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

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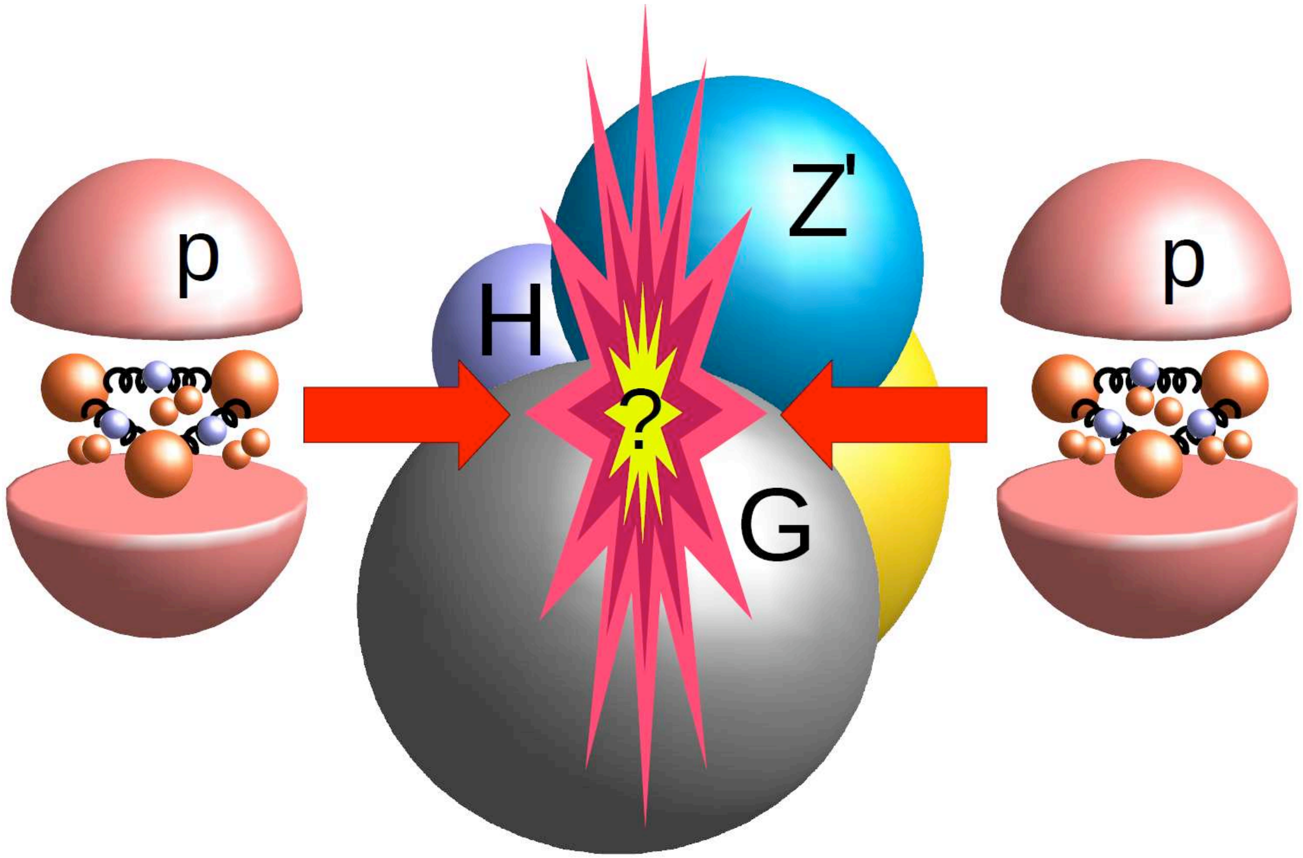
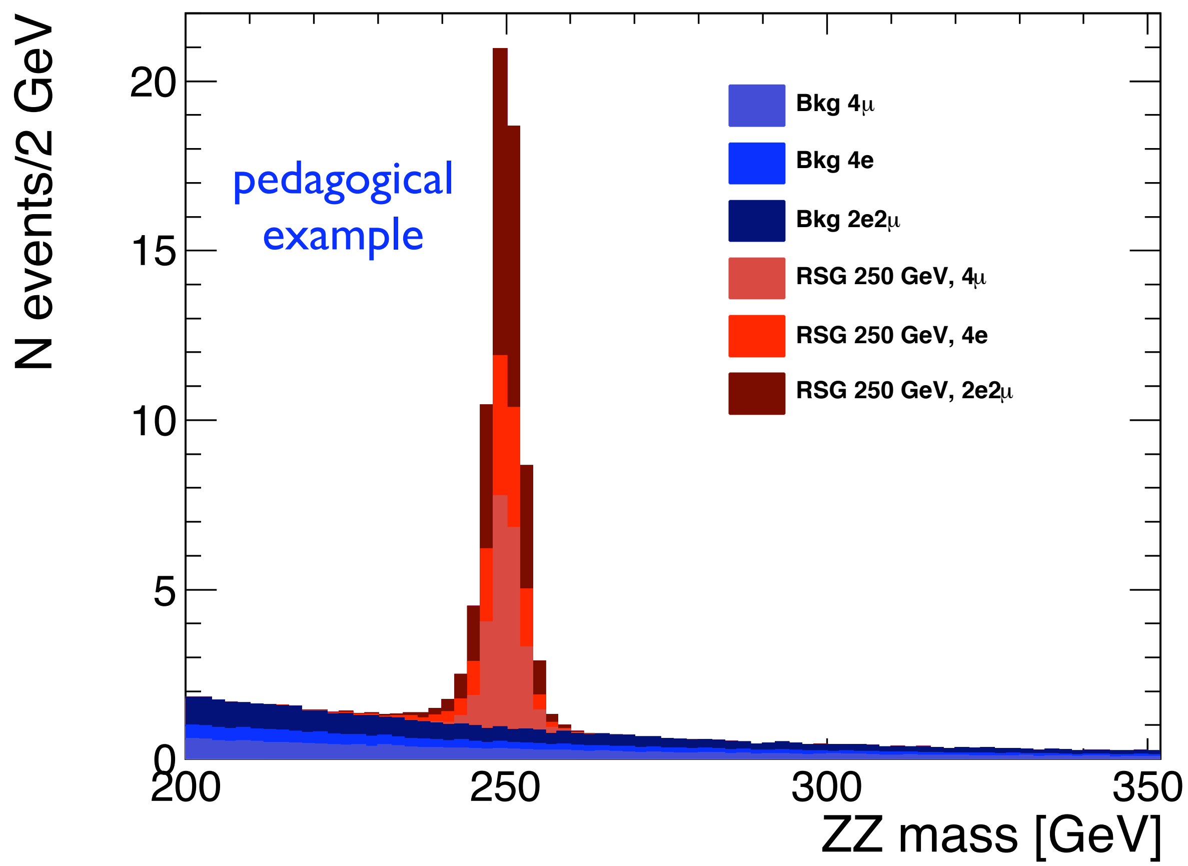
Executive Overview

- LHC is a discovery machine, with new resonances expected





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

References

- There have been a lot of efforts* on "spin/symmetry at LHC"
  - Most of works prior to this paper focused on understanding the angular distributions in the decays of scalar/pseudo-scalar Higgs, BSM vector particle and minimal coupling gravitons
  - The angular distributions in the literature were mostly based on partial production or decay kinematics, as slices of the angular distributions
- This presentation is based on the 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]
  - In this paper, we analyzed both production and decay mechanisms using full angular information (5 angles) for the first time; considered the most general couplings of the resonance to relevant SM fields; and implemented multivariate likelihood fit to do hypothesis testing and parameter fitting

* Please see the reference list in above paper

Outline

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

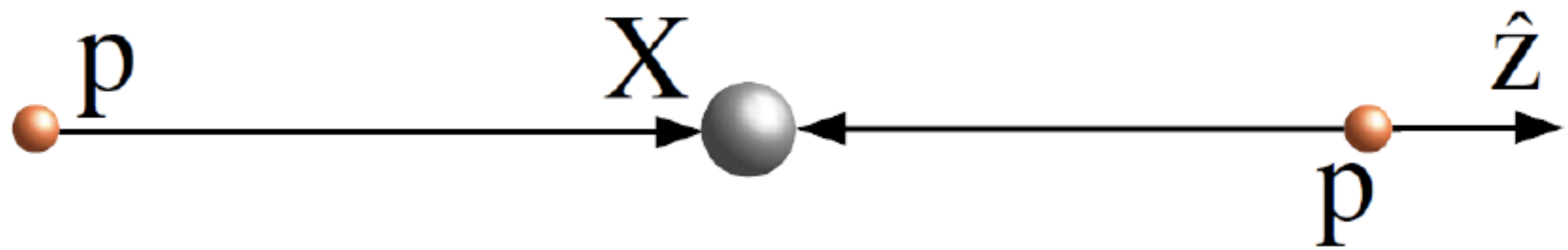
What resonances are we likely to see at LHC?

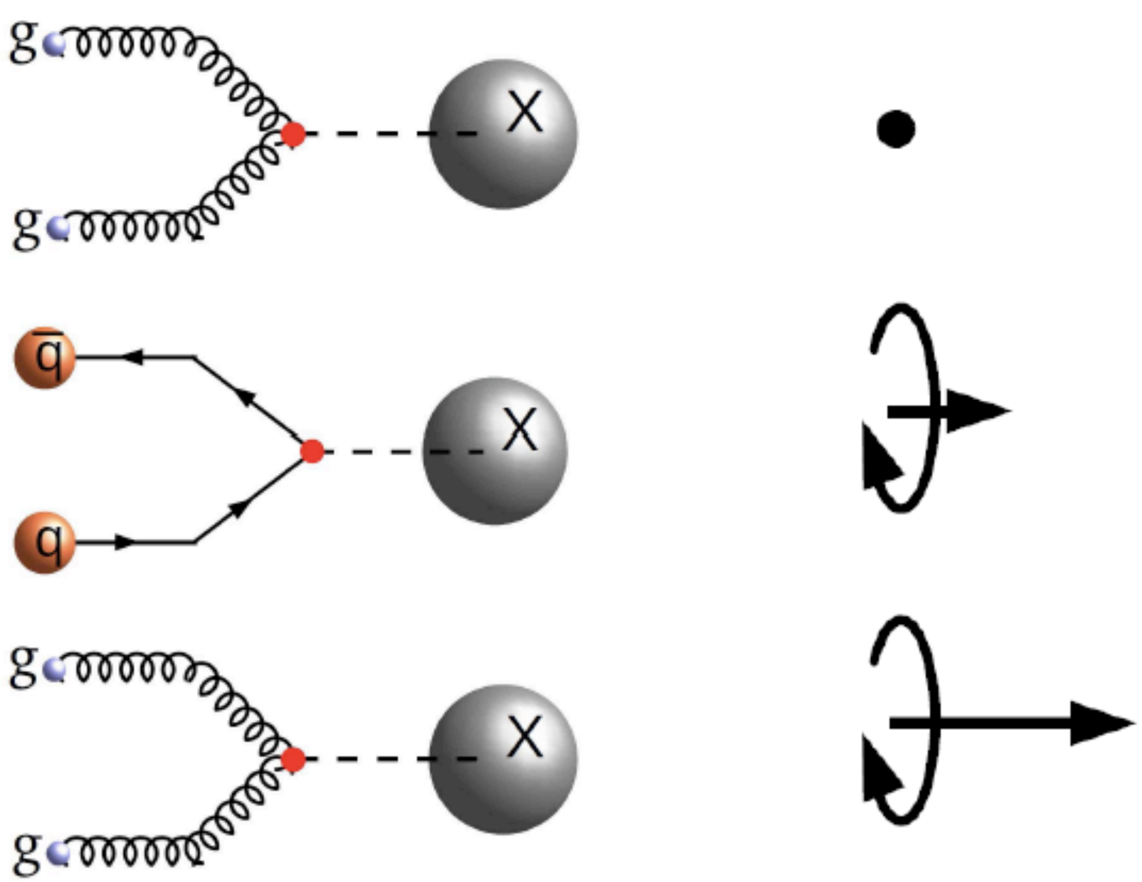
- Spin-0 higgs-like scalars
  - Parity even 0^+ (non-)SM Higgs-like scalars
  - Parity odd 0^- "multi-Higgs models"
- Spin-1 new gauge bosons
  - Parity odd/even KK gauge bosons, Z'
  - Plausible models in which X decays to WW and ZZ dominantly
- Spin-2 graviton-like tensors
  - Parity even RS Graviton, "warped extra-dimensions"
    - couples with SM fields minimally 2_M^+
    - couples with SM fields non-minimally 2_L^+
  - Exotic particles with odd parity 2^-

Production of New Resonance X at 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}

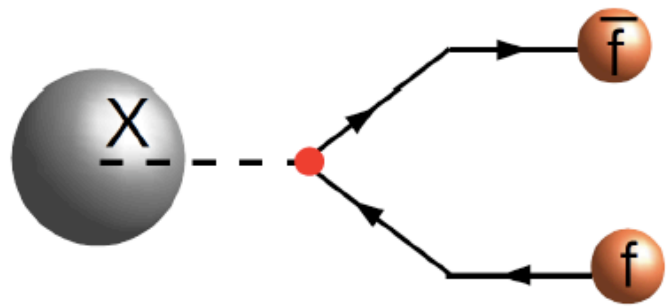
$J_z = \pm 1$ fraction f_{z1}

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

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

Decay of New Resonance X at LHC

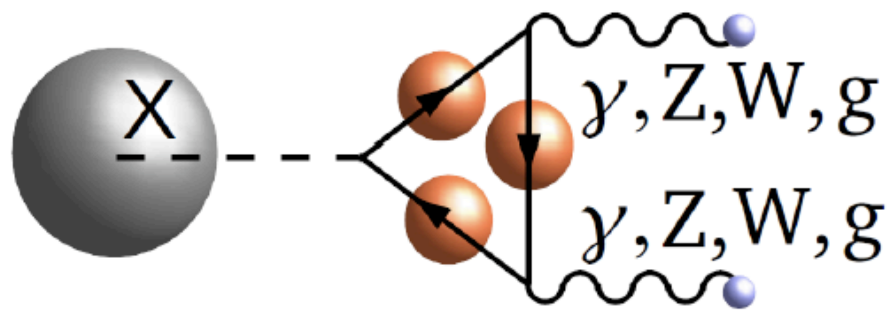
- Consider resonance X decays to SM fields



- Decay to fermions

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

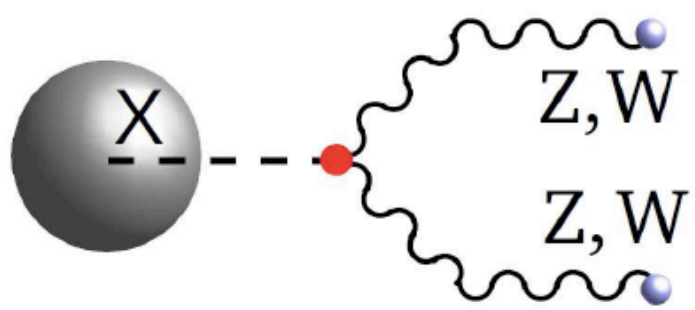
spin-0 excluded $m_f \to 0$



- 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

- Focus on the decay channel 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 Amplitude

- Helicity amplitude of 1→2 decay process

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

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}

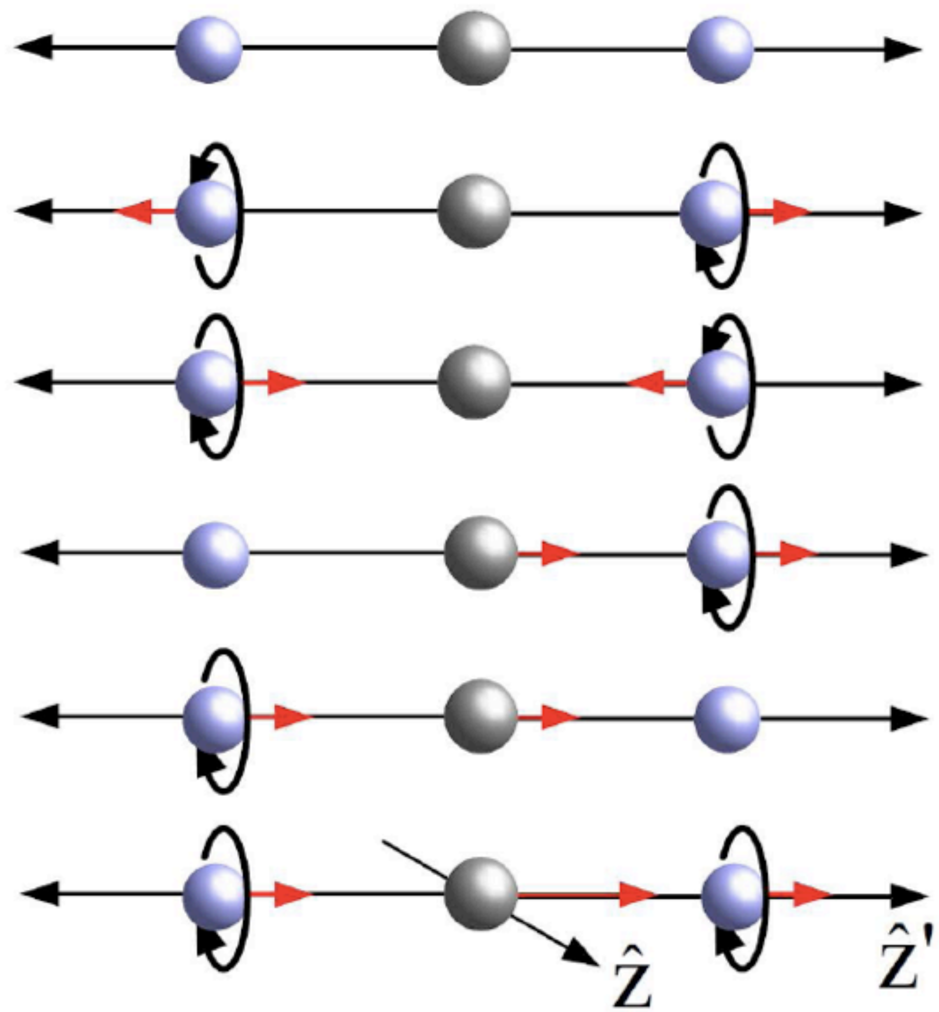
A_{++}

A_{--}

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

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

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



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

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

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

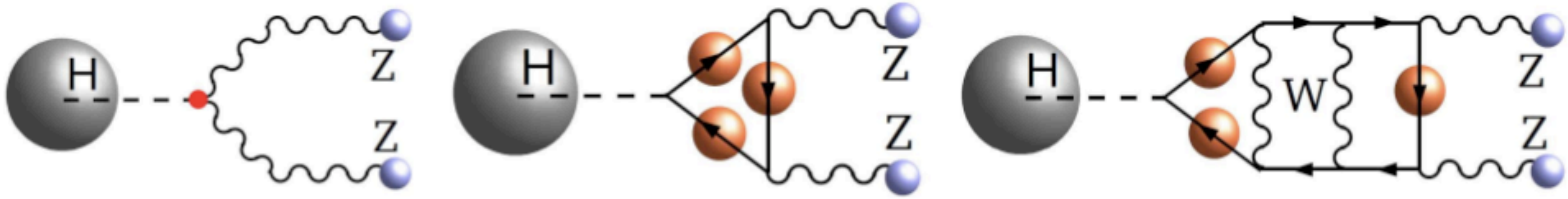
$|J_z| = 0,1,2 \Rightarrow f_{z0},\ f_{z1},\ f_{z2}$

X(J=0)→VV Amplitude

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

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

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



- 3 amplitudes ("experiment") ⇔ 3 coupling constants ("theory")

$$A_{00} = -\frac{M_X^4}{4 v M_V^2} \left(a_1 (1+\beta^2) + a_2 \beta^2 \right) \quad \leftarrow \text{SM dominates at } \frac{M_X}{M_V} \gg 1$$

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

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

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

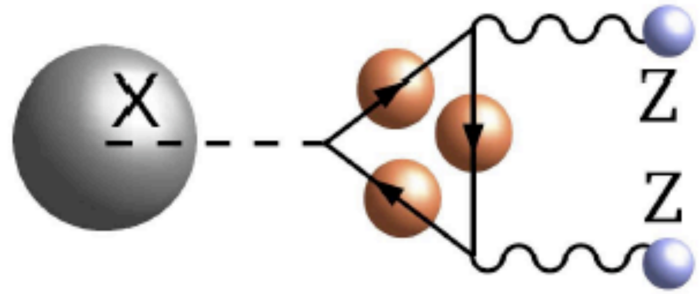
X(J=1)→VV Amplitude

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

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

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

Example:



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

$$A_{+0} \equiv -A_{0+} \quad = \quad \frac{\beta m_X^2}{2m_Z}(b_1 + i\beta b_2)$$

$$A_{-0} \equiv -A_{0-} \quad = \quad \frac{\beta m_X^2}{2m_Z}(b_1 - i\beta b_2)$$

X(J=2)→VV Amplitude

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

$$A = \frac{e_1^{*\mu}\, e_2^{*\nu}}{\Lambda}\Big[\boxed{c_1\, t_{\mu\nu}(q_1 q_2) + c_2\, g_{\mu\nu} t_{\alpha\beta}(q_1 - q_2)^\alpha (q_1 - q_2)^\beta}$$

$$\boxed{+\frac{c_3\, t_{\alpha\beta}}{M_X^2} q_{2\mu} q_{1\nu}(q_1 - q_2)^\alpha (q_1 - q_2)^\beta + 2c_4\left(t_{\mu\alpha} q_{1\nu} q_2^\alpha + t_{\nu\alpha} q_{2\mu} q_1^\alpha\right)}$$

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

$$+\frac{c_5 t_{\alpha\beta}}{M_X^2}(q_1 - q_2)^\alpha (q_1 - q_2)^\beta \epsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma + c_6 t^{\alpha\beta}(q_1 - q_2)_\beta \epsilon_{\mu\nu\alpha\rho} q^\rho$$

$$+\frac{c_7 t^{\alpha\beta}}{M_X^2}(q_1 - q_2)_\beta \left(\epsilon_{\alpha\mu\rho\sigma} q^\rho (q_1 - q_2)^\sigma q_\nu + \epsilon_{\alpha\nu\rho\sigma} q^\rho (q_1 - q_2)^\sigma q_\mu\right)\Big]$$

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

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

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

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

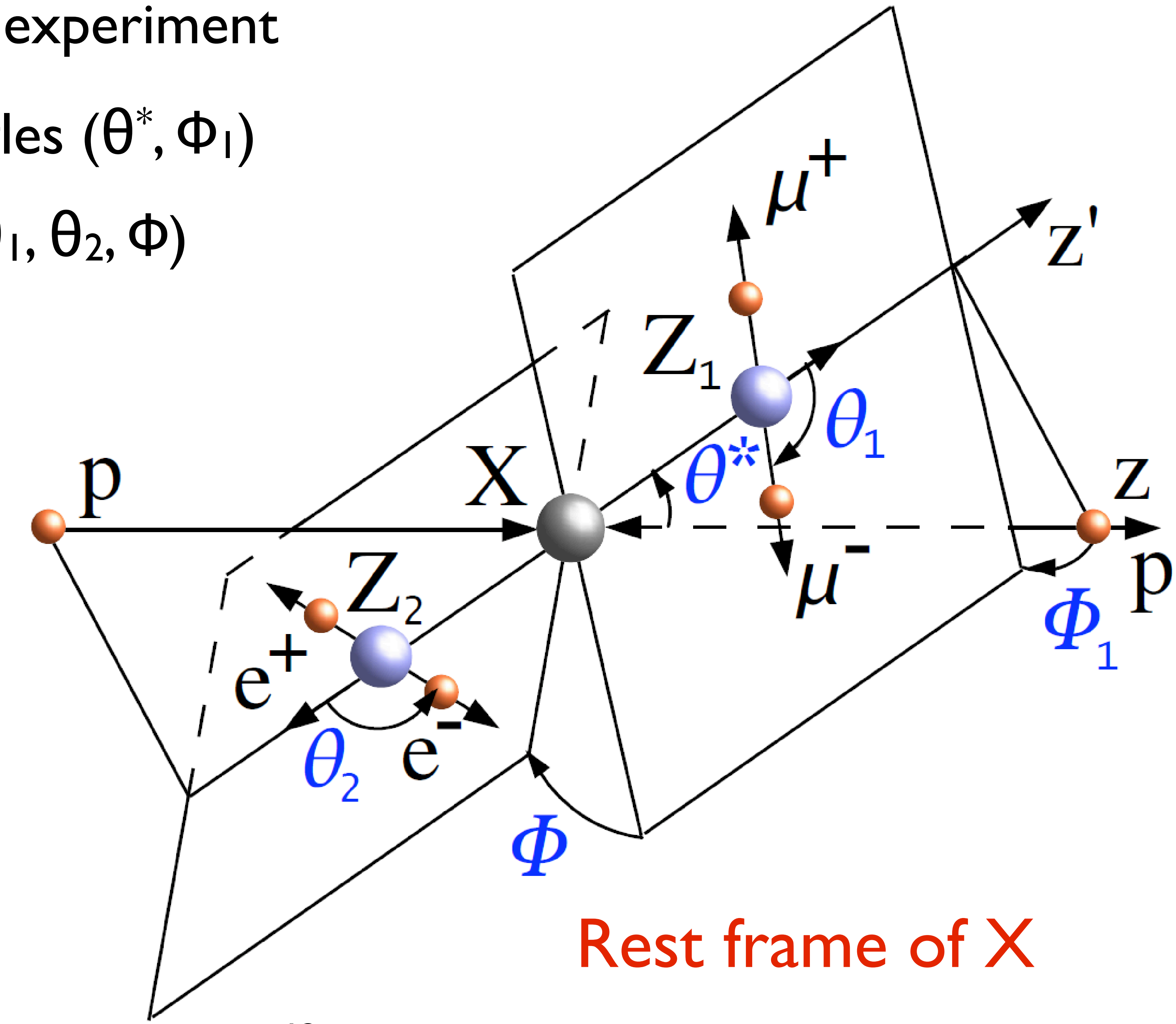
$$A_{+-} \equiv A_{-+} = \frac{M_X^2}{4\Lambda} c_1\left(1+\beta^2\right)$$

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: $q\bar{q} \to ZZ$ (the only irreducible bkg)
  - Others negligible: $Zb\bar{b}$, $t\bar{t}$, $W^+W^-b\bar{b}$, WWZ, $t\bar{t}Z$, $4b$

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 frame of X

Angular Distributions

- The helicity amplitudes and angular distributions

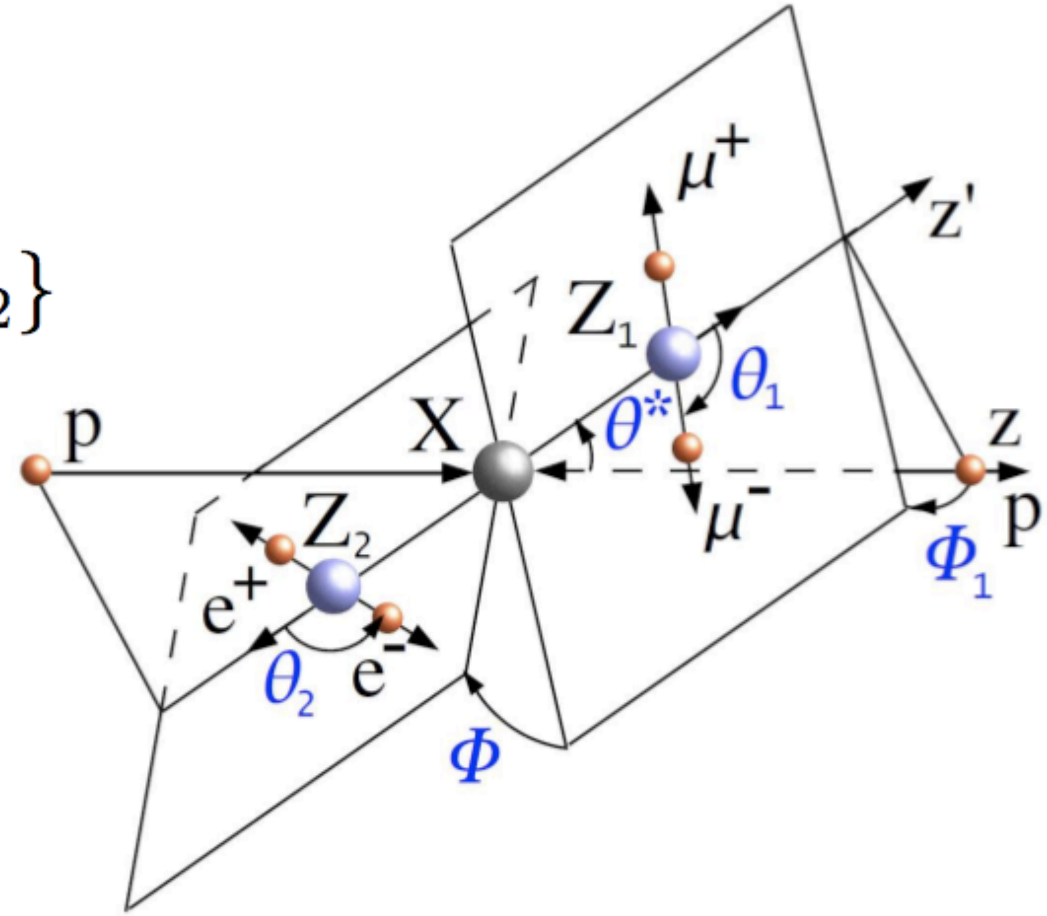
$$\boxed{\begin{aligned} A_{ab} \propto \quad & D^{J*}_{\chi_1-\chi_2,m}(\Omega^*)B_{\chi_1\chi_2} \times D^{J*}_{m,\lambda_1-\lambda_2}(\Omega)A_{\lambda_1\lambda_2} \\ & \times D^{s_1*}_{\lambda_1,\mu_1-\mu_2}(\Omega_1)T(\mu_1,\mu_2) \times D^{s_2*}_{\lambda_2,\tau_1-\tau_2}(\Omega_2)W(\tau_1,\tau_2)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

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

$$X \to Z_1Z_2, \ \Omega = (0,0,0), \ \{\lambda_1\lambda_2\}$$

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

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



- Polarization and phases

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

- Differential cross section: $\displaystyle\sum_{\{\chi,\mu,\tau\}}\left|\sum_{\{\lambda,m\}} A_{ab}(p_a, p_b; \{\chi, \lambda; m, \mu, \tau\}; \{\Omega\})\right|^2$

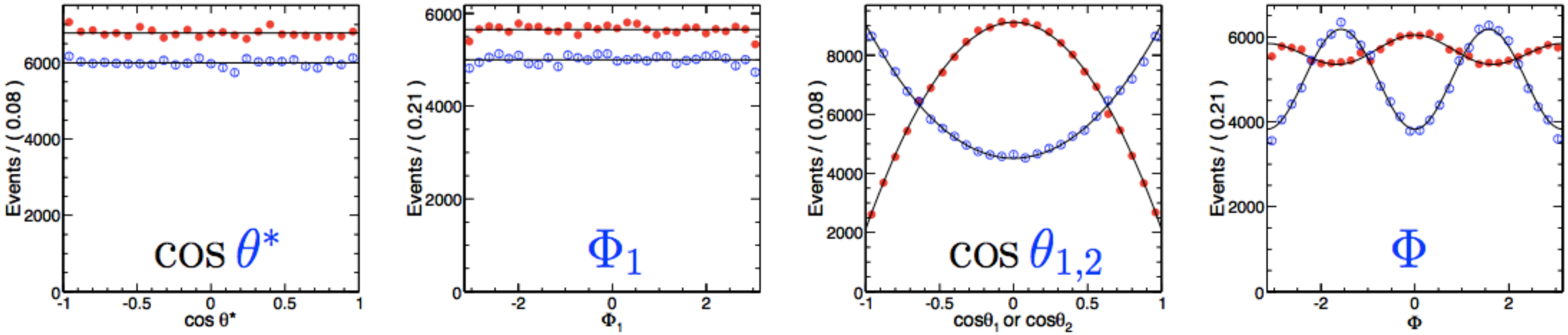
Construct Data Analysis

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

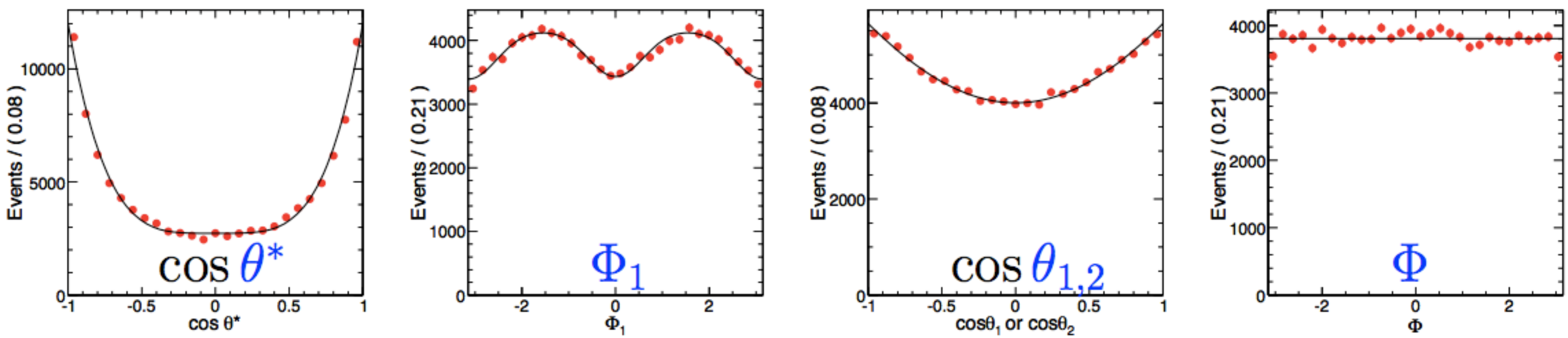
Scenario (J^P)	$X \to ZZ$ decay parameters	X production parameters	Comments
0^+	$a_1 \neq 0$ in Eq. (2)	$gg \to X$	SM Higgs-like scalar
0^-	$a_3 \neq 0$ in Eq. (2)	$gg \to X$	Pseudoscalar
1^+	$g_2^{(1)} \neq 0$ in Eq. (4)	$q\bar{q} \to X$: $\rho_1^{(1)}$, $\rho_2^{(1)} \neq 0$ in Eq. (9)	Exotic pseudovector
1^-	$g_1^{(1)} \neq 0$ in Eq. (4)	$q\bar{q} \to X$: $\rho_1^{(1)}$, $\rho_2^{(1)} \neq 0$ in Eq. (9)	Exotic vector
2_m^+	$g_1^{(2)} = g_5^{(2)} \neq 0$ in Eq. (5)	$gg \to X$: $g_1^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: $\rho_1^{(2)} \neq 0$ in Eq. (10)	Graviton-like tensor with minimal couplings
2_L^+	$c_2 \neq 0$ in Eq. (6)	$gg \to X$: $g_2^{(2)} = g_3^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: $\rho_1^{(2)}$, $\rho_2^{(2)} \neq 0$ in Eq. (10)	Graviton-like tensor longitudinally polarized and with $J_z = 0$ contribution
2^-	$g_8^{(2)} = g_9^{(2)} \neq 0$ in Eq. (5)	$gg \to X$: $g_1^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: $\rho_1^{(2)}$, $\rho_2^{(2)} \neq 0$ in Eq. (10)	"Pseudotensor"

Example of the Angular Distributions (1/2)

- Higgs 0^+ and 0^- at m_H=250GeV



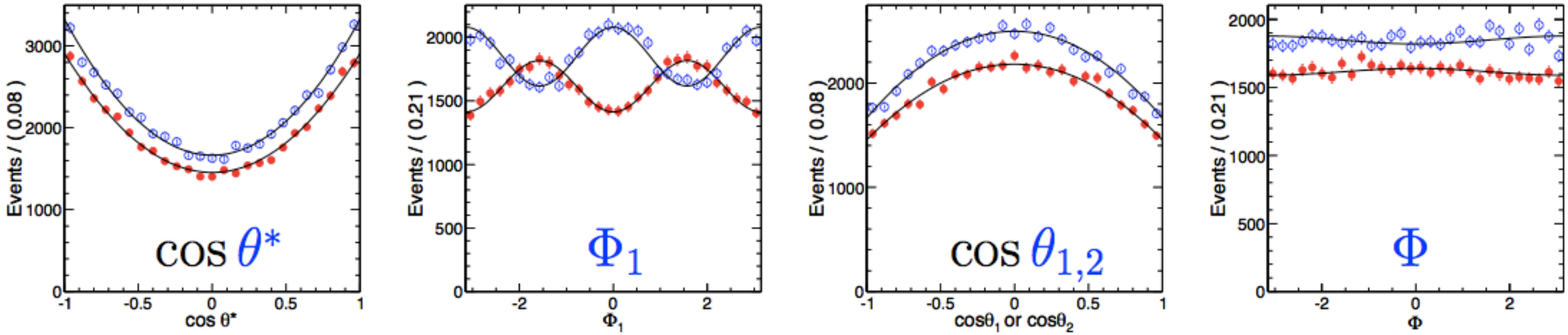
- Background $q\bar{q} \rightarrow ZZ$



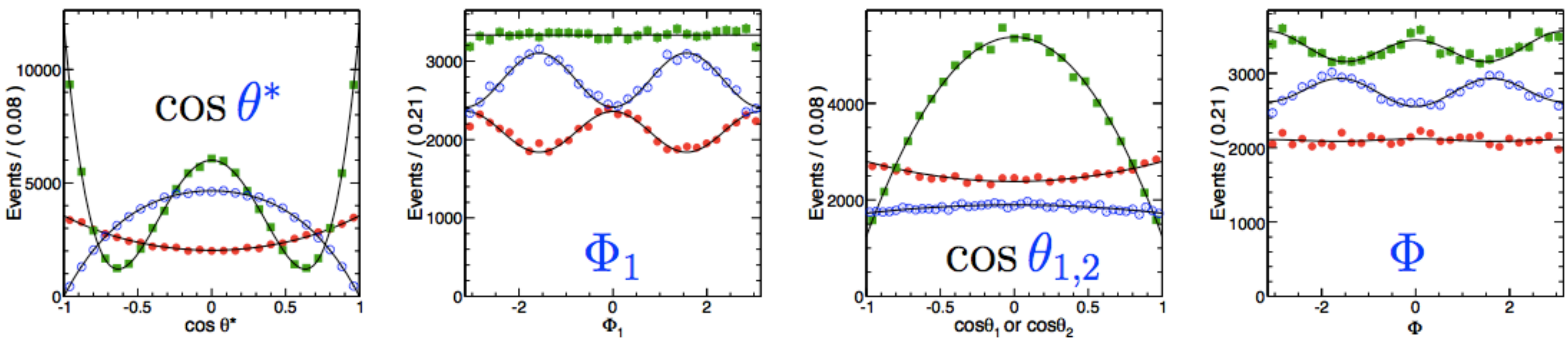
- Lines are the analytical functions, dots are the MC simulation

Example of 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



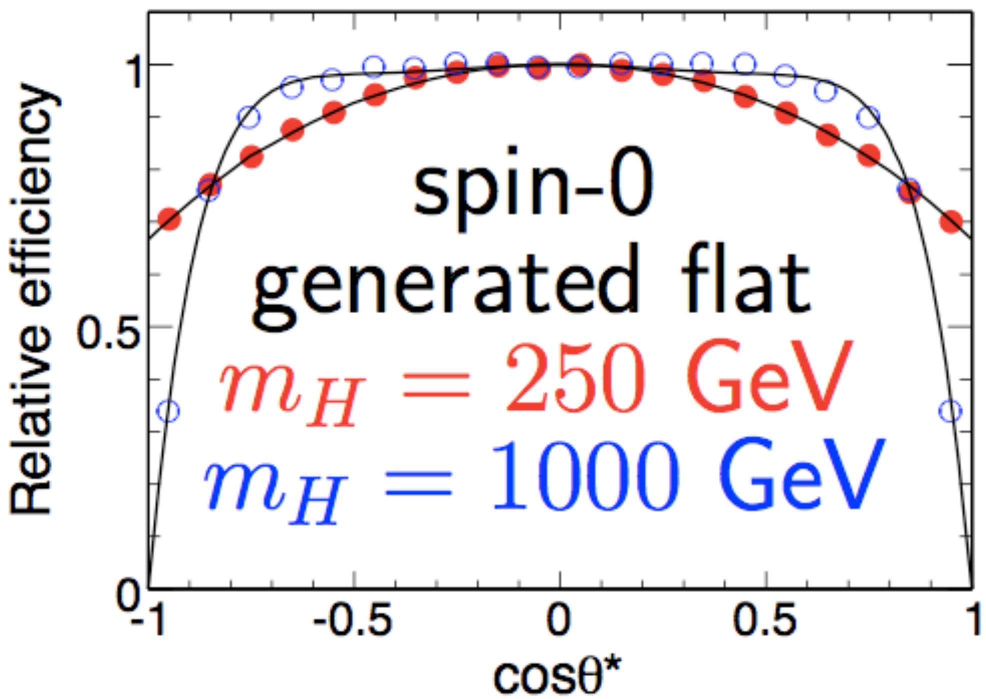
  - Lines are the analytical functions, dots are the MC simulation

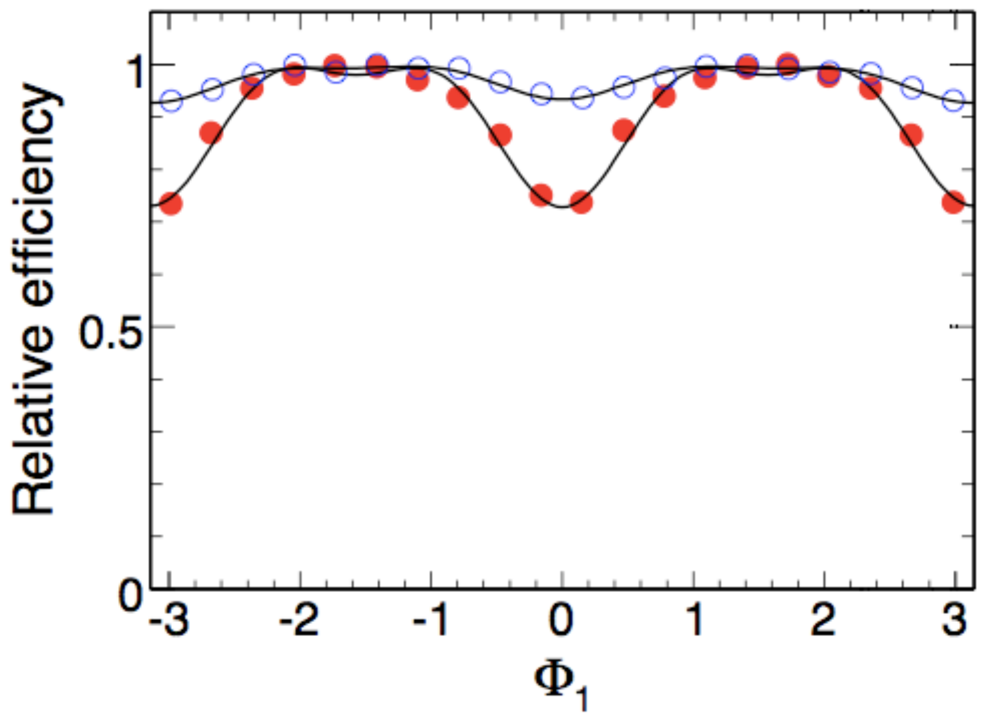
Detector Effects

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

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

  - 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 confident 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 ($A_{\lambda_1\lambda_2}$)
- Caveats
  - This analysis relies on the existence (m_X, Γ_X) of a (non-)SM resonance
  - The precision of the measurements is sensitive to statistics

Multivariate Maximum Likelihood Fit

- Likelihood fit on an event-by-event basis (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

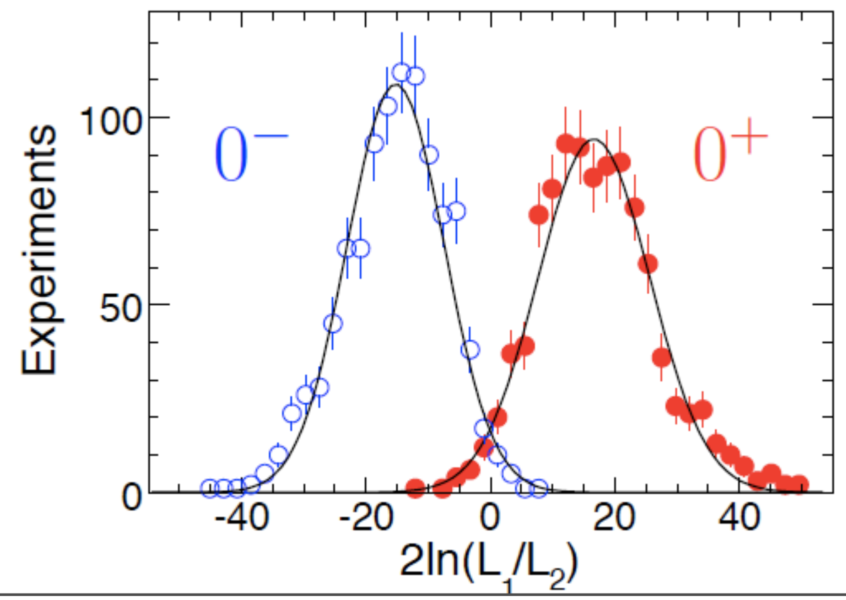
$$\boxed{\mathcal{L} = \exp\left(-\sum_{J=1}^{3} n_J - n_{\text{bkg}}\right) \prod_i^N \left(\sum_{J=1}^{3} n_J \times \mathcal{P}_J(\vec{x}_i;\ \vec{\zeta}_J;\ \vec{\xi}) + n_{\text{bkg}} \times \mathcal{P}_{\text{bkg}}(\vec{x}_i;\ \vec{\xi}) \right)}$$

  - 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 $2\ln(L_1/L_2)$

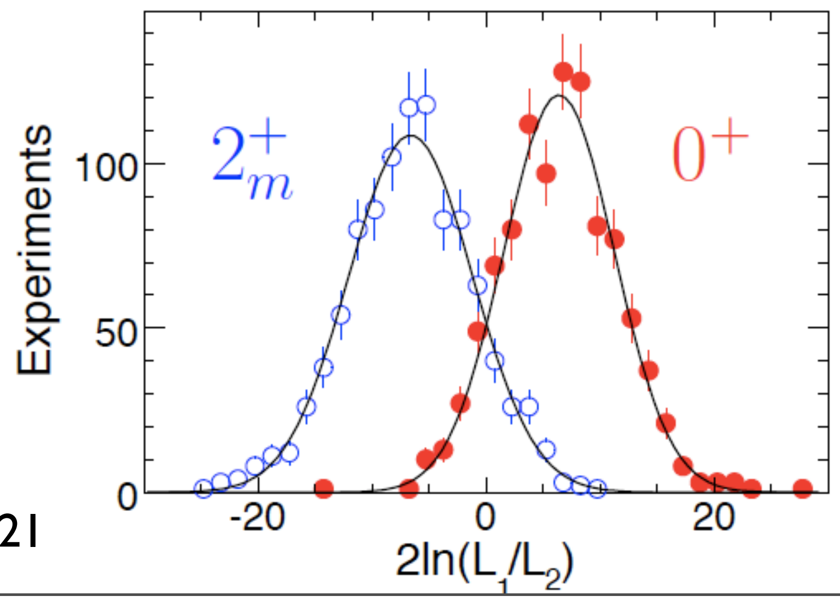
Hypothesis Testing Analysis (1/2)

- To illustrate the procedure, pick a test scenario
  - 30 $H \rightarrow ZZ$ signal events (SM Higgs rate)
  - 24 background events (Luminosity = 5/fb at 14 TeV)
  - S/B significance is 5.7 σ with only m_{ZZ}; increases by ~20% if includes 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^+ and 0^- hypothesis, which gives the L_1 and L_2 respectively, and then plot the $S = 2\ln(L_1/L_2)$ (Red curve)
  - Repeat with the 0^- data (Blue curve)
  - The hypo. test significance is the effective gaussian separation between two peaks

$\mathcal{S} = 4.1\sigma$



$\mathcal{S} = 2.5\sigma$



Hypothesis Testing Analysis (2/2)

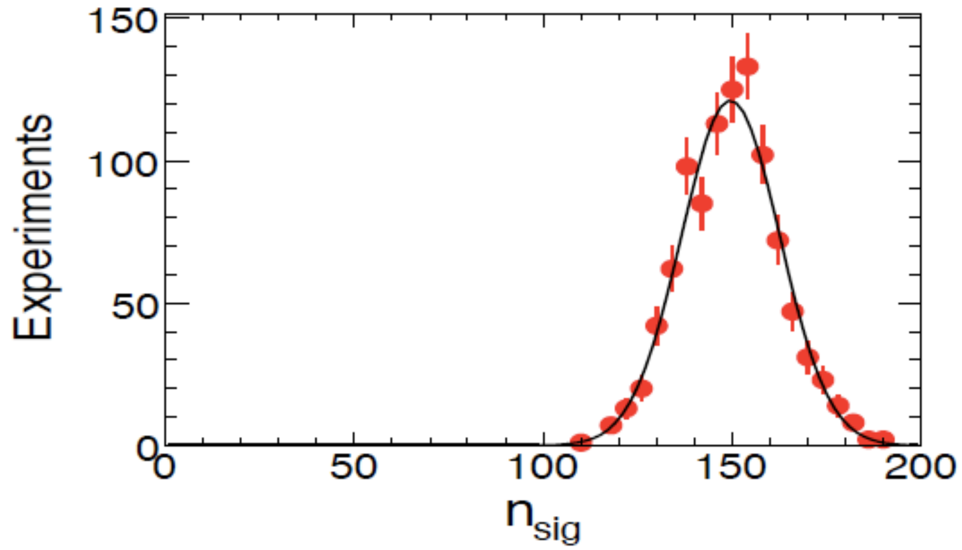
- Repeat the same procedure with each two hypothesis comb.
  - Assume m_X = 250 GeV (1TeV results in the paper)
  - Including more angles increases S/B significance
  - Hypothesis separation results
    - with 1D (θ^*) / 3D (θ_1, θ_2,Φ) / 5D (Φ_1, θ^*, θ_1, θ_2,Φ)

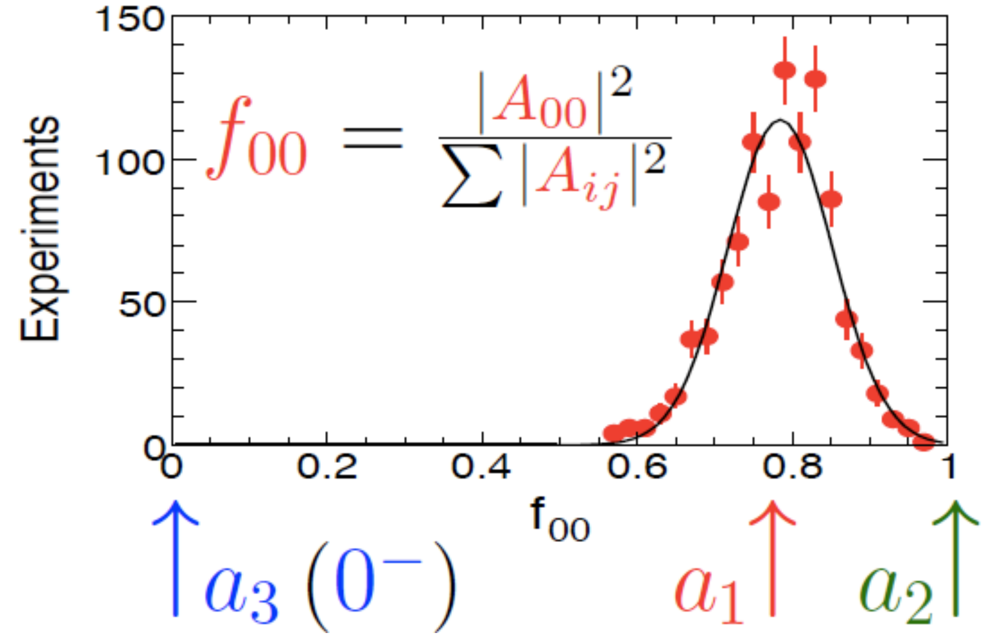
	0^-	1^+	1^-	2^+_m	2^+_L	2^-
0^+	0.0/3.9/4.1	0.8/1.8/2.3	0.9/2.5/2.6	0.8/2.4/2.8	2.6/0.0/2.6	1.6/2.4/3.3
0^-	–	0.8/2.8/3.1	0.9/2.5/3.0	0.8/1.7/2.4	2.9/4.1/4.8	1.6/2.0/2.9
1^+	–	–	0.0/1.1/2.2	0.1/1.3/2.6	2.8/1.9/3.6	2.5/1.2/2.9
1^-	–	–	–	0.1/1.3/1.8	2.8/2.5/3.8	2.5/0.6/3.4
2^+_m	–	–	–	–	2.9/2.6/3.8	2.3/0.5/3.2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

Parameter Fitting Analysis

- Assume a spin-0 Higgs-like resonance 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
$n_{\rm sig}$	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

- LHC is a discovery machine. Once a resonance X is found, it is more than a bump hunt
  - Assuming 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 the coupling constants to SM fields
  - The helicity amplitudes are derived theoretically from $X \to ZZ$ coupling. 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 detector effects
  - We have developed and validated multivariate ML fit to perform both hypothesis testing and parameter fitting analyses
    - At the time of discovery, we can separate hypotheses non-trivially and make statements of resonance's spin and parity
    - With ~150 signal events: we can measure its couplings to SM fields

Backup Slides

Parameters Used in the Angular Distributions

Explicit Angular Distribution Examples

- Production angles

- Decay angles

- Most general distributions with 5 angles are in the paper