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"Review of ATLAS results on heavy ion collisions"

ISCRA 2019
International Symposium on Cosmic Rays and Astrophysics
25-28 June 2019, MEPhI, Moscow
Outline:

• Reminder of ATLAS instrumentation.
• Run1 and Run 2 accumulated data summary.
• Photon-photon interaction with HI:
  ✓ Observation of the light-by-light scattering.
  ✓ Dimuon production from UPC.
  ✓ Observation of centrality-dependent acoplanarity of dimuon pairs from non-UPC.
• Flow and two-particle correlation.
• Propagation of partons through QGP:
  ✓ Jet “quenching”.
  ✓ Dijet asymmetry.
  ✓ Photon-jet transverse momentum correlations.
  ✓ Quarkonia production.
  ✓ Summary: $R_{AA}$ as function of $p_T$. 
ATLAS Instrumentation.

- Diameter: 25m, Length: 46m
- Barrel toroid length 26 m
- Overall weight 7 000 tones
- ~ 100 million electronic channels
- ~ 3 000 km of cables

Magnetic field:
- solenoid magnet 2T
- toroid magnets 4T

The pseudorapidity is defined in terms of the polar angle $\theta$, as $\eta = -\ln(\tan(\theta/2))$.

The MePHi team plays an important role in the TRT and in the NSW.

<table>
<thead>
<tr>
<th>Detector component</th>
<th>Required resolution</th>
<th>$\eta$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{p_T}/p_T = 0.05% p_T \oplus 1%$</td>
<td>Measurement: $\pm 2.5$</td>
</tr>
<tr>
<td>Tracking</td>
<td>$\sigma_E/E = 10%/\sqrt{E} \oplus 0.7%$</td>
<td>Trigger: $\pm 2.5$</td>
</tr>
<tr>
<td>EM calorimetry</td>
<td>$\sigma_E/E = 50%/\sqrt{E} \oplus 3%$</td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>Hadronic calorimetry (jets)</td>
<td>$\sigma_E/E = 100%/\sqrt{E} \oplus 10%$</td>
<td>$3.1 &lt;</td>
</tr>
<tr>
<td>barrel and end-cap</td>
<td></td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>forward</td>
<td></td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>$\sigma_{p_T}/p_T = 10%$ at $p_T = 1$ TeV</td>
<td>$\pm 2.7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trigger: $\pm 2.4$</td>
</tr>
</tbody>
</table>
ATLAS calorimeters. ATLAS was designed for gamma, jet and leptons detection.

In addition two Zero Degree Calorimeters (ZDC) were used for HI runs.
Accumulated HI-data with Run1 and Run2

<table>
<thead>
<tr>
<th>System</th>
<th>Years</th>
<th>$\sqrt{s_{NN}}$, [TeV]</th>
<th>$L^{\text{ATLAS}}<em>{\text{int}} \approx L^{\text{CMS}}</em>{\text{int}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-Pb</td>
<td>2010-2011</td>
<td>2.76</td>
<td>~0.14 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>5.02</td>
<td>~0.49 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>5.02</td>
<td>~1.7 nb$^{-1}$</td>
</tr>
<tr>
<td>Xe-Xe</td>
<td>2017</td>
<td>5.44</td>
<td>~3 μb$^{-1}$</td>
</tr>
<tr>
<td>p-Pb</td>
<td>2013</td>
<td>5.02</td>
<td>~29 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>5.02, 8.16</td>
<td>~0.5 nb$^{-1}$, ~0.16 pb$^{-1}$</td>
</tr>
<tr>
<td>pp</td>
<td>2011-2013</td>
<td>2.76, 8</td>
<td>~4 pb$^{-1}$, ~19.4 fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015, 2017</td>
<td>5.02</td>
<td>~270 pb$^{-1}$</td>
</tr>
</tbody>
</table>
Role of impact parameter.

Impact parameter and nucleus radius (or A) control most features of hadronic A-A collisions (multiplicity, hard processes rates, collective flow), deviations from geometric scaling led to discoveries, like jet quenching. The impact parameter is measured with the centrality and/or multiplicity of charge particles.

EM interaction at large impact parameters with no hadronic interaction = Ultra-peripheral collisions (UPC)
- Cross-section of the EM interactions enhanced by a large charge of Pb (~200b for single Pb dissociation).
- UPC: events with low activity: low track multiplicity and a clean signal in the barrel calorimeter.
Centrality of the collisions defined with energy deposited in both sides of the Forward Calorimeter $3.1<\eta<4.9$ (minimum bias events).

ATLAS CONF 2017-011
Nuclear overlap function:

\[ \langle T_{AA} \rangle = \frac{\langle N_{\text{coll}} \rangle}{\sigma_{\text{NN}}^{\text{inel}}} \]

For Pb-Pb:

<table>
<thead>
<tr>
<th>Centrality range</th>
<th>( \langle N_{\text{part}} \rangle )</th>
<th>( \langle T_{AA} \rangle ) [1/mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>70–80%</td>
<td>15.4 ± 1.0</td>
<td>0.22 ± 0.02</td>
</tr>
<tr>
<td>60–70%</td>
<td>30.6 ± 1.6</td>
<td>0.57 ± 0.04</td>
</tr>
<tr>
<td>50–60%</td>
<td>53.9 ± 1.9</td>
<td>1.27 ± 0.07</td>
</tr>
<tr>
<td>40–50%</td>
<td>87.0 ± 2.3</td>
<td>2.63 ± 0.11</td>
</tr>
<tr>
<td>30–40%</td>
<td>131.4 ± 2.6</td>
<td>4.94 ± 0.15</td>
</tr>
<tr>
<td>20–30%</td>
<td>189.1 ± 2.7</td>
<td>8.63 ± 0.17</td>
</tr>
<tr>
<td>10–20%</td>
<td>264.0 ± 2.8</td>
<td>14.33 ± 0.17</td>
</tr>
<tr>
<td>0–10%</td>
<td>358.8 ± 2.3</td>
<td>23.35 ± 0.20</td>
</tr>
</tbody>
</table>
The photon – photon HI interaction.

- Electromagnetic field of relativistic HI could be considered with Weizsacker-Williams method, using the standard route of the Feynman rules. It opens a possibility for studying photon-photon, photon-gluon, photon-nucleus physics.

- We will consider:
  ✓ Ultra-peripheral collision, hadrons of nucleus are not participate in the interaction. It is a coherent reaction, photon flux from each nucleus is $\sim Z^2$.
  ✓ Muon pair production at pre-colliding stage. This is a new method for probing the electromagnetic field inside colliding nuclei.
Display of an event with large rapidity gap taken with the ZDC_XOR trigger, firing on more than one spectator neutrons on one side and no neutrons on the other side. Rapidity gap is on the side with no neutrons in the ZDC. Event has two jet candidates.
Observation of light-by-light scattering in ultra peripheral Pb+Pb collisions at 2015 and 2018 Pb+Pb data

Feynmann diagram of the LbyL scattering, $\gamma\gamma \rightarrow \gamma\gamma$. This process proceeds via the virtual one-loop box diagram involving fermions or $W\pm$ bosons. In various extensions of the Standard Model (SM), also contributions from non-SM particles are possible, thus measurement of the LbyL scattering is sensitive to the new physics.
Two back-to-back photons ($E_T^{\gamma 1} = 3.1\text{ GeV}$ and $E_T^{\gamma 2} = 3.0\text{ GeV}$) are with an invariant mass of $9\text{ GeV}$, $A_\phi$ of 0.003, diphoton transverse momentum is more than $0.2\text{ GeV}$ and no additional activity in the detector are presented. All calorimeter cells with various $E_T$ thresholds are shown: $E_T > 400\text{ MeV}$ for EMB, EMEC and Tile, $E_T > 800\text{ MeV}$ for HEC, and $E_T > 1000\text{ MeV}$ for FCal. All charged-particle tracks with $p_T > 100\text{ MeV}$ are shown.
Light by Light scattering observation in 2018

ATLAS 2015

Luminosity: 0.48 nb⁻¹

Fiducial acceptance: \( E_T \gamma > 3 \text{ GeV}, |\eta| < 2.37, M_{\gamma\gamma} > 6 \text{ GeV}, p_{T\gamma\gamma} < 2 \text{ GeV}, A_{\text{co}} < 0.01 \)

Candidates/Expected background: 13/2.6 ± 0.7

Significance: 4.4 σ

ATLAS 2018

Luminosity: 1.7 nb⁻¹

Fiducial acceptance: \( E_T \gamma > 3 \text{ GeV}, |\eta| < 2.37, M_{\gamma\gamma} > 6 \text{ GeV}, p_{T\gamma\gamma} < 2 \text{ GeV}, A_{\text{co}} < 0.01 \)

Candidates/Expected background: 59/12 ± 3

Significance: 8.2 σ observation!

Acoplanarity: \( A_{\text{co}} = 1 - |\Delta \phi|/\pi \)
Event display for the highest-mass dimuon event recorded in the Pb+Pb data that passes all analysis selections. All tracks with $p_T>500$ MeV and all calorimeter cells with $E>500$ MeV are shown.
\( \mu^+\mu^- \) from UPC

MS: a track with low PT thresh. \( E_T \) Cal<50 GeV
HLT: track with \( P_T > 400 \) MeV
N events= 248095

integrated luminosity 515 \( \mu \text{b}^{-1} \)

Acoplanarity distributions for different selections in pair rapidity
\((0 < |Y_{\mu\mu}| < 0.8, 0.8 < |Y_{\mu\mu}| < 1.6, 1.6 < |Y_{\mu\mu}| < 2.4)\) for \( 10 < M_{\mu\mu} < 100 \) GeV.
The region under the dotted line gives a fraction of the data which is estimated to be background by extrapolating the background contribution down to \( \text{Aco}=0 \).
Observation of centrality-dependent acoplanarity for muon pairs via $\gamma\gamma \rightarrow \mu^+\mu^-$ in non-UPC

Integrated luminosity 0.49 nb$^{-1}$

ATLAS

$\sqrt{s_{\text{NN}}} = 5.02$ TeV

Pb+Pb, 0.49 nb$^{-1}$

FIG. 2. The background-subtracted distributions are shown for both data distributions are consistent with zero at the largest distributions from the collisions, the are not a significant contribution. A clear, centrality-Drell-Yan and

In peripheral collisions, similar to UPC/Starlight. In central, substantially broadened.

Data reveals balance of $P_T$


$\frac{1}{dN_s/dA}$ for different centrality intervals.

ATLAS
$\sqrt{s_{NN}} = 5.02$ TeV
Pb+Pb, 0.49 nb$^{-1}$

$A \equiv \frac{|p_T^+ - p_T^-|}{p_T^+ + p_T^-}$
Flow & two-particle correlation.

**Two-particle correlation method:**

\[
C(\phi_a, \phi_b, \eta_a, \eta_b) = \frac{\frac{d^4 N}{d\phi_a d\eta_a d\phi_b d\eta_b}}{\frac{d^2 N}{d\phi_a d\eta_a} \times \frac{d^2 N}{d\phi_b d\eta_b}}.
\]

In practice, the correlation function is usually studied as a function of relative azimuthal angle ($\Delta \phi$) and relative pseudorapidity ($\Delta \eta$), by averaging pair distributions over the detector acceptance:

\[
C(\Delta \phi, \Delta \eta) = \frac{S(\Delta \phi, \Delta \eta)}{B(\Delta \phi, \Delta \eta)}
\]
Long-range azimuthal correlations.

ATLAS Preliminary
\( s_{NN}=5.44 \text{ TeV}, 3 \mu b^{-1} \)
Xe+Xe

Two-particle correlations in \( \Delta \phi \) for \(| \Delta \eta | \in (2,5) \) and \( 2<p_T^{a,b}<3 \text{ GeV} \).

Each panel is a different centrality bin. Also shown is a Fourier fit to the correlation, that includes harmonics up to \( n=6 \).
Flow, $v_n$ in Xe+Xe and Pb+Pb collisions ratios

Anisotropic spatial collective motion could be described by a Fourier expansion of particles distribution in azimuthal angle $\phi$: $$\frac{dN}{d\phi} = \frac{N}{2\pi} \left( 1 + 2 \sum_{n=1}^{\infty} v_n(p) \cos[n(\phi - \Psi_n(p))] \right)$$

Higher order coefficients are associated with fluctuations of nucleon positions in the overlap.

The ratio of the Xe+Xe $v_n$ to the Pb+Pb $v_n$ as a function of centrality. From top to bottom each row corresponds to a different $n$. From left to right the three columns correspond to $p_T$ ranges of 0.5-1 GeV, 1-2 GeV and 2-3 GeV, respectively. The ratios are compared to theoretical prediction.
Parton propagation in “QGP”.

• Nuclear modification factor \( R_{AA} \) is a universal variable for parton propagation through strongly interacting hot high density nuclei matter (or QGP).

• Di-jet asymmetry, gamma-jet asymmetry are complimentary to \( R_{AA} \).
Nuclear modification factor.

\[ R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{Xe}+\text{Xe}}/d\eta dp_T}{d^2 \sigma_{pp}/d\eta dp_T} \]

Nuclear overlap function:

\[ \langle T_{AA} \rangle = \frac{\langle N_{\text{coll}} \rangle}{\sigma_{\text{inel}}} \]


ATLAS-CONF-2018-007

Charged hadron production cross-sections as a function of \( p_T \) measured in Xe+Xe collisions at \( \sqrt{s_{\text{NN}}} = 5.44 \text{ TeV} \) for five centrality intervals: 0-5%, 10-20%, 30-40%, 50-60% and 60-80%.

Significant suppression was observed in AA collisions.
Jet “quenching” (Jet $R_{AA}$).


- Strong suppression is observed by all LHC experiments
- No significant $\sqrt{s_{NN}}$ dependence is observed
- Theoretical models reproduce trends

Linear Boltzmann Transport (LBT - 1503.03313)
Soft Collinear Effective Field Theory (SCETg - 1509.02936)
Effective Quenching (EQ - 1504.05169)

arXiv:1011.6182
Dijet asymmetry in Xe+Xe and pp collisions.

Peripheral Xe+Xe consistent with pp in central collisions a shift in $x_J$ is observed.
Dijet asymmetry in Xe+Xe and pp collisions.

Consistency between Xe+Xe and Pb+Pb
Photon-jet transvers momentum correlation.


\[ x_{J\gamma} = \frac{p_T^{\text{jet}}}{p_T^{\gamma}} \]

The jet-to-photon transverse momentum ratio

**ATLAS**

\( pp \) 5.02 TeV, 25 pb\(^{-1}\)
\( Pb+Pb \) 5.02 TeV, 0.49 nb\(^{-1}\)

\( p_T^{\gamma} = 100-158 \text{ GeV} \)

- \( pp \) (same each panel)
- \( Pb+Pb \)
Photon-jet transvers momentum correlation.

“These results are sensitive to how partons initially produced opposite to a high-$p_T$ photon lose energy in their interactions with the hot nuclear medium. Taken together with other measurements of single-jet and dijet production, the data provide new, complementary information about how energy loss in the strongly coupled medium varies with the initial parton flavour and $p_T$.”

Quarkonia production.

The pseudo-proper decay time, $\tau$

$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}},$$

$L_{xy}$ is the distance between position of the reconstructed dimuon vertex and primary vertex projected onto the transverse plane.

Strong centrality dependence with similar suppression magnitude.
$\psi(2S)/J/\psi$ ratio.

Non-prompt $\psi(2S)$ to $J/\psi$ ratio corresponds to the fact that both mesons originate from $b$-quarks.
Data at high $p_T$ were described by color screening and energy loss models well, but they missed low $p_T$. And some models agree at low $p_T$, but fail at high $p_T$. 

The hypothesis of suppression universality of several different probes leads that prompt $J/\psi$ may also be sensitive to parton energy loss.
Outlook.

• Very intensive data analysis of 1.75nb\(^{-1}\) recorded by ATLAS during 2018 Pb+Pb @ 5.02 TeV data acquisition is running. The statistics of 2018 is larger by factor of 3.5 than in 2015. Peak luminosity of 6x10\(^{27}\) cm\(^{-2}\)s\(^{-1}\) reached several times, it is good prospects for the Run 3.

• Not covered topics:
  - Jet fragmentation functions at 5.02 TeV - 1805.05424
  - Flow cumulates - 1807.02012
  - J/\(\psi\) elliptic flow - 1807.05198 R\(_{AA}\) and muon flow-1805.05220
  - Heavy electroweak boson production in Pb+Pb collisions with ATLAS
  - ATLAS results on flow fluctuations in heavy ion collisions
Backup.
ATLAS Collaboration

183 institutions (232 individual institutes) from 38 countries
ATLAS trigger system

Schematic view of the trigger towers used as the input to the L1Calo trigger algorithms

DOI 10.1140/epjc/s10052-017-4852-3
ATLAS calorimeters for HI runs.
Electromagnetic field of relativistic HI could be considered with Weizsacker-Williams method, using the standard route of the Feynman rules. It opens a possibility for studying photon-photon, photon-gluon, photon-nucleus physics. Photons flux of a nucleus $Z^2$, probability $\gamma \gamma Z^4$.

The nucleus excitation level could be controlled with FCal and ZDC. Photo-nuclear dijet production is a nice example.
Distributions of ZDC energy in the photon-going and nucleus-going direction for events satisfying the UPC trigger. The vertical line indicates the location of the single-neutron selection applied in the analysis.

Centrality of the collisions defined with energy Deposited in both sides of the Forward Calorimeter 3.1<\eta<4.9 (minimum bias events).
Flow

Two particle correlation method.

\[ C(\phi_a, \phi_b, \eta_a, \eta_b) = \frac{d^4 N}{d\phi_a d\eta_a d\phi_b d\eta_b} \times \frac{d^2 N}{d\phi_b d\eta_b}. \]

In practice, the correlation function is usually studied as a function of relative azimuthal angle (\( \Delta \phi \)) and relative pseudorapidity (\( \Delta \eta \)), by averaging pair distributions over the detector acceptance:

\[ C(\Delta \phi, \Delta \eta) = \frac{S(\Delta \phi, \Delta \eta)}{B(\Delta \phi, \Delta \eta)}. \]

**ATLAS**

Pb-Pb at \( \sqrt{s_{NN}} = 2.76 \) TeV

L_{int} = 8 \mu b^{-1}

2 < p_{T}^{a}, p_{T}^{b} < 3 \text{ GeV}
Prompt $J/\psi$ $R_{AA}$ as a function of $N_{\text{part}}$.

Both models foresee the decrease in the double ratio, but fail in describing simultaneously all centralities.