Spin determination of single-produced resonances at hadron colliders

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Credits

- Disclaimer: analysis developed by authors publicly within CMS
  but does not represent official statement of CMS about its reach

"Spin determination of single-produced resonances at hadron colliders"

arXiv:1001.3396 [hep-ph] (Jan. 19, 2010) ⇒ PRD81,075022(2010)

Y.Gao[1,2,3,4], A.G.[1,3,4], Z.Guo[1,3,4], K.Melnikov[1], M.Schulze[1], N.Tran[1,3]

[1] JHU [2] now at FNAL [3] CMS [4] BaBar

- Another paper later (some of our CMS colleagues):

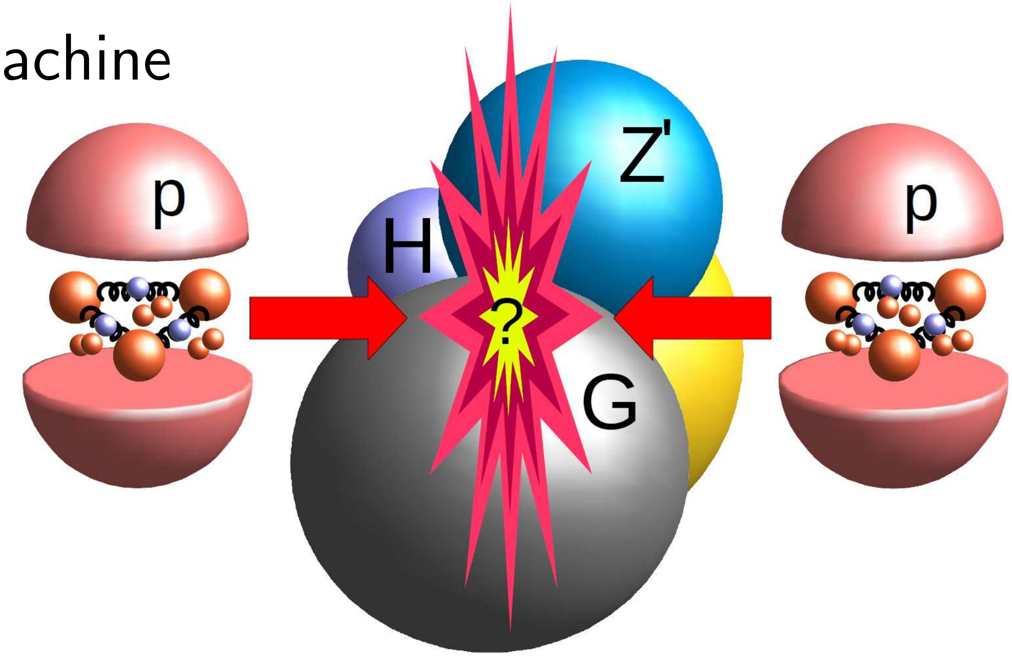
"Higgs look-alikes at the LHC" arXiv:1001.5300 [hep-ph] (Jan. 29, 2010)

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

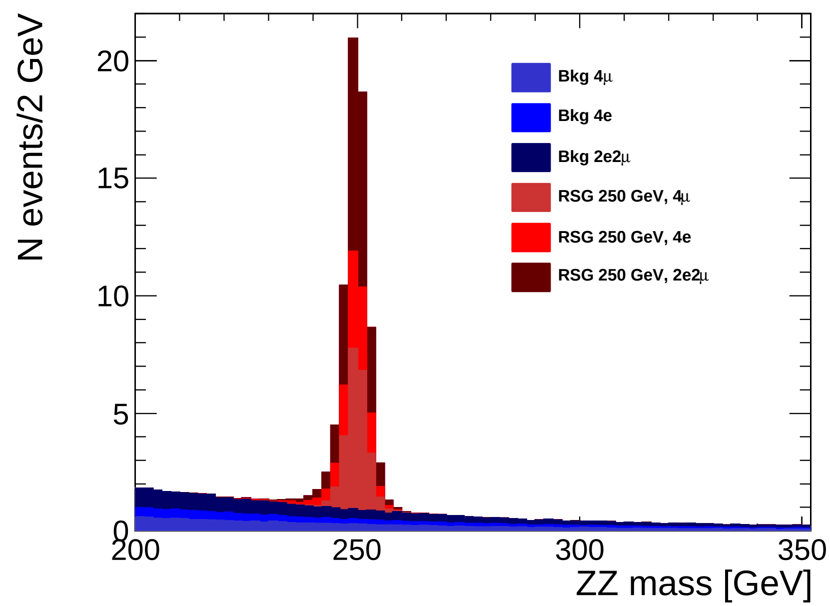
(see next talk)

Questions

- LHC is a discovery machine

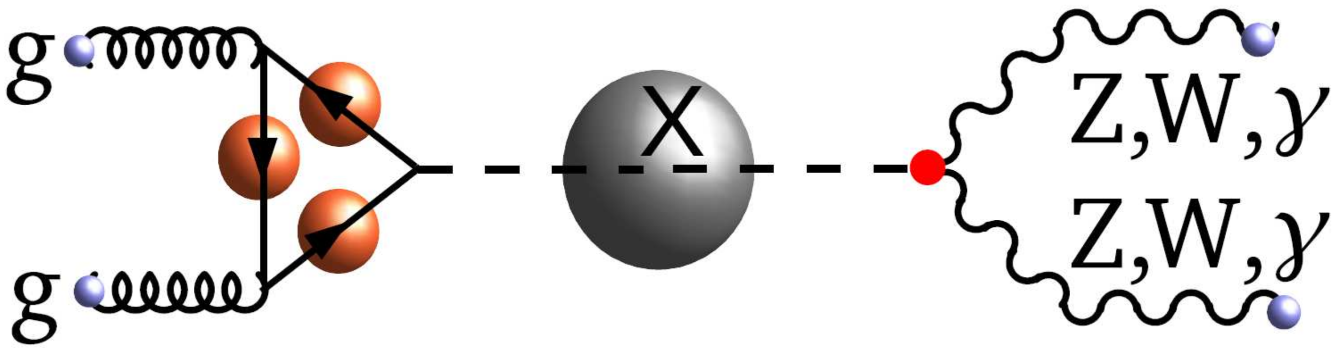


- If resonance is observed on LHC
  - significance over background
  - mass, width, rate (σ), branching
    can "see" on the mass plot(s) $\longrightarrow$
  - quantum numbers (spin, parity,..)?
  - couplings to SM fields?
  - maximum information?



Higgs Discovery

- Discovery of SM Higgs ($J^P = 0^+$): $H \to \gamma\gamma$, $ZZ^{(*)}$, W^+W^-,...



- However, other color-neutral & charge-neutral X resonances possible
  - final states (branchings), rate, width differentiate models
  - polarization of $X \to P_1 P_2 \Rightarrow$ spin & couplings (model-independent)

$$A(H_{J=0} \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

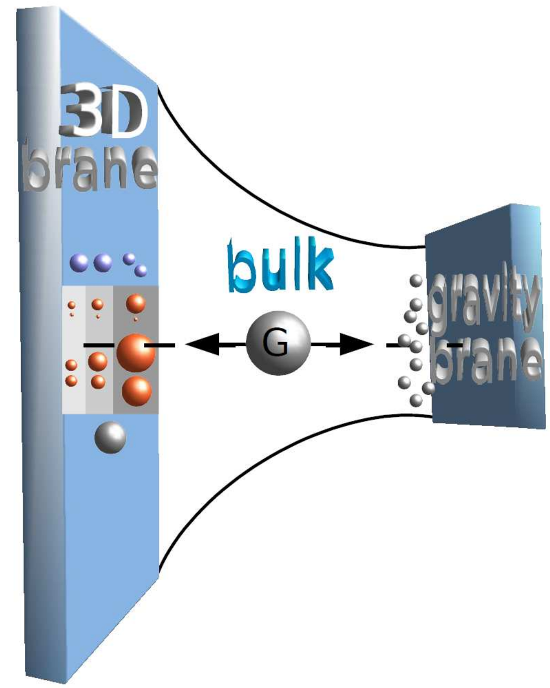
SM $H \to ZZ^{(*)}$, W^+W^- tree-level: $a_1 \neq 0$

SM $H \leftrightarrow \gamma\gamma$, gg, $(Z\gamma)$ loop-induced: $a_1 = -a_2/2 \neq 0$

Beyond SM: any spin and couplings, e.g. $a_3 \neq 0$ for $J^P = 0^-$

Do we expect such new resonances?

- Spin=0 (Higgs)
  - $J^P = 0^+$ SM $H \to \gamma\gamma$, $ZZ^{(*)}$, W^+W^-,...
  - $J^P = 0^-$ A multi-Higgs models



- Spin=1 (new gauge boson)
  - KK boson, $Z' \to l^+l^-$, $q\bar{q}$ dominant
  - models when ZZ and WW dominate

- Spin≥2 (KK graviton, "hidden glueballs")
  - RS Graviton 2^+ (minimal)

  SM on TeV brane

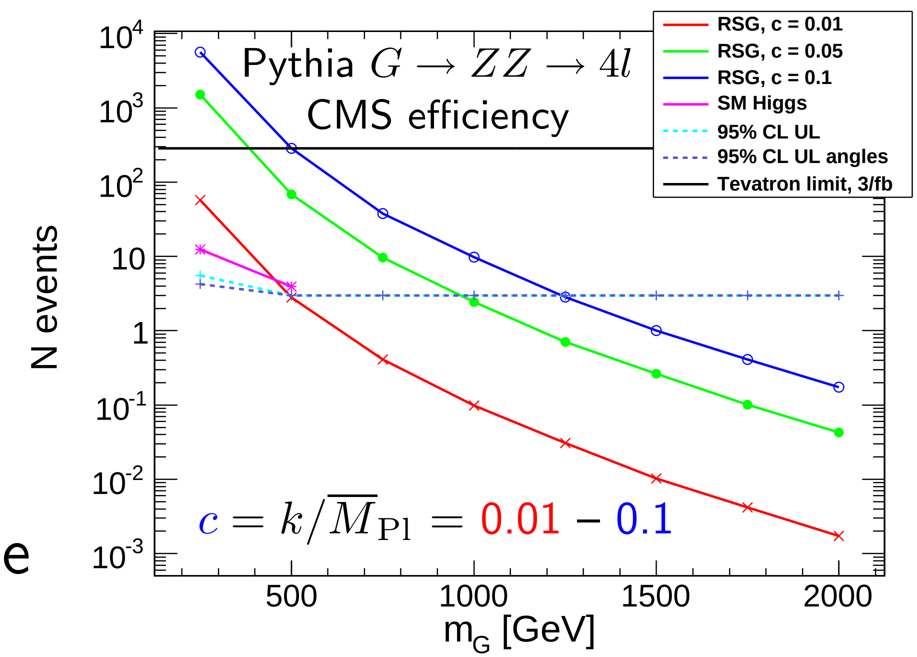
  $G_{\rm RS} \to \gamma\gamma$ and l^+l^- discovery

  - RS G 2^+ (non-minimal)

  light fermions in bulk

  $G_{\rm RS} \to W_L^+W_L^-$ and Z_LZ_L dominate

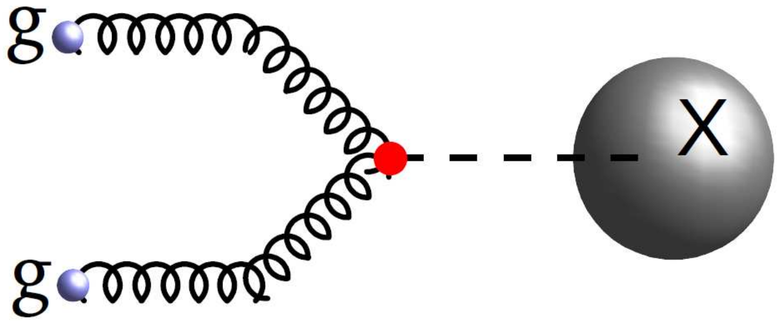
2/fb at $E_{pp} = 14$ TeV

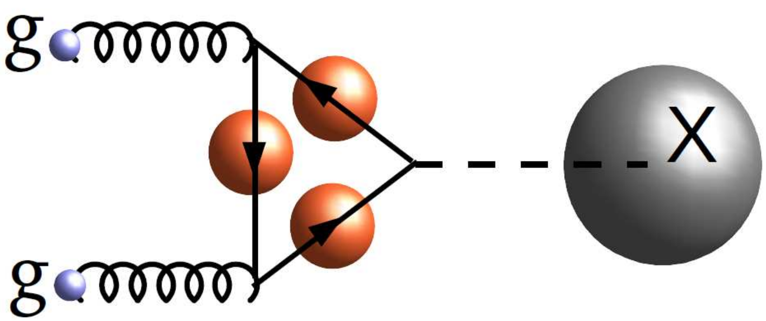


Production of New Resonances

- Consider two dominant production mechanisms

  of color-neutral
  & charge-neutral X



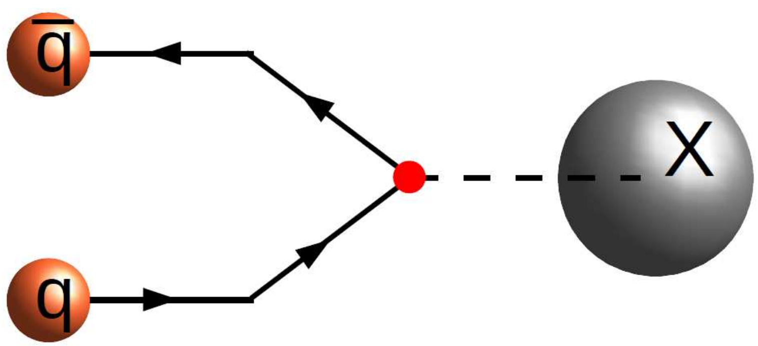


- Gluon fusion gg$\rightarrow X$

  $J = 0$ or 2

  $J_z = 0$ or ± 2

  expect to dominate at lower mass



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

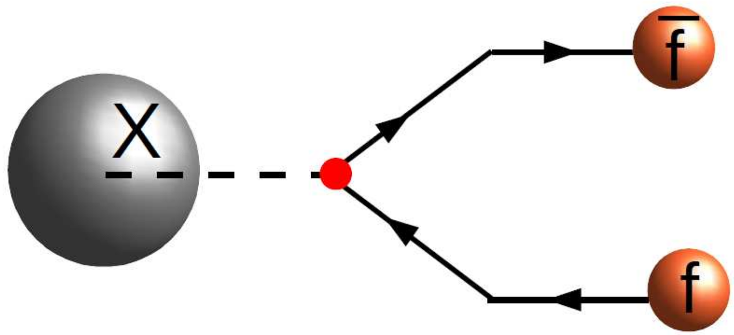
  $J = 1$ or 2

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

  assume chiral symmetry is exact

Decay of New Resonances

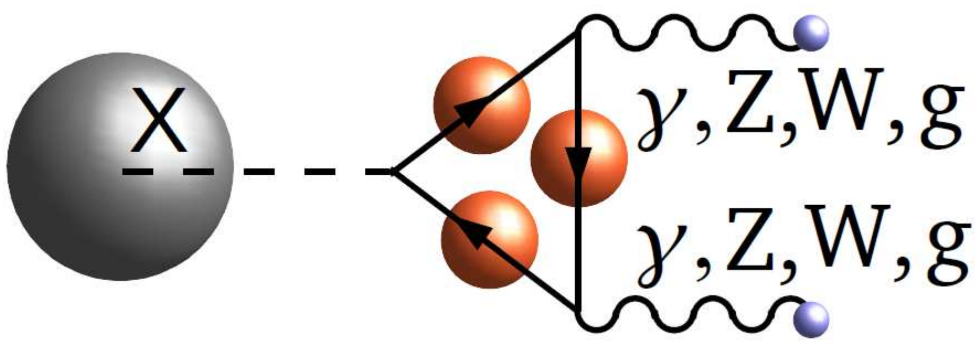
- Consider decay back to Standard Model particles



- Decay to fermions

$X \to l^+l^-,\ q\bar{q}$

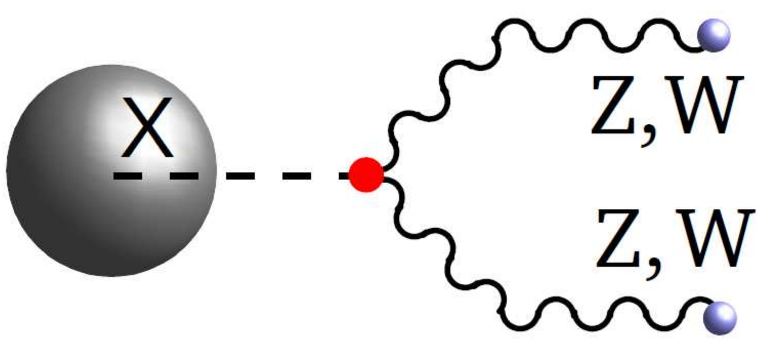
spin-0 excluded $m_f \to 0$



- Decay to gauge bosons

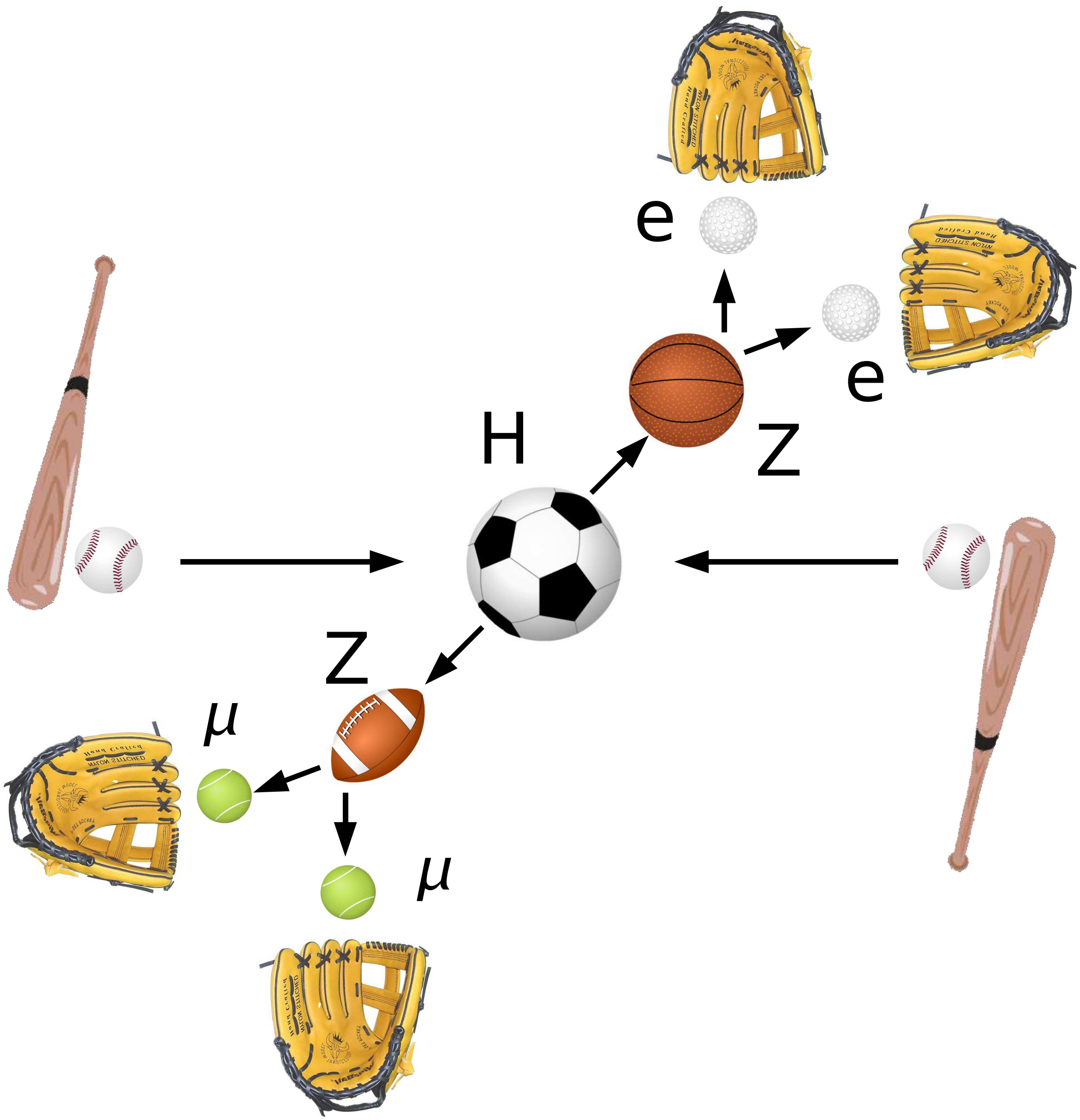
$X \to \gamma\gamma,\ WW,\ ZZ,\ Z\gamma,$ gg

spin-1 excluded with $\gamma\gamma$, gg



again X is color-neutral
& charge-neutral

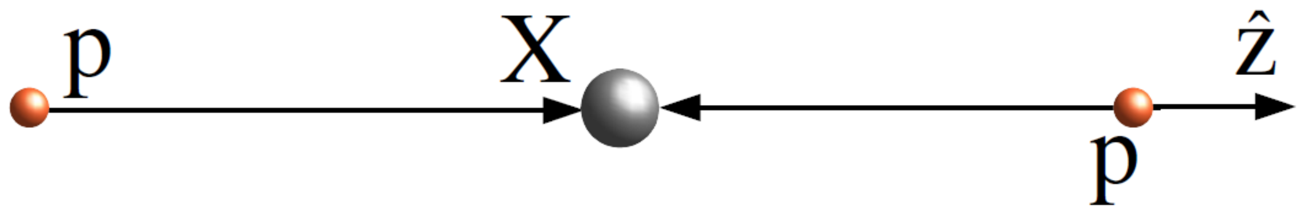
Cartoon of an Experiment

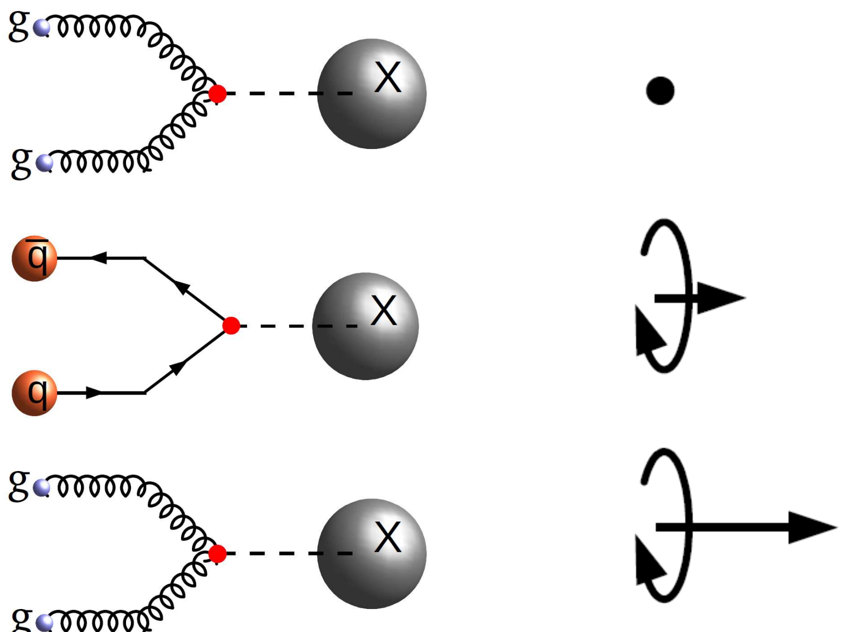


Kinematics in New Resonances Production

- $ab \to X$ polarization $\Leftrightarrow$ production mechanism and couplings

$$d\sigma_{pp}(\vec{\Omega}) = \sum_{ab} \int \mathrm{d}Y_X \, \mathrm{d}x_1 \mathrm{d}x_2 \, \tilde{f}_a(x_1) \, \tilde{f}_b(x_2) \, \frac{d\sigma_{ab}(x_1 p_1, x_2 p_2, \vec{\Omega})}{\mathrm{d}Y_X}\Big|_{Y_{ab}=\frac{1}{2}\ln\frac{x_1}{x_2}}$$





$J_z = 0$ fraction f_{z0}

$J_z = \pm 1$ fraction f_{z1}

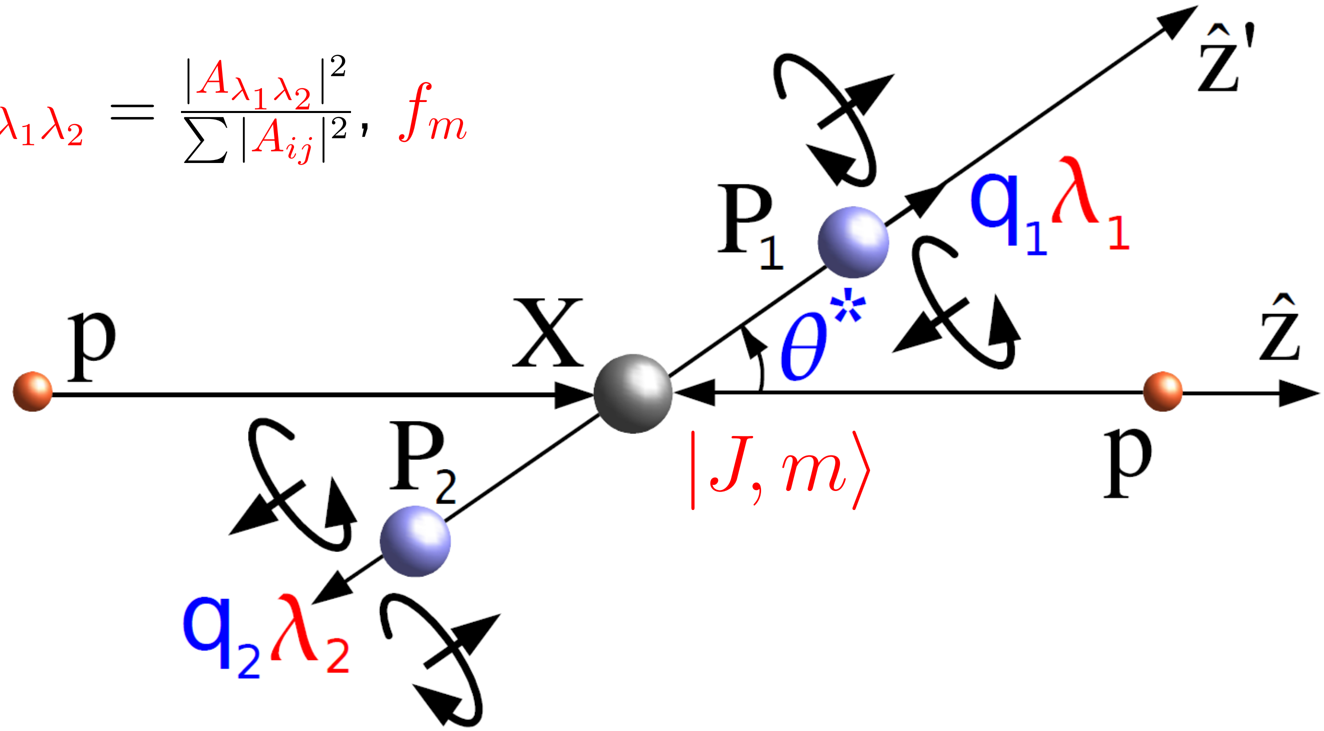
$J_z = \pm 2$ fraction f_{z2}

to change f_{z1}: vary LHC energy, sample Y_X

Kinematics in New Resonances Decay

- Only 1 angle θ^* for $X \to \gamma\gamma$, l^+l^-, $q\bar{q}$, gg (but more for ZZ, WW)

fraction $f_{\lambda_1\lambda_2} = \frac{|A_{\lambda_1\lambda_2}|^2}{\sum|A_{ij}|^2}$, f_m

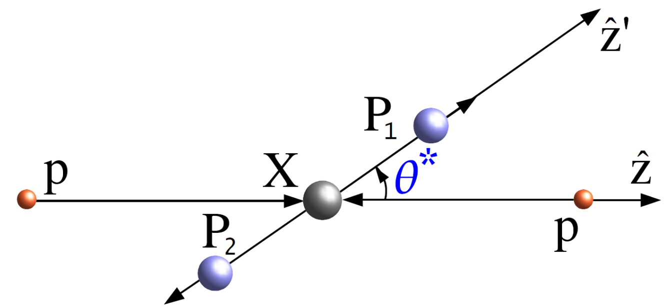


$$\frac{d\Gamma(X_J \to P_1P_2)}{\Gamma d\cos\theta^*} = \left(J + \frac{1}{2}\right) \sum_{\lambda_1,\lambda_2} f_{\lambda_1\lambda_2} \sum_m f_m \left(d^J_{m,\lambda_1-\lambda_2}(\theta^*)\right)^2$$

- Note: if $f_m = \frac{1}{J}$ $\Rightarrow$ $\cos\theta^*$ flat $\Rightarrow$ cannot determine spin

  requires f_m fine-tuning (breaks if vary LHC energy, sample Y_X,..)

Examples



- if $X \to \gamma\gamma$ found and $\cos\theta^*$ is flat

  (?) spin-0 Higgs $\Leftarrow$ spin-1 excluded

  (!) spin-2 not excluded

  $\cos\theta^*$ could be flat (but not with min coupling)

$$\frac{16\, d\Gamma}{5\,\Gamma d\cos\theta^*} = (2-2f_{z1}+f_{z2}) - 6(2-4f_{z1}-f_{z2})\cos^2\theta^* + 3(6-10f_{z1}-5f_{z2})\cos^4\theta^*$$
$$+f_{+-}\left\{(2+2f_{z1}-7f_{z2}) + 6(2-6f_{z1}+f_{z2})\cos^2\theta^* - 5(6-10f_{z1}-5f_{z2})\cos^4\theta^*\right\}$$

- if $X \to l^+l^-$ found and $d\Gamma \propto (1+\cos^2\theta^*)$

  (?) spin-1 Z' $\Leftarrow$ spin-0 excluded

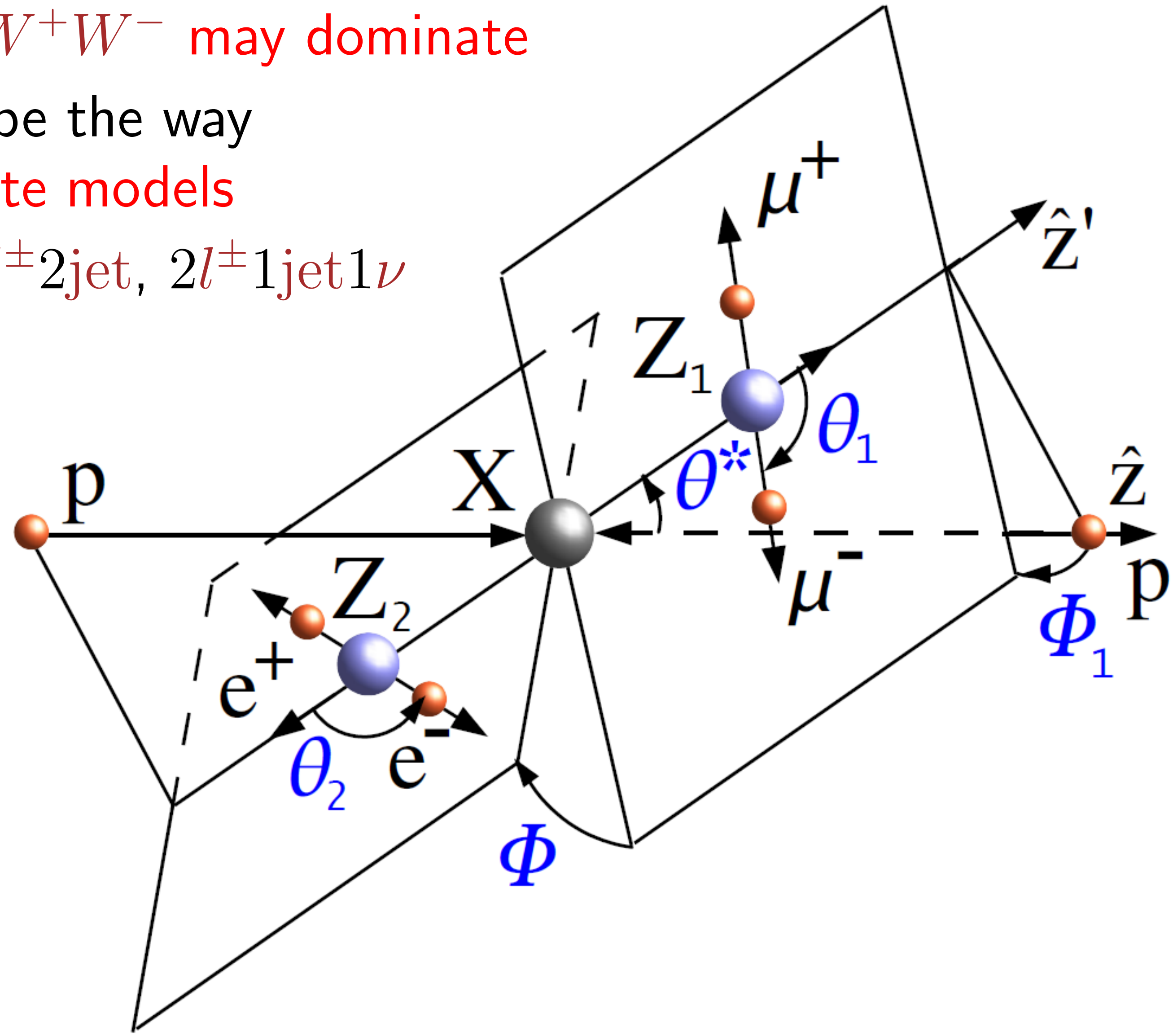
  (!) spin-2 not excluded

  $\cos\theta^*$ could be the same (but not with min coupling):

$$\frac{16\, d\Gamma}{10\,\Gamma d\cos\theta^*} = (f_{z1}+f_{z2}) + 3(2-3f_{z1}-2f_{z2})\cos^2\theta^* - (6-10f_{z1}-5f_{z2})\cos^4\theta^*$$

Kinematics of $X \to ZZ^{(*)}$ and W^+W^-

- Full information production & decay angles ⇒ multivariate analysis
  - $X \to ZZ^{(*)}$ & W^+W^- may dominate
  - if not, may still be the way to differentiate models
  - full reco: $4l^\pm$, $2l^\pm 2\mathrm{jet}$, $2l^\pm 1\mathrm{jet} 1\nu$



Decay $X \rightarrow ZZ$

- Experimental goal: measure all polarizations (both $\hat{z}$ and $\hat{z}'$)

  symmetry in $X \rightarrow ZZ$: $A_{\lambda_1\lambda_2}$=(-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)

A_{00}

A_{++}

A_{--}

$J = 0$ or 2

$J_{z'} = 0$

A_{+0}=(-1)$^J A_{0+}$

A_{0-}=(-1)$^J A_{-0}$

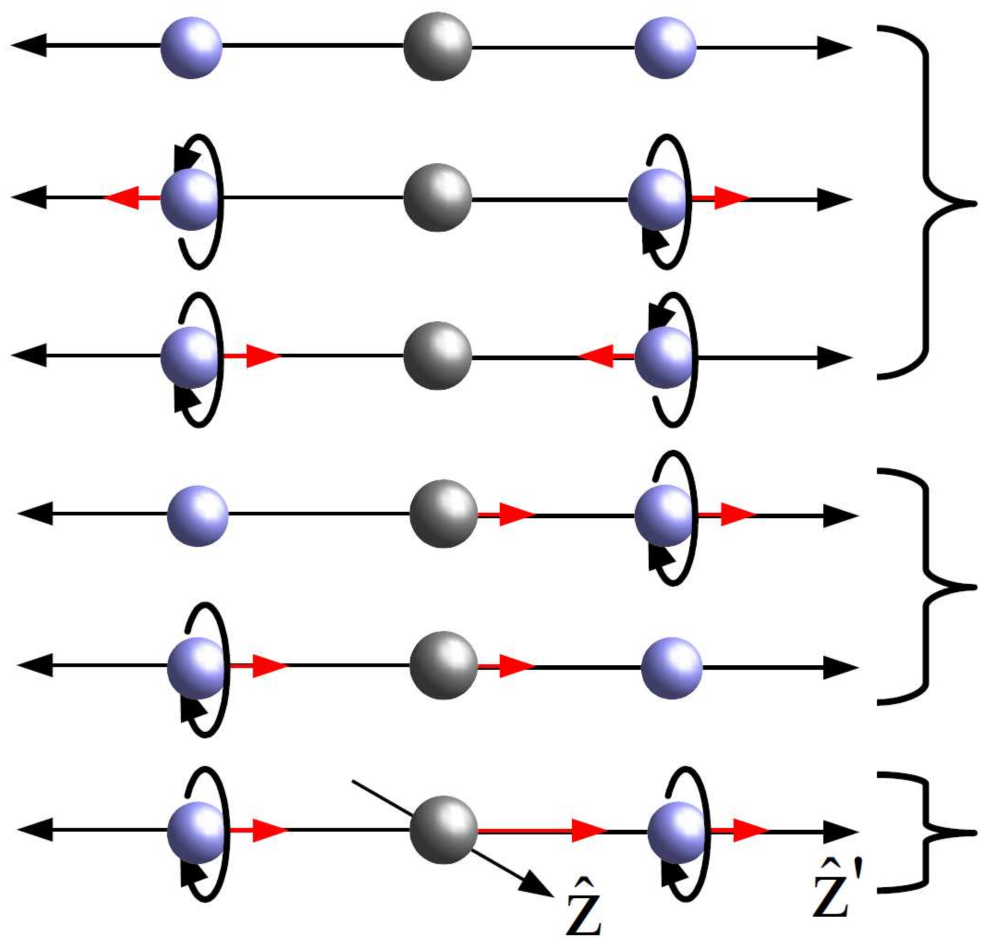
$J = 1$ or 2

$|J_{z'}| = 1$

A_{+-}=(-1)$^J A_{-+}$

$J = 2$

$|J_{z'}| = 2$



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

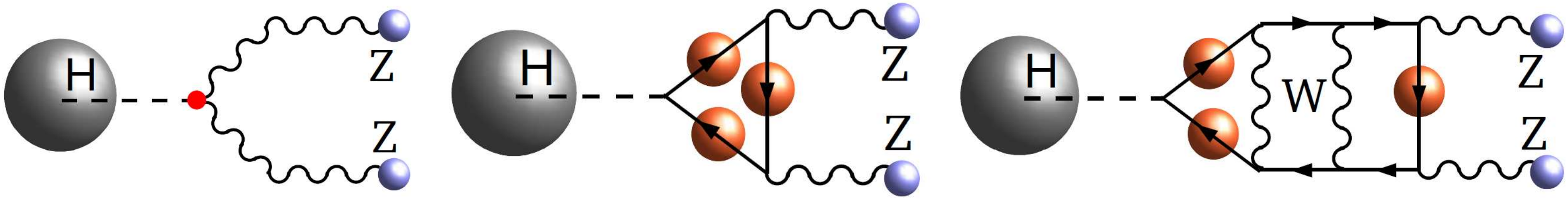
Connect “theory” and “experiment”

Amplitude for Spin-0

- Amplitude for $X_{J=0} \to V_1 V_2$ (compare $B \to V_1 V_2$ PRD45,193(1992))

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

- SM Higgs 0^+: (a_1) CP $\sim$few% (a_2) CP $\sim 10^{-10}$? (a_3) $\not{CP}$



(or beyond SM) (or beyond SM)

- 3 amplitudes ("experiment") $\Leftrightarrow$ 3 coupling constants ("theory")

$$A_{00} = -\frac{M_X^2}{v}\left(a_1 x + a_2 \frac{M_{V_1} M_{V_2}}{M_X^2} (x^2 - 1) \right)$$

$$A_{\pm\pm} = +\frac{M_X^2}{v}\left(a_1 \pm i a_3 \frac{M_{V_1} M_{V_2}}{M_X^2} \sqrt{x^2 - 1} \right)$$

$$\Leftarrow \quad x = \frac{M_X^2 - M_{V_1}^2 - M_{V_2}^2}{2 M_{V_1} M_{V_2}}$$

- Below threshold $Z_1 Z_2^*$: $M_{Z_2} < M_{Z_1}$, but generally $a_i(M_{Z_2})$

Higgs Examples

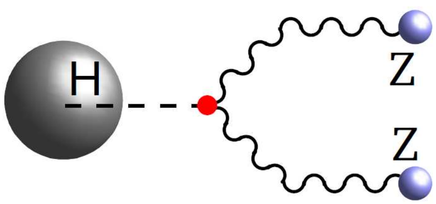
- For a general spin-0 $H \to V_1 V_2$, define 4 real parameters:

$$f_{\pm\pm} = \frac{|A_{\pm\pm}|^2}{\sum |A_{\lambda_1\lambda_2}|^2}; \quad \phi_{\pm\pm} = \arg\left(\frac{A_{\pm\pm}}{A_{00}}\right)$$

note: for $H \to \gamma\gamma, Z\gamma$, gg: $A_{00} \equiv 0 \Rightarrow$ 2 parameters

A_{++} & A_{--} $\Leftrightarrow$ a_3 & $a_1 \equiv -a_2/2$, but cannot measure (except $Z\gamma$)

- Assume tree-level SM Higgs decay ($J^P = 0^+$), both ZZ and W^+W^-



$$a_2 = a_3 = 0 \quad \Rightarrow \quad A_{++} = A_{--} = -A_{00} \times \frac{1-\beta^2}{1+\beta^2}$$

A_{00} dominates for $M_X \gg M_Z$ (or $\beta \to 1$)

at $m_H = 250$ GeV: $f_{++} = f_{--} = 0.104$; $\phi_{++} = \phi_{--} = \pi$

- Pseudoscalar Higgs $A \to ZZ$ or WW ($J^P = 0^-$): $a_3 \neq 0$

$$f_{++} = f_{--} = 0.500, \ (\phi_{++} - \phi_{--}) = \pi$$

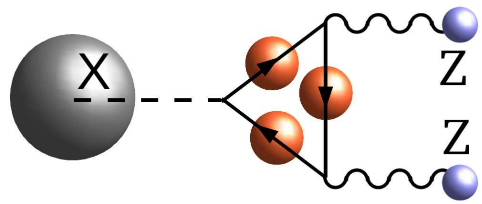
Amplitude for Spin-1

- Most general amplitude for $X_{J=1} \to ZZ$

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

1^- CP, 1^+ $\not{CP}$ (first term); 1^- $\not{CP}$, 1^+ CP (second term)

Example:



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

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

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

(compare $Z' \to ZZ$ by C.P.Buszello et al., Eur.Phys.J.C32,209(2004)
W.Y.Keung, I.Low, J.Shu, PRL101,091802(2008)
but consider b_1 and b_2 generally complex and use all angles, see later)

Amplitude for Spin-2

$$A = \frac{e_1^{*\mu}\, e_2^{*\nu}}{\Lambda}\Big[c_1\, t_{\mu\nu}(q_1 q_2) + c_2\, g_{\mu\nu} t_{\alpha\beta}(q_1-q_2)^\alpha (q_1-q_2)^\beta$$

2^+ CP
2^- $\not{CP}$

$$+\frac{c_3\, t_{\alpha\beta}}{M_X^2} q_{2\mu} q_{1\nu}(q_1-q_2)^\alpha(q_1-q_2)^\beta + 2c_4\left(t_{\mu\alpha} q_{1\nu} q_2^\alpha + t_{\nu\alpha} q_{2\mu} q_1^\alpha\right)$$

$$+\frac{c_5 t_{\alpha\beta}}{M_X^2}(q_1-q_2)^\alpha(q_1-q_2)^\beta \epsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma + c_6 t^{\alpha\beta}(q_1-q_2)_\beta \epsilon_{\mu\nu\alpha\rho} q^\rho$$

2^+ $\not{CP}$
2^- CP

$$+\frac{c_7 t^{\alpha\beta}}{M_X^2}(q_1-q_2)_\beta\left(\epsilon_{\alpha\mu\rho\sigma} q^\rho (q_1-q_2)^\sigma q_\nu + \epsilon_{\alpha\nu\rho\sigma} q^\rho (q_1-q_2)^\sigma q_\mu\right)\Big]$$

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

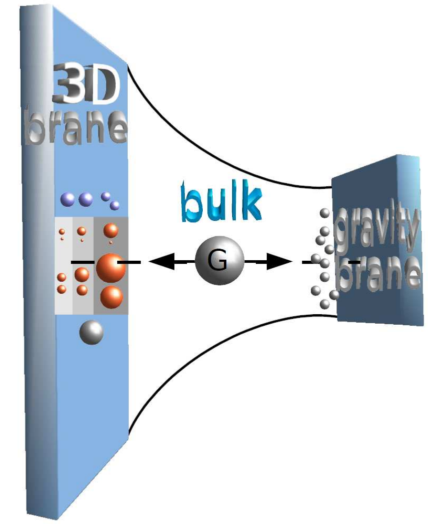
$$A_{00} = \frac{M_X^4}{M_V^2\sqrt{6}\Lambda}\left[\left(1+\beta^2\right)\left(\frac{c_1}{8} - \frac{c_2}{2}\beta^2\right) - \beta^2\left(\frac{c_3}{2}\beta^2 - c_4\right)\right]$$

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

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

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

Note about Graviton couplings



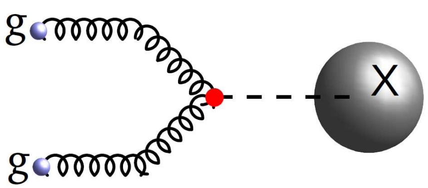
- Minimal $G_{\rm RS}$ coupling:

$$A \propto \frac{1}{\Lambda} t_{\mu\nu} \mathcal{T}^{\mu\nu}$$

$\rightarrow$ energy-mom tensor $\rightarrow$ SM field-strength tensor

$$\mathcal{T}_{\mu\nu} = F^{*(1)}_{\mu\alpha} F^{*(2)}_{\nu\beta}\, g^{\alpha\beta} + m_V^2 \epsilon_1^{*\mu} \epsilon_2^{*\nu} \;\&\; F^{(i)\mu\nu} = \epsilon_i^\mu q_i^\nu - \epsilon_i^\nu q_i^\mu$$

- Consequence: $c_2 = \frac{c_4}{2} \simeq -\frac{c_1}{4}$ (as $\beta \to 1$) $\Rightarrow A_{+-} \& A_{-+}$ dominate



$\Rightarrow$ gg$\rightarrow X$ only $J_z = \pm 2$ $\Rightarrow f_{z0} = 0 \Rightarrow$ polarized X

$X \to ZZ$ at $m_G = 250$ GeV: $f_{+-} + f_{-+} = 0.56,\ f_{00} = 0.11$

at $m_G = 1000$ GeV: $f_{+-} + f_{-+} = 0.89,\ f_{00} = 0.11$

- Non-minimal coupling (e.g. SM in the bulk)

generally $A_{00} \propto \frac{M_X^4}{M_V^2 \Lambda}$ dominates, $f_{00} \to 1.0$ for large M_X

- Notation later: 2^+_m minimal G; 2^+_L longitudinal, like Higgs (!)

Coupling to fermions

- For completeness $X \to q\bar{q}$, also to describe $q\bar{q} \to X$:

$$A_{J=0} = \frac{m_q}{v} \bar{u}_{q_1} \left(\rho_3^{(0)} + \rho_4^{(0)} \gamma_5 \right) v_{q_2}$$

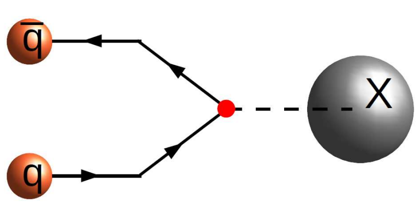
$$A_{J=2} = \frac{1}{\Lambda} t^{\mu\nu} \bar{u}_{q_1} \left(\gamma_\mu \Delta q_\nu \left(\rho_1 + \rho_2 \gamma_5 \right) + \frac{m_q}{\Lambda^2} \Delta q_\mu \Delta q_\nu \left(\rho_3 + \rho_4 \gamma_5 \right) \right) v_{q_2}$$

- 4 amplitudes (“experiment”) $\Leftrightarrow$ 4 coupling constants (“theory”)

$$A_{\pm\pm} = \frac{2\sqrt{2}\, m_q M_X \beta}{\sqrt{3}\Lambda} \left(\pm\rho_1 + \frac{\beta M_X^2}{2\Lambda^2} \left(\rho_4 \mp \rho_3 \beta \right) \right)$$

$$A_{\pm\mp} = \frac{M_X^2 \beta}{\Lambda} \left(\mp\rho_1 - \beta \rho_2 \right)$$

- Consequence of m_q (chiral symmetry)



$\Rightarrow A_{++} = A_{--} = 0$ at $m_q \to 0$

$\Rightarrow A_{\uparrow\downarrow}$, $A_{\uparrow\downarrow} \Rightarrow J_z = \pm 1$ in $q\bar{q} \to X$

How to measure polarization

How to Measure Polarization

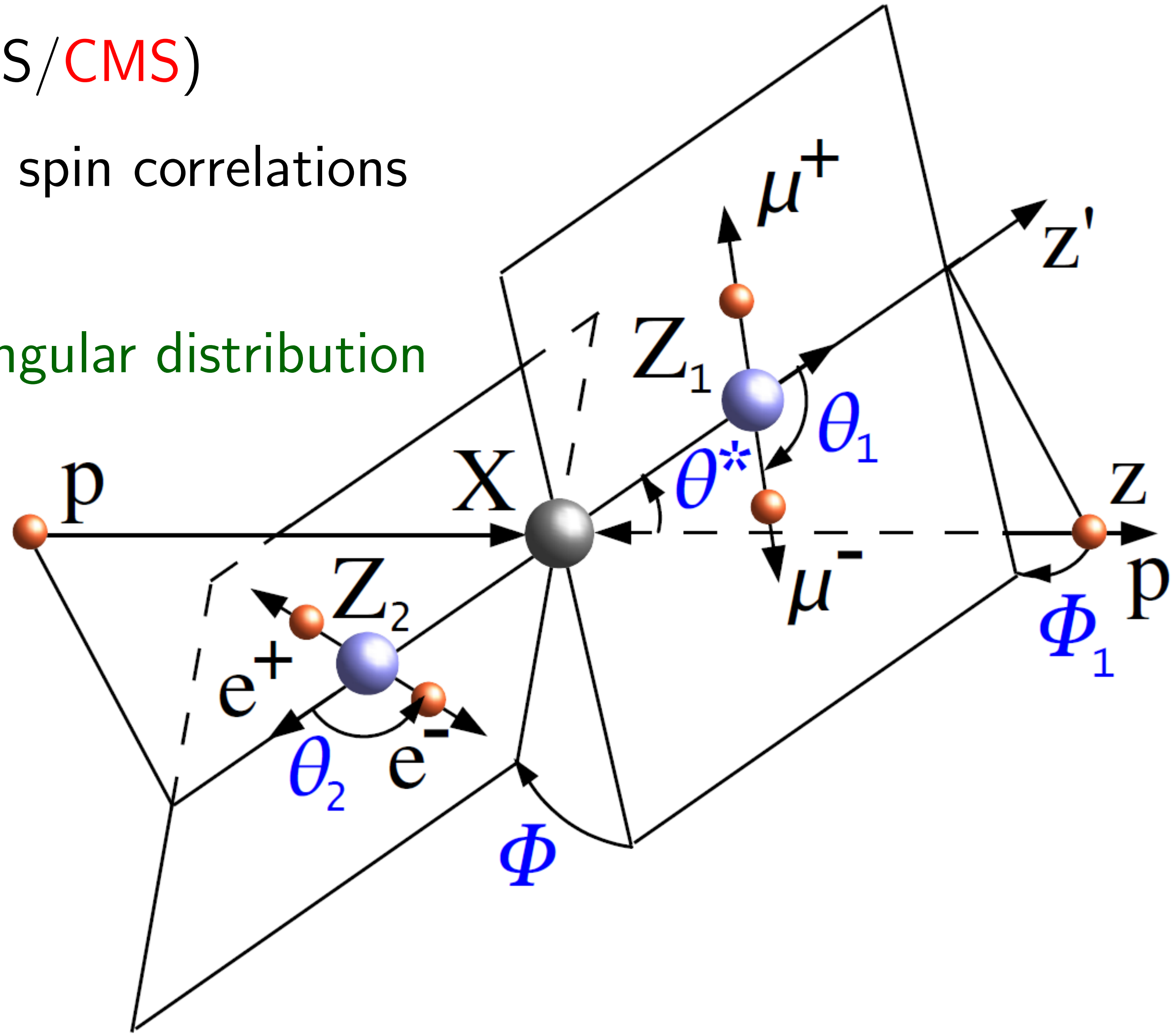
- Deduce all $A_{\lambda_1\lambda_2}$ from angular distributions for any J, but need:

  (1) detector (ATLAS/CMS)

  (2) full MC with all spin correlations
  (none before)

  (3) full analytical angular distribution
  (none before)

  (4) likelihood fit
  (learn from B's)

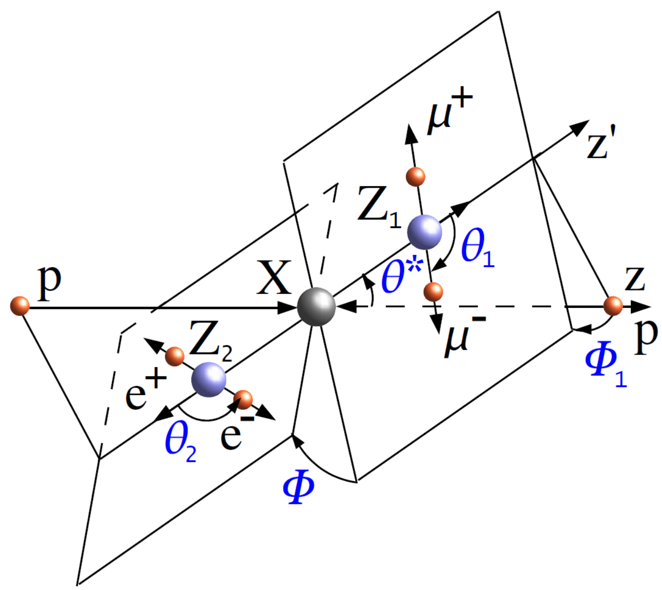


Monte Carlo Simulation

- MC program, open access: http://www.pha.jhu.edu/spin/
  - complete kinematic chain (BW) $ab \to X \to ZZ \to (f_1\bar{f}_1)(f_2\bar{f}_2)$
  - calculate matrix element $|M|^2$ (narrow-width approximation)
  - weigh or accept/discard events
- Important features:
  - most general couplings for $J = 0, 1, 2$

    e.g. Higgs radiative corrections

    e.g. non-minimal G couplings, $Z' \to ZZ$
  - any angular distribution from QM
  - interface to detector simulation (Pythia)

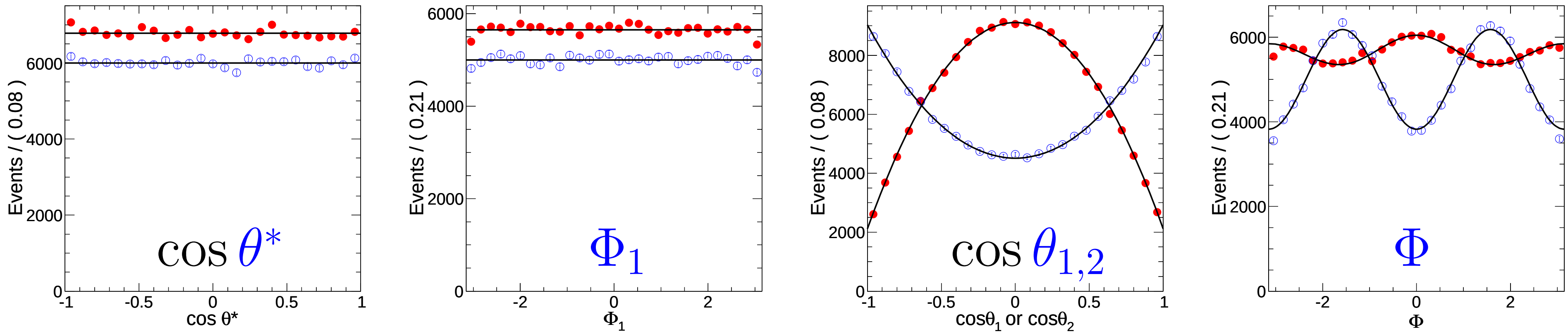


- Background
  - MadGraph: $q\bar{q} \to ZZ$ (gg$\to ZZ \sim 15\%$)
  - others negligible: $Zb\bar{b}$, $t\bar{t}$, $W^+W^-b\bar{b}$, WWZ, $t\bar{t}Z$, $4b$

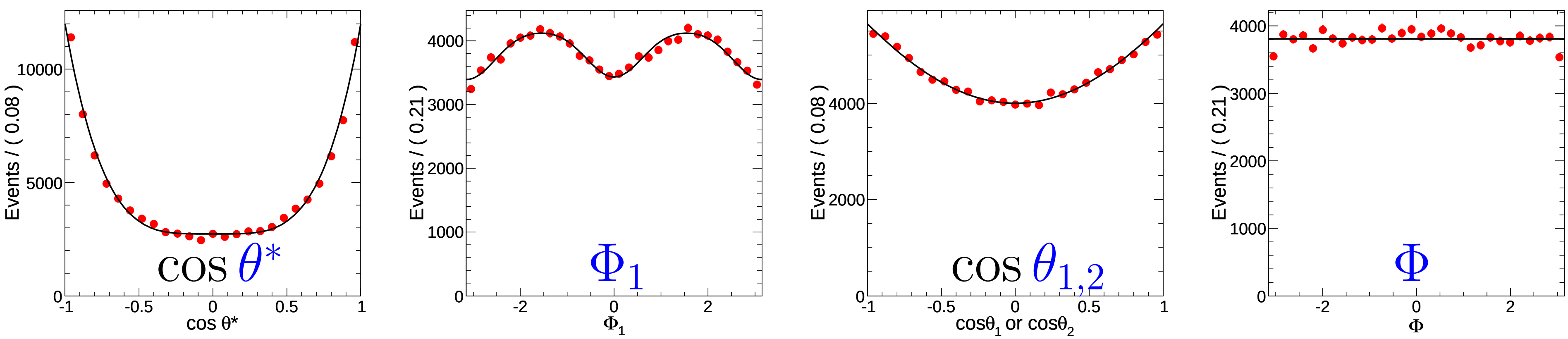
    $l^\pm$ isolation, $4l$ vertex, $2l$ mass, (no missing energy)...

Simulation Examples

- Higgs 0^+ (SM tree-level, a_1) and 0^- (a_3) at $m_H = 250$ GeV
  - lines from derived distributions (independent, next slides)



- Background $q\bar{q} \to ZZ$
  - lines empirical shape



Angular Distributions

- Connect amplitudes and angular distributions
  for any $J = 0, 1, 2, 3, 4, \ldots$ (to cover any "hidden glueball" etc...)

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

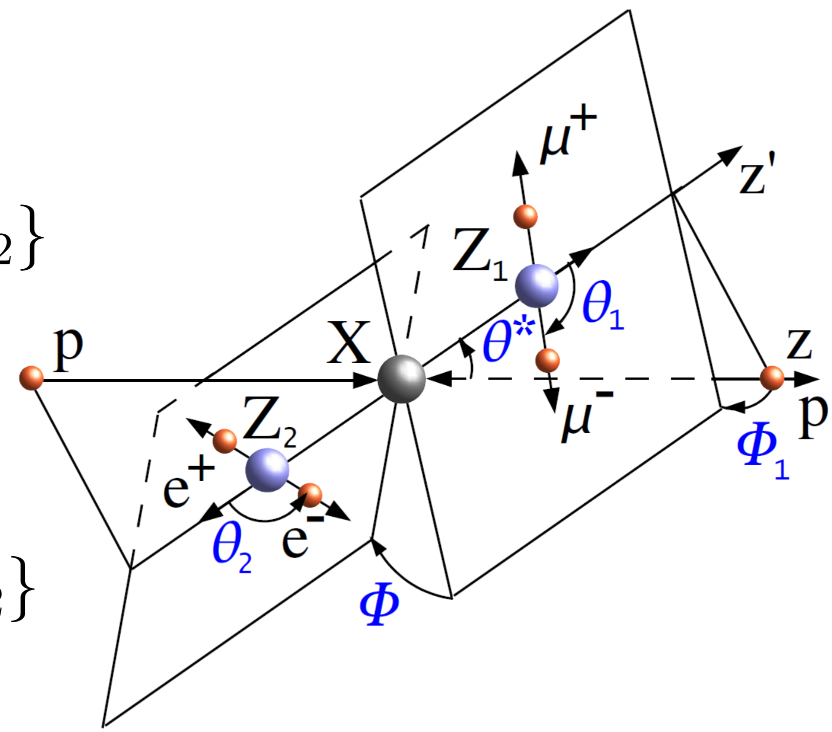
$$d\sigma \propto \sum_{\chi,\mu,\tau} \big| \sum_{\lambda,m} A_{ab}(\{\Omega\}) \big|^2$$

$ab \to X, \quad \Omega^* = (\Phi_1, \theta^*, -\Phi_1),\ \{\chi_1\chi_2\}$

$X \to Z_1 Z_2^{(*)},\ \Omega = (0,0,0),\ \{\lambda_1\lambda_2\}$

$Z_1 \to f_1\bar{f}_1,\ \Omega_1 = (0,\theta_1,0),\ \{\mu_1,\mu_2\}$

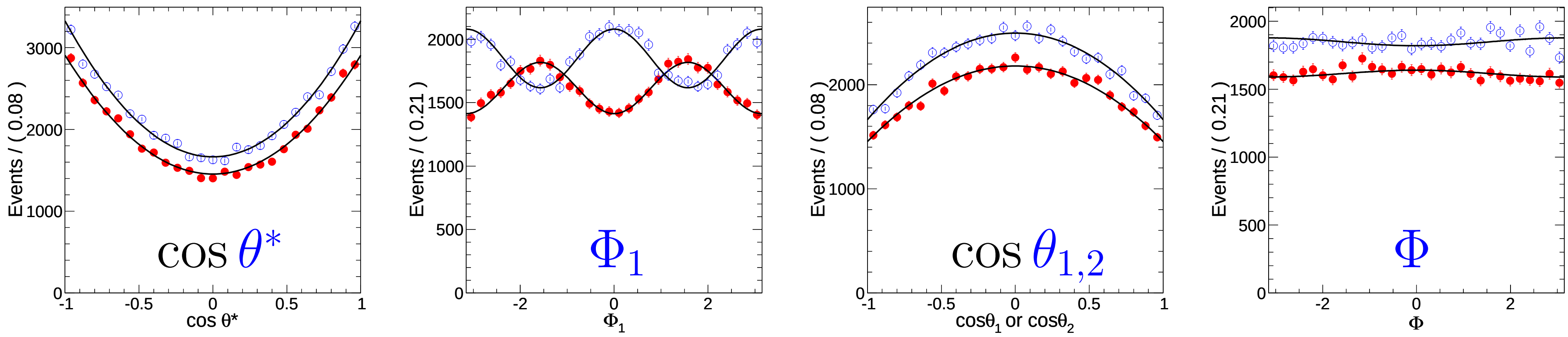
$Z_2^{(*)} \to f_2\bar{f}_2,\ \Omega_2 = (\Phi,\theta_2,-\Phi),\ \{\tau_1,\tau_2\}$



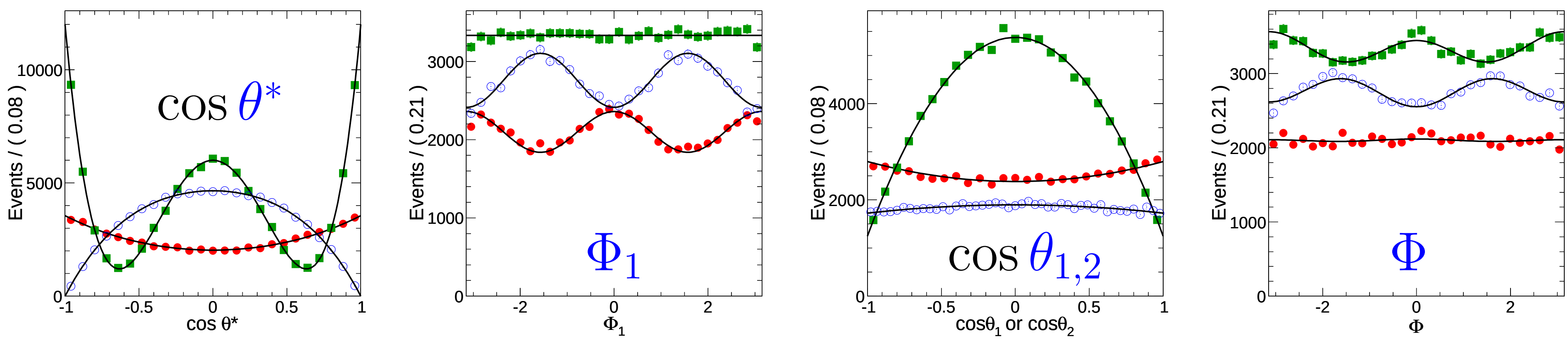
$r = c_A/c_V \Rightarrow R_{1,2} = 2r_{1,2}/(1 + {r_{1,2}}^2)$=0.15 ($l^{\pm}$), 0.67 ($u$), 0.94 ($d$)

More Distribution Examples

- Vector 1^- (b_1) and 1^+ (b_2) at $m_H = 250$ GeV
  – lines from derived distributions, points from MC



- G 2^+_m (minimal), 2^+_L (Higgs-like), and 2^- ($c_{5,6}$) at $m_H = 250$ GeV



Explicit Distributions for any J

- $d\Gamma(ab \to X_J \to Z_1 Z_2^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)) \propto$

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

spin $=0$ & ≥ 2

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

spin $=1$ & ≥ 2

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

spin ≥ 2 unique

$+$ other 26 interference terms for spin ≥ 2

where $\Psi = \Phi_1 + \Phi/2$ and $F^J_{ij}(\theta^*) = \sum_{m=0,\pm1,\pm2} f_m\, d^J_{mi}(\theta^*) d^J_{mj}(\theta^*)$

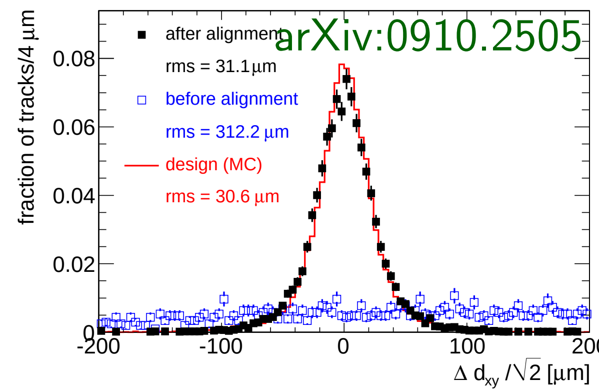
Detector Effects

- Detector effects shape angular distributions (CMS as a reference):

  (1) track parameter resolution

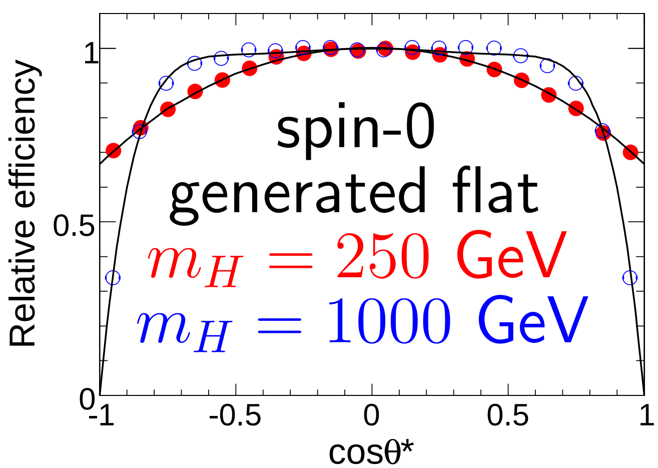
  $\Rightarrow \pm 0.01$ rad angles

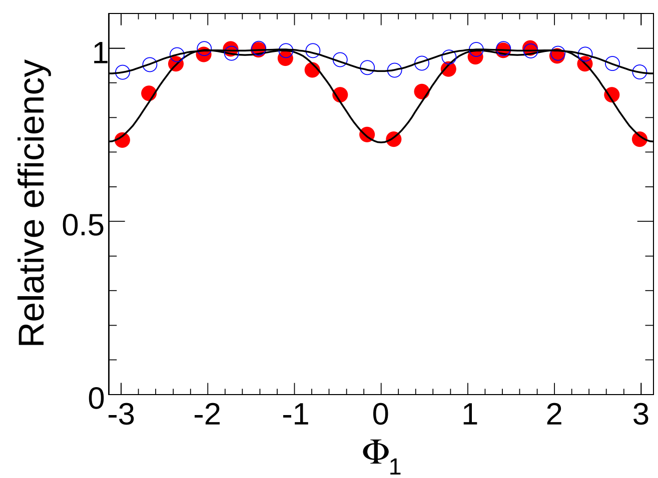
  ± 3.5 GeV mass at 250 GeV



  (2) loss of tracks at $\theta_{\rm lab} < \theta_{\rm min}$ ($\eta_{\rm max} = 2.5$)

  (along the beampipe)





  – major effect to account for in analysis

  acceptance function $\mathcal{G}(\Phi_1, \theta^*, \theta_1, \theta_2, \Phi; Y_X)$

- Fast MC: reject tracks and smear track parameters

Data Analysis (shown with MC)

Analysis Goals

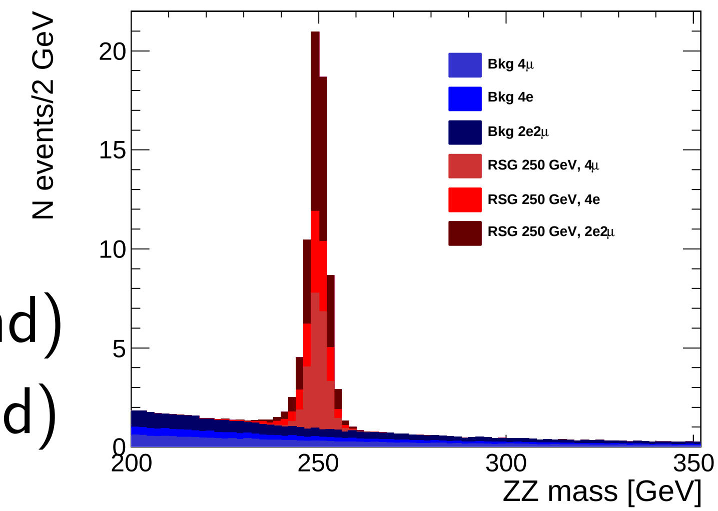
- Analysis depends on how we ask the question:

(0) hypothesis h1 fit self-consistency, goodness-of-fit, χ^2 test, etc...

(1) compare hypotheses h1 and h2: confidence in one vs the other

example (A): h1: signal + background
h2: only background

example (B): h1: signal 0^+ (+ background)
h2: signal 0^- (+ background)



(2) determine all parameters at once (ultimately the best one can do)

yield, mass, width

spin (J)

coupling constants (amplitudes $A_{\lambda_1\lambda_2}$)

production mechanism (initial polarization f_{zm})

Multivariate Maximum Likelihood Fit

- Maximize likelihood $\mathcal{L}$ (RooFit/MINUIT, from $B \to VV$):
  (BaBar PRD78,092008(2008))

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

$\vec{\zeta}_J = (f_{\lambda_1\lambda_2}, \phi_{\lambda_1\lambda_2}, f_{zm};\ \ m_X, \Gamma_X)$, float n_J, fix or float m_X, Γ_X

$\vec{x}_i = (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi;\ \ m_{ZZ}, ..)$

- Probability $\mathcal{P}$: (a) template (fixed multi-D histogram)

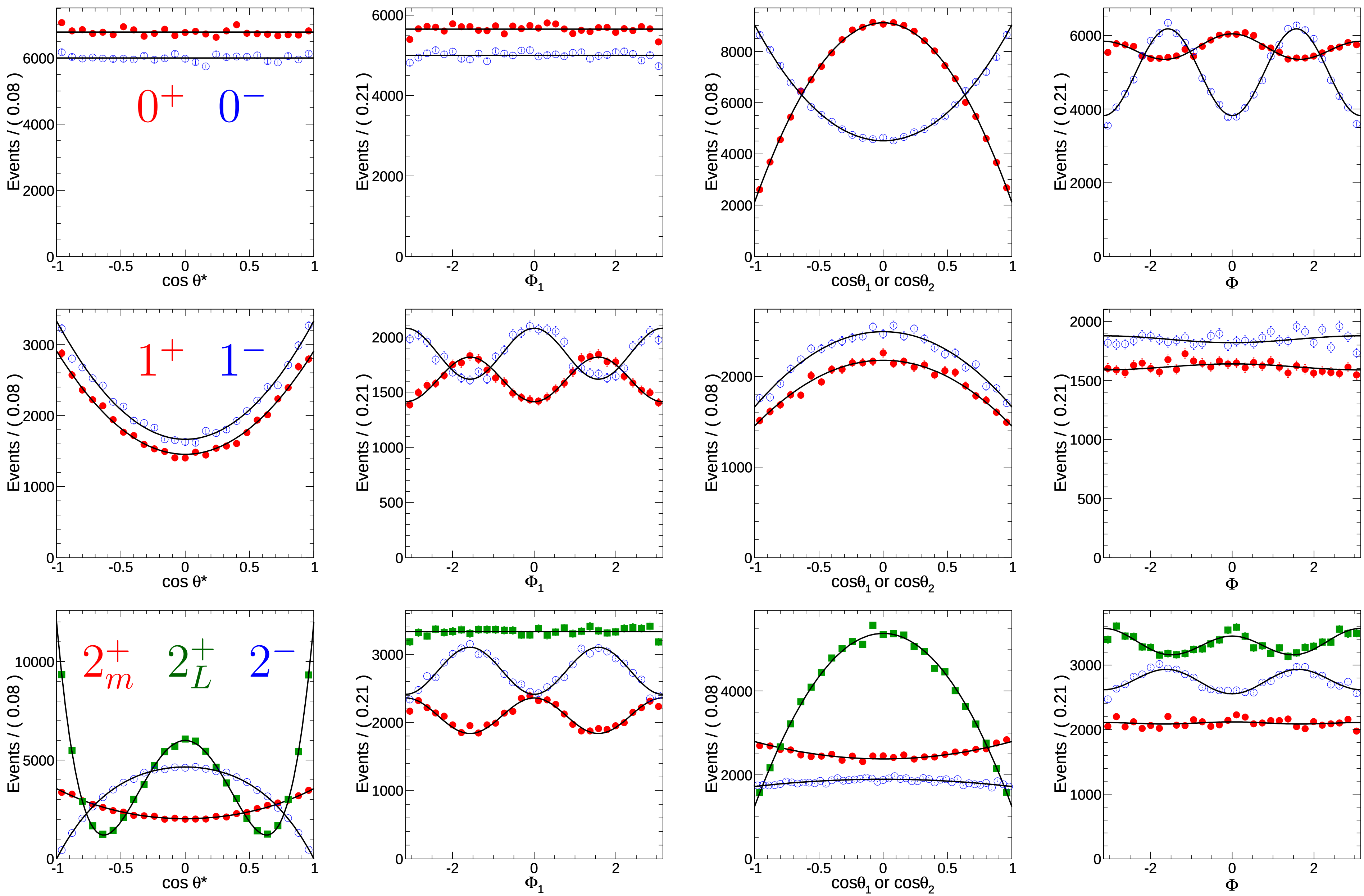
  (b) $\mathcal{P}_J = \mathcal{P}(m_{ZZ}, ...) \times \mathcal{P}_{\rm ideal}(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi) \times \mathcal{G}(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi; Y_X)$

- Our choice (b) $\Leftarrow$ both approaches (1) and (2) possible:

  (1) compare $\mathcal{L}_1$ vs $\mathcal{L}_2$ with parameters fixed $(f_{\lambda_1\lambda_2}, \phi_{\lambda_1\lambda_2}, f_{zm})$

  (2) fit for all parameters $(f_{\lambda_1\lambda_2}, \phi_{\lambda_1\lambda_2}, f_{zm})$

Distribution Examples (θ^*, Φ_1, θ_1, θ_2, Φ)

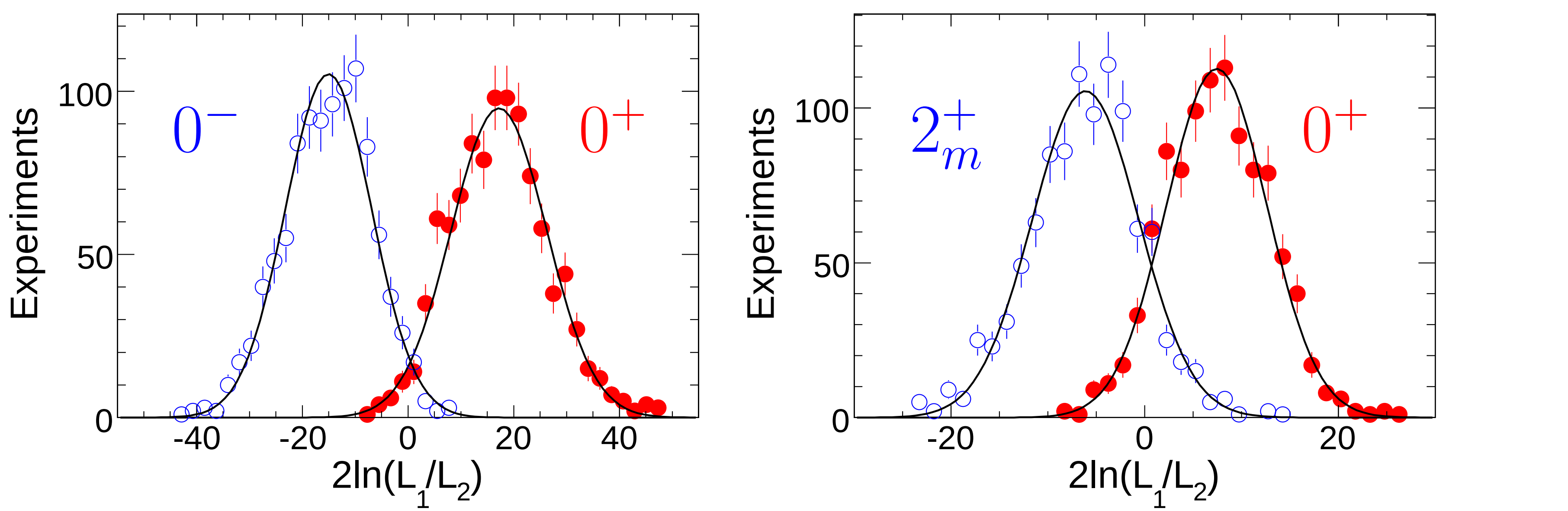


$\cos\theta^*$ Φ_1 $\cos\theta_{1,2}$ Φ

Analysis Approach (1)

- Pick a test scenario with Higgs $m_X = 250$ GeV
  - signal soon after discovery $\Rightarrow$ 30 events (SM Higgs rate)
  - 24 background ($m_{ZZ} = 250 \pm 20$ GeV, $\mathcal{L} = 5$/fb, $E_{pp} = 14$ TeV)
  - significance 5.7σ signal/background; $\sim 20\%$ gain with angles
- Generate experiments 1000 times
  - plot $2\ln(\mathcal{L}_1/\mathcal{L}_2)$ for h1 and h2
  - $\mathcal{S}$ effective separation of peaks (Gaussian σ)

$\mathcal{S} = 4.1\sigma$ $\mathcal{S} = 2.8\sigma$



Analysis Approach (1): Results

- Example of separation at $m_X = 250$ GeV (similar at 1000 GeV)

  $\longrightarrow$ with 30 events ~ 2 - 4σ separation

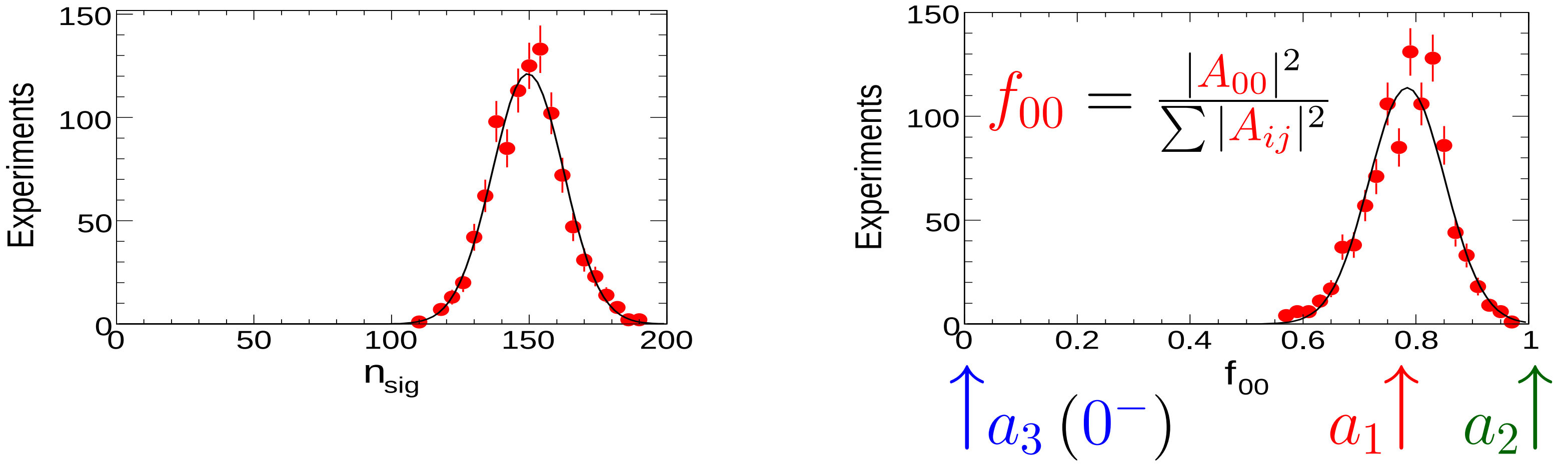
  $\longrightarrow$ full event info (production+decay) $\Rightarrow$ ultimate precision

  1D (θ^*) / 3D (θ_1, θ_2, Φ) / 5D ($\Phi_1, \theta^*, \theta_1, \theta_2, \Phi$)

	0^-	1^+	1^-	2^+_m	2^+_L	2^-
0^+	0.0/3.9/4.1	0.8/1.8/2.3	0.9/2.5/2.6	0.8/2.4/2.8	2.6/0.0/2.6	1.6/2.4/3.3
0^-	–	0.8/2.8/3.1	0.9/2.5/3.0	0.8/1.7/2.4	2.9/4.1/4.8	1.6/2.0/2.9
1^+	–	–	0.0/1.1/2.2	0.1/1.3/2.6	2.8/1.9/3.6	2.5/1.2/2.9
1^-	–	–	–	0.1/1.3/1.8	2.8/2.5/3.8	2.5/0.6/3.4
2^+_m	–	–	–	–	2.9/2.6/3.8	2.3/0.5/3.2
2^+_L	–	–	–	–	–	3.6/2.5/4.3

Analysis Approach (2)

- More general approach: fit all parameters (spin-0: Higgs 250 GeV)
  - $\times 5$ more events (150 signal & 120 background)



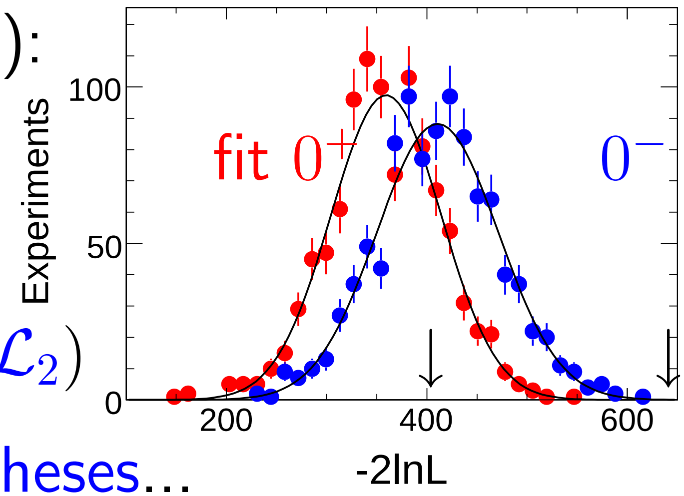
	generated	w/o detector	with detector
$n_{\rm sig}$	150	150 ± 13	153 ± 15
f_{00}	0.792	0.79 ± 0.07	0.77 ± 0.08
$(f_{++} - f_{--})/2$	0.000	0.00 ± 0.07	0.01 ± 0.07
$(\phi_{++} + \phi_{--})/2$	π	3.15 ± 0.73	3.20 ± 0.77
$(\phi_{++} - \phi_{--})/2$	0	0.00 ± 0.53	0.01 ± 0.55

- Tested all 7 hypotheses at $m_X = 250$ and 1000 GeV

Higgs or not Higgs?

- Three steps in analysis (include mass, yield):

  (1) hypothesis h1 fit self-consistency $\longrightarrow$
  $"\chi^2" = -2\ln(\mathcal{L}_1)$ from background & signal



  (2) compare hyp. h1 and h2 with $2\ln(\mathcal{L}_1/\mathcal{L}_2)$

  ($>$2) determine all parameters for all hypotheses...

- If found resonance is not truly SM Higgs
  and parameters are rather different $\Rightarrow$ exclude SM Higgs
  $\Rightarrow$ quote "range" of allowed hypotheses

- If true SM Higgs is found
  can we exclude all other hypotheses?

  $\Rightarrow$ only very fine-tuned hypotheses cannot be ruled out "easily"
  e.g. unpolarized "graviton" with Higgs-like couplings, rate, width...

  $\Rightarrow$ quote level of consistency and "range" of excluded hypotheses

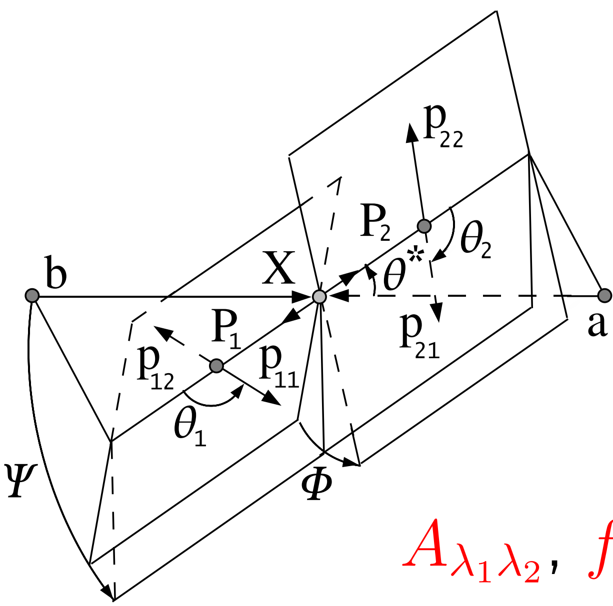
Conclusion

Conclusion

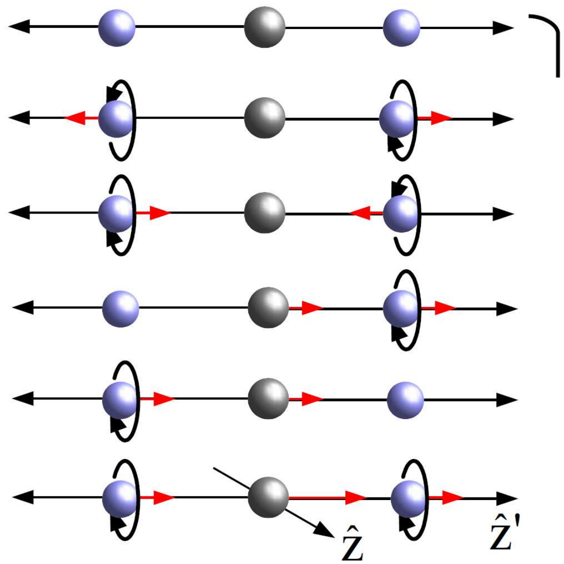
- Resonances at LHC: either within (Higgs) or beyond SM
  - maximum info $\Rightarrow$ spin, quantum numbers, couplings
  - powerful angular technique, example $X_J \to ZZ/WW$

    $\longrightarrow$ combine production and decay angles

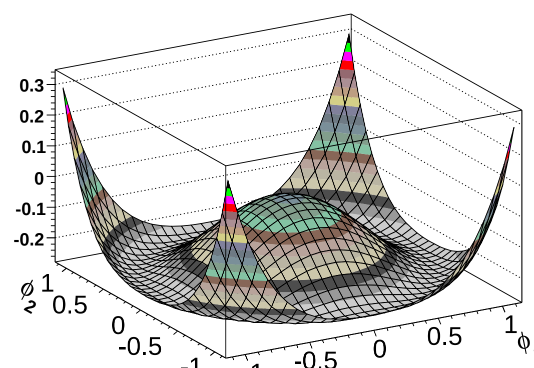
    $\longrightarrow$ MC, angular distributions, ML fit $\longrightarrow$ 3-4σ soon after discovery
  - helicity formalism ("exp.") $\leftrightarrow$ quantum n. & couplings ("theory")
  - model-independent approach (!)



$A_{\lambda_1\lambda_2}$, f_{zm}



J^P, a_1, a_2, a_3,...



BACKUP

$X \to ZZ$ polarization notation

- Polarization notation:

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

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

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

- Amplitude with field strength tensor $F^{\mu\nu}$ (e.g. graviton couplings):

$$A(X_{J=2} \to VV) = \Lambda^{-1}\Big[2g_1^{(2)} t_{\mu\nu} F^{*1,\mu\alpha} F^{*2,\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} F^{*1,\mu\alpha} F^{*2,\nu,\beta}$$

$$+g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (F^{*1,\mu\nu} F^{*2}_{\mu\alpha} + F^{*2,\mu\nu} F^{*1}_{\mu\alpha}) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} F^{*1,\alpha\beta} F^{*(2)}_{\alpha\beta}$$

$$+m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}\right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^*\right)$$

$$+g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} F^{*1,\alpha\beta} \tilde{F}^{*(2)}_{\alpha\beta} + g_9^{(2)} t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma$$

$$+\frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*)\right)\Big]$$