H→WW and the Discovery of the Higgs Boson at ATLAS

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Introduction

Projects on ATLAS

Basic Tracking / Commissioning with Cosmic-Rays
TRT Performance
Inner Detector Alignment (TRT)
Electron Identification
   Designing HLT Trigger / Offline Electron Definitions
Electron Efficiency
Multivariate Electron Identification

Physics on ATLAS

W/Z Cross section (300/nb, 35/pb)
WW Cross section (35/pb, 1/fb)
Search for H→WW
   W+jet Background
Observation of Higgs.
Outline

The Higgs: Introduction/Motivation

Why $H \rightarrow WW$.

$H \rightarrow WW \rightarrow l\nu l\nu$ ($WW \rightarrow l\nu l\nu$)

Results in broader context
Standard Model and the Higgs

- Simple/Accurate description elementary particles and their interactions

Matter Particles

\[
\begin{pmatrix}
\nu_e \\
e
\end{pmatrix}
\begin{pmatrix}
\nu_\mu \\
\mu
\end{pmatrix}
\begin{pmatrix}
\nu_\tau \\
\tau
\end{pmatrix}
\begin{pmatrix}
u \\\d
\end{pmatrix}
\begin{pmatrix}
c \\\s
\end{pmatrix}
\begin{pmatrix}
t \\\b
\end{pmatrix}
\]

- Quantum Field Theory. \textbf{Gauge Invariance} \( SU(3) \times SU(2) \times U(1) \)
Standard Model and the Higgs

- Simple/Accurate description elementary particles and their interactions

**Matter Particles**

\[
\begin{pmatrix}
(\nu_e) \\
(e) \\
(\nu_\mu) \\
(\mu) \\
(\nu_\tau) \\
(\tau) \\
(u) \\
(d) \\
(c) \\
(s) \\
(b) \\
(t)
\end{pmatrix}
\]

- Quantum Field Theory. **Gauge Invariance** \( SU(3) \times SU(2) \times U(1) \)

**Gauge Bosons**

\( g \quad W \quad Z \quad \gamma \)

- Consistent theory strong, weak, and electromagnetic forces.
- **Gauge Invariance** implies massless Matter Particles and Gauge Bosons
Standard Model and the Higgs

- Simple/Accurate description elementary particles and their interactions

**Matter Particles**

\[
\begin{pmatrix}
  v_e \\
  e \\
  v_\mu \\
  \mu \\
  v_\tau \\
  \tau \\
  u \\
  d \\
  c \\
  t \\
  s \\
  b
\end{pmatrix}
\]

- Quantum Field Theory. **Gauge Invariance** \(SU(3) \times SU(2) \times U(1)\)

**Gauge Bosons**

\[
g \quad W \quad Z \quad \gamma
\]

- Consistent theory strong, weak, and electromagnetic forces.
- **Gauge Invariance** implies massless Matter Particles and Gauge Bosons

**Higgs boson:**

“Spontaneously Symmetry Breaking”
Allows for Massive fermions, Massive Weak bosons and **Gauge Invariance**
Additional particle predicted by the theory.
Standard Model and the Higgs

- Simple/Accurate description elementary particles and their interactions

Matter Particles

\[
\begin{pmatrix}
    \nu_e \\
    e \\
    \nu_\mu \\
    \mu \\
    \nu_\tau \\
    \tau \\
    \nu_e \\
    e \\
    \nu_\mu \\
    \mu \\
    \nu_\tau \\
    \tau \\
    u \\
    d \\
    c \\
    s \\
    t \\
    b
\end{pmatrix}
\]

- Quantum Field Theory. **Gauge Invariance** $SU(3) \times SU(2) \times U(1)$

Gauge Bosons

\[
g \hspace{2cm} W \hspace{2cm} Z \hspace{2cm} \gamma
\]

- Consistent theory strong, weak, and electromagnetic forces.
- **Gauge Invariance** implies massless **Matter Particles** and **Gauge Bosons**

**Higgs boson:**

“Spontaneous Symmetry Breaking”

Prior to LHC, only element of theory not directly confirmed by experiment.
Figure 1.1: The lowest-order $s$-channel Feynman diagrams for $e^+e^- \rightarrow f f$. For $e^+e^-$ final states, the photon and the Z boson can also be exchanged via the $t$-channel. The contribution of Higgs boson exchange diagrams is negligible.

Figure 1.2: The hadronic cross-section as a function of centre-of-mass energy. The solid line is the prediction of the SM, and the points are the experimental measurements. Also indicated are the energy ranges of various $e^+e^-$ accelerators. The cross-sections have been corrected for the effects of photon radiation.
Hadron Collisions

\[ \int L \, dt = 0.035 - 1.04 \text{fb}^{-1} \]
\[ \sqrt{s} = 7 \text{TeV} \]

- Theory
- Data 2010 (~35 fb^{-1})
- Data 2011

ATLAS Preliminary

- W
- Z
- W_γ
- Z_γ
- tt
- t
- WW
- WZ
- ZZ
Predicting the Mass of the Top Quark

![Graphical representation of the mass of the top quark](image)

- **t, b**
- **Z**
- **e^-, e^+**
- **W**
- **W**
- **Z**
- **Z**

**m_t [GeV]**

**m_W [GeV]**

**LEP1 and SLD**

**68% CL**

**July 2010**
Predicting the Mass of the Top Quark

- Discovered Top Quark
- Precise measurement of $m_t$
- Precise measurement of $m_W$

Validation of SM radiative corrections
Same Game for Higgs
Now use measured $m_t$ and $m_W$ as inputs

$\Delta \chi^2$ vs. $m_H$ [GeV]

Theory uncertainty
$\Delta \alpha_{\text{had}}^{(5)} = 0.02750 \pm 0.00033$
$0.02749 \pm 0.00010$
Incl. low $Q^2$ data

$\text{Excluded}$

$m_{\text{Limit}} = 161 \text{ GeV}$

July 2011
Same Game for Higgs

Now use measured $m_t$ and $m_W$ as inputs
Overall view of the LHC experiments.
The ATLAS Experiment

3. The ATLAS Experiment

Figure 3y1: Cutaway view of the ATLAS detector, designed to measure the energy of electrons, photons, and hadrons. They are sensitive to both charged and neutral particles.

The Muon Spectrometer surrounds the calorimeters. All particles except muons and neutrinos are stopped by the calorimeter system. The MS is designed to measure the trajectories of muons leaving the calorimeters. The MS is composed of muon chambers operating in a magnetic field provided by the toroidal magnets.

A common coordinate system is used throughout ATLAS. The interaction point is defined as the origin of the coordinate system. The z-axis runs along the beam line. The x-y plane is perpendicular to the beam line and is referred to as the transverse plane. The positive x-axis points from the interaction point to the center of the LHC ring; the positive y-axis points upward to the surface of the earth. The detector half at positive z-values is referred to as the "A" side, the other half the "C" side. The transverse plane is often described in terms of \( r \) and \( \phi \) coordinates. The azimuthal angle \( \phi \) is measured from the positive x-axis around the beam. The radial dimension \( r \) measures the distance from the beam line. The polar angle \( \theta \) is defined as the angle from the positive z-axis. The polar angle is often reported in terms of pseudorapidity \( \eta \) defined as

\[
\eta = -\ln \tan \frac{\theta}{2}
\]

The distance \( \Delta R \) is defined...
The Basic Outputs:

- Inner Detector Tracks
- Electro-Magnetic Clusters
- Hadronic Clusters
- Muon Tracks

A lot of work goes into making/understanding these basic outputs. Chapter 4-7
$\nu_e \quad \nu_\mu \quad \nu_\tau \quad u \quad c \quad t$

e  \quad \mu \quad \tau \quad d \quad s \quad b
$v_e$, $v_\mu$, $v_\tau$, $u$, $c$, $t$, $d$, $s$, $b$
\( \nu_e \) \( \nu_{\mu} \) \( \nu_{\tau} \)
\( \nu_e \quad \nu_\mu \quad \nu_\tau \)

\( e \quad \mu \quad \tau \)

\( u \quad c \quad t \)

\( d \quad s \quad b \)
\( (H \rightarrow WW) \)  \( (H \rightarrow \gamma\gamma) \)  \( (H \rightarrow ZZ) \)
3. Reconstruction and Commissioning

Figure 3.2: Event display of a $t \bar{t}$ di-lepton candidate in the $e\mu$-channel with two b-tagged jets. The electron is shown by the green track pointing to a calorimeter cluster, the muon by the long red track intersecting the muon chambers, and the $E_{\text{miss}}$ direction is indicated by the blue dotted line in the x-y view. The secondary vertices of the two b-tagged jets are indicated by the orange ellipses in the upper right.
Higgs at the LHC

$\sqrt{s} = 7$ TeV

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

Branching ratios

$M_H \ [\text{GeV}]$

$M_H \ [\text{GeV}]$
How to look for the Higgs.

**WW → ℓνℓν** has Strongest sensitivity over broad range of m(H)

Critical in the region between LEP and SM prediction

*Mediator of EWK symmetry breaking must couple to the W and Z*
Tools needed for lvlv final state have wide applicability.
- Lepton ID
  ...Tracking/ Electron ID / Trigger
- W+jets background (ubiquitous)
  ...Data Driven W+jet modeling
- MeT modeling.

Broad range of physics lvlv final state has wide applicability.
- Higgs Physics.
- SM measurements.
  ...SM WW cross section, 35/pb, 1/fb
- SUSY / Exotic extensions to the SM.
Finding the Haystack

Continuum Standard Model WW production major background.
Finding $WW \rightarrow l\nu l\nu$

**Backgrounds:**

**Drell-Yan:** (lepton pair + ‘fake’ MeT)
- Require Large Missing Energy
- Reject events consistent w/Z mass

**Top:** (WW produced w/2 b-jets)
- Jet Veto

**W+Jets:** (lepton w/MeT + ‘fake’ lepton)
- Isolation / lepton Identification

**Other Diboson:** (WZ, ZZ, Wγ)
- remove events w/ > 2 leptons.
Finding WW→lνlν

**Backgrounds:**

**Drell-Yan:** (lepton pair + ‘fake’ MeT)
- Require Large Missing Energy
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**Top:** (WW produced w/2 b-jets)
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- Isolation / lepton Identification

**Other Diboson:** (WZ, ZZ, Wγ)
- remove events w/ > 2 leptons.

### DY /Top Background
- Large, but reduced w/ Event Selection
- Well modeled by MC
- Can be corrected to Data.
Finding \( \text{WW} \rightarrow \ell \nu \ell \nu \)

**Backgrounds:**

**Drell-Yan:** (lepton pair + ‘fake’ MeT)
- Require Large Missing Energy
- Reject events consistent w/Z mass

**Top:** (WW produced w/2 b-jets)
- Jet Veto

**W+Jets:** (lepton w/MeT + ‘fake’ lepton)
- Isolation / lepton Identification

**Other Diboson:** (WZ, ZZ, W\( \gamma \))
- remove events w/ > 2 leptons.

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**ATLAS**

\[ \int dt = 1.02 \text{ fb}^{-1} \]

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

**W+Jet Background**

- Small, but not suppressed w/ Event Selection
- Difficult to model in MC
- Important at Low Pt.
Finding $WW \rightarrow l\nu l\nu$

**Backgrounds:**

**Drell-Yan:** (lepton pair + ‘fake’ MeT)
- Require Large Missing Energy
- Reject events consistent w/ Z mass

**Top:** (WW produced w/ 2 b-jets)
- Jet Veto

**W+Jets:** (lepton w/ MeT + ‘fake’ lepton)
- Isolation / lepton Identification

**Other Diboson:** (WZ, ZZ, Wγ)
- remove events w/ > 2 leptons.

**Diboson Background**
- Small, and suppressed w/ Event Selection
- Well modeled by MC.
Background Estimation

**Top**

**DY**

**W+jet**

\[
N_{\text{Bkg}}^{W+\text{Jet}} = \mathcal{f} \times N(\text{Lepton+Denm})
\]

Measured in a di-jet sample

A lot of work goes into making/understanding bkg. prediction. Chapter 9-11
SM WW Cross Section Measurement

\[ \sigma_{\text{total}} \ [\text{pb}] \]

\begin{align*}
\sigma_{\text{total}} & = 10^5 \\
10^4 & \quad 10^3 \\
10^2 & \quad 10 \\
\end{align*}

\begin{align*}
\text{ATLAS Preliminary} \\
\int L \, dt = 0.035 - 1.04 \, \text{fb}^{-1} \\
\sqrt{s} = 7 \, \text{TeV} \\
\text{Theory} \\
\text{Data 2010} \ (\sim 35 \, \text{pb}^{-1}) \\
\text{Data 2011} \\
\end{align*}

Chapter 10
SM WW Cross Section Measurement

\[ \sigma_{\text{total}} [\text{pb}] \]

\[ 10^5 \]

\[ 10^4 \]

\[ 10^3 \]

\[ 10^2 \]

\[ 10 \]

\[ W \]

\[ Z \]

\[ W\gamma \]

\[ Z\gamma \]

\[ t\bar{t} \]

\[ t \]

\[ WW \]

\[ WZ \]

\[ ZZ \]

**ATLAS** Preliminary

\[ \int L \, dt = 0.035 - 1.04 \, \text{fb}^{-1} \]

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

- **Theory**
- **Data 2010** (~35 pb\(^{-1}\))
- **Data 2011**

Chapter 10
Finding the Needle

**H→WW analysis**
- Basic WW Selection.
  (Dominated by SM WW)
- Small opening angle.
- Fit mT

**Exploit spin-0 nature of Higgs.**

**H→WW**

**SM WW**

---

### Mll

ATLAS Preliminary

- **Data**
- **SM (sys + stat)**
- **WW**
- **WZ/ZZ/WW**
- **t\bar{t}**
- **Single Top**
- **Z+jets**
- **W+jets (data driven)**
- **H [150 GeV]**

Events / 10 GeV

<table>
<thead>
<tr>
<th>Mll (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

---

### Δφll

ATLAS Preliminary

- **Data**
- **SM (sys + stat)**
- **WW**
- **WZ/ZZ/WW**
- **t\bar{t}**
- **Single Top**
- **Z+jets**
- **W+jets**
- **H [150]**

Events / 0.31 rad

<table>
<thead>
<tr>
<th>Δφll (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

---

### mT

ATLAS

- **Data**
- **SM (sys + stat)**
- **WW**
- **WZ/ZZ/WW**
- **t\bar{t}**
- **Single Top**
- **Z+jets**
- **W+jets**
- **H [125 GeV]**

Events / 10 GeV

<table>
<thead>
<tr>
<th>mT (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
</tr>
<tr>
<td>60</td>
</tr>
</tbody>
</table>
Results H→WW

2012 Results  (5.8/fb 8 TeV)

**ATLAS**

\[ \sqrt{s} = 8 \text{ TeV}, \int \mathcal{L} = 5.8 \text{ fb}^{-1} \]

H→WW\(^(*)\)→ννμν/μνν + 0 jets

**ATLAS**

H→WW\(^(*)\)→ννμν/μνν

Higgs boson search at the LHC

\[ \sqrt{s} = 8 \text{ TeV}, \int \mathcal{L} = 5.8 \text{ fb}^{-1} \]
Results $H \rightarrow WW$

Combined Results  \( (5.8/\text{fb} \ 8 \ \text{TeV} + 4.7/\text{fb} \ 7 \ \text{TeV}) \)

Background Subtracted
Figure 11.1: Event display of a selected event with four identified electrons.

Figure 11.5: Event display of a selected event with four identified electrons.

Figure 11.6: The distributions of the invariant mass of di-photon candidates after all selections for 7 TeV and 8 TeV data sets are also shown separately. In the combined analysis, the lowest observed background in the absence of signal is seen in the figure. The excess of data with respect to the background fit are displayed in panels marked (c) and (d). The result of a fit using a function of the test Higgs mass is shown in panel (a). The distribution weighted according to the event categories is shown in the lower figure marked (b) and (d). The inclusion of events over the predicted background is seen in the figure. The SM signal with a 126.5 GeV mass is shown in panel (c).

Events / 2 GeV

Σ weights - Bkg

100 110 120 130 140 150 160

m_{\gamma\gamma} [GeV]

Data S/B Weighted
Sig+Bkg Fit (m_h=126.5 GeV)
Bkg (4th order polynomial)

ATLAS

Int L = 5.9 fb^{-1}
Int L = 4.8 fb^{-1}
Int L = 5.9 fb^{-1}

Data
Background ZZ
Background Z+jets, tt
Signal (m_h=125 GeV)
Syst.Unc.

Events / 5 GeV

m_{4l} [GeV]

ATLAS

H→ZZ^{(*)}→4l

H→\gamma\gamma

Other Higgs Searches
ATLAS 2011 - 2012

Combined Results

$\sqrt{s} = 7$ TeV: $\int Ldt = 4.8$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int Ldt = 5.8$ fb$^{-1}$

$\sqrt{s} = 7$ TeV: $\int Ldt = 4.7$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int Ldt = 5.8 - 5.9$ fb$^{-1}$

$\sqrt{s} = 7$ TeV: $\int Ldt = 4.6 - 4.8$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int Ldt = 5.8 - 5.9$ fb$^{-1}$

$\sqrt{s} = 7$ TeV: $\int Ldt = 4.7$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int Ldt = 5.8$ fb$^{-1}$
$\sqrt{s} = 7$ TeV: $\int L dt = 4.7$–4.8 fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int L dt = 5.8$–5.9 fb$^{-1}$

**ATLAS**

$\sqrt{s} = 7$ TeV: $\int L dt = 4.7$–4.8 fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int L dt = 5.8$–5.9 fb$^{-1}$

**2011 – 2012**

+ Best fit
- 68% CL
- 95% CL

**SM Prediction**

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$
- $H \rightarrow WW^{(*)} \rightarrow lvlv$
**ATLAS 2011 - 2012**

**W, Z, H \rightarrow bb**
\( \sqrt{s} = 7 \) TeV: \( \int L dt = 4.7 \) fb\(^{-1}\)

**H \rightarrow \tau \tau**
\( \sqrt{s} = 7 \) TeV: \( \int L dt = 4.6-4.7 \) fb\(^{-1}\)

**H \rightarrow WW^{(*)} \rightarrow l\ell l\ell**
\( \sqrt{s} = 7 \) TeV: \( \int L dt = 4.7 \) fb\(^{-1}\)
\( \sqrt{s} = 8 \) TeV: \( \int L dt = 5.8 \) fb\(^{-1}\)

**H \rightarrow \gamma \gamma**
\( \sqrt{s} = 7 \) TeV: \( \int L dt = 4.8 \) fb\(^{-1}\)
\( \sqrt{s} = 8 \) TeV: \( \int L dt = 5.9 \) fb\(^{-1}\)

**H \rightarrow ZZ^{(*)} \rightarrow 4l**
\( \sqrt{s} = 7 \) TeV: \( \int L dt = 4.8 \) fb\(^{-1}\)
\( \sqrt{s} = 8 \) TeV: \( \int L dt = 5.8 \) fb\(^{-1}\)

**Combined**
\( \sqrt{s} = 7 \) TeV: \( \int L dt = 4.6 - 4.8 \) fb\(^{-1}\)
\( \sqrt{s} = 8 \) TeV: \( \int L dt = 5.8 - 5.9 \) fb\(^{-1}\)

**\( \mu = 1.4 \pm 0.3 \)**

**Signal strength (\( \mu \))**

**m\(_{H} \) [GeV]**

**SM Prediction**

**m\(_{H} = 126.0 \) GeV**
Physicists Find Elusive Particle Seen as Key to Universe
Problem with the Higgs Mass

Loop Corrections to Higgs Mass

\[ m_h^2 = m_h^0{}^2 - \Lambda^2 \]

The Standard Model is incomplete.
- GUT, Gravity ...

\[ \Lambda^2 \sim 10^{36} \text{ GeV}^2 \]

implausible cancelation from \( m_h^0{}^2 \)
Problem with the Higgs Mass

Loop Corrections to Higgs Mass

\[ m_h^2 = m_h^0^2 - \Lambda^2 \]

The Standard Model is incomplete.
- GUT, Gravity ...

Super Symmetry

\[ \mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}}, \quad m_{\text{soft}} \sim \text{TeV scale} \]

\[ \Delta m_H^2 = m_{\text{soft}}^2 \left[ \frac{\lambda}{16\pi^2} \ln(\Lambda_{\text{UV}}/m_{\text{soft}}) + \ldots \right] \]
Conclusions

“We are, I think, in the right road of improvement,
for we are making experiments.”
– Benjamin Franklin

It's a great time to be doing particle physics!
Supporting Material
$Z \rightarrow \mu \mu$ at LEP (Opal)
$Z \rightarrow \mu\mu$ at LEP (Opal)

$Z \rightarrow \mu\mu$ at the LHC (ATLAS)

“Pile-up”

~10 cm
Transverse Mass

\[ m_T = \sqrt{(E_{T}^{ll} + E_{T}^{miss})^2 - |\mathbf{p}_{T}^{ll} + \mathbf{p}_{T}^{miss}|^2}, \]

**Figure 7.15: Transverse mass distribution after WW Physics**

- **Diboson**
- **Top**
- **Z+jets**
- **Higgs**
- **W+jets (data driven)**

Transverse mass is a result of the increase of the mass distribution shift with a peak slightly below the corresponding value.

Selected events are also required to have small lepton opening angles, but the additional requirement removes some additional contributions. A significant fraction of the events has a lower transverse momentum than the leptons produced from SM processes, in which the angle between the leptons is smaller than for continuum SM processes.

The leptons emerge from the decay products by the parity-violating weak interaction, which governs the production of the Higgs boson. The Higgs boson is predicted to be a spin-0 particle.
Figure 1.16: Comparison of direct and indirect determinations of the mass of the top quark, $m_t$, as a function of time. The shaded area denotes the indirect determination of $m_t$ at 68% confidence level derived from the analysis of radiative corrections within the framework of the SM using precision electroweak measurements. The dots with error bars at 68% confidence level denote the direct measurements of $m_t$ performed by the Tevatron experiments CDF and DØ. Also shown is the 95% confidence level lower limit on $m_t$ from the direct searches before the discovery of the top quark. Predictions and measurements agree well.
Spontaneous Symmetry Breaking

Add scalar field that couple to $SU(2) \times U(1)$ gauge fields:

Lagrangian preserve symmetry, but the state that describe reality does not
Higgs in CMS

The other guys see it too.

**Figure 19:** Values of $\sigma_\text{SM}$ for individual modes; they include both statistical and systematic uncertainties.

**Figure 7:** Distribution of $m_\ell\ell$ for the combination and for individual decay modes. These results are consistent, within uncertainties, with the expectations for a SM Higgs boson.

**Table:** Observed number of events, background estimates and signal predictions for $H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$, $H\to \tau\tau$, and $H\to bb$ in the $m_\ell\ell$ channel.

**Figure 9:** The $\sigma/\sigma_\text{SM}$ contour plots for the signal strength in the $H\to\gamma\gamma + H\to ZZ$ category, with $m_\ell\ell$ distribution for $H\to WW$ and $m_X$ distribution for $H\to \tau\tau$.

**Conclusions:**

In this combination, the relative signal strengths for the three decay modes are constrained by systematic uncertainties on the production cross section times the relevant branching fractions, relative to the SM expectation. The observed excesses seen in the $H\to WW$ and $H\to \tau\tau$ channels are consistent with the expectations for a SM Higgs boson.
mT and mW

\[
\begin{align*}
\text{CDF I} & \quad 80433 \pm 79 \\
\text{D0 I} & \quad 80483 \pm 84 \\
\text{DELPHI} & \quad 80336 \pm 67 \\
\text{L3} & \quad 80270 \pm 55 \\
\text{OPAL} & \quad 80416 \pm 53 \\
\text{ALEPH} & \quad 80440 \pm 51 \\
\text{D0 II} & \quad 80401 \pm 43 \\
\text{World Average (2009)} & \quad 80399 \pm 23 \\
\text{CDF II (preliminary)} & \quad 80387 \pm 19
\end{align*}
\]

\[
\begin{align*}
\text{CDF II} \quad & 173.00 \pm 0.65 \pm 1.06 \text{ GeV} \\
\text{CDF II} \quad & 174.94 \pm 0.83 \pm 1.24 \text{ GeV} \\
\text{CDF II} \quad & 176.1 \pm 5.1 \pm 5.3 \text{ GeV} \\
\text{CDF II} \quad & 180.1 \pm 3.6 \pm 3.9 \text{ GeV} \\
\text{CDF II} \quad & 172.47 \pm 1.43 \pm 1.40 \text{ GeV} \\
\text{CDF II} \quad & 186.0 \pm 10.0 \pm 5.7 \text{ GeV} \\
\text{CDF II} \quad & 170.28 \pm 1.95 \pm 3.13 \text{ GeV} \\
\text{CDF II} \quad & 174.00 \pm 2.36 \pm 1.44 \text{ GeV} \\
\text{CDF II} \quad & 167.4 \pm 10.3 \pm 4.9 \text{ GeV} \\
\text{CDF II} \quad & 168.4 \pm 12.3 \pm 3.6 \text{ GeV} \\
\text{CDF II} \quad & 172.32 \pm 1.80 \pm 1.82 \text{ GeV} \\
\text{CDF II} \quad & 166.90 \pm 9.00 \pm 2.82 \text{ GeV} \\
\text{CDF II} \quad & 173.18 \pm 0.56 \pm 0.75 \text{ GeV} \\
\end{align*}
\]

\[
\chi^2 / \text{dof} = 8.3 / 11
\]
Figure 7.13: Schematic diagram illustrating the correlation in lepton direction resulting from the spin-zero nature of the Higgs and the parity violating weak decays of the $W$ bosons. Two Higgs decays, with different spin orientations of the $W$s, are shown. The solid red arrows indicate the direction of the decay products in the rest frame of the Higgs. The dashed black arrows indicate the direction of the spin component along the direction of the Higgs decay products.

Figure 7.14: Kinematic variables used to separate SM $WW$ production from $H \rightarrow WW$ ($^*$) production. The cut value used in the low mass Higgs search is indicated in the figure.
95% CL Limit on $\mu$

ATLAS 2011 - 2012

$\sqrt{s} = 7$ TeV: $Ldt = 4.6$-4.8 fb$^{-1}$

$\sqrt{s} = 8$ TeV: $Ldt = 5.8$-5.9 fb$^{-1}$

Local $p_0$

Observed

Bkg. Expected

Signal strength ($\lambda$)

Observed

$-2 \ln \lambda(\mu) < 1$
Combined Higgs Results

\( \int L \, dt = 4.6-4.8 \, fb^{-1}, \sqrt{s} = 7 \, TeV \quad \int L \, dt = 5.8-5.9 \, fb^{-1}, \sqrt{s} = 8 \, TeV \)

\( \sigma / \sigma_{SM} \)

95\% CL Limit on \( m_H \) for the individual search channels and their combination. The expected limits are those for the background-only hypothesis in the absence of a Higgs boson signal.

The dominant background arises from \( Z \) + jet production. The sensitivity is improved by adding a dedicated \( ll \) subchannel. The invariant mass of the \( llq\bar{q} \) system is used as the final discriminating variable.

The final analysis included in the combined Higgs result is \( H \rightarrow WW^*(\sim) \rightarrow l\nu_\ell \bar{\nu}_\ell q\bar{q} \). This analysis is performed for \( m_H \) from 100 to 600 GeV. The mass of the two selected jets are required to be consistent with a \( W \) boson. This mass constraint allows for an event-by-event estimate of the Higgs mass. The reconstructed Higgs mass is then used as the final discriminating variable.

To provide a feeling for the relative sensitivity of the various Higgs search hypotheses in the different mass ranges, Figure uuruw shows the expected limits of the individual channels as a function of \( m_H \). At the lowest masses the sensitivity is driven by the \( H \rightarrow \gamma\gamma \) analysis; the \( H \rightarrow \tau\tau \) and \( H \rightarrow b\bar{b} \) analyses provide additional sensitivity.

From uvy to vtt GeV, the sensitivity is driven by the \( H \rightarrow WW^*(\sim) \rightarrow l\nu_\ell \nu_\ell \) and \( H \rightarrow ZZ^*(\sim) \rightarrow ll\nu_\ell \nu_\ell \) analyses. Above vtt GeV, \( H \rightarrow ZZ^*(\sim) \rightarrow llll \) is the strongest channel. The \( H \rightarrow ZZ^*(\sim) \rightarrow ll\nu_\ell \nu_\ell \) and \( H \rightarrow WW^*(\sim) \rightarrow l\nu_\ell q\bar{q} \) analyses provide additional sensitivity at high mass.

The analyses introduced above are combined using a statistical procedure similar to that described in previous sections. Different values of \( \mu \) are tested with a statistic described in Chapter up based on the profile likelihood ratio \( \chi^2 \). The likelihood function includes all the parameters that describe...
Jet Measurements

\[ \int L \frac{d\sigma}{dt} = 17 \text{ nb}^{-1} \quad (\sqrt{s} = 7 \text{ TeV}) \]

\[ \frac{d^2\sigma}{dp_T^2 dy} \text{ [pb/GeV]} \]

**ATLAS**

- |y| < 2.8
- NLO pQCD (CTEQ 6.6) \times Non-pert. corr.
- Systematic Uncertainties
- anti-k_t jets, R=0.4

\[ \int L \frac{d\sigma}{dt} = 37 \text{ pb}^{-1} \quad (\sqrt{s} = 7 \text{ TeV}) \]

**ATLAS**

- |y| < 0.3 (\times 10^3)
- 0.3 < |y| < 0.8 (\times 10^3)
- 0.8 < |y| < 1.2 (\times 10^3)
- 1.2 < |y| < 2 (\times 10^3)
- 2 (\times 10^3) < |y| < 2.1 (\times 10^3)
- 2.1 (\times 10^3) < |y| < 2.8 (\times 10^3)
- 2.8 (\times 10^3) < |y| < 3.6 (\times 10^3)
- 3.6 (\times 10^3) < |y| < 4.4 (\times 10^3)

**ATLAS**

- Data
- NLOJET++ (CT10, \mu_R = p_T^{max}) \times Non-pert. corr.
- Systematic uncertainties
Finding the Needle

\[ \sqrt{s} = 7 \text{ TeV, } \int L \, dt = 2.05 \text{ fb}^{-1} \]

\[ H \rightarrow WW \rightarrow \mu \nu \mu \nu \]
The electron and muon efficiencies are less than 10% on the global scale including flavor composition.

The uncertainty on the jet energy scale is constrained by Gaussian terms that include the systematic uncertainty, except the signal yield. All other components are normalized to their expectations scaled by nuisance parameters.

The systematic uncertainties include contributions from theoretical uncertainties, which are \(-8\%\)/+12% and \(-3.7\%\) from the luminosity [28], and from the 3.7% uncertainty in the luminosity [28]. The uncertainties on the acceptance for one top decay to survive the jet veto are not explicitly modeled in the fit as they are for top [27]. A sample enriched in top background is defined for the corresponding backgrounds in the fit. Since these corrections are not accounted for in the fit, the control sample measurements for the top background in the fit are not used.

The cross section of each bin, calculated from the approximation, is included separately as an uncertainty on the uncertainty in the assignment of events to jet multiplicity are assessed as described in Ref. [29]. In particular, the cross section as a function of the Higgs boson mass, the total for the extrapolation to the signal region is estimated as the square of the efficiency for one top decay to survive the jet veto and the contamination in the corresponding control region for the signal region is done using a scale factor computed using MC to account for the presence of single leptons with an additional uncertainty of up to 7%.

The horizontal lines in the curves indicate the points where the selection cuts change, and the bands around the points indicate the regions of uncertainty. The vertical lines in the curves indicate the points expected to be significant for the signal.

The vertical band indicates the range of the expected uncertainties, and the horizontal band indicates the range of the observed uncertainties. The observed deviation from the expected background is 1.9, and the 95% CL upper bound is set on the Higgs boson cross section as a function of the Higgs boson mass.

The model cross section, as a function of the Higgs boson mass, is presented in this Letter, 145 events are observed with an observed deviation from the expected background of 1.9, and the 95% CL upper limit on the cross section, normalized to the Standard Model expectation, is set as a function of the Higgs boson mass.

The expected (dashed) and observed (solid) 95% CL upper limits on the cross section, normalized to the Standard Model expectation, are shown as a function of the Higgs boson mass. The ATLAS collaboration measured the cross section for the Higgs boson production with a mass of 125 GeV in the WW channel and observed a deviation from the expected background of 1.9. The 95% CL upper limit on the cross section, normalized to the Standard Model expectation, is set as a function of the Higgs boson mass.
Figure srosy: Observed and expected limits on the Higgs production cross section as a function of $m_H$. The left hand plot shows $m_H$ in the range 95–250 GeV, the right hand plot focuses on $m_H$ between 110 and 185 GeV. The curves show the 95% CL upper limit. The green and yellow regions indicate the ±1σ and ±2σ uncertainty bands on the expected limit.
**Motivation:**
- Dominant Background to $H \rightarrow WW$ search
- Test EWK model, Sensitive to **Triple Gauge Couplings**

**Signature:**
- Performed Fully Leptonic Decays.
- 2 Opposite-Sign Leptons ($e, \mu$)
- Large Missing Energy

\[ \sigma_{WW} = \frac{N - N_{Bk, g}}{\epsilon \times A \times L} \]
Drell-Yan Background

Background from DY if “fake” MeT
Observed momentum imbalance that is not due to the presence of neutrinos.

Causes of fake MeT not necessarily expected to be reproduced by MC.

Use Data Events in the Z peak:
Quantify modeling of MeT in DY Events with:

$$S(E_{T}^{\text{miss,Rel}}) = \frac{N_{\text{Data}} - N_{\text{MC}}}{N_{\text{DY}}}$$

Measurement:

<table>
<thead>
<tr>
<th>Channel</th>
<th>$S$</th>
<th>- Given Data/MC consistency do not correct prediction.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>0.06 ± 0.08</td>
<td>- $S$ to assign systematic.</td>
</tr>
<tr>
<td>mm</td>
<td>0.05 ± 0.10</td>
<td></td>
</tr>
</tbody>
</table>
Top Background

Background from Top from lost Jets

Use Top control region in data

\[ N^{Bkg}_{Top}(0\text{-jet}) = N^{Data-CR}_{Top} \times \frac{N^{MC}_{Top}(0\text{-jet})}{N^{MC-CR}_{Top}} \]

Reduce systematics by applying SF measured in Tag sample.

\[ N^{Bkg}_{Top}(0\text{-jet}) = N^{Data}_{Top} \times SF \times \frac{N^{MC}_{Top}(0\text{-jet})}{N^{MC}_{Top}} \]

SF - scale factor from tag sample

Leads to cancelation of some of the JES uncertainty in jet-veto.

~20 % systematic vs ~40 % without SF.
Fake Factor Method

\[ N_{W+Jet}^{Bkg} = f \times N_{(Lepton+Denm)} \]

1) Define Denominator Definition
2) Measure \( f \) and its uncertainty in di-jet control sample
3) Select (Lepton-Denm.) pairs passing the Event selection
4) Subtract non-W+jet contribution to (Lep-Denm) pairs, with MC
5) Scale by \( f \) to predict W+jet event yields / kinematics.
### WW Cross Section Results

<table>
<thead>
<tr>
<th>Background Process</th>
<th>$e\mu$-channel</th>
<th>$ee$-channel</th>
<th>$\mu\mu$-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY</td>
<td>$13.0 \pm 2.1 \pm 1.6$</td>
<td>$12.5 \pm 2.3 \pm 1.4$</td>
<td>$10.9 \pm 2.5 \pm 1.4$</td>
</tr>
<tr>
<td>Top</td>
<td>$11.9 \pm 1.8 \pm 2.4$</td>
<td>$3.1 \pm 0.5 \pm 0.6$</td>
<td>$3.8 \pm 0.6 \pm 0.8$</td>
</tr>
<tr>
<td>$W$+jet</td>
<td>$10.0 \pm 1.6 \pm 2.1$</td>
<td>$4.1 \pm 1.3 \pm 0.9$</td>
<td>$4.2 \pm 1.1 \pm 1.3$</td>
</tr>
<tr>
<td>Di-boson</td>
<td>$5.1 \pm 1.0 \pm 0.7$</td>
<td>$2.1 \pm 0.8 \pm 0.3$</td>
<td>$2.9 \pm 0.4 \pm 0.4$</td>
</tr>
<tr>
<td>Total background</td>
<td>$40.0 \pm 3.3 \pm 3.6$</td>
<td>$21.7 \pm 2.8 \pm 1.8$</td>
<td>$21.8 \pm 2.8 \pm 2.1$</td>
</tr>
</tbody>
</table>

(Data Yields)  (202)  (59)  (64)

\[
\sigma(pp \rightarrow WW) = 54.4 \pm 4.0\text{(stat)} \pm 3.9\text{(syst)} \pm 2.0\text{(lumi)} \text{ pb},
\]

NLO SM prediction of $\sigma(pp \rightarrow WW) = 44.4 \pm 2.8 \text{ pb}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>3.7%</td>
</tr>
<tr>
<td>Background</td>
<td>9.6%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>7.4%</td>
</tr>
<tr>
<td>Systematic</td>
<td>13.1%</td>
</tr>
<tr>
<td>Statistical</td>
<td>8.3%</td>
</tr>
</tbody>
</table>
## Hww Cut Flows

### 2011

<table>
<thead>
<tr>
<th>0-jet</th>
<th>Signal</th>
<th>WW</th>
<th>Di-boson</th>
<th>$t\bar{t}$</th>
<th>Single Top</th>
<th>$Z/\gamma^*$</th>
<th>$W + \text{jets}$</th>
<th>Total Bkg.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Veto</td>
<td>56.7 ± 0.2</td>
<td>1273 ± 79</td>
<td>97 ± 4</td>
<td>174 ± 12</td>
<td>95 ± 7</td>
<td>1039 ± 28</td>
<td>217 ± 4</td>
<td>2893 ± 115</td>
<td>2849</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 50$ GeV</td>
<td>45.2 ± 0.2</td>
<td>312 ± 20</td>
<td>41 ± 3</td>
<td>29 ± 2</td>
<td>19 ± 2</td>
<td>168 ± 10</td>
<td>70 ± 2</td>
<td>639 ± 28</td>
<td>645</td>
</tr>
<tr>
<td>$p_T^{\ell\ell}$ cut</td>
<td>40.1 ± 0.2</td>
<td>282 ± 18</td>
<td>35 ± 3</td>
<td>28 ± 2</td>
<td>18 ± 2</td>
<td>28 ± 6</td>
<td>49 ± 2</td>
<td>439 ± 26</td>
<td>443</td>
</tr>
<tr>
<td>$\Delta\phi_{\ell\ell} &lt; 1.8$</td>
<td>39.0 ± 0.2</td>
<td>276 ± 17</td>
<td>33 ± 2</td>
<td>27 ± 2</td>
<td>18 ± 2</td>
<td>28 ± 6</td>
<td>44 ± 1</td>
<td>425 ± 26</td>
<td>429</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>1-Jet</th>
<th>Signal</th>
<th>WW</th>
<th>Di-boson</th>
<th>$t\bar{t}$</th>
<th>Single Top</th>
<th>$Z/\gamma^*$</th>
<th>$W + \text{jets}$</th>
<th>Total Bkg.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 jet</td>
<td>22.7 ± 0.1</td>
<td>343 ± 54</td>
<td>56 ± 3</td>
<td>1438 ± 60</td>
<td>436 ± 19</td>
<td>357 ± 17</td>
<td>85 ± 3</td>
<td>2715 ± 142</td>
<td>2706</td>
</tr>
<tr>
<td>$b$-jet veto</td>
<td>20.9 ± 0.1</td>
<td>319 ± 50</td>
<td>52 ± 3</td>
<td>412 ± 18</td>
<td>139 ± 7</td>
<td>332 ± 16</td>
<td>76 ± 3</td>
<td>1330 ± 84</td>
<td>1369</td>
</tr>
<tr>
<td>$</td>
<td>p_T^{\text{tot}}</td>
<td>&lt; 30$ GeV</td>
<td>14.0 ± 0.1</td>
<td>226 ± 35</td>
<td>34 ± 2</td>
<td>181 ± 8</td>
<td>80 ± 4</td>
<td>108 ± 8</td>
<td>37 ± 2</td>
</tr>
<tr>
<td>$Z \to \tau\tau$ veto</td>
<td>14.0 ± 0.1</td>
<td>220 ± 34</td>
<td>34 ± 2</td>
<td>173 ± 8</td>
<td>77 ± 4</td>
<td>85 ± 7</td>
<td>37 ± 2</td>
<td>627 ± 50</td>
<td>644</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 50$ GeV</td>
<td>10.9 ± 0.1</td>
<td>49 ± 8</td>
<td>14 ± 2</td>
<td>33 ± 2</td>
<td>18 ± 1</td>
<td>24 ± 3</td>
<td>12 ± 1</td>
<td>148 ± 12</td>
<td>170</td>
</tr>
<tr>
<td>$\Delta\phi_{\ell\ell} &lt; 1.8$</td>
<td>10.1 ± 0.1</td>
<td>44 ± 7</td>
<td>13 ± 2</td>
<td>31 ± 2</td>
<td>17 ± 1</td>
<td>10 ± 2</td>
<td>10 ± 1</td>
<td>126 ± 10</td>
<td>145</td>
</tr>
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</table>

### 2012

<table>
<thead>
<tr>
<th>0-jet</th>
<th>Signal</th>
<th>WW</th>
<th>Di-boson</th>
<th>$t\bar{t}$</th>
<th>Single Top</th>
<th>$Z/\gamma^*$</th>
<th>$W + \text{jets}$</th>
<th>Total Bkg.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Veto</td>
<td>47.5 ± 0.4</td>
<td>1308 ± 9</td>
<td>125 ± 4</td>
<td>184 ± 4</td>
<td>109 ± 6</td>
<td>850 ± 32</td>
<td>138 ± 4</td>
<td>2714 ± 34</td>
<td>2691</td>
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<tr>
<td>$p_T^{\ell\ell} &gt; 30$ GeV</td>
<td>43.4 ± 0.4</td>
<td>1077 ± 8</td>
<td>99 ± 4</td>
<td>165 ± 4</td>
<td>98 ± 5</td>
<td>47 ± 8</td>
<td>102 ± 2</td>
<td>1589 ± 14</td>
<td>1664</td>
</tr>
<tr>
<td>$m_{\ell\ell} &lt; 50$ GeV</td>
<td>34.9 ± 0.4</td>
<td>244 ± 4</td>
<td>33 ± 2</td>
<td>28 ± 2</td>
<td>17 ± 2</td>
<td>5 ± 2</td>
<td>29 ± 1</td>
<td>356 ± 6</td>
<td>421</td>
</tr>
<tr>
<td>$\Delta\phi_{\ell\ell} &lt; 1.8$</td>
<td>33.6 ± 0.4</td>
<td>234 ± 4</td>
<td>32 ± 2</td>
<td>27 ± 2</td>
<td>17 ± 2</td>
<td>4 ± 2</td>
<td>25 ± 1</td>
<td>339 ± 6</td>
<td>407</td>
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<table>
<thead>
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<th>Signal</th>
<th>WW</th>
<th>Di-boson</th>
<th>$t\bar{t}$</th>
<th>Single Top</th>
<th>$Z/\gamma^*$</th>
<th>$W + \text{jets}$</th>
<th>Total Bkg.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 jet</td>
<td>24.9 ± 0.3</td>
<td>396 ± 5</td>
<td>74 ± 3</td>
<td>1652 ± 12</td>
<td>479 ± 12</td>
<td>283 ± 20</td>
<td>68 ± 3</td>
<td>2953 ± 27</td>
<td>2874</td>
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<tr>
<td>$b$-jet veto</td>
<td>21.1 ± 0.3</td>
<td>334 ± 4</td>
<td>56 ± 2</td>
<td>349 ± 6</td>
<td>115 ± 6</td>
<td>236 ± 18</td>
<td>53 ± 2</td>
<td>1144 ± 21</td>
<td>1115</td>
</tr>
<tr>
<td>$</td>
<td>p_T^{\text{tot}}</td>
<td>&lt; 30$ GeV</td>
<td>12.2 ± 0.2</td>
<td>210 ± 3</td>
<td>30 ± 2</td>
<td>139 ± 4</td>
<td>63 ± 5</td>
<td>124 ± 14</td>
<td>23 ± 2</td>
</tr>
<tr>
<td>$Z \to \tau\tau$ veto</td>
<td>12.2 ± 0.2</td>
<td>204 ± 3</td>
<td>29 ± 2</td>
<td>133 ± 3</td>
<td>61 ± 5</td>
<td>98 ± 12</td>
<td>23 ± 2</td>
<td>547 ± 14</td>
<td>580</td>
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<tr>
<td>$m_{\ell\ell} &lt; 50$ GeV</td>
<td>9.2 ± 0.2</td>
<td>37 ± 1</td>
<td>10 ± 1</td>
<td>21 ± 1</td>
<td>12 ± 2</td>
<td>16 ± 5</td>
<td>8.0 ± 0.9</td>
<td>104 ± 6</td>
<td>122</td>
</tr>
<tr>
<td>$\Delta\phi_{\ell\ell} &lt; 1.8$</td>
<td>8.6 ± 0.2</td>
<td>34 ± 1</td>
<td>9 ± 1</td>
<td>20 ± 1</td>
<td>11 ± 2</td>
<td>3 ± 2</td>
<td>6.4 ± 0.7</td>
<td>84 ± 4</td>
<td>106</td>
</tr>
</tbody>
</table>
# Hww Systematics

## 2011

<table>
<thead>
<tr>
<th>Source (0-jet)</th>
<th>Signal (%)</th>
<th>Bkg. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive ggF signal ren./fact. scale</td>
<td>19</td>
<td>-</td>
</tr>
<tr>
<td>1-jet incl. ggF signal ren./fact. scale</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>W+jets fake factor</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>WW normalization</td>
<td>-</td>
<td>6</td>
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<tr>
<td>Jet energy scale</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Source (1-jet)</td>
<td>Signal (%)</td>
<td>Bkg. (%)</td>
</tr>
<tr>
<td>1-jet incl. ggF signal ren./fact. scale</td>
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</tr>
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<td>$E_T^{\text{miss}}$ modeling</td>
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<td>3</td>
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<tr>
<td>W+jets fake factor</td>
<td>-</td>
<td>7</td>
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<tr>
<td>$b$-tagging efficiency</td>
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<tr>
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## 2012

<table>
<thead>
<tr>
<th>Source (0-jet)</th>
<th>Signal (%)</th>
<th>Bkg. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive ggF signal ren./fact. scale</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>1-jet incl. ggF signal ren./fact. scale</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Jet energy scale</td>
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<td>4</td>
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<tr>
<td>WW normalization</td>
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<td>WW modeling and shape</td>
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<td>W+jets fake factor</td>
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<td>QCD scale acceptance</td>
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<tr>
<td>Source (1-jet)</td>
<td>Signal (%)</td>
<td>Bkg. (%)</td>
</tr>
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<tr>
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<td>$b$-tagging efficiency</td>
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<tr>
<td>W+jets fake factor</td>
<td>-</td>
<td>5</td>
</tr>
</tbody>
</table>
Relative Missing Energy

$E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$

$\Delta \phi_{l,j}$

$\rho_{l,j}^T$

$E_T$

$E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$ uses the component of the $E_{\text{miss}}^T$ perpendicular to the nearest lepton or jet. When $E_{\text{miss}}^T$ is close to a reconstructed object, only the component of $E_{\text{miss}}^T$ perpendicular to the object is used. The motivation for using $E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$ is to suppress fake $E_{\text{miss}}^T$ from mismeasured leptons and jets, and to remove $Z \rightarrow \tau\tau$ decays. Fake $E_{\text{miss}}^T$ can arise when the $p_T$ of a lepton or jet is mismeasured. In this case, the resulting $E_{\text{miss}}^T$ tends to point along the direction of the mismeasured object. The $E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$ variable is less sensitive to this type of fake $E_{\text{miss}}^T$. Similarly for $Z \rightarrow \tau\tau$, the lepton and neutrinos from the $\tau$ decay tend to be culminated, and thus a significant component of $E_{\text{miss}}^T$ is along the direction of the leptons. These events are suppressed by $E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$. The $E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$ distribution for dilepton events after the $Z$ veto is shown in Figure 7. The $Z/\gamma^*$ events populate low values of $E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$ in both the same-flavor and opposite-flavor channels. By requiring the events to have large $E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$, the dominate $Z/\gamma^*$ component is removed. Typical $E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$ requirements are greater than GeV for the same-flavor channel, and greater than $y$ GeV for the opposite-flavor channel. These cut values are indicated in the figure. Because the $Z/\gamma^*$ contribution is much larger in the same-flavor channel, the $E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$ requirement is stricter. As can be seen in the figure, the $E_{\text{miss}}^T$, $E_{\text{miss,Rel}}^T$ requirement results in a significant loss in $WW$ acceptance, particularly in the same-flavor channel, but dramatically improves the signal to background. After the requirement of large missing energy, the selected events are dominated by top quark background. The majority of this is from $t\bar{t}$ production, with $Wt$ contributing about $tsh$. Top events produce pairs of $W$ bosons in association with b jets. Thus, top background can be suppressed by removing events containing reconstructed jets. Figure 7 shows the distribution of the number of reconstructed jets after the $E_{\text{miss}}$, $E_{\text{miss,Rel}}$ cut. Most of the top background has reconstructed jets in the final state. By vetoing events with reconstructed jets, the top background can be significantly reduced. This requirement, referred to as a "jet veto," is effective in removing top and is fairly efficient for $WW$. As top is a major background for both same-flavor and opposite-flavor events, the jet veto is applied to all channels. The top background surviving the jet veto consists of roughly equal amounts of $t\bar{t}$ and $Wt$.
Electron Candidates in ATLAS

\[ \int L dt = 1.3 \text{ pb}^{-1} \]

\begin{itemize}
  \item Data 2010 (\(\sqrt{s} = 7 \text{ TeV}\))
  \item Monte Carlo
  \item Hadrons
  \item Conversions
  \item \(b\to e\)
  \item \(c\to e\)
  \item \(W/Z/\gamma^*\to e\)
\end{itemize}

ATLAS
Electron Identification

- Prompt Electrons
- Hadrons
- Heavy-Flavor Conversions

- Isolated electrons
- Background electrons

Fraction of high threshold TRT hits:

- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6

E/p:

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

ATLAS Preliminary Simulation
Low Low Mass

OPAL
\(\sqrt{s} = 91, 183-209\) GeV

Limit on \(k\)

\(m_{S^0}\) (GeV)

Efficiency (%)

Minimum

\(\sqrt{s} = 91.2\) GeV

\(Z^0 \rightarrow \mu^+\mu^-\)

\(\mu\mu\)

\(bb\)