Study of the Anomalous Couplings in On-shell $\mathrm{H} \rightarrow \mathrm{WW}^*$ analysis

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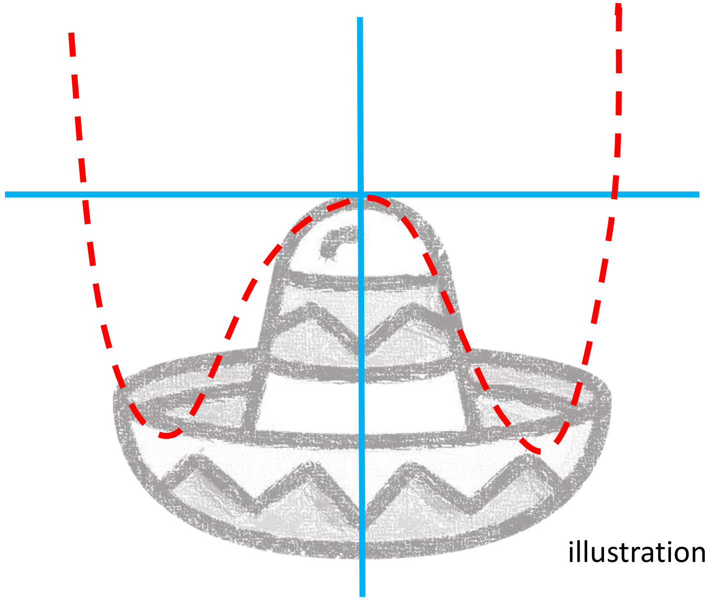
Motivation

Or is this resonance really SM Higgs that we measure?



- constrains were set on **spin-parity properties** of discovered resonance $m_h = 125.10\text{GeV}$

➡ Consistent with **SM-like Higgs boson** $\boldsymbol{J^{\mathrm{CP}} = 0^{++}}$

- exotic scenarios with $J^{\mathrm{CP}} = 1^-, 1^+, 2^+$ were excluded in Run-1 [ATLAS, CMS] but …
- allowing for small 0-spin **anomalous couplings (AC)** to gauge bosons (HVV)

$$\boxed{\mathrm{VV} \coloneqq \mathrm{WW}, \mathrm{ZZ}, \gamma\gamma, gg, \gamma Z}$$

- Run-2 results has improved constrains on AC in $\mathrm{H} \to \mathrm{ZZ} \to 4\mathrm{l}$ [HIG-19-009] and $H \to \tau\tau$ [HIG-20-007]

➡ Anticipated combination with $\mathbf{H} \to \mathbf{WW}$ should further improve limits

HVV scattering amplitude

$f^{(i)\mu\nu} = \varepsilon^{\mu}_{Vi} q^{\nu}_{Vi} - \varepsilon^{\nu}_{Vi} q^{\mu}_{Vi}$ field strength tensor

$\tilde{f}^{(i)}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma} f^{(i)\rho\sigma}$ dual field strength tensor

Λ_1 = scale of BSM physics

q_{Vi} = V boson momentum

- general form of minimum **0-spin expansion of SM** up to $\mathcal{O}(q^2)$

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

SM | BSM CP-even loop $0^+_{\Lambda 1}$ | SM-loop 0^+_h | BSM CP-odd loop 0^-

HWW/HZZ vertex

- Assume gauge invariance and real couplings so $\kappa_{1,2}^{\mathrm{WW}} = \kappa_{1,2}^{\mathrm{ZZ}} = -\exp(i\phi_{\Lambda 1}) = \pm 1$
- Assume custodial symmetry so $a_{\mathrm{i}}^{\mathrm{WW}} = a_{\mathrm{i}}^{\mathrm{ZZ}} \coloneqq a_{\mathrm{i}}$
- $a_1 \neq 0$ is SM coupling
- anomalous couplings a_2, a_3, Λ_1

CP-conserving anomalous couplings

$\Lambda_1 \longleftrightarrow 0^+_{\Lambda_1}$ $\quad \mathcal{O}(10^{-3} - 10^{-2})$

$a_2 \longleftrightarrow 0^+_h$ $\quad \mathcal{O}(10^{-3} - 10^{-2})$

$a_3 \longleftrightarrow 0^-$ $\quad \mathcal{O}(< 10^{-3})$

$$f^{(i)\mu\nu} = \varepsilon^{\mu}_{Vi} q^{\nu}_{Vi} - \varepsilon^{\nu}_{Vi} q^{\mu}_{Vi}$$ field strength tensor

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SM | BSM CP-even loop $0^+_{\Lambda 1}$ | ~~SM-loop 0^+_h~~ | ~~BSM CP-odd loop 0^-~~

HZγ/H$\gamma\gamma$ vertex

- Assume gauge invariance and real couplings so $\kappa_{1,2}^{\gamma\gamma} = 0; \kappa_{1,2}^{Z\gamma} = -\exp(i\phi_{\Lambda 1}) = \pm 1$
- $a_2^{\gamma\gamma/Z\gamma}, a_3^{\gamma\gamma/Z\gamma}$ constrained by direct H$\gamma\gamma$/HZγ measurements $\rightarrow$ ***to be ignored***
- anomalous coupling to be considered in VBF/VH production $\Lambda_1^{Z\gamma}$

CP-conserving anomalous couplings

$$\Lambda_1^{Z\gamma} \longleftrightarrow 0^{Z\gamma}_{\Lambda_1} \qquad \mathcal{O}(10^{-3} - 10^{-2})$$

HVV scattering amplitude

$f^{(i)\mu\nu} = \varepsilon^{\mu}_{Vi} q^{\nu}_{Vi} - \varepsilon^{\nu}_{Vi} q^{\mu}_{Vi}$ field strength tensor

$\tilde{f}^{(i)}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma} f^{(i)\rho\sigma}$ dual field strength tensor

Λ_1 = scale of BSM physics

q_{Vi} = V boson momentum

- general form of minimum **0-spin expansion of SM** up to $\mathcal{O}(q^2)$

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

SM | BSM CP-even loop $0^+_{\Lambda 1}$ | SM-loop 0^+_h | BSM CP-odd loop 0^-

Hgg vertex

- Assume gauge invariance and real couplings so $\kappa_{1,2}^{\mathrm{gg}} = 0$
- anomalous coupling to be considered in **ggF+2j production** a_2^{gg}, a_3^{gg} **with VBF-like topology**
- **Hgg effective couplings are induced by quark loops which means they have direct relation to Yukawa couplings**

CP-properties of Yukawa interaction to be probed by Hgg couplings

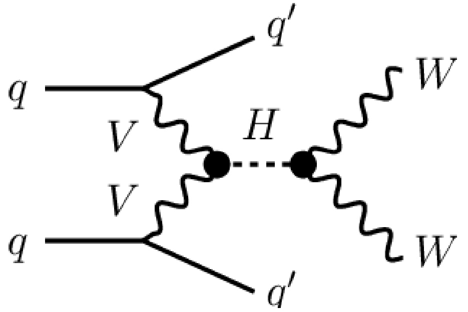
$a_2^{\mathrm{gg}} \longleftrightarrow 0^+_{\mathrm{gg}}$ $\quad \mathcal{O}(10^{-3} - 10^{-2})$

$a_3^{\mathrm{gg}} \longleftrightarrow 0^-_{\mathrm{gg}}$ $\quad \mathcal{O}(< 10^{-3})$

In this presentation

- Overview of the anomalous couplings $\mathbf{H} \rightarrow \boldsymbol{WW}^{*}$ analysis for Full Run-2 at CMS – more examples than full scale results
- Focus on **HWW couplings** in ggF 0/1-jet, VBF/VH 2-jet fully leptonic signal regions
- Additional study of **HZ$\boldsymbol{\gamma}$ coupling** in VBF/VH 2-jet regions and **Hgg couplings** with VBF-like topology region.
- Interpretation in terms of **anomalous couplings** but translation to **EFT** parametrisation is ongoing
- **DISCLAIMER:** analysis is still in **BLINDED** regime (no data in signal region and expected likelihood scans only)

Signal model parametrisation



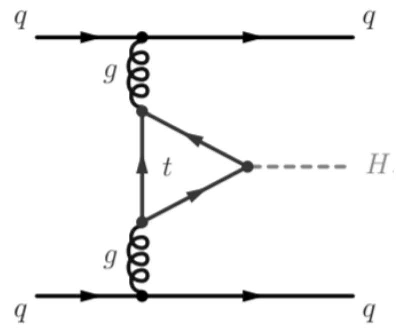
- Assume **one anomalous coupling** at the time
- **2 vertices** in case of **VBF/VH** production and **HWW** couplings (prod. + decay)

$$\boxed{\mathcal{A}(\mathrm{HWW}) = \left(a_1 A_1^{\mathrm{prod}} + a_{\mathrm{i}} A_{\mathrm{i}}^{\mathrm{prod}}\right) * \left(a_1 A_1^{\mathrm{decay}} + a_{\mathrm{i}} A_{\mathrm{i}}^{\mathrm{decay}}\right)}$$

- **1 vertex** in case of **ggF 0/1-jet** production and **HWW** couplings (decay only), similar in case of **ggF 2-jet** and **Hgg** couplings (production only)

$$\boxed{\mathcal{A}(\mathrm{HWW}) = \left(a_1 A_1^{\mathrm{decay}} + a_{\mathrm{i}} A_{\mathrm{i}}^{\mathrm{decay}}\right)}$$

$$\boxed{\mathcal{A}(\mathrm{Hgg}) = \left(a_1 A_1^{\mathrm{prod}} + a_{\mathrm{i}} A_{\mathrm{i}}^{\mathrm{prod}}\right)}$$



- In case of VBF/VH production and **HZ$\boldsymbol{\gamma}$** coupling we assume that decay vertex is not affected

$$\boxed{\mathcal{A}(\mathrm{HZ}\gamma) = \left(a_1 A_1^{\mathrm{prod}} + a_{\mathrm{i}} A_{\mathrm{i}}^{\mathrm{prod}}\right) * a_1 A_1^{\mathrm{decay}}}$$

Signal model parametrisation

- Instead of ACs, it is useful to use effective fractional cross-section $f_{\mathrm{a_i}}$

$$f_{a_{\mathrm{i}}} = \frac{|a_{\mathrm{i}}|^2\sigma_{\mathrm{i}}}{|a_{\mathrm{i}}|^2\sigma_{\mathrm{i}} + |a_1|^2\sigma_1} \qquad f_{a_1} = 1 - f_{a_{\mathrm{i}}} \qquad g = \sqrt{\frac{\sigma_1}{\sigma_i}}$$

$\sigma_i \leftrightarrow a_{\mathrm{i}} = 1, a_{\mathrm{i \neq j}} = 0$

ggF:

$$\boldsymbol{\mathcal{P}_{\mathrm{ggF}} = \mu_{\mathrm{F}}\left(f_{\mathrm{a_1}} * \mathrm{T_1} + \sqrt{f_{\mathrm{a_i}}}\sqrt{f_{\mathrm{a_1}}} * g * \mathrm{T_2} + f_{\mathrm{a_i}} * g^2 * \mathrm{T_3}\right)}$$

VBF/VH:

$$\boldsymbol{\mathcal{P}_{\mathrm{VBF/VH}} = \mu_{\mathrm{V}}^2\left(f_{a_1}^2 * \mathrm{T_1} + \sqrt{f_{a_1}}^3\sqrt{f_{a_i}} * g * \mathrm{T_2} + f_{a_1} f_{\mathrm{a_i}} * g^2 * \mathrm{T_3} + \sqrt{f_{a_1}}\sqrt{f_{a_i}}^3 * g^3 * \mathrm{T_4} + f_{a_i}^2 * g^4 * \mathrm{T_5}\right)}$$

$HZ\gamma$ case:

$$\boldsymbol{\mathcal{P}_{\mathrm{HZ\gamma}} = \mu_{\mathrm{HZ\gamma}}^2\left(f_{a_1}^2 * \mathrm{T_1} + \sqrt{f_{a_1}}^3\sqrt{f_{\Lambda_1^{Z\gamma}}} * g * \mathrm{T_2} + f_{a_1} f_{\Lambda_1^{Z\gamma}} * g^2 * \mathrm{T_3}\right)}$$

Where $\boldsymbol{T_{\mathrm{i}}}$ are distribution templates used in final fit: $\boldsymbol{T_1 \equiv \mathrm{SM}} \quad \boldsymbol{T_3^{\mathrm{ggF}}, T_5^{\mathrm{VBF/VH}} \equiv \mathrm{BSM}}$

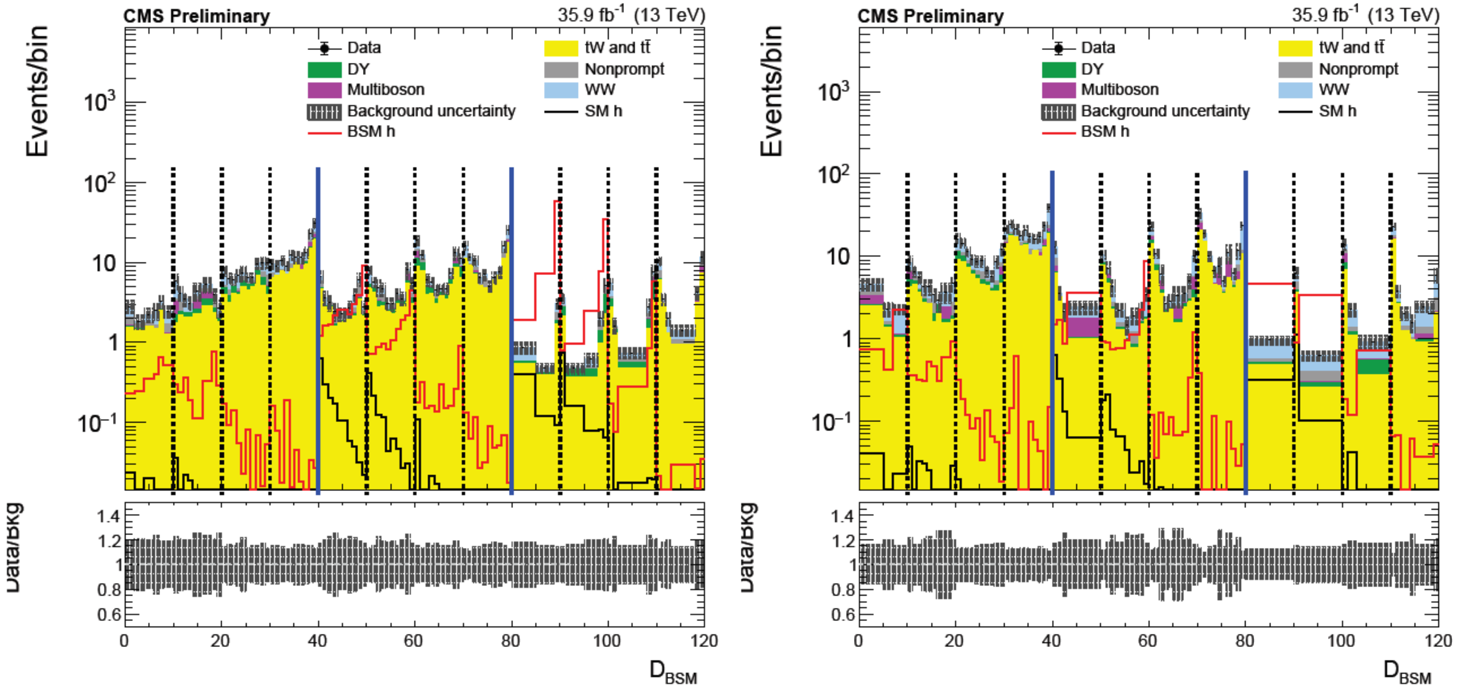
and $\boldsymbol{\mu}$ are signal strength parameters $\boldsymbol{T_{2\ldots4} \equiv \mathrm{Interference\ templates}}$

Analysis Strategy

1. Signal channels with 2 jets provide enough information to feed **MELA („Matrix Element Likelihood Approach“)** and calculate **Kinematic Discriminant (KD)**

   - MELA requires 3x 4-vector to calculate **per-event-probability** using **LO ME** (JHUGen)
   - **3 types of KDs +** $\boldsymbol{m_{\mathrm{ll}}}$ distribution is used to produce **multidimensional discriminant**

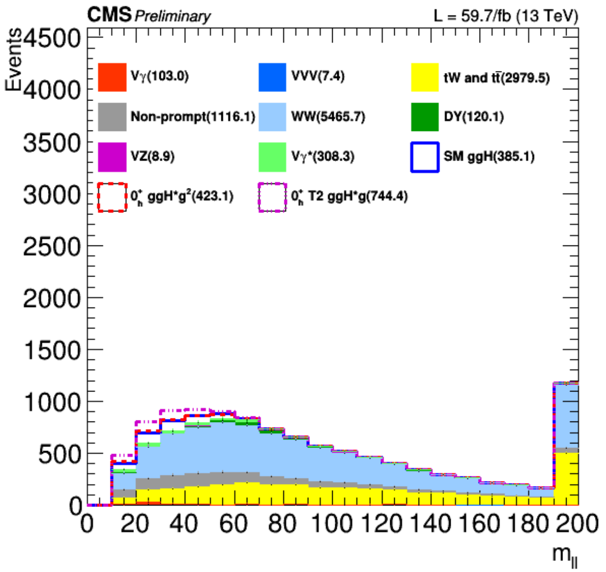
Example:
$\boldsymbol{D_{\mathrm{Int}}}$ **: INT vs. pure SM/BSM (2 plots)**
$\boldsymbol{D_{\mathrm{Prod}}}$**: ggF vs. VBF/VH (3 bins)**
$\boldsymbol{D_{\mathrm{BSM}}}$**: SM vs. BSM signal (10 bins)**
$\boldsymbol{m_{\mathrm{ll}}}$**: dilepton invariant mass (4 bins)**



Analysis Strategy

2. Signal channels with 0 or 1 jet cannot use MELA KDs and uses **2D m_{ll} vs. $m_{\mathrm{T}}^{\mathrm{H}}$ templates** instead (the same was done in Run-1)

Example of SM/BSM/SM-BSM ggH templates:



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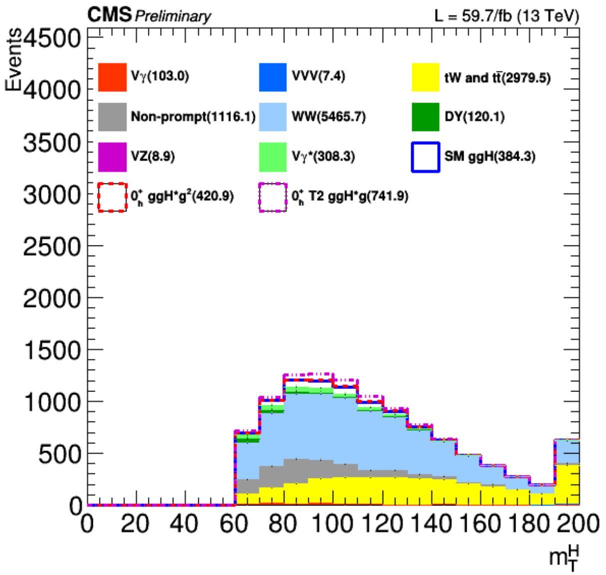

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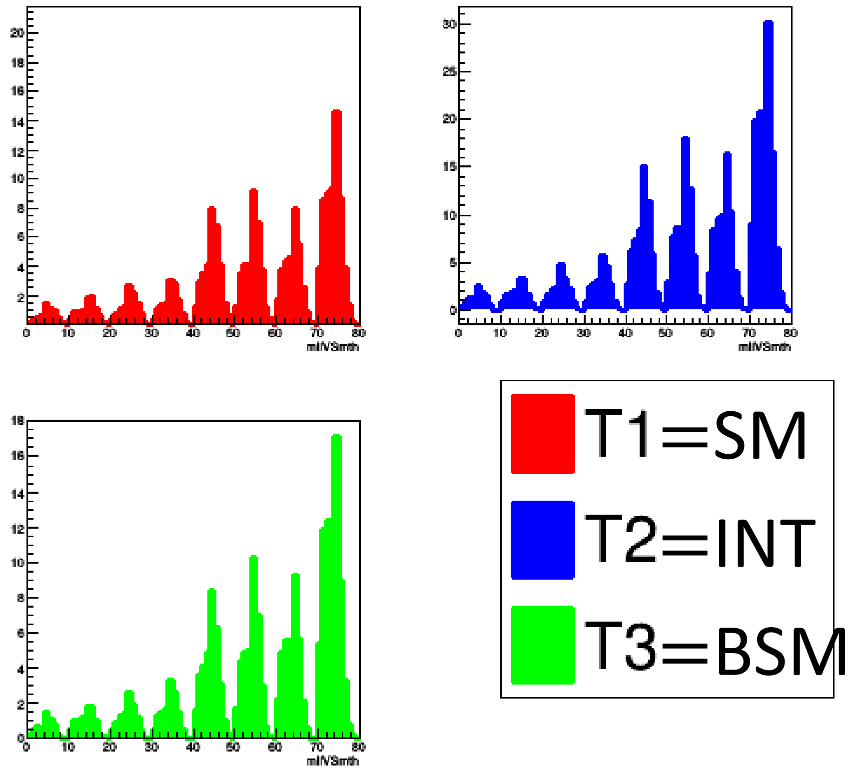
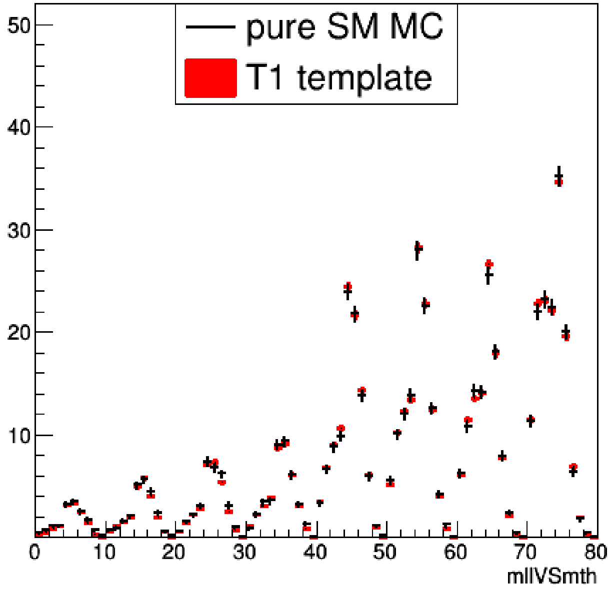
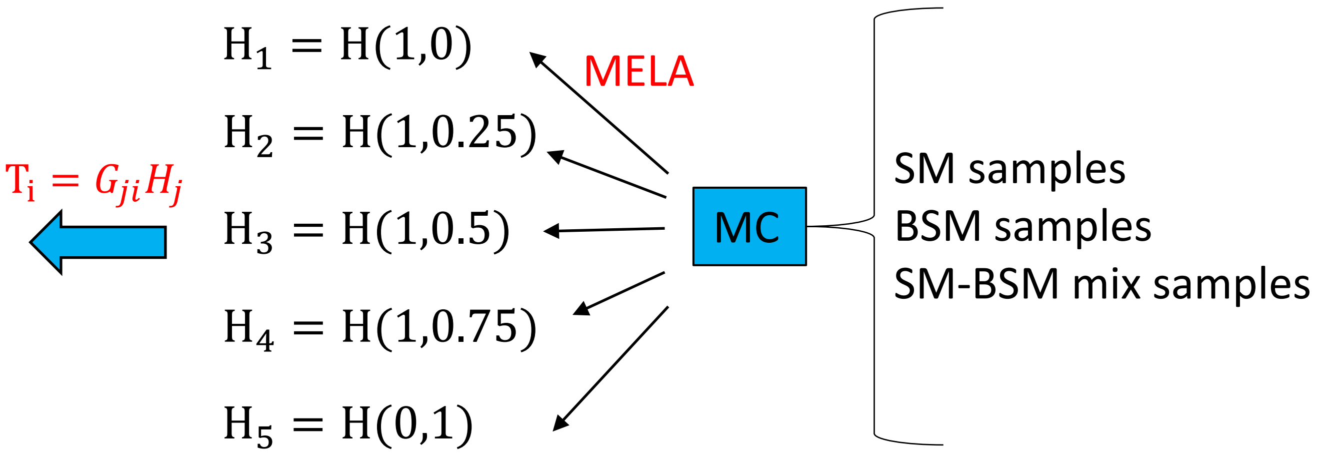


$$m_{\mathrm{T}}^{\mathrm{H}} = \sqrt{2 p_{\mathrm{T}}^{\ell\ell} p_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos \Delta\phi(\vec{p}_{\mathrm{T}}^{\ell\ell}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right]},$$

Signal Templates

- Signal samples (SM, BSM and SM-BSM mix) were generated by JHUGen V7 for 2016-2018
- each signal sample (pure SM, pure BSM and mixed SM-BSM) can be **re-weighted to considered AC hypothesis** (ggF: $H_1 - H_3$, VBF/VH: $H_1 - H_5$, HZγ: $H_1 - H_3$) using **MELA**





Trigger, Reconstruction & Base Selection

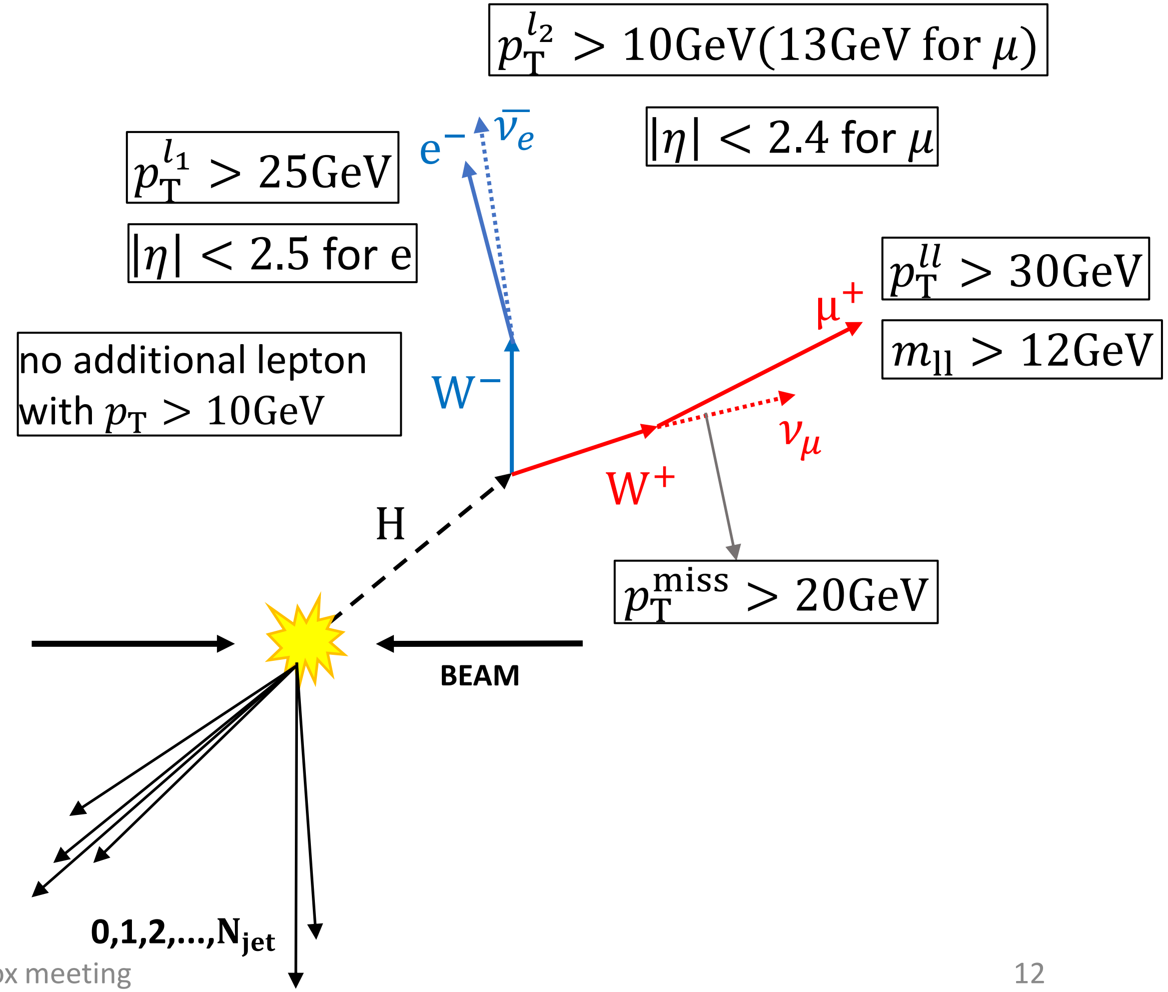
Trigger:

- Combination of both **single and double lepton triggers** is used with different p_{T} thresholds

Object reconstruction:

- **Electrons and muons** are reconstructed offline using **tight** MVA-based (e) and/or cut-based (e,μ) identification and isolation criteria
- **Jets (AK4 PF)** are clustered from particle flow candidates using the anti-kT algorithm ($\Delta R = 0.4$). Additional **tight selection ID** and **loose pile-up ID** criteria are applied to reduce noise and pile-up effects
- Fat **(AK8 PF)** jets were reconstructed as well ($\Delta R = 0.8$)
- **MET** is defined as the negative sum of the transverse momentum of all PF candidates

Base Selection:



Signal regions

$$m_T^{\ell_2} = \sqrt{2 p_T^{\ell_2} p_T^{\mathrm{miss}} \left[1 - \cos\Delta\phi(\vec{p}_T^{\ell_2}, \vec{p}_T^{\mathrm{miss}})\right]},$$

$$m_T^{\mathrm{H}} = \sqrt{2 p_T^{\ell\ell} p_T^{\mathrm{miss}} \left[1 - \cos\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{\mathrm{miss}})\right]},$$

ggF 0/1-jet

- **No clean AK4** jet with $p_T > 30\mathrm{GeV}$ in **0-jet**
- **1 clean AK4** jet with $p_T > 30\mathrm{GeV}$ in **1-jet**
- No clean AK8 jet
- bVeto
- $m_T^{l_2} > 30\mathrm{GeV}$
- $60\mathrm{GeV} \leq m_T^{H} < 125\mathrm{GeV}$

VH boosted

- **At least 1 clean fat AK8 jet** with $p_T > 200\mathrm{GeV}$
- $\mathrm{abs}(\eta_{\mathrm{AK8}}) < 2.4$
- $70 < \mathrm{AK8\ jet\ soft\ drop\ mass} < 110\ \mathrm{GeV}$
- bVeto
- $60\mathrm{GeV} \leq m_T^{H} < 125\mathrm{GeV}$
- $m_{ll} < 75\mathrm{GeV}$

2-jet categories

- **2 clean AK4** jets with $p_T > 30\mathrm{GeV}$
- no clean fat AK8 jet
- bVeto
- $m_T^{l_2} > 30\mathrm{GeV}$
- $60\mathrm{GeV} \leq m_T^{H} < 125\mathrm{GeV}$

VBF 2-jet

$\mathrm{abs}(\eta_{\mathrm{AK4}}) < 4.7$
$m_{jj} > 120\mathrm{GeV}$

VH resolved

$\mathrm{abs}(\eta_{\mathrm{AK4}}) < 2.4$
$60 \leq m_{jj} < 120$

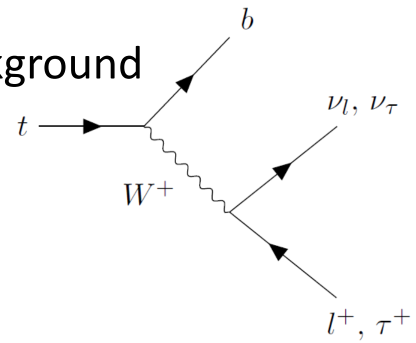
ggF 2-jet

$\mathrm{abs}(\eta_{\mathrm{AK4}}) < 4.7$
$m_{jj} > 300$

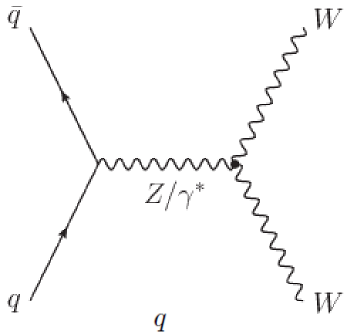
Validation Control Regions

Main Background Processes:

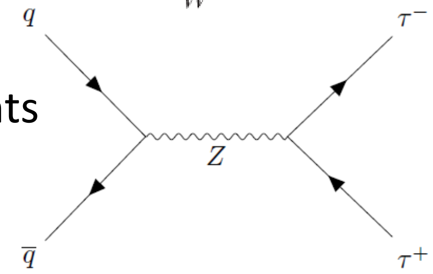
Top background



Non-resonant WW background



Drell Yan events

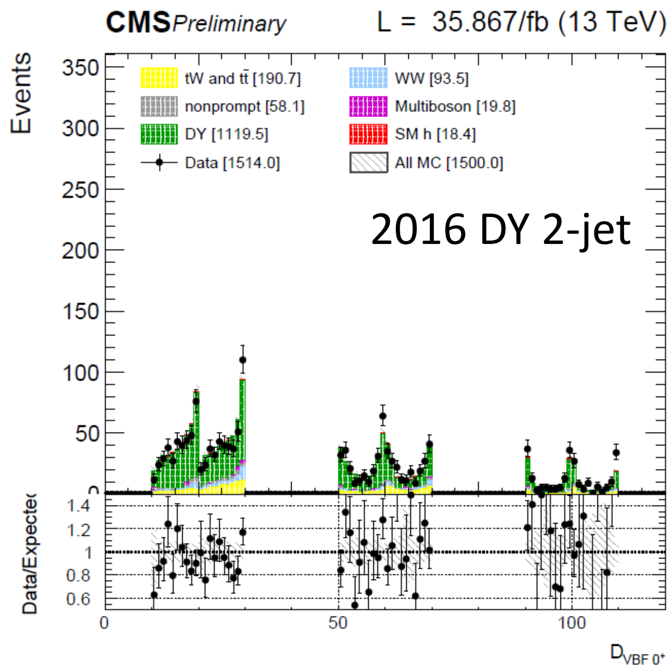


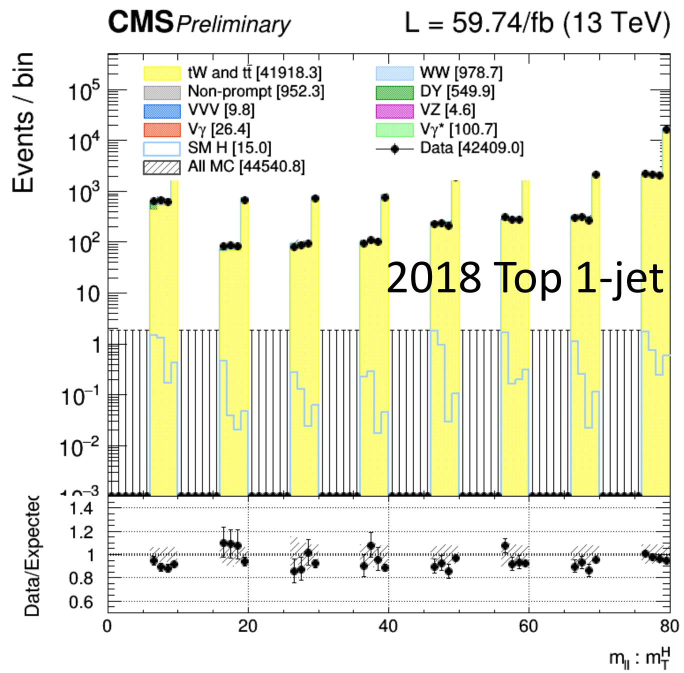
DY CRs

- bVeto
- $m_{\mathrm{T}}^{\mathrm{H}} < 60\mathrm{GeV}$
- $40 < m_{\mathrm{ll}} < 80\mathrm{GeV}$
- N_{jet} condition depending on subcategory

Top CRs

- bVeto inversion
- $m_{\mathrm{T}}^{\mathrm{l}_2} > 30\mathrm{GeV}$
- $m_{\mathrm{ll}} > 50\mathrm{GeV}$
- N_{jet} condition depending on subcategory





Uncertainties

- **Experimental, theoretical and statistical**
- Affect both background and signal MC
- Can be correlated/uncorrelated among years
- Enter Likelihood function in a form of **nuisance parameters**

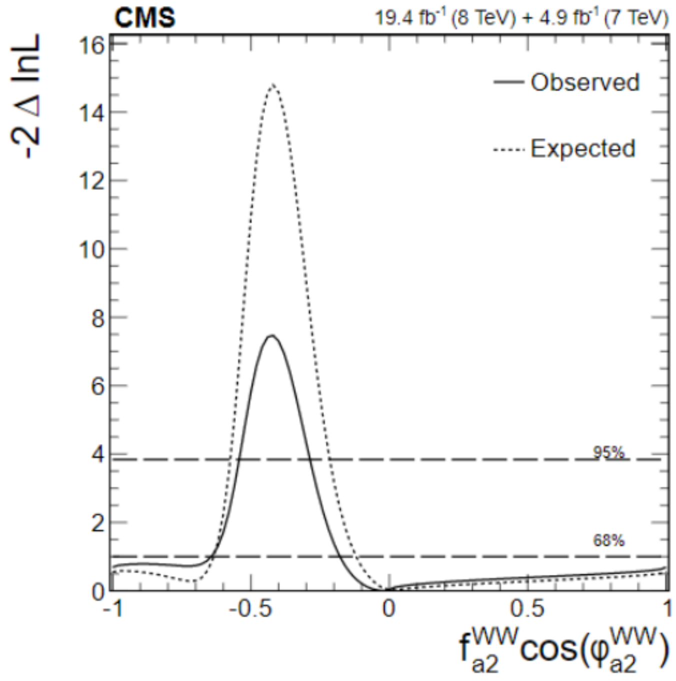
Uncertainty Group	Affected Process	Type	Correlation
Integrated Luminosity	All MC but top, WW, DY	normalization	partially
Fake rate (statistical)	non-prompt	shape	uncorrelated
Fake rate (30% jet composition)	non-prompt	normalization per basis observable bin	correlated
B-tag SF	all MC	shape	partially
Trigger efficiency	all MC	shape	uncorrelated
Prefiring weight	all MC	shape	uncorrelated, 2016 and 2017
Lepton ID efficiency	all MC	shape	uncorrelated
Lepton pT scale	all MC	normalization per basis observable bin	uncorrelated
Jet Energy Corrections	all MC	normalization per basis observable bin	uncorrelated
Jet Energy Resolution	all MC	normalization per basis observable bin	uncorrelated
Jet PU ID scale	all MC	shape	uncorrelated
Unclustered MET	all MC	normalization per basis observable bin	uncorrelated
Pileup reweighting	WW, top, DY, ggF and VBF	normalization per basis observable bin	uncorrelated
Parton showering	WW, ggF and VBF	normalization per basis observable bin	correlated, 2017 and 2018
Underlying event	WW, ggF and VBF	normalization per basis observable bin	correlated, 2017 and 2019
Single top/tt composition	top	shape	correlated
Top pT reweighting	top	shape	correlated
WW NNLL resummation	WW	shape	correlated
VgS cross-section	VgS	normalization	correlated
VZ cross-section	VZ	normalization	correlated
PDF (cross-section & acceptance)	all MC	normalization	correlated
Higher order QCD (cross-section and acceptance)	all MC	shape (bkg+ggF), normalization (rest)	correlated
CR/SR acceptance	top, DY	normalization on CRs	correlated
DY rateparam	DY	rateparam (floating in fit)	correlated
top rateparam	top	rateparam (floating in fit)	correlated
WW rateparam	WW	rateparam (floating in fit)	correlated
MC stat	all MC		

Maximum Log Likelihood scans - Preliminary

Example of a_2 (0_h^+ HWW) coupling expected likelihood values (CRs included in fits)

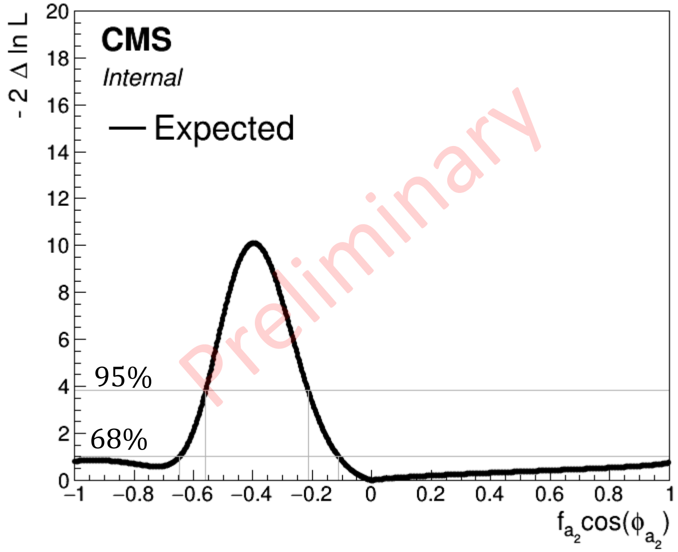
Comparison with Run-1

HIG-14-018 (did not consider VBF/VH)



Ongoing Run-2 analysis

0-jet + 1-jet ggH 2018

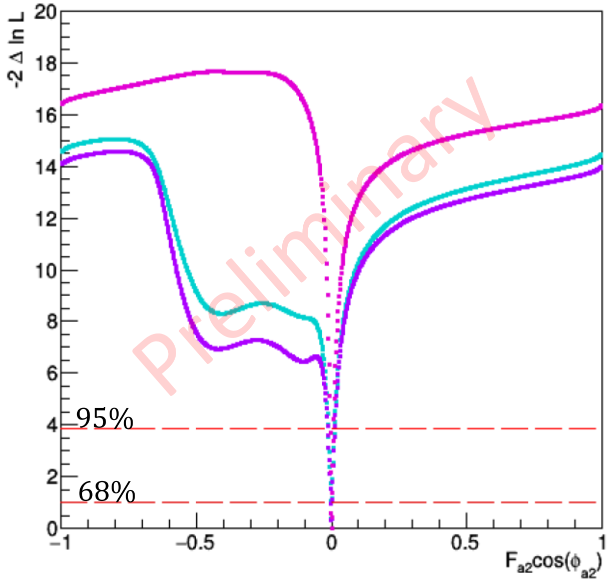


2016-2018

VBF+VH resolved+VH boosted

VBF+VH resolved

VBF

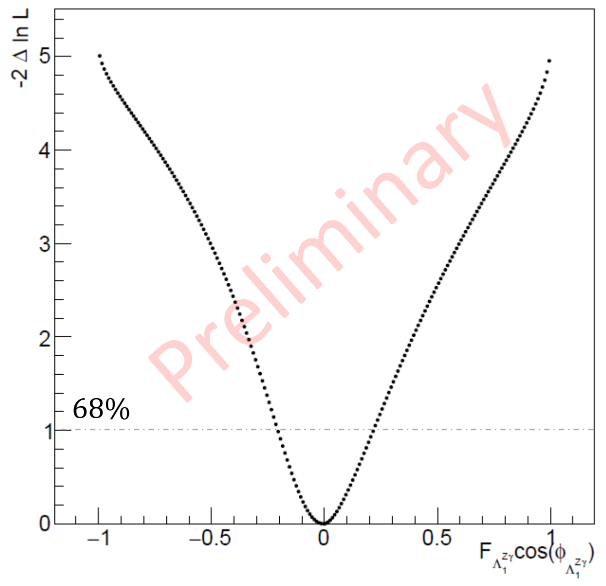


Maximum Log Likelihood scans - Preliminary

Example of $\Lambda_1^{Z\gamma}$(HZγ) coupling

Ongoing Run-2 analysis

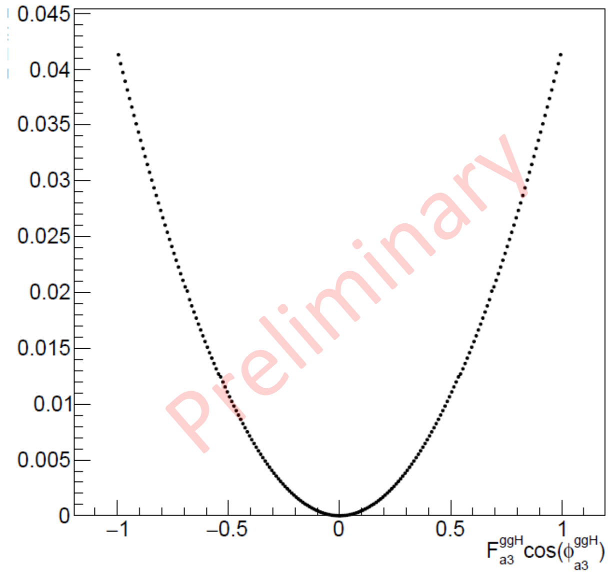
VBF+VH resolved 2016



Example of a_3^{gg} (0^-_{gg} Hgg) coupling

Ongoing Run-2 analysis

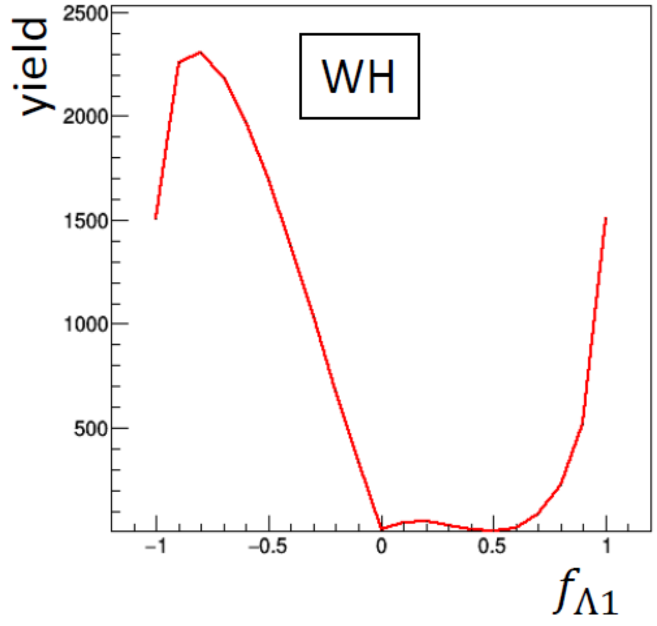
ggF+2j 2016



Challenges of the analysis

- Integral value of SM-BSM **interference templates can be negative** (destructive effect) → we check that the **combination** of templates **remains positive**
- Still some of the **uncertainties are problematic** – templates yield negative values/shapes are complicated/empty bins →we partially fix this by **treating them as symmetric normalized unc.** + other tricks (autorebin)
- UL datasets start to be available – we might need to switch to them
- Combination between channels is **technically demanding**

Weighted Sum of
5 WH templates



Summary

- Overview of of the anomalous couplings $\mathbf{H} \rightarrow \mathbf{WW}^*$ analysis for Full Run-2
- Showing examples of Likelihood scans for several anomalous couplings
- **Aiming for combination of all HWW channels among all years**
- Several technical issues, uncertainty studies still ongoing
- It is likely we will be **delayed by the switch to UL datasets**
- **EFT interpretation of AC is ongoing**
- Planning for combination with HZZ and H$\tau\tau$ analyses

Reference

[ATLAS]: ATLAS Collaboration. Determination of spin and parity of the Higgs boson in the $WW^* \rightarrow e\nu\mu\nu$ decay channel with the ATLAS detector. Eur. Phys. J. C75 (2015) 231. https://arxiv.org/abs/1503.03643

[CMS]: CMS Collaboration. Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV. Phys. Rev. D 92, 012004 (2015). https://arxiv.org/abs/1411.3441

[HIG-19-009]: CMS Collaboration. Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state. CERN-EP-2021-054 https://arxiv.org/abs/2104.12152

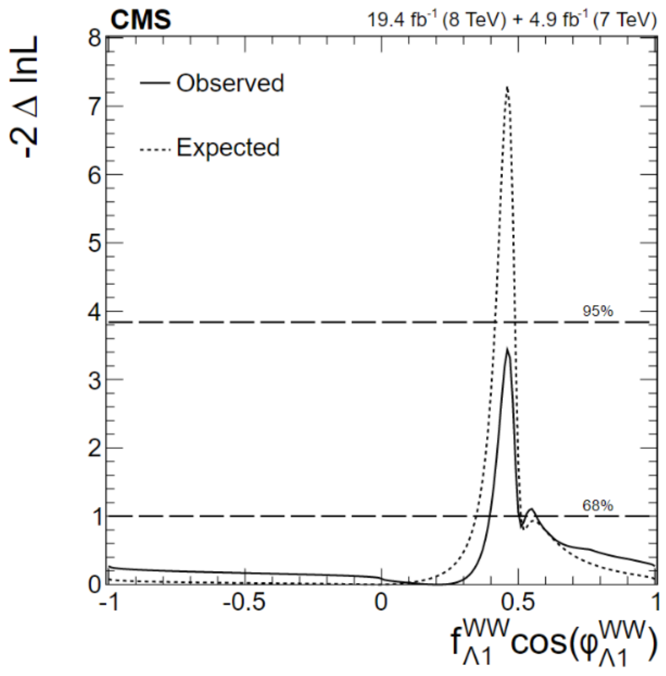
[EFT]: Andrei V. Gritsan, Jeffrey Roskes, Ulascan Sarica, Markus Schulze, Meng Xiao, Yaofu Zhou. New features in the JHU generator framework: constraining Higgs boson properties from on-shell and off-shell production. Phys. Rev. D 102, 056022 (2020). https://arxiv.org/abs/2002.09888

Maximum Log Likelihood scans - Preliminary

Example of Λ_1 ($0^+_{\Lambda 1}$ HWW) coupling expected likelihood values (CRs included in fits)

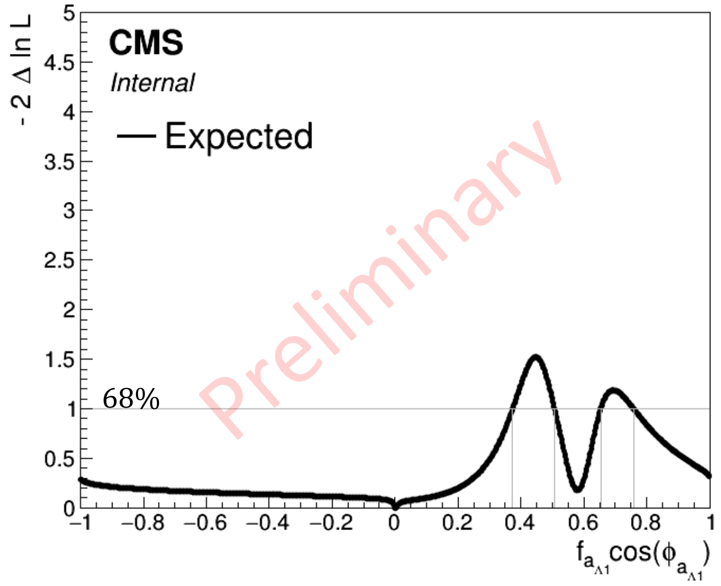
Comparison with Run-1

HIG-14-018 (did not consider VBF/VH)



Ongoing Run-2 analysis

0-jet + 1-jet ggH 2018

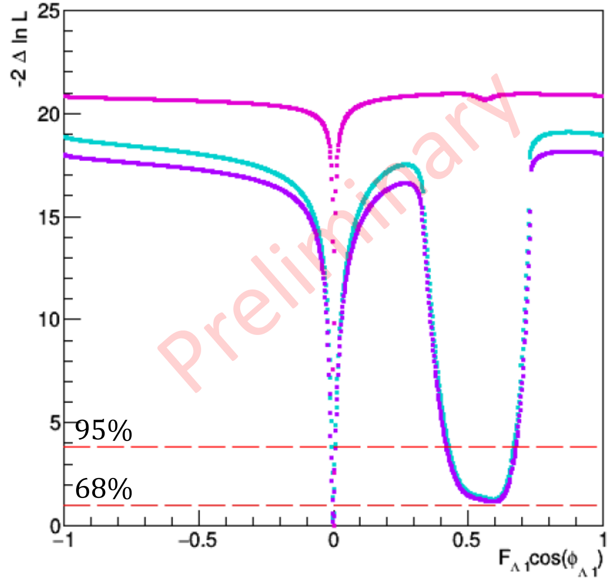


2016-2018

VBF+VH resolved+VH boosted

VBF+VH resolved

VBF

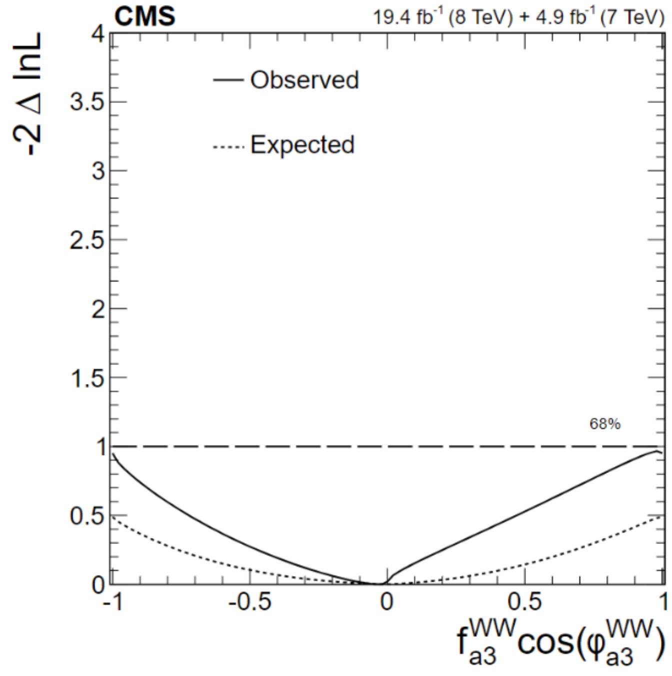


Maximum Log Likelihood scans - Preliminary

Example of a_3 (0^-HWW) coupling expected likelihood values (CRs included in fits)

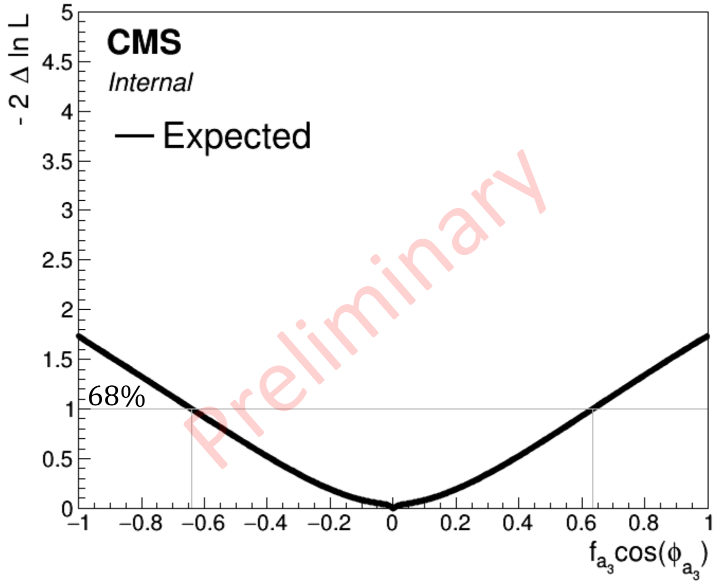
Comparison with Run-1

HIG-14-018 (did not consider VBF/VH)



Ongoing Run-2 analysis

0-jet + 1-jet ggH 2018

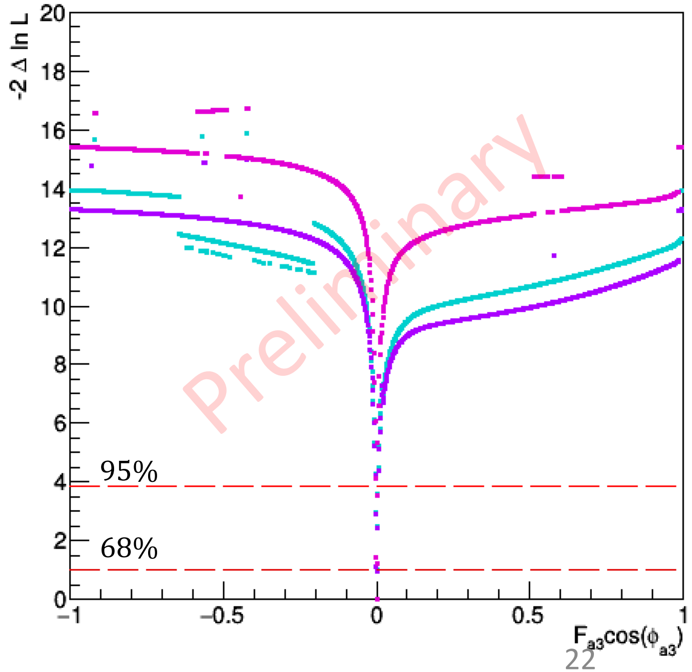


2016-2018

VBF+VH resolved+VH boosted

VBF+VH resolved

VBF



EFT interpretation

- HVV scattering amplitude approach is equivalent to effective Lagrangian in Higgs basis

$$\mathcal{L}^{\text{eff}}_{\text{hvv}} = \mathcal{L}^{\text{SM}}_{\text{hvv}} + \sum_{\text{n}=1}^{\infty} \underbrace{\sum_{\text{i}} \frac{c_{\text{i}}^{(\text{n})}}{\Lambda^{\text{n}}} \mathcal{O}_{\text{i}}^{(\text{n}+4)}}_{\text{dim 6 operators } \mathcal{O} \text{ terms}} \implies$$

$$\begin{aligned}
\mathcal{L}_{\text{hvv}} = \quad & \frac{h}{v}\Bigg[(1+\delta c_z)\,\frac{(g^2+g'^2)v^2}{4} Z_\mu Z_\mu + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu} Z_{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}\tilde{Z}_{\mu\nu} \\
& + (1+\delta c_w)\,\frac{g^2 v^2}{2} W^+_\mu W^-_\mu + c_{ww}\frac{g^2}{2} W^+_{\mu\nu} W^-_{\mu\nu} + c_{w\Box} g^2 \left(W^-_\mu \partial_\nu W^+_{\mu\nu} + \text{h.c.}\right) + \tilde{c}_{ww}\frac{g^2}{2} W^+_{\mu\nu}\tilde{W}^-_{\mu\nu} \\
& + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu} A_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu}\tilde{A}_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu} \\
& + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}\tilde{A}_{\mu\nu} + c_{gg}\frac{g_s^2}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \tilde{c}_{gg}\frac{g_s^2}{4} G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\Bigg],
\end{aligned}$$

- … so the ACs can be associated with Lagrangian couplings leaving only 4 independent parameters $a_1^{ZZ}, a_2^{ZZ}, a_3^{ZZ}$ and $\kappa_1^{ZZ}/\left(\Lambda_1^{ZZ}\right)^2$ + value of Weinberg angle

$$\delta c_z = \frac{1}{2} a_1^{ZZ} - 1, \qquad c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_2^{ZZ},$$

$$c_{z\Box} = \frac{m_Z^2 s_w^2}{e^2}\,\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}, \qquad \tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_3^{ZZ}.$$

See [EFT] for formulas

EFT interpretation

- Again we can use MELA to reweight templates to any EFT hypothesis

  →**Using SU(2)xU(1) symmetry we get relations:**

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

→**Assuming EFT scale $\boldsymbol{\Lambda = 100\mathrm{GeV}}$**

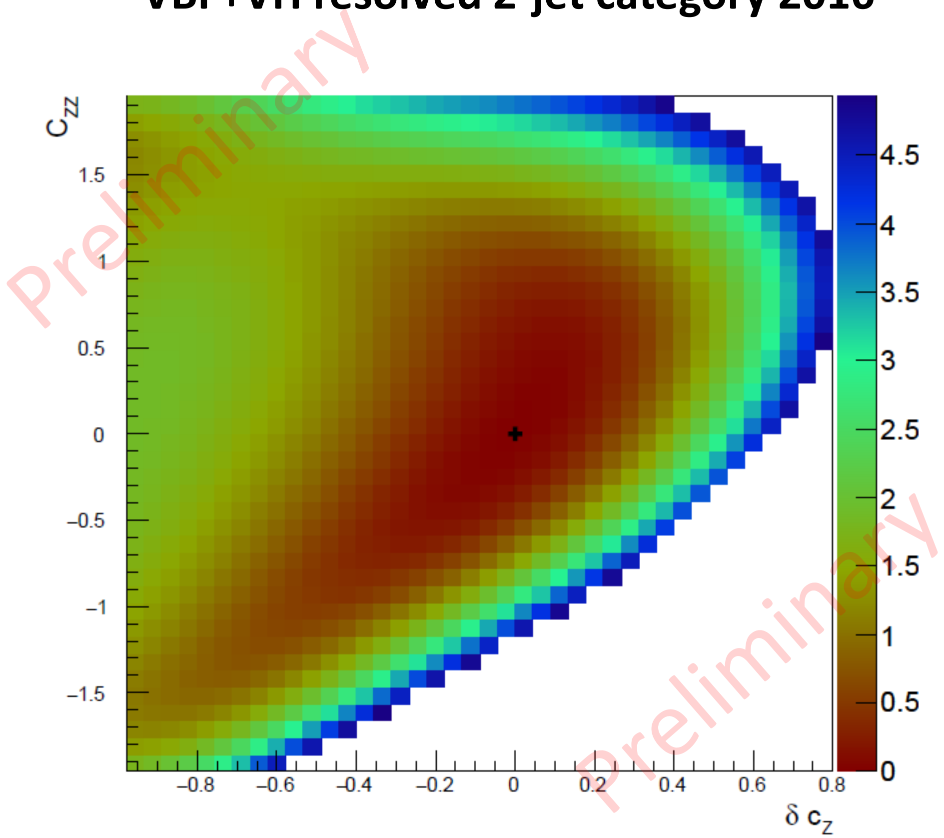
Example: for pure $\boldsymbol{0_h^+}$ (so $\boldsymbol{a_2^{ZZ} = 1}$) we need to set $\boldsymbol{a_2^{WW} = c_W^2}$ (neglecting $\boldsymbol{a_2^{\gamma\gamma}, a_2^{Z\gamma}}$ constrained in another study)

- One more issue with total Higgs width now changing with coupling adjustments (before it was „hidden“ in μ −parameter) ⇒ **fitting formula more complicated**

EFT interpretation

Example of c_{ZZ} vs. δc_Z scan (both linearly related to a_1^{ZZ}, a_2^{ZZ})

VBF+VH resolved 2-jet category 2016



Signal Templates

- Signal samples (SM, BSM and SM-BSM mix) were generated by JHUGen V7 for 2016-2018
- **To increase statistics**: each signal sample (pure SM, pure BSM and mixed SM-BSM) can be **re-weighted to considered AC hypothesis** (ggF: $H_{1..3}$, VBF/VH: $H_{1..5}$, HZγ: $H_{1..3}$)
- H_{i} is then averaged sum of all available re-weighted samples
- Interference templates are then derived as:

ggF: $T_2 = (H_2 - H_1 - H_3 * g^2)/g$

VBF/VH: $T_{\mathrm{i}} = G_{\mathrm{ji}}\, H_{\mathrm{j}}$

- Reweighting is done using **MELA (‘Matrix Element Likelihood Approach’)**

Maximum Log Likelihood Method

Profile Likelihood Ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

$\boldsymbol{\theta}$ are fitted to maximize L for a given value of μ

μ and $\boldsymbol{\theta}$ are both estimated to define maximum of L

$0 < \lambda(\mu) < 1$ Good agreement beween data and prediction

Likelihood function

$$L(\mu, \boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{(\mu\nu_{S,i} + \nu_{B,i})^{n_i}}{n_i!} e^{-(\mu\nu_{S,i}+\nu_{B,i})} \prod_{j=1}^{M} \frac{u_j^{m_j}}{m_j!} e^{-u_j}$$

$$L(\mu, \boldsymbol{\theta}) = \mathrm{Poisson}(\mu\nu_{S,i}(\boldsymbol{\theta}) + \nu_{B,i}(\boldsymbol{\theta})) \times \mathrm{Poisson}(u_j(\boldsymbol{\theta})) \times \mathrm{Gauss}(\boldsymbol{\theta}, 0, 1)$$

constrained by unitary Gauss distibution

Profile Likelihood test statistics

$$q_\mu = -2 \ln \lambda(\mu) \longrightarrow \chi^2$$

zero hypothesis $\Leftrightarrow$ BKG only $\Leftrightarrow \mu = 0 \Leftrightarrow q_0$ test statistics

p-value evaluated for q_0^{exp} instead of q_0^{obs} because of blinded regime