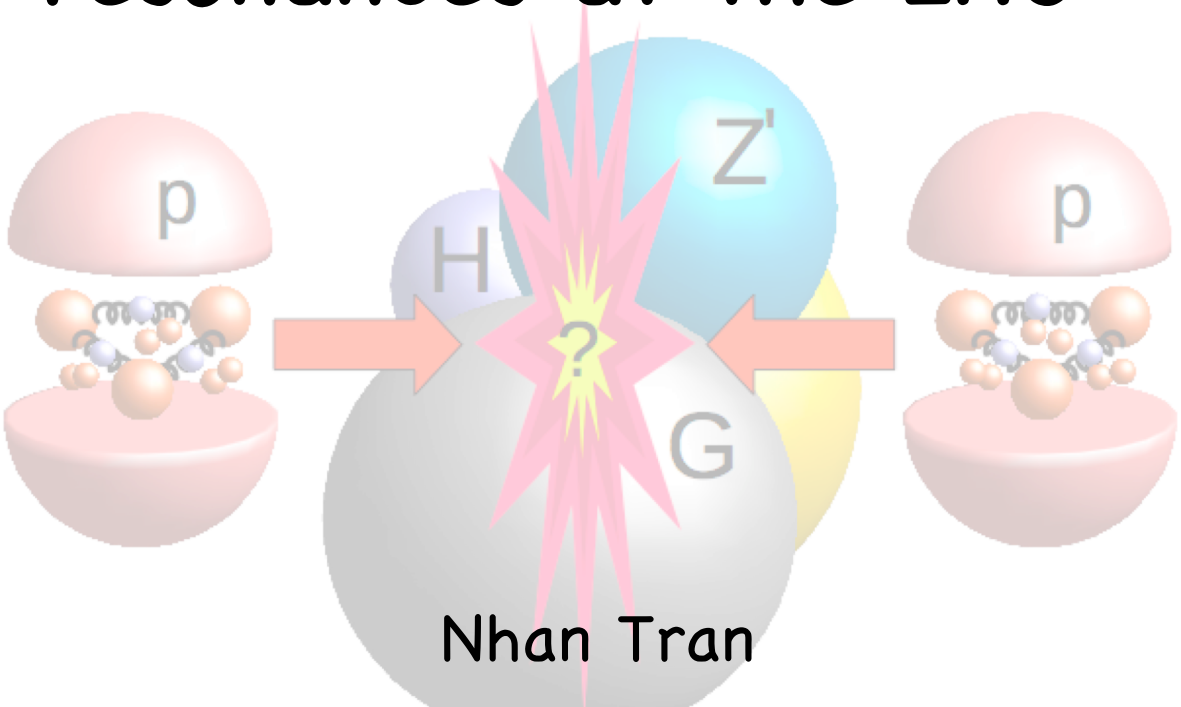
Spin determination of single-produced resonances at the LHC



Nhan Tran

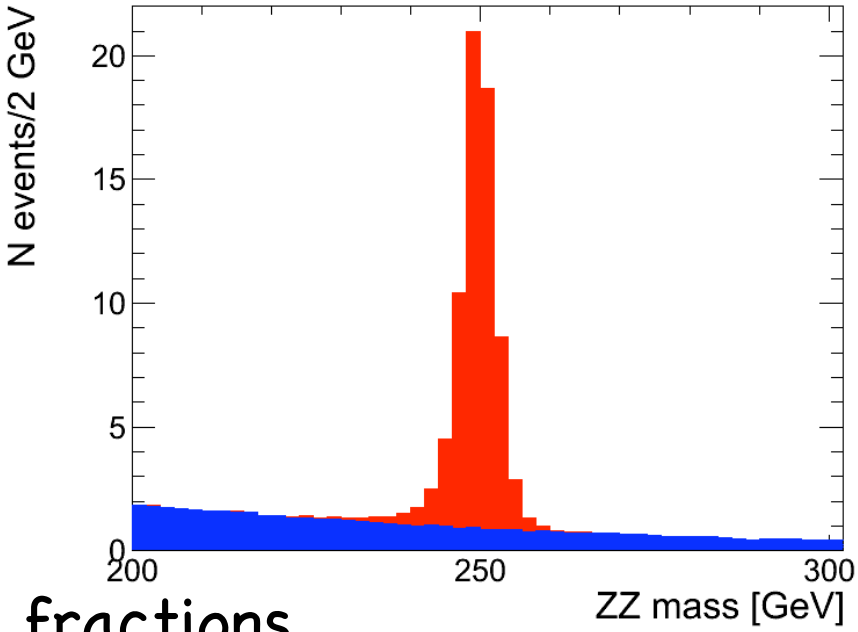
Johns Hopkins University

Fermilab Users' Meeting 2010

06.02.2010

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



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.

Power of Spin Correlations

- Techniques used for nearly 50 years

  Phys. Rev. 126, 1844 (1962)

PHYSICAL REVIEW VOLUME 126, NUMBER 5 JUNE 1, 1962

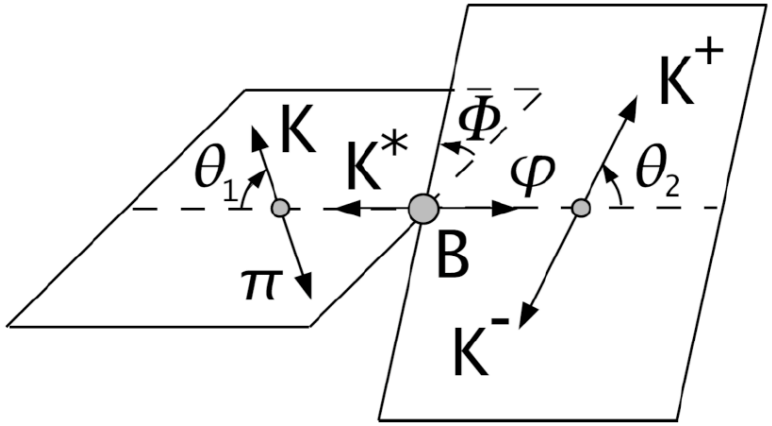
Parity of the Neutral Pion and the Decay $\pi^0 \rightarrow 2e^+ + 2e^-$†

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

AND

R. PLANO,* A. PRODELL,‡ M. SCHWARTZ, AND J. STEINBERGER
Columbia University, New York, New York

- Experience and techniques from *B* decays ($B \rightarrow VV$)

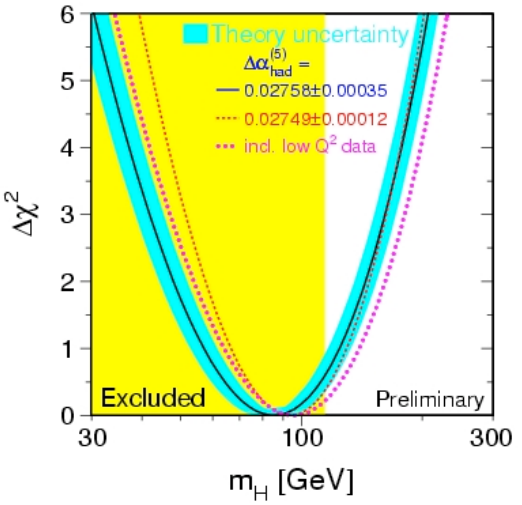


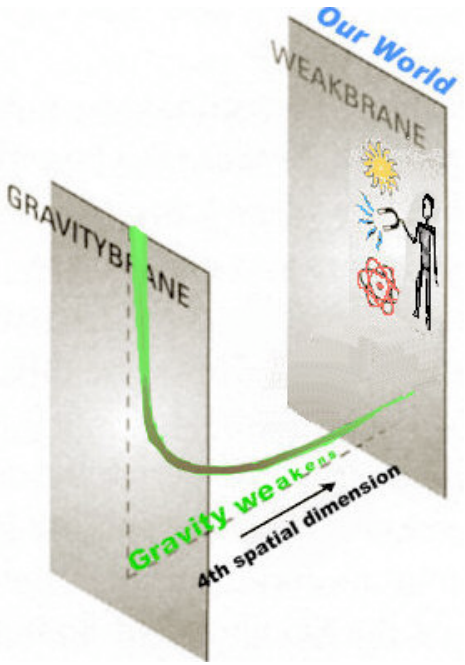
- Lesson: there can be surprises, SM or beyond

  example in $B \rightarrow \varphi K^*$, BaBar Collaboration, Phys. Rev. D 78, 092008 (2008)

Some motivated examples

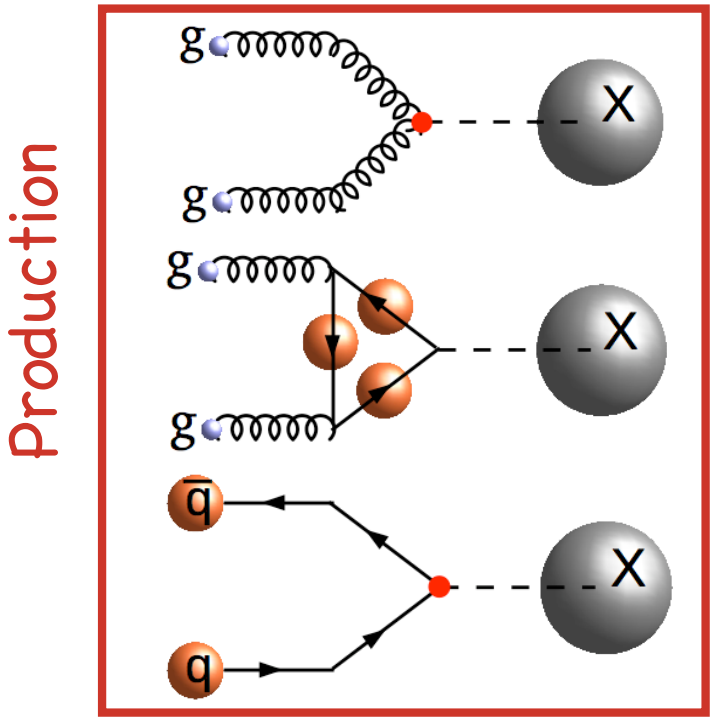
- Spin-zero
  - SM Higgs, $J^P = 0^+$, or other non-SM scalar
  - Pseudoscalar $J^P = 0^-$, multi-Higgs case
- Spin-one
  - Heavy photon
  - Kaluza-Klein gluon
- Spin-two
  - RS Graviton, $J^P = 2^+$: classic model
    - SM fields localized to TeV brane
  - Non-classic RS Graviton model
    - SM fields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

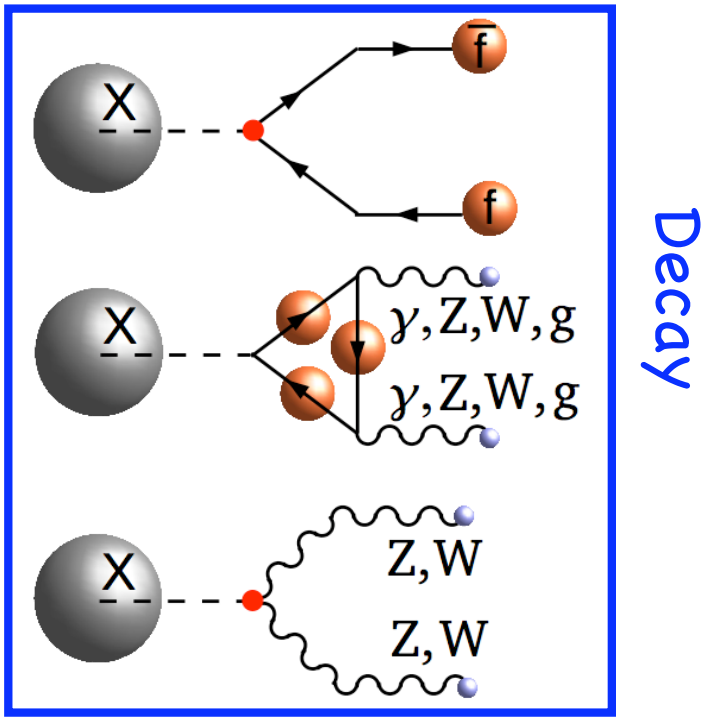




Single-produced resonances at the LHC

Consider a colorless, chargeless X with $J = 0,1,2$ and $J_Z = 0,\pm1,\pm2$



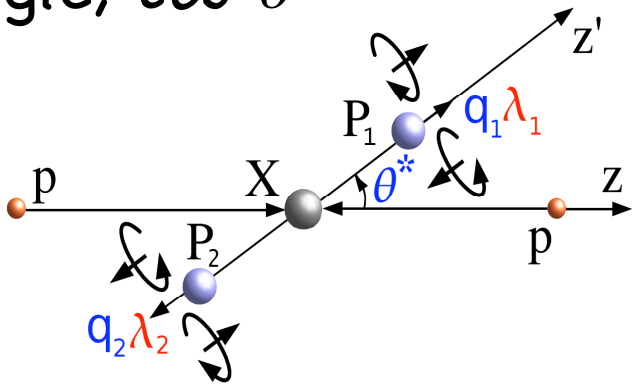


- gluon fusion: $J = 0,2$
  - $J_Z = 0$ or $J_Z = \pm2$
  - expect to dominate at low mass
- q-qbar: $J = 1,2$
  - $J_Z = \pm1$
  - assume chiral symmetry exact

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

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^-: $2\to2$ analysis via production angle, $\cos\theta^*$
- Focus on the $X\to ZZ\to 4l$ 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

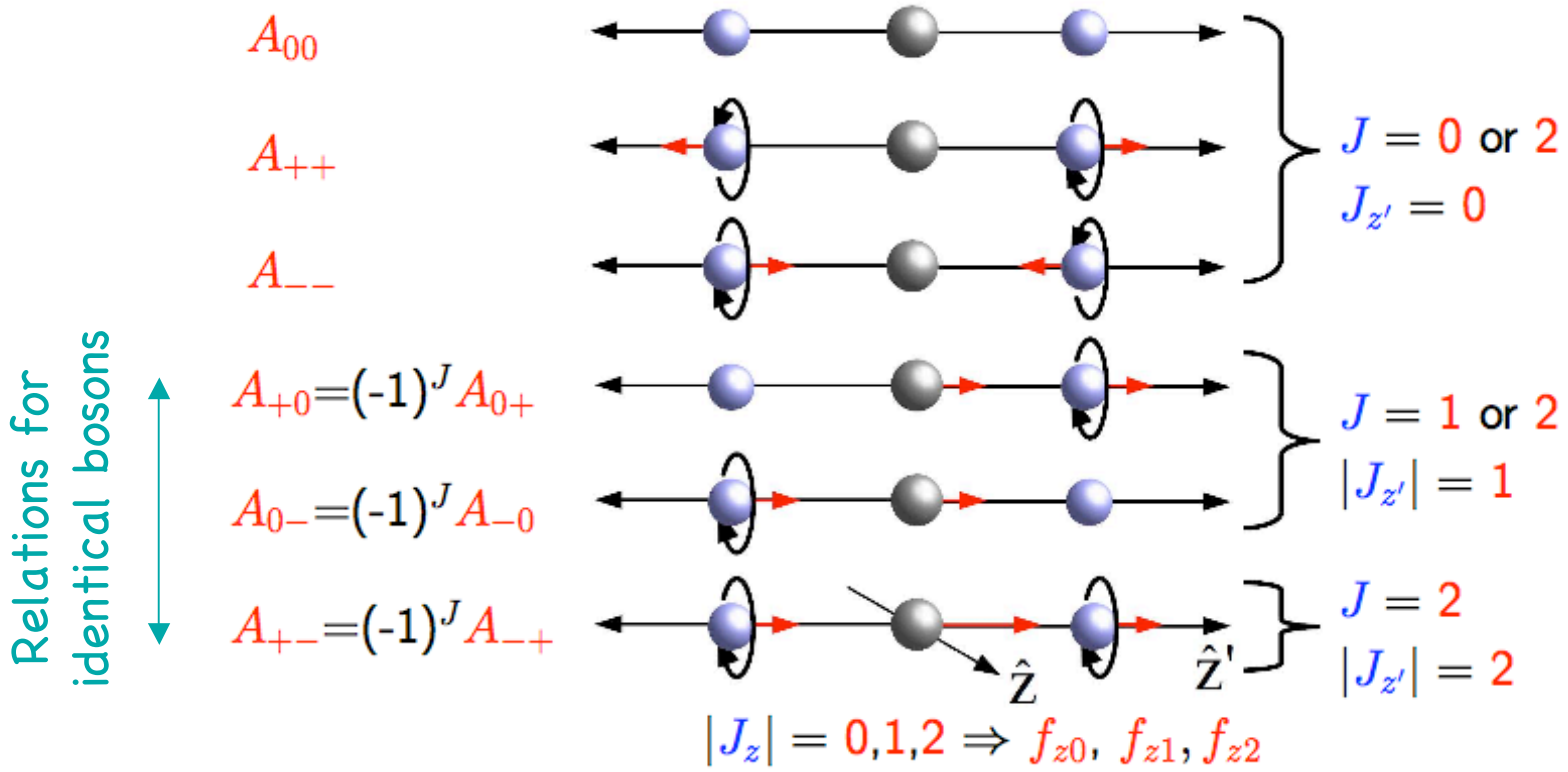
*data = MC generator based on amplitudes

Helicity amplitudes

Helicity amplitudes: contributions to the total amplitude from the different daughter helicities; determine angular distributions

Example:

Massive gauge bosons (W,Z) have J_z = 0,±1 possible helicity states; 9 total amplitudes, A_{kl}



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



General amplitudies to helicity amplitudes

Interactions of spin-two X to two gauge bosons:

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

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

$$A_{+-} = A_{-+} = \frac{m_X^2}{4\Lambda} c_1 (1+\beta^2) ,$$
$$A_{++} = \frac{m_X^2}{\sqrt{6}\Lambda} \left[\frac{c_1}{4} (1+\beta^2) + 2c_2\beta^2 + i\beta(c_5\beta^2 - 2c_6) \right] ,$$
$$A_{--} = \frac{m_X^2}{\sqrt{6}\Lambda} \left[\frac{c_1}{4} (1+\beta^2) + 2c_2\beta^2 - i\beta(c_5\beta^2 - 2c_6) \right] ,$$
$$A_{+0} = A_{0+} = \frac{m_X^3}{m_V\sqrt{2}\Lambda} \left[\frac{c_1}{8} (1+\beta^2) + \frac{c_4}{2}\beta^2 - \frac{c_6 + c_7\beta^2}{2} i\beta \right] ,$$
$$A_{-0} = A_{0-} = \frac{m_X^3}{m_V\sqrt{2}\Lambda} \left[\frac{c_1}{8} (1+\beta^2) + \frac{c_4}{2}\beta^2 + \frac{c_6 + c_7\beta^2}{2} i\beta \right] ,$$
$$A_{00} = \frac{m_X^4}{m_V^2\sqrt{6}\Lambda} \left[(1+\beta^2) \left(\frac{c_1}{8} - \frac{c_2}{2}\beta^2 \right) - \beta^2 \left(\frac{c_3}{2}\beta^2 - c_4 \right) \right] .$$

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



Helicity amplitudes

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

$J_X = 0$	$J_X = 1$	$J_X = 2$
Production: gg^	Production: qqbar*	Production: gg or qqbar
Allowed spin projection: 0	Allowed spin projection: ±1^	Allowed spin projection: 0, ±1, ±2
Helicity Amplitudes: A_{00}, A_{++}, A_{--}	Helicity Amplitudes: $A_{+0} = -A_{0+}$, $A_{0-} = -A_{-0}$	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

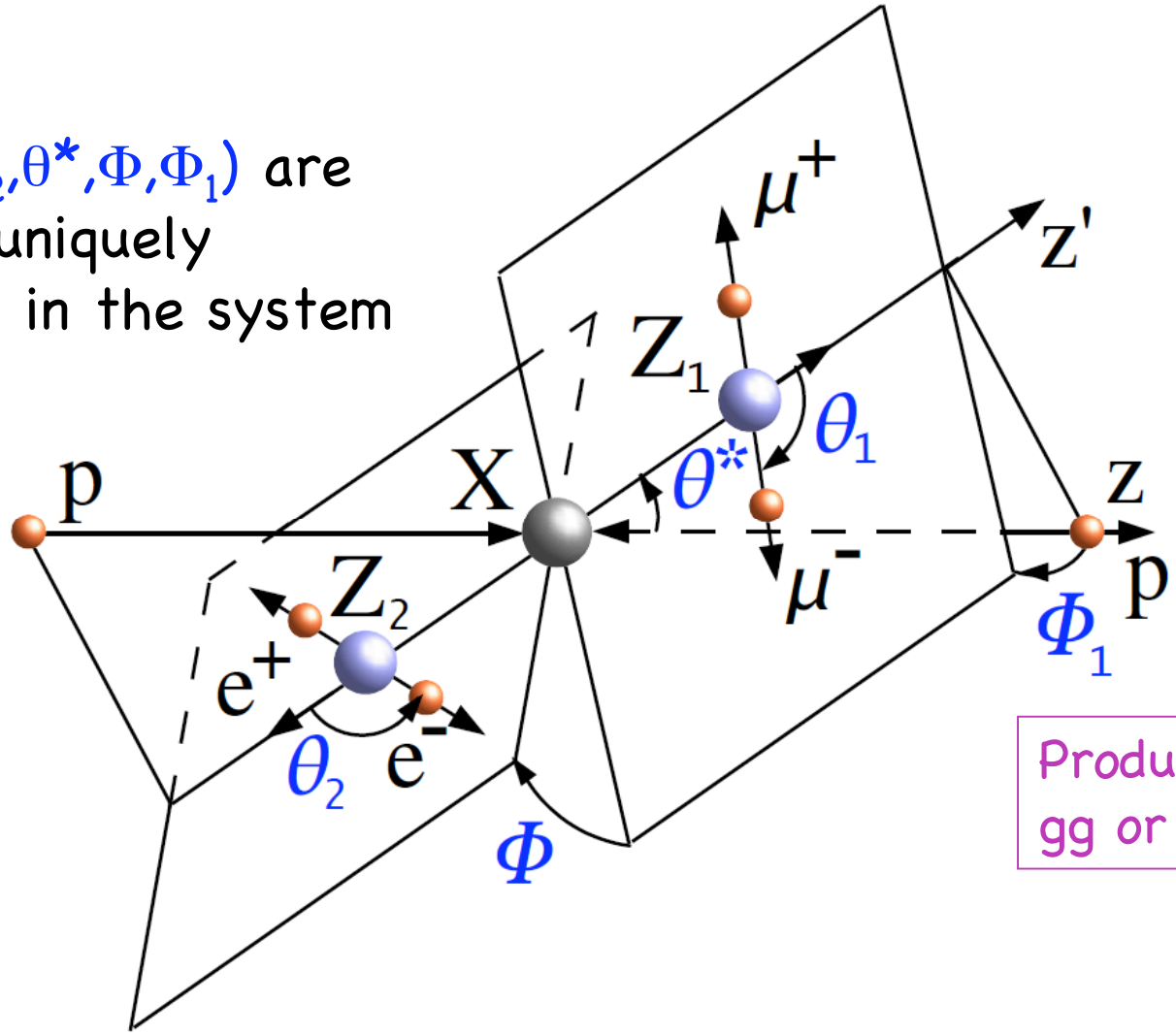
For identical vector bosons: $A_{kl} = (-1)^J A_{lk}$

For definite CP states: $A_{kl} = \eta_P(-1)^J A_{-k-l}$

Definition of the system

X→ZZ→4l:

5 angles (θ_1,θ_2,θ^*,Φ,Φ_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

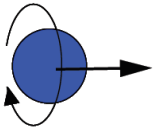
$$
\begin{aligned}
&F^J_{00}(\theta^*) \times \Big\{ 4\, f_{00} \sin^2\theta_1 \sin^2\theta_2 + (f_{++} + f_{--}) \left((1+\cos^2\theta_1)(1+\cos^2\theta_2) + 4R_1R_2\cos\theta_1\cos\theta_2 \right) \\
&\quad - 2\,(f_{++} - f_{--}) \left(R_1\cos\theta_1(1+\cos^2\theta_2) + R_2(1+\cos^2\theta_1)\cos\theta_2 \right) \\
&\quad + 4\sqrt{f_{++}f_{00}}\,(R_1 - \cos\theta_1)\sin\theta_1 (R_2 - \cos\theta_2)\sin\theta_2 \cos(\Phi + \phi_{++}) \\
&\quad + 4\sqrt{f_{--}f_{00}}\,(R_1 + \cos\theta_1)\sin\theta_1 (R_2 + \cos\theta_2)\sin\theta_2 \cos(\Phi - \phi_{--}) \\
&\quad + 2\sqrt{f_{++}f_{--}}\sin^2\theta_1 \sin^2\theta_2 \cos(2\Phi + \phi_{++} - \phi_{--}) \Big\} \\
&+4F^J_{11}(\theta^*) \times \Big\{ (f_{+0} + f_{0-})(1 - \cos^2\theta_1\cos^2\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_1\sin^2\theta_2 + R_2\sin^2\theta_1\cos\theta_2) \\
&\quad + 2\sqrt{f_{+0}f_{0-}}\sin\theta_1\sin\theta_2 (R_1R_2 - \cos\theta_1\cos\theta_2)\cos(\Phi + \phi_{+0} - \phi_{0-}) \Big\} \\
&+(-1)^J \times 4F^J_{-11}(\theta^*) \times \Big\{ (f_{+0} + f_{0-})(R_1R_2 + \cos\theta_1\cos\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_2 + R_2\cos\theta_1) \\
&\quad + 2\sqrt{f_{+0}f_{0-}}\sin\theta_1\sin\theta_2\cos(\Phi + \phi_{+0} - \phi_{0-}) \Big\} \sin\theta_1\sin\theta_2\cos(2\Psi) \\
&+2F^J_{22}(\theta^*) \times f_{+-} \Big\{ (1+\cos^2\theta_1)(1+\cos^2\theta_2) - 4R_1R_2\cos\theta_1\cos\theta_2 \Big\} \\
&+(-1)^J \times 2F^J_{-22}(\theta^*) \times f_{+-}\sin^2\theta_1\sin^2\theta_2\cos(4\Psi)
\end{aligned}
$$

+ interference terms

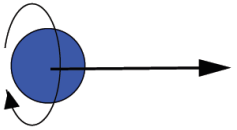
$J_z = 0$



$J_z = \pm 1$



$J_z = \pm 2$

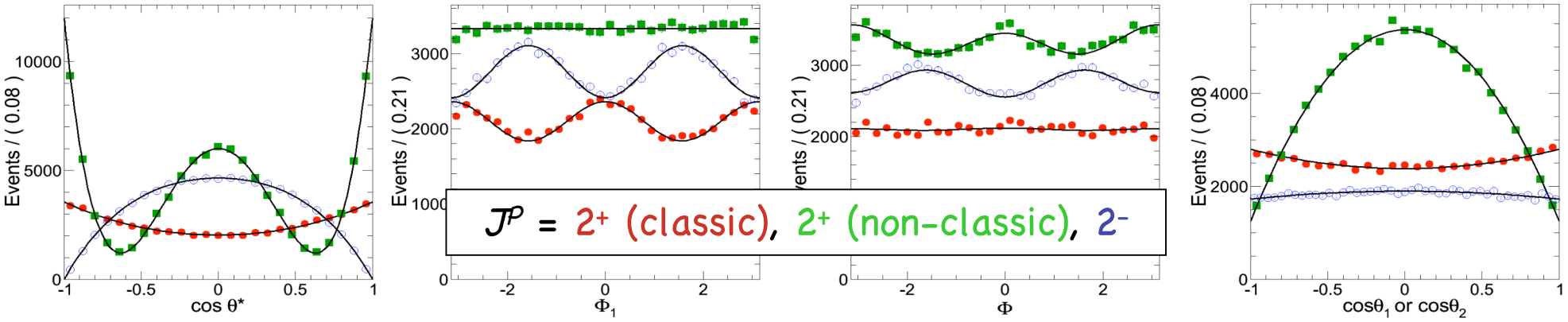


- Spin-zero *X*: only $J_z = 0$ part contributes
- Spin-one *X*: only $J_z = \pm 1$ part contributes
- Spin-two *X*: all contributions exist $J_z = 0, \pm 1, \pm 2$

MC Simulation

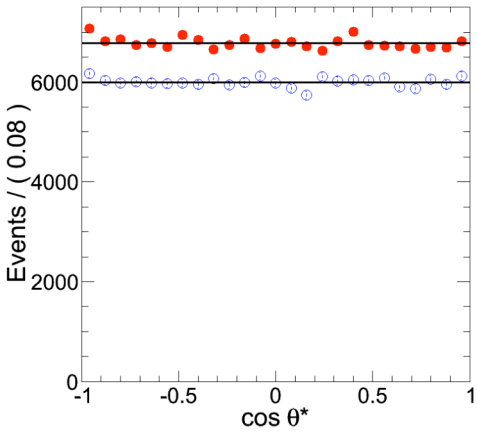
- A MC program developed to simulate production and decay of X with spin-zero, -one, or -two
  - Includes all spin correlations and all general couplings
  - Inputs are general dimensionless couplings, calculates matrix elements
  - Both gg and qqbar production
  - Contains both final states for $ZZ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

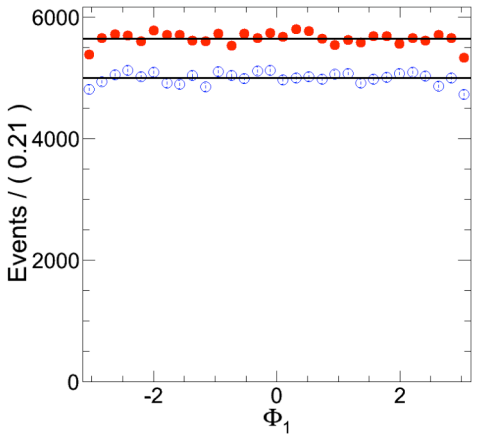
Example of agreement for MC (points) and angular distributions (lines)

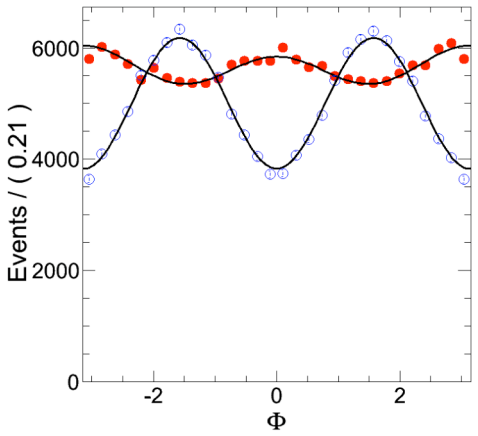


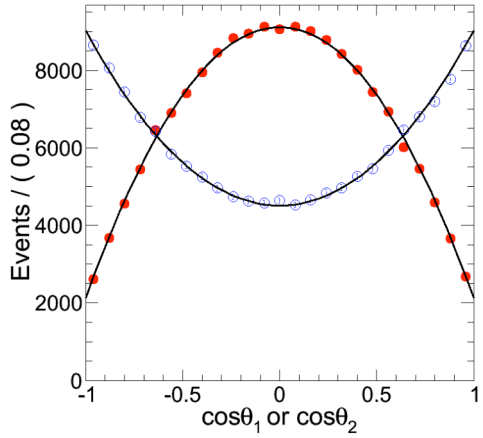
MC Simulation

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

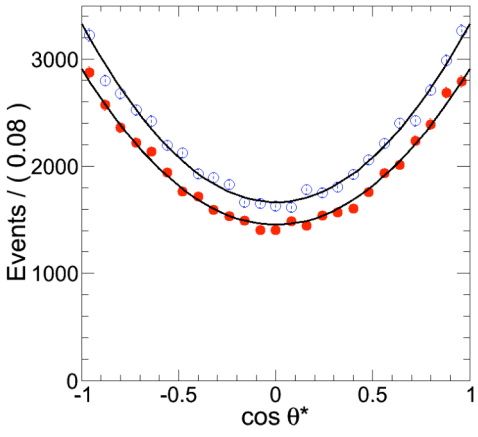


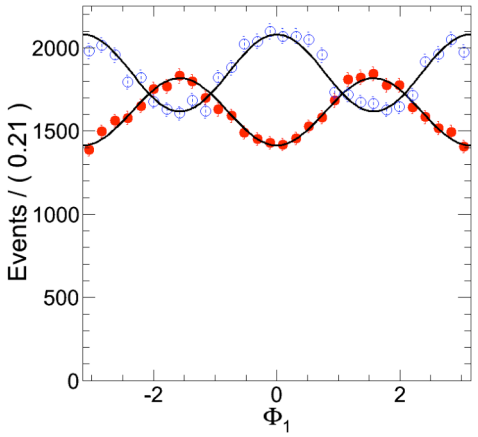


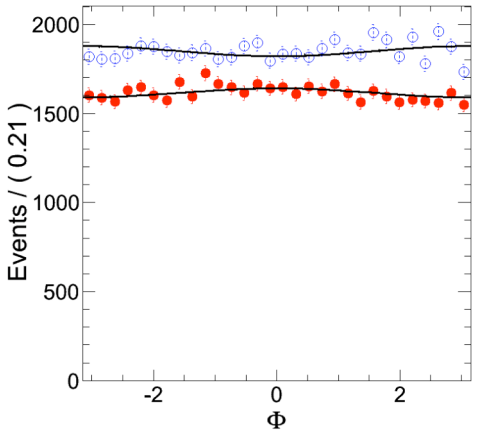


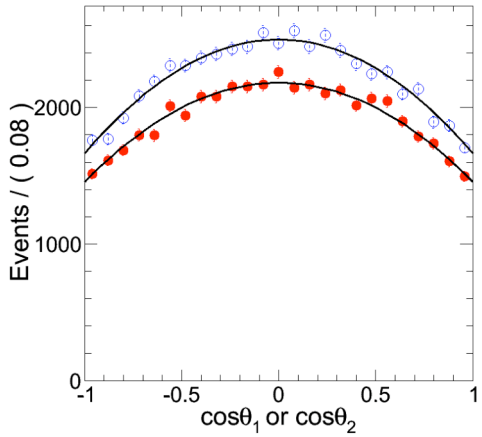


Spin One: $J^P = 1^+, 1^-$





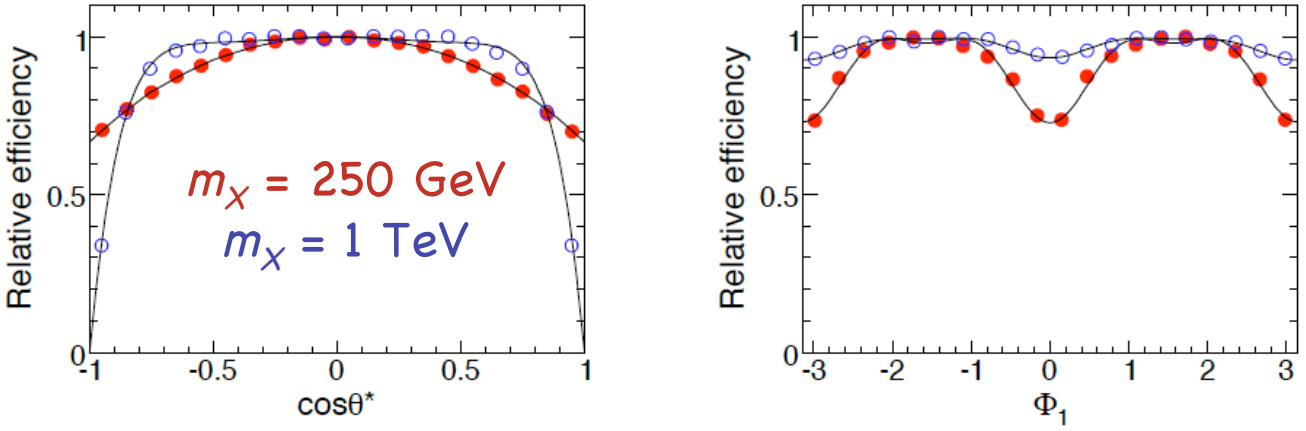




N.B. 1D projections of angles for illustration,
statistical power comes from 5D *angular correlations*

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

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

$$x_i = \{m_{ZZ},\ \theta_1, \theta_2, \Phi,\ \theta^*, \Phi_1\}_i$$
$$\zeta_J = \{f_{kl},\ \phi_{kl}, f_m\}$$

Multivariate techniques

- Use the likelihood method 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 in a general case?

Hypothesis separation: example of 0^+ vs 0^- at 250 GeV

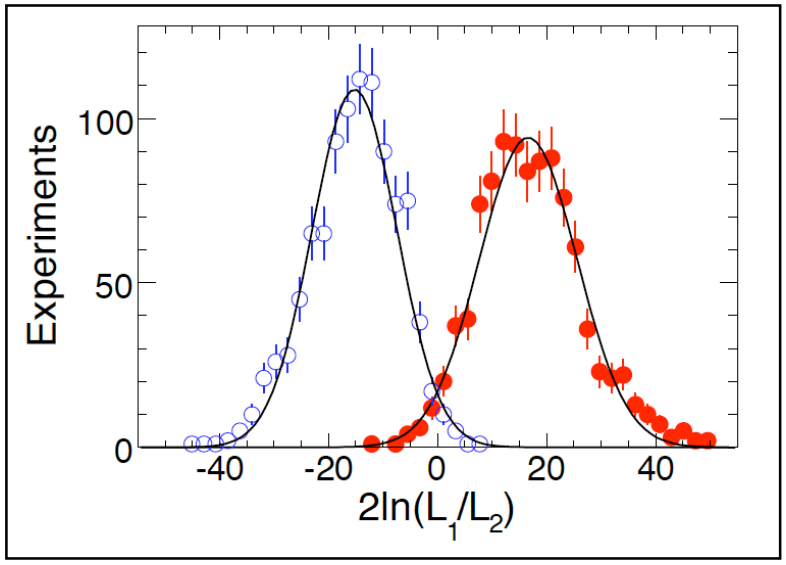
Statistics approx. for 2.5 fb^{-1} of SM Higgs CMS+ATLAS at 14 TeV

Separation of:

- Signal scenarios (right)

or

- Signal vs. Background





Multivariate analysis

Hypothesis separation of signal scenarios:

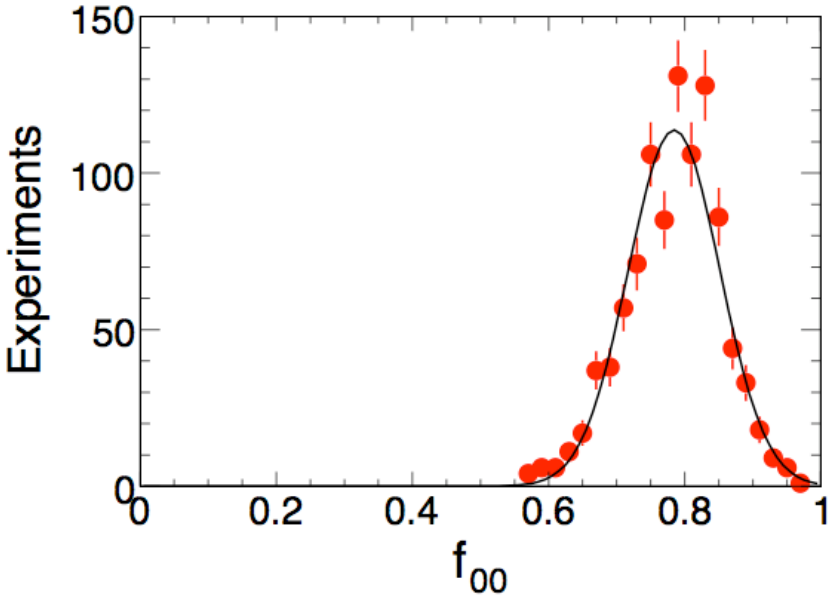
At or around the time of discovery, we can already start to make a statement about resonance spin/CP

Example table, 250 GeV resonance
Comparison of various signal hypotheses
Statistics give ~5.7σ discovery significance

	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

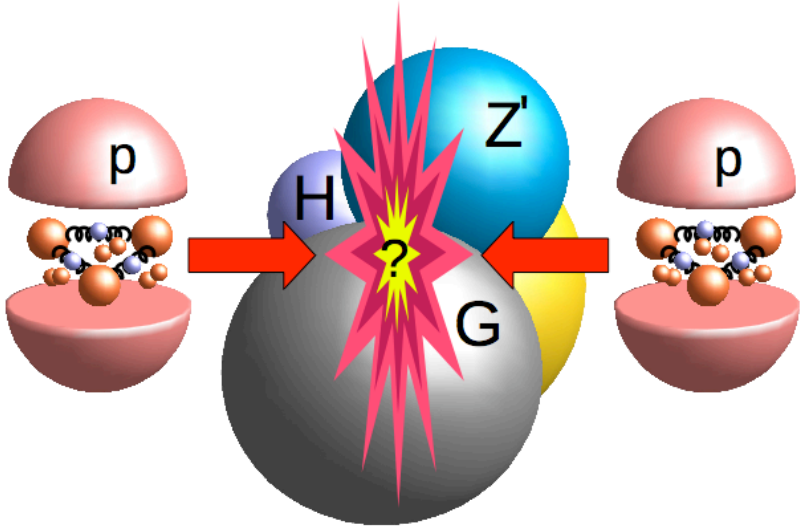
Parameter fitting:

With more statistics (x5), can say something about specific couplings to SM fields



Example fit, longitudinal contribution in case of a spin-0 resonance

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
  - At time of discovery, can already constrain spin/CP