Tools for the Higgs boson CP studies: JHUGen and MELA

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Theory, experiment

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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

$gg \to H$

$gg/gq \to H + \text{jet}$

$gg/gq/qq' \to H + 2$ jets (QCD)

$qq' \to H + 2$ jets (VBF)

$q\bar{q} \to Z^* \to Z + H$

$q\bar{q}' \to W^* \to W + H$

$gg/q\bar{q} \to t\bar{t}H$

$t \to Wb \to l\nu b/q\bar{q}'b$

$q\bar{q} \to$ spin 1

$gg/q\bar{q} \to$ spin 2

Interface to MCFM for $gg \to ZZ$ offshell with anomalous couplings

Decay:

$\to$ $ZZ^* + Z\gamma^* + \gamma^*\gamma^* \to$ any combination of l^+l^-, $\nu\bar{\nu}$, $q\bar{q}$

$\to$ $W^+W^- \to$ any combination of $l\nu$ and $q\bar{q}'$

$\to$ $Z\gamma$, $\gamma\gamma$

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

$$A(HVV) \sim \left[a_1 + \frac{q_{V_1}^2 + q_{V_2}^2}{(\Lambda_1)^2} + \frac{(q_{V_1} + q_{V_2})^2}{(\Lambda_Q)^2}\right] m_{V_1}^2 \epsilon_{V_1}^* \epsilon_{V_2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

$$\begin{aligned}
L(HVV) \sim\ & a_1^{ZZ} \frac{m_Z^2}{2} H Z^\mu Z_\mu - \frac{1}{\left(\Lambda_1^{ZZ}\right)^2} m_Z^2 H Z^\mu \Box Z_\mu - \frac{1}{2\left(\Lambda_Q^{ZZ}\right)^2} m_Z^2 \Box H Z^\mu Z_\mu - \frac{1}{2} a_2^{ZZ} H Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3^{ZZ} H Z^{\mu\nu} \tilde{Z}_{\mu\nu} \\
& + a_1^{WW} m_W^2 H W^{+\mu} W_\mu^- - \frac{1}{\left(\Lambda_1^{WW}\right)^2} m_W^2 H \left(W_\mu^- \Box W^{+\mu} + W_\mu^+ \Box W^{-\mu}\right) \\
& \quad - \frac{1}{\left(\Lambda_Q\right)^2} m_W^2 \Box H W^{+\mu} W_\mu^- - a_2^{WW} H W^{+\mu\nu} W_{\mu\nu}^- - a_3^{WW} H W^{+\mu\nu} \tilde{W}_{\mu\nu}^- \\
& + \frac{1}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 H Z_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} H F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} H F^{\mu\nu} \tilde{Z}_{\mu\nu} \\
& - \frac{1}{2} a_2^{\gamma\gamma} H F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} H F^{\mu\nu} \tilde{F}_{\mu\nu} \\
& - \frac{1}{2} a_2^{gg} H G_a^{\mu\nu} G_{\mu\nu}^a - \frac{1}{2} a_3^{gg} H G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a
\end{aligned}$$

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

Predictions are leading order QCD

POWHEG (NLO QCD) $gg \to H \longrightarrow$ 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_gg_G_VV	EvalAmp_HJ
EvalAmp_H_VV	EvalAmp_qqb_G_VV	EvalXSec_PP_TTBH
EvalAmp_VHiggs	EvalAmp_G_VV	EvalAmp_GG_TTBH
EvalAmp_qqb_Zprime_VV	EvalAmp_WBFH	EvalAmp_QQB_TTBH
EvalAmp_Zprime_VV	EvalAmp_SBFH	

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: $\text{weight}\left(d\Pi\right) = \frac{P(J^P_{\text{target}}, d\Pi)}{P(J^P_{\text{sample}}, d\Pi)}$

$$d\Pi = \begin{cases} \theta^*, \theta_1, \theta_2, \phi, \phi_1, m_1, m_2, m_H \\ p_1, p_2, p_3, p_4 \end{cases}$$

For reweighting, $d\Pi = d\Pi_{\text{generator}}$

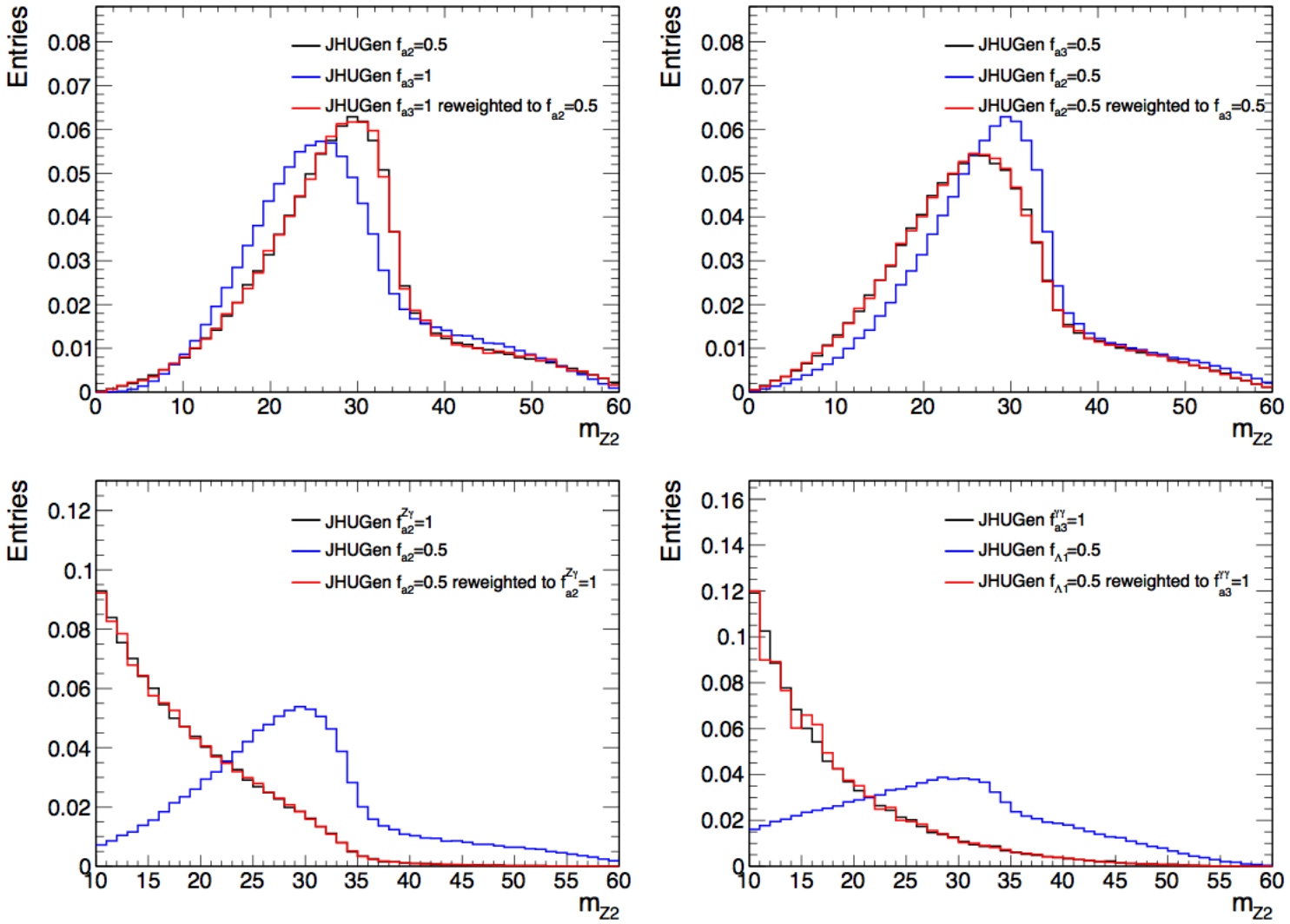
(For fitting, $d\Pi = d\Pi_{\text{observed}}$)

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

or $\sim f_i^p\left(x_1\right) f_j^p(x_2) \left|\mathcal{M}\left(d\Pi\right)\right|^2$

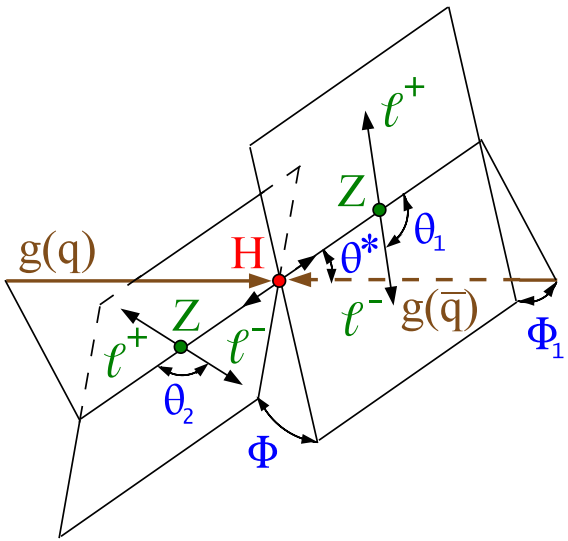
Validation of reweighting

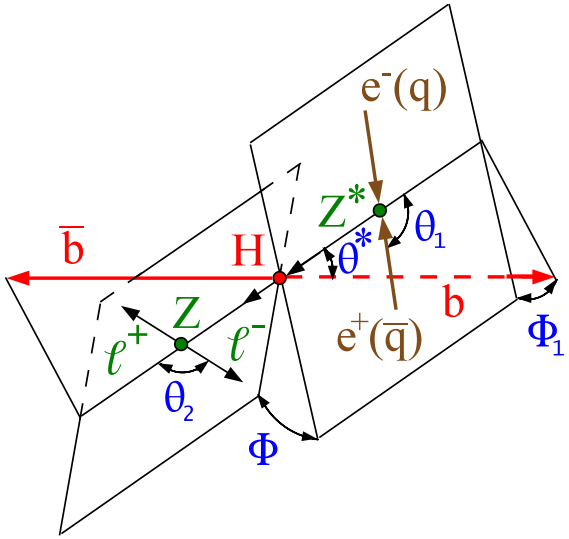
Compare reweighted sample vs. dedicated production

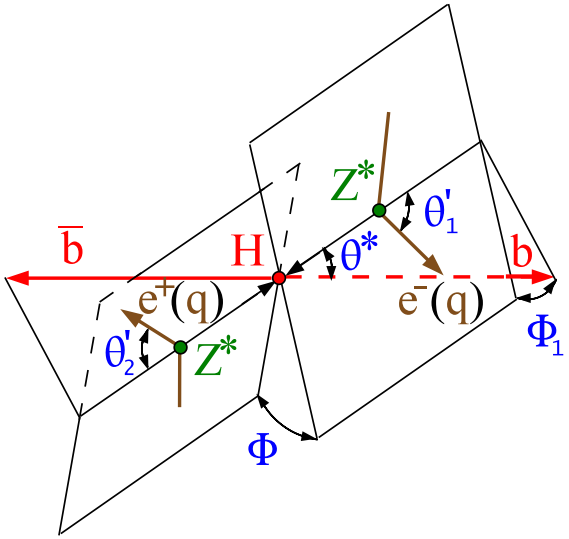


HVV vertex kinematics

arXiv:1309.4819







$[gg \to] H \to ZZ \to 4l$

$q\bar{q} \to Z^* \to ZH$

$Z \to l^+ l^- \left[H \to b\bar{b}\right]$

VBF

$qq' \to Z^* Z^* \to H \left[\to b\bar{b}\right]$

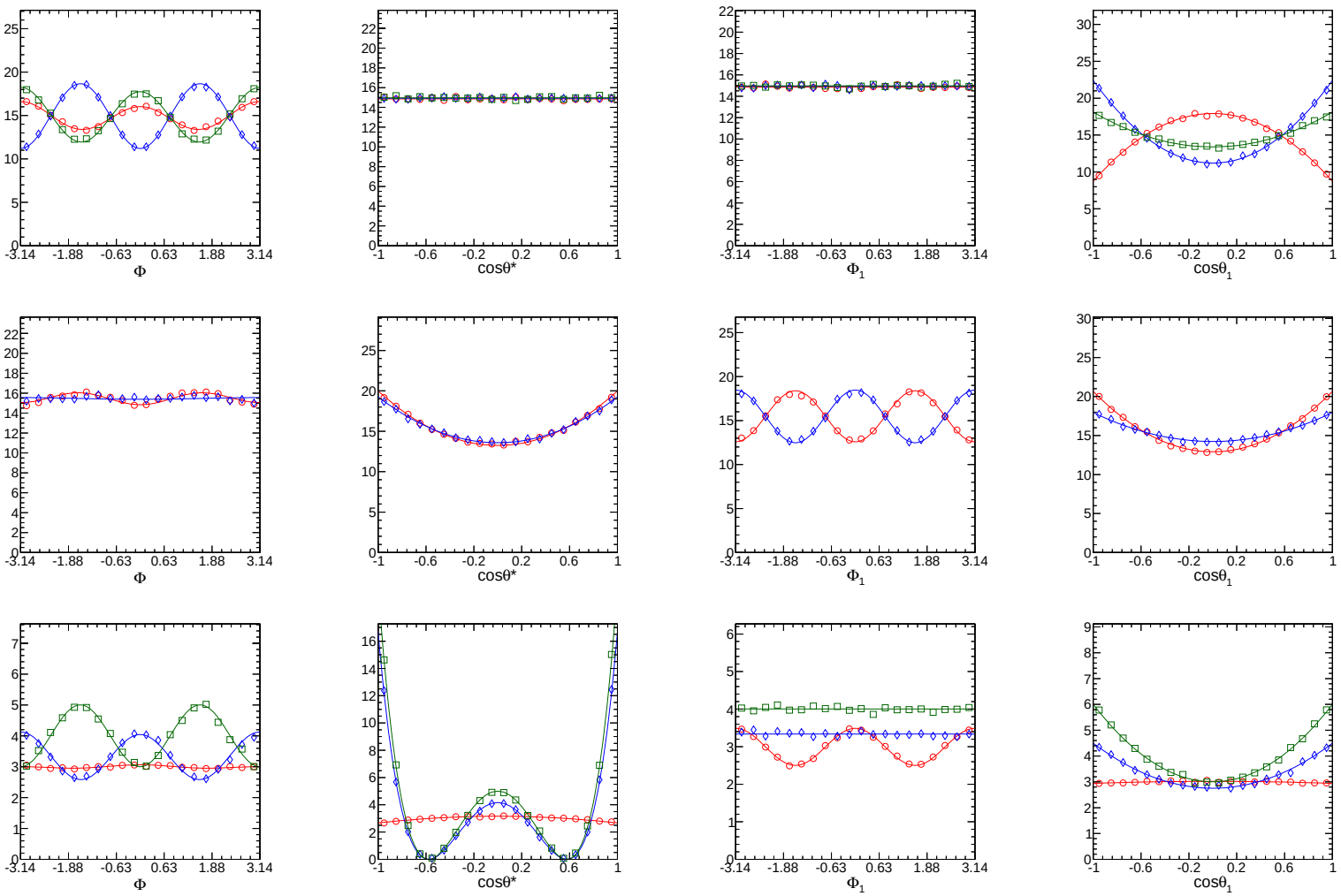
Applications for discriminating spin and CP properties

$H \to ZZ \to 4l$ decay arXiv:1208.4018

Spin 0
0^+ 0^- 0_h^+

Spin 1
1^+ 1^- 1_h^+

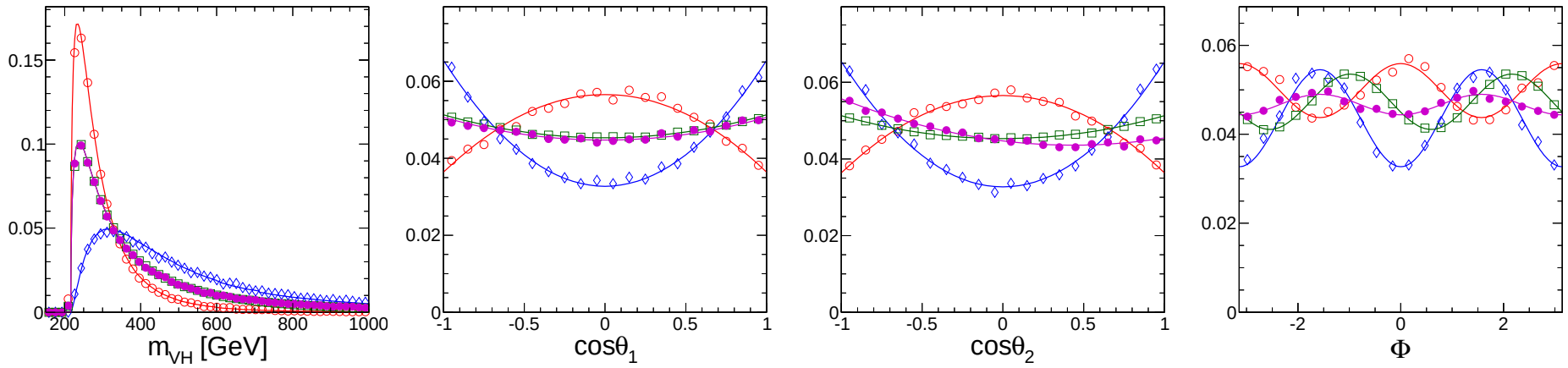
Spin 2
2^+ 2^- 2_h^+



Applications for discriminating CP properties

VH 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

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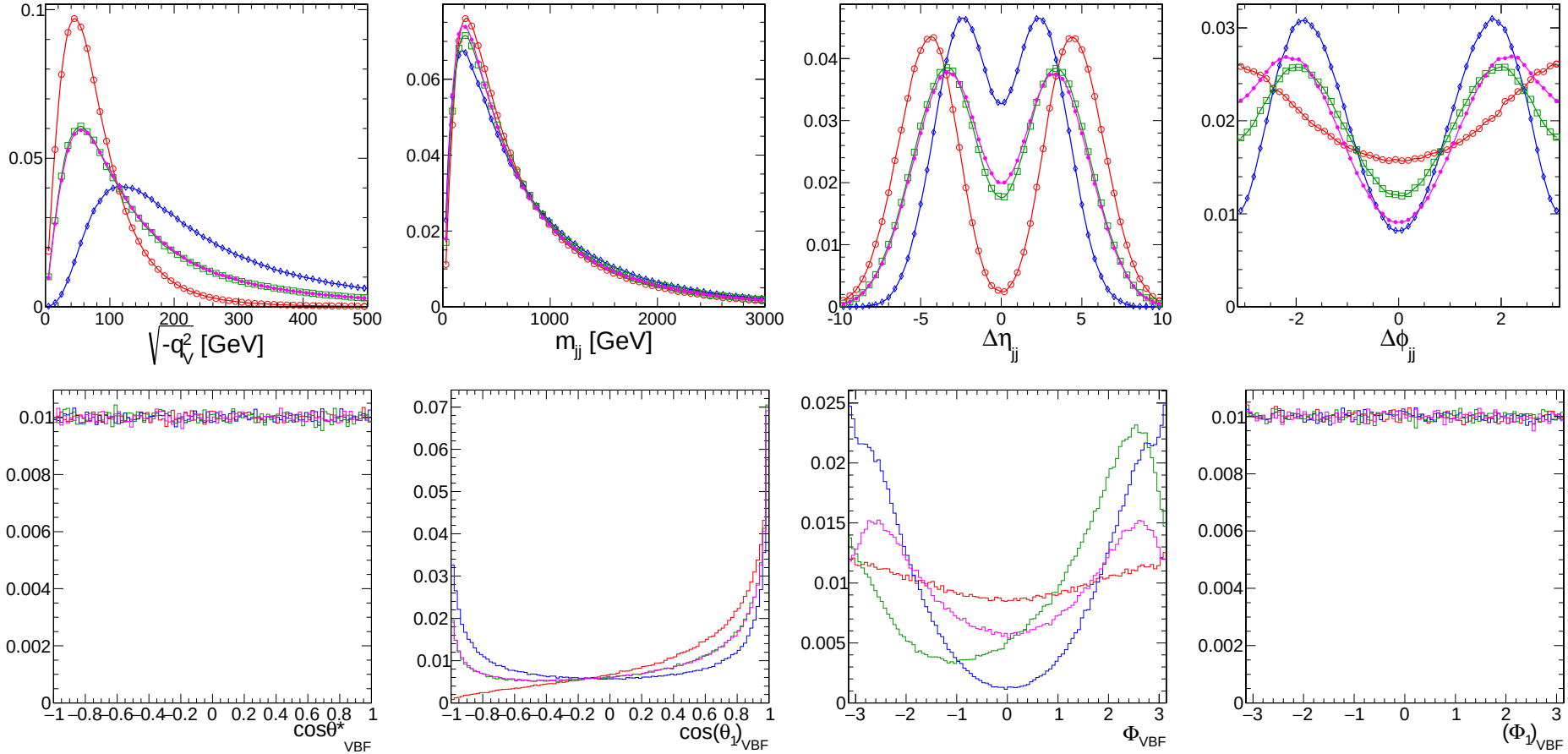


Applications for discriminating CP properties

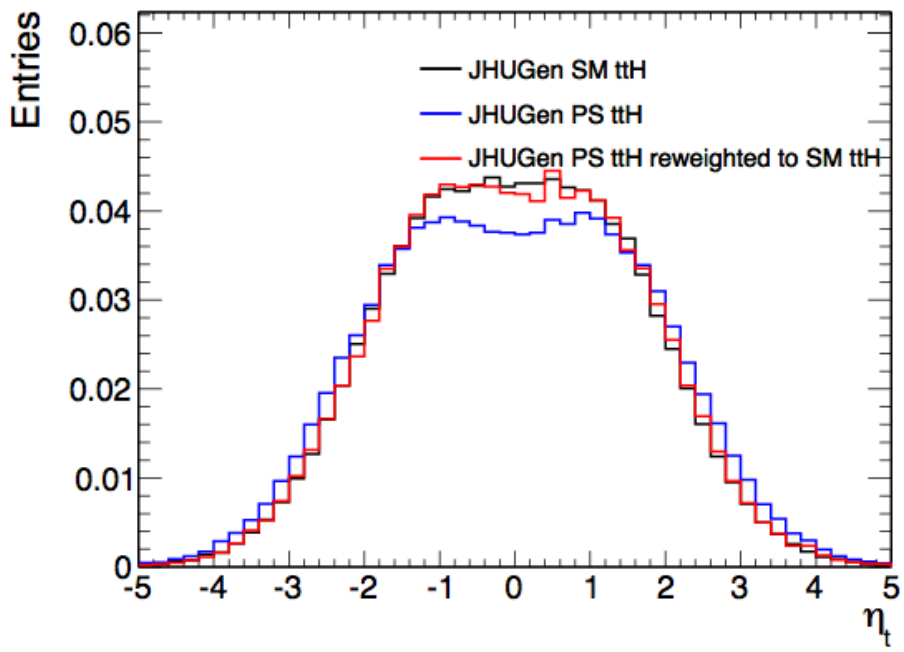
Summary table

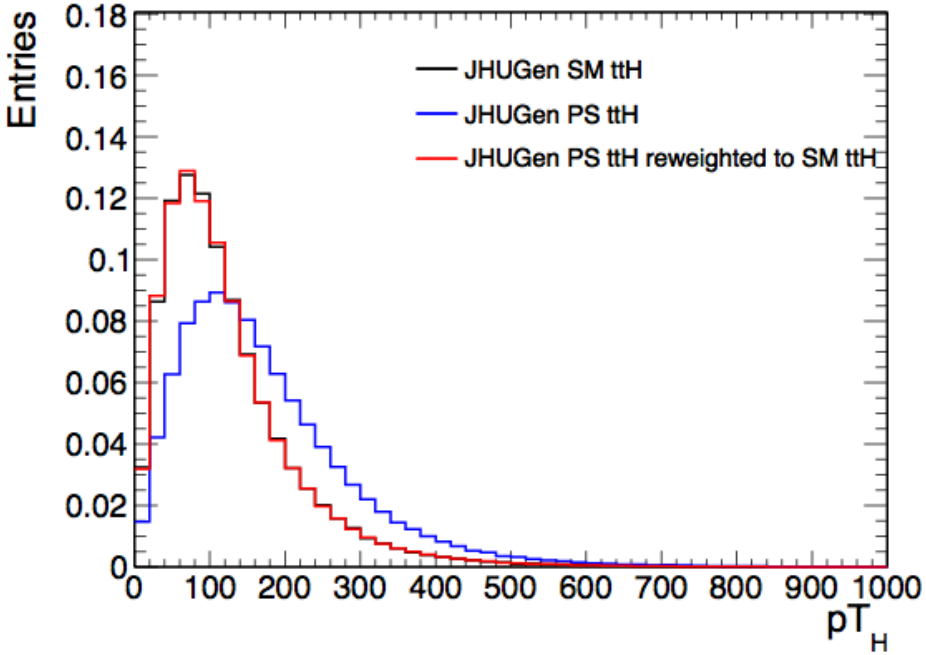
arXiv:1309.4819

process description					MC simulation parameters						expected precision			
collider	energy	mode	σ_2/σ_1	σ_4/σ_+	$\lvert g_2/g_1\rvert$	$\lvert g_4/g_+\rvert$	f_{a2}	$f_{a2}^{\rm dec}$	f_{a3}	$f_{a3}^{\rm dec}$	δf_{a2}	$\delta f_{a2}^{\rm dec}$	δf_{a3}	$\delta f_{a3}^{\rm dec}$
any	any	$H \to ZZ^*$	0.362	0.153	0	1.20		0		0.18		–		0.06
					0	0.67		0		0.06		–		0.02
					0.78	0		0.18		0		0.088		–
					0.42	0		0.06		0		0.014		–
any	any	$H \to WW^*$	0.776	0.322	0	1.76		0		0.50		–		–
					1.13	0		0.50		0		–		–
any	any	$H \to \gamma\gamma, gg$	N/A	1.0	N/A	1.0		0		0.50		–		–
any	any	$H \to Z\gamma$	N/A	1.0	N/A	1.0		0		0.50		–		–
pp	14 TeV	$gg \to H$	N/A	1.0	N/A	1.0	0	0	0.50	0.50		–	0.50	0.50
		$(H \to ZZ^*)$			N/A	1.0	0	0	0.50	0.50		–	0.16	0.16
pp	14 TeV	$V^*V^* \to H$	14.0	11.3	0	0.299	0	0	0.50	0.013		–	0.190	7×10^{-3}
		$(H \to ZZ^*)$			0	0.109	0	0	0.12	0.0018		–	0.036	6×10^{-4}
pp	14 TeV	$V^*V^* \to H$	14.0	11.3	0	0.109	0	0	0.12	0.0018		–	0.04	7×10^{-4}
		$(H \to \gamma\gamma)$			0	0.052	0	0	0.030	0.0004		–	0.009	1.3×10^{-4}
pp	14 TeV	$V^* \to VH$	76.1	46.8	0	0.145	0	0	0.50	0.0032		–	0.32	3×10^{-3}
		$(V \to q\bar{q}', H \to ZZ^*)$			0	0.095	0	0	0.30	0.0014		–	0.10	6×10^{-4}
pp	14 TeV	$V^* \to VH$	76.1	46.8	0	0.061	0	0	0.15	0.0006		–	0.09	4×10^{-4}
		$(V \to \ell^+\ell^-, H \to b\bar{b})$			0	0.049	0	0	0.10	0.0004		–	0.029	1.2×10^{-4}
e^+e^-	250 GeV	$Z^* \to ZH$	34.1	8.07	0	0.117	0	0	0.10	2×10^{-3}		–	0.032	7×10^{-4}
					0.057	0	0.10	1.2×10^{-3}	0	0	0.033	4×10^{-4}		–
e^+e^-	350 GeV	$Z^* \to ZH$	84.2	50.6	0	0.0469	0	0	0.10	3×10^{-4}		–	0.031	1.1×10^{-4}
					0.025	0	0.05	2×10^{-4}	0	0	0.015	7×10^{-5}		–
e^+e^-	500 GeV	$Z^* \to ZH$	200.8	161.1	0	0.0263	0	0	0.10	1.1×10^{-4}		–	0.034	4×10^{-5}
					0.024	0	0.10	2×10^{-4}	0	0	0.033	7×10^{-5}		–
e^+e^-	1 TeV	$Z^* \to ZH$	916.5	870.8	0	0.0113	0	0	0.10	2×10^{-5}		–	0.037	8×10^{-6}
					0.014	0	0.15	7×10^{-5}	0	0	0.049	3×10^{-5}		–

ttH

Study top quarks produced in association with Higgs





Associated top production is very sensitive to the incoming partons

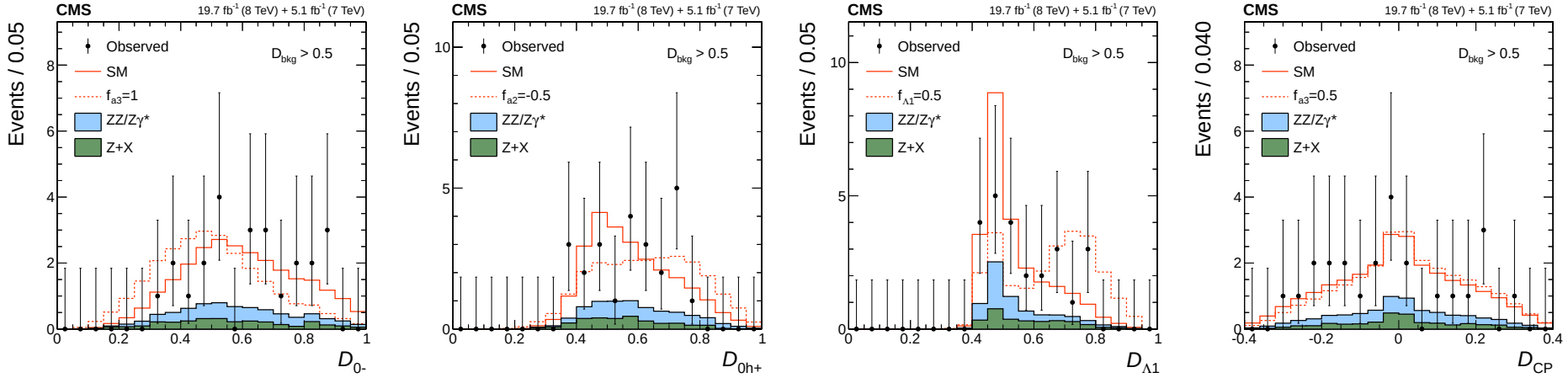
$\Rightarrow$ Include PDF in MELA weight

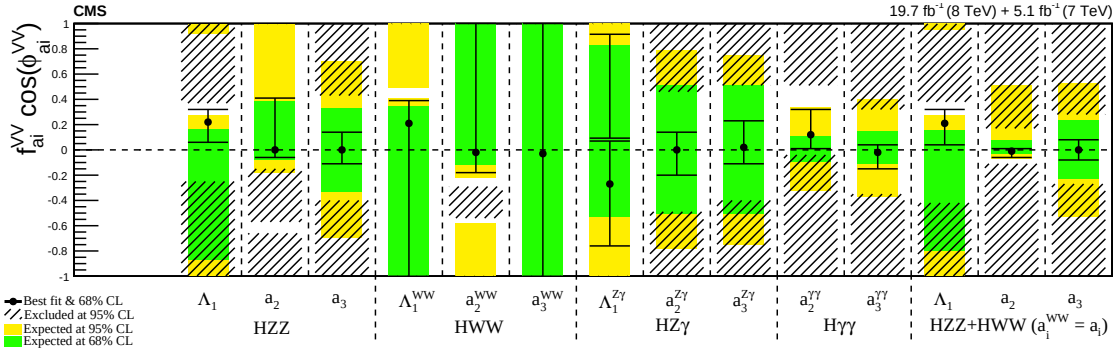
$$\sim f_i^p(x_1)\, f_j^p(x_2) \times |\mathcal{M}(d\Pi)|^2$$

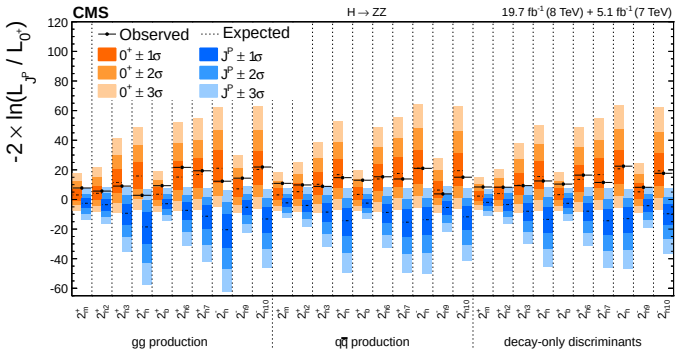
Similar for VBF, VH, $H + j\,(j)$

JHUGen in action: Generation, reweighting, discriminants

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



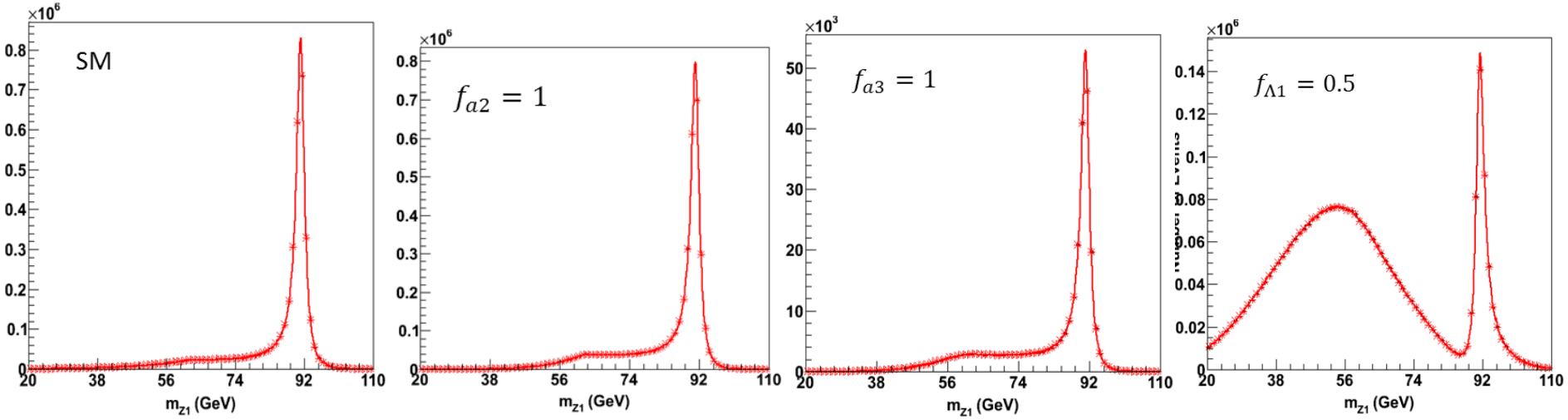




JHUGen in action: Applications of reweighting

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

JHUGen generator level:



Generate 24 base models

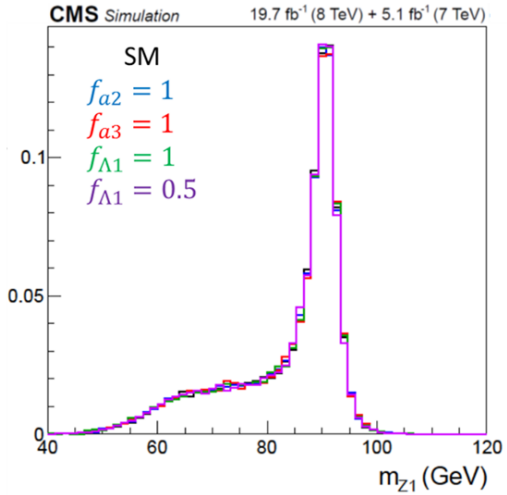
Create 52 target models through reweighting

To increase statistics:

Reweight *everything to everything*

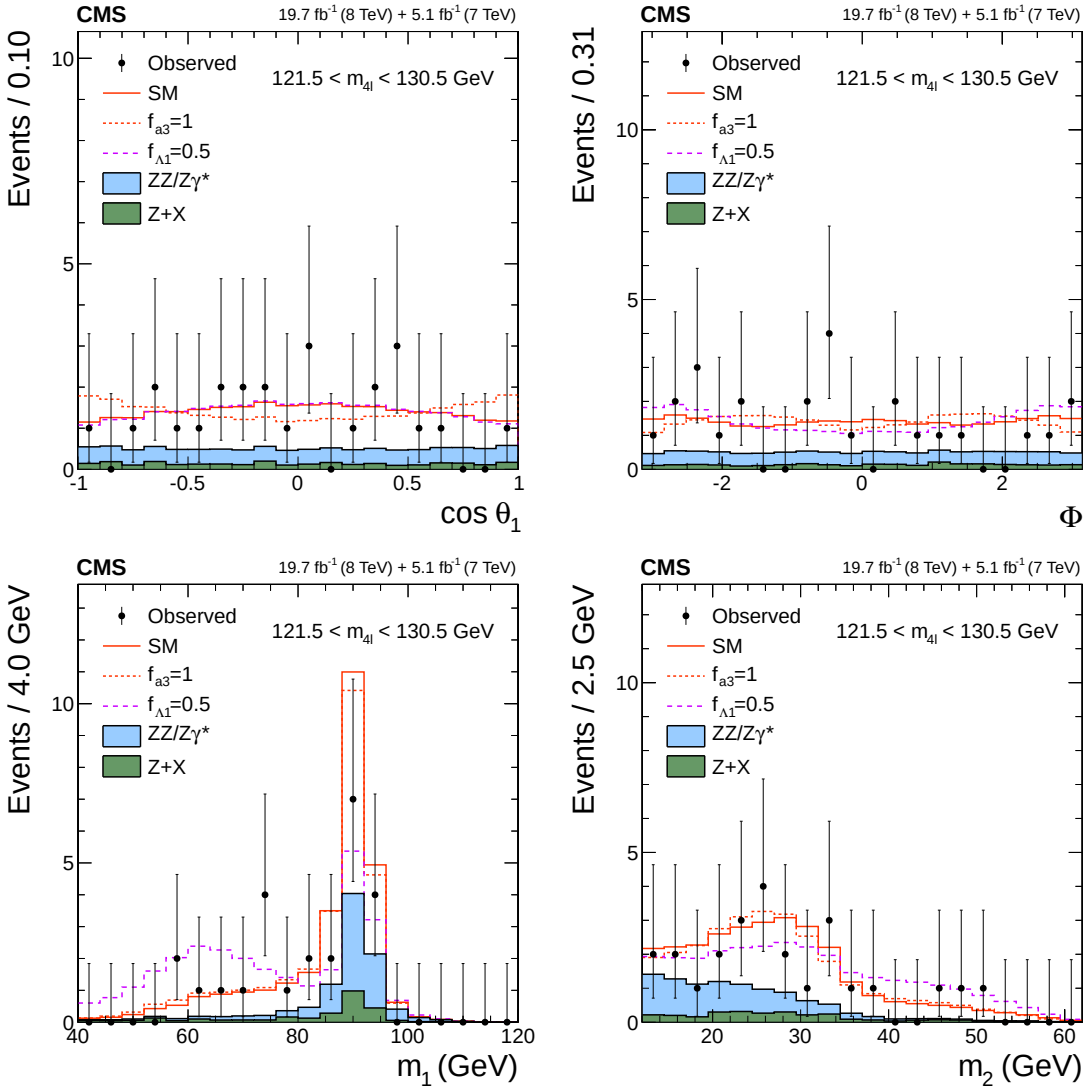
Effectively increase sample size by $\times 24$.

JHUGen detector level (everything reweighted to SM):



JHUGen in action

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

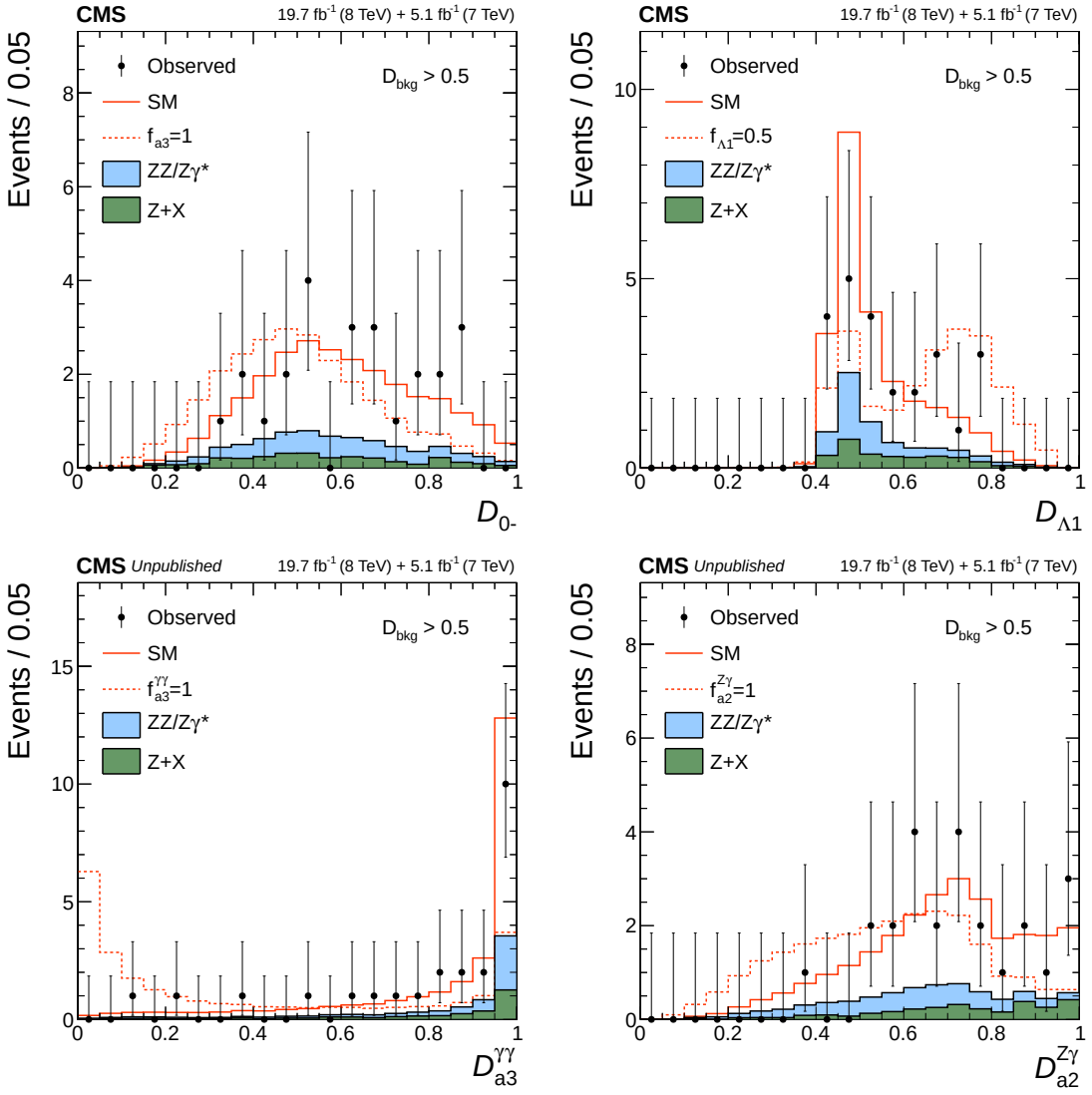


angular and mass variables for on-shell kinematics

all signal distributions obtained via reweighting

JHUGen in action

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

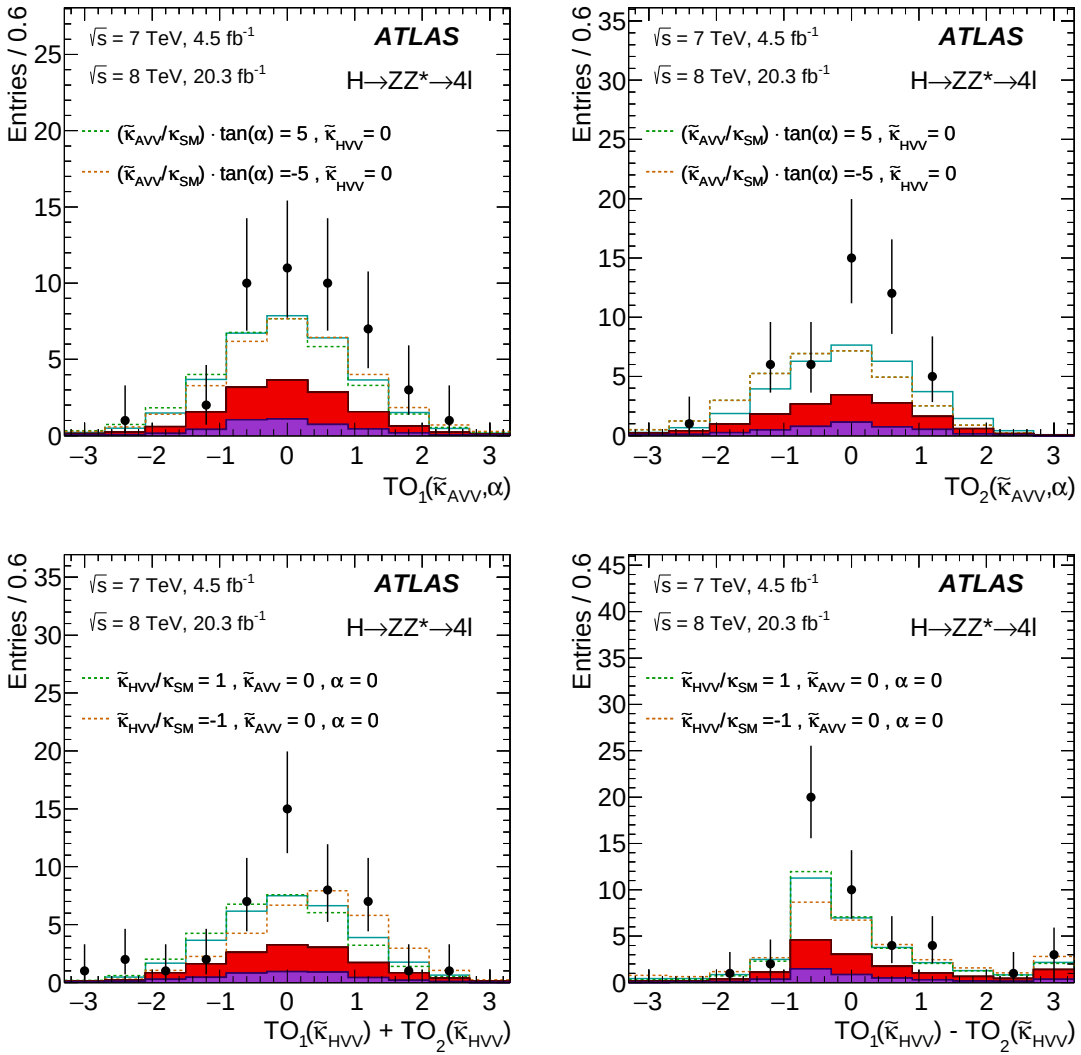


discriminants for on-shell kinematics

all signal distributions obtained via reweighting

JHUGen in action

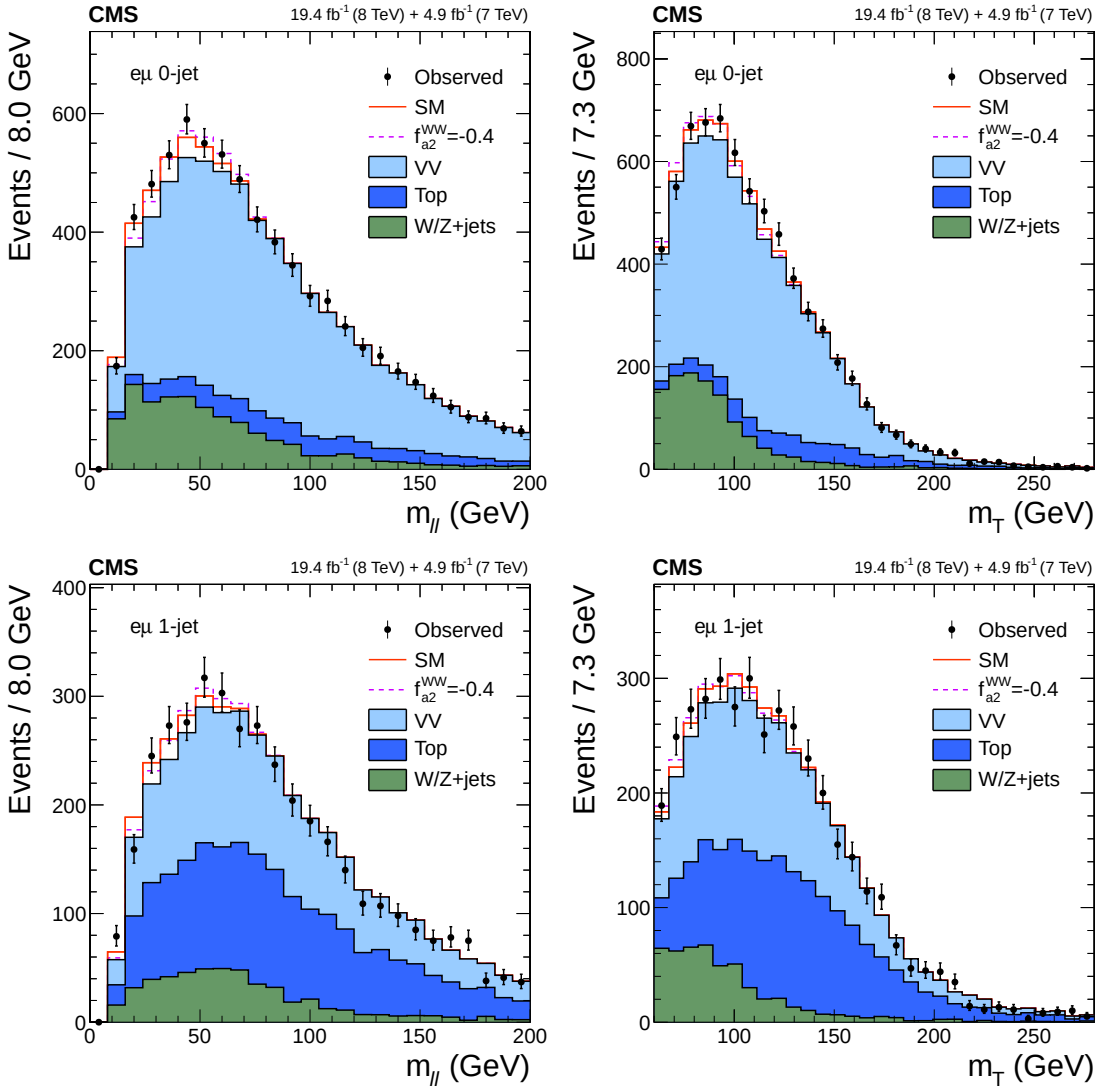
ATLAS analysis $H \to ZZ^* \to 4l$ [ATLAS-HIGG-2013-17] arXiv:1506.05669



Distributions of anomalous couplings were obtained by reweighting the base sample using JHUGen.

JHUGen in action

CMS analysis $H \to WW$ [CMS-HIG-14-018] arXiv:1411.3441



mass variables for on-shell kinematics

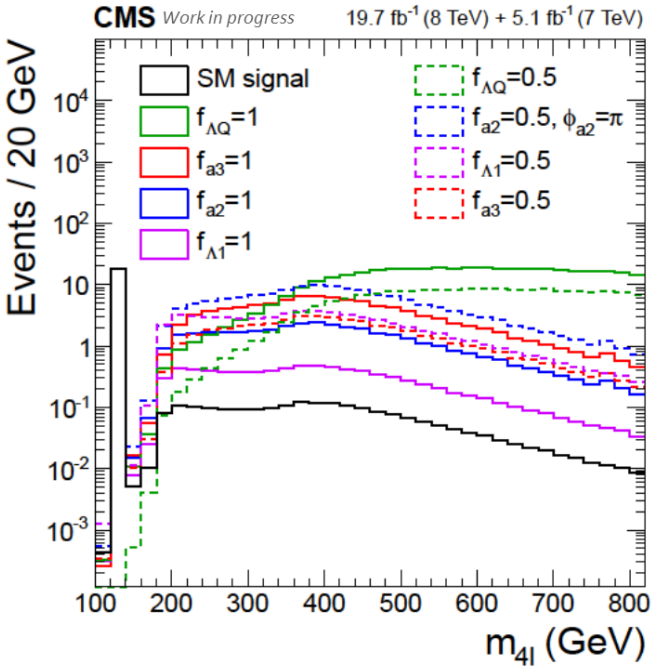
all signal distributions obtained via reweighting of all models to all models

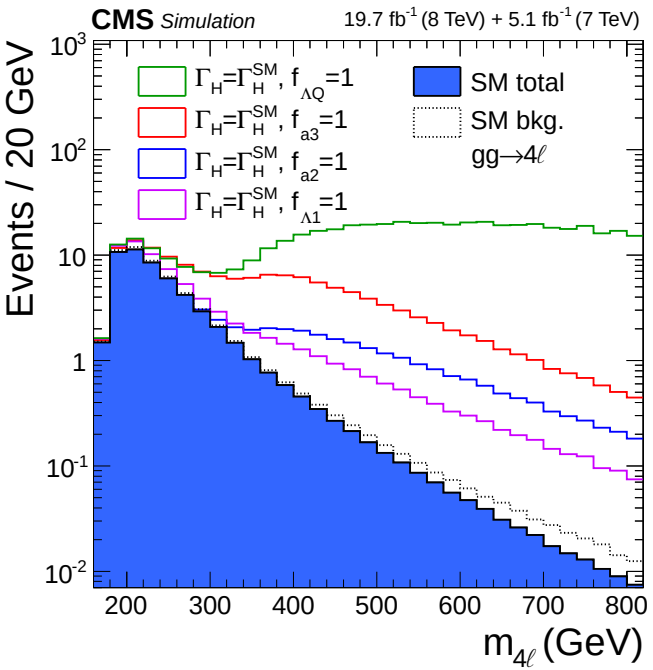
JHUGen in action: Off-shell reweighting

CMS Higgs off-shell analysis [CMS-HIG-14-036] `arXiv:1507.06656`

$$\sigma^{\text{on-shell}}_{vv\to H\to ZZ} \sim \mu_{vvH} \Rightarrow \sigma^{\text{off-shell}}_{vv\to H\to ZZ} \sim \mu_{vvH} \times \Gamma_H$$

Gluon fusion signal only





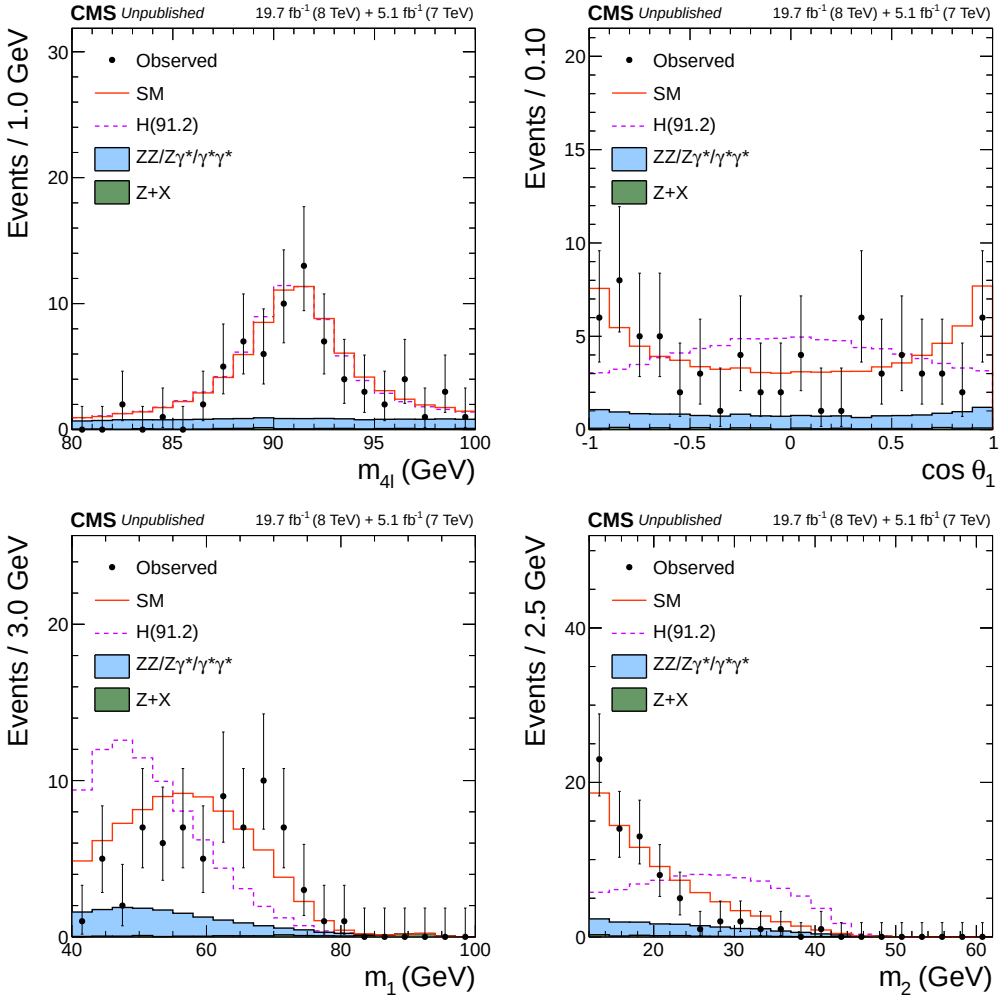
Gluon fusion signal + bkg. + int.

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 $Z \to 4l$ data*
http://meetings.aps.org/link/BAPS.2015.APR.X16.8



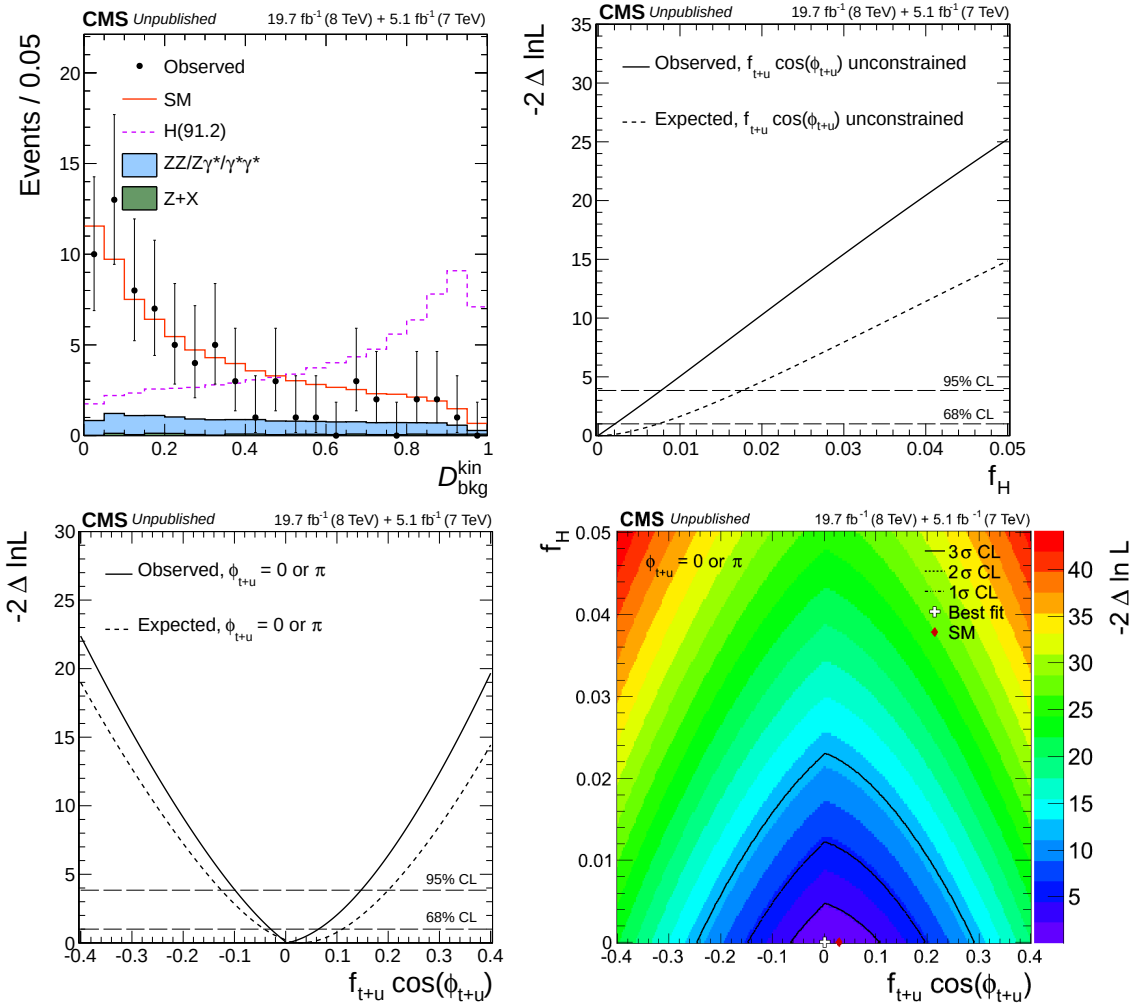
Mixture of s, t, and u channels generated with POWHEG

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 $Z \to 4l$ data*
http://meetings.aps.org/link/BAPS.2015.APR.X16.8



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.

VBF	$t\bar{t}H$
H+1 or 2 QCD jets	More to come
VH	

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