Higgs Properties in CMS

A. Gritsan, N. Tran, **A. Whitbeck**

on behalf of CMS collaboration

Johns Hopkins University

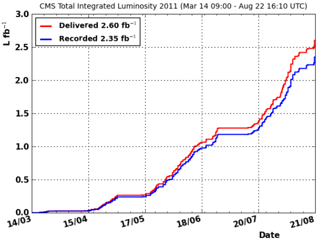
August 31, 2011

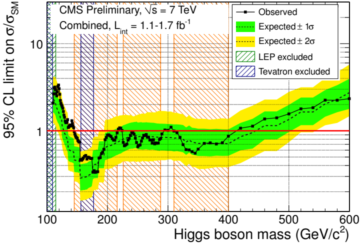
Outline

- Intro: status of CMS
- Properties of SM Higgs
- Angular distributions
- Discriminating signal/background
- Separating hypotheses
- Measuring parameters
- Conclusions

Status of LHC/CMS

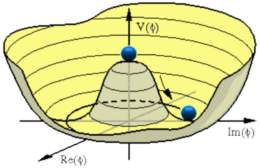
- LHC continues to perform better than expected
  - Already $\sim 2.5\, fb^{-1}$ on tape!
- Can expect to $\sim$ double int. lumi. in 2011
- 2012: $10\, fb^{-1}$ per experiment?
- Allowed parameter space for SM Higgs shrinking quickly

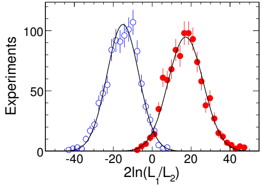




Properties of the SM Higgs

- Only free parameter of SM Higgs is its mass
  - Assuming a given mass, all properties of SM Higgs can, in principle, be calculated
- Given large excess in data what will we know:
  - mass, width, cross section
- What about Higgs specific properties?
  - $J^P = 0^+$
  - full angular correlations of final state particles
  - unique manifestations of J^P
  - has been demonstrated to be good handle for determining spin and parity of resonances





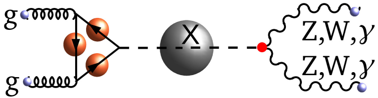
Amplitude for H→VV

- 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 psuedo-scalar Higgs $a_3 \neq 0$
  - One can write a general formula for all fermionic final states
  - Can be applied to spin 1 & 2 resonances as well

- Including amplitude for production of X and decay of V's and integrating: $\frac{d\Gamma(\vec{\Omega};a_1,a_2,a_3)}{\Gamma d\vec{\Omega}}$



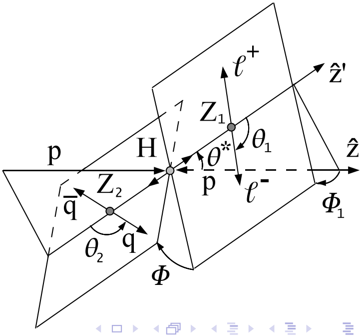
- Kinematics of final state fermions can be separated into three sets of (mostly) uncorrelated variables
  - P_T^X, Y^X
  - $m_{f1,f2}$, $m_{f3,f4}$, $m_{f1,f2,f3,f4}$
  - $\cos\theta^*$, Φ_1, $\cos\theta_1$, $\cos\theta_2$, Φ
- $\cos\theta^*$, Φ_1 are related to production of the Z's (production angles)
- $\cos\theta_1$, $\cos\theta_2$, Φ are related to Z decays (helicity angles)

- The production/helicity angular distributions determined by helicity amplitudes

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

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

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



Helicity Angular Distribution ($J_X = 0$)

$$d\Gamma(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi) \propto$$

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

- Flat distribution of production angles, $\cos\theta^*, \Phi_1$ (background & $J > 0$ have non-trivial distributions)

- f_{ij} and ϕ_{ij} determined by helicity amplitudes$\rightarrow$ couplings

$$f_{ij} = |A_{ij}|^2 / \sum_{k,l} |A_{kl}|^2,$$

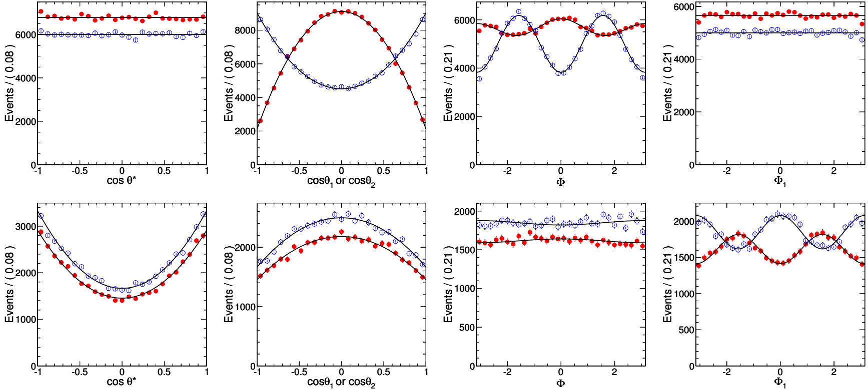
$$\phi_{ij} = arg(A_{ij}/A_{00})$$

- $R_{1,2}$ determined by fermion type

fermion	$R \simeq$
l	.15
u,d	.67,.94
jets	0

Angular Distributions ($X \to ZZ \to 4l$)

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

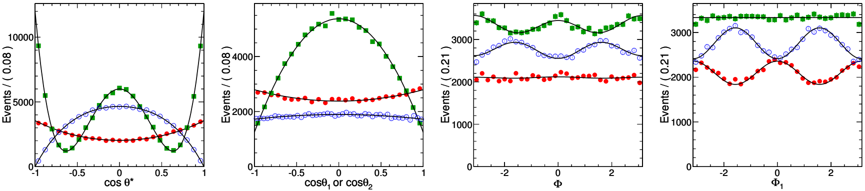


1D projections for Vector, Pseudo-Vector
(generator from arxiv.org:1001.3396)

‡Note there are no detector effects here.

Angular Distributions cont.

1D projections for $J^P = {\color{red}2^+_M}, {\color{blue}2^+_L}, {\color{green}2^-}$
(generator from arxiv.org:1001.3396)



RS graviton with minimal coupling$\rightarrow {\color{red}2^+_M}$
longitudinally polarized graviton$\rightarrow {\color{blue}2^+_L}$
"pseudo-tensor" $\rightarrow {\color{green}2^-}$

Helicity Angles as a Background Discriminant

- Simplest application of angular distributions
- Within the $H \to ZZ$ decay channel this was applied to two final states, 4l and 2l2j
- Has been shown to increase sensitivity in 4l final state by $\sim 20\%$ ([1], arxiv.org:1001.3396)

- Model angular distributions as seen in detector
- Signal: (Ideal)$\times$(uncorrelated acceptance)

$$P_{sig} = P_{IDEAL}(\theta^*, \theta_1, \theta_2, \Phi, \Phi_1; \vec{\xi}) A_{\theta^*}(\theta^*) A_{\theta_1}(\theta_1) A_{\theta_2}(\theta_2) A_{\Phi}(\Phi) A_{\Phi_1}(\Phi_1)$$

- $\xi = (f_{ij}, \phi_{ij})$ fixed to SM Higgs values
- Background: product of 1D, uncorrelated functions

$$P_{bkg} = D_{\theta^*}(\theta^*) D_{\theta_1}(\theta_1) D_{\theta_2}(\theta_2) D_{\Phi}(\Phi) D_{\Phi_1}(\Phi_1)$$

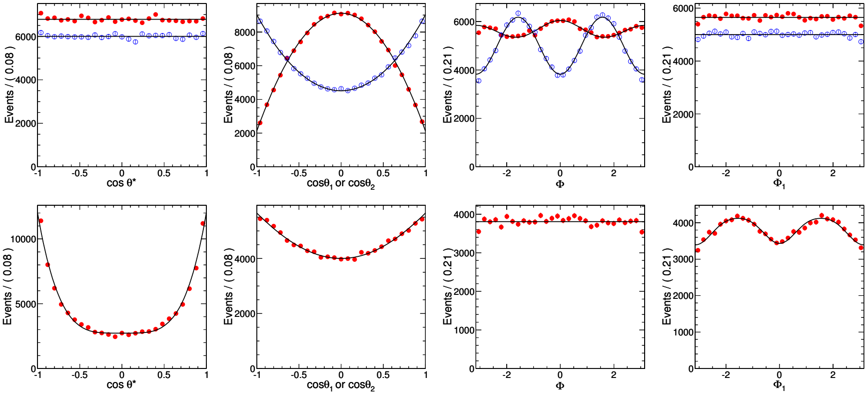
- Define discriminant as:

$$D = \frac{P_{sig}}{P_{sig} + P_{bkg}}$$

- $D \epsilon [0,1]$; cuts applied to D (e.g. $D > .7$ are signal-like)

Angular Distributions ($ZZ \to 4l$)

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

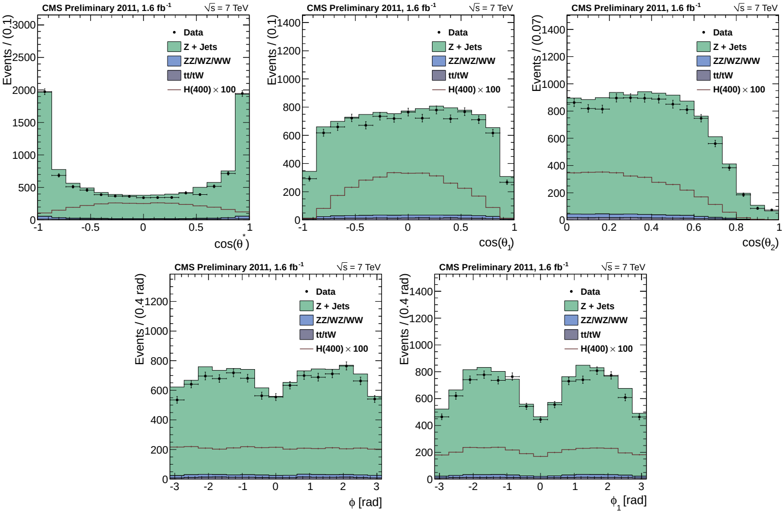


1D projections for SM ZZ
(Madgraph) Neglecting $gg \to ZZ \sim O(10\%)$

Angular Distributions ($ZZ \to 2l2j$)

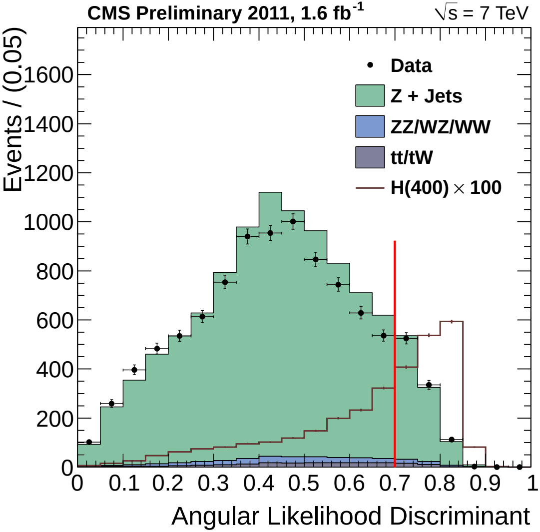
Madgraph Z+jets, SM Higgs

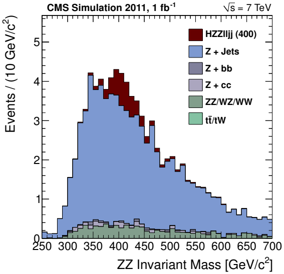
data points$\sim 1.6 fb^{-1}$ (after preselection)

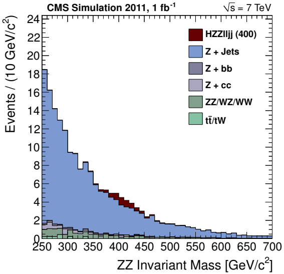


Helicity Likelihood Discriminant ($ZZ \to 2l2j$)

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

Likelihood Approach

- Cutting on D$\rightarrow$ lose information
- Instead, maximum likelihood (ML) fit would be better

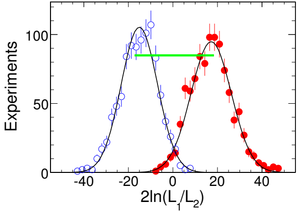
$$L = exp(-n_{sig} - n_{bkg}) \prod_{i}^{N} (n_{sig} \times P_{sig}(\vec{\Theta}_i, m_{ZZ}; \vec{\xi}) + n_{bkg} \times P_{bkg}(\vec{\Theta}_i, m_{ZZ}))$$

- Fixing $\vec{\xi}$ and floating n_{bkg}, n_{sig} one can calculate upper limit, significance, etc. of n_{sig} for a given resonance hypothesis

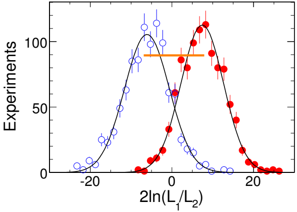
Separating Signal Hypotheses ($ZZ \to 4l$)

- 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 psuedo-experiments, separation significance can be calculated
- Example: resonance with
  $m = 250,\ n_{sig} = 30,\ n_{bkg} = 24\,(\sim 5\,fb^{-1} \text{ @ } \sqrt{s} = 14\ TeV)$
  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



(A)



S=2.8

(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

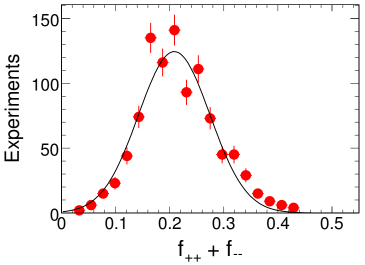
- Most values are $\gtrsim 3$ and almost all are > 2

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)

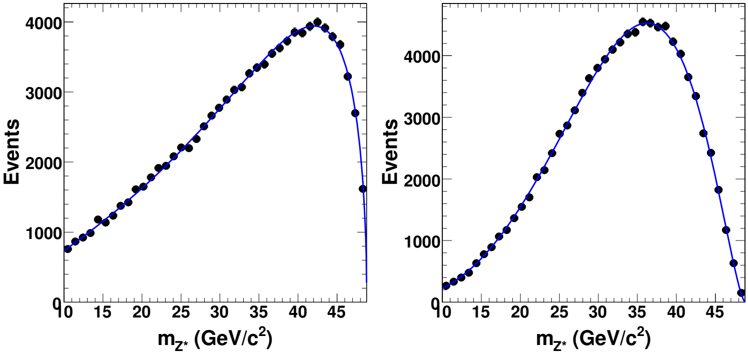
(A)	generated	$m_X = 250$ GeV fitted without detector	with detector
$n_{\rm sig}$	150	150 ± 13	153 ± 15
$(f_{++} + f_{--})$	0.208	0.21 ± 0.07	0.23 ± 0.08
$(f_{++} - f_{--})$	0.000	0.01 ± 0.13	0.01 ± 0.14
$(\phi_{++} + \phi_{--})$	2π	6.30 ± 1.46	6.39 ± 1.54
$(\phi_{++} - \phi_{--})$	0	0.00 ± 1.06	0.01 ± 1.09

(B)	generated	$m_X = 250$ GeV fitted without detector	with detector
$n_{\rm sig}$	150	150 ± 13	151 ± 15
$(f_{++} + f_{--})$	1.000	1.00 ± 0.05	1.00 ± 0.06
$(f_{++} - f_{--})$	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



$ZZ \to 4l$ below threshold

- All of the above is valid below threshold also
- Angular distributions require an additional parameter: m_{Z^*}



$$J^P = 0^+(left), 0^-(right)$$

- Separation significance between $0^+/0^-$: S=3.3
  $n_{sig} = 20,\ n_{bkg} = 30,\ m = 140\ GeV (\sim 10\ fb^{-1} @ \sqrt{s} = 7\ TeV)$

Conclusions

- Angular distributions have been very beneficial to Higgs searches thus far
  - have been exploited for signal/background discrimination
  - has been shown to improve sensitivity in the $ZZ \to 4l$ channel by $\sim 20\%$
  - can ultimately help to discover new resonances
- Angular variables are physically motivated
  - have been parameterized in terms of helicity amplitude (coupling constants)
  - can be used to measure properties of new resonances
- Methods described above are already being implemented in analyses
  - Already implemented in $ZZ \to 2l2j$ analysis
  - Will be implemented in $ZZ \to 4l$ analysis

BACKUP SLIDES

References

CMS documentation

[1] Y.Gao, A.Gritsan, Z.Guo, K.Melnikov, M.Schulze, N.Tran, "Spin determination of single-produced resonances at hadron colliders"
http://arxiv.org/abs/1001.3396

ATLAS documentation

[2] C.P.Buszello, I.Fleck, P.Marquard and J.J. van der Bij, "Prospective Analysis of Spin- and CP-sensitive Variables in $H \to ZZ \to l^+l^-l^+l^-$ with ATLAS", (Eur Phys J C32,209,2004SN-ATLAS-2003-025)

Generator Description

- JHU generator is intended for generating resonances with the following decay topologies:

$$ab \to X \to ZZ \to 4l,$$

$$ab \to X \to ZZ \to 2l2j$$

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