The Power of Spin Correlations:
from B-decays to Higgs and Beyond at the LHC

Andrei Gritsan

Johns Hopkins University

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Fermilab Joint Experimental-Theoretical Seminar

Credits

- Based on two topics:

"Spin determination of single-produced resonances at hadron colliders"
arXiv:1001.3396 [hep-ph] (Jan. 19, 2010) $\Rightarrow$ 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

"Time-dependent and time-integrated angular analysis of $B \to \phi(K\pi)$"
BABAR Collaboration arXiv:0808.3586 [hep-ex] $\Rightarrow$ PRD78,092008(2008)
and references

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

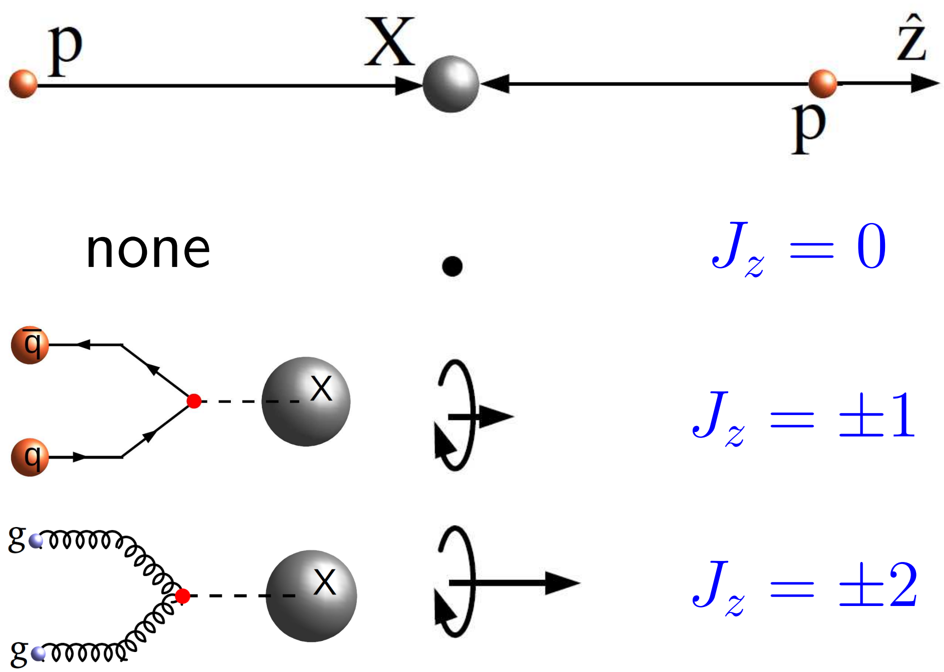
"Higgs look-alikes at the LHC" arXiv:1001.5300 [hep-ph] (Jan. 29, 2010)

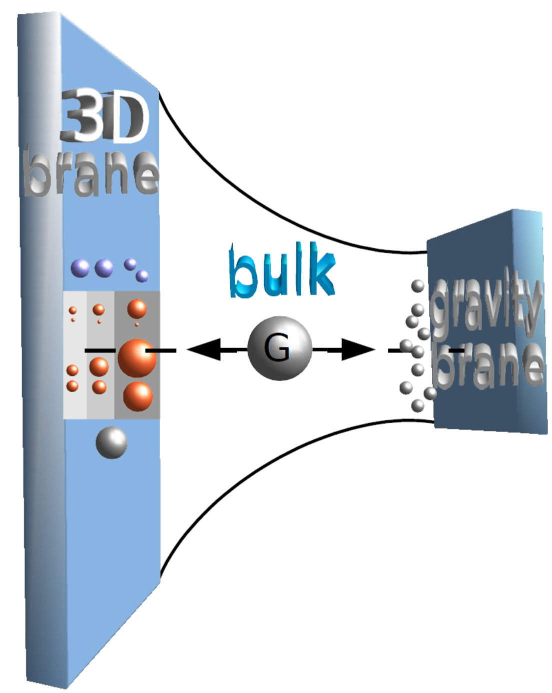
A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M. Spiropulu

Start with One Specific Question for LHC

- KK Graviton couples to SM through energy-momentum tensor

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

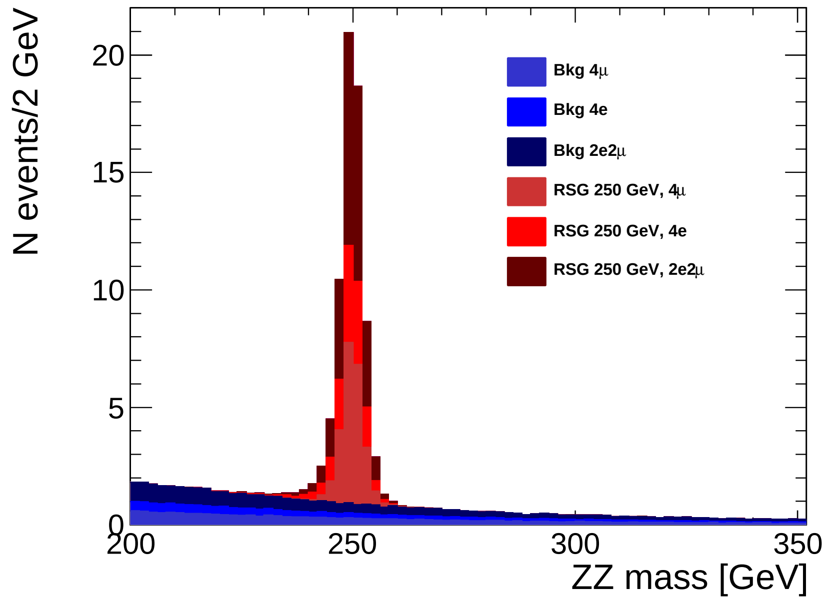




  - consequence: $J_z \neq 0$
  - only a model ("minimal"), try most general approach
  - spin correlations $\Rightarrow$ spin determination, and a lot more...

Questions

- If resonance is observed on LHC
  - mass, width, rate, branching
  - quantum numbers?
  - couplings to SM fields?
  - maximum information?



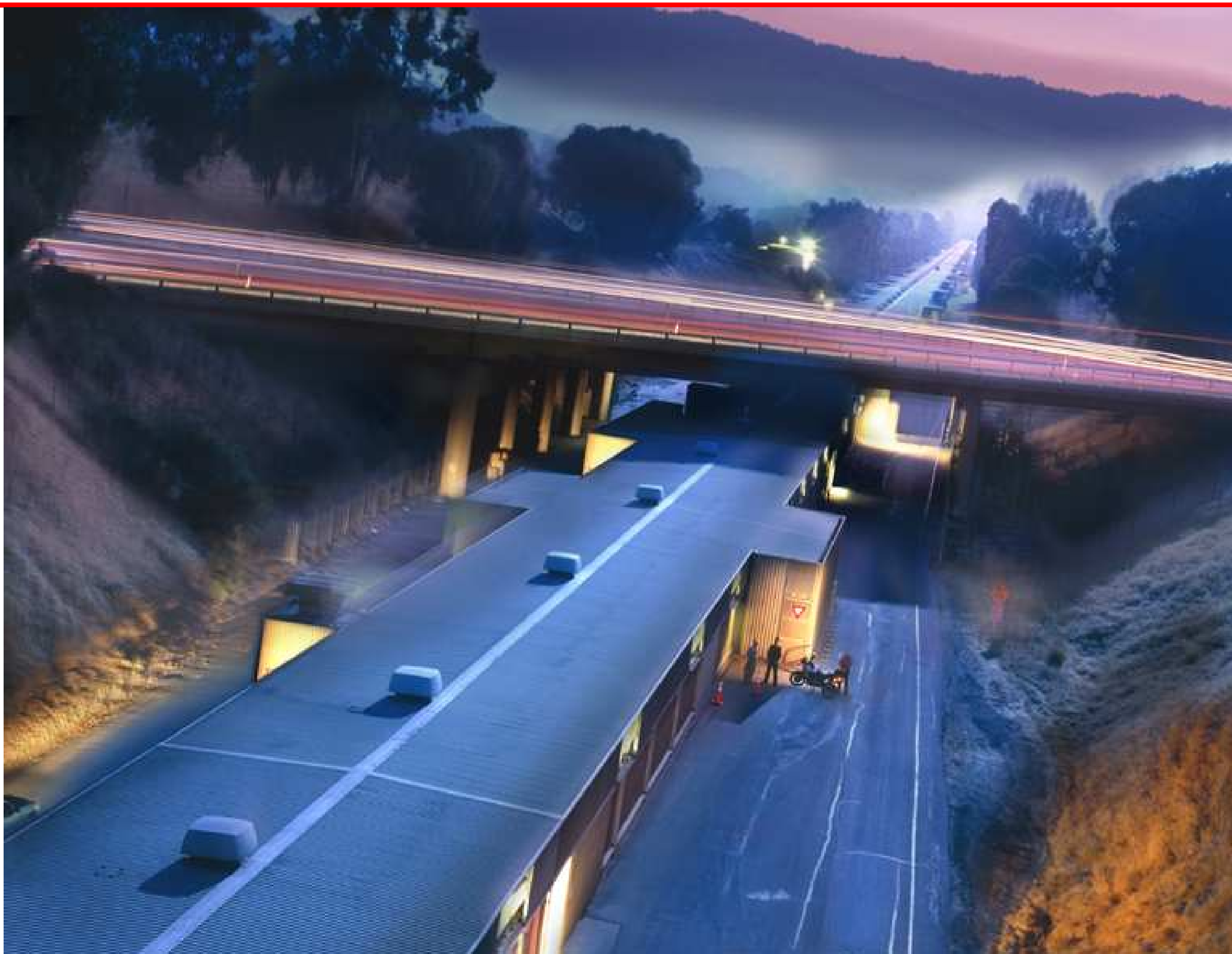
- Build on recent experience in B-physics

  production $e^+e^- \to \Upsilon \to B\bar{B}$ (analogy to $q\bar{q} \to X$)
  decay $B \to VV$ (analogy to $H \to VV$)
  weak and strong interaction dynamics (effective couplings)

  build on full angular/helicity formalism

- There is a long history (e.g. $\pi^0 \to e^+e^-e^+e^-$; $e^+e^- \to J/\psi$ ...)

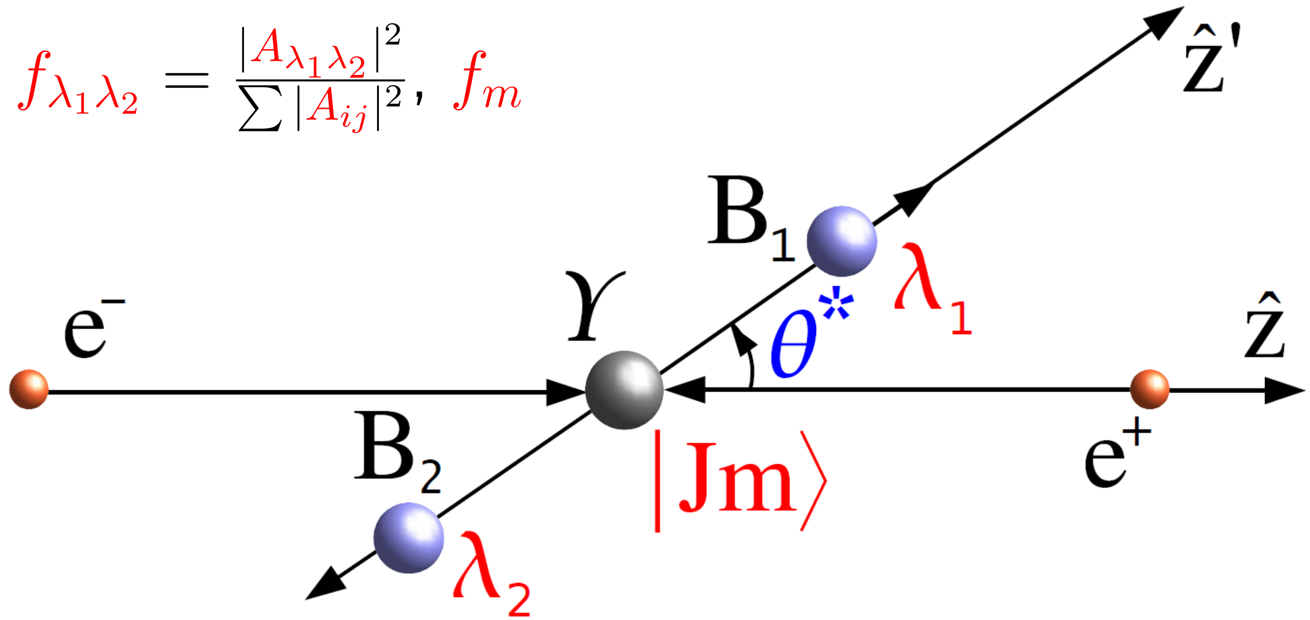
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ at SLAC



Kinematics in Production

- 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



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

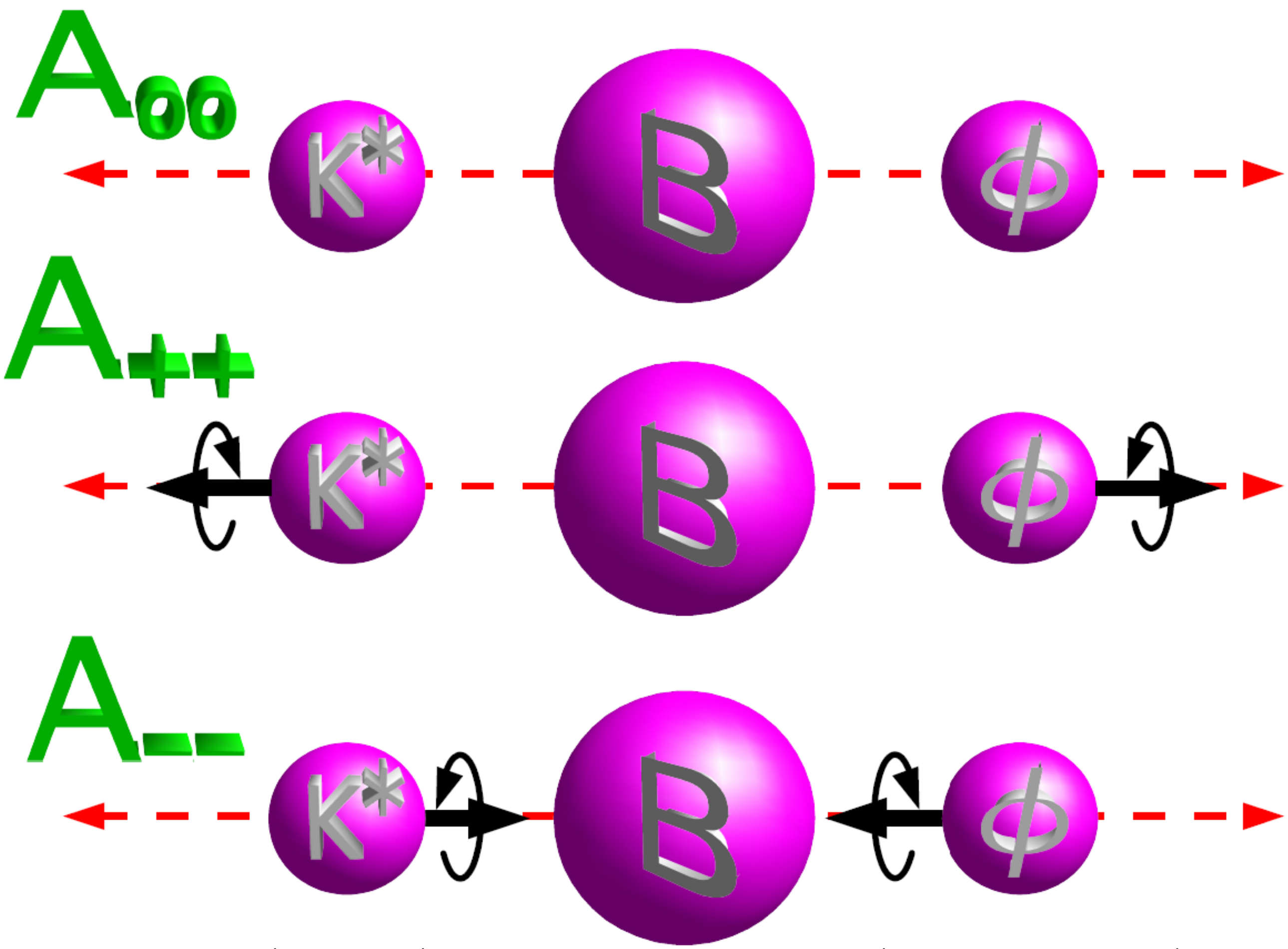
- For $\Upsilon \to B\bar{B}$:
  $\lambda_1 = \lambda_2 = 0$, $J=1$, $m=\pm 1$

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

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

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

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



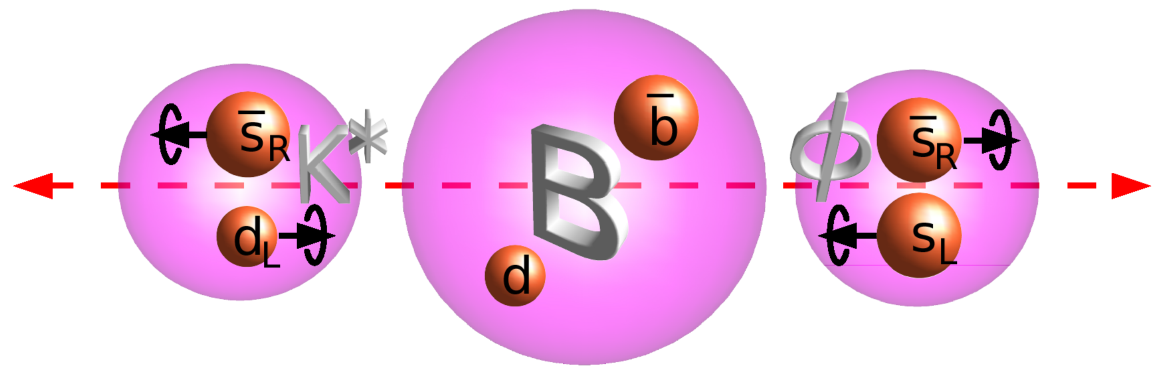
$|J, \lambda_1\rangle$ $\qquad$ $|J_\varphi = 1, \lambda_2\rangle$

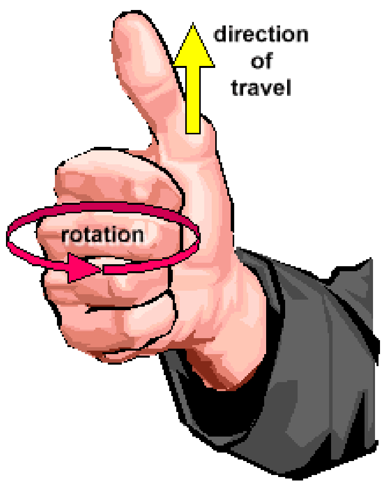
- Try $K_J^{(*)} \to K\pi(\pi)$ with $J^P = 0^+, 0^-, 1^+, 1^-, 2^+, 2^-, 3^-, 4^+, \ldots$

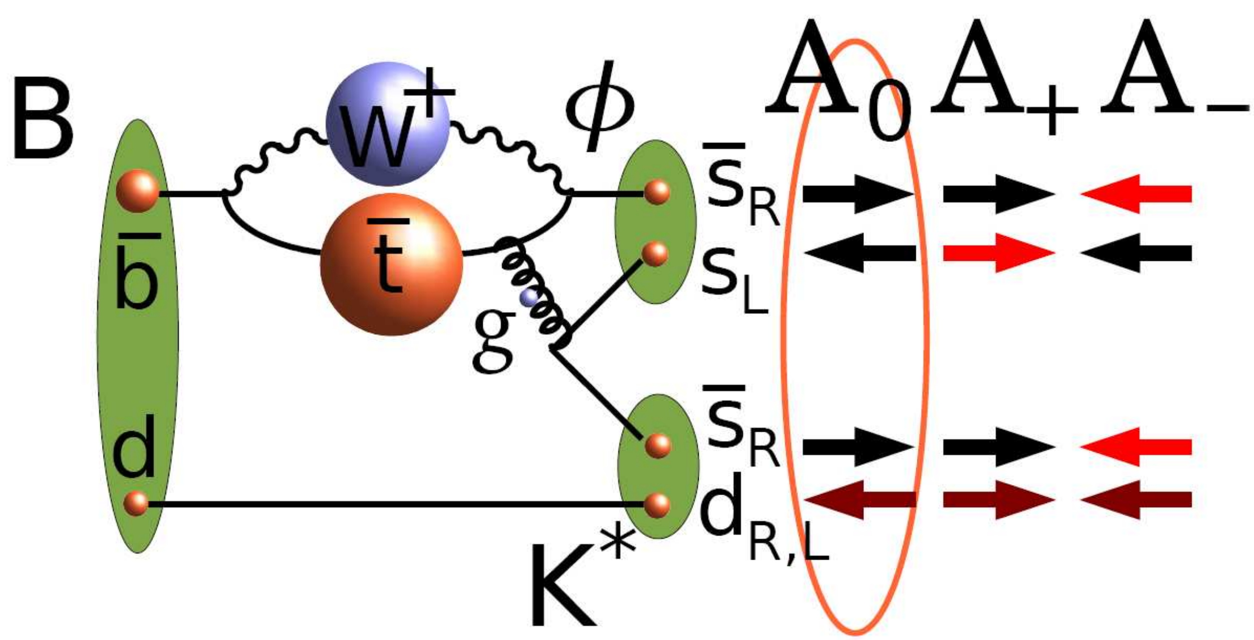
Polarization in B Decays

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

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



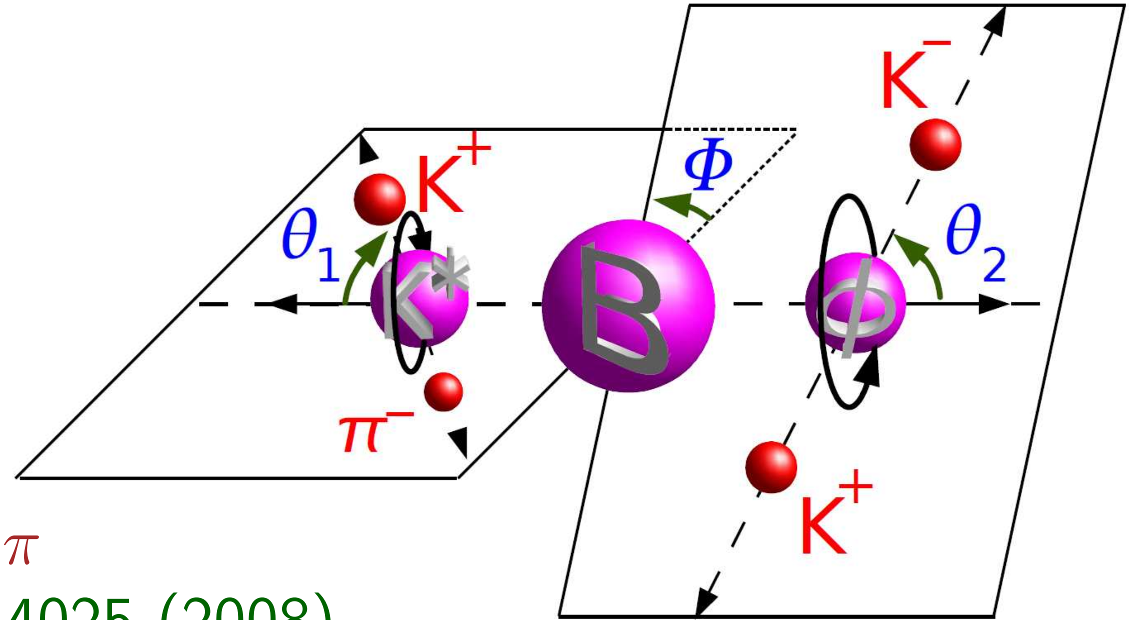




$|A_{00}|^2 \gg |A_{++}|^2 \gg |A_{--}|^2$ suppression$\sim(m_\varphi/m_B)^2\sim 1/25$

Angular Measurements

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



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

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

$$d\Gamma_{J=1} \propto \Bigg\{ \frac{1}{4} \boxed{\overset{\text{transverse}}{\sin^2\theta_1 \sin^2\theta_2 \left(|A_{++}|^2 + |A_{--}|^2\right)}} + \boxed{\overset{\text{longitudinal}}{\cos^2\theta_1 \cos^2\theta_2 |A_{00}|^2}}$$

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

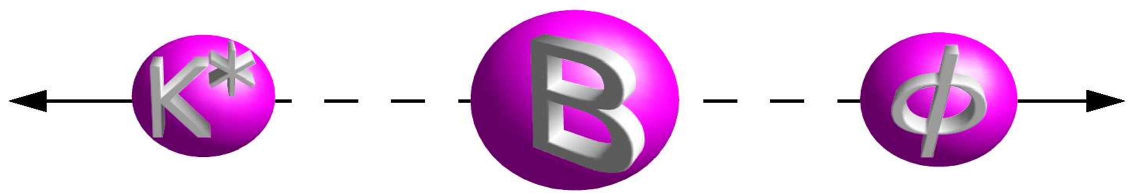
$$+\frac{1}{4}\sin 2\theta_1 \sin 2\theta_2 \left[\cos\Phi\ \mathrm{Re}\left(A_{++}A^*_{00} + A_{--}A^*_{00}\right) - \sin\Phi\ \mathrm{Im}\left(A_{++}A^*_{00} - A_{--}A^*_{0}\right)\right] \Bigg\}$$

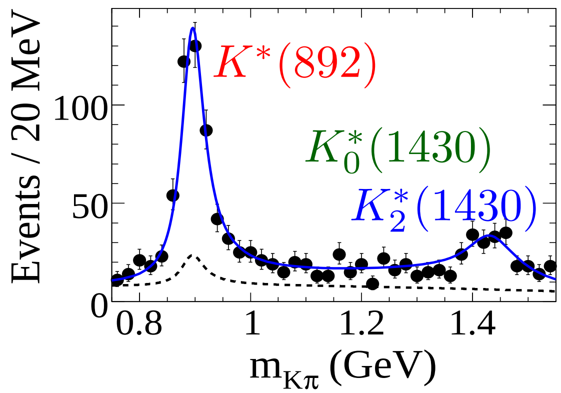
Polarization in $B \to \varphi K_J^{(*)}$ Decays

- Complex multivariate analysis with 12 parameters per channel

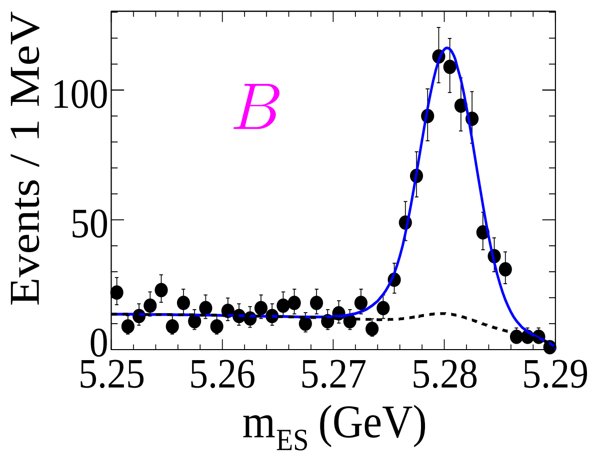
B (matter): $|A_{00}|, |A_{++}|, |A_{--}|, \arg(A_{00}), \arg(A_{++}), \arg(A_{--})$

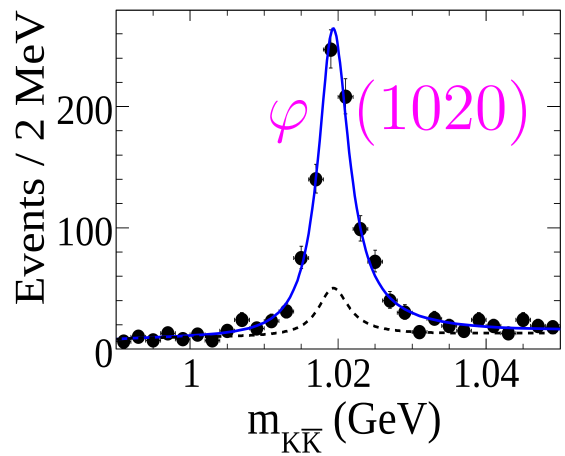
$\bar{B}$ (antimatter): $|\bar{A}_{00}|, |\bar{A}_{++}|, |\bar{A}_{--}|, \arg(\bar{A}_{00}), \arg(\bar{A}_{++}), \arg(\bar{A}_{--})$

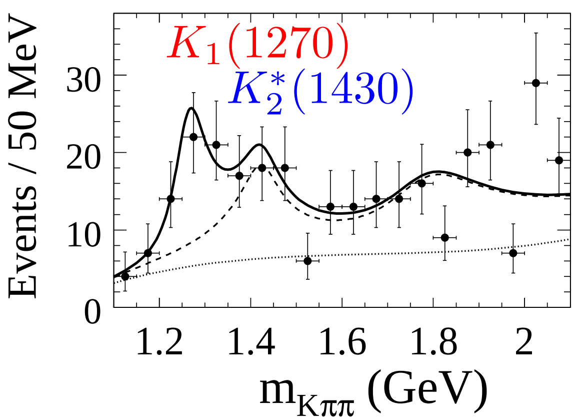




BABAR PRD78,092008(2008)





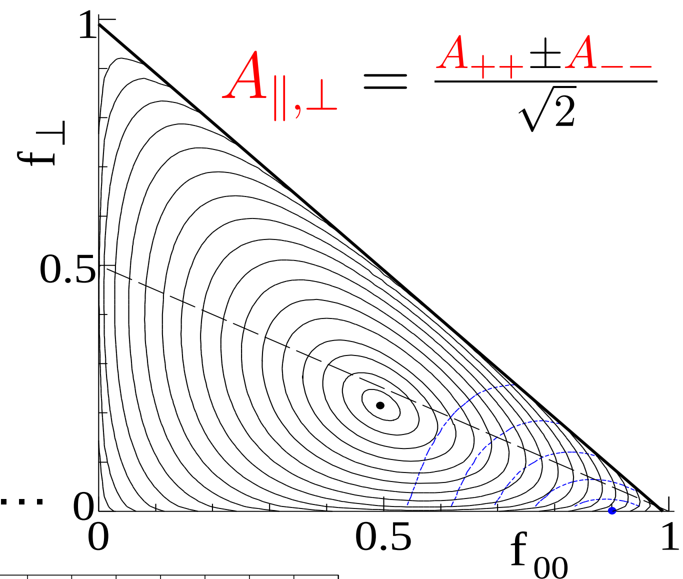


BABAR PRL101,161801(2008)

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

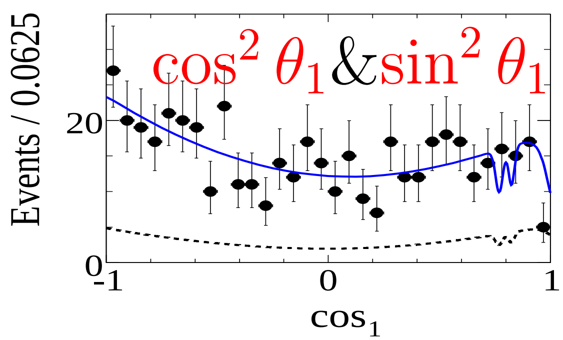
- Puzzle $J = 1$, not 2: $|A_{00}|^2 \simeq |A_{++}|^2 \gg |A_{--}|^2$; $\arg(\frac{A_{00}}{A_{++}}) \neq 0, \pi$

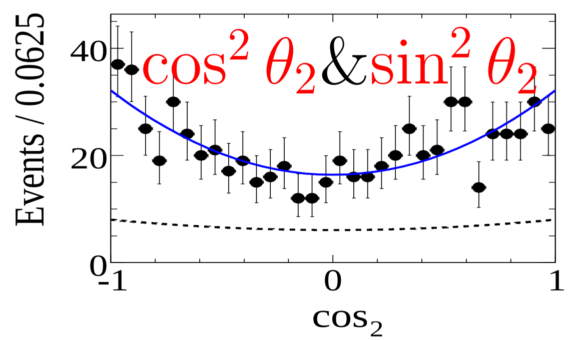
BABAR	J^P	$f_{00} = \frac{\vert A_{00}\vert^2}{\sum \vert A_{\lambda\lambda}\vert^2}$
$B \to \varphi K^*(892)^0$	1^-	$0.494 \pm 0.034 \pm 0.013$
$B \to \varphi K^*(892)^+$	1^-	$0.49 \pm 0.05 \pm 0.03$
$B \to \varphi K_1(1270)^+$	1^+	$0.46\ ^{+0.12}_{-0.13}\ ^{+0.03}_{-0.07}$
$B \to \varphi K_2^*(1430)^0$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

$K^*(892)$

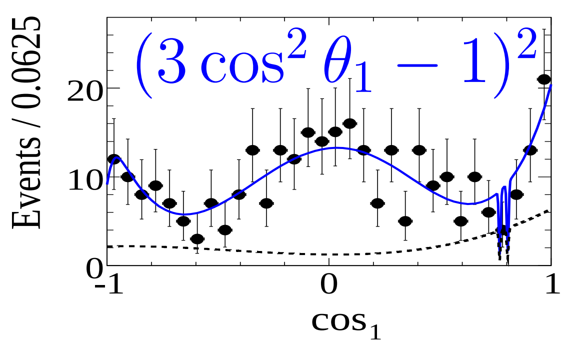


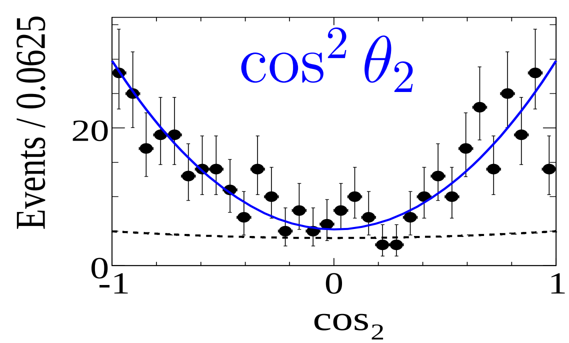


$\varphi(1020)$

$K_2^*(1430)$

$K_0^*(1430)$





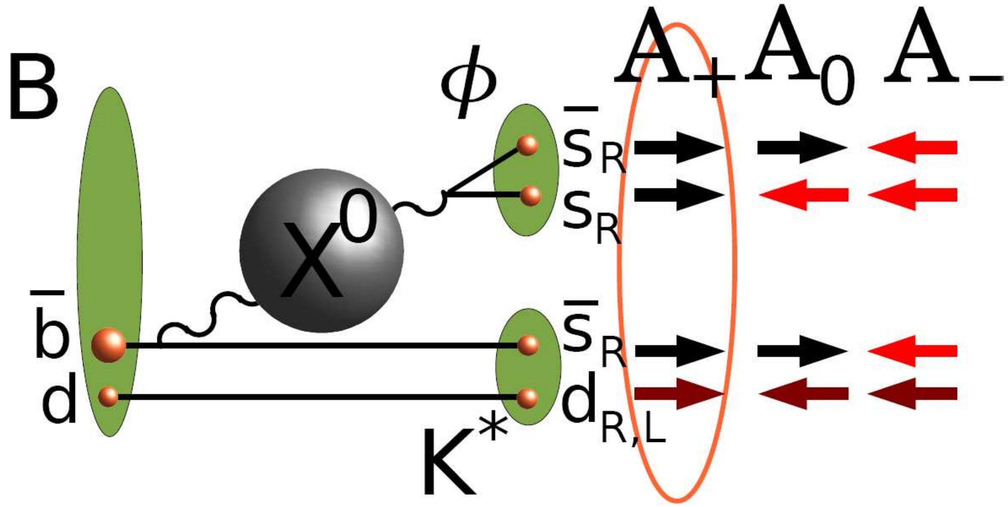
$\varphi(1020)$

New Physics in B Decay Polarization

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

scalar (tensor) interaction

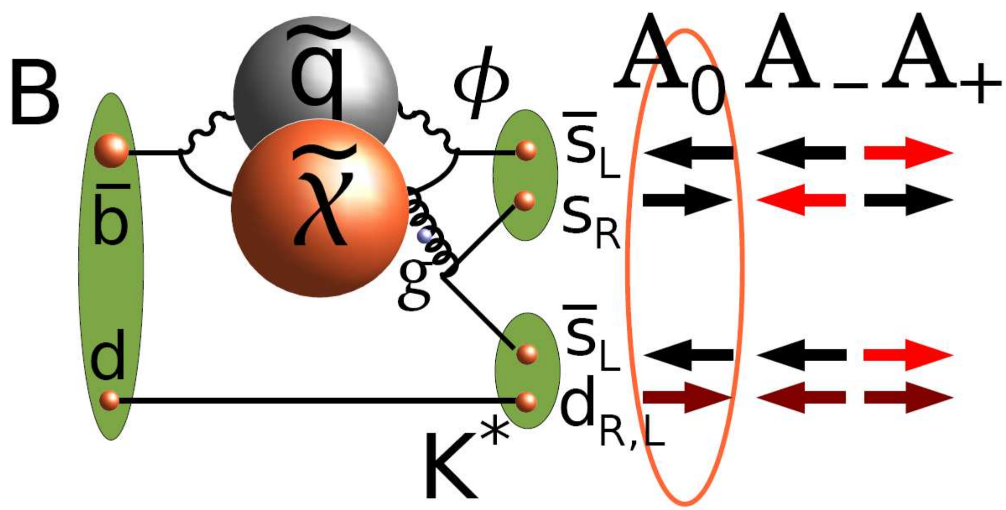
SM: $\bar{q}\gamma^\mu(1-\gamma^5)q$



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

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

supersymmetry



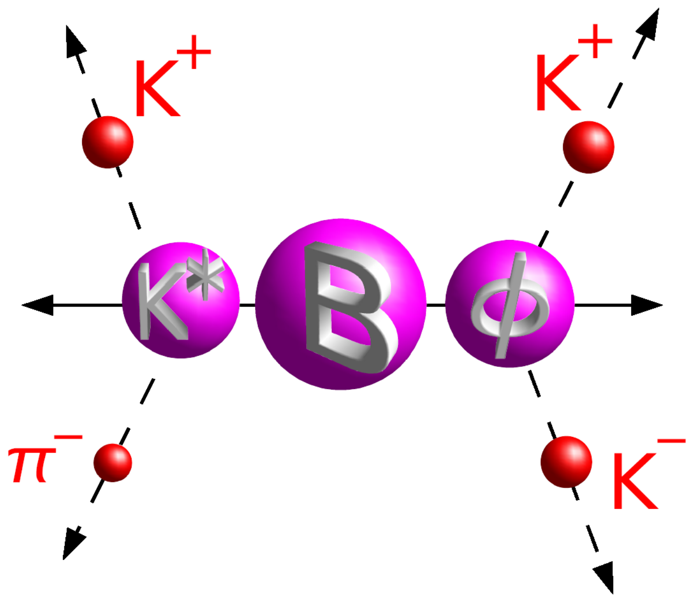
$|A_{00}|^2 \gg |A_{--}|^2 \gg |A_{++}|^2$

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

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

What we have learned

from B decays:



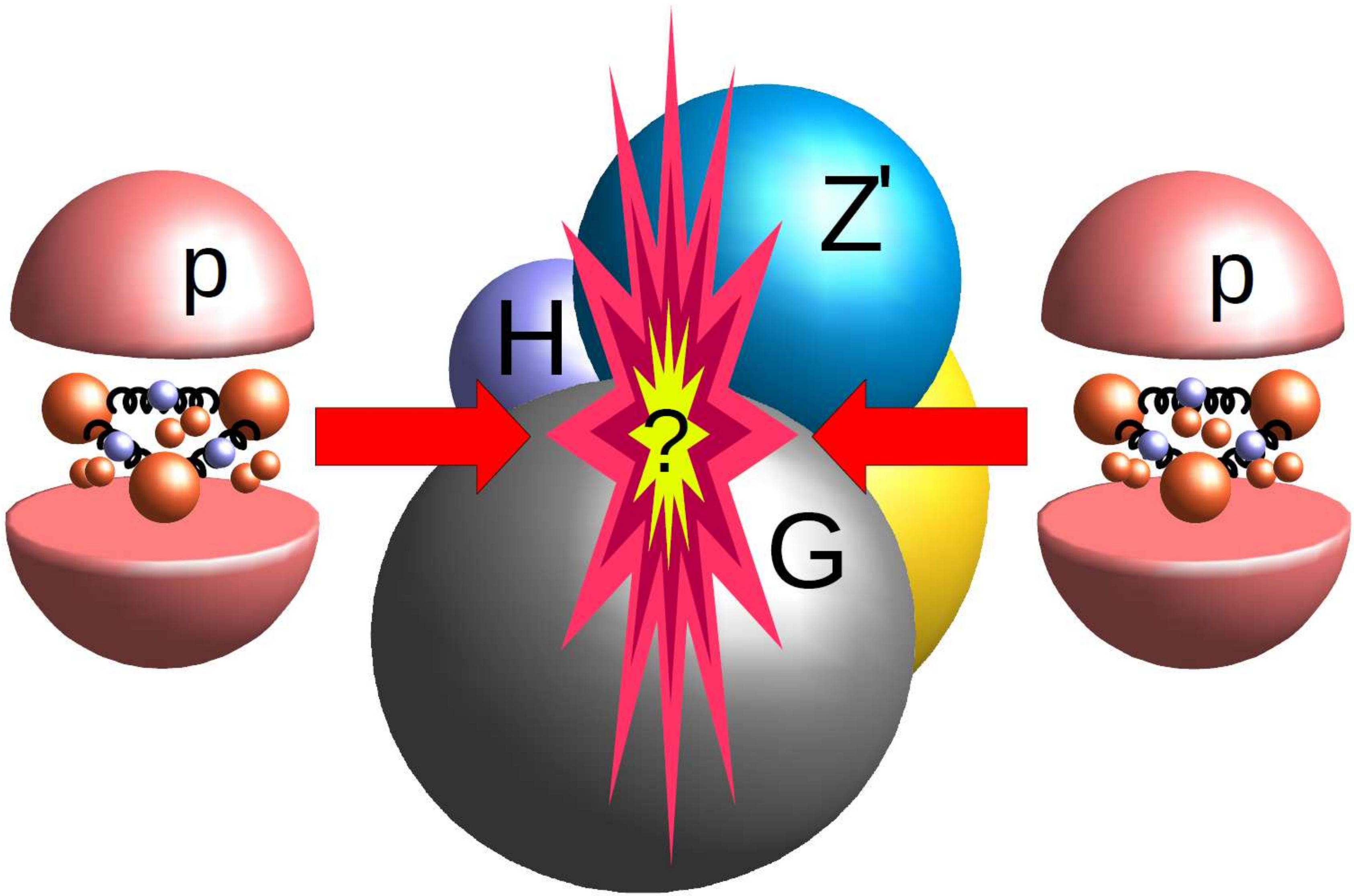
- power of spin correlations
- extract maximum information
- production and decay angular formalism
- surprises (either within or beyond SM)
- better to look for beyond SM in direct production

if energy reachable $\Rightarrow$ move to LHC

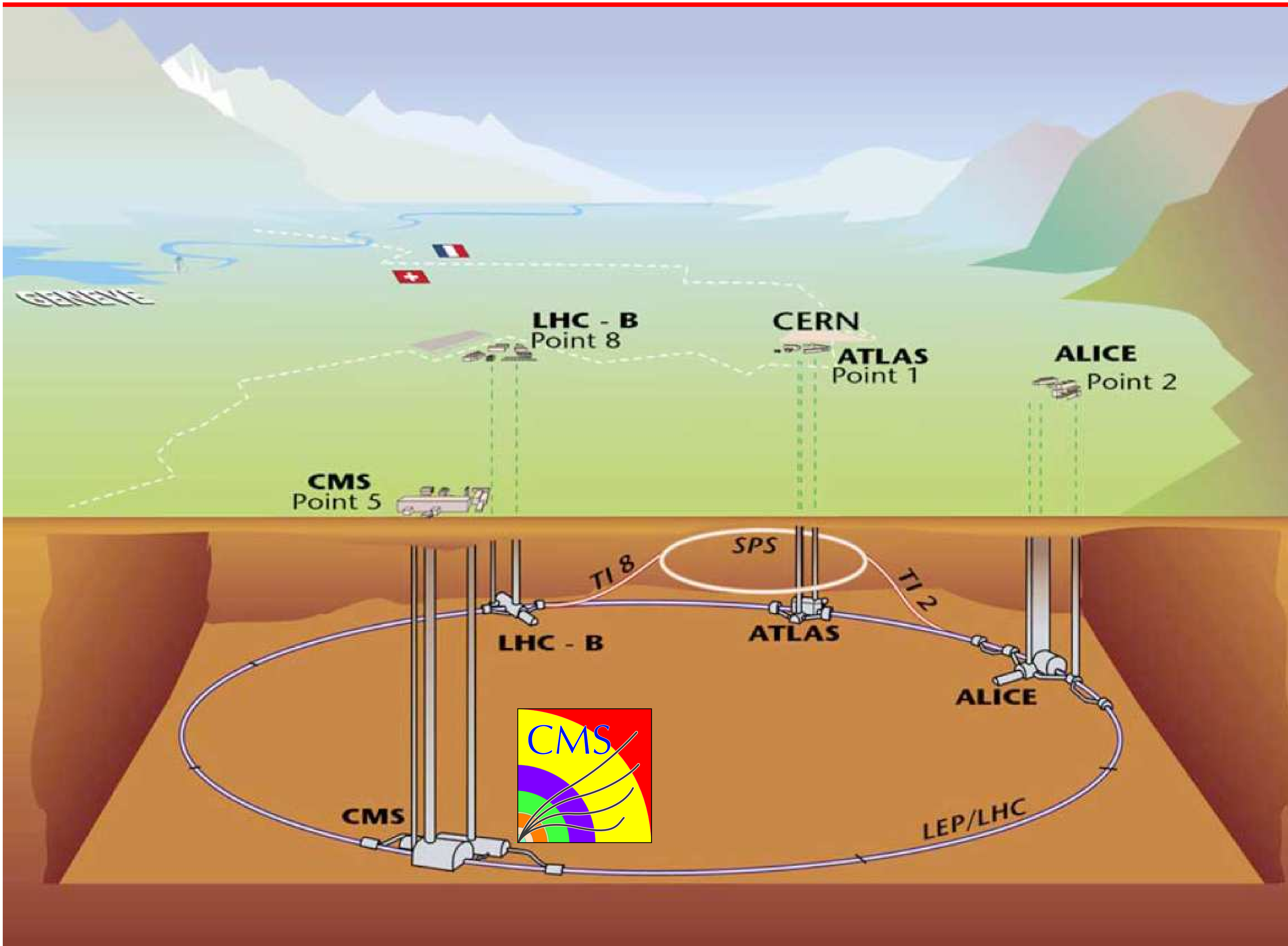
Production and decay of new resonances
at hadron colliders

Production of New Resonances

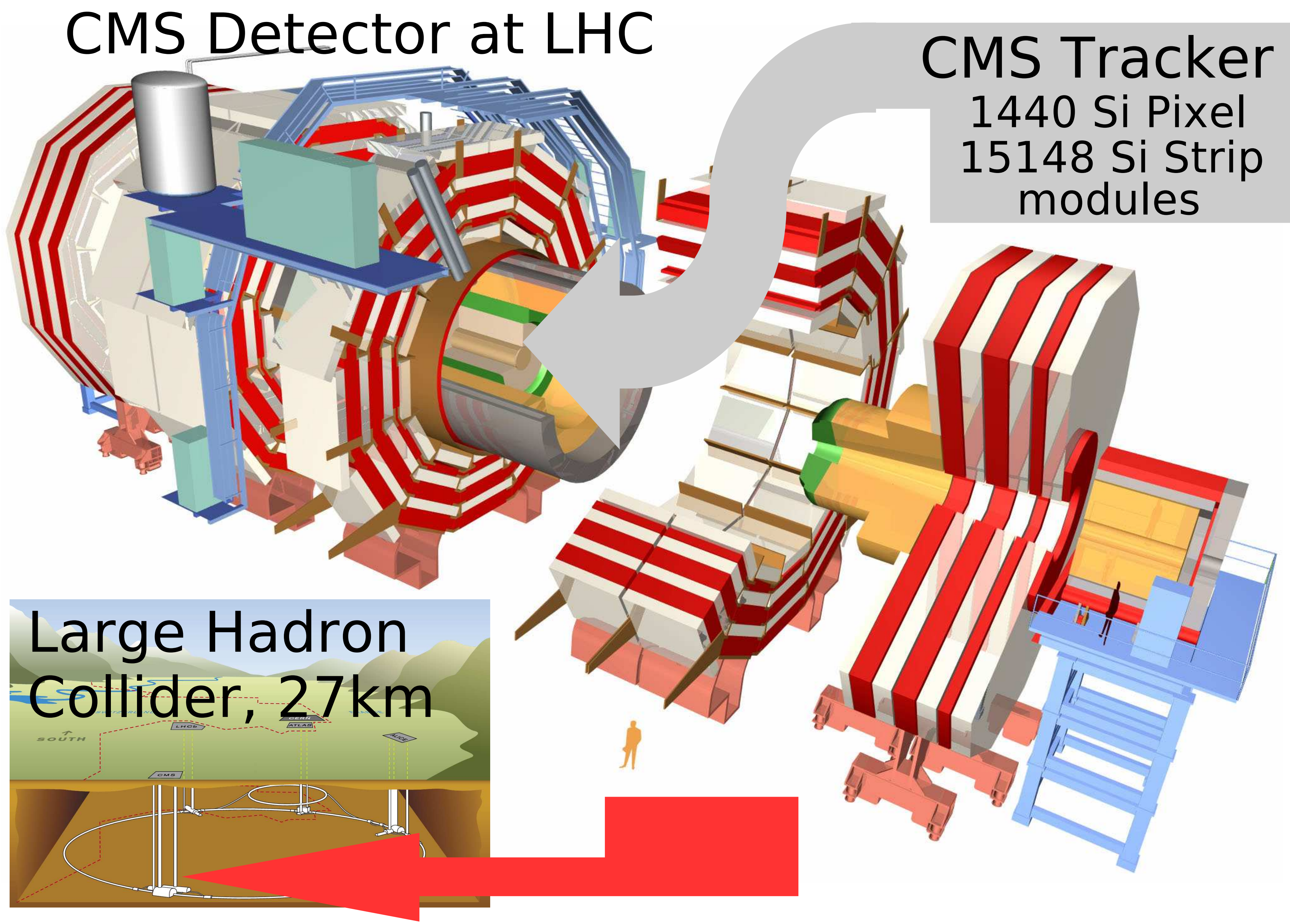
- Large Hadron Collider is a discovery machine



Large Hadron Collider: starting now

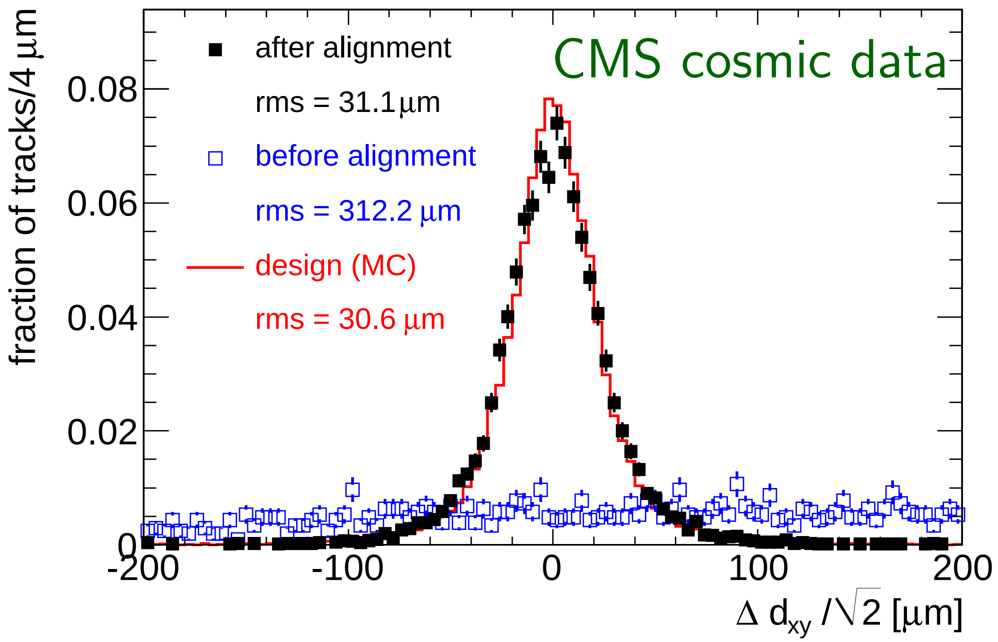


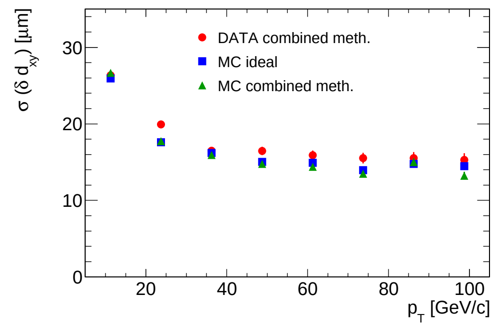
Example: Tracker in the CMS Detector



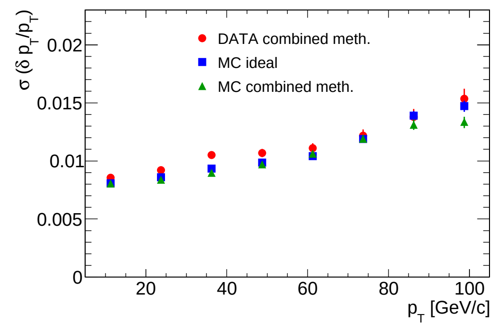
CMS Tracker Performance

- Excellent performance; use parameterization for studies in this talk:





$\sigma(\delta d_{xy})$



$\sigma(\delta p_T/p_T)$

- First paper signed by CMS collaboration (2443 authors), in JINST:

Alignment of the CMS Silicon Tracker during
Commissioning with Cosmic Rays

arXiv:0910.2505v2 [physics.ins-det] 22 Nov 2009

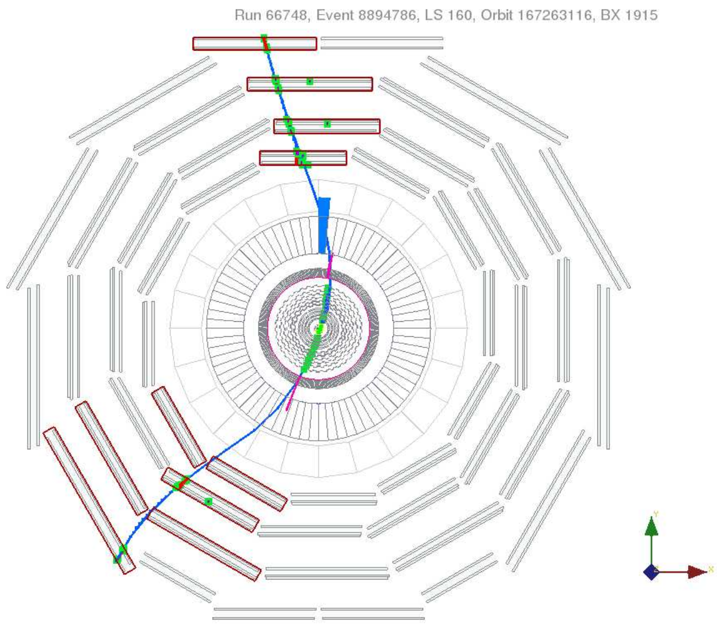
The CMS Collaboration*

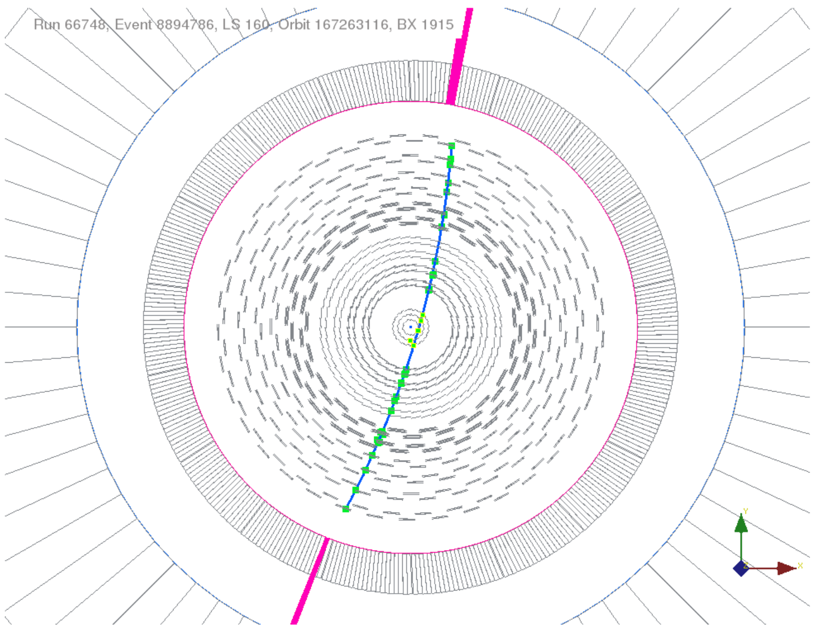
*See Appendix A for the list of collaboration members

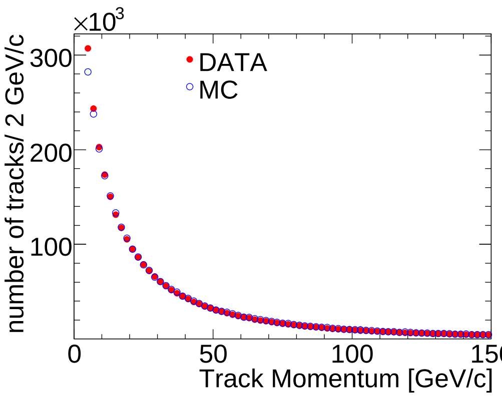
- CMS Times in March (article "Alignment of a Giant"):
  http://cms.web.cern.ch/cms/Media/Publications/CMStimes/2010/03_01/

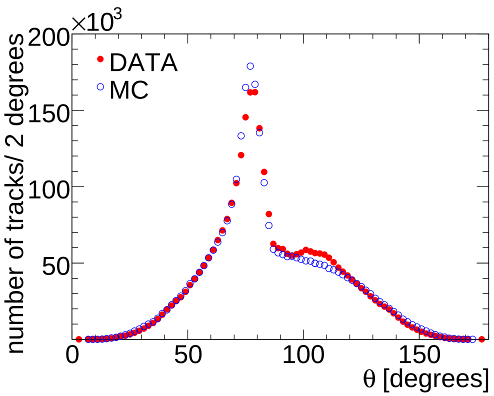
CMS Readiness

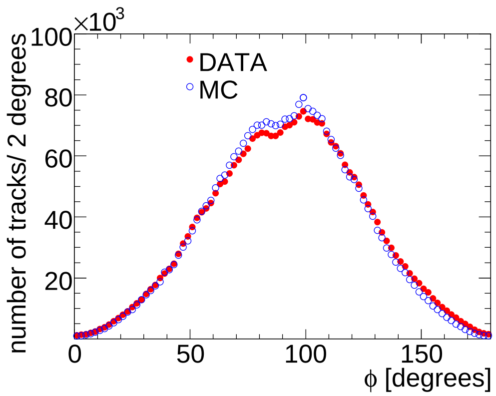
- Imagine $Z' \to \mu^+\mu^-$
  - may look the same as one cosmic μ^+
  - CMS has been collecting cosmic data in 2007-2010







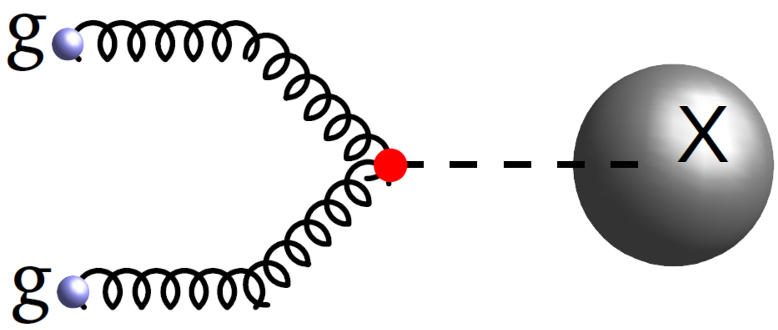


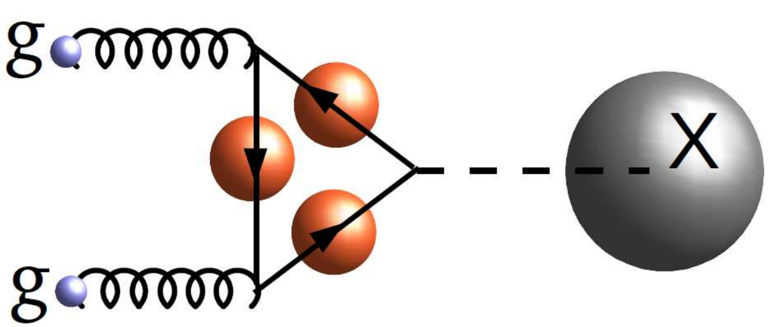


Production of New Resonances

- Consider two dominant production mechanisms

  of color-neutral
  & charge-neutral X



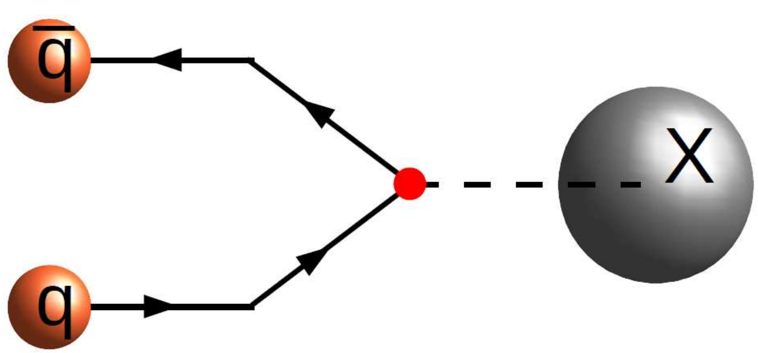


- Gluon fusion $gg \to X$

  $J = 0$ or 2

  $J_z = 0$ or ± 2

  expect to dominate at lower mass



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

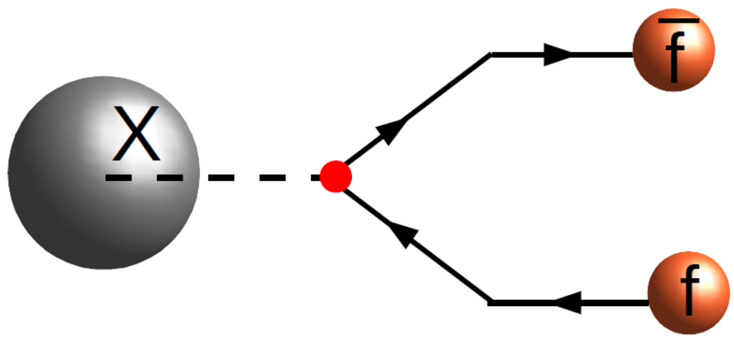
  $J = 1$ or 2

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

  assume chiral symmetry is exact

Decay of New Resonances

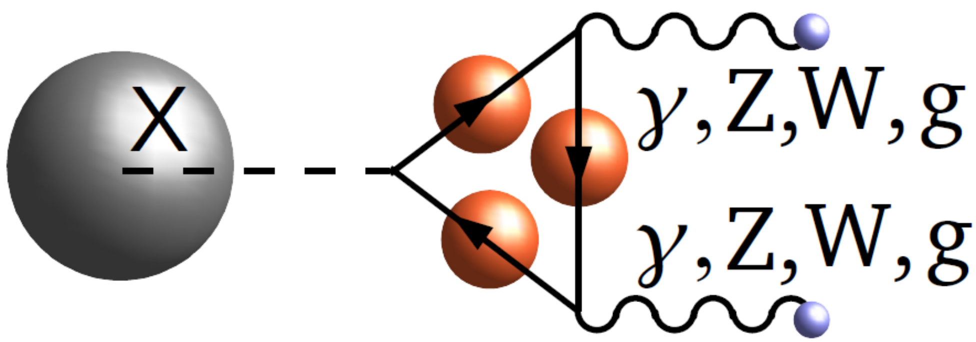
- Consider decay back to Standard Model particles



- Decay to fermions

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

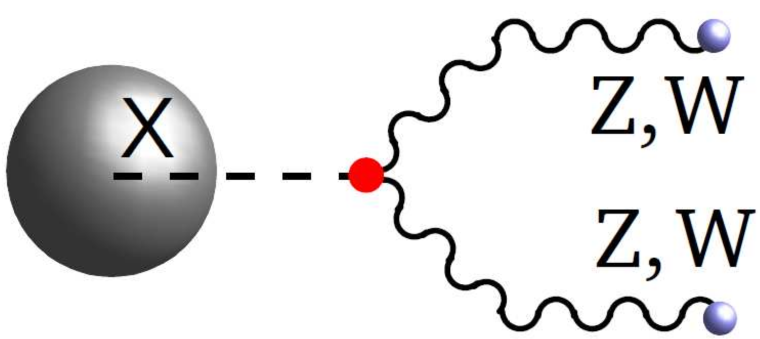
spin-0 excluded $m_f \to 0$



- Decay to gauge bosons

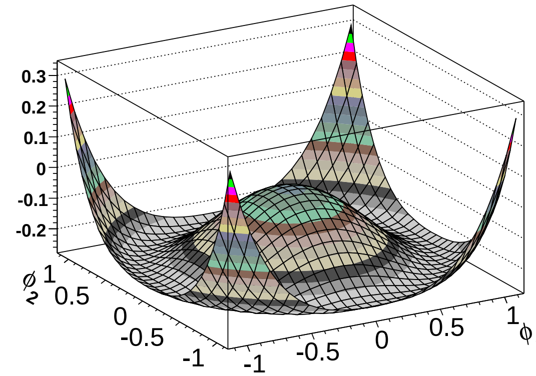
$X \to \gamma\gamma$, W^+W^-, ZZ, gg

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



again X is color-neutral
& charge-neutral

Do we expect such new resonances?



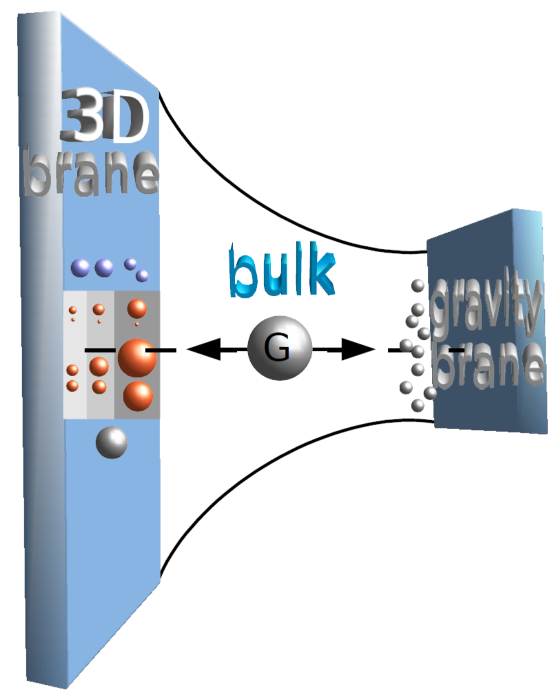
- Spin=0 (Higgs)
  - $J^P = 0^+$ SM $H \to \gamma\gamma$, W^+W^-, ZZ, $b\bar{b}$, $t\bar{t}$
  - $J^P = 0^-$ A multi-Higgs models
- Spin=1 (new gauge boson)
  - KK boson, $Z' \to l^+l^-$, $q\bar{q}$ dominant
  - plausible models when ZZ and WW dominate ("heavy photon")
- Spin=2 ("graviton")
  - RS Graviton 2^+ (minimal) $\Leftrightarrow$ extra dim.

    SM on TeV brane, $G_{\rm RS}$ near TeV brane

    $G_{\rm RS} \to \gamma\gamma$ and l^+l^- discovery, flavor problem
  - RS G 2^+ (non-min.), light fermions in bulk

    (K.Agashe et al., hep-ph/0701186)

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



Example of $G_{\mathrm{RS}} \to ZZ \to 4l$

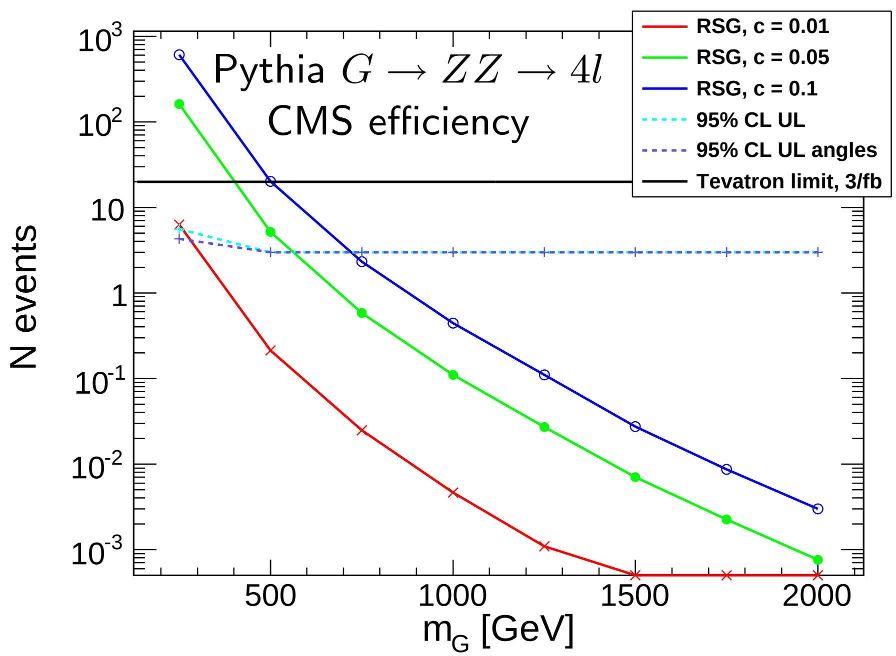
- RS graviton (1st excitation) couplings $\propto 1/\Lambda = 1/(\overline{M}_{\mathrm{Pl}} \times e^{-kr_c\pi})$

  2 parameters: $m_G \sim \mathrm{few} \times k \times e^{-kr_c\pi}$

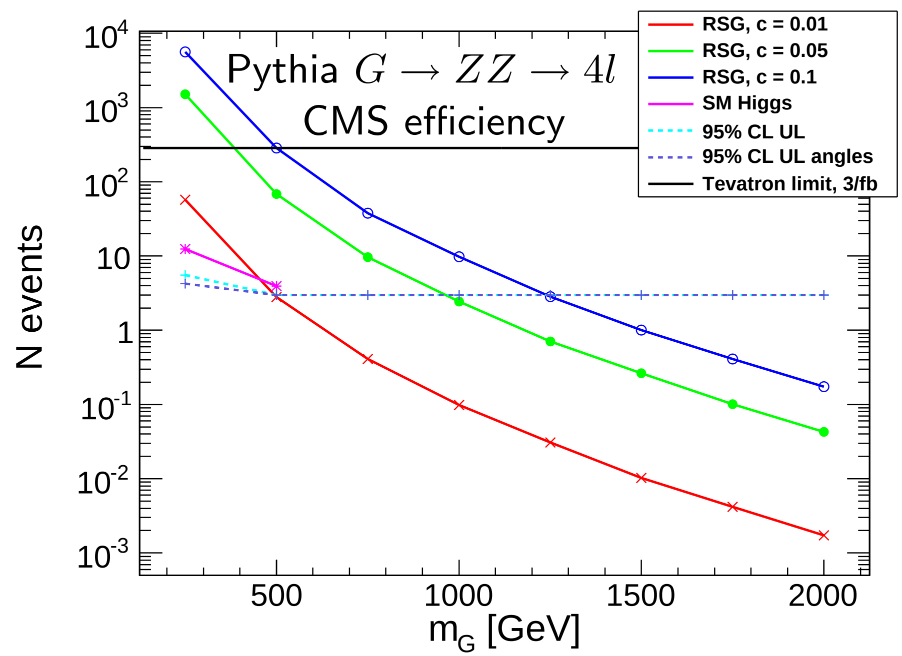
  $c = k/\overline{M}_{\mathrm{Pl}} =$ 0.01 – 0.1 – ~1 (?)

- LHC – range of possible yields or limit tighter than Tevatron
  - at lower mass, Higgs and G_{RS} with $c = 0.01$ similar rate

first LHC run
1/fb at $E_{pp} = 7$ TeV

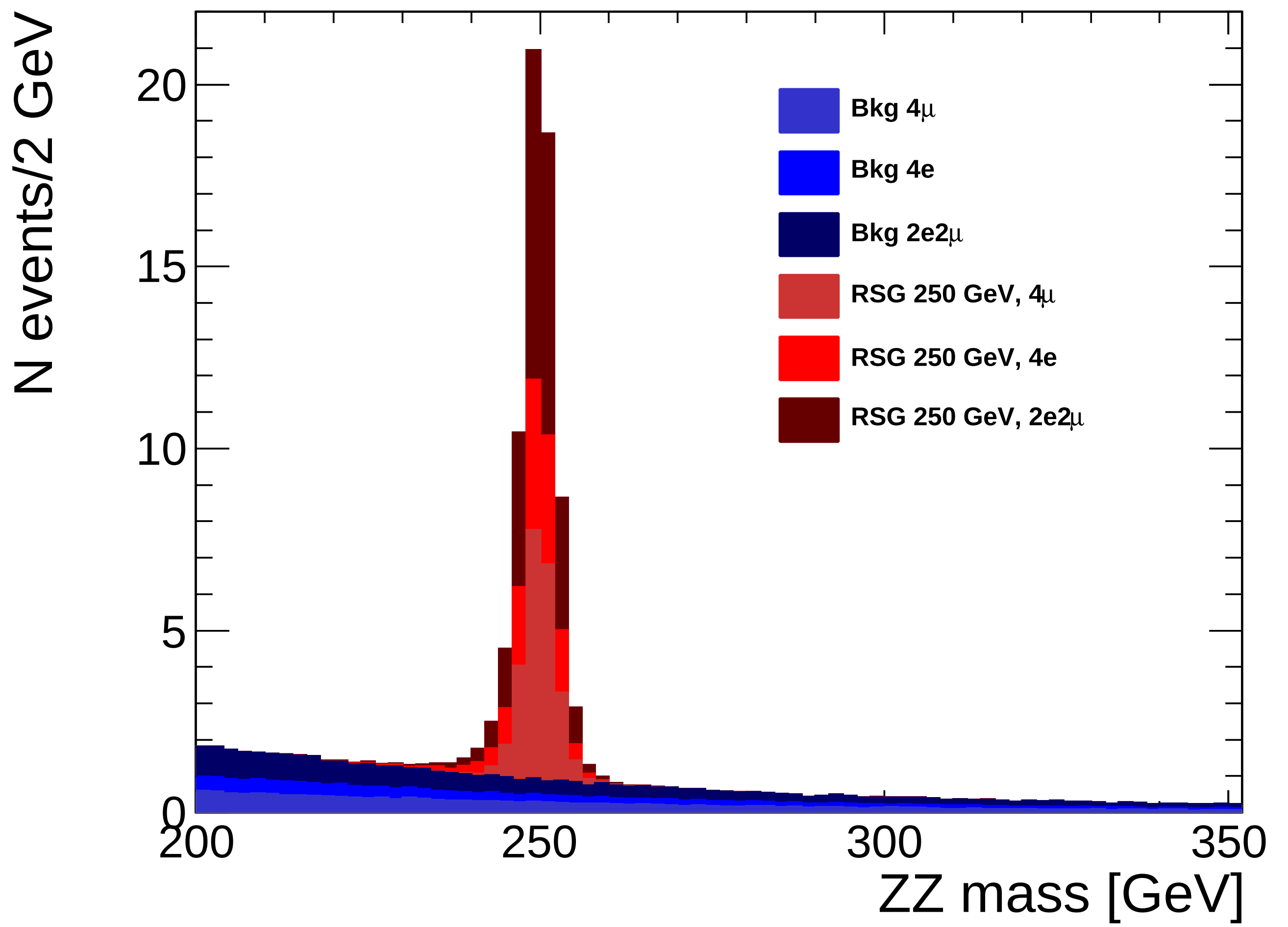


next LHC run
2/fb at $E_{pp} = 14$ TeV



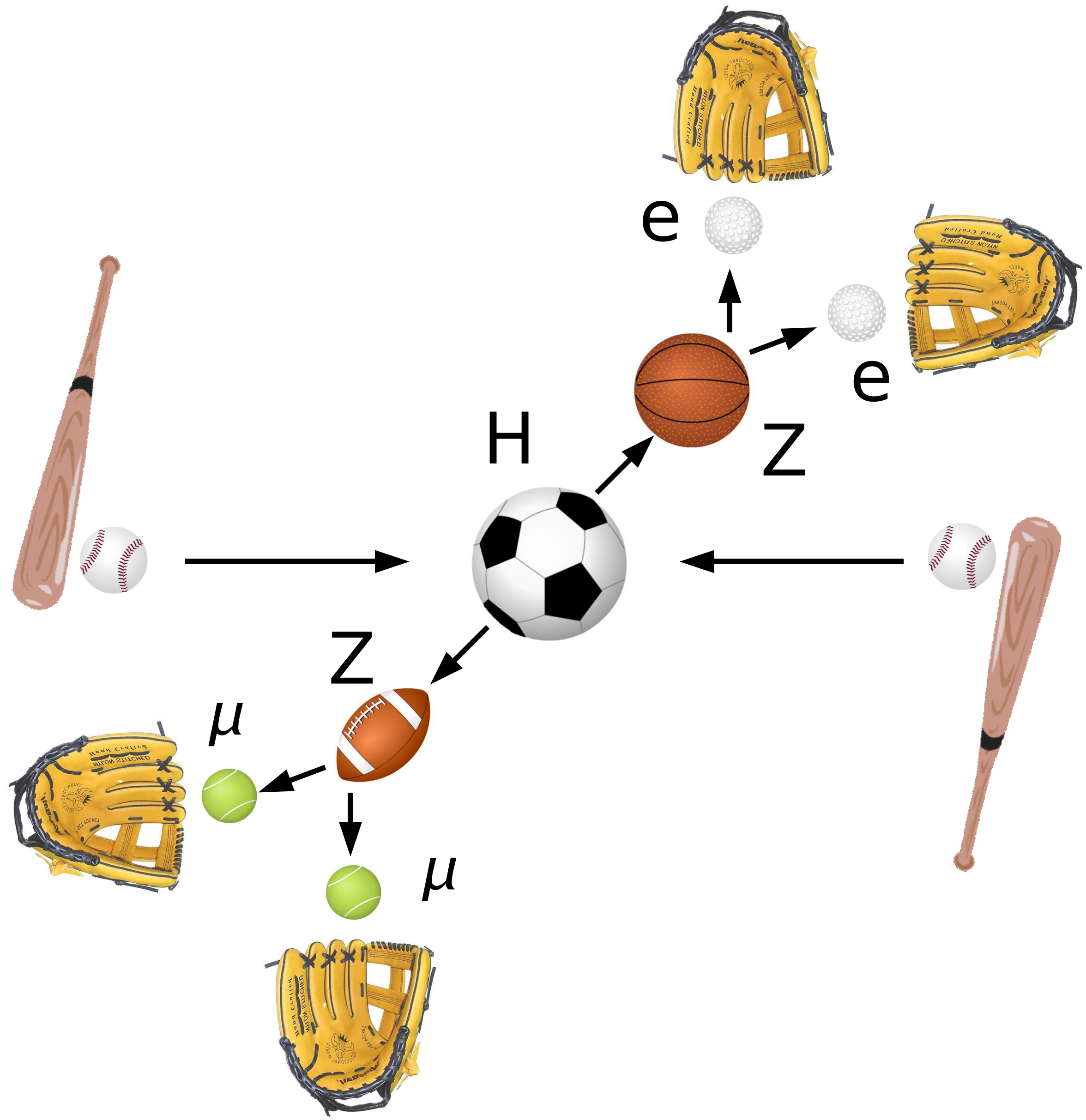
Next Steps

- Assume resonance is found $\Rightarrow$ extract maximum information
  - re-visit $X \to \gamma\gamma,\ l^+l^-,\ q\bar{q}$ (well-studied, but with min couplings)
  - concentrate on $X \to ZZ$, similar WW (a lot more to be done)
  - $X \to ZZ \to 4l$ clean example, method is general (+jet/met)



Kinematics of production and decay

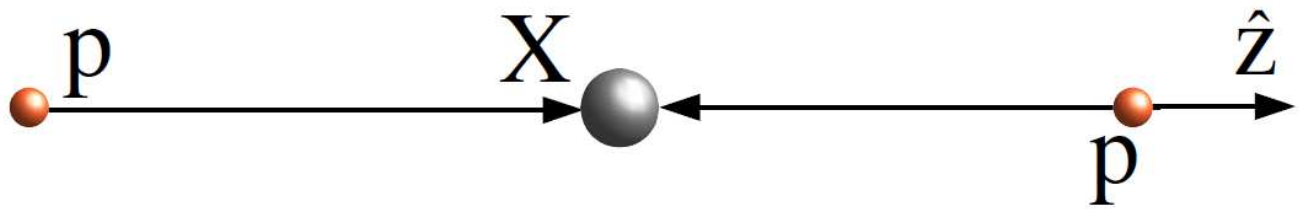
Cartoon of an Experiment

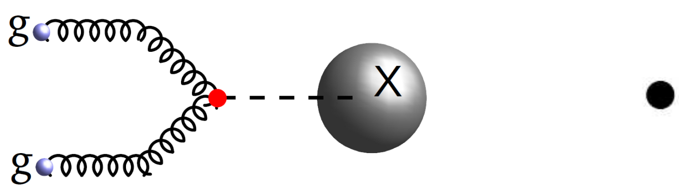


Kinematics in New Resonances Production

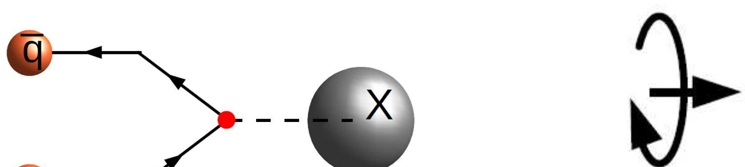
- $ab \to X$ polarization $\Leftrightarrow$ production mechanism and couplings

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

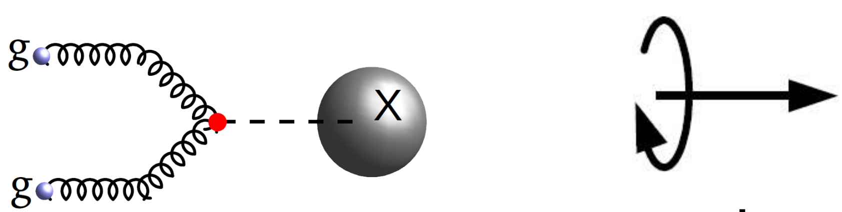




$J_z = 0$ fraction f_{z0}



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



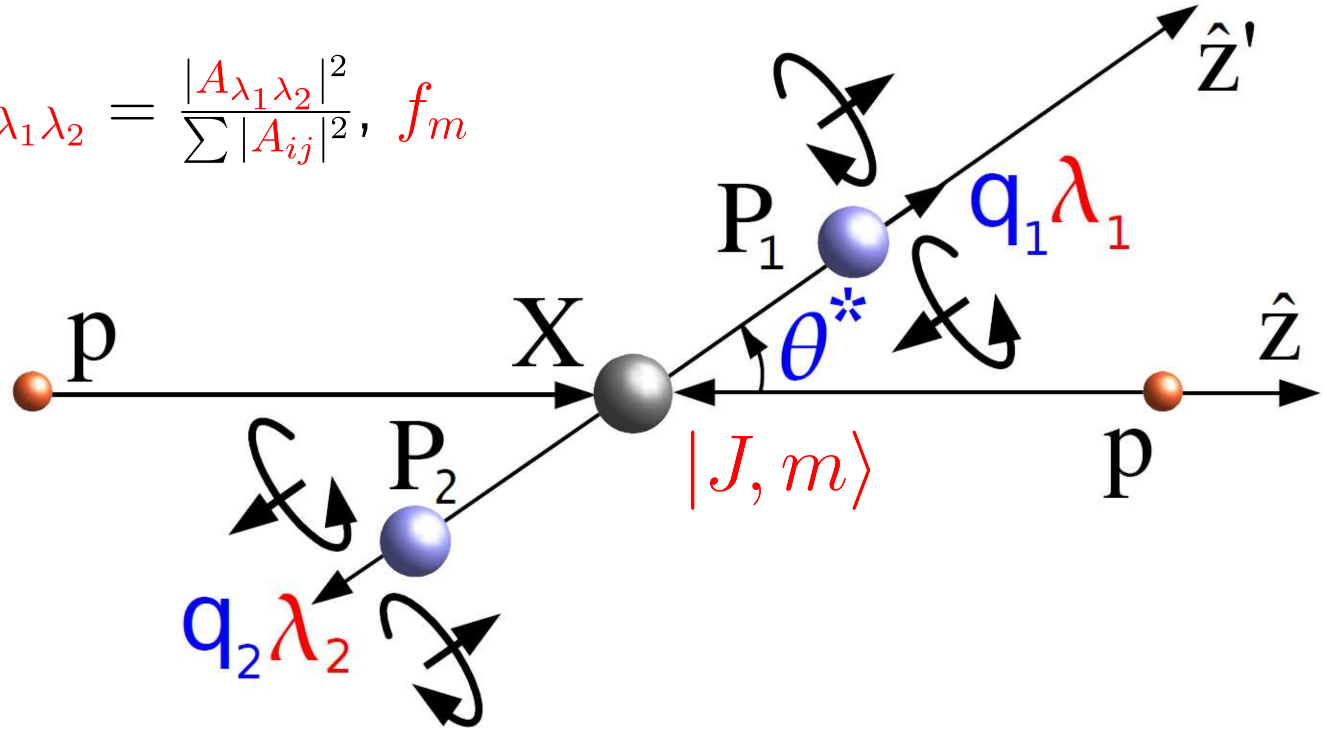
$J_z = \pm 2$ fraction f_{z2}

in general depend on LHC energy

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



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

- 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)

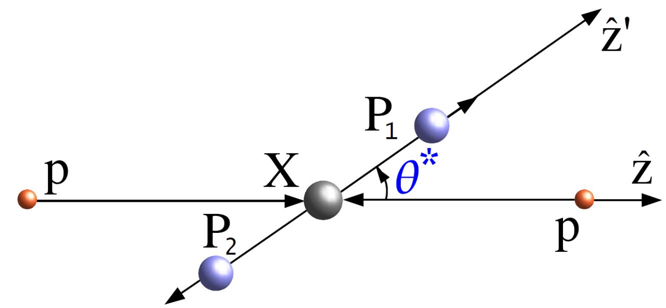
Examples

- 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

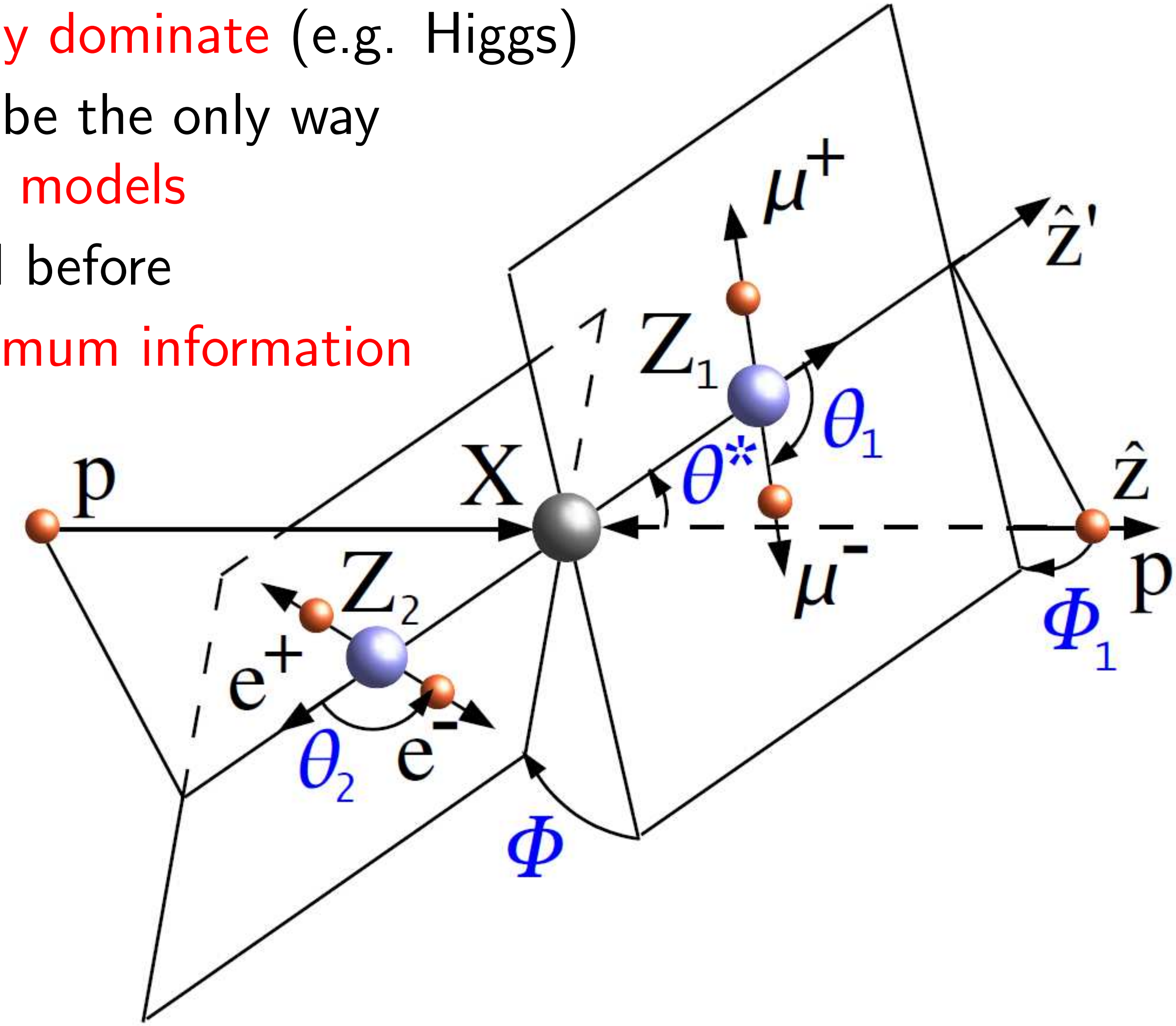
  (!) spin-2 not excluded

  $\cos\theta^*$ 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 WW

- Full information production & decay angles $\Rightarrow$ multivariate analysis
  - ZZ & WW may dominate (e.g. Higgs)
  - if not, may still be the only way to differentiate models
  - not fully studied before
  - concept of maximum information



Decay of New Resonances

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

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

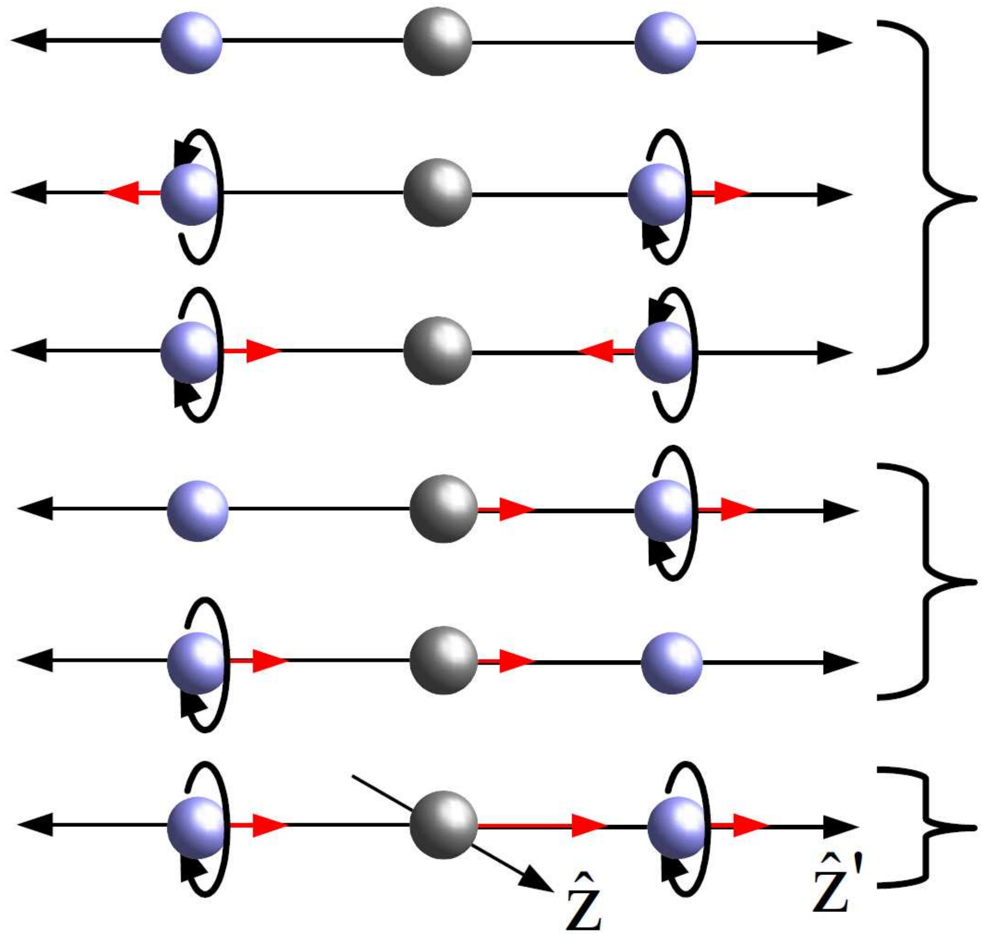
A_{++}

A_{--}

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

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

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



$J = 0$ or 2

$J_{z'} = 0$

$J = 1$ or 2

$|J_{z'}| = 1$

$J = 2$

$|J_{z'}| = 2$

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

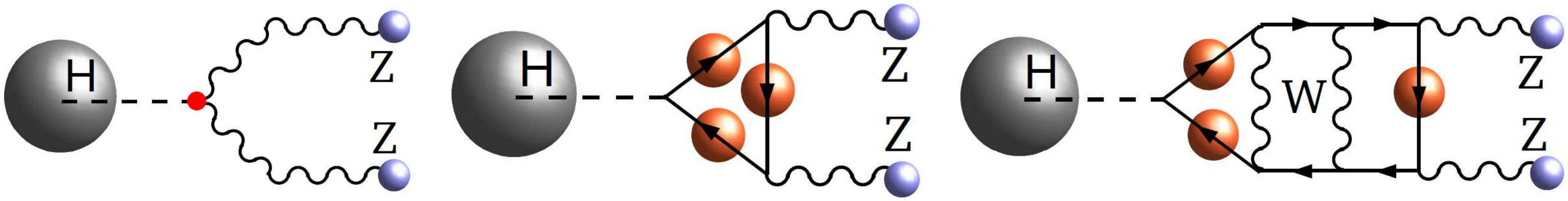
Connect “theory” and “experiment”

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) $\cancel{CP}$



(or beyond SM) (or beyond SM)

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

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

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

e.g. $M_{Z_2} < M_{Z_1}$
at $M_H < 2M_Z$
but $a_i(M_{Z_2})$

$$x = \frac{M_X^2 - M_{V_1}^2 - M_{V_2}^2}{2 M_{V_1} M_{V_2}} \gg 1 \text{ for } \frac{M_X}{M_V} \gg 1 \Rightarrow A_{00} \text{ dominates for } 0^+$$

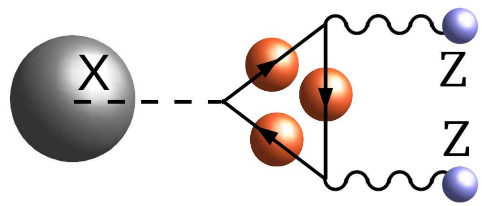
Amplitude for Spin-1

- 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^- $\cancel{CP}$
1^+ $\cancel{CP}$ | 1^+ CP

Example:



- 2 amplitudes (“experiment”) $\Leftrightarrow$ 2 coupling constants (“theory”)

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

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

(compare $Z' \to ZZ$ PRL101,091802(2008)
but b_1 and b_2 generally complex)

Amplitude for Spin-2

2^+ CP
2^- $\cancel{CP}$

2^+ $\cancel{CP}$
2^- CP

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

- 6 amplitudes ("experiment") $\Leftrightarrow$ 6 combinations of coupl. const.

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

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

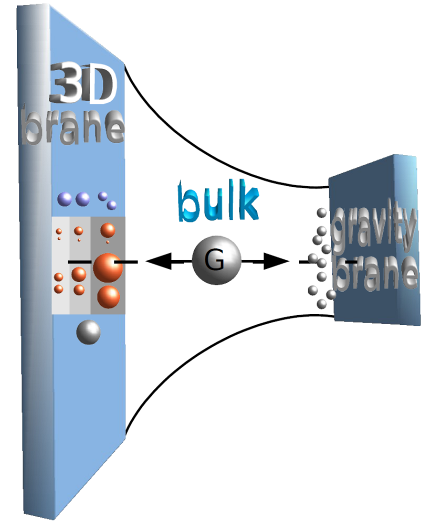
$$A_{\pm 0} \equiv A_{0\pm} = \frac{M_X^3}{M_V\sqrt{2}\Lambda}\left[\frac{c_1}{8}\left(1+\beta^2\right) + \frac{c_4}{2}\beta^2 \mp i\beta\frac{(c_6 + c_7\beta^2)}{2}\right]$$

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

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

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

  $\Rightarrow$ decay at $m_G = 250$ GeV $\quad f_{+-} + f_{-+} = 0.56,\ f_{00} = 0.11$

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

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

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

- Notation later: 2_m^+ (minimal G), 2_L^+ (longitudinal G)

Coupling to fermions

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

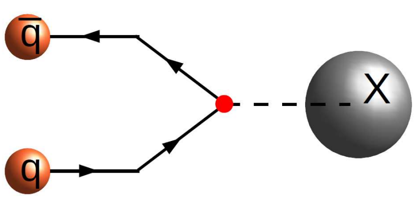
$$A = \frac{1}{\Lambda} t^{\mu\nu} \bar{u}_{q_1} \left(\gamma_\mu \Delta q_\nu \left(\rho_1 + \rho_2 \gamma_5 \right) + \frac{m_q}{\Lambda^2} \Delta q_\mu \Delta q_\nu \left(\rho_3 + \rho_4 \gamma_5 \right) \right) v_{q_2}$$

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

How to measure polarization

How to Measure Polarization

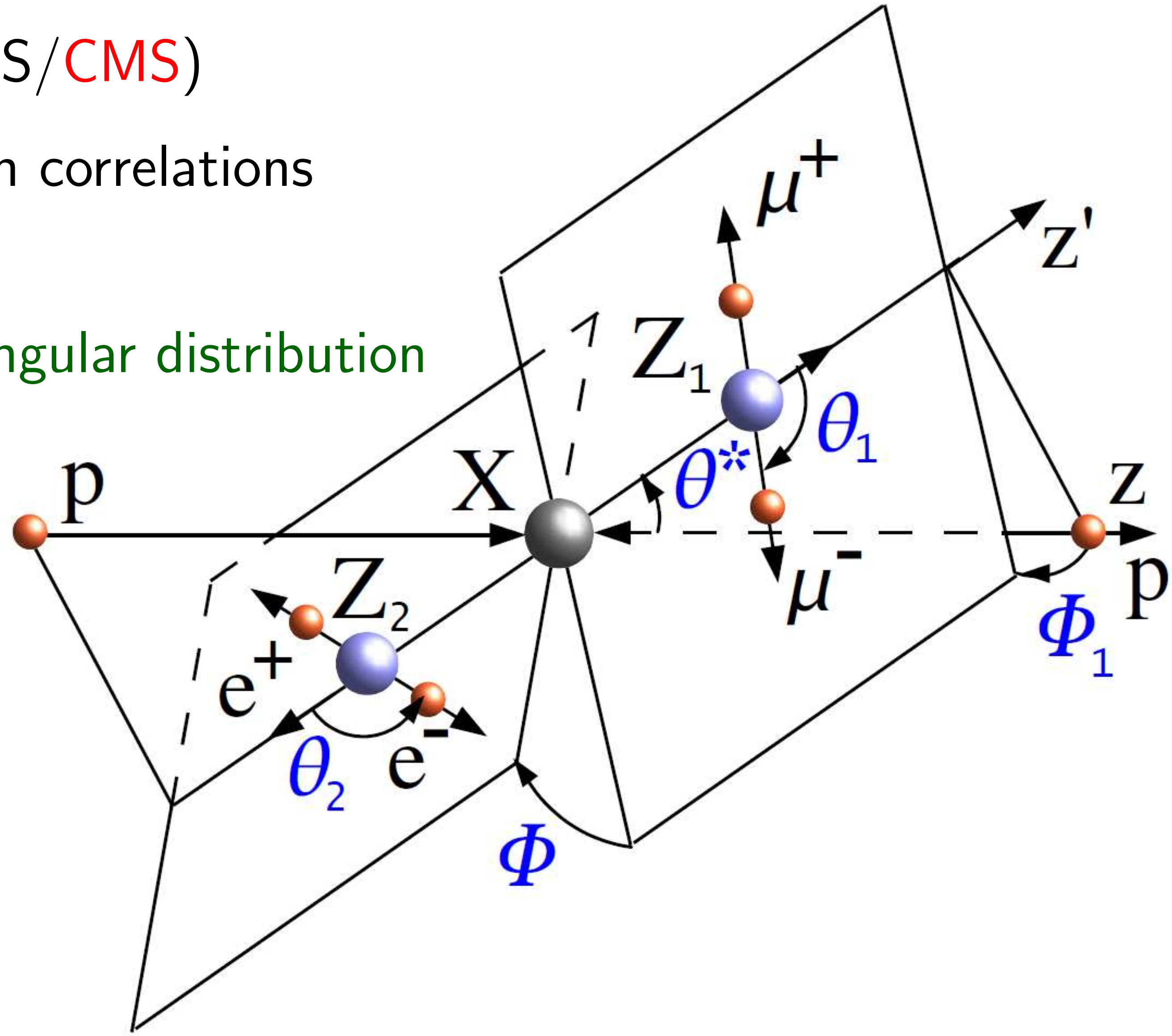
- Deduce all $A_{\lambda_1\lambda_2}$ from angular distributions, but need:

  (1) detector (ATLAS/CMS)

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

  (3) full analytical angular distribution
  (none before)

  (4) fit
  (learn from B's)



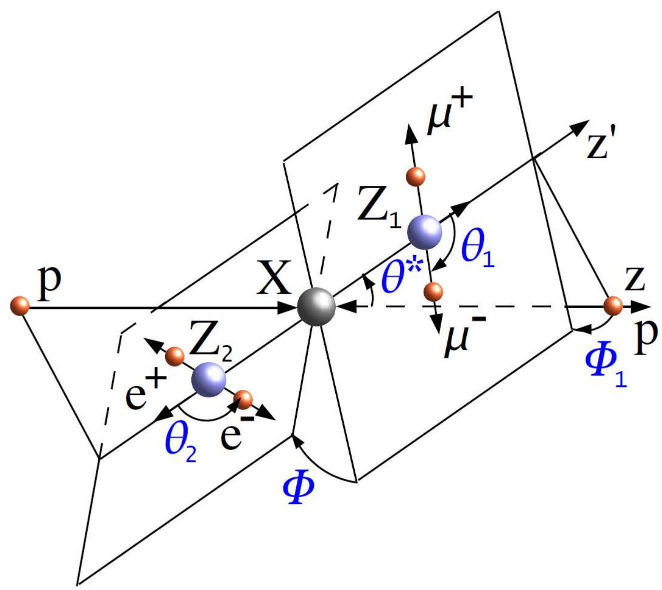
Monte Carlo Simulation

- 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)

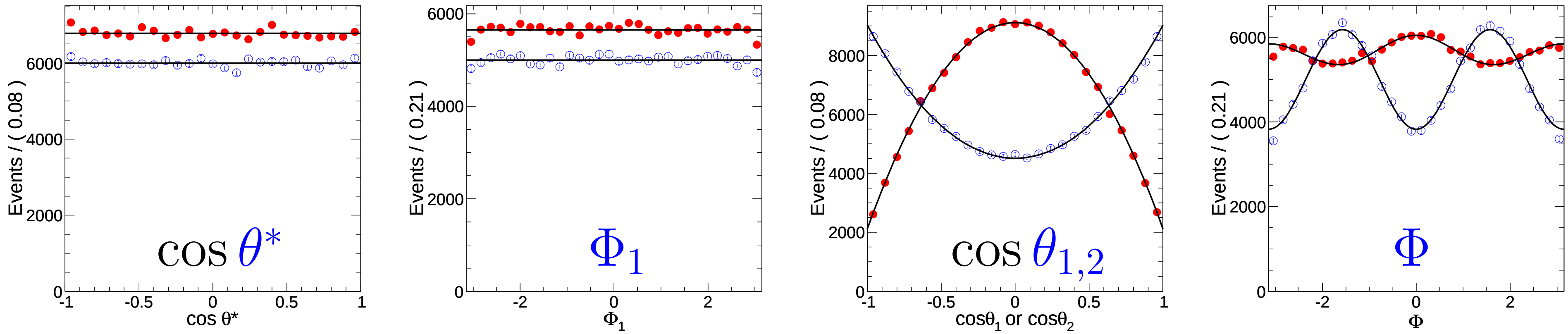


- Background
  - MadGraph: $q\bar{q} \to ZZ$ (gg$\to ZZ \sim 15\%$)
  - others negligible: $Zb\bar{b}$, $t\bar{t}$, $W^+W^-b\bar{b}$, WWZ, $t\bar{t}Z$, $4b$

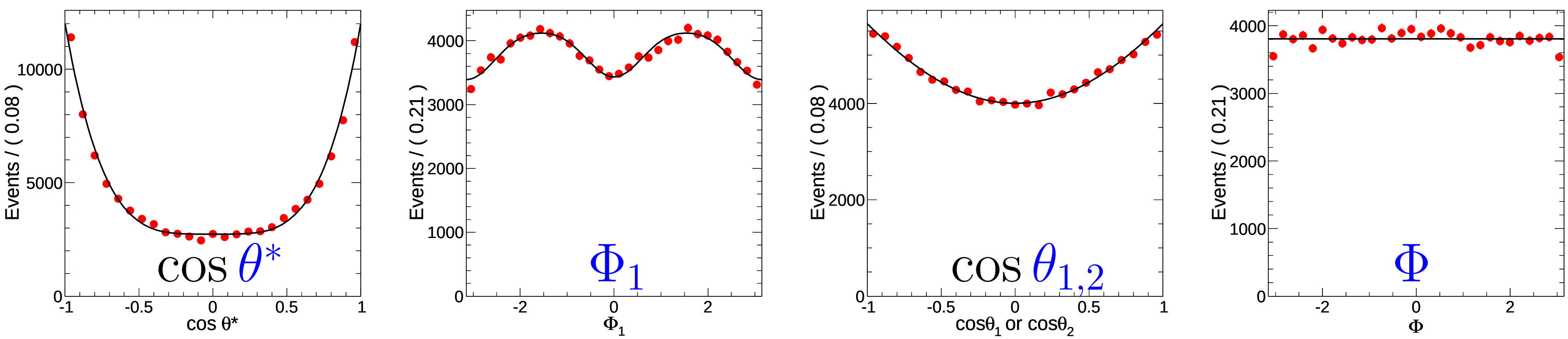
    $l^\pm$ isolation, $4l$ vertex, $2l$ mass, (no missing energy)...

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 $J = 0, 1, 2, 3, 4, \ldots$

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

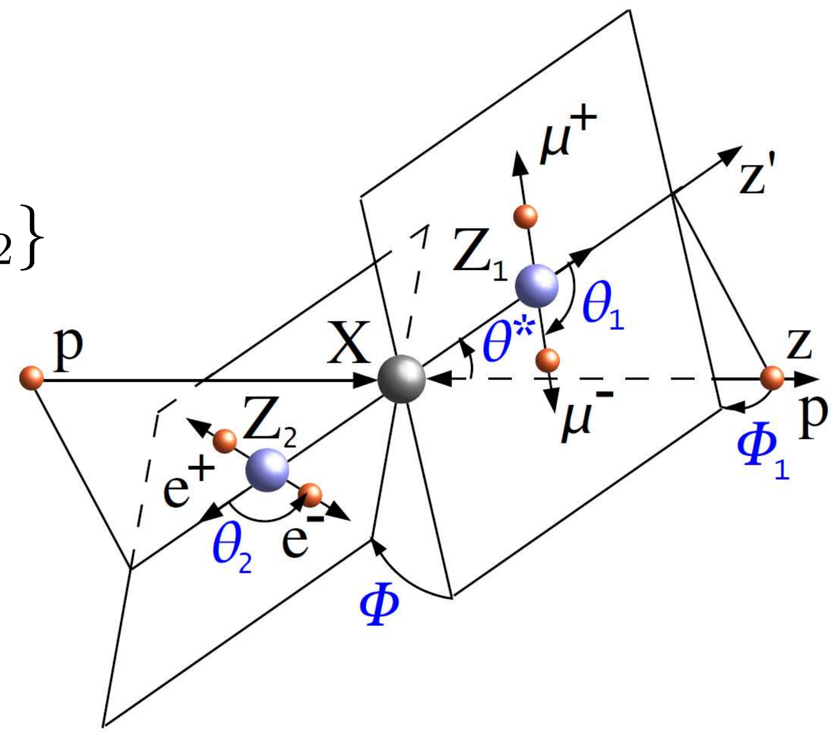
$$d\sigma \propto \sum_{\chi,\mu,\tau} \left| \sum_{\lambda,m} A_{ab}(\{\Omega\})\right|^2$$

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

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

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

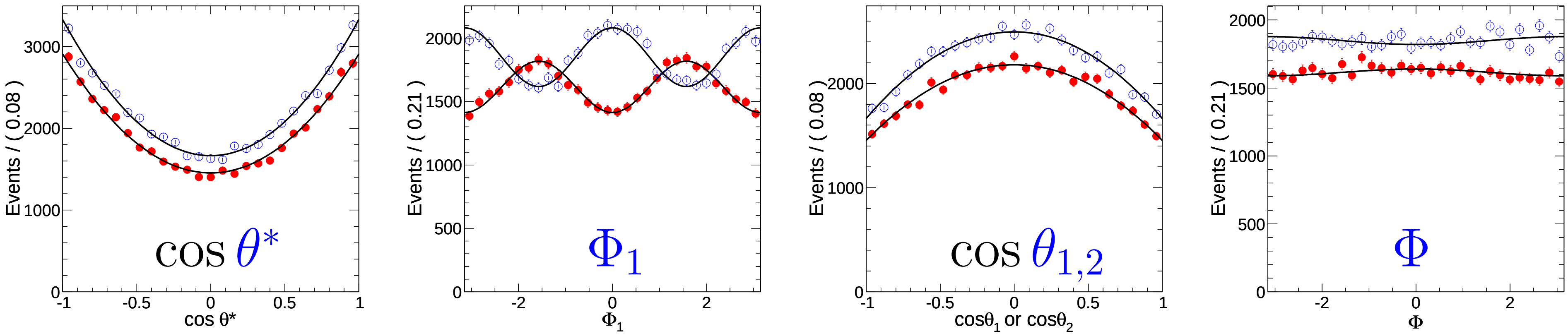
$$Z_2 \to f_2\bar{f}_2,\ \Omega_2 = (\Phi,\theta_2,-\Phi),\ \{\tau_1,\tau_2\}$$



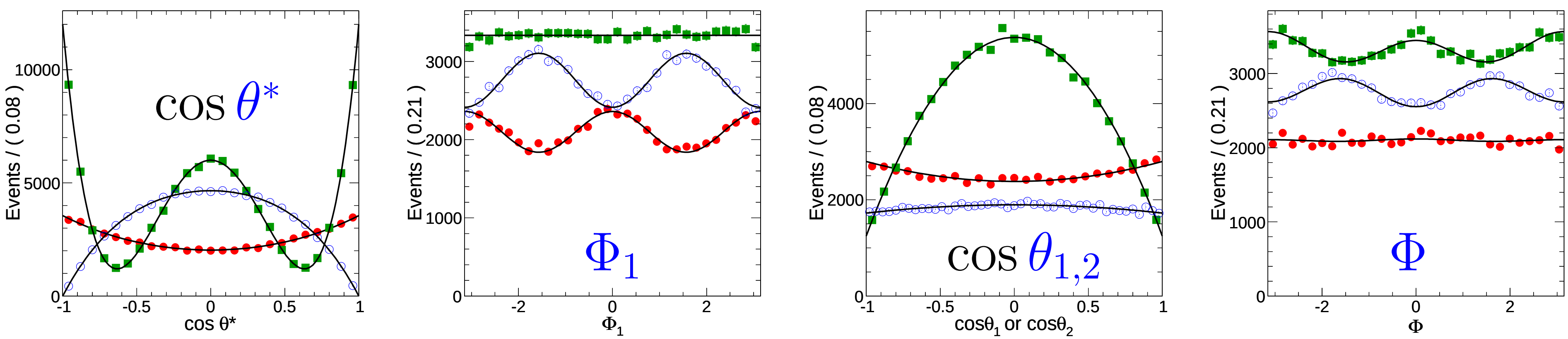
$$r = c_A/c_V \Rightarrow R_{1,2} = 2r_{1,2}/(1+{r_{1,2}}^2) = 0.15\ (l^\pm),\ 0.67\ (u),\ 0.94\ (d)$$

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

- $d\Gamma(ab \to X_J \to ZZ \to (f_1\bar{f}_1)(f_2\bar{f}_2)) \propto$

$$
\begin{aligned}
F^J_{00}(\theta^*) \times \Big\{ & 4\, f_{00}\, \sin^2\theta_1 \sin^2\theta_2 + (f_{++} + f_{--}) \left((1+\cos^2\theta_1)(1+\cos^2\theta_2) + 4R_1R_2\cos\theta_1\cos\theta_2\right) \\
& - 2\,(f_{++} - f_{--}) \left(R_1\cos\theta_1(1+\cos^2\theta_2) + R_2(1+\cos^2\theta_1)\cos\theta_2\right) \\
& + 4\sqrt{f_{++}f_{00}}\,(R_1 - \cos\theta_1)\sin\theta_1(R_2 - \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++}) \\
& + 4\sqrt{f_{--}f_{00}}\,(R_1 + \cos\theta_1)\sin\theta_1(R_2 + \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--}) \\
& + 2\sqrt{f_{++}f_{--}}\,\sin^2\theta_1\sin^2\theta_2\cos(2\Phi + \phi_{++} - \phi_{--}) \Big\} \qquad \text{spin}=0\ \&\ \geq 2
\end{aligned}
$$

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

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

$+$ other 26 interference terms for spin ≥ 2

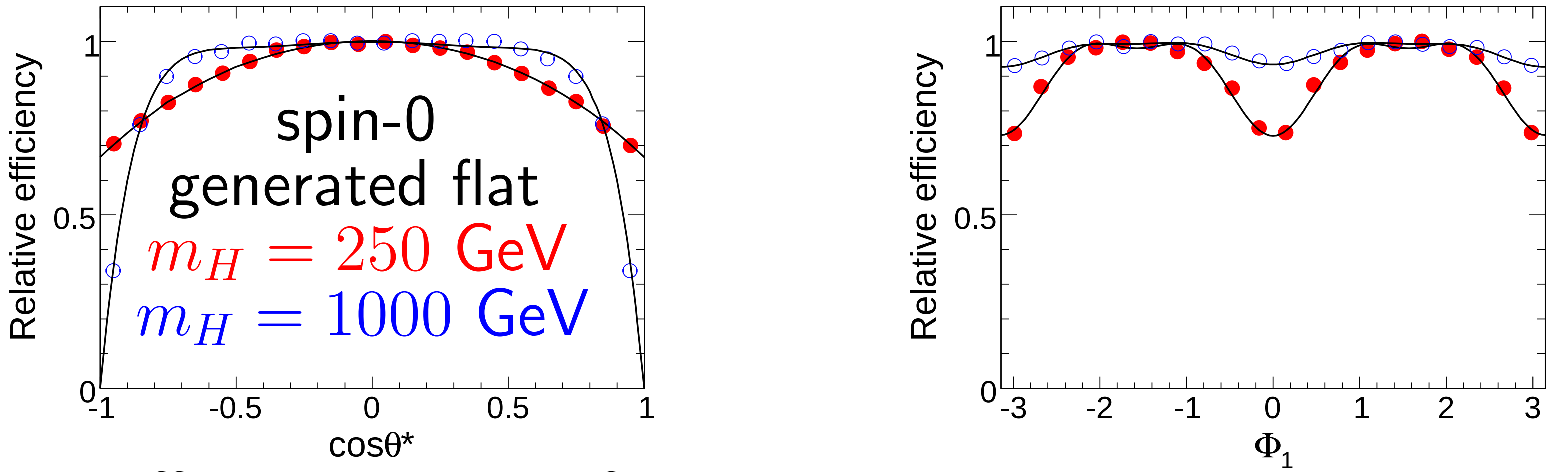
where $\Psi = \Phi_1 + \Phi/2$ and $F^J_{ij}(\theta^*) = \sum\limits_{m=0,\pm1,\pm2} f_m\, d^J_{mi}(\theta^*) d^J_{mj}(\theta^*)$

Detector Effects

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

  (1) track parameter resolution $\Rightarrow$ ± 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)

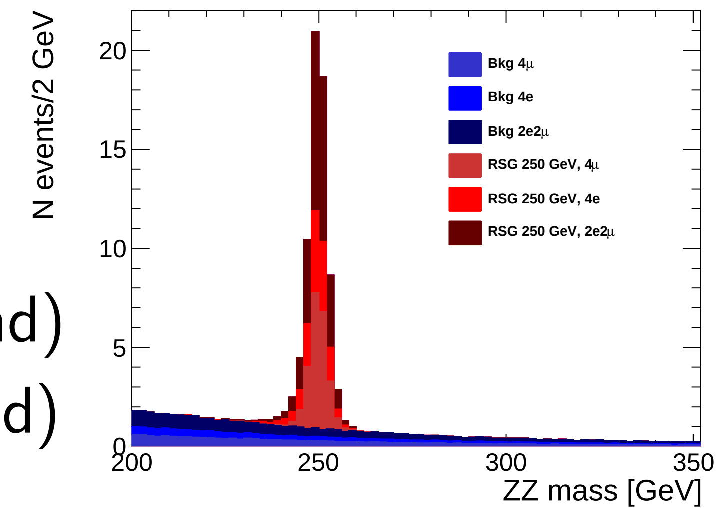
Analysis Goals

- Analysis depends on how we ask the question:

(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 $B \to VV$):

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

$\vec{\zeta}_J = (f_{\lambda_1\lambda_2}, \phi_{\lambda_1\lambda_2}, f_{zm};\ \ m_X, \Gamma_X)$, 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)

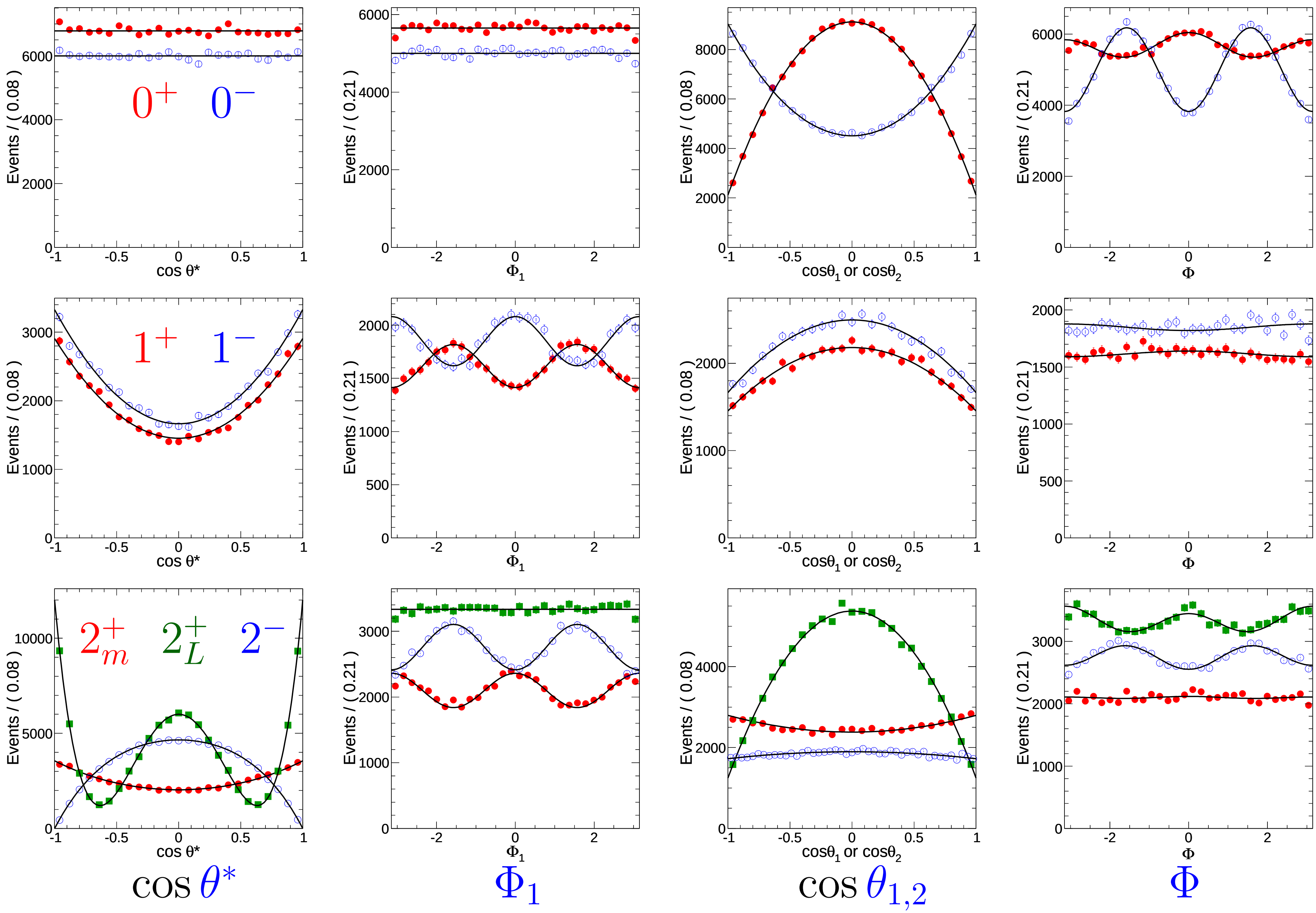
(b) $\mathcal{P}_J{=}\mathcal{P}(m_{ZZ}, ...){\times}\mathcal{P}_{\rm ideal}(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi){\times}\mathcal{G}(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi; Y_X)$

- 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 $(f_{\lambda_1\lambda_2}, \phi_{\lambda_1\lambda_2}, f_{zm})$

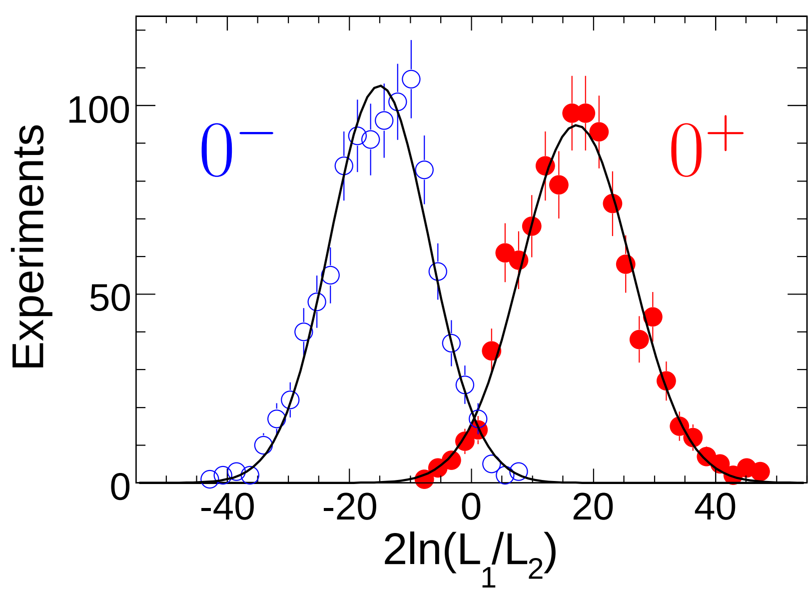
Distribution Examples (θ^*, Φ_1, θ_1, θ_2, Φ)

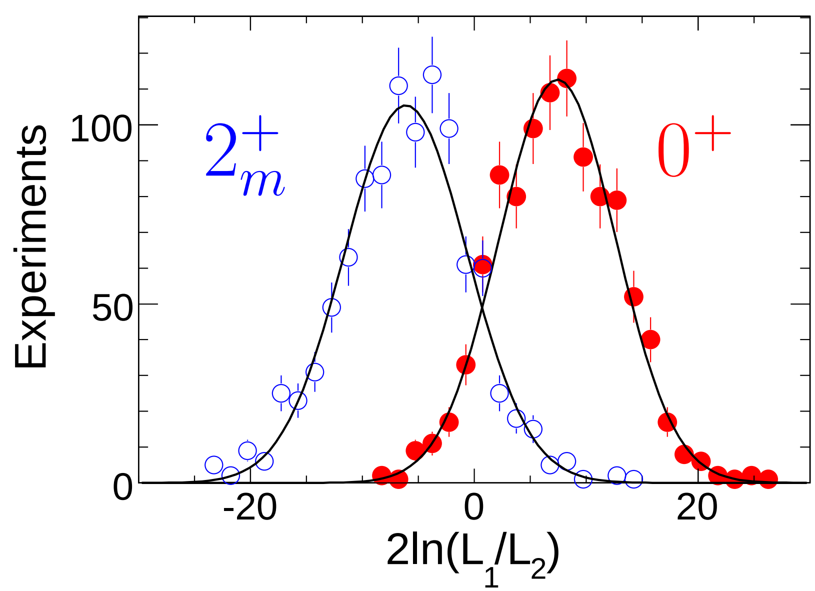


Analysis Approach (1)

- 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)

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





Analysis Approach (1): Results

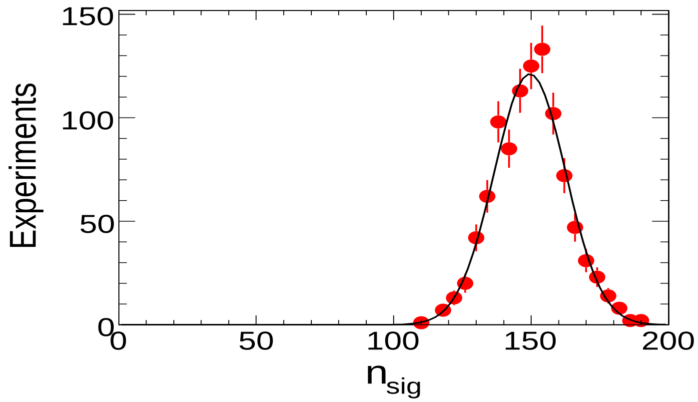
- Example of separation at $m_X = 250$ GeV (similar at 1000 GeV)
  - $\longrightarrow$ with 30 events ~ 2 - 4σ separation
  - $\longrightarrow$ full event info (production+decay) $\Rightarrow$ ultimate precision

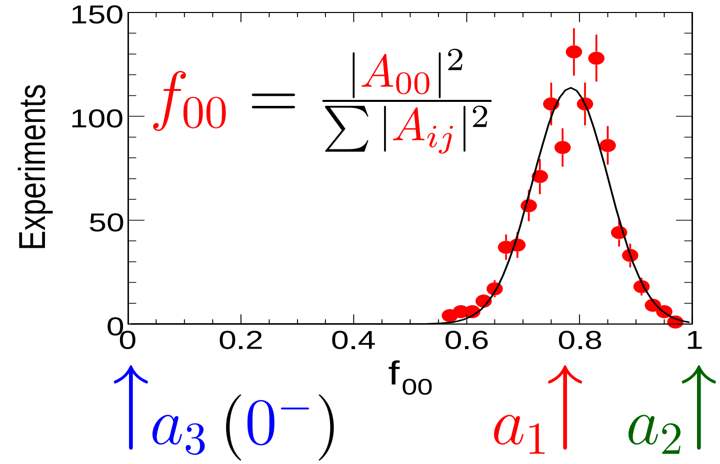
1D (θ^*) / 3D (θ_1, θ_2, Φ) / 5D ($\Phi_1, \theta^*, \theta_1, \theta_2, \Phi$)

	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

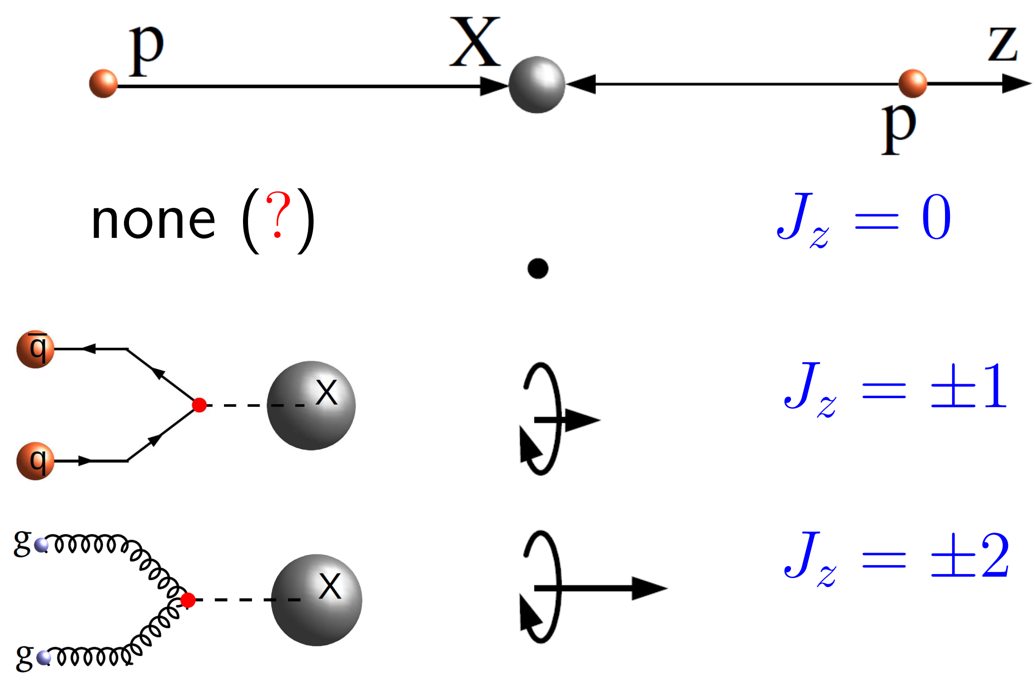
Conclusion

Conclusion

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

    $\to$ MC, angular distributions, ML fit $\to$ 3-4σ soon after discovery
  - model-independent approach (!)

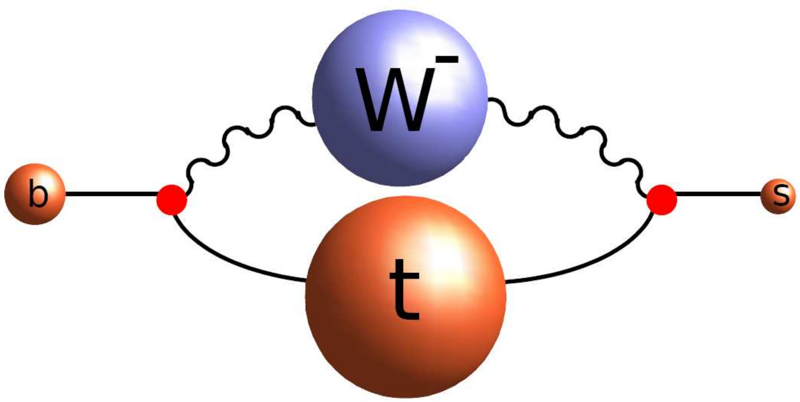
$$A \propto \frac{1}{\Lambda} t_{\mu\nu} \mathcal{T}^{\mu\nu} \quad (?)$$



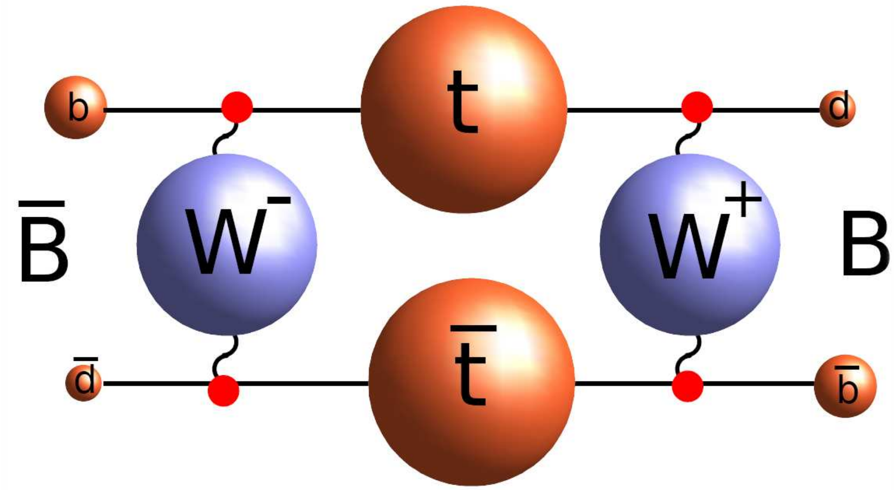
BACKUP

Loops

"penguin" loop



mixing "box"



- B-meson physics: test $A = |A| \times e^{i\phi}$

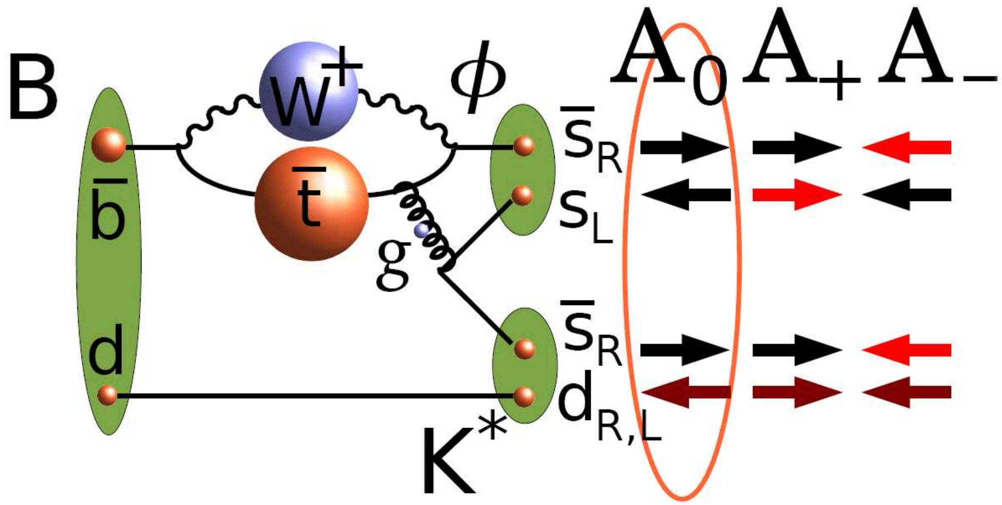
  (1) transition rate $|A|^2$

  (2) phase ϕ=arg(A)

  Best constraints on supersymmetry and New Physics

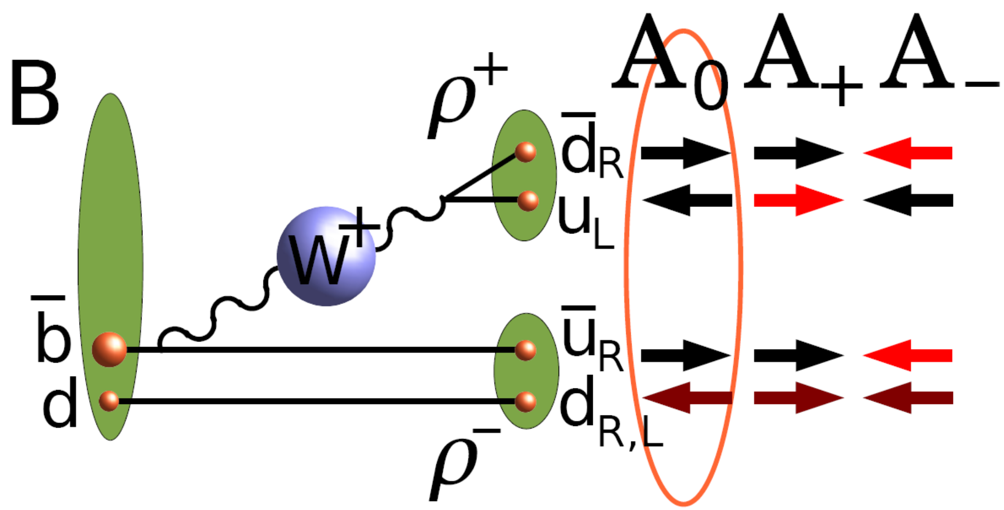
Spin Does Not Flip

- Observation $|A_{00}|^2 \simeq |A_{++}|^2 \gg |A_{--}|^2$ violates expectation



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

- It works: $B \to \rho^+\rho^-$ $|A_{00}|^2/(|A_{++}|^2 + |A_{--}|^2 + |A_{00}|^2) = 0.977^{+0.028}_{-0.024}$

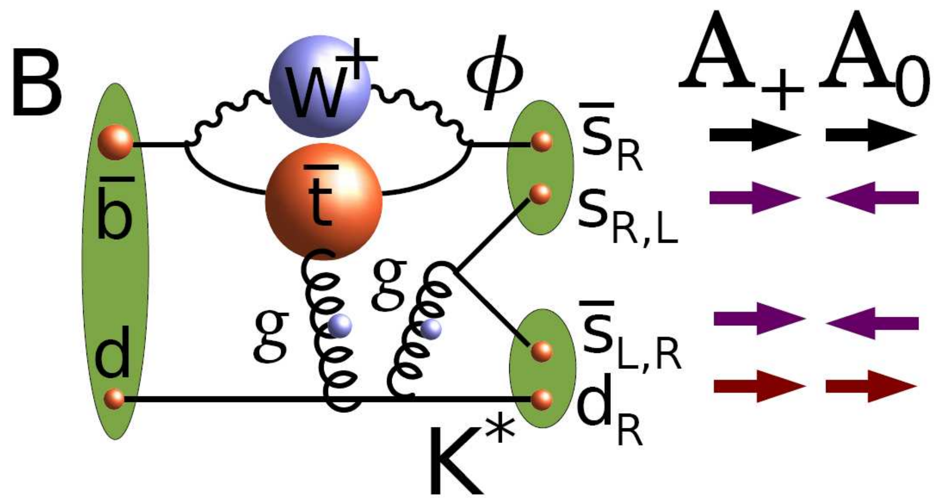


no loop contribution

ideal for CP studies in SM

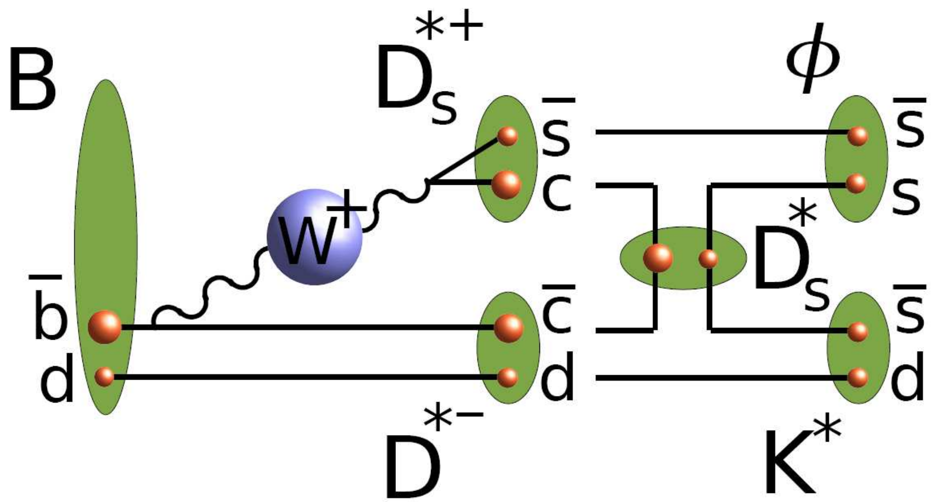
Scrambling to Explain A_{++}

- "Annihilation" mechanism



gluon to other quark
unlikely $\sim 1/m_B$
need to cancel A_{00}

- "Rescattering" mechanism (final state interaction)



spin-flip heavy > 2GeV states
violates both $|A_{00}|^2 \gg |A_{\pm\pm}|^2$
and $|A_{++}|^2 \gg |A_{--}|^2$

- No satisfactory solution

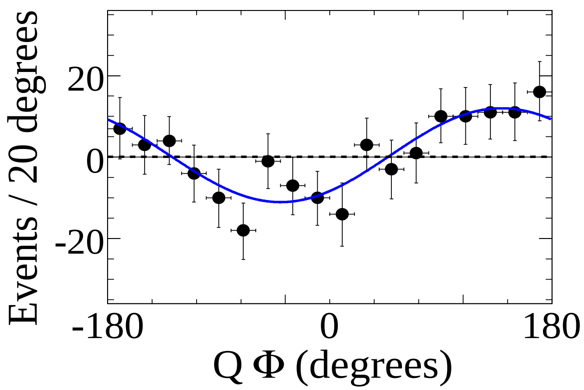
$B \to \varphi K^*$ polarization results

- Complex analysis with 12 independent results:

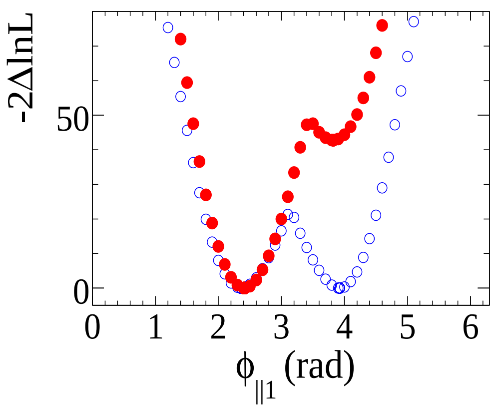
B (matter): $|A_{00}|, |A_{++}|, |A_{--}|, \arg(A_{00}), \arg(A_{++}), \arg(A_{--})$

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

- Examples:



$\Rightarrow \arg(A_{00}) \neq \arg(A_{\pm\pm})$



$K^*(892)/K_0^*(1430)$ interference

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

- Bottom line:

$$|A_{00}|^2 \simeq |A_{++}|^2 \gg |A_{--}|^2$$
$$\arg(A_{00}) \neq \arg(A_{++})$$

$X \to ZZ$ 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):

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

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

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

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

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

The five angles