The ATLAS Experiment at LHC
Status and First Results

ATLAS Barrel Toroid

2005

Event with $K_S \rightarrow \pi^+\pi^-$ Candidate

Beate Heinemann, UC Berkeley and LBNL
SLUO, SLAC, August 2010
Outline

- Introduction
  - LHC and ATLAS
  - Data Taking, Luminosity and Trigger+DAQ

- First Physics Results
  - Minimum Bias
  - J/psi and Upsilon
  - Jets
  - W’s and Z’s
  - Towards Top
  - New Physics

- Conclusions and Outlook

- (*) Arizona, Oregon, SLAC, UCB/LBNL, UCSC, UCI, Washington
The Large Hadron Collider (LHC)

Circumference: 16.5 miles

\[ \sqrt{s} = 7 \text{ TeV} \]
ATLAS Detector

- Muon Detectors
- Tile Calorimeter
- Liquid Argon Calorimeter
- Toroid Magnets
- Solenoid Magnet
- SCT Tracker
- Pixel Detector
- TRT Tracker
ATLAS Detector

**Inner Detector: |\(\eta|<2.5\)**
- Si Pixels: 40x800 \(\mu\)m
- Si Strips: 80 \(\mu\)m
- Transition Rad. Tracker
- Solenoid: \(B=2\) T
- \(\sigma/p_T = 3.8 \times 10^{-4} \ p_T/\text{GeV} \oplus 0.015\) (e.g. 4% at 100 GeV)
ATLAS Detector

Calorimeters: $|\eta|<4.9$
- Lead/LAr: Electromagnetic
- Cu/LAr: Hadronic Endcap
- Tile (steel/plastic scintillator): Hadronic Barrel
- EM: $\sigma/E = 10\% \sqrt{E}$ (e.g. 1% at 100 GeV)
- HAD: $\sigma/E = 50\% \sqrt{E} \pm 3\%$
ATLAS Detector

Muon System: $|\eta|<2.5$
- Precision chambers (MDT and CSC)
- Trigger chambers (RPC and TGC)
- Air-core toroid magnet ($\int B dL = 1-7.5 \text{Tm}$)
- 10% $p$ resolution at 1 TeV
• Several forward detectors
  – LUCID, MBTS, ZDC
  – Luminosity measurement and forward physics
March 30th 2010: first 7 TeV Collisions
Luminosity

\[ \mathcal{L} = \frac{n_b f_r I_1 I_2}{2\pi \Sigma_x \Sigma_y} \]

- Delivered \( \int L \, dt = 3.6 \, \text{pb}^{-1} \)
  - calibrated using a Van-der-Meer scan to 11% precision
    - Dominated by 10% uncertainty on beam current normalization
- ATLAS recorded 93.9% of the data on tape
Peak Luminosity Evolution

$L = \frac{n_b f_r I_1 I_2}{2\pi \Sigma_x \Sigma_y}$

- Protons/bunch $I_1 \approx I_2$; $10^{11}$
- # of bunches $n_b$; up to 36
- Beam size $\Sigma_x \approx \Sigma_y$; 60 μm
- Revolution frequency $f_r$; 11 kHz

• LHC achieved 10,000 fold increase in past 6 months
  - Increase in bunch current (factor $10^2$) and number of bunches (factor 36) and decrease in beam size (factor 3)
• Aim at increase by another factor of 10 by end of Oct.
  - $L = 10^{32}$ cm$^{-2}$s$^{-1}$ equivalent to $\sim 10$ pb$^{-1}$ in 24h
ATLAS Detector Operation

- **Operational Fraction:**
  - 97-100% of subdetector channels fully operational
- **Data Quality:**
  - 94-100% of data good for physics analyses

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>80 M</td>
<td>97.4%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>99.2%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>98.0%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>98.5%</td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td>9800</td>
<td>97.3%</td>
</tr>
<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
<td>99.9%</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>99.9%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>370 k</td>
<td>99.5%</td>
</tr>
<tr>
<td>LVL1 Muon TGC trigger</td>
<td>320 k</td>
<td>100%</td>
</tr>
<tr>
<td>MDT Muon Drift Tubes</td>
<td>350 k</td>
<td>99.7%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>98.5%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>370 k</td>
<td>97.0%</td>
</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>98.6%</td>
</tr>
</tbody>
</table>

Fraction of recorded data with subdetector **good**

<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LAr EM</td>
<td>LAr HAD</td>
</tr>
<tr>
<td>Pixel</td>
<td>97.7</td>
<td>94.4</td>
</tr>
<tr>
<td>SCT</td>
<td>96.4</td>
<td>98.7</td>
</tr>
<tr>
<td>TRT</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams at $\sqrt{s}=7$ TeV between March 30th and August 14th (in %)
Triggers and DAQ

- **Collision rate:**
  - 1st 2010 run: 50 Hz
  - Recent runs: 200 kHz

- **Trigger rate today:**
  - L1 ~10 kHz
  - To tape: ~300 Hz
L1 Trigger well understood, agrees also with simulation.
• High-level trigger commissioned
• Used also for online beamspot measurement
  – Important e.g. for b-jet trigger

ATLAS Preliminary
30 Mar. 2010 (LHC Fill 1005)
\[ \sqrt{s} = 7 \text{ TeV} \]

Online primary vertex
- \( N_{\text{track}} \) per vertex \( \geq 2 \)
- \( p_T > 0.5 \text{ GeV}, |\eta| < 2.5 \)

ATLAS Preliminary
16.2 nb\(^{-1}\)

Tracking (using e’s)

Efficiency / 0.75 GeV

ATLAS Preliminary

Online vertex

\( \mu = (1.030 \pm 0.097) \text{ mm} \)
\( \sigma = (22.143 \pm 0.066) \text{ mm} \)

\( \times 10^3 \)

Number of vertices per 1 mm

Vertex z [mm]
Minimum Bias Physics


one of the first 7 TeV collision events recorded on March 30th
Minimum Bias Physics

• Total cross section ~100 mb
  – About 70% inelastic
• Measurements of charged particle multiplicities in
  – Inclusive selection
  – Diffraction enhanced selection
  – Underlying event dominated regions
• Rely on understanding of low $p_T$ tracking of charged hadrons
  – Also important for $b$-tagging
Inner Detector: Material

Map material using hadronic interactions

Map material with photon conversions

- Excellent agreement between data and simulation
  - Small discrepancies already fixed for new MC production starting now
Resolution and Mass Scale using resonances

\[ \Phi \rightarrow K^+ K^- \]

Particle identification using Pixel dE/dx and TRT transition radiation
Inclusive Charged Particle Spectra

- Systematic error ~3%
- MC models agree to within 50%
  - But require further tuning
- Multiplicity rises with energy
Charged particles spectra in diffractive-enhanced sample:
veto events with hits on both sides of MBTS detector

Phojet describes data best
Charged Particles in diffractive events, the Underlying Event and Jets

Charged particle spectra in diffractive-enhanced sample: veto events with hits on both sides of MBTS detector

Transverse region w.r.t. leading track: sensitive to initial-state radiation and multiple parton-parton interactions

Pyhjet describes data best

Phojet tunes underestimate both at 0.9 and 7 TeV
Charged Particles in diffractive events, the Underlying Event and Jets

Use tracks to form jets => test fragmentation of jets

10 GeV $< p_T^{\text{jet}} <$ 15 GeV

Transverse region w.r.t. leading track: sensitive to initial-state radiation and multiple parton-parton interactions

MC tunes have varying success in describing the fragmentation

Pythia tune underestimates both at 0.9 and 7 TeV

Pythia6 tunes underestimates both at 0.9 and 7 TeV
J/ψ and Υ

J/ψ candidate events

J/ψ → μ+μ− candidate in 7 TeV collisions

run #: 152409, evt #: 2452006

Inv. Mass = 3.1 GeV

P(μ+) = 28 GeV, η = 0.93

P(μ−) = 15 GeV, η = 0.95
Dimuon Mass Spectrum

\[ \int L \approx 0.9 \text{ pb}^{-1} \]

\[ \text{ATLAS Preliminary} \]

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

Will now also constitute excellent calibration samples
J/ψ Cross Sections

Inclusive cross section

- Kin. range: $p_T = 1-12$ GeV, $|y|<2.25$
- Syst. Uncertainty ~30%
  - Completely dominated by polarization uncertainty
- $p_T$ and $y$-dependence of $\sigma(J/\psi)$ agrees with Pythia color octet model
  - Normalization off by factor 10
J/ψ Cross Sections

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Prompt fraction determined
From pseudo-proper time distribution

\[ \tau = \frac{L_{\text{xy}} m(J/\psi)}{p_T(J/\psi)} \]

Non-prompt fraction

- Data: ratio of non-prompt to prompt $\sigma_{J/\psi}$
- Pythia+NRQCD

ATLAS Preliminary
$L_{\text{int}} = 17.5$ nb$^{-1}$
Jets

Run Number: 152166, Event Number: 810258
Date: 2010-03-30 14:56:29 CEST

Di-jet Event at 7 TeV

Raw measured jet energy: 300 GeV
Calorimeter Response

- Calorimeter energy in R=0.2 cone around track / track p
- Measures response of calorimeter to charged pions
  - Critical for jet calibration

- Data generally very well described by MC
Jet Energy Scale uncertainty 6-10% depending on p_T and η (dominated by EM scale and hadronic shower model)

Workshop on SLAC last week

- Jet cross section measured using anti-k_T algorithm
  - Up to p_T=500 GeV (with 17 nb^{-1})
  - Dominant systematic uncertainty: jet energy scale
- Data in good agreement with QCD prediction

anti-k_T jets, R=0.6, |y_j| ≤ 2.8

\[ \int L dt = 17 \text{ nb}^{-1} \wedge s = 7 \text{ TeV} \]
Dijet Mass

**ATLAS** Preliminary

anti-$k_T$ jets, $R=0.6$

\[ \int dt \Delta t = 17 \text{ nb}^{-1}, \sqrt{s} = 7 \text{ TeV} \]

- 2.1 < $|y|_{\text{max}}$ < 2.8 (x 1e8)
- 1.2 < $|y|_{\text{max}}$ < 2.1 (x 1e6)
- 0.8 < $|y|_{\text{max}}$ < 1.2 (x 1e4)
- 0.3 < $|y|_{\text{max}}$ < 0.8 (x 1e2)
- 0.0 < $|y|_{\text{max}}$ < 0.3 (x 1e0)

- Total syst. unc.
- NLO pQCD + non-pert.

\[ \frac{1}{N} \frac{d^2\sigma}{dM_{jj} \, dy} \] [GeV]

\[ M_{jj} \] [GeV]

Data extend beyond Tevatron’s $\sqrt{s}$

- Excellent agreement of data with QCD prediction
W → eνe

W→ev candidate in 7 TeV collisions

p_T(e+) = 34 GeV
η(e+) = -0.42
E_T^{miss} = 26 GeV
M_T = 57 GeV
$W \rightarrow \mu \nu \mu$

Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST

$\sqrt{s} = 7$ TeV collisions

$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV
$
p_T(\mu^-) = 40$ GeV
$\eta(\mu^-) = 2.0$

$W \rightarrow \mu \nu$ candidate in 7 TeV collisions
**W’s**

- $p_T(e/\mu)>20$ GeV (isolated), $E_T^{miss}>25$ GeV, $m_T>40$ GeV
  - about 3000 candidates/lepton type in $\int Ldt=1$ pb$^{-1}$
- Data well modeled by simulation

![W decay to eν and μν](image-url)
$Z \rightarrow e^+ e^-$

Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST

$M_{ee} = 89$ GeV

Z-ee candidate in 7 TeV collisions
Z → μ⁺μ⁻

p_T(μ⁺) = 27 GeV  η(μ⁺) = 0.7
p_T(μ⁻) = 45 GeV  η(μ⁻) = 2.2
M_{μμ} = 87 GeV

Z+μμ candidate
in 7 TeV collisions
- Two leptons with $p_T>20$ GeV
  - About 200 (300) $Z$ candidates in $e^+e^-$ ($\mu^+\mu^-$) channel in $\sim1$ pb$^{-1}$
  - Very precious for detector calibration
- Resolution in data slightly worse than simulation
  - Calibration and/or alignment efforts ongoing
W and Z Cross Section

<table>
<thead>
<tr>
<th>Process</th>
<th>Data</th>
<th>Background</th>
<th>L (nb⁻¹)</th>
<th>Cross Section (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W→ev</td>
<td>46</td>
<td>2.6±0.4</td>
<td>17</td>
<td>8.5 ± 1.3 (stat) ± 0.7 (syst) ± 0.9 (lum)</td>
</tr>
<tr>
<td>W→μν</td>
<td>72</td>
<td>5.3±0.7</td>
<td>17</td>
<td>10.3 ± 1.3 (stat) ± 0.8 (syst) ± 1.1 (lum)</td>
</tr>
<tr>
<td>Z→ee</td>
<td>46</td>
<td>0.49±0.09</td>
<td>219</td>
<td>0.72 ± 0.11 (stat) ± 0.10 (syst) ± 0.08 (lum)</td>
</tr>
<tr>
<td>Z→μμ</td>
<td>79</td>
<td>0.17±0.01</td>
<td>229</td>
<td>0.89 ± 0.10 (stat) ± 0.07 (syst) ± 0.10 (lum)</td>
</tr>
</tbody>
</table>
Towards the Top Quark
W and Z+jets

- Major backgrounds to top and New Physics searches (e.g. SUSY)
- Raw $N_{\text{jet}}$ spectrum agrees well with MC (Alpgen+Herwig)
  - Already $\sim 100$ W+3-jet events in 1 pb$^{-1}$ of data
- Looking forward to corrected cross sections to be compared with NLO QCD predictions
  - E.g. recent predictions by BLACKHAT collaboration

Similar result available for Z+jets
Towards the Top Quark

- Theoretical cross section: 160 pb
- $p_T(e/\mu)>20$ GeV, $E_T^{\text{miss}}>20$ GeV
- 4 jets ($p_T>20$ GeV), at least one b-tagged
  - B-tag based on secondary vertex
  - Decay length significance well modeled: require $L/\sigma(L)>5.7$
- In 0.3 pb$^{-1}$: observe 11 events

![Graph showing jet multiplicity and number of events for different jet multiplicities and flavors.](image)
New Physics

Supersymmetry

Micro Black Hole
New Physics Potential

\[ M_X = \sqrt{x_1 \cdot x_2 \cdot s} \]

\[
\begin{array}{|c|c|c|}
\hline
\text{Process} & M_X & \frac{\sigma(\text{LHC @ 7 TeV})}{\sigma(\text{Tevatron})} \\
\hline
\bar{q}q \rightarrow W & 80 \text{ GeV} & 3 \\
\bar{q}q \rightarrow Z'_{\text{SM}} & 1 \text{ TeV} & 50 \\
gg \rightarrow H & 120 \text{ GeV} & 20 \\
\bar{q}q/gg \rightarrow \bar{t}t & 2 \times 173 \text{ GeV} & 15 \\
gg \rightarrow \bar{g}g & 2 \times 400 \text{ GeV} & 1000 \\
\hline
\end{array}
\]

- \( \int L \, dt = 1 \, \text{fb}^{-1} \) at LHC competitive with 10 fb\(^{-1} \) at Tevatron for many high mass processes
  - Already competing now for some new physics scenarios though!
Supersymmetry Searches

4 jets+0 leptons, $p_T^1>70$ GeV, $p_T^{2,3,4}>30$ GeV

- $E_T^{\text{miss}}>40$ GeV
- $d\phi(E_T,p_T^{\text{jet}})>0.2$
- $E_T/M_{\text{eff}}>0.2$

• Data consistent with background
  – Excellent control of missing $E_T$
• Possibly sensitive beyond Tevatron for non-mSUGRA type models already
  – Alvez, Izaguirre, Wacker: arXiv:1008.0407
Supersymmetry Searches

4 jets+0 leptons, \( p_T^1 > 70 \) GeV, \( p_T^{2,3,4} > 30 \) GeV

- 0 leptons, 3 jets, \( \geq 1 \) b-tag
- \( p_T^1 > 70 \) GeV, \( p_T^{2,3} > 30 \) GeV
- \( E_T^{\text{miss}}/\sqrt{\sum E_T} > 2 \) \( \sqrt{\text{GeV}} \)

First steps towards 3\textsuperscript{rd} generation squarks

- Data consistent with background
  - Excellent control of missing \( E_T \)
- Possibly sensitive beyond Tevatron for non-mSUGRA type models already
Dijet Resonance: q*

- $p_T^{\text{jet1}} > 80$ GeV, $p_T^{\text{jet2}} > 30$ GeV, $|\eta^{\text{jet1}} - \eta^{\text{jet2}}| < 1.3$
- No evidence for peak in dijet mass spectrum
- Constrain $m(q^*) > 1.26$ TeV
  - Supersedes published CDF limit of 0.87 TeV (with 1 fb$^{-1}$)

\[ \text{arXiv: 1008.2461} \]
\[ \text{submitted to PRL} \]
More Searches for New Physics

Search for W’ bosons

Search for high-multiplicity events (as expected from micro-Black Hole)

Background study to search for “R-hadrons” in empty bunches (split-SUSY,..)
Conclusions and Outlook

• The LHC era has started
  – LHC performance remarkable and improving week by week
    • On track for 1 fb$^{-1}$ in 2011
  – ATLAS is efficiently taking high quality
• ATLAS has made many physics measurements
  – Thanks to excellent performance of detector, simulation, reconstruction, data distribution (grid) … and many many people!
  – Major contributions to many aspects by US west coast
• If Nature is kind LHC experiments can find something in 2010/2011

Z’ H Ï?
How to get to 1 fb⁻¹?

<table>
<thead>
<tr>
<th></th>
<th>LHC (now)</th>
<th>LHC (end of 2010)</th>
<th>LHC (design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s [TeV]</td>
<td>7</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td># of colliding bunches</td>
<td>Up to 35</td>
<td>384</td>
<td>2808</td>
</tr>
<tr>
<td>Protons/bunch [10¹⁰]</td>
<td>10</td>
<td>10</td>
<td>11.5</td>
</tr>
<tr>
<td>Energy stored (MJ)</td>
<td>2.7</td>
<td>21.5</td>
<td>362</td>
</tr>
<tr>
<td>Peak Luminosity [cm⁻²s⁻¹]</td>
<td>1x10³¹</td>
<td>~1 x 10³²</td>
<td>10³⁴</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>3 pb⁻¹</td>
<td>~40 pb⁻¹ (?)</td>
<td>10-100 fb⁻¹/yr</td>
</tr>
</tbody>
</table>

(*) plan constantly adjusted in reaction to what is learned

- In following weeks
  - **Increase number of bunches each week by factor ~2**
    - Involves using “bunch trains”: 150ns separation between collisions

- 2011
  - Further focus the beam (β*: 3.5m => 2m)
  - Deliver ∫Ldt=1 fb⁻¹ (requires e.g. 30% LHC up-time at 1.5 x 10³² cm⁻²s⁻¹)