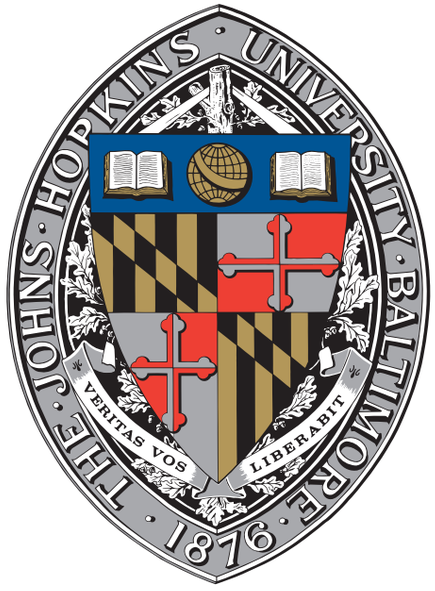
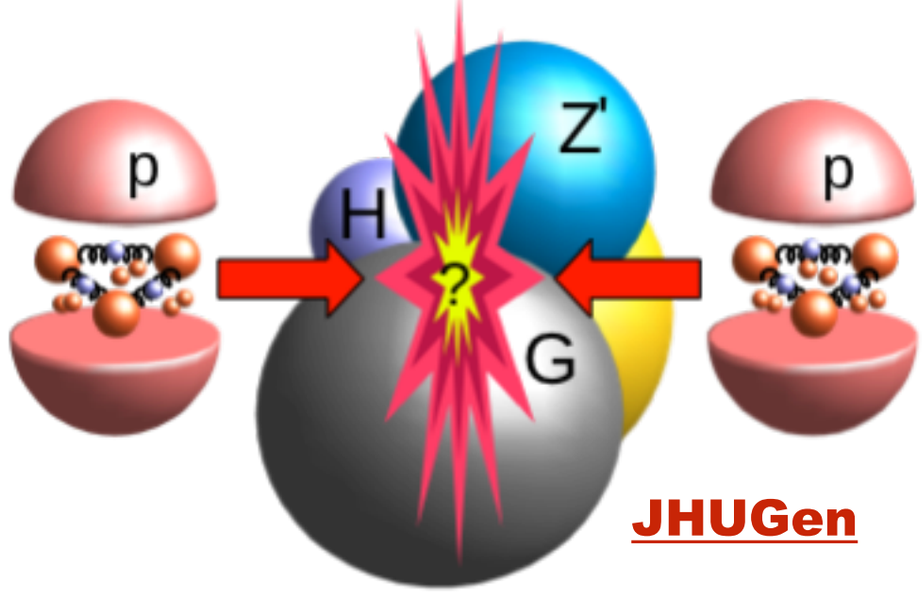
Off-shell Higgs EFT measurements with the **JHUGen**+**MCFM** framework

Andrei Gritsan
Johns Hopkins University
for the developers (see next slide)





October 22, 2019

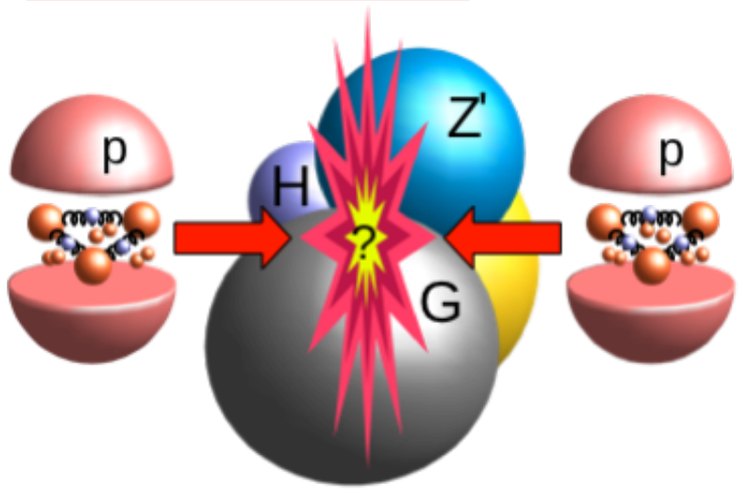
LHC Higgs (XS) WG Off-shell & Interference Meeting

JHUGen framework (for EFT)

JHUGen — generator

MELA — Matrix Element library

JHUGenLexicon — basis translation …



https://spin.pha.jhu.edu

Theory + Experiment collaboration

MC Generator based on the papers:

"Spin Determination of Single-Produced Resonances at Hadron Colliders"
Yanyan Gao, Andrei V. Gritsan, Zijin Guo, Kirill Melnikov, Markus Schulze, and Nhan V.Tran
http://arxiv.org/abs/1001.3396

"On the Spin and Parity of a Single-Produced Resonance at the LHC"
Sara Bolognesi, Yanyan Gao, Andrei V. Gritsan, Kirill Melnikov, Markus Schulze, Nhan V. Tran, and Andrew Whitbeck
http://arxiv.org/abs/1208.4018

"Constraining anomalous HVV interactions at proton and lepton colliders"
Ian Anderson, Sara Bolognesi, Fabrizio Caola, Yanyan Gao, Andrei V. Gritsan, Christopher B. Martin, Kirill Melnikov, Markus Schulze, Nhan V. Tran, Andrew Whitbeck, and Yaofu Zhou
http://arxiv.org/abs/1309.4819

"Constraining anomalous Higgs boson couplings to the heavy flavor fermions using matrix element techniques"
Andrei V. Gritsan, Raoul Rontsch, Markus Schulze, and Meng Xiao
http://arxiv.org/abs/1606.03107

"New features in the JHU generator framework: constraining Higgs boson properties from on-shell and off-shell production"
Andrei V. Gritsan, Jeffrey Roskes, Ulascan Sarica, Markus Schulze, Meng Xiao, and Yaofu Zhou
http://arxiv.org/abs/2002.09888

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New features in the JHU generator framework: Constraining Higgs boson properties from on-shell and off-shell production

Andrei V. Gritsan,[1,*] Jeffrey Roskes,[1,†] Ulascan Sarica,[1,2,‡] Markus Schulze,[3,§] Meng Xiao,[1,4,‖] and Yaofu Zhou[1,5,¶]

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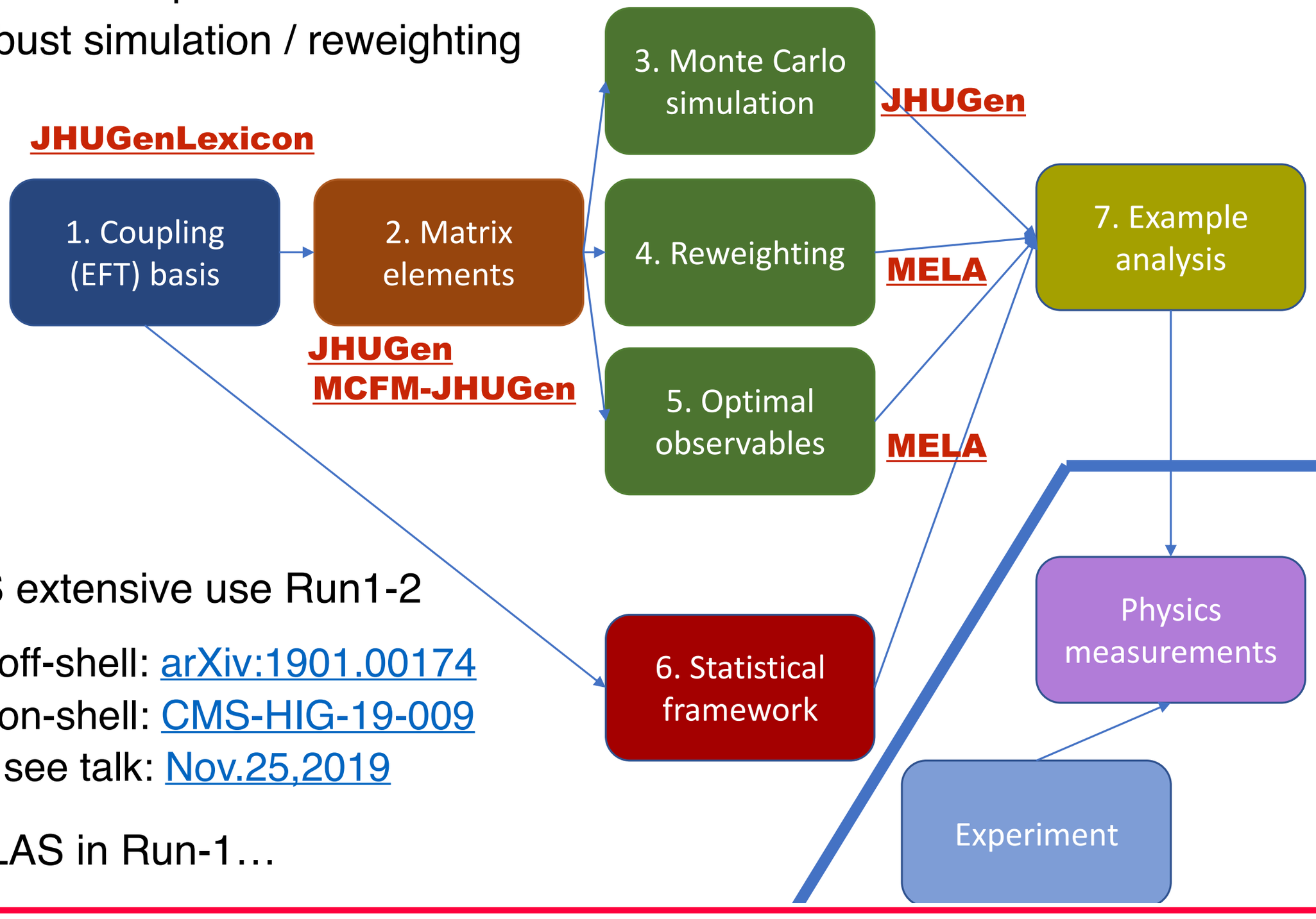
arXiv:2002.09888

JHUGen framework (for EFT)

- Support: detector-level studies
  optimal observables
  robust simulation / reweighting

see talks [H.Roskes at Pheno-2020](#)
[M.Xiao at ICHEP-2020](#)



- CMS extensive use Run1-2

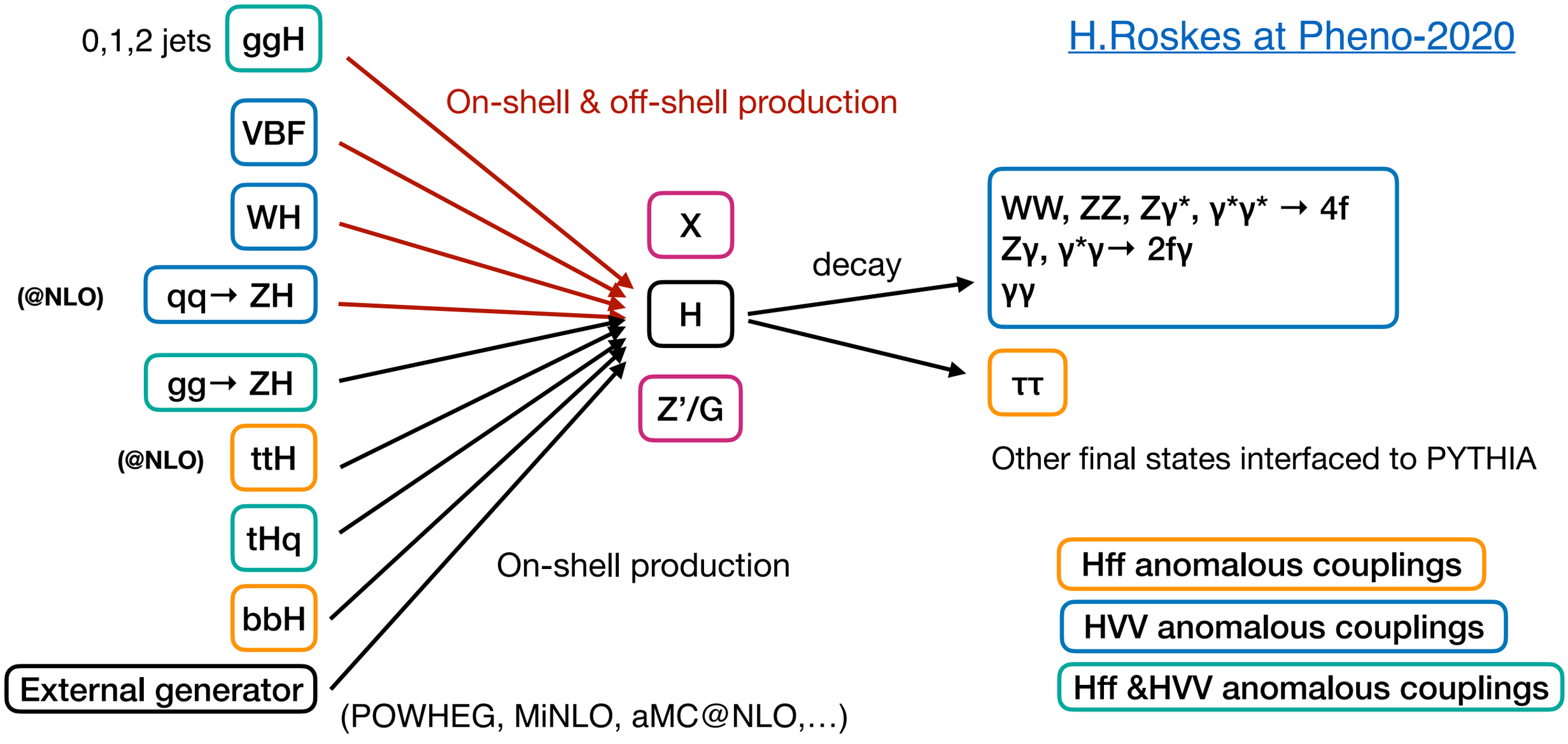
EFT in off-shell: [arXiv:1901.00174](#)
EFT in on-shell: [CMS-HIG-19-009](#)
see talk: [Nov.25,2019](#)

- ATLAS in Run-1…

JHUGen Physics (EFT)

- Framework for studies of anomalous couplings / EFT of the Higgs
  — name attached by our ATLAS colleagues in 2012, so we learned to live with it…
- Available processes:

see talks [M.Xiao at ICHEP-2020](#)
[H.Roskes at Pheno-2020](#)



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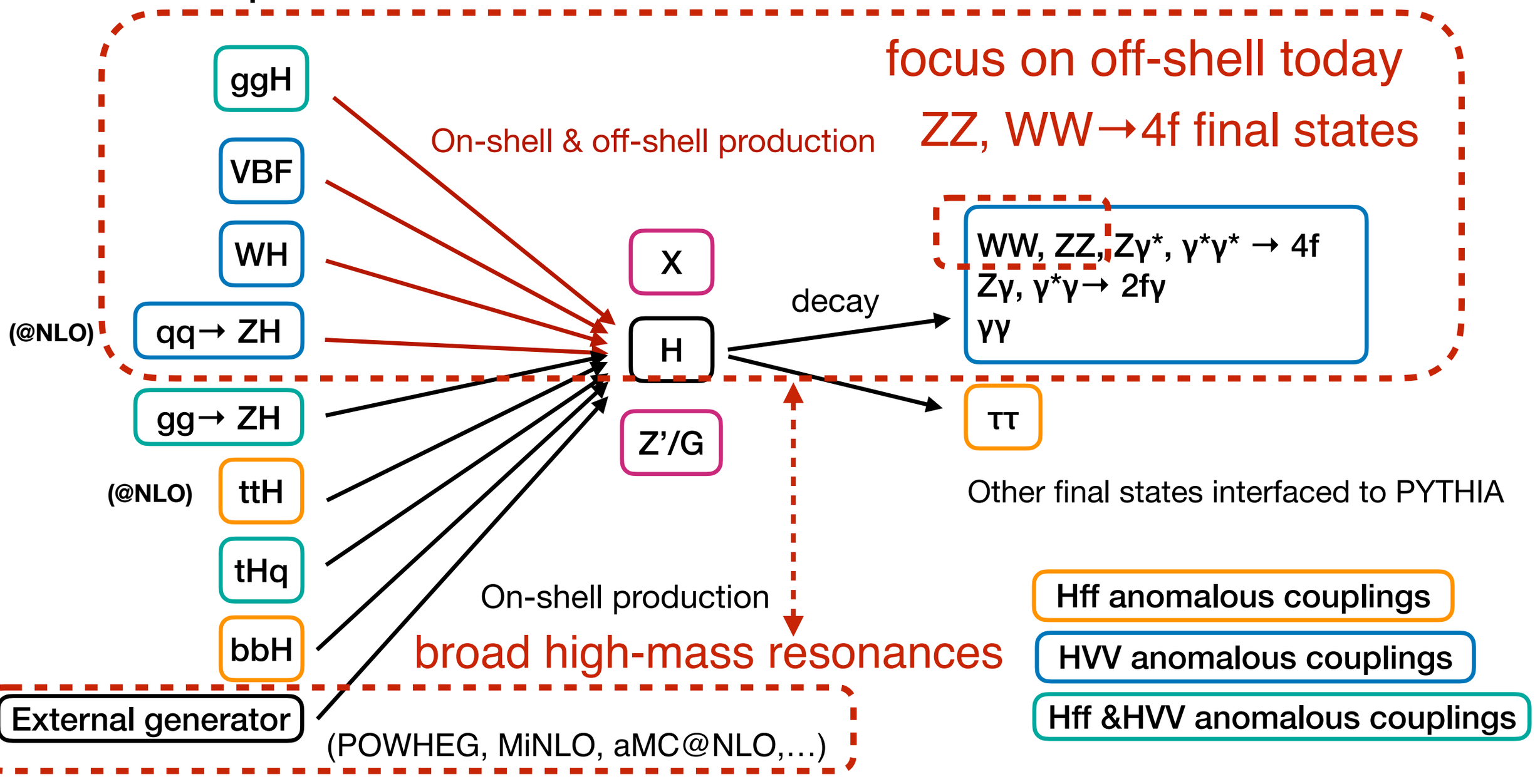


JHUGen Physics with off-shell Higgs

- Coherent framework to treat four effects in “off-shell”
  - EW (VBF+VH) and ggH processes
  - H* + X + continuum + interference
  - EFT with H* (X) in production and decay

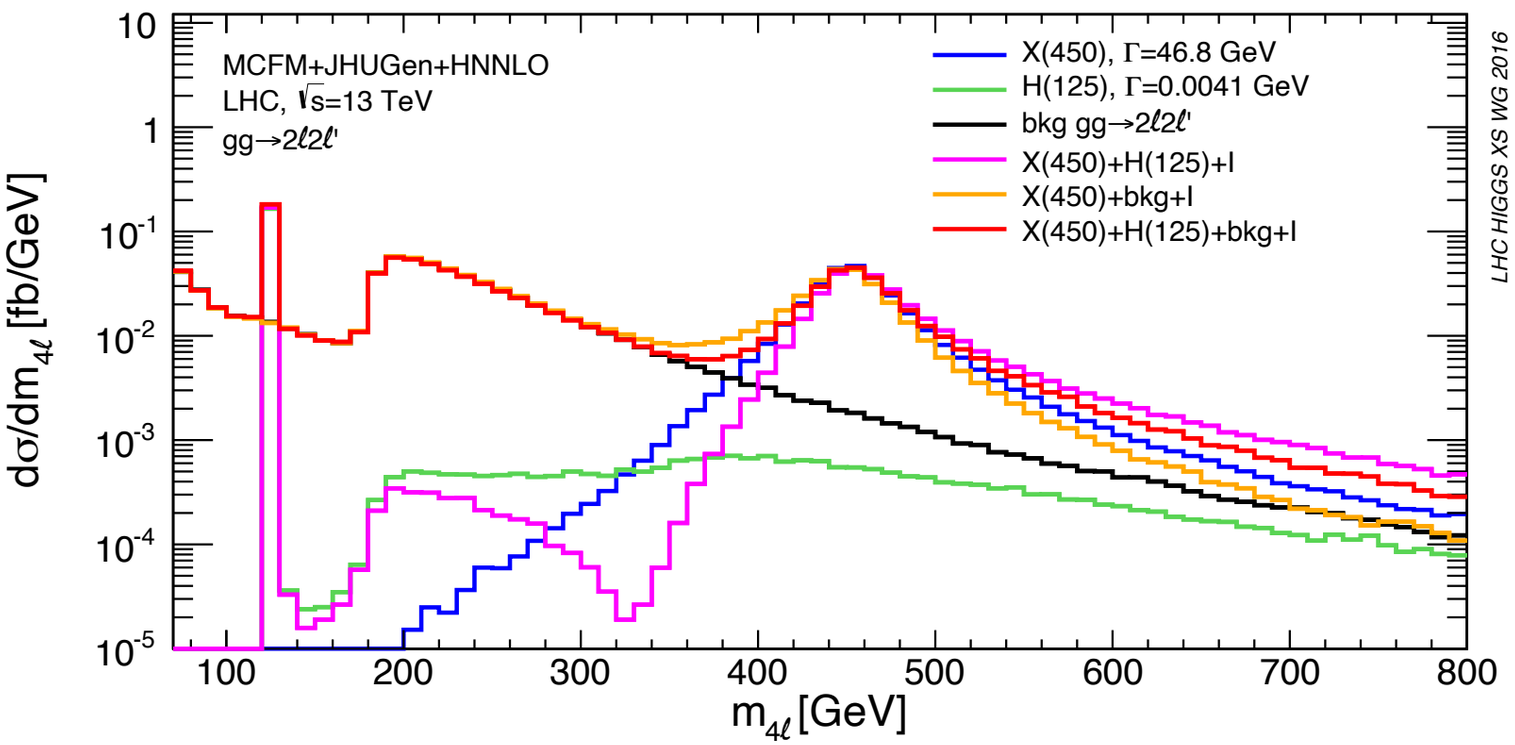
(1) width Γ_H modification

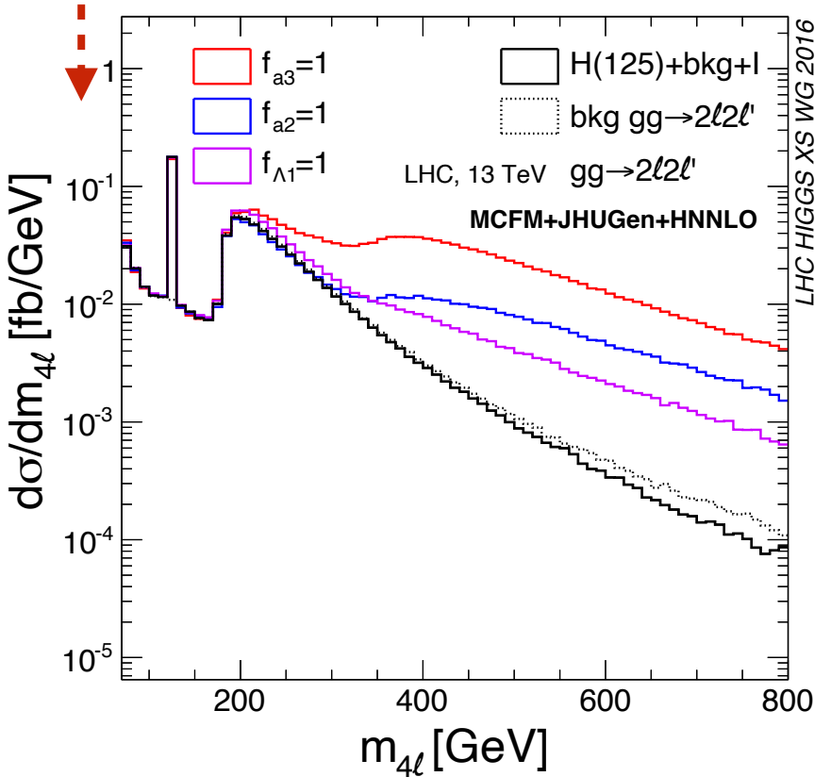
(2) new resonance(s) X

(3) EFT in H / X couplings

(4) anomalous VBS

- Documented in YR4 of LHC H WG:
  - topics span across WG1, WG2, WG3…

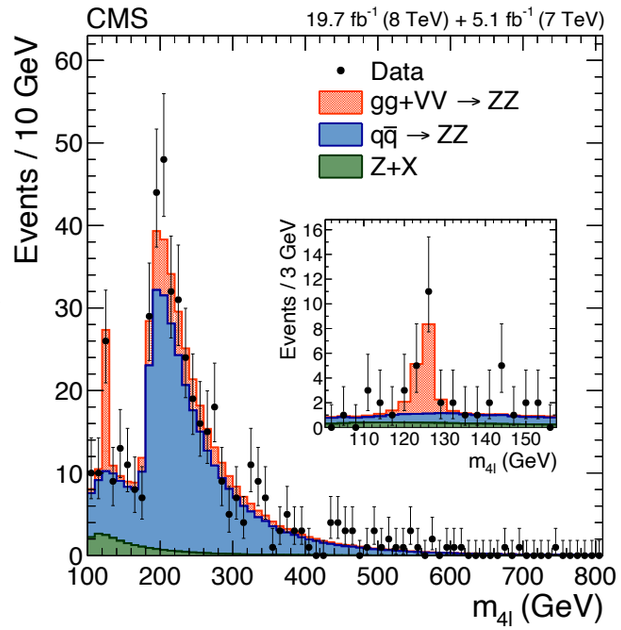




Some Background Information

- First off-shell H* simulation used on LHC:
  - ggH: **gg2VV** (arXiv:1206.4803)
  - EW: **PHANTOM** (arXiv:0801.3359)
- Complemented by **MCFM**:
  - ggH: (arXiv:1311.3589)
  - EW: (arXiv:1502.02990)

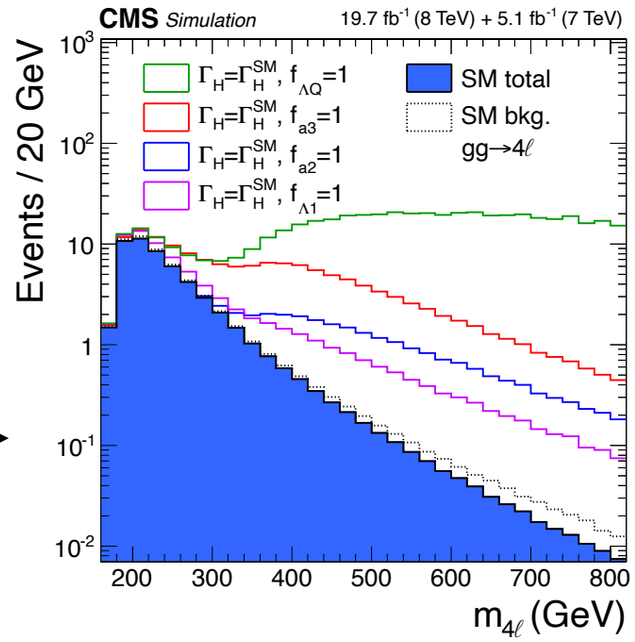
(arXiv:1405.3455)



- Target of **JHUGen**:
  - EFT modeling in “signal” (since ~2009)
  - complement **MCFM** with EFT in off-shell
  - integrate into **MELA**

(since ~2015)

(arXiv:1507.06656)



Higher-order effects

- **MCFM** off-shell is a LO simulation, so is **JHUGen+MCFM**

(1) apply k factor as a function of m_{4f}

— ggH ~ known at NLO for H* (sig), bkg, interference

— NNLO for H* (sig) (e.g. **MCFM+HNNLO** for illustration of ggH)

(2) matching of parton shower with Pythia is important

— effect in EW production is less important

2 leading jets come from matrix element, effect in 3rd jet…

— effect in ggH production off-shell is more critical

2jet correlation is not modeled for CP in ggH off-shell (!)

p_T or m_{JJ},… tuning required

solution in experiment: tune jets with **HJJ-MiNLO+JHUGen**

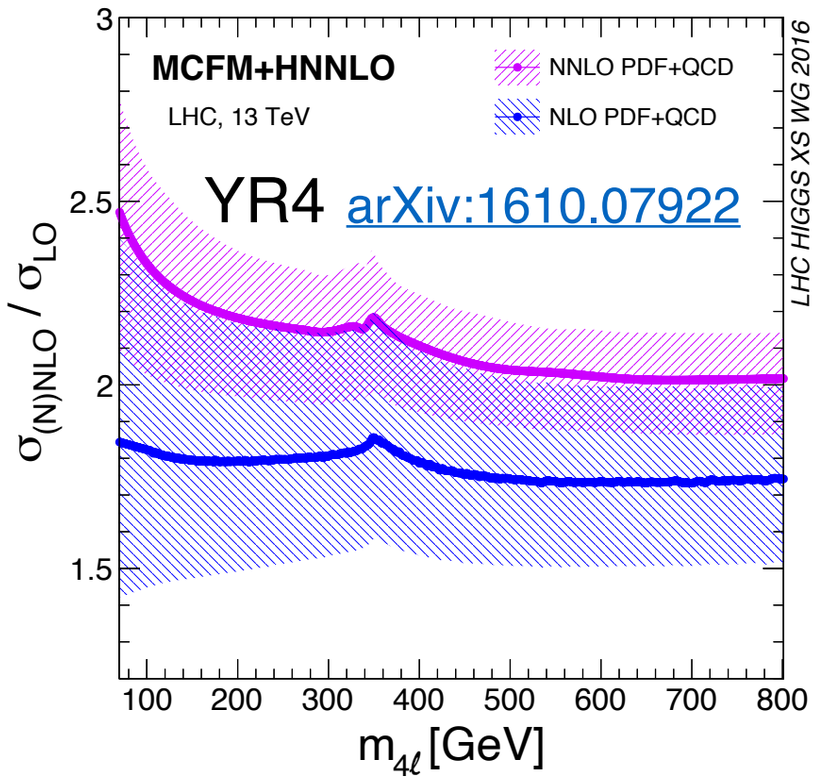
or **POWHEG+JHUGen**

$$pp \to X(\to 4f) + \text{jet(s)}$$

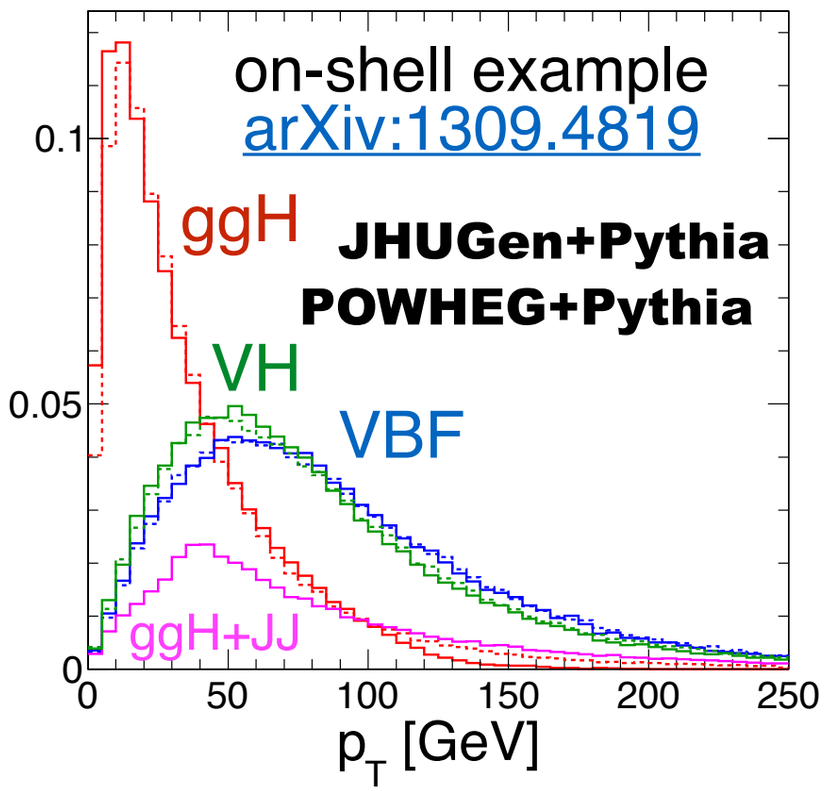
Higher-order effects (part II)

- Approximate: same QCD effect for SM & BSM sig, bkg, interference

(1) apply k factor



(2) matching of parton shower



tune ggH+jets e.g. **POWHEG**

on-shell not an issue

EW off-shell not a big issue

(a) tune jet observables

(b) re-weight **POWHEG** with **MELA**
(approx.: LO ME applied to NLO gen)

(c) model ggH*+jets for signal only…

$$pp \to H^*(\to VV \to 4f) + \text{jet(s)}$$

Note on jet correlations (for EFT)

- Plan to perform comparison (a,b,c) and other programs…
- Test (c): $pp \to H^*(\to VV \to 4f) + \text{jet(s)}$

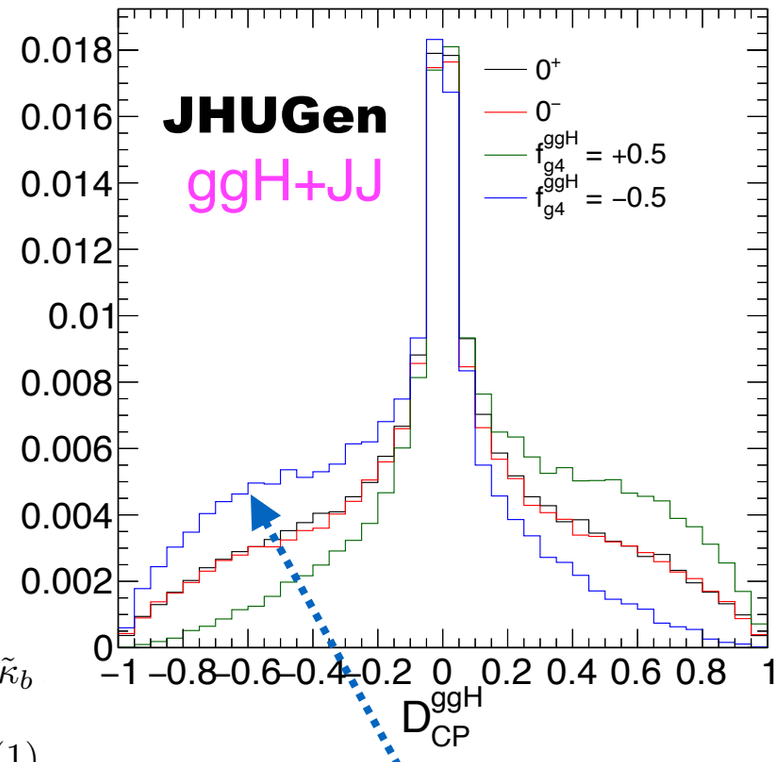
— tested **MadGraph** process for comparison

have not succeeded with full off-shell generation

interested to learn…

discovered sign difference in connecting CP-odd and CP-even couplings on-shell

$$\mathcal{L}_{hff} = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + \mathrm{i}\,\tilde{\kappa}_f\gamma_5\right)\psi_f\, h\,,$$



effect in observable distributions

$$R_{gg} = \begin{aligned}& 1.1068\,\kappa_t^2 + 0.0082\,\kappa_b^2 - 0.1150\,\kappa_t\kappa_b + 2.5717\,\tilde{\kappa}_t^2 + 0.0091\,\tilde{\kappa}_b^2 - 0.1982\,\tilde{\kappa}_t\tilde{\kappa}_b \\ & + 1.0298\,\kappa_Q^2 - 1.2095\,\kappa_Q\kappa_t - 0.1109\,\kappa_Q\kappa_b + 2.3170\,\tilde{\kappa}_Q^2 + 4.8821\,\tilde{\kappa}_Q\tilde{\kappa}_t - 0.1880\,\tilde{\kappa}_Q\tilde{\kappa}_b\end{aligned}$$

The κ_Q and $\tilde{\kappa}_Q$ couplings are connected to the g_2^{gg} and g_4^{gg} point-like interactions introduced in Eq. (1)

arXiv:2002.09888

$$g_2^{gg} = -\alpha_s\kappa_Q/(6\pi)\,, \qquad g_4^{gg} = -\alpha_s\tilde{\kappa}_Q/(4\pi)$$

same sign, but opposite in **MadGraph** arXiv:1306.6464

JHUGen consistent with hep-ph/9701277, arXiv:1511.05584

- important to sort out for both off-shell and on-shell…

EFT modeling of production in ggH

- $H(125)$

$$R_{gg} = 1.1068\,\kappa_t^2 + 0.0082\,\kappa_b^2 - 0.1150\,\kappa_t\kappa_b + 2.5717\,\tilde{\kappa}_t^2 + 0.0091\,\tilde{\kappa}_b^2 - 0.1982\,\tilde{\kappa}_t\tilde{\kappa}_b + 1.0298\,\kappa_Q^2 - 1.2095\,\kappa_Q\kappa_t - 0.1109\,\kappa_Q\kappa_b + 2.3170\,\tilde{\kappa}_Q^2 + 4.8821\,\tilde{\kappa}_Q\tilde{\kappa}_t - 0.1880\,\tilde{\kappa}_Q\tilde{\kappa}_b$$

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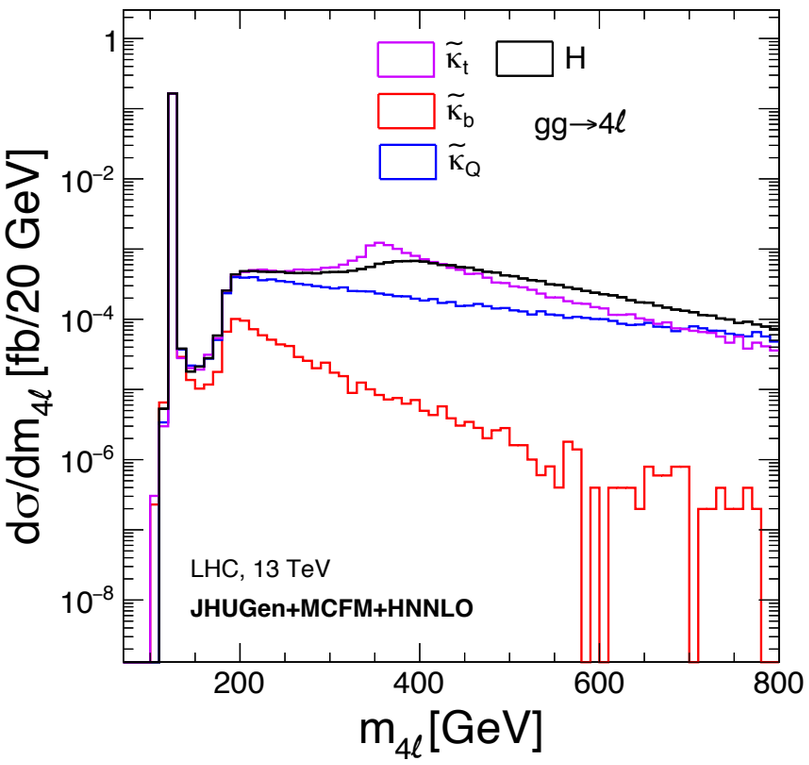
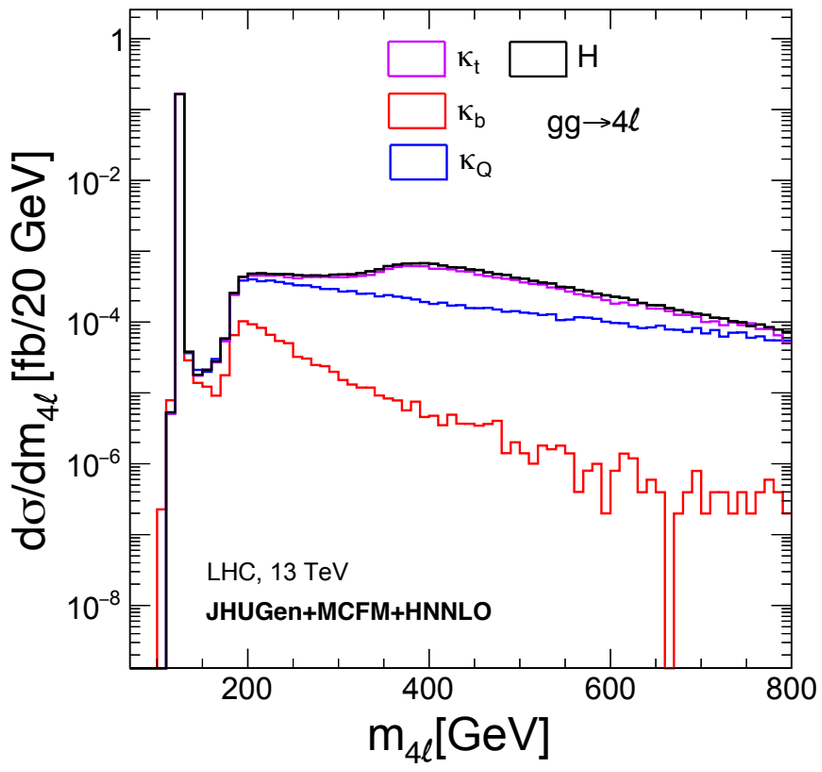
$$\mathcal{L}_{hff} = -\frac{m_f}{v}\bar{\psi}_f\,(\kappa_f + \mathrm{i}\,\tilde{\kappa}_f\gamma_5)\,\psi_f\,h\,, \qquad g_2^{gg} = -\alpha_s\kappa_Q/(6\pi)\,, \qquad g_4^{gg} = -\alpha_s\tilde{\kappa}_Q/(4\pi)$$

- EFT effect in production: may disentangle point-like interaction…

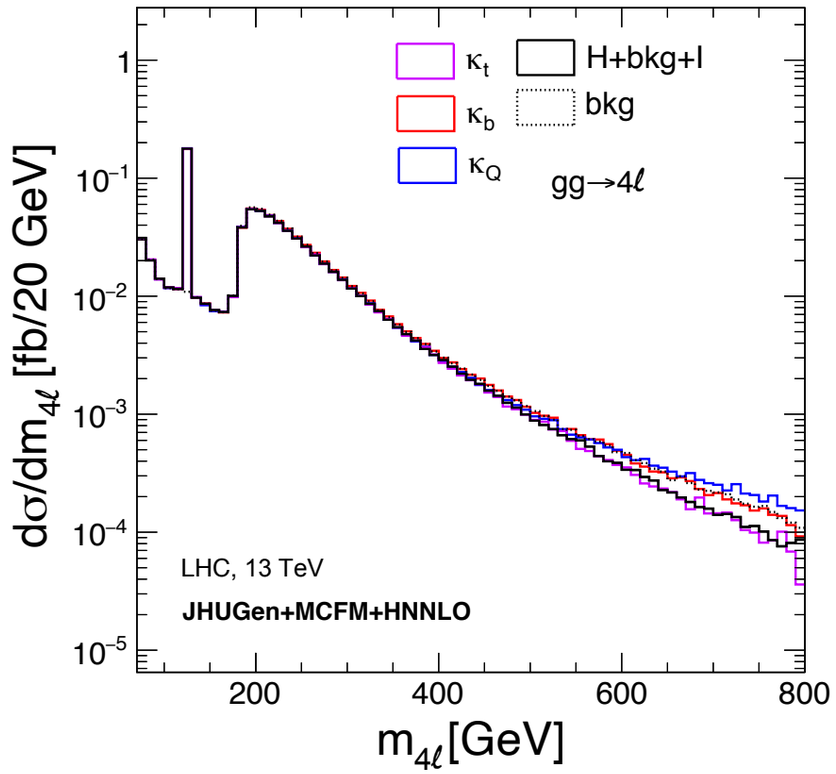
CP-odd signal $\tilde{\kappa}_t$, $\tilde{\kappa}_b$, $\tilde{\kappa}_Q$



CP-even signal κ_t (~SM), κ_b, κ_Q

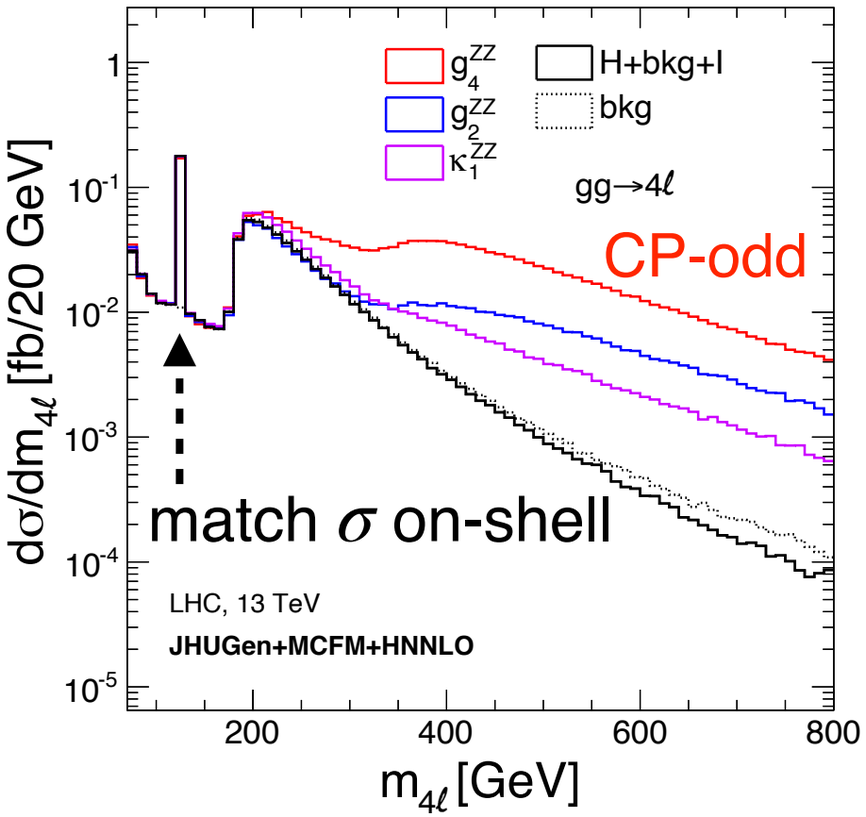


sig.+bkg.+interf.



EFT modeling of decay H→VV in ggH

- sig.+bkg.+interference in $gg \to (H^*) \to VV \to 4f$



- use mass eigenstate basis (Z^*, γ^*)

— off-shell effect interplay of H→ZZ* (or WW*) vs H*→ZZ (or WW)

— off-shell effect does not work with H→Vγ*

— mixing H→Zγ*, γ*γ*, ZZ* leads to x2 more "flat" parameters, more coding

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

- **JHUGenLexicon**
  interface to relate to either Higgs or Warsaw bases
  similar to **Rosetta**, but integrated into the framework

JHUGenLexicon for EFT

- **JHUGen** "basis" does not have to be SMEFT, could be HEFT
- interface to the Higgs basis, with or without $SU(2) \times U(1)$

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

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

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

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

not in offshell

ggH

- interface to Warsaw basis

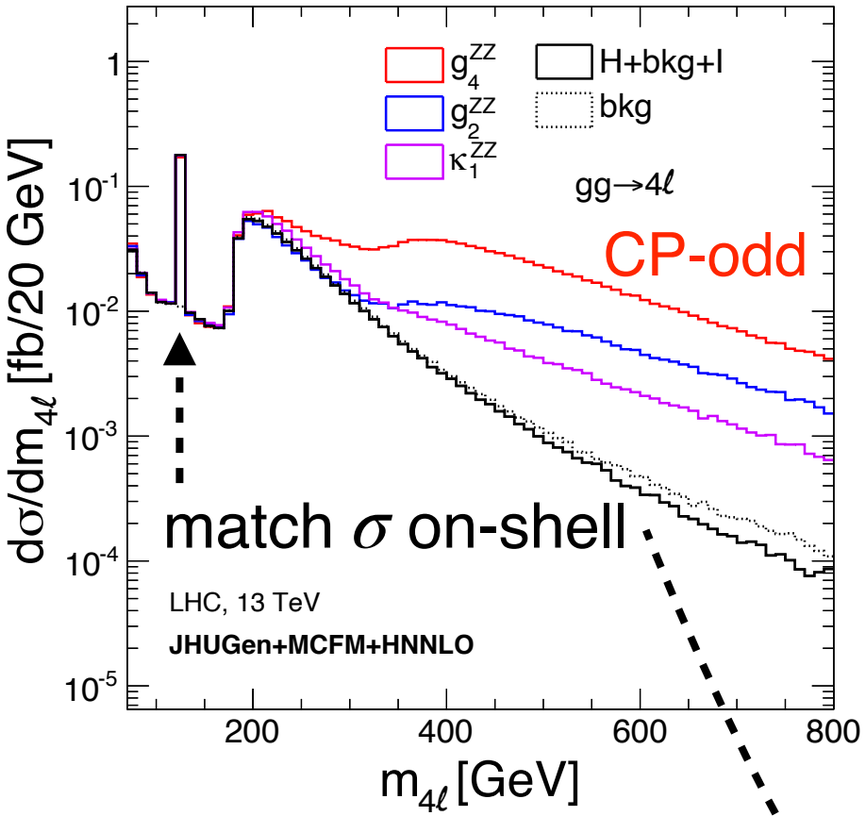
$$\begin{aligned}
g_4^{ZZ} &= -2\frac{v^2}{\Lambda^2}\left(s_w^2 w_{\phi\tilde{B}} + c_w^2 w_{\phi\tilde{W}} + s_w c_w w_{\phi B\tilde{W}}\right), \\
g_4^{\gamma\gamma} &= -2\frac{v^2}{\Lambda^2}\left(c_w^2 w_{\phi\tilde{B}} + s_w^2 w_{\phi\tilde{W}} - s_w c_w w_{\phi B\tilde{W}}\right), \\
g_4^{Z\gamma} &= -2\frac{v^2}{\Lambda^2}\left(s_w c_w (w_{\phi\tilde{W}} - w_{\phi\tilde{B}}) + \frac{1}{2}(s_w^2 - c_w^2) w_{\phi B\tilde{W}}\right), \\
g_4^{gg} &= -2\frac{v^2}{\Lambda^2} w_{\phi\tilde{G}}.
\end{aligned}$$

- additional symmetries
  - "custodial" symmetry $g_1^{ZZ} = g_1^{WW}$ motivated by M_W

- **JHUGenLexicon** with **JHUGen** and standalone

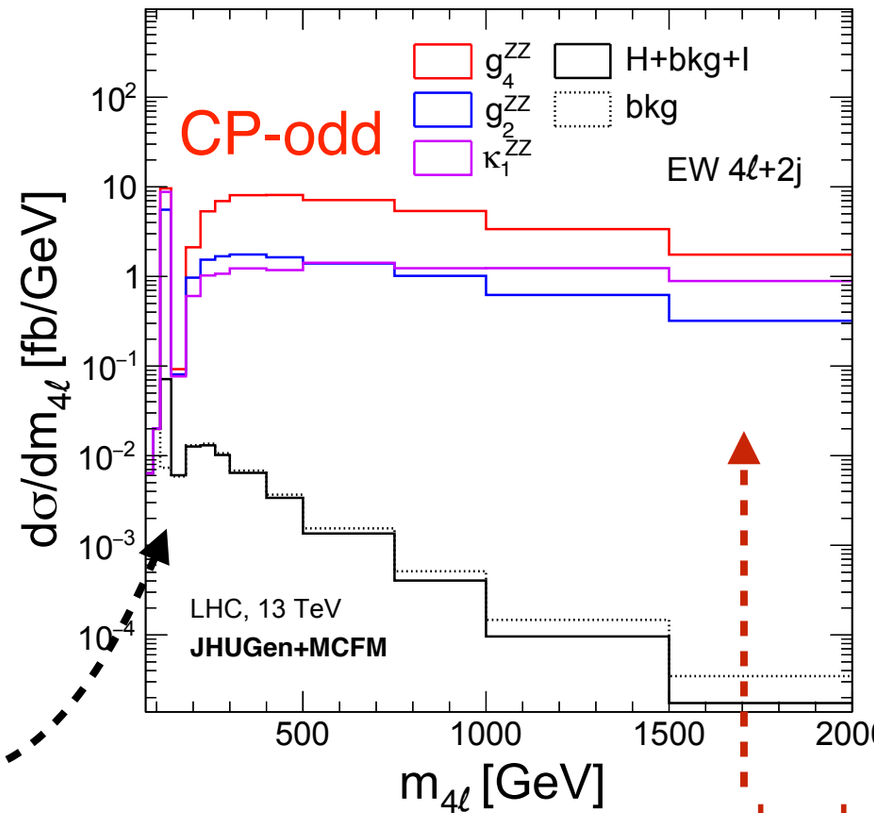
EFT modeling of VV→H→VV in EW production

- sig.+bkg.+interference in $gg \to (H^*) \to VV \to 4f$



- in $qqVV \to (qqH^*) \to qqVV \to 6f$

  including $(VH^*) \to VVV \to 6f$



- cut off q^2 growth:

$$\frac{\Lambda_{V1,i}^2 \Lambda_{V2,i}^2 \Lambda_{H,i}^2}{(\Lambda_{V1,i}^2 + |q_{V1}^2|)(\Lambda_{V2,i}^2 + |q_{V2}^2|)(\Lambda_{H,i}^2 + |(q_{V1} + q_{V2})^2|)}$$

Off-shell H* should enter EFT Higgs fits!

see talk: July 1,2020

$$\sigma_j^{\text{prod}} \times \mathcal{B}^{\text{dec}} \propto \frac{\left(\sum_{il} \alpha_{il}^{(\text{prod j})} a_i a_l\right)\left(\sum_{mn} \alpha_{mn}^{(\text{dec})} a_m a_n\right)}{\Gamma_H}$$

not in off-shell

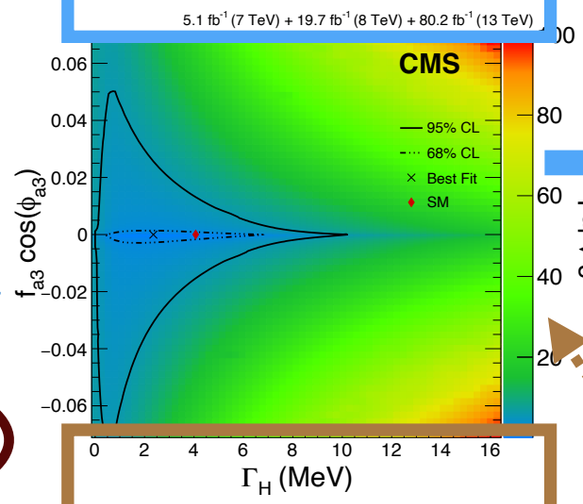
$$\Gamma_H = \sum_f \Gamma_f^{\text{SM}} \sum_{lm} \alpha_{lm}^{(f)} c_l c_m + \Gamma_{\text{invisible}} + \Gamma_{\text{undetected}}$$

optional parameters

on-shell $H \to 4f$ full simulation of BSM

dedicated binning

match fullsim BSM to data



other

other

Proof of principle

CMS arXiv:1901.00174

orthogonal selection

off-shell $H* \to 4f$ full simulation of BSM

dedicated binning

applies to $H \to WW, ZZ$ only!

match fullsim BSM to data

mass basis (LO EFT)

on-shell

2 $H\gamma\gamma$ couplings

2 $HZ\gamma$ couplings

3+1 HZZ couplings

off-shell

(!) γ^* highly suppressed in off-shell

$gg \to ZZ/Z\gamma^*/\gamma^*\gamma^* \to 4f$

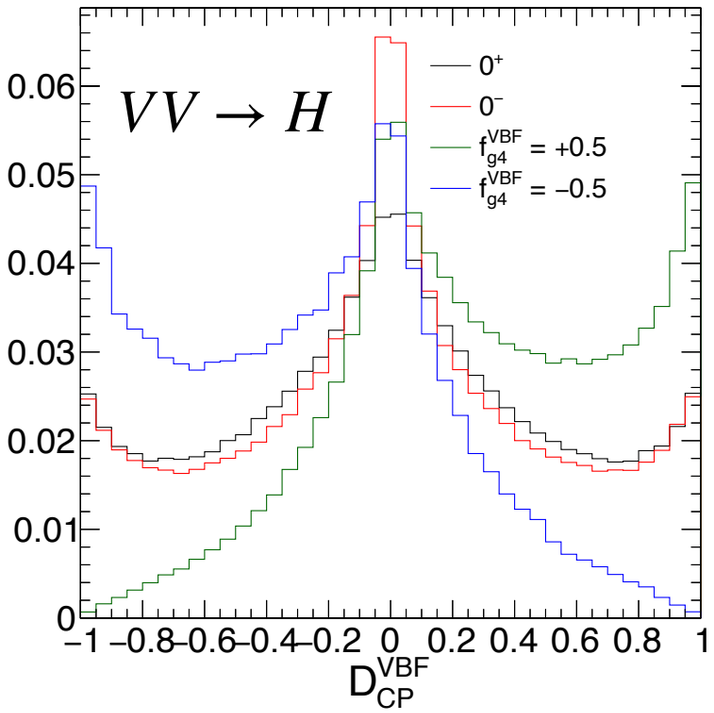
MELA: Re-weighting and Optimal observables for EFT

- Optimal and fully correct analysis to be done at detector level
  full detector simulation is expensive, re-use events for EFT

MELA: re-weighting of any **JHUGen** production and/or decay at LO
extensively used for EFT on LHC hep-ex since 2012

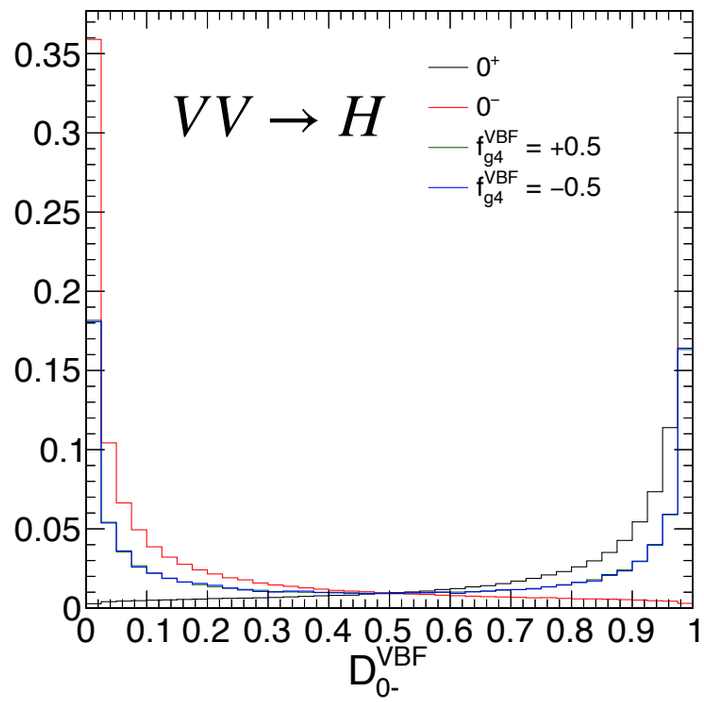
MELA: optimal observables for most Higgs processes, since discovery
provides guidance for Machine Learning approach

see talk: July 1,2020



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

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



Connection to EW in VBS in **JHUGen**

- Higgs SMEFT analyses to be done with EFT effects in “background”
- Example of quartic-gauge couplings / VBS:

$$\mathcal{L}_{\rm qgc} = e^2(W^+_\mu A_\mu W^-_\nu A_\nu - W^+_\mu W^-_\mu A_\nu A_\nu) + \frac{e^2}{2s_w^2}(1+2c_w^2\,\delta g_{1,z})(W^+_\mu W^+_\mu W^-_\nu W^-_\nu - W^+_\mu W^-_\mu W^+_\nu W^-_\nu)$$
$$+\; e^2\frac{c_w^2}{s_w^2}(1+2\delta g_{1,z})(W^+_\mu Z_\mu W^-_\nu Z_\nu - W^+_\mu W^-_\mu Z_\nu Z_\nu)$$
$$+\; e^2\frac{c_w}{s_w}(1+\delta g_{1,z})(W^+_\mu Z_\mu W^-_\nu A_\nu + W^+_\mu A_\mu W^-_\nu Z_\nu - 2W^+_\mu W^-_\mu Z_\nu A_\nu) \;+\ldots$$

0 in SM

- Relate Higgs and EW in SMEFT:

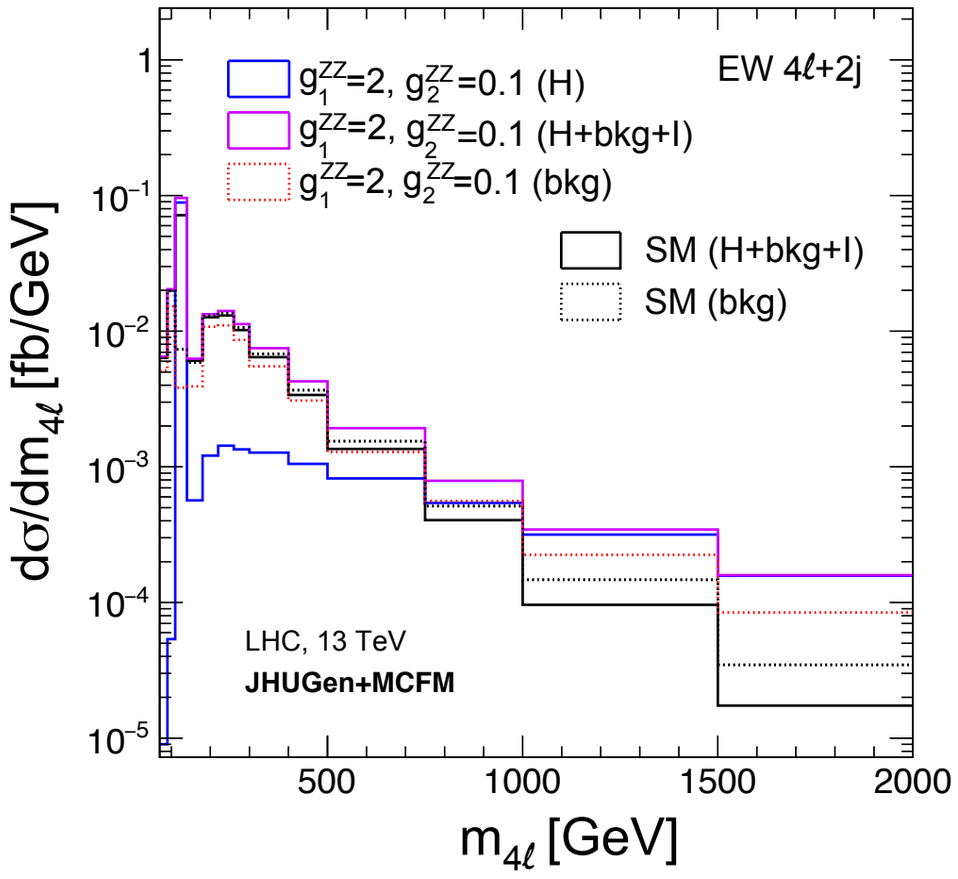
$$\delta g_{1,z} = \frac{1}{2}\left(\frac{s_w^2}{c_w^2}d^{ZZWW} - 1\right) = \frac{s_w}{c_w}d^{Z\gamma WW} - 1$$
$$d^{ZZWW} = \frac{c_w^2}{s_w^2}\left(2d_2^Z - 1\right)$$

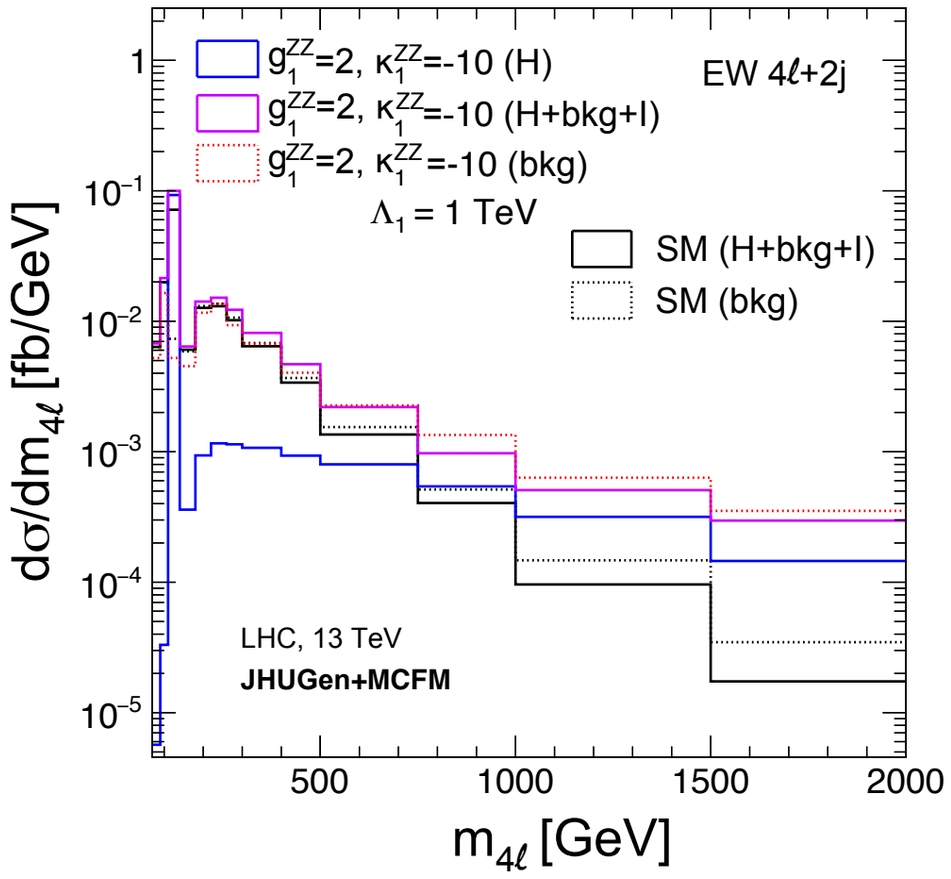
CP-even HVV couplings

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

Connection to EW / top in SMEFT

- Effect of Higgs - EW coupling relationship in EW offshell:



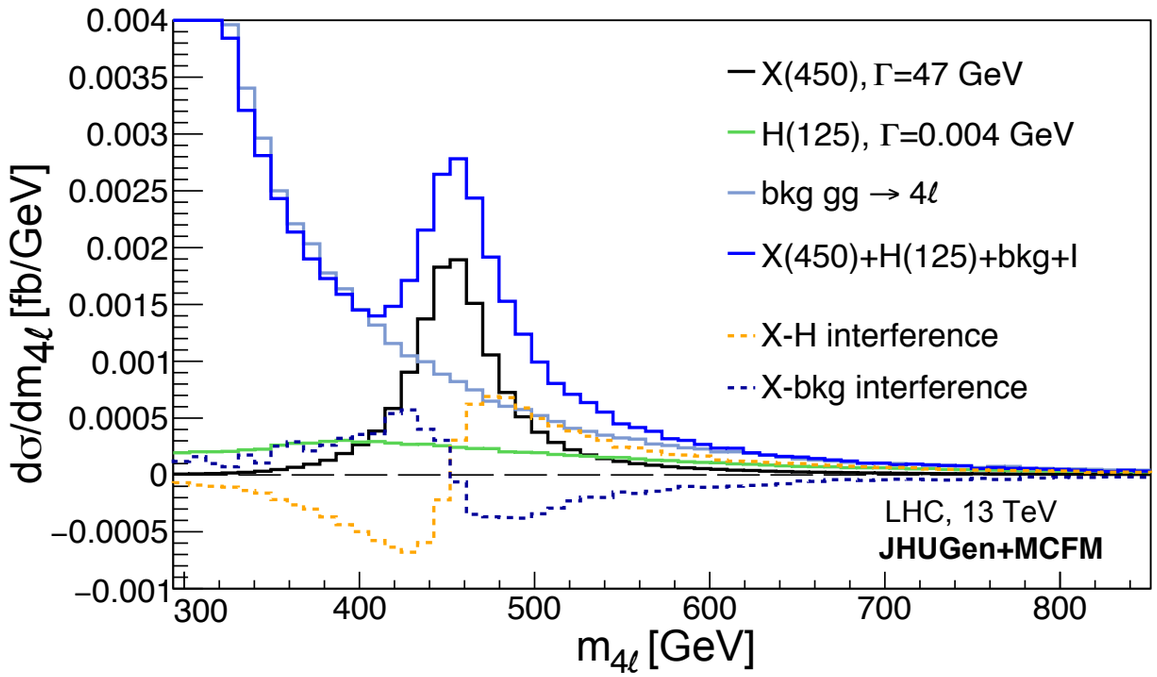


- Related: *Vtt* coupling in ggH within **MCFM** framework

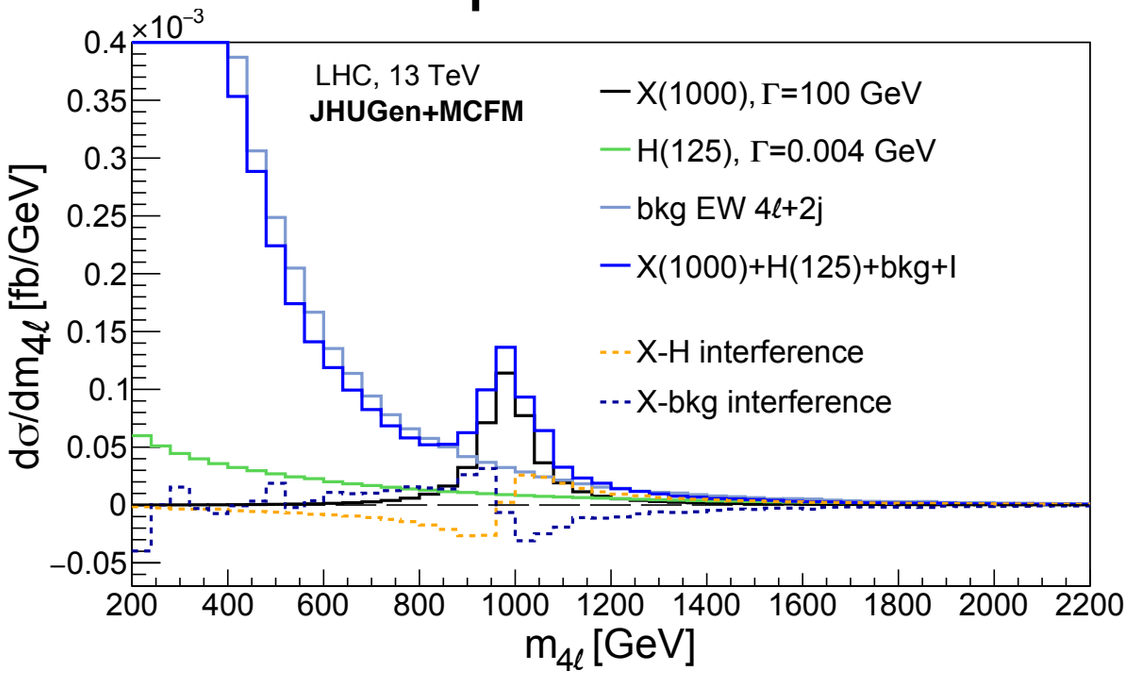
  see talk by Oscar Eboli: Sep.24,2020

Interference with a second resonance X

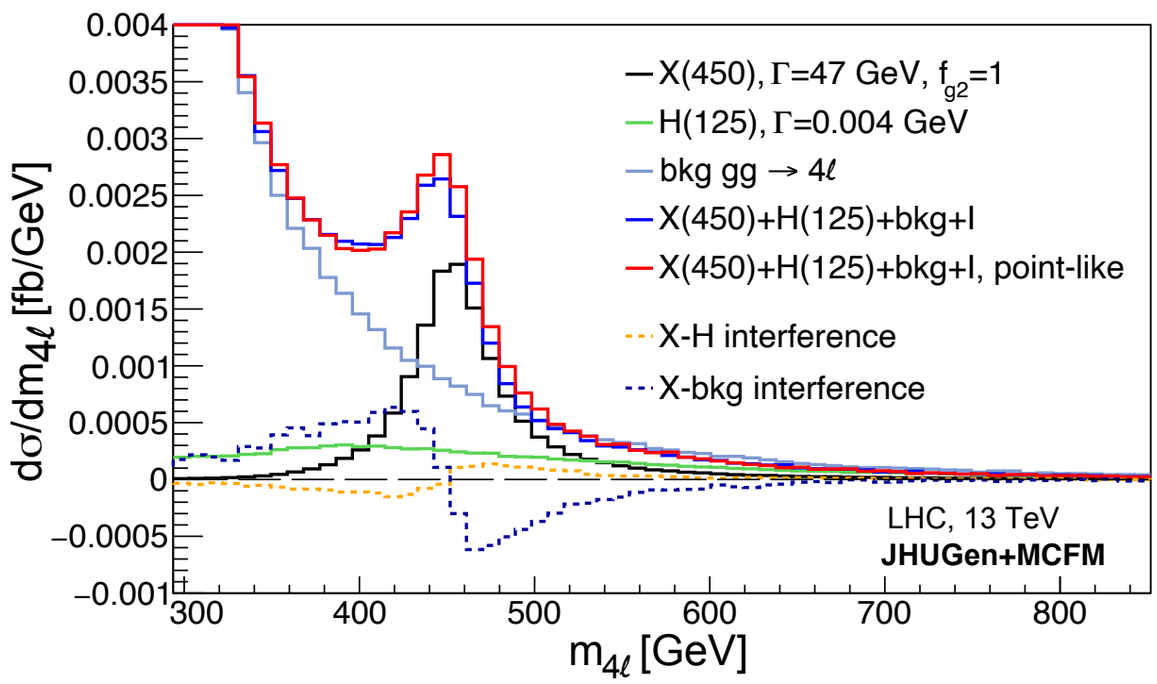
- Broad X with **JHUGen+MCFM**
  - H* + X + continuum + interference
  - full "EFT" treatment of X&H*
- Broad X with **POWHEG+JHUGen**
  - account for X→ZZ,WW effects



EW production



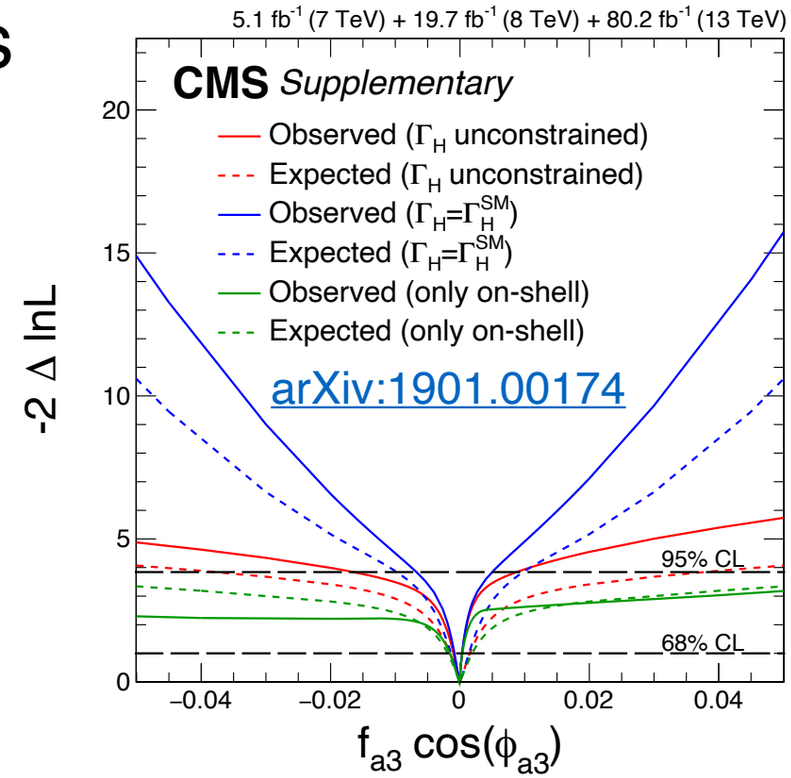
ggH production



- for application on LHC, see e.g. [arXiv:1804.01939]

Summary on **JHUGen** framework (for EFT)

- Coherent framework for studies of EFT with on+off-shell Higgs
  - full simulation of all H*+bkg+I production and decay processes
  - re-weighting to increase statistics and cover all EFT models
  - observables to be optimal to full kinematics
  - fitting tools to pull it all together



- Goal: introduce off-shell H* into EFT fits

- Focus on experimental aspects
  - target detector-level studies
  - in experiment limited in statistics and practical application
  - **JHUGen** / **MELA** were designed to address both
  - experience in practical EFT application to off-shell in hep-ex