Higgs search in WW* and ZZ* 

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July, 29 2011
Higgs production at LHC

- **Gluon Fusion** $(gg \rightarrow H)$
- **Vector Boson Fusion** $(qq \rightarrow q'q'H)$
- **W,Z Associated Prod.** $(qq \rightarrow VH)$
- **tt Associated Prod.** $(gg \rightarrow ttH)$

$gg \rightarrow H$ is the dominant production

For $m_H > 140$ GeV:
- $gg \rightarrow H$ cross section > 15 times that at 2 TeV
H→WW, ZZ decays

* H→WW→2l2ν + 0,1,2 jets: the leader mode for m_H=130 - 200 GeV

* H→ZZ: 3 final states studied: llqq, 2l2ν, 4l

Irreducible backgrounds (WW,ZZ):

originate from qq, which rises slowly in pp respect pp
⇒ better S/B wrt Tevatron
Higgs→WW* search

CMS PAS HIG-11-003
H→WW*→2l2ν strategy

- The pioneer of Higgs hunting with o(1 fb⁻¹): combines large BR with a clean final state
  - maximal sensitivity at \( m_H \approx 2m_W \)
  - the price to pay: no mass peak \( \Rightarrow \) counting experiment with reduced \( m_H \) sensitivity
  - two opposite sign leptons (e,μ) with \( p_T^{\text{max(min)}} > 20 \) (10) GeV (preserve sensitivity for \( m_H=120 \) GeV, higher thresholds for larger \( m_H \))
  - large \( E_T^{\text{miss}} \) due to 2 undetected ν’s
  - 0, 1 high \( p_T \) jets (dedicated selection for VBF production with 2 jets)
  - small lepton opening angle (\( \Delta\phi_{ll} \)) \( H\rightarrow WW^* \) vs large angle \( qq, gg \rightarrow WW^* \) due to spin correlations
## H→WW*→2l2ν: backgrounds

<table>
<thead>
<tr>
<th>process</th>
<th>characteristic</th>
<th>rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+jets (31000 pb)</td>
<td>lepton + fake lepton</td>
<td>2 well identified and isolated leptons</td>
</tr>
<tr>
<td>Z+jets (5000 pb)</td>
<td>Z peak, no real $E_T^{\text{miss}}$</td>
<td>* proj $E_T^{\text{miss}} &gt; 40 \text{ GeV}(ee,\mu\mu)$, 20 GeV (e\mu)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* $</td>
</tr>
<tr>
<td>tt (158 pb), tW (11 pb)</td>
<td>additional (b-)jets</td>
<td>* classify events in 0-,1-jet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* anti b-tagging</td>
</tr>
<tr>
<td>W,Z + γ (165 pb)</td>
<td>electron from γ conversion</td>
<td>* conversion veto</td>
</tr>
<tr>
<td>WW (43 pb)</td>
<td>non resonant</td>
<td>* small $\Delta \phi_{ll}$</td>
</tr>
<tr>
<td>WZ (18 pb), ZZ (6 pb)</td>
<td>Z peak</td>
<td>* $</td>
</tr>
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</table>

Relative importance after selection depends on $m_H$
The pileup challenge on $E_T^{\text{miss}}$

- Pileup worsen $E_T^{\text{miss}}$ resolution

- Two estimators considered:
  - **particle-flow $E_T^{\text{miss}}$:** charged + neutral component
  - **track $E_T^{\text{miss}}$:** only tracks consistent with nominal primary vertex ⇒ reduced PU dependency

- **take the min of the two**

- Project along ll-system ($Z \rightarrow \tau\tau$ rejection):

$$\text{proj}E_T^{\text{miss}} = \begin{cases} 
E_T^{\text{miss}} & \text{if } \Delta\phi_{\text{min}} \geq \frac{\pi}{2}, \\
E_T^{\text{miss}} \sin(\Delta\phi_{\text{min}}) & \text{if } \Delta\phi_{\text{min}} < \frac{\pi}{2}
\end{cases}$$

$$\Delta\phi_{\text{min}} = \min(\Delta\phi(\ell_1, E_T^{\text{miss}}), \Delta\phi(\ell_2, E_T^{\text{miss}}))$$

1.1 fb$^{-1}$
Jet multiplicity boxes

- Sample with 2 leptons, large $E_T^{\text{miss}}$, $Z$ veto is dominated by $W^+W^-$, top and $W+\text{jets}$ (low $m_H$-only)

- subdivide events by jet multiplicity (jet $p_T>30$ GeV, $|\eta|<5$)

  - **0-jet**: dominated by $WW$. Apply anti $b$-tagging on low $p_T$ jets

  - **1-jet**: dominated by $t\bar{t}+tW$, apply anti $b$-tagging on all jets

  - **2-jets**: specific VBF selections (see A. Benaglia’s talk)
$W^+W^-$ + 0, 1, 2 jets

$\Delta \phi_{ll}$, 0-jet

$\Delta \phi_{ll}$, 1-jet

$\Delta \eta_{jj}$, 2-jet

$H \rightarrow WW^* \rightarrow 2l2\nu$

1.1 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>data</th>
<th>all bkg.</th>
<th>$qq \rightarrow W^+W^-$</th>
<th>$gg \rightarrow W^+W^-$</th>
<th>$tt + tW$</th>
<th>$W + \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet</td>
<td>626</td>
<td>568.6 ± 52.2</td>
<td>349.7 ± 30.3</td>
<td>17.2 ± 1.6</td>
<td>63.8 ± 15.9</td>
<td>8.7 ± 1.7</td>
</tr>
<tr>
<td>1-jet</td>
<td>334</td>
<td>316.0 ± 24.7</td>
<td>101.4 ± 9.3</td>
<td>5.9 ± 0.5</td>
<td>141.1 ± 14.1</td>
<td>2.4 ± 0.8</td>
</tr>
<tr>
<td>2-jet</td>
<td>175</td>
<td>164.6 ± 18.0</td>
<td>22.1 ± 2.0</td>
<td>1.1 ± 0.1</td>
<td>99.3 ± 9.9</td>
<td>1.1 ± 0.5</td>
</tr>
</tbody>
</table>

$WZ/ZZ$ not in $Z/\gamma^* \rightarrow \ell^+\ell^-$

0-jet 8.5 ± 0.9
1-jet 7.2 ± 0.8
2-jet 1.5 ± 0.2

$Z/\gamma^* \rightarrow \ell^+\ell^- + WZ + ZZ$

0-jet 12.2 ± 5.3
1-jet 10.5 ± 11.5
2-jet 19.2 ± 13.5

$Z/\gamma^* \rightarrow \tau^+\tau^-$

0-jet 1.6 ± 0.4
1-jet 10.6 ± 1.2
2-jet 3.9 ± 0.7

$W + \text{jets}$

0-jet 106.9 ± 38.9
1-jet 36.9 ± 13.8
2-jet 16.4 ± 6.4
With this selected sample, in the 0-jet bin, the WW cross section is measured

- 626 events selected on data, with 201.7 ± 42.4 background events
- total $W^+W^-$ signal efficiency $\varepsilon = (6.69 \pm 0.51)\%$

$$\sigma(pp \rightarrow WW + X) = 55.3 \pm 3.3\text{(stat.)} \pm 6.9\text{(syst.)} \pm 3.3\text{(lumi.)} pb$$

- consistent with $\sigma^{\text{th.}}\text{(NLO)} = 43 \pm 2\ pb$ at 1$\sigma$ level

CMS PAS EWK-11-010 (measurement of WW, WZ, ZZ cross sections)
Higgs cut-based/MVA selection

- \( m_H \)-dependent cuts are applied on: \( p_T^{\text{min}}, p_T^{\text{max}}, m_{ll}, \Delta\phi_{ll}, m_T \) and count after subtracting backgrounds (estimated from data):

- \( W+\text{jets} \) (from fake-rate prediction), top (from b-tagged sample), \( Z+\text{jets} \) (events under Z-peak extrapolation), \( WW \) (high \( m_{ll} \) region)

- or a BDT is trained with above variables, plus some other (\( \Delta R_{ll}, \text{lepton flavor} \))

- (binned) BDT output distribution used to extract signal

Friday, July 29, 2011
Systematic uncertainties

- Largest systematics from background estimation
  - W+jets: ≈40% (do not improve with statistics)
  - Drell-Yan: 60%
  - Top: 25%
  - WW: 15-30%
  - lepton efficiency (momentum scale) 2%, 1.5%
- Theory Higgs cross section: 15%, which includes jet bin uncertainty: 7, 10, 20% between 0-,1-,2-jet bins.
  - 0-jet efficiency estimated with Z+jets events
- Luminosity: 6%

H→WW*→2l2ν
1.1 fb⁻¹
H → WW* cut based limits/jet bin

Higgs boson mass (GeV/c^2)

0 jet

1 jet

2 jets (VBF)
H→WW* MVA limits/jet bin

* for the 2 jet bin only cut-based analysis has been performed
H→WW* exclusion limit

- Analysis performed in m_H=115 - 600 GeV, sensitivity with 1 fb^{-1} in m_H=130 - 200 GeV. Limits with CLs (95% C.L.)

MVA analysis vs cut-based analysis

Exp.: [130 - 200] GeV
Obs.: [150 - 193] GeV

Exp.: [135 - 190] GeV
Obs.: [150 - 190] GeV

- one single channel, one single experiment, competitive with Tevatron
Higgs→ZZ* search

CMS PAS HIG-11-005 (ZZ→2l2ν)
CMS PAS HIG-11-006 (ZZ→2l2q)
CMS PAS HIG-11-004 (ZZ→4l)
H→ZZ→2l2ν: strategy

* Large yield: BR(ZZ→2l2ν)≈6 BR(ZZ→4l) for m_H=[250 - 600] GeV

* Same final state as WW: 2 leptons + large E_T^{miss}

  * Same problematics: no mass peak, large backgrounds

* Selection:

  * two opposite sign same flavor leptons (p_T>20 GeV)

  * large E_T^{miss}

  * large E_T^{miss} - jet separation (\Delta\phi_{MET,Jet}): fake E_T^{miss} in Z+jets is aligned with a mis-measured jet

  * large transverse mass (m_T)
Expected and observed events

\( H \rightarrow ZZ^* \rightarrow 2l2\nu \) 

1.1 fb\(^{-1}\)

2e2\(\nu\), \( m_H = 350 \) GeV

2\(\mu\)2\(\nu\), \( m_H = 350 \) GeV

*Main backgrounds:* Z+jets (estimated with \( \gamma + \text{jets} \)), ZZ (MC), top+WW (estimated with e\(\mu\) events)
Exclusion limits

- Close to Standard Model sensitivity in $m_H = [300 - 500]$ GeV

- with 4-th generation of (heavy) quarks, enhanced cross section:
  - $\Rightarrow m_H = [250 - 550]$ GeV is excluded @95% C.L.
H→ZZ→2l2q: strategy

- Large Yields: BR(Z→qq)=70%
- Closed kinematics: full event reconstruction
- Price to pay:
  - large backgrounds (Z+jets)
  - limited mass resolution due to jets
- Selection:
  - 2 opposite sign, same flavor leptons ($p_T>20,40$ GeV), 2 jets ($p_T>30$ GeV)
  - $m_{ll}$, $m_{jj}$ close to Z peak
Angular analysis & jet composition

- 5 angles define the kinematics of scalar \( H \rightarrow ZZ \rightarrow llqq \): used in a likelihood discriminant
  - advantage: little correlation with \( m_{lljj} \), possibility to measure \( Z+jets \) background from mass sidebands

- Signal \( Z \rightarrow qq \): 2 jets from quarks (light + b,c): use b-tag & g/q discriminator
  - main bkg: 2 jets from gluons
2l2jet invariant mass

- Full distribution of $m_{ZZ}$ used to extract the signal (default) OR cut-and-count
- Background modeled from $m_{jj}$ sidebands: $(60 < m_{jj} < 75 \text{ GeV}) \cup (105 < m_{jj} < 130 \text{ GeV})$
- $e\mu jj$ used also as control sample (Z+jets free)

$H \rightarrow ZZ^* \rightarrow 2l2\nu$

$1.1 \text{ fb}^{-1}$
Exclusion limits

* Best sensitivity with the fit to $m_{ZZ}$ distribution. Including shape systematics estimated in $m_{jj}$ sidebands

* reaching sensitivity to SM Higgs around 350 GeV.

* With 4$^{th}$ fermion generation, exclude $m_H = [226 - 445]$ GeV
- Cleanest H mode, closed kinematics: high sensitivity to $m_H$
- small BR, low yields expected
- Two pair of opposite sign, same flavor leptons: $p_{T1,2} > 20,10$ GeV, $p_{T3,4} > 7(e),5(\mu)$: preserve efficiency for low mass Higgs
- Two Z bosons selection: 1 tight (on shell) + 1 loose (off shell)

$Z1: m_{ll} > 60$ GeV

$Z2: m_{ll} > 20$ GeV
Backgrounds estimation

* non resonant ZZ: scale factor data/MC obtained from single Z→ll, and corrected for ZZ phase space

* fake-lepton induced (Z+jets): apply fake-rate to Z + loosely identified leptons control sample

* Z→bb, tt: do not use flavor and charge requirement; require high impact parameter

H→ZZ*→4l

1.1 fb⁻¹
4 leptons ZZ candidates

- 15 events selected (3 in 4e, 6 in 4µ, 6 in 2e2µ)

- 6 events with \(m_{\text{ZZ}} < 180\text{ GeV}\), but not compatible with one SM Higgs of defined mass. With events having 2 Z’s with \(m_{ll} > 60\text{ GeV}\):

\[
\sigma(pp \rightarrow ZZ + X) \times B(ZZ \rightarrow 4\ell) = 17.5^{+6.3}_{-4.4}\text{(stat.)} \pm 0.7\text{(syst.)} \pm 1.1\text{(lumi.)} \text{ fb}
\]

\[
\sigma^\text{th. (NLO)} = 28.32 \pm 1.95 \text{ fb}
\]
The highest mass ZZ event
**Exclusion limits**

- Signal extraction: full mZZ used:
  - signal: Breit Wigner (decay) $\otimes$ Crystal-Ball function (resolution)
  - background: empirical parametric model

- Sensitivity to [1-2] x SM cross section in $m_H = 180 - 420$ GeV

- In the 4th fermion generation scenario excludes 2 ranges:
  - $m_H = [138 - 162]$ GeV
  - $m_H = [178 - 502]$ GeV
Conclusions

- CMS searched for Standard Model Higgs in WW and ZZ with 1.1 fb$^{-1}$ at 7 TeV
- No convincing evidence for Higgs boson has been observed (yet)
- H$\rightarrow$WW$^*$→2l2$\nu$ excludes a Higgs boson in the mass range 150 < $m_H$ < 193 GeV
- Broad excess within 2$\sigma$ in the range 120 < $m_H$ < 170 GeV
- H$\rightarrow$ZZ$^*$→2l2$\nu$ and 2l2$q$ contribute to H$\rightarrow$WW$^*$ for Higgs exclusion at high masses (see J.Olsen’s talk on combination)
- H$\rightarrow$ZZ$^*$→4l consistent with SM backgrounds, slightly more events than expected for $m_H$<180 GeV

LHC restarted after technical stop: eagerly looking at new data!
Backup
Drell-Yan estimation in $H\to WW^*$

- Primary DY estimate in each mass bin using “$R_{\text{out/in}}$” method
  - Land in signal region due to fake MET:
    - mis-measurement of leptons, recoiling jets, instrumental noise
    - fake MET increases with increasing pile-up
  - Events counted in Z-peak and propagated back to signal region
  - $R_{\text{out/in}}$ taken from MC and cross checked in data
  - Other background subtracted out using opposite flavor counts
  - WZ and ZZ contribution subtracted out from data
  - 10% conservative error given to this contribution

\[
N_{\text{out}}^{ll, \text{exp}} = R_{\text{out/in}}^{ll, \text{loose}} \left( N_{\text{in}}^{ll} - 0.5N_{\text{in}}^{el}k_{ll} - N_{ZV, \text{sim. control}}^{ZV} \right)
\]

- opposite flavor events measured in Z-peak
- same flavor events measured in Z-peak
- correction for differences in lepton efficiency
H→WW* + 0 jet kinematics
H→WW* + 1 jet kinematics
H→WW* BDT output

0 jet, opposite flavor

0 jet, same flavor

1 jet, opposite flavor

1 jet, same flavor
H→ZZ*→2l2ν: kinematics

* $E_T^{\text{miss}}$ modeled with $\gamma$+jets control sample
H→ZZ*→2l2ν: SM and 4th generation

- Limits evaluated on $\sigma_H \times \text{BR}(H\rightarrow ZZ\rightarrow 2l2\nu)$

- BR(H→ZZ) enhanced in presence of a 4th generation of heavy fermions

**Standard Model cross section**

**4th generation cross section**
H→ZZ*→2l2q: 4th generation limits
HZZ(4l): SM zoom and SM4

SM, zoom

4th generation