Heavy Ion Physics
with the ATLAS Detector

Iwona Grabowska-Bold (UC Irvine, AGH-UST Kraków)

On behalf of the ATLAS Collaboration

Epiphany, Kraków, Jan 10-12th, 2011
Heavy Ions at the LHC

• First lead-lead data from the LHC collected on tape in 2010,
  – Excellent performance of the LHC machine,
  – Excellent performance of the detectors,
• Huge energy jump from RHIC: a factor 14!

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s_{NN}</td>
<td>PbPb 17.3 GeV</td>
<td>AuAu 200 GeV</td>
<td>PbPb 2760 GeV</td>
</tr>
</tbody>
</table>

• Highest temperatures ever achieved in the laboratory,
• Access to new probes and processes,
• In this talk two topics are discussed:
  – Observation of a di-jet asymmetry in E_T,
  – Di-muon production: J/ψ and Z.
ATLAS Detector

Three main components: Inner tracker, electromagnetic (EM) and hadronic (HAD) calorimeters, and muon system

<table>
<thead>
<tr>
<th>Measurements</th>
<th>$\eta$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Tracker</td>
<td>(-2.5, 2.5)</td>
</tr>
<tr>
<td>Muon Spectrometer</td>
<td>(-2.7, 2.7)</td>
</tr>
<tr>
<td>EM Calorimeter</td>
<td>(-3.2, 3.2)</td>
</tr>
<tr>
<td>HAD Calorimeter</td>
<td>(-4.9, 4.9)</td>
</tr>
</tbody>
</table>

Full azimuthal acceptance
Heavy Ion Run in 2010

- First heavy ion run at $\sqrt{s_{\text{NN}}} = 2.76\,\text{TeV}$
  - Nov 4$^{\text{th}}$-Dec 6$^{\text{th}}$, 2010,
  - ATLAS recorded 9.17 $\mu\text{b}^{-1}$ of PbPb data,
  - Data recording efficiency > 95%
  - Fraction of data passing data-quality criteria > 99%

---

<table>
<thead>
<tr>
<th>Inner Tracking Detectors</th>
<th>Calorimeters</th>
<th>Muon Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>SCT</td>
<td>TRT</td>
</tr>
<tr>
<td>99.7</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76\,\text{TeV}$ between November 8$^{\text{th}}$ and 17$^{\text{th}}$ (in %).
Data Triggering

Triggering strategy:
- record to tape a minimum bias sample, trigger efficiency 100% for \( n_{\text{tracks}} > 20 \).

Main minimum bias triggers:
- Minimum Bias Trigger Scintillators (MBTS),
- Zero Degree Calorimeter (ZDC),
- Hits counting in the Inner Tracker (ID),
- The LUCID integrating Cherenkov detector

Recording rates: \(~500\) Hz in the peak

ATLAS Online Luminosity
\[ \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \]
Peak Lumi: \( 30.4 \times 10^{24} \text{ cm}^2 \text{s}^{-1} \)

Above \( 5 \times 10^{24} \text{cm}^2\text{s}^{-1} \) High Level Trigger (HLT) applied to filter out beam backgrounds and improve event selection. No selection based on physics objects like jets, muons, etc.
Minimum bias, centrality

Characterize centrality by percentiles of the total cross-section using forward calorimeter (FCal) $\Sigma E_\tau$ ($3.2 < |\eta| < 4.9$)
Jet quenching

Key question: How do parton showers in hot, dense medium differ from those in vacuum?

- Strong quenching effects were observed in single particle spectra and particle correlations at $\sqrt{s_{NN}}=200$ GeV at RHIC (indirect observation),
- Direct jet reconstruction possible at RHIC but very difficult (jet energies comparable to the underlying event energy),
- NLO QCD calculations predict abundant rates of jets above 100 GeV at the LHC,
  - This opens perspectives for the LHC experiments.
Asymmetric jets
Centrality dependent di-jet asymmetry

– Use R = 0.4 anti-\(k_T\) jets
  • calibrated using energy density cell weighting,
  • underlying event (UE) estimated and subtracted for each longitudinal layer and for 100 slices of \(\Delta \eta = 0.1\),

– Select events with leading jet, \(E_{T,1} > 100 \text{ GeV}, |\eta| < 2.8\)
  • 1693 events after cuts in 1.7 \(\mu\text{b}^{-1}\)

– Sub-leading: highest \(E_T\) jet in opposite hemisphere, \(\Delta \phi = |\phi_1 - \phi_2| > \pi/2\) with \(E_{T,2} > 25 \text{ GeV}, |\eta| < 2.8\)
  • 5% of selected have no sub-leading jet

– Introduce new variable to quantify di-jet imbalance
  • Not used before in jet quenching literature:
    – Asymmetry: \(A_j = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}}\)
    – Measurement of an azimuthal angle separation, \(\Delta \phi\).
Di-jet energy asymmetry

$$A_j = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}}$$

$$\Delta \phi = |\phi_1 - \phi_2|$$

$A_j$ broadens with centrality, the mean shifts to higher values, a new peak visible at higher centralities. The $\Delta \phi$ distribution predominantly is still back to back at higher centrality values.
The di-jet asymmetry results published in December 2010 in PRL with the ATLAS event display on the cover.
Di-lepton studies

- **Quarkonia** dissociation due to color screening is considered as a promising signature of quark-gluon plasma (QGP) formation
  - Various quarkonia states are expected to “melt” at different temperatures,

- $J/\psi$ suppression has already been seen at SPS and RHIC but details are poorly understood, interplay of cold and hot effects,

- $J/\psi$ enhancement by regeneration of $J/\psi$ from the (large) number of uncorrelated $cc$ pairs could also be tested at the LHC,

- **Weak bosons** have not been observed in Au-Au collisions at RHIC,
  - Test of nuclear PDFs,
  - Standard candle for other processes,

- This opens perspectives for the LHC experiments.
J/ψ production in ATLAS

Analysis selection:
- Integrated luminosity analyzed: 6.7 μb⁻¹,
- J/ψ→μ⁺μ⁻ channel explored,
- Primary vertex required in the minimum bias-triggered data sample,
- Muons combined in the Inner Tracker and Muon Spectrometer with \( p_T > 3 \) GeV and |\( \eta \)| < 2.5. This results in 80% of J/ψ with \( p_T > 6.5 \) GeV,
- 80-100% centrality bin excluded from the analysis.

Peripheral events

Central events

J/ψ yields in each centrality bin are obtained using a sideband technique. Fits are used as a cross check.
Hypothesis: linear scaling of a number of J/ψ with a number of binary nucleon-nucleon collisions

- Relative J/ψ yield normalized to the yield in the most peripheral bin 40-80%,
- Normalized J/ψ yield with a number of binary nucleon-nucleon collisions significantly decreases from peripheral to central collisions,
- Centrality dependence is found to be qualitatively similar to trends observed at previous, lower energy experiments.
$Z \rightarrow e^+e^-$ candidate
$Z \rightarrow \mu^+ \mu^-$ candidate
Z production

Analysis selection similar to J/ψ:
- Integrated luminosity analyzed: 6.7 μb⁻¹,
- \( Z \rightarrow \mu^+\mu^- \) channel explored,
- Primary vertex required in the minimum bias-triggered data sample,
- Muons combined in the Inner Tracker and Muon Spectrometer with \( p_T > 20 \text{ GeV} \) and |\( \eta \)|<2.5.

- First published observation of the Z boson peak at the LHC,
- 38 candidates are selected in the mass window of 66 to 116 GeV,
- No conclusion can be inferred about the Z yield scaling with a number of binary collisions, because of limited statistics.
Summary

• ATLAS recorded first lead-lead data in Nov-Dec 2010,
   – LHC machine was performing excellently,
   – Integrated luminosity about 5 times higher than expected,
   – Many millions of minimum bias events on tape to analyze,
• First physics results are coming out
     • The analysis continues to understand the asymmetry phenomenon in more detail, and look at the properties of single jets as well,
   – They show first evidence of a new era in heavy ion physics.
Back-up slides
Jet reconstruction (1)


Use anti-$k_T$ clustering algorithm

cone-like but infrared and collinear safe

- Perform anti-$k_T$ reconstruction prior to any background subtraction
  - $R = 0.4$ for main analysis
  - $R = 0.2, 0.6$ for cross-check (+ physics)
- Input: $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ towers
Jet reconstruction (2)

Take maximum advantage of ATLAS segmentation

- Underlying event estimated and subtracted for each longitudinal layer and for 100 slices of $\Delta \eta = 0.1$
  
  \[ E_{T_{\text{sub}}}^{\text{cell}} = E_T^{\text{cell}} - \rho^{\text{layer}}(\eta) \times A^{\text{cell}} \]

- $\rho$ is energy density estimated event-by-event
  
  - From average over $0 < \phi < 2\pi$

- Avoid biasing $\rho$ due to jets

  - Using anti-$k_T$ jets:
    
    - Exclude cells from $\rho$ if
      
      \[ D = \frac{E_T^{\text{tower}}}{E_T^{\max}} / \langle E_T^{\text{tower}} \rangle > 5 \]

- Cross check
  
  - Sliding Window algorithm

- NO jet removal on basis of $D$, or any other quantity
HLT Selection

- At HLT only a simple selection on a time difference between two MBTS sides is applied
  - No requirement on physics objects as jets, electrons, muons, etc.
J/ψ suppression

- J/ψ suppression in HI collisions as a function of centrality already observed in past experiments
- PHENIX measurement in Au-Au collisions @ √S_{NN}=200 GeV

\[
R_{AA} = \frac{d^2N_{J/\psi}^{AA}/dp_Tdy}{N_{coll}d^2N_{J/\psi}^{pp}/dp_Tdy},
\]

FIG. 3 (color online). J/ψ R_{AA} versus p_T for several centrality bins in Au + Au collisions. Mid (forward) rapidity data are shown with open (solid) circles. See text for description of the errors and Ref. [21] for data tables.
J/ψ in pp in ATLAS

• Cross-section and prompt / non-prompt yields measured by ATLAS
**J/ψ suppression**

**Comparison with other measurements**

\[
R_{cp}(J/\psi) = \frac{N_{\text{cent}}/\text{Width}_{\text{cent}}}{N_{\text{peri}}/\text{Width}_{\text{peri}}} R_{\text{coll}} \left( \frac{1}{\varepsilon_{\text{relative}}} \right)
\]

- **Atlas Pb+Pb** \( p_{T,\mu} > 3 \text{ GeV, } |y_{\mu}| < 2.5 \text{ } (40-80\%) \)
- **Phenix Au+Au** \( p_{T,\mu} > 0 \text{ GeV, } |y_{\mu}| < 0.35 \text{ } (40-93\%) \)

Data from P. Steinberg
Glauber fits for ATLAS

- We are using FCal energy sum, as before
  - \( R=6.62 \text{ fm}, a=0.546 \text{ fm} \) (skin depth)
- Assume both participants and collisions contribute
  - “Two component model”, controlled by parameter “x”
    \[
    \sum E_{T,FCal} = E_{T,pp} \left( 1 - x \right) \frac{N_{part}}{2} + x N_{coll}
    \]
  - \( x=0.13\pm0.01(\text{stat})\pm0.05(\text{syst}) \) found to describe RHIC data
- Incorporate FCal energy resolution and noise
  - Let detector noise be a free parameter (sum of cells)
  - Resolution assumed to be 100%/\( \sqrt{E(\text{GeV})} \)
- Input data distribution is FCal Et from mbSpTrk selection
  - Cuts requiring good vertex (>1 track), MBTS (DeltaT<3ns), ZDC (AND)