HARD PROBES IN PB-PB COLLISIONS AT ATLAS

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On behalf of ATLAS Collaboration
XLVII Rencontres de Moriond, QCD and High Energy Interactions
March 10-17th, 2012
Two runs in 2010-11 with lead-lead data from the LHC collected on tape,
- Excellent performance of the LHC machine,
- Excellent performance of the detectors,

Huge energy jump from RHIC
- factor of 14 in the center-of-mass energy!

Highest temperatures ever achieved in the laboratory,
Access to new probes and processes,
In this talk we discuss:
- Di-jets and inclusive jets
- Charged-particle spectra
- Di-muon production: $J/\psi$ and $Z$
- $W$ production.

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

Hard Probes in ATLAS, March 10-17th, 2012
ATLAS Detector

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

Measurements

<table>
<thead>
<tr>
<th></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

Hard Probes in ATLAS, March 10-17th, 2012
Heavy-Ion Runs in 2010-11

**Heavy-ion runs at** $\sqrt{s_{_{NN}}} = 2.76\text{TeV}$

- Nov 4th-Dec 6th, 2010 and Nov 12th-Dec 7th, 2011
- In 2010 ATLAS recorded $9.2~\mu b^{-1}$ of PbPb data,
  - With 1 $\mu b^{-1}$ magnetic field-off data,
  - Minimum bias triggers only,
  - Physics results based on this data set will be shown,
- In 2011 ATLAS recorded $158~\mu b^{-1}$ of PbPb data,
  - Various High Level Triggers used,
  - 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>LAr EM</td>
<td>MDT</td>
</tr>
<tr>
<td>99.7</td>
<td>99.2</td>
<td>100</td>
</tr>
<tr>
<td>SCT</td>
<td>LAr HAD</td>
<td>RPC</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>99.6</td>
</tr>
<tr>
<td>TRT</td>
<td>LAr FWD</td>
<td>CSC</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>TGC</td>
</tr>
</tbody>
</table>
| Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76\text{TeV}$ between November 8th and 17th (in %).
Characterize centrality by percentiles of the total cross-section using forward calorimeter (FCal) $\Sigma E_T$ ($3.2 < |\eta| < 4.9$)

- Peripheral collisions
- Mid-central collisions
- Central collisions
Jets in ATLAS

Hard Probes in ATLAS, March 10-17th, 2012
Anti-\( k_T \) jet reconstruction with two jet sizes 0.2 and 0.4,

- calibrated using energy density cell weighting,
- underlying event (UE) estimated and subtracted for each longitudinal layer and for 100 slices of \( \Delta \eta = 0.1 \),

- Di-jet asymmetry \( A_j \) measured for back-to-back jets,

- \( A_j \) broadens with centrality, the mean shifts to higher values and excess of events with large asymmetries at higher centralities for both jet sizes (0.2 and 0.4),

- The \( \Delta \phi \) distribution predominantly is still back-to-back at higher centrality values,

- Caveat: \( A_j \) is less sensitive to events where each jet in a di-jet pair loses a comparable amount of energy.

\[ A_j = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}} \]
- Observable which is sensitive to the \textit{``inclusive''} jet quenching in the spectrum of single jets,
- Prediction of the impact of medium-induced \textit{radiative energy loss} on the jet yield due to the radiation falling outside the reconstructed jet cone,
- ATLAS data inconsistent with this expectation
  - $R_{cp}$ similar for two jet sizes 0.2 and 0.4.

Prediction by Vitev, Zhang, Wicks

More in: ATLAS-CONF-2011-075
Another observable sensitive to the “inclusive” jet quenching is the charged fragmentation spectrum:

- **Longitudinal:** \( z = \frac{p_T^{\text{part}}}{E_T^{\text{jet}}} \cos \Delta R \)
- **Transverse:** \( j_T = p_T^{\text{part}} \sin \Delta R \)

- Radiative quenching is expected to re-distribute the energy among the final-state hadrons and suppress those with a large jet momentum fraction,

- ATLAS observes no substantial change between central and peripheral jets despite the large change in the yield.
Charged particle spectra

- Global look at hard probes via inclusive spectra at large $p_T$.
- Tracks reconstructed in Pixel+SCT in $|\eta| < 2.5$.
- ATLAS measurement agrees with ALICE result for $|\eta| < 0.8$.
- Medium modification explored via $R_{CP}$.
  - Minima around 7 GeV then rise, no $\eta$ dependence.

$$R_{CP} = \frac{N_{coll}^C}{N_{coll}^P} \frac{N_{evt}^P}{N_{evt}^C} \frac{d^2N^C/d\eta dp_T}{d^2N^P/d\eta dp_T}$$
J/ψ, Z and W in ATLAS
**J/ψ production**

**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,
- This was seen by SPS and RHIC experiments

**Analysis selection:**
- Integrated luminosity analyzed: 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 |η| < 2.5,
- This results in 80% of J/ψ with p_T > 6.5 GeV,
- No distinction between prompt and non-prompt components of J/ψ.
- $J/\psi$ yield is normalized to the 80-40% peripheral bin,
- ATLAS observes a centrality-dependent suppression of the $J/\psi$ yield,
- Consistent with the PHENIX result over $p_T$ despite different momentum ranges,
- ALICE shows the weaker suppression than ATLAS but at much larger $|\eta|$ and lower $p_T$. 

Hard Probes in ATLAS, March 10-17, 2012
First published observation of the Z boson peak in PbPb collisions 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.

Analysis selection:
- Integrated luminosity analyzed: 7 μ b⁻¹,
- Z → 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 > 20 GeV and | η | < 2.5.
W production

- Theory predicts an order of magnitude more W than Z produced at 2.76 TeV,
- Measurement of $W \rightarrow \mu \nu$ requires missing energy term to be reconstructed, which is unreliable in a Pb+Pb environment,
- Therefore, we try to rely only on a $p_T$ distribution of muons
  - Muons from W are on average more energetic than muons from QCD processes,
  - At high $p_T$ two dominating sources of single muons are $b$-quark decays and W decays,
  - Veto di-muons with $m_{\mu \mu} > 66$ GeV (Z/DY candidates),
  - Find the best estimate of number of W by fitting signal and background to data
    - Template method.

Divide Pb+Pb dataset in subsets of charge, pseudorapidity ($\eta$) and centrality and fit each subset independently.
No suppression hypothesis (flat line) is fitted to the data with $\chi^2$/dof = 5.72/3 (p=0.13).

- Result is consistent with no suppression of W bosons,
- Statistical uncertainty dominates, systematics come from a number of binary collisions and template fits,

- Ratio $R_{W/Z} = 10.5 \pm 2.3$ for $5 \ \mu b^{-1}$
  - Good agreement with Standard Model prediction!

- Precision test of W charge asymmetry provides information on PDFs,
  - Nuclear effects may give modifications to PDFs,
  - Statistical uncertainty is still limiting but with higher accumulated statistics a detailed measurement of the charge asymmetry as a function of centrality will be feasible.
ATLAS has released results on a variety of hard probes produced in heavy-ion collisions at $\sqrt{s_{NN}}=2.76$ TeV:

- Di-jets, inclusive jets, charged hadrons with high $p_T$, J/psi, weak bosons,
- Measurements based on statistics from 2010 data,
- We have $O(15)$ times more statistics from 2011 data,

First confirmation of jet quenching reported in Dec 2010 and confirmed in more advanced studies:

- Various jet sizes, di-jet asymmetry, $R_{cp}$ and fragmentation functions,

Observation of suppression of $J/\psi$ in deconfined matter which is consistent with results from earlier lower-energy experiments:

- But details are not yet understood,

Observation of no suppression for $W/Z$ bosons – their yields follow a binary scaling with centrality.
Back-up slides
$Z \rightarrow e^+ e^-$ candidate
Dijet asymmetry for 0.4 jets

Hard Probes in ATLAS, March 10-17th, 2012
Impact of medium-induced radiative energy loss on the jet yield due to the radiation falling outside the angular coverage of the jet measurement.
In 2010: Peak luminosity $3 \times 10^{25} \text{cm}^{-2}\text{s}^{-1}$ which gives 350 Hz of min bias rate at L1
- Record all min bias events to tape,

In 2011: Peak luminosity $5.1 \times 10^{26} \text{cm}^{-2}\text{s}^{-1}$ which gives 6 kHz of min bias rate at L1,
- High Level Trigger (HLT) essential to bring an output rate down to 200 Hz,
- Two approaches used:
  - Full scan reconstruction at HLT on all minimum bias events triggered by L1 (jets, muons),
  - Region-Of-Interest (RoI)-based reconstruction seeded of the lowest-$p_T$ threshold at L1 (muons, photons, electrons),
- In addition to min bias data high-$p_T$ jets, muons, electrons, photons and UPC were enhanced.

<table>
<thead>
<tr>
<th>Signature</th>
<th>Trigger</th>
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</thead>
<tbody>
<tr>
<td>Jets</td>
<td>single jet $p_T &gt; 20 \text{ GeV}$</td>
</tr>
<tr>
<td>Muons</td>
<td>single muon $p_T &gt; 4 \text{ GeV}$, di-muon $p_T &gt; 2 \text{ GeV}$</td>
</tr>
<tr>
<td>Egamma</td>
<td>single egamma $p_T &gt; 14 \text{ GeV}$, di-egamma $p_T &gt; 5 \text{ GeV}$</td>
</tr>
<tr>
<td>UPC</td>
<td>low track multiplicity cut</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stream</th>
<th>Events Taken</th>
<th>Reco CPU/evt [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Bias</td>
<td>60M</td>
<td>70</td>
</tr>
<tr>
<td>Hard Probes</td>
<td>54M</td>
<td>140</td>
</tr>
<tr>
<td>UPC</td>
<td>6.6M</td>
<td>30</td>
</tr>
</tbody>
</table>

Hard Probes in ATLAS, March 10-17th, 2012
Earlier J/ψ measurements

- J/ψ suppression in HI collisions as a function of centrality already observed in past experiments
- Various experiments roughly consistent with each other
- Possible dependence on rapidity and also transverse momentum.
MC control plots

MC samples with superimposed $J/\psi$ events from pp at $\sqrt{s}=2.76$ TeV from PYTHIA onto PbPb events from HIJING,

- MC used for reconstruction efficiency determination,
- For comparisons tracks selected with $p_T>500$ MeV,
- Two centrality bins explored: 0-10% and 40-80%,
  - MC describes data very well
  - Also centrality dependence reproduced.
Systematic uncertainties for $J/\psi$

- **Reconstruction efficiency**
  - Variation of the reconstruction efficiency with centrality due to the larger occupancy in the Inner Tracker,
  - Stringent track quality requirements are made w.r.t. the pp ones,

- **Extraction of a number of signal events**
  - Use un-binned maximum likelihood fit with mass resolution as a free parameter,
  - Explore two different background parameterizations with a first or second order polynomial.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Reco. eff. [%]</th>
<th>Sig. extr. [%]</th>
<th>Total syst. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>6.8</td>
<td>5.2</td>
<td>8.6</td>
</tr>
<tr>
<td>10-20%</td>
<td>5.3</td>
<td>6.5</td>
<td>8.4</td>
</tr>
<tr>
<td>20-40%</td>
<td>3.3</td>
<td>6.8</td>
<td>7.5</td>
</tr>
<tr>
<td>40-80%</td>
<td>2.3</td>
<td>5.6</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Central events Pb

Peripheral events Pb Pb

25
ATLAS published results on $J/\psi \rightarrow \mu \mu$ studies in PbPb collisions so far,
Aim for using pp data at $\sqrt{s} = 2.76$TeV for normalization,
In 2011 we increased our statistics by a factor of 15,
- Access to prompt and non-prompt components of $J/\psi$,
- Access to other resonances,
Further PbPb results will be reported soon.
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 in HI collisions as a function of centrality already observed in past experiments

PHENIX measurement in Au-Au collisions @ √S_{NN}=200 GeV

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

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.
Cross-section and non-prompt / prompt yields measured by ATLAS

Nuclear Physics B 850 (2011), 387
Muons in 2011 data

**J/ψ** mass window in the muon channel

**Inclusive muon spectrum**

**J/ψ** mass window in the muon channel in UPC

**Z** mass window in the muon channel
Glauber fits for ATLAS

- We are using FCal energy sum, as before
  - R=6.62 fm, a=0.546 fm (skin depth)
- Assume both participants and collisions contribute
  - "Two component model", controlled by parameter "x"
    \[ \sum E_{T,FCal} = E_{T,pp} \left( (1 - x) \frac{N_{part}}{2} + x N_{coll} \right) \]
  - x=0.13±0.01(stat)±0.05(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(GeV)}
- Input data distribution is FCal Et from mbSpTrk selection
  - Cuts requiring good vertex (>1 track), MBTS (DeltaT<3ns), ZDC (AND)