The JHU generator framework: EFT applications in Higgs physics

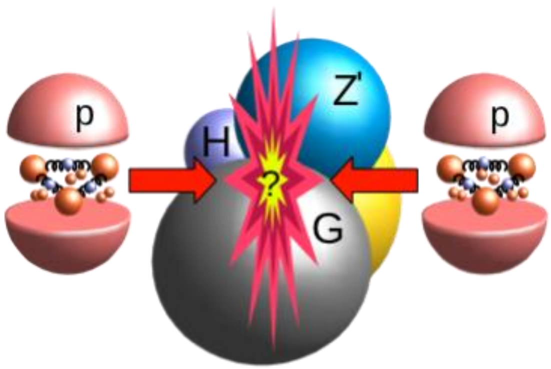
Jeffrey Davis (JHU)

for the JHUGen authors

JHUGen Framework

See talks:
[H. Roskes at LHC EFT WG]
[H. Roskes at Pheno 2020]
[M. Xiao at ICHEP 2020]
[U. Sarica at Higgs 2020]
[A. Gritsan at LHC Higgs WG]
[M. Schulze at LHC Higgs WG]

- JHUGenerator https://spin.pha.jhu.edu/
  - Simulate wide range of processes involving spin 0,1,2 particles with a general coupling model
- JHUGen MELA – Matrix Element Likelihood Approach
  - Calculate observables to optimally isolate processes or operators
  - Reweight generated samples from one hypothesis to another
- JHUGenLexicon
  - Tool for translation between different EFT bases and the JHUGen amplitude basis convention

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*                             JHU Generator v7.5.0                            *
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*                                                                             *
*   Spin and parity determination of single-produced resonances at hadron colliders   *
*                                                                             *
*        I. Anderson, S. Bolognesi, F. Caola, J. Davis, Y. Gao, A. Gritsan,   *
*         Z. Guo, C. Martin, K. Melnikov, R. Rontsch, H. Roskes, U. Sarica,   *
*                M. Schulze, N. Tran, A. Whitbeck, M. Xiao, Y. Zhou           *
*                   Phys.Rev. D81 (2010) 075022;  arXiv:1001.3396  [hep-ph],  *
*                   Phys.Rev. D86 (2012) 095031;  arXiv:1208.4018  [hep-ph],  *
*                   Phys.Rev. D89 (2014) 035007;  arXiv:1309.4819  [hep-ph],  *
*                   Phys.Rev. D94 (2016) 055023;  arXiv:1606.03107 [hep-ph],  *
*                   Phys.Rev. D102 (2020) 056022; arXiv:2002.09888 [hep-ph],  *
*                                                 arXiv:2104.04277 [hep-ph].  *
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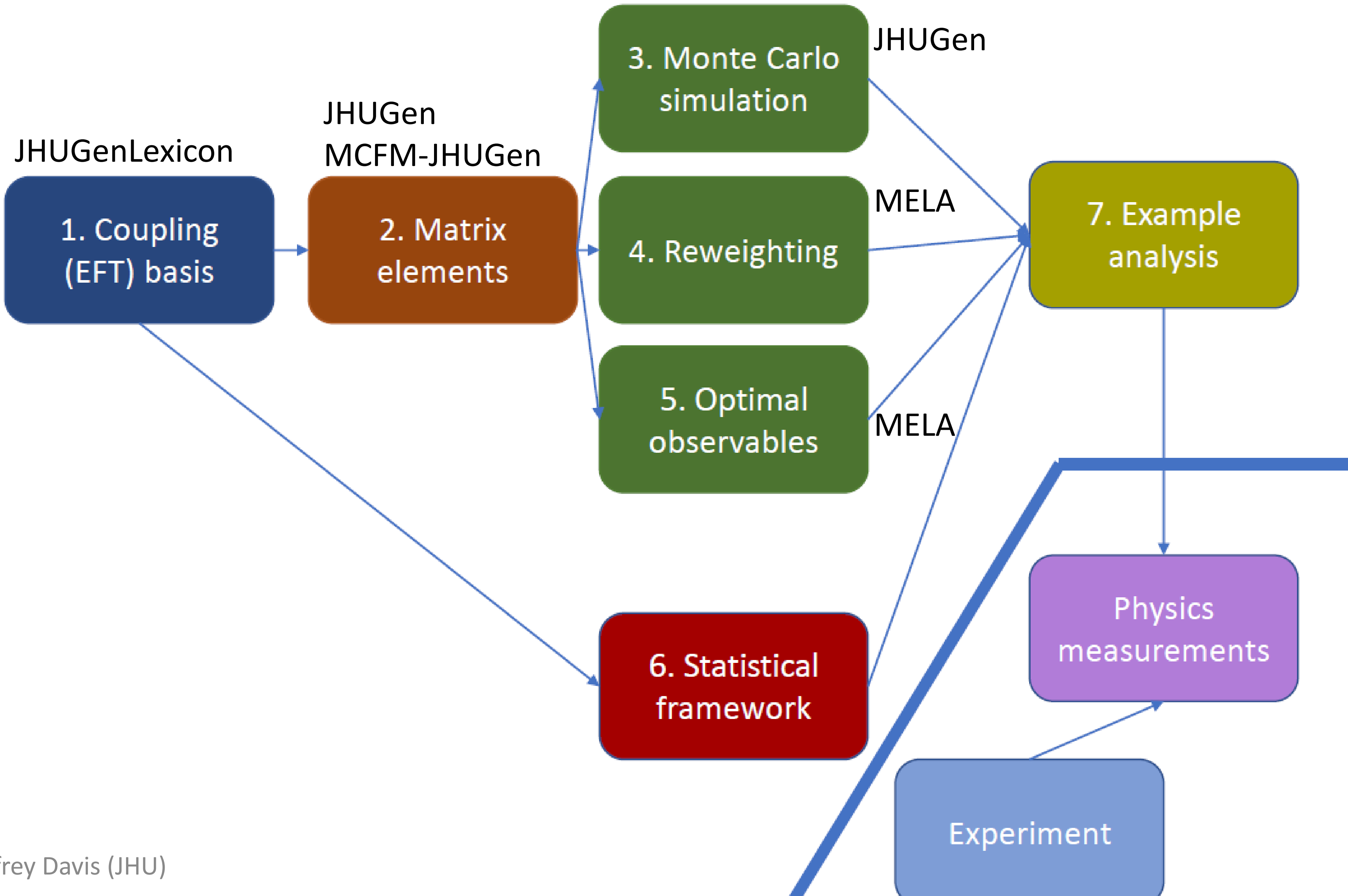
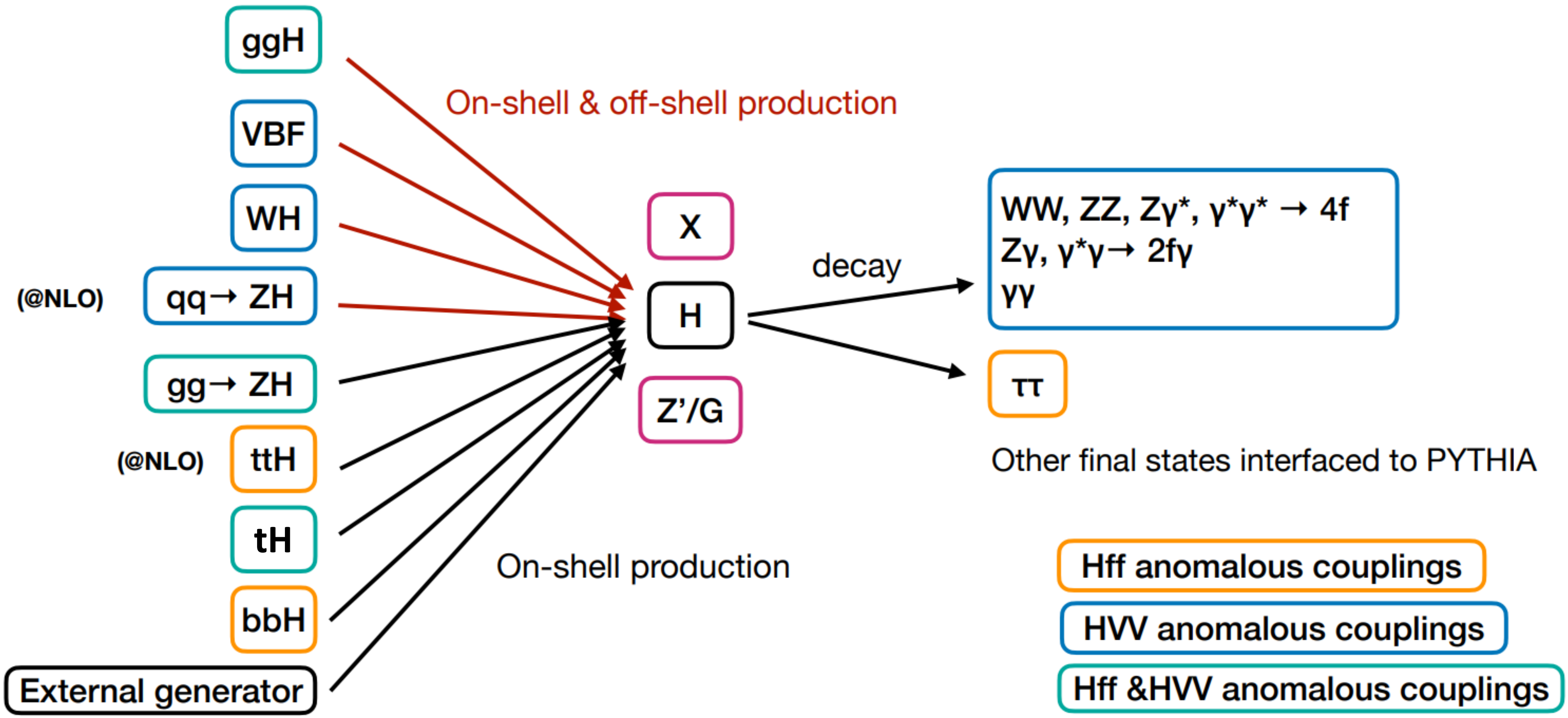
JHUGen Framework



JHUGenerator

See recently:
[arxiv: 2104.04277]
[arxiv:2002.09888]

- New support for tWH process



Anomalous Couplings and EFT

- HVV couplings parameterized by tensor structures which allow for modelling of any EFT effects

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

- EFT effects in VBS are included in off-shell simulation
- Using JHUGenLexicon we can map these amplitude couplings to any other EFT basis we want:
  - Enforce SU(2) x U(1) to translate between Amplitude basis and EFT bases

$$\delta g_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(2w_{\phi bx}+\frac{6e^2}{s_w^2}w_{\phi BW}+(\frac{3c_w^2}{2s_w^2}-\frac{1}{2})w_{\phi D}\right),$$
$$\kappa_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(-\frac{2e^2}{s_w^2}w_{\phi BW}+(1-\frac{1}{2s_w^2})w_{\phi D})\right),$$
$$g_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2w_{\phi B}+c_w^2w_{\phi W}+s_wc_ww_{\phi BW}\right),$$
$$g_2^{Z\gamma} = -2\frac{v^2}{\Lambda^2}\left(s_wc_w(w_{\phi W}-w_{\phi B})+\frac{1}{2}(s_w^2-c_w^2)w_{\phi BW}\right),$$
$$g_2^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2w_{\phi B}+s_w^2w_{\phi W}-s_wc_ww_{\phi BW}\right),$$
$$g_2^{gg} = -2\frac{v^2}{\Lambda^2}w_{\phi G},$$

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

$Z\gamma$ & $\gamma\gamma$ couplings well constrained by direct $H\rightarrow Z\gamma, \gamma\gamma$ measurements

External Constraints

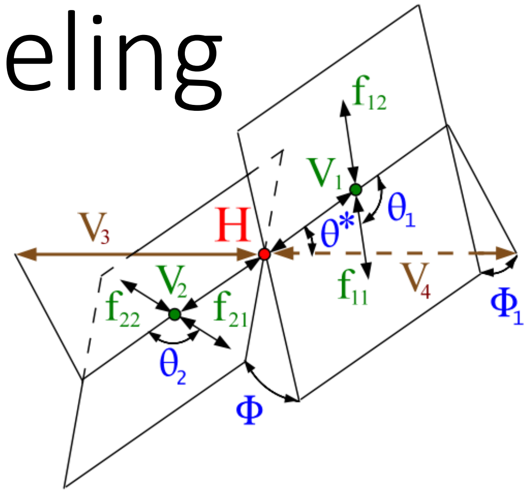
- Any EFT Basis with SU(2) x U(1) symmetry allows for some shift to the W mass and Zff couplings, etc.
  - δm in Higgs Basis, c_{HWB} in Warsaw Basis (W mass)
  - c_{HWB} shifts Zff couplings
- Some EFT effects better constrained by EW precision measurements. Enforce these constraints in JHUGenLexicon
  - "Custodial Symmetry"
    - Fixes W mass to SM value

$$\delta g_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(2w_{\phi bx} + \frac{6e^2}{s_w^2}w_{\phi BW} + (\frac{3c_w^2}{2s_w^2} - \frac{1}{2})w_{\phi D}\right),$$

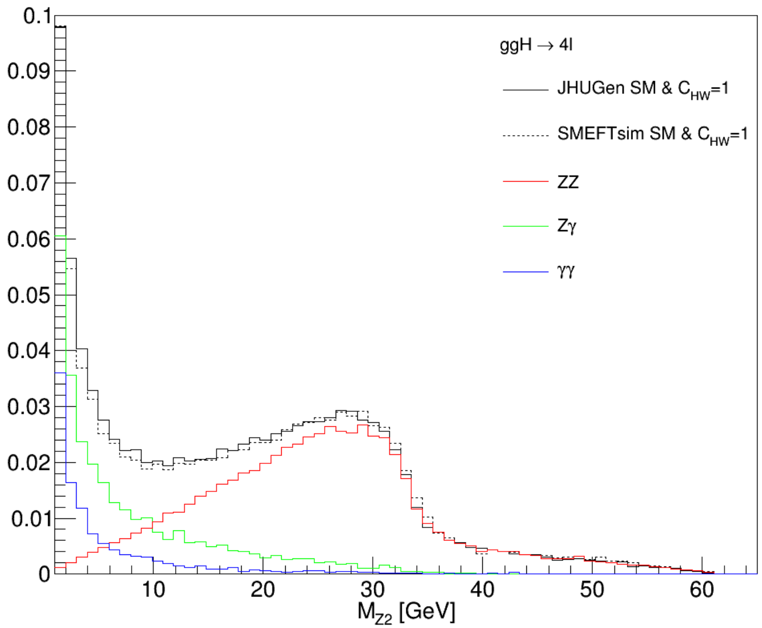
$$\kappa_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(-\frac{2e^2}{s_w^2}w_{\phi BW} + (1 - \frac{1}{2s_w^2})w_{\phi D})\right),$$

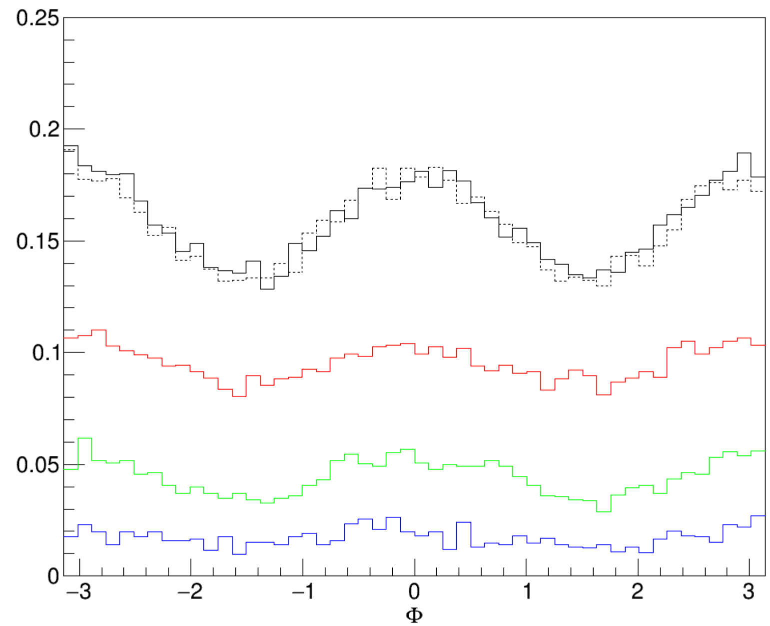
	$\delta g_1^{ZZ} = \delta g_1^{WW}$	κ_1^{ZZ}	g_2^{ZZ}	$g_2^{Z\gamma}$	$g_2^{\gamma\gamma}$	g_4^{ZZ}	$g_4^{Z\gamma}$	$g_4^{\gamma\gamma}$	$\kappa_2^{Z\gamma}$	κ_1^{WW}	g_2^{WW}	g_4^{WW}
$c_{H\Box}$	0.1213	0	0	0	0	0	0	0	0	0	0	0
c_{HD}	0.2679	−0.0831	0	0	0	0	0	0	−0.1320	−0.1560	0	0
c_{HW}	0	0	−0.0929	−0.0513	−0.0283	0	0	0	0	0	−0.1212	0
c_{HWB}	0.1529	−0.0613	−0.0513	0.0323	0.0513	0	0	0	0.1763	0.0360	0	0
c_{HB}	0	0	−0.0283	0.0513	−0.0929	0	0	0	0	0	0	0
$c_{H\tilde{W}}$	0	0	0	0	0	−0.0929	−0.0513	−0.0283	0	0	0	−0.1212
$c_{H\tilde{W}B}$	0	0	0	0	0	−0.0513	0.0323	0.0513	0	0	0	0
$c_{H\tilde{B}}$	0	0	0	0	0	−0.0283	0.0513	−0.0929	0	0	0	0

Comparison of EFT Modeling



- Mass Eigenstates useful for simulation in experiment
  - Need to be able to generate samples in both Mass (Amplitude/Higgs) and Gauge Eigenstate basis (Warsaw)
  - JHUGen v7.5.1 – parameterize directly in anomalous couplings
  - SMEFTSim v 2.1 – parameterize in Warsaw Basis





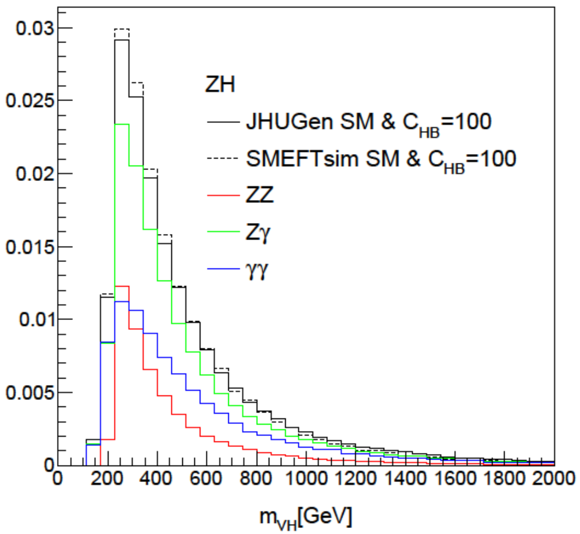
Simulate SM & $c_{HW} = 1$

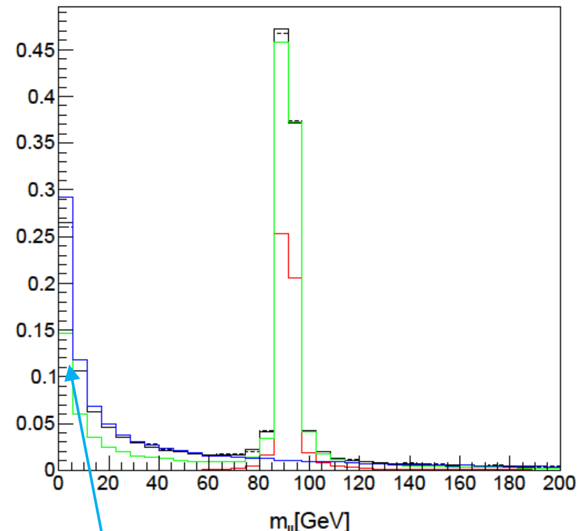
$$c_{HW} = -0.0929 g_2^{ZZ} - 0.0513 g_2^{Z\gamma} - 0.0281 g_2^{\gamma\gamma}$$

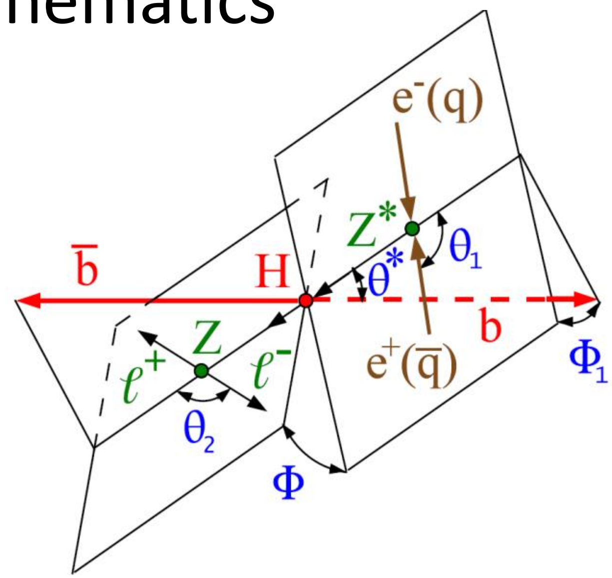
Agreement between JHUGen (Amplitude Basis) and SMEFTSim (Warsaw Basis)

Comparison of EFT Modeling $Z/\gamma^* H$

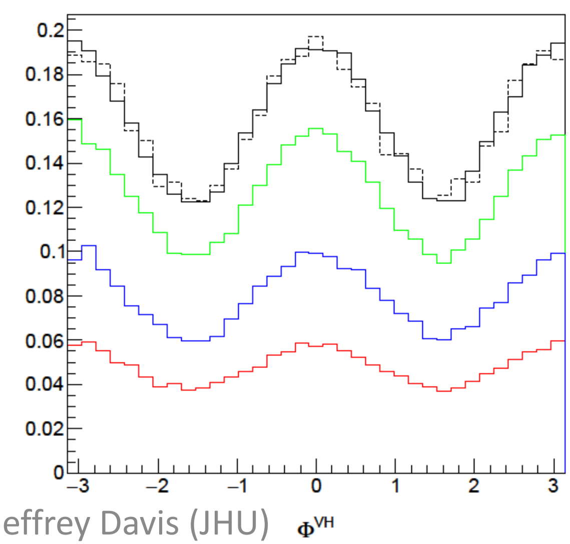
- We observe agreement in production kinematics







EFT introduces $\gamma^* H$ contributions at low q^2

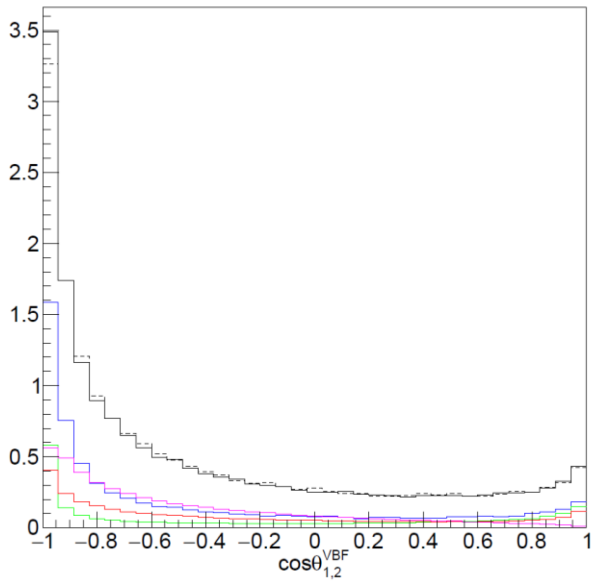


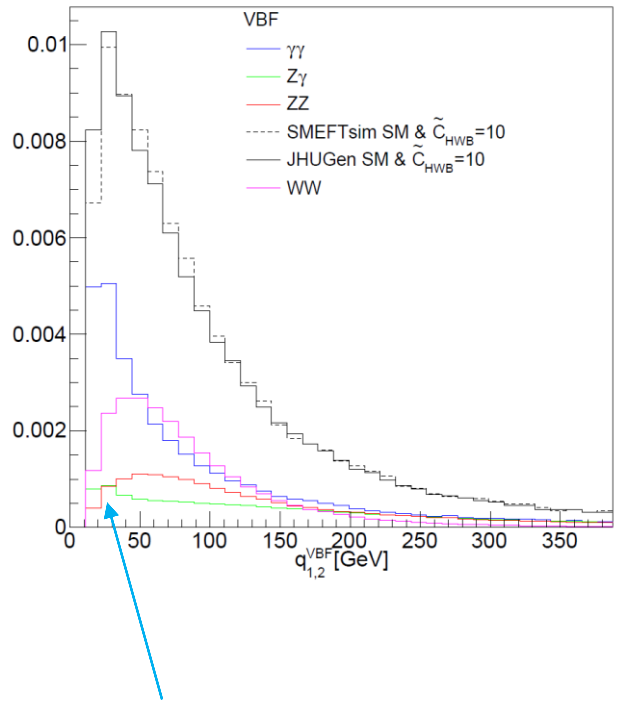
ZH production

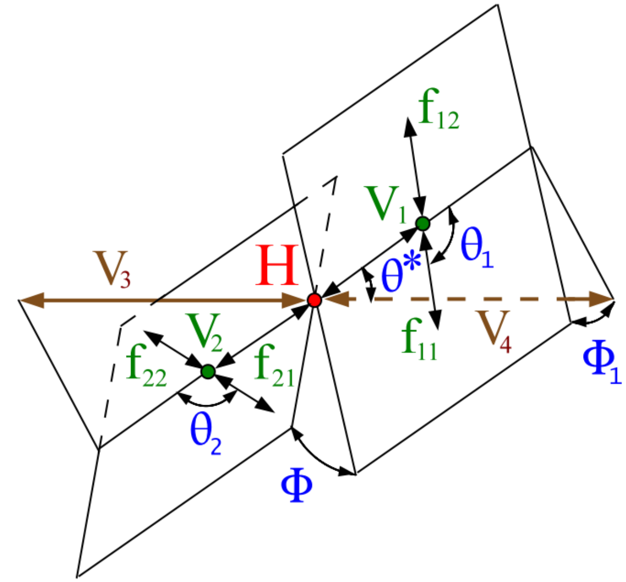
SM couplings & c_{HB} = 100

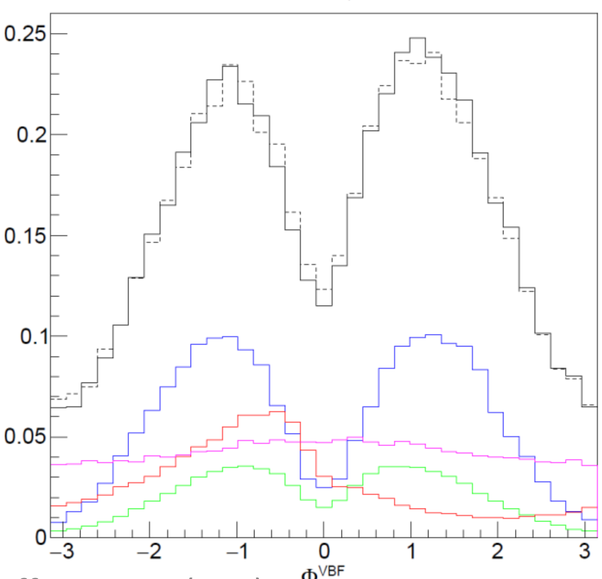
$$c_{HB} = -0.0283 g_2^{ZZ} + 0.0513 g_2^{Z\gamma} - 0.0929 g_2^{\gamma\gamma}$$

Comparison of EFT Modeling VBF









EFT introduces $\gamma\gamma$ and $Z\gamma$ fusion enhanced contributions at low q^2

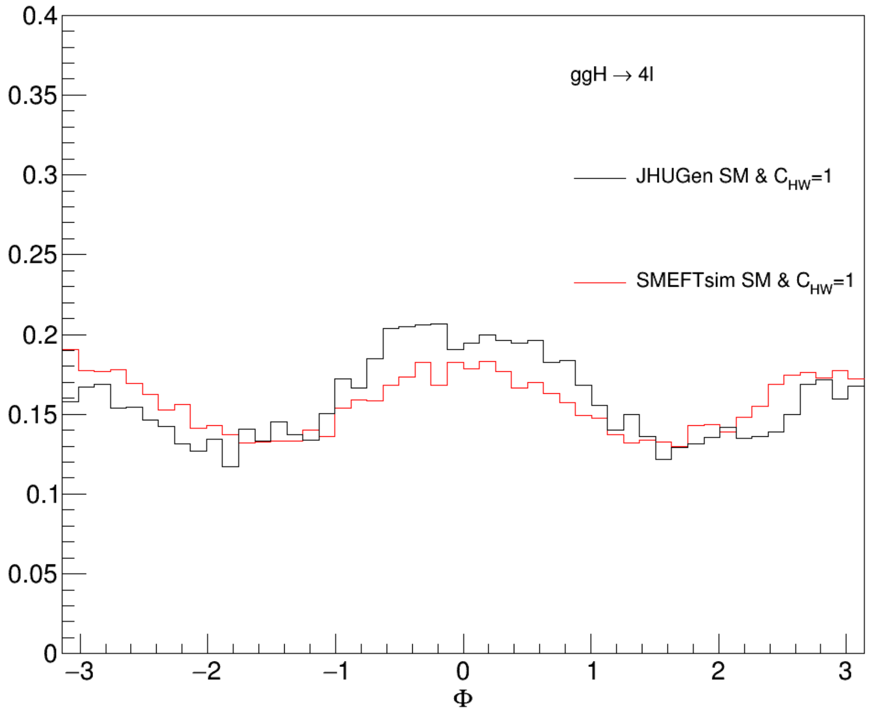
VV->H

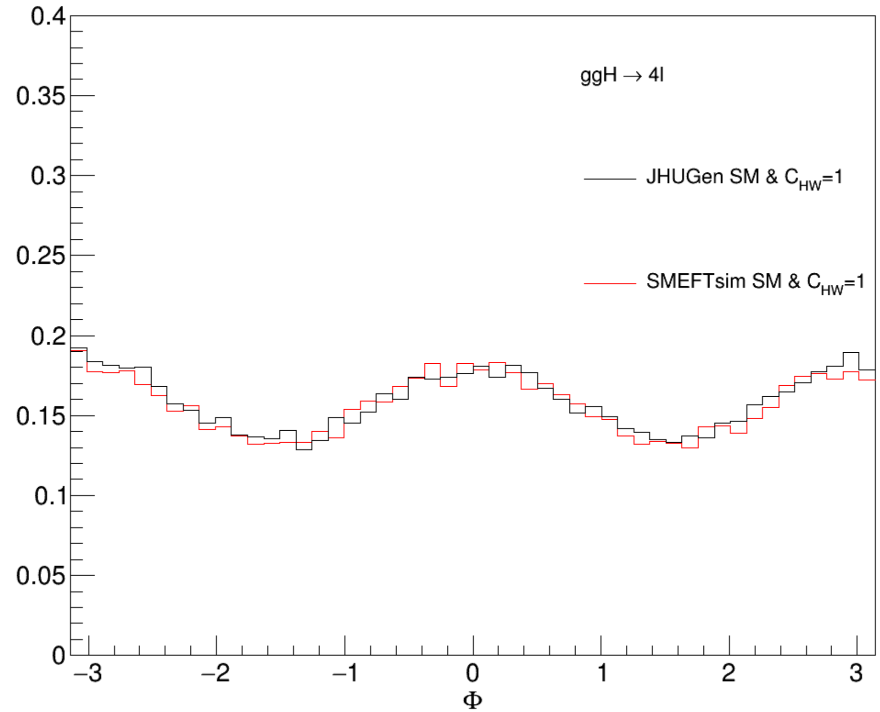
Example: Simulate SM & $\tilde{C}_{HWB} = 10$

$$\tilde{C}_{HWB} = -0.0513 g_4^{ZZ} + 0.0323 g_4^{Z\gamma} + 0.0513 g_4^{\gamma\gamma}$$

Sign Conventions in Various Tools

- Relative sign between $c_{z\gamma}$ in **JHUGen** and **SMEFTSim** are opposite
- Interference between $Z\gamma$ couplings and others depend on relative sign





Difference in ϕ Distributions when assumed convention is the same

$c_{z\gamma} \rightarrow -c_{z\gamma}$

Agreement in ϕ Distributions when difference in conventions is correctly accounted for

Taking $c_{z\gamma}$ = 1 —> -1 In JHUGen

Summary of sign conventions

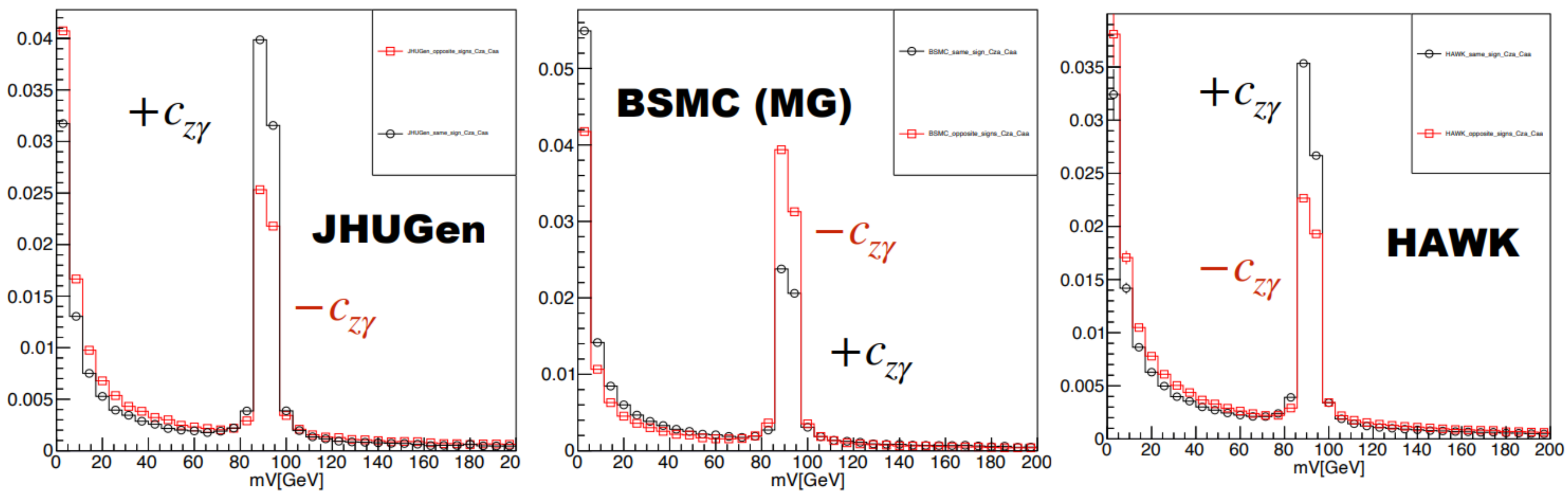
(1) $\epsilon_{0123} = +1$ in **MadGraph, JHUGen,** and **Analytical**

$\epsilon^{0123} = +1 \Rightarrow \epsilon_{0123} = -1$ in **HAWK**

(2) $D_\mu = \partial_\mu - \mathrm{i}\dfrac{e}{2s_w}\sigma^i W^i_\mu - \mathrm{i}\dfrac{e}{2c_w}B_\mu$ in **MadGraph** and **Analytical**

$D_\mu = \partial_\mu - \mathrm{i}\dfrac{e}{2s_w}\sigma^i W^i_\mu + \mathrm{i}\dfrac{e}{2c_w}B_\mu$ in **HAWK** and **JHUGen**

Interference effects between $c_{Z\gamma}$ and SM $c_{\gamma\gamma}$ couplings dependent on sign convention



EFT Analysis

- Measure Higgs cross section as a function of anomalous couplings

$$\frac{d\sigma(i \to H \to f)}{d\vec{\Omega}} \propto \frac{\left(\sum \alpha_{jk}^{(i)} a_j a_k\right)\left(\sum \alpha_{lm}^{(f)} a_l a_m\right)}{\Gamma_{\text{tot}}}$$

Maximum likelihood calculated for EFT hypothesis to match measured cross section/kinematic distributions

α are functions of kinematic observables $\vec{\Omega}$ and can usually be factorized into both production and decay

Γ_{tot} purely dependent on anomalous couplings

- Each event has a probability of belonging to a certain hypothesis

EFT Analysis

$$\sigma(i \to H \to f) \propto \frac{\left(\sum \alpha_{jk}^{(i)} a_j a_k\right)\left(\sum \alpha_{lm}^{(f)} a_l a_m\right)}{\Gamma_{\text{tot}}}$$

Total width directly dependent on anomalous couplings

$$\Gamma_{\text{known}} = \Gamma_{\text{tot}}^{\text{SM}} \times \sum_f \left(\frac{\Gamma_f^{\text{SM}}}{\Gamma_{\text{tot}}^{\text{SM}}} \times \frac{\Gamma_f}{\Gamma_f^{\text{SM}}}\right) = \sum_f \Gamma_f^{\text{SM}} R_f$$

(Function of anomalous couplings)

$f = b\bar{b}, c\bar{c}, W^+W^-, gg, \tau^+\tau^-, ZZ/Z\gamma^*/\gamma^*\gamma^*, Z\gamma, \gamma\gamma, \mu^+\mu^-$

- Analytic formulas are calculated for R_f

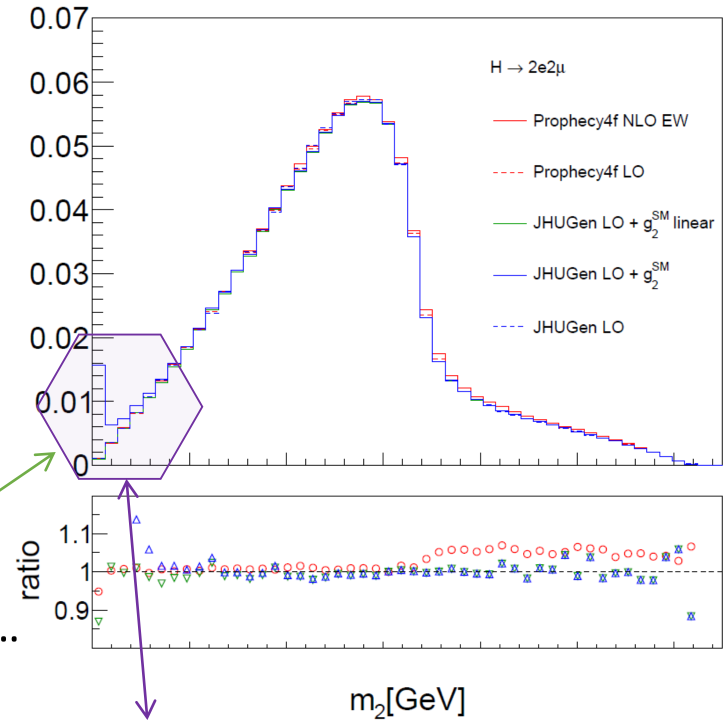
$$\begin{aligned} R_{\gamma\gamma} = \quad & 1.61011\left(\frac{g_1^{WW}}{2}\right)^2 + 0.07408\,\kappa_t^2 - 0.69098\left(\frac{g_1^{WW}}{2}\right)\kappa_t + 0.00002\,\kappa_b^2 + 0.06831\,\kappa_Q^2 \\ & -0.00186\,\kappa_t\kappa_b + 0.00912\left(\frac{g_1^{WW}}{2}\right)\kappa_b + 0.14231\,\kappa_t\kappa_Q - 0.00181\,\kappa_b\kappa_Q \; -0.66373\left(\frac{g_1^{WW}}{2}\right)\kappa_Q \\ & +0.20543\,\tilde{\kappa}_t^2 + 0.00006\,\tilde{\kappa}_b^2 - 0.00300\,\tilde{\kappa}_t\tilde{\kappa}_b + 0.18235\,\tilde{\kappa}_Q^2 + 0.38709\,\tilde{\kappa}_t\tilde{\kappa}_Q - 0.00269\,\tilde{\kappa}_b\tilde{\kappa}_Q \end{aligned}$$

$$g_2^{\gamma\gamma,Q} = -\frac{\alpha}{3\pi} N_c\, Q_Q^2\, \kappa_Q \qquad\qquad g_4^{\gamma\gamma,Q} = -\frac{\alpha}{2\pi} N_c\, Q_Q^2\, \tilde{\kappa}_Q$$

Sensitivity to EW corrections

- Sometimes EW corrections are modelled as effective point-like couplings $g_2^{Z\gamma}$ and $g_2^{\gamma\gamma}$ which model $H \rightarrow Z\gamma, \gamma\gamma$

Type of Correction	Correction to SM ggH->4l Cross Section
EW NLO (Prophecy4f)	+1.50 %
LO+Effective g2 (JHUGen)	+1.96 %
LO+Effective g2 (Linear Only)	-0.60 %



$$\sigma_{gg\rightarrow H\rightarrow 4l} \propto (g_1^{ZZ})^2 + \underbrace{(g_1^{ZZ})(g_2^{Z\gamma,SM})}_{\text{Linear Terms, Full EW NLO}} + \cdots + \underbrace{(g_2^{\gamma\gamma,SM})^2}_{\text{Squared Terms, Effective g2}} + \ldots$$

Squared terms for effective point-like couplings have different decay kinematics than NLO EW corrections

$g_2^{Z\gamma,SM}$ = -0.00659 $\qquad g_2^{\gamma\gamma,SM} = 0.00377$

MELA Observables

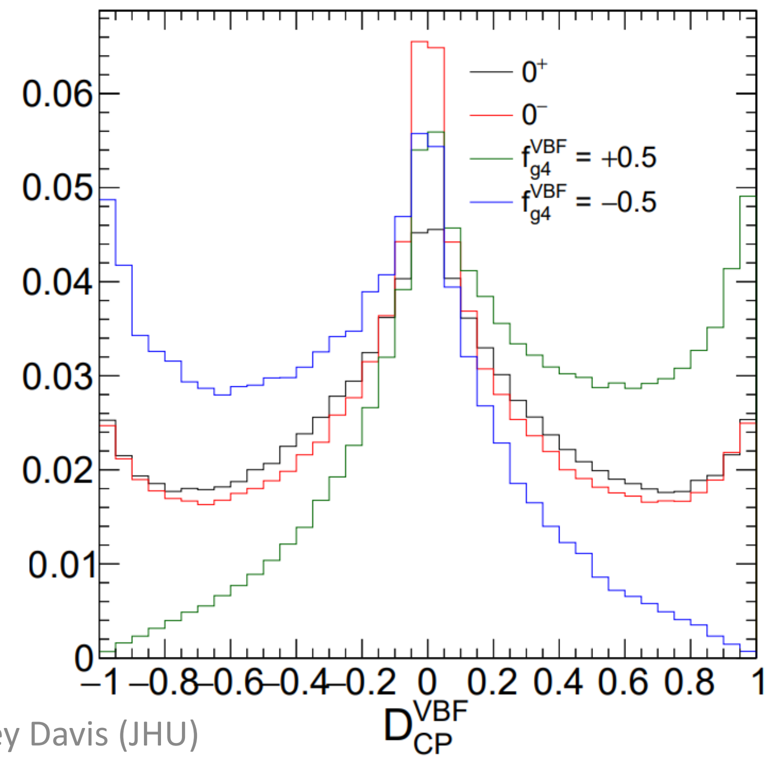
- Events have many kinematic observables
- We construct observables that utilize all kinematic information

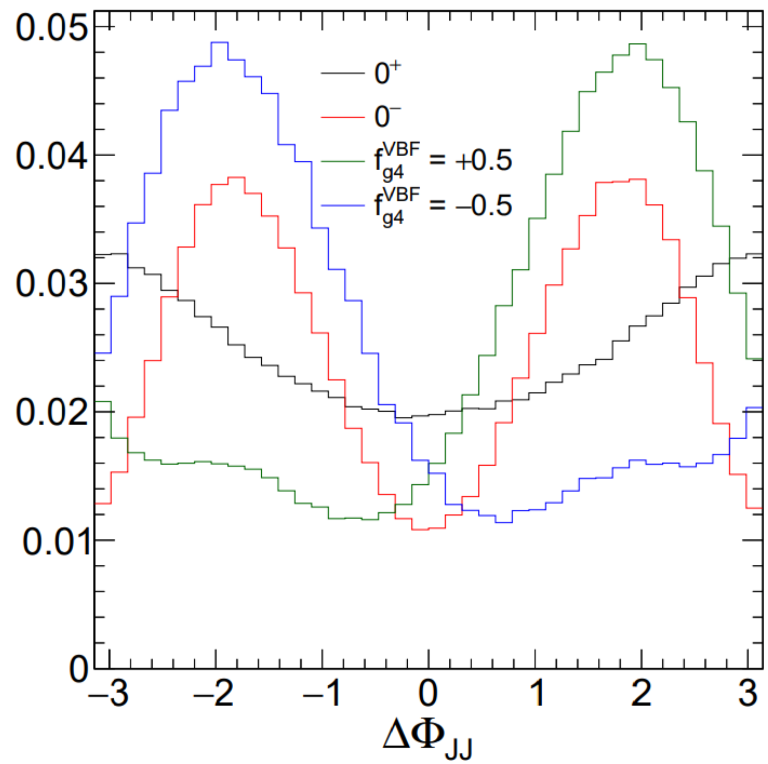
$$\mathcal{D}_{\mathrm{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\mathrm{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\mathrm{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\mathrm{alt}}(\mathbf{\Omega})}$$

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

$$\frac{\boxed{\left(\sum \alpha^{(i)}_{jk} a_j a_k\right)\left(\sum \alpha^{(f)}_{lm} a_l a_m\right)}}{\Gamma_{\mathrm{tot}}}$$

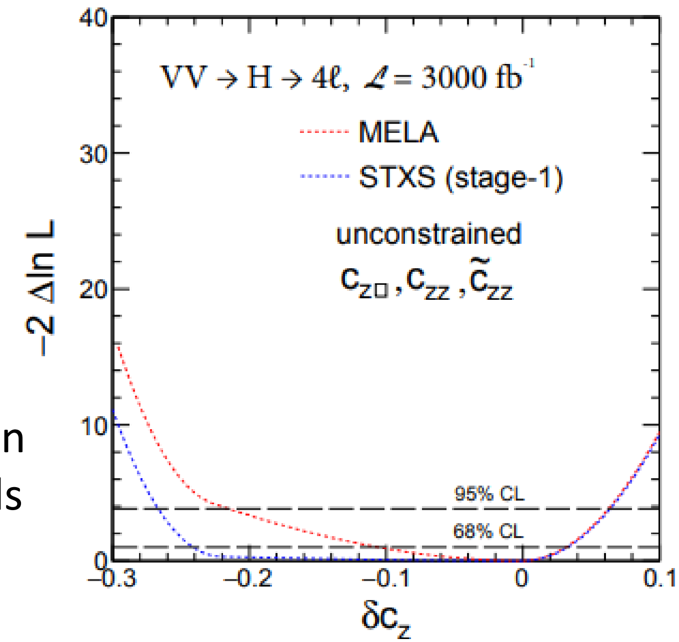
MELA calculates optimal observables from matrix elements to distinguish between various anomalous coupling hypotheses

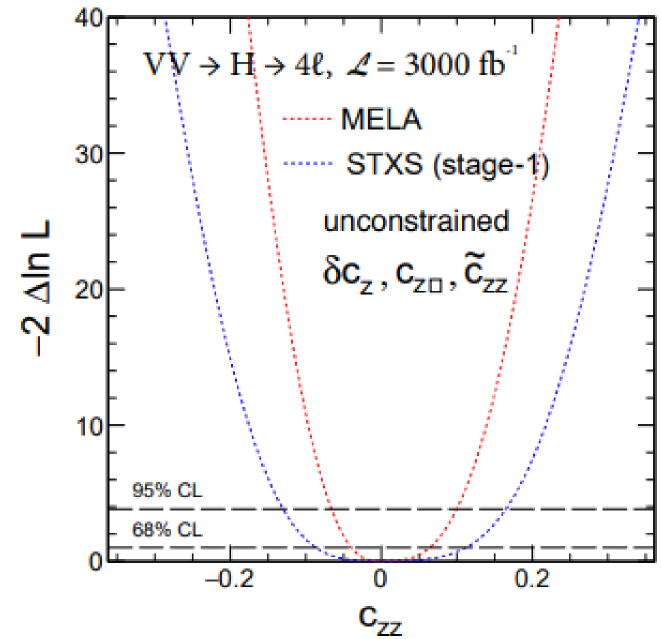




Constraints on EFT couplings

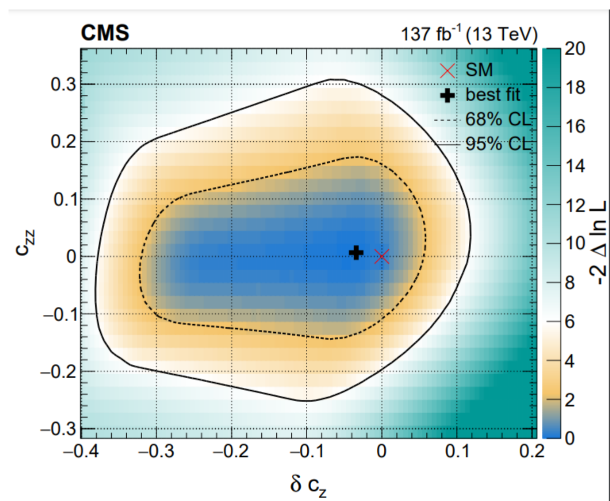
Projected constraints on Higgs basis couplings for 3000 fb





Better constraints than more general methods (STXS) for specific couplings only

CMS placed constraints on EFT couplings in Warsaw and mass-eigenstate bases using JHUGen, MELA, and JHUGenLexicon



Coupling	Observed	Expected
$c_{H\Box}$	$0.04^{+0.43}_{-0.45}$	$0.00^{+0.75}_{-0.93}$
c_{HD}	$-0.73^{+0.97}_{-4.21}$	$0.00^{+1.06}_{-4.60}$
c_{HW}	$0.01^{+0.18}_{-0.17}$	$0.00^{+0.39}_{-0.28}$
c_{HWB}	$0.01^{+0.20}_{-0.18}$	$0.00^{+0.42}_{-0.31}$
c_{HB}	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.08}$
$c_{H\tilde{W}}$	$-0.23^{+0.51}_{-0.52}$	$0.00^{+1.11}_{-1.11}$
$c_{H\tilde{W}B}$	$-0.25^{+0.56}_{-0.57}$	$0.00^{+1.21}_{-1.21}$
$c_{H\tilde{B}}$	$-0.06^{+0.15}_{-0.16}$	$0.00^{+0.33}_{-0.33}$

CMS: arXiv:2104.12152

Conclusion

- Careful construction of MELA discriminants allows for tighter constraints on specific EFT couplings
  - Amplitude (mass-eigenstate) basis clearly separates event topologies to make optimal MELA observables
  - Use external constraints from non-EFT measurements
    - W mass, $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$
  - Rotate results back to Warsaw (gauge-eigenstate) basis to place constraints on eft couplings in different basis
- JHUGen package used extensively for EFT analysis on LHC
- Sensitivity to $g_2^{Z\gamma,SM}$, $g_2^{\gamma\gamma,SM}$ implies sensitivity to NLO EW corrections.