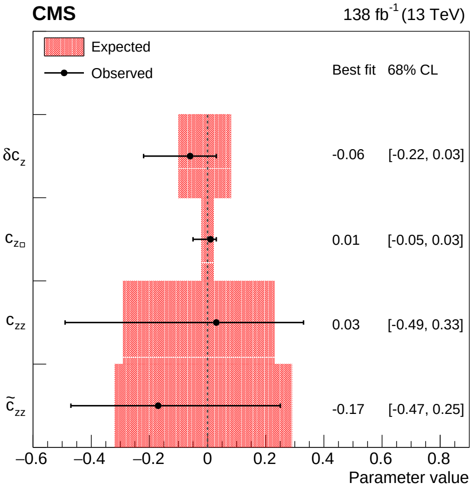
(Best constraints at the **per mille level**)

Coupling likelihood scans (Higgs basis)



All couplings floated simultaneously

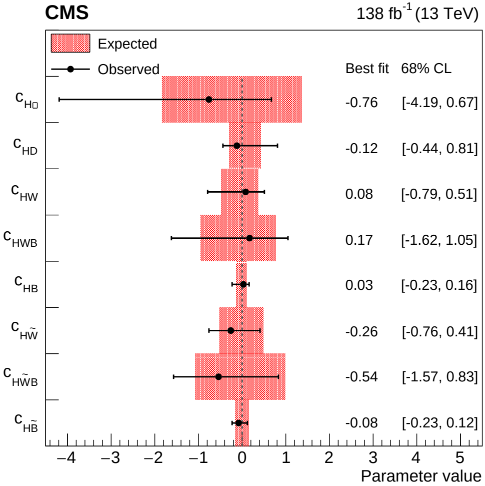
Coupling constraints (Higgs basis)



Possible to rotate from **Higgs** to **Warsaw basis**

(Mass → gauge eigenstate basis)

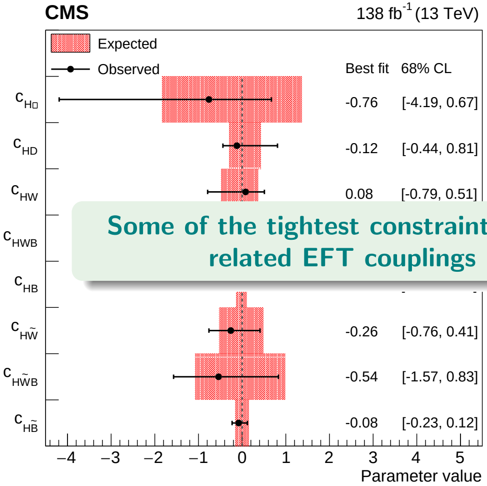
Coupling constraints (Warsaw basis)



Only one of $[c_{\mathbf{HW}}$, $c_{\mathbf{HWB}}$, $c_{\mathbf{HB}}]$ and $[c_{\mathbf{H\tilde{W}}}$, $c_{\mathbf{H\tilde{W}B}}$,$c_{\mathbf{H\tilde{B}}}]$ is independent

(Due to $\mathbf{H}\gamma\gamma$, $\mathbf{HZ}\gamma$ assumptions)

Coupling constraints (Warsaw basis)



Some of the tightest constraints yet on related EFT couplings

Only one of $[c_{\mathbf{HW}}, c_{\mathbf{HWB}}, c_{\mathbf{HB}}]$ and $[c_{\mathbf{H\tilde{W}}}, c_{\mathbf{H\tilde{W}B}}, c_{\mathbf{H\tilde{B}}}]$ is independent

(Due to **H**$\gamma\gamma$, **HZ**γ assumptions)

Hgg anomalous coupling parametrization

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

2 independent Hgg couplings :

a_2 **: SM loop**

a_3 **: CP-Odd AC**

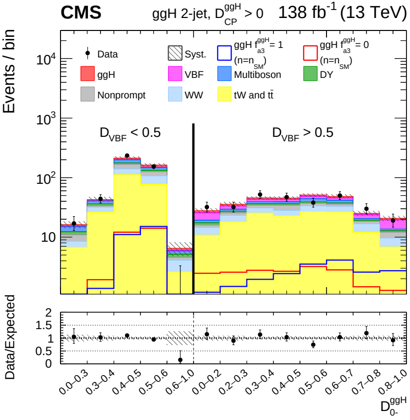
ggH + 2 jets process sensitive to Hgg AC at production vertex

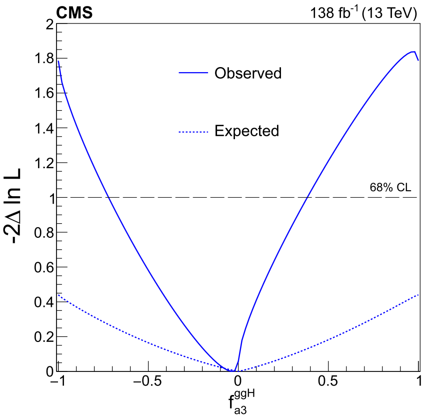
categorization and KDs :

Hgg	2-jet ggH	$\mathcal{D}_{CP}^{\mathrm{ggH}}$	$[\mathcal{D}_{\mathrm{VBF}}, \mathcal{D}_{0-}^{\mathrm{ggH}}]$
	0- & 1-jet ggH	—	$[m_{\mathrm{T}}, m_{\ell\ell}]$

Hgg AC analysis

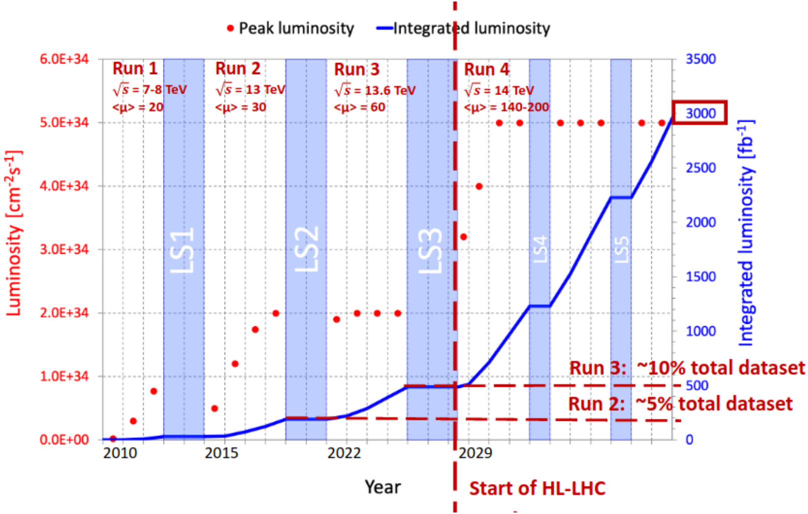
signal strength μ + f_{a3}^{ggH} floating





$f_{ai} \sim 0$ consistent with SM Higgs boson

Analysis is currently statistically limited



→ So a lot to gain in the future..

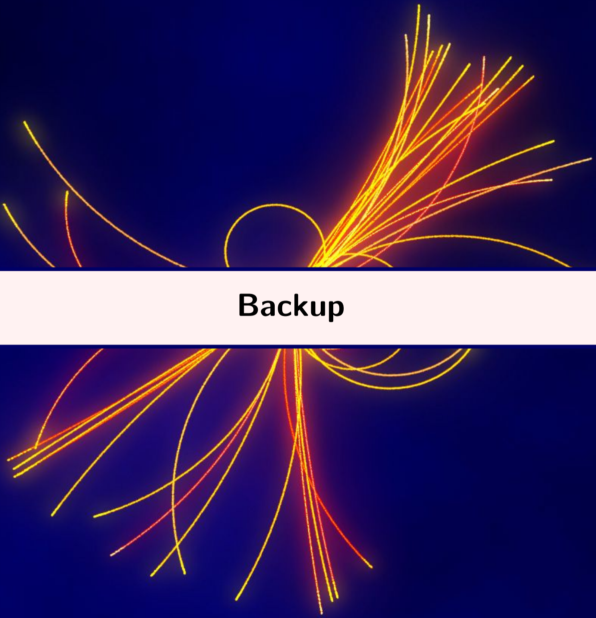
Conclusions

Measurement of HVV coupling structure a crucial test of SM

Dedicated study in HWW channel with full Run 2 data presented

Measurements **Consistent with SM Higgs boson** (**Best constraints on f_{ai}** at the **per mille level**)

Some of the **tightest constraints yet** on related **EFT couplings**



Backup

Selection + categorization

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	—

SU(2) x U(1) relationship between HWW and HZZ

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

Higgs and Warsaw basis relationships

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

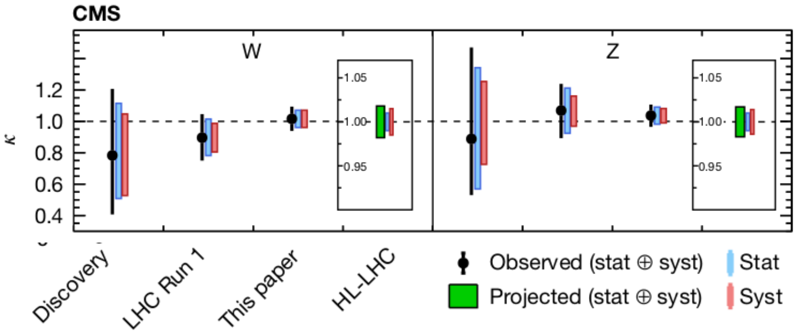
$$\delta a_1^{ZZ} = \frac{v^2}{\Lambda^2} \left(2 c_{H\Box} + \frac{6e^2}{s_w^2} c_{HWB} + (\frac{3c_w^2}{2s_w^2} - \frac{1}{2}) c_{HD} \right),$$
$$\kappa_1^{ZZ} = \frac{v^2}{\Lambda^2} \left(-\frac{2e^2}{s_w^2} c_{HWB} + (1 - \frac{1}{2s_w^2}) c_{HD} \right),$$
$$a_2^{ZZ} = -2 \frac{v^2}{\Lambda^2}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

Systematic breakdown

Uncertainty source	$\Delta\mu/\mu$	$\Delta\mu_{ggH}/\mu_{ggH}$	$\Delta\mu_{VBF}/\mu_{VBF}$	$\Delta\mu_{WH}/\mu_{WH}$	$\Delta\mu_{ZH}/\mu_{ZH}$
Theory (signal)	4%	5%	13%	2%	<1%
Theory (background)	3%	3%	2%	4%	5%
Lepton misidentification	2%	2%	9%	15%	4%
Integrated luminosity	2%	2%	2%	2%	3%
b tagging	2%	2%	3%	<1%	2%
Lepton efficiency	3%	4%	2%	1%	4%
Jet energy scale	1%	<1%	2%	<1%	3%
Jet energy resolution	<1%	1%	<1%	<1%	3%
p_T^{miss} scale	<1%	1%	<1%	2%	2%
PDF	1%	2%	<1%	<1%	2%
Parton shower	<1%	2%	<1%	1%	1%
Backg. norm.	3%	4%	6%	4%	6%
Stat. uncertainty	5%	6%	28%	21%	31%
Syst. uncertainty	9%	10%	23%	19%	11%
Total uncertainty	10%	11%	36%	29%	33%

*From legacy HWW analysis (HIG-20-013)

Timeline for vector boson couplings



MELA at the production vertex

MATRIX ELEMENT LIKELIHOOD APPROACH (MELA): Event by event discriminator build upon matrix elements

Contain the maximal amount of theoretical information available for the hard process

Combined with reconstruction level information:

✓ 4-vector of the 2 associated jets in the production.

✓ Higgs-proxy 4-vector (2 leptons + MET).

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

ggH ↔ VBF

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

SM coupling ↔ BSM coupling (one for each coupling)

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

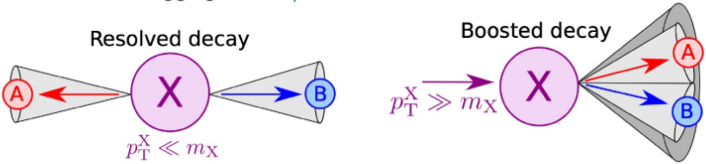
Interference ↔ Pure SM/BSM (used for a_2 and a_3)

Boosted VH

+ AK8 jets (anti-kt, R=0.8): Reconstruction of **Boosted** V bosons from **VH production**.

Substructure: 2 sub-jets (A & B)

V-Tagging: softdrop mass + Tau21 + JECs corrections



Samples

DATA — LHC RUN 2 Dataset

pp collisions from the years 2016-2018 → $\mathcal{L}_{int}$ = 138 fb^{-1}

- Dilepton triggers are applied.
- Single lepton triggers are used to recover efficiency.
- Trigger efficiencies for MC are estimated from data.

SM SAMPLES

- **POWHEGv2 NLO**
- ggH sample reweighting to NNLOPS (p_T and number of jets)
- For ggH events with ≥ 1 jet → MINLO HJJ at NLO

BACKGROUNDS

- ttbar: POWHEGv2 NLO + top p_T reweighting
- DY→$\tau\tau$ embedded samples
- Non-resonant WW POWHEGv2 NLO reweighted to NNLO + NNLL in ptWW
- W+jets with jets misidentification (non-prompt) → Data driven estimation
- Minor backgrounds taken from simulation: WZ, ZZ, Vγ, Vγ*, VVV (V=W, Z)

Normalization taken from data in dedicated control regions

AC SAMPLES

ggH, VBF, and VH signals for studying HVV:

- Generated with JHUGEN at LO QCD
- MELA reweighting of AC samples to any signal hypothesis to increase statistics.

ggH+2 jets signals for studying Hgg vertex:

- Generated with MINLO at NLO.
- Reweighting to increase statistics.