Measurements of the azimuthal anisotropy and substructure of jets in Pb+Pb collisions with the ATLAS detector

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existing, precise, measurements of jet $R_{AA}$ in PbPb collisions

definition: $R_{AA}$

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jet $v_n$

$n > 2$ & large kinematic reach

substructure dependent $R_{AA}$

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how do we understand the observed suppression in terms of geometry & jet structure?

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absolutely normalized measurements to directly compare energy loss
measurements of the jet rates as a function of 2, 3 & 4th order event planes

sensitive to the path length dependence of jet energy loss

accepted in PRC, 2111.06606
analysis procedure

- jet angle measured wrt event plane measured with $4.0 < |\eta| < 4.9$
- reduces any bias on the event plane from the away side jet
- jet momentum is unfolded
- jet position resolution is greatly improved by using small $R = 0.2$ jets

2111.06606
jet $v_2$

- $v_2 > 0$ observed for all but the most central collisions
- $v_2$ decreases with increasing $p_T$ but remains $> 0$ in mid-central collisions up to at least 250 GeV
centrality dependence of jet $v_n$

- $v_2$ largest in mid-central collisions; consistent with 0 in the most central collisions
- $v_3 \sim 1\%$ for mid-central/central collisions
  - for both $v_2$ & $v_3$ the centrality dependence is similar to that of hydrodynamic $v_n$ which is driven by the initial collision geometry
- suggests the same geometry plays a significant role in jet quenching
- $v_4$ consistent with 0
  - larger uncertainties from poor 4th order event plane resolution
comparison to previous measurements

- full Run 2 data & jets provide large increase in precision and kinematic range over 2.76 TeV results & charged hadron measurements
comparisons to theory

both LBT (1811.08975) and LIDO (2010.13680) get the size of the $v_2$ & $v_3$ well, except for the $p_T$ dependence of the $v_2$ below ~100 GeV which is stronger in data than the models

2111.06606
substructure dependent $R_{AA}$

does $R_{AA}$ depend on the structure of the jet?

increasing distance between subjets
large R jets

\[ \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12} \]

- R = 1.0 jets composed of R = 0.2 jets with \( p_T > 35 \) GeV
- removes soft, diffuse energy from the jets

if there is only a single sub-jet (SSJ) \( \rightarrow \sqrt{d_{12}} = 0 \)
$R_{AA}$ of these jets

$R = 1.0$ jets suppressed out to 800 GeV

jets with a single sub-jet (SSJ) are less suppressed than those with >1 sub-jet
track-calo clusters (TCCs)

TCCs use the tracks to improve the substructure performance of the clusters & allow a closer look at small angles than is possible in the $\sqrt{s_{12}}$ measurement.

Here TCCs with $p_T > 4$ GeV are used to reduce the effect of the underlying event.

Jets are the same calorimeter jets as in previous ATLAS HI measurements to allow for direct comparison to other measurements.
analysis procedure

• Jets are reclustered with C/A algorithm and iteratively declustered till the subjets satisfy the Soft Drop (SD) condition

• jets are $R = 0$ calorimeter jets; substructure constituents are TCCs

  • $r_g$ and jet $p_T$ are unfolded using 2D Bayesian unfolding to the truth level

\[ z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left( \frac{\Delta R_{i,j}}{R} \right)^\beta \]

\[ z_{cut} = 0.2 \quad \beta = 0 \]

\[ r_g = \Delta R_{i,j} \quad \text{between the subjets satisfying the SD condition} \]
\( r_g \) distributions

\[ \langle T_{AA} \rangle \frac{1}{N_{\text{evt}}} \frac{d^2N}{d_r \, d_g \, dp_T^\text{jet}} \]

**ATLAS Preliminary**

Pb+Pb 5.02 TeV, 1.72 nb\(^{-1}\)

\( p_T^{\text{jet}} > 158 \) GeV

- 158 < \( p_T^{\text{jet}} \) < 200 GeV (×0.05)
- 200 < \( p_T^{\text{jet}} \) < 315 GeV (×0.5)
- 315 < \( p_T^{\text{jet}} \) < 501 GeV (×5)

\( z_{\text{cut}} = 0.2, \beta = 0 \)

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\( r_g \) distribution shape has jet \( p_T \) dependence but little centrality dependence

**ATLAS-CONF-2022-026**
$r_g$ dependence of suppression

**ATLAS Preliminary**

*pp* 5.02 TeV, 260 pb$^{-1}$

$Pb+Pb$ 5.02 TeV, 1.72 nb$^{-1}$

$z_{cut} = 0.2$, $\beta = 0$

large $r_g$ jets more suppressed

similar trends with $r_g$ for all centralities

**ATLAS-CONF-2022-026**
$r_g$ dependence of suppression

- clear $r_g$ dependence to $R_{AA}$
- $r_g$, not jet $p_T$, determines the $R_{AA}$
Summary

Jet azimuthal anisotropies show path length dependence of jet quenching.

Jet suppression shows strong $r_g$ dependence within $R = 0.4$ jets.

Both geometry and substructure play a significant role in jet quenching.

See all ATLAS Heavy Ion results here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
backups
theory comparison

ATLAS Preliminary

Inclusive

$R_{AA}$

$p_T^{jet}$ [GeV]

$|z| < 1.8$ GeV

$Q_s < 1.2$ GeV

$0.17 < \alpha_{med} < 0.35$

$0.26 < r_g < 0.40$

$0.11 < r_g < 0.26$

$0.02 < r_g < 0.11$

$r_g = 0$

$0.00 < r_g < 0.02$

$|y| = 0.4$ jets, $|R_t| < 0.2,

$\beta = 0$

$\gamma < 2.1$

$pp 5.02$ TeV, $260 \text{ pb}^{-1}$

$Pb+Pb 5.02$ TeV, $1.72 \text{ nb}^{-1}$

Caucal et al.

$0 - 10 \%$