Spin and Symmetry in Analysis of Single-Produced Resonances at the LHC

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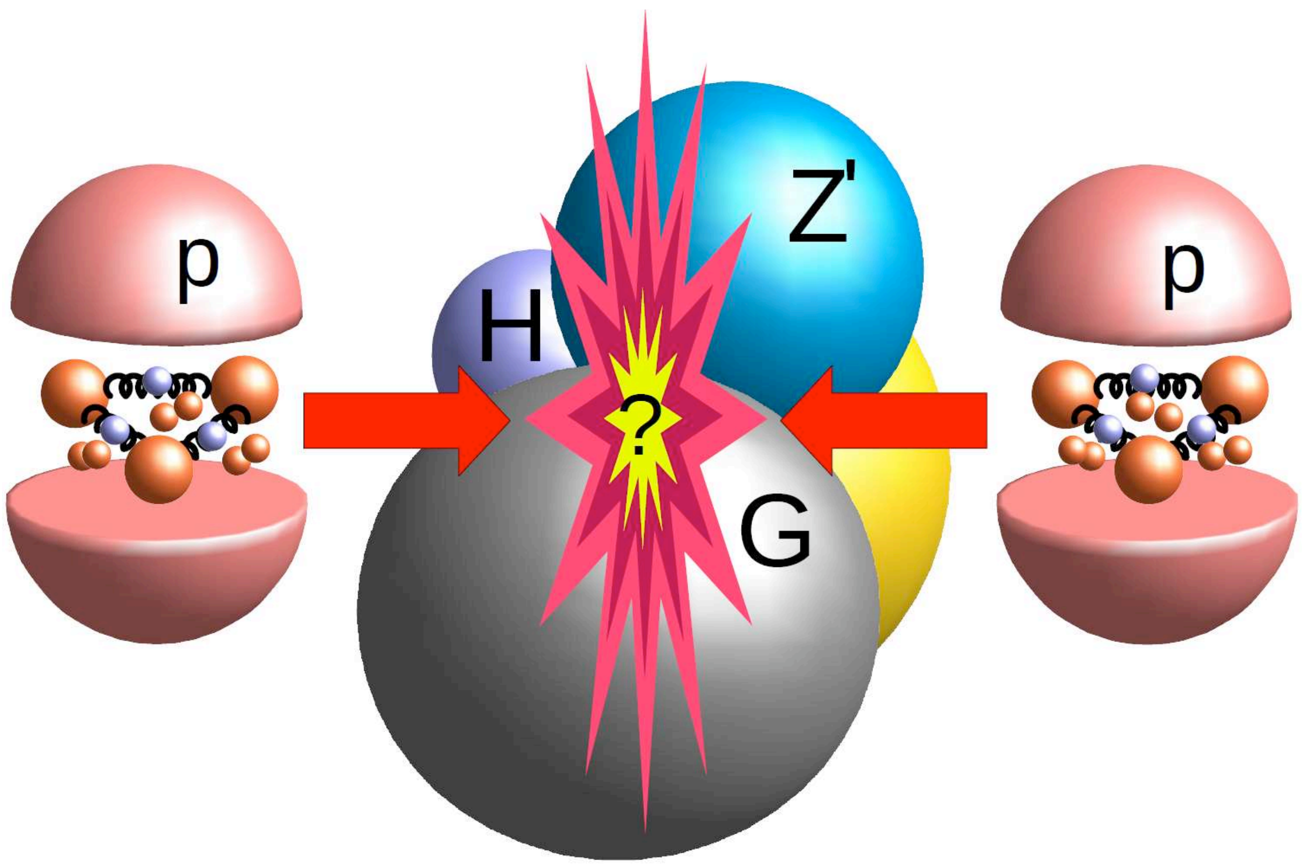
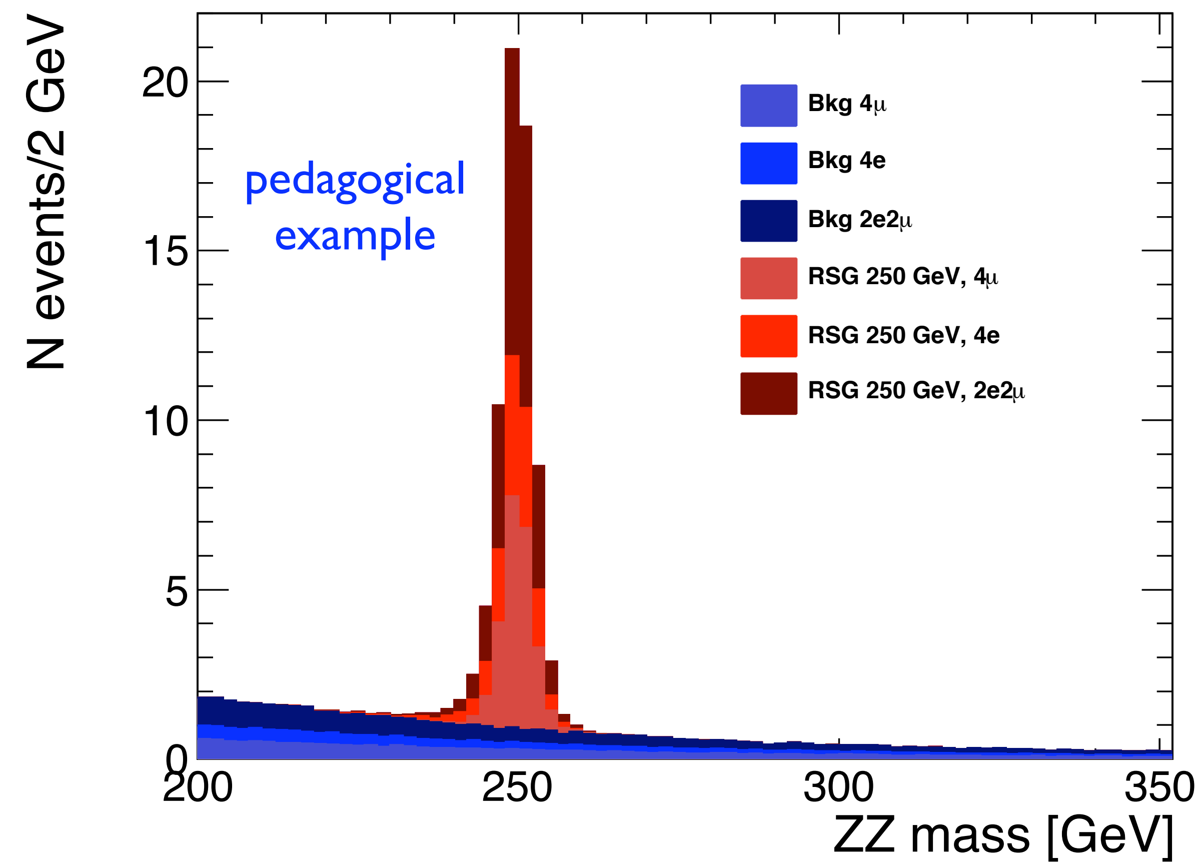
Executive Overview

- The LHC is a discovery machine, new resonances expected





- Assume a color/charge neutral resonance X is found
  → extract the maximum information about it
  - decay mechanisms (rate, branching ratios)
  - mass and quantum numbers (spin, parity)
  - couplings with the SM fields

References

- Angular analysis to measure J^P of a resonance is not new

Parity of the Neutral Pion and the Decay $\pi^0 \to 2e^+ + 2e^-$†

N. P. Samios
Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

AND

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Columbia University, New York, New York

(Received January 17, 1961)

- Lots of efforts on "spin/symmetry at the LHC"
    - Most work focuses on the angular distributions in decays of scalar and pseudoscalar Higgs, BSM vector particles, and minimal coupling gravitons
    - The angular distributions in the literature are largely based on partial production or decay kinematics, as slices of the full distributions
- This presentation is based on our recent paper
    - "Spin determination of single-produced resonances at hadron colliders", Y. Gao, A. Gritsan, Z. Guo, K. Melnikov, M. Schulze, N. Tran, Phys. Rev. D 81, 075022 (2010); preprint arXiv:1001.3396 [hep-ph]

Outline

- Start with some basic questions
  - What kind of resonances might we see at the LHC?
  - If a resonance is found, how can we determine its properties?
- Probe the production and decay of X from theoretical side
  - Start with the most general couplings to the relevant SM fields
  - New MC generator to simulate the production and decay of X
  - Derive the helicity amplitudes from coupling constants
- Measure the helicity amplitudes experimentally
  - Develop full angular analysis formalism (production+decay angles)
  - Account for detector effects in the MC simulation
  - Implement a general maximum likelihood fit to extract simultaneously the physics quantities of interest (mass, width, spin, parity, etc)

What resonances might we see at LHC?

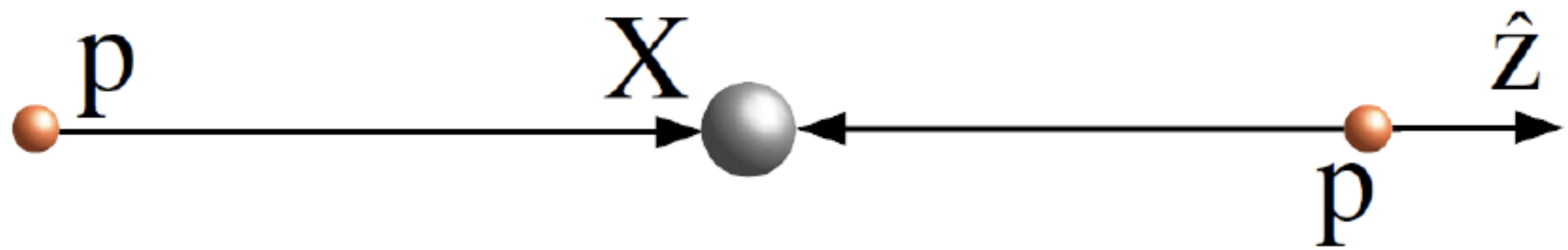
- Spin-0 higgs-like scalars
  - Parity even 0^+ (non-)SM Higgs-like scalars
  - Parity odd 0^- "multi-Higgs models"
- Spin-1 new gauge bosons
  - Parity odd/even KK gauge bosons, Z'
  - Plausible models in which X decays to WW and ZZ dominantly
- Spin-2 graviton-like tensors
  - Parity even RS Graviton - "warped extra-dimensions"
    - Classic Graviton: "minimal coupling" with SM fields (in TeV brane)
    - Non-Classic Graviton: "non-minimal coupling" with SM fields (bulk)
  - Exotic particles with odd parity 2^- ("hidden valley")

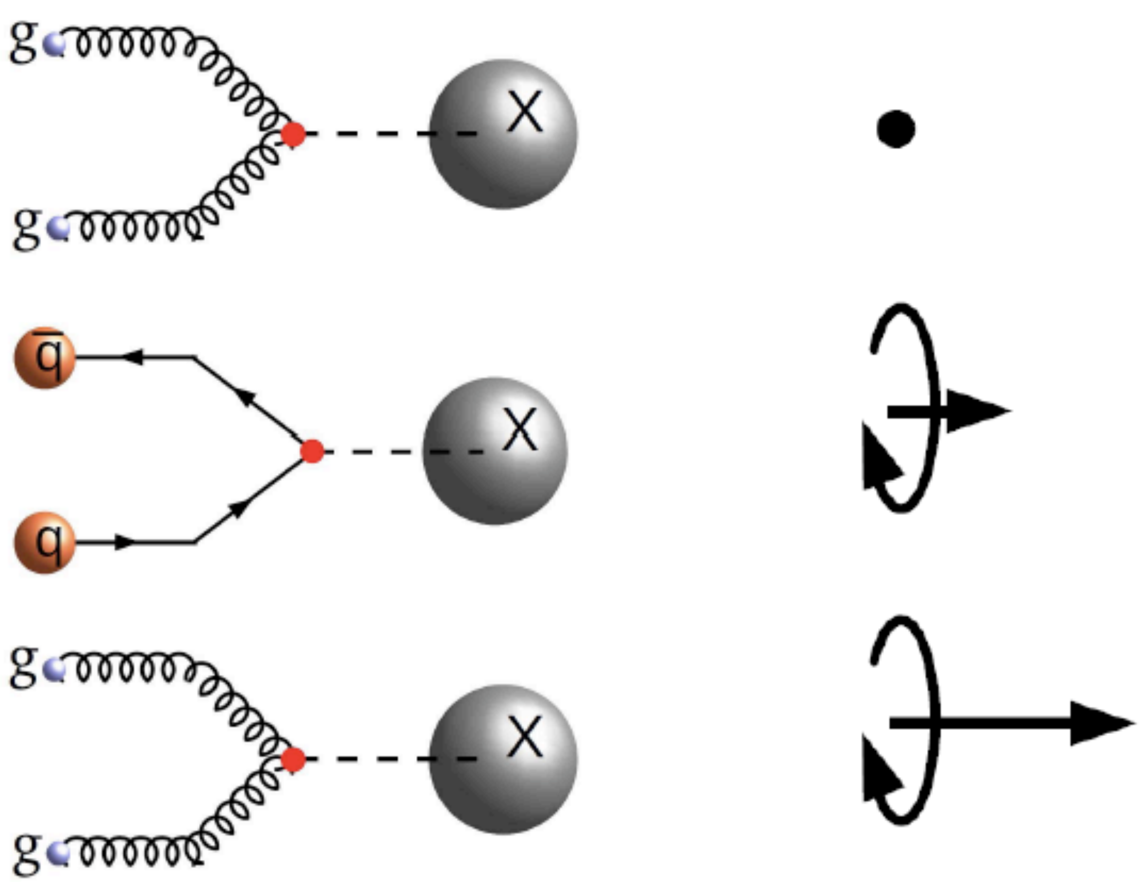
Production and Decay Amplitudes of Resonance X

Resonance Productions at the LHC

- Consider two dominant production mechanism at LHC

$$d\sigma_{pp}(\vec{\Omega}) = \sum_{ab} \int \mathrm{d}Y_X \, \mathrm{d}x_1 \mathrm{d}x_2 \; \tilde{f}_a(x_1) \; \tilde{f}_b(x_2) \; \frac{d\sigma_{ab}(x_1 p_1, x_2 p_2, \vec{\Omega})}{\mathrm{d}Y_X} \Big|_{Y_{ab}=\frac{1}{2}\ln\frac{x_1}{x_2}}$$





$J_z = 0$ fraction f_{z0}

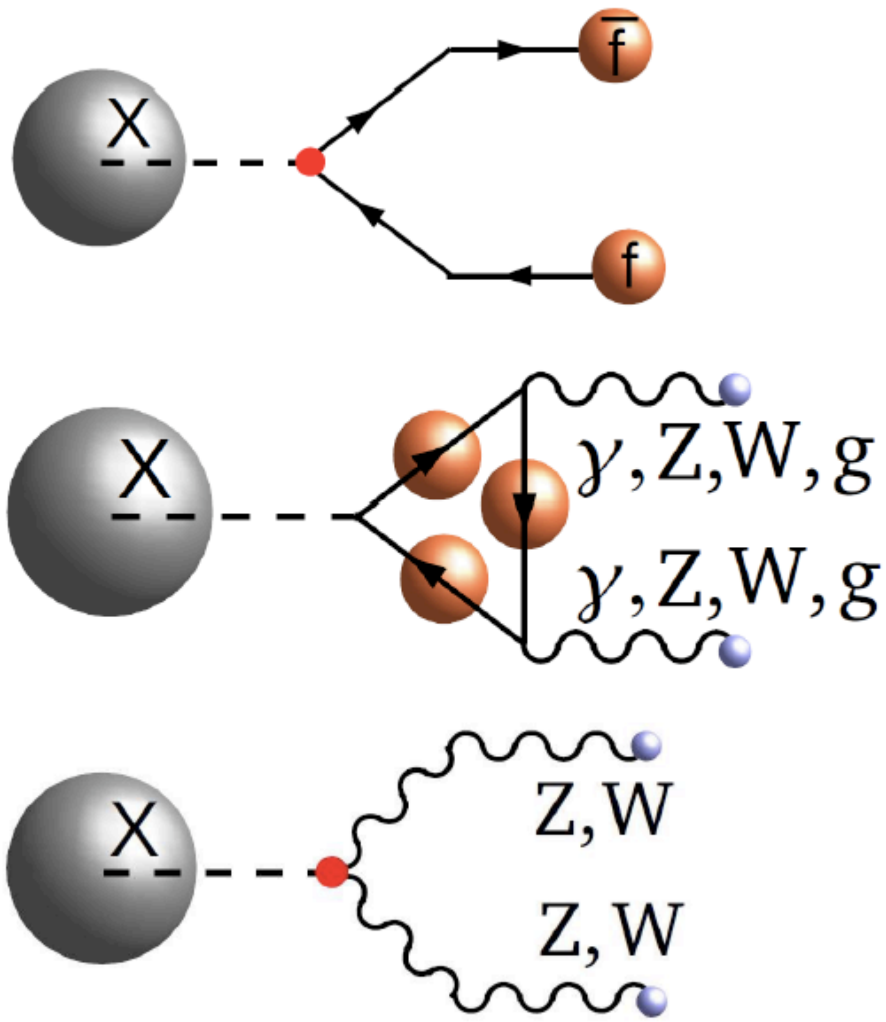
$J_z = \pm 1$ fraction f_{z1}

$J_z = \pm 2$ fraction f_{z2}

* Relative fraction between gg and qqbar depends on the LHC Energy

Resonance Decays

- Examples of the resonance decays to SM fields



- Decay to fermions

  $X \to l^+l^-,\ q\bar{q}$

  spin-0 excluded $m_f \to 0$

- Decay to gauge bosons

  $X \to \gamma\gamma,\ W^+W^-,\ ZZ,$ gg

  spin-1 excluded with $\gamma\gamma$, gg

assume X is color-neutral
charge-neutral

- Now we focus on X→ZZ→4l (w/o jets or MET)
  - Sizable (if not dominant) decay b.r. is plausible in many models
  - All final states can be reconstructed with high eff. and good resolution
  - More information can be extracted through 4-body decay

Helicity Amplitudes

- Helicity amplitude of 1→2 decay process

$$\langle \Omega, \lambda_1, \lambda_2 | S | Jm \rangle = \sqrt{\frac{(2J+1)}{4\pi}} D^{J*}_{m,\lambda_1-\lambda_2}(\Omega) A_{\lambda_1 \lambda_2}$$

  - In the case of X→ZZ

symmetry in $X \to ZZ$: $A_{\lambda_1\lambda_2} = (-1)^J A_{\lambda_2\lambda_1}$

if parity is a symmetry: $A_{\lambda_1\lambda_2} = \eta_X (-1)^J A_{-\lambda_1-\lambda_2}$ (do not use)

A_{00}

A_{++}

A_{--}

$J = 0$ or 2, $J_{z'} = 0$

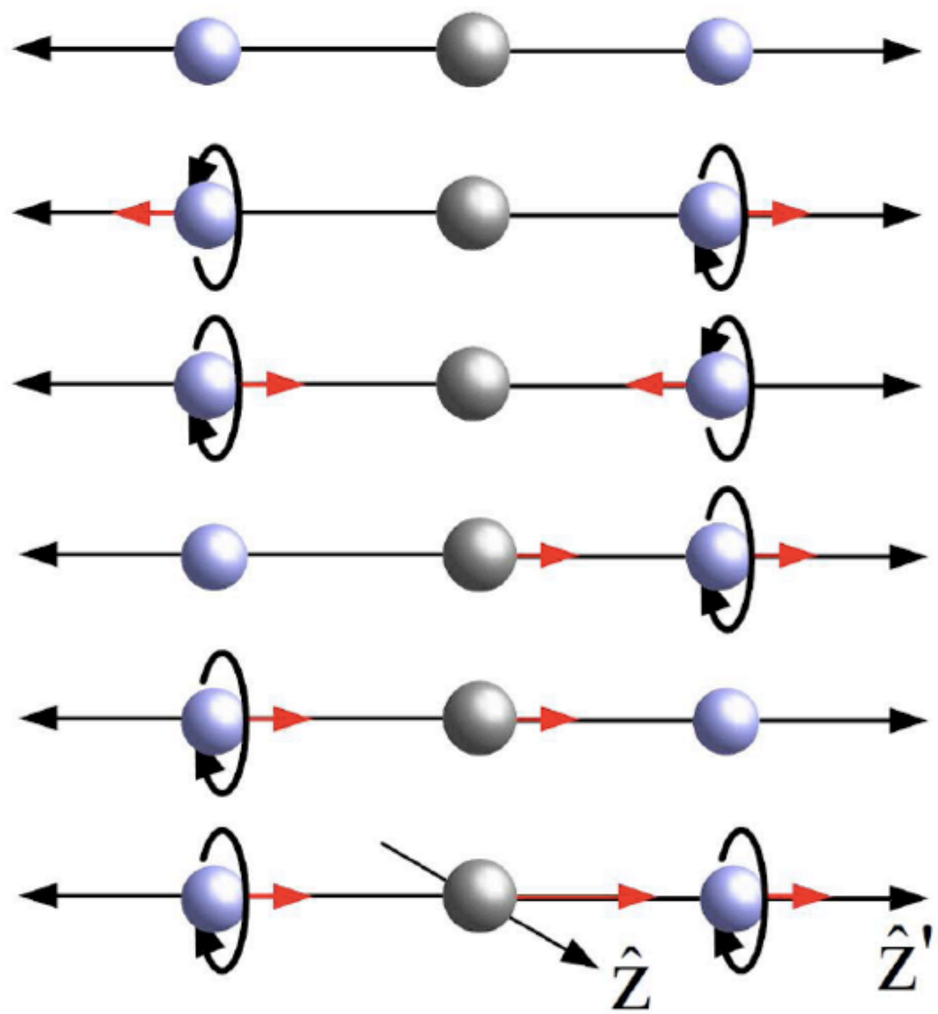
$A_{+0} = (-1)^J A_{0+}$

$A_{0-} = (-1)^J A_{-0}$

$J = 1$ or 2, $|J_{z'}| = 1$

$A_{+-} = (-1)^J A_{-+}$

$J = 2$, $|J_{z'}| = 2$



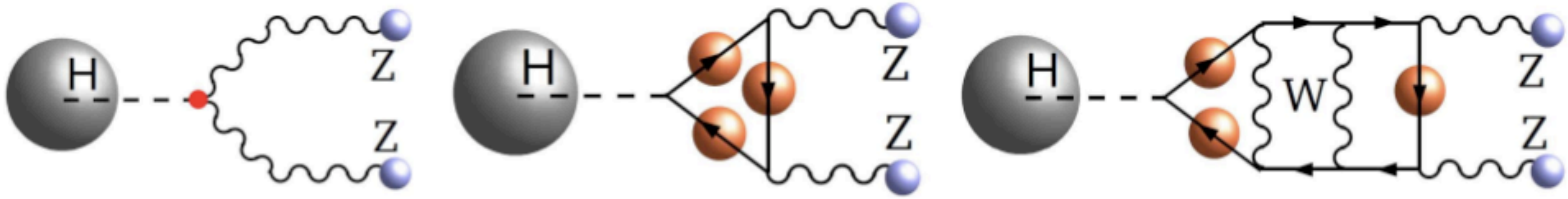
$|J_z| = 0,1,2 \Rightarrow f_{z0}, f_{z1}, f_{z2}$

$X(J=0) \to VV$ Amplitude

- Most general amplitude for $X_{J=0} \to V_1 V_2$

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

- SM Higgs 0^+: (a_1) CP $\sim$few% (a_2) CP $\sim 10^{-10}$? (a_3) $\not{CP}$



- 3 amplitudes ("experiment") $\Leftrightarrow$ 3 coupling constants ("theory")

$$A_{00} = -\frac{M_X^4}{4 v M_V^2} \left(a_1 (1+\beta^2) + a_2 \beta^2 \right)$$

$\leftarrow$ SM dominates at $\dfrac{M_X}{M_V} \gg 1$

$$A_{++} = \frac{M_X^2}{v} \left(a_1 + \frac{i a_3 \beta}{2} \right)$$

$$A_{--} = \frac{M_X^2}{v} \left(a_1 - \frac{i a_3 \beta}{2} \right)$$

- Beyond SM: look for all a_2 $(J^P = 0^+)$ and a_3 $(0^-,\ A)$

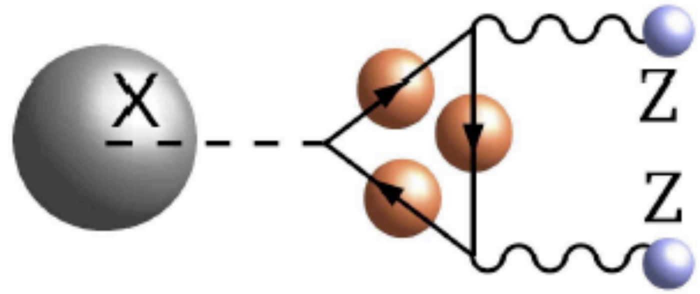
X(J=1)→VV Amplitude

- Most general amplitude for $X_{J=1} \to ZZ$

$$A = b_1 \boxed{\left[(\epsilon_1^* q_2)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q_1)(\epsilon_1^* \epsilon_X)\right]} + b_2 \boxed{\epsilon_{\alpha\mu\nu\beta}\,\epsilon_X^{\alpha}\,\epsilon_1^{*,\mu}\,\epsilon_2^{*,\nu}\,(q_1 - q_2)^{\beta}}$$

$$\boxed{\begin{array}{ll} 1^- & CP \\ 1^+ & \cancel{CP} \end{array}} \qquad \boxed{\begin{array}{ll} 1^- & \cancel{CP} \\ 1^+ & CP \end{array}}$$

Example:



- 2 amplitudes ("experiment") ⇔ 2 coupling constants ("theory")

$$\boxed{\begin{array}{l} A_{+0} \equiv -A_{0+} \\ \\ A_{-0} \equiv -A_{0-} \end{array}} \begin{array}{l} = \dfrac{\beta m_X^2}{2 m_Z}(b_1 + i\beta b_2) \\ \\ = \dfrac{\beta m_X^2}{2 m_Z}(b_1 - i\beta b_2) \end{array}$$

X(J=2)→VV Amplitude

2^+ CP
2^- $\cancel{CP}$

2^+ $\cancel{CP}$
2^- CP

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

- 6 amplitudes ("experiment") ⇔ 6 combinations of coupl. const.

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

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

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

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

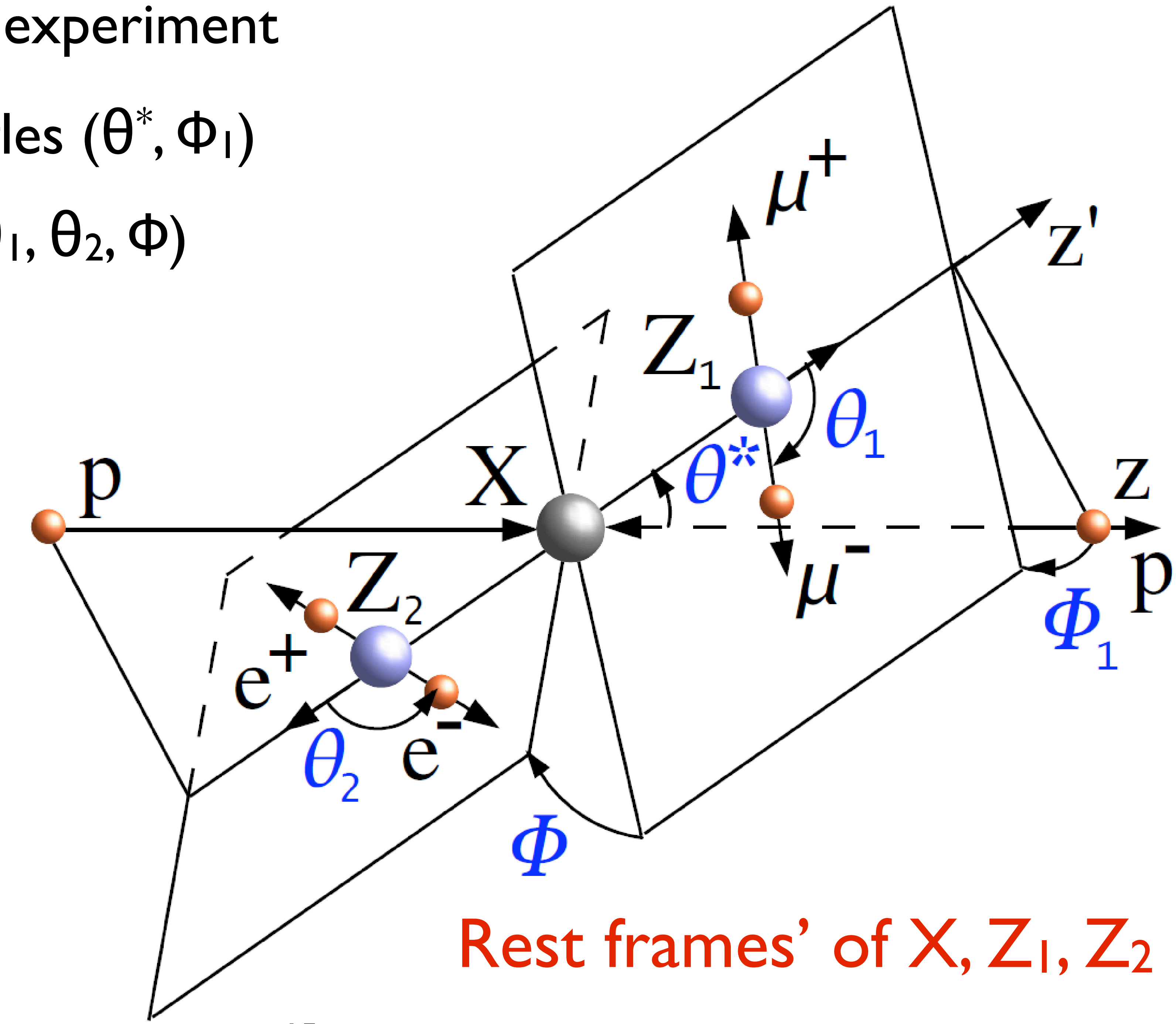
Monte Carlo Simulation

- We have written a MC simulation program, based on the matrix element calculations of the complete kinematic chain
  - $ab \to X \to ZZ \to (f_1\bar{f}_1)(f_2\bar{f}_2)$
- Important features in this program (www.pha.jhu.edu/spin)
  - It has the option of weighting, accepting or discarding events
  - Output in LHE format, which can interface with PYTHIA for hadronization
  - The inputs are general couplings (previous slides),
    - including Higgs radiative corrections
    - containing both non-minimal/minimal graviton couplings
- Background
  - Madgraph: $q\bar{q} \to ZZ$ (irreducible bkg)
  - Others negligible: $Zb\bar{b}$, $t\bar{t}$, $W^+W^-b\bar{b}$, WWZ, $t\bar{t}Z$, $4b$

Production and Decay Angular Distributions

Angular Variables

- The production/decay kinematics involve 3 sequential rotations
- To fully describe the kinematics, we need 5 angles
  - directly measured in experiment
    - production angles (θ^*, Φ_1)
    - decay angles (θ_1, θ_2, Φ)



Rest frames' of X, Z_1, Z_2

Angular Distributions

- The helicity amplitudes

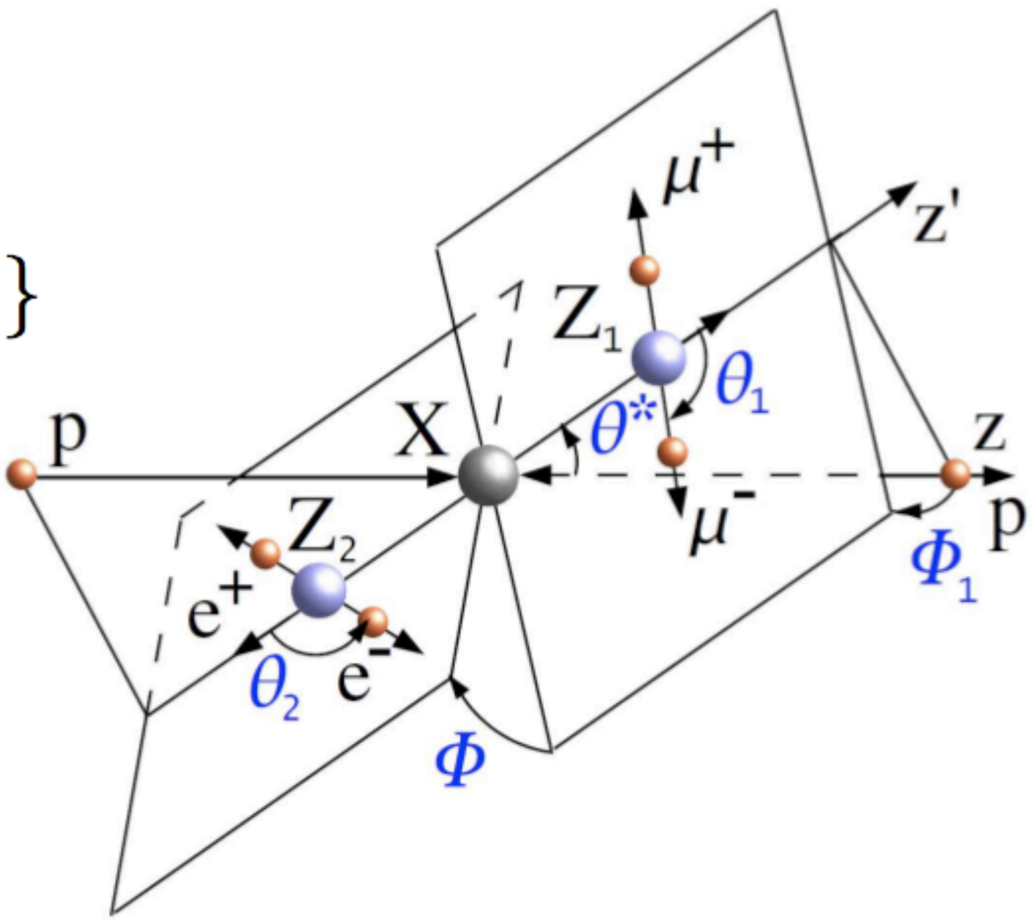
$$\boxed{\begin{aligned} A_{ab} \propto \quad & D^{J*}_{\chi_1-\chi_2,m}(\Omega^*) B_{\chi_1\chi_2} \times D^{J*}_{m,\lambda_1-\lambda_2}(\Omega) A_{\lambda_1\lambda_2} \\ & \times D^{s_1*}_{\lambda_1,\mu_1-\mu_2}(\Omega_1) T(\mu_1,\mu_2) \times D^{s_2*}_{\lambda_2,\tau_1-\tau_2}(\Omega_2) W(\tau_1,\tau_2)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

$$ab \to X, \quad \Omega^* = (\Phi_1, \theta^*, -\Phi_1), \ \{\chi_1\chi_2\}$$

$$X \to Z_1 Z_2, \ \Omega = (0,0,0), \ \{\lambda_1\lambda_2\}$$

$$Z_1 \to f_1\bar{f}_1, \ \Omega_1 = (0,\theta_1,0), \ \{\mu_1,\mu_2\}$$

$$Z_2 \to f_2\bar{f}_2, \ \Omega_2 = (\Phi,\theta_2,-\Phi), \ \{\tau_1,\tau_2\}$$



- Angular distributions

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

- Polarization and phases

$$f_{\lambda_1\lambda_2} = |A_{\lambda_1\lambda_2}|^2 / \sum |A_{ij}|^2 \qquad \phi_{\lambda_1\lambda_2} = \arg(A_{\lambda_1\lambda_2}/A_{00})$$

Explicit Angular Distribution

- $d\Gamma(ab \to X_J \to Z_1 Z_2^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)) \propto$

$$F_{00}^J(\theta^*) \times \Big\{4\, f_{00}\, \sin^2\theta_1 \sin^2\theta_2 + (f_{++} + f_{--})\left((1+\cos^2\theta_1)(1+\cos^2\theta_2) + 4R_1R_2\cos\theta_1\cos\theta_2\right)$$
$$-2\,(f_{++} - f_{--})\left(R_1\cos\theta_1(1+\cos^2\theta_2) + R_2(1+\cos^2\theta_1)\cos\theta_2\right)$$
$$+4\sqrt{f_{++}f_{00}}\,(R_1 - \cos\theta_1)\sin\theta_1(R_2 - \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++})$$
$$+4\sqrt{f_{--}f_{00}}\,(R_1 + \cos\theta_1)\sin\theta_1(R_2 + \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--})$$
$$+2\sqrt{f_{++}f_{--}}\,\sin^2\theta_1\sin^2\theta_2\cos(2\Phi + \phi_{++} - \phi_{--})\Big\}$$

spin $= 0$ & ≥ 2

$$+4F_{11}^J(\theta^*) \times \Big\{(f_{+0} + f_{0-})(1 - \cos^2\theta_1\cos^2\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_1\sin^2\theta_2 + R_2\sin^2\theta_1\cos\theta_2)$$
$$+2\sqrt{f_{+0}f_{0-}}\,\sin\theta_1\sin\theta_2(R_1R_2 - \cos\theta_1\cos\theta_2)\cos(\Phi + \phi_{+0} - \phi_{0-})\Big\}$$
$$+4F_{-11}^J(\theta^*) \times (-1)^J \times \Big\{(f_{+0} + f_{0-})(R_1R_2 + \cos\theta_1\cos\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_2 + R_2\cos\theta_1)$$
$$+2\sqrt{f_{+0}f_{0-}}\,\sin\theta_1\sin\theta_2\cos(\Phi + \phi_{+0} - \phi_{0-})\Big\}\sin\theta_1\sin\theta_2\cos(2\Psi)$$

spin $= 1$ & ≥ 2

$$+2F_{22}^J(\theta^*) \times f_{+-}\Big\{(1+\cos^2\theta_1)(1+\cos^2\theta_2) - 4R_1R_2\cos\theta_1\cos\theta_2\Big\}$$
$$+2F_{-22}^J(\theta^*) \times (-1)^J \times f_{+-}\,\sin^2\theta_1\sin^2\theta_2\cos(4\Psi)$$

spin ≥ 2 unique

$+$ other 26 interference terms for spin ≥ 2

where $\Psi = \Phi_1 + \Phi/2$ and $F_{ij}^J(\theta^*) = \sum_{m=0,\pm1,\pm2} f_m\, d_{mi}^J(\theta^*) d_{mj}^J(\theta^*)$

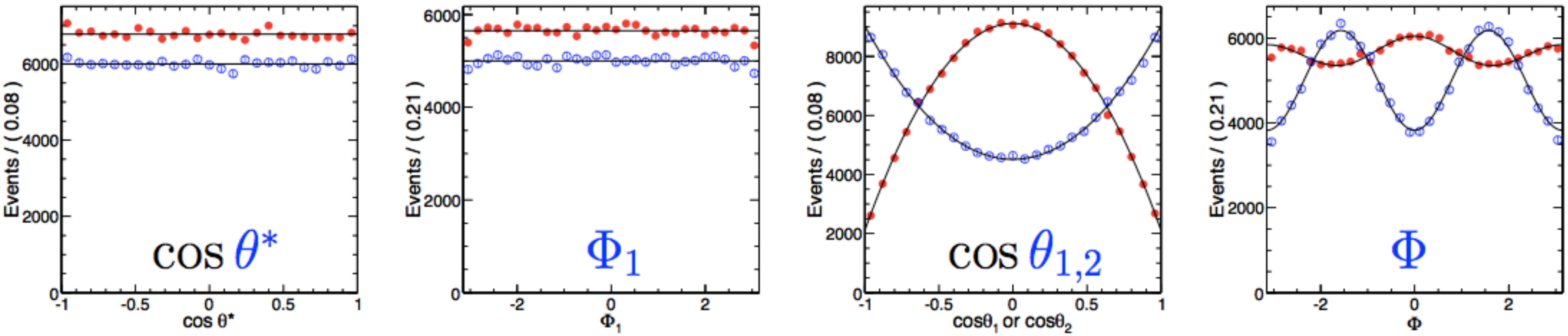
Construct Data Analysis

Due to the large parameter space, we select 7 scenarios to illustrate the general analysis procedure

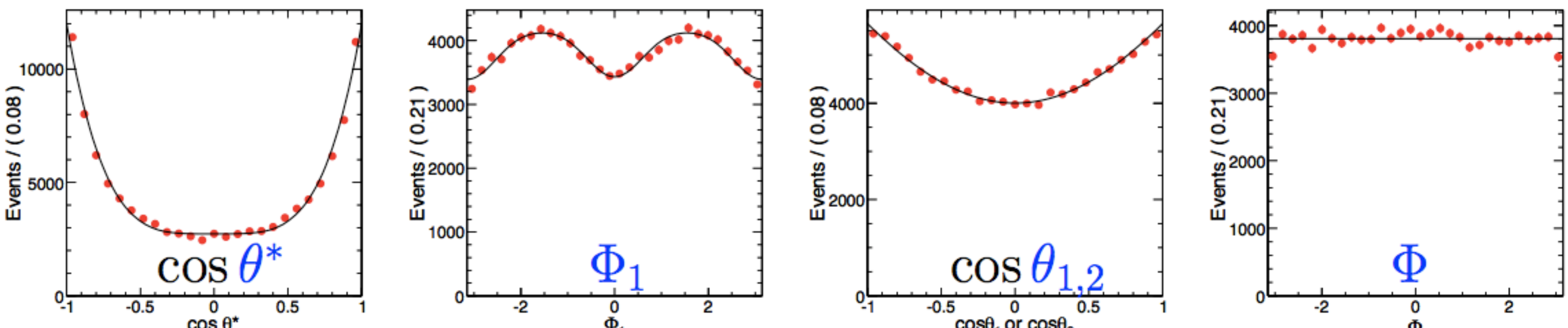
J^P	0^+	0^-	1^+	1^-	2_m^+	2_L^+	2^-
scenario	SM Higgs-like scalar	Pseudo-scalar	Exotic Pseudo-vector	Exotic Vector	Graviton-like tensor with minimal coupl.	Graviton-like tensor with long. polarization (J_z=0)	Exotic Pseudo-tensor

Validate the Angular Distributions (1/2)

- Validate the MC simulation, angular formalism and fit
    - lines: fitted analytical functions; dots: generated MC data
- Higgs 0^+ and 0^- at m_H=250GeV

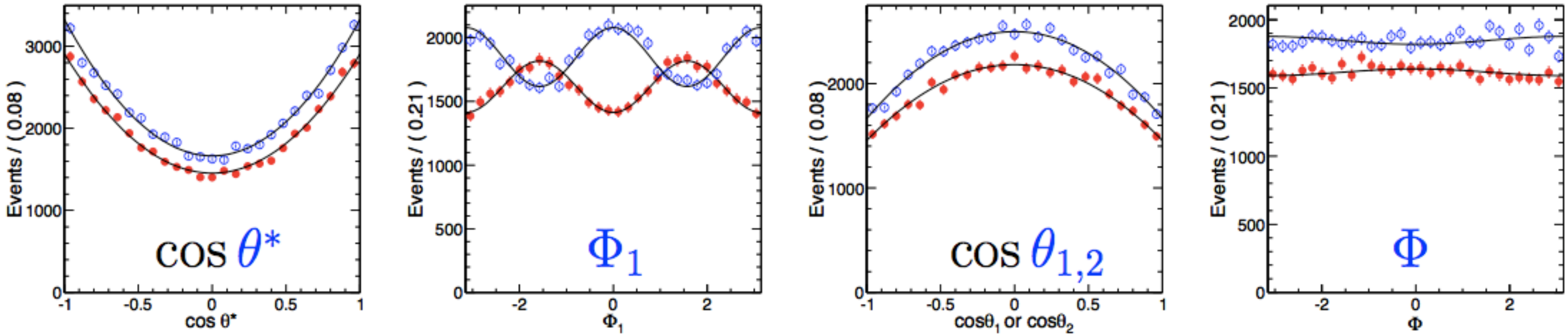


- Background $q\bar{q} \rightarrow ZZ$

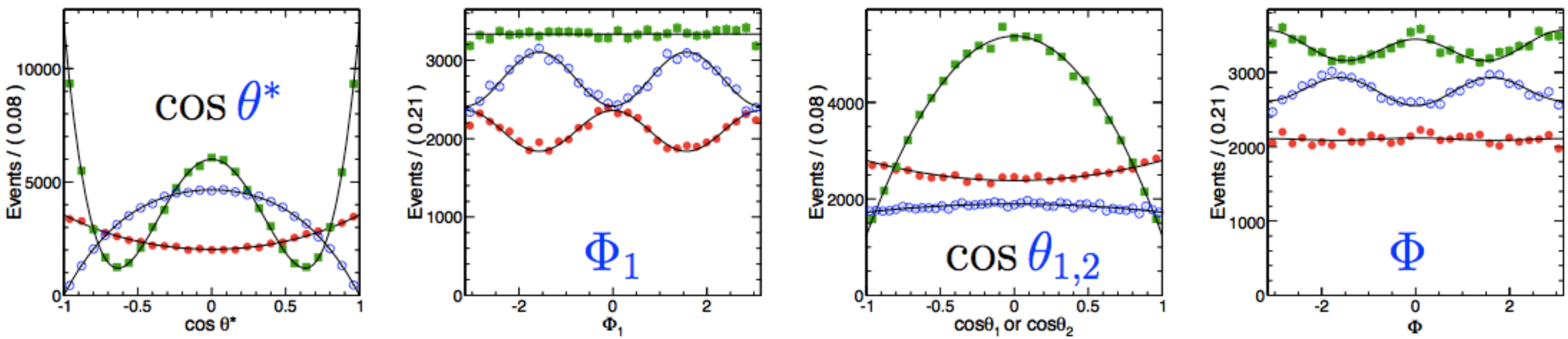


Validate the Angular Distributions (2/2)

- Vector $1^-(b_1)$ and axial-vector $1^+(b_2)$



- Gravitons, 2_m^+(minimal), 2_L^+(Higgs-like) and 2^- at m_X=250GeV



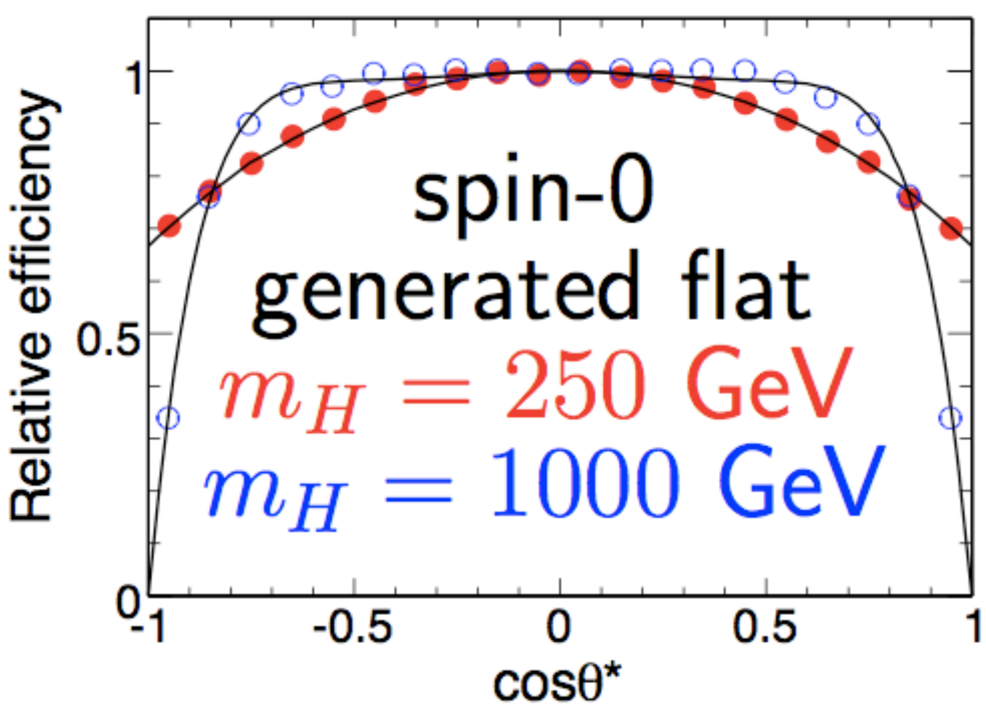
  - Good agreement between MC simulation/fit/analytical functions
  - Full angular distributions give the best separation between signals/bkg

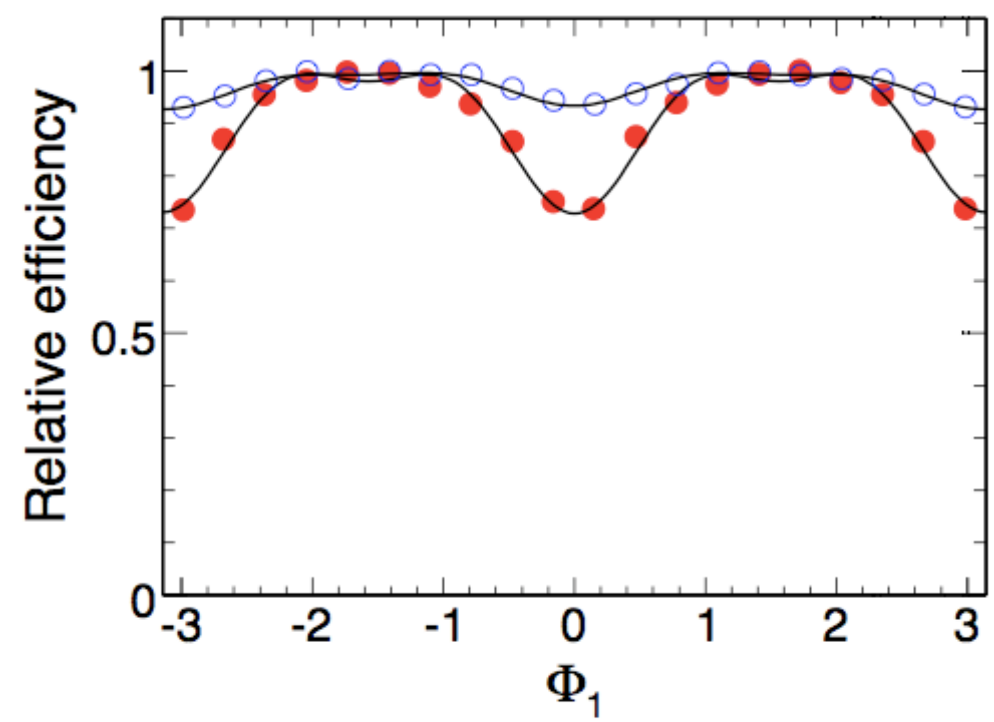
Detector Effects

- The angle measurements depend on the momenta measurement of the 4 final states leptons. Detector performance is crucial:
  - track pT and impact parameter resolutions
  - non-uniform reconstruction efficiency of the detector
- Account for detector effects in MC, with acceptance function

$$\boxed{\mathcal{G}(\Phi_1, \theta^*, \theta_1, \theta_2, \Phi; Y_X)}$$ <u>on top of ideal distribution</u>

  - Smear the track parameters by CMS track resolution → 0.01 rad in angles
  - Consider only tracks within |η|<2.5





Data Analysis in a Nutshell

- Imagine that we observed some (non-)SM resonance events
  - Hypothesis testing analysis
    - Compute a confidence level to separate one hypothesis from the other

example (A): h1: signal + background
h2: only background

example (B): h1: signal 0^+ (+ background)
h2: signal 0^- (+ background)

  - Parameter fitting analysis (once we have established decent stat.)
    - perform multivariate fit to extract simultaneously: production mechanism f_{zm}, yields, polarization, mass, coupling constants ($A_{\lambda 1 \lambda 2}$)

Multivariate Maximum Likelihood Fit

- Likelihood fit on an ensemble of events (RooFit/MINUIT)
  - Each event is described by observable: $\vec{x}_i = (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi; m_{ZZ}, ..)$
  - Each event has a probability of being a certain event type (sig/bkg). The probability is given by probability density function (PDF):

$$\mathcal{P}_J = \mathcal{P}(m_{ZZ}, ...) \times \mathcal{P}_{\text{ideal}}(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi) \times \mathcal{G}(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi; Y_X)$$

  - The signal PDF contains the parameters of interest

$$\vec{\zeta}_J = (f_{\lambda_1\lambda_2}, \phi_{\lambda_1\lambda_2}, f_{zm}; m_X, \Gamma_X)$$

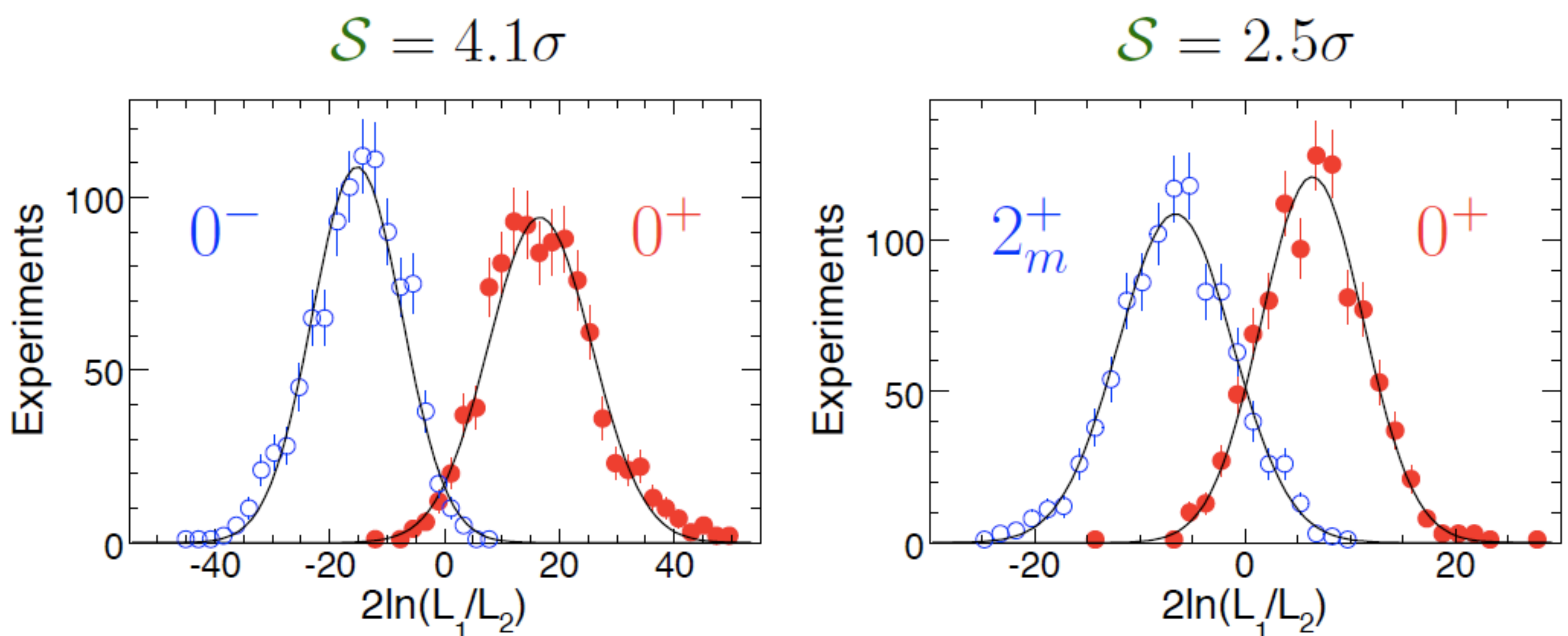
- The total likelihood

$$\boxed{\mathcal{L} = \exp\left(-\sum_{J=1}^{3} n_J - n_{\text{bkg}}\right) \prod_{i}^{N} \left(\sum_{J=1}^{3} n_J \times \mathcal{P}_J(\vec{x}_i;\ \vec{\zeta}_J;\ \vec{\xi}) + n_{\text{bkg}} \times \mathcal{P}_{\text{bkg}}(\vec{x}_i;\ \vec{\xi}) \right)}$$

  - Maximize it to extract the yields and signal parameters at once
  - Depending on the statistics, we can choose to fix or float any parameter
  - The significance btw two hypotheses can be calculated via $2\ln(L_1/L_2)$

Hypothesis Testing Analysis (1/2)

- For illustration, pick a scenario (Luminosity = 5/fb @14 TeV)
  - 30 Higgs signal events (SM Higgs rate, m_X=250GeV) and 24 bkg events
  - S/B significance is 5.7 σ with only m_{ZZ}; increases ~20% if adding angular information
- At the time of discovery, we can perform signal separation hypothesis tests (generating 1000 pseudo-experiments)
  - In each experiment, fit the generated 0^+ data with both $0^+/0^-$ hypotheses and obtain $2\ln(L_1/L_2)$ (Red curve); Repeat with the 0^- data (Blue curve)
  - The hypo. separation significance is the effective gaussian separation between two peaks



Hypothesis Testing Analysis (2/2)

- Tabulate the hypothesis separation results with each two hypothesis combination
  - with 1D (θ^*) / 3D (θ_1, θ_2, Φ) / 5D ($\Phi_1, \theta^*, \theta_1, \theta_2, \Phi$)

	0^-	1^+	1^-	2^+_m	2^+_L	2^-
0^+	0.0/3.9/4.1	0.8/1.8/2.3	0.9/2.5/2.6	0.8/2.4/2.8	2.6/0.0/2.6	1.6/2.4/3.3
0^-	–	0.8/2.8/3.1	0.9/2.5/3.0	0.8/1.7/2.4	2.9/4.1/4.8	1.6/2.0/2.9
1^+	–	–	0.0/1.1/2.2	0.1/1.3/2.6	2.8/1.9/3.6	2.5/1.2/2.9
1^-	–	–	–	0.1/1.3/1.8	2.8/2.5/3.8	2.5/0.6/3.4
2^+_m			–	–	2.9/2.6/3.8	2.3/0.5/3.2
2^+_L	–	–	–	–	–	3.6/2.5/4.3

m_X=250GeV*

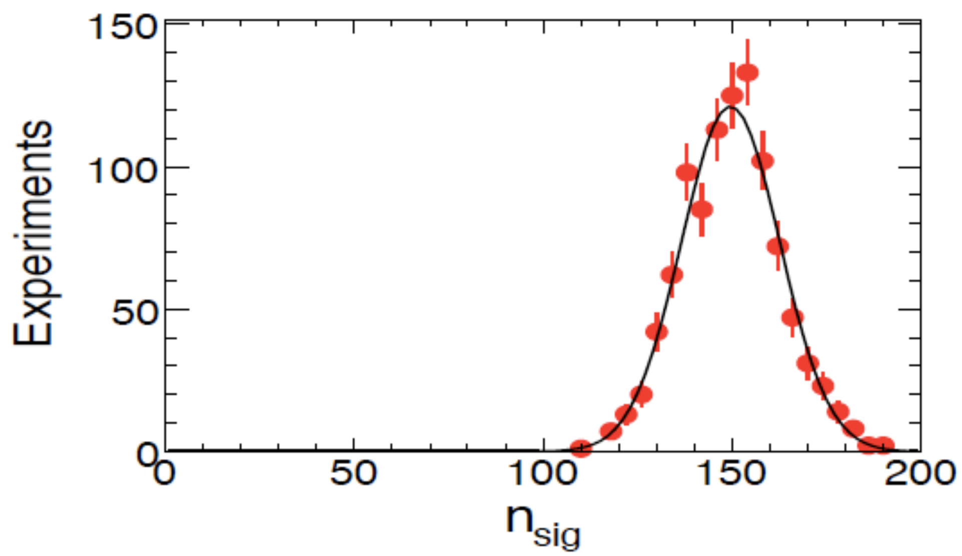
- Including more angles improves hypothesis separation and S/B
- With ~30 signal events, can start to make statement about spin/CP of X

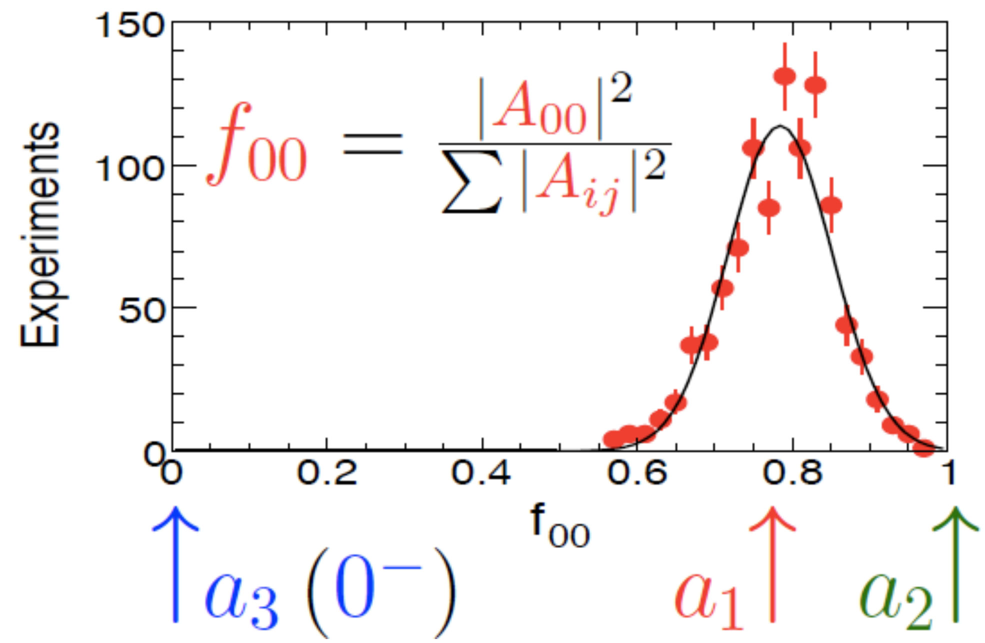
* 1 TeV results in the paper

Parameter Fitting Analysis

- If a resonance (eg. spin-0 Higgs-like) is found with large stat.
  - 150 signal and 120 background events
  - Perform ML fit to extract more parameters (Fit agrees with Gen. Value!)

	generated	w/o detector	with detector
n_{sig}	150	150 ± 13	153 ± 15
f_{00}	0.792	0.79 ± 0.07	0.77 ± 0.08
$(f_{++} - f_{--})/2$	0.000	0.00 ± 0.07	0.01 ± 0.07
$(\phi_{++} + \phi_{--})/2$	π	3.15 ± 0.73	3.20 ± 0.77
$(\phi_{++} - \phi_{--})/2$	0	0.00 ± 0.53	0.01 ± 0.55





Summary and Conclusions

- We have developed a general analysis to determine the spin/parity (+more) of a single-produced resonance (X) at the LHC
  - Assume the most general couplings of X to the relevant SM fields
  - For each potential resonance, we have studied its production and decay mechanisms, as well as its coupling constants to the SM fields
  - The helicity amplitudes are derived from the general $X \rightarrow ZZ$ couplings. They can be experimentally measured through angular distributions
  - We have written a MC simulation program to generate the production and decay of X, accounting for the detector effects
  - We have implemented and validated a multivariate ML fit to perform both hypothesis testing and parameter fitting analyses
    - At the time of discovery, we can separate hypotheses statistically and start to make statements of resonance's J and P
    - With more statistics, we can measure its couplings to SM fields