Evidence for a new boson in the search of the SM $H \rightarrow ZZ \rightarrow 4l$

$pp$ collisions
$7$ TeV and $8$ TeV

Stéphanie Baffioni (LLR), on behalf of the CMS collaboration

Higgs Hunting, Orsay, 19/07/2012
“Golden channel” $H \rightarrow ZZ \rightarrow 2\ell 2\ell'$

$(\ell, \ell' = e, \mu; \ell' = \tau$ for high mass studies)

- The most sensitive in $[120 - \text{not excluded}]
- Very clean signature: 4 primary isolated leptons, full 4$\ell$ mass reco, narrow resonance
- Low level of backgrounds
- But needs the highest efficiencies and performance

General strategy in 2012 $[110 - 600]$ GeV

- Blinding for the 2012 and 2011 data:
  $110 \leq m_{4\ell} \leq 140$ and $m_{4\ell} \geq 300$
- Reoptimize analysis: ID, isolation, FSR recovery, use of full kinematics

20% gain in significance for $m_H = 126$ GeV
Results @ 7 TeV 4.7 fb\(^{-1}\)

Exclusion of the SM Higgs boson in the ranges [134 - 158], [180 - 305], and [340 - 465] GeV

Small excesses of events around masses of 119, 126, and 320 GeV → observed limits weaker than expected in the absence of a signal

Ingredients

Data
- 5.05 fb^{-1} @ 7 TeV and 5.26 fb^{-1} @ 8 TeV

CMS detector

Trigger
- Excellent performance of the L1 and HLT triggers
- Double lepton ee, \mu\mu and e\mu with E(P)_{T} thresholds of 17 and 8 GeV

Leptons
- Reconstruction, ID, isolation

Analysis selection

Background control and estimation

Statistical analysis
Electrons

Electrons in analysis $|\eta| \leq 2.5 \ p_T \geq 7 \text{ GeV}$

- Superclusters in ECAL ($E_T > 4 \text{ GeV}$) + dedicated track finding and GSF fit (before candidate id.)
  - collect energy spread in phi
  - change of curvature and hit collection up to ECAL
- ECAL-seed complemented by tracker-seed (efficiency gain at low $p_T$)
- Electron classes brem sensitive
- Momentum from $E-p$ combination

Scale and resolution

- Z peak for different electron categories

Golden barrel electrons combined $E-p$

+ control low $p_T$ with J/ψ
**Electrons ID**

**Multivariate in 2012 (BDT)**

- Observables sensitive to bremsstrahlung, geometrical and momentum matching
- Background from data samples
- Performances optimized for $H \rightarrow ZZ \rightarrow 4l$
- Efficiency measured via Z Tag&Probe

ECAL variable:

\[ \sigma_{\eta\eta} \text{ in barrel, } p_T < 20 \text{ GeV} \]

Tracker variable:

\[ fbrem \text{ in endcaps, } p_T < 20 \text{ GeV} \]

**e-ID efficiency in barrel**

30% efficiency gain in 4e for $m_H = 126 \text{ GeV}$ (same fake rate) wrt 2011

**Signal Efficiency**

- $p_T > 10 \text{ GeV}$: BDT, 2011
- $p_T < 10 \text{ GeV}$: BDT, 2011

**Background Efficiency**

- $0.1 < 0.2 < 0.3$
**Muons in analysis** $|\eta| \leq 2.4 \ p_T \geq 5 \text{ GeV}

- Combination of inner tracker tracks and muon system tracks

- Particle Flow ID: NEW
  - inner and muon tracks quality and matching
  - 99 % efficient for same fake rate as in 2011

- Efficiency measured via Z and J/\psi Tag & Probe

5% efficiency gain in 4\mu for $m_H = 126 \text{ GeV}$ (same fake rate) wrt 2011

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Particle-based isolation

- In $\Delta R = 0.4$ cone around the lepton from the charged and neutral hadrons, photons: $\Sigma_{\text{iso}} / p_T < 0.4$
- No double counting for the charged particles, automatic lepton removal

10 to 15% efficiency gain per lepton (same fake rate) wrt 2011

Pile-up (PU) contribution:

- Charged: negligible (required from the vertex)
- Neutrals: corrected using the average energy density from the PU and underlying event
- $\rightarrow$ quite stable with respect to $n_{\text{PU}}$
Analysis selection

- **Trigger**
- **Leptons**
  - Electrons $|\eta| \leq 2.5$ $p_T \geq 7$ GeV
  - Muons $|\eta| \leq 2.4$ $p_T \geq 5$ GeV
  - Isolated, ID, compatible with PV
  - $p_T \geq 20, 10, p_T^{min}$
- **Final State Radiation (FSR) recovery**
- **Kinematics**
  - $Z_1$ closest to $Z_{PDG}$: $40 \leq m_{Z_1} \leq 120$ GeV
  - $Z_2$ with the highest $p_T$ remaining pair
    - $12 \leq m_{Z_2} \leq 120$ GeV + all $l^+l^-$ pairs $m_{l^+l^-} \geq 4$ GeV
  - $m_{4l} \geq 100$ GeV

for 2l2τ see: Search for the Standard Model Higgs boson in $H \rightarrow ZZ \rightarrow l^+l^-\tau^+\tau^-$ decay channel with CMS (S.CHHIBRA, young scientist forum)
Algorithm

ParticleFlow photons near the Z leptons:
- $|\eta| \leq 2.4$
- $P_T \geq 2\,\text{GeV}$ if $\Delta R \leq 0.07$
- $P_T \geq 4\,\text{GeV}$, isolated, if $0.07 \leq \Delta R \leq 0.5$

Associates photon with Z if
- $m_{\ell\ell+\gamma} < 100\,\text{GeV}$
- $|m_{\ell\ell+\gamma} - m_Z| < |m_{\ell\ell} - m_Z|$

Removes associated photons from lepton isolation calculation

Expected Performance for $m_H = 126\,\text{GeV}$
- 6% of events affected
- Efficiency 50% for purity of 80%

2% efficiency gain for $m_H = 126\,\text{GeV}$
**Irreducible ZZ→4l**
- MC and theoretical NLO σ
- Corrected for data/MC scale factors
- Phenomenological shape models

**Reducible backgrounds**
- Zbb, tt, WZ+jets, Z+jets
- From data - 50 % uncertainty
  - fake rate method

- applied from signal-free control samples
- validation (data wrong flavors and charges)

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**Higgs Hunted** 19/07/12
4l + 2l2τ  √s = 8 TeV  5.26 fb⁻¹

- 4l: as for the Higgs analysis
  - 60 ≤ m_{Z1} ≤ 120 GeV
  - 60 ≤ m_{Z2} ≤ 120 GeV

- 2l2τ:
  - Z1 → e⁺e⁻ or μ⁺μ⁻, p_T > 20, 10 GeV
  - 60 ≤ m_{Z1} ≤ 120
  - Z2 → τ⁺τ⁻, p_T > 10, p_T^{th} > 20 GeV
  - 20-30 ≤ m_{ττ} ≤ 90 GeV

Results

<table>
<thead>
<tr>
<th>Channel</th>
<th>4e</th>
<th>4μ</th>
<th>2e2μ</th>
<th>2l2τ</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>11.6 ± 1.4</td>
<td>20.3 ± 2.2</td>
<td>32.4 ± 3.5</td>
<td>6.5 ± 0.8</td>
</tr>
<tr>
<td>Background</td>
<td>0.4 ± 0.2</td>
<td>0.4 ± 0.3</td>
<td>0.5 ± 0.4</td>
<td>5.6 ± 1.4</td>
</tr>
<tr>
<td>Total</td>
<td>12.0 ± 1.4</td>
<td>20.7 ± 2.2</td>
<td>32.9 ± 3.5</td>
<td>12.1 ± 1.6</td>
</tr>
<tr>
<td>Observed</td>
<td>14</td>
<td>19</td>
<td>38</td>
<td>13</td>
</tr>
</tbody>
</table>

- Measured σ(pp → ZZ) = 8.4 ± 1.0(stat.) ± 0.7(sys.) ± 0.4(lumi.) pb
- Good agreement with NLO prediction: σ_{th}(pp → ZZ) = 7.7 ± 0.4 pb
### Systematics

#### Theoretical

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$\sigma_H$</td>
<td>17 - 20 %</td>
</tr>
<tr>
<td>$H$ Branching fraction</td>
<td>2 %</td>
</tr>
<tr>
<td>$ZZ$ cross section</td>
<td>8 %</td>
</tr>
</tbody>
</table>

#### Experimental

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value details</th>
</tr>
</thead>
<tbody>
<tr>
<td>trigger</td>
<td>1.5 %</td>
</tr>
<tr>
<td>lepton reco + ID + iso</td>
<td>1.2 % $4\mu$ high masses to 11% $4e$ low masses</td>
</tr>
<tr>
<td></td>
<td>from T&amp;P studies</td>
</tr>
<tr>
<td>lepton momentum scale</td>
<td>$\leq 0.4$ %</td>
</tr>
<tr>
<td></td>
<td>affects signal shape</td>
</tr>
<tr>
<td>lepton momentum resolution</td>
<td>20 %</td>
</tr>
<tr>
<td></td>
<td>affects signal shape</td>
</tr>
<tr>
<td>$\tau_h$ ID and iso</td>
<td>6 %</td>
</tr>
<tr>
<td>$\tau_h$ energy scale</td>
<td>3 %</td>
</tr>
<tr>
<td>reducible background</td>
<td>50 %</td>
</tr>
<tr>
<td>luminosity</td>
<td>4.4% (8TeV) 2.2% (7TeV)</td>
</tr>
<tr>
<td></td>
<td>ZZ background + $\sigma$ measurement + signal yields</td>
</tr>
</tbody>
</table>
Results

- $m_{4l}$ distribution
  - Low mass range
  - Data only
  - Blinded

![Graph showing $m_{4l}$ distribution](image)
**Results**

- **$m_{4l}$ distribution**
  - Low mass range
  - Data only
  - Un-Blinded

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![Graph showing $m_{4l}$ distribution](image_url)

**Legend:**
- **Data**
- **4l**

**Note:**
- CMS Preliminary
  - $\sqrt{s} = 7$ TeV, $L = 5.05$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV, $L = 5.26$ fb$^{-1}$
Results

- $m_{4l}$ distribution
  - Low mass range
  - Un-Blinded
  - Background expectation

![Graph showing events vs $m_{4l}$ distribution](image)

CMS Preliminary $\sqrt{s} = 7$ TeV, $L = 5.05$ fb$^{-1}$, $\sqrt{s} = 8$ TeV, $L = 5.26$ fb$^{-1}$

- Data
- $Z+X$
- $Z\gamma^*, ZZ$

Events / 3 GeV

$m_{4l}$ [GeV]
Higgs Hunted

$m_{4l}$ distribution

- Low mass range

- Un-Blinded

- Background expectation

- Signal $m_H = 126$ GeV expectation
**Results**

- **$m_{4l}$ distribution**
  - Low mass range

- **Un-Blinded**
  - Background expectation
  - Signal $m_H = 126$ GeV expectation
  - Event by event errors

![Graph showing $m_{4l}$ distribution with data points and error bars.](image)

![Graph showing CMS Preliminary results with different event categories.](image)
**Results**

- $m_{4l}$ distribution
  - Full mass range
  - Un-Blinded
  - Background expectation
  - Signal $m_H = 126, 350$ GeV expectation
  - Event Yields

### Yields for $m_{4l} = [110 - 160]$ GeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>$4e$</th>
<th>$4\mu$</th>
<th>$2e2\mu$</th>
<th>$4l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ background</td>
<td>2.65 ± 0.31</td>
<td>5.65 ± 0.59</td>
<td>7.17 ± 0.76</td>
<td>15.48 ± 1.01</td>
</tr>
<tr>
<td>Z+X</td>
<td>1.20 ± 0.78</td>
<td>0.92 ± 0.65</td>
<td>2.29 ± 1.81</td>
<td>4.41 ± 2.21</td>
</tr>
<tr>
<td>All backgrounds</td>
<td>3.85 ± 0.84</td>
<td>6.58 ± 0.88</td>
<td>9.36 ± 1.96</td>
<td>19.88 ± 2.43</td>
</tr>
<tr>
<td>$m_H = 126$ GeV</td>
<td>1.51 ± 0.48</td>
<td>2.99 ± 0.60</td>
<td>3.81 ± 0.89</td>
<td>8.31 ± 1.18</td>
</tr>
<tr>
<td>Observed</td>
<td>6</td>
<td>6</td>
<td>9</td>
<td>21</td>
</tr>
</tbody>
</table>

### Yields for $m_{4l} = [100 - 800]$ GeV:
- expected: $164 ± 11$ events
- observed: 172
2l invariant masses

\[ 121 \leq m_{4l} \leq 131 \text{ GeV} \]

\[ \sum_{1} \leq m_{4l} \leq 131 \text{ GeV} \]

\[ \sum_{1} \leq m_{4l} \leq 131 \text{ GeV} \]

\[ Z_1 \text{ and } Z_2 \text{ masses seem too low for signal and background} \]
Matrix Element Likelihood Analysis (MELA)

- Kinematic inputs for signal to background discrimination
- 2D analysis \( \{m_{4l}, \text{MELA}\} \)

\[ 121 \leq m_{4l} \leq 131 \text{ GeV} \]
Matrix Element Likelihood Analysis (MELA)

- Kinematic inputs for signal to background discrimination
- 2D analysis \( \{m_{4\ell}, \text{MELA}\} \)

\[
121 \leq m_{4\ell} \leq 131 \text{ GeV}
\]
Results (95% CL limits)

Expected limits

- **full mass range**

- **zoomed mass range**

→ expected exclusion of the SM Higgs [121 - 570]
Results (95% CL limits)

Observed limits

→ expected exclusion of the SM Higgs [121 - 570]
→ observed exclusion of the SM Higgs [131 - 162] [172 - 525]
→ observed excess of events in the region $m_H \sim 125$ GeV
Results (p-values)

p-values

full mass range

expected for a Higgs boson

zoomed mass range

expected for a Higgs boson

→ expected local significance $m_H = 125.5$ GeV : 3.8 $\sigma$

→ observed local significance $m_H = 125.5$ GeV : 3.2 $\sigma$
Search for $H \rightarrow ZZ \rightarrow 4l$ in the range [110 - 600] GeV

- @7 TeV $5.1 \text{ fb}^{-1}$ and @8 TeV $5.3 \text{ fb}^{-1}$ analysed with significant improvement with respect to 2011 analysis
- Including $2l2\tau$ analysis

ZZ cross section:

- Predicted: $\sigma_{\text{th}}(pp \rightarrow ZZ) = 7.7 \pm 0.4 \text{ pb (NLO)}$
- Observed: $\sigma(pp \rightarrow ZZ) = 8.4 \pm 1.0(\text{stat.}) \pm 0.7(\text{sys.}) \pm 0.4(\text{lumi.}) \text{ pb}$

SM Higgs exclusion

- Expected: exclusion of the SM Higgs [121 - 570]
- Observed: exclusion of the SM Higgs [131 - 162] [172 - 525]
Evidence for a new massive boson: 3.2 $\sigma$ at 125.5 GeV

- Best mass = $125.6 \pm 1.2$ GeV
- Best signal strength: $\mu = 0.7 \pm 0.4$
References

CMS-PAS-HIG-016: Evidence for a new state in the search for the standard model Higgs boson in the $H \rightarrow ZZ \rightarrow 4l$ channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV

CMS-PAS-HIG-014: Measurement of ZZ production cross section in $ZZ \rightarrow 2l2l'$ decay channel in pp collisions at $\sqrt{s} = 8$ TeV

Event Display 4e event

4-lepton Mass : 122.4 GeV

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Event Display 4μ event
Event Display 2e2μ event

4-lepton Mass: 126.9 GeV

μ*(Z₁) p_T: 43 GeV

μ*(Z₁) p_T: 24 GeV

e*(Z₂) p_T: 10 GeV

e*(Z₂) p_T: 21 GeV

μ*(Z₁) p_T: 43 GeV

e*(Z₂) p_T: 10 GeV

e*(Z₂) p_T: 21 GeV

μ*(Z₁) p_T: 24 GeV

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Results (p-values with $\tau$)