Precision studies of collective dynamics in lead-lead and proton-lead collisions with the ATLAS detector

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- Initial spatial fluctuations of nucleons lead to higher moments of deformations in the fireball, each with its own orientation.
- The spatial anisotropy is transferred to momentum space by collective flow.

\[ \varepsilon_n = \sqrt{\frac{\langle r^n \cos(n\phi) \rangle + \langle r^n \sin(n\phi) \rangle}{r^n}} \]

\[ \tan(n\Phi_n) = \frac{\langle r^n \sin(n\phi) \rangle}{\langle r^n \cos(n\phi) \rangle} \]

- The harmonics \( v_n \) carry information about the medium: initial geometry, \( \eta/s \).
- Measuring harmonics = Understanding initial geometry & medium properties
Centrality, $p_T$ & $\eta$ dependence of $\langle v_n \rangle$

- **Features of Fourier coefficients**
  - $v_n$ coefficients rise and fall with centrality.
  - $v_n$ coefficients rise and fall with $p_T$.
  - $v_n$ coefficients are $\sim$boost invariant.

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Phi_n)$$

ATLAS Unique measurements

- Event-by-Event $v_n$ measurements
- $v_n - v_m$ correlations
- $\Phi_n - \Phi_m$ correlations
The large acceptance of the ATLAS detector and large multiplicity at LHC makes EbE $v_n$ measurements possible for the first time.
\( v_3 \) distributions are consistent with pure Gaussian fluctuations

\[
p(v_n) \propto v_n \exp\left(-\frac{v_n^2}{2\delta_n^2}\right)
\]

deviations in the tail (increases central->midcentral)

For \( v_2 \) pure Gaussian fits only work for most central (2%) events.
Measuring the hydrodynamic response: $v_2$

$\nu_n \propto \epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$

For Glauber and CGC mckln

Both models fail describing $p(v_2)$ across the full centrality range
Unfolding in different $p_T$ ranges: 20-25%

Distributions for higher $p_T$ bin is broader, but they all have ~same reduced shape. Hydrodynamic response factorizes into a $p_T$ dependent and geometry dependent part.
Mean and sigma of $v_n$ distributions

for gaussian fluctuations: $\sigma_n / \langle v_n \rangle \approx 0.523$
Mean and sigma of $v_n$ distributions

for gaussian fluctuations: $\sigma_n / \langle v_n \rangle \approx 0.523$
Different methods give different results as each is affected differently by fluctuations

Can directly calculate cumulants from EbyE $v_n$ measurements and compare
Much more variation in $v_2$ within one centrality than variation of mean $v_2$ across all centralities

Should also study the variation of $v_n$ at fixed centrality but varying event-geometry: “event-shape-selected $v_n$ measurements” (arXiv 1208.4563 Schukraft et al.)
\[ v_2 e^{i2\Phi_2} \propto \varepsilon_2 e^{i2\Phi_2^*}, \quad v_3 e^{i3\Phi_3} \propto \varepsilon_3 e^{i3\Phi_3^*} \]

- Correlations can arise from initial geometry effects.
- Glauber calculations show anti-correlations between \( \varepsilon_2 \) and \( \varepsilon_3 \) that can lead to anti-correlations between \( v_2 \) and \( v_3 \).

Measure correlations = Understand geometry of initial state

- Correlations can arise from non-linear response to \( \varepsilon_n \).

\[ v_4 e^{i4\Phi_4} = a_0 \varepsilon_4 e^{i4\Phi_4^*} + a_1 \left( \varepsilon_2 e^{i2\Phi_2^*} \right)^2 + \ldots \]

Collective response to eccentricities

\[ = c_0 \varepsilon_4 e^{i4\Phi_4^*} + c_1 \left( v_2 e^{i2\Phi_2} \right)^2 + \ldots , \]

- Measure correlations = Understand hydro response

Pb+Pb, \( b_{\text{imp}} = 10 \text{ fm} \)

arXiv 1311.7091
**v_n-v_2 correlations: centrality dependence**

- First correlation without event v_2-selection, 5% steps

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**v_2 (higher p_T)**

- ATLAS Preliminary
- √S_{NN}=2.76 TeV
- |Δη|>2, Pb+Pb
- L_{int} = 7 μb\(^{-1}\)
- Central (0-5%)
- Peripheral (65-70%)

“Boomerang” reflects stronger viscous damping at higher p_T and peripheral

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**V_3**

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- √S_{NN}=2.76 TeV
- 0.5 < p_T < 2 GeV
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- Peripheral

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**V_4**

- ATLAS Preliminary
- √S_{NN}=2.76 TeV
- 0.5 < p_T < 2 GeV
- |Δη|>2, Pb+Pb
- Central
- Peripheral
Fix system size and vary the ellipticity!

- **Linear correlation within a given centrality** → viscous damping controlled by system size, not shape

\( v_n - v_2 \) correlations: within fixed centrality

**Probe** \( p(v_n, v_2) \)
\( v_n - v_2 \) correlations: within fixed centrality

- Fix system size and vary the ellipticity!
- Overlay \( \varepsilon_3 - \varepsilon_2 \) and \( \varepsilon_4 - \varepsilon_2 \) correlations, rescaled

**\( v_2 \) (higher \( p_T \))**

Linear correlation within a given centrality \( \rightarrow \) viscous damping controlled by system size, not shape

**\( V_3 \)**

Clear anti-correlation,

**\( V_4 \)**

quadratic rise from non-linear coupling to \( v_2^2 \)

Probe \( p(v_n, v_2) \)
**v_n-v_2 correlations: within fixed centrality**

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- Overlay $\varepsilon_3-\varepsilon_2$ and $\varepsilon_4-\varepsilon_2$ correlations, rescaled

**v_2 (higher p_T)**

Linear correlation within a given centrality $\rightarrow$ viscous damping controlled by system size, not shape

**V3**

Clear anti-correlation, mostly initial geometry effect!!

**V4**

quadratic rise from non-linear coupling to $v_2^2$ initial geometry does not work!!

Initial geometry describe $v_3$-$v_2$ but fails $v_4$-$v_2$ correlation
linear ($\varepsilon_4$) and non-linear ($v_2^2$) component of $v_4^{17}$

- $v_4$-$v_2$ correlation for fixed centrality bin $v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4} + c_1 \left( v_2 e^{i2\Phi_2} \right)^2 \Rightarrow$ Fit by $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$

- Fit $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$ to separate linear ($\varepsilon_4$) and non-linear ($v_2^2$) component
- $v_4$-$v_2$ correlation for fixed centrality bin $v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^*} + c_1 (v_2 e^{i2\Phi_2})^2 \Rightarrow$ Fit by $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$

- Fit $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$ to separate linear ($\varepsilon_4$) and non-linear ($v_2^2$) component

- Extracted linear and non-linear component as a function of centrality
Two-particle correlations show long range correlation structure along $\Delta \eta$ at $\Delta \phi = 0$.

Is there an effective mechanism that rules them all? Is it initial state effect, final state effect or both?

- Final state effect may not imply hydro

Is there an away-side ridge in $pp$ and $pPb$?

What is its detailed $p_T$, $\eta$, and centrality dependence?
Peripheral subtraction

- Estimate contribution of jet & recoil correlations using low multiplicity events
- Subtract from correlations in high-multiplicity events to obtain “true” long-range correlations

Central - Peripheral=True correlation
$p + Pb$ $v_n$

$ATLAS$ Preliminary

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

$L_{int} = 28$ nb$^{-1}$

$p + Pb$

$220 \leq N^{rec}_{ch} < 260$

$1 < p_T^{n} < 3$ GeV, $|\eta| > 2$

- $n=2$
- $n=3$
- $n=4$
- $n=5$

$CMS$, $220 \leq N^{off}_{trk} < 260$

$V_2$, $N^{off}_{trk} < 20$ sub.

$V_3$, $N^{off}_{trk} < 20$ sub.
$p+Pb \, v_n$

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$V_3$, $N^{\text{off}}_\text{trk} < 20$ sub.

$V_2$

$0.4 < p_T^{a,b} < 3 \text{ GeV}$

$2 < |\Delta\eta| < 5$

$ATLAS$ Preliminary

$L_{\text{int}} \approx 28 \text{ nb}^{-1}$

$p+Pb$

$V_3$

$V_4$
Compare p+Pb with Pb+Pb $v_n$

Right panels adjust p+Pb $p_T$ scale by 4/5 to account for difference in $<p_T>$ (Teany et al arXiv:1312.6770)

Pb+Pb $v_2$ and $v_4$ multiplied by 0.66 to match p+Pb

Good agreement between p+Pb and Pb+Pb when including $p_T$ and $v_2$, $v_4$ rescaling
ATLAS has measured collective phenomena in Pb+Pb collisions
  - Two-particle correlations, Event-plane & Cumulants

Unique ATLAS measurements
  - Event-by-Event probability distribution of $v_2$-$v_4$
  - $v_m$-$v_2$ correlations
  - Event-Plane correlations

Direct understanding of fluctuations in initial geometry & nature of hydrodynamic response to the fluctuations

Measured long-range correlations in p+Pb events
  - Estimated and removed jet and recoil contributions using peripheral events
  - Extracted $v_1$-$v_5$ using two-particle correlations
  - Harmonics qualitatively similar to those in Pb+Pb correlations
Cumulant measurements

Measured $v_2$ using 2, 4, 6 & 8-particle cumulants

Measured $v_3$, $v_4$ using 2 & 4-particle cumulants
Correlation between $\Phi_2$ and $\Phi_4$

- Results expressed as function of $N_{\text{part}}$.
- Very different from correlations in initial state (Glauber).
- What happens if we include final-state-interactions?
Correlation between $\Phi_2$ and $\Phi_4$

- Results expressed as function of $N_{\text{part}}$.
- Very different from correlations in initial state (Glauber)
- What happens if we include final-state-interactions?
- Correlations well reproduced in AMPT model
  - AMPT results from arXiv:1307.0980 (Bhalerao et. al.)
- Conclusion: large fraction of $v_4$ originates from $\varepsilon_2$ during hydrodynamic expansion !!!
Correlation of $\Phi_2$ or $\Phi_3$ with $\Phi_6$

- $\Phi_2$ and $\Phi_3$ both strongly correlated with $\Phi_6$
- They show opposite centrality dependence though:
  - $\Phi_2$-$\Phi_6$ correlation may due to average geometry..
  - But $\Phi_3$-$\Phi_6$ correlation?
  - $v_6$ dominated by non-linear contribution: $v_2^3$, $v_3^2$?
Correlation of $\Phi_2$ or $\Phi_3$ with $\Phi_6$

- Final state interactions reproduce the correlations

- Conclusion: large contribution to $v_6$ from $(\epsilon_2)^3$ & $(\epsilon_3)^2$ during hydrodynamic expansion !!!
\( p+Pb \) vs. \( v_n \)

**ATLAS** Preliminary

- \( s_{NN} = 5.02 \text{ TeV} \)
- \( L_{\text{int}} \approx 28 \text{ nb}^{-1} \)

**Conditions:**
- \( 220 \leq N_{\text{ch}}^{\text{rec}} < 260 \)
- \( 1 < p_T^b < 3 \text{ GeV}, |\Delta \eta| > 2 \)
- \( V_2, N_{\text{off}}^{\text{sub}} < 20 \)
- \( V_3, N_{\text{off}}^{\text{sub}} < 20 \)

**CMS,** \( 220 \leq N_{\text{off}}^{\text{trk}} < 260 \)

**Graphs:**
- **Fig. 1:**
  - \( V_2 \)
  - \( V_3 \)
  - \( V_4 \)

**Equations:**
- \( 0.4 < p_T^{a,b} < 3 \text{ GeV} \)
- \( 2 < |\Delta \eta| < 5 \)

**ATLAS** Preliminary

- \( s_{NN} = 5.02 \text{ TeV} \)
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**Figures:**
- **Fig. 2:** \( 0.5 < p_T^b < 1 \text{ GeV} \)
- **Fig. 3:** \( 2 < |\Delta \eta| < 5 \)

**Legend:**
- \( \bullet \) \( N_{\text{ch}}^{\text{rec}} \geq 260 \)
- \( \circ \) \( 220 \leq N_{\text{ch}}^{\text{rec}} < 260 \)
- \( \triangle \) \( 180 \leq N_{\text{ch}}^{\text{rec}} < 220 \)
- \( \square \) \( 140 \leq N_{\text{ch}}^{\text{rec}} < 180 \)
- Tracking coverage: $|\eta|<2.5$
- FCal coverage: $3.2<|\eta|<4.9$ (used to determine Event Planes)
- For event-plane correlations use entire EM calorimeters ($-4.9<\eta<4.9$)