JHU generator framework: New features for Higgs boson studies

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Higgs 2020: EFT Session
28.10.2020

Available packages

→ JHUGenerator: Event generator for a spin-0, 1 or 2 resonance:
  → A key simulation tool in experiments to study resonances with BSM effects since Run 1
  → Has been a framework to study anomalous couplings/EFT effects in Run 2 as well
  → Focus on the anomalous/EFT couplings of the Higgs boson today
  → Interface to MCFM matrix elements for off-shell Higgs processes

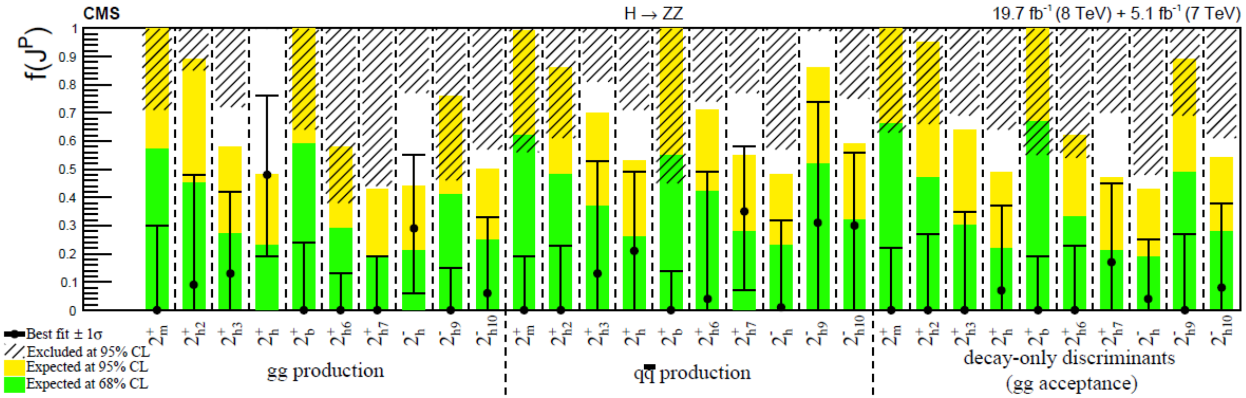
→ JHUGenMELA: Matrix element library with an object-oriented C++/Python interface and related numerical convenience tools for analysis, usable for
  → Reweighting of existing simulation via ratios of $|M|^2$.
  → Constructing discriminants for the analysis of couplings and background suppression

→ JHUGenLexicon: Translation tool for between different EFT and Warsaw bases, and the JHUGen amplitude convention of anomalous couplings

→ More details on tool availability and versions: https://spin.pha.jhu.edu

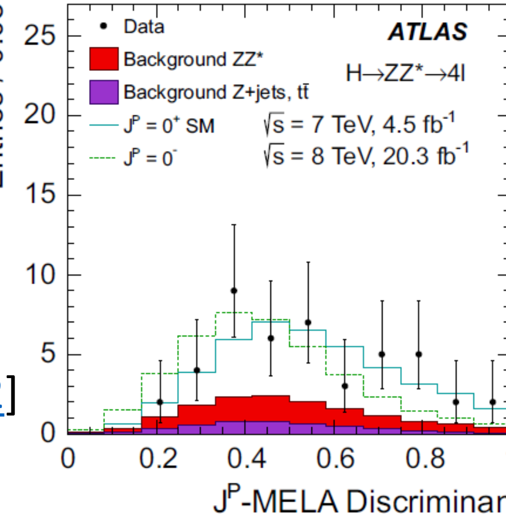
→ References:
Phys.Rev. D81 (2010) 075022, arXiv:1001.3396
Phys.Rev. D86 (2012) 095031, arXiv:1208.4018
Phys.Rev. D89 (2014) 035007, arXiv:1309.4819
Phys.Rev. D94 (2016) 055023, arXiv:1606.03107
Phys.Rev. D102 (2020) 056022, arXiv:2002.09888

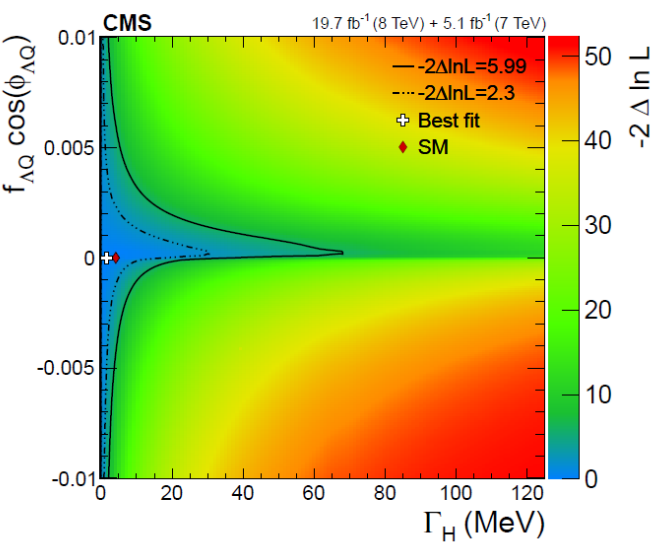
Examples of past and recent uses in analyses



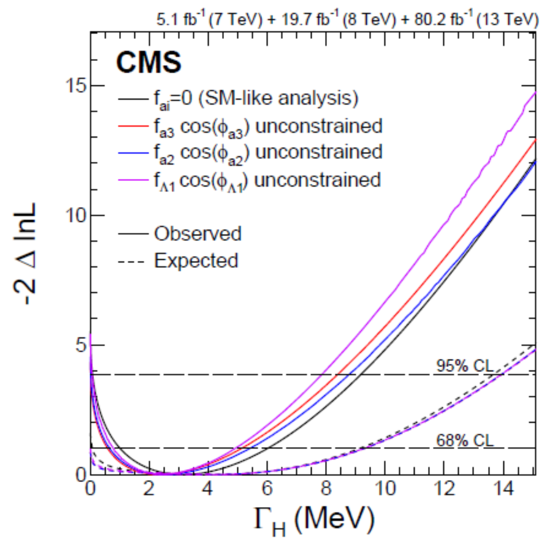
[1]

[2]





[3]



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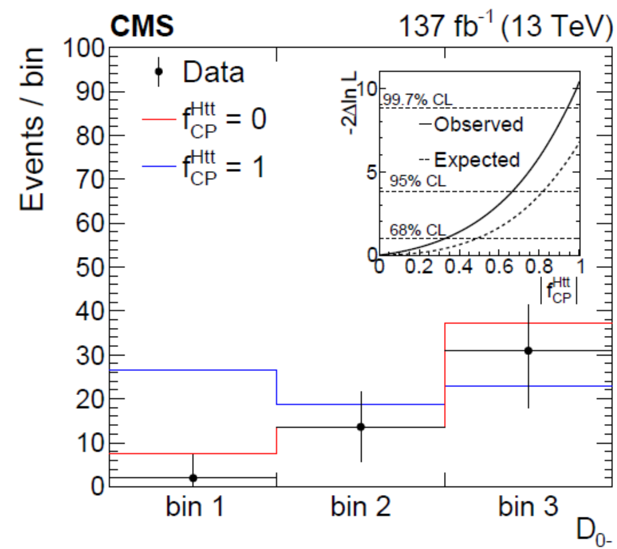


[5]

Available processes for Higgs simulation

Single resonance
production modes

$gg \to H$

QCD H production with 1 or 2 jets

VBF

$q\bar{q} \to Z/W/\gamma\ H$

(LO or NLO in QCD)

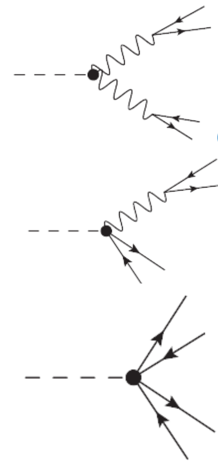
$gg \to ZH$

$t\bar{t}H$

(LO or NLO* in QCD)

tH

$b\bar{b}H$



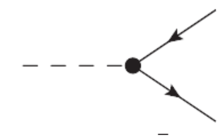
Single resonance decay modes
with production coming from
elsewhere (e.g. POWHEG, JHUGen)

$H \to ZZ/Z\gamma^*/\gamma^*\gamma^*/WW \to 4f$

$H \to \gamma\ Z/\gamma^* \to \gamma\ 2f$

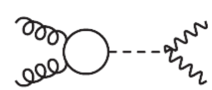
$H \to \gamma\gamma$

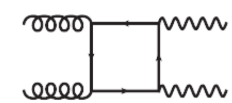
$H \to \tau\tau$

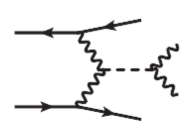


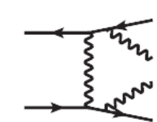
Off-shell mixed modes

$ZZ/Z\gamma^*/\gamma^*\gamma^*/WW$ $\to$ 4f production
via gluon fusion, and
$ZZ/Z\gamma^*/\gamma^*\gamma^*/WW$ $\to$ 4f + 2 jets or V
electroweak production, both featuring
Higgs, VV continuum and
Higgs+continuum with their
interference, or an additional spin-0
resonance









(*) NLO $t\bar{t}H$ is available separately upon request

Resonance couplings

HV_1V_2: $$A(HV_1V_2) = \frac{1}{v}\left\{ M_{V_1}^2 \left(g_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{(\Lambda_Q^{VV})^2} + \frac{2 q_1 \cdot q_2}{M_{V_1}^2} g_2^{VV} \right)(\varepsilon_1 \cdot \varepsilon_2) - 2 g_3^{VV} (\varepsilon_1 \cdot q_2)(\varepsilon_2 \cdot q_1) - 2 g_4^{VV} \varepsilon_{\varepsilon_1 \varepsilon_2 q_1 q_2} \right\}$$

=2 for V_1V_2 =ZZ, WW in SM at tree level additional HVV anomalous couplings

Vff: $$\varepsilon_i^\mu(q_i) \to j_i^\mu = e \frac{\bar{\psi}_{f'} \gamma^\mu (g_L^{Vf'f} \omega_L + g_R^{Vf'f} \omega_R) \psi_f}{q_i^2 - M_V^2 + iM_V\Gamma_V}$$ or $$\frac{\bar{\psi}_{f'} \gamma^\mu (e_L^{V'f'f} \omega_L + e_R^{V'f'f} \omega_R) \psi_f}{q_i^2 - M_{V'}^2 + iM_{V'}\Gamma_{V'}}$$

SM Vff couplings

additional $V'ff$ or
contact interaction under $M_{V'} \to \infty$
with a separate set of HV(')V(') couplings

Hff: $$A(Hf\bar{f}) = -\frac{m_f}{v} \bar{\psi}_f (\kappa_f + i\tilde{\kappa}_f \gamma_5) \psi_f$$

=1 in SM pseudoscalar anomalous coupling

The parametrization of the amplitude as above can easily be interpreted in other conventions, e.g. the EFT Higgs basis [1]:

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

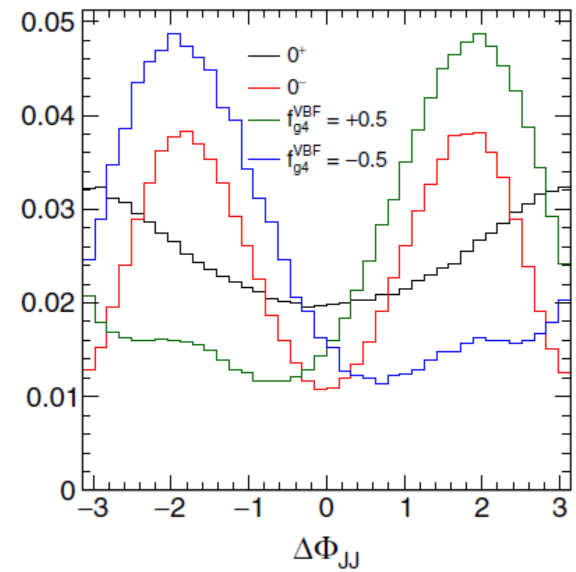
Case study: VBF CP analysis (HVV)

→ For a VBF CP analysis, one could examine $\Delta\phi_{JJ}$ or a multivariate discriminant using more kinematic information

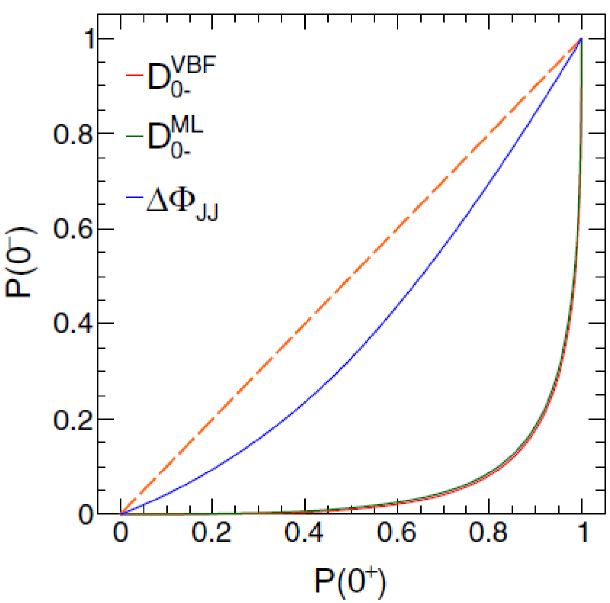
→ For optimal analysis, construct MELA discriminants of form

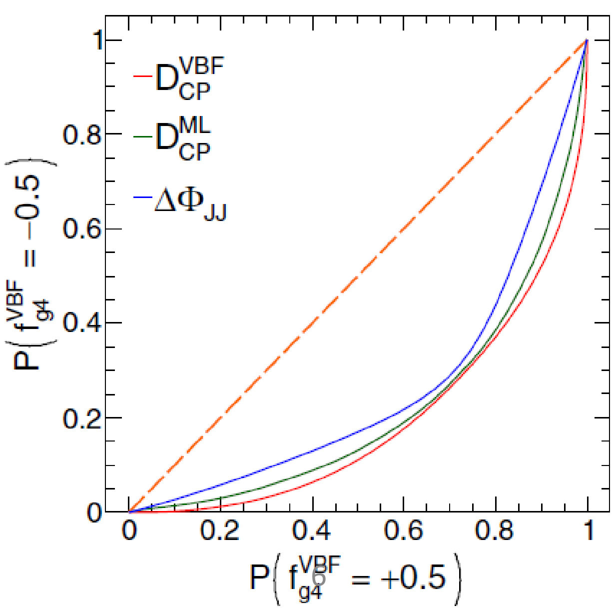
$$\mathcal{D}_{\text{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\text{alt}}(\mathbf{\Omega})} \qquad \mathcal{D}_{\text{int}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) \times \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}}$$

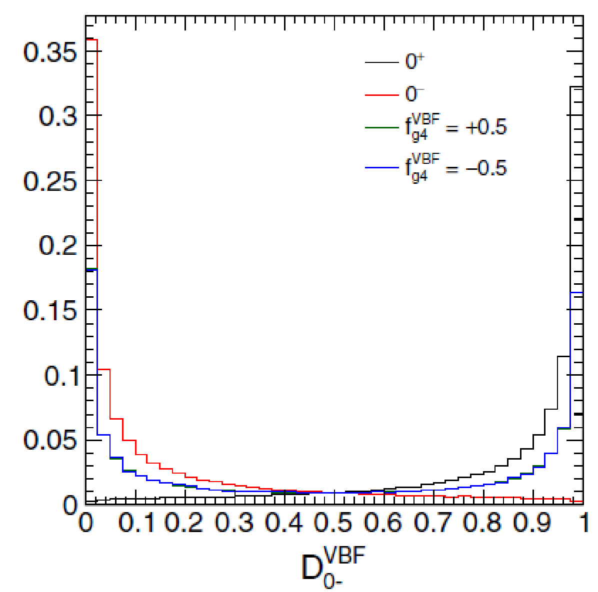
(here, sig=0^-, alt=0^+ $[SM]$, int [CP]=interference extracted using $f_{g4}^{VBF} = +0.5$)



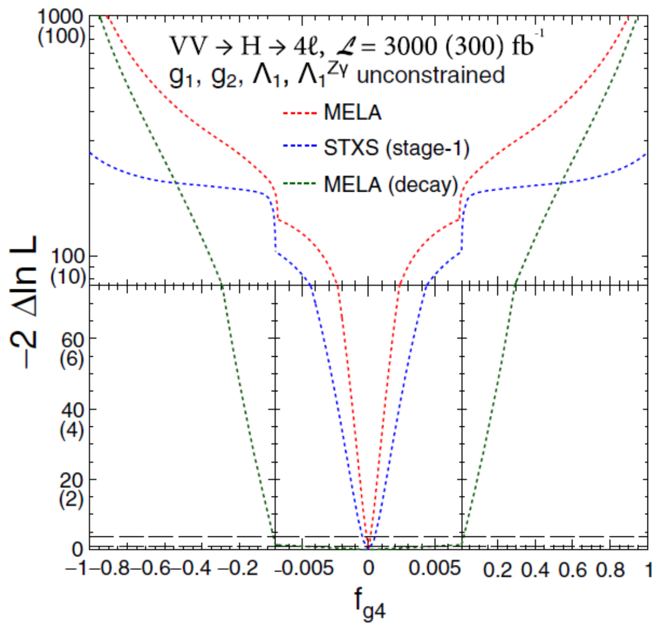
→ MELA discriminants contain full kinematic information and can outperform single-variable or other multivariate techniques

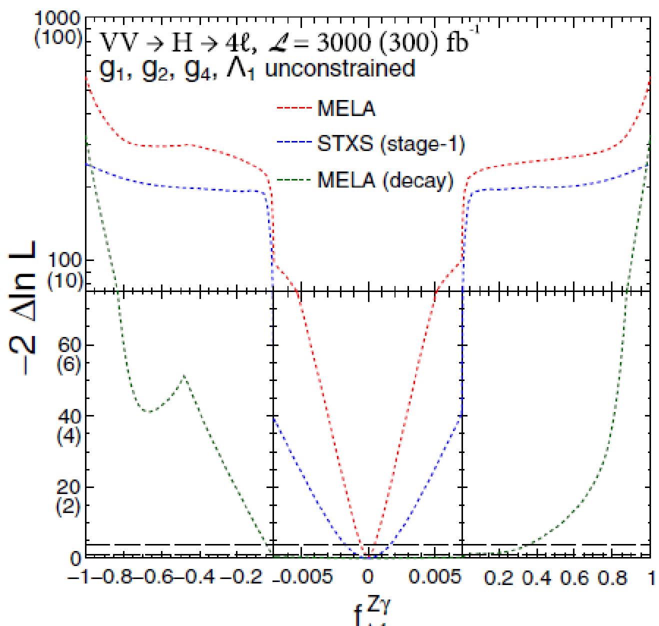






Full case study: HVV coupling constraints from 4ℓ





→ Case study of constraints on the HVV couplings using VBF $H \rightarrow 4\ell$ events

→ Different interference components can be obtained via dedicated simulation or reweighting existing simulated events

→ Comparison of constraints at 300 and 3000 fb^{-1} made using

a) full set of MELA discriminants D_{alt} and D_{int} with production and decay information

b) set of MELA discriminants D_{alt} and D_{int} with decay information only

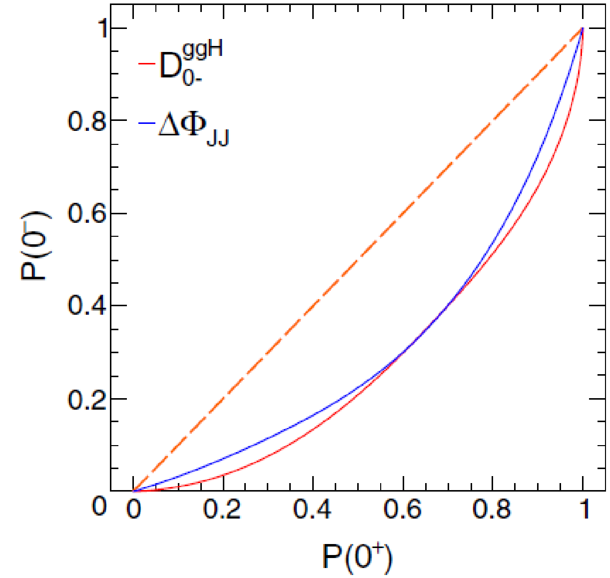
c) Binning of observables following the STXS 1.1 binning

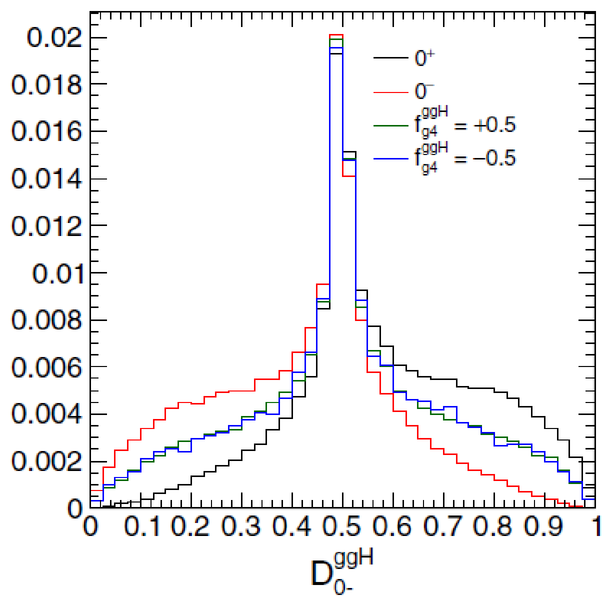
→ Analysis with a MELA-based binning in 4ℓ with production and decay information combined can be more sensitive to couplings than a decay-only analysis or STXS 1.1 binning

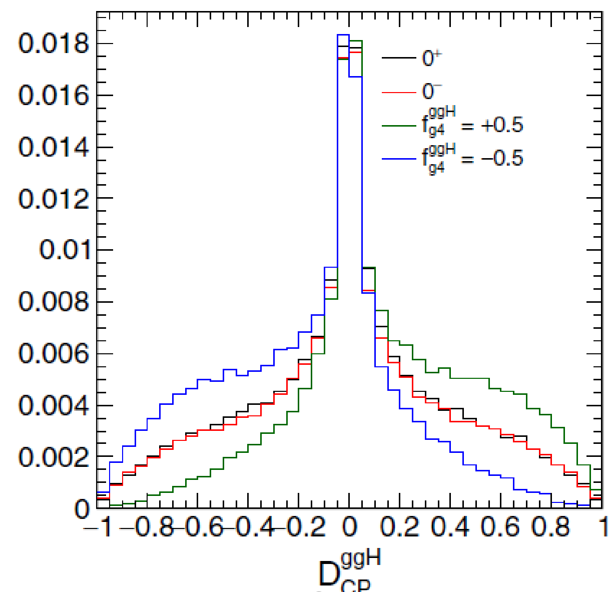
Case study: ggH+2 jets CP analysis (Hgg)

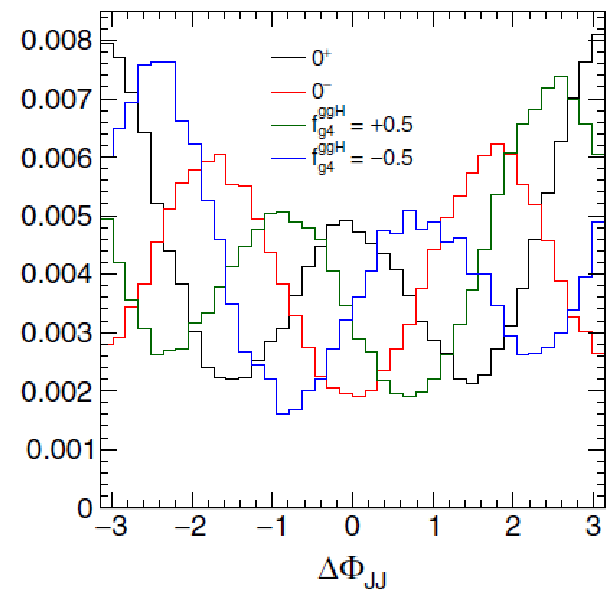
→ Similar to a VBF CP analysis, one could examine $\Delta\phi_{JJ}$ or construct MELA discriminants
→ Only quark-initiated MEs are sensitive, so discriminants are constructed only out of those.

→ MELA discriminants could outperform $\Delta\phi_{JJ}$





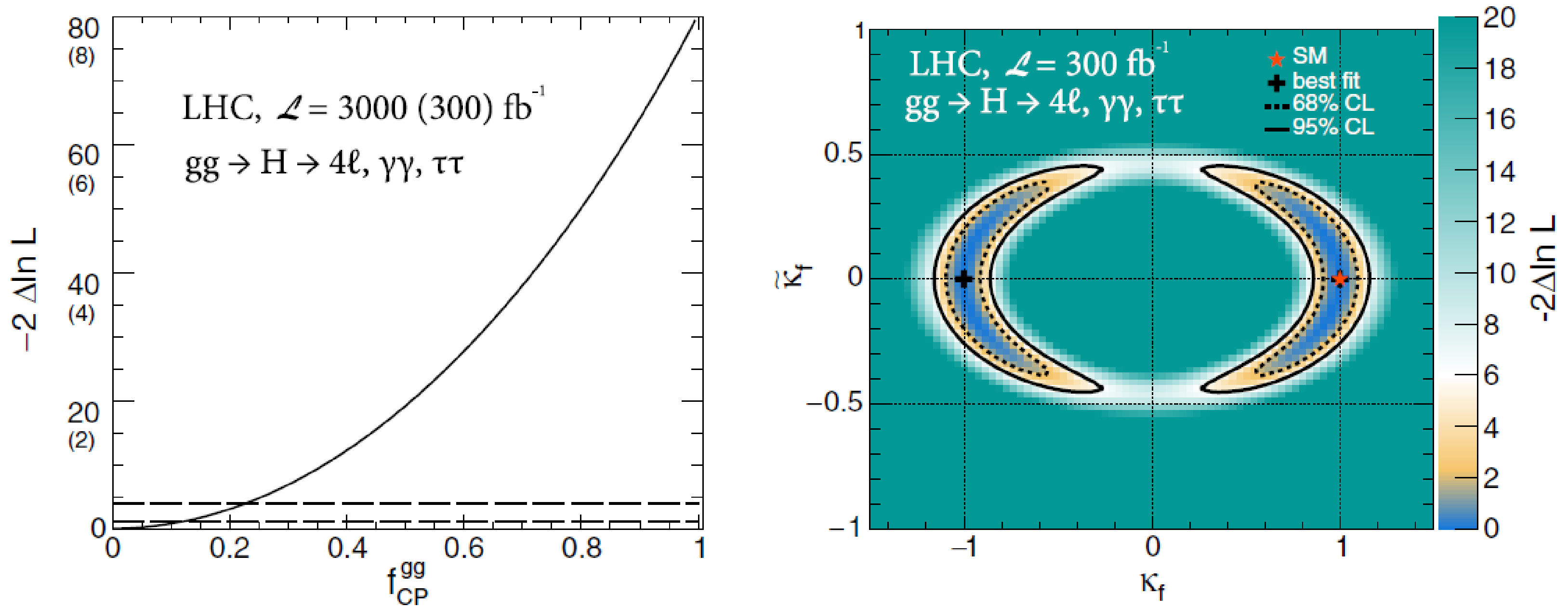




Full case study: Hgg coupling constraints

→ Shown constraints are obtained using 4ℓ events, but expected yields are scaled to include $\gamma\gamma$ and $\tau\tau$ channels to illustrate the effect of combination

→ No statistical sensitivity on the modification of the loop to Higgs p_T, ignored at the moment in the projections.



Translation of couplings

→ Conversion between the couplings in the JHUGen amplitude conventions and the EFT Higgs basis, or the Warsaw basis, is possible using the JHUGenLexicon:

$$\delta c_z = \frac{1}{2} g_1^{ZZ} - 1, \quad c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} g_2^{ZZ}, \quad c_{z\Box} = \frac{M_Z^2 s_w^2}{e^2} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}, \quad \tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} g_4^{ZZ},$$

$$\delta c_w = \frac{1}{2} g_1^{WW} - 1, \quad c_{ww} = -\frac{2 s_w^2}{e^2} g_2^{WW}, \quad c_{w\Box} = \frac{M_W^2 s_w^2}{e^2} \frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}, \quad \tilde{c}_{ww} = -\frac{2 s_w^2}{e^2} g_4^{WW},$$

$$c_{z\gamma} = -\frac{2 s_w c_w}{e^2} g_2^{Z\gamma}, \quad \tilde{c}_{z\gamma} = -\frac{2 s_w c_w}{e^2} g_4^{Z\gamma}, \quad c_{\gamma\Box} = \frac{s_w c_w}{e^2} \frac{M_Z^2}{(\Lambda_1^{Z\gamma})^2} \kappa_2^{Z\gamma},$$

$$c_{\gamma\gamma} = -\frac{2}{e^2} g_2^{\gamma\gamma}, \quad \tilde{c}_{\gamma\gamma} = -\frac{2}{e^2} g_4^{\gamma\gamma}, \quad c_{gg} = -\frac{2}{g_s^2} g_2^{gg}, \quad \tilde{c}_{gg} = -\frac{2}{g_s^2} g_4^{gg}.$$

Higgs basis coefficients, see [1]

$$d_1^\gamma = 1 + (g_2^{\gamma\gamma} - g_2^{ZZ}) c_w^2 + g_2^{Z\gamma} \left(\frac{c_w}{s_w} - 2 s_w c_w \right),$$

$$d_4^\gamma = (g_4^{\gamma\gamma} - g_4^{ZZ}) c_w^2 + g_4^{Z\gamma} \left(\frac{c_w}{s_w} - 2 s_w c_w \right),$$

$$d_1^Z = 1 - 2 \frac{s_w^2 c_w^2}{c_w^2 - s_w^2} (g_2^{\gamma\gamma} - g_2^{ZZ}) - 2 s_w c_w g_2^{Z\gamma} - \frac{M_Z^2}{2(c_w^2 - s_w^2)} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2},$$

$$d_2^Z = d_3^Z = 1 - \frac{s_w^2}{c_w^2 - s_w^2} (g_2^{\gamma\gamma} - g_2^{ZZ}) - \frac{s_w}{c_w} g_2^{Z\gamma} - \frac{M_Z^2}{2(c_w^2 - s_w^2)} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2},$$

$$d_4^Z = -\frac{s_w^2}{c_w^2} d_4^\gamma,$$

$$d^{ZZWW} = \frac{c_w^2}{s_w^2} (2 d_2^Z - 1), \quad d^{Z\gamma WW} = \frac{c_w}{s_w} d_2^Z.$$

aT/QGC contributions, see [2]

Warsaw basis coefficients, see [3]

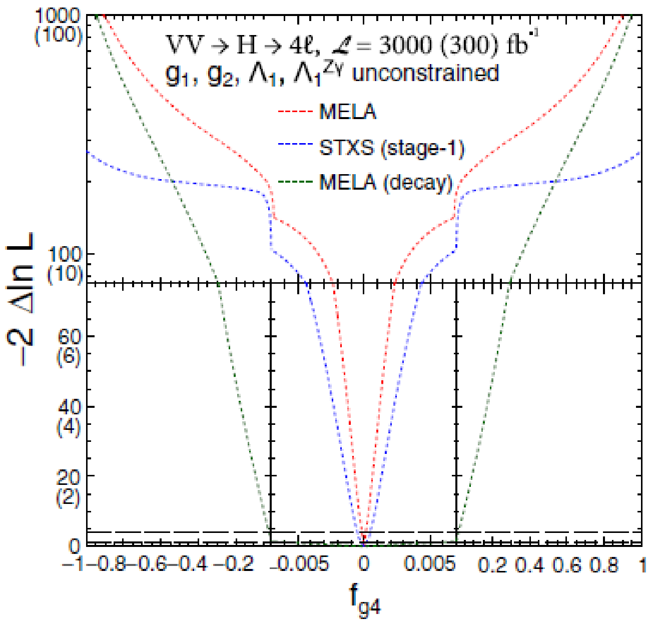
$$g_4^{ZZ} = -2 \frac{v^2}{\Lambda^2} \left(s_w^2 w_{\phi\tilde{B}} + c_w^2 w_{\phi\tilde{W}} + s_w c_w w_{\phi B\tilde{W}} \right),$$

$$g_4^{\gamma\gamma} = -2 \frac{v^2}{\Lambda^2} \left(c_w^2 w_{\phi\tilde{B}} + s_w^2 w_{\phi\tilde{W}} - s_w c_w w_{\phi B\tilde{W}} \right),$$

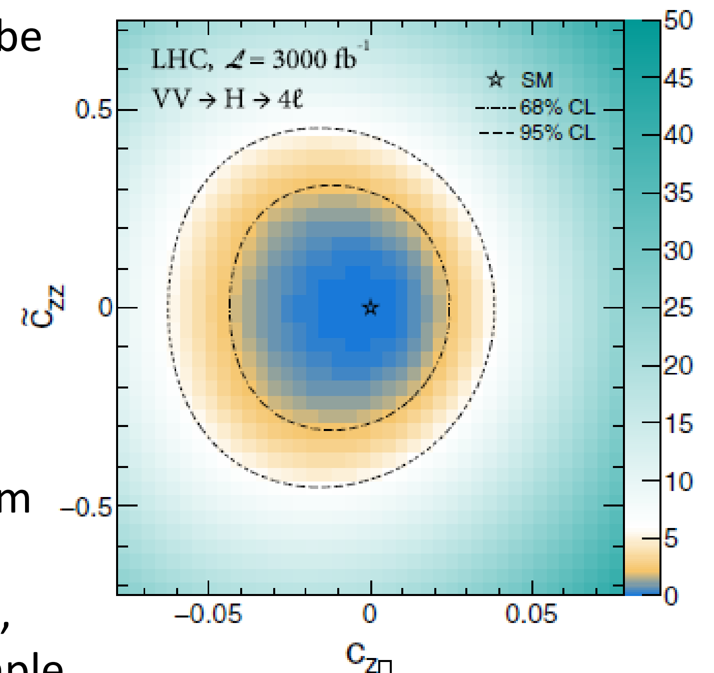
$$g_4^{Z\gamma} = -2 \frac{v^2}{\Lambda^2} \left(s_w c_w (w_{\phi\tilde{W}} - w_{\phi\tilde{B}}) + \frac{1}{2} (s_w^2 - c_w^2) w_{\phi B\tilde{W}} \right)$$

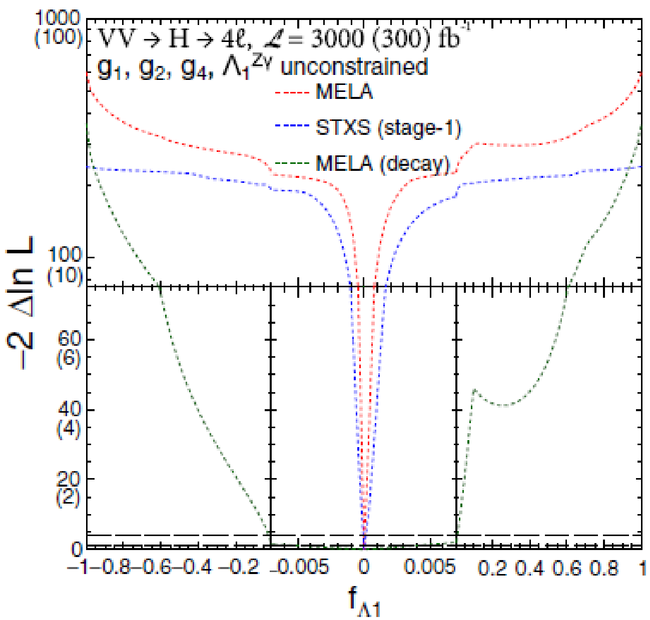
$$g_4^{gg} = -2 \frac{v^2}{\Lambda^2} w_{\phi\tilde{G}}.$$

Translation of couplings: HVV example



→ Constraints shown in red for either of the couplings can be interpreted in a joint multi-parameter form.





→ The multi-parameter form can be translated to other bases using JHUGenLexicon, here Higgs basis as an example.

Off-shell (mixed) processes

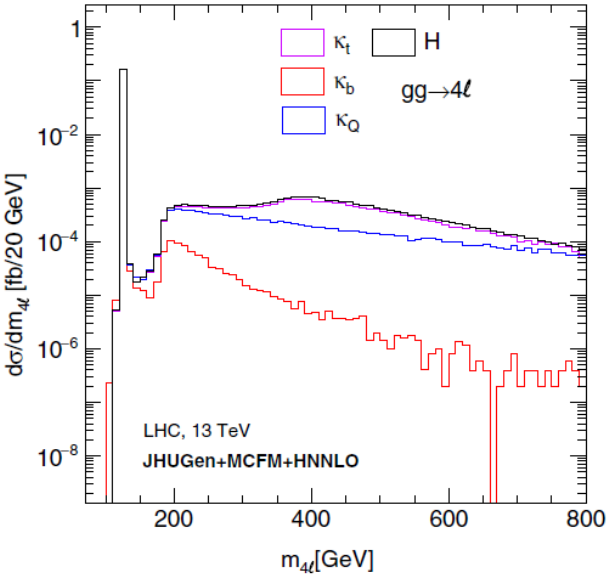
→ We utilize the MCFM matrix elements for the gg-initiated 0-jet VV production (since 2015), or the EW VV production with 2 jets (since 2017):

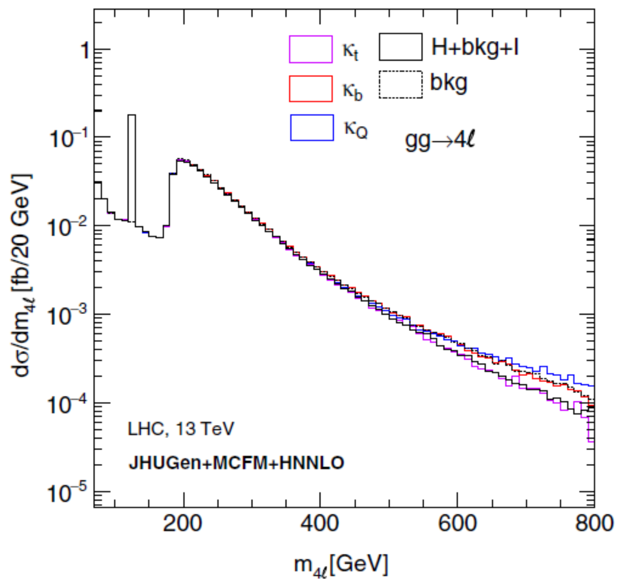
→ Added additional anomalous couplings of the Higgs (HVV, Hgg, or $Hf\bar{f}$), an additional t'/ b' loop in gluon fusion case, also triple and quartic V coupling contributions in EW VV production with 2 jets continuum amplitudes for a full EFT treatment.

→ Also added a second resonance to the amplitudes with equivalent but separate sets of couplings

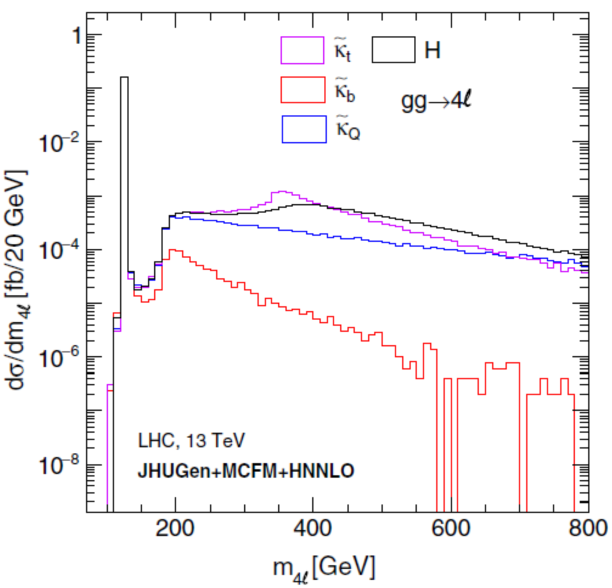
→ Expanded the EW MEs to allow separate generation for each initial-final state configuration, and the triple-V production MEs to also feature leptonic decays of the associated V for ME reweighting purposes.

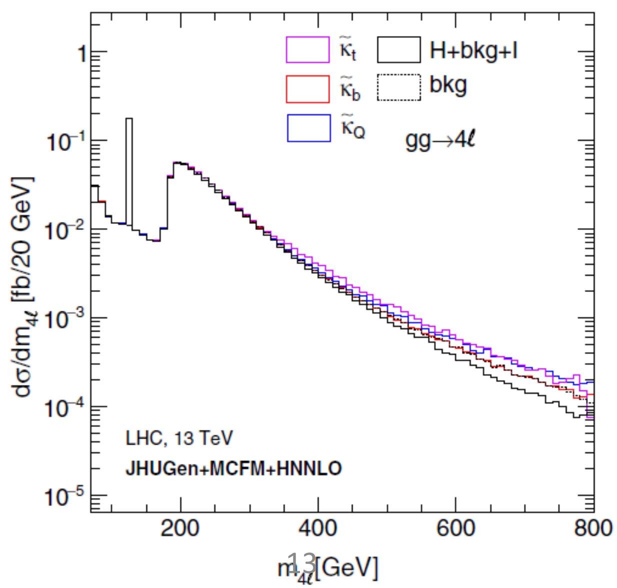
Off-shell processes: Hgg couplings





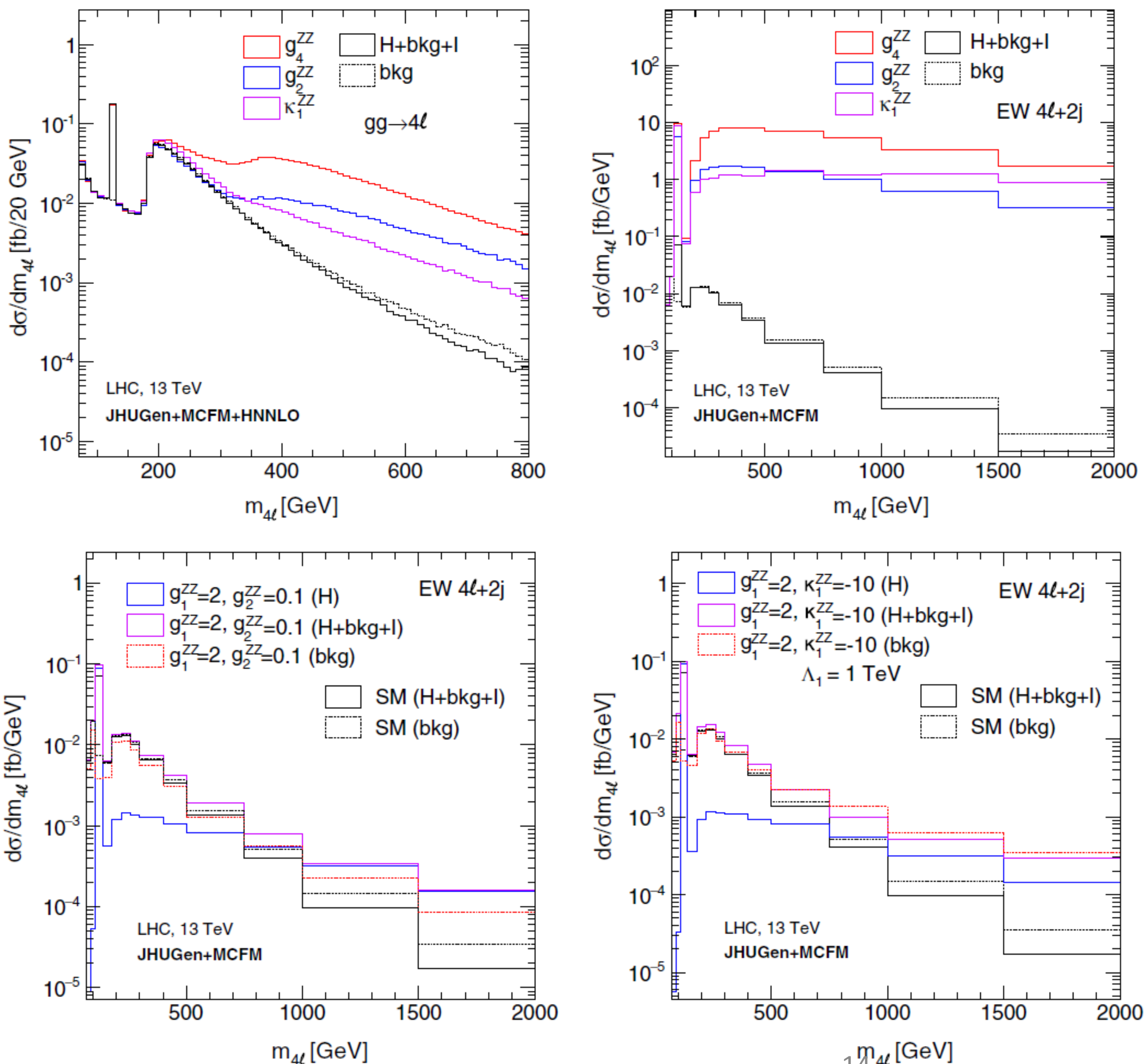
→ Individual top (κ_t) and bottom (κ_b) contributions for scalar Higgs scenario (+ full continuum bkg), as well as their sum, or a point-like interaction ($\kappa_Q \sim g_2^{gg}$)





→ Individual top ($\tilde{\kappa}_t$) and bottom ($\tilde{\kappa}_b$) contributions for pseudoscalar Higgs scenario (+ full continuum bkg), as well as their sum, or a point-like interaction ($\tilde{\kappa}_Q \sim g_4^{gg}$)

Off-shell processes: HVV couplings

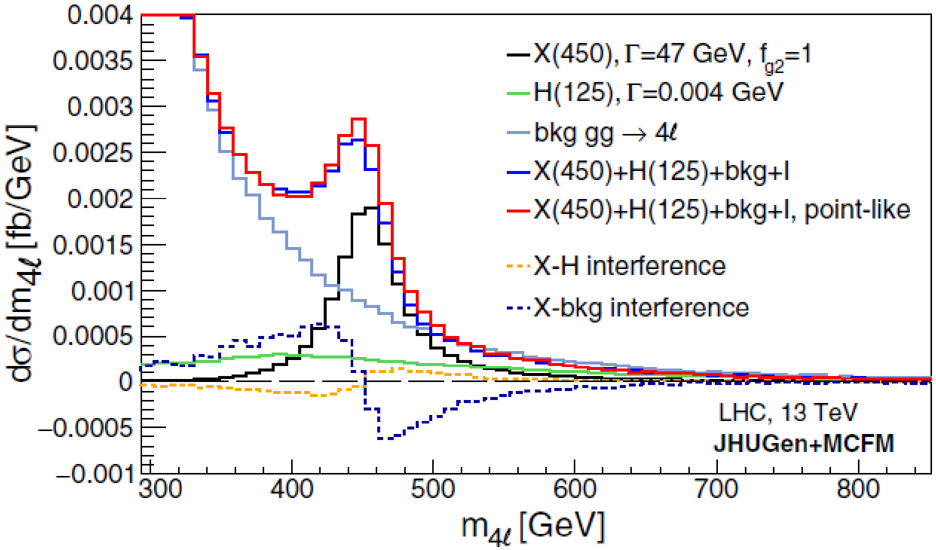


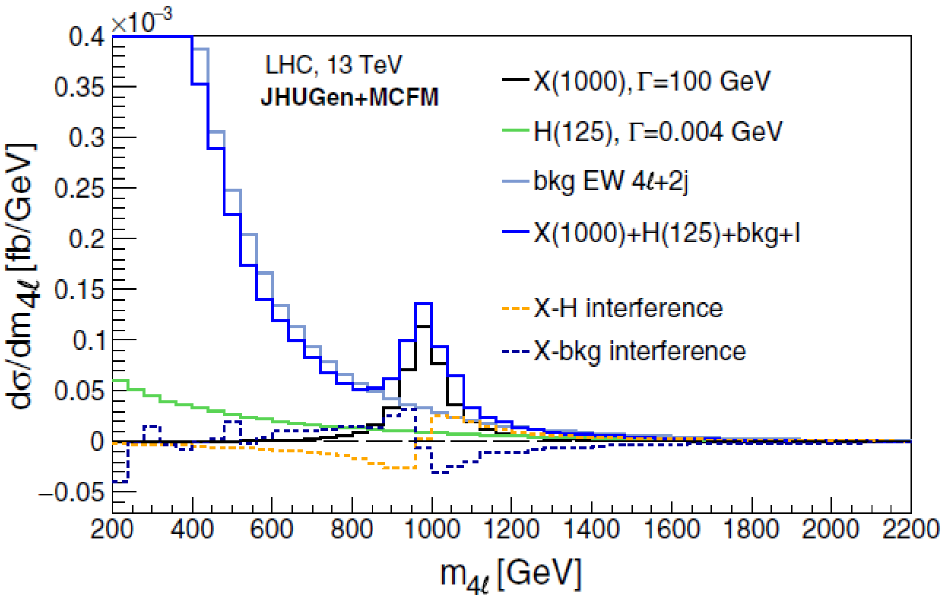
→ Changes in the VV invariant mass shape due to HVV anomalous couplings in $gg \to 4\ell$ or $4\ell + 2j$ EW production (assuming no changes in the continuum amplitudes)

→ m_{VV} shape with two different exemplary HVV anomalous couplings in $4\ell + 2j$ EW production, assuming triple and quartic gauge couplings are affected by the changes in Higgs couplings (see [1] for correspondence details)

→ Different components can be obtained using dedicated simulation or reweighting

Off-shell processes: Second resonance





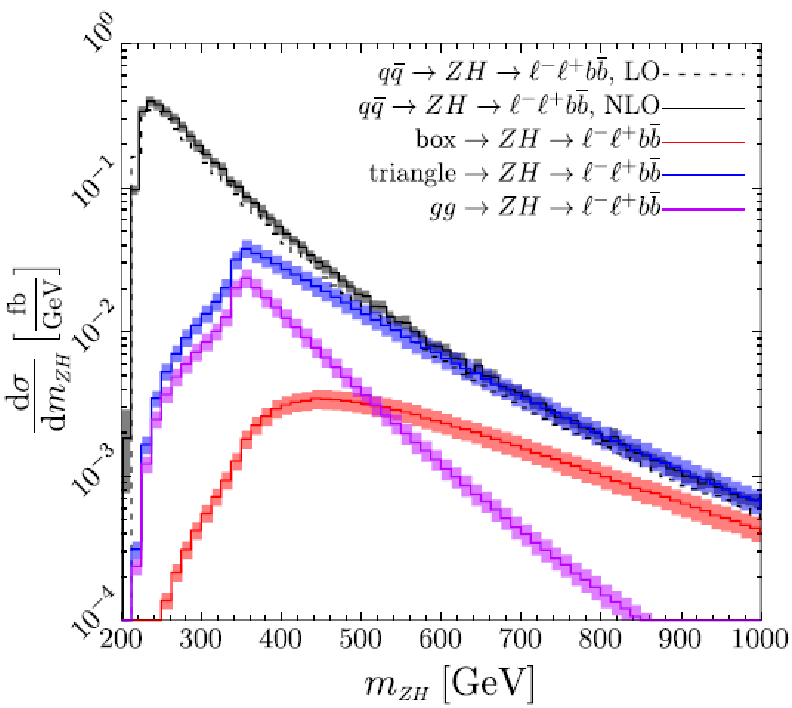
→ Illustrating different spin-0 X masses and couplings in the gg → 4ℓ (top) or EW $4\ell + 2$j (bottom) processes.

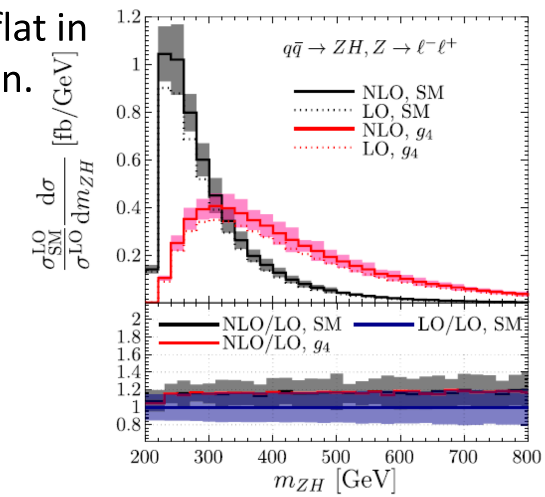
→ Full interference with the first resonance (H) and the continuum amplitude are implemented, allowing expansion of additional resonance searches in ZZ and WW final states.

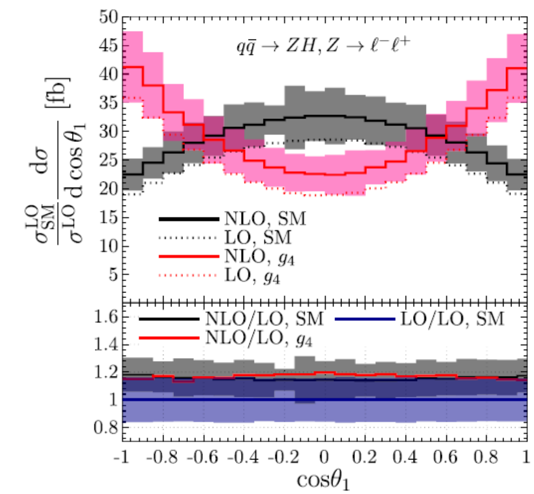
New features in VH production

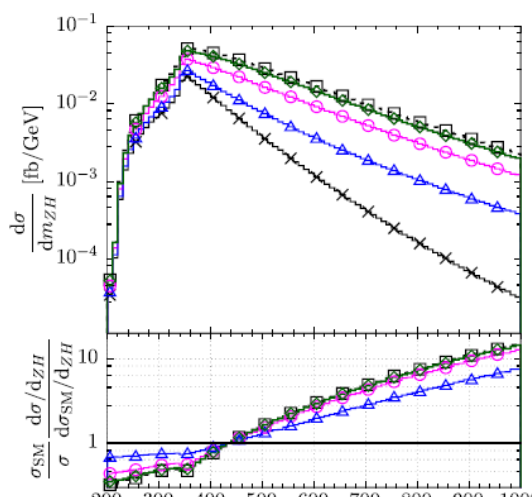
→ VH production at LO in QCD had been available in our package for several years. We now add NLO production capability, and the $gg \to ZH$ contribution.

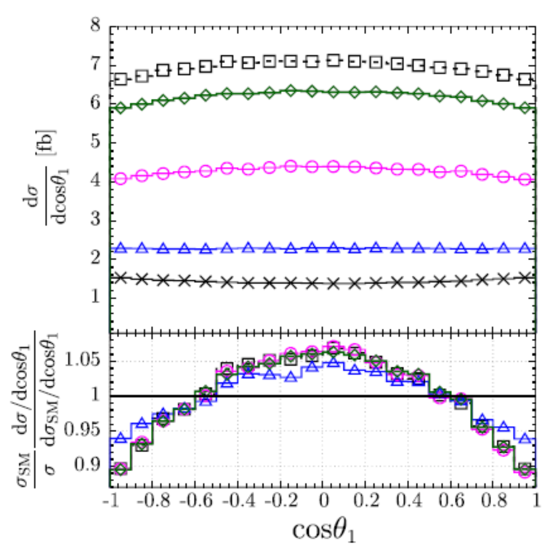
$LO \to NLO$ corrections are relatively flat in relevant kinematics within a 5% margin.











Shown are different $\kappa, \tilde{\kappa}$ combinations in $gg \to ZH$

Summary

→ Presented a coherent and self-contained framework to simulate, measure and analyze Higgs boson properties

→ Provide an amplitude implementation to analyze and translate the couplings to any preferred basis for analysis – anomalous couplings, EFT, pseudo-observables...

→ Exemplify ME discriminant-based analyses for optimal observables in the analysis of the couplings

→ Interface to a modified version of MCFM matrix elements to model changes in kinematics due to Higgs and continuum amplitudes under different anomalous couplings/EFT treatment

→ Also adding the capability to simulate a second resonance for additional resonance searches

→ Expand the VH production to include NLO treatment with anomalous couplings

→ NLO in $q\bar{q} \to VH$, and adding $gg \to ZH$

→ See our latest paper, or https://spin.pha.jhu.edu for more details

Thank you!