Model-independent spin and coupling determination of Higgs-like resonances

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Higgs Hunting 2010

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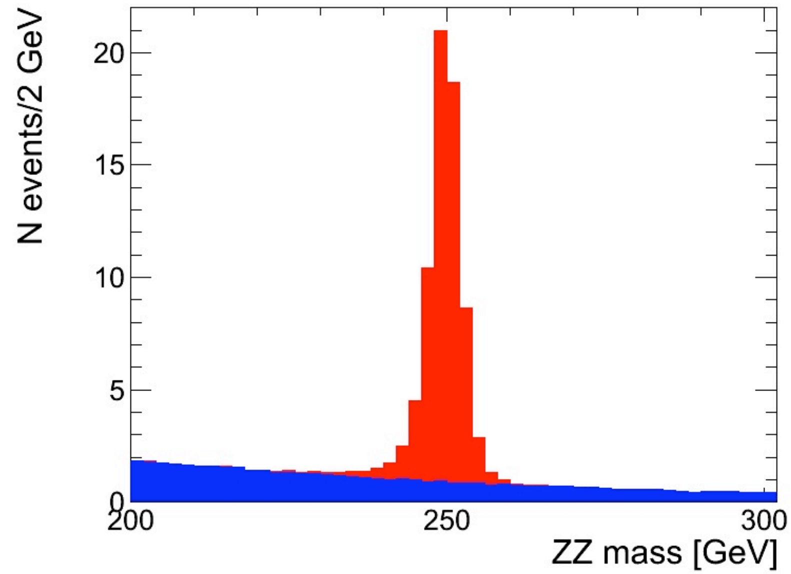
What if a resonance is found?

- Resonances could be sign of Higgs...or something else!



- 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

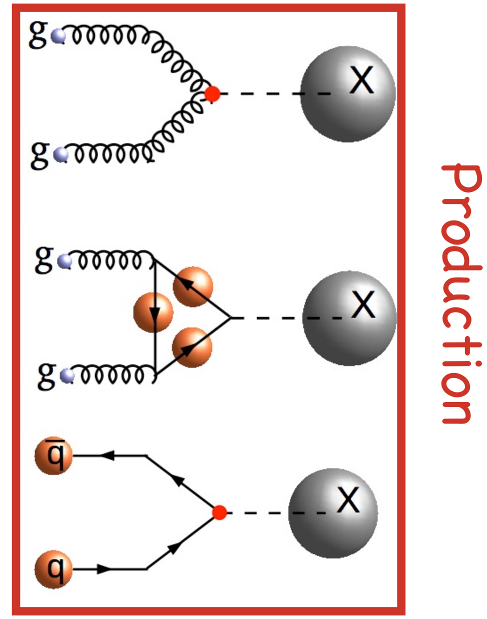
Gao, Gritsan, Guo, Melnikov, Schulze, N.T. 2010 [arXiv:1001.3396] PRD81,075022(2010)

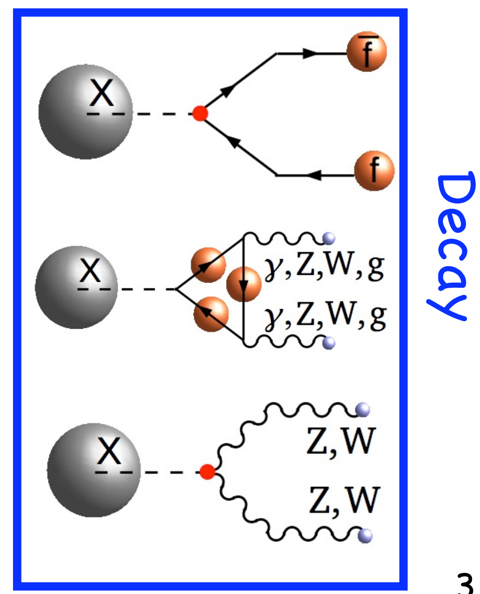
De Rujula, Lykken, Pierini, Spiropulu, Rogan 2010 [arXiv:1001.5300]

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

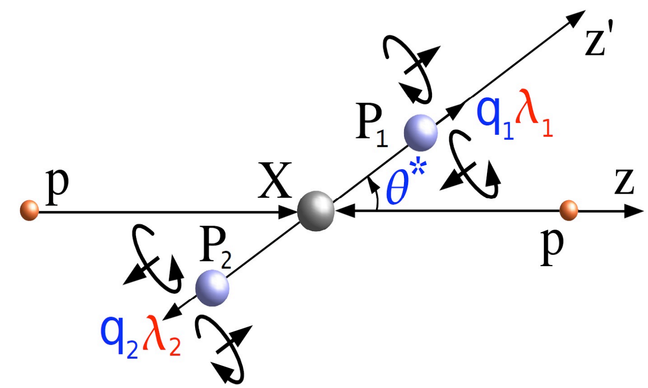
- Spin-zero
  - SM Higgs, $J^P = 0^+$,
    or other non-SM scalar
  - Pseudoscalar $J^P = 0^-$, multi-Higgs case
- Spin-one
  - Heavy photon
  - Kaluza-Klein gluon
- Spin-two
  - RS Graviton, $J^P = 2^+$: classic model
    - SM fields localized to TeV brane
  - Non-classic RS Graviton model
    - SM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





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

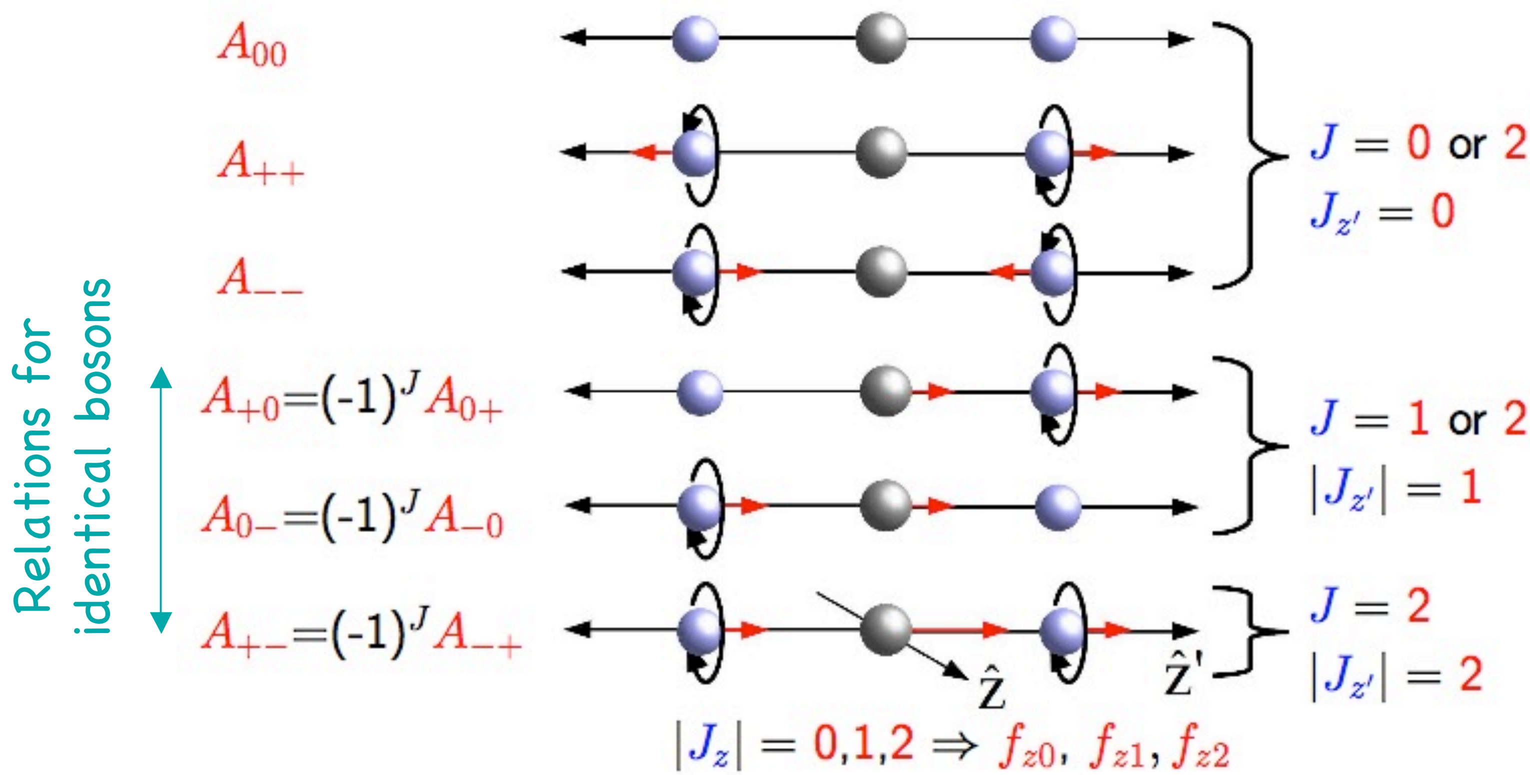
Helicity amplitude formalism

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 $J_z = 0, \pm 1$ possible helicity states;
9 total amplitudes, A_{kl}



Theory to experiment:

General amplitudies to helicity amplitudes

Interactions of spin-zero X to two gauge bosons:

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

Dimensionless *complex* coupling constants

Gauge boson polarization vectors

e.g. For SM Higgs: $a_1 \to$ tree level, $a_2 \to$ radiative corrections O(%), $a_3 \to$ 3-loop CP-violating $O(10^{-11})$

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

$$A_{00} = -\frac{m_X^4}{4 v m_V^2} \left(a_1 (1 + \beta^2) + a_2 \beta^2 \right) ;$$

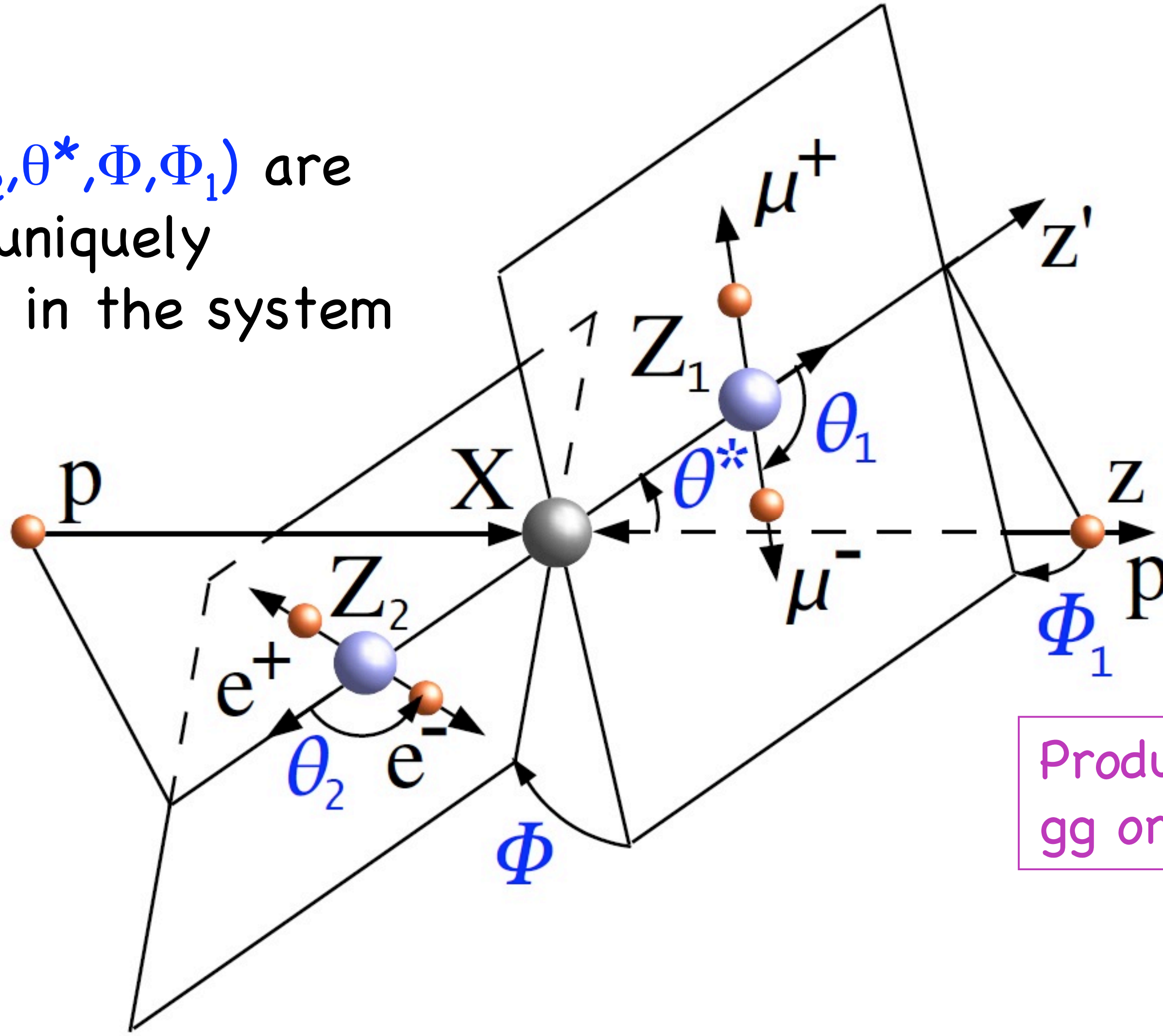
$$A_{++} = \frac{m_X^2}{v} \left(a_1 + \frac{i a_3 \beta}{2} \right) ; \quad A_{--} = \frac{m_X^2}{v} \left(a_1 - \frac{i a_3 \beta}{2} \right)$$

We do the same thing for spin-one and spin-two *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

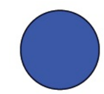
$$
\begin{aligned}
& F^J_{00}(\theta^*) \times \Big\{ 4\, f_{00}\, \sin^2\theta_1 \sin^2\theta_2 + (f_{++} + f_{--}) \left((1+\cos^2\theta_1)(1+\cos^2\theta_2) + 4R_1R_2\cos\theta_1\cos\theta_2 \right) \\
& \quad - 2\,(f_{++} - f_{--}) \left(R_1 \cos\theta_1 (1+\cos^2\theta_2) + R_2(1+\cos^2\theta_1)\cos\theta_2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

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

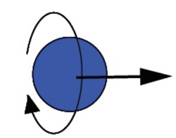
$$
\begin{aligned}
& +2F^J_{22}(\theta^*) \times f_{+-} \Big\{ (1+\cos^2\theta_1)(1+\cos^2\theta_2) - 4R_1R_2\cos\theta_1\cos\theta_2 \Big\} \\
& +(-1)^J \times 2F^J_{-22}(\theta^*) \times f_{+-}\sin^2\theta_1\sin^2\theta_2\cos(4\Psi)
\end{aligned}
$$

+ interference terms

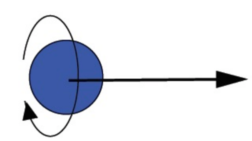
$J_z = 0$



$J_z = \pm 1$



$J_z = \pm 2$

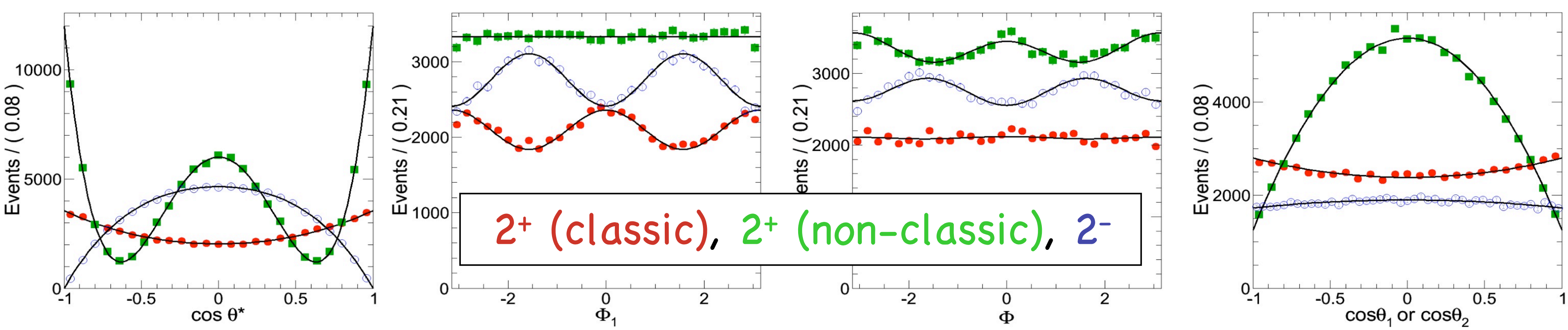


- Spin-zero *X*: only $J_z = 0$ part contributes
- Spin-one *X*: only $J_z = \pm 1$ part contributes
- Spin-two *X*: all contributions exist $J_z = 0, \pm 1, \pm 2$

MC Simulation

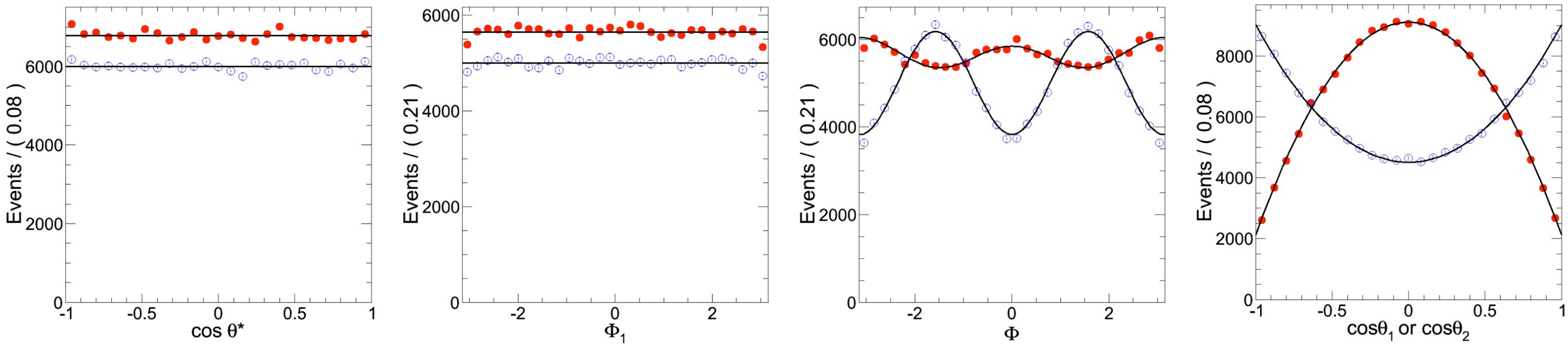
- A MC program developed to simulate production and decay of X with spin-zero, -one, or -two
  - Includes all spin correlations and all general couplings
  - Inputs are general dimensionless couplings - calculates matrix elements
  - Both gg and qqbar production
  - Contains both final states for $ZZ \to 4l$ and $ZZ \to 2l2j$
  - Output 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)

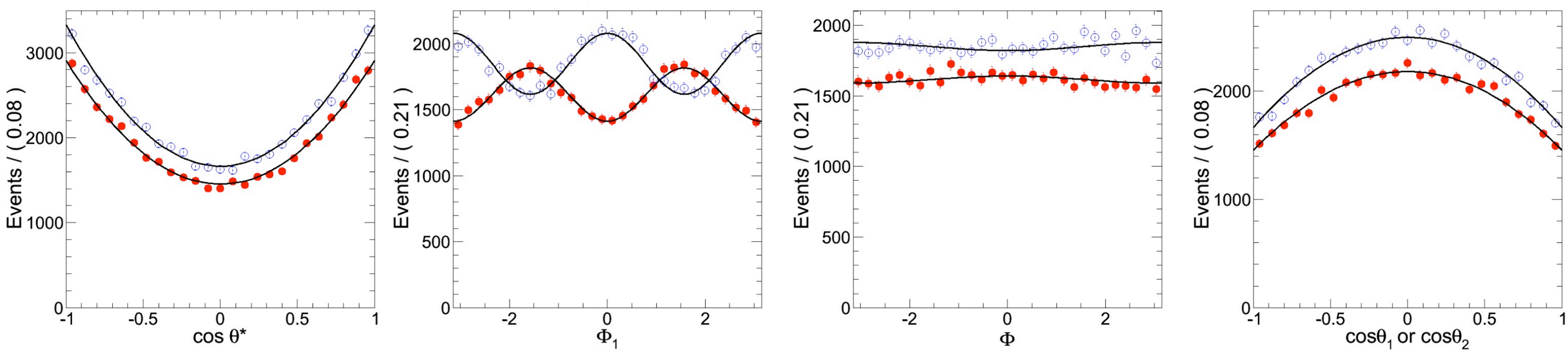


MC Simulation

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

Backup

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_{--} $A_{+0} = A_{0+}$ $A_{0-} = A_{-0}$ $A_{+-} = A_{-+}$
4 [free parameters]	2	10

*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: $A_{kl} = \eta_P(-1)^J A_{-k-l}$

Theory to experiment:

General amplitudies to helicity amplitudes

Interactions of spin-two X to two gauge bosons:

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

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

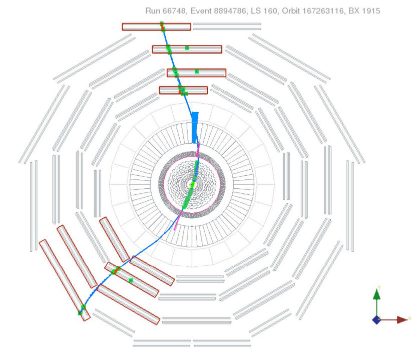
$$A_{+-} = A_{-+} = \frac{m_X^2}{4\Lambda} c_1 (1+\beta^2), \qquad A_{+0} = A_{0+} = \frac{m_X^3}{m_V \sqrt{2}\Lambda} \left[\frac{c_1}{8}(1+\beta^2) + \frac{c_4}{2}\beta^2 - \frac{c_6 + c_7\beta^2}{2} i\beta \right],$$

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

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

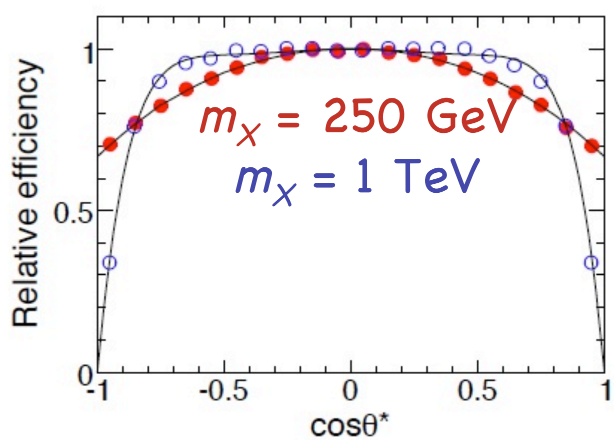
We do the same thing for spin-zero and spin-one *X*

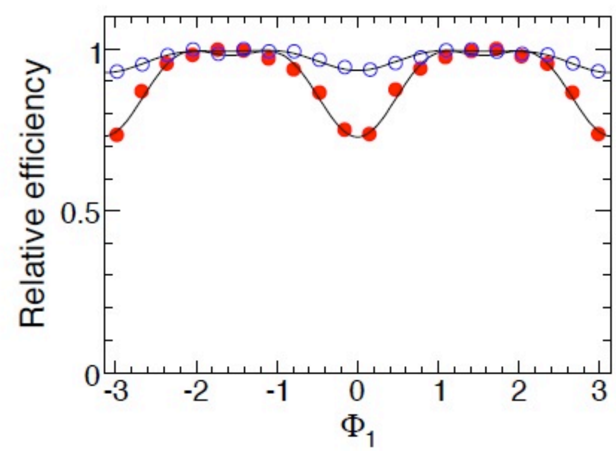
Detector Effects



- Experimental effects addressed in standalone ROOT
  - Parameter resolution: we smear four-momenta of decay products in pT and angular resolution by values determined from CMS cosmic ray studies *(JINST)*
    - Angular resolution very good; on the order of 0.01 radians
  - Geometric acceptance: assume hermetic detector out to η =2.5
    - Helicity angles weakly dependent on detector acceptance
    - Production angles most directly affected
    - Parameterize acceptance in PDF by:

$$\mathcal{P}(\text{angles}) = \mathcal{P}_{\text{ideal}}(\text{angles}) * G_{\text{acc}}(\text{angles})$$





Multivariate Techniques

- Using RooFit: unbinned maximum-likelihood fit
- Joint fit to combine all 3 channels: 4μ, $4e$, $2e2\mu$

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

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

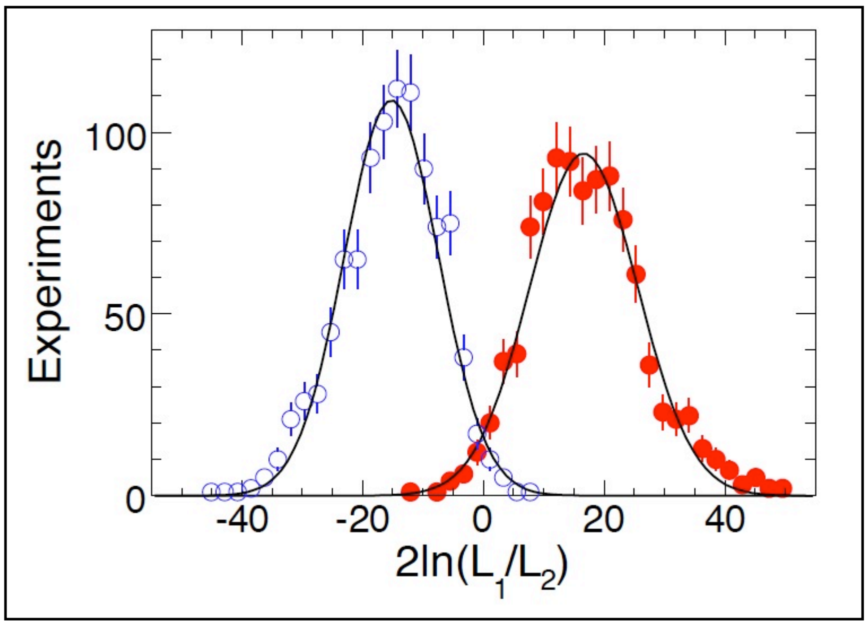
- Use the multivariate likelihoods for:
  - Distinguishing between different signal hypotheses
  - Improving background suppression – both in case of signal or no signal
  - Parameter determination for a certain hypothesis

Hypothesis Separation

Neyman-Pearson hypothesis testing:
Run 1000 toy experiments…
Determine likelihood ratio estimator [$S = 2*\ln(L_A/L_B)$] for data samples "A" and "B". Quote effective separation of Gaussian peaks.

Probability Density Function constructed of m_{ZZ} + angular distributions

Example case of 0^+ vs 0^- at 250 GeV



Separation of:
- Signal scenarios (left)
- Signal vs. Background
  L_A (S+B) and L_B (B only)

e.g. SM Higgs: can achieve 5.7σ using kinematic variables only. We can improve by ~16% if we include angular variables

Parameter fitting

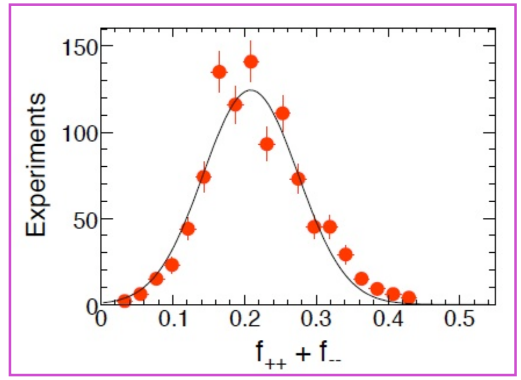
- Fit w/ and w/out detector effects for 2 mass points, compare with generated parameters
- As an example, we take 0^+ and 0^- cases

0^+

	generated	$m_X = 250$ GeV fitted without detector	$m_X = 250$ GeV fitted with detector	generated	$m_X = 1$ TeV fitted without detector	$m_X = 1$ TeV fitted with detector
n_{sig}	150	150 ± 13	153 ± 15	150	150 ± 12	152 ± 12
$(f_{++} + f_{--})$	0.208	0.21 ± 0.07	0.23 ± 0.08	0.000	0.00 ± 0.03	0.00 ± 0.03
$(f_{++} - f_{--})$	0.000	0.01 ± 0.13	0.01 ± 0.14	0.000	0.00 ± 0.02	0.00 ± 0.02
$(\phi_{++} + \phi_{--})$	2π	6.30 ± 1.46	6.39 ± 1.54	2π	free	free
$(\phi_{++} - \phi_{--})$	0	0.00 ± 1.06	0.01 ± 1.09	0	free	free

0^-

	generated	$m_X = 250$ GeV fitted without detector	$m_X = 250$ GeV fitted with detector	generated	$m_X = 1$ TeV fitted without detector	$m_X = 1$ TeV fitted with detector
n_{sig}	150	150 ± 13	151 ± 15	150	151 ± 12	150 ± 13
$(f_{++} + f_{--})$	1.000	1.00 ± 0.05	1.00 ± 0.06	1.000	1.00 ± 0.05	1.00 ± 0.06
$(f_{++} - f_{--})$	0.000	0.00 ± 0.35	0.00 ± 0.40	0.000	0.00 ± 0.31	-0.01 ± 0.32
$(\phi_{++} + \phi_{--})$	N/A	free	free	N/A	free	free
$(\phi_{++} - \phi_{--})$	π	3.15 ± 0.31	3.14 ± 0.41	π	3.15 ± 0.31	3.14 ± 0.33



0^+: $f_{++}+f_{--} = 0.23 \pm 0.08$
0^-: $f_{++}+f_{--} = 1.00 \pm 0.06$
A naïve separation between $0^+/0^-$ of ~10σ