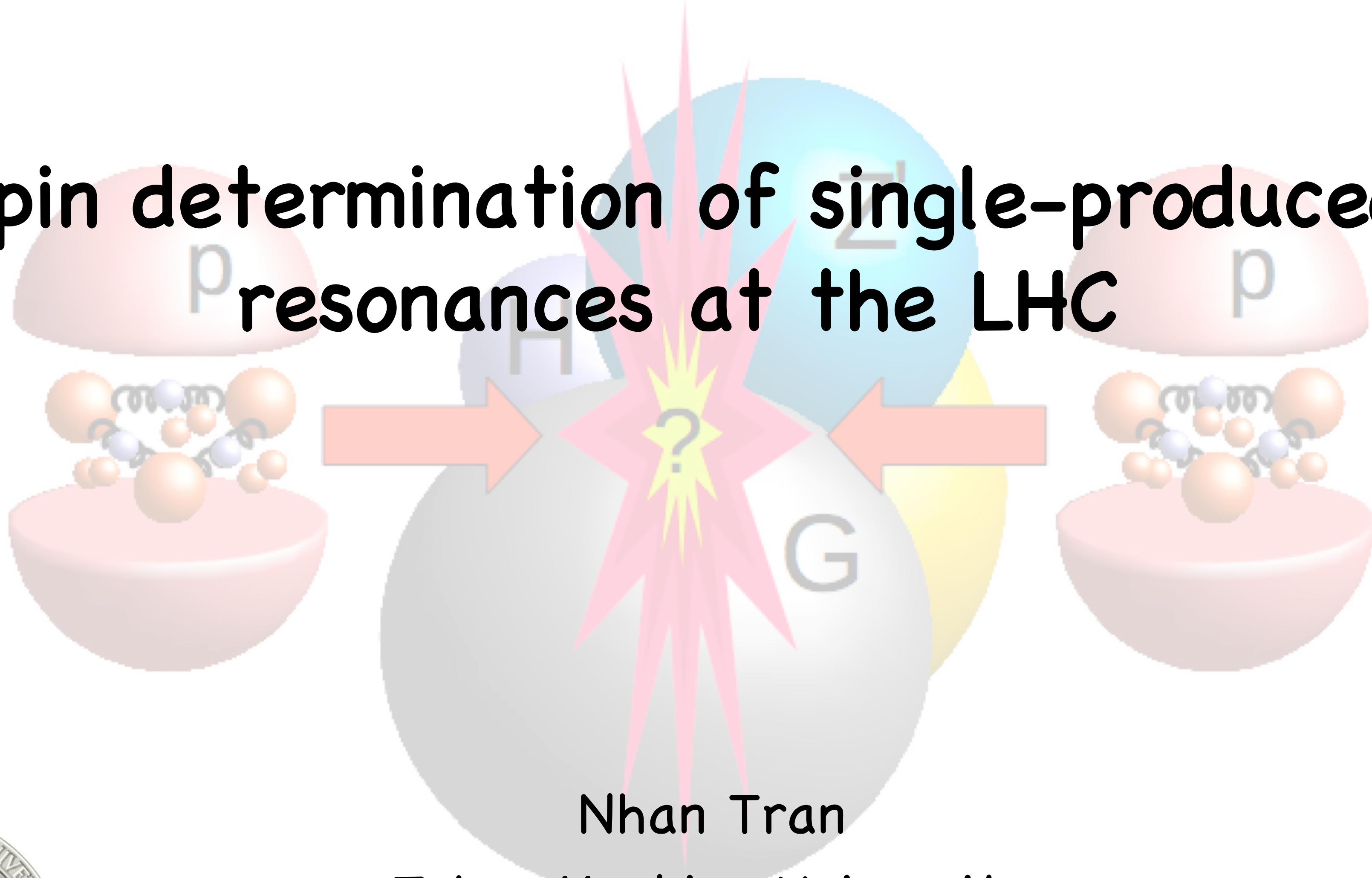
Spin determination of single-produced resonances at the LHC



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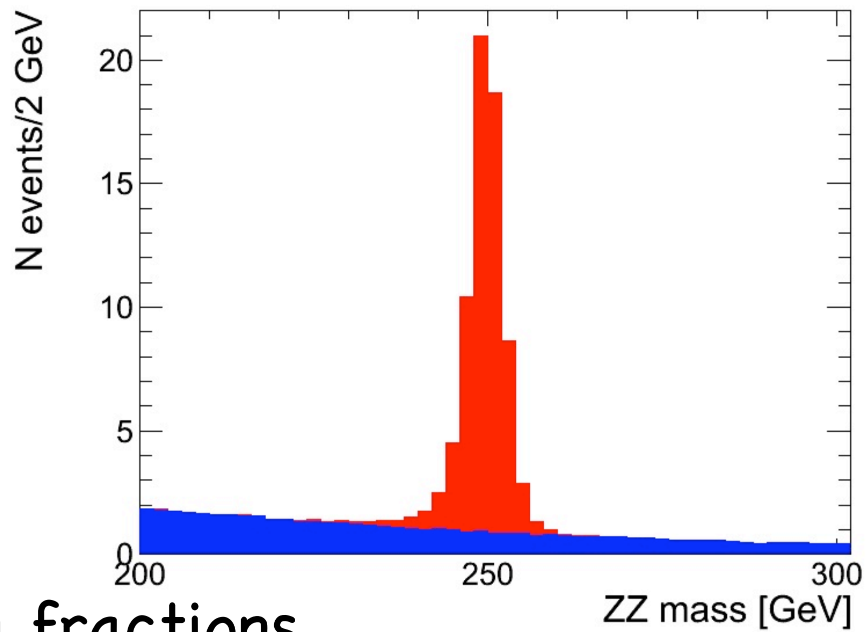
What if we find a resonance at the LHC?

- LHC is a discovery machine
- Resonances a sign of Higgs or beyond SM physics
- But which?
  And how can we distinguish?
  - Mass and width
  - Cross-section and branching fractions
  - Angular distributions and spin correlations



past contributions countless, most recent advances to be discussed

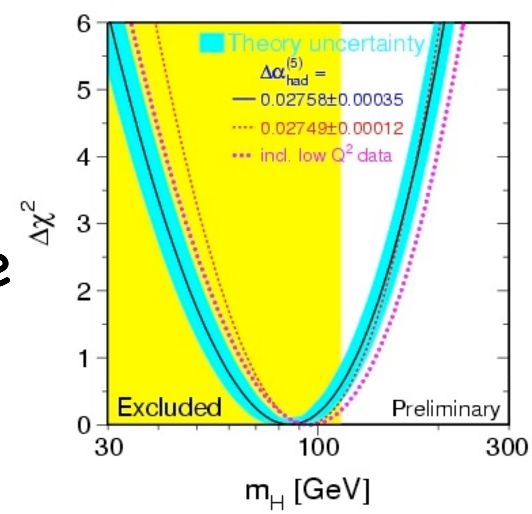
Gao, Gritsan, Guo, Melnikov, Schulze, N.T. 2010 [arXiv:1001.3396] PRD81,075022(2010)

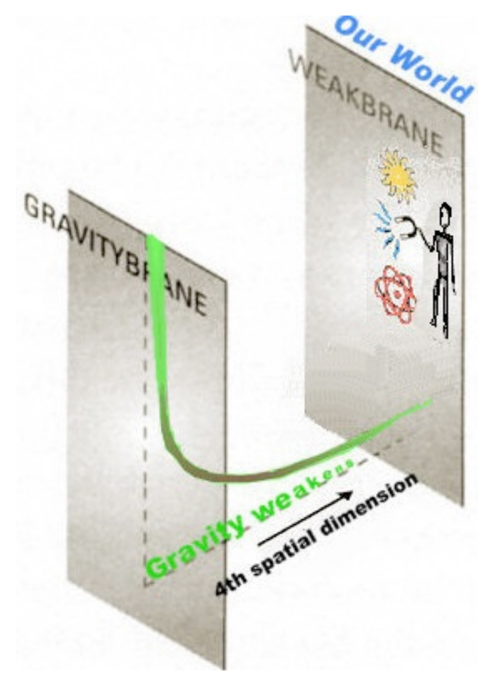
De Rujula, Lykken, Pierini, Spiropulu, Rogan 2010 [arXiv:1001.5300]

Techniques and analysis tools for determining the spin, parity, and interactions with SM fields of a resonance by analyzing the angular distributions of its decay products.

Some motivated examples

- Spin-zero
  - SM Higgs, $J^P = 0^+$,
    or other non-SM scalar
  - Pseudoscalar $J^P = 0^-$, multi-Higgs case
- Spin-one
  - Heavy photon
  - Kaluza-Klein gluon
- Spin-two
  - RS Graviton, $J^P = 2^+$: classic model
    - SM fields localized to TeV brane
  - Non-classic RS Graviton model
    - SM fields in the bulk
- Hidden valley models
  - "Hidden glueballs"

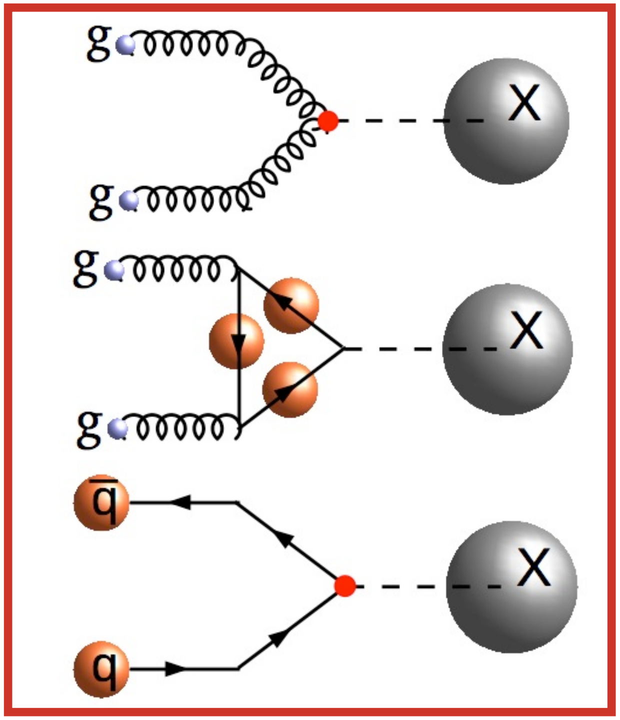




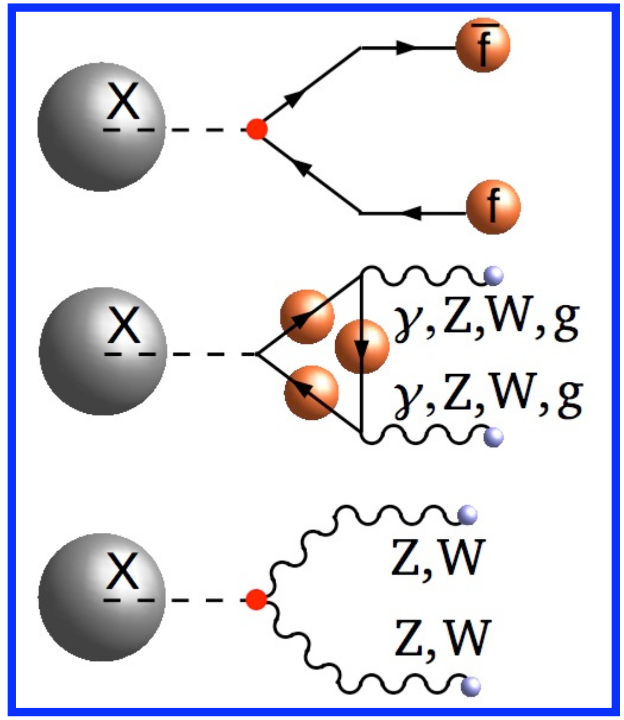
Single-produced resonances

Consider a colorless, chargeless X with J = 0,1, or 2 and J_z = 0,±1, or ±2

Production



Decay

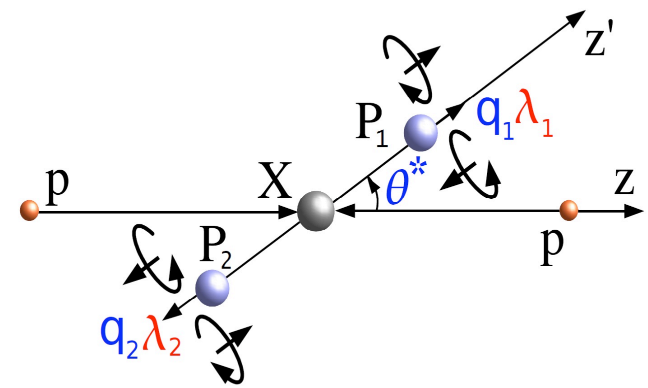


- gluon fusion: J = 0,2
  - J_z = 0 or J_z = ±2
  - expect to dominate at low mass
- q-qbar: J = 1,2
  - J_z = ±1
  - assume chiral symmetry exact

- Decay to fermions
  - $X \rightarrow l^+l^-, q\bar{q}$bar
  - As $m_f \rightarrow 0$, J = 0 excluded
- Decay to gauge bosons
  - $X \rightarrow ZZ, W^+W^-, gg, \gamma\gamma$

Program

- A model independent approach: choose most general couplings of a spin-zero, -one, -two particle to SM fields
- Analysis applicable to many cases such as ZZ, W^+W^-, $\gamma\gamma$, gg, l^+l^-: $2 \rightarrow 2$ analysis via production angle, $\cos\theta^*$
- Focus on the $X \rightarrow ZZ \rightarrow 4l$ decay channel
  - Final state fully reconstructed accurately
  - More information in four-body final state
  - ZZ decay can be large or even dominant



general, model-independent amplitudes for spin-0/1/2

↓

compute helicity amplitudes for production and decay

→

general angular distributions parameterized by helicity amplitudes

↓

fit angular distributions to data via multivariate analysis

*data = MC generator based on amplitudes

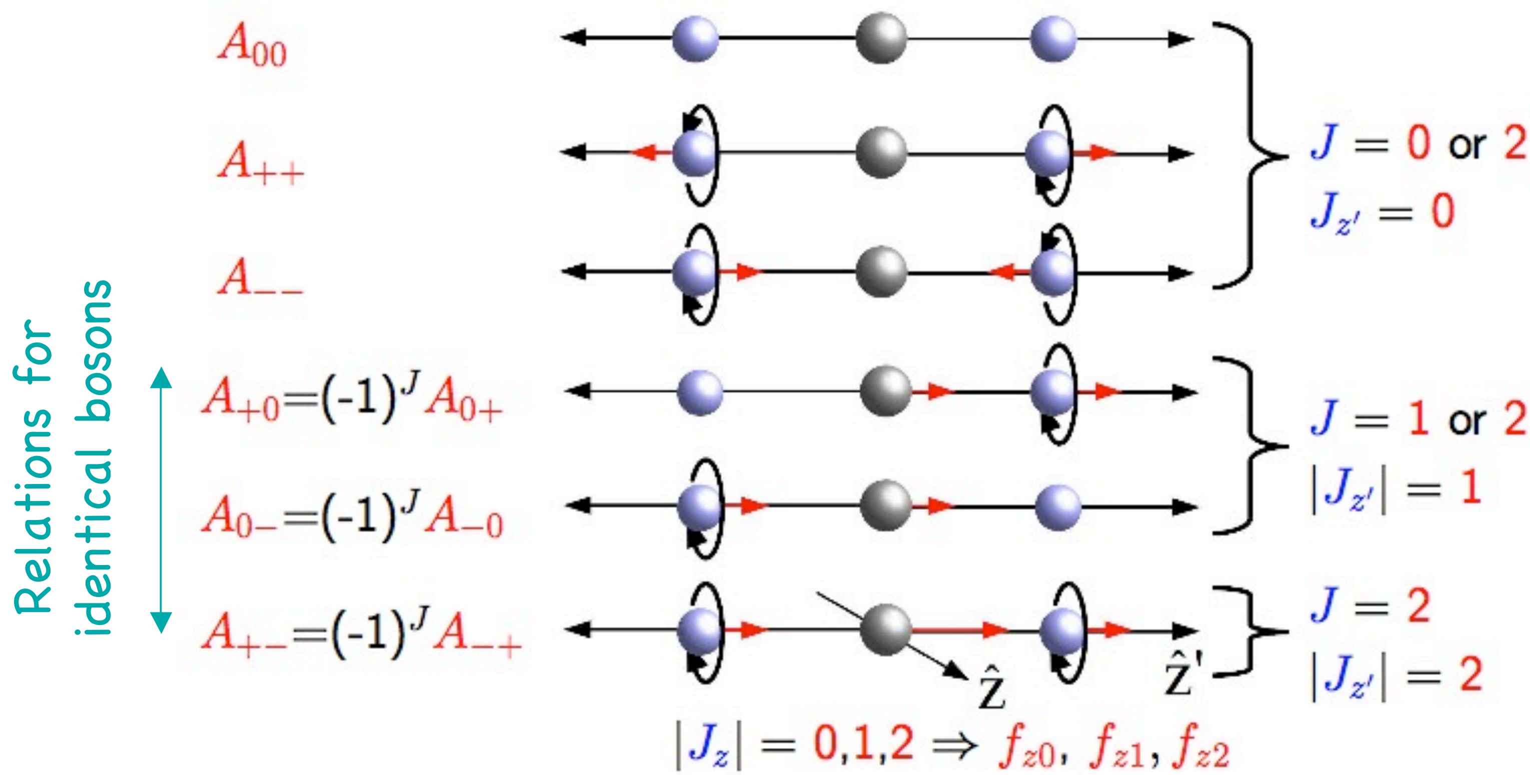
Helicity amplitude formalism

Helicity amplitudes: contributions to the total amplitude from the different daughter helicities

Determined by theory, measured by experiment

Example:

Massive gauge bosons (W,Z) have $J_z = 0,\pm1$ possible helicity states; 9 total amplitudes, A_{kl}



Theory to experiment:

General amplitudies to helicity amplitudes

Interactions of spin-two X to two gauge bosons:

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

Dimensionless *complex* coupling constants

Gauge boson polarization vectors

By applying gauge boson polarization vectors to the general amplitudes, we can read off the helicity amplitudes

For massive gauge boson, can have 9 A_{kl} where $k,l = 0,\pm 1$

$$A_{+-} = A_{-+} = \frac{m_X^2}{4\Lambda} c_1 (1+\beta^2)\,, \qquad A_{+0} = A_{0+} = \frac{m_X^3}{m_V \sqrt{2}\Lambda} \left[\frac{c_1}{8}(1+\beta^2) + \frac{c_4}{2}\beta^2 - \frac{c_6 + c_7\beta^2}{2} i\beta \right],$$

$$A_{++} = \frac{m_X^2}{\sqrt{6}\Lambda} \left[\frac{c_1}{4}(1+\beta^2) + 2c_2\beta^2 + i\beta(c_5\beta^2 - 2c_6) \right], \qquad A_{-0} = A_{0-} = \frac{m_X^3}{m_V \sqrt{2}\Lambda} \left[\frac{c_1}{8}(1+\beta^2) + \frac{c_4}{2}\beta^2 + \frac{c_6 + c_7\beta^2}{2} i\beta \right],$$

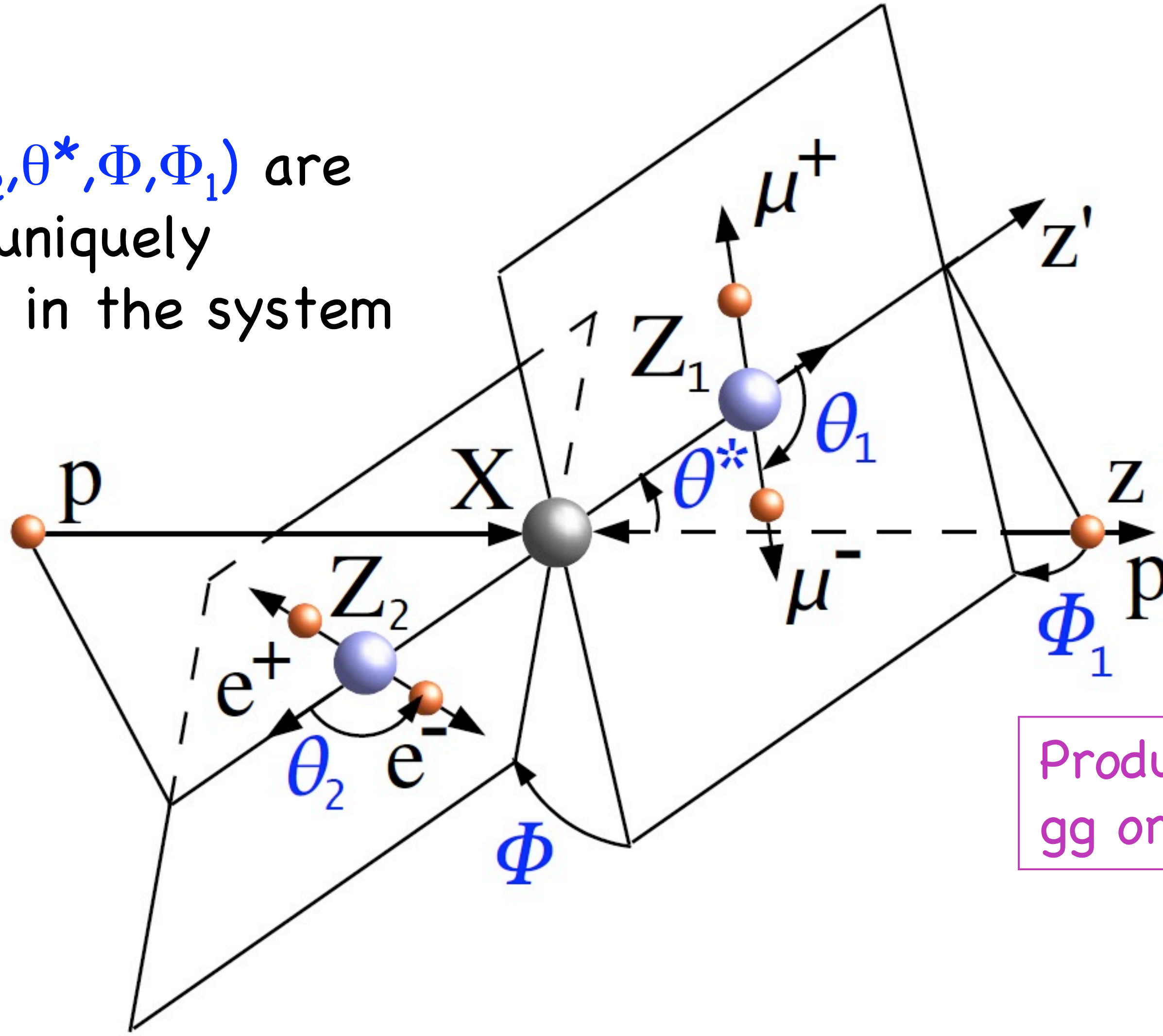
$$A_{--} = \frac{m_X^2}{\sqrt{6}\Lambda} \left[\frac{c_1}{4}(1+\beta^2) + 2c_2\beta^2 - i\beta(c_5\beta^2 - 2c_6) \right], \qquad A_{00} = \frac{m_X^4}{m_V^2 \sqrt{6}\Lambda} \left[(1+\beta^2)\left(\frac{c_1}{8} - \frac{c_2}{2}\beta^2\right) - \beta^2 \left(\frac{c_3}{2}\beta^2 - c_4\right) \right].$$

We do the same thing for spin-zero and spin-one X

Definition of the system

$X \to ZZ \to 4l$:

5 angles $(\theta_1, \theta_2, \theta^*, \Phi, \Phi_1)$ are the maximal, uniquely defined angles in the system



Production via gg or qqbar

θ^*, Φ_1: *production* angles

θ_1, θ_2, Φ: *helicity* angles, *independent of production*

Angular distributions

General spin-J angular distribution

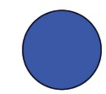
$$
\begin{aligned}
&F^J_{00}(\theta^*) \times \Big\{4\, f_{00}\, \sin^2\theta_1 \sin^2\theta_2 + (f_{++} + f_{--})\left((1+\cos^2\theta_1)(1+\cos^2\theta_2) + 4R_1R_2\cos\theta_1\cos\theta_2\right) \\
&\quad - 2\,(f_{++} - f_{--})\left(R_1\cos\theta_1(1+\cos^2\theta_2) + R_2(1+\cos^2\theta_1)\cos\theta_2\right) \\
&\quad + 4\sqrt{f_{++}f_{00}}\,(R_1 - \cos\theta_1)\sin\theta_1(R_2 - \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++}) \\
&\quad + 4\sqrt{f_{--}f_{00}}\,(R_1 + \cos\theta_1)\sin\theta_1(R_2 + \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--}) \\
&\quad + 2\sqrt{f_{++}f_{--}}\,\sin^2\theta_1\sin^2\theta_2\cos(2\Phi + \phi_{++} - \phi_{--})\Big\}
\end{aligned}
$$

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

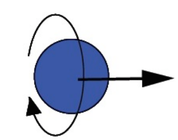
$$
\begin{aligned}
&+2F^J_{22}(\theta^*) \times f_{+-}\Big\{(1+\cos^2\theta_1)(1+\cos^2\theta_2) - 4R_1R_2\cos\theta_1\cos\theta_2\Big\} \\
&+(-1)^J \times 2F^J_{-22}(\theta^*) \times f_{+-}\sin^2\theta_1\sin^2\theta_2\cos(4\Psi)
\end{aligned}
$$

+ interference terms

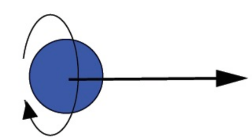
J_z = 0



J_z = ±1



J_z = ±2

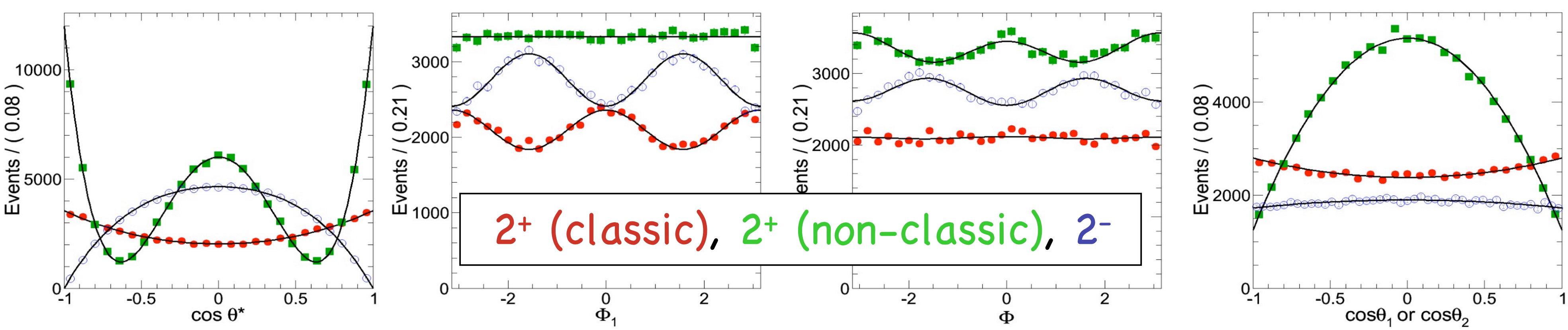


- Spin-zero X: only J_z = 0 part contributes
- Spin-one X: only J_z = ±1 part contributes
- Spin-two X: all contributions exist J_z = 0,±1,±2

MC Simulation

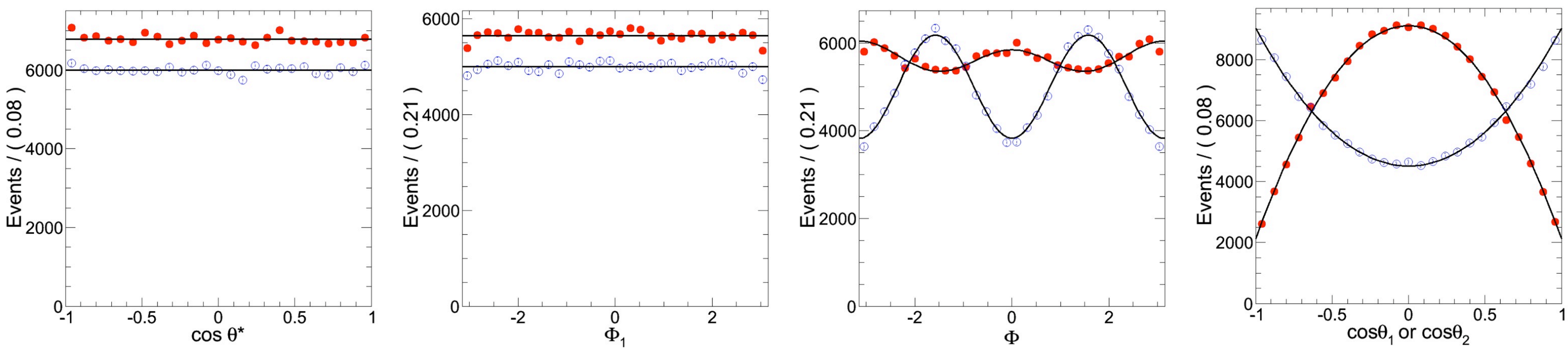
- A MC program developed to simulate production and decay of X with spin-zero, -one, or -two
  - Includes all spin correlations and all general couplings
  - Inputs are general dimensionless couplings - calculates matrix elements
  - Both gg and qqbar production
  - Contains both final states for $ZZ \rightarrow 4l$ and $ZZ \rightarrow 2l2j$
  - Output in LHE format; can interface to Pythia
  - All code publicly available: **www.pha.jhu.edu/spin**

Example of agreement for MC (points) and angular distributions (lines)

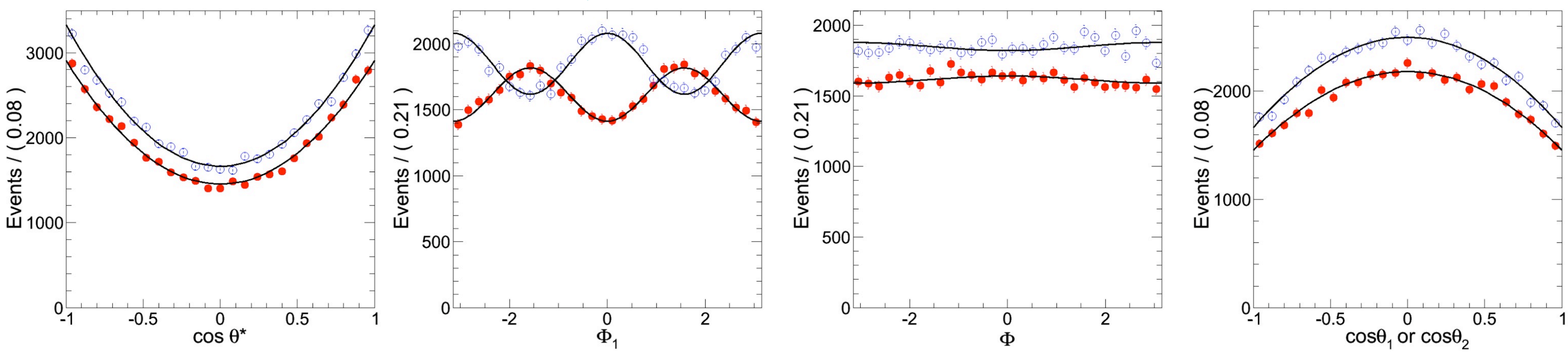


MC Simulation

Spin Zero: J^P = 0^+, 0^-



Spin One: J^P = 1^+, 1^-



N.B. 1D projections of angles for illustration, statistical power comes from 5D *angular correlations*

What we do in practice…

- To determine the helicity amplitudes, we need
  - Data: our MC generator
  - Angular distributions
  - Detector: approximate model with acceptance and smearing
  - Fit: multivariate likelihood method
- Fit used for
  - "Hypothesis separation" study: lower statistics, how much separation between different signal hypotheses achieved?
  - "Parameter fitting" study: higher statistics, how well can we determine the parameters of a certain hypothesis?

Example:
Hypothesis separation of signal scenarios near time of discovery

We can already make a statement about spin/CP!

	0^-	1^+	1^-	2^+_m	2^+_L	2^-
0^+	4.1	2.3	2.6	2.8	2.6	3.3
0^-	–	3.1	3.0	2.4	4.8	2.9
1^+	–	–	2.2	2.6	3.6	2.9
1^-	–	–	–	1.8	3.8	3.4
2^+_m	–	–	–	–	3.8	3.2
2^+_L	–	–	–	–	–	4.3

Conclusion and outlook

- A program is developed to determine the spin of a resonance in a model-independent way
- A MC generator is introduced which simulates production and decay of spin-zero, -one, -two resonance including all spin correlations
- Data analysis is performed using multivariate likelihood method for both hypothesis separation and parameter fitting

- We need to be ready for anything!
  - Should not be limited to certain models; consider most general cases
- Use all information available!
  - Full 5D formalism provides the best separation and background suppression
  - At time of discovery, can already constrain spin/CP