Determination of properties of a **Higgs-like resonance at LHC: separation of spin hypotheses**

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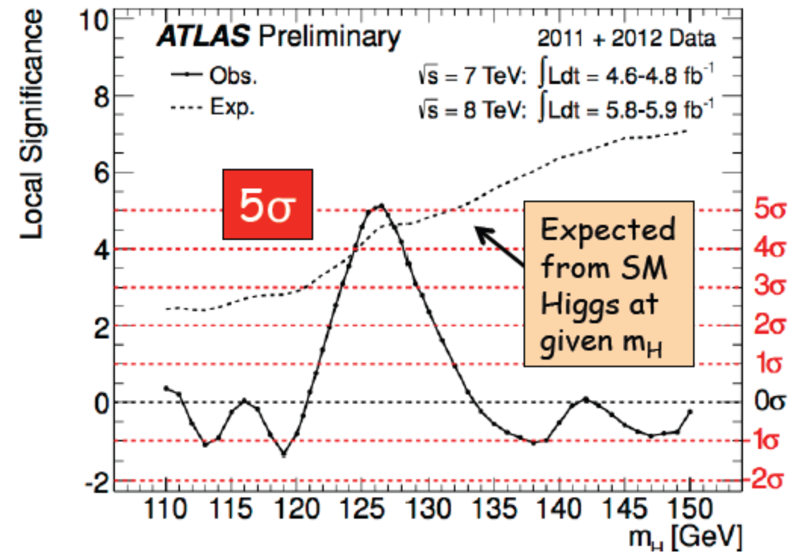
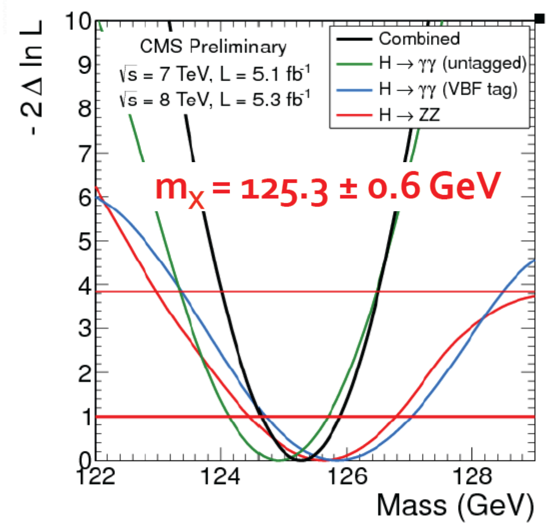
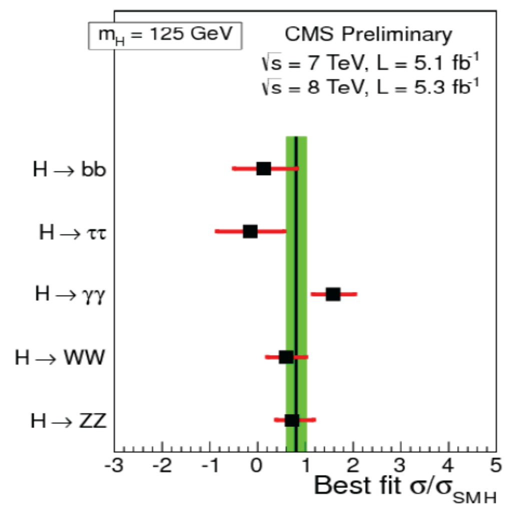
Properties measurement

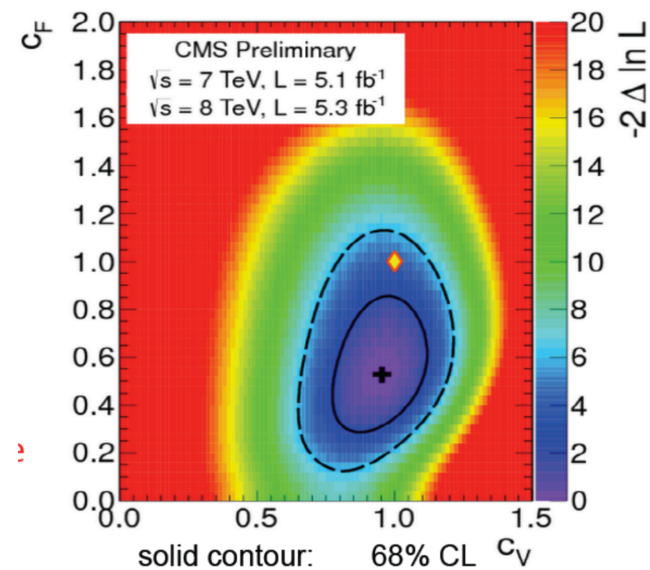
❑ **The signal observation is just the beginning … long road ahead of us: properties measurement**

- observation of an excess -> **mass and width**
- measure amplitude in different channels -> **xsec, branching ratios and couplings to V and f**









solid contour: 68% CL
dashed contour: 95% CL

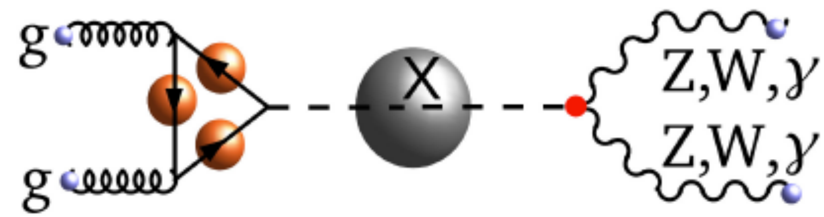
- differential distributions -> study tensor structure of the amplitudes: **spin/parity and couplings**

❑ All properties are correlated

"Higgs-like" most general amplitude

❑ Same amplitude for production (VV->X) and decay (X->VV):

- **Spin 0:** $A\left(X\to V_1V_2\right) = v^{-1}\varepsilon_1^{*\mu}\varepsilon_2^{*\nu}\left(a_1 g_{\mu\nu}M_X^2 + a_2 q_{1\mu}q_{2\nu} + a_3\varepsilon_{\mu\nu\alpha\beta}q_1^{\alpha}q_2^{\beta}\right)$
  - SM Higgs→ZZ,WW: $a_1 \neq 0, a_2 \sim O(10^{-2}), a_3 \sim O(10^{-11})$
  - SM Higgs→ $\gamma\gamma$: $a_1 = -a_2/2 \neq 0$
  - BSM pseudo-scalar Higgs $a_3 \neq 0$



- **Spin 1:** $A(X\to ZZ) = g_1^{(1)}\left[(\epsilon_1^* q)(\epsilon_2^*\epsilon_X) + (\epsilon_2^* q)(\epsilon_1^*\epsilon_X)\right] + g_2^{(1)}\epsilon_{\alpha\mu\nu\beta}\epsilon_X^{\alpha}\epsilon_1^{*,\mu}\epsilon_2^{*,\nu}\tilde{q}^{\beta}.$

- **Spin 2:**

$$A(X\to ZZ) = \Lambda^{-1}e_1^{*\mu}\,e_2^{*\nu}\left[c_1\,(q_1q_2)t_{\mu\nu} + c_2\,g_{\mu\nu}t_{\alpha\beta}\tilde{q}^{\alpha}\tilde{q}^{\beta} + c_3\,\frac{q_{2\mu}q_{1\nu}}{m_X^2}t_{\alpha\beta}\tilde{q}^{\alpha}\tilde{q}^{\beta} + 2c_4\,(q_{1\nu}q_2^{\alpha}t_{\mu\alpha} + q_{2\mu}q_1^{\alpha}t_{\nu\alpha}) + c_5 t_{\alpha\beta}\frac{\tilde{q}^{\alpha}\tilde{q}^{\beta}}{m_X^2}\epsilon_{\mu\nu\rho\sigma}q_1^{\rho}q_2^{\sigma} + c_6 t^{\alpha\beta}\tilde{q}_{\beta}\epsilon_{\mu\nu\alpha\rho}q^{\rho} + \frac{c_7 t^{\alpha\beta}\tilde{q}_{\beta}}{m_X^2}\left(\epsilon_{\alpha\mu\rho\sigma}q^{\rho}\tilde{q}^{\sigma}q_{\nu} + \epsilon_{\alpha\nu\rho\sigma}q^{\rho}\tilde{q}^{\sigma}q_{\mu}\right)\right].$$

- **Similarly for decay into fermions:**

$$A(X_{J=0}\to q\bar{q}) = \frac{m_q}{v}\bar{u}_{q_1}\left(\rho_1^{(0)} + \rho_2^{(0)}\gamma_5\right)v_{q_2},$$

$$A(X_{J=1}\to q\bar{q}) = \epsilon^{\mu}\bar{u}_{q_1}\left(\gamma_{\mu}\left(\rho_1^{(1)} + \rho_2^{(1)}\gamma_5\right) + \frac{m_q\tilde{q}_{\mu}}{\Lambda^2}\left(\rho_3^{(1)} + \rho_4^{(1)}\gamma_5\right)\right)v_{q_2},$$

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

(arXiv:1001.3396)

From couplings to angular analysis

- General amplitudes implemented in JHU MC -> able to generate any spin hypothesis !!!

  QCD LO production but NLO correction to decay can be included in effective couplings a_i

  (arXiv:1011.3396, http://www.pha.jhu.edu/spin/)

$$A(X \to V_1 V_2) = v^{-1} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2 q_{1\mu} q_{2\nu} + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$

- Analytical computation of helicity amplitudes

$$A_{00} = -\frac{M_X^4}{v}\left(a_1 x + a_2 \frac{M_{Z1} M_{Z2}}{M_X^2}\left(x^2 - 1\right)\right) \qquad x = \frac{M_X^2 - M_{Z1}^2 - M_{Z2}^2}{2 M_{Z1} M_{Z2}}$$

$$A_{\pm\pm} = \frac{M_X^2}{v}\left(a_1 \pm i a_3 \frac{M_{Z1} M_{Z2}}{M_X^2} \sqrt{x^2 - 1}\right)$$

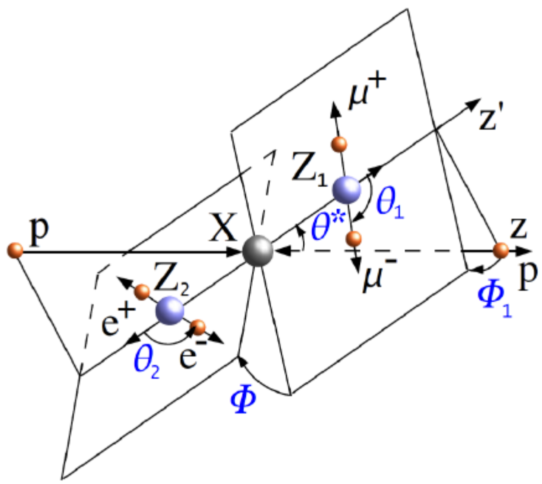
- Amplitudes parameterize angular distributions -> they can be extracted from data

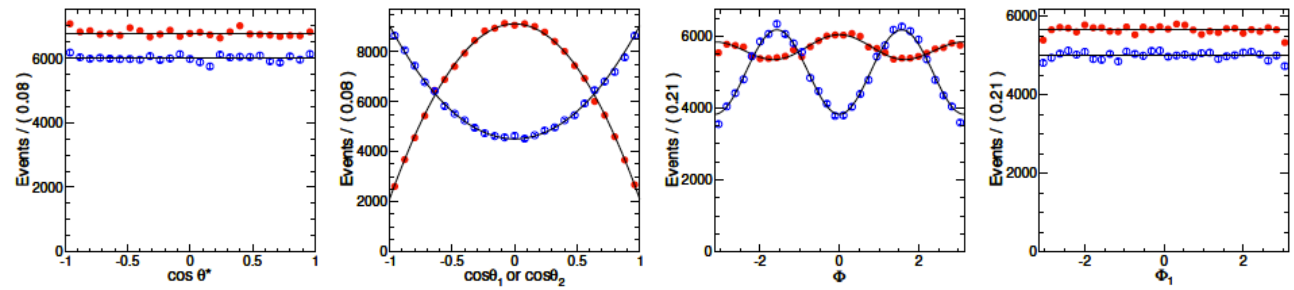
eg, 0+ angular distribution:

$$\begin{aligned} &4(1 - f_{++} - f_{--}) \sin^2\theta_1 \sin^2\theta_2 \\ &+(f_{++} + f_{--})((1 + cos^2\theta_1)(1 + \cos^2\theta_2) + 4 R_1 R_2 \cos\theta_1 \cos\theta_2) \\ &-2(f_{++} - f_{--})(R_1 cos\theta_1 (1 + cos^2\theta_2) + R_2 (1 + cos^2\theta_1) \cos\theta_2) \\ &+4\sqrt{f_{++}(1 - f_{++} - f_{--})}(R_1 - \cos\theta_1) \sin\theta_1 (R_2 - \cos\theta_2) \sin\theta_2 \cos(\Phi + \phi_{++}) \\ &+4\sqrt{f_{--}(1 - f_{++} - f_{--})}(R_1 + \cos\theta_1) \sin\theta_1 (R_2 + \cos\theta_2) \sin\theta_2 \cos(\Phi - \phi_{--}) \\ &+2\sqrt{f_{++} f_{--}} \sin^2\theta_1 \sin^2\theta_2 \cos(2\Phi + \phi_{++} - \phi_{--}) \end{aligned}$$

$$f_{ij} = |A_{ij}|^2,\ \phi_{ij} = arg(A_{ij}/A_{00}),\ R_{1,2} = \frac{2c_A/c_V}{1 + c_A^2/c_V^2} \ (=.15 \text{ for leptons})$$

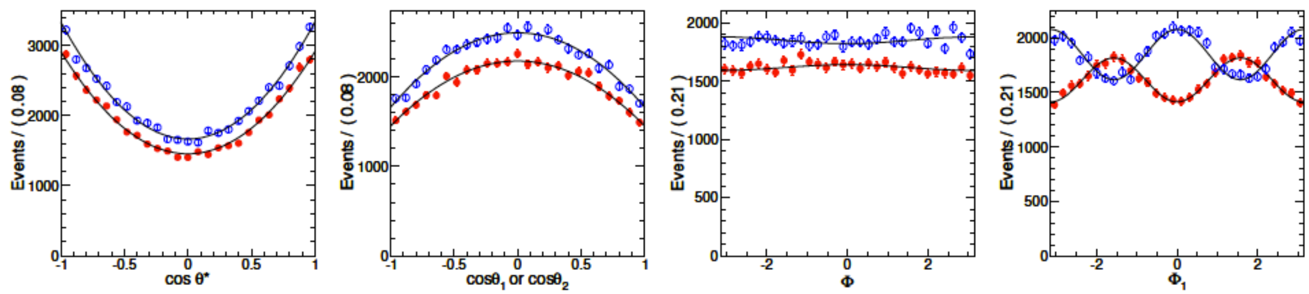
Angular distributions for X->ZZ (250 GeV)



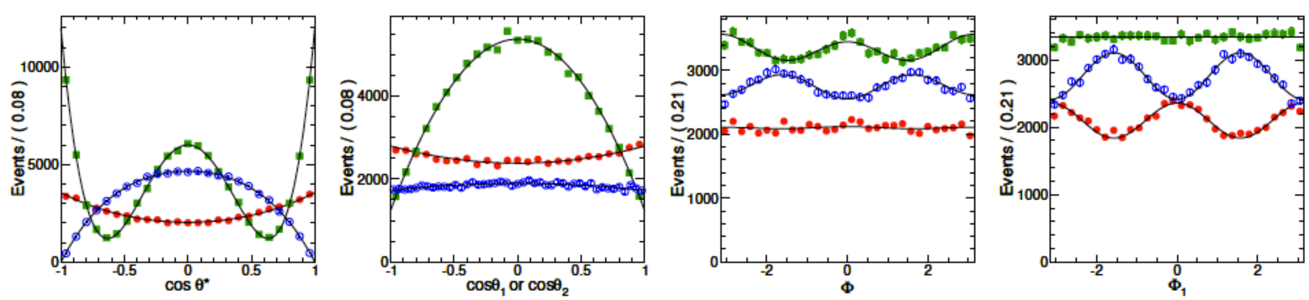


SM Higgs, Pseudo-Scalar (generator from arxiv.org:1001.3396) 5 / 19

1D projections for Vector, Pseudo-Vector
(generator from arxiv.org:1001.3396)



1D projections for $J^P = 2^+_M, 2^+_L, 2^-$
(generator from arxiv.org:1001.3396)



- "production" angles: θ^*, ϕ_1
- decay angles: θ_1, θ_2, ϕ

lines = analytical computation

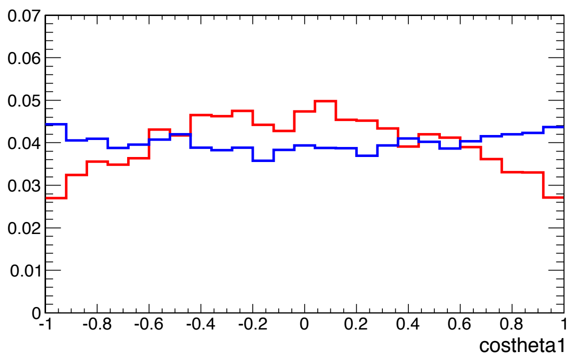
dots =MC generation

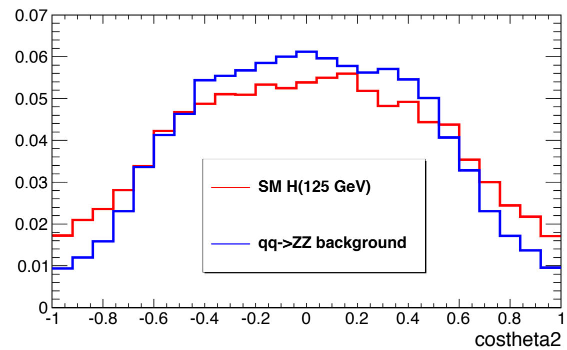
(much info also from correlations!)

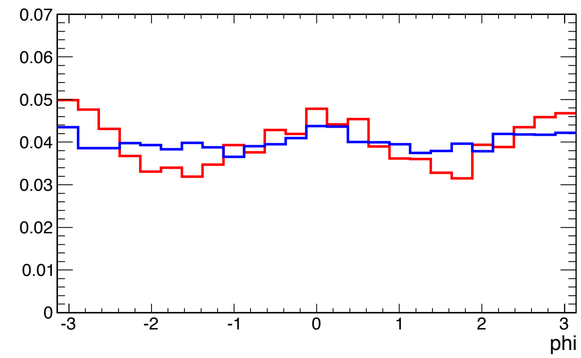
Angular analysis for Higgs->ZZ search

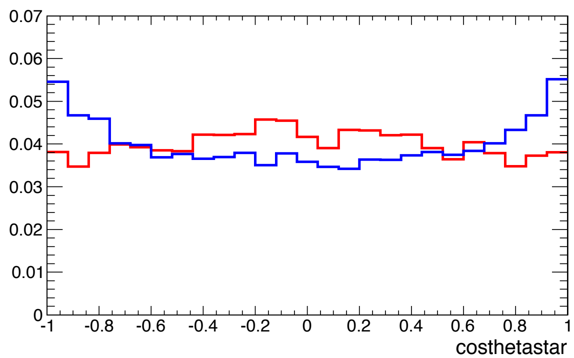
Signal vs background -> Higgs search

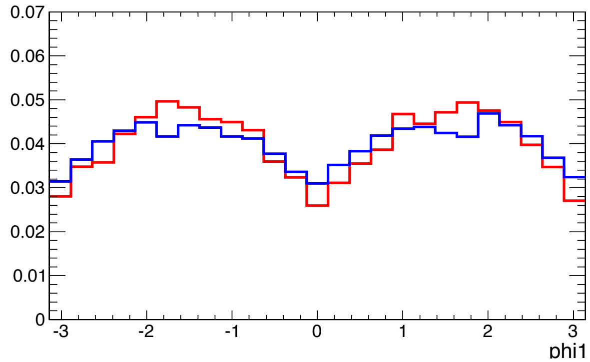
- Angular information can be used to separate Higgs signal from ZZ background

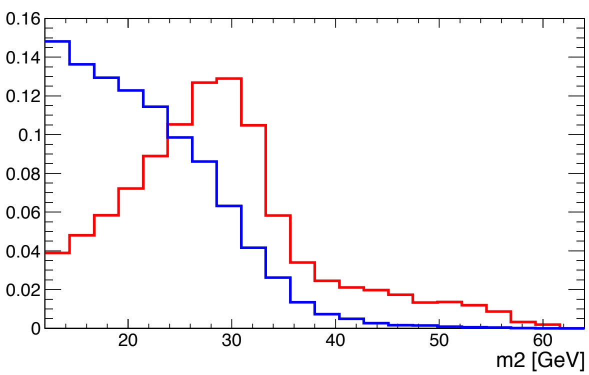


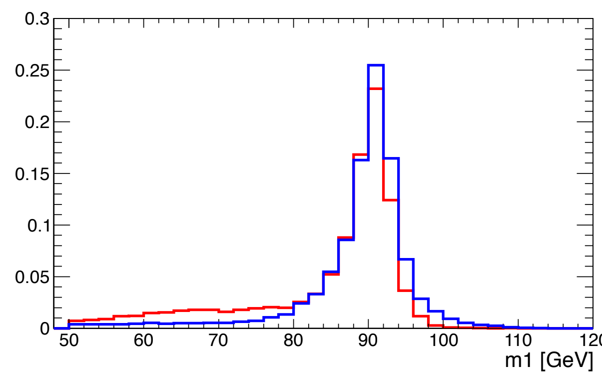












- 5 angles + mZ1, mZ2 + mZZ
  - plots with toy MC: CMS-like resolution and acceptance (shape comparison, normalized to 1)
  - angles correlated with mZZ
  - offshell (mH<2*mZ) mZ_2 and mZ_1-mZ_2 correlations very powerful to separate S/B

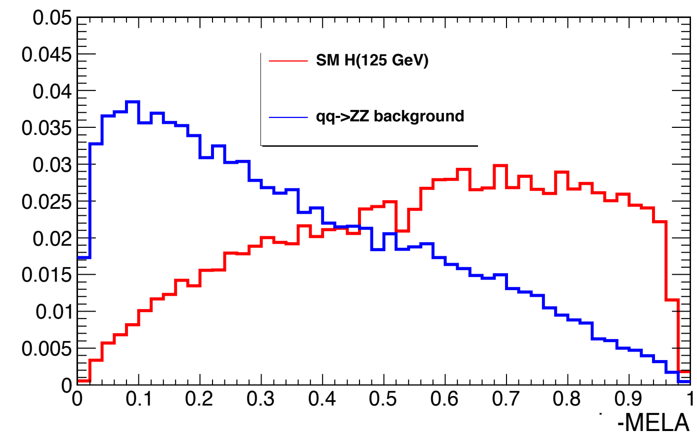
(arXiv:1108.2274 arXiv:1001.3396)

MELA for Higgs search

- **Matrix Element Likelihood Approach: analytical likelihood built from angular distributions**

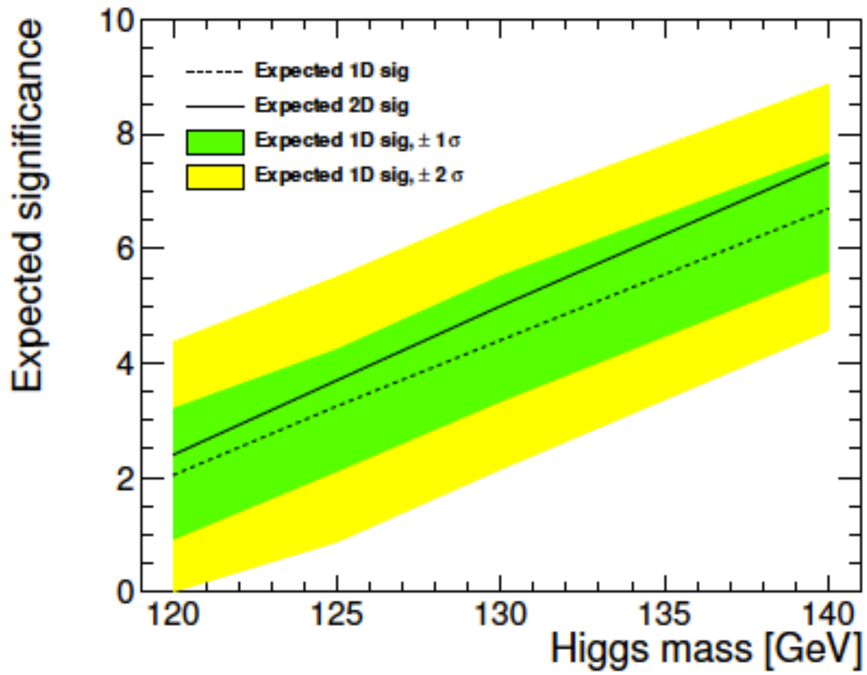
$$\text{MELA} = \frac{P_{sig}}{P_{sig} + P_{bkg}}$$

  - acceptance effects cancel in the ratio to first order
  - unaccounted effects make likelihood suboptimal



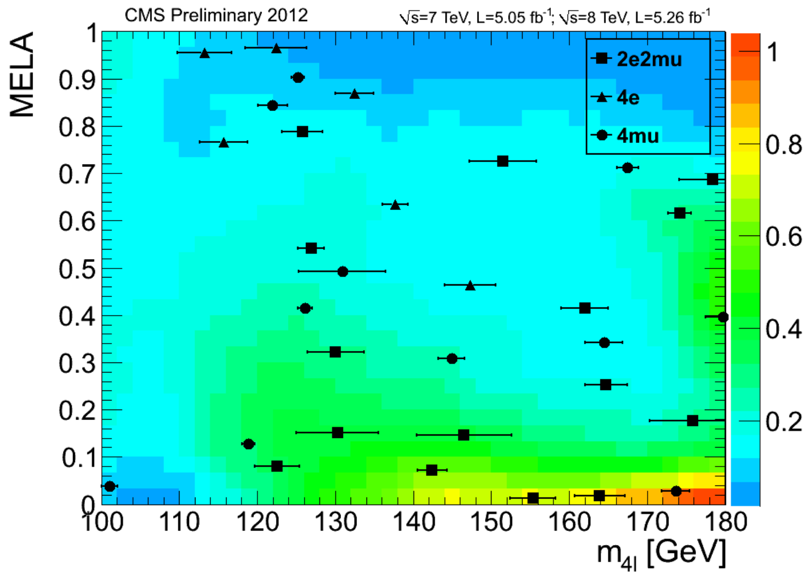
- **Toy analysis with MC applying CMS-like resolution and acceptance effects:**

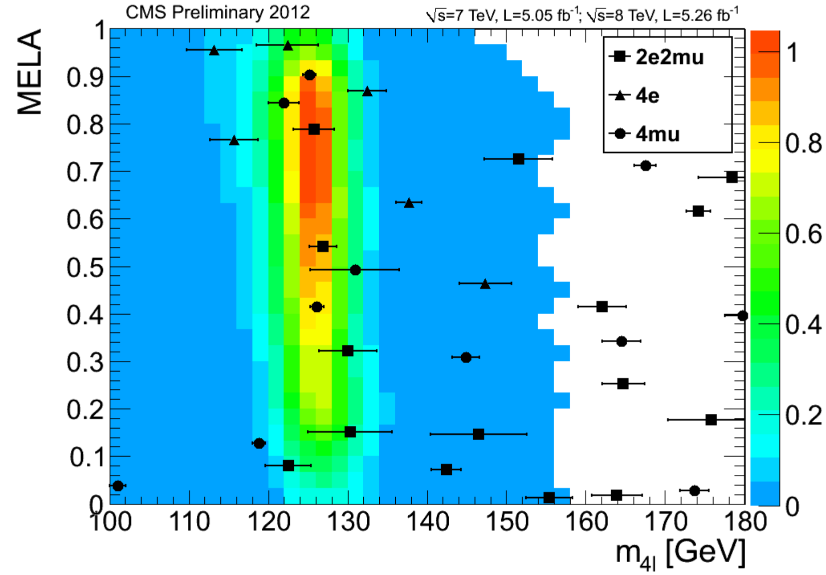
increase in significance 15%-30% from low to high Higgs mass



Example from CMS: H->ZZ->4lep angular analysis

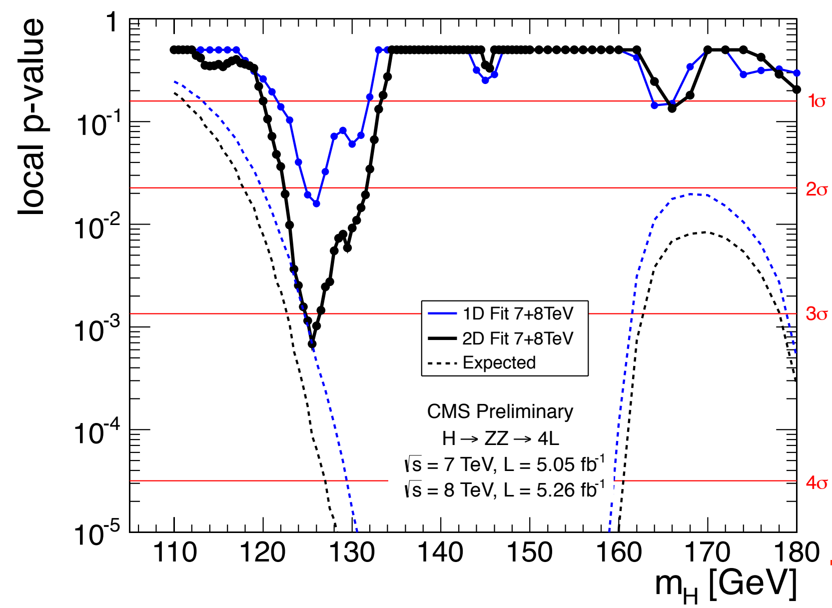
- Signal extraction from 2D fit: m(4l) vs MELA





- Significance with 10 fb^{-1}

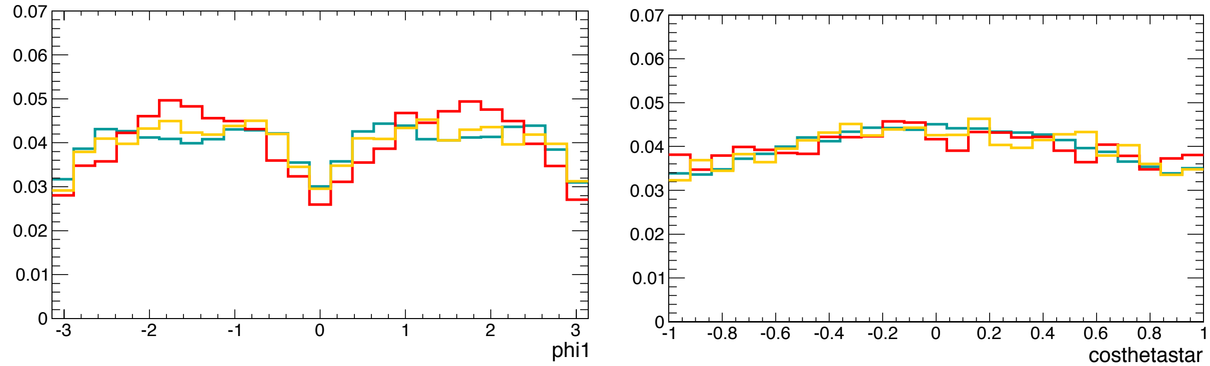
	1D	2D
expected	3.2	3.8
observed	2.2	3.2



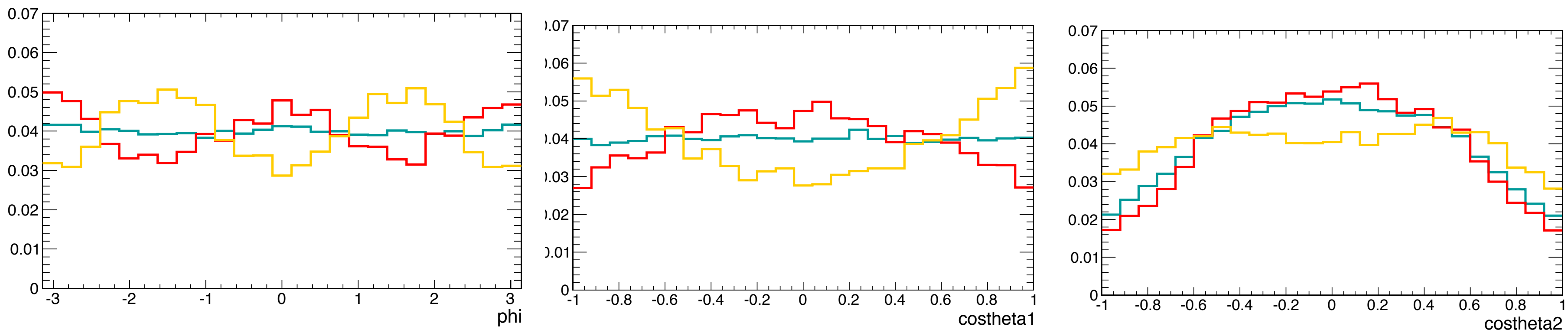
see: M.Klute talk, CMS HIG-12-016

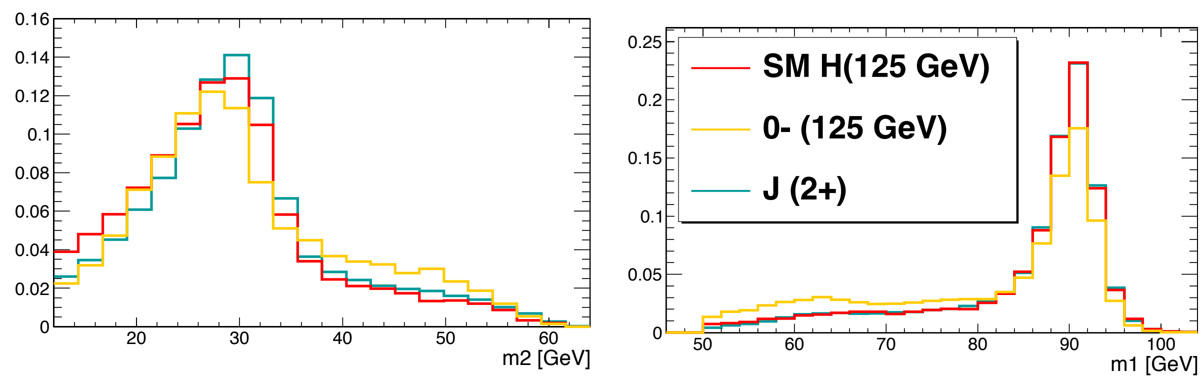
Analysis for X->ZZ spin / parity measurement

Different spin/parity for X->ZZ (mX 125 GeV)



- Plots with toy MC: CMS-like resolution and acceptance
(shape comparison, normalized to 1)

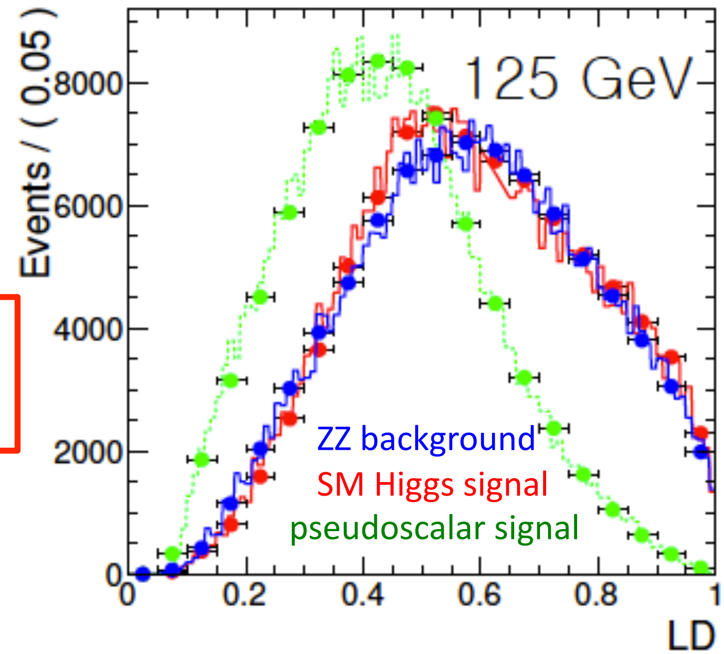




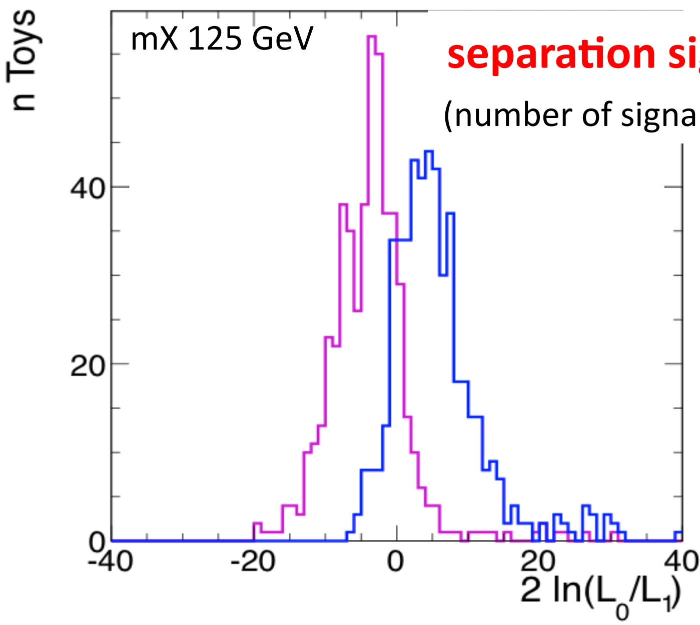
PseudoMELA:
scalar vs pseudoscalar

- Similar approach for spin-hypothesis separation

$$\text{pseudoMELA} = \frac{P_{0+}}{P_{0+} + P_{0-}}$$

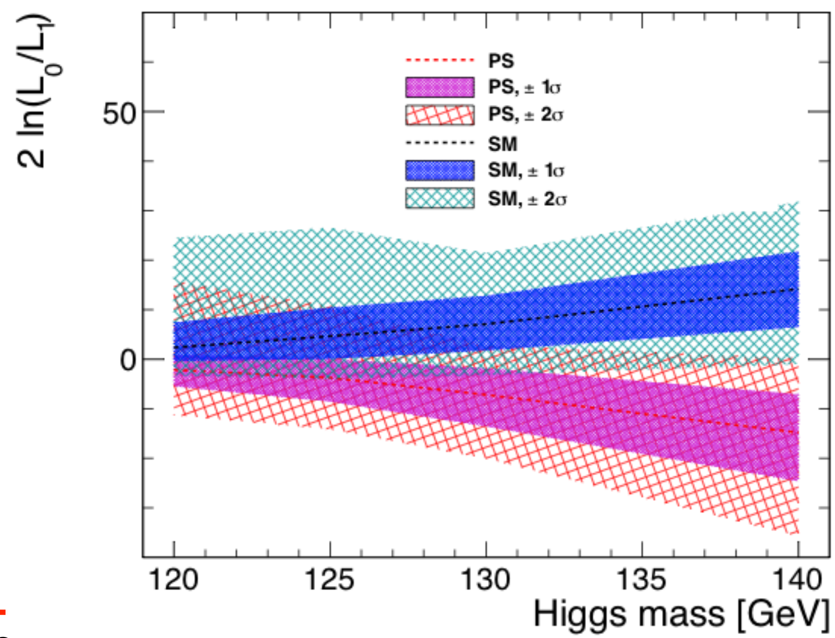


Toy results: hypothesis separation with 20 fb^{-1}
(assume same signal strength as SM)



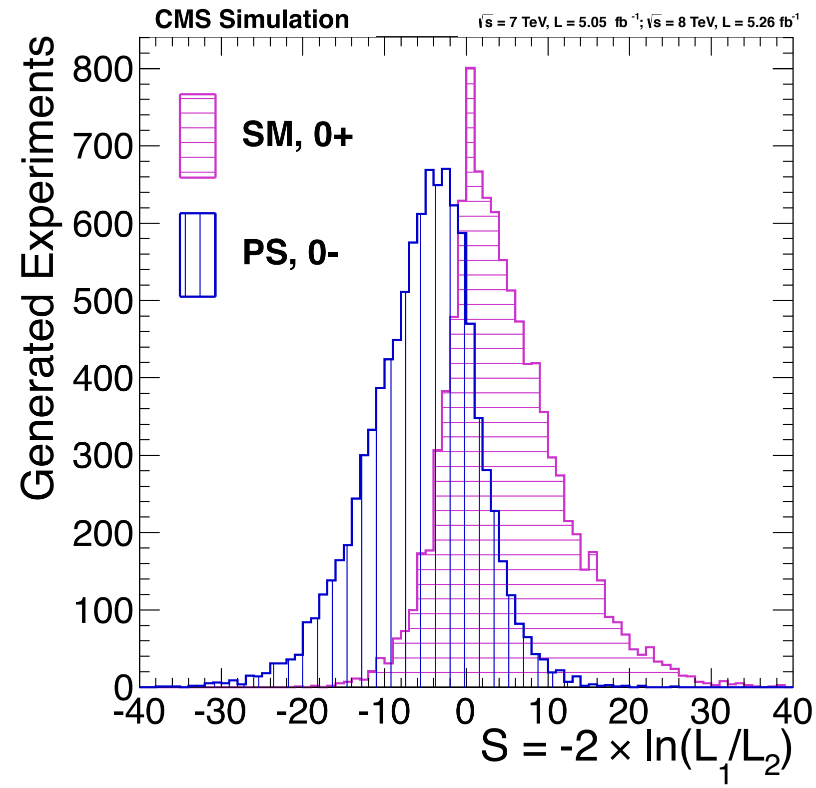
separation signif: 2.1 σ

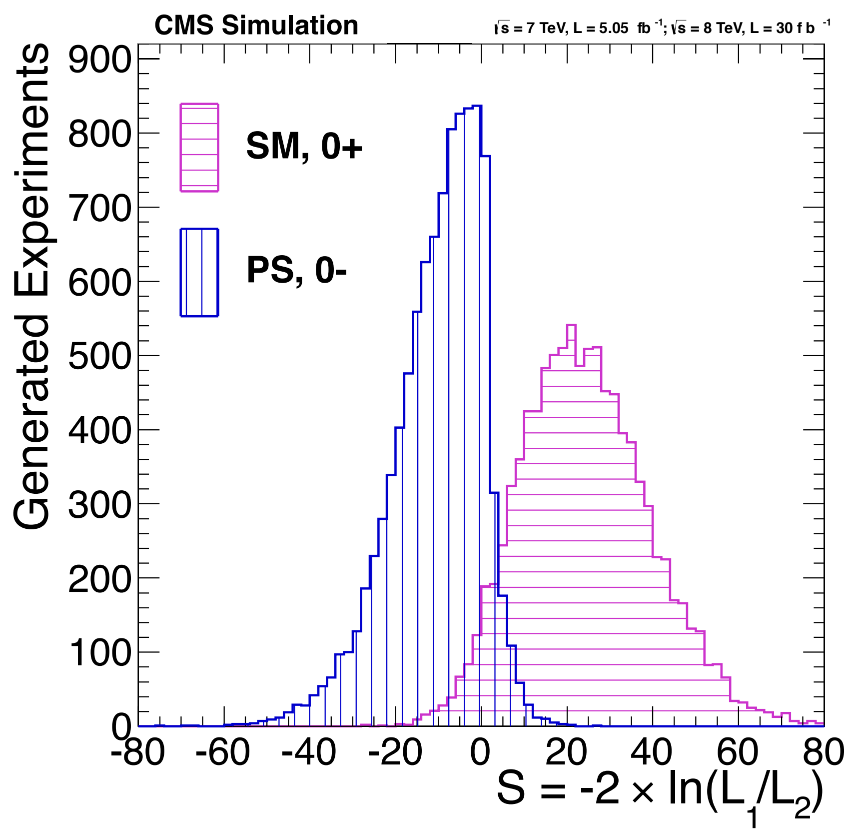
(number of signal events ~11)



Example from CMS

- Full CMS simulation, with complete H->ZZ analysis (as published)
  - status: **1.6 σ** expected separation with 5+5 fb^{-1}
  - prospects: **3 σ** separation before shutdown

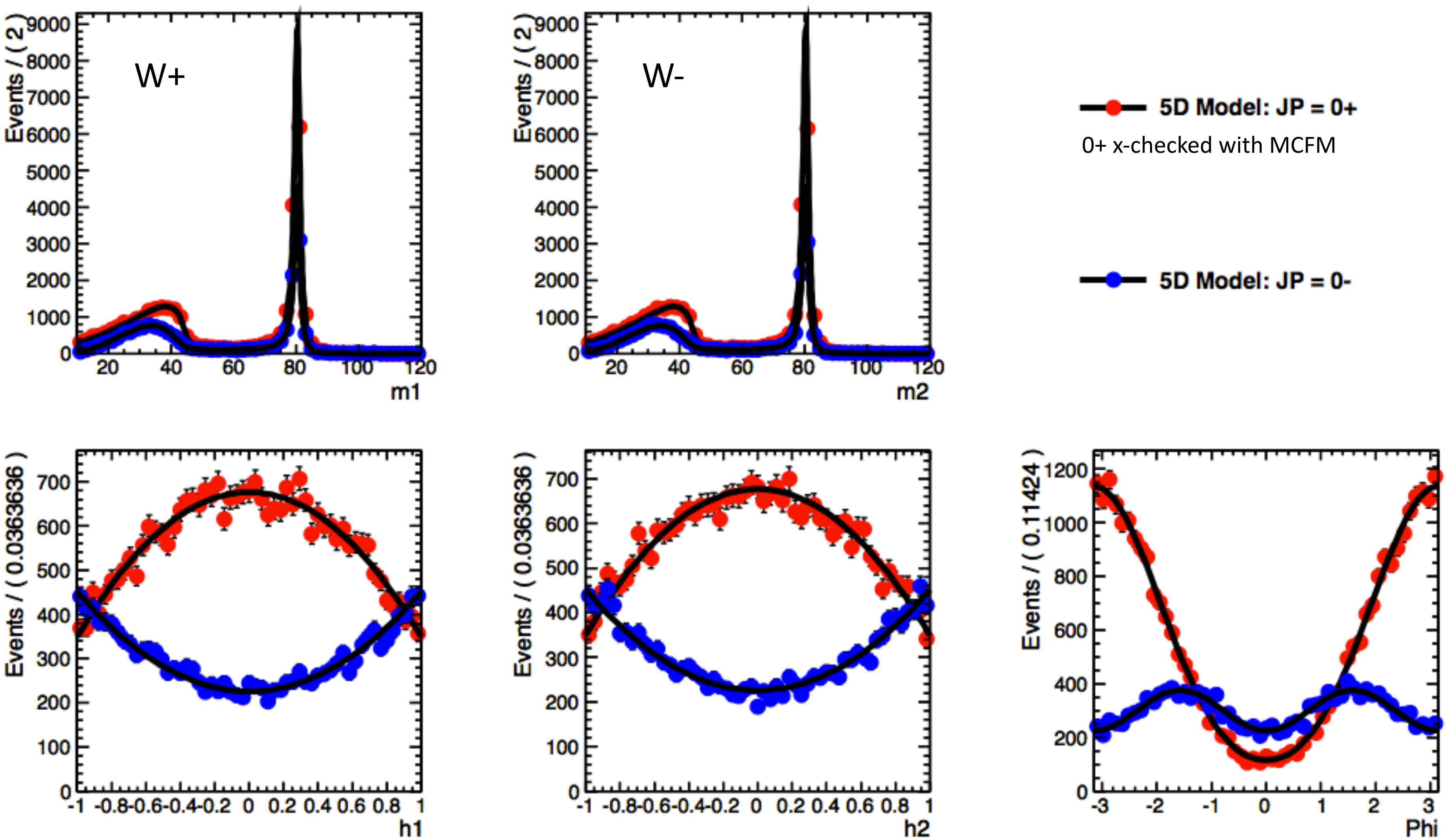




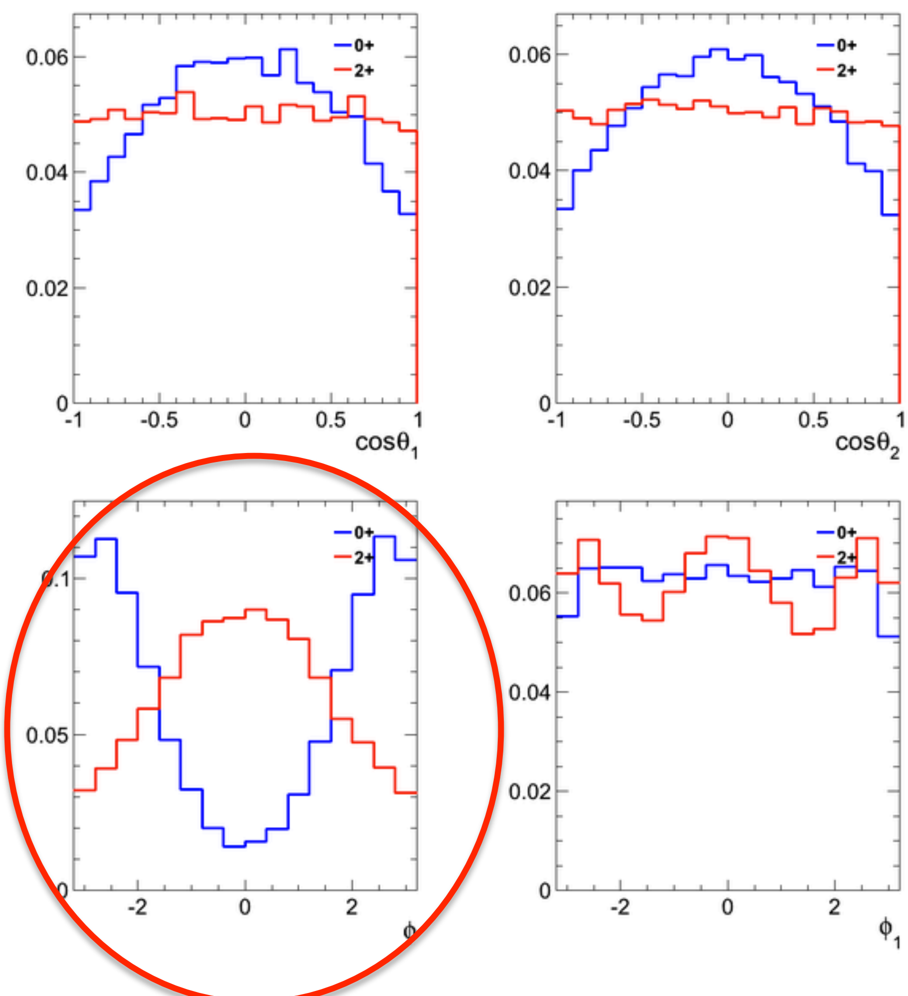
Integ. Lumi. 7 (8) TeV	Expected Separation
5/fb (5/fb)	1.6σ
5/fb (20/fb)	2.6σ
5/fb (30/fb)	3.1σ

Spin/parity analysis in X->WW channel

0+ vs 0- in WW channel (125 GeV)



0+ vs 2+m in WW channel (125 GeV)



- Δϕ variable (used to discriminate Higgs from WW background) also very powerful to discriminate different spin hypothesis

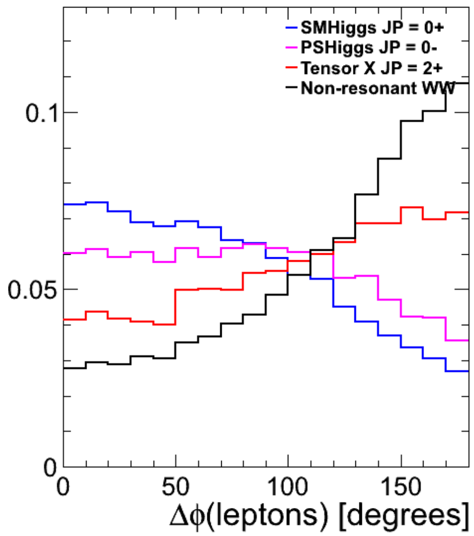
see also Ellis et al. arXiv:1202.6660

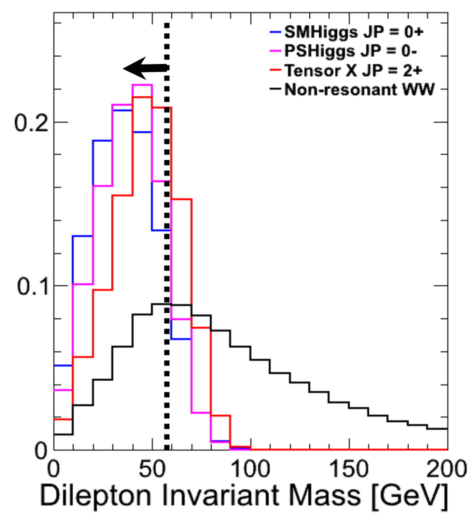
2D fit: $\Delta\phi$, m(ll) or mT

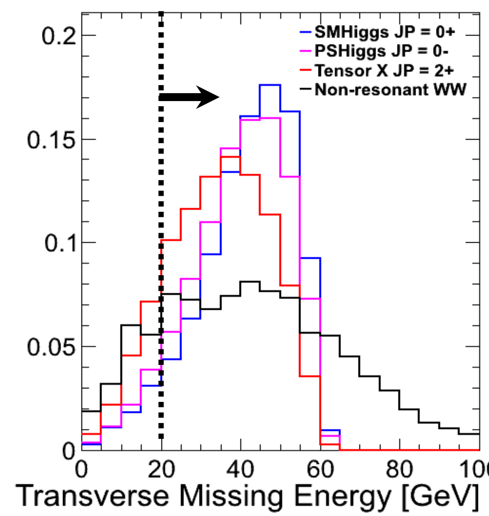
- **Toy studies:** only partial info available (kinematic not fully reconstructable)

  CMS-like acceptance cuts, only 0-jets opposite-flavor channel

  loose cuts to avoid sculpting distribution -> 25/250 signal/background events per fb^{-1}







-> 2D fit: mll, mT

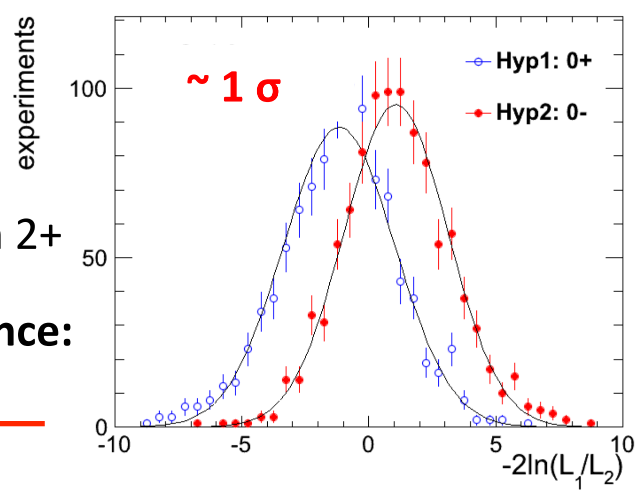
- 10 fb^{-1}, NO SYSTEMATICS

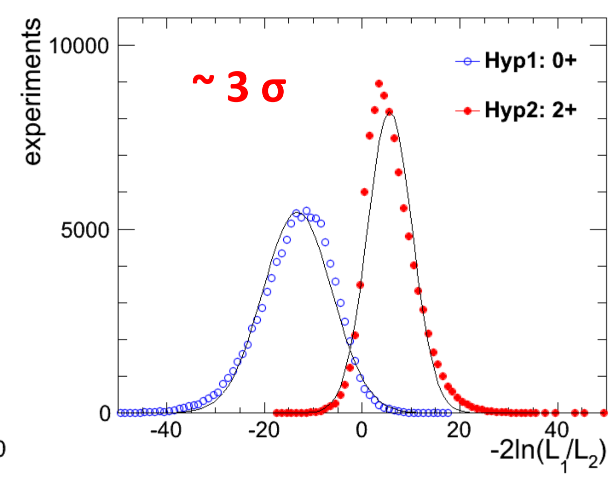
  only WW background

  - **Signal significance:**

    ~4.5 for spin 0, ~ 3 for spin 2+

  - **Spin separation significance:**





Conclusions and prospects

- ❑ **JHU MC available for any spin VV->X->VV**

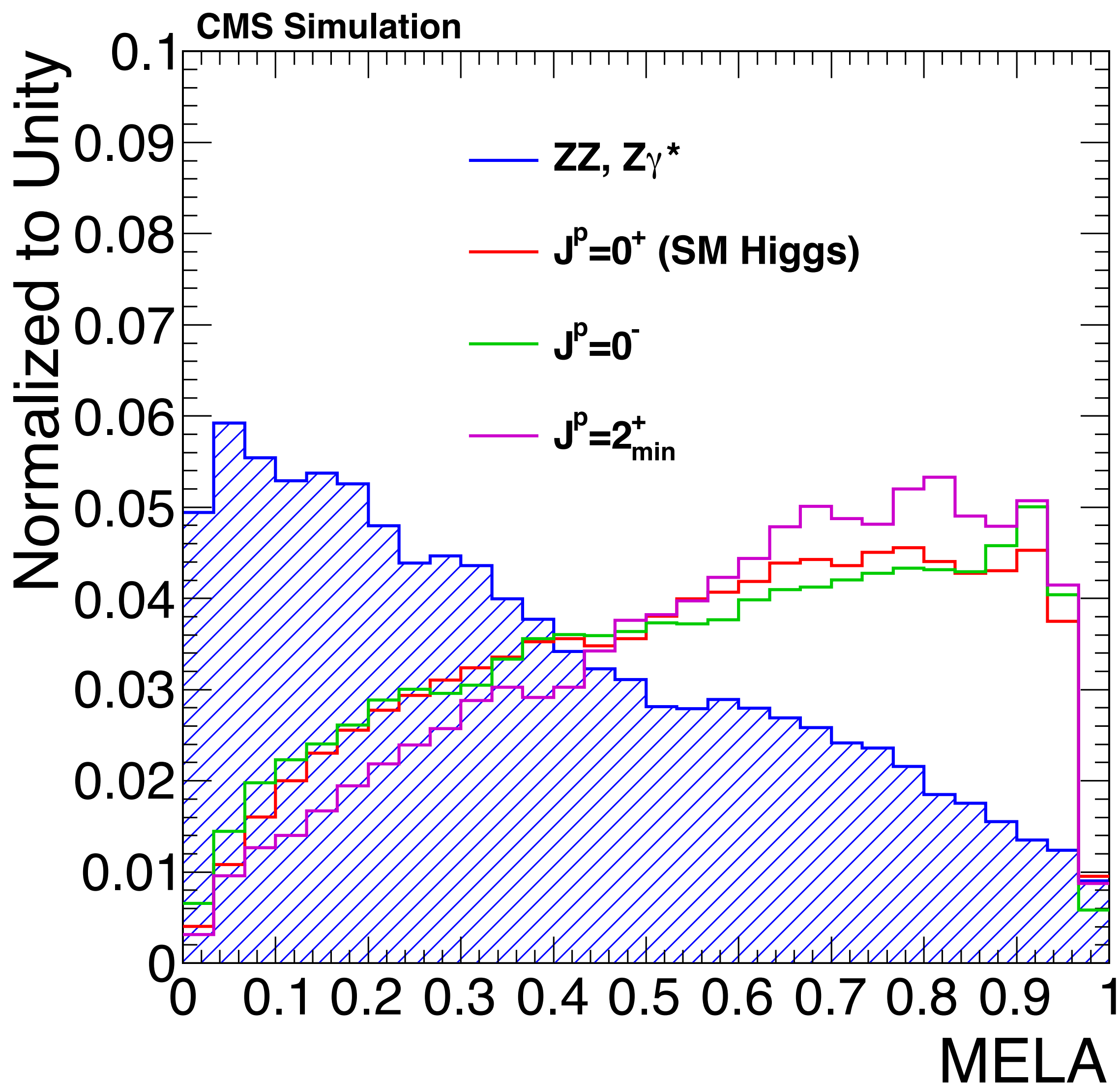
- ❑ **Angular analysis based with analytical likelihood (MELA) successfully used**
  - **to boost signal search in X->ZZ: 3σ -> 4σ**
  - **to separate X spin hypothesis: 3σ separation 0+/0- before shutdown**

- ❑ Combination of various channels (eg ZZ, WW):
  - increase signal sensitivity
  - complementary information

- ❑ All models can be tested, starting from most general couplings

BACKUP

MELA for S/B: model independent



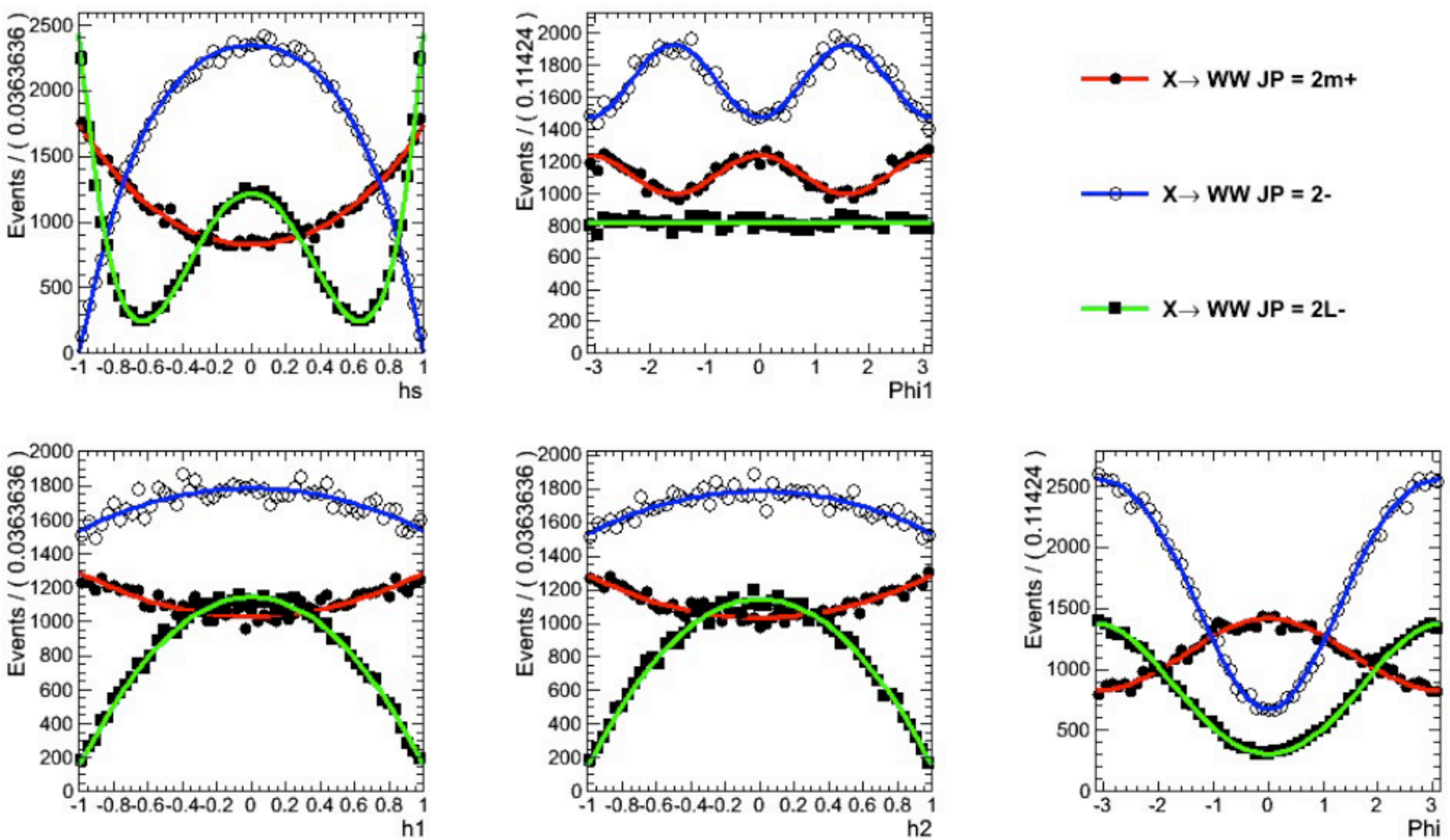
Scenarios studied in arXiv:1001.3396

TABLE I: The list of scenarios chosen for the analysis of the production and decay of an exotic X particle with quantum numbers J^P. For the two 2^+ cases, the superscripts m (minimal) and L (longitudinal) distinguish two scenarios, as discussed in the last column. When relevant, the relative fraction of gg and $q\bar{q}$ production is taken to be 1:0 at $m_X = 250$ GeV and 3:1 at $m_X = 1$ TeV. The spin-zero X production mechanism does not affect the angular distributions and therefore is not specified.

scenario (J^P)	$X \to ZZ$ decay parameters	X production parameters	comments
0^+	$a_1 \neq 0$ in Eq. (2)	$gg \to X$	SM Higgs-like scalar
0^-	$a_3 \neq 0$ in Eq. (2)	$gg \to X$	pseudo-scalar
1^+	$g_{12} \neq 0$ in Eq. (4)	$q\bar{q} \to X$: ρ_{11}, $\rho_{12} \neq 0$ in Eq. (9)	exotic pseudo-vector
1^-	$g_{11} \neq 0$ in Eq. (4)	$q\bar{q} \to X$: ρ_{11}, $\rho_{12} \neq 0$ in Eq. (9)	exotic vector
2^+_m	$g_1^{(2)} = g_5^{(2)} \neq 0$ in Eq. (5)	$gg \to X$: $g_1^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: $\rho_{21} \neq 0$ in Eq. (10)	Graviton-like tensor with minimal couplings
2^+_L	$c_2 \neq 0$ in Eq. (6)	$gg \to X$: $g_2^{(2)} = g_3^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: ρ_{21}, $\rho_{22} \neq 0$ in Eq. (10)	Graviton-like tensor longitudinally polarized and with $J_z = 0$ contribution
2^-	$g_8^{(2)} = g_9^{(2)} \neq 0$ in Eq. (5)	$gg \to X$: $g_1^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: ρ_{21}, $\rho_{22} \neq 0$ in Eq. (10)	"pseudo-tensor"

WW: JHU generator validation (J=2)

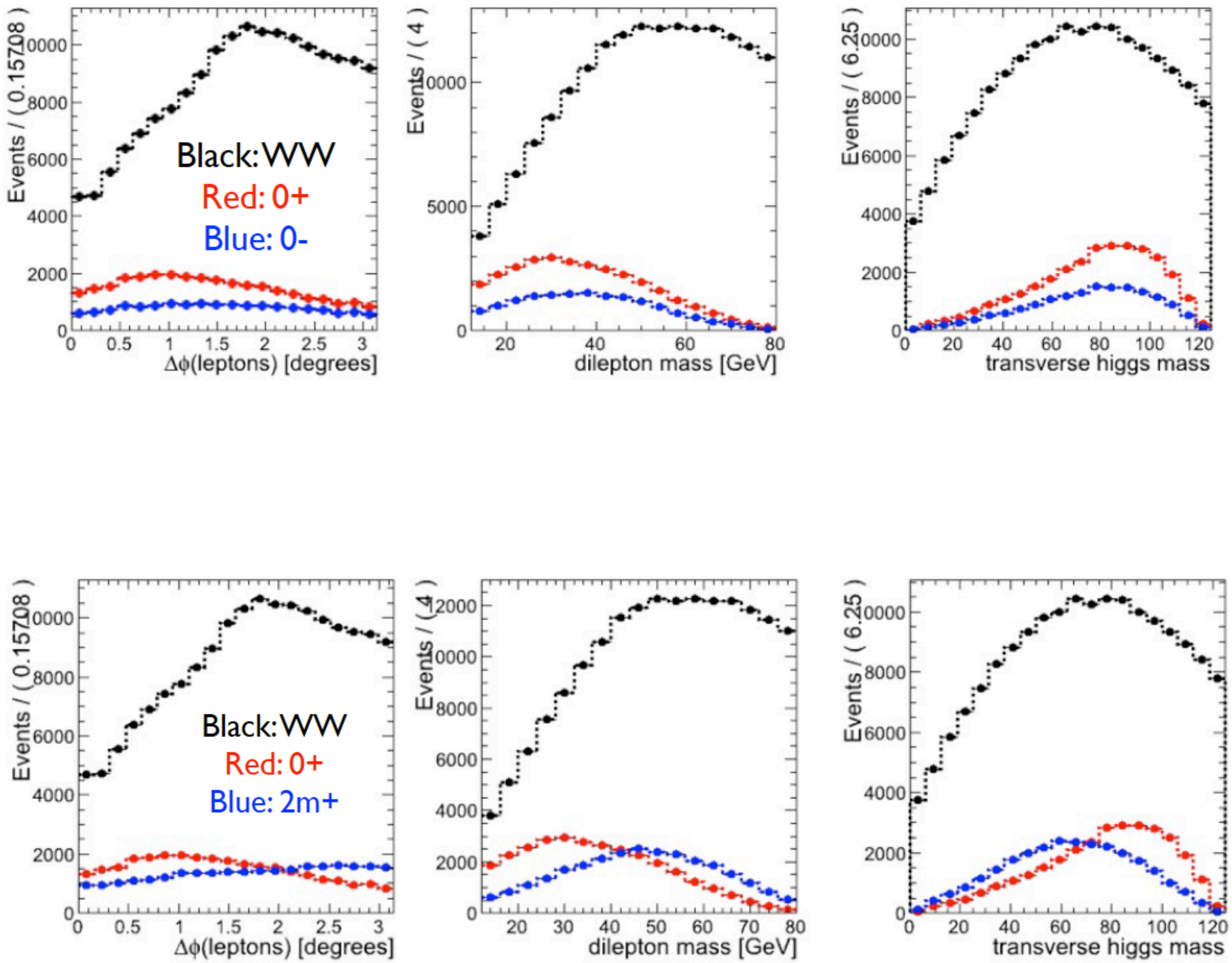
MX = 250 GeV (MC validation)



WW

- Define a minimal selections for the hypothesis separations
  - Lepton acceptance (20, 10) selections
  - dilepton mass range [12-80] GeV
  - transverse higgs mass [0 - 125] GeV
- With this selection the number of events per luminosity at 8 TeV
  - Signal: 25
  - Background: 250

Hypothesis separation in WW



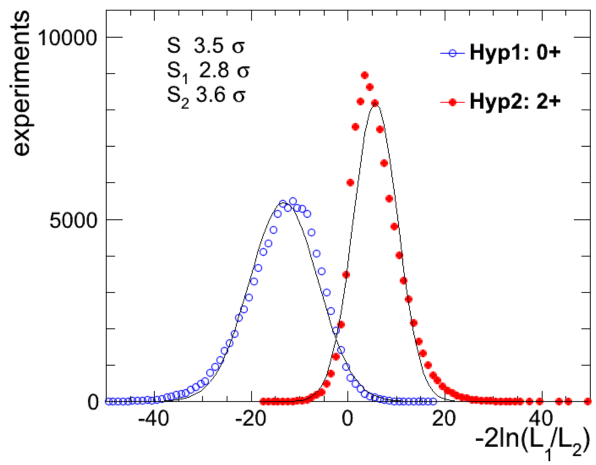
Hypothesis separation in WW

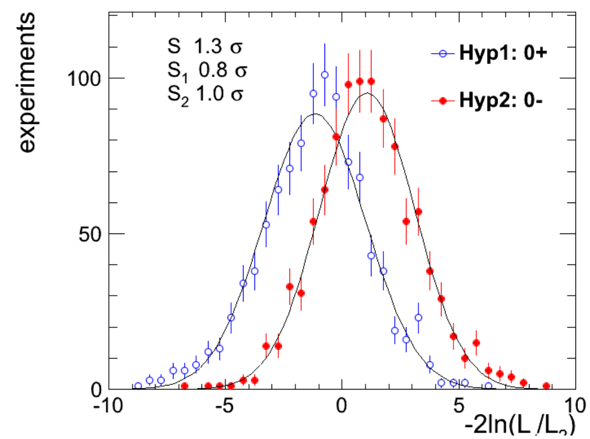
signal significance

	2D (mll/MT)	2D (Δ Φ/MT)
0+	4.6 ± 1.0	3.2 ± 1.0
0-	4.4 ± 1.0	2.8 ± 1.0

	2D (mll/MT)	2D (Δ Φ/MT)
0+	4.6 ± 1.0	3.0 ± 1.0
2+	3.0 ± 1.1	2.5 ± 1.0

2D: mll/mT





2D: ΔΦ/mT