Recent measurements with hard probes in heavy-ion collisions by ATLAS

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OUTLINE

➤ Introduction
➤ Part 1: electroweak bosons, quarkonia and heavy flavour
➤ Part 2: jets
➤ Part 3: ultra-peripheral collisions
➤ Summary

➤ Disclaimer: no discussion of soft physics
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 trying to disentangle the original of this behaviour

One of the main goals of heavy-ion physics is to study the QGP
ATLAS DETECTOR

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

Full azimuthal acceptance
Broad coverage in pseudorapidity

Centrality

In Pb+Pb: total FCal $E_T$
In p+Pb: FCal $E_T$ on Pb-going side
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>
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<tr>
<th>System</th>
<th>Year</th>
<th>$\sqrt{s_{NN}}$ [TeV]</th>
<th>$L_{\text{int}}$</th>
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<tr>
<td>Pb+Pb</td>
<td>2011</td>
<td>2.76</td>
<td>0.14 nb$^{-1}$</td>
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<tr>
<td>pp</td>
<td>2012</td>
<td>8</td>
<td>19.4 fb$^{-1}$</td>
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<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>
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<tr>
<td>low-mu pp</td>
<td>2015-16</td>
<td>13</td>
<td>0.9 pb$^{-1}$</td>
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<tr>
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<td>2015</td>
<td>5.02</td>
<td>28 pb$^{-1}$</td>
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<tr>
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<td>Xe+Xe</td>
<td>2017</td>
<td>5.44</td>
<td>3 mb$^{-1}$</td>
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<tr>
<td>pp</td>
<td>2017</td>
<td>5.02</td>
<td>270 pb$^{-1}$</td>
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</table>
Dedicated trigger strategies developed for HI collisions

Many effort put to preserve constant trigger efficiency w/ centrality

Also offline performance reoptimised for HI collisions
(I) Hard probes:
Electroweak bosons
Quarkonia
Heavy flavour
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/<T_{AA} > are approximately flat vs. N_{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]
R_{pPb} measured and compared to JETPHOX with nPDF from EPPS16 and nCTEQ15

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
**INCLUSIVE PHOTONS: CNM EFFECTS**

- $R_{pPb}$ measured and compared to JETPHOX with nPDF from EPPS16 and nCTEQ15
- $R_{pPb}$ 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
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  - With the current uncertainties, the data can not distinguish between free PDF and nPDF
**Inclusive Photons: CNM Effects**

- $R_{pPb}$ 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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- 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

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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
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
(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
  - It is flat with rapidity below 316 GeV
  - It decreases with rapidity at higher $p_T$
    - Change in the spectra steepness and in the flavour composition

\[ ATLAS-CONF-2017-09 \]
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
- $N_{ch}$ 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
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
PHOTON-JET CORRELATIONS IN Pb+Pb

In Pb+Pb 0-10% centrality:

- $x_{J\gamma}$ is shifted towards lower values and shape is modified wrt predictions for all photon $p_T$ bins
- Shape of the $\Delta\phi$ distribution is consistent with that in pp collisions and in simulated Pb+Pb events
- Observation qualitatively consistent with results at 2.76 TeV
PHOTON-TAGGED JET FF: FLAVOUR DEPENDENCE

➤ 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 18)
  - 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

**ATLAS-CONF-2017-074**

ATLAS Preliminary

- Ratios of \( D(z) \)
  - Inclusive jets 2.76 TeV (0-10% / 30-40%)
  - Photon-tagged jets 5.02 TeV (0-10% / 30-40%)

- Ratios of \( D(\rho) \)
  - Inclusive jets 2.76 TeV (30-40%)
  - Photon-tagged jets 5.02 TeV (30-40%)
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 $p_T$: $x_J = p_{T2}/p_{T1}$

- $x_J$ 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 has just been published
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

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 $x_A$
(III) Ultra-peripheral collisions
**HIGH-\(p_T\) EXCLUSIVE DIMUON PRODUCTION**

- **Ultra Peripheral Collisions (UPC) with \(b > 2R\)**
  - Intense source of photons (\(\sim Z^4\))
  - 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 \((A_{co} = 1 - |\Delta\phi|/\pi)\)
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
Many new results from ATLAS have been released recently

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

New preliminary results have been shown 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

ATLAS also has new important results in soft physics

- Will be discussed by Adam Trzupek at a seminar “Bialasówka” on Friday

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults)
Back-up slides
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
(III) Soft physics
from small to large systems


**RIDGE IN SMALL SYSTEMS: EVIDENCE FOR COLLECTIVITY?**

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-Q2 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 1/fb, where 6.2M Z bosons are found

Main challenge is high pileup: average $\mu$ is 20 (c.f. $\mu = 1$ 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 $8 \pm 6\%$ above that in the inclusive collisions at 13 TeV
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 $v_2\{4\}$

\[ v_2\{4\} = \sqrt{-c_2\{4\}} \]

- 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
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
MULTI-PARTICLE CUMULANTS IN Pb+Pb

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 $v_2$

NEW
2PC correlations for $D^*-h$

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

- $D^{*-\pm}$–hadron correlation is broadly consistent with what one would expect from the observed muon–hadron correlations
In pp $v_2$ is flat with $N_{\text{ch}}$ and non-zero even for low $N_{\text{ch}}$ 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 ($\tau$) to distinguish between two production mechanisms
  - Non-prompt fraction consistent between three rapidity intervals in pp and also between 5 and 13TeV data
High-$p_T$ Exclusive Dimuon Production

- **Ultra Peripheral Collisions (UPC) with b>2R**
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- **UPC dimuon pair should have** $p_T < 200$ MeV and thus small acoplanarity ($A_{\text{co}} = 1 - |\Delta\phi|/\pi$)
  - STARLIGHT does not include FSR photons → broadening of the Aco distribution expected