Overview of recent results from the ATLAS experiment

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Kraków, Poland, Sept 18th, 2017
INTRODUCTION

➤ Use variety of final states to provide insight into various stages of heavy-ion (HI) collision

➤ Hard probes:

➤ Colorless objects e.g. electroweak bosons – standard candles in the medium, look for nuclear effects on PDFs

➤ Color objects e.g. jets, hadrons – insight into partonic energy loss in the QGP

➤ Bulk particle production:

➤ Sensitivity to initial geometry, initial conditions, collective behaviour, etc

➤ Disentangle initial- and final-state effects using p+Pb and pp systems

➤ Ridge measurements suggest collective behaviour: systematic study vs. energy, system, and multiplicity to try and disentangle the original of this behaviour

One of the main goals of heavy-ion physics is to study the QGP
Three main components: inner tracker, electromagnetic (EM) and hadronic (HAD) calorimeters, and muon system.

Full azimuthal acceptance

Sub-detectors $|\eta|$ coverage

| Sub-detectors       | $|\eta|$ coverage |
|---------------------|-------------------|
| Inner Tracker       | <2.5              |
| Muon                | <2.7              |
| EM Calorimeter      | <3.2              |
| HAD                 | <4.9              |
| ZDC                 | >8.3              |
HEAVY-ION DATA SETS

➤ Run 1 (2010-2013) provided collisions of pp, p+Pb and Pb+Pb systems
   ➤ In addition to the bulk of pp data at 0.9, 7 and 8 TeV at high luminosity

➤ In Run 2 (2015-present) the center-of-mass energy has almost been doubled
   ➤ Opportunity to study energy dependence 2.76 TeV vs 5.02 TeV

<table>
<thead>
<tr>
<th>System</th>
<th>Year</th>
<th>$\sqrt{s_{NN}}$ [TeV]</th>
<th>$L_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb+Pb</td>
<td>2011</td>
<td>2.76</td>
<td>0.14 nb$^{-1}$</td>
</tr>
<tr>
<td>pp</td>
<td>2012</td>
<td>8</td>
<td>19.4 fb$^{-1}$</td>
</tr>
<tr>
<td>pp</td>
<td>2013</td>
<td>2.76</td>
<td>4 pb$^{-1}$</td>
</tr>
<tr>
<td>p+Pb</td>
<td>2013</td>
<td>5.02</td>
<td>29 nb$^{-1}$</td>
</tr>
<tr>
<td>low-mu pp</td>
<td>2015-16</td>
<td>13</td>
<td>0.9 pb$^{-1}$</td>
</tr>
<tr>
<td>pp</td>
<td>2015</td>
<td>5.02</td>
<td>28 pb$^{-1}$</td>
</tr>
<tr>
<td>Pb+Pb</td>
<td>2015</td>
<td>5.02</td>
<td>0.49 nb$^{-1}$</td>
</tr>
<tr>
<td>p+Pb</td>
<td>2016</td>
<td>5.02</td>
<td>0.5 nb$^{-1}$</td>
</tr>
<tr>
<td>p+Pb</td>
<td>2016</td>
<td>8.16</td>
<td>0.16 pb$^{-1}$</td>
</tr>
</tbody>
</table>

Results shown for the first time
(I) Hard probes:
Electroweak bosons
Quarkonia & HF
Z AND W BOSONS: STANDARD CANDLES OF HI COLLISIONS

➤ Z and W boson production yields measured in the muon channel using 5.02 TeV Pb+Pb data

➤ Improvement in statistics by a factor of four wrt Run 1

➤ Yields/\langle T_{AA} \rangle > are approximately flat vs. \(N_{\text{part}}\): implying scaling with the number of binary collisions

➤ W+ yields by 10% larger comparing to W- yields

➤ Data consistent with POWHEG scaled to NNLO accuracy

➤ Fiducial yields are 5 times higher for W than Z bosons (expected due to acceptance)

➤ Lepton charge asymmetry consistent with theory with some small deviations in the forward direction
Measurement of isolated prompt photons in p+Pb collisions at 8.16 TeV

- Photon kinematics: $E_T > 25$ GeV, $|\eta| < 2.37$ and three bins in $\eta^*$

- ATLAS reaches photon $E_T$ of 500 GeV at mid-rapidity and covers five orders of magnitude in cross sections

- Dominant systematics: photon energy scale, photon PID (low photon $E_T$) and luminosity (6.2%)

- JETPHOX with CT14+EPPS16 underpredict the data by about 20%, consistent with JETPHOX results for pp [JHEP 08 (2016) 005]

Talk by P. Janus on Wed 18:00
INCLUSIVE PHOTONS: CNM EFFECTS

ATLAS-CONF-2017-072

- \( R_{pPb} \) measured and compared to JETPHOX with nPDF from EPPS16, nCTEQ15, as well as with parton energy-loss models by medium-induced gluon bremsstrahlung [I. Vitev et al., PRD 93, 074030 (2016)]

- \( R_{pPb} \) cancels out the 20% scale problem, no dependence on Glauber modelling, 8 TeV pp data is extrapolated to 8.16 TeV for reference, requiring sizeable correction above 100 GeV

- At forward rapidity and for low/intermediate photon \( E_T \), \( R_{pPb} \) is consistent with unity

- At high photon \( E_T \), in the backward rapidity \( R_{pPb} \) is significantly below unity which is due to a change in up/down quark mixture wrt pp system

- With the current uncertainties, the data can not distinguish between free PDF and nPDF

\[
R_{pPb} = \frac{d\sigma_{pPb}^{pPb}}{dE_T^\gamma} \times A \frac{d\sigma_{pp}^{pp}}{dE_T^\gamma}
\]

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- Data are unable to discern a substantial energy loss in the initial state.
Quarkonia measurement in p+Pb/pp collisions at 5.02 TeV

- Prompt and non-prompt cross sections of J/ψ, ψ(2S), as well as inclusive yields of Y(nS) (n = 1, 2, 3) are extracted
- Significant reduction of systematic uncertainties after switching from preliminary result [ATLAS-CONF-2015-023] to the pp reference data
- J/ψ R_{pPb} is consistent with unity for p_T between 8-40 GeV
- Y(1S) R_{pPb} is found to be suppressed for p_T<15 GeV
- Prompt ψ(2S) to J/ψ production double ratio shows a decreasing trend
- J/ψ cross-sections are in agreement with NRQCD (prompt) and FONLL (non-prompt) predictions

NEW

Talk by P.Gallus on Wed 17:20
HEAVY FLAVOUR: D MESONS

➤ First ATLAS measurement on D meson production
  ➤ Prompt D⁰ and D* production in p+Pb at 8.16 TeV
  ➤ D⁰ → Kπ: 3 < p_T < 30 GeV
  ➤ D* → Kππ: 5 < p_T < 30 GeV
  ➤ Rapidity: −1.5 < y* < 0.5
  ➤ Cross-sections in p_T and y* compared to FONLL predictions which are plotted with scale and PDF uncertainties
    ➤ Good agreement found
  ➤ Forward-backward R_FB ratios show no significant deviation from unity

Talk by P.Gallus on Wed 17:20
(II) Hard probes: jets
INCLUSIVE JETS: QUENCHING IN THE QGP

Substantial advance with the increased Run-2 statistics:

- More precise measurements with better control over the underlying event subtraction and unfolded so they can be directly compared to theory
- Reduction of systematic uncertainties
- Addressing questions such as what is the flavour dependence of jet quenching, do jets stop being affected by the plasma if they are high enough energy, what happens in boson+jet systems, etc.

\( R_{AA} \) vs jet \( p_T \)

- Access to jets at TeV scale in Pb+Pb at 5TeV
- \( R_{AA} \) is still about 0.5 in 0-10% centrality
- \( R_{AA} \) rises with jet \( p_T \) until \( \sim 300 \) GeV where it begins to flatten
- \( R_{AA} \) is independent of \( \sqrt{s_{NN}} \) when comparing 2.76 and 5.02 TeV results

Ratio of \( R_{AA} \) vs rapidity

- Large cancelation of systematics in the ratio
- \( R_{AA} \) is flat with rapidity below 316 GeV
- \( R_{AA} \) decreases with rapidity at higher \( p_T \)
  - Change in the spectra steepness and in the flavour composition
JET FRAGMENTATION FUNCTIONS: CNM EFFECTS

- Measure how particles within the jet are distributed using fragmentation functions (FF)
  - R=0.4 jets with charged tracks starting at 1 GeV for Pb+Pb and p+Pb
  - \(N_{\text{ch}}\) is the particle multiplicity associated with a jet
  - Jet FF are background subtracted, corrected for tracking efficiency, and fully unfolded in 2D jet \(p_T\) and \(z\)

- \(R_{D(p_T)}\) is a ratio of jet FF in p+Pb and pp systems at 5.02 TeV presented in bins of jet \(p_T\)
  - No modification of jet structure within experimental precision in the p+Pb system
  - Result consistent with unmodified hadron \(R_{pPb}\) measured with the 5.02 TeV pp reference data [ATLAS-CONF-2016-108]
  - Result submitted for publication

\[
D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz} \\
\begin{align*}
\Delta R &= \frac{p_T \cos \Delta R}{p_T^{\text{jet}}} \\
D(p_T) &= \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dp_T}
\end{align*}
\]
Measure $R_{D(p_T)}$ and $R_{D(z)}$ in the Pb+Pb system wrt pp at 2.76 TeV

- As a function of jet $p_T$ and centrality
- In central collisions (0-10%): enhancement at low $p_T$, suppression at intermediate $p_T$, enhancement at high $p_T$ in all jet $p_T$ bins
- In peripheral collisions (60-80%): the magnitude of these modifications decreases
- No jet $p_T$ dependence
- No CM energy dependence: jet FF comparable between 2.76 and 5.02 TeV
Investigate flavour dependence in jet FF

- Photon-tagged jets are more likely to be initiated by quarks
- Measurement done systematically in pp and Pb+Pb systems
  - Kinematic requirements:
    - photon $E_T$: 79.6-126 GeV
    - jet $p_T$: 63.1-144 GeV
    - Difference in azimuthal angle between jet and photon $>7\pi/8$
- Differences between photon-tagged and inclusive jet FF seen already in pp
  - Different flavour composition in photon-tagged vs inclusive jet FF
- FF is systematically harder for photon-tagged jets
- PYTHIA8 reproduces data well for low and intermediate $p_T$ values, while for higher $p_T$ overpredicts the data
PHOTON-TAGGED JET FF: FLAVOUR DEPENDENCE?

- Ratios of jet FF for photon-tagged and inclusive in Pb+Pb and pp systems
  - Two centrality bins: 0-30% (central) and 30-80% (peripheral)
  - No difference expected due to CM energy difference between 2.76 vs 5.02 TeV (slide 14)
  - In peripheral: similar behaviour for photon-tagged and inclusive jets
  - In central: differences between photon-tagged and inclusive jet FF - additional suppression at high $p_T$ and enhancement at low $p_T$
- Ratios of jet FF for photon-tagged and inclusive in central to peripheral
  - Inclusive: tends to be consistent with unity
  - Photon-tagged: additional modification of FF

NEW

ATLAS-CONF-2017-074
First attempts to measure jet quenching were through the dijet asymmetry

- Dijets are the most probable configuration for jets in pp (and Pb+Pb) collisions
- Sensitive to energy loss differences due to anti-correlation in path length and jet-by-jet fluctuations

- Use dijet momentum fraction - ratio of the sub-leading (2) jet $p_T$ to the leading (1) jet $p_T$:
  \[ x_J = \frac{p_{T2}}{p_{T1}} \]
  - $x_J$ has been unfolded
  - In pp: most probable configuration is $x_J \sim 1$
  - In Pb+Pb: more asymmetric in more central collisions
    - In 0-10%: $x_J \sim 0.5$
    - As Pb+Pb becomes more peripheral the distribution is like pp
  - Consistent results between $R=0.4$ and 0.3 jets

- Final result submitted for publication
Photo-nuclear dijet production provides a unique opportunity to study nPDF

Events satisfying the 0nXn topology in ZDC and rapidity-gap requirement

Data corrected for trigger and event selection, not unfolded for detector effects

\[ H_T = \sum_i p_T^i, \quad m_{\text{jets}} = \left[ \left( \sum_i E_i \right)^2 - \left( \sum_i p_T^i \right)^2 \right]^{1/2}, \quad y_{\text{jets}} = \frac{1}{2} \ln \left( \frac{\sum_i E_i + \sum_i p_z^i}{\sum_i E_i - \sum_i p_z^i} \right) \]

Double-differential cross sections span many orders of magnitude

Comparison to reweighed Pythia+STARLIGHT model with normalisation scaled to data

Relatively good agreement over a large kinematic range is found

Less good agreement at the largest and smallest \( x_A \)

Talk by P. Steinberg on Wed 14:30
LIGHT-BY-LIGHT SCATTERING IN UPC EVENTS

- Search for signal diphoton candidates using:
  - Two photons with $E_T > 3$ GeV
  - Backgrounds subtracted from exclusive di-electron production and centra-exclusive production (CEP)

- Excess in the data consistent with the light-by-light signal
  - First direct observation of the light-by-light signal
  - Has attracted interest to HI collisions from outside the field [e.g. arXiv:1703.08450]

Signal significance: $4.4\sigma$, expected significance: $3.8\sigma$
Measured cross section:
$$\sigma_{\text{fid}} = 70 \pm 20 \text{ (stat)} \pm 17 \text{ (syst)} \text{ nb}$$
In agreement with predictions [arXiv:1601.07001, 1305.7142]

Looking forward to more events in the 2018 Pb+Pb run

Talk by P. Steinberg on Wed 14:30
(III) Soft physics
from small to large systems
One of hallmarks for collective behaviour in Pb+Pb collision are two-particle correlations (2PC) in $\Delta\eta$–$\Delta\phi$ so-called “ridge”

- Surprisingly same behaviour found in pp (2010) and p+Pb (2012) collisions
  - Open questions: Can the pp ridge be attributed to collective flow effects? Can the bulk of the matter created in high-multiplicity collisions be described in terms of hydrodynamics? How can thermalisation happen in such small systems?

- What have we learnt about the ridge so far?
  - Large contribution from non-flow background in small systems —> Dedicated techniques developed to evaluate and subtract it (e.g. ATLAS template-fit method)
  - Ridge is a feature of all $N_{ch}$ values: $v_2$ flat with $N_{ch}$ in pp, while grows and then saturates in p+Pb
  - Has no CM energy dependence
  - Ridge is observed to persist for heavy flavour, a hint of non-zero flow signal in $D^*$–hadron correlations in p+Pb as well
First attempt to control the impact parameter in pp collisions by selecting a high-Q^2 process

ATLAS measures 2PC of hadrons in events where the Z boson is also present

Analysis based on full 2012 pp data at 8 TeV with L=19.4 fb^-1, where 6.2M Z bosons are found

Main challenge is high pileup: average μ is 20 (c.f. μ = 1 in previous ATLAS ridge studies)

New technique is developed to subtract the pileup contribution in 2PC measurements (~20% correction)

v_2 is found to be 8±6% above that in the inclusive collisions at 13 TeV

Talk by S. Milov on Tue 18:00
Multi-particle cumulants are another tool to explore collective nature of the system

- Using well-established Q-cumulant method
- Expressed in terms of $c_2\{4\}$ which relates directly to elliptic flow $v_2\{4\}$

$\quad v_2\{4\} = \sqrt{-c_2\{4\}}$

- Very detailed studies of pp (5.02 and 13 TeV), p+Pb (5.02 TeV) and low-multiplicity Pb+Pb (2.76 TeV) collisions

- Non-collective sources from dijet dominate the statistical properties of two- or multi-particle correlations

- Standard multi-particle cumulants have strong sensitivity to multiplicity class definition and multiplicity bin-width

- $c_2\{4\}$ values change dramatically as the event-class definition is varied

Talk by M. Zhou on Tue 17:40
ATLAS developed a technique to suppress a non-flow contribution in multi-particle cumulants

- Improved cumulant method based on particles from different sub-events separated in $\eta$
- Studies in PYTHIA have demonstrated its effectiveness in suppressing no-flow [arXiv: 1701.03830]

Negative $c_2\{4\}$ in pp and p+Pb
- $c_2\{4\}$ nearly independent of $<N_{ch}>$ starting at low multiplicity $<N_{ch}> \sim 40$
  - Indirect support for the template-fit bkg subtraction in 2PC
- Direct evidence of collective flow in pp and p+Pb collisions
Cumulants capture event-by-event flow fluctuations

- Three-subevent cumulant method also applied to check residual non-flow

- Studies based on full 2015 Pb+Pb data set
  - Measure centrality and $p_T$ dependence of $c_n\{4\}$, $n=1,2,3,4$
  - Observation of $c_2\{4\} > 0$ in ultra-central collisions: strong indication of non-Gaussian flow fluctuations
  - First measurement of non-zero $c_1\{4\}$ in high $p_T$ with standard and three-subevent method: non-Gaussian nature of dipolar eccentricity fluctuation in the initial-stage geometry
  - Sign change of $c_4\{4\}$ with better precision: consistent with a nonlinear contribution to $v_4$ from $v_2$
Many new results from ATLAS have been presented

- Spanning all collision systems and including first precision studies in Pb+Pb data at 5.02 TeV
- Take advantage of three collision systems recorded at the CM energy of 5.02 TeV

Brand new preliminary results have been presented on

- **W boson** yields in the muon channel in Pb+Pb are unaffected by the presence of the QGP
  - Yields consistent with both free and nPDF
- **Inclusive photons** in p+Pb at 8.16 TeV have power to rule out some initial-state parton energy-loss models
  - \( R_{ppb} \) consistent with both free and nPDF
- **Photon-tagged jet fragmentation functions** carry additional modifications on top of inclusive jet FF
  - Sensitive to jet flavour dependence or perhaps also other effects
- **Prompt D meson** production studied in ATLAS for the first time
  - Forward-backward ratio \( R_{FB} \) consistent with unity
- **2PC hadron-hadron \( v_2 \) in Z-tagged pp collisions** is measured for the first time
  - \( 8 \pm 6\% \) larger to inclusive \( v_2 \) in pp
- **New sub-event cumulant method utilised in Pb+Pb collisions at 5.02 TeV**
  - Observation of \( c_2\{4\} > 0 \) in ultra-central collisions
CONTRIBUTIONS TO FROM ATLAS

Paralel talks:
- Petr Balek “Azimuthally-dependent femtoscopy in central p+Pb collisions at 5 TeV with ATLAS”
- Dominik Derendarz “Longitudinal multiplicity fluctuations and flow decorrelations in Pb+Pb collisions with the ATLAS detector”
- Petr Gallus “Heavy flavour and quarkonia measurement with ATLAS detector”
- Qipeng Hu “Measurement of two-particle hadron-hadron and muon-hadron correlations in pp and p+Pb collisions with the ATLAS detector”
- Piotr Janus “Electroweak boson production in heavy ion collisions with the ATLAS detector”
- Alexander Milov “Measurement of long-range correlations in pp collisions characterized by presence of a Z-boson”
- Peter Steinberg “Measurements of jet production and electromagnetic processes in ultra-peripheral Pb+Pb collisions with the ATLAS detector”
- Mingliang Zhou “Measurement of multi-particle azimuthal correlations with the sub-event cumulant method in pp and p+Pb collisions with the ATLAS detector”

Posters:
- Qipeng Hu “D meson production and long-range azimuthal correlation in 8.16 TeV p+Pb collisions with ATLAS”
- Jakub Kremer “Measurement of W boson production in Pb+Pb and pp collisions at 5.02 TeV with the ATLAS detector”
- Dennis Perepelitsa “Measurement of the fragmentation function for photon-tagged jets in 5.02 TeV Pb+Pb and pp collisions with the ATLAS detector”

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
Dedicated trigger strategies developed for HI collisions

Many effort put to preserve constant trigger efficiency w/ centrality

Also offline performance reoptimized for HI collisions
R_{pPb} measured and compared to JETPHOX with nPDF from EPPS16, nCTEQ15, as well as with parton energy-loss models by medium-induced gluon bremsstrahlung [I.Vitev et al., PRD 93, 074030 (2016)]

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D-HADRON CORRELATIONS

➤ 2PC correlations for D*-h

➤ Coefficients of cos(2\Delta\phi) modulation in the inclusive D^*± mesons and charged particles azimuthal angle correlation are measured with the template fits

➤ D^*±–hadron correlation is broadly consistent with what one would expect from the observed muon–hadron correlations
In Pb+Pb 0-10% centrality:

- $x_{J\gamma}$ is shifted towards lower values and shape is modified in all $p_T$ bins.
- Shape of the $\Delta\phi$ distribution is consistent with that in pp and Pb+Pb events.
- Observation qualitatively consistent with results at 2.76 TeV.
Z, W and γ boson production has been studied in Pb+Pb system at 2.76TeV

- They are produced in hard scattering before the QGP is created
- Their production yield per binary collision is flat with centrality and consistent with the NNLO or NLO calculations
  - They do not interact with the QGP and are established as standard candles for measurements tracking partonic energy loss
- In case of W boson production, yields can be only described after including the isospin effect
- Nuclear modifications to PDFs remain unclear within the precision reached in the Pb+Pb system
**HIGH-\(p_T\) EXCLUSIVE DIMUONS**

- **Ultra Peripheral Collisions (UPC) with \(b>2R\)**
  - Intense source of photons (~Z²)
  - Well described by Weizsacker-Williams (EPA)

- **MC simulation: STARLIGHT 1.1 (integrated over nuclear excitation states)**

- **Signal requirements:** two good muons from the common vertex with unlike signs in the fiducial range: \(p_{T,1}, p_{T,2} > 4\) GeV, \(|\eta_1|, |\eta_2| < 2.4\), \(M_{\mu\mu} > 10\) GeV

- **UPC dimuon pair should have \(p_T < 200\) MeV and thus small acoplanarity \((Aco = 1 - |\Delta\phi|/\pi)\)**
  - STARLIGHT does not include FSR photons \(\rightarrow\) broadening of the Aco distribution expected
In pp, $v_2$ is flat with $N_{ch}$ and non-zero even for low $N_{ch}$ values.

Agreement in all Fourier coefficients between 5 and 13 TeV pp collisions.

$v_2$ and $v_3$ harmonics larger in p+Pb collisions and raise monotonically.

$v_4$ tends to be consistent between the two collision systems.
CHARMONIUM PRODUCTION IN Pb+Pb

- **J/ψ and ψ(2S) production measured in pp and Pb+Pb at 5TeV**

  - Kinematic region: 9<p_T<40 GeV and |y|<2
  - Tool to provide information on temperature and degree of deconfinement of the QGP
  - Test response of medium to prompt (cc-bar) and non-prompt (b decay) components
    - Use pseudo-proper decay time (τ) to distinguish between two production mechanisms
  - Non-prompt fraction consistent between three rapidity intervals in pp and also between 5 and 13TeV data