Measurements of Higgs boson production and properties in the WW decay channel using the CMS detector

4th August 2016
Andrea Massironi (Northeastern University) on behalf of the CMS collaboration
**Higgs production and decay**

**Production mechanisms**
- Gluon fusion is the dominant production mechanism
- VBF, VH and ttH allow to test H properties
- ttH, see M. Peruzzi presentation this afternoon
  
  http://indico.cern.ch/event/432527/contributions/1072545/

**Higgs decay**
- **WW** is one of the Higgs decays with larger BR and a reasonable level of irreducible backgrounds

\[ m_H = 125 \text{ GeV} \]

**Cross Sections**
- \( ggH \) 48.58 pb
- \( qqH \) 3.78 pb
- \( WH+ZH \) 2.38 pb
- \( ttH+bbH \) 1.0 pb

2.3/fb collected in 2015

Background composition varies w.r.t. number of jets

- 0 jets: WW, W+jets
- 1 jet: WW, Top
The background menu

- $W \rightarrow l\nu +\text{jets}$: 
  - $q \rightarrow W \rightarrow l\nu +\text{jets}$
  - $\sim 61 \text{ nb}$

- $WW \rightarrow l\nu l\nu$:
  - $q \rightarrow W \rightarrow l\nu l\nu$
  - $\sim 12 \text{ pb}$

- $DY \rightarrow ll$:
  - $q \rightarrow Z \rightarrow ll$
  - $\sim 6 \text{ nb}$

- $t\bar{t} \rightarrow WWbb \rightarrow l\nu l\nu bb$:
  - $q \rightarrow t\bar{t} \rightarrow WWbb \rightarrow l\nu l\nu bb$
  - $\sim 87 \text{ pb}$
Analysis strategy

- Neutrinos $\rightarrow$ impossible reconstruct an invariant mass spectrum
- In transverse plane momentum conservation
  - Build a transverse mass variable:
    - 2 neutrinos $\rightarrow$ more complicated than in simple $W \rightarrow l\nu$ decay
    - Di-leptons and MET system considered
      $$ m_T^{\ell\ell} E_T^{\text{miss}} = \sqrt{2 \cdot p_T^{\ell\ell} \cdot E_T^{\text{miss}} \left(1 - \cos \Delta \phi_{\ell\ell}, E_T^{\text{miss}} \right)} $$
    - $\Delta \phi$ (ll,MET) = angle between di-lepton system and MET
    - $p_T^{\ell\ell}$ = momentum of di-lepton system
  - 2D template fit based on $m_{ll}/m_T^{ll\text{MET}}$ as in Run 1
    - 0 jet and 1 jet to have different background contamination
    - $e\mu$ and $\mu e$ $p_T$ ordered leptons, to exploit different fake rate for electrons and muons

0 jet $H \rightarrow WW$

1 jet $H \rightarrow WW$

- $e\mu$ and $\mu e$ $p_T$ ordered leptons, to exploit different fake rate for electrons and muons
Tackling backgrounds

Lepton selections:
- 2 opposite charge leptons (|\eta|<2.5 for e, |\eta|<2.4 for \mu) with optimized lepton isolation and identification criteria
- \pT^{leading \ lepton} > 20 GeV and \pT^{2nd \ lepton} > 10 (13) GeV for \mu(e)

WW selections
- Low mass resonances: \mll > 12 GeV
- Kinematic cut: \pT^{ll} > 30 GeV
- Extra lepton veto: 2 leptons only with \pT > 10 GeV

\Emiss selection:
- \Emiss > 20 GeV
- \mll^{MET} > 60 GeV

Jet selections:
- B-veto:
  - b jets identified looking at tracks associated to the jet exploiting lifetime of B mesons and soft muons coming from leptonic b decays (combined MVA)
Lepton selections:
- 2 opposite charge leptons ($|\eta|<2.5$ for e, $|\eta|<2.4$ for $\mu$) with **optimized lepton isolation and identification criteria**
- $p_T^{\text{leading lepton}} > 20$ GeV and $p_T^{\text{2nd lepton}} > 10$ (13) GeV for $\mu(e)$

WW selections
- Low mass resonances: $m_{ll} > 12$ GeV
- Kinematic cut: $p_T^{ll} > 30$ GeV
- Extra lepton veto: 2 leptons only with $p_T > 10$ GeV

$E_T^{\text{miss}}$ selection:
- $E_T^{\text{miss}} > 20$ GeV
- $m_T^{ll,\text{MET}} > 60$ GeV

Jet selections:
- B-veto:
  - b jets identified looking at tracks associated to the jet exploiting lifetime of B mesons and soft muons coming from leptonic b decays (combined MVA)

\[ W \rightarrow l + jets \quad \sim 61 \text{ nb} \]
**W+jets**

- Data driven estimation based on **fake-rate** method: probability for a jet to be reconstructed as a lepton

- **Control region** in **same-sign** 2-leptons phase space:

  0 jet

  1 jet

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A. Massironi (Northeastern University)  CMS H > WW
Tackling backgrounds

Lepton selections:
- 2 opposite charge leptons ($|\eta|<2.5$ for e, $|\eta|<2.4$ for $\mu$) with optimized lepton isolation and identification criteria
- $p_T^{\text{leading lepton}} > 20$ GeV and $p_T^{\text{2nd lepton}} > 10$ (13) GeV for $\mu$ (e)

WW selections
- **Low mass resonances:** $m_{ll} > 12$ GeV
- **Kinematic cut:** $p_T^{ll} > 30$ GeV

Extra lepton veto: 2 leptons only with $p_T > 10$ GeV

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- $E_T^{\text{miss}} > 20$ GeV

$m_T^{ll,\text{MET}} > 60$ GeV

Jet selections:
- B-veto:
  - b jets identified looking at tracks associated to the jet exploiting lifetime of B mesons and soft muons coming from leptonic b decays (combined MVA)

$DY \rightarrow ll \sim 6 \text{ nb}$
MC based with **normalization** from control region

- low $m_T^{\|\text{MET}}$ region
- $m_T^{\|\text{MET}} < 60$ GeV

**DY $\rightarrow \tau\tau$**

![Diagram showing $m_T$ distributions with 0 jet and 1 jet](image)

**CMS Preliminary**  
$L = 2.3/\text{fb} (13 \text{ TeV})$
Tackling backgrounds

Lepton selections:
- 2 opposite charge leptons ($|\eta|<2.5$ for e, $|\eta|<2.4$ for $\mu$) with optimized lepton isolation and identification criteria
- $p_T^{\text{leading lepton}} > 20$ GeV and $p_T^{\text{2nd lepton}} > 10$ (13) GeV for $\mu$ (e)
- WW selections
  - Low mass resonances: $m_{ll} > 12$ GeV
  - Kinematic cut: $p_T^{ll} > 30$ GeV
- Extra lepton veto: 2 leptons only with $p_T > 10$ GeV
- $E_T^{\text{miss}}$ selection:
  - $E_T^{\text{miss}} > 20$ GeV
- $m_{Tll\text{MET}} > 60$ GeV

Jet selections:
- B-veto:
  - b jets identified looking at tracks associated to the jet exploiting lifetime of B mesons and soft muons coming from leptonic b decays (combined MVA)

Details on b-tag in M. Verzetti’s talk on Saturday morning
http://indico.cern.ch/event/432527/contributions/1072114/

$\bar{t}t \rightarrow WWbb \rightarrow l\nu l\nu bb \sim 87$ pb
Requiring at least a jet identified as a \textbf{b-induced jet}
- 0 jet $p_T > 30$ GeV
- 1 jet $p_T > 30$ GeV

Top shape from MC and \textbf{normalization} from data, measured separately in 0/1 jet category

\begin{align*}
\mathcal{m}_{ll} & \quad \mathcal{m}_{Tll} \quad \text{MET}
\end{align*}
HWW @ 13 TeV results

2D un-rolled distribution based on $m_\ell/m_T^{\mu\mu\text{MET}}$: trains of $m_\ell$ in $m_T^{\mu\mu\text{MET}}$ windows

- Signal strength
  \[ \frac{\sigma}{\sigma_{\text{SM}}} = 0.3 \pm 0.5 \]

- Significance = \(0.7\sigma\) (expected 2.0\sigma)
Recent results @ 7/8 TeV

- Characterization of the new boson
  - Spin tests
  - Anomalous couplings

- Recent results:
  - Higgs width measurement
  - Differential measurement $p_T^H$
Higgs width

- Measurement of Higgs boson width by looking at the off-shell production
- Simultaneous measurement of on-shell and off-shell Higgs cross section

\[ \sigma_{\text{off-peak}}^{H \rightarrow VV} \quad \sigma_{\text{on-peak}}^{gg \rightarrow H \rightarrow VV} = \Gamma_H \]

- WW and ZZ final state: \( \Gamma_H < 13 \text{ MeV} \)

CMS

<table>
<thead>
<tr>
<th>CMS</th>
<th>19.4 fb(^{-1}) (8 TeV) + 4.9 fb(^{-1}) (7 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow WW )</td>
<td></td>
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<tr>
<td>0-jet (obs)</td>
<td>0-jet (exp)</td>
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<tr>
<td>1-jet (obs)</td>
<td>1-jet (exp)</td>
</tr>
<tr>
<td>2-jet (obs)</td>
<td>2-jet (exp)</td>
</tr>
<tr>
<td>( H \rightarrow ZZ )</td>
<td></td>
</tr>
<tr>
<td>0+1+2 jet (obs)</td>
<td>0+1+2 jet (exp)</td>
</tr>
<tr>
<td>( H \rightarrow ZZ+WW )</td>
<td></td>
</tr>
</tbody>
</table>

Details on coupling/width in U. Sarica’s talk this afternoon
http://indico.cern.ch/event/432527/contributions/1071465/
Differential measurement of Higgs transverse momentum

- With MET resolution, but still $p_T^H$ good observable

Result unfolded at generation level in fiducial phase space

Inputs: measure the Higgs cross section in windows of $p_T^H$ MET
Results

- **7/8 TeV H → WW** characterization
  - Cross section
  - Different production modes targeted
  - Anomalous couplings
  - Higgs width indirect measurement
  - Differential measurement of Higgs transverse momentum
  - Some measurement still statistically dominated

- **13 TeV** search mode
  - Signal strength $\sigma/\sigma_{\text{SM}} = 0.3 \pm 0.5$
  - More data → characterization at 13 TeV

Stay tuned for new results based on more data at 13 TeV
backup
References

CMS DETECTOR

- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
2D shape analysis

- Di-lepton invariant mass: $m_{ll}$
  \[ m_{ll} = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{miss} \left(1 - \cos \Delta \phi_{\ell \ell, E_T^{miss}}\right)} \]

- Lepton + MET transverse mass:
  
  - 7 bins in $m_T H$: 60 – 200 GeV [20 GeV width]
  
  - 5 bins in $m_{ll}$: 10-110 GeV [20 GeV width]

Unrolled 1D distribution
The complete $H \rightarrow WW$ searches at 7/8 TeV

- $ggH$ 0 jet
- $ggH$ 1 jet
- $H \rightarrow WW$ 2 jet
- $VBF$ $H \rightarrow WW$ 2 jet
- $VH \rightarrow WW$ 2 jet
- $WH H \rightarrow WW$ 3 leptons
- $ZH H \rightarrow WW \rightarrow lvjj$ 3 leptons
- $ttH H \rightarrow WW$ 2 same-sign, 3 leptons, 4 leptons
How significant is the excess at 7/8 TeV?

<table>
<thead>
<tr>
<th></th>
<th>Significance</th>
<th>( \sigma / \sigma_{SM} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>combination</strong></td>
<td>4.3(\sigma)</td>
<td>5.8(\sigma)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.72 +0.20 -0.18</td>
</tr>
<tr>
<td><strong>e(\mu) alone</strong></td>
<td>4.0(\sigma)</td>
<td>5.2(\sigma)</td>
</tr>
<tr>
<td><strong>0/1 jet</strong></td>
<td></td>
<td>0.76 (\pm) 0.21</td>
</tr>
</tbody>
</table>
Hunting different production mechanisms

H → WW (all channels)
\[ \frac{\sigma}{\sigma_{SM}} = 0.72^{+0.20}_{-0.18} \]

2l2ν + 0/1-jet
\[ \frac{\sigma}{\sigma_{SM}} = 0.74^{+0.22}_{-0.20} \]

2l2ν + 2-jets, VBF tag
\[ \frac{\sigma}{\sigma_{SM}} = 0.60^{+0.57}_{-0.46} \]

2l2ν + 2-jets, VH tag
\[ \frac{\sigma}{\sigma_{SM}} = 0.39^{+1.97}_{-1.87} \]

3l3ν, WH tag
\[ \frac{\sigma}{\sigma_{SM}} = 0.56^{+1.27}_{-0.95} \]

Best fit for \( \frac{\sigma}{\sigma_{SM}} \)
Signal strength vs Higgs mass

CMS

$\sqrt{s} = 8$ TeV

$\sigma \times BR$ [pb]

$M_H$ [GeV]

$e\mu$ 0/1-jet

$\sigma/\sigma_{SM}$

4.9 fb$^{-1}$ (7 TeV) + 19.4 fb$^{-1}$ (8 TeV)

Observed

68% CL Observed

95% CL Observed
Candidate $H \rightarrow WW \rightarrow \mu\mu\nu\nu$
Cross section

$\sqrt{s} = 8 \text{ TeV}$

$\sigma(pp \rightarrow H+X) [pb]$ vs $M_H [\text{GeV}]$

- $pp \rightarrow H$ (NNLO+NNLL QCD + NLO EW)
- $pp \rightarrow qqH$ (NNLO QCD + NLO EW)
- $pp \rightarrow WH$ (NNLO QCD + NLO EW)
- $pp \rightarrow ZH$ (NNLO QCD + NLO EW)
- $pp \rightarrow t\bar{t}H$ (NLO QCD)
Branching ratio

![Graph showing branching ratios for different decay modes of a Higgs boson. The graph plots the Higgs BR + Total Uncert against the Higgs boson mass (M_H) in GeV. The decay modes include WW, ZZ, bb, γγ, ZZ, and μμ, each with a different line of varying color and style. The x-axis represents the Higgs boson mass, with values ranging from 80 to 200 GeV. The y-axis represents the branching ratio, with values ranging from 10^-4 to 1.]

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Spin testing

CMS H → WW → 2l2ν eμ 0-jet

VS

CMS

2ν_m H → WW → 2l2ν eμ 0-jet

m_ν [GeV]

Events / bin

m_T [GeV]

4.9 fb⁻¹ (7 TeV) + 19.4 fb⁻¹ (8 TeV)

Probability density

WW → 2l2ν + 0/1-jet

0^+

2ν_m^+(f_{qg}=100%)

CMS data

(CL_{obs} = 0.2%)
Spin testing

-2 \times \ln \left( \frac{L_p}{L_{0+}} \right)

<table>
<thead>
<tr>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^+ \pm 1\sigma</td>
<td>J^P \pm 1\sigma</td>
</tr>
<tr>
<td>0^+ \pm 2\sigma</td>
<td>J^P \pm 2\sigma</td>
</tr>
<tr>
<td>0^+ \pm 3\sigma</td>
<td>J^P \pm 3\sigma</td>
</tr>
</tbody>
</table>

CMS

X \rightarrow WW

19.4 fb^{-1} (8 TeV) + 4.9 fb^{-1} (7 TeV)

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Anomalous couplings

\[ A(HV_1 V_2) \sim \left[ a_1^{V_1 V_2} + \frac{\kappa_1^{V_1 V_2} q_{V_1}^2 + \kappa_2^{V_1 V_2} q_{V_2}^2}{(\Lambda_1^{V_1 V_2})^2} \right] \]

- **\( \Lambda_1 \) term**
  - leading momentum expansion

- **\( a_2 \) term**
  - CP even state

- **\( a_3 \) term**
  - CP odd state

\[ f_{a3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4 + ...} \]

\[ \phi_{a3} = \arg \left( \frac{a_3}{a_1} \right) \]
Anomalous couplings

CMS H $\rightarrow$ WW

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Couplings in $k$-framework

\[
\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_{g}^{2} & \kappa_{b}, \kappa_{t}, m_{H} \\ \kappa_{g}^{2} & \kappa_{b}, \kappa_{t}, m_{H} \end{cases}
\]

\[
\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_{W}^{2}
\]

\[
\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_{Z}^{2}
\]

\[
\frac{\Gamma_{bb}}{\Gamma_{bb}^{SM}} = \kappa_{b}^{2}
\]

\[
\frac{\Gamma_{\tau^{-}\tau^{+}}}{\Gamma_{\tau^{-}\tau^{+}}^{SM}} = \kappa_{\tau}^{2}
\]

\[
\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_{\gamma}^{2} & \kappa_{b}, \kappa_{t}, \kappa_{\tau}, \kappa_{W}, m_{H} \\ \kappa_{\gamma}^{2} & \kappa_{b}, \kappa_{t}, \kappa_{\tau}, \kappa_{W}, m_{H} \end{cases}
\]

\[
\kappa_{H}^{2}(\kappa_{i}, m_{H}) = \sum_{j = WW^{(*)}, ZZ^{(*)}, b\bar{b}, \tau^{-}\tau^{+}, \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}, \mu^{-}\mu^{+}} \frac{\Gamma_{j}(\kappa_{i}, m_{H})}{\Gamma_{H}^{SM}(m_{H})}
\]
Couplings results from HWW

$$\mu_{ggH} \ast \sigma_{ggH} + \mu_{VBF,VH} \ast (\sigma_{VBF} + \sigma_{VH})$$

$$k_V^2 k_f^2 / k_H^2 \ast \sigma_{ggH} + k_V^2 k_f^2 / k_H^2 (\sigma_{VBF} + \sigma_{VH})$$

$$k_H^2 \sim k_f^2$$
Rare channels: $2l + 2$ jets

**VH**

**VBF**

![Diagram showing VH and VBF processes with particles and leptons](image)

In the CMS experiment, with an integrated luminosity of 19.4 fb$^{-1}$ at 8 TeV, the mass of the Higgs boson ($m_H$) is 125 GeV, and the dilepton 2-jets search is performed.
Rare channels: VH and VBF

VH

VBF

Events / bin

Events / bin

CMS preliminary

CMS preliminary

L = 19.5 fb$^{-1}$

L = 19.5 fb$^{-1}$

$\sqrt{s} = 8$ TeV

$\sqrt{s} = 8$ TeV

$M_{H} = 125$

$M_{H} = 125$

$V+\gamma/V+\gamma^*$

$V+\gamma/V+\gamma^*$

$W+\text{jets}$

$W+\text{jets}$

$\text{DY+jets}$

$\text{DY+jets}$

$WZ/ZZ$

$WZ/ZZ$

data

data

$\text{WW}$

$\text{WW}$

$\text{VH m}_H = 125$

$\text{VH m}_H = 125$

$\text{top}$

$\text{top}$

$\text{ggH m}_H = 125$

$\text{ggH m}_H = 125$

$\text{V+\gamma/V+\gamma^* VH 2jet}$

$\text{V+\gamma/V+\gamma^* VH 2jet}$

$\text{W+jets}$

$\text{W+jets}$

$\text{WW}$

$\text{WW}$

$\text{CMS preliminary}$

$\text{CMS preliminary}$

$\text{L} = 19.5 \text{ fb}^{-1}$

$\text{L} = 19.5 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}$

$\sqrt{s} = 8 \text{ TeV}$

$\text{VBF 2jet}$

$\text{VBF 2jet}$

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Rare channels: 3l (+2jet)

**WH**

**ZH**

![Diagrams showing WH and ZH processes](image)

**Events**

- **CMS**
  - Data
  - $W_H$
  - VH
  - Non-prompt
  - ZZ
  - WZ

- **$m_H = 125$ GeV**
- **3l + 2jet**

![Histograms showing event distribution](image)

- **Events / 0.8**
- **$\Delta R_{ll}$**

- **CMS**
  - Data
  - $10 \times ZH$
  - ZZ
  - WZ + VV

- **$m_{T^{VV}}$ [GeV]**
- **Events / 38 GeV**
$p_T^H$ response matrix

**Folding**

**Unfolding**

<table>
<thead>
<tr>
<th>$p_T^{H,\text{gen}}$ [GeV]</th>
<th>$p_T^{H,\text{reco}}$ [GeV]</th>
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<tbody>
<tr>
<td>[0,15]</td>
<td>[0,15]</td>
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<tr>
<td>[165,∞]</td>
<td>[165,∞]</td>
</tr>
</tbody>
</table>

- Folding matrix
- Unfolding matrix

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Higgs width distributions

CMS

19.4 fb^{-1} (8 TeV)

Data
SM off-shell 30 x \Gamma_{SM}^{
u}
On-shell
V_{\gamma}^{(*)}
W+jets

WZ+ZZ+VVV
Top
DY+jets
ggWW
WW

Bkg uncertainty

m_H = 125.6 GeV

Data / MC

0
0.5
1
1.5

MVA discriminant

-1
-0.5
0
0.5
1

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2015 analysis strategy

H → WW
# jets

0 jet H → WW

1 jet H → WW

eμ, μe, Top 0 jet, DY 0 jet

eμ, μe, Top 1 jet, DY 1 jet

- Signal phase space
- Phase space to normalize the backgrounds