Tools for the Higgs boson CP studies: JHUGen and MELA


Johns Hopkins University

Theory, experiment

2015 meeting, APS Division of Particles and Fields
Ann Arbor, MI

August 4, 2015
Framework

JHUGen
Event generation

JHUGenMELA
Discriminants for anomalous coupling fits and background suppression
Reweighting

AnalyticMELA
Discriminants for anomalous coupling fits and background suppression
Analytic multidimensional fits
Validation

http://www.pha.jhu.edu/spin/
arXiv:1001.3396
arXiv:1208.4018
arXiv:1309.4819
JHU Generator

\[ gg \rightarrow H \]
\[ gg/gq \rightarrow H + \text{jet} \]
\[ gg/gq/qq' \rightarrow H + 2 \text{ jets (QCD)} \]
\[ qq' \rightarrow H + 2 \text{ jets (VBF)} \]
\[ q\bar{q} \rightarrow Z^* \rightarrow Z + H \]
\[ q\bar{q}' \rightarrow W^* \rightarrow W + H \]

\[ gg/q\bar{q} \rightarrow t\bar{t}H \]
\[ t \rightarrow Wb \rightarrow l\nu b/q\bar{q}'b \]
\[ q\bar{q} \rightarrow \text{spin 1} \]
\[ gg/q\bar{q} \rightarrow \text{spin 2} \]

Interface to MCFM for \( gg \rightarrow ZZ \)
offshell with anomalous couplings

Decay:
\[ \rightarrow ZZ^* + Z\gamma^* + \gamma^*\gamma^* \rightarrow \text{any combination of } l^+l^-, \nu\bar{\nu}, q\bar{q} \]
\[ \rightarrow W^+W^- \rightarrow \text{any combination of } l\nu \text{ and } q\bar{q}' \]
\[ \rightarrow Z\gamma, \gamma\gamma \]

Production and decay in one step for spin 1 and spin 2

ReadLHE mode for other processes or to decay events from other generators
Parameterization

\[ A(HVV) \sim \left[ a_1 + \frac{q_v^2 + q_{v_2}^2}{(\Lambda_1)^2} + \frac{(q_v + q_{v_2})^2}{(\Lambda_Q)^2} \right] m_{V_1}^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{(1)} f^{(2)\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}_{\mu\nu}^{*(2)} \]

\[ L(HVV) \sim \]

\[ a_1^{ZZ} \frac{m_Z^2}{2} HZ^\mu Z_\mu - \frac{1}{(\Lambda_{ZZ})^2} m_Z^2 HZ^\mu \square Z_\mu - \frac{1}{2(\Lambda_{QQ})^2} m_Z^2 HZ^\mu Z_\mu - \frac{1}{2} a_2^{ZZ} HZ^\mu Z_{\mu\nu} - \frac{1}{2} a_3^{ZZ} HZ^\mu \tilde{Z}_{\mu\nu} \]

\[ + a_1^{WW} m_W^2 HW^+ \mu W^- \mu - \frac{1}{(\Lambda_{WW})^2} m_W^2 H W^+ \mu + W^- \mu \]

\[ - \frac{1}{(\Lambda_Q)^2} m_W^2 \square HW^+ \mu W^- \mu - a_2^{WW} HW^+ \mu \nu W^- \mu - a_3^{WW} HW^+ \mu \nu \tilde{W}^- \mu \nu \]

\[ + \frac{1}{(\Lambda_{ZZ})^2} m_Z^2 H(Z^\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} HF^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} HF^{\mu\nu} \tilde{Z}_{\mu\nu} \]

\[ - \frac{1}{2} a_2^{\gamma\gamma} HF^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} HF^{\mu\nu} \tilde{F}_{\mu\nu} \]

\[ - \frac{1}{2} a_2^{gg} HG_{\mu\nu}^{\mu\nu} G_{\mu\nu}^a - \frac{1}{2} a_3^{gg} HG_{\mu\nu}^{\mu\nu} \tilde{G}_{a\mu\nu} \]

Similar for spin 1 and spin 2, and similar terms for fermion couplings

Predictions are leading order QCD

POWHEG (NLO QCD) \( gg \rightarrow H \rightarrow JHUGen \) anomalous decay

Anomalous couplings do not affect 1 jet correlations
JHUGenMELA
Matrix Element Likelihood Approach

Library including matrix elements for all presented processes

- EvalAmp_gg_H_VV
- EvalAmp_H_VV
- EvalAmp_VHiggs
- EvalAmp_qqb_Zprime_VV
- EvalAmp_Zprime_VV
- EvalAmp_gg_G_VV
- EvalAmp_qqb_G_VV
- EvalAmp_G_VV
- EvalAmp_WBFH
- EvalAmp_SBFH
- EvalAmp_HJ
- EvalXSec_PP_TTBH
- EvalAmp_GG_TTBH
- EvalAmp_QQB_TTBH

Complemented and validated by AnalyticMELA
Interface to MCFM for offshell production with anomalous couplings and \( ZZ/Z\gamma/\gamma\gamma \) SM background [Campbell, Ellis, Williams]

Can be used for:
- optimal discriminants for anomalous coupling fits
- background suppression
- reweighting
Reweighting with JHUGenMELA

Basic idea: 
weight \( (d\Pi) = \frac{P(J^P_{\text{target}},d\Pi)}{P(J^P_{\text{sample}},d\Pi)} \)

\( d\Pi = \{ \theta^*, \theta_1, \theta_2, \phi, \phi_1, m_1, m_2, m_H \) 

\( d\Pi = \{ p_1, p_2, p_3, p_4 \) 

For reweighting, 
(For fitting, 
\( d\Pi = d\Pi_{\text{generator}} \) 
\( d\Pi = d\Pi_{\text{observed}} \) 

Probability distribution: 
\( P \sim |\mathcal{M}(d\Pi)|^2 \) 

or \( \sim f^P_i(x_1) f^P_j(x_2) |\mathcal{M}(d\Pi)|^2 \)
Validation of reweighting

Compare reweighted sample vs. dedicated production
**HVV vertex kinematics**

\[ gg \rightarrow H \rightarrow ZZ \rightarrow 4l \]

\[ q\bar{q} \rightarrow Z^* \rightarrow ZH \]

\[ Z \rightarrow l^+ l^- \ [H \rightarrow b\bar{b}] \]

\[ qq' \rightarrow Z^*Z^* \rightarrow H \ [\rightarrow b\bar{b}] \]

**VBF**
Applications for discriminating spin and CP properties

$H \rightarrow ZZ \rightarrow 4l$ decay

arXiv:1208.4018

Spin 0

$0^+ 0^- 0^+_h$

Spin 1

$1^+ 1^- 1^+_h$

Spin 2

$2^+ 2^- 2^+_h$
Applications for discriminating CP properties

\[ f_{a3} = 1 \text{ (pseudoscalar)} \]

\[ f_{a3} = 0.5, \phi_{a3} = 0 \]

\[ f_{a3} = 0.5, \phi_{a3} = \pi/2 \]
Applications for discriminating CP properties

VBF

arXiv:1309.4819

SM $f_{a3} = 1$ (pseudoscalar) $f_{a3} = 0.5$, $\phi_{a3} = 0$ $f_{a3} = 0.5$, $\phi_{a3} = \pi/2$
## Applications for discriminating CP properties

**Summary table**

<table>
<thead>
<tr>
<th>process description</th>
<th>MC simulation parameters</th>
<th>expected precision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$g_2/g_1$     $g_4/g_{1+}$</td>
<td>$f_{a2}$          $f_{a3}$          $f_{a4}$          $f_{a5}$          $f_{dec}$          $f_{dec}$          $f_{dec}$         $f_{dec}$</td>
</tr>
<tr>
<td>any any $H \to ZZ^*$</td>
<td>0.362 0.153            0 0.18 0.06 0.088 0.014</td>
<td>– 0.06 0.02 0.008</td>
</tr>
<tr>
<td>any any $H \to WW^*$</td>
<td>0.776 0.322            0 0.18 0.06 0.088 0.014</td>
<td>– 0.06 0.02 0.008</td>
</tr>
<tr>
<td>any any $H \to \gamma\gamma, gg$</td>
<td>N/A 1.0</td>
<td>N/A 1.0 0.50 0.50</td>
</tr>
<tr>
<td>any any $H \to Z\gamma$</td>
<td>N/A 1.0</td>
<td>N/A 1.0 0.50 0.50</td>
</tr>
<tr>
<td>any any $H \to Z^+$</td>
<td>N/A 1.0</td>
<td>N/A 1.0 0.50 0.50</td>
</tr>
<tr>
<td>pp 14 TeV $gg \to H$</td>
<td>N/A 1.0</td>
<td>N/A 1.0 0.50 0.50</td>
</tr>
<tr>
<td>pp 14 TeV $V^+V^- \to H$</td>
<td>14.0 11.3</td>
<td>0 0.299 0.219 0.013</td>
</tr>
<tr>
<td>pp 14 TeV $V^+V^- \to H$</td>
<td>14.0 11.3</td>
<td>0 0.109 0.069 0.0018</td>
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<tr>
<td>pp 14 TeV $V^+V^- \to H$</td>
<td>14.0 11.3</td>
<td>0 0.052 0.030 0.0004</td>
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<tr>
<td>pp 14 TeV $V^+V^- \to H$</td>
<td>76.1 46.8</td>
<td>0 0.145 0.030 0.0032</td>
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<tr>
<td>pp 14 TeV $V^+V^- \to H$</td>
<td>76.1 46.8</td>
<td>0 0.095 0.030 0.0014</td>
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<tr>
<td>pp 14 TeV $V^+V^- \to H$</td>
<td>76.1 46.8</td>
<td>0 0.061 0.015 0.0006</td>
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<tr>
<td>pp 14 TeV $V^+V^- \to H$</td>
<td>76.1 46.8</td>
<td>0 0.049 0.010 0.0004</td>
</tr>
<tr>
<td>e⁺e⁻ 250 GeV $Z^+ \to ZH$</td>
<td>34.1 8.07</td>
<td>0 0.117 0 0.10 2×$10^{-3}$</td>
</tr>
<tr>
<td>e⁺e⁻ 350 GeV $Z^+ \to ZH$</td>
<td>84.2 50.6</td>
<td>0 0.0469 0 0.10 3×$10^{-4}$</td>
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<tr>
<td>e⁺e⁻ 500 GeV $Z^+ \to ZH$</td>
<td>200.8 161.1</td>
<td>0 0.0263 0 0.10 1.1×$10^{-4}$</td>
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<td>e⁺e⁻ 1 TeV $Z^+ \to ZH$</td>
<td>916.5 870.8</td>
<td>0 0.0113 0 0.10 2×$10^{-5}$</td>
</tr>
</tbody>
</table>
Study top quarks produced in association with Higgs

Associated top production is very sensitive to the incoming partons
⇒ Include PDF in MELA weight

\[ \sim f_i^p (x_1) f_j^p (x_2) \times |M(d\Pi)|^2 \]

Similar for VBF, VH, $H + j (j)$
JHUGen in action: Generation, reweighting, discriminants

CMS analysis $H \rightarrow ZZ^*/Z\gamma^*/\gamma^*\gamma^* \rightarrow 4l$  [CMS-HIG-14-018] arXiv:1411.3441
JHUGen in action: Applications of reweighting

CMS analysis $H \rightarrow ZZ^*/Z\gamma^*/\gamma^*\gamma^* \rightarrow 4l$ [CMS-HIG-14-018] arXiv:1411.3441

JHUGen generator level:

Generate 24 base models
Create 52 target models through reweighting
To increase statistics:
    Reweight everything to everything
Effectively increase sample size by $\times 24$.

JHUGen detector level (everything reweighted to SM):

$fa_2 = 1$
$fa_3 = 1$
$fa_1 = 0.5$
JHUGen in action

CMS analysis $H \rightarrow ZZ^*/Z\gamma^*/\gamma^*\gamma^* \rightarrow 4l$  


angular and mass variables for on-shell kinematics
all signal distributions obtained via reweighting
JHUGen in action

CMS analysis $H \rightarrow ZZ^*/Z\gamma^*/\gamma^*\gamma^* \rightarrow 4l$


discriminants for on-shell kinematics
all signal distributions obtained via reweighting
Distributions of anomalous couplings were obtained by reweighting the base sample using JHUGen.
mass variables for on-shell kinematics all signal distributions obtained via reweighting of all models to all models
JHUGen in action: Off-shell reweighting

CMS Higgs off-shell analysis


\[
\sigma_{\nu\nu \to H \to ZZ}^{\text{on-shell}} \sim \mu_{\nu\nu H} \Rightarrow \sigma_{\nu\nu \to H \to ZZ}^{\text{off-shell}} \sim \mu_{\nu\nu H} \times \Gamma_H
\]

Gluon fusion signal only

all signal distributions obtained via re-weighting

use add-on for MCFM to implement anomalous couplings and interface MELA with MCFM to include signal + background + interference
JHUGen in action: Background reweighting

H. Roskes, Validation of the Higgs boson spin-parity analysis with $Z \rightarrow 4l$ data

http://meetings.aps.org/link/BAPS.2015.APR.X16.8

Mixture of $s$, $t$, and $u$ channels generated with POWHEG

MELA reweighting used $s$ and $t + u$ channels separately, along with interference

$gg$ background is obtained by reweighting $q\bar{q}$
JHUGen in action: Background reweighting

H. Roskes, Validation of the Higgs boson spin-parity analysis with $Z \rightarrow 4l$ data

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MELA discriminant $D_{\text{kin}}^{\text{bkg}}$ to separate $Z$ boson from alternative Higgs hypothesis. Higgs hypothesis excluded at > 99% CL
Summary

JHUGen is a flexible framework for studies of anomalous couplings in spin-0,1,2 resonance production and other associated production modes.

\[
\begin{align*}
\text{VBF} & \quad t\bar{t}H \\
H + 1 \text{ or 2 QCD jets} & \quad \text{More to come} \\
\text{VH} & \\
\end{align*}
\]

JHUGenMELA provides respective matrix elements for:
- optimal discriminants for anomalous coupling fits
- background suppression
- re-weighting

Fruitful application in various analyses by CMS and ATLAS

Future developments:
- Application to more Higgs production mechanisms and decay channels