A search for the Higgs boson in $H \rightarrow ZZ^{(*)}$ mode with the CMS detector

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on behalf of CMS collaboration

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SM Higgs production

\[ \sigma(pp \rightarrow H + X) [\text{pb}] \]

- **gg fusion**
  - \( g \rightarrow H \)
  - \( t, b \rightarrow H \)

- **associated production with** \( Q\bar{Q} \)

- **vector boson fusion**
  - \( q \rightarrow H \)
  - \( W, Z \rightarrow H \)

\[ s = 7 \text{ TeV} \]

\[ M_H [\text{GeV}] \]

- \( 0 \)
- \( 200 \)
- \( 400 \)
- \( 600 \)
- \( 800 \)
- \( 1000 \)

- \( 10^{-4} \)
- \( 10^{-3} \)
- \( 10^{-2} \)
- \( 10^{-1} \)
- \( 10 \)
- \( 10^2 \)
- \( 10^3 \)
- \( 10^4 \)
SM Higgs decay modes

Decay branching ratio

Cross section x branching ratio
CMS detector

Certified luminosity
1.1 fb$^{-1}$ (2011)
36 pb$^{-1}$ (2010)
Physical objects

Leptons
\[ H \rightarrow ZZ \rightarrow llqq/\nu\nu: \]
standard leptons selection for Z measurement
\[ H \rightarrow ZZ^{(*)} \rightarrow llll: \]
low p_T leptons with high selection efficiency

Missing Transverse Energy
Particle Flow MET

Jets
Particle Flow Jets
\textit{anti-}k_T\textit{ algorithm} (R = 0.5)

b-tagging
Track Counting High Efficiency algorithm
\textit{uses displaced tracks in a jet to compute the discriminator}

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low p_T-high p_T</td>
<td>low p_T-high p_T</td>
</tr>
<tr>
<td>electron</td>
<td>(95-97)%</td>
<td>(90-95)%</td>
</tr>
<tr>
<td>muon</td>
<td>(97-98)%</td>
<td>(98-99)%</td>
</tr>
</tbody>
</table>

reconstruction+identification in \[ H \rightarrow ZZ^{(*)} \rightarrow llll \]
Large Yields
✓ Exploits very large BR(Z → qq) = 70%
✓ Full decay chain reconstructed

Challenge
✓ Large Z+jet background
✓ Limited resolution coming from jets

Background
✓ Resonant: Z+jet
✓ Non-Resonant: ttbar/tW
✓ EWK: ZZ/WZ/WW

Good for exclusion and discovery
Sensitive to high mass Higgs boson: $m_H \ [200-600] \ \text{GeV/c}^2$
Selection Procedure

Two Opposite-Sign Same-Flavor isolated leptons
\( p_T,1/2 > 40/20 \text{ GeV/c} \) & \( |\eta_\mu| < 2.4 \) \( |\eta_e| < 2.5 \)
At least two jets
\( p_T,1/2 > 30 \text{ GeV/c} \) & \( |\eta_j| < 2.4 \)

Background suppression

\( 70 < m_{ll} < 110 \text{ GeV/c}^2 \)
\( 75 < m_{jj} < 105 \text{ GeV/c}^2 \)

Angular Likelihood Discriminant

Quark-Gluon Likelihood Discriminant

Tagging of b-flavor

Three b-tag categories: 0/1/2 b jet
Background from DATA

Estimation from the $m_{jj}$ sidebands
$(60 < m_{jj} < 75 \text{ GeV/c}^2) \cup (105 < m_{jj} < 130 \text{ GeV/c}^2)$

\[
N_{\text{bkg}}(m_{ZZ}) = N_{\text{sb}}(m_{ZZ}) \times \frac{N_{\text{sim,bkg}}(m_{ZZ})}{N_{\text{sim,sb}}(m_{ZZ})} = N_{\text{sb}}(m_{ZZ}) \times \alpha(m_{ZZ})
\]

Additional information on ttbar background using the mixed-flavor $e\mu jj$ sample

Dominant $Z+$jet background is absent
Invariant Mass

CMS Preliminary 2011, 1.0 fb$^{-1}$ \( \sqrt{s} = 7 \text{ TeV} \)

MC Signal expectation
\( \eejj + \mumu jj \)

<table>
<thead>
<tr>
<th>Mass (GeV/c$^2$)</th>
<th>0 b-tag</th>
<th>1 b-tag</th>
<th>2 b-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>2.57 ± 0.37</td>
<td>3.43 ± 0.49</td>
<td>0.70 ± 0.19</td>
</tr>
<tr>
<td>300</td>
<td>5.84 ± 0.83</td>
<td>4.97 ± 0.69</td>
<td>1.75 ± 0.46</td>
</tr>
<tr>
<td>400</td>
<td>5.33 ± 0.76</td>
<td>4.83 ± 0.67</td>
<td>1.96 ± 0.50</td>
</tr>
<tr>
<td>500</td>
<td>2.21 ± 0.34</td>
<td>2.21 ± 0.32</td>
<td>0.97 ± 0.24</td>
</tr>
<tr>
<td>600</td>
<td>0.83 ± 0.21</td>
<td>0.86 ± 0.21</td>
<td>0.39 ± 0.15</td>
</tr>
</tbody>
</table>

L = 1.0 fb$^{-1}$

\( H \rightarrow ZZ \rightarrow l^+ l^- q\bar{q} \)
Upper Limits

Shape analysis:
✓ Signal parametrized with a Breit–Wigner convoluted with a Crystal-Ball
✓ Background parametrized with an empirical probability function normalized from data estimation (m_\text{jj} sideband)

Higgs boson with a mass in the 226-445 GeV/c^2 range is excluded at 95% CL but in two windows between 261-270 GeV/c^2 and 370-381 GeV/c^2

L = 1.0 fb^{-1}
H \rightarrow ZZ \rightarrow l^+l^-qq
\( H \to ZZ \to l^+l^-\nu\bar{\nu} \)

**Ref:** CMS-PAS-HIG-11-005

**Large Yields**
- ✓ BR(ZZ → ll\nu\nu) \(\sim 6\times\) BR(ZZ → llll)

**Challenge**
- ✓ Looking for Z+MET signature
- ✓ Large Z+jet background
- ✓ No Higgs peak

**Background**
- ✓ Resonant: Z+jet
- ✓ Non-Resonant: ttbar/WW
- ✓ EWK: WZ/ZZ

Good for exclusion
Sensitive to high mass Higgs boson: \(m_H\ [250-600]\ \text{GeV/c}^2\)

\(\sqrt{s} = 7\text{TeV}\)

**SM**

\(WW \to t\bar{t}\nu\bar{\nu}\)

\(ZZ \to l^+l^-\nu\bar{\nu}\)

\(ZZ \to l^+l^-\nu\bar{\nu}\)

\(WH \to t\nu\bar{\nu}\)

\(ZH \to t\bar{t}b\bar{b}\)

\(W^+W^-\)\(\to l^+l^-\nu\bar{\nu}\)

\(\gamma\gamma\)

\(q = udscb\)

\(l = e, \mu\)

\(\nu = \nu_e, \nu_\mu, \nu_\tau\)
Selection Procedure

Two Opposite-Sign Same-Flavor isolated leptons
\[ p_{T,1/2} > 20 \text{ GeV/c} \quad \text{and} \quad |\eta_\mu| < 2.4 \quad |\eta_e| < 2.5 \quad |m_{ll} - m_Z| < 15 \text{ GeV/c}^2 \]

Background suppression

*Mass independent cuts:*
- Veto events with a b-jet
- Veto events with a third lepton

*Mass dependent cuts:*
- Missing transverse energy (MET)
- MET-jet separation
- Transverse Mass (M_T)

\[ \text{CMS preliminary, } \sqrt{s}=7 \text{TeV, } 1.1 \text{ fb}^{-1} \]

\[ H \rightarrow ZZ \rightarrow l^+l^-\nu\nu \]
Transverse Mass

$H \rightarrow ZZ \rightarrow l^+l^-\nu\nu$

$L = 1.1 \text{ fb}^{-1}$

$H \rightarrow ZZ \rightarrow l^+l^-\nu\nu$

Background estimation

- Resonant (Z+jet) → gamma+jet
- Non-Resonant (ttbar/WW) → e\mu final states
- Electroweak (WZ/ZZ) → MC

**Channel**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Total background</th>
<th>$m_H$ (250 GeV/c²)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>22 ± 5</td>
<td>3.1 ± 0.5</td>
<td>29</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>30 ± 5</td>
<td>3.9 ± 0.5</td>
<td>28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Total background</th>
<th>$m_H$ (350 GeV/c²)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>11 ± 2</td>
<td>3.2 ± 0.6</td>
<td>8</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>13 ± 2</td>
<td>3.9 ± 0.5</td>
<td>11</td>
</tr>
</tbody>
</table>
Upper Limits

SM with a 4th fermion family of high mass

Higgs boson with a mass in the 250-550 GeV/c² range is excluded at 95% CL

Cut & Count analysis
final discriminator $M_T$

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>250</td>
<td>&gt; 216 AND &lt; 272</td>
</tr>
<tr>
<td>350</td>
<td>&gt; 267 AND &lt; 386</td>
</tr>
<tr>
<td>450</td>
<td>&gt; 315</td>
</tr>
<tr>
<td>550</td>
<td>&gt; 357</td>
</tr>
</tbody>
</table>
Golden channel

✓ Clean experimental signature, four primary and isolated leptons
✓ Narrow resonance in 4 leptons, invariant mass spectrum

Challenge

✓ Small Branching Ratio
✓ Low $p_T$ leptons

Background

✓ Instrumental: $Z+$fakes
✓ Reducible: $Zbb$/ttbar/$WZ$
✓ Irreducible: $ZZ^{(*)}$

Good for exclusion and discovery

Sensitive to whole mass Higgs boson range: $m_H$ [110-600] GeV/c²
Selection Procedure

\[ H \rightarrow ZZ^{(*)} \rightarrow ℓ+ℓ−+ℓ+ℓ− \]

2e2µ

CMS Preliminary 2011

\( \sqrt{s} = 7 \text{ TeV} \)

\( L = 1.13 \text{ fb}^{-1} \)

- DATA
- QCD
- t\bar{t}
- Z+jets
- Zb\bar{b}/c\bar{c}
- Z+gamma
- W+jets
- Single top
- WW
- WZ
- ZZ
- \( m_H = 250 \text{ GeV}/c^2 \)
- \( m_H = 200 \text{ GeV}/c^2 \)
- \( m_H = 150 \text{ GeV}/c^2 \)
Selection Procedure

Best 4l candidate choice

✓ Two pair of Opposite-Sign Same-Flavor identified leptons:
  \[ p_{T,1/2} > 20,10 \text{ GeV/c} \quad p_{T,3/4} > 7(e),5(\mu) \text{ GeV/c} \]
  
  Z boson candidate
  \[ m_{4l} > 100 \text{ GeV/c}^2 \]

\[ Z_1 \to ZZ(*) \to l^+l^-l^+l^- \]

Retaining the maximal signal efficiency
Preserving the phase space for the background control

\[ L = 1.13 \text{ fb}^{-1} \]
Reducible background suppression
✓ Relative isolation on leptons
✓ Impact parameter on leptons

Minimal signal efficiency loss while preserving optimal phase space
Selection Procedure

Kinematics (Z and Z*)

**Low-mass/Baseline selection**
✓ \( \text{min}(m_{Z^2}) = 20 \text{ GeV/c}^2 \)
  to search for all Higgs mass hypotheses

**High-mass/Two Zs “on-shell”**
✓ \( \text{min}(m_{Z^2}) = 60 \text{ GeV/c}^2 \)
  to search for high Higgs mass hypotheses

\( H \rightarrow ZZ(*) \rightarrow l^+l^-l^+l^- \)

L = 1.13 fb\(^{-1}\)

\( \sqrt{s} = 7 \text{ TeV} \)

High-mass/Two Zs coincides with ZZ cross section measurement

\( L = 1.13 \text{ fb}^{-1} \)
Background from DATA

Control of ZZ continuum
normalization to Z rates in DATA

\[ \frac{\sigma_{qq \to ZZ \to 4\ell}}{\epsilon_{MC}} + \frac{\sigma_{gg \to ZZ \to 4\ell}}{\epsilon_{MC}} = \epsilon_{Z \to 2\ell} \]

Control of reducible backgrounds
Relax flavor and charge requirements
High impact parameter

Control of instrumental backgrounds
Use fake rate measurements

CMS Preliminary 2011
\( \sqrt{s} = 7 \text{ TeV} \), \( L = 1.13 \text{ fb}^{-1} \)

\( p_T \), GeV/c

Fake Rate (Reco_ID_Isolation)

CMS Preliminary 2011
Electron in ECAL Barrel
\( \sqrt{s} = 7 \text{ TeV} \), \( L = 1.13 \text{ fb}^{-1} \)
**Invariant Mass**

*Low-mass/Baseline selection*

$\sqrt{s} = 7$ TeV $\ L = 1.13$ fb$^{-1}$

$H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l^+l^-$

$60 < m_{Z1} < 120$ GeV/c$^2$

$20 < m_{Z2} < 120$ GeV/c$^2$

<table>
<thead>
<tr>
<th>$m_H$</th>
<th>4e</th>
<th>4$\mu$</th>
<th>2e2$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 GeV/c$^2$</td>
<td>$2.76 \pm 0.18$</td>
<td>$4.10 \pm 0.27$</td>
<td>$6.72 \pm 0.45$</td>
</tr>
<tr>
<td>200 GeV/c$^2$</td>
<td>$0.38 \pm 0.07$</td>
<td>$0.06 \pm 0.01$</td>
<td>$0.41 \pm 0.07$</td>
</tr>
<tr>
<td>150 GeV/c$^2$</td>
<td>$0.368$</td>
<td>$0.637$</td>
<td>$0.996$</td>
</tr>
</tbody>
</table>

Background estimated with data
The total cross section for a pair WW/WZ/ZZ bosons has been measured and found to be in agreement with the expectation from the Standard Model.

See CMS EWK di-boson talk in this conference for more details.
Upper Limits

Higgs boson with a mass in the 138-162 GeV/c^2 and 178-502 GeV/c^2 ranges is excluded at 95% CL.

Shape analysis:

✓ Signal parametrized with a Breit–Wigner convoluted with a Crystal-Ball
✓ ZZ/reducible backgrounds parametrized by an empirical probability function, normalization from data
Conclusion

✓ A search of the H boson in the ZZ mode has been performed for the first time in CMS

✓ The ZZ* decays into $llqq, ll\nu\nu$ and $llll$ ($l = e, \mu$) have been measured and examined at $\sqrt{s} = 7$ TeV

✓ No evidence of a SM-like Higgs bosons has been found

✓ At $m_{4l} > 100$ GeV/c$^2$: 15 events observed, $14.4 \pm 0.6$ events expected
  At $m_{4l} < 2 \times m_Z$: 6 events observed, $1.9 \pm 0.1$ events expected

✓ Upper limits are obtained at 95% CL on the cross section$\times$B.R. for a Higgs boson with SM-like decays for masses in the range $110 < m_H < 600$ GeV/c$^2$

✓ In the context of the Standard Model with a massive fourth fermion family, a Higgs boson with a mass in the ranges $138$-$162$ GeV/c$^2$ and $178$-$550$ GeV/c$^2$ is excluded at 95% C.L.
BACKUP
CMS preliminary 2011

1.13 fb\(^{-1}\) at \(\sqrt{s} = 7\) TeV

95\% CL limit on \(\sigma/\sigma_{SM}\)

\[ M_H \text{ [GeV/c}^2\text{]} \]

- CL\(_S\) Observed Limit
- CL\(_S\) Expected Limit
- CL\(_S\) Expected ± 1\(\sigma\)
- CL\(_S\) Expected ± 2\(\sigma\)

SM

CMS Preliminary 2011

\(\sqrt{s} = 7\) TeV L = 1.13 fb\(^{-1}\)

- DATA
- \(Z+\text{jets}\)
- ZZ
- \(m_H = 250\) GeV/c\(^2\)
- \(m_H = 200\) GeV/c\(^2\)
- \(m_H = 150\) GeV/c\(^2\)

Events/10 GeV/c\(^2\)

\(M_{4l}\) [GeV/c\(^2\)]