Higgs-related SM Measurements at ATLAS

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April 19, 2012
Outline

- Introduction
- Isolated $\gamma\gamma$ cross section (37 pb$^{-1}$, Phys. Rev. D 85, 012003 (2012))
- $WW \rightarrow l\nu l\nu$ cross section measurement (4.7 fb$^{-1}$, ATLAS-CONF-2012-025)
- $ZZ \rightarrow llll$ cross section measurement (4.7 fb$^{-1}$, ATLAS-CONF-2012-026)
- $ZZ \rightarrow ll\nu\nu$ cross section measurement (4.7 fb$^{-1}$, ATLAS-CONF-2012-027)
- Conclusions
Introduction

- Importance of Higgs-related SM Measurements:
  - Precise measurements of inclusive and differential cross sections
  - Validation of SM predictions
  - Constraints on anomalous triple gauge couplings
  - Major backgrounds for SM Higgs and other new physics searches
  - Important for measurements of Higgs properties if it does exist
The ATLAS Detector
Prompt $\gamma\gamma$ Production at Hadron Colliders

- Prompt $\gamma\gamma$ production at hadron collider via QCD interactions:
  - $gg$ scattering: despite $O(\alpha_s^2)$ suppression relative to $qq\bar{q}$ process, the large gluon luminosity can make this contribution sizable in particular kinematic regions
  - Several sources of enhancement corrections: ISR, FSR, other possible small-$x$ logs (resummation)
  - Fragmentation contributions can be suppressed via experimental photon isolation requirement and $p_T(\gamma\gamma)<M(\gamma\gamma)$

- "Direct" photon
- Single photon fragmentation

- Double photon fragmentation (not included in any theoretical predictions)
  - Low mass and small angle $\gamma\gamma$ pairs
$\gamma\gamma$: Theoretical Predictions

- **PYTHIA**
  - $qq \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$ matrix elements
  - All orders resummation to LL accuracy via parton shower
  - No fragmentation contributions included

- **DIPHOX**
  - Fixed-order NLO calculation (except for $gg \rightarrow \gamma\gamma$ which is at LO)
  - No resummation: usually avoid divergence by requiring asymmetric cut $p_T(\gamma_1) - p_T(\gamma_2) > 0$
  - Single-photon fragmentation (to NLO) included

- **RESBOS**
  - All-order resummation (to NNLL accuracy) matched to NLO
  - Single photon fragmentation included via parameterization that approximates rate predicted by NLO fragmentation functions
  - Partonic isolation applied
  - PYTHIA/DIPHOX/RESBOS predictions need to be corrected for non-perturbative effects: underlying event and hadronization
\( \gamma \gamma \): Photon Identification

- Seeded by a cluster in the EM calorimeter
  - Unconverted \( \gamma \): no tracks pointing to the cluster
  - Converted \( \gamma \): one or two tracks associated to the cluster
- Cut on \( f_{EM} \), narrow shower width, no second significant maximum in the 1\(^{st}\) ECAL layer (high granularity strips in \( \eta \)), shower shape in the 2\(^{nd}\) ECAL layer
- Reconstruction efficiency: 80-85\% (barrel) and 70\% (endcap)
- Photon isolation: \( E_T^{(iso)} < 3 \) GeV within cone \( R < 0.4 \)
- \( E_T^{(iso)} \) is used to estimate the contribution from jet background

Use electron isolation to predict photon isolation

ATLAS Simulation

- (a) background extraction
- (b) non-TIGHT normalization
- (c) signal extraction

\( E_T^{(iso)} > 7 \) GeV for normalization

Signal vs jet-like photon subtraction

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\( \gamma\gamma: \) Subtracting Backgrounds

- 4x4 matrix method: classify events into 4 categories (PP/PF/FP/FF) using photon isolation cut \((E_T^{\text{iso}})<3 \text{ GeV}\) and construct an efficiency matrix \(E\) (\(\varepsilon: 80-95\%, f: 20-40\%\))

- 2D isolation template fits \([E_T^{\text{iso}1} \text{ vs } E_T^{\text{iso}2}]\): isolation templates for \(\gamma\gamma\), \(\gamma j\) and \(jj\) events are built from data (using electron extrapolations and non-tight control sample)

- 2D sideband method for the case of two photon candidates: for events with the leading candidate in A region, a second 2D matrix is used for the second candidate
$\gamma\gamma$: Extracting the Signal Yield

- 2022 diphoton events selected with $p_T > 16$ GeV within fiducial region, tight photon quality and isolated ($E_T^{\text{iso}} < 3$ GeV)
- All three background estimation methods agree fairly well with comparable systematic uncertainty ($\sim 15\%$)
- Electron background subtracted using $N(Z\rightarrow ee) \times f(e\rightarrow \gamma)$
**γγ: Data/Theory Comparison**

- **Single differential cross section:**
  \[
  \frac{d\sigma}{dX} = \frac{N - N_{bkg}}{\varepsilon \cdot A \cdot L \cdot \Delta}
  \]
  \[X = M_{\gamma\gamma}, p_T^{\gamma\gamma}, \Delta \phi_{\gamma\gamma}\]

- Some disagreement especially in the low \(\Delta \phi\) region and \(\Delta \phi \sim \pi\) (missing double photon fragmentation?)

- Qualitatively compatible with measurements from D0, CDF and CMS

- Double differential cross section measurements with larger dataset will be useful
**SM WW Cross Section Measurement**

- Irreducible background to the Higgs search in $H \rightarrow WW \rightarrow l\nu l\nu$

\[ \begin{align*}
\text{NLO prediction: } & \sigma(pp \rightarrow WW) = 45.1 \pm 2.8 \text{ pb} \\
\text{Two high } p_T \text{ leptons (e, } \mu) \text{ with large MET} \\
\text{Sequential decays to electrons or muons via tau leptons are included as signals} \\
\text{Dominant backgrounds: Z+jets, top and W+jets} \\
\text{Cross section is measured as (fiducial vs total cross sections):} \\
\sigma(pp \rightarrow W^+W^-) &= \frac{N_{\text{data}} - N_{\text{bg}}}{A_{WW} \times C_{WW} \times \mathcal{L} \times BR} 
\end{align*} \]
**WW → lνlν Event Selection**

- **WW → lνlν**: two high p\(T\) leptons and large MET
  - Electrons: isolated, shower shape, inner track matched with p\(T\)>20 GeV
  - Muons: isolated, combined muon and inner detector track with p\(T\)>20 GeV (|\(\eta\)|<2.4)
  - Leading lepton with p\(T\)>25 GeV
  - Dilepton invariant mass cut: |\(M_{ll}-M_Z\)|>15 GeV for ee and \(\mu\mu\)
  - MET\(^{rel}\) cut
  - No jets with p\(T\)>25 GeV and |\(\eta\)|<4.5
  - Reject events with at least one b-jet with p\(T\)>20 GeV

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![Graphs showing event selection criteria](image-url)
**WW \rightarrow l\nu\nu** Event Selection

- **MET\text{rel}** is defined as
  \[ E_\text{T, rel} = \begin{cases} 
  E_\text{T} & \text{if } \Delta\phi < \pi/2 \\
  E_\text{T} \times \sin(\Delta\phi) & \text{if } \Delta\phi \geq \pi/2 
  \end{cases} \]

- **MET\text{rel}** > 50 GeV for ee, 55 GeV for \(\mu\mu\) and 25 GeV for e\(\mu\)

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**WW → ℓνℓν Cut Flow**

<table>
<thead>
<tr>
<th>Selections</th>
<th>ee + $E_T^{\text{miss}}$</th>
<th>$μμ + E_T^{\text{miss}}$</th>
<th>$eμ + E_T^{\text{miss}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 leptons (SS+OS)</td>
<td>1049296</td>
<td>1823285</td>
<td>21549</td>
</tr>
<tr>
<td>2 leptons (OS)</td>
<td>1043310</td>
<td>1822980</td>
<td>20677</td>
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<tr>
<td>leading lepton $p_T &gt; 25$ GeV</td>
<td>1025363</td>
<td>1773911</td>
<td>15618</td>
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<td>trigger matching</td>
<td>1024912</td>
<td>1763886</td>
<td>15579</td>
</tr>
<tr>
<td>$m_{ℓ\ell'} &gt; 15/15/10$ GeV</td>
<td>1021200</td>
<td>1753923</td>
<td>15563</td>
</tr>
<tr>
<td>$Z$ mass veto</td>
<td>95889</td>
<td>178777</td>
<td>15563</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ Rel cut</td>
<td>1303</td>
<td>1784</td>
<td>6653</td>
</tr>
<tr>
<td>Jet veto (No. of jet=0)</td>
<td>254</td>
<td>357</td>
<td>1265</td>
</tr>
<tr>
<td>b-jet veto</td>
<td>229</td>
<td>325</td>
<td>1176</td>
</tr>
<tr>
<td>sub-leading lepton $p_T &gt; 20$ GeV</td>
<td>196</td>
<td>287</td>
<td>1041</td>
</tr>
</tbody>
</table>

1524 candidates observed for 4.7 fb$^{-1}$ of data
Electron efficiency: 64-78%
Muon efficiency: 93%
**WW → lνlν Signal Estimation**

- **WW → lνlν** generated with **MC@NLO (gg2WW)** with **HERWIG** for parton shower and **JIMMY** for underlying event simulation
- Mean number of interactions per event in MC is reweighted to reproduce that observed in data
- Corrections for lepton identification efficiencies, energy/momentum scale and resolution, MET resolution applied
- Corrections for jet-veto efficiency: 
  \[ f_Z = \frac{\varepsilon_{Z\text{ data}}}{\varepsilon_{Z\text{ mc}}} = 0.953 \pm 0.048 \] 
determined from Z events

<table>
<thead>
<tr>
<th>Sources</th>
<th>$e^+e^-E_T^{\text{miss}}$</th>
<th>$\mu^+\mu^-E_T^{\text{miss}}$</th>
<th>$e^+\mu^-E_T^{\text{miss}}$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{WW}$ uncertainties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>1.4%</td>
<td>1.4%</td>
<td>1.4%</td>
<td>1.2%</td>
</tr>
<tr>
<td>Scale ($\mu_R$, $\mu_F$)</td>
<td>2.1%</td>
<td>1.6%</td>
<td>1.7%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Jet Veto (MC modeling)</td>
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<td>5.0%</td>
<td>5.0%</td>
<td>5.0%</td>
</tr>
<tr>
<td>$C_{WW}$ uncertainties</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>0.3%</td>
<td>0.6%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electron Scale</td>
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<td>0.0%</td>
<td>0.3%</td>
<td>0.3%</td>
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<tr>
<td>Electron Resolution</td>
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<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Muon Scale</td>
<td>0.0%</td>
<td>0.9%</td>
<td>0.2%</td>
<td>0.3%</td>
</tr>
<tr>
<td>ID Muon Resolution</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>MS Muon Resolution</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>0.0%</td>
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<td>Electron Reconstruction</td>
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<td>0.0%</td>
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<tr>
<td>Electron ID</td>
<td>2.3%</td>
<td>0.0%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Muon ID</td>
<td>0.0%</td>
<td>0.7%</td>
<td>0.4%</td>
<td>0.4%</td>
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<tr>
<td>Lepton Isolation</td>
<td>4.0%</td>
<td>2.3%</td>
<td>2.3%</td>
<td>2.3%</td>
</tr>
<tr>
<td>B Tagging</td>
<td>0.4%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ Pile-Up</td>
<td>2.5%</td>
<td>2.8%</td>
<td>0.7%</td>
<td>1.2%</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ Cluster</td>
<td>1.8%</td>
<td>1.8%</td>
<td>0.5%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Jet Energy Scale &amp; Resolution</td>
<td>3.2%</td>
<td>3.2%</td>
<td>1.9%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Total Acceptance uncertainty</td>
<td>8.7%</td>
<td>7.5%</td>
<td>6.4%</td>
<td>6.7%</td>
</tr>
</tbody>
</table>
**WW → lνlν Background Estimation**

- **W+jets**: scale the W+jet control sample (one fully identified lepton + a jet-rich lepton) by a measured fake factor, cross checked with same-sign dilepton events enhanced in W+jets.

- **Z+jets**: shape determined from MC simulation, for ee and μμ channels, the normalization is corrected with a scale factor derived from the MET_{rel} tail distributions in data and MC with |M_{ll}-M_{Z}|<15 GeV.

- **Top**: Using the number of observed top events in the N-jet bins (N≥2):

\[
N_{\text{top}}^{\text{zero-jet}}(\text{estimate}) = N_{\text{MC top}}^{\text{zero-jet}} \times \left( \frac{N_{\text{data}}^{\geq 2-jets}}{N_{\text{MC top}}^{\geq 2-jets}} \right)
\]
WW → lνlν Cross Section Measurement

- **Fiducial cross section**: same cuts as used for event selection except using $p_T^{\nu\nu}$ and jets reconstructed at the generator level

- **Total cross section** (-0.3σ for ee, +1.4σ for $\mu\mu$, +1.5σ for $e\mu$): $\sigma(WW) = 45.1\pm2.8$ pb

- 2.9, 5.4 and 19.6 Higgs events expected for $m_H=125$ GeV

<table>
<thead>
<tr>
<th>Final State</th>
<th>$e^+e^-E_T^{miss}$</th>
<th>$\mu^+\mu^-E_T^{miss}$</th>
<th>$e^+\mu^-E_T^{miss}$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Events</td>
<td>196</td>
<td>287</td>
<td>1041</td>
<td>1524</td>
</tr>
<tr>
<td>Total expected events (S+B)</td>
<td>202.9±7.2±15.3</td>
<td>250.1±7.4±15.9</td>
<td>916.9±10.0±68.9</td>
<td>1370.1±14.3±96.5</td>
</tr>
<tr>
<td>MC WW Signal</td>
<td>88.5±1.3±10.1</td>
<td>137.0±1.6±14.4</td>
<td>613.6±3.6±59.8</td>
<td>839.0±4.2±83.3</td>
</tr>
</tbody>
</table>

- **Background estimations**
  - Top (data-driven): 14.0±2.0±2.9
  - W+jets (data-driven): 19.8±0.5±10.5
  - Drell-Yan (MC/data-driven): 72.0±6.7±3.2
  - Other dibosons (MC): 8.6±1.2±1.9
  - Total background: 114.4±7.1±11.5

- **Significance (S/√B)**: 8.3, 12.9, 35.2, 36.4

- **Expected events**
  - $e^+e^-$: 44.9±3.7 (fb)
  - $\mu^+\mu^-$: 38.0±3.1 (fb)
  - $e^+\mu^-$: 237.4±19.4 (fb)

- **Measured events**
  - $e^+e^-$: 41.4 (fb)
  - $\mu^+\mu^-$: 48.2 (fb)
  - $e^+\mu^-$: 284.9 (fb)

- **Uncertainties**
  - $\Delta\sigma_{stat}$: ±6.5, ±4.6, ±12.7
  - $\Delta\sigma_{syst}$: ±5.7, ±3.8, ±14.1
  - $\Delta\sigma_{lumi}$: ±1.6, ±1.9, ±11.1

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SM ZZ Cross Section Measurements

- Irreducible backgrounds to the $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow ZZ \rightarrow ll\nu\nu$ searches
- Mainly produced through $q\bar{q}$ annihilation, $\sim 6\%$ contribution from gluon fusion
- Study $ZZZ$ and $ZZ\gamma$ neutral TGCs

- $\sigma_{NLO}(pp \rightarrow ZZ) = 6.5^{+0.3}_{-0.2}$ pb (MCFM with MSTW2008 NLO PDF)
- Production cross section $\sim 5$ times larger than at the Tevatron
- Results from two decay channels presented here: 4l and ll\nu\nu
  - 4l: 0.5\% of the total ZZ cross section, clean detector signature
  - ll\nu\nu: has six times higher cross section but larger backgrounds

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ZZ → 4l Event Selection

- ZZ → 4l: two pairs of opposite-sign dilepton (e⁺e⁻e⁺e⁻, μ⁺μ⁻μ⁺μ⁻, e⁺e⁻μ⁺μ⁻)
  - Electrons: isolated, shower shape, inner track matched with \( p_T > 7 \) GeV and \( |\eta| < 2.47 \)
  - Muons: isolated, combined muon and inner detector track with \( p_T > 7 \) GeV (\( |\eta| < 2.5 \)) or muon track with \( p_T > 10 \) GeV (\( 2.5 < |\eta| < 2.7 \))
  - At least one lepton with \( p_T > 20 \) (25) GeV for a muon (electron)
  - Two Z candidates with \( 66 < m_{ll} < 116 \) GeV (for e⁺e⁻e⁺e⁻ and μ⁺μ⁻μ⁺μ⁻, use the pairs which results in the smaller value of the sum of the two \(|m_{ll}-m_Z|\) values)

![Expected Background in signal region: 0.7 ± 1.3 (stat) ± 1.3 (syst) Total Expected Background: 12.3 ± 3.8 (stat) ± 3.9 (syst)](image)
**ZZ → 4l Signal and Backgrounds**

- **Signal**: LO SHERPA generator used with CTEQ66 PDF
  - Interference terms between the Z and γ* also included \((m_{Z/\gamma^*}>7\text{GeV})\)
  - Normalized to the NLO calculation using MCFM with MSTW2008 NLO PDF

- Reconstruction correction factor from data to the ZZ fiducial phase space:
  - \(0.46 \pm 0.02 \pm 0.04\) (4e), \(0.81 \pm 0.02 \pm 0.02\) (eμ), \(0.60 \pm 0.01 \pm 0.02\) (2e2μ)

- Dominant systematics arise from \(\varepsilon_e\) (5.8% for 4e and 2.8% for 2e2μ) and \(\varepsilon_\mu\) (1.3% for 4μ and 0.6% for 2e2μ)

- **Background**: W/Z+jets, WW and WZ: one or two jets misidentified as isolated leptons

- Define lepton-like jets: fail isolation or \(d_0\) significance requirement (muon), fail isolation or identification requirement (electron)

- Fake factor for jets: \(f = \varepsilon_{\text{lepton}}/\varepsilon_{\text{lepton-like jet}}\)

\[
N(\text{background}) = N(\ell\ell\ell j) \times f - N(\ell\ell jj) \times f^2 - N(\text{ZZ in control sample})
\]
ZZ → 4l: Data/MC Comparison

All cuts applied except $M_{ll}$ cut

Estimated Background:
12.3 ± 3.8 (stat) ± 3.9 (syst)

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All cuts applied

Estimated Background:
0.7 $^{+1.3}_{-0.7}$ (stat) $^{+1.3}_{-0.7}$ (syst)
Number of observed and expected ZZ candidates:

<table>
<thead>
<tr>
<th>Final state</th>
<th>eee</th>
<th>μμμ</th>
<th>eeeμμ</th>
<th>combined (lℓlℓl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>15</td>
<td>21</td>
<td>26</td>
<td>62</td>
</tr>
<tr>
<td>Signal(MC)</td>
<td>9.9 ± 0.5 ± 0.8</td>
<td>16.6 ± 0.6 ± 0.3</td>
<td>26.8 ± 0.8 ± 1.0</td>
<td>53.2 ± 1.1 ± 1.9</td>
</tr>
<tr>
<td>Bkg(d.d.)</td>
<td>0.6^{+0.7+0.8}_{-0.6-0.6}</td>
<td>&lt; 0.3^{+0.5}_{-0.2}</td>
<td>0.3^{+0.9+0.8}_{-0.3-0.3}</td>
<td>0.7^{+1.3+1.3}_{-0.7-0.7}</td>
</tr>
<tr>
<td>Bkg(MC)</td>
<td>0.3 ± 0.3</td>
<td>&lt; 0.8</td>
<td>0.6 ± 0.6</td>
<td>1.0 ± 0.6</td>
</tr>
</tbody>
</table>

A maximum likelihood method is applied to extract the ZZ cross section from these three channels ($l = e, \mu$)

$$\sigma_{ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-}^{\text{fid}} = 21.2^{+3.2}_{-2.7}\text{ (stat)} +^{1.0}_{-0.9}\text{ (syst)} \pm 0.8\text{ (lumi)} \text{ fb}$$

17% overall uncertainty

Consistent with the SM prediction of 19±1 fb

Numbers from three individual channels:

- $4e$: $6.6^{+2.0}_{-1.6}\text{ (stat)} ^{+0.8}_{-0.5}\text{ (syst)} ^{+0.3}_{-0.2}\text{ (lumi)} \text{ fb}$
- $4\mu$: $5.5^{+1.3}_{-1.1}\text{ (stat)} ^{+0.2}_{-0.1}\text{ (syst)} ^{+0.3}_{-0.2}\text{ (lumi)} \text{ fb}$
- $2e2\mu$: $9.1^{+2.1}_{-1.7}\text{ (stat)} ^{+0.5}_{-0.4}\text{ (syst)} ^{+0.4}_{-0.3}\text{ (lumi)} \text{ fb}$

Total on-shell ZZ cross section:

$$\sigma_{ZZ}^{\text{tot}} = 7.2^{+1.1}_{-0.9}\text{ (stat)} ^{+0.4}_{-0.3}\text{ (syst)} \pm 0.3\text{ (lumi)} \text{ pb}$$
ZZ → llνν Event Selection

- ZZ → llνν: two oppositely-charged high p_T electrons or muons
- Isolated in both calorimeter and tracker: reduce QCD multijet
- Dilepton invariant mass |m_{ll}-m_Z| < 15 GeV: reduce W+jets, top and WW
- MET^axial > 80 GeV (MET projected to the Z p_T direction): reduce Z+jets
- Zero jets with p_T>25 GeV reconstructed: reduce top and Z+jets
- Fractional p_T difference |MET-p_T^Z|/p_T^Z<0.6: reduce WW

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ZZ → llνν Signal Estimation

- NLO generator MC@NLO with CT10 PDF used
- ZZ bosons are treated as on-shell with zero width
- Production due to gg initial states is not included (MC@NLO predictions scaled up by 6.3%)
- Cut flow table for both channels:

<table>
<thead>
<tr>
<th>Channels</th>
<th>eeνν</th>
<th>μμνν</th>
<th>ℓℓνν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two leptons</td>
<td>140.5 ± 1.5</td>
<td>179.6 ± 1.6</td>
<td>320.1 ± 2.2</td>
</tr>
<tr>
<td>Z mass</td>
<td>138.4 ± 1.5</td>
<td>167.3 ± 1.6</td>
<td>305.7 ± 2.2</td>
</tr>
<tr>
<td>Axial $E_T^{\text{miss}}$</td>
<td>29.4 ± 0.6</td>
<td>35.4 ± 0.7</td>
<td>64.8 ± 0.9</td>
</tr>
<tr>
<td>Jet veto</td>
<td>19.8 ± 0.5</td>
<td>24.0 ± 0.6</td>
<td>43.8 ± 0.8</td>
</tr>
<tr>
<td>Frac. $p_T$ diff.</td>
<td>19.3 ± 0.5 ± 1.2</td>
<td>23.0 ± 0.6 ± 0.9</td>
<td>42.3 ± 0.8 ± 1.8</td>
</tr>
</tbody>
</table>
**ZZ → llνν Background Estimation**

- **MC-based estimation:** WZ (two real leptons and large MET) and Wγ

- **Data-driven estimation:** top, WW, Z → ττ, W+jets and Z+jets
  - Top, WW, Z → ττ: using opposite-sign eμ events with |m_{eμ} - m_Z| < 15 GeV with corrections for electron and muon acceptance and identification applied
  - Z+jets: estimated from γ+jets events with γ p_T reweighted to Z p_T
  - W+jets: 4×4 matrix method using tight and loose leptons

<table>
<thead>
<tr>
<th>Final State</th>
<th>e⁺e⁻νν</th>
<th>μ⁺μ⁻νν</th>
<th>ℓ⁺ℓ⁻νν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>33</td>
<td>45</td>
<td>78</td>
</tr>
<tr>
<td>Expected ZZ</td>
<td>19.3 ± 0.5 ± 1.2</td>
<td>23.0 ± 0.6 ± 0.9</td>
<td>42.3 ± 0.8 ± 1.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background estimations:</th>
<th>e⁺e⁻νν</th>
<th>μ⁺μ⁻νν</th>
<th>ℓ⁺ℓ⁻νν</th>
</tr>
</thead>
<tbody>
<tr>
<td>W^± Z (MC)</td>
<td>9.4 ± 0.5 ± 1.5</td>
<td>13.3 ± 0.6 ± 2.1</td>
<td>22.7 ± 0.8 ± 3.5</td>
</tr>
<tr>
<td>W^±+ν (MC)</td>
<td>0.20 ± 0.10 ± 0.01</td>
<td>0.09 ± 0.06 ± 0.01</td>
<td>0.29 ± 0.12 ± 0.01</td>
</tr>
<tr>
<td>t̅, W^± t, W±W⁻ and Z → ττ (data-driven)</td>
<td>6.5 ± 1.8 ± 0.3</td>
<td>8.2 ± 2.3 ± 0.3</td>
<td>14.7 ± 4.1 ± 0.6</td>
</tr>
<tr>
<td>Z+jets (data-driven)</td>
<td>0.8 ± 0.4 ± 0.4</td>
<td>0.9 ± 0.3 ± 0.4</td>
<td>1.7 ± 0.5 ± 0.8</td>
</tr>
<tr>
<td>W^±+jets (data-driven)</td>
<td>1.1 ± 0.4 ± 0.3</td>
<td>0.2 ± 0.1 ± 0.1</td>
<td>1.3 ± 0.4 ± 0.3</td>
</tr>
<tr>
<td>Total Background</td>
<td>18.0 ± 2.0 ± 1.6</td>
<td>22.7 ± 2.4 ± 2.1</td>
<td>40.7 ± 4.3 ± 3.7</td>
</tr>
</tbody>
</table>
Data and MC Comparison

All cuts applied except $M_{ll}$

All cuts applied except $E_T^{miss}$ axial

All cuts applied except $N_{jet}$

All cuts applied
Cross Section Measurement

- Fiducial region: same cuts as used for event selection except using $p_T^{\nu\nu}$ and jets reconstructed at the generator level
  \[
  \sigma_{ZZ \rightarrow \ell^+\ell^-\nu\nu}^{\text{fid}} = 12.2^{+3.0}_{-2.8} \text{(stat.)} \pm 1.9 \text{(syst.)} \pm 0.5 \text{(lumi.)} \text{ fb}
  \]

- Fiducial acceptance: 0.084 ± 0.013 (uncertainties include PDF, QCD scale, acceptance difference between $gg \rightarrow ZZ$[gg2zz] and $qqbar \rightarrow ZZ$[MC@NLO])
  \[
  \sigma_{ZZ}^{\text{tot}} = 5.4^{+1.3}_{-1.2} \text{(stat.)}^{+1.4}_{-1.0} \text{(syst.)} \pm 0.2 \text{(lumi.)} \text{ pb}
  \]

- Consistent with the SM NLO prediction using MC@NLO
Conclusions

- Good agreement between data and SM expectation for $\gamma\gamma$, $WW$ and $ZZ$ cross section measurements
- Experimental precision will start to challenge theory calculations soon
- After a Higgs-like particle is discovered, it is important to understand these irreducible SM backgrounds in order to measure the Higgs boson properties

$\sigma_{\text{total}}$ with $m_H=130$ GeV

$\int L \, dt = 0.035 - 4.7 \, fb^{-1}$

$\sqrt{s} = 7$ TeV

$\sim \sigma(H \rightarrow WW)$ with $m_H=130$ GeV