Heavy Ion results from ATLAS experiment

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on the Physics in LHC Run2
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ATLAS detector

Three main subsystems:
- Inner detector – tracking
- Calorimetry
- Muon Spectrometer
ATLAS detector

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Calorimetry
- EM & HCal $|\eta| < 3.2$
- Jets, Photons, Electrons
ATLAS detector

Inner detector – tracking
• $p_T > 0.5$ GeV & $|\eta| < 2.5$
• Charged hadrons spectra
• Correlations

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FCal – Forward calorimeter
• $3.1 < |\eta| < 4.9$
• Collision centrality & event shape
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Muons reconstruction - combined information from ID/Calo/MS
Datasets & physics goals

Datasets collected in 2010-2015

<table>
<thead>
<tr>
<th>Datasets</th>
<th>Energy (TeV)</th>
<th>Year(s)</th>
<th>Luminosity (μb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb+Pb</td>
<td>2.76</td>
<td>2010 &amp; 2011</td>
<td>160</td>
</tr>
<tr>
<td>Pb+Pb</td>
<td>5.1</td>
<td>2015</td>
<td>680</td>
</tr>
<tr>
<td>p+Pb</td>
<td>5.02</td>
<td>2013</td>
<td>28</td>
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<td>p+p</td>
<td>2.76</td>
<td>2013</td>
<td>4</td>
</tr>
<tr>
<td>p+p</td>
<td>13</td>
<td>2015</td>
<td>27</td>
</tr>
</tbody>
</table>

28 papers & 49 public conference notes
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Study the strongly coupled QGP using soft and hard probes by

- Collective response of the plasma to the initial conditions
- Modification of the energetic parton shower in the plasma
- Calibrate observed phenomena to p+Pb and p+p collisions
Study of the QGP with collective flow

\[
\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_2)
\]
Study of the QGP with collective flow

\[
\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_2)
\]

\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n \cos n(\phi - \Phi_n)
\]

\(v_n\) harmonics sensitive to initial shape of the interaction region & viscosity of the QGP

- Larger initial shape fluctuation lead to larger \(v_n\)’s
- Small viscosity ensure efficient transport of the initial shape (fluctuation) to the final state
Differential measurements of $v_n$ harmonics

• $v_n$ harmonics measured in the broad centrality, $p_T$ & $\eta$ range

• Different sensitivity to $v_n$’s fluctuations of the different measurement methods

• Provides constraint to the hydro models
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More details in K. Burka talk tomorrow 3:12pm
Event by event flow harmonics

- Unfolded probability distributions of the $E_{\text{byE}}$ $v_n$'s - new observables (also $E_{\text{byE}}$ event plane angles correlations)

- Impose even stronger constraint on the hydro models
Event by event flow harmonics

- Unfolded probability distributions of the EbyE $v_n$’s - new observables (also EbyE event plane angles correlations )

- Impose even stronger constraint on the hydro models

- Very good consistency between cumulant and EbyE measurement
Event shape engineering

- 1st order event shape selection: Centrality (Sum Et FCal) **system size**
- 2nd order event shape selection: ellipticity by $v_2^{\text{obs}}$ **system shape**
- 2nd order event shape selection: triangularity $v_3^{\text{obs}}$ **system shape**

- Selecting events with the same geometric size but different ellipticity
Event shape engineering

Correlation between $v_2$ and higher order flow harmonics

Fit with a two component function with linear and non-linear response terms

- Selecting events with the same geometric size but different ellipticity
Eccentricity scaling

- Separate “linear” and “non-linear” components
- Linear component has weak centrality dependence, non-linear component has strong centrality dependence
- Consistent with results from event plane correlations
Eccentricity scaling

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Flow in small systems

Approximately:
- 30,000 particles*
- 1,000 particles*
- 150 particles*

*Raw number of charged particles (integrated over entire phase space) produced in events with high activity

What is the smallest droplet of the QGP created in these collisions?
Flow in small systems

p+Pb and p+p collisions reveal collective/flow like behavior
Flow in small systems

• Measurement of two-particle correlation in p+Pb and p+p
• New method (template) for p+p measurement reduces bias in ZYAM
• Weak trend as a function of $N_{ch}$ and beam energy
• Phenomenon not restricted to only high multiplicity events

ATLAS p+Pb
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ L_{\text{int}} \approx 28 \text{ nb}^{-1} \]
Flow in small systems

- Characteristic “hydrodynamic like” $p_T$ dependence

Open questions:
- Does the observation of the collectivity in NN imply any quantitative consequences in AA?
- Is the final state particle anisotropy a reflection of the initial state like in AA?
Study of the QGP with hard probes

Leading particle

JHEP09 (2015) 050
Study of the QGP with hard probes

Leading particle

Jet sub-structure

JHEP09 (2015) 050

PLB 739 (2014) 320-342
Updated in
ATLAS-CONF-2015-055
ATLAS-CONF-2015-022 (pPb)
Study of the QGP with hard probes

Leading particle

Jet sub-structure

Di-jets

PLB 739 (2014) 320-342
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JHEP09 (2015) 050

PRL 105 (2010) 252303
Updated in
ATLAS-CONF-2015-052
Study of the QGP with hard probes

Leading particle

Jet sub-structure

Di-jets

Path-length dependence

JHEP09 (2015) 050

PLB 739 (2014) 320-342
Updated in ATLAS-CONF-2015-055
ATLAS-CONF-2015-022 (pPb)

PRL 105 (2010) 252303
Updated in ATLAS-CONF-2015-052

PRL 111, 152301 (2013)
ATLAS-CONF-2015-052
Study of the QGP with hard probes

- Leading particle: JHEP09 (2015) 050
- Flavor & color dependence: Z/γ, W
Z boson production

- No centrality dependence
- Can be used as a calibration tool to investigate energy loss of color object created in association with Z boson

PRL 110, 022301 (2013)

**ATLAS**
Pb+Pb \( s_{NN} = 2.76 \) TeV
Data 2011 \( L_{int} = 0.15 \) nb\(^{-1}\)
\begin{align*}
\text{All } p_T^Z \\
10 < p_T^Z < 30 \text{ GeV} \\
p_T^Z > 30 \text{ GeV}
\end{align*}

\begin{align*}
&\Delta Z \rightarrow ee \\
&\blacklozenge Z \rightarrow ll \\
&\blacktriangledown Z \rightarrow \mu\mu
\end{align*}

PRL 110, 022301 (2013)

**ATLAS**
p+Pb 2013, \( L_{int} = 29 \) nb\(^{-1}\)
\( s_{NN} = 5.02 \) TeV

\begin{align*}
10^3 (dN_Z/dy_Z)/(dN/dn) \\
10^3 (dN_Z/dy_Z)/(dN/dn)
\end{align*}

**Glauber** (\( \omega_o=0 \))

**GGCF** (\( \omega_o=0.11 \))

**GGCF** (\( \omega_o=0.2 \))

- Z boson production used to test Glauber model extension for fluctuations of the underlying nucleon-nucleon cross section
W bosons production

- No centrality dependence of the W production
- Glauber model extension for fluctuations of the underlying nucleon-nucleon cross section in pPb
Initial conditions – parton distributions

\[ A_l = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}} \]

\( A_l \) sensitive to nuclear modification of PDF + spin conservation in W boson production

No sensitivity for nuclear modifications within the experimental precision of Run1 Pb+Pb data

**RFC\( \eta \) - forward-to-central production ratio of direct photons**

**ARXIV:1506.08552**
In medium energy loss leads to suppression in leading particle and jet yield

\[ R_{AA} = \frac{dN_{cent} / dp_T}{\langle T_{AA}^{cent} \rangle d\sigma^{pp} / dp_T} \]

\[ \langle T_{AA}^{cent} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{pp} \]
Nuclear modification factor for high $p_T$ particles and jets - PbPb

In medium energy loss leads to suppression in leading particle and jet yield

$$R_{AA} = \frac{dN^{cent}}{dp_T} \frac{\langle T^{cent}_{AA} \rangle d\sigma^{pp}}{dp_T}$$

$$\langle T^{cent}_{AA} \rangle = \langle N_{coll} \rangle / \sigma^{pp}_{inel}$$

- Suppression of the factor of 2 in the most central collisions
- Measured up to 400 GeV, for the first time possible hints of the increase of $R_{AA}$ with $p_T$
- $R_{AA}$ shows little dependence on $y$
Nuclear modification factor for high $p_T$ particles and jets - pPb

No large deviations observed in the inclusive $R_{pPb}$

**ATLAS**

$+2.1 < y^* < +2.8$

$+0.8 < y^* < +1.2$

$-0.3 < y^* < +0.3$

$-1.2 < y^* < -0.8$

$|s_{NN} = 5.02$ TeV

anti-$k_T$, $R=0.4$

EPS09 calculation
Nuclear modification factor for high $p_T$ particles and jets - $pPb$

No large deviations observed in the inclusive $R_{pPb}$

At large energy see correlation between hard scattering and total event activity

Suggestive that geometric size of proton correlated with $x$ of hard scattering

EPS09 calculation
Modification of the jet sub-structure

\[ D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz} \]

\[ z = \frac{p_{T}^{\text{trk}}}{p_{T}^{\text{jet}}} \cos \Delta R \]

Significant modifications at high \( z \) observed in updated result in Pb+Pb
Modification of the jet sub-structure

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Modifications at high \( z \) in p+Pb?
5 TeV p+p reference from run2 crucial for this study.

MC based extrapolation of p+p at 2.76 to 5.02 TeV
Di-jets asymmetry

\[ A_j = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}} \]

2D unfolding of di-jet \((p_{T1}, p_{T2})\) spectra

\[ x_j = \frac{p_{T2}}{p_{T1}} \]

Account for \(p_T\) migration and switch between \(p_{T1}\) & \(p_{T2}\)

- In p+p most probable configuration is \(x_j \sim 1\) balanced di-jets
- In central Pb+Pb most probable configuration is \(x_j \sim 0.5\) – half of the jet energy is deposited in the medium

Can be directly compared with theory
Jet quenching path length dependence

\[ R_{AA}(\phi) = R_{AA} \left[ 1 + 2v_2 \cos 2\Delta \phi \right] \]

\[ \Delta \phi = \phi_{\text{jet}} - \Phi_2 \]
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\[ R_{AA}(\phi) = R_{AA} \left[ 1 + 2v_2 \cos 2\Delta\phi \right] \]

\[ \Delta\phi = \phi_{\text{jet}} - \Phi_2 \]

- Decrease of jet \( v_2 \) at high \( p_T \) consistent with smaller quenching (larger \( R_{AA} \) at high \( p_T \))
- Very small, but significant anti-correlation between EP angle and \( \langle A_j \rangle \)
Summary

- Many observables to study hydrodynamic response to EbyE fluctuating initial conditions
- Variety of measurements of vector bosons in both Pb+Pb and p+Pb do not reveal (yet) the modification of the nuclear parton distributions
- Jet probes of heavy ion collisions provide detailed information about the physics of jet-quenching
- Studying small collisions systems (p+Pb, p+p) reveal unexpected phenomena
  - Observed collectivity in the p+Pb and p+p collisions
  - Jets in p+Pb – proton size depends on x

Run2 data (Pb+Pb and p+p) will substantially help to understand the phenomena observed in Run1

\[ N_{jet/W/Z/\gamma} = [L_{AA} \sigma_{AA \rightarrow jet/W/Z/\gamma}] \]

Both factors higher in run 2