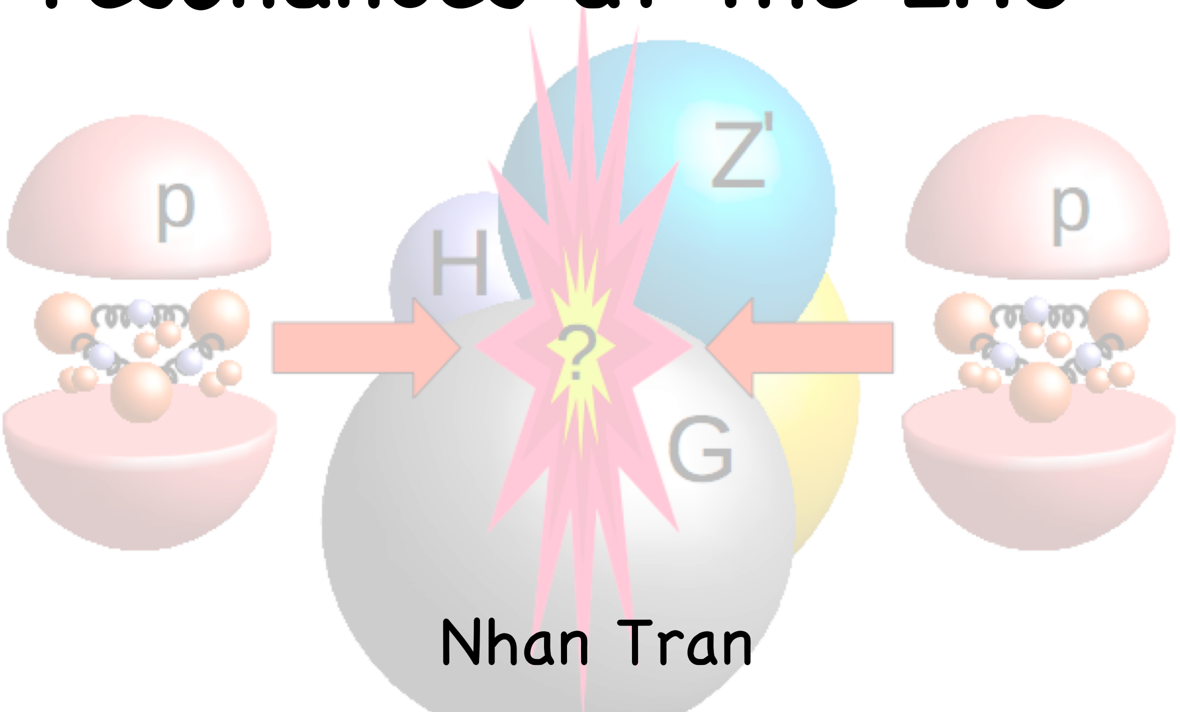
Spin determination of single-produced resonances at the LHC



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Credits

Based on the paper:

Spin determination of single-produced resonances at hadron colliders

Phys. Rev. D 81, 075022 (2010)

Y. Gao[1,2,3,4], A.V. Gritsan[1,3,4], Z. Guo[1,3,4], K. Melnikov[1], M. Schulze[1], N.T.[1,3]

(1) JHU; (2) Now at FNAL; (3) CMS; (4) BaBar

arXiv:1001.3396

Similar study:

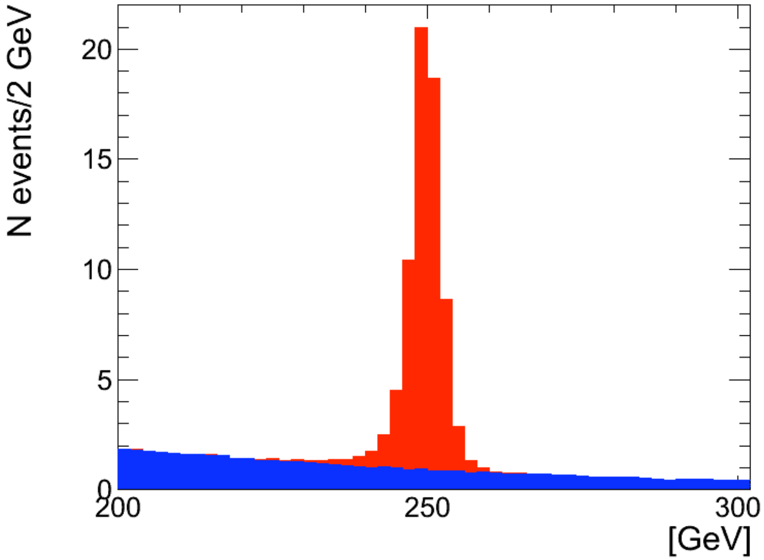
Higgs look-alikes at the LHC

arXiv:1001.5300

A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M. Spiropulu

Introduction

- What if we find a resonance at the LHC?



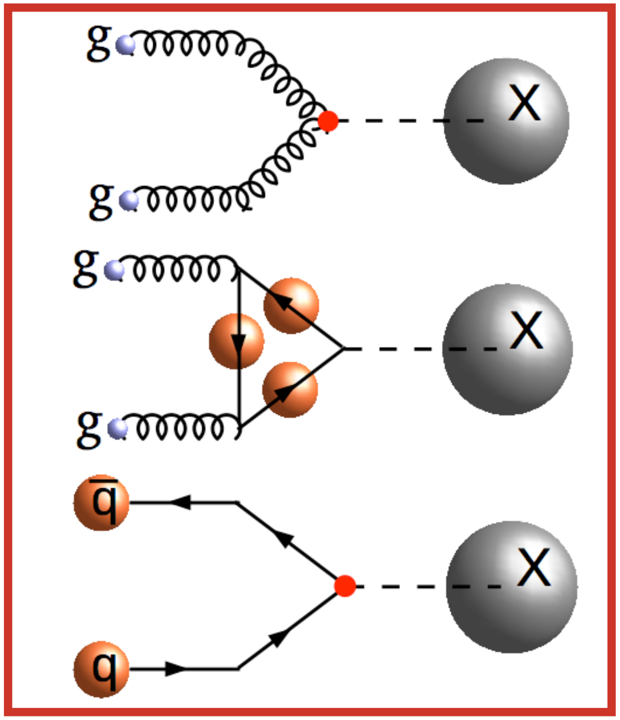
- Want to know:
  - Mass and width
  - Cross-section and branching fractions
  - Quantum numbers and couplings to SM fields

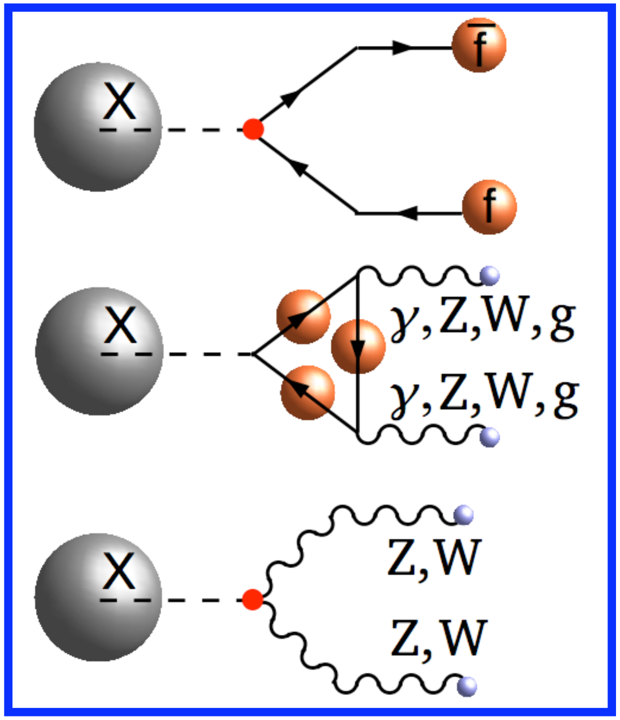
We present techniques and analysis tools for determining the spin, parity, and interactions with SM fields of a resonance by analyzing the angular distributions of its decay products.

Single-produced resonances

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

Production





Decay

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

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

Motivated Examples

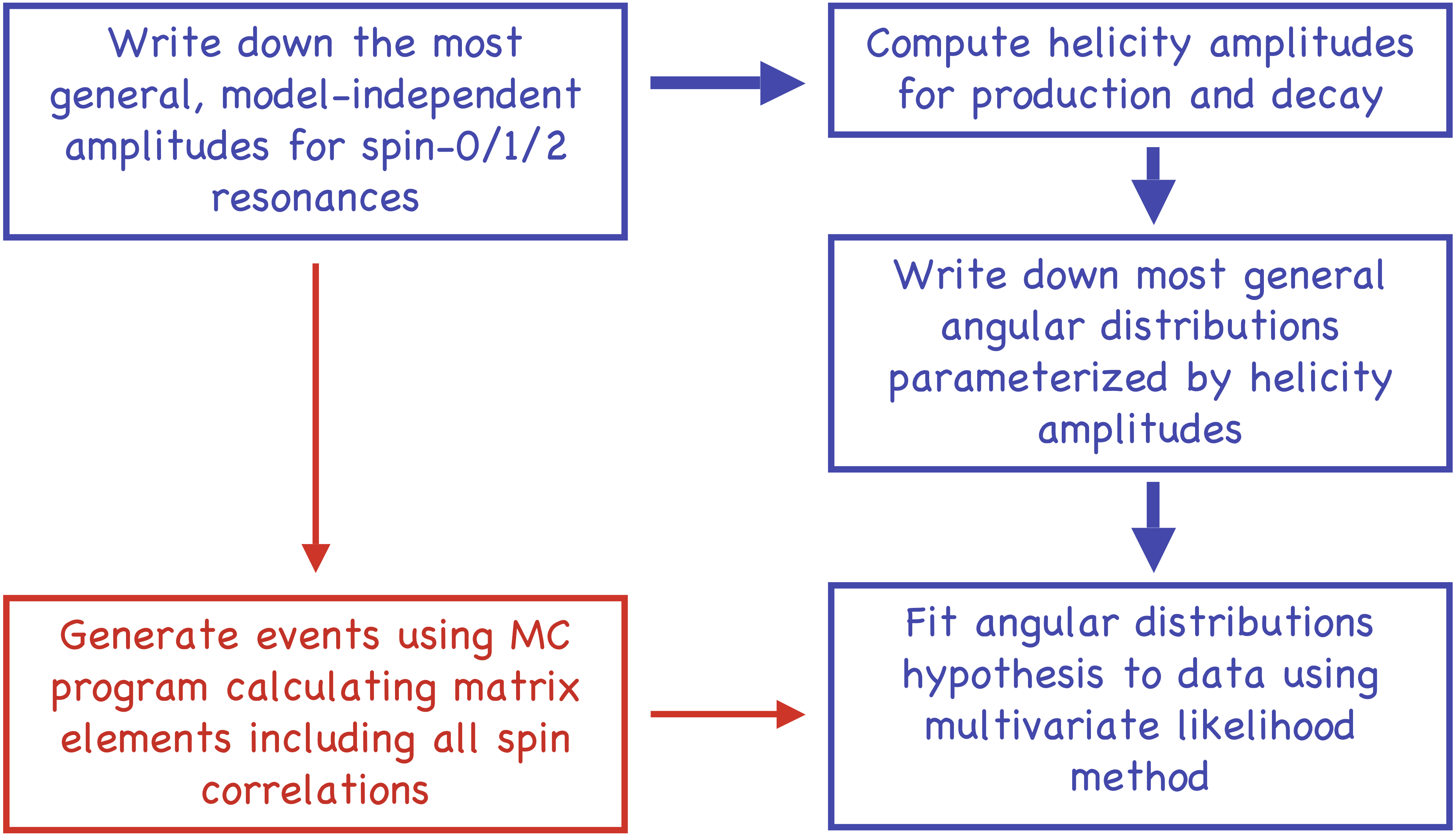
- Spin-zero (Higgs)
  - SM Higgs ($J^P = 0^+$) or possible non-SM scalar
  - Pseudoscalar A ($J^P = 0^-$) in multi-Higgs models
- Spin-one (new gauge boson)
  - Heavy photon or KK gluon
  - Models where ZZ and WW channels could dominate
- Spin-two (graviton)
  - RS Graviton, $J^P = 2^+$: classic model
    - Most common in literature; SM fields localized to TeV brane
  - Non-classic RS Graviton model

    K. Agashe et. al (hep-ph/0701186)
    - SM fields in the bulk
    - ZZ and WW decay channels could dominate

Program

- Instead of considering certain models, choose the most general couplings of a spin-zero, spin-one, and spin-two particle to relevant SM fields
- Focus on the $X \to ZZ \to 4l$ decay channel
  - Final state fully reconstructed accurately
  - More information contained in four-body final state
  - In certain cases, *ZZ* decay contribution large or even dominant
- Related extensions
  - Much of the analysis is applicable to other cases such as *ffbar*, W^+W^-, $\gamma\gamma$, *gg*
  - Analysis can be extended to final states with missing energy and jets

Program



Write down the most general, model-independent amplitudes for spin-0/1/2 resonances

Compute helicity amplitudes for production and decay

Write down most general angular distributions parameterized by helicity amplitudes

Fit angular distributions hypothesis to data using multivariate likelihood method

Generate events using MC program calculating matrix elements including all spin correlations

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 $k,l = 0,\pm 1$

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

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

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

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

Helicity amplitudes

In general, 9 complex amplitudes, A_{kl}, where k,l = 0,±1

$J_X = 0$

Production: gg^

Allowed spin projection:
0

Helicity Amplitudes:
A_{00}
A_{++}, A_{--}

$J_X = 1$

Production: qqbar*

Allowed spin projection:
±1^

Helicity Amplitudes:
$A_{+0} = -A_{0+}$
$A_{0-} = -A_{-0}$

$J_X = 2$

Production: gg or qqbar

Allowed spin projection:
0, ±1, ±2

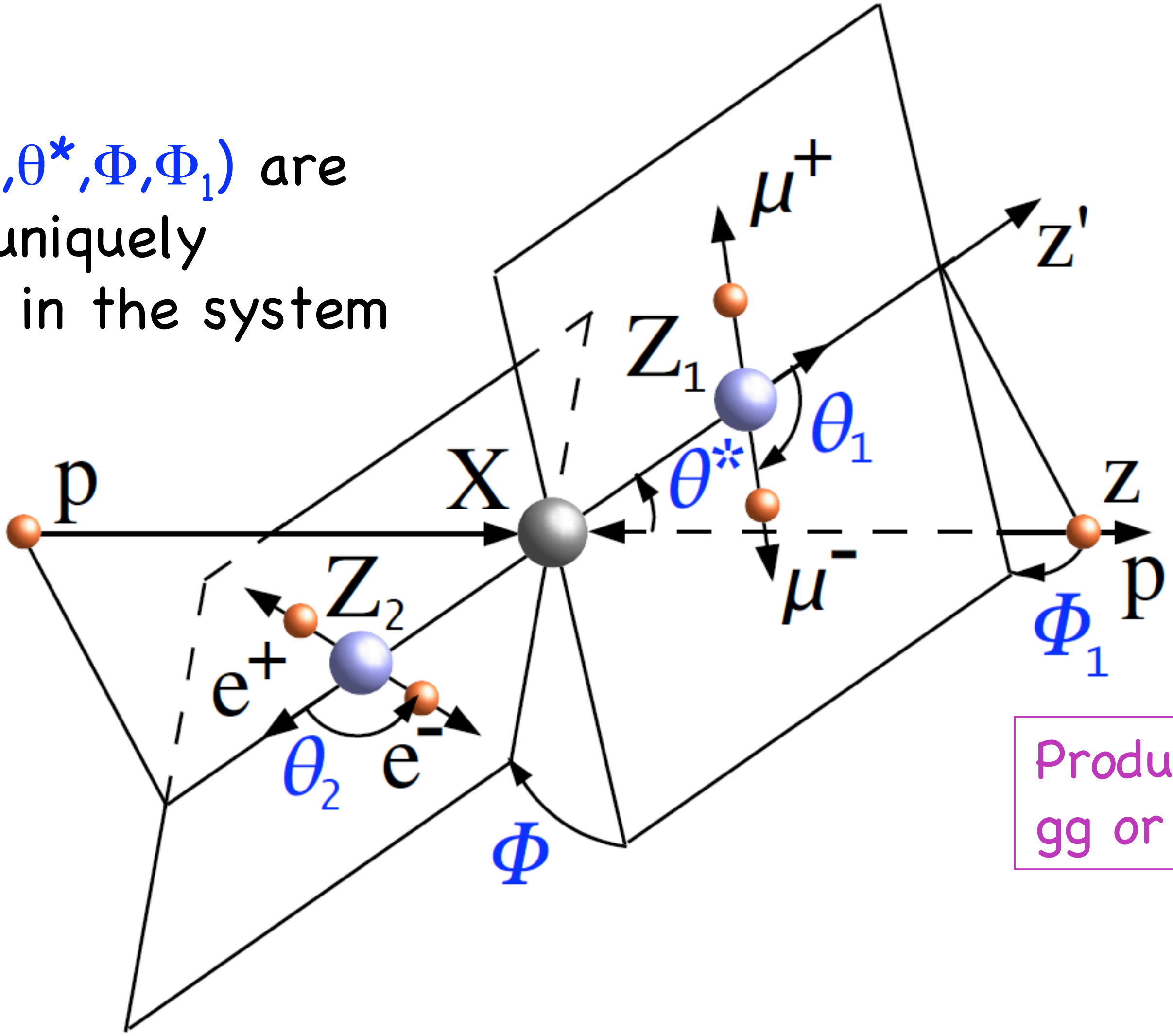
Helicity Amplitudes:
A_{00},
A_{++}, A_{--}
$A_{+0} = A_{0+}$
$A_{0-} = A_{-0}$
$A_{+-} = A_{-+}$

*gg fusion forbidden due to Landau-Yang theorem
^assume chirality a good quantum number for massless quarks
For identical vector bosons: $A_{kl} = (-1)^J A_{lk}$
For definite CP states: $A_{kl} = \eta_P(-1)^J A_{-k-l}$

Definition of the system

$X \rightarrow ZZ \rightarrow 4l$:

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

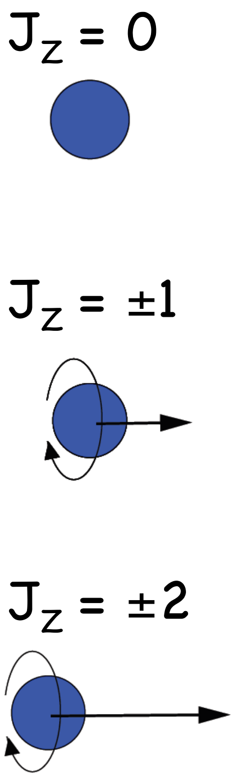
General spin-J angular distribution

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

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

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

+ interference terms

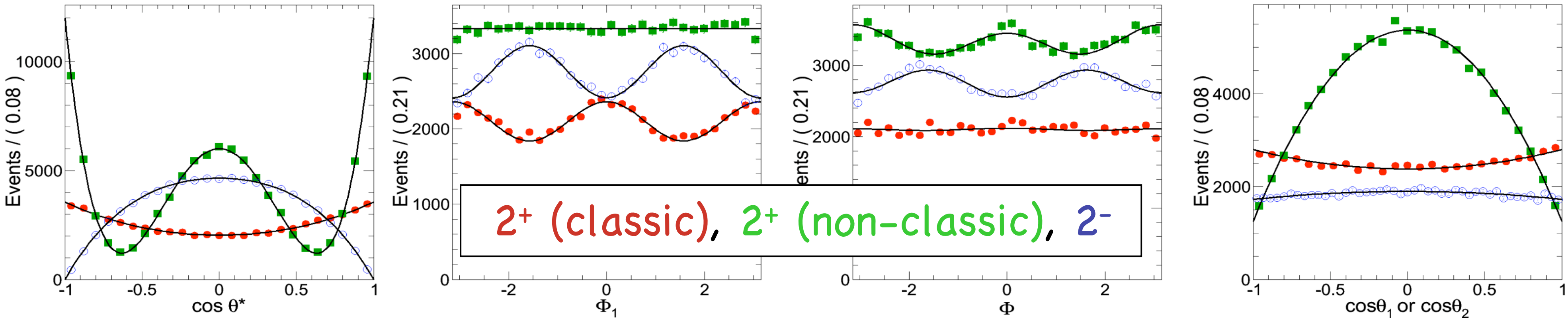


- Spin-zero *X*: only J_z = 0 part contributes
- Spin-one *X*: only J_z = ±1 part contributes
- Spin-two *X*: all contributions exist J_z = 0,±1,±2

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

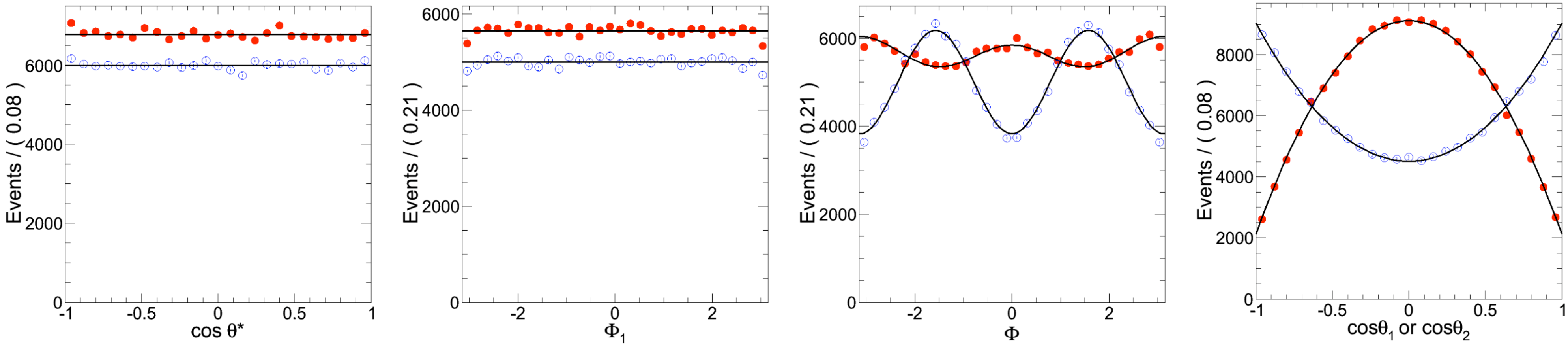
Example of agreement for MC (points) and angular distributions (lines)



MC Simulation

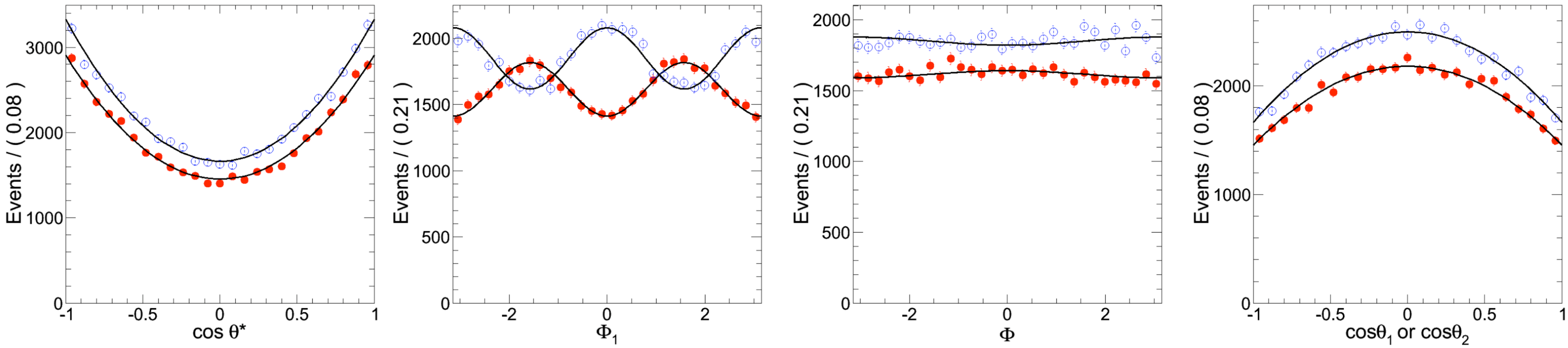
Spin Zero

0+, 0-



Spin One

1+, 1-



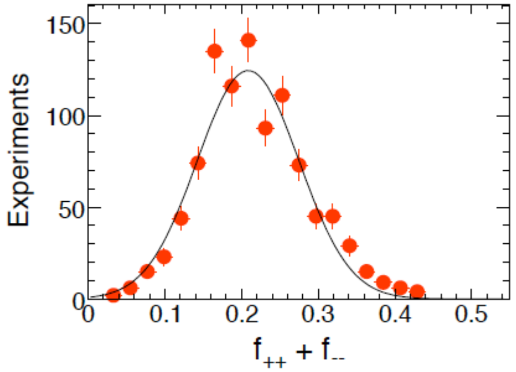
What we do in practice…

- 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?

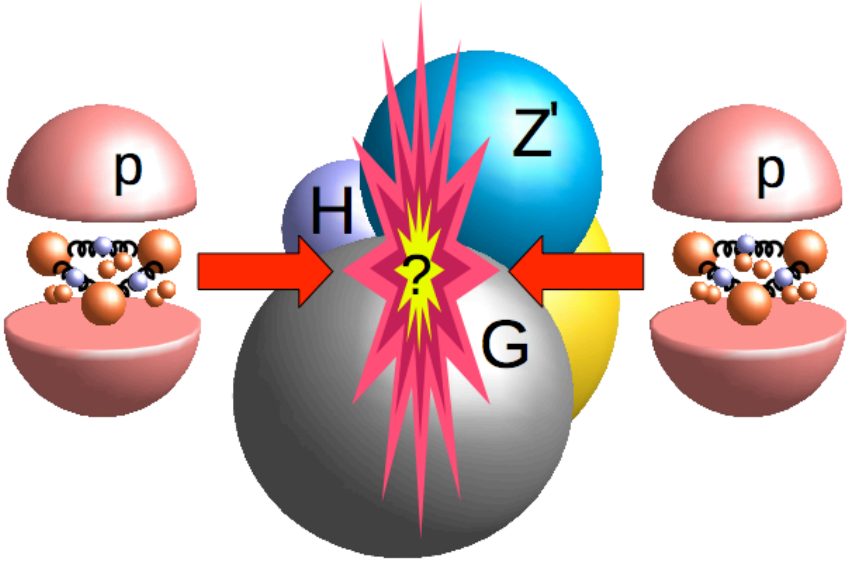
hypothesis separation of signal scenarios

	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

parameter fitting



Conclusion



- 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
  - Distinguish between signal hypotheses and fit for parameters in given hypothesis

Summary

- We present a program for determining the spin of a resonance and its couplings to SM fields
- Using the most general couplings and angular distributions, we can connect theory to experiment via helicity amplitudes
- 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