W Physics at ATLAS

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A Familiar Particle in a New Setting

- $W \rightarrow l \nu$ at CERN in 1982
  - Observation (with Z) establishes the Standard Model

- $W \rightarrow l \nu$ at CERN in 2010
  - First source of high momentum leptons
  - Standard Model in new energy regime
Search for physics beyond what we know must be based on a solid understanding of the detector and the Standard Model

- **W signature**
  - Charged leptons
  - Missing energy (from weakly-interacting neutrals)
  - Modeling of pp collisions

- Leptons flag electroweak interactions in a sea of strong interactions (jets)
  - Generically, something new could participate in either interaction, or both
  - But leptonic signatures are easier to distinguish from background

- Weakly-interacting neutrals pretty interesting, too
Overview

- The LHC and the ATLAS detector
- W candidate sample
  - Lepton definitions
  - Backgrounds
- Measurements
  - Inclusive cross section
  - Charge asymmetry
  - Differential ($d\sigma/dP_T$)
The LHC at CERN

Overall view of the LHC experiments.
LHC @ 7 TeV

- Rapid LHC startup
- 2010 Instantaneous luminosity record = $2.1 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
  \[\rightarrow \text{Tevatron record} \sim 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\]

- $2 \rightarrow 368$ bunches
  \[\rightarrow 2808 \text{ possible}\]
- $\sim 10^{11}$ p/bunch
- $> 20$ MJ stored energy
  \[\rightarrow \text{Tevatron: 2 MJ}\]

ATLAS Online Luminosity $\sqrt{s} = 7$ TeV
- Total Delivered: 48.1 pb$^{-1}$
- Total Recorded: 45.0 pb$^{-1}$

- Ongoing analysis $\sim 30$ pb$^{-1}$
- Publication $\sim 310$ nb$^{-1}$
The ATLAS Detector

Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

Detector characteristics
- Width: 44m
- Diameter: 22m
- Weight: 7000t

CERN AC - ATLAS V1997
\[ \eta = 0 \quad \theta = \frac{\pi}{2} \]

\[ \eta = -\ln(\tan(\theta/2)) \]

\[ \eta = -\infty \quad \theta = \pi \]

\[ \bar{p}_T = (p_x, p_y) \quad p_T = p \sin \theta, \quad E_T = E \sin \theta \]

\[ \bar{E}_T^{\text{miss}} = -\sum_{\text{clusters } i} E_i \hat{n}_i \]

beam axis
\[ \eta = +\infty \quad \theta = 0 \]
**Electrons in ATLAS**

- EM calorimeter cluster, possibly matched to inner detector (ID) track
- \( E_T > 20 \text{ GeV}, \ |\eta| < 2.47 \)
  - exclude gap between barrel and endcap \( 1.37 < |\eta| < 1.52 \)
- “Loose” selection
  - shower shape in middle layer of calorimeter
- “Medium” selection
  - add fine-granularity shower shape and track match
- “Tight” selection
  - add \( E/p \), more track quality, high-threshold TRT hits, conversion veto
- Trigger: Level 1 (hardware) requires coarse-granularity cluster with \( |\eta| < 2.5 \) and \( E_T > 10 \text{ GeV} \)
Muons in ATLAS

- Combined muon: matched inner detector (ID) and muon spectrometer (MS) track
- Selection:
  - $p_T$ (combined) > 15 GeV
  - $p_T$ (MS) > 10 GeV
  - $|p_T(\text{MS}) - p_T(\text{ID})| < 15$ GeV
  - $|\eta| < 2.4$ (trigger geometry)
- Trigger: L1 (hardware)
  - $p_T > 6$ GeV
Level 1 Muon Trigger

- Collisions (ultimately) at almost 40 MHz, write to disk at 200 Hz
- Three-stage trigger: Level 1, Level 2, and “Event Filter”
- Level 1 implemented through on-detector electronics

1) Seed from hits in “pivot” plane
2) Draw road
3) Search for coincidence (low-$p_T$)
4) Search for coincidence (high-$p_T$)
Muon Trigger Performance

- **L1 trigger (6 GeV threshold)** for first papers – HLT not commissioned
- Measure trigger efficiency for reconstructed muons in orthogonal (calo) trigger

- Inefficiency in barrel = gaps in geometry
- Endcap: some TGC inefficiencies not modeled, uncalibrated trigger roads

\[ \int L \, dt = 331 \text{ nb}^{-1} \]

- $|\eta| < 1.05$ **barrel**
  - Data 2010 ($\sqrt{s} = 7$ TeV)
  - $W \rightarrow \mu \nu$ MC

- $|\eta| > 1.05$ **endcap**
  - Data 2010 ($\sqrt{s} = 7$ TeV)
  - $W \rightarrow \mu \nu$ MC
Cross section:

\[ \sigma = \frac{N_{\text{cand}} - N_{\text{background}}}{A_W \times C_W \times \int L \, dt} \]

- \( A_W \times C_W \) = fraction of signal expected to pass selection
- \( \int L \, dt \) = integrated lumi.

Backgrounds:

- \( Z \rightarrow ee, \mu\mu \)
- \( W \rightarrow \tau\nu \)
- \( Z \rightarrow \tau\tau \)
- \( tt \) with \( t \rightarrow Wb, W \rightarrow \text{In} \)
- “QCD”
  - heavy quark decays
  - hadronic “fakes”
W Cross Section Measurement

$\sigma_W \times Br(W \rightarrow l \nu)$ [nb] vs $\sqrt{s}$ [TeV]

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# Event Selection

<table>
<thead>
<tr>
<th>electron</th>
<th>muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T &gt; 20$ GeV</td>
<td>$p_T &gt; 20$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>pass “tight” criteria</td>
<td>isolated from other charged particles</td>
</tr>
</tbody>
</table>

$E_T^{\text{miss}} > 25$ GeV

transverse mass $M_T > 40$ GeV
The High-$p_T$ Electron Data

Electrons with $E_T > 20$ GeV in events firing L1 electron trigger:

“Loose” electrons → “Tight” electrons
The High-$p_T$ Muon Data

- Muons with $p_T > 15$ GeV in events firing L1 trigger
- Refine muon selection:
  - $p_T > 20$ GeV
  - Relative Track Isolation

\[
\text{iso} = \left( \frac{\sum p_T^{\text{track}}}{p_T^\mu} \right) < 0.2
\]

in cone if $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.4$
Selecting the $W$ signal (II)

- Missing Transverse Energy
  \[ \vec{E}_T^{\text{miss}} = - \sum_{\text{clusters } i} E_i \hat{n}_i - \vec{p}_T^\mu + E_{\text{loss}}^\mu \hat{p}_T^\mu \]
- Reduce backgrounds by requiring $E_T^{\text{miss}} > 25$ GeV

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\[ \int L \, dt = 315 \text{ nb}^{-1} \]

**electron channel** $E_T^{\text{miss}}$ [GeV]

\[ \int L \, dt = 310 \text{ nb}^{-1} \]

**muon channel** $E_T^{\text{miss}}$ [GeV]
Selecting the $W$ signal (III)

- Transverse mass \( M_T = \sqrt{2(p_T^\mu)(E_{T\text{miss}})}(1 - \cos(\phi^\mu - \phi^{E_{T\text{miss}}})) \)
- Clean up sample with $M_T > 40$ GeV

Yield: 1069 candidates

Yield: 1181 candidates
**Backgrounds to W → eν**

- **“Electroweak” backgrounds** ($Z \rightarrow ee$, $W \rightarrow \tau ν$, $Z \rightarrow ττ$, ttbar): $33.5 \pm 3.0$ (stat+sys) events
- $N_{QCD} = 28 \pm 3$ (stat) $\pm 10$ (sys) events

- **QCD: Template fit to $E_T^{miss}$ distribution** (after all other requirements)
  - $W \rightarrow eν$ and $W \rightarrow τν$ templates from simulation
  - QCD template from data
    - Some electron ID cuts reversed, veto events with isolated electrons
  - **Systematic**
    - Vary requirements for QCD template
    - Restrict fit range
Backgrounds to $W \rightarrow \mu\nu$

- "Electroweak" backgrounds ($Z \rightarrow \mu\mu$, $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$, ttbar) $77.6 \pm 5.4$ (stat+sys) events
- Cosmics: $1.7 \pm 0.8$ event
- QCD: $21.1 \pm 9.8$ (stat+sys) events

$\rightarrow N_{all}$ candidates before isolation req.
  - $N_{isol}$ pass
  - $N_{QCD}$ are from QCD, $N_{non-QCD}$ are not

$\rightarrow$ Apply isolation requirement, with different efficiencies from each sample
  - Measure $\epsilon_{non-QCD}$ (i.e. signal efficiency) from Zs
  - Measure $\epsilon_{QCD}$ in QCD-dominated data ($15 < p_T^\mu < 20$ GeV), and extrapolate to $p_T^\mu > 20$ GeV using simulated dijet events

$\rightarrow$ Solve, and $\epsilon_{QCD}N_{QCD}$ is the pred. background

$\rightarrow$ Systematic from extrapolation of $\epsilon_{QCD}$, significant statistical uncertainty, too
\[ W \rightarrow \ell \nu \text{ Acceptance} \]

<table>
<thead>
<tr>
<th>channel</th>
<th>( A_W )</th>
<th>( C_W )</th>
<th>acceptance x efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons</td>
<td>0.462 ± 0.014</td>
<td>0.659 ± 0.046</td>
<td>0.304 ± 0.023</td>
</tr>
<tr>
<td>muons</td>
<td>0.480 ± 0.014</td>
<td>0.758 ± 0.030</td>
<td>0.364 ± 0.018</td>
</tr>
</tbody>
</table>

- Factorize acceptance times efficiency
  - \( A_W = \text{geometric & kinematic acceptance (measured at truth level)} \)
    - From Pythia 6.4 (LO)
  - \( C_W = \text{detection efficiency} \)
    - GEANT 4 simulation of ATLAS, corrected to data
- Common systematic uncertainty on \( A_W \) is 3%
  - Dominated by PDF dependence
  - Includes LO-NLO differences
- Systematic uncertainties on \( C_W \) = 7% for electrons and 4% for muons
  - Reconstruction and trigger (\( \mu \)) efficiencies
  - Energy / momentum scale/resolution
### W Cross Section Results

<table>
<thead>
<tr>
<th>channel (lumi)</th>
<th>$N_{\text{cand}}$</th>
<th>$N_{\text{background}}$</th>
<th>cross section (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron (315 nb$^{-1}$)</td>
<td>1069</td>
<td>61.5 ± 10.8</td>
<td>10.5 ± 0.3 (stat) ± 0.8 (sys) ± 1.1 (lum)</td>
</tr>
<tr>
<td>muon (310 nb$^{-1}$)</td>
<td>1181</td>
<td>100.4 ± 11.2</td>
<td>9.6 ± 0.3 (stat) ± 0.5 (sys) ± 1.1 (lum)</td>
</tr>
<tr>
<td>combined</td>
<td>2250</td>
<td>-</td>
<td>10.0 ± 0.2 (stat) ± 0.5 (sys) ± 1.1 (lum)</td>
</tr>
</tbody>
</table>

- Cross section times branching ratio $\text{BR}(W \rightarrow l \nu)$
- Theoretical prediction:
  - $10.46 \pm 0.02$ nb
  - $\text{FEWZ w/ MSTW2008 pdfs}$
- Luminosity uncertainty is 11%

$$\sigma = \frac{N_{\text{cand}} - N_{\text{background}}}{A_W \times C_W \times \int L \, dt}$$
**W Cross Section in Context**

\[ \sigma_W \times \text{Br}(W \rightarrow l \nu) [\text{nb}] \]

**ATLAS**

Data 2010 (\(\sqrt{s} = 7 \text{ TeV}\))

\[ \int L \, dt = 310-315 \text{ nb}^{-1} \]

- \(W \rightarrow l \nu\)
- \(W^+ \rightarrow l^+ \nu\)
- \(W^- \rightarrow l^- \nu\)

**NNLO QCD**

- \(W(p\bar{p})\)
- \(W(pp)\)
- \(W^+(pp)\)
- \(W^-(pp)\)

- \(CDF \, W \rightarrow (l/e) \nu\)
- \(D0 \, W \rightarrow (e/\mu) \nu\)
- \(UA1 \, W \rightarrow l \nu\)
- \(UA2 \, W \rightarrow e \nu\)
- \(Phenix \, W^\pm \rightarrow (e^+/e^-) \nu\)

\(\sqrt{s}[\text{TeV}]\)
$W^+ - W^-$ Charge Asymmetry

- $W^+$ favored in proton-proton collisions in eta-dependent way
  \[ \text{twice as much } u \text{ as } d \text{ in the proton, harder } u \text{-quark PDF} \]

\[ A = \frac{\sigma^{\ell^+} - \sigma^{\ell^-}}{\sigma^{\ell^+} + \sigma^{\ell^-}} \]

Charge Asymmetry Inputs

\[ \int L \ dt = 315 \text{ nb}^{-1} \]

**e^+**

\[ \int L \ dt = 310 \text{ nb}^{-1} \]

**\mu^+**

\[ \int L \ dt = 315 \text{ nb}^{-1} \]

**e^-**

\[ \int L \ dt = 310 \text{ nb}^{-1} \]

**\mu^-**
**Charge Asymmetry Results**

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \]

<table>
<thead>
<tr>
<th>integral combined result</th>
<th>0.20 ± 0.02 (stat) ± 0.01 (sys)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC@NLO with CTEQ6.6</td>
<td>0.218^{+0.008}_{-0.009}</td>
</tr>
<tr>
<td>MC@NLO with HERAPDF 1.0</td>
<td>0.202 ± 0.019</td>
</tr>
<tr>
<td>DYNNLO with MSTW 08</td>
<td>0.184^{+0.011}_{-0.012}</td>
</tr>
</tbody>
</table>

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• In progress: \( d\sigma/dp_T \) for the W
• Characterize hadronic recoil system (vector \( u \))

\[
\begin{align*}
\frac{\rho_{p_T}}{M_T} &= \frac{\rho_{p_T}}{E_T^{\text{miss}}} = -\vec{p}_T - \vec{u} \\
\vec{p}_T^W &= \vec{p}_T^\ell + \vec{p}_T^\nu = \vec{p}_T^\ell - \vec{p}_T^\nu - \vec{u} \\
M_T &= \sqrt{2(p_T^\mu)(p_T^\nu)(1 - \cos(\phi^\mu - \phi^\nu))}
\end{align*}
\]
Calorimeter resolution → measured and reconstructed $W_p_T$ may be quite different

$\rightarrow$ Related by a Response Matrix $R$

- Can build response matrix from $W$ Monte Carlo events
  $\rightarrow$ Have both true and reconstructed $W_p_T$
  $\rightarrow$ But, accurate modeling of recoil?
- Better: build from $Z$ data
  $\rightarrow$ “Truth” from $Z_p_T$ reconstructed from leptons
  $\rightarrow$ “Reco” from hadronic recoil
  $\rightarrow$ Correct for slight differences in $W$ and $Z$ kinematics (sum $E_T$)
$W p_T$ Unfolding

- Response Matrix $R$ relates measured and reconstructed $W p_T$

- Can “unfold”: invert matrix, map back to truth

- Measurement to be completed in coming weeks
Summary of W Measurements

- Benchmark high-p$_T$ electroweak processes at the LHC by characterizing W production at ATLAS
  - Inclusive cross section
  - Lepton charge asymmetry
  - $d\sigma/dp_T$

- Feeds back into physics
  - Standard Model
    - PDFs
    - QCD modeling (perturbative and non-perturbative)
  - Detector response
    - Hadronic recoil and $E_T^{\text{miss}}$
    - High-p$_T$ electrons and muons
WZ candidate event

- Rarer processes ($\sigma_{WZ} = 18$ pb) are beginning to appear

\[
\begin{align*}
M_{\mu\mu} &= 96 \text{ GeV} \\
M_T(e-E_T^{\text{miss}}) &= 57 \text{ GeV} \\
\mathcal{P}_T(\mu^+) &= 65 \text{ GeV} \\
\mathcal{P}_T(\mu^-) &= 40 \text{ GeV} \\
\mathcal{P}_T(e) &= 64 \text{ GeV} \\
E_T^{\text{miss}} &= 21 \text{ GeV}
\end{align*}
\]
What’s next

• Build on knowledge from W sample
  → Better modeling of signals and backgrounds
  → Understanding of muons, electrons, $E_T^{miss}$
  → Go after multilepton signals
    ▪ Start from WZ (for example), test for supersymmetry or anomalies in the triple
gauge boson coupling
  → Longer term: search for very massive particles
    ▪ Still anchor event selection on leptons for trigger, background rejection
    ▪ New event topologies?

• Representatives from experiments and accelerator are meeting
  now at Chamonix
  → $\sqrt{s} = 7$ or $8 \text{ TeV}$?
  → run through 2012 or stop at the end of 2011 to go for $14 \text{ TeV}$?
Backup
**More on Electrons**

- Trigger: sliding-window algorithm using reduced-granularity clusters $\Delta \eta \times \Delta \varphi = 0.1 \times 0.1$
- Offline reconstruction: sliding window of 3x5 cells or 0.075 x 0.125 in $\eta \times \varphi$
  - $\rightarrow$ **Electron** = cluster with $E_T > 2.5$ GeV and matched track with $p_T > 0.5$ GeV
- Reconstruction: exact requirements vary with $E_T$ and $|\eta|$, but three categories:
  - **Loose electrons**
    - $\rightarrow$ **Fiducial**: $|\eta| < 2.37$ and exclude $1.37 < |\eta| < 1.52$
    - $\rightarrow$ **Shower shape in middle (largest) layer of calorimeter**: cluster width in $\eta$
    - $\rightarrow$ **Hadronic leakage**: $E_T$(innermost later of HCAL) / cluster $E_T$
  - **Medium electrons**: loose $\pm$
    - $\rightarrow$ **Shower shape in innermost (finely segmented in $\eta$) layer of calorimeter**
    - $\rightarrow$ **Track match** ($\Delta \eta$)
    - $\rightarrow$ **Track quality** (pixel, SCT hits and impact parameter)
  - **Tight electrons**: medium $\pm$
    - $\rightarrow$ **High-threshold hits in transition-radiation tracker (TRT); hit in innermost pixel layer**
    - $\rightarrow$ $E/p$
Muon L1 Trigger

Holes in Barrel Trigger Acceptance

Endcap L1 Trigger (TGC)
Muon High Level Trigger

- On L1 accept, location of muon (Region of Interest or RoI, about $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ in barrel, smaller in endcap) sent to Level 2
- Level 2: full-granularity reconstruction of muon within RoI
  - Spectrometer segment finding by LUT
  - ID track match included
- Event Filter (Level 3): identical to offline reconstruction
- Improving momentum resolution $\Rightarrow$ better background rejection
- Work ongoing
  - Alignment, algorithm optimisation
Muon Reconstruction Efficiency

\begin{center}
\includegraphics[width=\textwidth]{Muon_Reconstruction_Efficiency.png}
\end{center}

\textbf{ATLAS Preliminary}

Data 2010 (s=7 TeV)

\begin{itemize}
  \item data
  \item Z-\(\mu\mu\) MC
\end{itemize}

\begin{equation}
\int L \, dt = 310 \text{ nb}^{-1}
\end{equation}

\begin{itemize}
  \item Data 2010 (s=7 TeV)
  \item W MC component
  \item Pion MC component
  \item Fit result
\end{itemize}

\begin{itemize}
  \item Associated hit distance for ID tag [mm]
\end{itemize}
# LHC design parameters

<table>
<thead>
<tr>
<th>Quantity</th>
<th>number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>26 659 m</td>
</tr>
<tr>
<td>Dipole operating temperature</td>
<td>1.9 K (-271.3°C)</td>
</tr>
<tr>
<td>Number of magnets</td>
<td>9593</td>
</tr>
<tr>
<td>Number of main dipoles</td>
<td>1232</td>
</tr>
<tr>
<td>Number of main quadrupoles</td>
<td>392</td>
</tr>
<tr>
<td>Number of RF cavities</td>
<td>8 per beam</td>
</tr>
<tr>
<td>Nominal energy, protons</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Nominal energy, ions</td>
<td>2.76 TeV/u (*)</td>
</tr>
<tr>
<td>Peak magnetic dipole field</td>
<td>8.33 T</td>
</tr>
<tr>
<td>Min. distance between bunches</td>
<td>~7 m</td>
</tr>
<tr>
<td>Design luminosity</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>No. of bunches per proton beam</td>
<td>2808</td>
</tr>
<tr>
<td>No. of protons per bunch (at start)</td>
<td>$1.1 \times 10^{11}$</td>
</tr>
<tr>
<td>Number of turns per second</td>
<td>11 245</td>
</tr>
<tr>
<td>Number of collisions per second</td>
<td>600 million</td>
</tr>
</tbody>
</table>

(*) Energy per nucleon