Characterization of a single-produced resonance at the LHC: prospects for 2012 and beyond

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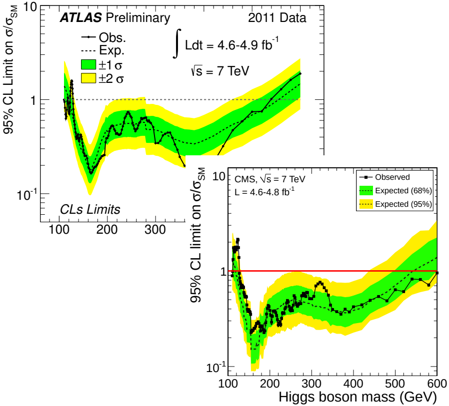
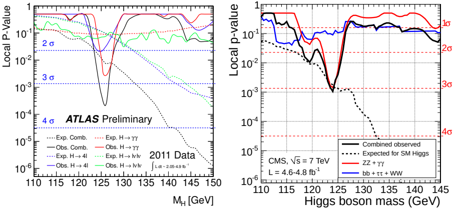
Status of LHC

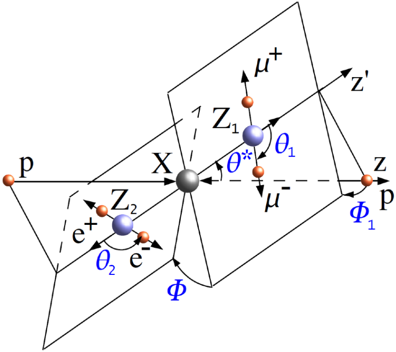
- 2011 - A spectacular year for LHC
  - ATLAS/CMS analyzed 5/fb each!
  - hint @ 125 GeV
- Hopes for 2012:
- 5 σ discovery
- Measuring properties
  mass,width - ZZ,$\gamma\gamma$
  branching fractions - bb,$\tau\tau$
  couplings - ZZ



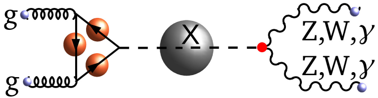


Kinematics of Decay

- Kinematics of final state fermions can be separated into three sets of variables:
  - $m_Z, m_{Z^{(*)}}, m_{4l}$
  - $\cos\theta^*, \Phi_1, \cos\theta_1, \cos\theta_2, \Phi$
  - P_T^X, Y^X (PDF/NLO QCD)
- $\cos\theta^*$, Φ_1 are related to production of the Z's (production angles)
- $\cos\theta_1$, $\cos\theta_2$, Φ are related to Z decays (helicity angles)



Amplitude for X→VV



- For scalar resonance decaying into 2 vector bosons, most general amplitude:

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

- 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 $a_3 \neq 0$

$$A_{00} = -\frac{m_X^4}{v}\left(a_1 x + a_2 \frac{M_Z M_*}{M_X^2}(x^2 - 1)\right),$$

$$A_{\pm\pm} = \frac{m_X^2}{v}\left(a_1 \pm i a_3 \frac{M_Z M_*}{M_H^2}\sqrt{x^2 - 1}\right)$$

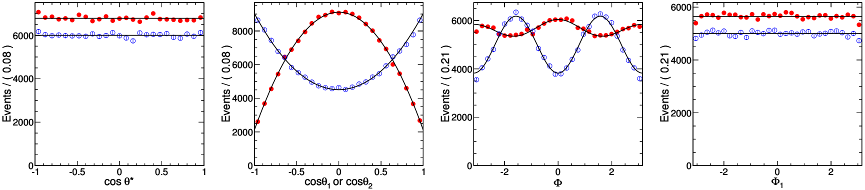
$$x = \frac{M_H^2 - M_Z^2 - {M_*}^2}{2 M_Z M_*}$$

Angular Distribution ($J_X = 0$)

$$
\begin{aligned}
d\Gamma(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi) \propto \quad & 4(1 - f_{++} - f_{--}) \sin^2\theta_1 \sin^2\theta_2 \\
& + (f_{++} + f_{--})((1 + cos^2\theta_1)(1 + \cos^2\theta_2) + 4R_1R_2 \cos\theta_1 \cos\theta_2) \\
& - 2(f_{++} - f_{--})(R_1 cos\theta_1(1 + cos^2\theta_2) + R_2(1 + cos^2\theta_1)\cos\theta_2) \\
& + 4\sqrt{f_{++}(1 - f_{++} - f_{--})}(R_1 - \cos\theta_1)\sin\theta_1(R_2 - \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++}) \\
& + 4\sqrt{f_{--}(1 - f_{++} - f_{--})}(R_1 + \cos\theta_1)\sin\theta_1(R_2 + \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--}) \\
& + 2\sqrt{f_{++}f_{--}}\sin^2\theta_1\sin^2\theta_2\cos(2\Phi + \phi_{++} - \phi_{--})
\end{aligned}
$$

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

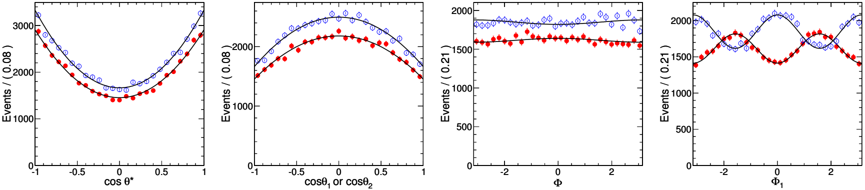
- Flat distribution of production angles, $\cos\theta^*, \Phi_1$
  (background & $J > 0$ have non-trivial distributions)
- Same machinery can be applied to J=1,2
  - Additional parameters, $f_{z1,z2}$, determining X polarization



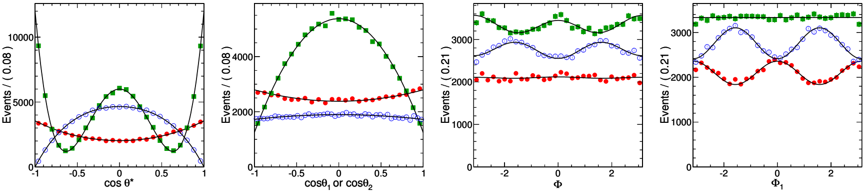
SM Higgs, Pseudo-Scalar (generator from arxiv.org:1001.3396)

Angular Distribution ($J_X > 0$)

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

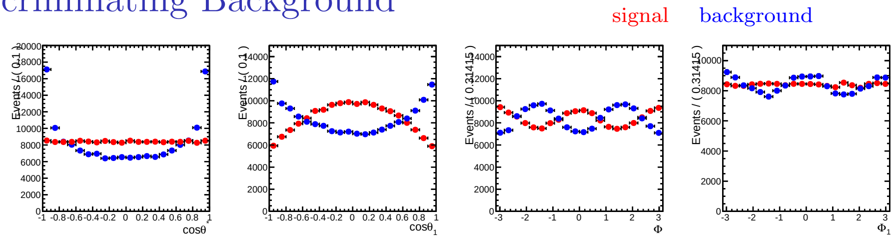


1D projections for $J^P = 2^+_M, 2^+_L, 2^-$
(generator from arxiv.org:1001.3396)

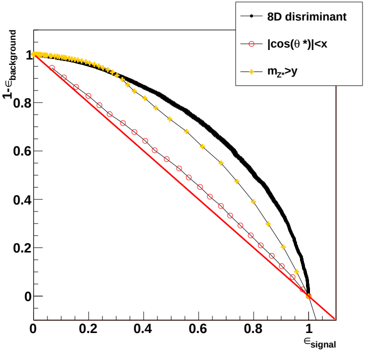


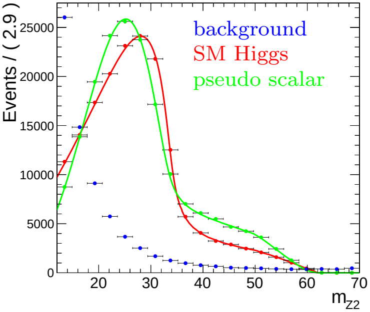
RS graviton with minimal coupling $\rightarrow 2^+_M$
longitudinally polarized graviton $\rightarrow 2^+_L$

Discriminating Background



Below ZZ threshold m_{Z^*} becomes strong discriminant
Shape of m_{Z^*} also depends on helicity amplitudes



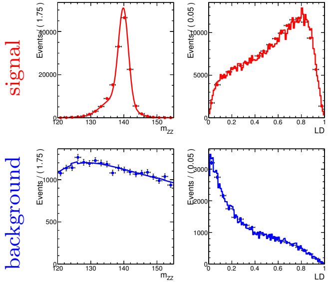


MELA (Matrix Element Likelihood Approach)

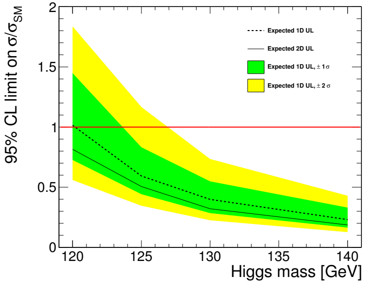
- Compress 8D PDFs down to 2D:

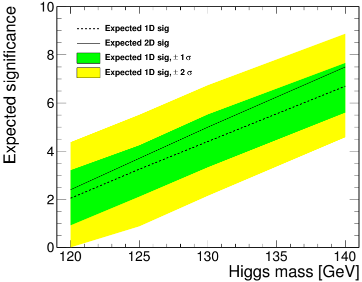
$$\mathcal{D}(m_1, m_2, \vec{\Omega}|m_{4l}) = \left(1 + \frac{\mathcal{P}_{bkg}(m_1, m_2, \vec{\Omega}|m_{4l})}{\mathcal{P}_{0+}(m_1, m_2, \vec{\Omega}|m_{4l})}\right)^{-1}$$

(signal vs background)



- Use MC to describe shape of $\mathcal{D}$
  - Applying CMS-like detector effects





$\sim 15\%$ increase in sensitivity

MELA - signal separation

- Signal hypothesis separation

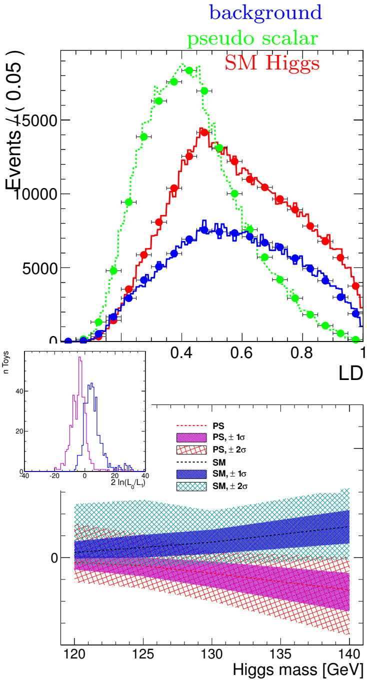
$$\mathcal{D}(m_1, m_2, \vec{\Omega}|m_{4l}) = \left(1 + \frac{\mathcal{P}_{0-}(m_1, m_2, \vec{\Omega}|m_{4l})}{\mathcal{P}_{0+}(m_1, m_2, \vec{\Omega}|m_{4l})}\right)^{-1}$$

(0^++bkg vs 0^-+bkg)

- using MELA to separate signal (0^+ vs 0^-) yields $\sim 20/\text{fb}$ @ $\sqrt{s} = 8\text{TeV}$
- Neyman-Pearson hypothesis testing

$$2ln(\mathcal{L}_0/\mathcal{L}_1)$$

- at 125 GeV, significance $\sim 2\sigma$



Conclusions and Outlook

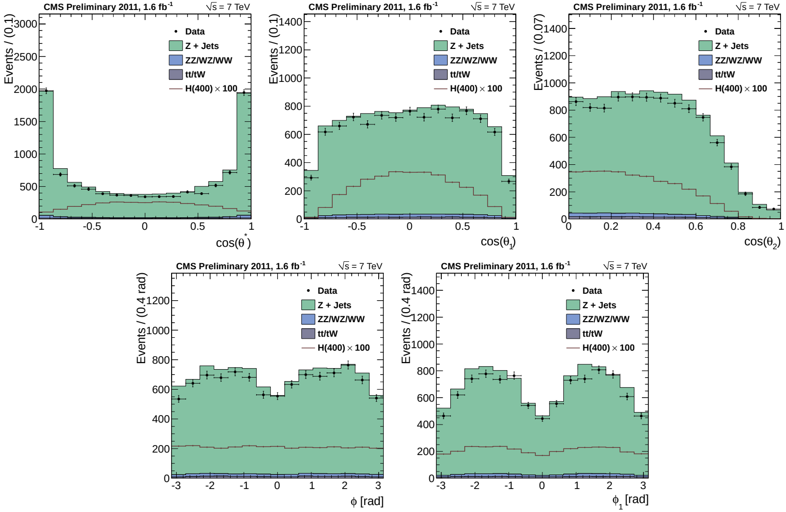
- Developed a formalism for characterizing new resonances in terms of spin, CP, and couplings in ZZ decay channel
  - Additional kinematic information increases sensitivity to signal by $\sim 15\%$
  - near future: hypothesis separation at 3σ discovery, can separate $0^+/0^-$ at 2σ
  - long term: 8D likelihood to fit for helicity amplitudes
- Working to include more signal hypothesis and other decay channels

BACKUP

Angular Distributions ($ZZ \to 2l2j$)

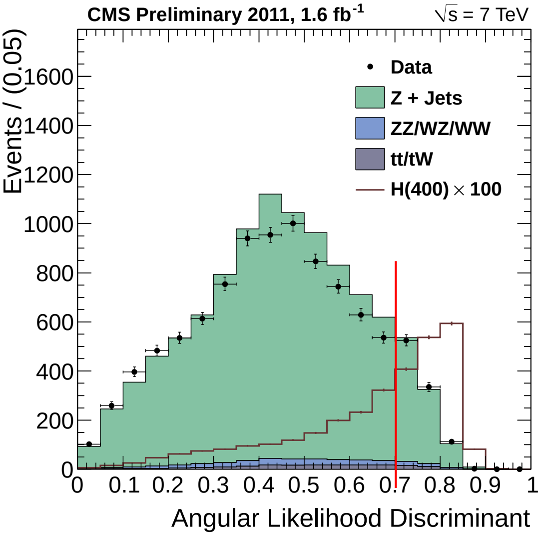
Madgraph Z+jets, SM Higgs

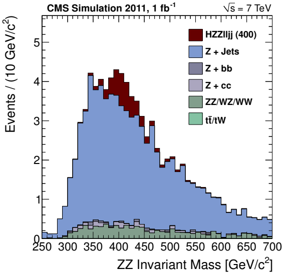
data points$\sim 1.6 fb^{-1}$ (after preselection)

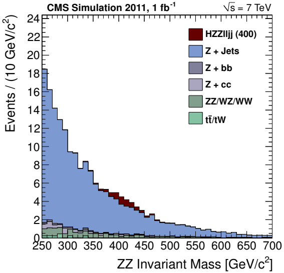


Helicity Likelihood Discriminant ($ZZ \to 2l2j$)

Putting it all together...







‡ For more details, see twiki/PAS here - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Background Parameterization

- 4l final state: SM ZZ production is the major background
- Use MC, fit helicity amplitudes to
  $q\bar{q} \to ZZ \to 4l$,
  $gg \to ZZ \to 4l$
- Using helicity amplitudes as basis for fits can recover correlations in background

- Example of helicity amplitude fit to SM ZZ events near 250 GeV
- Can use to measure fraction of gg vs $q\bar{q}$ initiated events in data

parameter	$q\bar{q} \to ZZ$	$gg \to ZZ$
f_{00}	0.025	0.398
f_{++}	0.206	0.430
f_{--}	0.005	0.012
f_{+0}	0.007	0.047
f_{0-}	0.147	0.007
f_{+-}	0.228	0.026

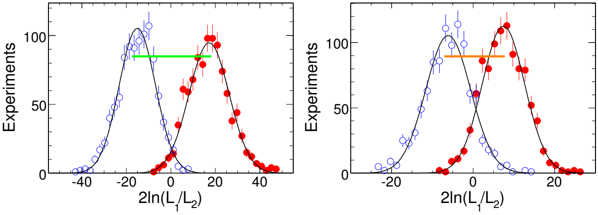
Separating Signal Hypotheses ($ZZ \to 4l$)

mass	discovery sgn	separation sgn
120	2.8 σ	1.6 σ
125	4.3 σ	2.1 σ
130	5.8 σ	2.7 σ
140	8.8 σ	3.8 σ

Separating Signal Hypotheses ($ZZ \to 4l$)

- Using 5D likelihood for a given model (SM Higgs, pseudo-scalar, RS graviton, SM ZZ...)
  - evaluate $-2ln(L_1/L_2)$ for data and two choice models (e.g. SM Higgs, pseudo-scalar)
  - using MC pseudo-experiments, separation significance can be calculated
- Example: resonance with
  $m = 250$, $n_{sig} = 30$, $n_{bkg} = 24\,(\sim 5\,fb^{-1}\,@\,\sqrt{s} = 14\,TeV)$
  model 1: $J^P = 0^+$, model 2: $J^P = 0^-$ (A)
  model 1: $J^P = 0^+$, model 2: $J^P = 2^+_m$ (B)

S=4.1



S=2.8

(A) (B)

Separating Signal Hypotheses ($ZZ \to 4l$) contd

- Separation significance, S, has been calculated for a number of hypothetical models (S - # of widths between peaks)
  - all using a resonace of 250 GeV,
    $n_{sig} = 30$, $n_{bkg} = 24\,(\sim 5\,fb^{-1}\,@\,\sqrt{s} = 14\,TeV)$

	0^-	1^+	1^-	2^+_m	2^+_L	2^-
0^+	4.1	2.3	2.6	2.8	2.6	3.3
0^-		3.1	3.0	2.4	4.8	2.9
1^+			2.2	2.6	3.6	2.9
1^-				1.8	3.8	3.4
2^+_m					3.8	3.2
2^+_L						4.3

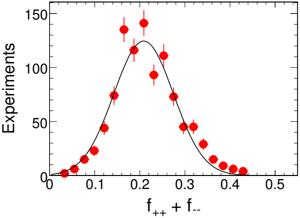
- Most values are $\gtrsim 3$ and almost all are > 2

Measuring Helicity Amplitudes

- floating $\vec{\xi}$ one could use the ML to measure helicity amplitudes of a given spin hypothesis
- Example study:
  - for $ZZ \to 4l$ final state
  - $n_{sig} = 150$, $n_{bkg} = 120\,(\sim 25\,fb^{-1}\,@\,\sqrt{s} = 14\,TeV)$
  - Generate MC for $J^p = 0^+, 0^-$ resonance at 250 GeV (A), (B)

(A)	generated	$m_X = 250$ GeV fitted without detector	with detec
$n_{\rm sig}$	150	150 ± 13	153 ± 15
$(f_{++} + f_{--})$	0.208	0.21 ± 0.07	0.23 ± 0.0
$(f_{++} - f_{--})$	0.000	0.01 ± 0.13	0.01 ± 0.1
$(\phi_{++} + \phi_{--})$	2π	6.30 ± 1.46	6.39 ± 1.5
$(\phi_{++} - \phi_{--})$	0	0.00 ± 1.06	0.01 ± 1.0

(B)	generated	$m_X = 250$ GeV fitted without detector	with detec
$n_{\rm sig}$	150	150 ± 13	151 ± 15
$(f_{++} + f_{--})$	1.000	1.00 ± 0.05	1.00 ± 0.0
$(f_{++} - f_{--})$	0.000	0.00 ± 0.35	0.00 ± 0.40
$(\phi_{++} + \phi_{--})$	N/A	free	free
$(\phi_{++} - \phi_{--})$	π	3.15 ± 0.31	3.14 ± 0.41



Generator Description

- JHU generator can produce resonances with the following decay topologies:

$$q\bar{q}, gg \rightarrow X \rightarrow ZZ \rightarrow 4l, 2l2q, 2l2\nu$$

$$q\bar{q}, gg \rightarrow X \rightarrow WW \rightarrow l\nu qq, 2l2\nu, l\nu\tau\nu$$

$$q\bar{q} \rightarrow X \rightarrow \gamma\gamma$$

- Proper angular correlations are computed
- Resonances can be spin 0,1,2 with arbitrary couplings
- Output is a standard LHE file (i.e. can be interfaced with Pythia)
- Code and further documentation can be found here: http://www.pha.jhu.edu/spin/