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
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 $H \rightarrow VV$

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

$$A(X \rightarrow V_1 V_2) = \nu^{-1} \epsilon^*_{\mu} \epsilon^*_{\nu} \left( a_1 g_{\mu\nu} M_X^2 + a_2 q_1^\mu q_2^\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$

- 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 $a_3 \neq 0$
- 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:

$$\frac{d\Gamma(\tilde{\Omega};a_1,a_2,a_3)}{\Gamma d\tilde{\Omega}}$$
Kinematics of Decay

- Kinematics of final state fermions can be separated into three sets of (mostly) uncorrelated variables
  - $P^X_T, \gamma^X$
  - $m_{f1,f2}, m_{f3,f4}, m_{f1,f2,f3,f4}$
  - $\cos \theta^*, \Phi_1, \cos \theta_1, \cos \theta_2, \Phi$
- $\cos \theta^*, \Phi_1$ are related to production of the Z’s (production angles)
- $\cos \theta_1, \cos \theta_2, \Phi$ are related to Z decays (helicity angles)

- The **production/helicity** angular distributions determined by helicity amplitudes
  - $A_{00} = -\frac{m_X^4}{v} (a_1 x + a_2 \frac{M_Z M_*}{M_H^2} (x^2 - 1))$
  - $A_{\pm \pm} = \frac{m_X^2}{v} (a_1 \pm ia_3 \frac{M_Z M_*}{M_H^2} \sqrt{x^2 - 1})$
  - $x = \frac{M_H^2 - M_Z^2 - M_*^2}{2 M_Z M_*}$
Helicity Angular Distribution ($J_X = 0$)

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

\begin{align*}
&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{align*}

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

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

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

<table>
<thead>
<tr>
<th>Fermion Type</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>l</td>
<td>.15</td>
</tr>
<tr>
<td>u,d</td>
<td>.67,.94</td>
</tr>
<tr>
<td>jets</td>
<td>0</td>
</tr>
</tbody>
</table>
Angular Distributions \( (X \rightarrow ZZ \rightarrow 4l) \)

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 $J^P = 2^+_M, 2^+_L, 2^-$

(generator from arxiv.org:1001.3396)

RS graviton with minimal coupling $\rightarrow 2^+_M$
longitudinally polarized graviton $\rightarrow 2^+_L$
”pseudo-tensor” $\rightarrow 2^-$
Helicity Angles as a Background Discriminant

- Simplest application of angular distributions
- Within the $H \rightarrow ZZ$ 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)

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

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

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

Define discriminant as:

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

$D \in [0, 1]$; cuts applied to $D$ (e.g. $D > 0.7$ are signal-like)
Angular Distributions \((ZZ \rightarrow 4l)\)

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

1D projections for SM \(ZZ\)
(Madgraph) Neglecting \(gg \rightarrow ZZ \sim O(10\%)\)
Angular Distributions ($ZZ \rightarrow 2l2j$)

Madgraph $Z+jets$, SM Higgs
data points $\sim 1.6fb^{-1}$ (after preselection)
Helicity Likelihood Discriminant ($ZZ \rightarrow 2l2j$)

Putting it all together...

CMS Preliminary 2011, 1.6 fb$^{-1}$  $\sqrt{s} = 7$ TeV

- Data
  - Z + Jets
  - ZZ/WZ/WW
  - tt/tW
  - $H(400) \times 100$

‡ For more details, see twiki/PAS here - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
4l final state: SM ZZ production is the major background
Use MC, fit helicity amplitudes to 
\[ q\bar{q} \rightarrow ZZ \rightarrow 4l, \]
\[ gg \rightarrow ZZ \rightarrow 4l \]
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

<table>
<thead>
<tr>
<th>parameter</th>
<th>( q\bar{q} \rightarrow ZZ )</th>
<th>( gg \rightarrow ZZ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{00} )</td>
<td>0.025</td>
<td>0.398</td>
</tr>
<tr>
<td>( f_{++} )</td>
<td>0.206</td>
<td>0.430</td>
</tr>
<tr>
<td>( f_{--} )</td>
<td>0.005</td>
<td>0.012</td>
</tr>
<tr>
<td>( f_{+0} )</td>
<td>0.007</td>
<td>0.047</td>
</tr>
<tr>
<td>( f_{0-} )</td>
<td>0.147</td>
<td>0.007</td>
</tr>
<tr>
<td>( f_{+-} )</td>
<td>0.228</td>
<td>0.026</td>
</tr>
</tbody>
</table>
Likelihood Approach

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

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

- Fixing $\vec{\xi}$ and floating $n_{\text{bkg}}, n_{\text{sig}}$ one can calculate upper limit, significance, etc. of $n_{\text{sig}}$ for a given resonance hypothesis
Separating Signal Hypotheses ($ZZ \rightarrow 4l$)

- Using 5D likelihood for a given model (SM Higgs, pseudo-scalar, RS graviton, SM ZZ...)
  - evaluate $-2 \ln(L_1/L_2)$ for data and two choice models (e.g. SM Higgs, pseudo-scalar)
  - using MC psuedo-experiments, separation significance can be calculated

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

- model 1: $J^P = 0^+$, model 2: $J^P = 0^-$ (A)
- model 1: $J^P = 0^+$, model 2: $J^P = 2^+_m$ (B)

![Graphs showing separation significance S=4.1 and S=2.8 for models A and B](slide-content)
Separation significance, $S$, has been calculated for a number of hypothetical models ($S$ - # of widths between peaks)

all using a resonance of 250 GeV,

$n_{sig} = 30$, $n_{bkg} = 24$ ($\sim 5 \text{fb}^{-1} \oplus \sqrt{s} = 14 \text{ TeV}$)

<table>
<thead>
<tr>
<th></th>
<th>$0^-$</th>
<th>$1^+$</th>
<th>$1^-$</th>
<th>$2^+_m$</th>
<th>$2^+_L$</th>
<th>$2^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+$</td>
<td>4.1</td>
<td>2.3</td>
<td>2.6</td>
<td>2.8</td>
<td>2.6</td>
<td>3.3</td>
</tr>
<tr>
<td>$0^-$</td>
<td>3.1</td>
<td>3.0</td>
<td>2.4</td>
<td>4.8</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>$1^+$</td>
<td>2.2</td>
<td>2.6</td>
<td>3.6</td>
<td>2.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1^-$</td>
<td>1.8</td>
<td>3.8</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^+_m$</td>
<td></td>
<td>3.8</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2^+_L$</td>
<td></td>
<td>4.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 $ZZ \rightarrow 4l$ final state
  - $n_{\text{sig}} = 150$, $n_{\text{bkg}} = 120$ ($\sim 25 \text{ fb}^{-1} @ \sqrt{s} = 14 \text{ TeV}$)
  - Generate MC for $J^P = 0^+, 0^-$ resonance at 250 GeV (A), (B)

<table>
<thead>
<tr>
<th></th>
<th>generated</th>
<th>$m_X = 250$ GeV</th>
<th>with detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td></td>
<td>without detector</td>
<td>fitted</td>
</tr>
<tr>
<td>$n_{\text{sig}}$</td>
<td>150</td>
<td>$150 \pm 13$</td>
<td>$153 \pm 15$</td>
</tr>
<tr>
<td>$(f_{++} + f_{--})$</td>
<td>0.208</td>
<td>$0.21 \pm 0.07$</td>
<td>$0.23 \pm 0.08$</td>
</tr>
<tr>
<td>$(f_{++} - f_{--})$</td>
<td>0.000</td>
<td>$0.01 \pm 0.13$</td>
<td>$0.01 \pm 0.14$</td>
</tr>
<tr>
<td>$(\phi_{++} + \phi_{--})$</td>
<td>$2\pi$</td>
<td>$6.30 \pm 1.46$</td>
<td>$6.39 \pm 1.54$</td>
</tr>
<tr>
<td>$(\phi_{++} - \phi_{--})$</td>
<td>0</td>
<td>$0.00 \pm 1.06$</td>
<td>$0.01 \pm 1.09$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>generated</th>
<th>$m_X = 250$ GeV</th>
<th>with detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B)</td>
<td></td>
<td>without detector</td>
<td>fitted</td>
</tr>
<tr>
<td>$n_{\text{sig}}$</td>
<td>150</td>
<td>$150 \pm 13$</td>
<td>$151 \pm 15$</td>
</tr>
<tr>
<td>$(f_{++} + f_{--})$</td>
<td>1.000</td>
<td>$1.00 \pm 0.05$</td>
<td>$1.00 \pm 0.06$</td>
</tr>
<tr>
<td>$(f_{++} - f_{--})$</td>
<td>0.000</td>
<td>$0.00 \pm 0.35$</td>
<td>$0.00 \pm 0.40$</td>
</tr>
<tr>
<td>$(\phi_{++} + \phi_{--})$</td>
<td>N/A</td>
<td>free</td>
<td>free</td>
</tr>
<tr>
<td>$(\phi_{++} - \phi_{--})$</td>
<td>$\pi$</td>
<td>$3.15 \pm 0.31$</td>
<td>$3.14 \pm 0.41$</td>
</tr>
</tbody>
</table>
ZZ → 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 $0^+ / 0^-$: $S=3.3$
- $n_{sig} = 20$, $n_{bkg} = 30$, $m = 140 \text{ GeV} (\sim 10 \text{ fb}^{-1} @ \sqrt{s} = 7 \text{ TeV})$
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 $ZZ \rightarrow 4l$ 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 $ZZ \rightarrow 2l2j$ analysis
  - Will be implemented in $ZZ \rightarrow 4l$ analysis
BACKUP SLIDES
CMS documentation


ATLAS documentation

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/