Higgs anomalous couplings and CP properties at CMS

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On behalf of the CMS Collaboration

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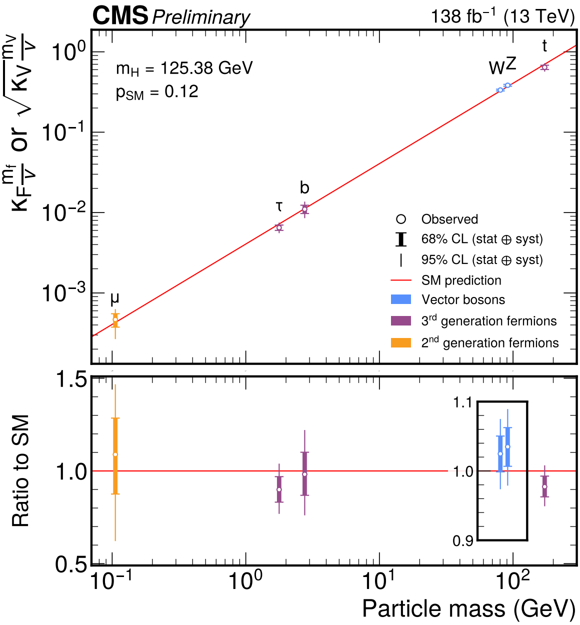
Why is the Higgs boson so light?

BSM ideas to solve the Hierarchy problem :

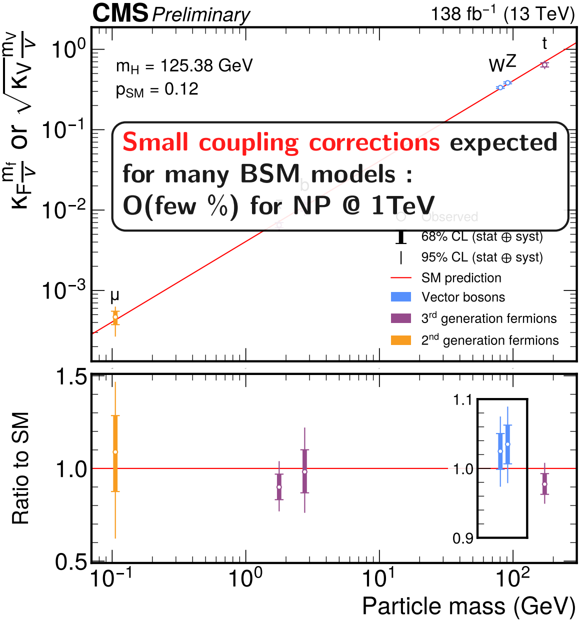
- A new symmetry protects the higgs mass : **SUSY**
- Higgs is a bound state of new strong interaction : **Composite Higgs**

Can significantly alter Higgs phenomenology

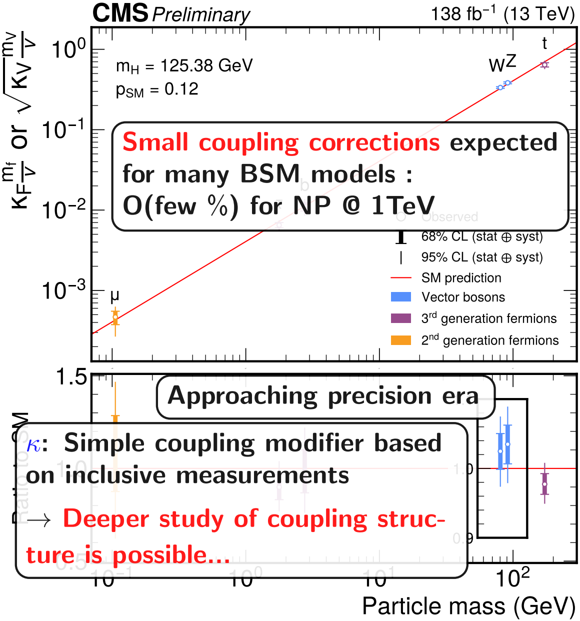
SM picture observed so far



SM picture observed so far



SM picture observed so far



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

Approaching precision era

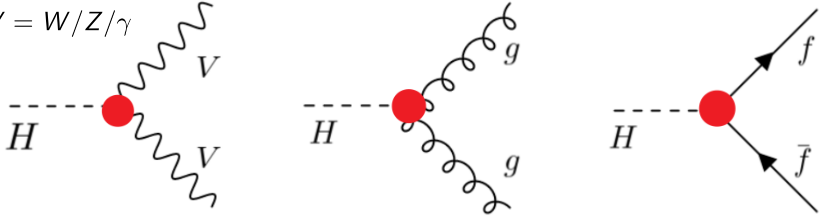
κ: Simple coupling modifier based on inclusive measurements

$\rightarrow$ Deeper study of coupling structure is possible...

Anomalous couplings (AC) approach

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

$V = W/Z/\gamma$



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

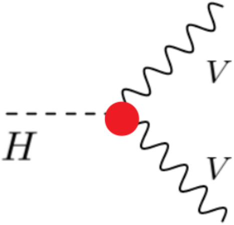
Exploit **full event kinematics** to constrain contributions

AC have q^2 **dependance** $\rightarrow$ Effects at **production vertex** dominate

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**

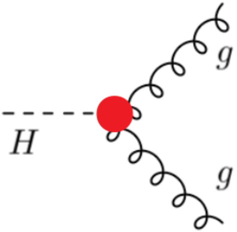
a_3 **: CP-Odd AC**

$\rightarrow$ Target **VBF, VH** production + **HWW/HZZ** decay

Higgs to gluons

Hgg scattering amplitude :

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



Hgg couplings :

a_2 **: SM loop**

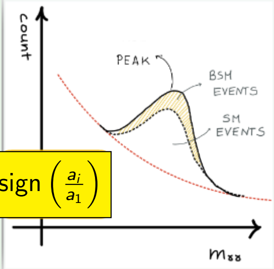
a_3 **: CP-Odd AC**

$\rightarrow$ Target **ggH + 2 Jets** process (VBF-like events)

Higgs to gluons

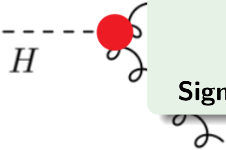
$\mathcal{A}(\mathrm{HVV}) \sim$ ... $f^{*(1)}_{\mu\nu} \tilde{f}^{*(2)\mu\nu}$

Convenient to measure fractional contribution of AC to σ :



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

Signal model includes signal strength μ and f_{ai}



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

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 discriminants

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

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

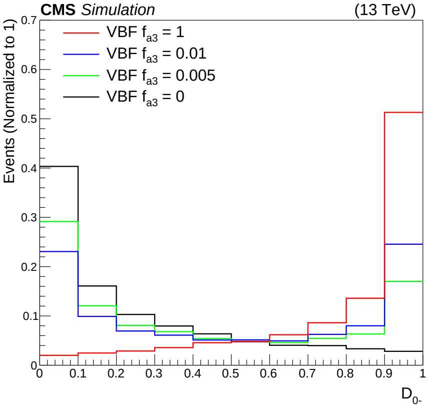
With **MELA** can target AC contribution to H signal :

Pure term $\propto a_i^2$

e.g D_{0-} for a_3

Interference term $\propto a_i$

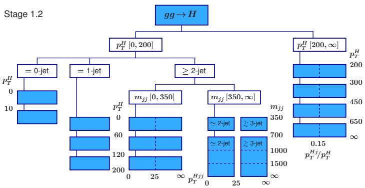
e.g D_{CP} for a_3

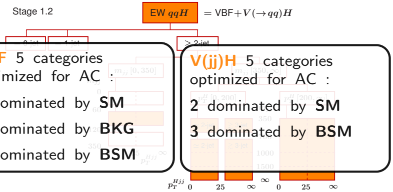


Will present **latest Run 2 results today**

HVV AC in H$\gamma\gamma$ channel

STXS H$\gamma\gamma$ but with **VBF** and **VH** (jj, 0-ℓ, 1-ℓ, 2-ℓ) categorisation based on dedicated AC discriminants





VBF 5 categories optimized for AC :

1 dominated by **SM**

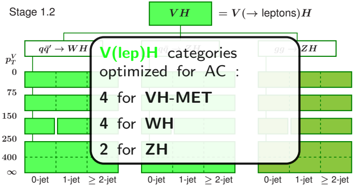
2 dominated by **BKG**

2 dominated by **BSM**

V(jj)H 5 categories optimized for AC :

2 dominated by **SM**

3 dominated by **BSM**

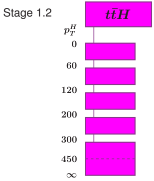


V(lep)H categories optimized for AC :

4 for **VH-MET**

4 for **WH**

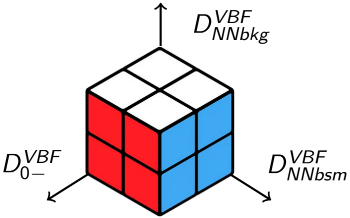
2 for **ZH**

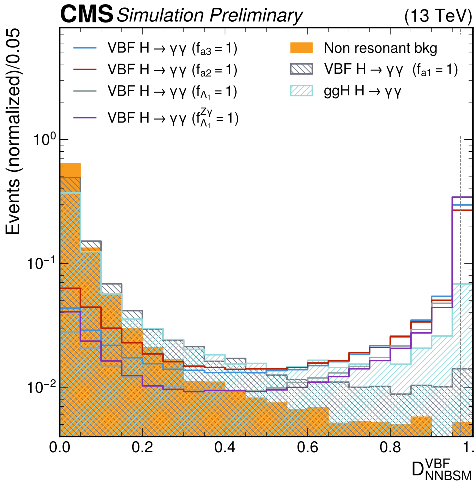


Signal extracted through **fit to m$_{\gamma\gamma}$** in each category

VBF H$\gamma\gamma$ 3D categorisation

2 bins each for D_{0-}^{VBF} and a pair of **DNN SM/BSM/bkg classifier** discriminants :



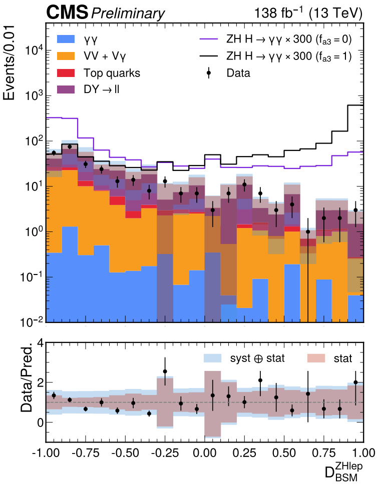


5 categories (with sufficient statistical power) included in final **HVV** analysis

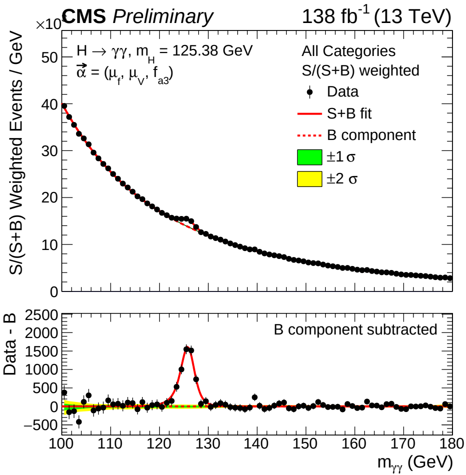
→ Similar **2D** approach in **VH** channels

HVV AC in H$\gamma\gamma$ channel

Z($\ell\ell$)H BDT (SM Vs BSM) :

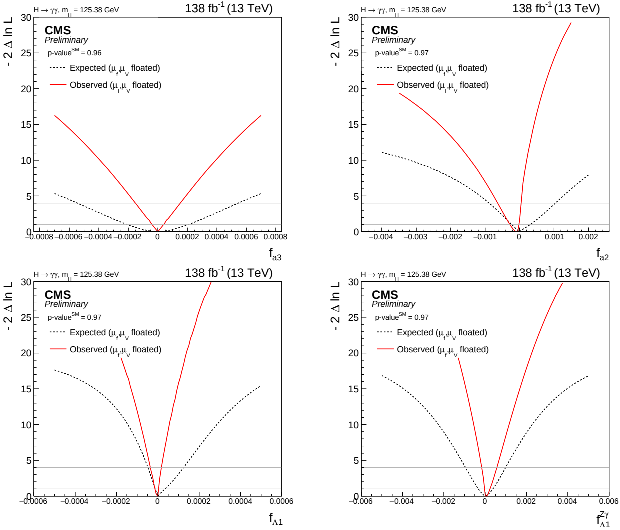


Signal(μ_V, μ_f, f_{a3}) + Bkg fit
to data (all categories combined) :



HVV f_{ai} scans

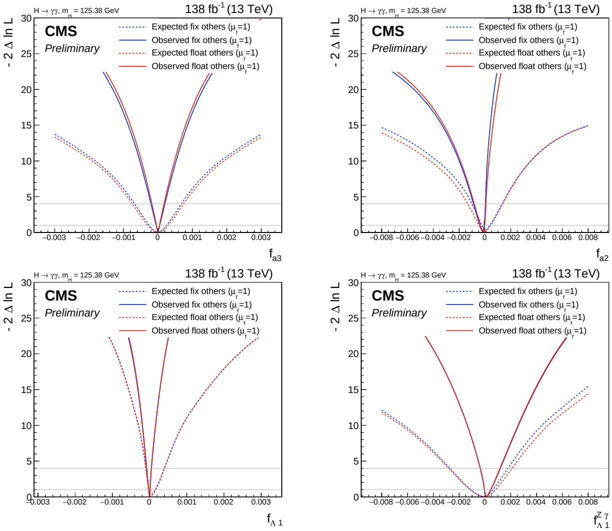
4 f_{ai} **analyzed independently** (μ_V and μ_F floating)



$\mathbf{f}_{ai} \sim 0$ consistent with SM H (**Constraints at the** 10^{-4} **level**)

HVV f_{ai} scans

4 f_{ai} analyzed simultaneously (μ_V floating)

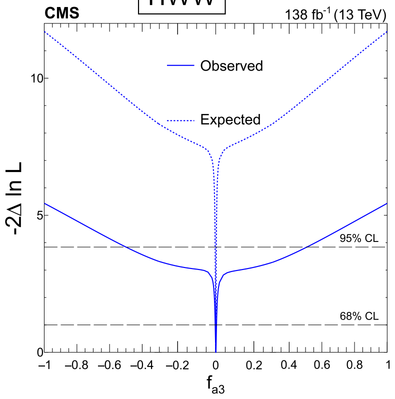


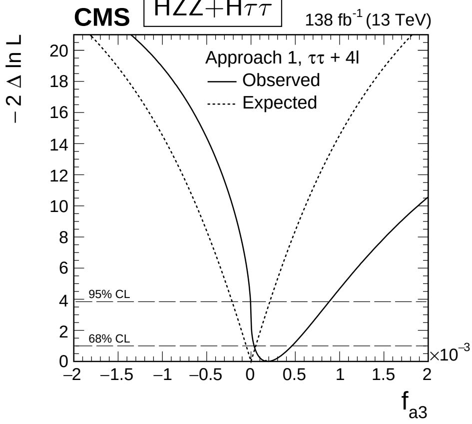
$f_{ai} \sim 0$ consistent with SM H (**Constraints at the 10^{-4} level**)

HVV f_{ai} scans

HVV measurements **consistent** across **several decay channels**

HWW

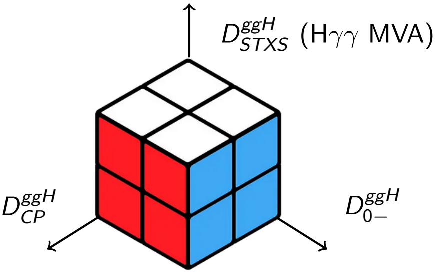


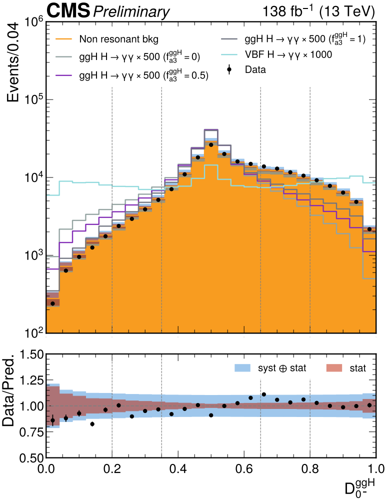


Hgg AC in H$\gamma\gamma$ channel

ggH+2jets selection with BDT signal/bkg classifiers

3D Categorisation :

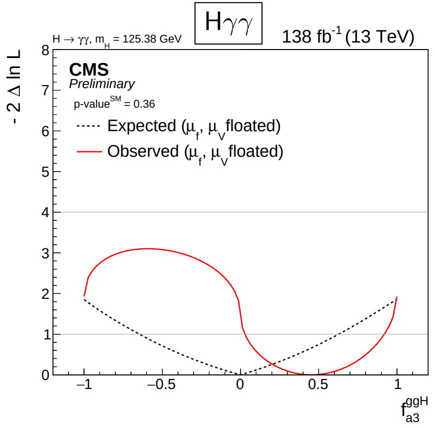


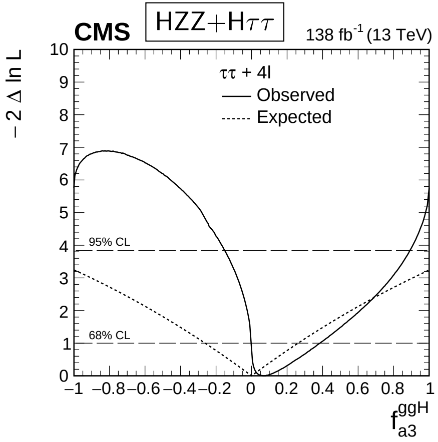


30 categories included in final Hgg analysis

Hgg f_{ai} scans

f_{a3}^{ggH} scanned with **signal strengths floating**

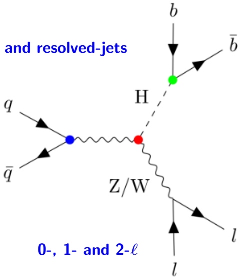




CP-Odd effective fraction in Hgg consistent with SM

VH(→bb) EFT study

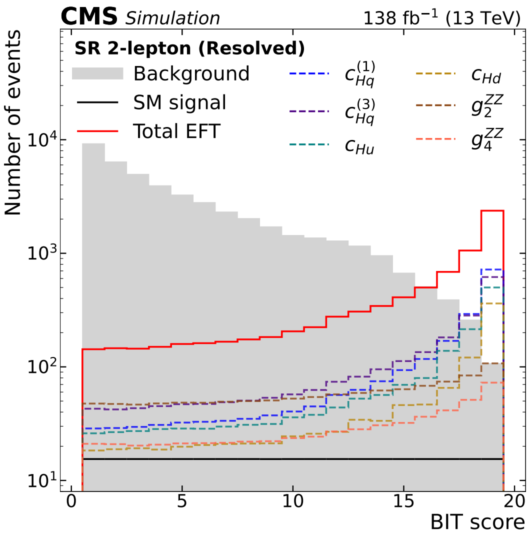
merged- and resolved-jets



0-, 1- and 2-ℓ

BDT regression using full event kinematics to construct **likelihood ratios** between SM/EFT hypotheses

→ **Single discriminant** with sensitivity to **multiple couplings**



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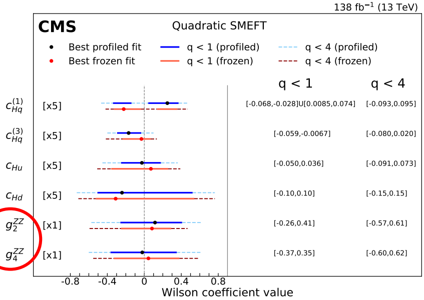
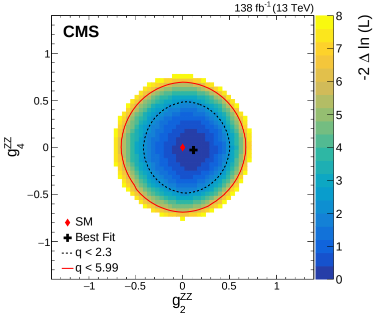
VH($\rightarrow$bb) EFT study

Fit considers **several Warsaw basis** coefficients simultaneously

g_2^{ZZ}/g_4^{ZZ} : **rotate to mass eigenstate basis**

$[g_2^{ZZ} \sim c_{HW} + c_{HWB} + c_{HB}]$





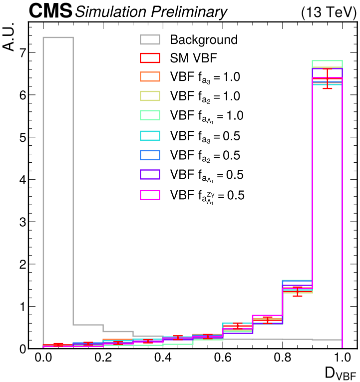
Results **consistent with SM** expectation

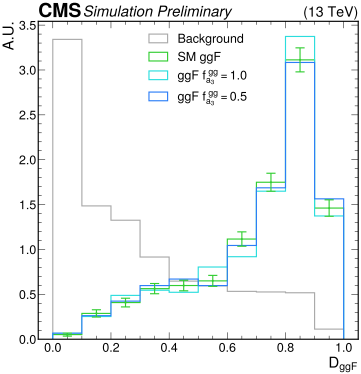
HWW + 2 jets - $\Delta\phi_{jj}$

Differential σ measurement in the **CP sensitivity variable** $\Delta\phi_{jj}$

Discriminate signal from background but be **agnostic about signal hypothesis**

$\rightarrow$ **Adversarial** Deep Neural Networks [ADNNs]



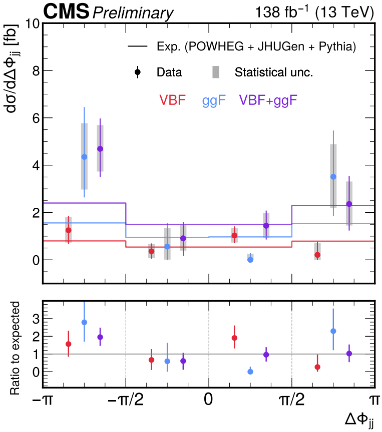


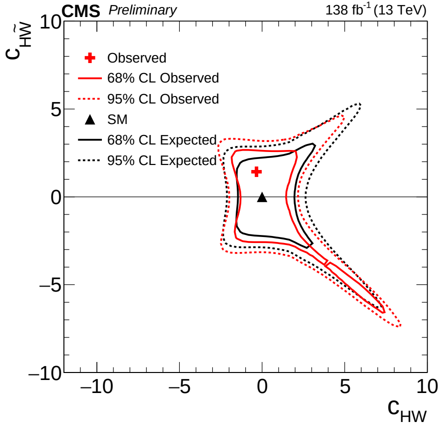
Fit to 2D $D_{VBF} - D_{ggF}$ variable in **4** $\Delta\phi_{jj}$ **bins**

HWW + 2 jets - $\Delta\phi_{jj}$

Likelihood-based unfolding to extract **ggF and VBF** σ

Parameterize diff σ & decay as functions of **CP-even vs CP-odd** c_i





Conclusions

Measurement of Higgs boson coupling structure
a crucial test of SM

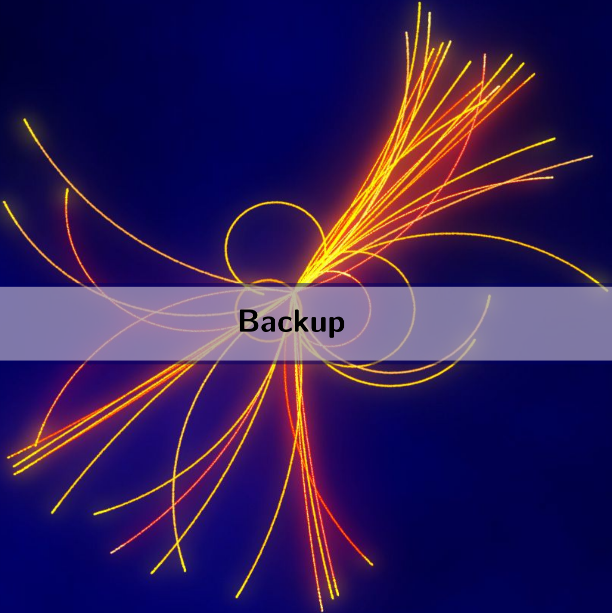
Recent dedicated studies in multiple channels
with full Run 2 data presented

Covering Higgs to electroweak vector bosons
and gluons

To date measurements consistent with SM
Higgs boson

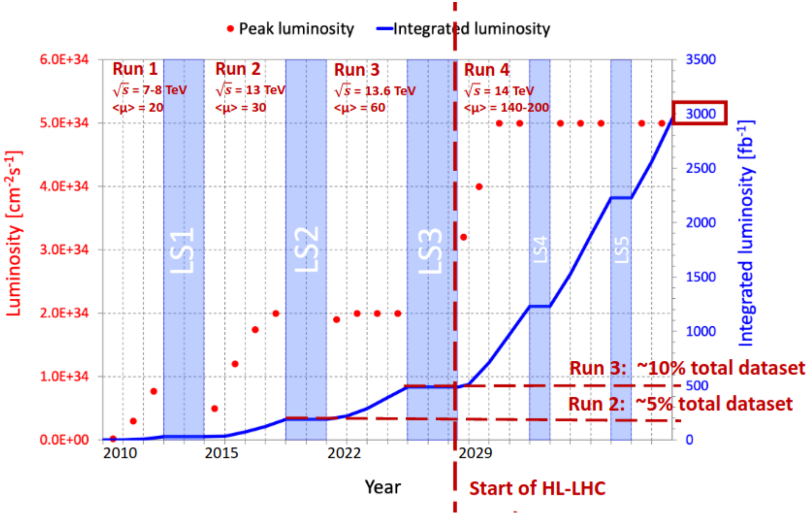
Many of these analyses are statistically limited

→ 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

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

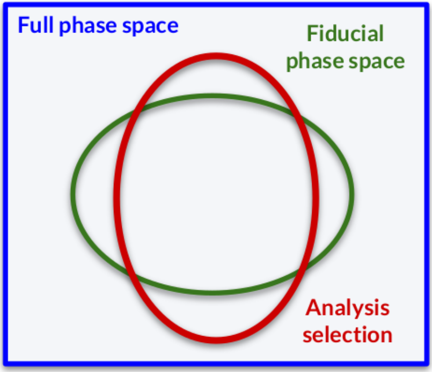
$$
\begin{gathered}
\delta c_{\mathrm{z}} = \frac{1}{2} a_1^{\mathrm{ZZ}} - 1, \\
c_{\mathrm{zz}} = -\frac{2 s_{\mathrm{w}}^2 c_{\mathrm{w}}^2}{e^2} a_2^{\mathrm{ZZ}}, \\
\tilde{c}_{\mathrm{zz}} = -\frac{2 s_{\mathrm{w}}^2 c_{\mathrm{w}}^2}{e^2} a_3^{\mathrm{ZZ}}, \\
c_{\mathrm{z}\Box} = \frac{m_{\mathrm{Z}}^2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

Fiducial differential Higgs measurements

Measure σ in bins of some **observable [p_T^H, m_{jj}..]**

Fiducial : restricted phase space that matches as closely as possible the experimental selections

[**Reduced model dependence**]



HWW + 2 jets ADNN

Two ADNNs have been trained within the **inclusive SR** :

	VBF-ADNN	GGH-ADNN
Signal label	SM VBF + 7 AC hypotheses	SM ggF + 2 AC hypotheses
Background label	All backgrounds + SM ggF	All backgrounds + SM VBF

Classifier: Binary NN trained on signal and background for S Vs B

Adversary: Multiclass NN trained only on signals, aims to infer the physics model of signal events

→**Penalize classifier** if its data representation is sensitive to the signal hypothesis

HWW + 2 jets ADNN inputs

$p_T^{j_1}, p_T^{j_2}$	Magnitudes of the transverse momentum of the leading jets
η_{j_1}, η_{j_2}	Pseudorapidity of the leading jets
m_{jj}	Invariant mass of the dijet system
$\Delta\eta_{jj}$	Pseudorapidity gap between the leading jets
ϕ_{j_1}, ϕ_{j_2}	Azimuthal angle of the leading jets
$p_T^{\ell 1}, p_T^{\ell 2}$	Magnitudes of the transverse momentum of the leading leptons
$p_T^{\ell\ell}$	Magnitudes of the transverse momentum of the dilepton system
$\eta_{\ell_1}, \eta_{\ell_2}$	Pseudorapidity of the leading leptons
$\phi_{\ell_1}, \phi_{\ell_2}$	Azimuthal angle of the leading leptons
$m_{\ell\ell}$	Invariant mass of the dilepton system
$\Delta\phi_{\ell\ell}, \Delta R_{\ell\ell}$	Angular and radial separation between the leading leptons
$m_{\ell j}$	Invariant mass of the lepton-jet system ($\ell = \{\ell_1, \ell_2\}, j = \{j_1, j_2\}$)
C_{tot}	Centrality, defined as $C_{tot} = \log\left(\sum_{\ell_1,\ell_2} \lvert(2\eta_\ell - \sum_{j_1,j_2} \eta_j)\rvert / \lvert\Delta\eta_{jj}\rvert\right)$
E_T^{miss}	Missing transverse energy
qgl_{j_1}, qgl_{j_2}	Quark-gluon likelihood discriminant for the leading jets
m_T	Transverse mass
m^{vis}	Visible mass
$\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{E}_T^{miss})$	Azimuthal opening angle between $\vec{p}_T^{\,\ell\ell}$ and $\vec{E}_T^{miss}$
h_T	Hadronic activity, defined as the scalar sum of the transverse momenta of all jets in the event
$\mathcal{D}^{(ME)}_{VBF\_ggF}$	ME-based discriminant between the VBF and ggH productions
$\mathcal{D}^{(ME)}_{VBF\_VH}$	ME-based discriminant between the VBF and VH productions
$\mathcal{D}^{(ME)}_{ggF\_VH}$	ME-based discriminant between the ggH and VH productions
$\mathcal{D}^{(ME)}_{VBF\_DY}$	ME-based discriminant between the VBF and DY productions
y_{2016}	Boolean indicator of the 2016 data set
y_{2017}	Boolean indicator of the 2017 data set
y_{2018}	Boolean indicator of the 2018 data set