Soft probes of p+Pb and Pb+Pb collisions in the ATLAS experiment at the LHC

Sooraj Radhakrishnan
for the ATLAS Collaboration
Soft probes in p+Pb and Pb+Pb collisions

- Collective flow in Pb+Pb:
  - Flow fluctuations, flow correlations, event-by-event measurements..
  - More tools to constrain initial conditions and medium response (viscosity, equation of state, ..)

- ‘Flow’/Ridge in p+Pb:
  - Long range correlations in p+Pb: Flow in small systems?.
  - Measurement of Fourier harmonics associated with ridge to high $p_T$ ($\sim 10$ GeV)
  - First and higher order harmonics
  - Comparison of flow harmonics in p+Pb and Pb+Pb. Common origin?
Flow, correlations and fluctuations in Pb+Pb
Flow harmonics from multi-particle cumulants

If flow fluctuations are Gaussian,
\[ p(\vec{v}_n) = \frac{1}{2\pi\delta v_n^2} e^{-\left(\frac{(\vec{v}_n - \vec{v}_n^{RP})^2}{2\delta v_n^2}\right)} \]

\[ v_n\{4\} = v_n\{6\} = v_n\{8\} = v_n^{RP} \]

Also non-flow contributions are suppressed in \( v_n \) from higher order cumulants

arXiv:1408.4342
Flow harmonics from multi-particle cumulants

If flow fluctuations are Gaussian, \( p(\vec{v}_n) = \frac{1}{2\pi\delta v_n^2} e^{-\frac{(v_n - \vec{v}_n^{RP})^2}{2\delta v_n^2}} \)

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Ratio of higher order cumulants close to 1
Event by event flow and flow fluctuations

- $\nu_n\{2k\}$ can also be calculated from $P(\nu_n)$ from EbE flow measurements

$ATLAS$ Pb+Pb

| Centrality | $\sqrt{s_{NN}}$ | $L_{int}$ | $p_T > 0.5$ GeV, $|\eta| < 2.5$ |
|------------|-----------------|-----------|---------------------------------|
| 2-3%       | 2.76 TeV        | 7 $\mu$b$^{-1}$ |                                 |
| 5-10%      |                 |            |                                 |
| 20-25%     |                 |            |                                 |
| 30-35%     |                 |            |                                 |
| 40-45%     |                 |            |                                 |
| 60-65%     |                 |            |                                 |

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Comparison of EbyE and cumulant results

- $\nu_n\{2k\}$ can also be calculated from $P(\nu_n)$ from EbyE flow measurements

- Good consistency between the two set of measurements.

$\text{arXiv:1408.4342}$
Flow correlations – Event shape selection

- Can measure correlations between $\nu_n$ by selecting on event-shape

- For each centrality select on $\nu_2$ in the FCal ($3.2 < |\eta| < 4.9$)
Flow correlations – Event shape selection

- Can measure correlations between $v_n$ by selecting on event-shape
  - For each centrality select on $|\vec{Q}|$ in the FCal ($3.2 < |\eta| < 4.9$)
  - Control on event-shape: $v_2$ in ID ($|\eta| < 2.5$) varies by ~ a factor of 3.

- Measure $v_n$ in ID ($|\eta| < 2.5$) for each class using 2PC.
- Study correlations between $v_n$ -> insensitive to selection bias from statistical smearing

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Linear and non-linear contributions, $\nu_4$

- Non-linear response: $\nu_4 e^{i4\varphi_4} = c_0 e^{i4\varphi_4^*} + c_1 (\nu_2 e^{i2\varphi_2})^2$

- Fit with $\nu_4 = \sqrt{c_0^2 + (c_1 \nu_2^2)^2}$ to separate linear($\varepsilon_4$) and non-linear ($\nu_2^2$) components.
Non-linear response: 

\[ v_4 e^{i4\varphi_4} = c_0 e^{i4\varphi_4^*} + c_1 (v_2 e^{i2\varphi_2})^2 \]

Fit with 

\[ v_4 = \sqrt{c_0^2 + (c_1 v_2^2)^2} \]

to separate linear (\(\varepsilon_4\)) and non-linear (\(v_2^2\)) components.

Linear component dominates in central classes, non-linear in peripheral.
Ridge in p+Pb

More results and details in arXiv:1409.1792
Long-range correlations (‘ridge’) observed in high multiplicity p+Pb collisions.

Ridge present on both near and away sides.

Arising from final state interactions or initial state correlations?
$Y(\Delta \phi, \Delta \eta) = Y_{\text{Ridge}}(\Delta \phi) + Y_A(\Delta \phi, \Delta \eta) + Y_N(\Delta \phi, \Delta \eta)$

- Signal of interest
- Away-side recoil
- Near-side jet peak

- Jet peak & recoil in central collisions are estimated from the peripheral collisions and subtracted.
2PC Analysis – recoil subtraction

\[ Y_{\text{corr}}(\Delta \phi, \Delta \eta) = \frac{\int B(\Delta \phi, \Delta \eta) d\Delta \phi d\Delta \eta}{\pi \eta_\Delta^{\text{max}}} \left( \frac{S(\Delta \phi, \Delta \eta)}{B(\Delta \phi, \Delta \eta)} - b_{\text{ZYAM}} \right) \]

per-trigger yield in 2D

\[ b_{\text{ZYAM}} \]

combinatorial background

\[ Y_{\text{sub}}(\Delta \phi, \Delta \eta) = Y(\Delta \phi, \Delta \eta) - \alpha Y_{\text{peri}}^{\text{corr}}(\Delta \phi, \Delta \eta) \]

\[ \alpha \] is chosen such that

\[ \alpha Y_{\text{peri}}^{\text{corr}} \]

\[ Y_{N-\text{peak}} \]

\[ Y_{N-\text{Peak}} = \int_{|\Delta \eta|<1} Y(\Delta \eta) d\Delta \eta - \frac{1}{3} \int_{2<|\Delta \eta|<5} Y(\Delta \eta) d\Delta \eta \]
2PC Analysis – recoil subtraction

\[ Y_{\text{sub}}(\Delta \phi, \Delta \eta) = Y(\Delta \phi, \Delta \eta) - \alpha Y_{\text{peri}}^{\text{corr}}(\Delta \phi, \Delta \eta) \]

Before subtraction

After subtraction

ATLAS Preliminary
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV}, \ L_{\text{int}} = 31 \text{ nb}^{-1} \]
\[ 1 < p_T^{a,b} < 3 \text{ GeV} \]
- 2\textsuperscript{nd} 3\textsuperscript{rd} and 4\textsuperscript{th} order harmonics cancel in the difference.
  - Yield from recoil matches the yield difference for $1 < \pt^b < 3 \text{ GeV}$
  - Holds irrespective of $\pt^a$

- At other $\pt^b$, differences are seen
  - consistent with a long range $\nu_1$. 

$Y_{int} = \int_a^b Y^{corr}(\Delta\phi) \, d\Delta\phi$
Near-side ridge visible through the entire $p_T$ range studied.

Origin of high- $p_T$ ridge?
- Non-zero $v_2$, $v_3$ at high $p_T$ (~10 GeV).
- $v_n$ decrease with increasing $n$.
- Rise with $p_T$ at low $p_T$ and then decrease.
- Factorizes within a few percent for $p_T^b < 4$ GeV.

$$Y^\text{sub}(\Delta \phi) \sim 1 + \sum_n 2v_n, n \cos(n\Delta \phi)$$

$$v_n(p_T^a) = \frac{v_{n,n}(p_T^a,p_T^b)}{\sqrt{v_{n,n}(p_T^b,p_T^b)}}$$
Fourier harmonics

- Non-zero $v_2, v_3$ at high $p_T$ (~10 GeV).
- $v_n$ decrease with increasing $n$.
- Rise with $p_T$ at low $p_T$ and then decrease.

- Less variation in integrated $v_2$ for $N_{ch}^{\text{rec}} > 150$, $v_3$ continues to increase.
After recoil subtraction, $p_T^{a,b}$ dependence of $v_{11}$ similar to that seen in Pb+Pb collisions

- In Pb+Pb, attributed to long-range $v_1$ from density fluctuations which is $-$ve at low $p_T$ and $+$ve at higher $p_T$. 

$\nu_{1,1}$ - First order harmonic in $p+Pb$
Employ similar factorization as other harmonics, but account for sign change

\( v_{1,1} \) can be factorized as

\[
v_1(p_T) \equiv \frac{v_{1,1}(p_T, p_T^{\text{ref}})}{v_1(p_T^{\text{ref}})}
\]

\[
v_1(p_T^{\text{ref}}) = \text{sign}(p_T - p_T^0) \sqrt{|v_{1,1}(p_T^{\text{ref}}, p_T^{\text{ref}})|}
\]

\[
p_T^0 = 1.5 \text{ GeV}
\]

Good agreement for different \( p_T^{\text{ref}} \), suggesting a single particle modulation.
Peripheral Pb+Pb collisions have comparable multiplicity as ultra central p+Pb collisions.

Larger jet contribution in p+Pb than Pb+Pb in events with similar multiplicity.
Comparison of $\nu_n$ in p+Pb and peripheral Pb+Pb.

- Significantly larger $\nu_2$ and $\nu_4$ in Pb+Pb, but comparable magnitudes for $\nu_3$
  - Large elliptic geometry from overlap in PbPb
  - $\nu_4$ gets contribution from $\nu_2$

- Compare $\nu_n (p_T)_{p+Pb}$ with $\nu_n (p_T/K)_{Pb+Pb}$, (Teaney et.al)
  - $K=1.25$, ratio of $<p_T>$.

- p+Pb: $<N_{ch}> \pm \sigma = 259 \pm 13$
- Pb+Pb: $<N_{ch}> \pm \sigma = 241 \pm 43$
\( \nu_n \) scaling between the p+Pb and Pb+Pb systems.

- \( \nu_2 \) values, after scaling the \( p_T \) axis, differ only by a scale factor between the two systems.
- Suggests a similar origin for \( \nu_2 \) in the two systems?
Summary and Conclusions

- **Flow and fluctuations in Pb+Pb**
  - Consistent results from cumulant and EbE measurements.
  - Correlations of $v_2$ with higher order $v_n \rightarrow$ Event shape selection
  - Linear and non-linear components separated for $v_4$ and $v_5$

- **Ridge in p+Pb**
  - Non-zero near-side ridge and $v_n$ at higher $p_T$ (~10 GeV)
  - $v_1$ in p+Pb: changes sign around 1.5 GeV, reaches 0.1 for $p_T > 4$
  - Similar $p_T$ dependence as $v_n$ from peripheral Pb+Pb, after scaling the $p_T$ axis for Pb+Pb by mean $p_T$:
    - Suggests a similar origin for $v_2$ in the two systems?