Tools for Higgs boson properties with the JHUGen / MELA framework

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on behalf of

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Pheno '17 – 08.05.2017

Introduction

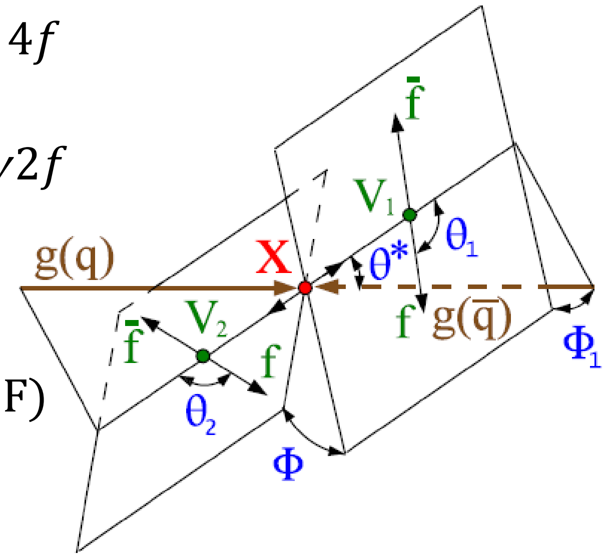
- JHUGenerator:
  → Event generation
- JHUGenMELA and AnalyticalMELA :
  → Discriminants
    → Spin and anomalous couplings of a resonance
    → Background suppression
  → Reweighting tools
  → Cross-validation between different models and generators
- See http://spin.pha.jhu.edu/ for more details
  → Tools to study properties of resonances
  → Modelling and exploiting kinematic degrees of freedom
  → Free access generator download and documentation
- References:

Spin Determination of Single-Produced Resonances at Hadron Colliders
arxiv 1001.3396
On the Spin and Parity of a Single-Produced Resonance at the LHC
arxiv 1208.4018
Constraining anomalous HVV interactions at proton and lepton colliders
arxiv 1309.4819
Constraining anomalous Higgs boson couplings to the heavy flavor fermions using matrix element techniques
arxiv 1606.03107

JHUGenerator

- Processes with production and decay:

$$pp \to \begin{cases} Spin\ 0 \\ Spin\ 1 \\ Spin\ 2 \end{cases} \to \begin{cases} ZZ/Z\gamma^*/\gamma^*\gamma^* \to 4f \\ W^+W^- \to 4f \\ \gamma\gamma \text{ or } \gamma Z/\gamma\gamma^* \to \gamma 2f \end{cases}$$



- Processes with production, stable Higgs:

$$pp \to \begin{cases} Spin\ 0 + jet \\ Spin\ 0 + 2\ jets\ (\text{QCD or VBF}) \\ V + Spin\ 0 \\ t\bar{t} + Spin\ 0 \\ tq + Spin\ 0 \\ b\bar{b} + Spin\ 0 \end{cases}$$

$$\text{ee} \to V + Spin\ 0$$

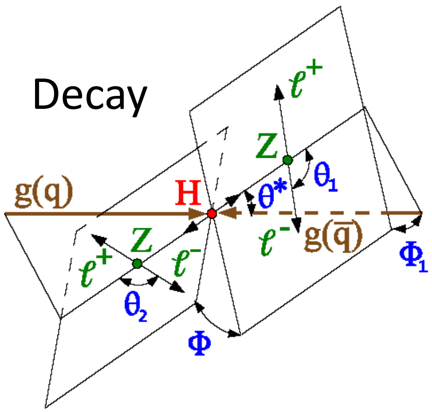
- ReadLHE capability to read spin-0 Higgs (JHUGen, POWHEG and MadGraph) to decay
  → Also supports $H \to \tau\tau$ with subsequent τ decay

- Interface with MCFM (Campbell, Ellis, Williams) in gluon fusion and VBF/VH for
  → Off-shell decay with signal-bkg interference with different anomalous couplings
  → High mass resonance with various interferences with SM Higgs or bkg

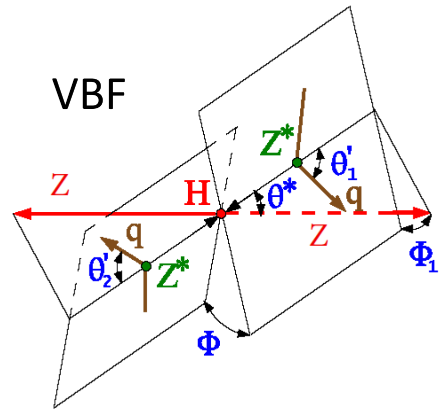
JHUGenMELA

- 8 independent observables
  $(m_{H^*}, m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1)$ in decay,
  5 more from production $(m_1{}^{prod}, m_2^{prod}, \theta_1{}^{prod}, \theta_2{}^{prod}, \Phi^{prod})$

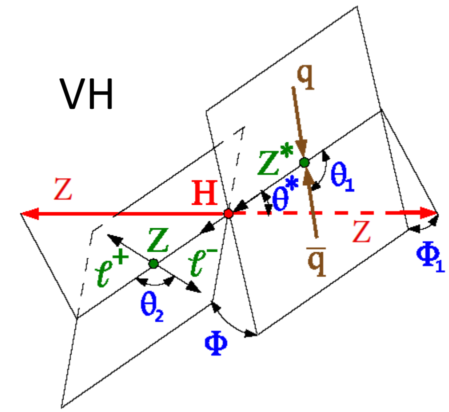
Decay



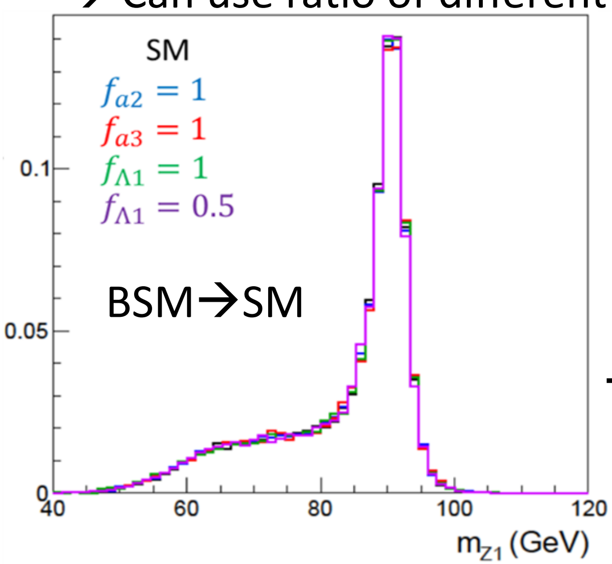
VBF



VH



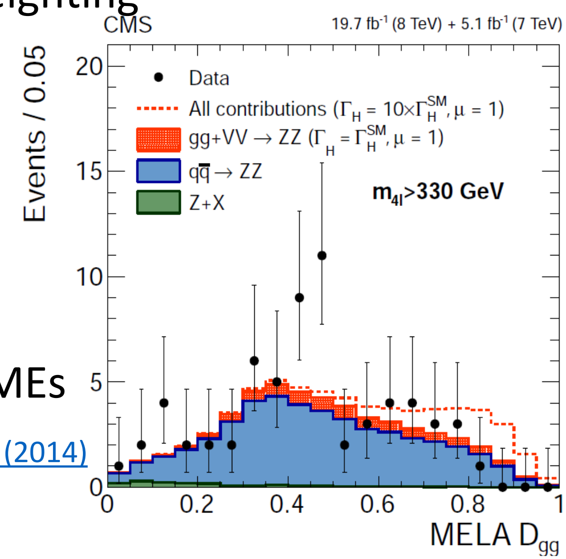
- For each process that can be generated in JHUGenerator, can extract the ME $|\mathcal{M}|^2$:
  $d\sigma = |\mathcal{M}|^2 d\Pi$
  → Can use ratio of different $|\mathcal{M}|^2$ in either discriminants or reweighting



$$weight(A \to B) = {|\mathcal{M}_B|^2}/{|\mathcal{M}_A|^2}$$

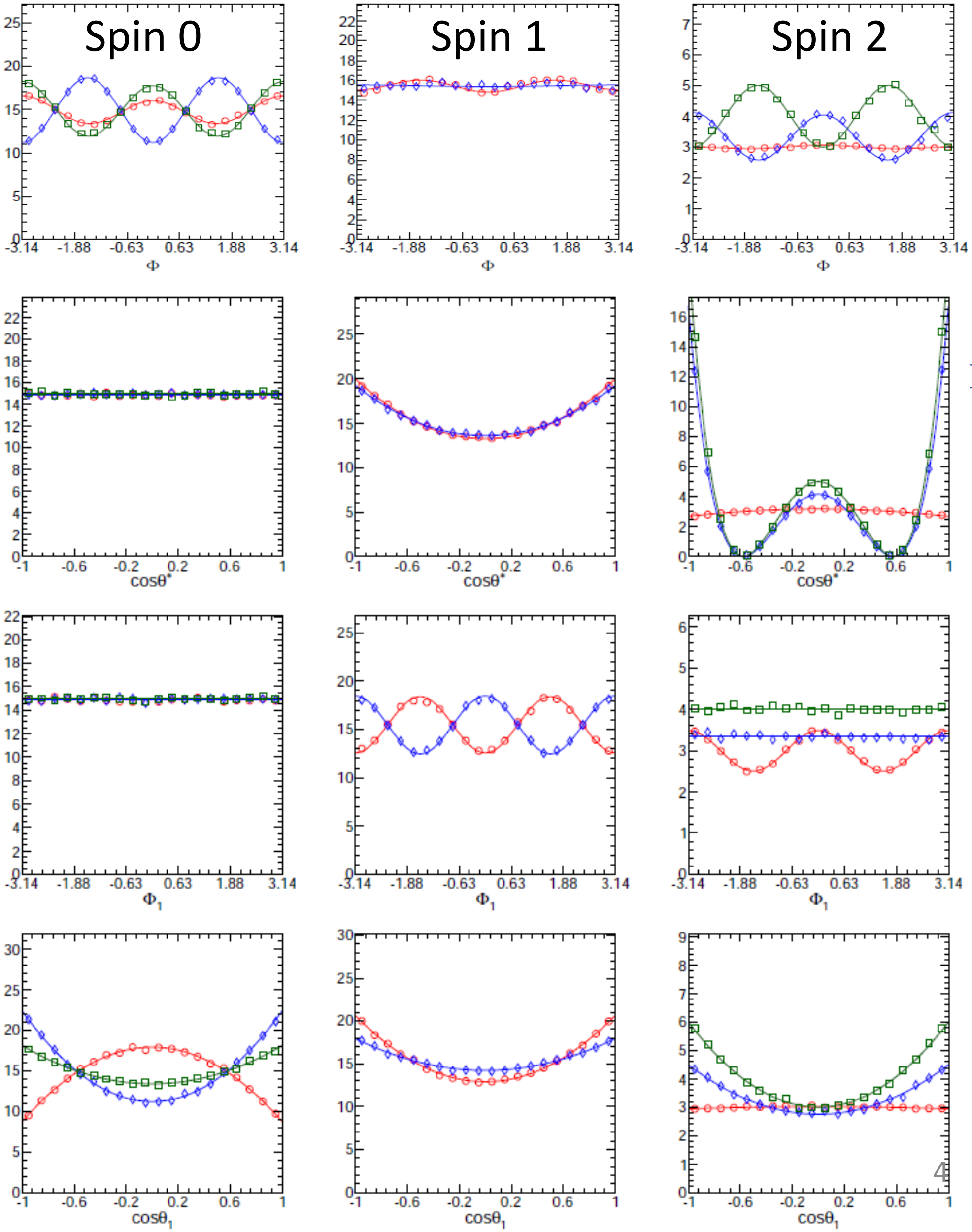
$$D\ (A\ vs\ B) = \frac{|\mathcal{M}_A|^2}{|\mathcal{M}_A|^2 + |\mathcal{M}_B|^2}$$

→ Can also use MCFM signal or bkg MEs



Phys. Lett. B 736 (2014)

AnalyticalMELA

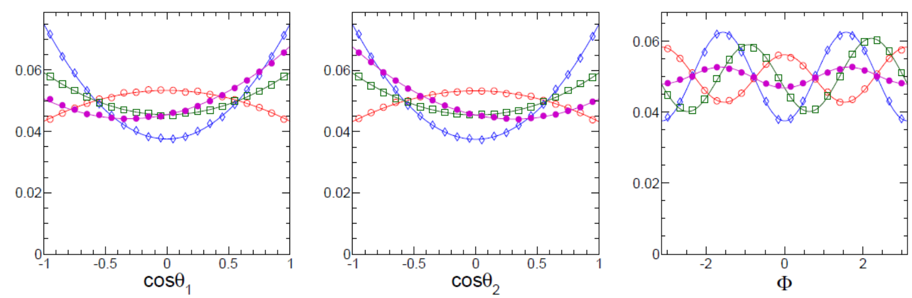


- For the different observables in decay or production, can calculate many of the MEs analytically

  → Using different formalisms allows fast validation of generator MEs

Bolognesi, Gao, Gritsan, Melnikov
Tran, Whitbeck, Schulze
arxiv 1208.4018

$e^+e^- \to HZ(\to 2l)$



Anderson, Bolognesi, Caola, Gao,
Gritsan, Martin, Melnikov, Tran,
Whitbeck, Zhou, Schulze
arxiv 1309.4819

JHUGen / MELA in action

HVV anomalous couplings: Decay information

$$A(HVV) \sim \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1} + q_{V2})^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2 + q_{V2}^2)}{\Lambda_1^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + \mathrm{a}_2 \mathrm{f}_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \mathrm{a}_3 \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

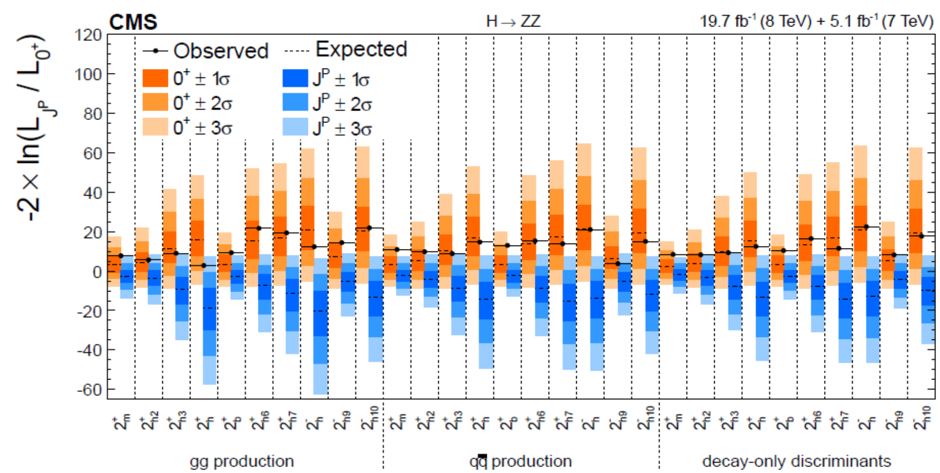
→ Similar amplitude formalism for spin 1 or spin 2

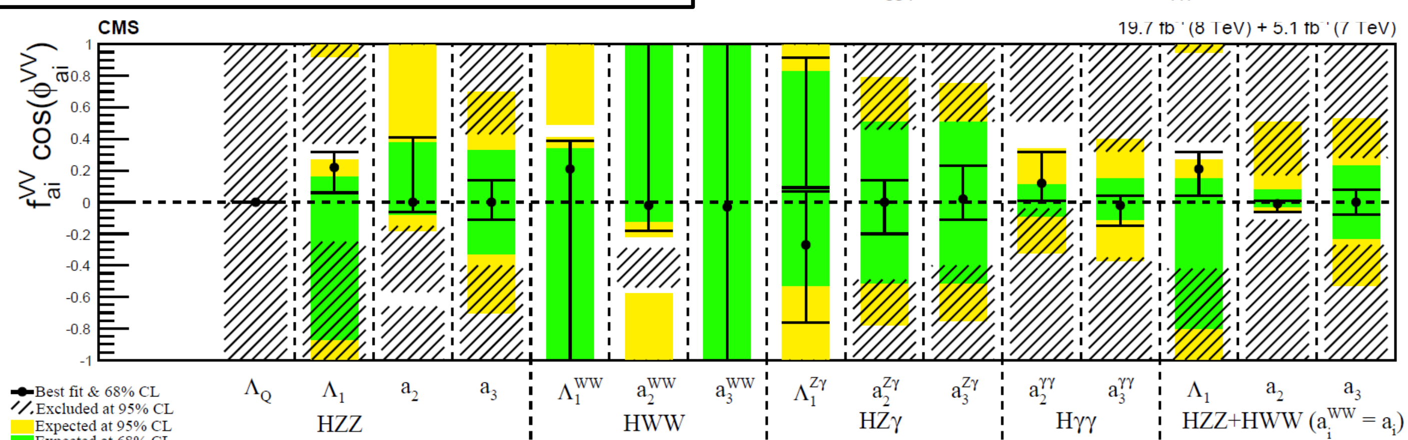
Phys. Rev. D 92 (2015) 012004
(CMS)

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4 + \ldots}, \qquad \phi_{\Lambda 1},$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

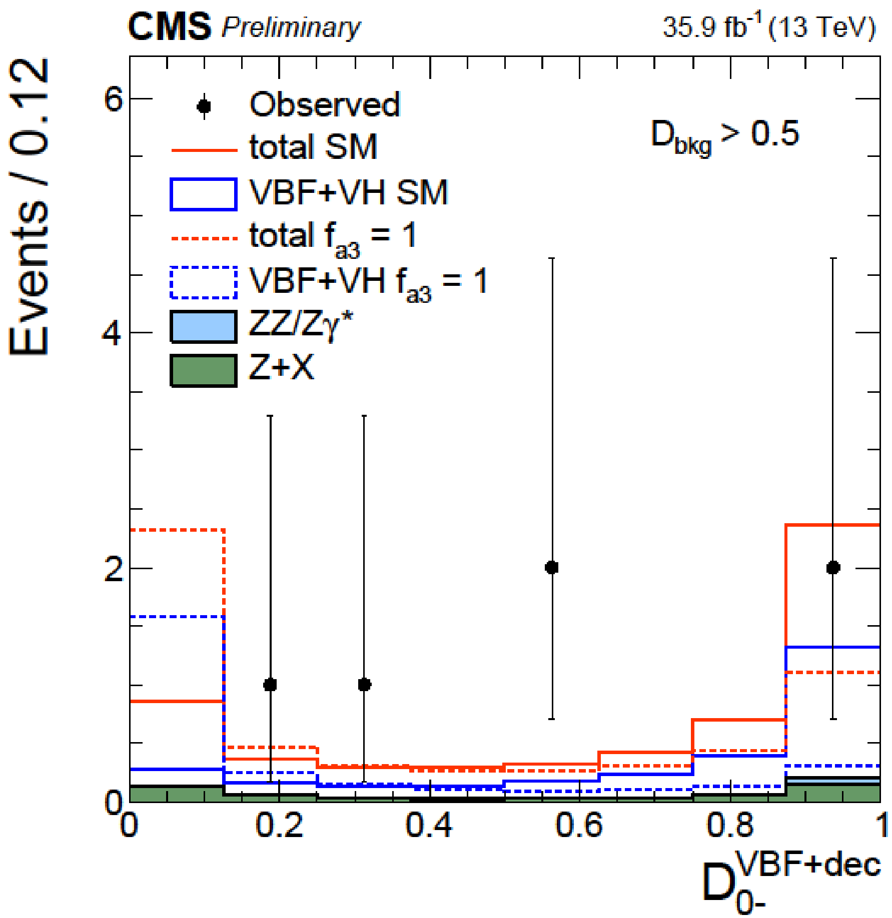
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

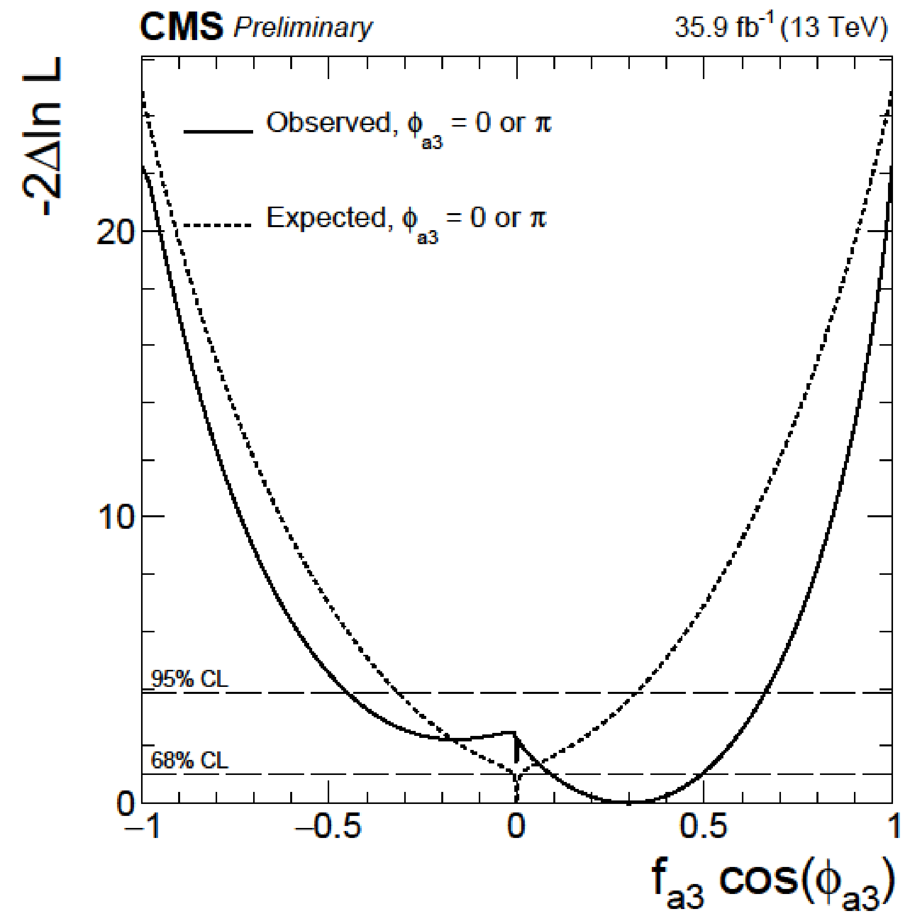




HVV anomalous couplings: +Production

$$A(VVHVV) = \sum_r a_r A_r^{VVH}(\{p_j\}) \sum_s a_s A_s^{HVV}(\{q_k\})$$





CMS-PAS-HIG-17-011

→ Small dip effect of production

→ More statistics > Very tight exclusions

High mass and offshell techniques

$$P_{total}^{on-shell} = \mu_F \times P_{sig}^{gg+t\bar{t}} + \mu_V \times P_{sig}^{VV} + P_{bkg}^{gg} + P_{bkg}^{VV} + P_{bkg}^{q\bar{q}} + P_{bkg}^{Z+X}$$

$$d\sigma \propto \frac{g_{prod}^2 g_{dec}^2}{(q_H^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

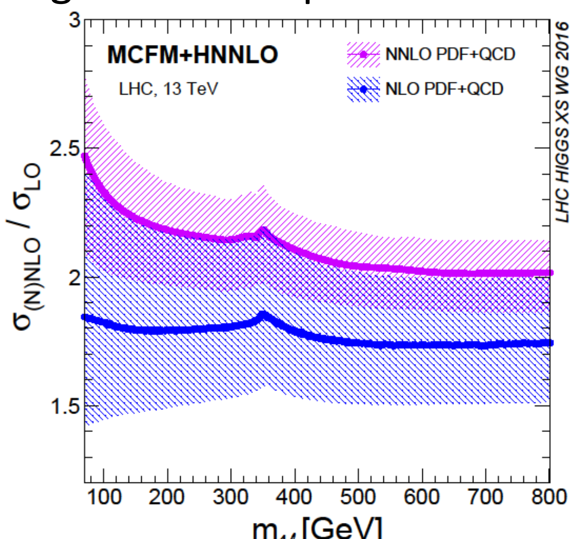
Onshell: $\rightarrow \frac{g_{prod}^2 g_{dec}^2}{m_H^2\Gamma_H^2}$

Offshell: $\rightarrow \frac{g_{prod}^2 g_{dec}^2}{(q_H^2 - m_H^2)^2}$

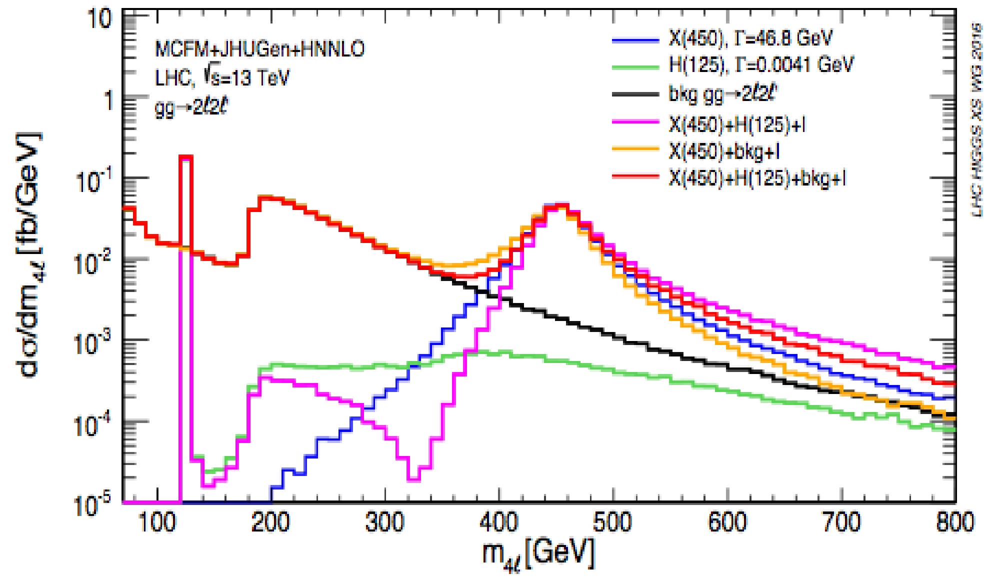
$$P_{total}^{off-shell} = \left[\mu_F . r \times P_{sig}^{gg} + \sqrt{\mu_F . r} \times P_{int}^{gg} + P_{bkg}^{gg}\right] + \left[\mu_V . r \times P_{sig}^{VV} + \sqrt{\mu_V . r} \times P_{int}^{VV} + P_{bkg}^{VV}\right] + P_{bkg}^{q\bar{q}} + P_{bkg}^{Z+X}$$

$$r = \Gamma_H / \Gamma_0$$

- P_{sig} and P_{int} may be modified based on the anomalous couplings
- Anomalous couplings in the HVV vertex, so gluon fusion production does not change.



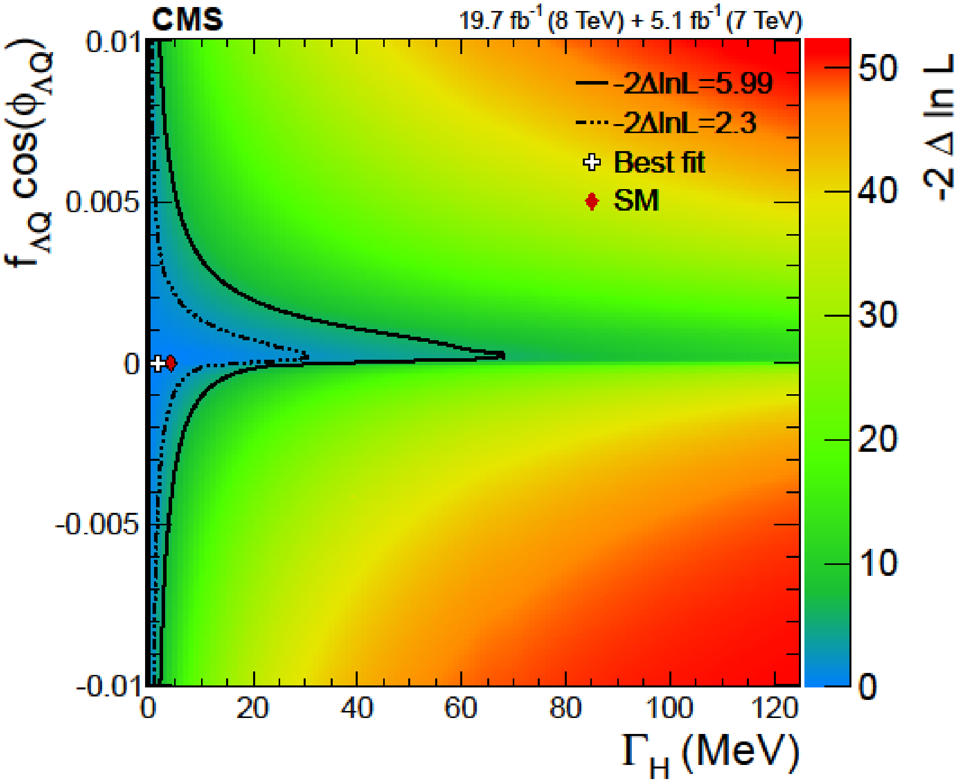
YR4



→ Model can also be extended for an additional Higgs of arbitrary Γ_X with interference to SM Higgs or bkg (example from gluon fusion)

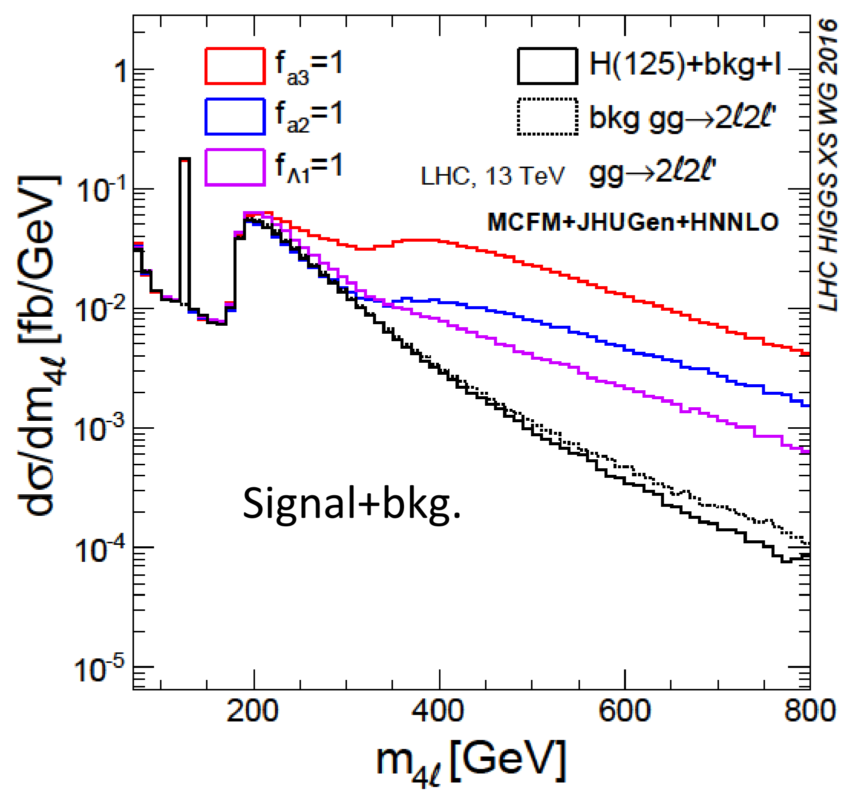
Offshell HVV anomalous couplings in action

Phys. Rev. D 92 (2015) 072010 (CMS)



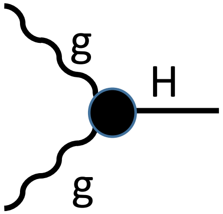
→ Λ_Q term ~q_H^2 in amplitude
→ First joints constraints on anomalous couplings and Γ_H
→ JHUGen / MELA framework allows for constraints of Γ_H vs other couplings as well

YR4



→ Example distributions with signal-bkg interference effects included
→ Showing m_{H^*}
→ All spin correlations also taken into account

Hff anomalous couplings



$$A(Hgg) \sim \left[\sum_{f=t,b\,(t',b')} \kappa_f F_f\left(k_1.k_2\ \epsilon_{V1}^*.\epsilon_{V2}^* | m_f\right) + \tilde{\kappa}_f \tilde{F}_f\left(\epsilon_{\mu\nu\alpha\beta} {\epsilon_{V1}^*}^{\mu} {\epsilon_{V2}^*}^{\nu} k_1^{\alpha} k_2^{\beta}\ | m_f\right) \right]$$

↑**SM** fermion loops

$$+a_2^{gg} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}$$

$$+a_3^{gg} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

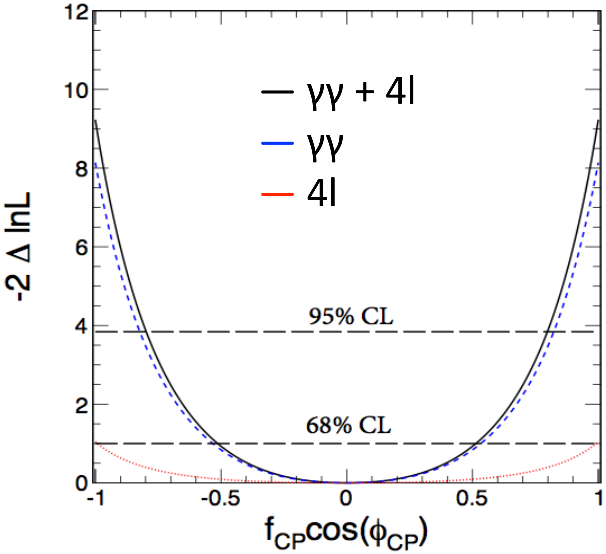
- At LO QCD:

$$F_f\left(k_1.k_2\ \epsilon_{V1}^*.\epsilon_{V2}^* | m_f \to \infty\right) = f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}$$

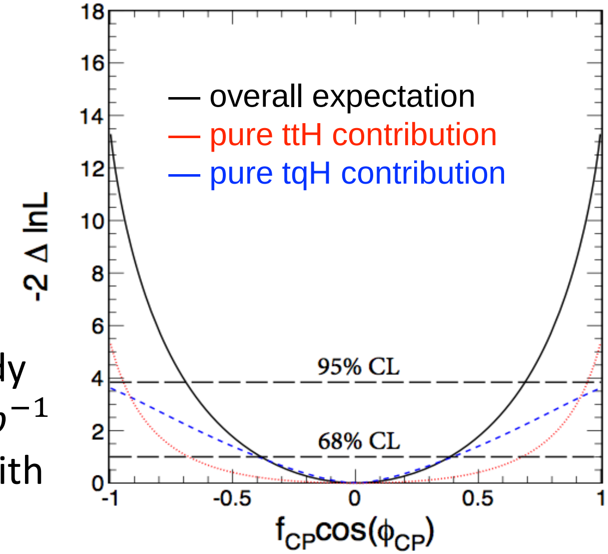
$$\tilde{F}_f\left(\epsilon_{\mu\nu\alpha\beta} {\epsilon_{V1}^*}^{\mu} {\epsilon_{V2}^*}^{\nu} k_1^{\alpha} k_2^{\beta}\ | m_f \to \infty\right) = f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \times (3/2)$$

- Framework allows different (could be complex) values of m_f, κ_f, $\tilde{\kappa}_f$ for 4 different types of f (t, b, t', b')
  a_2^{gg}, a_3^{gg}

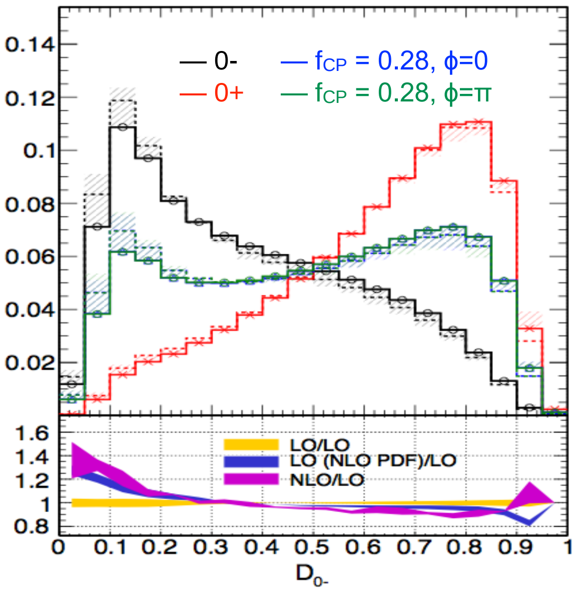
Hff anomalous couplings from onshell



→ $t\bar{t}H$ (semileptonic) CP study
→ Projections for 300 fb^{-1}
→ Includes NLO QCD simulation through JHUGen

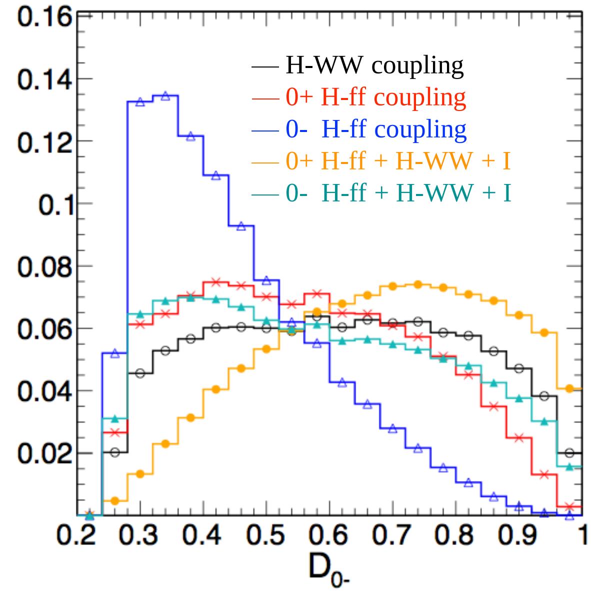


→ tqH ($H \rightarrow \gamma\gamma$) CP study
→ Projections for 300 fb^{-1}
→ Strong interference with WW-induced production

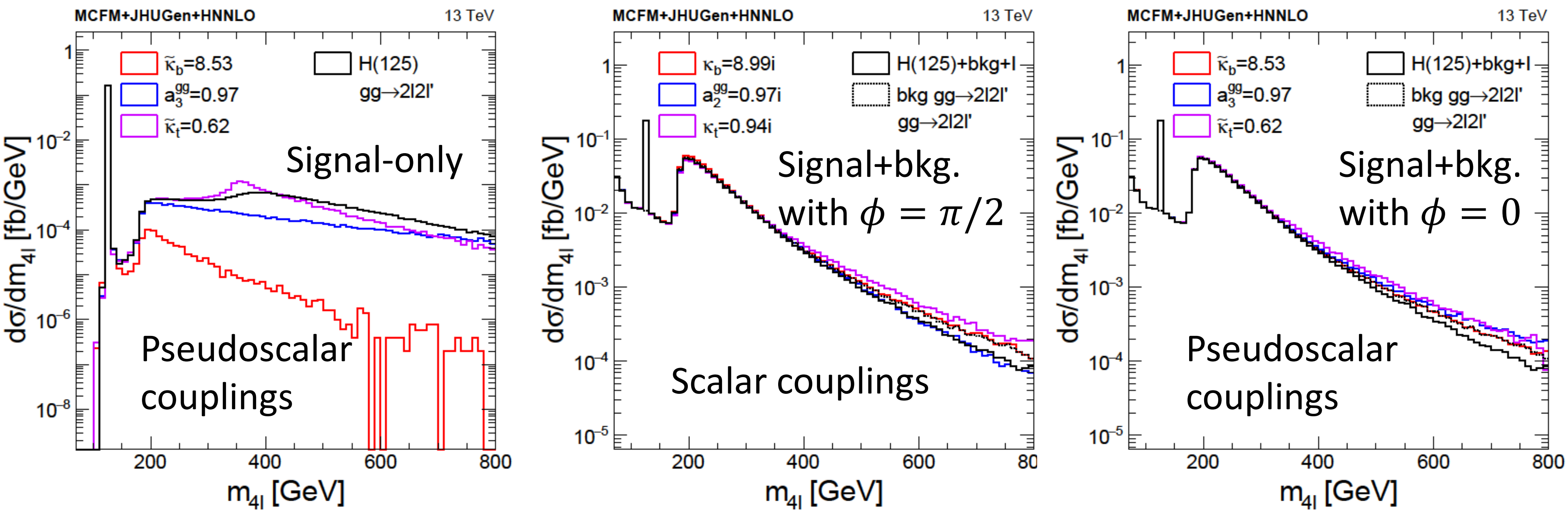


Gritsan, Röntsch, Schulze, Xiao
[arxiv 1606.03107]

→ Study also covers $H \rightarrow \tau\tau$ decay, and bbH production



Anomalous couplings in gluon fusion loop



→ Chosen values of couplings correspond to SM signal XS around 125 GeV-peak
- → $a_{2,3}^{gg}$ vs $\kappa_t, \tilde{\kappa}_t$ differences observable in signal
  - → Around $2m_t$ threshold
  - → Slope of m_{4l} at high mass (might be interesting in high mass searches)
- → No effect on decay tensor structure:
  - → Discrimination based purely on mass shape possible
  - → Production-dependent discriminants from JHUGen/MELA could also help

Summary

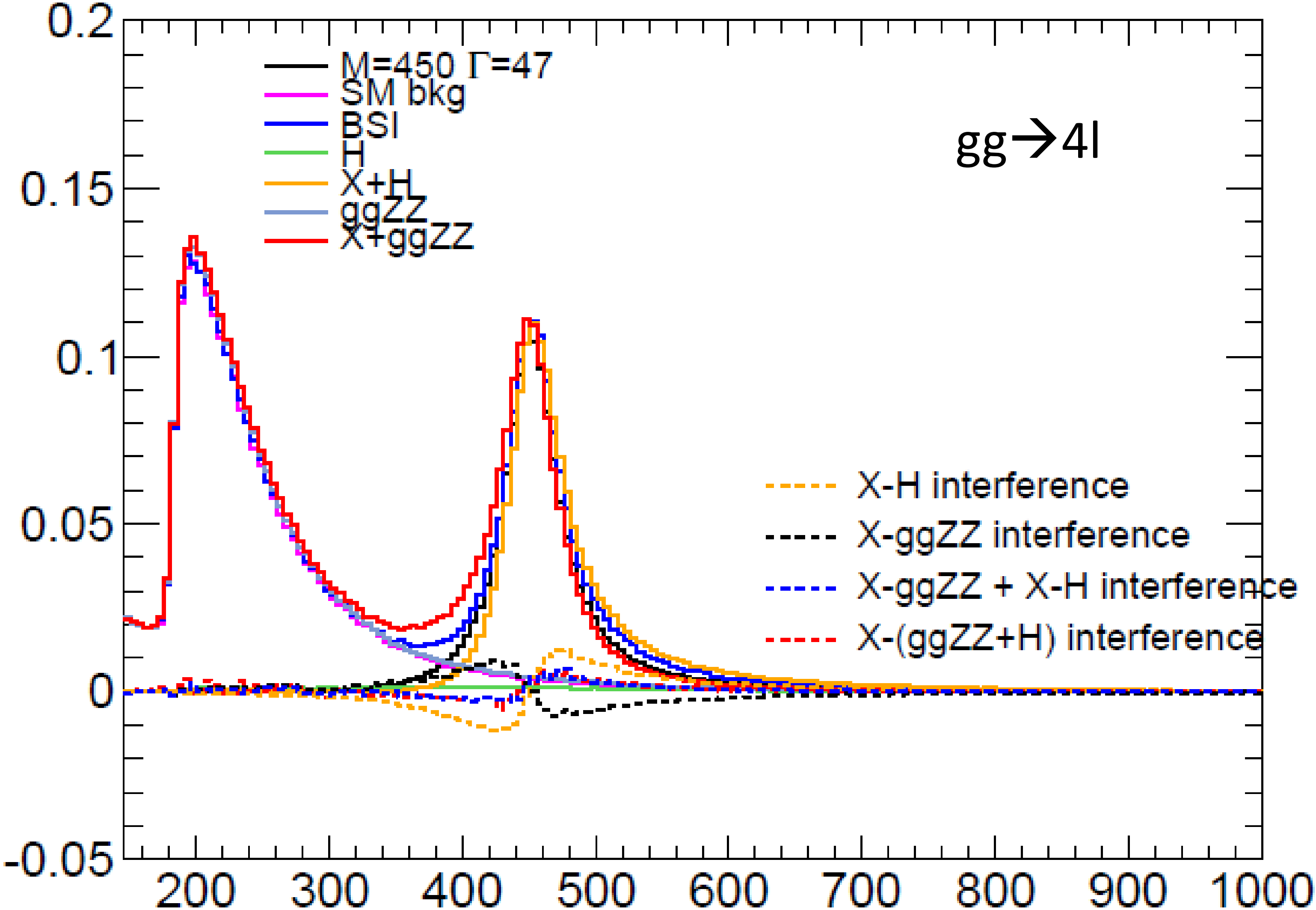
- Presented an interconnected package of tools for the study of Higgs properties:
  → JHUGenerator for event generation
  → JHUGenMELA and AnalyticalMELA for
    → Anomalous couplings and background suppression discriminants
    → Reweighting
    → Cross-validation between different models and generators
  → Interfacing MCFM

- Example analyses where JHUGen / MELA package is utilized:
  → Onshell Higgs spin-parity studies
  → Anomalous couplings in spin 0 HVV and Hff vertices
  → Offshell studies of total width and anomalous couplings

- See http://spin.pha.jhu.edu/ for more details
  → Free access generator download and documentation

Backup

High mass interference effects



Offshell HVV anomalous couplings: P_{sig}, P_{int}

→ General parameterization of signal and interference probabilities with HVV decay:

$$P_{sig}^{gg}=\sum_{i=1..n}\sum_{j=1..n}\sqrt{|f_{ai}||f_{aj}|}sgn(f_{ai}f_{aj})\left(S_{ij}^{Re}\cos(\phi_{aj}-\phi_{ai})+S_{ij}^{Im}\sin(\phi_{aj}-\phi_{ai})\right)$$

$$P_{int}^{gg}=\sum_{i=1..n}\sqrt{|f_{ai}|}sgn(f_{ai})\left(I_{i}^{Re}\cos(\phi_{ai})+I_{i}^{Im}\sin(\phi_{ai})\right)$$

$$P_{sig}^{VV}=\sum_{i=1..n}\sum_{j=1..n}\sqrt{|f_{ai}||f_{aj}|^{3}}sgn(f_{ai}f_{aj})\left(V_{ij}^{Re}\cos(\phi_{aj}-\phi_{ai})+V_{ij}^{Im}\sin(\phi_{aj}-\phi_{ai})\right)$$
$$+|f_{ai}||f_{aj}|(1-\delta_{ij})\left(H_{ij}^{Pos}+H_{ij}^{Re}\cos\left(2(\phi_{aj}-\phi_{ai})\right)+H_{ij}^{Im}\sin\left(2(\phi_{aj}-\phi_{ai})\right)\right)$$

$$P_{int}^{VV}=\sum_{i=1..n}\sum_{j=1..n}\sqrt{|f_{ai}||f_{aj}|}sgn(f_{ai}f_{aj})\left(Y_{ij}^{Re}\cos(\phi_{aj}+\phi_{ai})+Y_{ij}^{Im}\sin(\phi_{aj}+\phi_{ai})\right)$$