Prospects for ATLAS hard probes measurements in Run 2

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Short overview of run 1

- In run 1, ATLAS collected $L_{\text{int}}^{\text{PbPb}} = 0.15 \, \text{nb}^{-1}$ of Heavy-Ion (HI) and $L_{\text{int}}^{pp} = 4.2 \, \text{pb}^{-1}$ of $pp$ data at $\sqrt{s_{NN}} = 2.76 \, \text{TeV}$
- Many interesting studies published: (di)jets, W and Z bosons, J/$\psi$’s, photons and charged tracks
- All of these measurements provided information on HP production rates, parton energy loss and medium properties
- Physics impact of some measurements was reduced by the large statistical errors, some measurements were impossible to do
The main advantage of the new data is the large increase in integrated luminosity ($L_{\text{int}, \text{run1}} = 0.15 \text{ nb}^{-1}$ vs $L_{\text{int}, \text{run2}} = 0.515 \text{ nb}^{-1}$).

Along with the increased cross section for some processes this will provide opportunity to improve statistical precision.

New channels become feasible.

All the possible collision systems, $pp$, $p+\text{Pb}$ and $\text{Pb}+\text{Pb}$ measured at the same energy.
ATLAS experiment

- ATLAS is multi-purpose detector with excellent performance for measurements of heavy-ion collisions
- Precise tracking within $|\eta| < 2.5$. Combination of silicon pixel and strip detectors and transition radiation tracker.
- Large acceptance calorimeter system with fine granularity covers $|\eta| < 4.9$, surrounded by muon spectrometer covering $|\eta| < 2.7$
Electroweak bosons are a useful channel to test the production rates in HI collisions, its clear signal being the large advantage.

Statistical uncertainties have been a limiting factor for some channels, e.g. Z+jet.

New data opens possibility to measure jets and electroweak probes simultaneously and differentially.
\( W \) bosons

- \( W \) production yield per binary collision shows no significant dependence on \( \langle N_{\text{part}} \rangle \) and is consistent with POWHEG prediction.
- Lepton charge asymmetry agrees with theoretical predictions incorporating no nuclear modifications, as well as the small EPS09 modifications.
Z mass peaks

- Dielectron (left) and dimuon (right) invariant mass distributions centered around Z peak for opposite and like-sign pairs
- Run 2 measurements left and middle, run 1 on the right
- $\approx$10 times more Z’s with the new data
Variable that expresses the size of the suppression/enhancement is the $R_{AA}$ defined as

$$R_{AA} = \frac{1}{N_{\text{evt}}} \left. \frac{d^2 N_{\text{Pb+Pb}}}{d p_T dy} \right|_{\text{centr}} \frac{\langle T_{AA} \rangle}{\langle T \rangle} \frac{d^2 \sigma_{pp}}{d p_T dy}$$

- $R_{AA}$ is the nuclear suppression factor, which characterizes the modification of the spectrum due to the nuclear environment
- Data are corrected for tracking efficiency, contributions from fake tracks, and momentum resolution
Very strong suppression at intermediate $p_T$, hint of presence of plateau at $p_T \approx 60$ GeV
Run 2 charged particles

- Uncorrected charged particle spectra from $pp$ at $\sqrt{s} = 5.02$ TeV (left)
- Charged tracks spectra used for $R_{AA}$ measurement in run 1 (right)
- Measurement was possible up to $p_T = 150$ GeV, new data should allow to reach at least 200 GeV and possibly higher

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**ATLAS Preliminary**

$pp \sqrt{s} = 5.02$ TeV $26$ $\text{pb}^{-1}$

$1/(2\pi p_T^2 d^2\sigma/dp_T^2)$ $[\text{mb GeV}^{-2}]$

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$ATLAS$

$p+p$, $\text{Pb}+\text{Pb}$

$\sqrt{s}$, $\sqrt{s_{NN}} = 2.76$ TeV

$p_{T\text{PbPb}}$ $= 0.15$ nb$^{-1}$

$L_{\text{int}}^\text{PbPb} = 4.2$ pb$^{-1}$

$|\eta| < 2.0$

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• Jets probe the medium created in the Pb+Pb collisions
• ATLAS has published results from run 1 on dijet asymmetry, jet $R_{AA}$, jet fragmentation and production of nearby jets
• New data will allow significant improvements relative to the older measurements, mainly:
  ▶ extended $p_T$ reach for jet $R_{AA}$ (measured up to $\approx 300$ GeV in run 1)
  ▶ differential measurements of jet fragmentation functions
  ▶ reduced statistical uncertainties in measurement of nearby jets
\( R_{AA} \) plots clearly show suppression down to \( \approx 0.5 \) for the most central collisions.

- Weak dependence of \( R_{AA} \) on the \( p_T \) and rapidity
Uncorrected yields of inclusive, leading and subleading jets in Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV as a function of $p_T$, $|\eta| < 2.1$

Run 1 jet spectra as a function of $p_T$ for different centrality and rapidity bins
Jet Fragmentation Functions (FF) $D(p_T)$ and $D(z)$ are defined as

$$D(p_T) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dp_T^{\text{ch}}} \quad D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz} \quad z = \frac{p_T}{p_T^{\text{jet}}} \cos \Delta R$$

- Run 1 FF measurement at $\sqrt{s_{\text{NN}}} = 2.76$ TeV of $R = 0.4$ jets done differentially in $\eta$ and $p_T^{\text{jet}}$
- Jet substructure measured using charged tracks starting at $p_T = 1$ GeV
- FF are background subtracted, efficiency corrected and fully unfolded with 2-D Bayesian unfolding
$D(p_T)$ Ratios

- $R_D(p_T)$ for 4 centralities in 4 $p_T^{\text{jet}}$ bins
- No dependence on $p_T^{\text{jet}}$ observed except change of trends at highest $p_T$
The rate of the neighbouring jets that accompany a test jet was measured in run 1

$R_{\Delta R}$ is defined as

$$R_{\Delta R} = \frac{1}{dN_{\text{jet, test}}/dE_T^{\text{test}}} \sum_{i=1}^{N_{\text{jet, test}}} \frac{dN_{\text{jet, i}}}{dE_T^{\text{test}}} (E_T^{\text{test}}, E_T^{\text{nbr}, \text{min}}, \Delta R)$$
The ratio of $R_{\Delta R}$ for three centrality bins to 40-80% centrality bin suppression by a factor $\approx 2$ in central collisions, no strong $E_T$ dependence observed

With increased statistics in Run 2, expect significant reduction in statistical uncertainties

Moreover new type of jet substructure measurements possible
Ultra Peripheral Collisions (UPC) are collisions at large impact parameter where strong interaction is not possible; nuclei interact via photons (photon-photon (a) or photon-ion (b)) emitted coherently from the entire nucleus.

One way to better understand the photon flux induced by the electromagnetic fields surrounding heavy nuclei is to measure high-mass dimuon pairs.

In the presented measurement, cross section for exclusive dimuon pairs with $M_{\mu\mu} > 10$ GeV is compared with STARLIGHT 1.1 calculations.

Measured cross section was corrected for muon trigger efficiency, muon reconstruction efficiency and vertex reconstruction efficiency.
High-mass dimuon pairs in UPC

Cross section for dimuon production in UPC as a function of pair mass (left) and pair rapidity (right).

- Mass distribution provided for two rapidity regions $|Y_{\mu\mu}| < 2.4$ and $|Y_{\mu\mu}| > 1.6$
- Rapidity distribution provided for three mass ranges $10 < M_{\mu\mu} < 20$ GeV, $20 < M_{\mu\mu} < 40$ GeV, $40 < M_{\mu\mu} < 100$ GeV
Results from run 1 show that production of EW bosons is not influenced by the medium created in HI collisions.

But strong suppression of charged particles and jet production in central collisions, suppression of nearby jets and modest but significant modification of jet FF is observed.

With the new data we’ll be able to extend old measurements, do them more differentially and with higher precision; new measurements will be possible with increased statistics.

High-mass dimuon pairs measurement shows good agreement between data and STARLIGHT calculations, enabling precise future measurements of UPC collisions.
Backup
High-mass dimuon pairs in UPC

**ATLAS** Preliminary

$\text{Pb+Pb} \rightarrow \text{Pb}^{+}+\text{Pb}^{-}+\mu^{+}+\mu^{-}$

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

$L_{\text{int}} = 515 \mu b^{-1}$

$p_{\text{T}, \mu} > 4 \text{ GeV, } |\eta_{\mu}| < 2.4$

- Data/MC $|Y_{\mu\mu}| < 2.4$
- Data/MC $1.6 < |Y_{\mu\mu}| < 2.4$

- Data/MC $10 < M < 20 \text{ GeV}$
- Data/MC $20 < M < 40 \text{ GeV}$
- Data/MC $40 < M < 100 \text{ GeV}$

- The ratios of data and STARLIGHT calculations
- Good agreement between calculations and data