Selection of highlights from heavy-ion programs at the LHC

Anthony Timmins
Heavy-ion collisions deposit large energy in small volume

✓ Nuclear matter “melts”

✓ Quarks & gluons begin to become deconfined ➤ Quark Gluon Plasma (QGP)
Heavy-ion program at the LHC

- Run 1 (2010-2013)
  - Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
  - p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

- Run 2 (2015-2018)
  - Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
  - p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
Understanding properties of the QGP

- Collisions at LHC provide high temperatures and longest lasting system

- Measurements often grouped into two categories
  ✓ Soft probes: Azimuthal flow
  ✓ Hard Probes: Modification of jets in the medium
• Spatial anisotropies in the initial QGP state converted to momentum anisotropies
  ✓ Known as “azimuthal flow”
  ✓ Magnitude sensitive to details of initial state and transport properties of QGP
How is azimuthal flow measured?

- Azimuthal particle distribution can be represented by Fourier series:
  \[
  \frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\varphi - \psi_n))
  \]

- Coefficients $v_n$ reflect magnitude of $n^{\text{th}}$ order flow

- Second order (elliptic flow) typically the largest coefficient due to overlap geometry
Elliptic, triangular, and quadrangular flow

- Hydrodynamic calculations used to investigate QGP’s shear viscosity/entropy ($\eta/s$)
  - Lower bound conjectured to be $1/4\pi$ in ads/CFT
  - Comparisons to flow harmonics indicate QGP has $\eta/s$ close to $1/4\pi$
Pb-Pb 5.02 TeV results

- ~4% increase going from 2.76 to 5.02 TeV for $v_2$
  - ✔ Small event sample used for 5.02 TeV
  - ✔ Increase consistent with hydrodynamic predictions (PRC 93 (2016) 014912 & arXiv:1511.06289)
Identified particle flow

- Mass splitting observed due to common radial flow velocity
- Provide further constraints for hydrodynamical calculations...

Parallel Talk: I. Altsybeev
Correlations between different flow harmonics

- **SC(m,n)** measures covariance between \(v_m^2\) and \(v_n^2\)
  - Negative correlations between \(n=2\) & \(n=3\), positive for \(n=2\) & \(n=4\)
  - Sensitive tool to constrain temperature dependence of \(\eta/s\)
Evidence of azimuthal flow in light systems

PRL 115 (2015) 012301

PRL 115 (2015) 012301

PLB 726 (2013) 164–177

Parallel Talks: A. Toia and I. Altsybeev

- Azimuthal “flow” signals also observed in high multiplicity p-Pb collisions
  - Does this mark the onset of QGP creation?
  - What other mechanisms can generate flow?

CMS PbPb $|\eta| < 2.4$, $0.3 < p_T < 3.0$ GeV/c, $N_{trk}^{off}$

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CMS PbPb $|\eta| > 0.8$ (Near side only)

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| $v_2(2, |\Delta\eta| > 2)$ |
|--------------------------|
| 0.05 |
| 0.10 |

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CMS pPb $|\eta| < 3.0$ GeV/c, $N_{trk}^{off}$

CMS pPb $|\eta| < 3.0$ GeV/c, $N_{trk}^{off}$

CMS pPb $|\eta| < 3.0$ GeV/c, $N_{trk}^{off}$

[ALI-PUB-52116]
What happens in pp collisions?

- Negative $c_2\{4\}$ signals multiple particle correlations:
  - ✓ Results from ATLAS and CMS inconsistent
Hard probes

- High $p_T$ partons produced in initial stages of heavy-ion collisions
  - Will be influenced differently in QGP compared to vacuum.
  - Modification with medium often calculable in QCD
Nuclear modification factor ($R_{AA}$)

- Defined as charged hadron yield in Pb-Pb collisions / yield in pp collisions

- Suppression at high $p_T$ linked to jet quenching
Mass dependence of $R_{AA}$

- Heavier charm particles less suppressed
- Colour-charge dependence of parton energy loss?

Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

- $\pi^\pm$ (ALICE) $8 < p_T < 16$ GeV/c, $|y| < 0.8$
- D mesons (ALICE) $8 < p_T < 16$ GeV/c, $|y| < 0.5$
- Non-prompt $J/\psi$ (CMS Preliminary)
  $6.5 < p_T < 30$ GeV/c, $|y| < 1.2$

(empty) filled boxes: (un)correlated syst. uncert.
(*) 50-100% for non-prompt $J/\psi$
Gamma-jet correlations

- Gamma-jets produced in hard processes: $x_{\gamma J} = p_T^{\text{jet}}/ p_T^{\gamma}$
  - Photons not influenced by QGP
  - Jet momentum shifted to lower values in Pb-Pb collisions

\begin{itemize}
  \item $60 < p_T^{\gamma} < 80 \text{ GeV}$
    \begin{itemize}
      \item 0-10\% Pb+Pb, 0.49 nb$^{-1}$
      \item $pp$, 26 pb$^{-1}$
      \item PYTHIA 8 + Data Overlay
    \end{itemize}
  \item $80 < p_T^{\gamma} < 100 \text{ GeV}$
    \begin{itemize}
      \item ATLAS Preliminary
    \end{itemize}
  \item $100 < p_T^{\gamma} < 150 \text{ GeV}$
\end{itemize}
Evolution of the jet-peak

- Di-hadron correlations help examine jet peak
  - Jet peak broadens in central Pb-Pb collisions
  - Demonstrates medium also influences jet fragments
Summary

1. Measurements of azimuthal flow indicate QGP has very small viscosities
   ✓ Close to conjectured lower bound, almost perfect fluid made at the LHC
   ✓ Evidence of collectively in small systems

2. Strong jet medication seen at LHC energies
   ✓ $R_{AA}$ drops to ~0.15 and has mass dependence
   ✓ Jet fragments clearly altered by the medium
Particle production at large transverse momentum

ALICE Collaboration

$\sqrt{s_{NN}} = 2.76$ TeV
charged particles, $|\eta| < 0.8$

ALICE (0-5%)
CMS (0-5%)
HT (Chen et al.) lower density
HT (Chen et al.) higher density
HT (A.M.)
ASW (T.R.)
YaJEM-D (T.R.)
elastic (T.R.) large $P_{\text{esc}}$
elastic (T.R.) small $P_{\text{esc}}$
WHDG (W.H.) $\pi^0$ upper limit
WHDG (W.H.) $\pi^0$ lower limit

$R_{AA}$ vs. $p_T$ (GeV/c)