Spin Determination of Single-Produced Resonances at LHC

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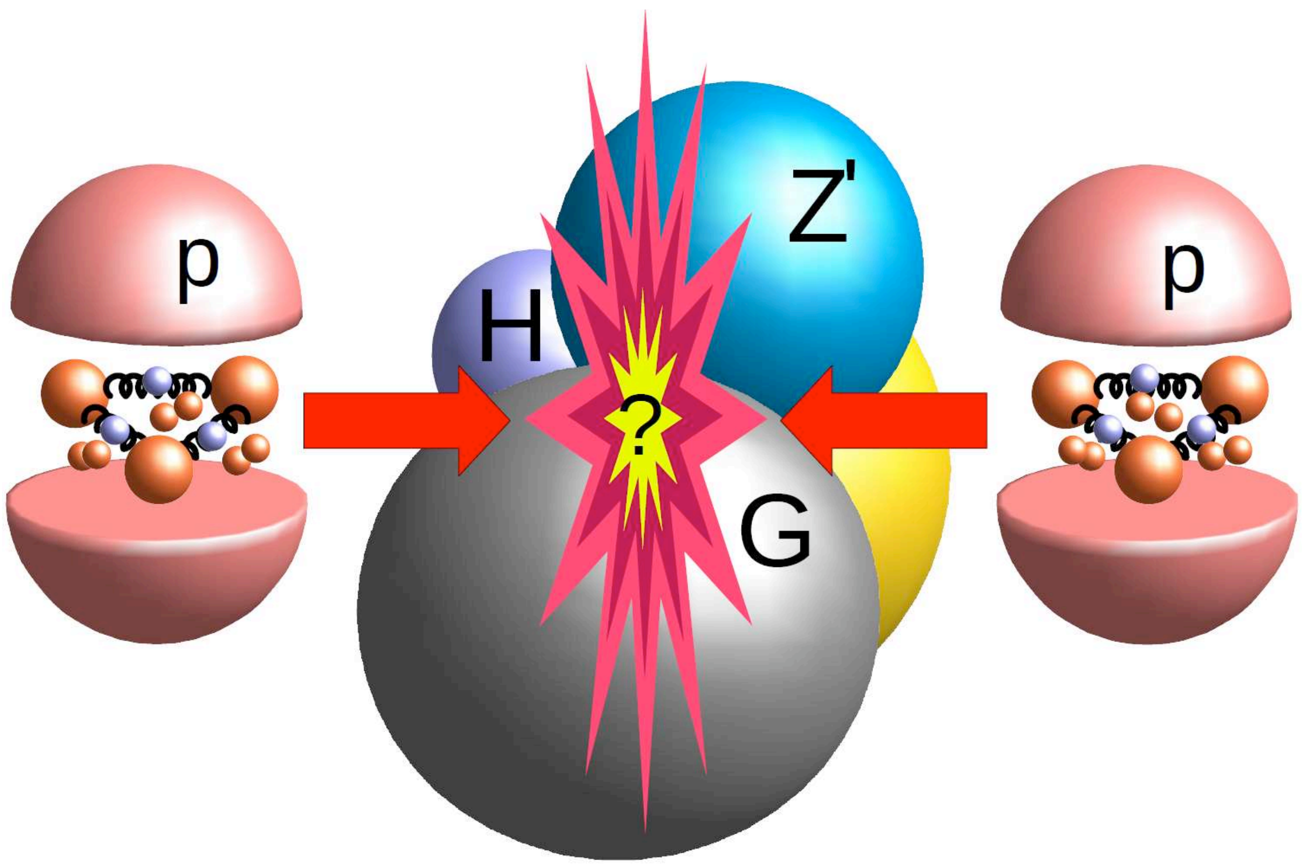
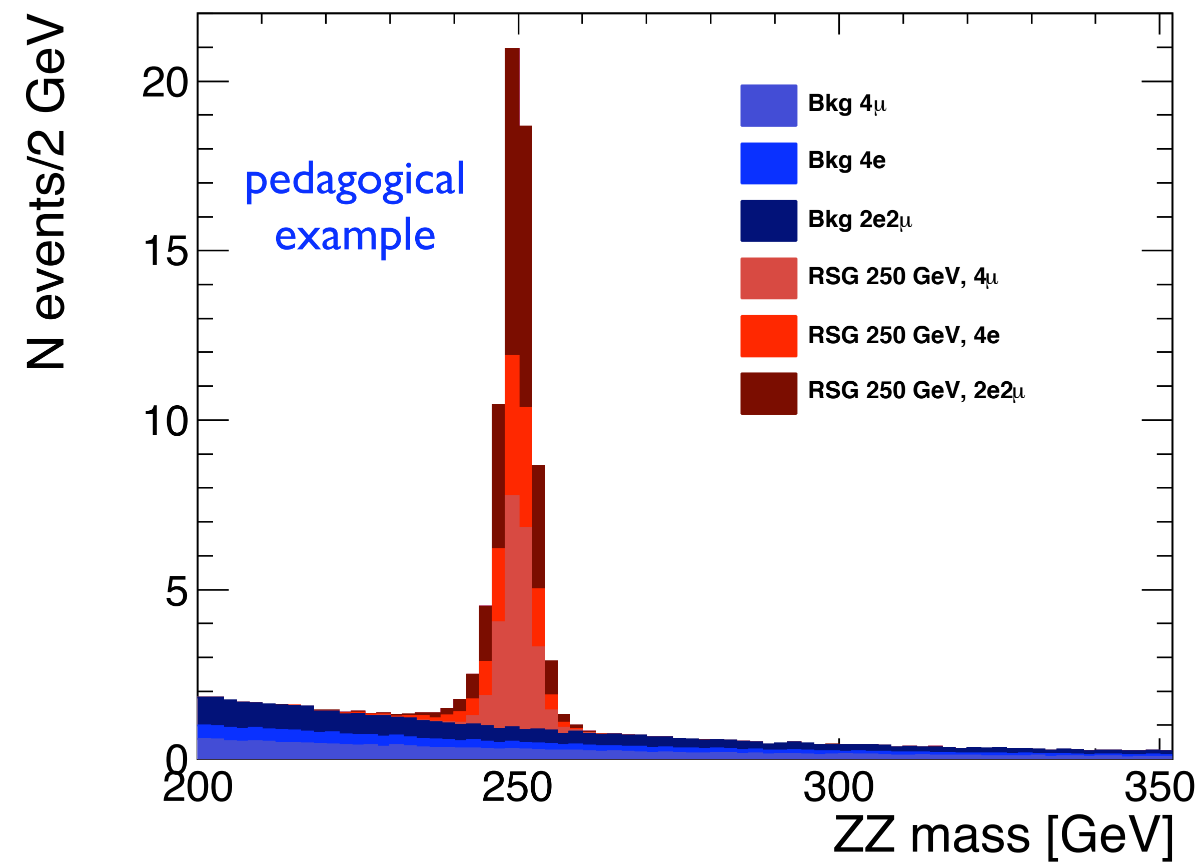
Executive Overview

- 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

- 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]
- There are a few other papers, such as
  - "Higgs look-alikes in LHC"
    - A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M. Spiropulu
    - preprint arXiv:1001.5300[hep-ph]
  - Add more
    - Add more
    - Add more

Outline

- Start with the basic questions
  - What kind of resonances are we likely to see in LHC?
- Probe the production and decay of X from theoretical side
  - Consider many potential resonances with $J^P=0^+, 0^-, 1^+, 1^-, 2_M^+, 2_L^+\ 2^-$
  - Assume the most general couplings of X to the relevant SM fields
  - Simulate the production and decay of X through MC generator
  - Connect the coupling constants (TH) with the helicity amplitudes(EX)
- Extract the helicity amplitudes from experimental side
  - Derive full angular analysis formalism
  - Account for the detector effect in the simulation data
  - Utilize maximum likelihood fit technique to obtain simultaneously the physics quantities of interest (resonance mass, width, spin, parity etc)

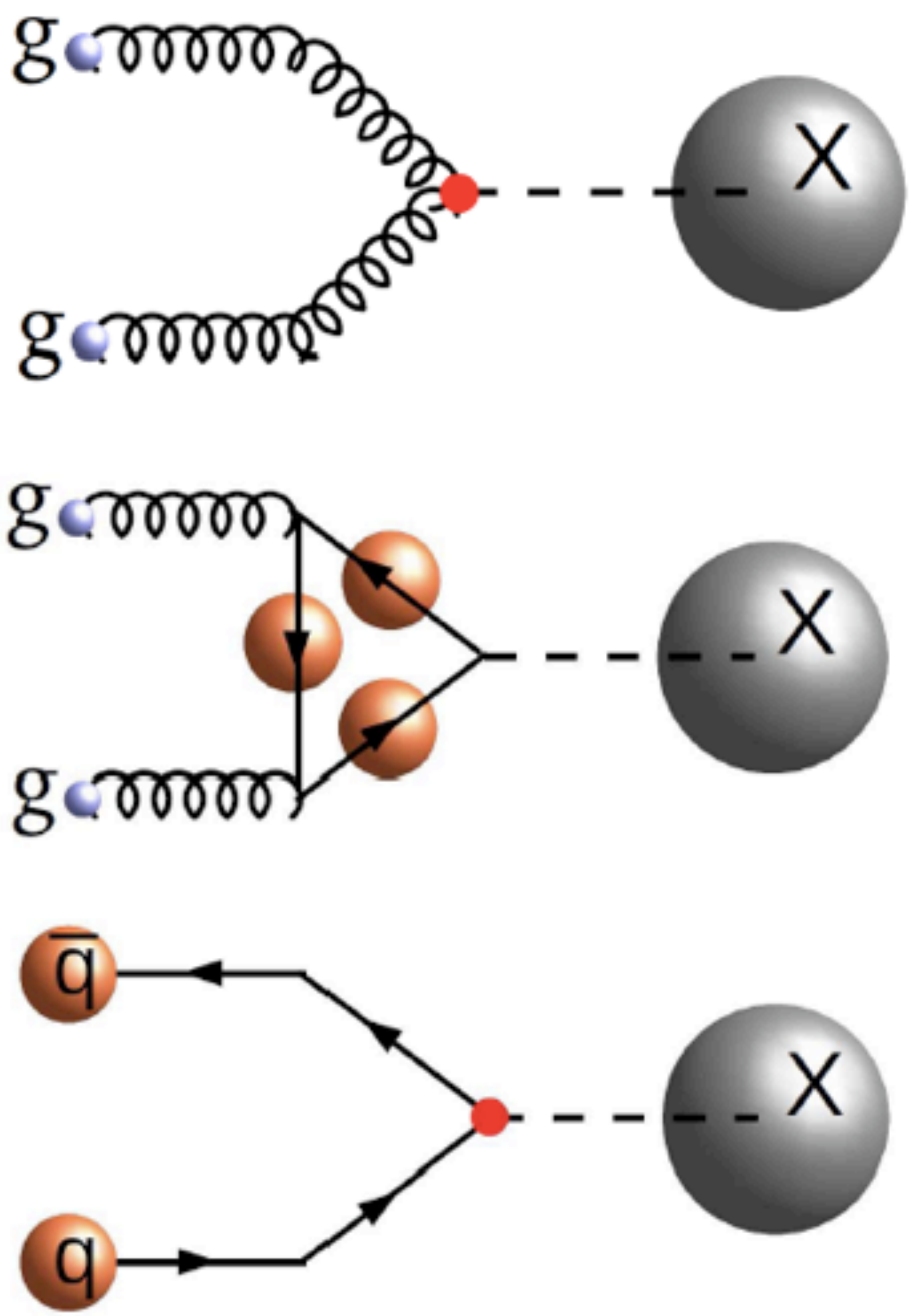
Do we expect new resonances? →YES

- Spin-0 higgs-like
  - Parity odd 0^- standard model higgs
  - Parity even 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
  - Parity even RS Graviton, extra-dimension indicator
    - couples with SM fields minimally 2_M+
    - couples with SM fields non-minimally 2_L+
  - Exotica particles with odd parity 2^-

Theoretical View of the Production and Decay of Resonance X

Production of New Resonance X at LHC

- Consider two dominant production mechanism at LHC



- Gluon fusion $gg \rightarrow X$

  $J = 0$ or 2

  $J_z = 0$ or ± 2

  expect to dominate at lower mass

- Quark-antiquark $q\bar{q} \rightarrow X$

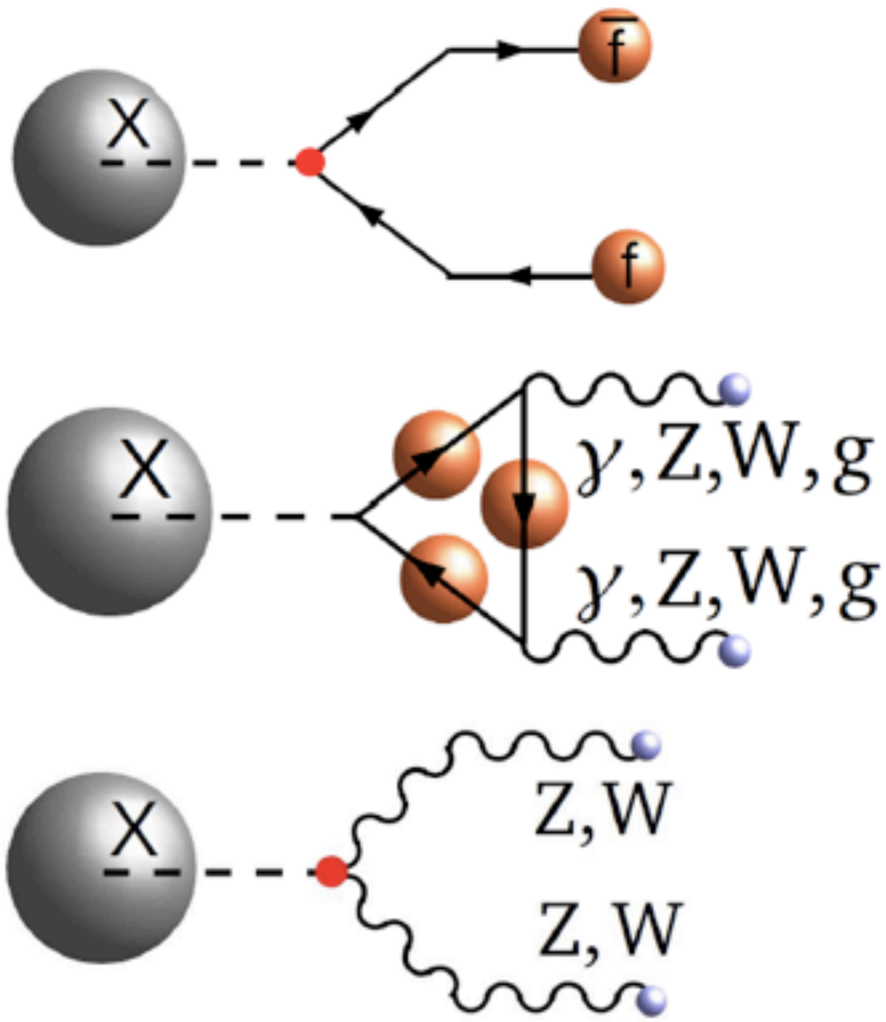
  $J = 1$ or 2

  $J_z = \pm 1 \qquad (m_q \rightarrow 0)$

  assume chiral symmetry is exact

Decay of New Resonance X at LHC

- Consider two dominant production mechanisms



- 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 decay b.r. is expected in many models especially at high m_X
  - All final states can be reconstructed with high eff. and good resolution
  - More information can be extracted through 4-body decay

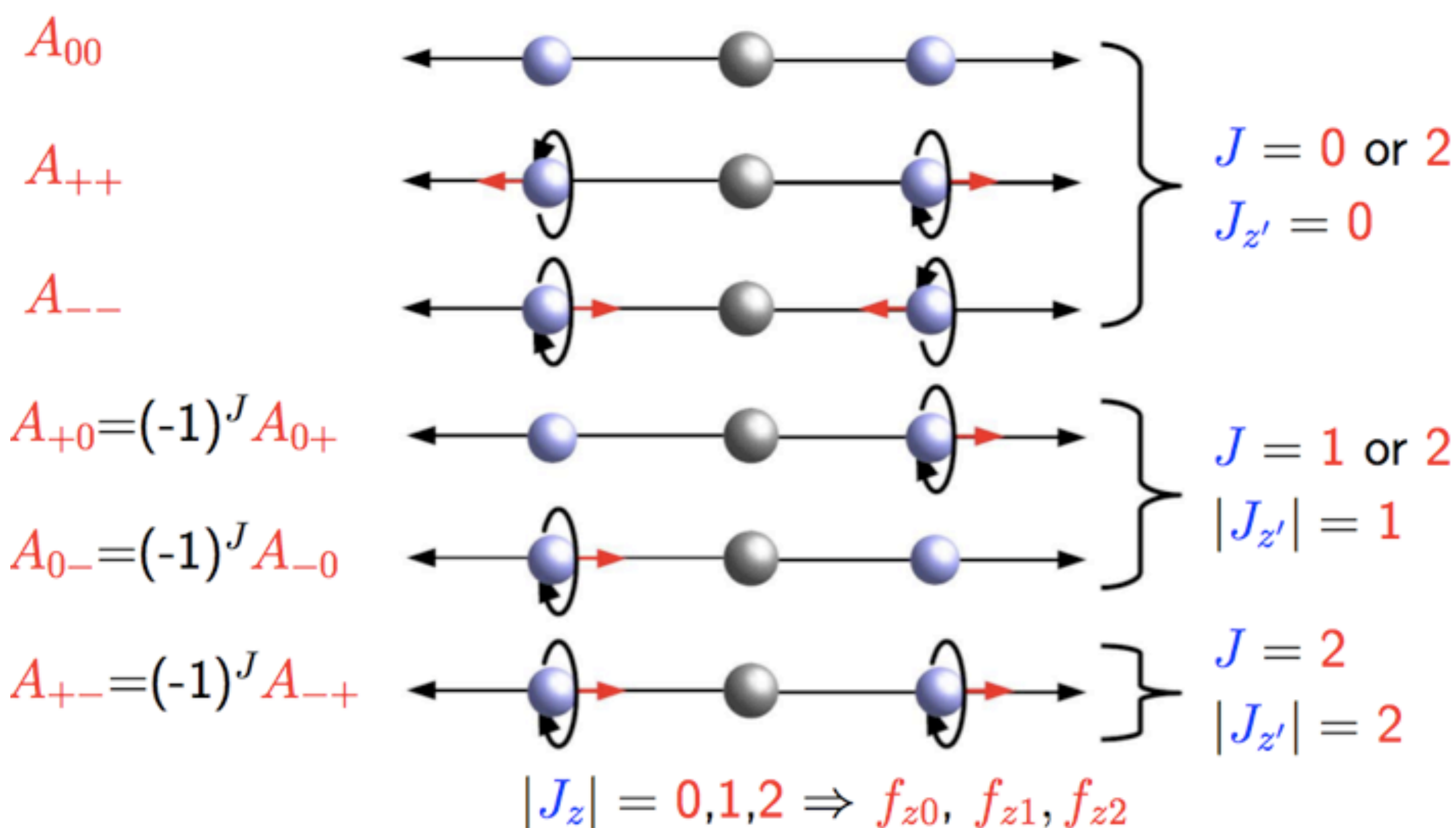
Helicity Amplitude

- Helicity amplitude of A→1+2 decay process

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

  - Ω: polar and azimuthal angle of 1 in A's rest frame; λi: the helicity of 1 and 2

- symmetry in $X \to ZZ$: $A_{\lambda_1\lambda_2}$=(-1)$^J A_{\lambda_2\lambda_1}$
  if parity is a symmetry: $A_{\lambda_1\lambda_2}$=η_X(-1)$^J A_{-\lambda_1-\lambda_2}$ (do not use)

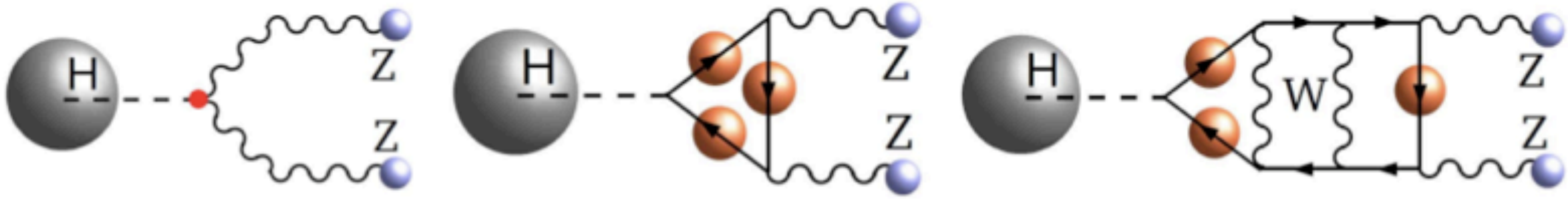


X (Spin 0)→VV Amplitude

- 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) $\cancel{CP}$



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

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

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

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

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

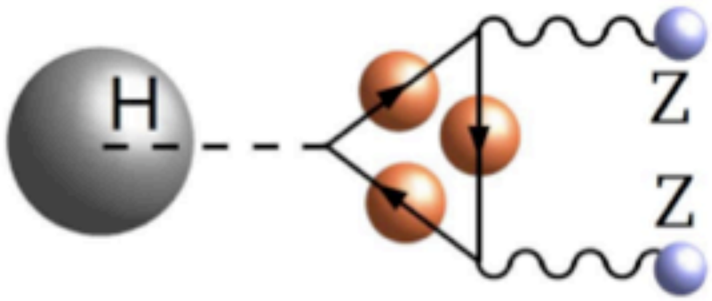
Spin-1 X→VV Amplitudes

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

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

1^- CP | 1^- $\cancel{CP}$
1^+ $\cancel{CP}$ | 1^+ CP

Example:



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

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

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

X (Spin-2)→VV Amplitude

- Most general amplitude for $X_{J=2} \rightarrow VV$

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

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

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

- Polarization notation:

$$e_1^\mu(\lambda_1=0) = \left(\tfrac{\beta M_X}{2M_V}, 0, 0, \tfrac{M_X}{2M_V}\right) \quad \perp \quad q_1^\mu = \left(\tfrac{M_X}{2}, 0, 0, \tfrac{\beta M_X}{2}\right)$$

$$e_1^\mu(\lambda_1=\pm) = \tfrac{1}{\sqrt{2}}(0, \mp 1, -i, 0)$$

$t^{\mu\nu}(J_{z'}=+2) = e_X^\mu(+) e_X^\nu(+)$, etc...

- Note: c_2, c_3, c_5 like spin-0

X (Spin-2)→VV Amplitudes

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

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

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

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

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

- Note: again A_{00} dominates, unless c_i fine-tuned
  - minimal coupling: dominant A_{+-} for $\beta \to 1$ and $c_2 = \frac{c_4}{2} \simeq -\frac{c_1}{4}$

    A_{00} small, $A_{++}, A_{--}, A_{+0}, A_{0-} \to 0$

$\Rightarrow$ only $J_z = \pm 2$ with minimal gg$\to X$

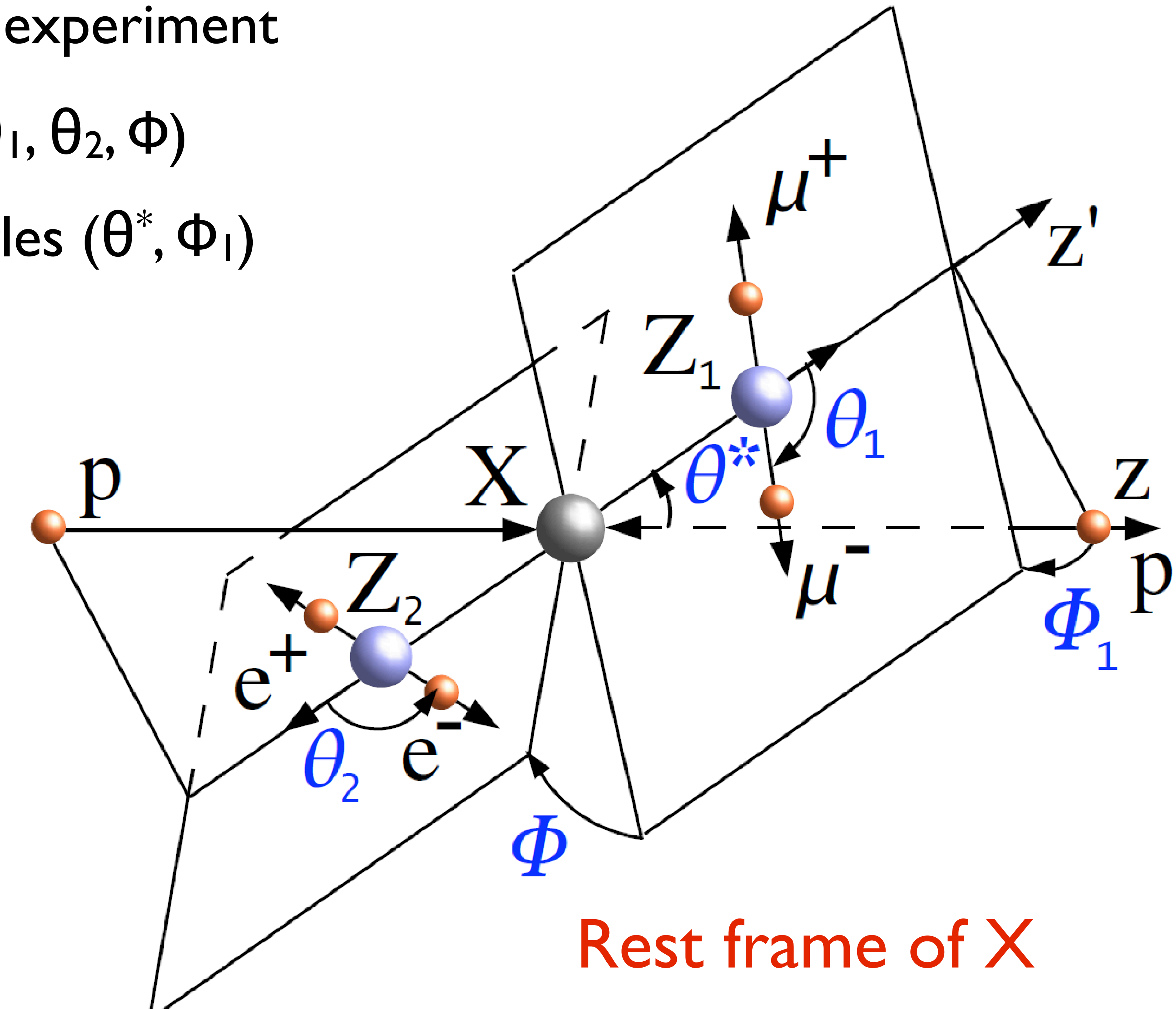
Monte Carlo Simulation

- 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
    - It contains interface to detector simulation (Pythia)
    - It uses only general couplings,
        - includes Higgs radiative corrections
        - considers both non-minimal/minimal 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, $t\bar{t}Z$, $4b$

Experimental View of the Production and Decay of Resonance X

Angular Variables

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



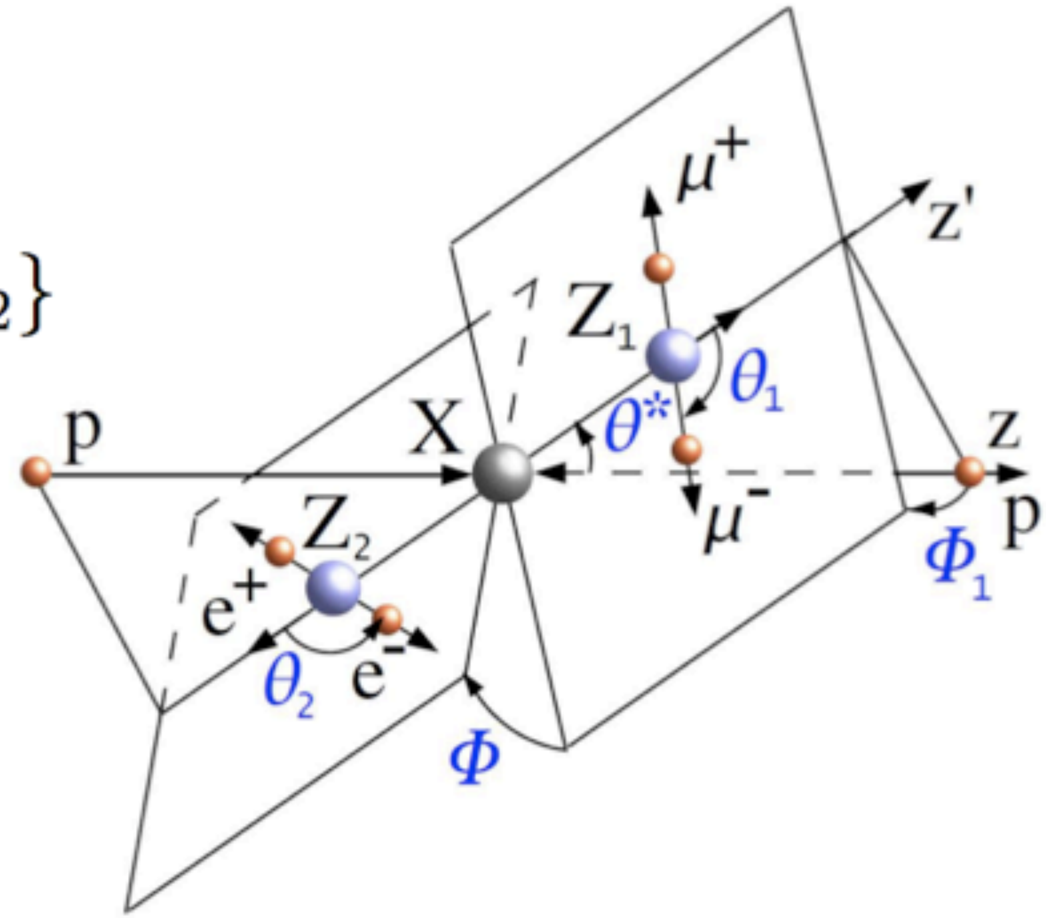
Rest frame of X

Angular Distributions

- The helicity amplitudes and angular distributions

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

$$ab \to X, \quad \Omega^* = (\Phi_1, \theta^*, -\Phi_1), \ \{\chi_1\chi_2\}$$
$$X \to Z_1Z_2, \ \Omega = (0,0,0), \ \{\lambda_1\lambda_2\}$$
$$Z_1 \to f_1\bar{f}_1, \ \Omega_1 = (0,\theta_1,0), \ \{\mu_1,\mu_2\}$$
$$Z_2 \to f_2\bar{f}_2, \ \Omega_2 = (\Phi,\theta_2,-\Phi), \ \{\tau_1,\tau_2\}$$



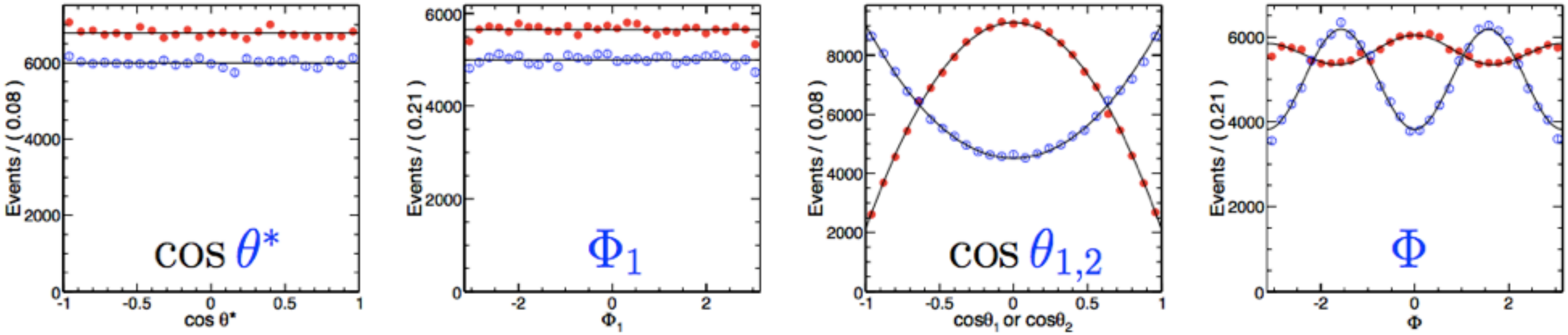
- Polarization:

$$f_{\lambda_1\lambda_2} = |A_{\lambda_1\lambda_2}|^2/\sum|A_{ij}|^2$$

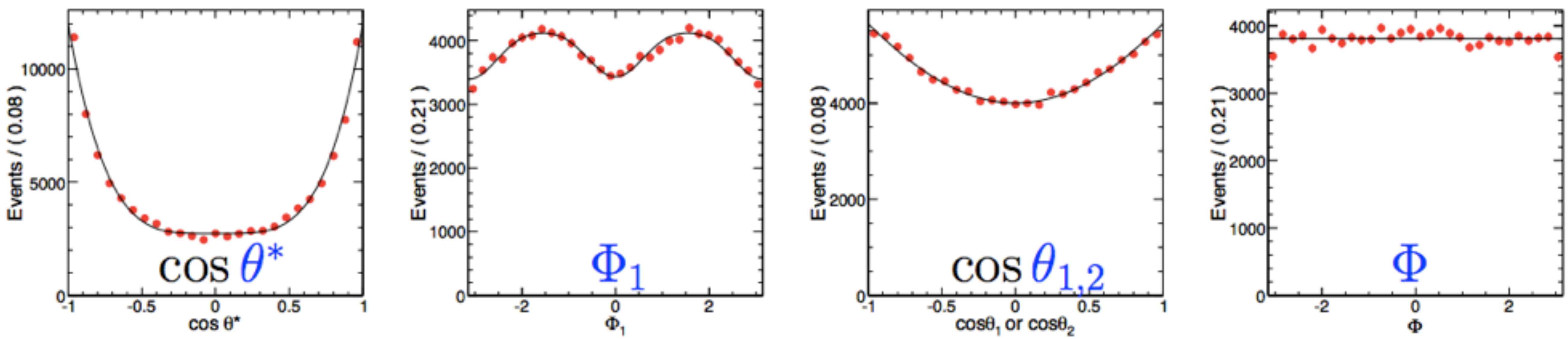
- Differential cross section: $\sum_{\{\chi,\mu,\tau\}} \left| \sum_{\{\lambda,m\}} A_{ab}(p_a, p_b; \{\chi, \lambda; m, \mu, \tau\}; \{\Omega\}) \right|^2$

Example of the Angular Distributions (1/2)

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



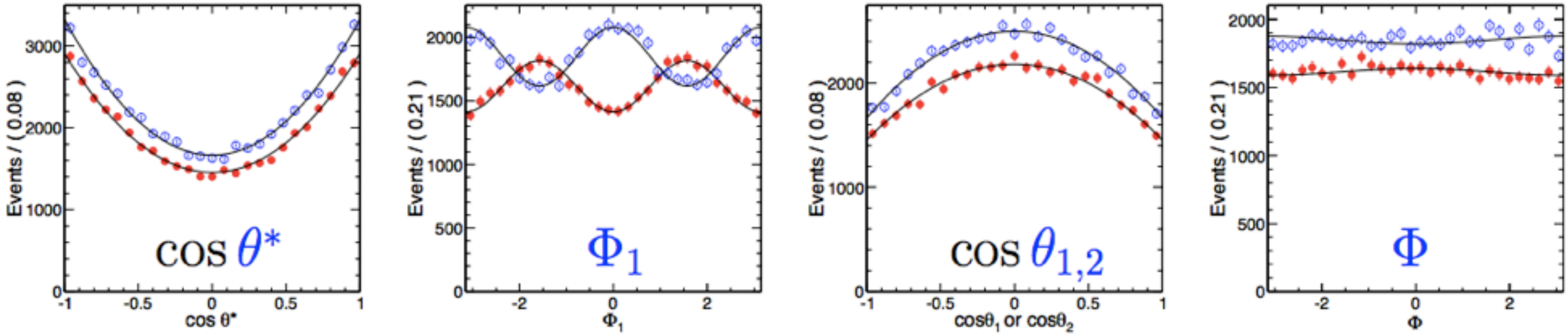
- Background $q\bar{q} \rightarrow ZZ$



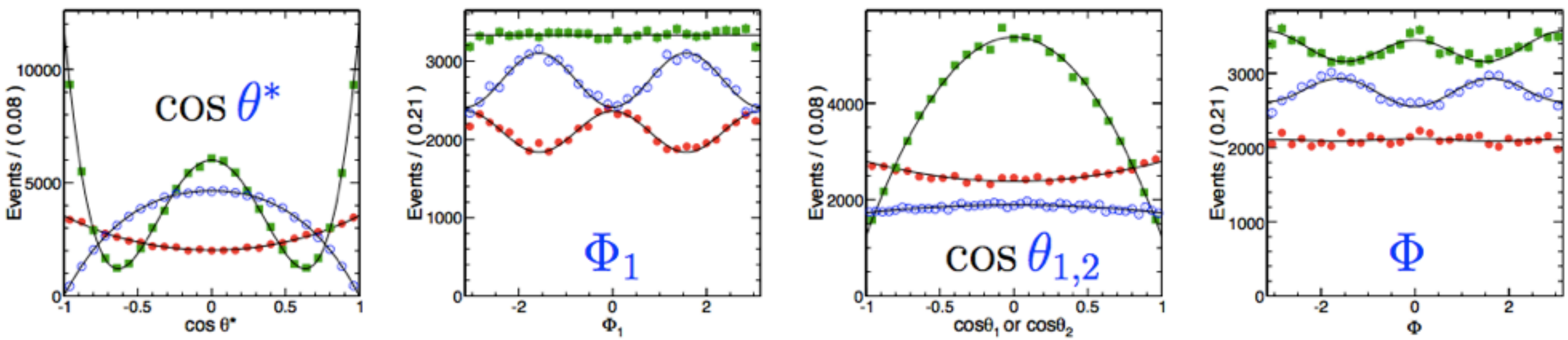
- Lines are the analytical functions, dots are the MC simulation

Example of the Angular Distributions (2/2)

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



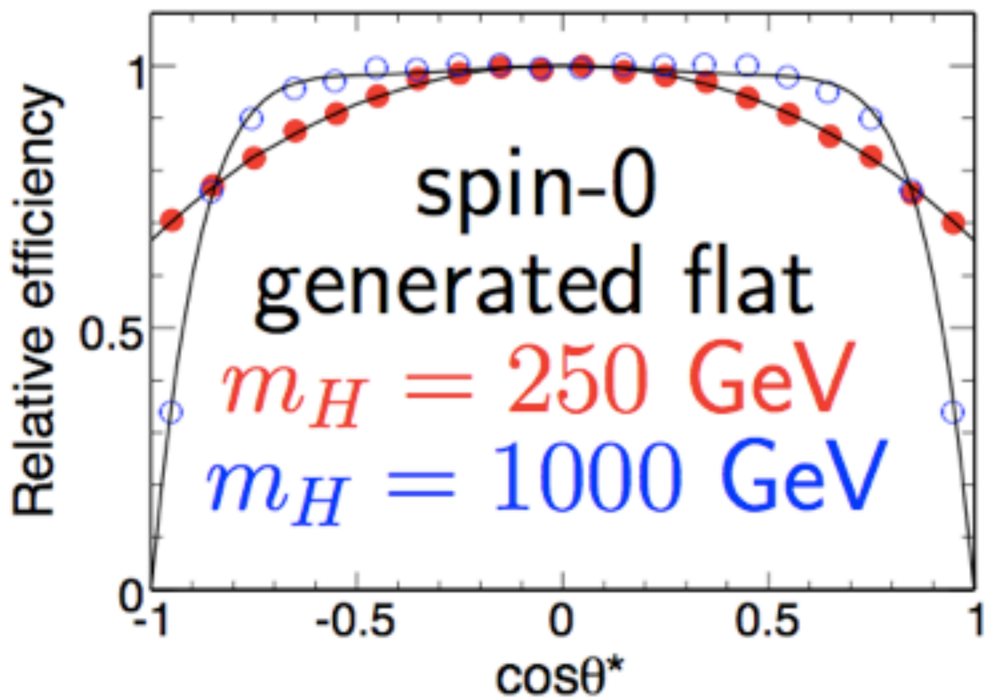
- Gravitons, 2_m^+(minimal), 2_L^+(Higgs-like) and 2^+ at m_X=250GeV

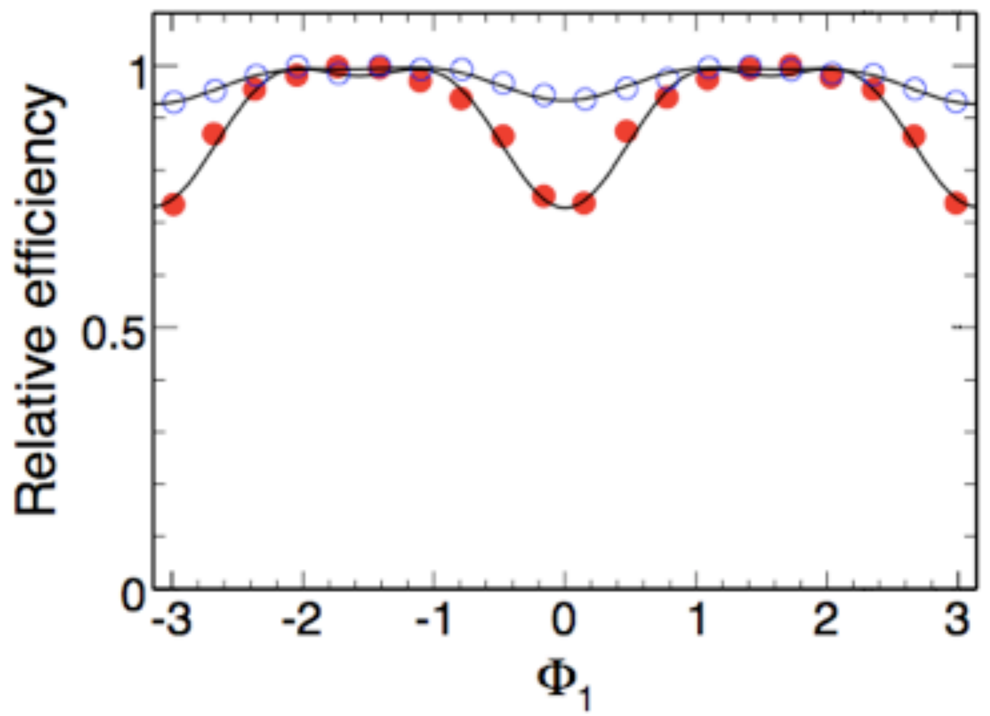


- Lines are the analytical functions, dots are the MC simulation

Detector Effects

- The measurement of the angles depends on the 4-momenta measurement of the 4 leptons in the final states, especially
  - the track pT and impact parameter resolutions
  - non-uniform reconstruction efficiency of the detector
- Account for detector effects in the MC $\mathcal{G}(\Phi_1, \theta^*, \theta_1, \theta_2, \Phi)$
  - Smear the track parameters by CMS track resolution → 0.01 rad in angles
  - Consider |η|<2.5





Perform Angular Analysis

Data Analysis in a Nutshell

- Imagine that we observed 30 non-SM resonance events
  - Hypothesis testing analysis
    - Compute a confident level in which one hypo can be separated 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 the 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: $\vec{x}_i = (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi; m_{ZZ}, ..)$
  - Event event has a probability of being a certain event type (sig/bkg). The probability is given by probability density function (PDF):

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

  - The signal PDF contains the parameters of interest

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

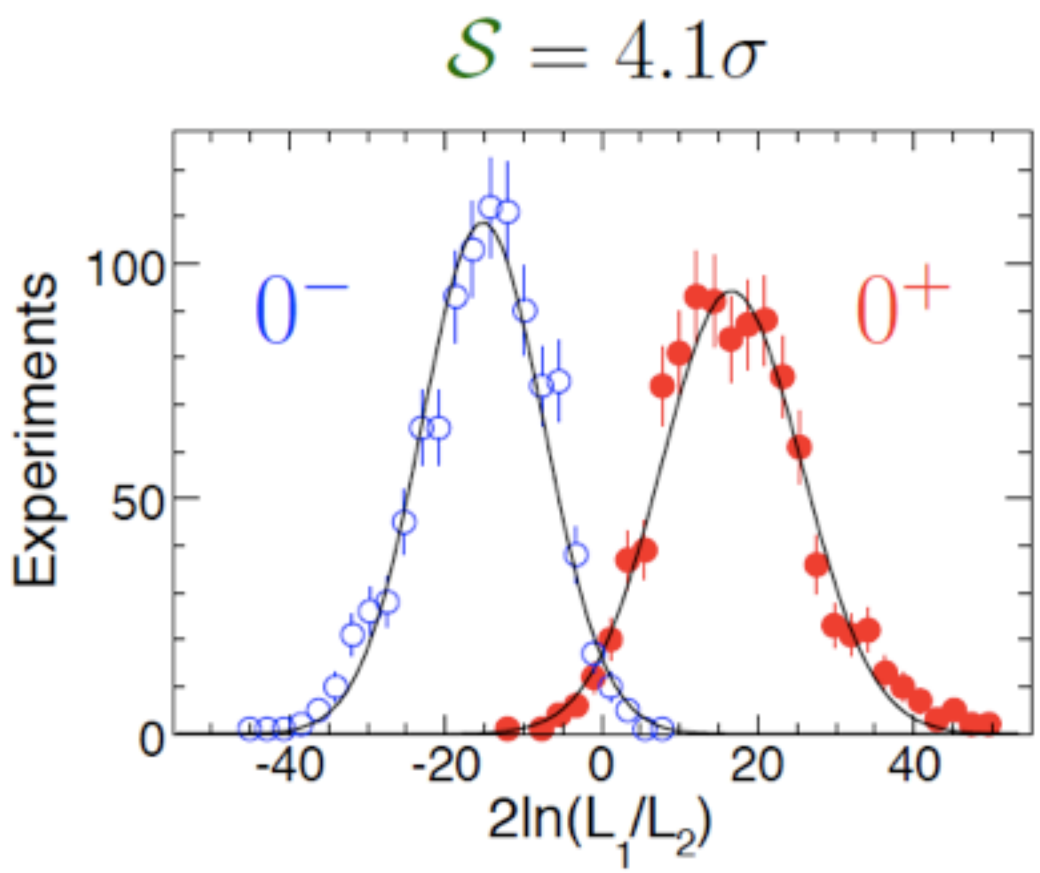
- The total likelihood

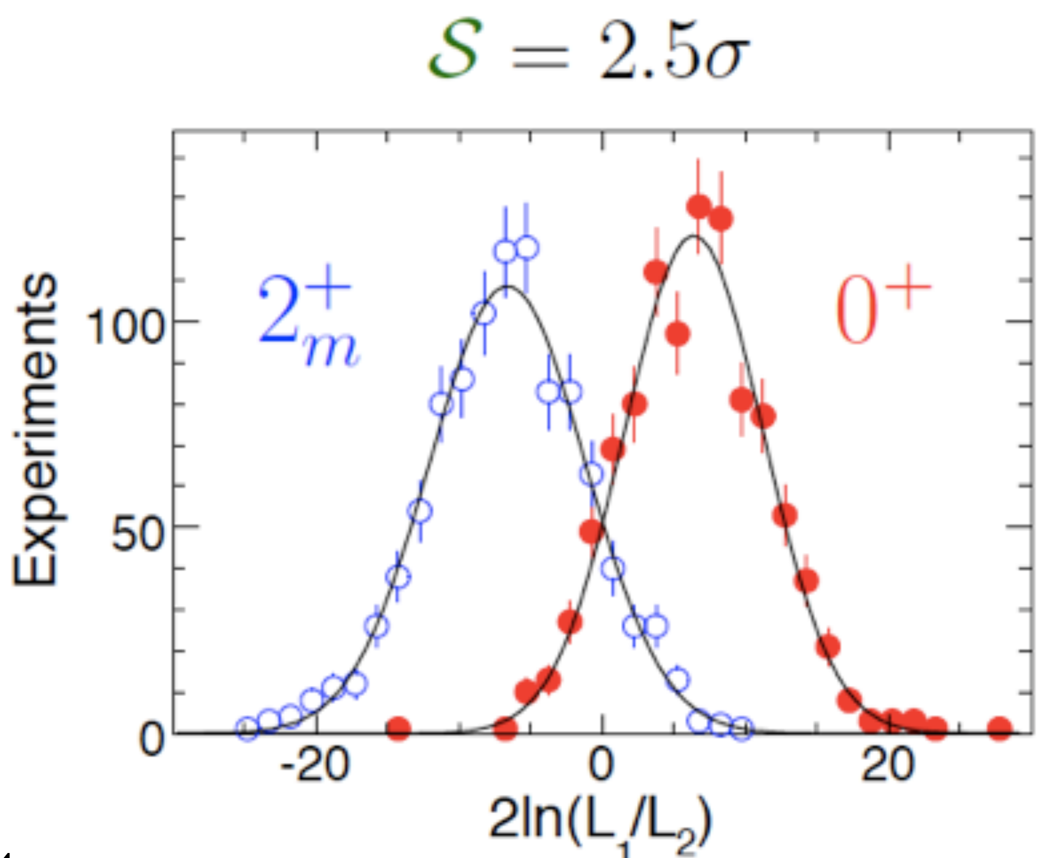
$$\boxed{\mathcal{L} = \exp\left(-\sum_{J=1}^{3} n_J - n_{\text{bkg}}\right) \prod_{i}^{N} \left(\sum_{J=1}^{3} n_J \times \mathcal{P}_J(\vec{x}_i;\ \vec{\zeta}_J;\ \vec{\xi}) + n_{\text{bkg}} \times \mathcal{P}_{\text{bkg}}(\vec{x}_i;\ \vec{\xi}) \right)}$$

  - 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 case 1
  - 30 $H \rightarrow ZZ$ signal events and 24 background events (m_{ZZ}=250±20GeV)
  - If only the (ZZ) invariant mass is used, statistical significance is 5.7 σ
  - The S/B increases if additional angular information is included
- Generate pseudo-MC experiments 1000 times
  - S measures the effective separation between two peaks





Hypothesis Testing Analysis (2/2)

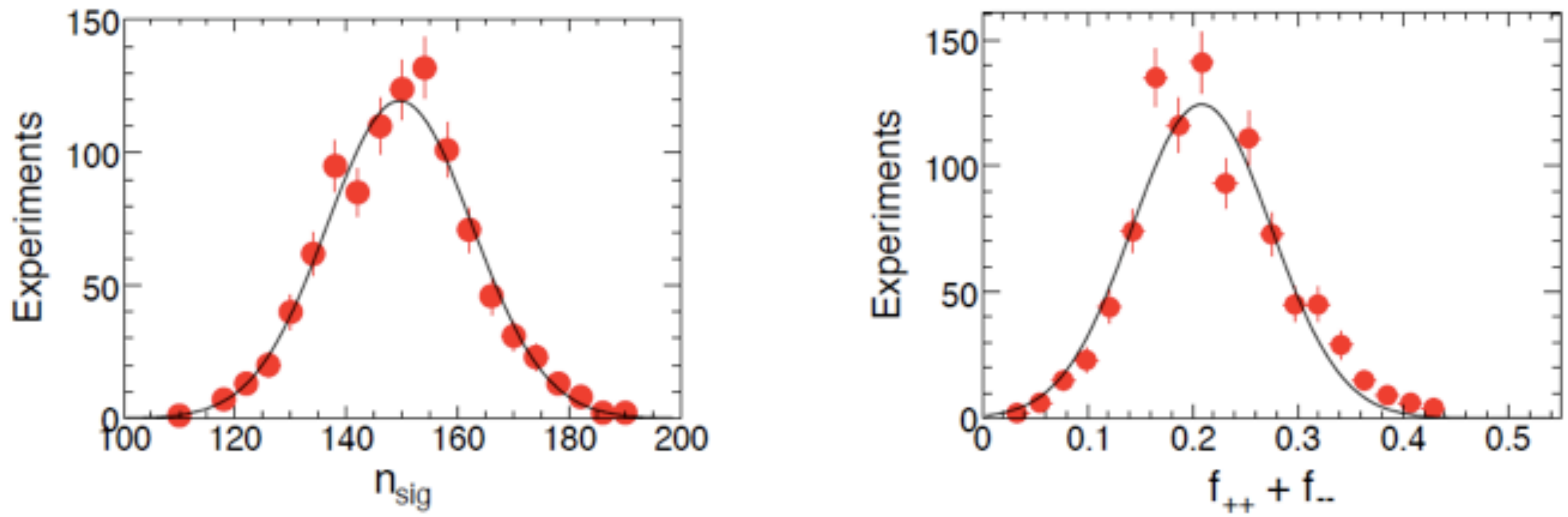
- Now repeat the same procedure with all possible resonances
  - Assume mX = 250 GeV (1TeV results in the paper)

1D (θ^*) / 2D (θ^*, Φ_1) /
3D $(\theta_1, \theta_2, \Phi)$ / 4D $(\theta^*, \theta_1, \theta_2, \Phi)$

	0^-	1^+	1^-	2^+_m	2^+_L	2^-
0^+	0.0/0.0/ 3.9/4.1	0.8/1.0/ 1.8/1.9	0.9/1.0/ 2.5/2.6	0.8/0.9/ 2.4/2.5	2.6/2.6/ 0.0/2.6	1.6/1.7/ 2.4/3.0
0^-	– –	0.8/1.2/ 2.8/3.0	0.9/1.0/ 2.5/2.8	0.8/0.8/ 1.7/2.0	2.9/2.9/ 4.1/4.8	1.6/1.7/ 2.0/2.7
1^+	– –	– –	0.0/1.1/ 1.1/1.2	0.1/1.2/ 1.3/1.4	2.8/2.8/ 1.9/3.5	2.5/2.4/ 1.2/2.7
1^-	– –	– –	– –	0.1/0.1/ 1.3/1.5	2.8/2.9/ 2.5/3.8	2.5/2.6/ 0.6/2.8
2^+_m	– –	– –	– –	– –	2.9/2.9/ 2.6/3.6	2.3/2.5/ 0.5/2.5
2^+_L	– –	– –	– –	– –	– –	3.6/3.6/ 2.5/4.2

Parameter Fitting Analysis (Case 1)

- Assume a Higgs-alike resonance is found with large statistics
  - 150 signal events + 120 background events
  - Perform the full angular analysis to extract helicity amplitudes



	generated	w/o detector	with detector
$n_{\rm sig}$	150	150 ± 13	153 ± 15
$(f_{++} + f_{--})$	0.208	0.21 ± 0.07	0.23 ± 0.08
$(f_{++} - f_{--})$	0.000	0.01 ± 0.13	0.01 ± 0.14
$(\phi_{++} + \phi_{--})$	2π	6.30 ± 1.46	6.39 ± 1.54
$(\phi_{++} - \phi_{--})$	0	0.00 ± 1.06	0.01 ± 1.09

- Fit results agree with the generated values → Fit is validated!

Parameter Fitting Analysis (Case 2)

- Test the fit for more complicated angular structures
  - 150 signal ($J^P=2^+$, m_X = 250 GeV) events + 120 background events

	generated	w/o detector	with detector
$n_{\rm sig}$	150	150 ± 13	151 ± 16
f_{z2}	1.000	1.00 ± 0.17	0.84 ± 0.17
f_{z1}	0.000	0.00 ± 0.19	0.00 ± 0.25
f_{++}	0.013	0.01 ± 0.04	0.00 ± 0.05
f_{+-}	0.282	0.28 ± 0.04	0.31 ± 0.05
f_{+0}	0.075	0.07 ± 0.04	0.06 ± 0.05
ϕ_{++}	0	0.00 ± 1.75	0.04 ± 1.76

  - Good agreement between fit/generated values are seen→ Fit is validated!
- All 7 potential resonances with mass (250GeV/1TeV) are tested

Summary and Conclusions

- LHC is a discovery machine with new resonances expected
- Once a resonance X is found, it is more than a bump hunt
    - Assuming the most general (not just minimal) couplings of X to the relevant SM fields, we have considered 7 resonances (higgs, Z', Gravitons..) with $J^P=0^+, 0^-, 1^+, 1^-, 2_M^+, 2_L^+ 2^-$
    - 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 from the theory side in terms of the coupling constants, and the experimental side in the angular distributions
    - We have written a MC simulation program to generate the production and decay of X, accounting for detector effects
    - We have developed a multivariate maximum likelihood fit technique to obtain simultaneously the physics quantities of interest (resonance mass, width, spin, parity, production mechanism...)
    - The fit is validated using MC data for 7 resonances m_X=250GeV/1TeV