On the Spin and Parity of the New Boson at the LHC

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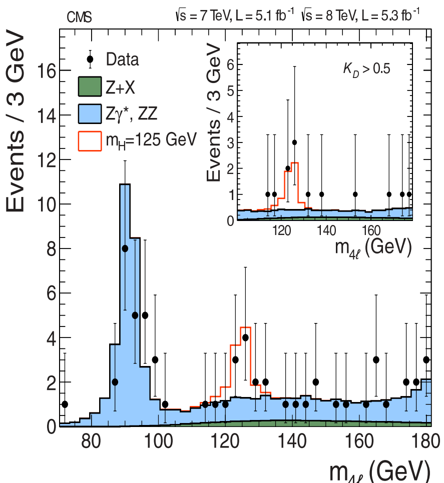
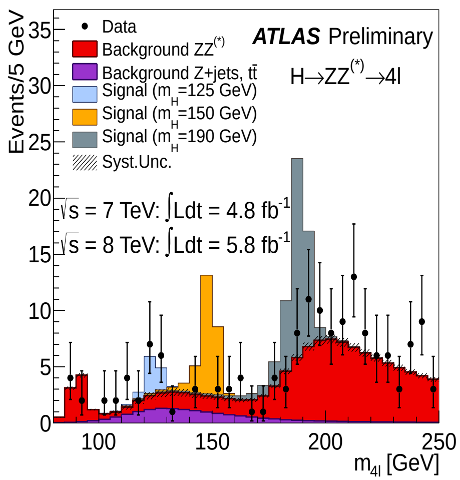
LEPP Journal Club, Cornell University

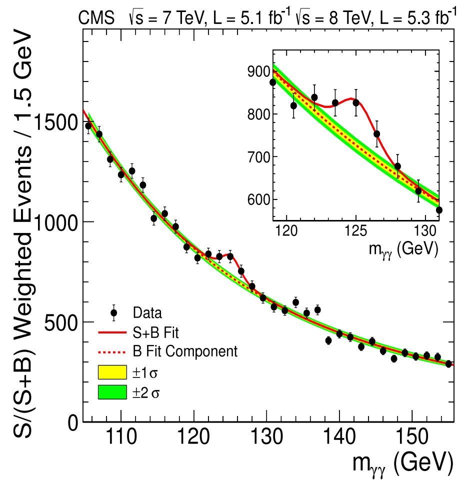
New Boson on LHC

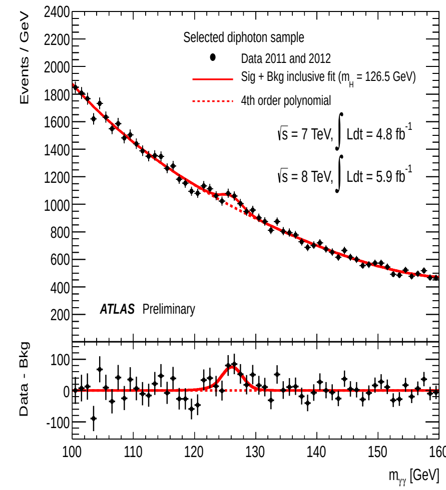
- Observation of a New Boson on CMS and ATLAS

$$X \to Z^{(*)}Z^{(*)} \qquad\qquad X \to \gamma\gamma$$









- What we know:
  - it is a boson, spin$\neq$1 $\Rightarrow$ spin $=$ 0 or 2... (nothing like this before)
  - it couples to vector bosons, consistent with the Higgs boson

- What we do not know:
  - if it is the Higgs boson, if couples to Fermions (matter)
  - expect it to be elementary, if not $\Rightarrow$ may be more interesting...
  - if it is a tip of an iceberg of new exciting states of matter / energy

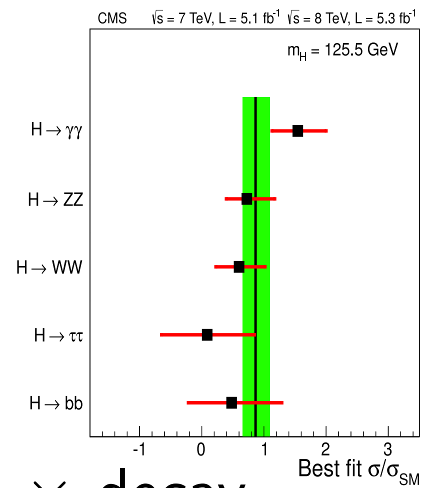
Is it the SM Higgs Boson?

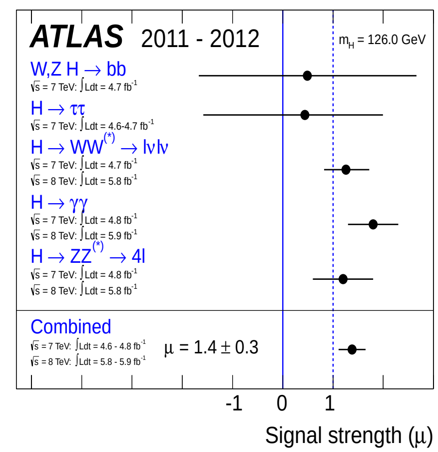
- Study the properties of the New Boson

(1) mass m_X and width Γ_X

$m_X \sim 125.7 \pm 0.5$ GeV

$\Gamma_X \sim$ small (expect 4 MeV)





(2) rates of production and decay

– tension, but consistent with SM

– unfolding the matrix production × decay

(3) structure of the couplings in production and decay

– quantum numbers: spin & parity (SM $J^P = 0^+$); tensor structure

Naively: (1) is the x-scale of the mass plot

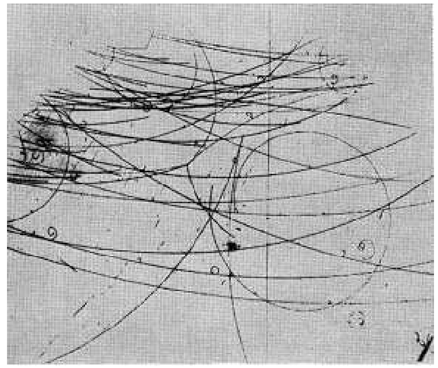
(2) is the y-scale of the mass plot

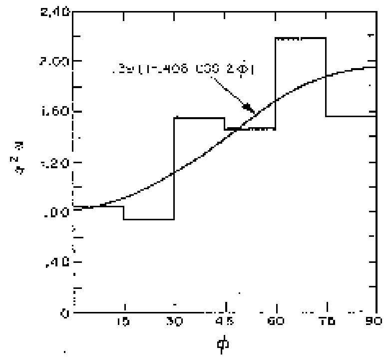
(3) is the other dimension, the focus of this presentation

Some History and Credits

- Study of Parity of $\pi^0 \to \gamma\gamma$ and $\pi^0 \to \gamma^*\gamma^* \to e^+e^-e^+e^- \quad \Rightarrow \quad J^P = 0^-$

  Samios *et al.* (1962)





- A lot of progress over the past 50 years, with application to a Higgs-like boson

J. R. DellAquila *et al.*, Phys. Rev. D **33**, 80 (1986); C. A. Nelson, Phys. Rev. D **37**, 1220 (1988); A. Soni *et al.*, Phys. Rev. D **48**, 5259 (1993); V. Barger *et al.*, Phys. Rev. D **49**, 79 (1994); B. C. Allanach *et al.*, JHEP **0212**, 039 (2002); S. Y. Choi *et al.*, Phys. Lett. B **553**, 61 (2003); C. P. Buszello *et al.*, Eur. Phys. J. C **32**, 209 (2004); R. M. Godbole *et al.*, J. High Energy Phys. **12**, 031 (2007); W. Y. Keung *et al.*, Phys. Rev. Lett. **101**, 091802 (2008); O. Antipin *et al.*, J. High Energy Phys. **10**, 018 (2008); K. Hagiwara *et al.*, J. High Energy Phys. **07**, 101(2009); Q.-H. Cao *et al.*, Phys. Rev. D **81**, 015010 (2010); Y. Gao *et al.*, Phys. Rev. D **81**, 075022 (2010); A. De Rujula *et al.*, Phys. Rev. D **82**, 013003 (2010); C. Englert *et al.*, Phys. Rev. D **82**, 114024 (2010); J. S. Gainer *et al.*, HEP **1111**, 027 (2011); J. Ellis *et al.*, to appear in JHEP, arXiv:1202.6660 [hep-ph], etc...

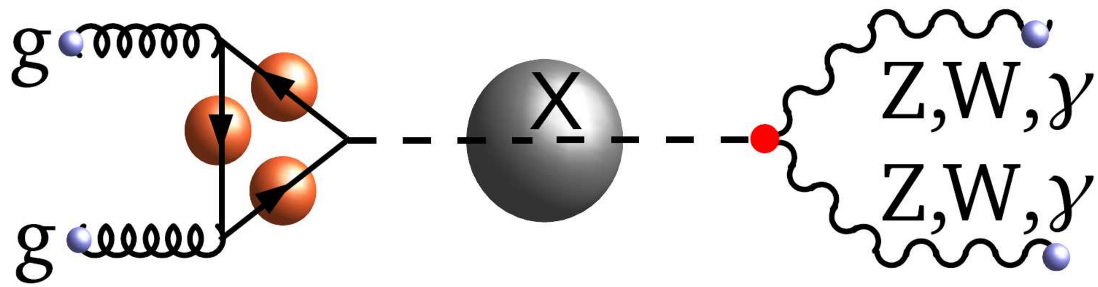
- Discuss "On the spin and parity of a single-produced resonance at the LHC" arXiv:1208.4018 [hep-ph] (Aug. 20, 2012)

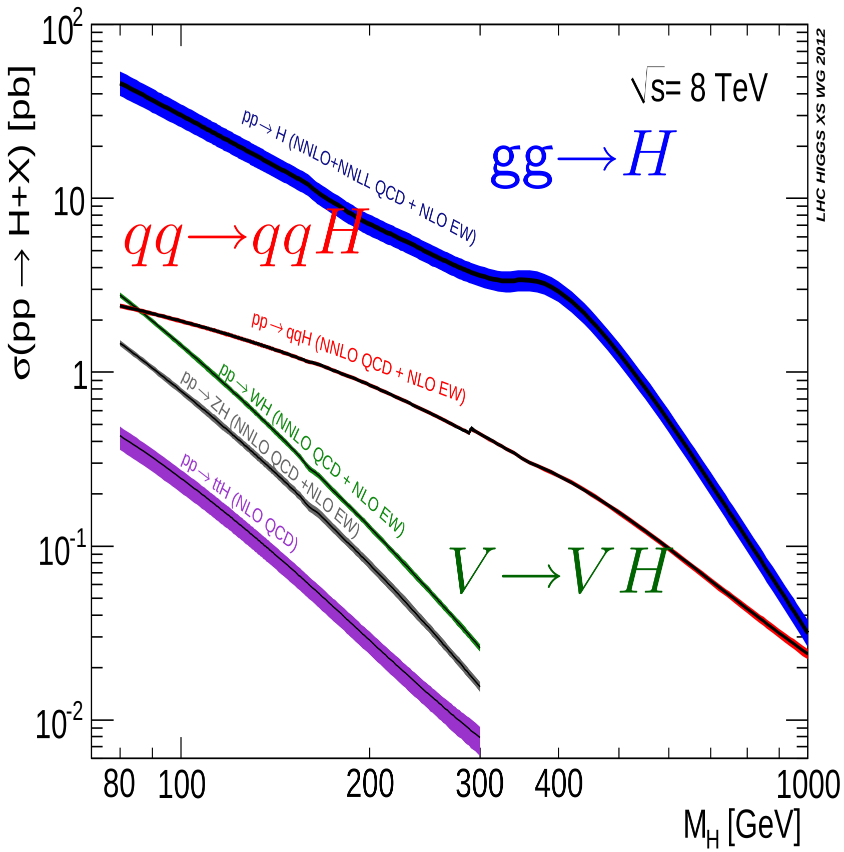
S.Bolognesi[1,4], Y.Gao[2,4], A.G.[1,4], K.Melnikov[1], M.Schulze[3], N.Tran[2,4] A.Whitbeck[1,4],

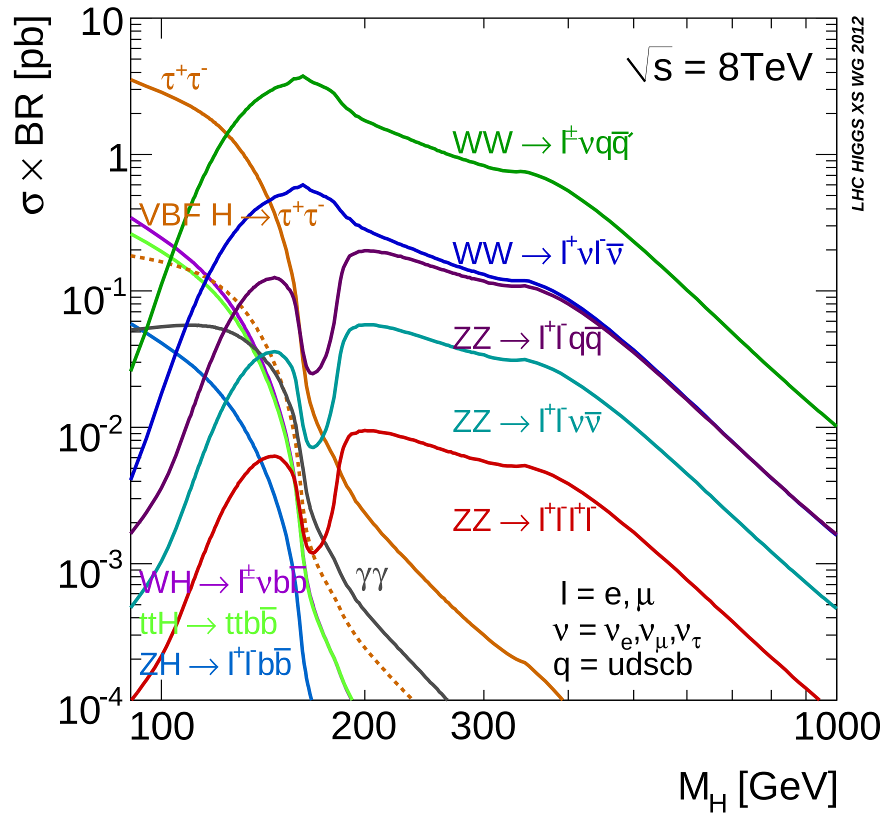
[1] JHU [2] FNAL [3] ANL [4] CMS

The Higgs Boson: Production and Decay

- Excite vacuum: gg,.. $\rightarrow H \rightarrow ZZ^{(*)}, WW^{(*)}, \gamma\gamma, \tau^+\tau^-, b\bar{b}$,..



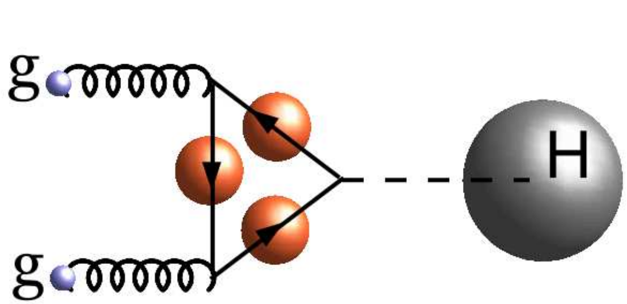




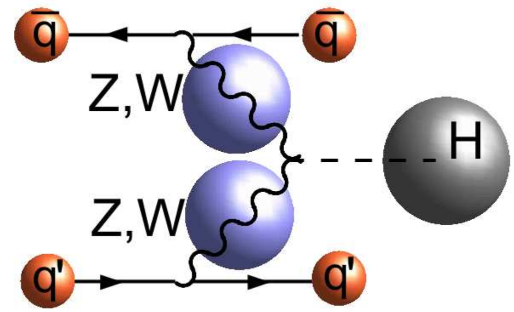
Production Modes and Background

- At LHC gluon fusion expected to dominate (7% VBF...)

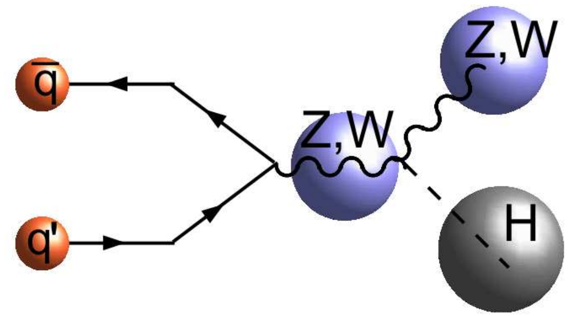
gluon fusion



weak boson fusion

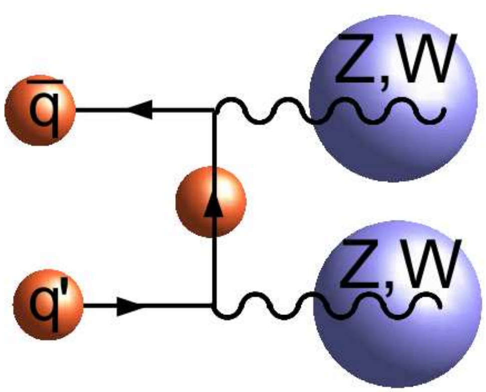


associated production

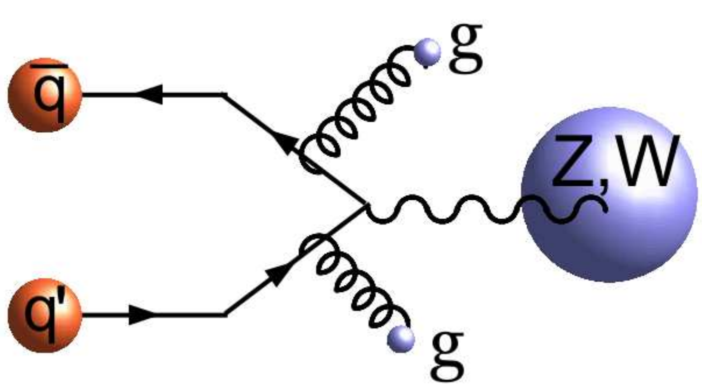


- The challenge is to distinguish signal from backgrounds, examples:

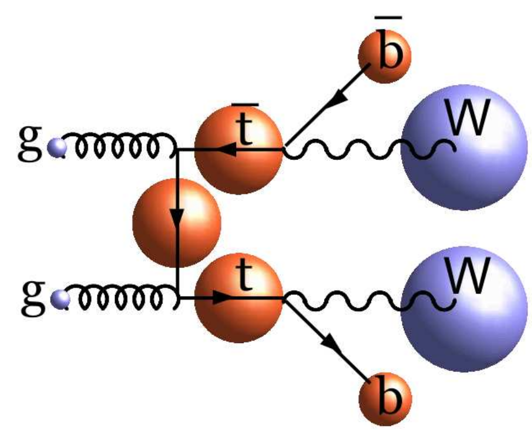
$q\bar{q} \to ZZ^{(*)}(\gamma^{(*)})$



$q\bar{q} \to Z(\gamma)+$jets

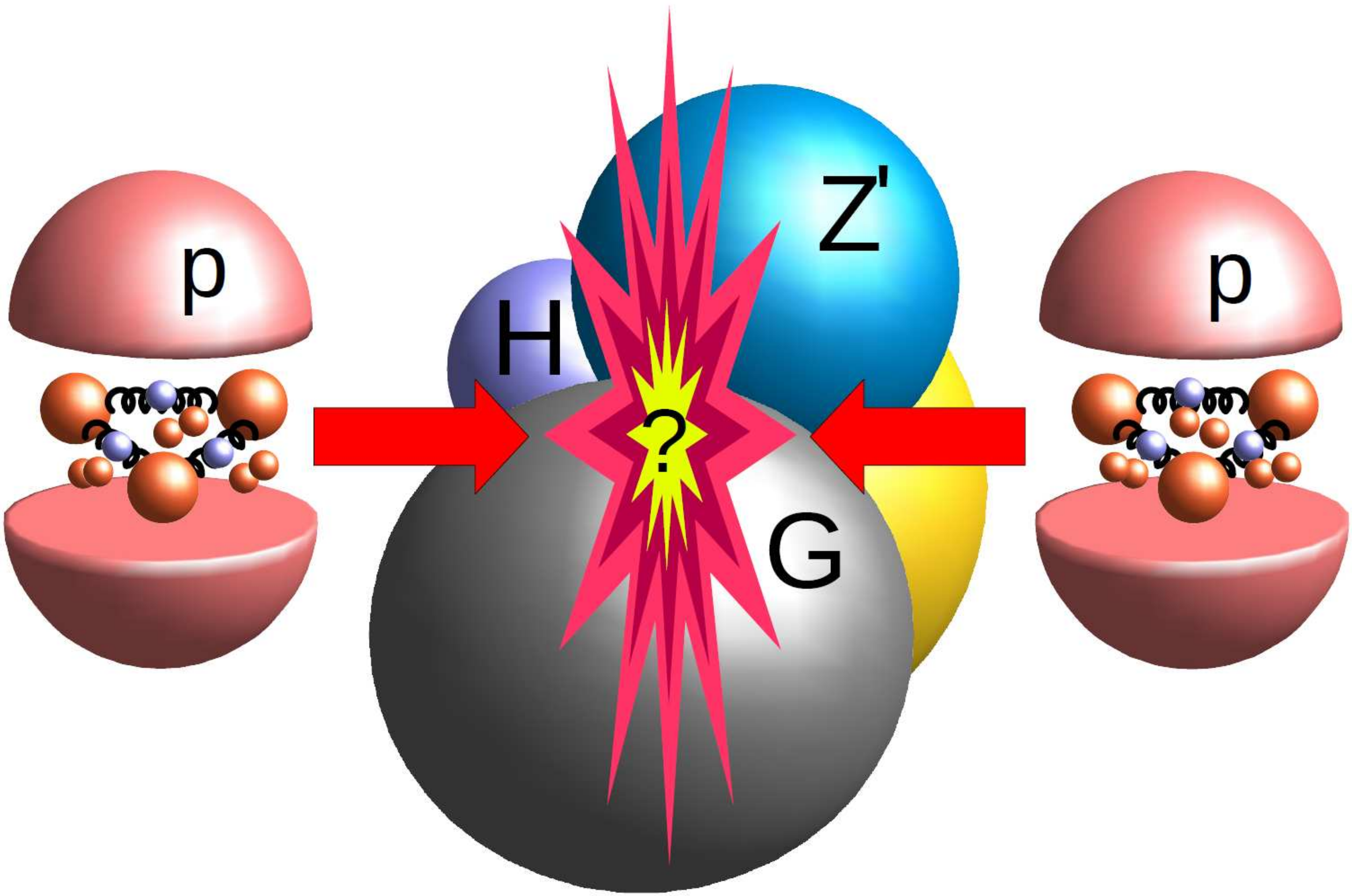


gg$\to t\bar{t}$



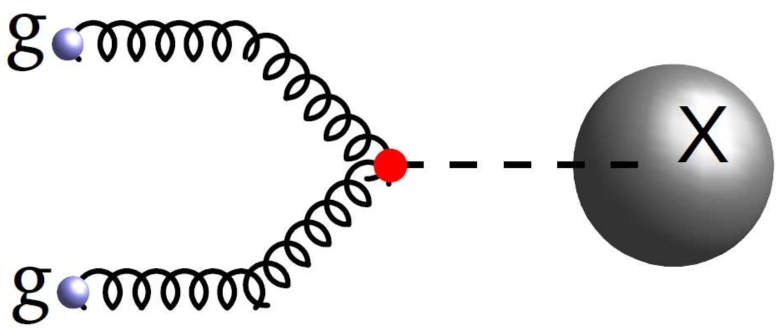
Production of New Resonances

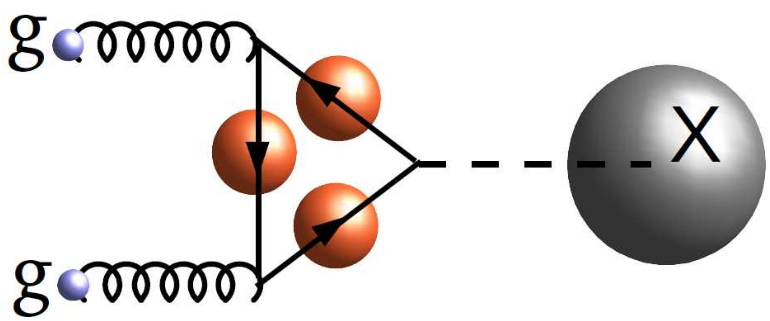
- Large Hadron Collider is a discovery machine

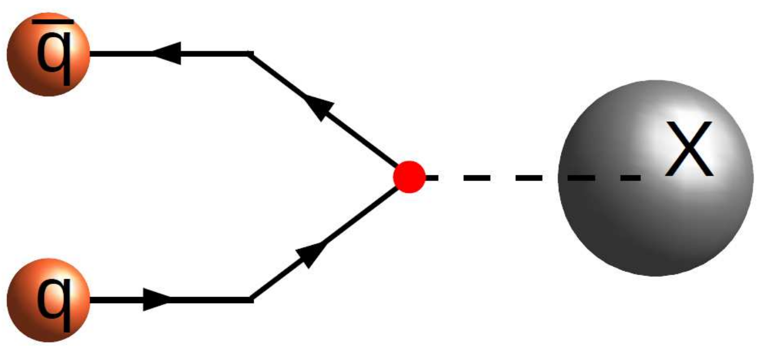


Production of New Resonances

- Consider two dominant production mechanisms







of color-neutral
& charge-neutral X

- Gluon fusion gg$\to X$

  $J =$ 0 or 2

  $J_z =$ 0 or $\pm$2

  expect to dominate at lower mass

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

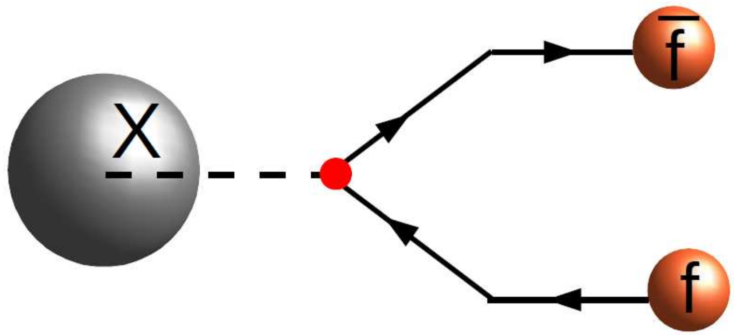
  $J =$ 1 or 2

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

  assume chiral symmetry is exact

Decay of New Resonances

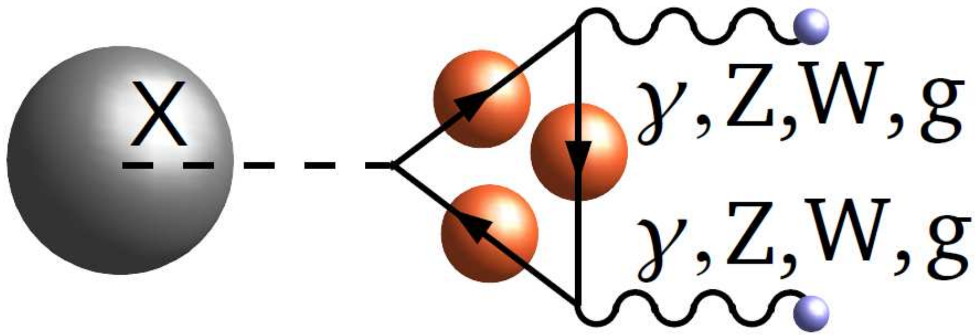
- Consider decay back to Standard Model particles



- Decay to fermions

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

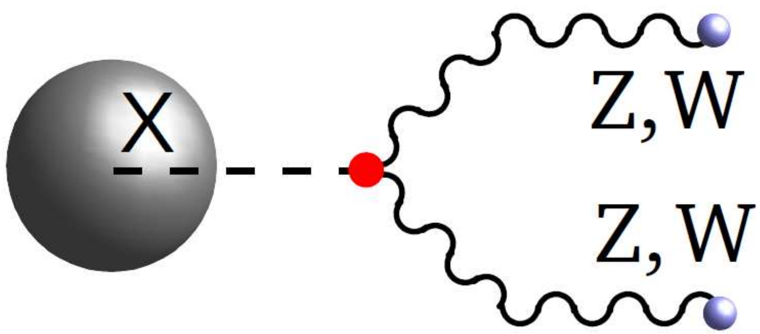
spin-0 excluded $m_f \to 0$



- Decay to gauge bosons

$X \to \gamma\gamma,\ W^+W^-,\ ZZ,$ gg

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

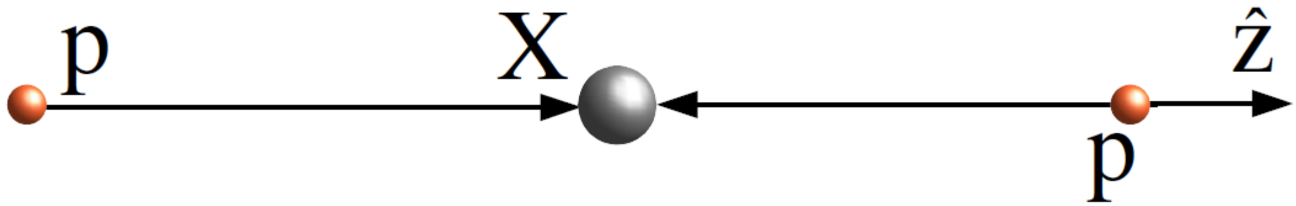


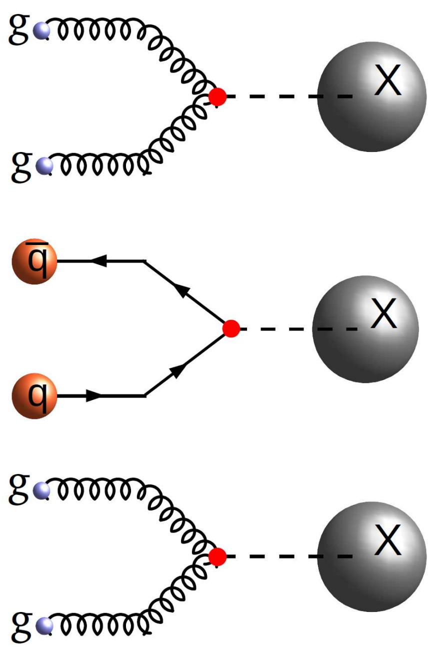
again X is color-neutral
& charge-neutral

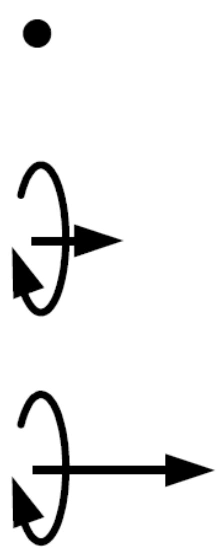
Kinematics in New Resonances Production

- $ab \to X$ 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}

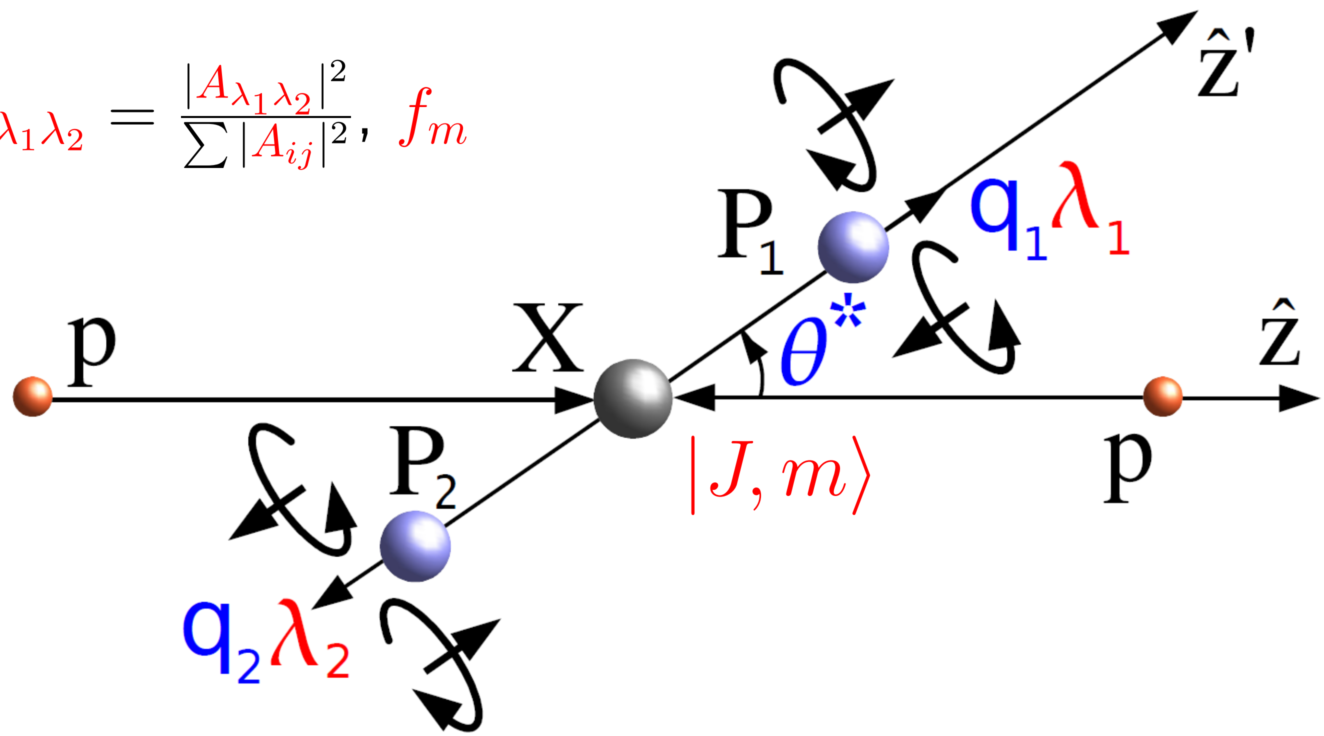
$J_z = \pm 2$ fraction f_{z2}

in general depend on LHC energy

Kinematics in New Resonances Decay

- Only 1 angle θ^* for $X \to \gamma\gamma$, $\ell^+\ell^-$, $q\bar{q}$, 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



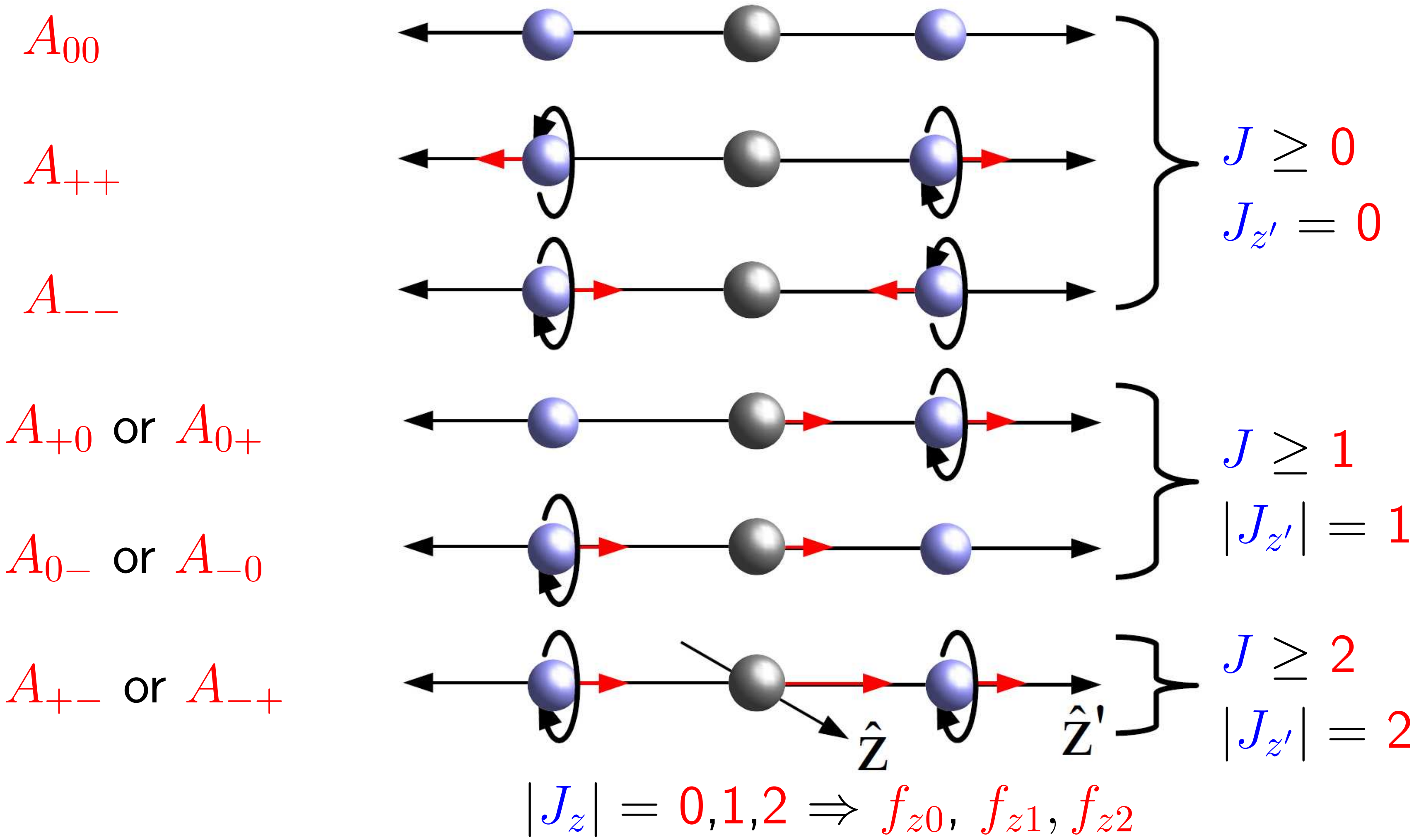
$$\frac{d\Gamma(X_J \to P_1P_2)}{\Gamma d\cos\theta^*} = \left(J + \frac{1}{2}\right) \sum_{\lambda_1,\lambda_2} f_{\lambda_1\lambda_2} \sum_m f_m \left(d^J_{m,\lambda_1-\lambda_2}(\theta^*)\right)^2$$

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

  requires f_m fine-tuning (breaks by changing LHC energy)

Decay of a New Resonance to ZZ or WW

- "experimental" goal: measure all polarizations ($\hat{z}'$, $\hat{z}$): $A_{\lambda_1\lambda_2}$, f_{zm}
- "theoretical" goal: connect to underlying physics (spin, parity, etc...)



How to Measure Polarization in $X \to VV$

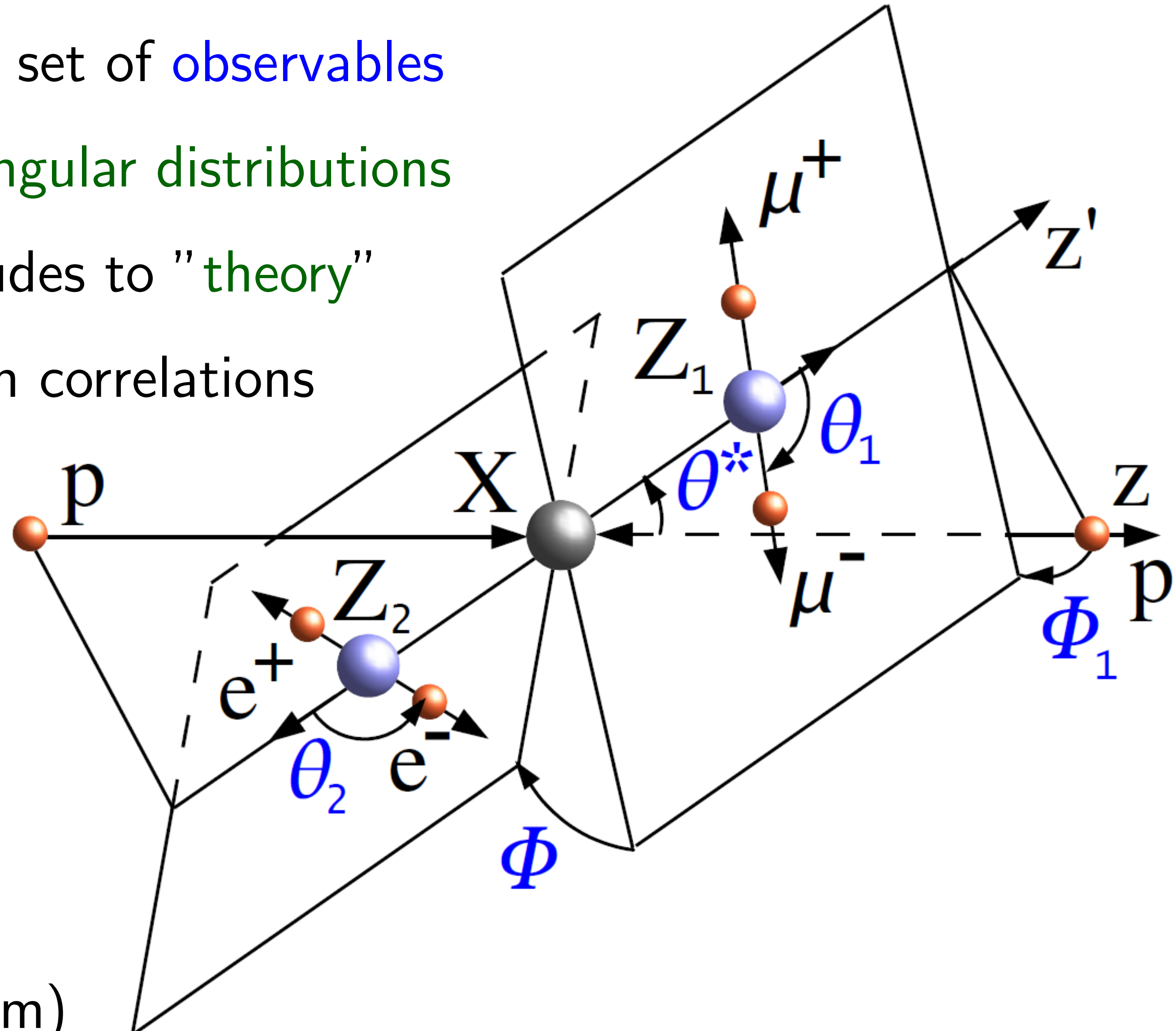
- Deduce all $A_{\lambda_1\lambda_2}$ and f_{zm} from angular distributions, but need:

  (1) define complete set of observables

  (2) full analytical angular distributions

  (3) connect amplitudes to "theory"

  (4) MC with all spin correlations



m_X, m_1, m_2

$\vec{p}_X$ ("QCD")

θ^*, Φ^* (arbitrary)

θ_1, Φ_1

θ_2, $(\Phi_2 - \Phi_1) = \Phi$

(12 degrees of freedom)

Angular Distributions

- Connect amplitudes and angular distributions for any $J = 0, 1, 2, 3, 4, ...$

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

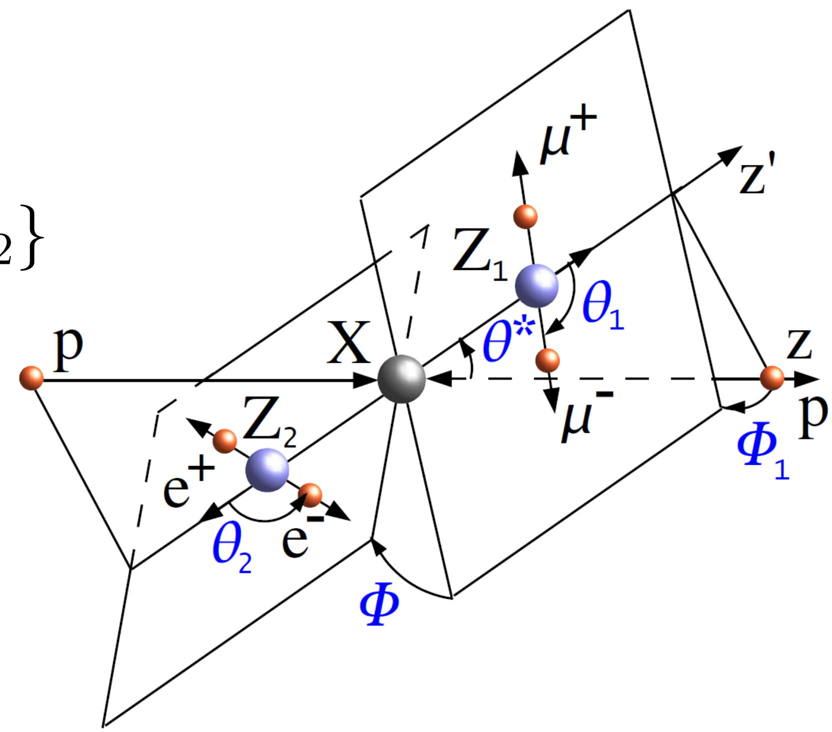
$$d\sigma \propto \sum_{\chi,\mu,\tau} \Big| \sum_{\lambda,m} A_{ab}(\{\Omega\}) \Big|^2$$

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

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

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

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



$r = c_A/c_V \Rightarrow A_f = 2r_{1,2}/(1+r_{1,2}{}^2)$=0.15 ($\ell^-\ell^+$), 1 ($\ell\nu$)

Explicit Distributions for any Spin J

$$F^J_{0,0}(\theta^*) \times \Big[4\,|A_{00}|^2 \sin^2\theta_1 \sin^2\theta_2 + 2|A_{++}||A_{--}| \sin^2\theta_1 \sin^2\theta_2 \cos(2\Phi - \phi_{--} + \phi_{++})\Big]$$

$$+ |A_{++}|^2 \left(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right)$$

$$+ |A_{--}|^2 \left(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right)$$

spin $= 0$ & ≥ 1

$$+ 4|A_{00}||A_{++}|(A_{f_1} + \cos\theta_1)\sin\theta_1(A_{f_2} + \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++})$$

$$+ 4|A_{00}||A_{--}|(A_{f_1} - \cos\theta_1)\sin\theta_1(A_{f_2} - \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--})$$

$$+F^J_{1,1}(\theta^*) \times \Big[2|A_{+0}|^2(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)\sin^2\theta_2 + 2|A_{0-}|^2\sin^2\theta_1(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)$$

$$+ 2|A_{-0}|^2(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)\sin^2\theta_2 + 2|A_{0+}|^2\sin^2\theta_1(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)$$

$$+ 4|A_{+0}||A_{0-}|(A_{f_1} + \cos\theta_1)\sin\theta_1(A_{f_2} - \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{+0} - \phi_{0-})$$

$$+ 4|A_{0+}||A_{-0}|(A_{f_1} - \cos\theta_1)\sin\theta_1(A_{f_2} + \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{0+} - \phi_{-0})\Big]$$

spin ≥ 1

$$+F^J_{1,-1}(\theta^*) \times \Big[4|A_{+0}||A_{0+}|(A_{f_1} + \cos\theta_1)\sin\theta_1(A_{f_2} + \cos\theta_2)\sin\theta_2\cos(2\Psi - \phi_{+0} + \phi_{0+})$$

$$+ 4|A_{0-}||A_{-0}|(A_{f_1} - \cos\theta_1)\sin\theta_1(A_{f_2} - \cos\theta_2)\sin\theta_2\cos(2\Psi - \phi_{0-} + \phi_{-0})$$

$$+4|A_{+0}||A_{-0}|\sin^2\theta_1\sin^2\theta_2\cos(2\Psi - \Phi - \phi_{+0} + \phi_{-0}) + 4|A_{0-}||A_{0+}|\sin^2\theta_1\sin^2\theta_2\cos(2\Psi + \Phi - \phi_{0-} + \phi_{0+})\Big]$$

$$+F^J_{2,2}(\theta^*) \times \Big[|A_{+-}|^2(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)$$

$$+ |A_{-+}|^2(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)\Big]$$

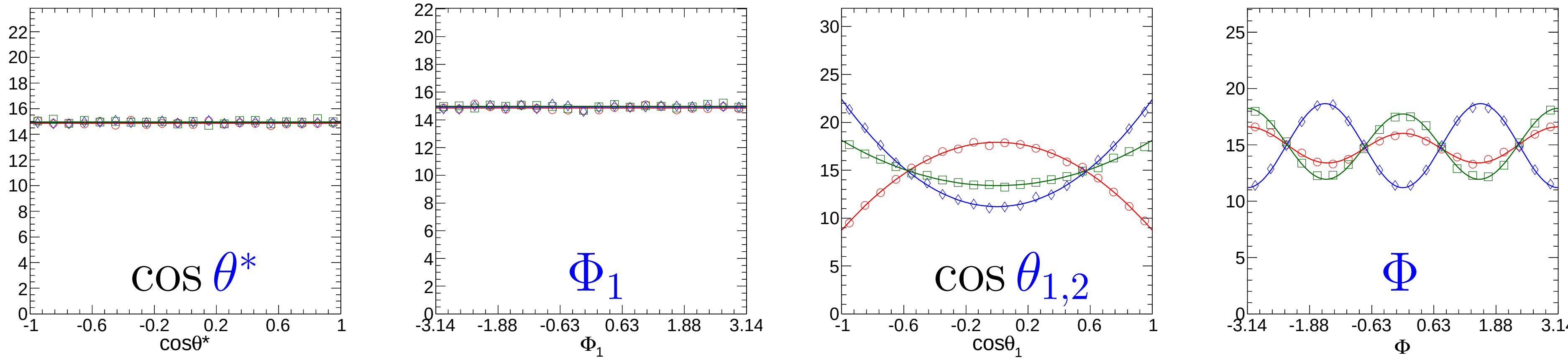
spin ≥ 2

$$+F^J_{2,-2}(\theta^*) \times \Big[2|A_{+-}||A_{-+}|\sin^2\theta_1\sin^2\theta_2\cos(4\Psi - \phi_{+-} + \phi_{-+})\Big] +$$ other 26 interference terms for spin

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

Examples of Distributions for $X \to ZZ \to 4\ell$

- SM Higgs 0^+, BSM scalar 0^+, pseudocalar 0^- at $m_X = 125$ GeV
  - lines projections of analytical distributions, points from MC

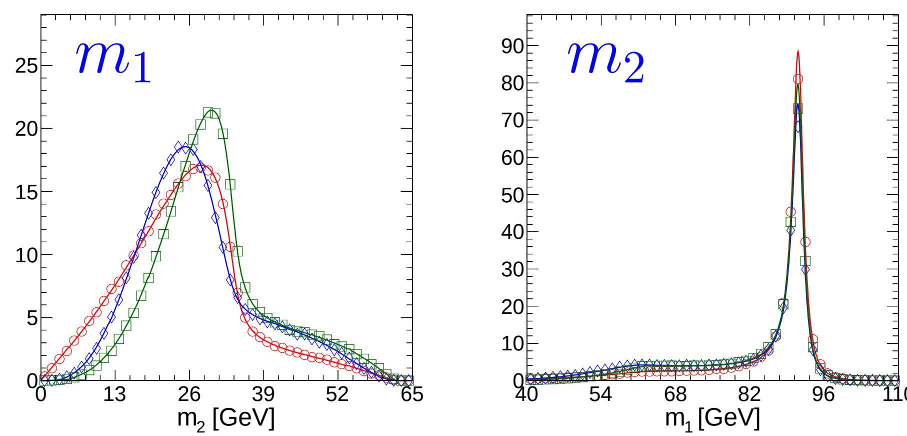


- $X \to Z^*Z^*$ with $m_1 > m_2$, $m_X < 2m_Z$ $\Rightarrow$ at least one Z^* off-shell

m_1, m_2 dependence from

$\Sigma |A_{\lambda_1\lambda_2}(m_1, m_2)|^2$

BW and phase-space $p_Z(m_1, m_2)$



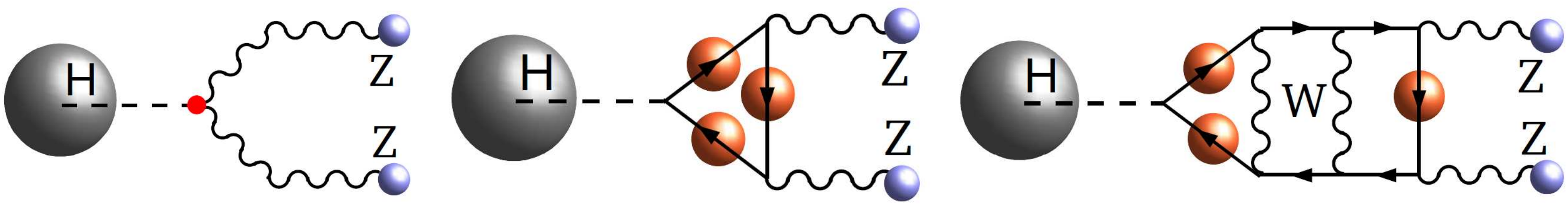
Amplitude for Spin-0 $X \to VV$

- Amplitude for $X_{J=0} \to V_1 V_2$

$$A = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

form-factors g_i: g_1 for $H \to ZZ$, g_2 for $H \to \gamma\gamma$

- SM Higgs 0^+: (g_1) CP $\sim$few% (g_2) CP $\sim 10^{-10}$? (g_4) $\not{CP}$



(or beyond SM)   (or beyond SM)

$$\mathcal{L} \sim g_1^{(0)} X Z_\mu Z^\mu \quad \Leftrightarrow \quad g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^*$$

$$\mathcal{L} \sim g_2^{(0)} X Z_{\mu\nu} Z^{\mu\nu} \quad \Leftrightarrow \quad g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}$$

$$\mathcal{L} \sim g_3^{(0)} Z_{\mu\alpha} Z^{\nu\beta} \left[\partial_\beta \partial_\alpha X\right] \quad \Leftrightarrow \quad g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2}$$

$$\mathcal{L} \sim g_4^{(0)} X Z^{\mu\nu} \tilde{Z}_{\mu\nu} \quad \Leftrightarrow \quad g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Amplitude for Spin-0 $X \to VV$

- Express through Lorenz structures ($f^{\mu\nu}_{(i)} = \epsilon^{\mu}_{i} q^{\nu}_{i} - \epsilon^{\nu}_{i} q^{\mu}_{i}$ field strength tensor)

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

$$a_3 = -2 g_4^{(0)}\,, \quad a_2 = -2 g_2^{(0)} - g_3^{(0)} \frac{s}{\Lambda^2}\,, \quad a_1 = g_1^{(0)} \frac{m_V^2}{m_X^2} - \frac{s}{m_X^2} a_2$$

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

$$A_{00}(m_1, m_2) = -\frac{m_X^2}{v} \left(a_1 \sqrt{1+x} + a_2 \frac{m_1 m_2}{m_X^2} x \right)$$

$$A_{\pm\pm}(m_1, m_2) = \frac{m_X^2}{v} \left(a_1 \pm i a_3 \frac{m_1 m_2}{m_X^2} \sqrt{x} \right)$$

$$s = \frac{m_X^2 - m_1^2 - m_2^2}{2}; \quad x = (s/m_1 m_2)^2 - 1$$

- Compare $B \to V_1 V_2$, see e.g. PRD45,193(1992)

Amplitude for Spin-1 $X \to VV$

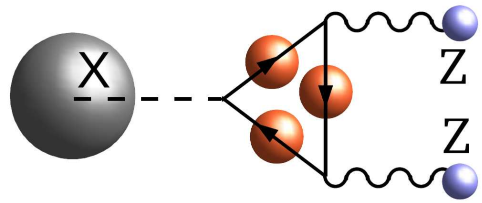
- Most general amplitude for $X_{J=1} \to VV$

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

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

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

Example:



$$A_{\pm\pm} = \pm i\, b_2 \frac{(m_1^2 - m_2^2)}{m_X}; \qquad A_{00} = b_1 \frac{(m_1^2 - m_2^2)}{m_X} \sqrt{x}$$

$$A_{\pm 0} = b_1 m_1 \sqrt{x} \pm i\, b_2 \frac{m_2}{m_X^2} \left[\frac{1}{2}\left(m_X^2 - m_1^2 + m_2^2\right)\left(\frac{m_1^2}{m_2^2} - 1\right) + 2 m_1^2 x\right]$$

$$A_{0\pm} = -b_1 m_2 \sqrt{x} \mp i\, b_2 \frac{m_1}{m_X^2} \left[\frac{1}{2}\left(m_X^2 + m_1^2 - m_2^2\right)\left(\frac{m_2^2}{m_1^2} - 1\right) + 2 m_2^2 x\right]$$

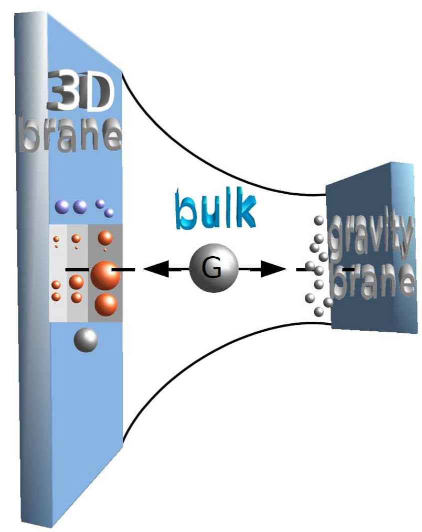
- Reconfirm Landau-Yang theorem for $X \to \gamma\gamma$

$m_1 = m_2 = 0$, $\lambda \neq 0$ $\quad \Rightarrow \quad$ $A_{\lambda_1 \lambda_2} = 0$ for $J = 1$

Amplitude for Spin-2 $X \to VV$

$$A(X \to V_1 V_2) = 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta}$$
$$+g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
$$+g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta}$$
$$+m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right)$$

- Minimal coupling (∼gravity) $\quad A \propto \frac{1}{\Lambda} t_{\mu\nu} \mathcal{T}^{\mu\nu}$



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

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

- Many options, for illustration: $g_1^{(2)}$ & $g_5^{(2)}$ (2_m^+), $g_4^{(2)}$ (2_h^+), $g_8^{(2)}$ (2_h^-)

Amplitude for Spin-2 $X \to VV$

- Similarly, express through Lorenz structures...

$$A(X \to V_1 V_2) = \Lambda^{-1} e_1^{*\mu}\, e_2^{*\nu} \left[c_1\, (q_1 q_2) t_{\mu\nu} + c_2\, g_{\mu\nu} t_{\alpha\beta} \tilde{q}^\alpha \tilde{q}^\beta + \text{more...} \right]$$

- Just for illustration, generally 9 amplitudes:

$$c_1 = 2g_1^{(2)} + 2g_2^{(2)} \frac{s}{\Lambda^2} \left(1 + \frac{m_1^2}{s}\right) \left(1 + \frac{m_2^2}{s}\right) + 2g_5^{(2)} \frac{m_V^2}{s}\;; \ldots$$

$$A_{00} = \frac{m_X^4}{m_1 m_2 \sqrt{6}} \frac{c_1}{8} + \frac{m_1 m_2}{\sqrt{6}} \left[c_1 \frac{1}{2} (1 + x) - c_2 2x + c_{41} 2x + c_{42} 2x \right] - \frac{(m_1^4 + m_2^4)}{m_1 m_2 \sqrt{6}} \frac{c_1}{4}$$
$$+ \frac{m_1 m_2 (m_1^2 - m_2^2)}{m_X^2 \sqrt{6}} (c_{41} - c_{42}) 2x + \frac{m_1^3 m_2^3}{m_X^4 \sqrt{6}} \left[c_1 \left(\frac{3}{4} + x\right) - c_2 \left(4x + 8x^2\right) - c_3 8x^2 \right]$$
$$+ \frac{(m_1^8 + m_2^8)}{m_X^4 m_1 m_2 \sqrt{6}} \frac{c_1}{8} + \frac{m_1 m_2 (m_1^4 + m_2^4)}{m_X^4 \sqrt{6}} \left[-c_1 \frac{1}{2} (1 + x) + c_2 2x \right]\;; \ldots$$

- Minimal $g_1^{(2)}$: $c_1 \simeq$ -4$c_2 =$ -2c_{4i} (as $m_i \to 0$) $\Rightarrow A_{+-} \& A_{-+}$ dominate

  $\Rightarrow$ production gg$\to X$ only $J_z = \pm 2$ $\Rightarrow f_{z0} = 0$

Coupling to fermions

- For completeness $X \to q\bar{q}$, also to describe $q\bar{q} \to X$:
  - example of spin-2:

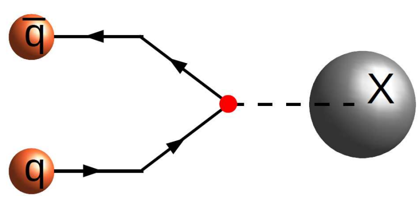
$$A = \frac{1}{\Lambda} t^{\mu\nu} \bar{u}_{q_1} \left(\gamma_\mu \Delta q_\nu \left(\rho_1 + \rho_2 \gamma_5 \right) + \frac{m_q}{\Lambda^2} \Delta q_\mu \Delta q_\nu \left(\rho_3 + \rho_4 \gamma_5 \right) \right) v_{q_2}$$

- 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)

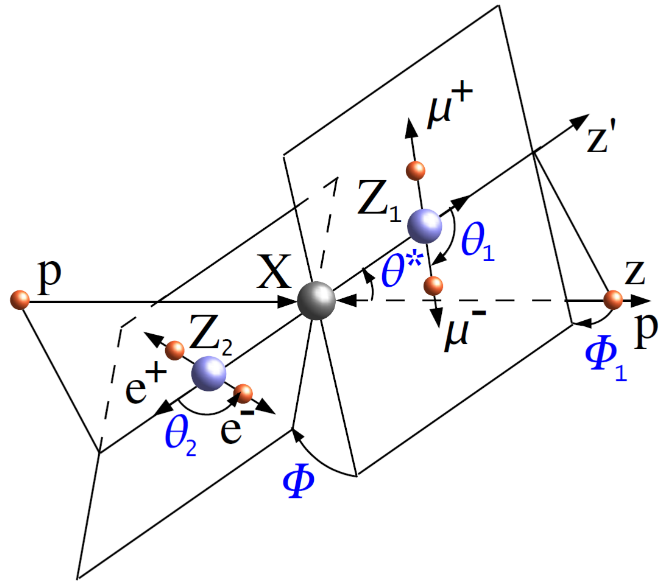


$\Rightarrow A_{++} = A_{--} = 0$ at $m_q \to 0$

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

Monte Carlo Simulation

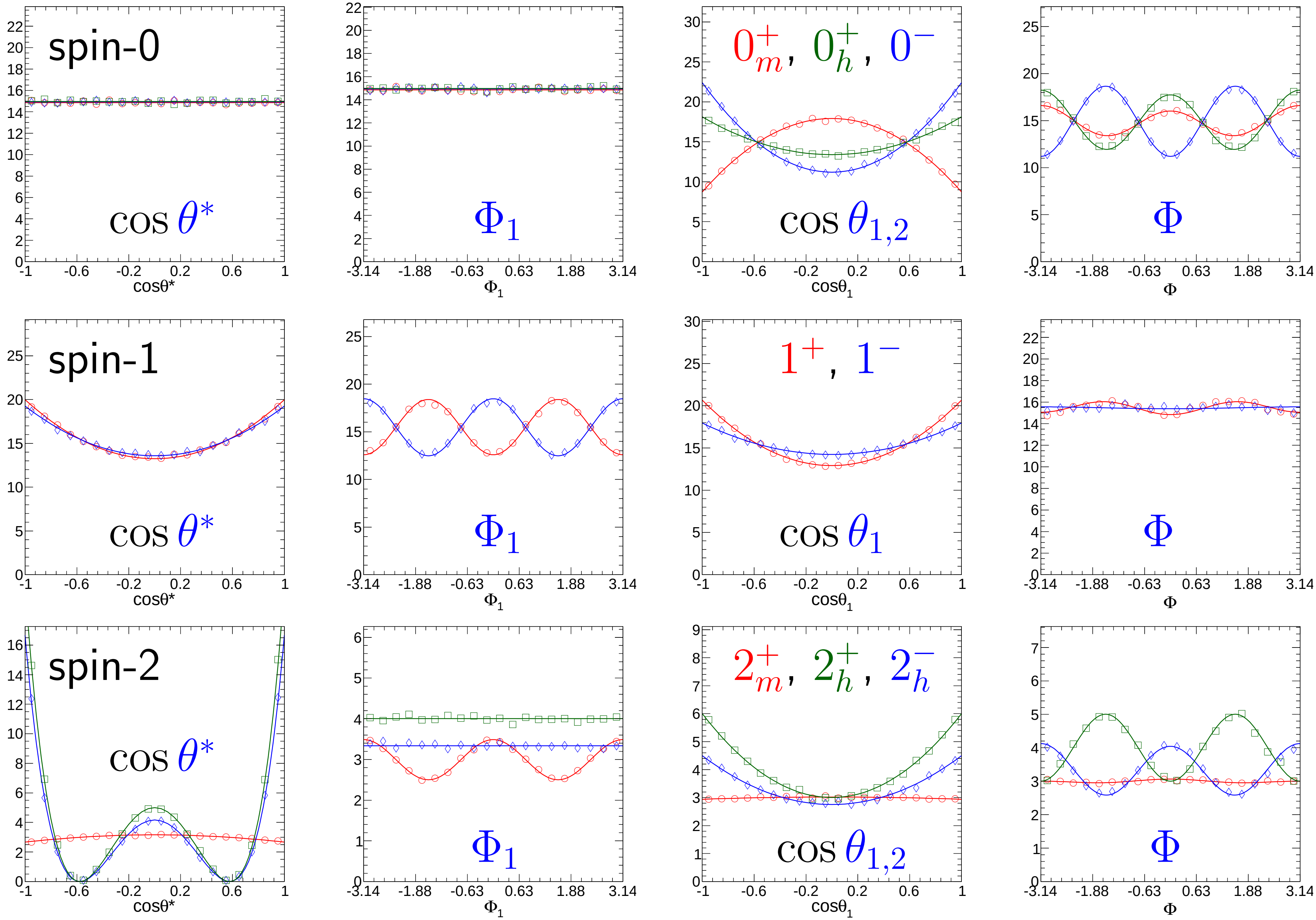
- MC program, open access: http://www.pha.jhu.edu/spin/
  - complete chain $ab \to X \to \gamma\gamma$ or $Z^*Z^*/W^*W^* \to (f_1\bar{f}_1')(f_2\bar{f}_2')$
  - calculate matrix element $|M|^2$
  - weigh or accept/discard events



- 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 (LHE)

- Background and detector: simplified model for illustration
  - POWHEG / MadGraph: $q\bar{q} \to ZZ, WW, \gamma\gamma$
  - others backgrounds smaller, account by rescaling the rate
  - detector: acceptance loss and energy smearing of $\ell^\pm, \gamma$

Simulation Examples of $X \to ZZ \to 4\ell$

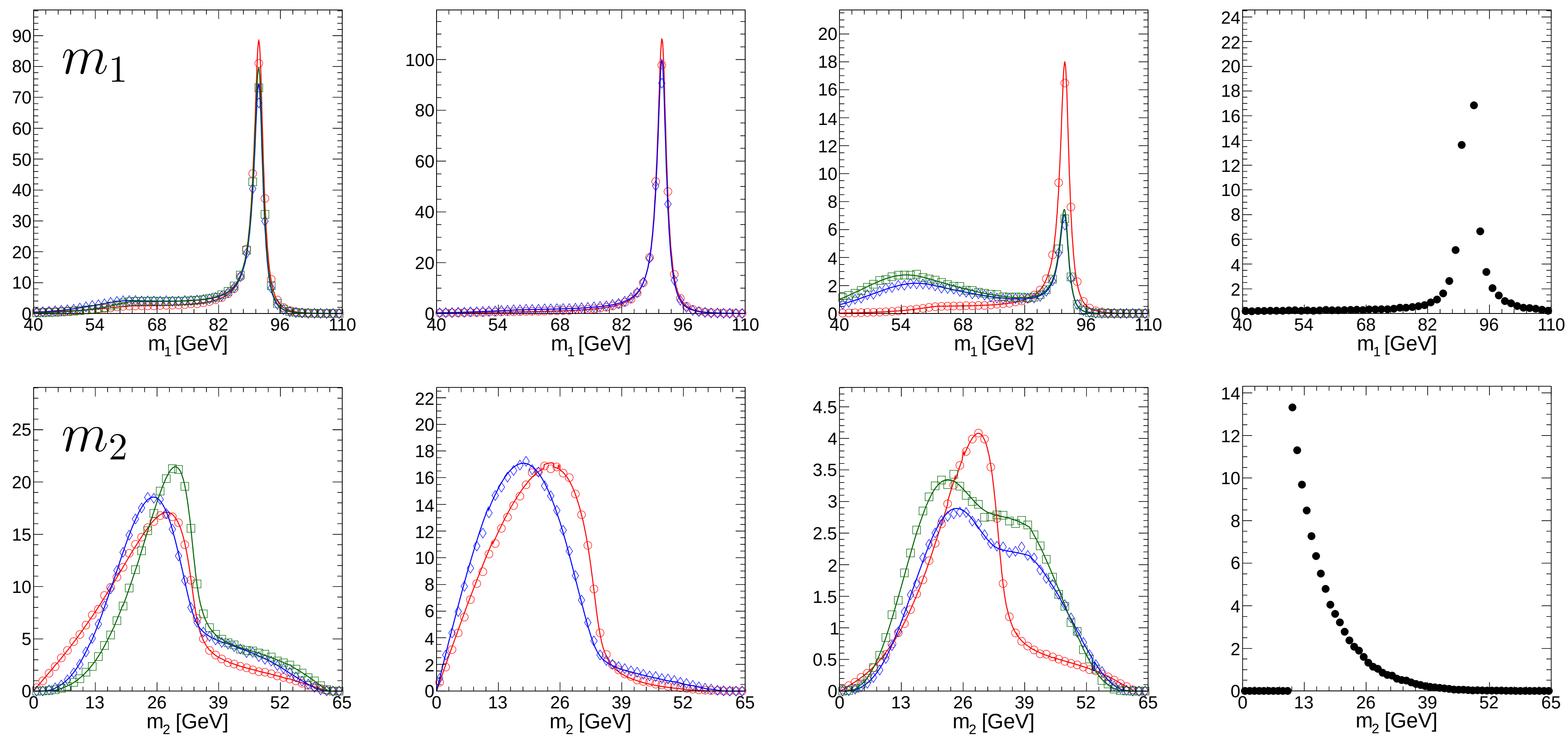


Simulation Examples: Masses

- m_1 and m_2 different between signal models and from background

  all signals gg $(J=0,2)$ or $q\bar{q}$ $(J=1) \to X \to Z^*Z^*$ at 125 GeV

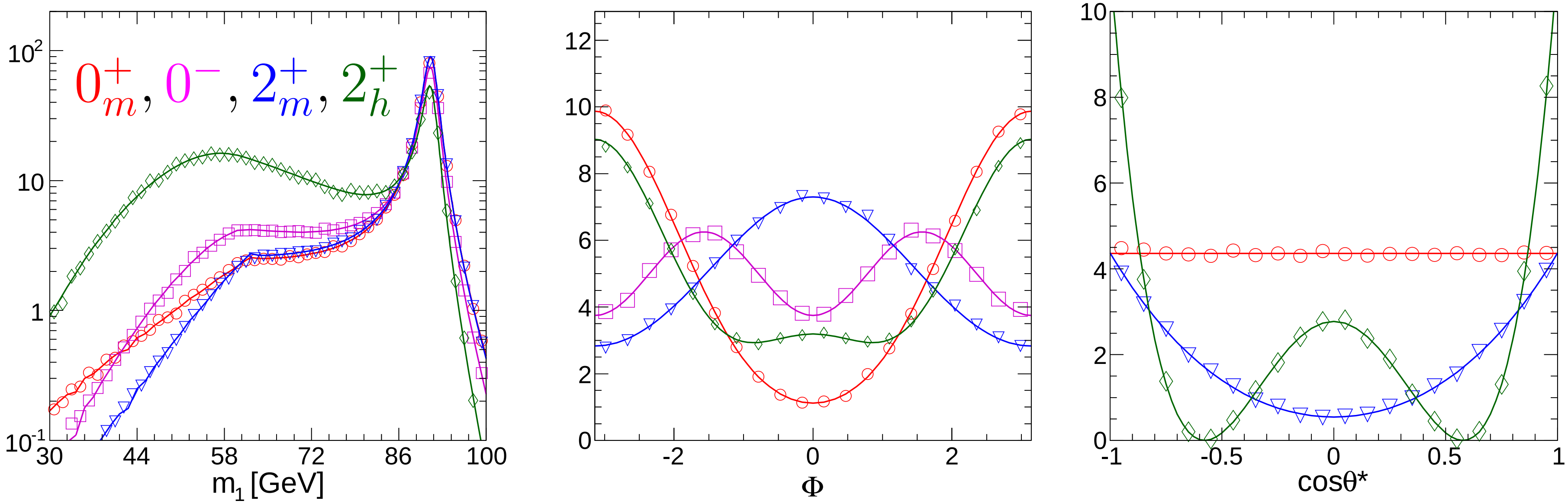
0^+_m, 0^+_h, 0^- | 1^+, 1^- | 2^+_m, 2^+_h, 2^-_h | $q\bar{q} \to ZZ^*/Z\gamma^*$



$\to$ lines projections of analytical distributions, points from MC

Simulation Examples: Other Channels

$X \to Z^*Z^* \to 4\ell$ $\qquad X \to W^*W^* \to 2\ell 2\nu$ $\qquad X \to \gamma\gamma$

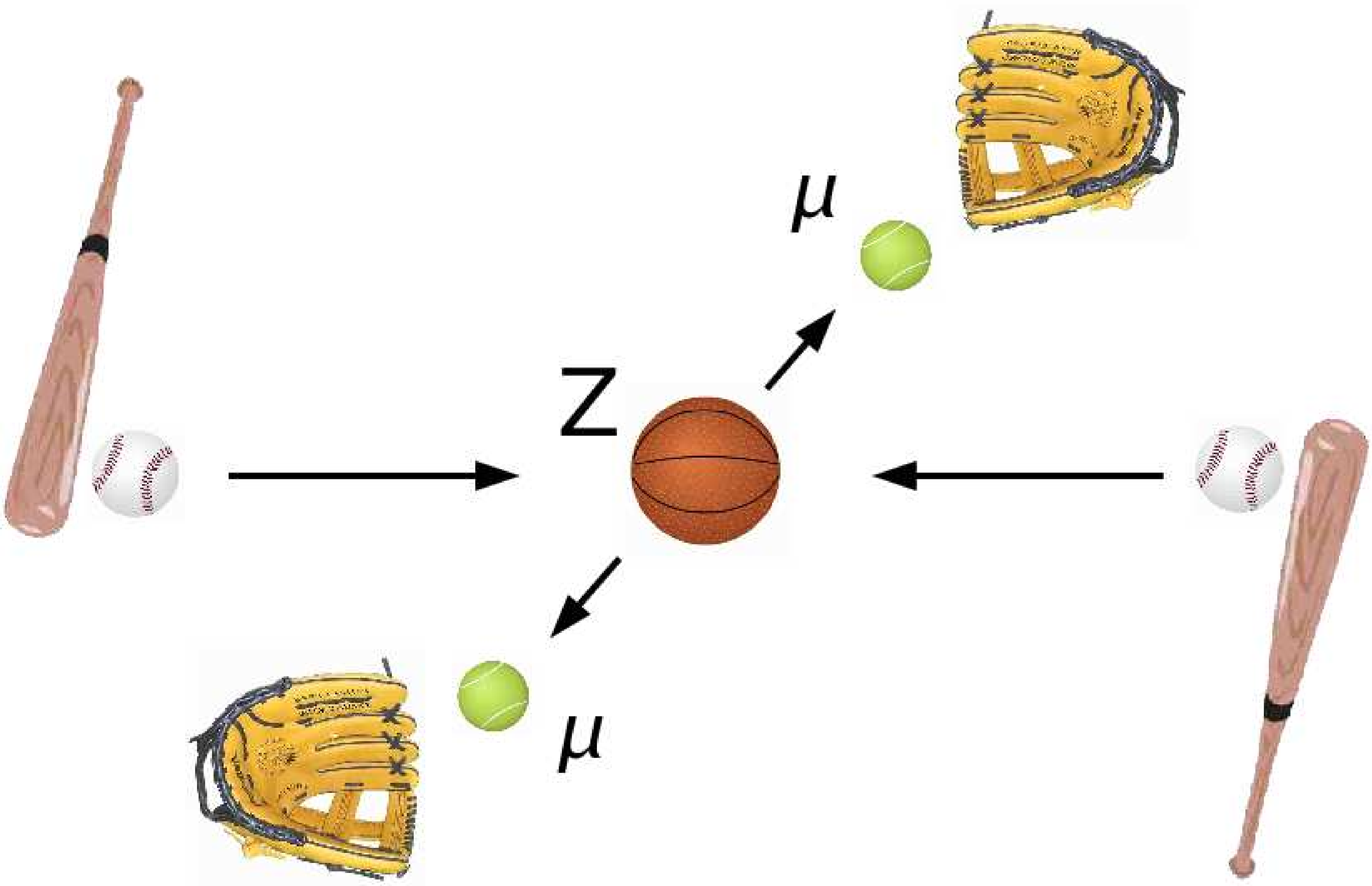


- $X \to \gamma\gamma$
  - only 1 angle $\cos\theta^*$

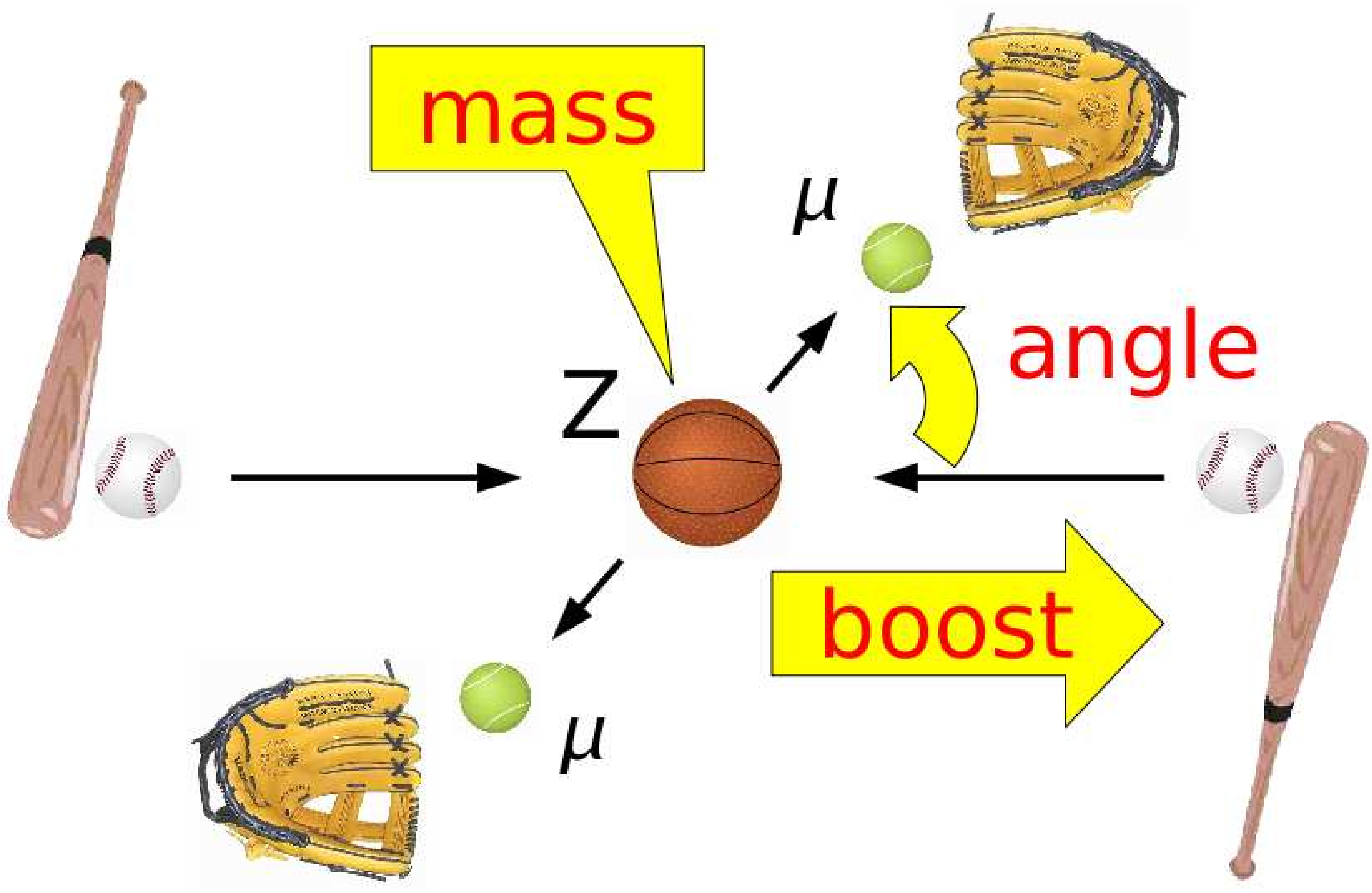
- $X \to W^*W^* \to 2\ell 2\nu$
  - no exclusive reco due to 2ν
  - but stronger Φ modulation $\Rightarrow$ reflected in reco observables

LHC DATA

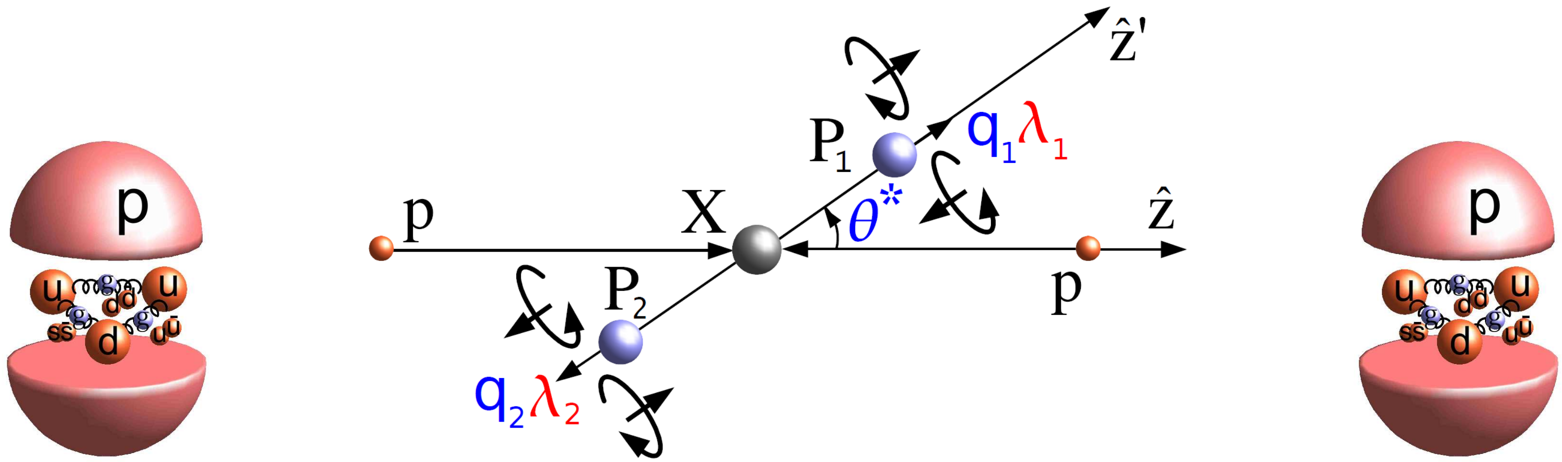
Experiment I



Experiment I

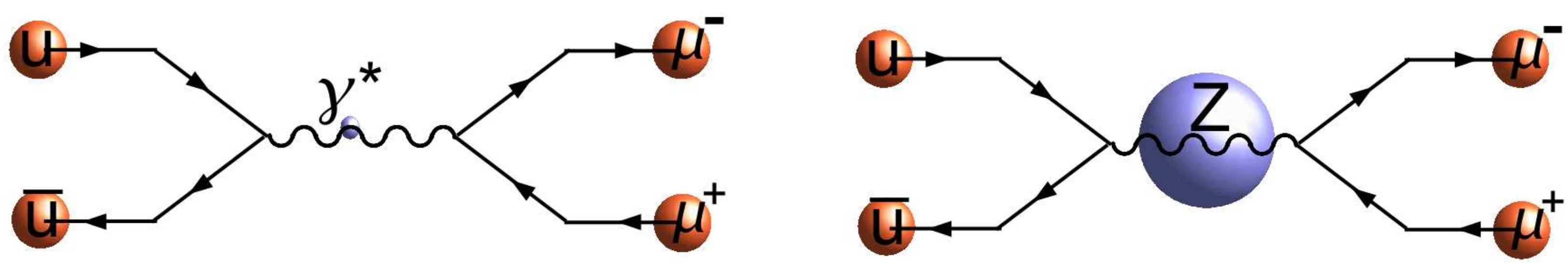


Quark-Antiquark Process



$$\hat{\sigma}_{q\bar{q}}(m^2, \theta^*) \propto \frac{1}{m^2} \sum_{\chi_1,\chi_2,\lambda_1,\lambda_2=\uparrow\downarrow} \left(d^{J=1}_{\chi_1-\chi_2,\lambda_1-\lambda_2}(\theta^*) \right)^2 \times$$

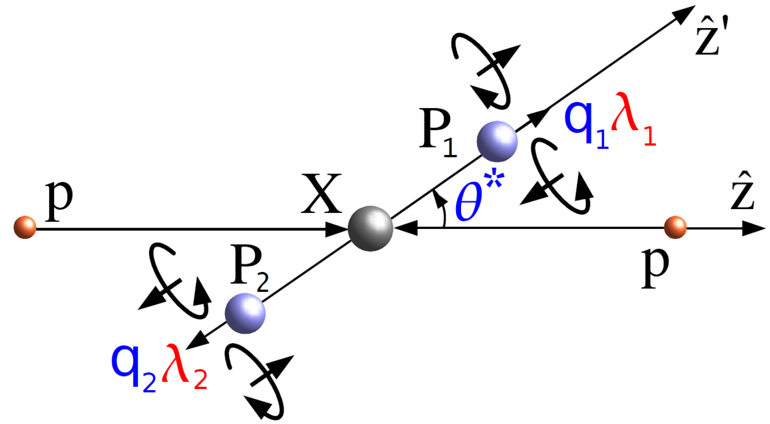
$$\left| A^{(q\bar{q}\to\gamma)}_{\chi_1,\chi_2} A^{(\gamma\to\ell\ell)}_{\lambda_1,\lambda_2} + A^{(q\bar{q}\to Z)}_{\chi_1,\chi_2}(\theta_W) A^{(Z\to\ell\ell)}_{\lambda_1,\lambda_2}(\theta_W) \times \frac{m^2}{(m^2 - {m_Z}^2) + i m_Z \Gamma_Z} \right|^2$$



where $A_{\chi_1,\chi_2} \propto (\chi_1 - \chi_2) c_V - c_A$

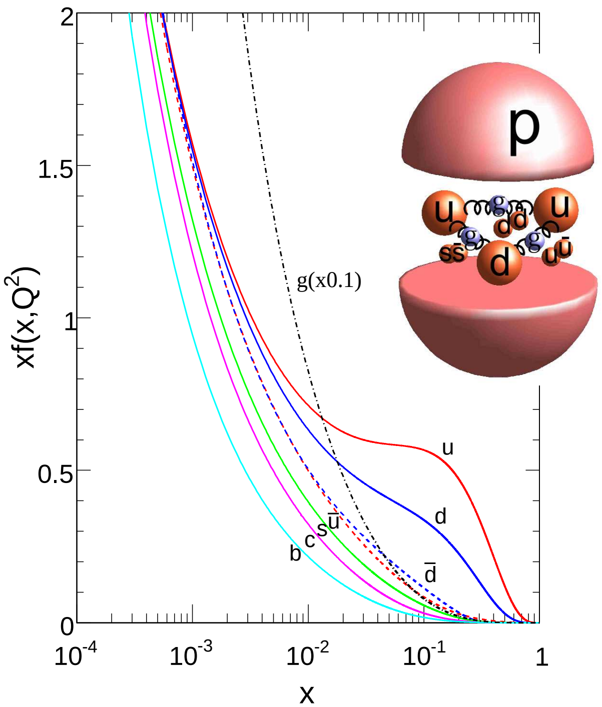
Proton-Proton Process

- Now spread in boost $Y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$



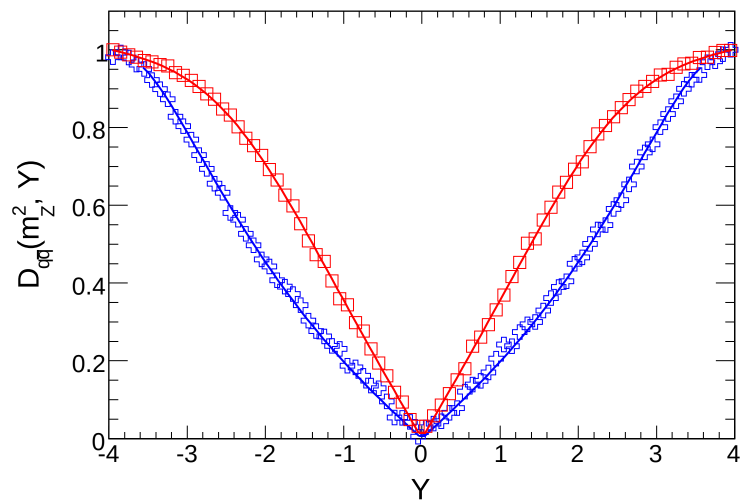
$$\frac{d\sigma_{\rm observe}(Y, m^2, \theta^*; \vec{\zeta})}{dY\, dm^2\, d\cos\theta^*} \propto$$

$$\sum_{q=udscb} F_{q\bar{q}}(m, Y) \times [\hat{\sigma}^{\rm even}_{q\bar{q}}(m^2, \cos^2\theta^*) + D_{q\bar{q}}(m, Y) \times \hat{\sigma}^{\rm odd}_{q\bar{q}}(m^2, \cos^1\theta^*)]$$



challenge at LHC: q vs $\bar{q}$ direction

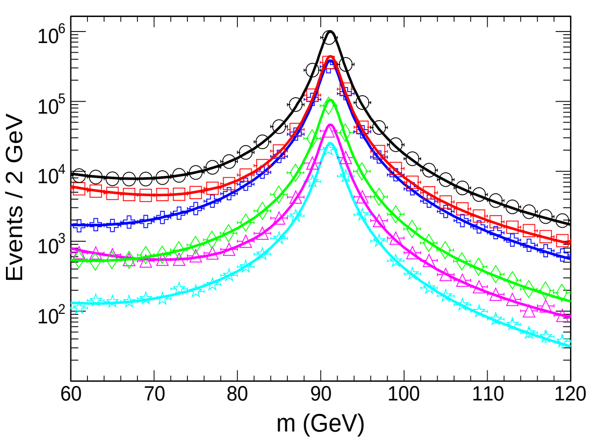
$\Rightarrow$ Dilution $D_{u\bar{u},\, d\bar{d}} < 1$

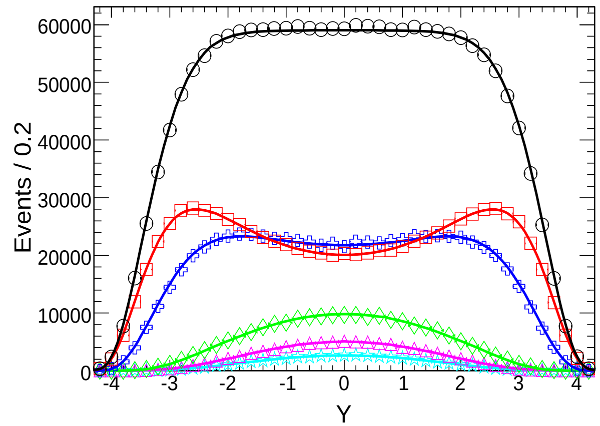


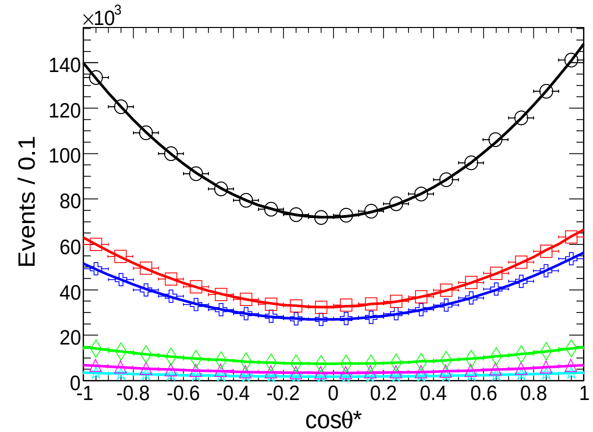
Process in the Detector

- Combine $q\bar{q}$: $u\bar{u}$ (46%), $d\bar{d}$ (37%), $s\bar{s}$ (10%), $c\bar{c}$ (5%), $b\bar{b}$ (3%)

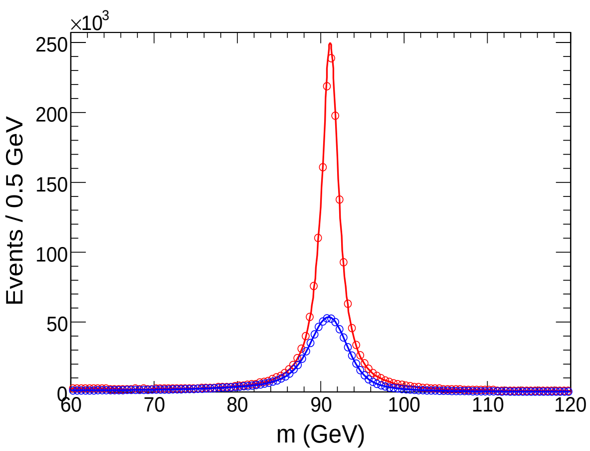
mass m boost Y angle $\cos\theta^*$

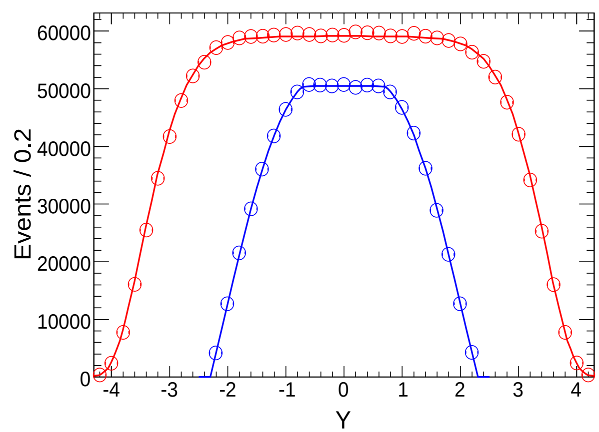


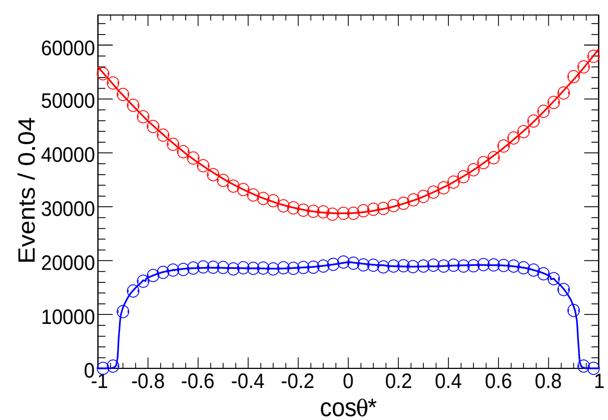




- Detector effects: lost particles and resolution







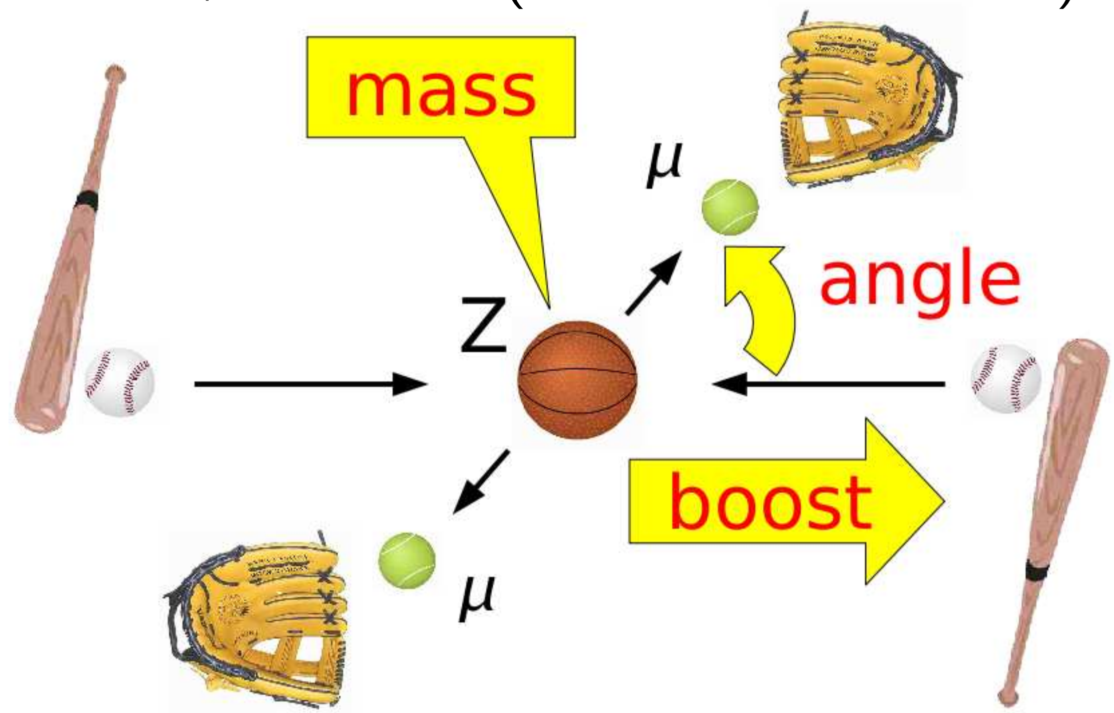
Mixing Angle θ_W on CMS: PRD84,112002(2011)

- Repeat $q\bar{q} \to \gamma^*/Z \to \mu^-\mu^+$ ~300,000 times (from 1 fb^{-1} of data)

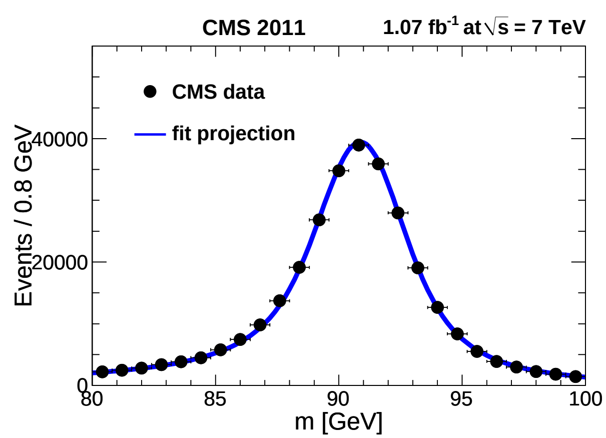
$\sin^2\theta_W =$
$0.2287 \pm 0.0020 \pm 0.0025$
$\sim 1.4\%$ precision

- Prior (LEP/SLC) results

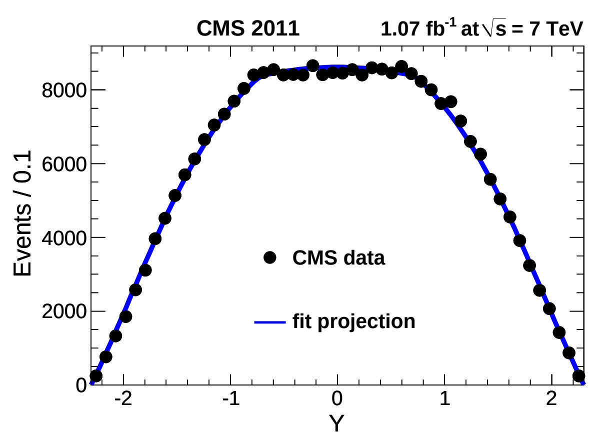
$\sim 0.1\%$ precision (0.2312)
but with $e^-e^+ \leftrightarrow \gamma^*/Z$



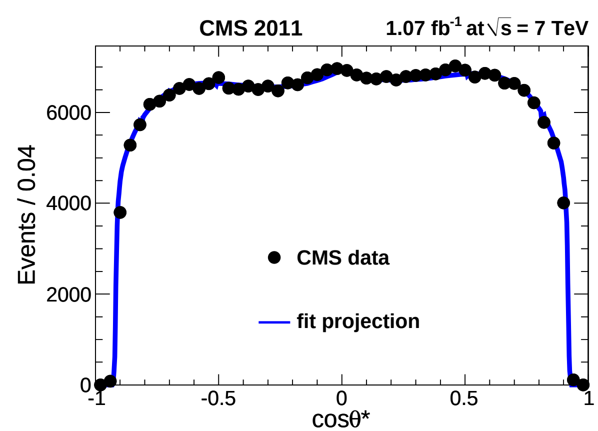
mass m



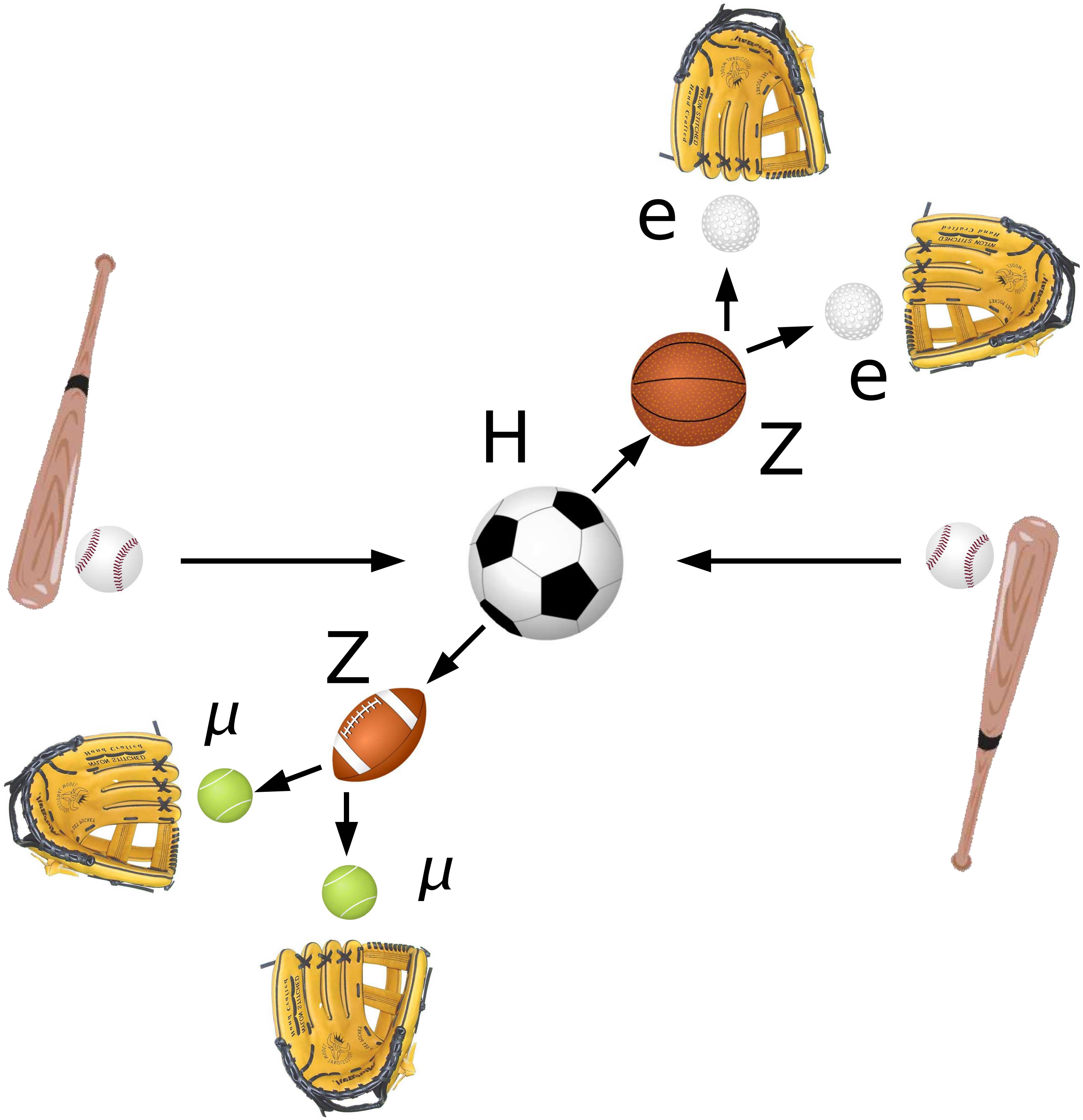
boost Y



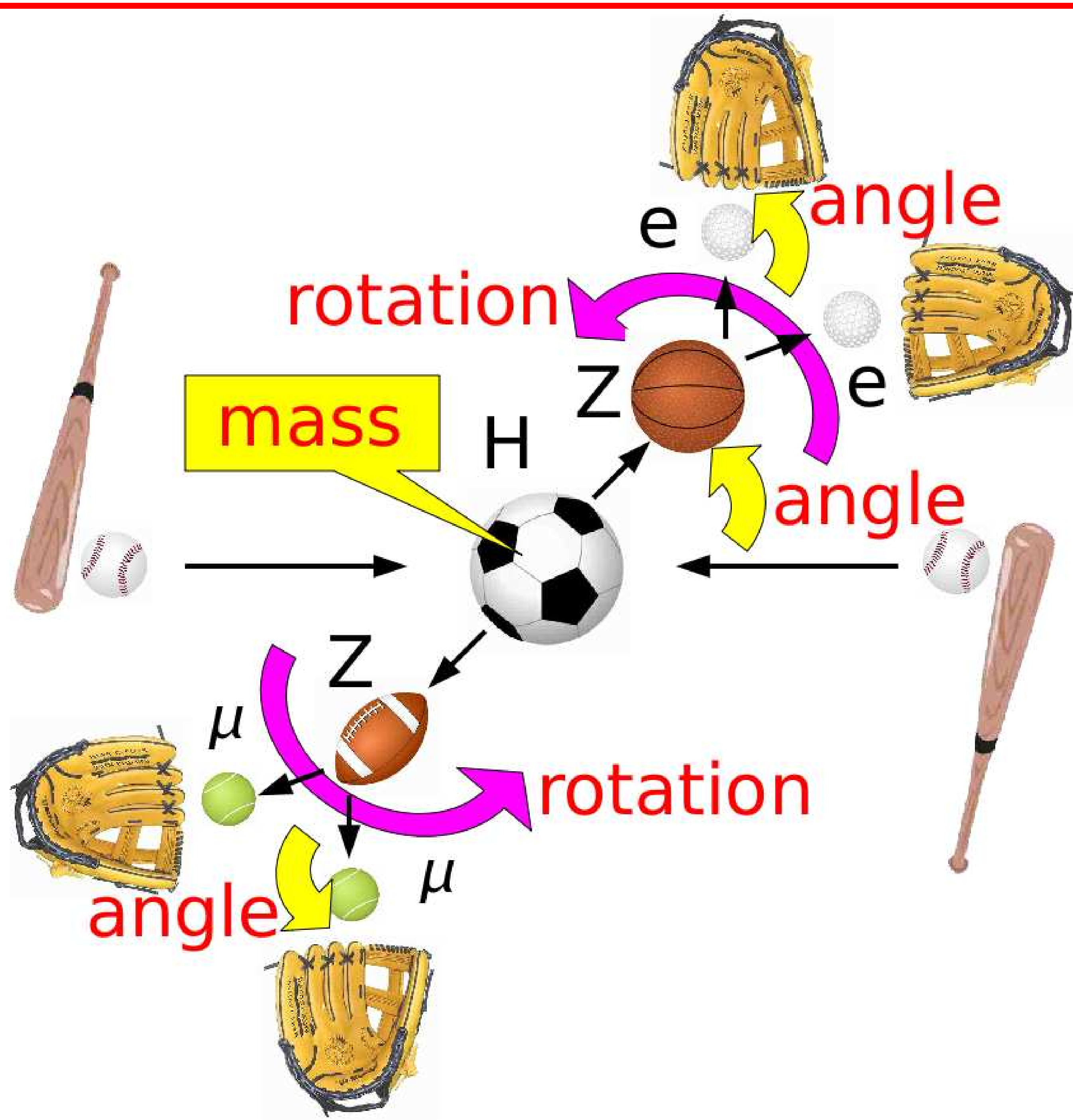
angle $\cos\theta^*$



Experiment II



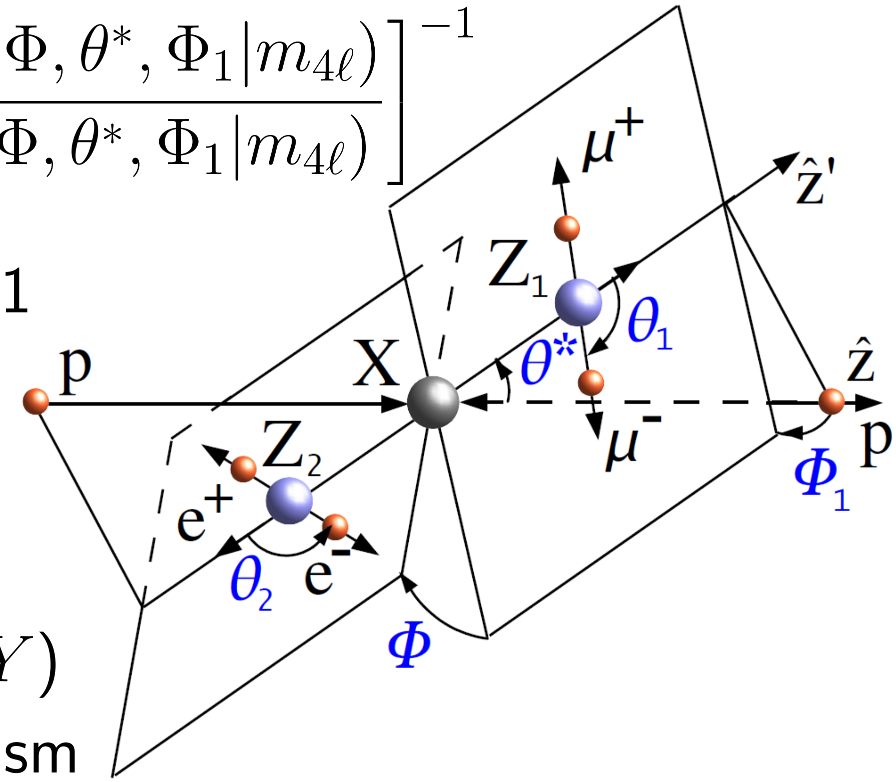
Experiment II



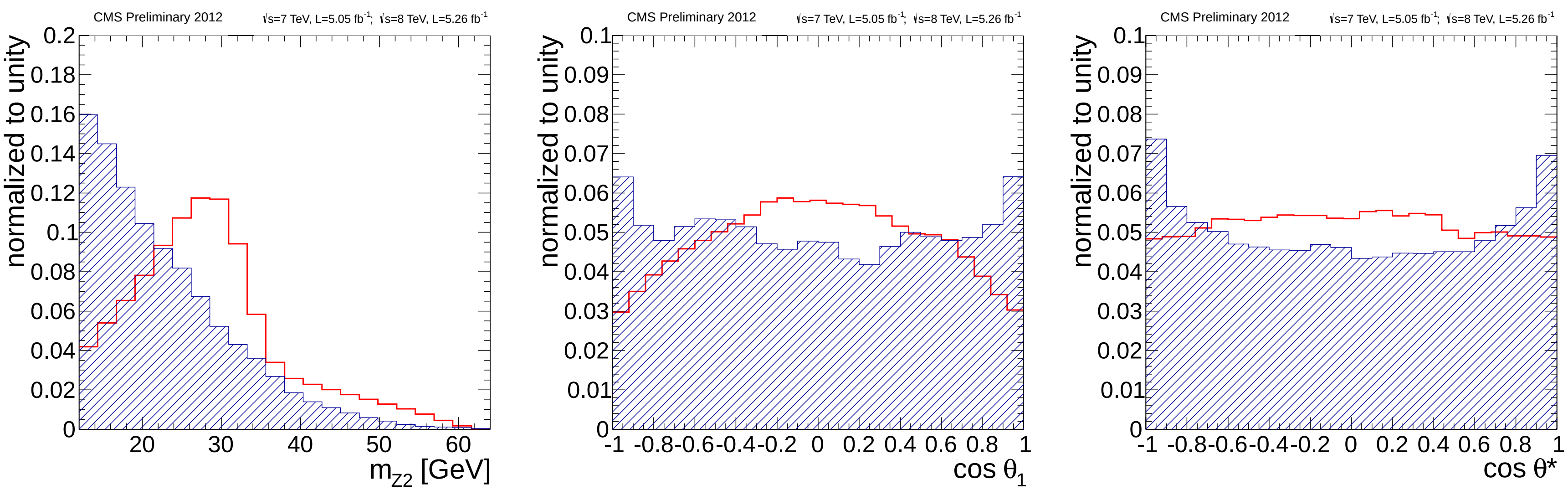
CMS MELA: Matrix Element Likelihood Analysis

$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

- Used in $H \to ZZ^{(*)} \to 2q2\ell$ in 2011
  JHEP04(2012)036
  from PRD81,075022(2010)



- Discriminate signal vs background
  – QCD effects suppressed (no p_T, Y)
  independent of production mechanism

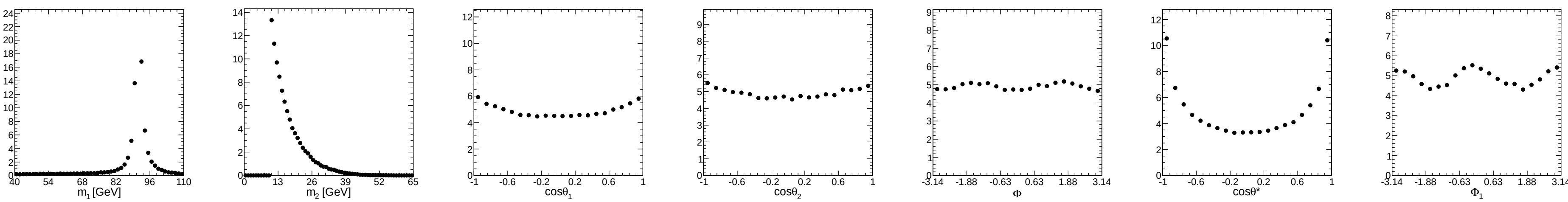


MELA Parameterization

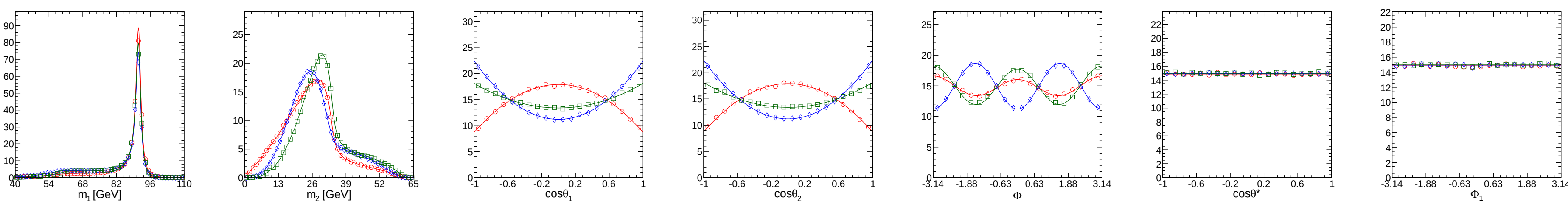
$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})} \right]^{-1}$$

$\rightarrow$ detector acceptance cancels in the ratio, correlations included

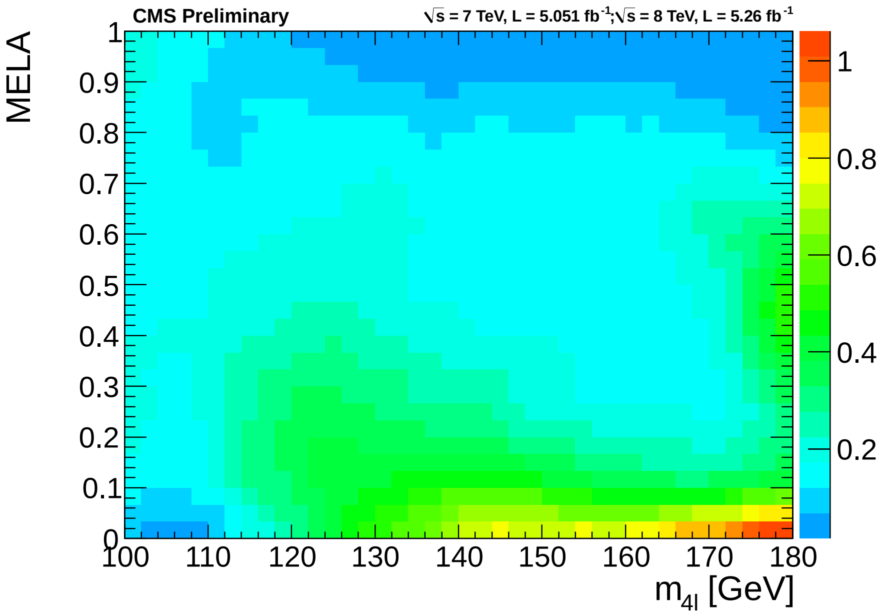
- $\mathcal{P}_{\text{bkg}} \propto$ JHEP11(2011)027 $(m_{4\ell} > 180$ GeV$)$: dominant $q\bar{q} \rightarrow ZZ$
  $\propto$ POWHEG template $(m_{4\ell} < 180$ GeV$)$: dominant $q\bar{q} \rightarrow Z\gamma^*$

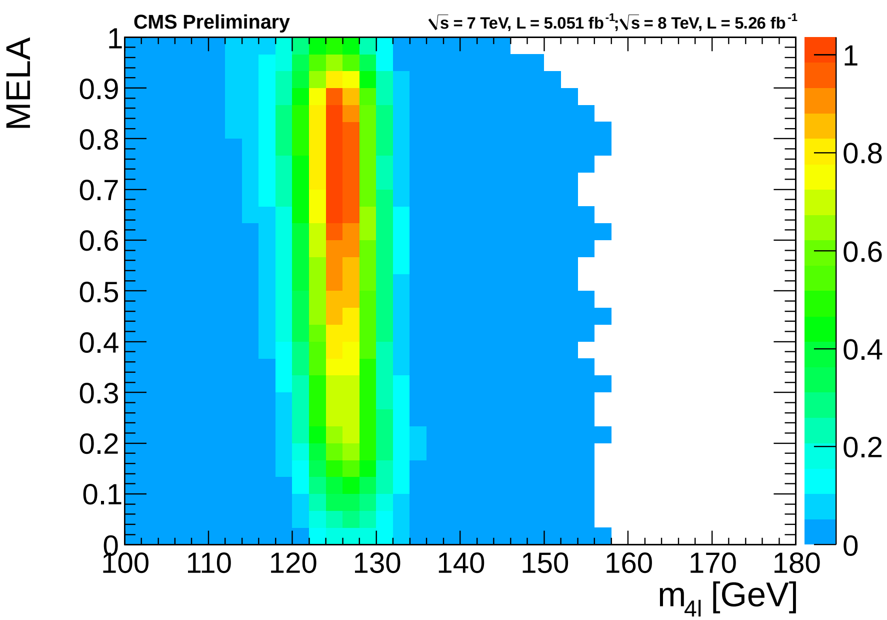


- $\mathcal{P}_{\text{sig}} \propto$ analytical signal distributions

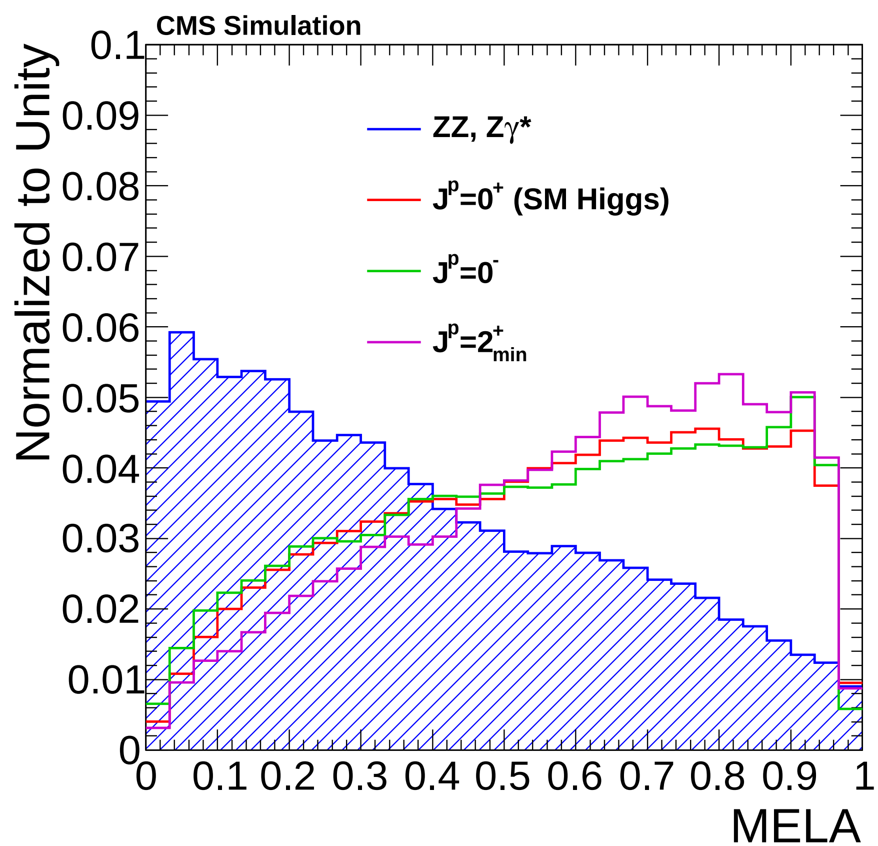


CMS: 2D analysis MELA vs $m_{4\ell}$

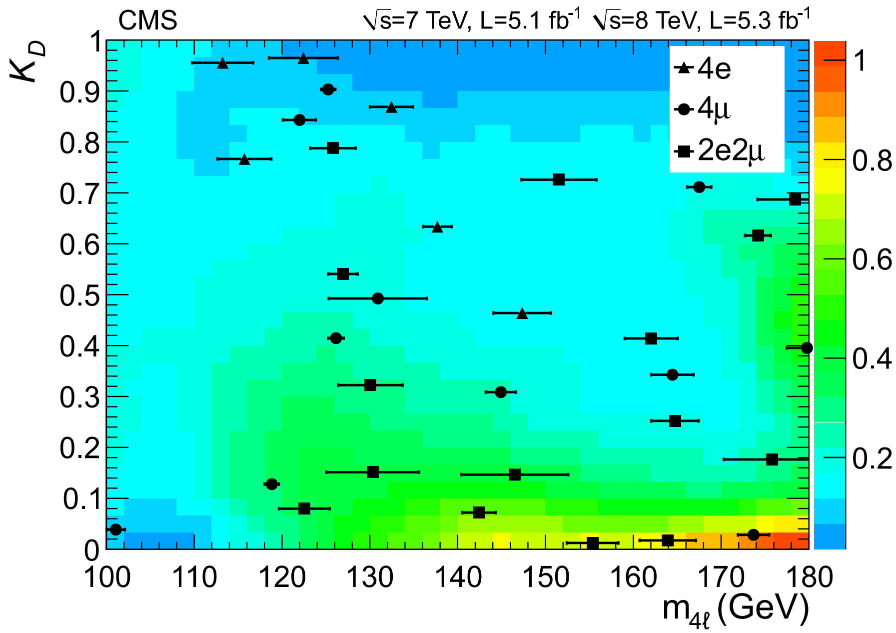


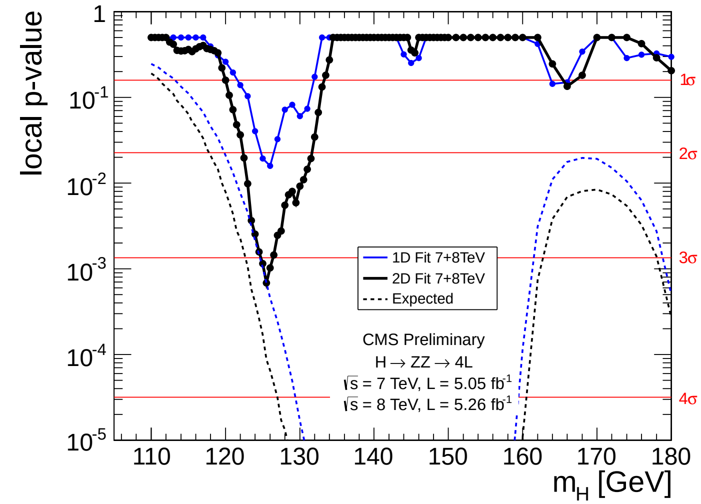


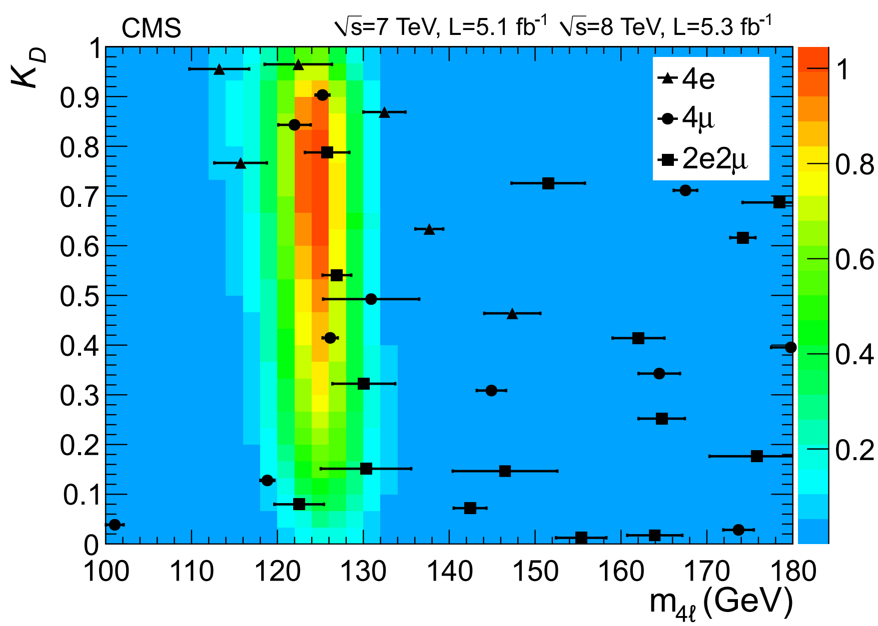
- Model with full simulation
  - include interference
  - powerful sig.-bkg. separation
  - little model-dependence

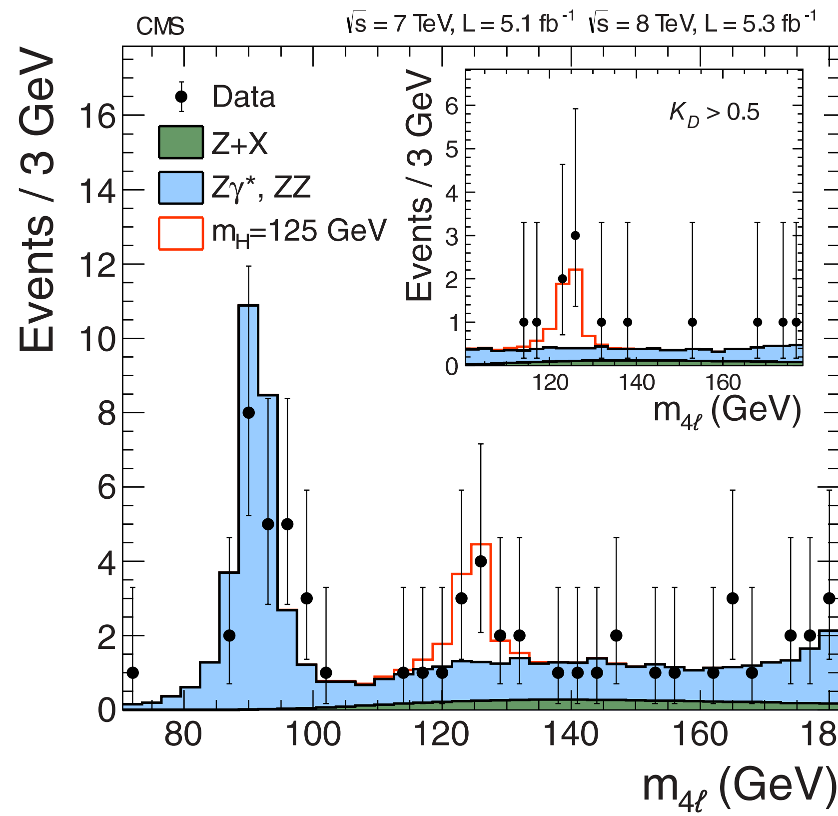


CMS: 2D analysis MELA vs $m_{4\ell}$



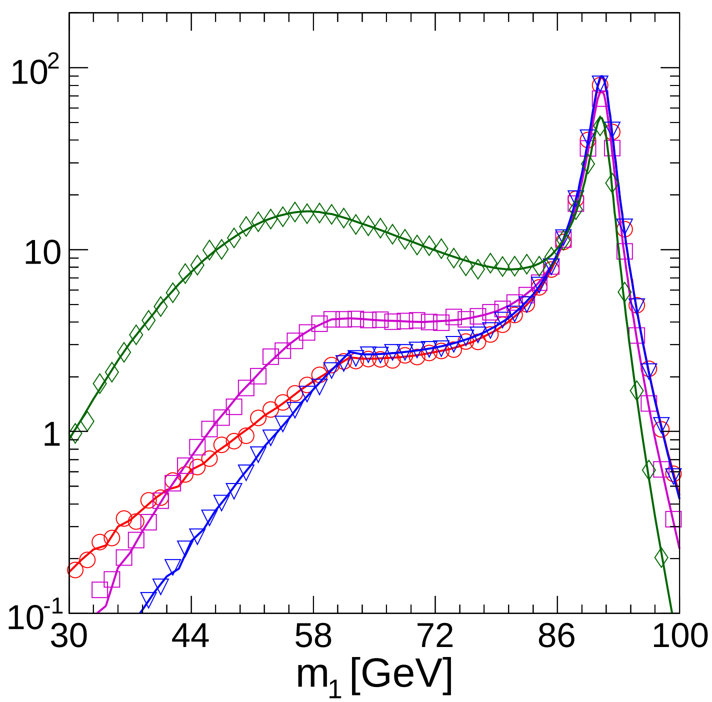


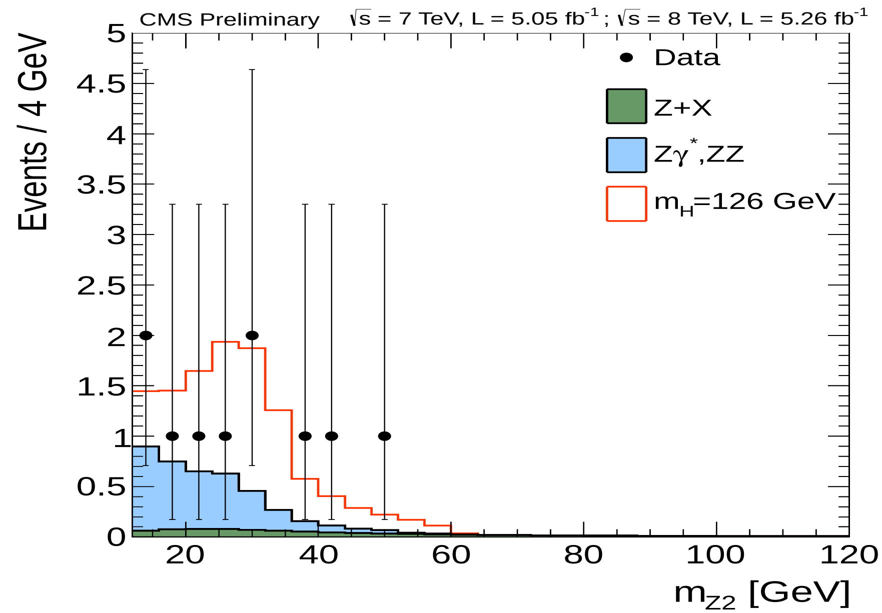


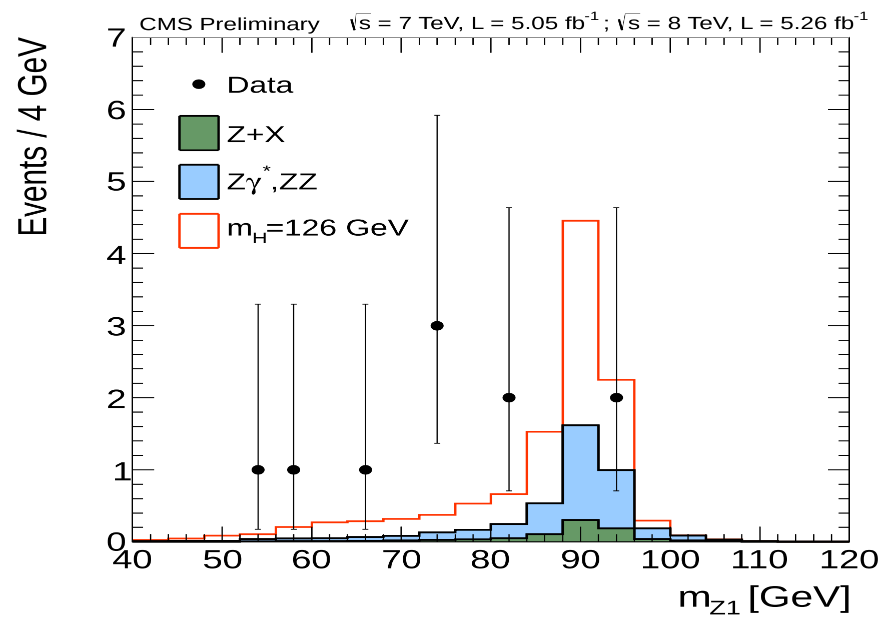


CMS: Interesting Feature in $H \to Z^{(*)}Z^{(*)} \to 4\ell$

- CMS data favors both Z^* off-shell
  - too early to speculate
  - need to watch

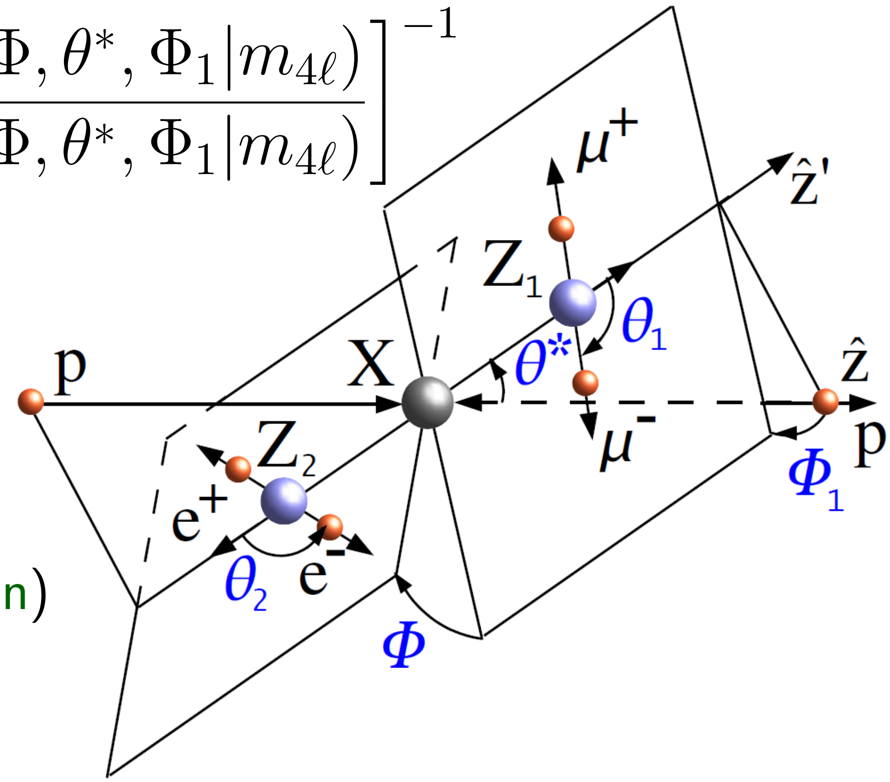




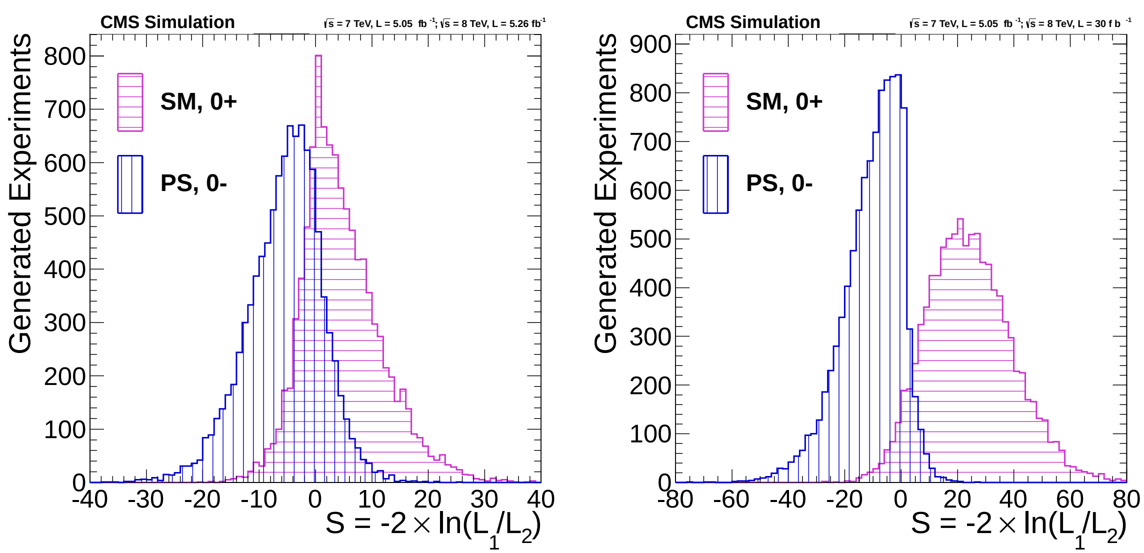


CMS: MELA for Spin / Parity

$$\text{psMELA} = \left[1 + \frac{\mathcal{P}_{0-}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{0+}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

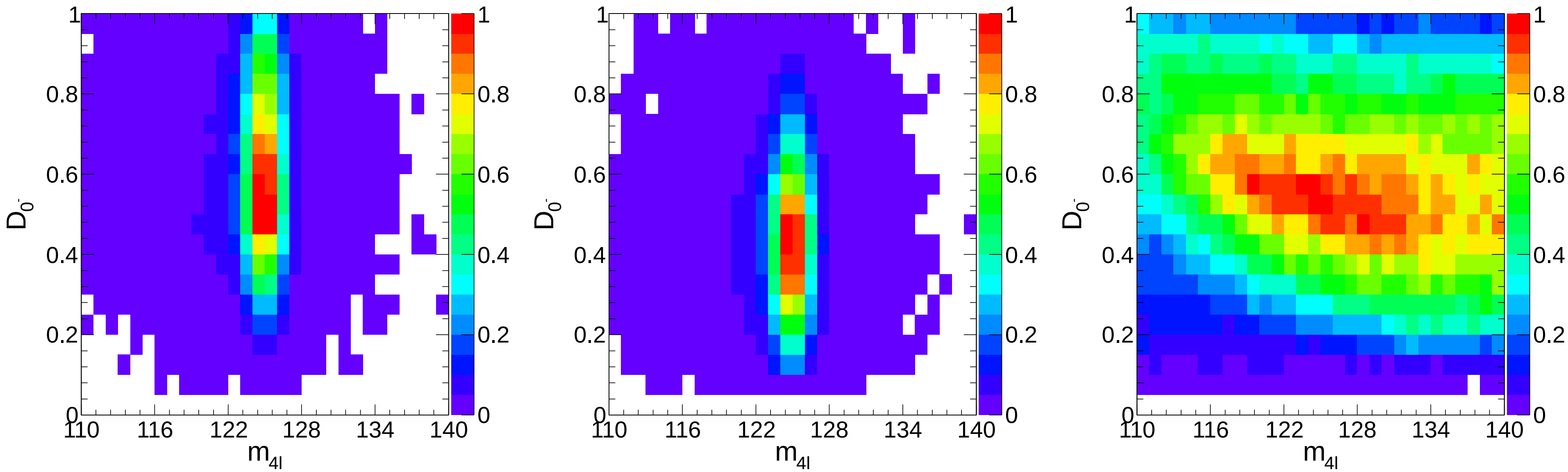


- Hypothesis testing
  - scalar (0^+) vs pseudoscalar (0^-)
  - may include any other model
- Simulation (http://www.pha.jhu.edu/spin)
  - expected separation 1.6σ now
  - 3.1σ with 5+30 fb^{-1}

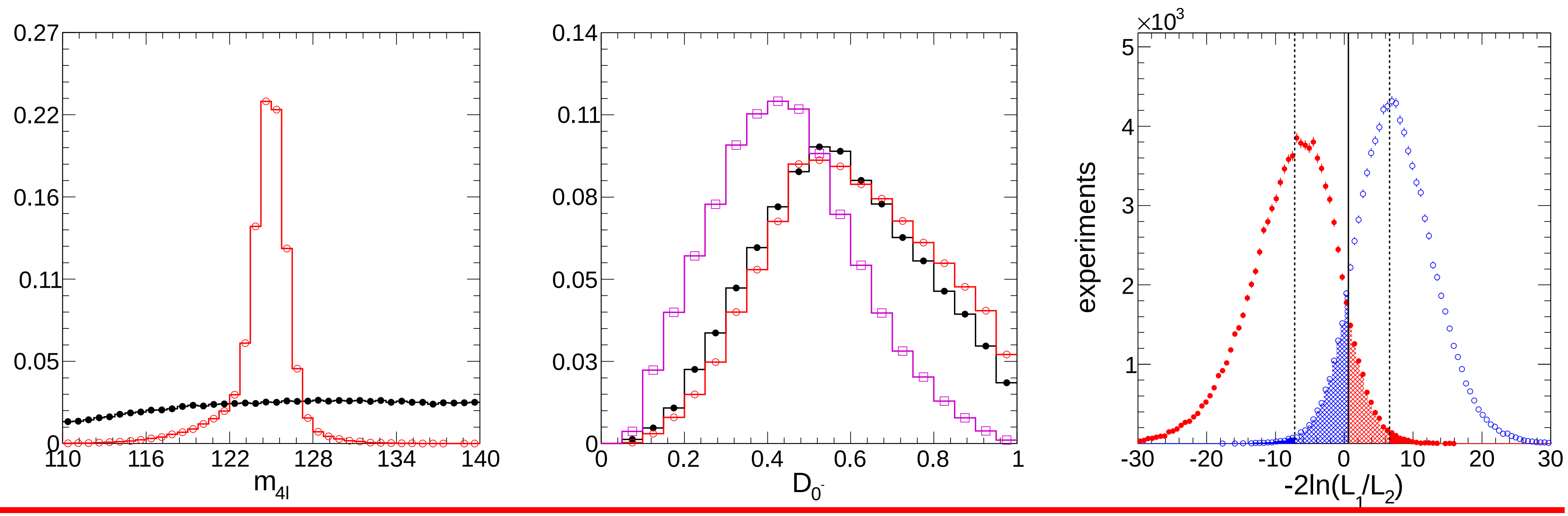


Simplified study: $H \to ZZ \to 4\ell$

- Perform 2D analysis $(m_{4\ell}, \text{psMELA})$

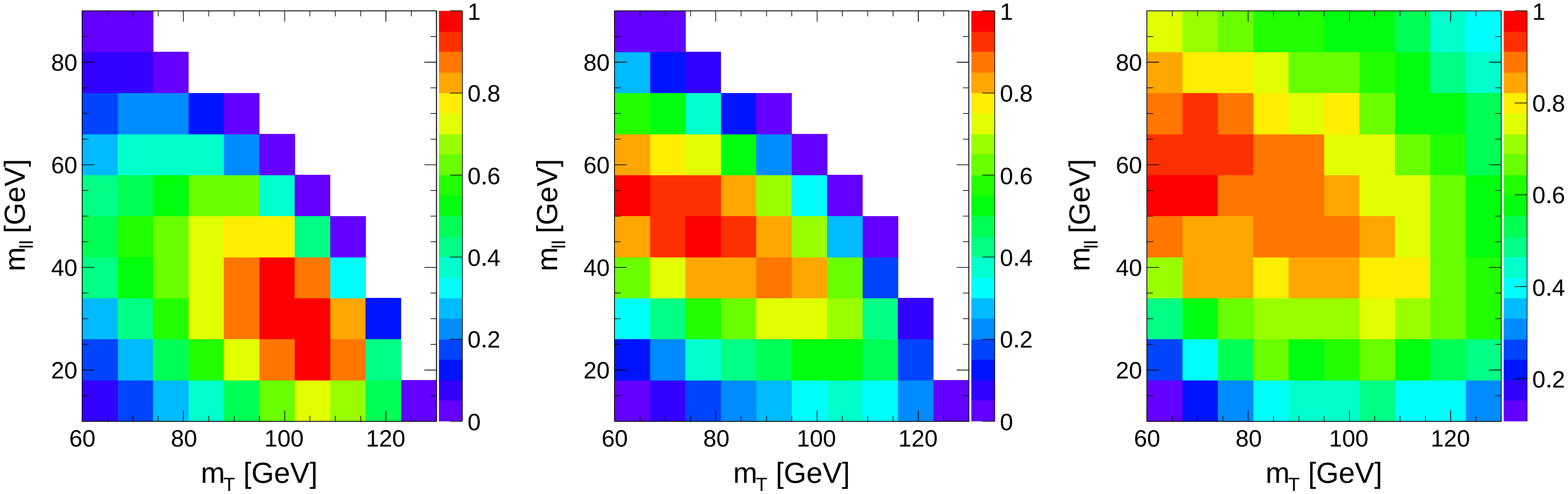


- Hypothesis testing: 0^+_m (SM) vs 0^- at 2.9σ when sig vs bkg 5σ

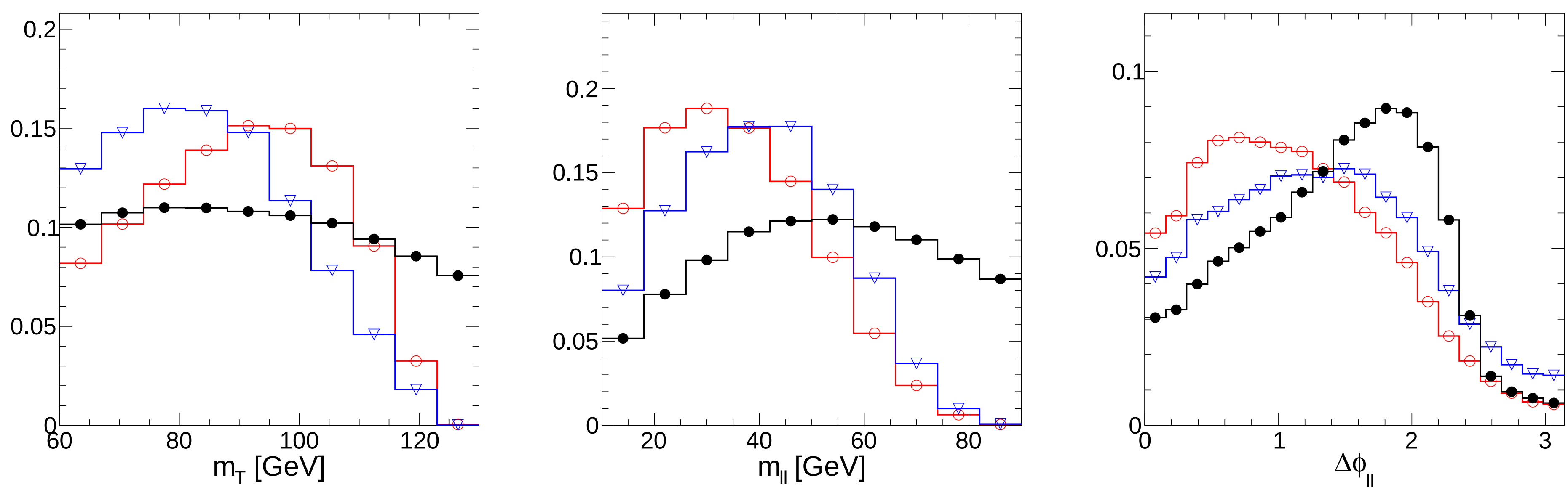


Simplified study: $H \to WW \to 2\ell 2\nu$

- 2D analysis $(m_T, m_{\ell\ell})$, $m_T = (2p_T^{\ell\ell} E_T^{\rm miss}(1-\cos\Delta\phi_{\ell\ell - E_T^{\rm miss}}))^{1/2}$

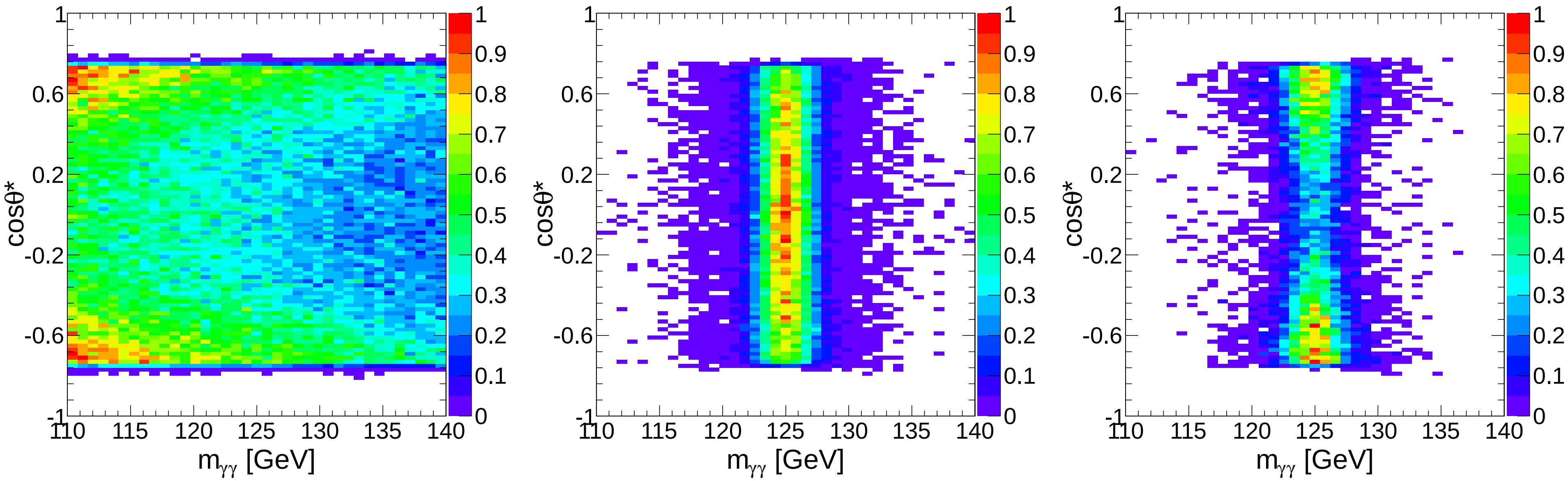


- Hypothesis testing: 0_m^+ (SM) vs 2^+ at 2.8σ when sig vs bkg 5σ

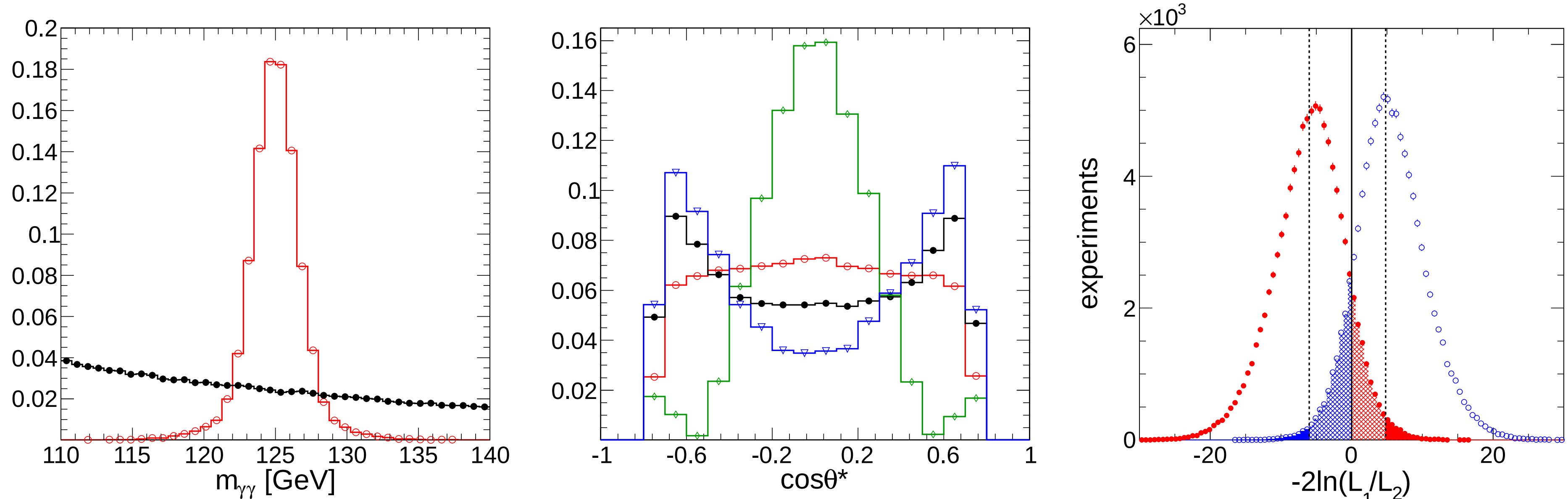


Simplified study: $H \to \gamma\gamma$

- 2D analysis $(m_{\gamma\gamma}, \cos\theta^*)$



- Hypothesis testing: 0^+_m (SM) vs 2^+ at 2.4σ when sig vs bkg 5σ

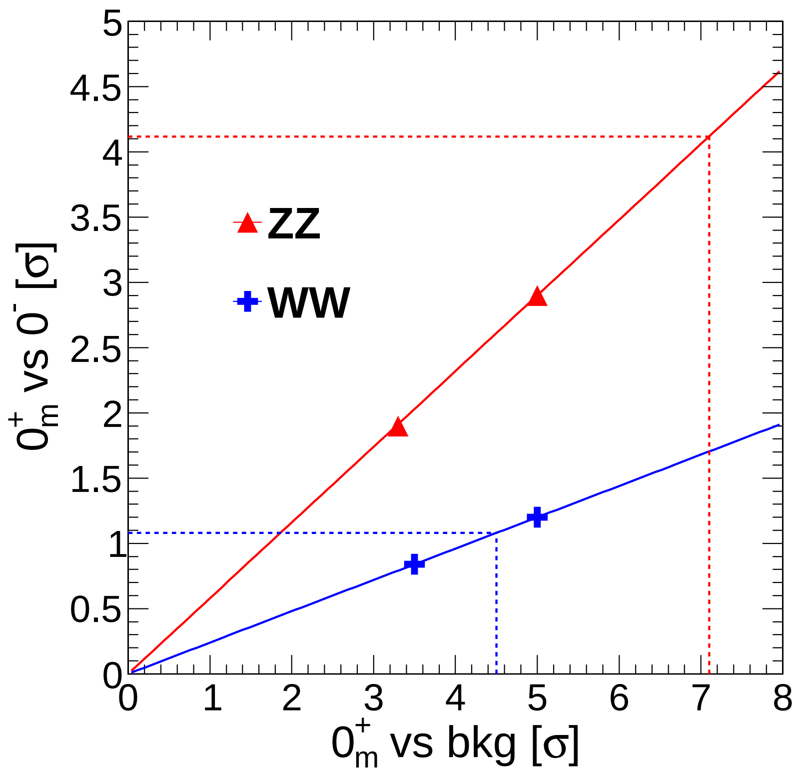


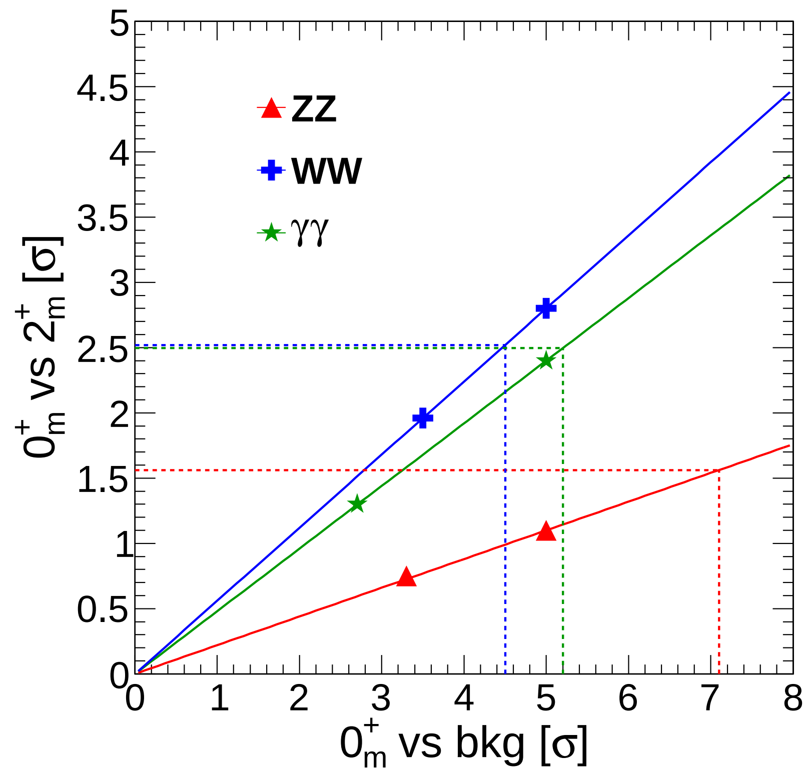
Scan different hypothese

- Take 5σ yield as a reference, compare to current status at ICHEP:

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$
0_m^+ vs bkg	5.0	5.0	5.0
CMS now (expect/observe)	(3.8/3.2)	(2.4/1.6)	(2.8/4.1)
0_m^+ vs 0_h^+	1.8	1.1	0.0
0_m^+ vs 0^-	2.9	1.2	0.0
0_m^+ vs 1^+	2.1	2.0	–
0_m^+ vs 1^-	2.8	3.2	–
0_m^+ vs 2_m^+	1.1	2.8	2.4
0_m^+ vs 2_h^+	$\sim$5	1.1	3.1
0_m^+ vs 2_h^-	$\sim$5	2.5	3.1

Optimistic projecting into the future (5+30/fb)

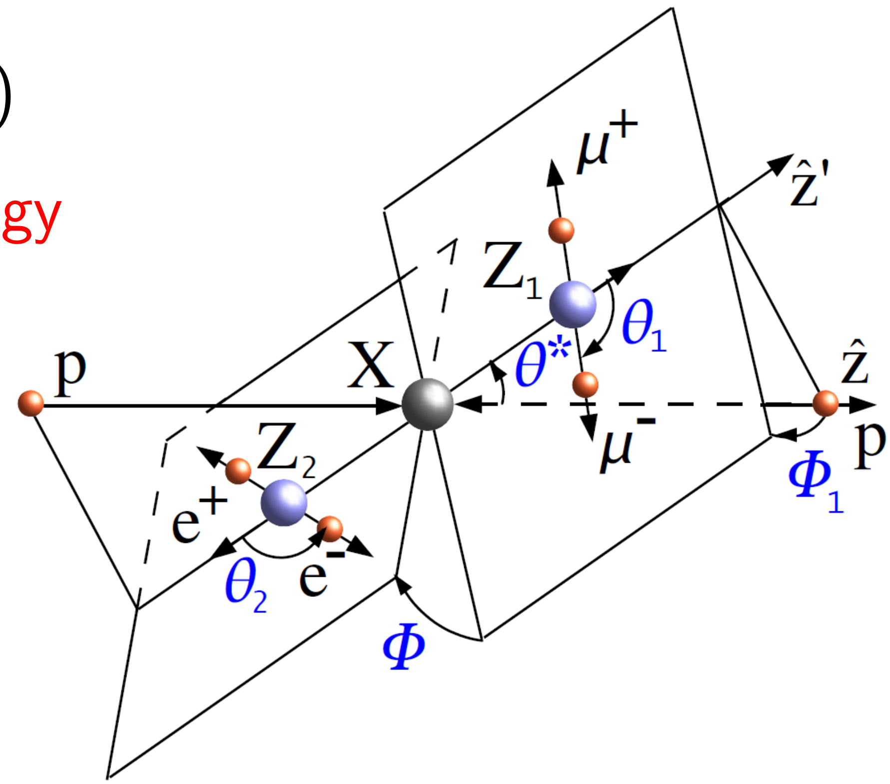




scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0^+_m vs bkg	7.1	4.5	5.2	9.9
0^+_m vs 0^-	4.1	1.1	0.0	4.2
0^+_m vs 2^+_m	1.6	2.5	2.5	3.9

Conclusion

- New boson on LHC (CMS+ATLAS)
  - new exciting form of matter/energy
- Need to understand what it is
  - find its quantum numbers
  - find its couplings to matter
- Angular & mass analysis
  - should work well with LHC data
- Next 6 months will be exciting
  - we will more than double our data
  - we will measure more than the rate
- It will be a long adventure in either case...

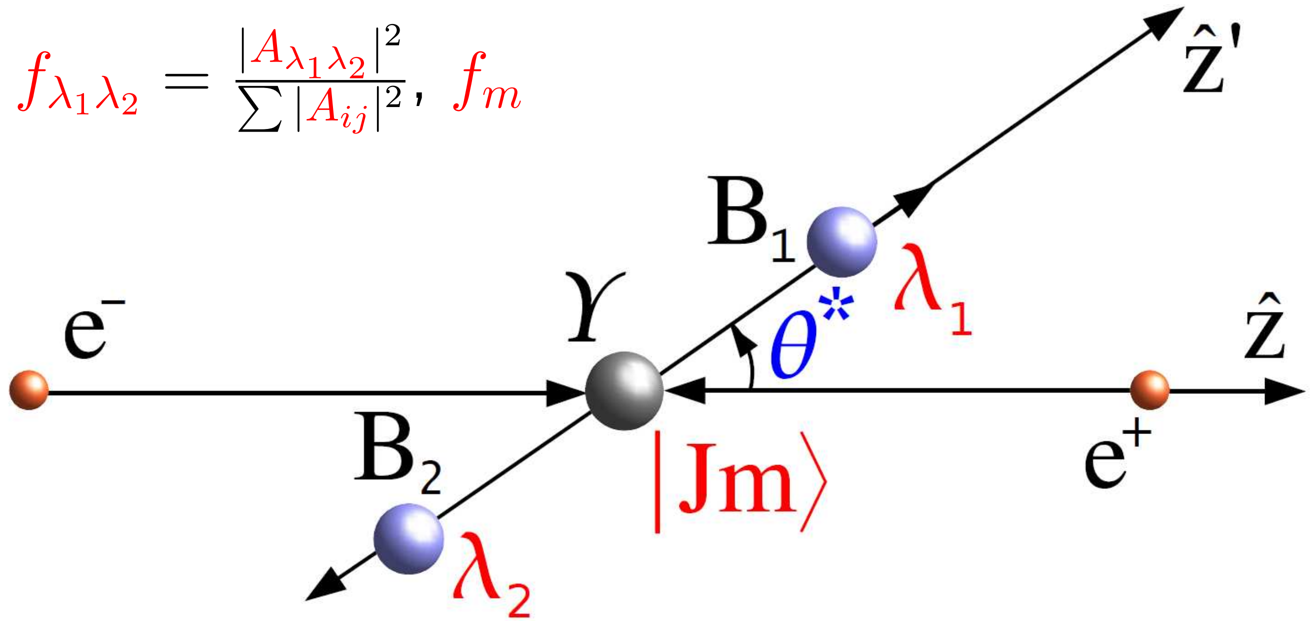


BACKUP

Kinematics in e^+e^- with $\boldsymbol{B \to VV}$

- Angular distribution of $X \to P_1 P_2$

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



$$\frac{d\Gamma(X_J \to P_1 P_2)}{\Gamma d\cos\theta^*} = \left(J + \frac{1}{2}\right) \sum_{\lambda_1,\lambda_2} f_{\lambda_1\lambda_2} \sum_m f_m |d^J_{m,\lambda_1-\lambda_2}(\theta^*)|^2$$

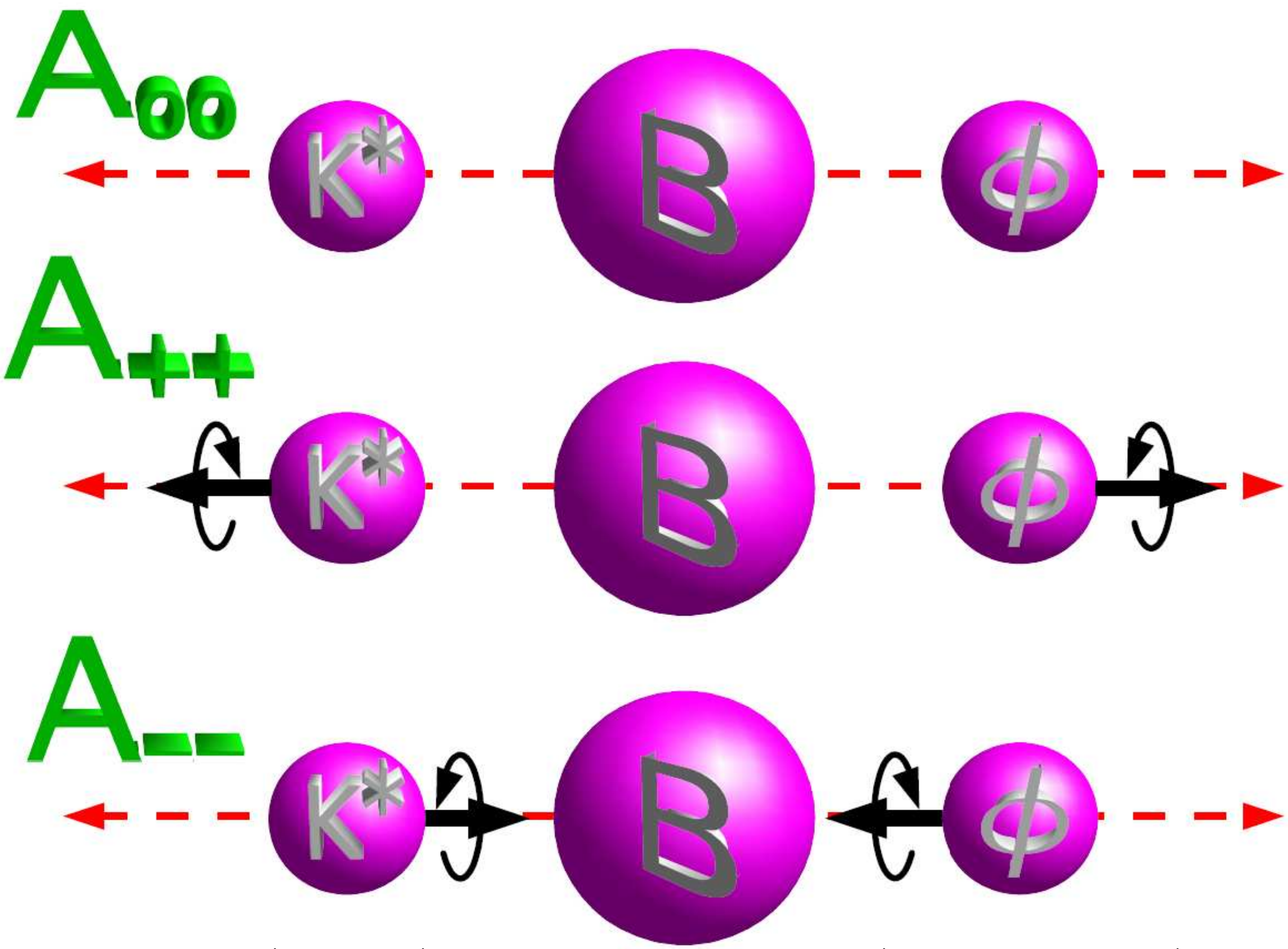
- For $\Upsilon \to B\bar{B}$:
  $\lambda_1{=}\lambda_2{=}0$, $J{=}1$, $m{=}\pm 1$

$$\frac{d\Gamma(\Upsilon \to B\bar{B})}{\Gamma d\cos\theta^*} \propto |d^1_{1,0}(\theta^*)|^2 \propto \sin^2\theta^*$$

Polarization Experiment with $\boldsymbol{B \to VV(T)}$

- 3 spin configurations $\Rightarrow$ 3 amplitudes $A_{\lambda_1\lambda_2}$ (similar to $H \to ZZ$...)

$$|J_B, m\rangle = |0,0\rangle \quad \Rightarrow \lambda_1 = \lambda_2$$



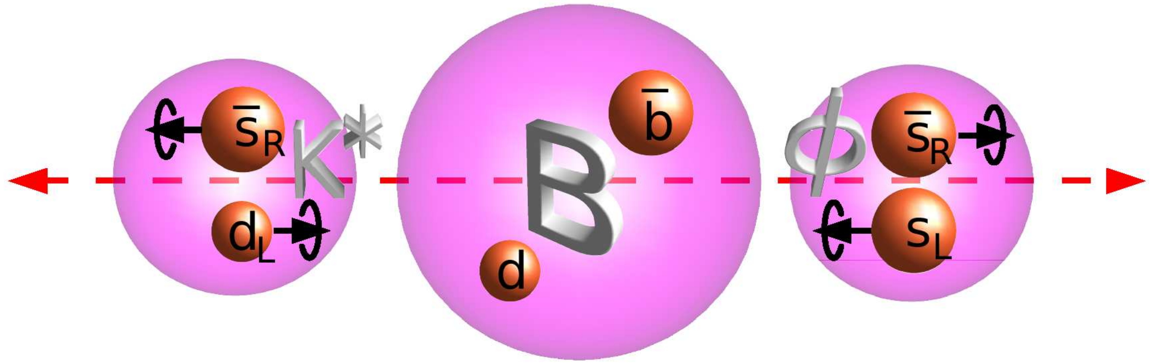
$$|J, \lambda_1\rangle \qquad\qquad |J_\varphi = 1, \lambda_2\rangle$$

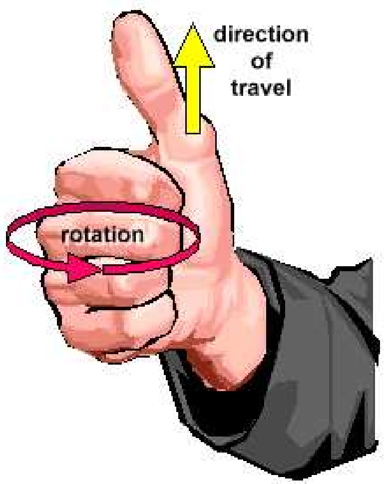
- Try $K_J^{(*)} \to K\pi(\pi)$ with $J^P = 0^+, 0^-, 1^+, 1^-, 2^+, 2^-, 3^-, 4^+, \ldots$

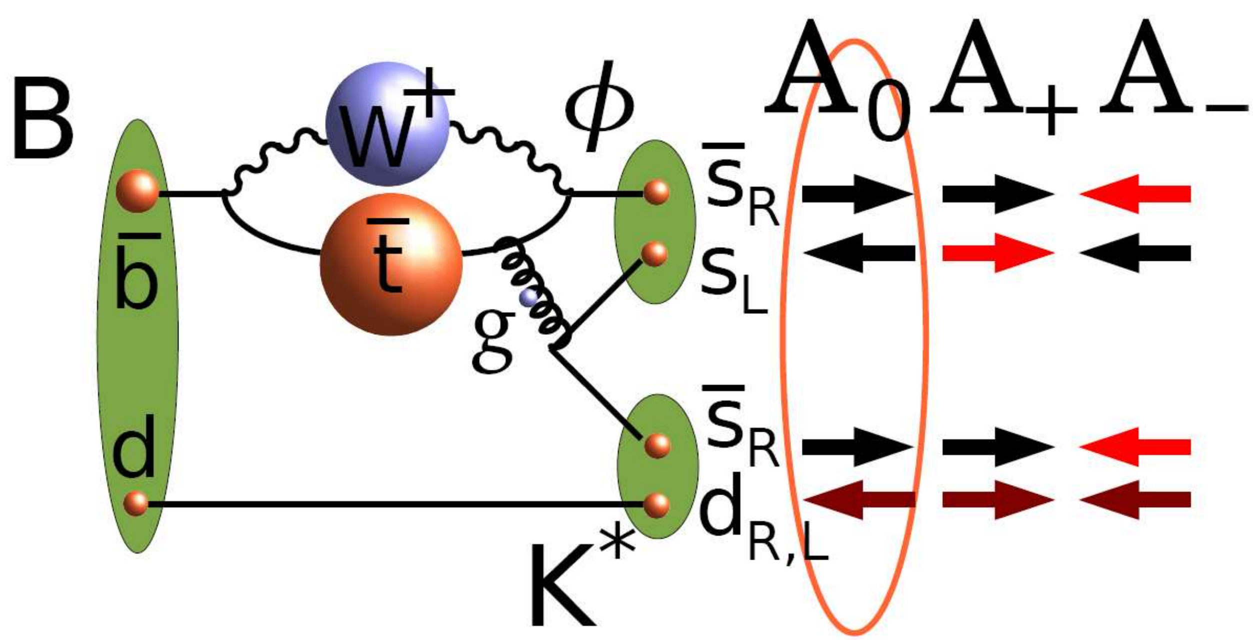
Polarization in B Decays

- "penguin" $B \to \varphi K^*$ with vector (tensor) mesons

polarization puzzle BABAR arXiv:hep-ex/0303020; BELLE arXiv:hep-ex/0307014



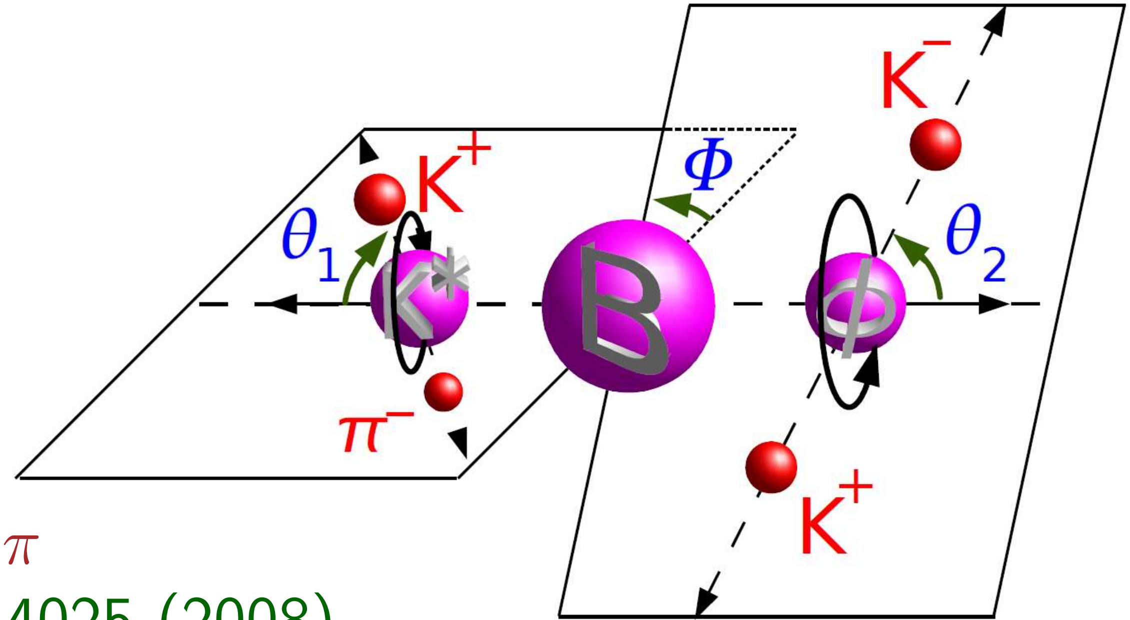




$|A_{00}|^2 \gg |A_{++}|^2 \gg |A_{--}|^2$ suppression$\sim(m_\varphi/m_B)^2\sim 1/25$

Angular Measurements

- For $K^* \to K\pi$:



- For $K_J^{(*)} \to K\pi\pi$
  see PRD 77, 114025 (2008)

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto \left| \sum_J \sum_{\lambda=\pm,0} A^J_{\lambda\lambda} \times Y_J^{\lambda}(\theta_1, \Phi) \times Y_1^{-\lambda}(\pi - \theta_2, 0) \right|^2$$

transverse; longitudinal

$$d\Gamma_{J=1} \propto \Big\{ \frac{1}{4} \sin^2\theta_1 \sin^2\theta_2 \left(|A_{++}|^2 + |A_{--}|^2\right) + \cos^2\theta_1 \cos^2\theta_2 |A_{00}|^2$$

$$+\frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 \left[\cos 2\Phi \ \mathrm{Re}(A_{++}A^*_{--}) - \sin 2\Phi \ \mathrm{Im}(A_{++}A^*_{--})\right]$$

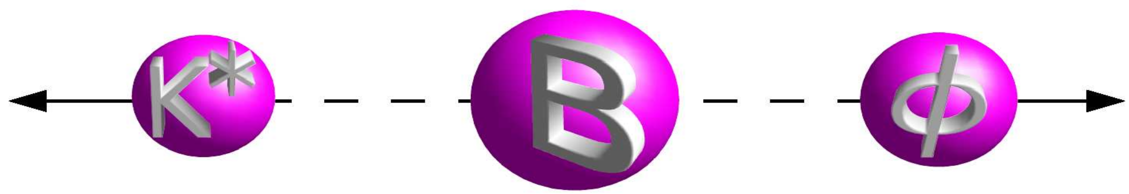
$$+\frac{1}{4}\sin 2\theta_1 \sin 2\theta_2 \left[\cos\Phi \ \mathrm{Re}\left(A_{++}A^*_{00} + A_{--}A^*_{00}\right) - \sin\Phi \ \mathrm{Im}\left(A_{++}A^*_{00} - A_{--}A^*_{0}\right)\right]\Big\}$$

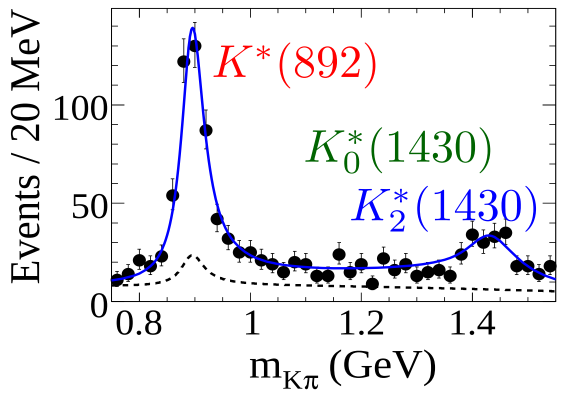
Polarization in $B \to \varphi K_J^{(*)}$ Decays

- Complex multivariate analysis with 12 parameters per channel

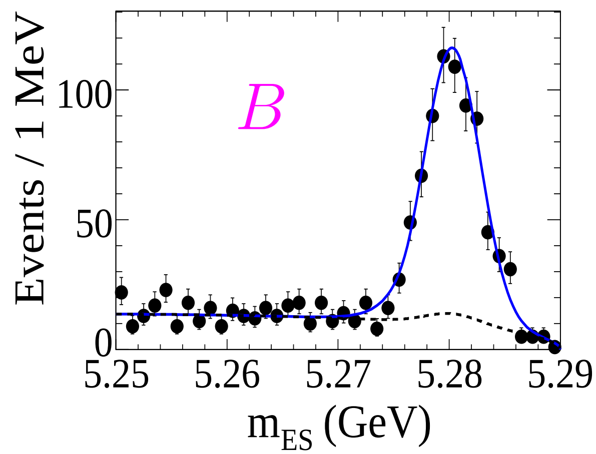
B (matter): $|A_{00}|, |A_{++}|, |A_{--}|, \arg(A_{00}), \arg(A_{++}), \arg(A_{--})$

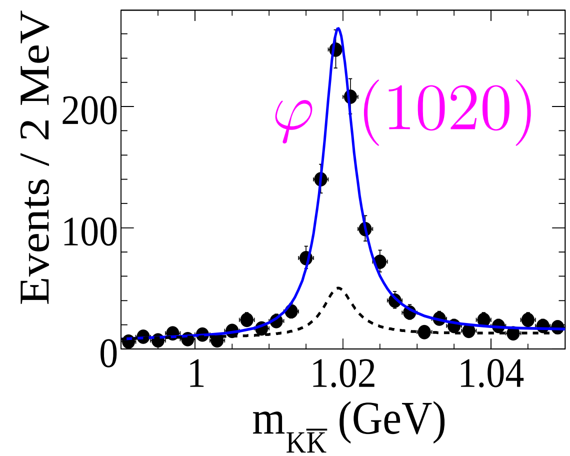
$\bar{B}$ (antimatter): $|\bar{A}_{00}|, |\bar{A}_{++}|, |\bar{A}_{--}|, \arg(\bar{A}_{00}), \arg(\bar{A}_{++}), \arg(\bar{A}_{--})$

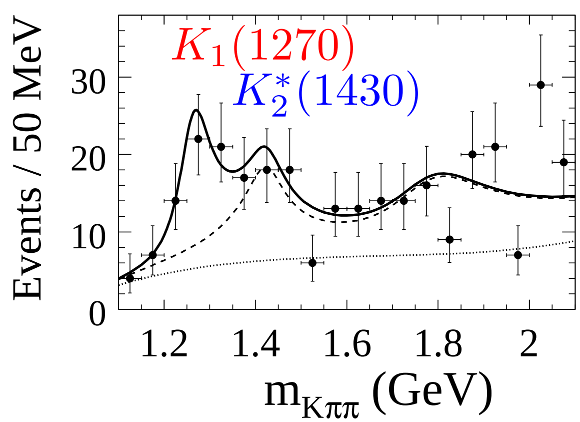




BABAR PRD78,092008(2008)





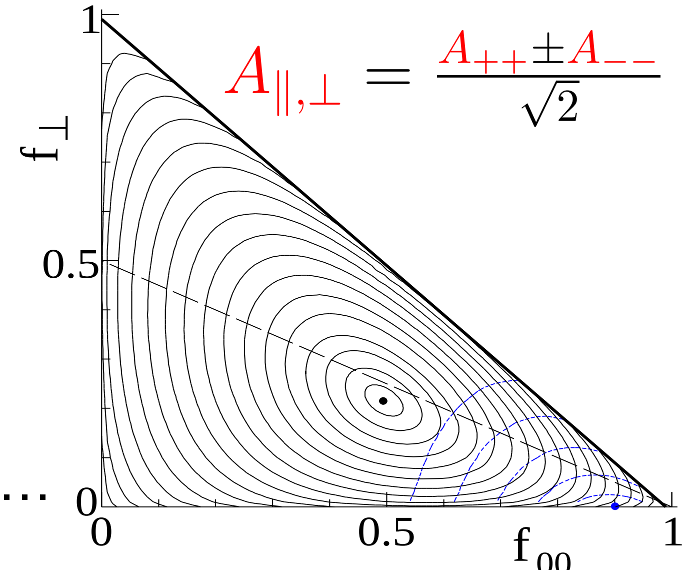


BABAR PRL101,161801(2008)

Polarization in $B \to \varphi K_J^{(*)}$ Decays

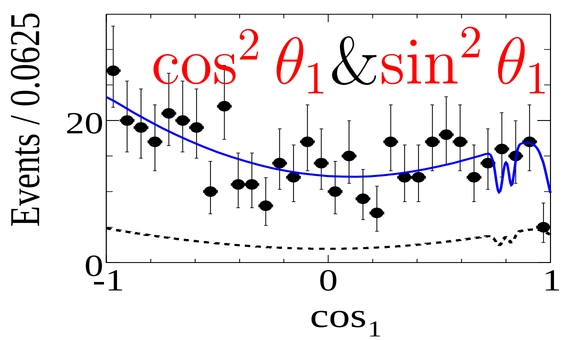
- Puzzle $J = 1$, not 2: $|A_{00}|^2 \simeq |A_{++}|^2 \gg |A_{--}|^2$; $\arg(\frac{A_{00}}{A_{++}}) \neq 0, \pi$

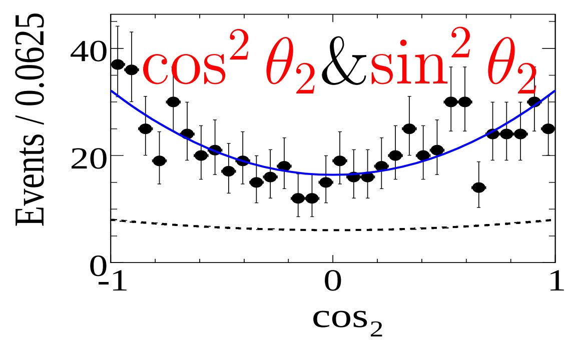
BABAR	J^P	$f_{00} = \frac{\lvert A_{00}\rvert^2}{\sum \lvert A_{\lambda\lambda}\rvert^2}$
$B \to \varphi K^*(892)^0$	1^-	$0.494 \pm 0.034 \pm 0.013$
$B \to \varphi K^*(892)^+$	1^-	$0.49 \pm 0.05 \pm 0.03$
$B \to \varphi K_1(1270)^+$	1^+	$0.46\ ^{+0.12}_{-0.13}\ ^{+0.03}_{-0.07}$
$B \to \varphi K_2^*(1430)^0$	2^+	$0.901^{+0.046}_{-0.058} \pm 0.037$
$B \to \varphi K_2^*(1430)^+$	2^+	$0.80\ ^{+0.09}_{-0.10} \pm 0.03$



looked for $K_J^{(*)}$ with 2^-, 3^-, 4^+, none found...

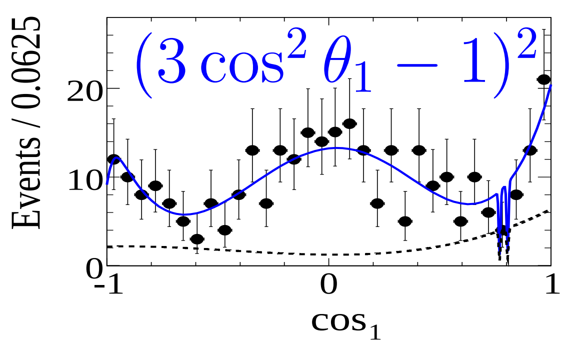
$K^*(892)$

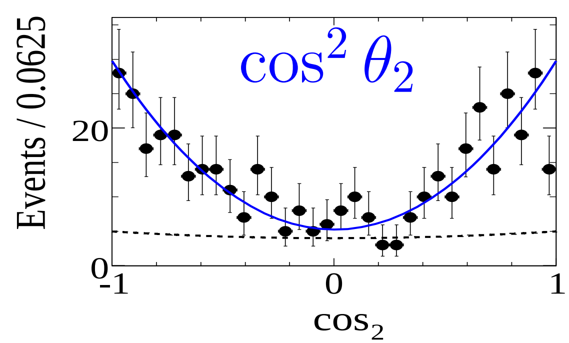




$\varphi(1020)$

$K_2^*(1430)$
$K_0^*(1430)$





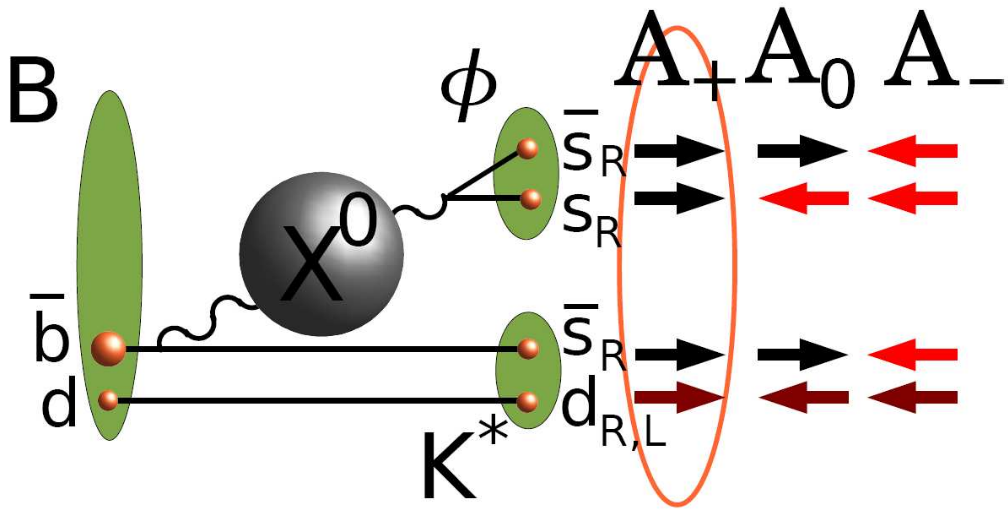
$\varphi(1020)$

New Physics in B Decay Polarization

violate $|A_{00}|^2 \gg |A_{++}|^2 \gg |A_{--}|^2$

SM: $\bar{q}\gamma^\mu(1-\gamma^5)q$

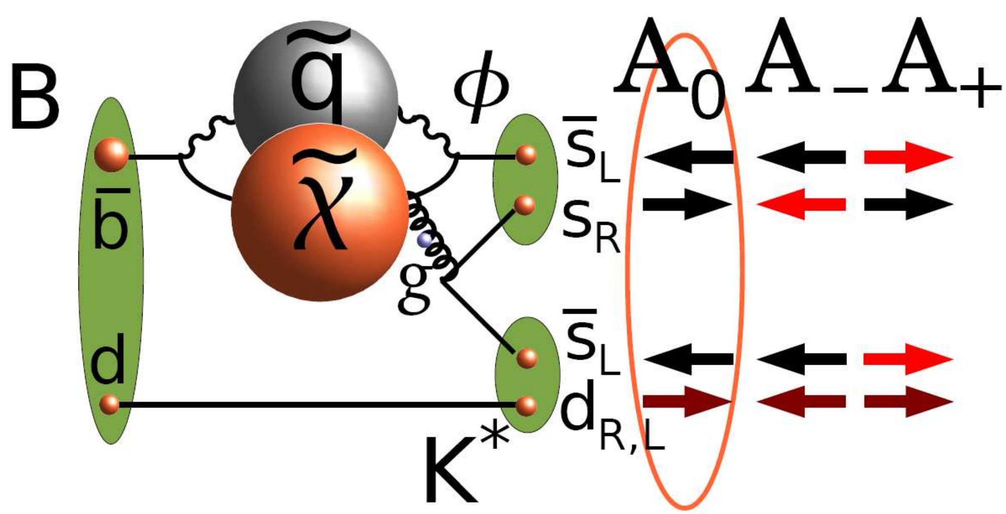
scalar (tensor) interaction



$|A_{++}|^2 \gg |A_{00}|^2 \gg |A_{--}|^2$

$\bar{q}(1+\gamma^5)q$

supersymmetry



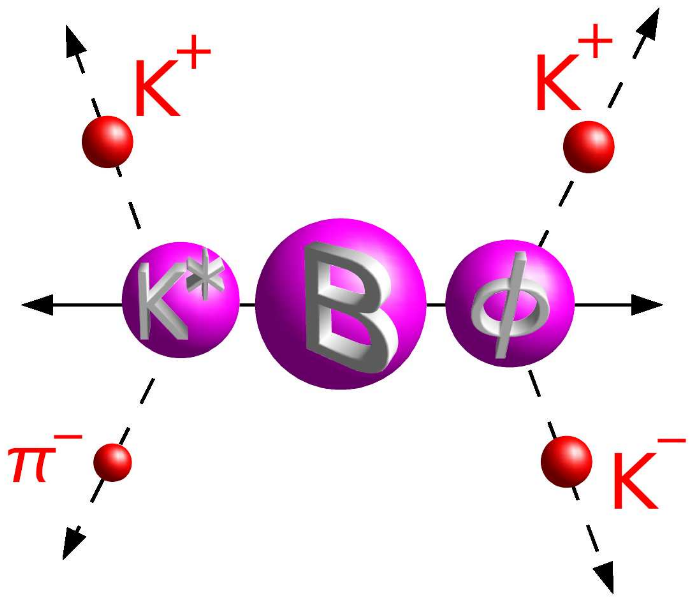
$|A_{00}|^2 \gg |A_{--}|^2 \gg |A_{++}|^2$

$\bar{q}\gamma^\mu(1+\gamma^5)q$

QCD rescattering,
penguin annihilation ???
no satisfactory solution...

What we have learned

from B decays:



- power of spin correlations
- extract maximum information
- production and decay angular formalism
- surprises (either within or beyond SM)
- better to look for beyond SM in direct production

  if energy reachable at LHC