Property Measurements of Higgs-like Single Resonance at LHC

"The JHU Generator"

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On behalf of

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Outline

- Review the pp→X→VV interactions
  - The JHU Generator is used to simulate the pp→X→VV interactions
  - Quick comparison to the VBF@NLO for the spin 2 X→γγ couplings
- Review the angular analysis and perform generator validations
- Summary

Describe pp→X→VV Interactions

The JHU Generator

- A MC program developed to simulate production and decay of $X \rightarrow VV$ with X spin <= 2
  - $X \rightarrow ZZ \rightarrow$ 4l, 2l2τ, 2l2ν, 2l2q
  - $X \rightarrow WW \rightarrow$ 2l2ν, lντν, lνqq
  - $X \rightarrow \gamma\gamma$
- Includes all spin correlations and all possible couplings
  - Inputs are general dimensionless couplings - calculates matrix elements
- For the production of X, both gg and qq are considered
- Output in LHE format; e.g. can interface to Pythia for hadronization
- All code publicly available: www.pha.jhu.edu/spin
  - A dedicated manual is in preparation, aiming to release soon

X→VV Amplitude for Spin-0

- Model independent amplitude

$$A = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$$f^{(i),\mu\nu} = \epsilon_i^\mu q_i^\nu - \epsilon_i^\nu q_i^\mu \qquad \tilde{f}_{\mu\nu}^{(i)} = 1/2\ \epsilon_{\mu\nu\alpha\beta} f^{(i),\alpha\beta} = \epsilon_{\mu\nu\alpha\beta}\epsilon_i^\alpha q_i^\beta$$

- Rewrite it in terms of polarization vectors

$$A = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right)$$

  - The couplings a_1-a_3 terms are expressed in terms of the couplings g_1-g_4, see reference paper

- The total amplitude is then expressed as the sum of 3 independent helicity amplitudes, which later can be used in angular analysis

$$A_{00} = -\frac{M_X^2}{v}\left(a_1 x + a_2 \frac{M_{V_1} M_{V_2}}{M_X^2}(x^2 - 1)\right)$$

$$A_{\pm\pm} = +\frac{M_X^2}{v}\left(a_1 \pm i a_3 \frac{M_{V_1} M_{V_2}}{M_X^2}\sqrt{x^2 - 1}\right) \qquad \Leftarrow \quad x = \frac{M_X^2 - M_{V_1}^2 - M_{V_2}^2}{2 M_{V_1} M_{V_2}}$$

X→VV Amplitude for Spin-2

- Model independent amplitude including 10 dimensionless couplings with arbitrary parity

$$A = \Lambda^{-1}\left[2g_1^{(2)} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}\right.$$

$$+g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$

$$+m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}\right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^*\right)$$

$$+g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + g_9^{(2)} t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma \Bigg)$$

$$\left. + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*)\right)\right]$$

X→VV Helicity Amplitudes for Spin-2

- Rewrite the amplitude in terms of polarization amplitudes for the on-shell decay

$2^+\ CP$, $2^-\ \not{CP}$

$$
\begin{aligned}
A = \frac{e_1^{*\mu} e_2^{*\nu}}{\Lambda} \Big[& c_1\, t_{\mu\nu}(q_1 q_2) + c_2\, g_{\mu\nu} t_{\alpha\beta}(q_1-q_2)^\alpha (q_1-q_2)^\beta \\
& + \frac{c_3\, t_{\alpha\beta}}{M_X^2} q_{2\mu} q_{1\nu} (q_1-q_2)^\alpha (q_1-q_2)^\beta + 2c_4 \left(t_{\mu\alpha} q_{1\nu} q_2^\alpha + t_{\nu\alpha} q_{2\mu} q_1^\alpha \right) \\
& + \frac{c_5 t_{\alpha\beta}}{M_X^2} (q_1-q_2)^\alpha (q_1-q_2)^\beta \epsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma + c_6 t^{\alpha\beta} (q_1-q_2)_\beta \epsilon_{\mu\nu\alpha\rho} q^\rho \\
& + \frac{c_7 t^{\alpha\beta}}{M_X^2} (q_1-q_2)_\beta \left(\epsilon_{\alpha\mu\rho\sigma} q^\rho (q_1-q_2)^\sigma q_\nu + \epsilon_{\alpha\nu\rho\sigma} q^\rho (q_1-q_2)^\sigma q_\mu \right) \Big]
\end{aligned}
$$

$2^+\ \not{CP}$, $2^-\ CP$

  - The couplings c_1-c_7 terms are expressed in terms of the couplings g_1-g_{10}, see reference paper

- It is then expressed in terms of 9 helicity amplitudes to be used in angular analysis

$$A_{00} = \frac{M_X^4}{M_V^2 \sqrt{6}\Lambda} \left[\left(1+\beta^2\right) \left(\frac{c_1}{8} - \frac{c_2}{2}\beta^2 \right) - \beta^2 \left(\frac{c_3}{2}\beta^2 - c_4 \right) \right]$$

$$A_{\pm\pm} = \frac{M_X^2}{\sqrt{6}\Lambda} \left[\frac{c_1}{4} \left(1+\beta^2\right) + 2c_2\beta^2 \pm i\beta (c_5\beta^2 - 2c_6) \right]$$

$$A_{\pm 0} \equiv A_{0\pm} = \frac{M_X^3}{M_V \sqrt{2}\Lambda} \left[\frac{c_1}{8} \left(1+\beta^2\right) + \frac{c_4}{2}\beta^2 \mp i\beta \frac{(c_6 + c_7\beta^2)}{2} \right]$$

$$A_{+-} \equiv A_{-+} = \frac{M_X^2}{4\Lambda} c_1 \left(1+\beta^2\right)$$

- The full helicity amplitudes for the off-shell case are in preparation for manuscript

Connect to VBF@NLO for spin 2

- We compare the equations 1-2 to the VBF@NLO release note
  - http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/wiki/lib/exe/fetch.php?media=documentation:vbfnlo_releasenote26.pdf

For the singlet spin-2 field, $T^{\mu\nu}$, the effective Lagrangian is

$$\mathcal{L}_{\rm singlet} = \frac{1}{\Lambda} T_{\mu\nu} \left(\boxed{f_1 B^{\alpha\nu} B^{\mu}_{\alpha} + f_2 W_i^{\alpha\nu} W^{i,\mu}_{\alpha}} + \boxed{f_3 \widetilde{B}^{\alpha\nu} B^{\mu}_{\alpha} + f_4 \widetilde{W}_i^{\alpha\nu} W^{i,\mu}_{\alpha}} + \boxed{2 f_5 (D^\mu \Phi)^\dagger (D^\nu \Phi)} \right), \quad (1)$$

and for the spin-2 triplet field, $T_j^{\mu\nu}$, the effective Lagrangian is given by

$$\mathcal{L}_{\rm triplet} = \frac{1}{\Lambda} T_{\mu\nu j} \left(\boxed{f_6 (D^\mu \Phi)^\dagger \sigma^j (D^\nu \Phi) + f_7 W^{j,\mu}_{\alpha} B^{\alpha\nu}} \right), \quad (2)$$

- The approximate corresponding couplings in the JHUGen

g1 g5 g9

- Technical parameters for generating the 2m+
  - JHUGen: g1 = g5 = 1
  - VBF@NLO: F1=F2=F5 = 1

Technical Details on Generating 0+/0-/2m+

A more comprehensive manual is in preparation

Technical Detail on the 0+/0- Decay

- Coupling constants setup for the file mod_Parameters.F90

0+

```
!-- parameters that define off-shell spin 0 coupling to SM fields, see note
   complex(8), public, parameter :: ghg2 = (1.0d0,0d0)
   complex(8), public, parameter :: ghg3 = (0.0d0,0d0)
   complex(8), public, parameter :: ghg4 = (0.0d0,0d0)   ! pseudoscalar
   complex(8), public, parameter :: ghz1 = (1.0d0,0d0)
   complex(8), public, parameter :: ghz2 = (0.0d0,0d0)
   complex(8), public, parameter :: ghz3 = (0.0d0,0d0)
   complex(8), public, parameter :: ghz4 = (0.0d0,0d0)   ! pseudoscalar
```

0-

```
!-- parameters that define off-shell spin 0 coupling to SM fields, see note
   complex(8), public, parameter :: ghg2 = (0.0d0,0d0)   ! scalar
   complex(8), public, parameter :: ghg3 = (0.0d0,0d0)
   complex(8), public, parameter :: ghg4 = (1.0d0,0d0)   ! pseudoscalar
   complex(8), public, parameter :: ghz1 = (0.0d0,0d0)   ! scalar
   complex(8), public, parameter :: ghz2 = (0.0d0,0d0)
   complex(8), public, parameter :: ghz3 = (0.0d0,0d0)
   complex(8), public, parameter :: ghz4 = (1.0d0,0d0)   ! pseudoscalar
```

- Follow the instructions of the README for the executable command

Technical Details on the 2m+ Decay

- Coupling constants setup for the file mod_Parameters.F90

```
!-- parameters that define spin 2 coupling to SM fields, see note
! minimal coupling corresponds to a1 = b1 = b5 = 1 everything else 0
  complex(8), public, parameter :: a1 = (1.0d0,0d0)    ! g1  -- c.f. draft
  complex(8), public, parameter :: a2 = (0.0d0,0d0)    ! g2
  complex(8), public, parameter :: a3 = (0.0d0,0d0)    ! g3
  complex(8), public, parameter :: a4 = (0.0d0,0d0)    ! g4
  complex(8), public, parameter :: a5 = (0.0d0,0d0)    ! pseudoscalar, g8
  complex(8), public, parameter :: graviton_qq_left  = (1.0d0,0d0)! graviton coupling to quarks
  complex(8), public, parameter :: graviton_qq_right = (1.0d0,0d0)

!-- see mod_Graviton
  logical, public, parameter :: generate_bis = .true.
  logical, public, parameter :: use_dynamic_MG = .true.

  complex(8), public, parameter :: b1 = (1.0d0,0d0)    !  all b' below are g's in the draft
  complex(8), public, parameter :: b2 = (0.0d0,0d0)
  complex(8), public, parameter :: b3 = (0.0d0,0d0)
  complex(8), public, parameter :: b4 = (0.0d0,0d0)
  complex(8), public, parameter :: b5 = (1.0d0,0d0)
  complex(8), public, parameter :: b6 = (0.0d0,0d0)
  complex(8), public, parameter :: b7 = (0.0d0,0d0)
  complex(8), public, parameter :: b8 = (0.0d0,0d0)
  complex(8), public, parameter :: b9 = (0.0d0,0d0)
  complex(8), public, parameter :: b10 =(0.0d0,0d0)  ! this coupling does not contribute for gamma+gamma final states
```

Review Angular Analysis and Perform JHUGen Validation

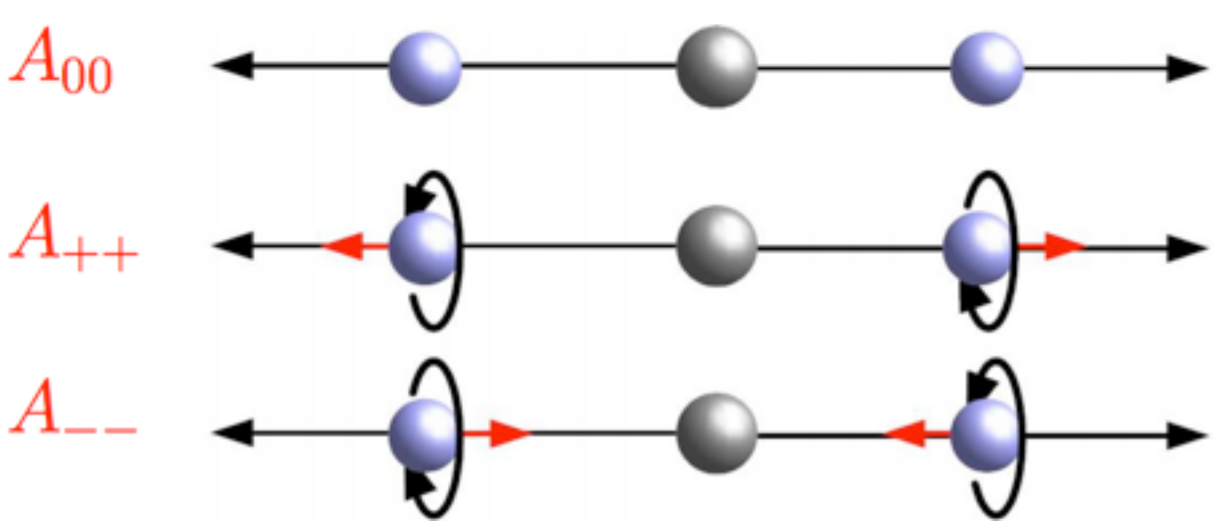
Angular Analysis

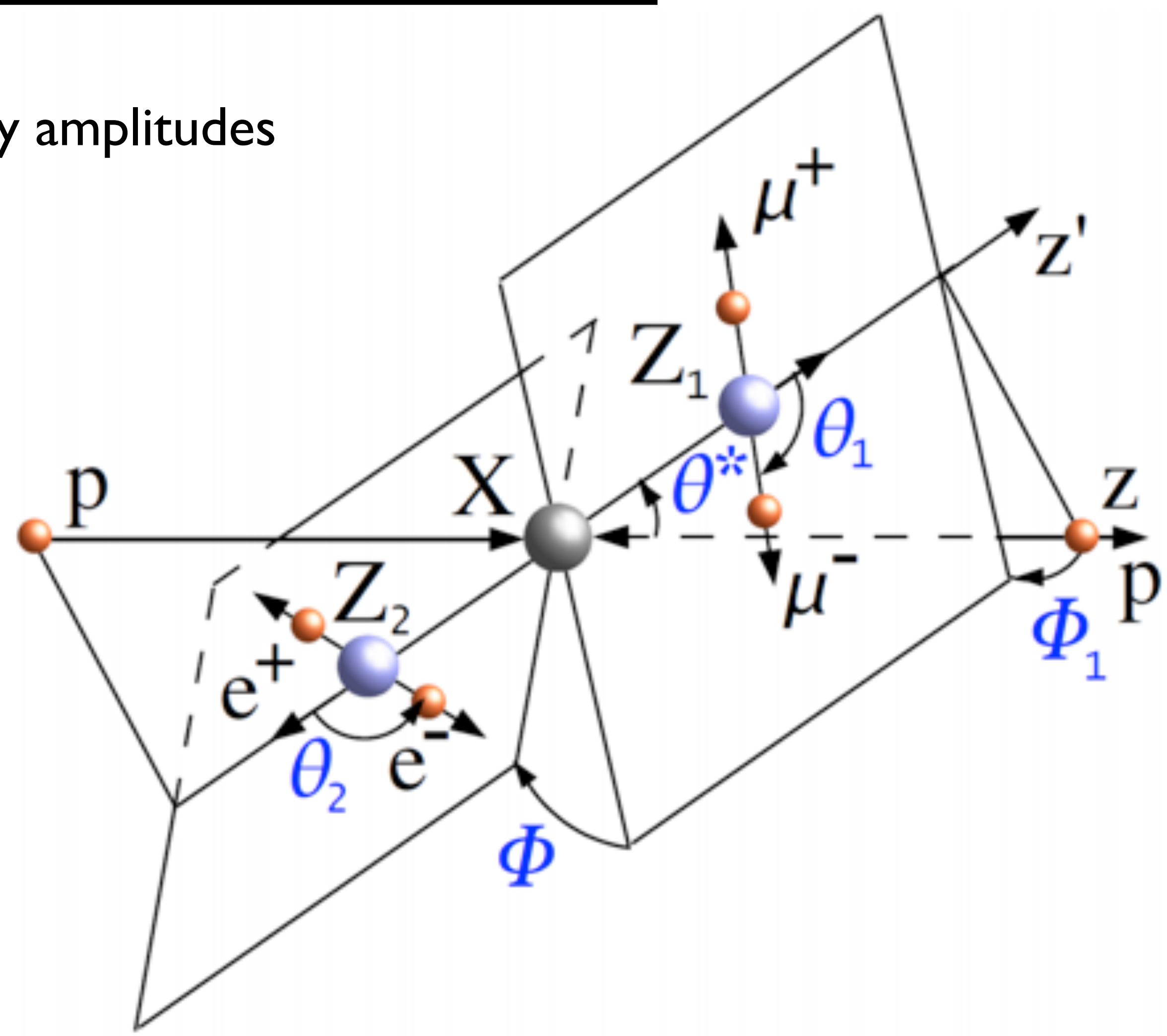
- The helicity amplitudes can be measured from angular analysis

$$d\sigma \propto \sum_{\chi,\mu,\tau} \left| \sum_{\lambda,m} A_{ab}(\{\Omega\}) \right|^2$$

$$A_{ab} \propto \quad D^{J*}_{\chi_1-\chi_2,m}(\Omega^*) B_{\chi_1\chi_2} \times D^{J*}_{m,\lambda_1-\lambda_2}(\Omega) A_{\lambda_1\lambda_2}$$
$$\times D^{s_1*}_{\lambda_1,\mu_1-\mu_2}(\Omega_1) T(\mu_1,\mu_2) \times D^{s_2*}_{\lambda_2,\tau_1-\tau_2}(\Omega_2) W(\tau_1,\tau_2)$$

- For example, a Higgs like spin 0 resonance has 3 helicity amplitudes



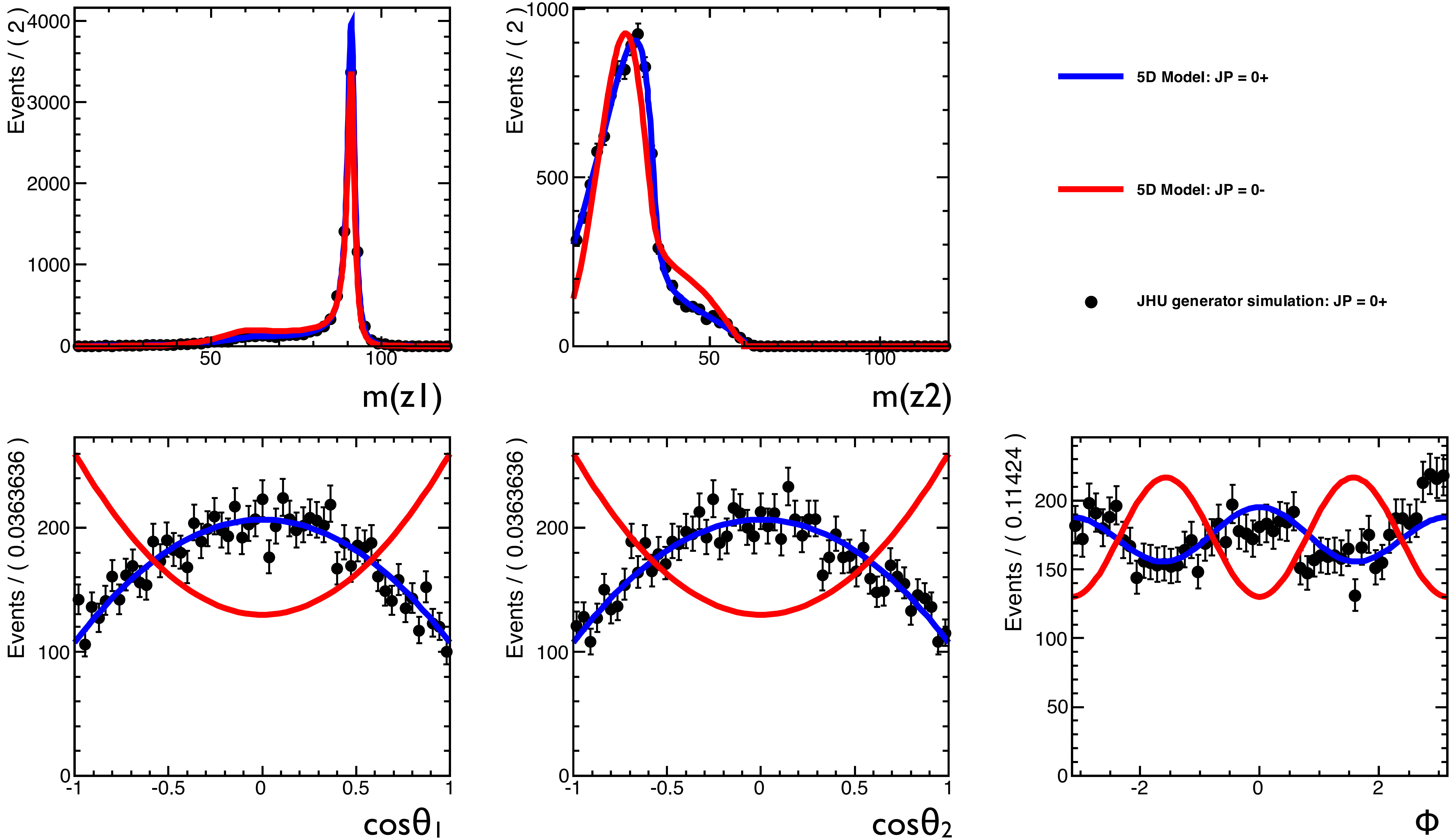


Need only 5 angles $\{\theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$
to fully describe the production/decay

- Detailed expressions for the spin 1 and spin 2 can be found in the reference *PhysRevD.81.075022*

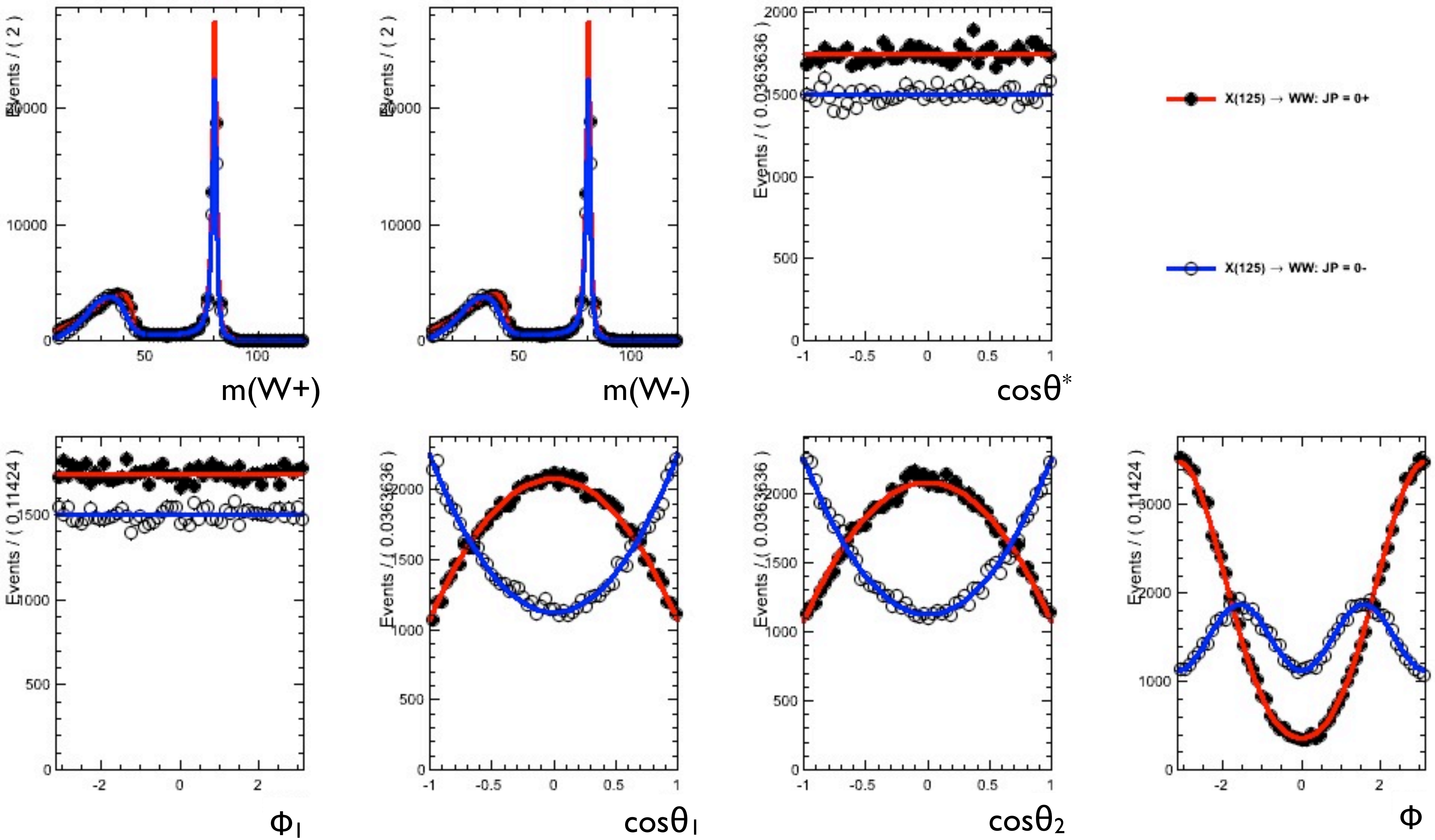
Generator Validation (X→ZZ 0+/0-)

- In this test mX = 125 GeV

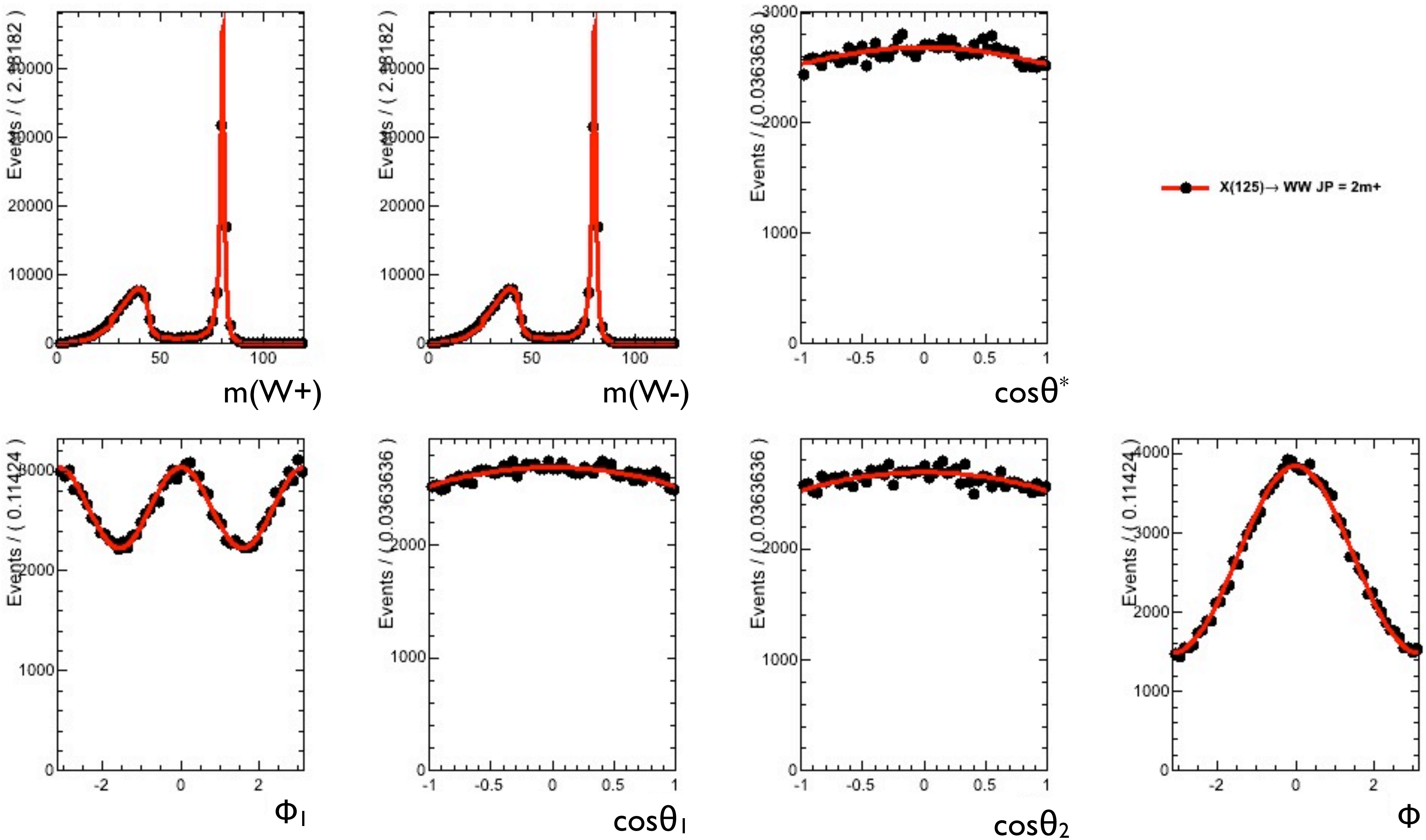


Generator Validation (X→WW 0+/0-)

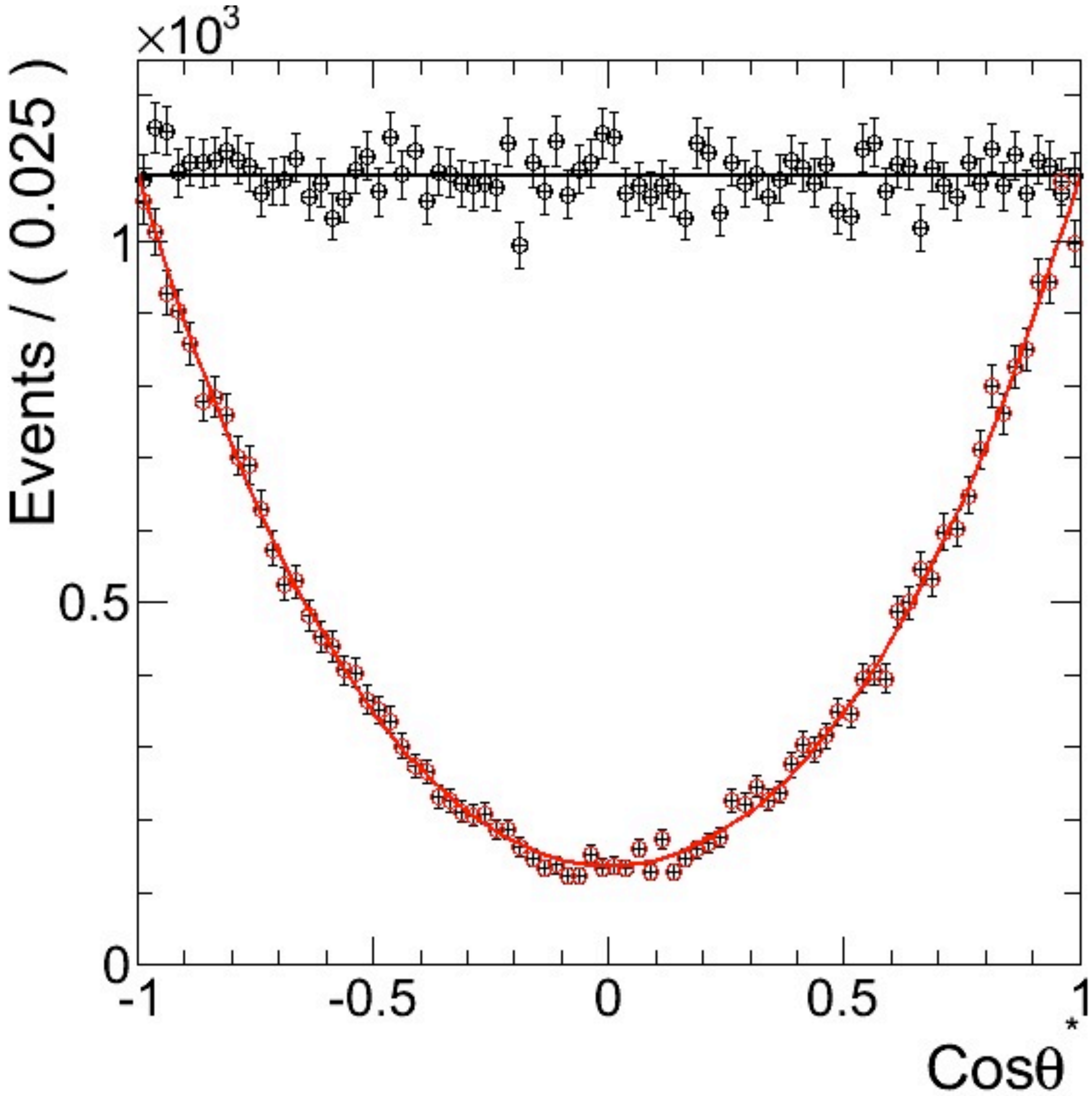
- In this test mX = 125 GeV



Generator Validation (X→WW 2m+)



Generator Validation ($X \to \gamma\gamma$)



0+

2m+

Summary

- We reviewed the model-independent amplitude for X→VV→4 fermions interaction
- We reviewed the JHU generator for production and decay of X→VV with X spin <= 2
  - X→ZZ→ 4l, 2l2τ, 2l2ν, 2l2q
  - X→WW → 2l2ν, lντν, lνqq
  - X→γγ
- Make a quick comparison to the VBF@NLO for the spin 2 model
  - JHUGen considers more general couplings
  - Both generators can generate the minimal couplings 2m+ models