Recent Results on Soft Probes of the Quark-Gluon Plasma from the ATLAS Experiment at the LHC

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(on behalf of the ATLAS Collaboration)
Recent results from lead-lead collisions:

- Collective flow with higher-order cumulants in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC, ATLAS-CONF-2014-027
- Measurement of event-plane correlations in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector, arXiv:1403.0489
- Measurement of the centrality and pseudorapidity dependence of the integrated elliptic flow in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector, arXiv:1405.3936
- Measurement of the correlation between elliptic flow and higher-order flow harmonics in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV, ATLAS-CONF-2014-022

Recent results from proton-lead collisions:

- Measurement of long-range pseudorapidity correlations and azimuthal harmonics in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector, ATLAS-CONF-2014-021
The ATLAS detector

Detector coverage:

Inner Detector (ID):
\[ |\eta| < 2.5 \]

Calorimeter (CAL):
\[ |\eta| < 3.2 \text{ (EM)} \]
\[ |\eta| < 4.9 \text{ (HAD)} \]
\[ 3.2 < |\eta| < 4.9 \text{ (FCal)} \]

Zero Degree Cal. (ZDC):
\[ |\eta| > 8.3 \quad @z = \pm 140 \text{ m} \]

MB Trig. Scint. (MBTS):
\[ 2.1 < |\eta| < 3.9 \]

Magnetic fields:
- 2T solenoid field in ID
- Toroidal field in MS

Identification of minimum-bias Pb+Pb collisions:
measurement of spectator neutrons in Zero Degree Calorimeters (ZDCs) and charged particles (pulse height and arrival times) in Minimum Bias Trigger Scintillators (MBTS).

Pb+Pb data (2010): \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}, L = 7 \mu\text{b}^{-1} \).

p+Pb data (2013): \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, L = 28 \text{ nb}^{-1} \).
Centrality determination in Pb+Pb and p+Pb

- Centrality is measured using forward calorimeters ($3.2 < |\eta| < 4.9$):
  - in Pb+Pb use sum of $E_T$ on both sides,
  - in p+Pb use sum of $E_T$ on Pb-going side only,
  - for Pb+Pb use Glauber MC for geometry,
  - for p+Pb use both Glauber and Glauber-Gribov color fluctuation model (PLB 633: 245 (2006)).
  - Average number of participants ($N_{\text{part}}$) for each centrality bin resulting from fits to the measured $E_T$ distribution for p+Pb.
Theoretical framework

Final state momentum anisotropy is studied via Fourier decomposition of the azimuthal angle:

\[
E \frac{d^3 N}{dp^3} = \frac{1}{p_T} \frac{d^3 N}{d\phi dp_T dy} = \frac{1}{2\pi p_T} \frac{E}{p} \frac{d^2 N}{dp_T d\eta} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n) \right)
\]

\(\Phi_n\) - azimuthal angle of the \(n\)-th order symmetry plane of the initial geometry,

\(v_n \equiv \langle e^{in(\phi-\Phi_n)} \rangle = \langle \cos n(\phi - \Phi_n) \rangle\) - magnitude of the \(n\)-th flow harmonics.

- Event plane method:

\[\Phi_n = \frac{1}{n} \arctan \left( \frac{\sum E_{T_i} w_i \sin(n\phi_i)}{\sum E_{T_i} w_i \cos(n\phi_i)} \right)\]

\[v_n = \frac{\langle \cos [n(\phi_{i,P,N} - \Phi_{n,P})] \rangle}{\sqrt{\langle \cos [n(\Phi_{n,P} - \Phi_{n,N})] \rangle}}\]

- Cumulant method:

\[\langle corr_n \{2k\} \rangle = \langle \langle e^{i n(\phi_1 + \ldots + \phi_k - \phi_{k+1} - \ldots - \phi_{2k})} \rangle \rangle = \langle v_n \{2k\} \{2k\} \rangle\]

\[c_n \{4\} = \langle corr_n \{4\} \rangle - 2\langle corr_n \{2\} \rangle^2\]

\[v_n \{4\}(p_T, \eta) = -d_n \{4\} / 3^4 \sqrt{-c_n \{4\}}\]
\(2k\)-particle cumulants are insensitive to lower order correlations (\(<2k\))
- non-flow effects (i.e. not related to the initial geometry) are eliminated.

Generating function is used to obtain \(2k\)-particle correlations and cumulants (N.Borghini et al., arXiv:nucl-ex/0110016)

Transverse momentum dependence of flow harmonics:

- strong reduction of \(v_n\) by using more than 2-particle correlations,
  in general: \(v_n\{2\} > v_n\{EP\} > v_n\{4\} \approx v_n\{6\} \approx v_n\{8\}\)
- good agreement of \(v_2\{4\}\) with ALICE and CMS,
Pseudorapidity dependence of flow harmonics:

- integrated over $0.5 < p_T < 20$ GeV,
- $v_n\{2\}, v_n\{EP\} > v_n\{2k\}$ for $k > 1$,
- no strong dependence on pseudorapidity,

Centrality dependence of flow harmonics:

- integrated over $p_T$ and $\eta$,
- $v_n\{2\} > v_n\{EP\} > v_n\{EbyE\} > v_n\{4\}$
- $v_n\{EbyE\}$ - ”event by event” from $p(v_n)$ distr.
- large contribution from the 2-particle correlations present in $v_n\{2\}$ are suppressed in $v_n\{EP\}$,
- negative contribution of flow fluctuations to $v_n\{4\}$. 
Correlation between $\Phi_n$ and $\Phi_m$ is described by the differential event yield:

$$
\frac{dN_{evts}}{d(k(\Phi_n - \Phi_m))} \propto 1 + 2 \sum_{j=1}^{\infty} V^j_{n,m} \cos jk(\Phi_n - \Phi_m)
$$

$$
V^j_{n,m} = \langle \cos jk(\Phi_n - \Phi_m) \rangle
$$

- can be generalized for three or more event planes,
- use EP or SP method (PR C87, 044907 (2013)),
- poor agreement with Glauber model,
- good agreement with AMPT (PR C72, 064901 (2005))

$\Rightarrow$ significant non-linear flow contributions to higher order harmonics
Comparison of three plane correlators:

- Good agreement with AMPT model,
- Poor agreement with Glauber model.
Central dependence of integrated $v_2$:

- **Three tracking techniques used to minimize the low $p_T$ limit ($p_{T,0}$):**
  - IDT - default tracking, $p_T > 0.5$ GeV
  - PXT - low $p_T$ tracking, $p_T > 0.1$ GeV
  - TKT - field off data, $p_T > 0.07$ GeV (estimated with MC)

- Consistent results with different tracking techniques for matching $p_{T,0}$.

- No need to extrapolate to $p_{T,0} = 0$ to obtain reliable estimate of $v_2$ integrated over whole kinematic range in $p_T$. 
Centrality dependence of integrated $v_2$:
- clear dependence on $p_{T,0}$,
- integrated elliptic flow increases with centrality, reaching maximum for mid-central collisions (40-50%) and then decreases for the more central collisions.
- good agreement with CMS results (Phys. Rev. C87, 014902 (2013))

Pseudorapidity dependence of integrated $v_2$:
- very weak dependence on pseudorapidity
- good agreement with CMS measurement.
Study correlations between $v_2$ and $v_n$ ($n = 2, 3, 4, 5$) for various centrality intervals using two-particle correlation function with $|\Delta \eta| > 2$:

- boomerang-like structure seen in all correlation plots:
  - reflects the characteristic centrality dependence of $v_2$
  - is consistent with hydrodynamic predictions of stronger viscous-damping effects for $v_3$ than $v_2$ for $p_T < 3$ GeV or for $0 - 50\%$ centrality interval,
  - significant non-linear contributions to $v_4$ from $v_2$ make the boomerang-like structure less pronounced in $v_2 - v_4$ correlations.
Correlations between $v_2$ and higher order flow harmonics

- Events within each centrality are subdivided into $q_2$ (flow vector) intervals:

$$
\bar{q}_2 = \frac{1}{\sum w_i} \left( \sum [w_i \cos 2\phi_i], \sum [w_i \sin 2\phi_i] \right) - \langle \bar{q}_2 \rangle_{evts}
$$

where $w_i = E^{FCal}_T, i$

- Fix initial geometry (system size) and vary elipticity:

Clear anti-correlation, mostly initial geometry effect (AMPT calculations).

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

Quadratic rise from non-linear coupling to $v_2^2$, initial geometry does not work.

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Soft Probes of QGP with ATLAS

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Flow non-linearity in $v_4$ and $v_5$

- $v_4 - v_2$ correlation for fixed centrality bin: $v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^*} + c_1 (v_2 e^{i2\Phi_2})^2$

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

- Extract linear and non-linear terms $v_{4L} = c_0$, $v_{4NL} = \sqrt{v_4^2 - c_0^2}$ as a function of centrality.

- Non-linear behaviour observed also in $v_5 - v_2$ correlation, fit $v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2}$.
Long range correlations in p+Pb collisions

- Measurement of two-particle correlation function in p-Pb collisions:
  - low-activity evt. - yield function contains mainly short-range correlations,
  - high-activity evt. - also important contribution from long-range ‘ridge’ correl.
  - to obtain long-range component, estimate first short-range component from peripheral events and then subtract,

- extract flow harmonics from the correlation function for high activity events:
Compare flow harmonics in p+Pb and Pb+Pb collisions

- Significantly larger $v_2$ and $v_4$ in Pb+Pb but comparable magnitudes for $v_3$, ($v_2$ and $v_4$ are coupled $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$).
- Compare $v_n(p_T)_{p+Pb}$ with $v_n(p_T/K)_{Pb+Pb}$, (Taney et al. nucl-th/1312.6770)

- $p+Pb$: $\langle N_{ch} \rangle \approx 259 \pm 13$
- Pb+Pb: $\langle N_{ch} \rangle \approx 241 \pm 43$
- $K = 1.25$ - ratio of $\langle p_T \rangle$
- $v_2$ after scaling the $p_T$ axis differ only by scale factor between the two systems.
- This suggests that long-range ridge correlations in high multiplicity p+Pb collisions and peripheral Pb+Pb collisions are driven by similar dynamics.
ATLAS has provided several new results on soft probes of QGP:

- Flow coefficients $v_n$ were obtained with higher order cumulants. The elliptic flow obtained with four-particle cumulants provides a measure of $v_2$ with non-flow correlations strongly suppressed.
- Event-plane correlations involving two and three event planes of different order have been measured as a function of centrality, good description by the Glauber model including the final state collective dynamics.
- The $p_T$ integrated elliptic flow measured with different methods shows clear dependence on $p_{T,0}$.
- Correlations between elliptic flow in different $p_T$ ranges show non-trivial centrality dependence, while they are found to be linear within narrow centrality intervals, which indicates that viscous effects are controlled by the system size, not its shape.
- Correlations of $v_2$ with higher order flow harmonics $v_n$, $n = 4, 5$, disagree with predictions based on initial geometry models, but are consistent with combined contributions of linear and non-linear terms.
- Long range correlations and flow harmonics have been studied in p+Pb collisions.

More on https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Thank you for your attention!
Backup slides

\[ v_2 \]

\[ p_T \] [GeV]

\[ \eta \]

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ L_{\text{int}} \approx 7 \mu \text{b}^{-1} \]

\[ |\eta| < 2.5 \]

\[ v_2(\eta) \]

\[ v_2(2) \]

\[ v_2(4) \]

\[ v_2(6) \]

\[ v_2(8) \]

\[ \eta \]

\[ ATLAS \ Preliminary \]

\[ Pb+Pb \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ L_{\text{int}} \approx 7 \mu b^{-1} \]

\[ 0.5 < p_T < 20 \text{ GeV} \]
Probability distributions of the flow harmonics in Pb+Pb (JHEP 11 (2013) 183):

- Relative widths provide direct constraints on the hydrodynamic response to initial geometry fluctuations.
Event plane correlations

Centrality dependence of two-plane correlators in Pb+Pb (hep-ex/1403.0489):

\[
\langle \Phi \rangle_{N_{\text{part}}} = 0, 100, 200, 300, 400
\]

\[
4 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
\langle \Phi \rangle_{N_{\text{part}}} = 0, 100, 200, 300, 400
\]

\[
3 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
2 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
\langle \Phi \rangle_{N_{\text{part}}} = 0, 100, 200, 300, 400
\]

\[
5 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
6 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
\langle \Phi \rangle_{N_{\text{part}}} = 0, 100, 200, 300, 400
\]

\[
7 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
8 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
\langle \Phi \rangle_{N_{\text{part}}} = 0, 100, 200, 300, 400
\]

\[
9 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
10 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
\langle \Phi \rangle_{N_{\text{part}}} = 0, 100, 200, 300, 400
\]

\[
11 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
12 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
\langle \Phi \rangle_{N_{\text{part}}} = 0, 100, 200, 300, 400
\]

\[
13 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
14 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
\langle \Phi \rangle_{N_{\text{part}}} = 0, 100, 200, 300, 400
\]

\[
15 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]

\[
16 \Phi - \Phi \cos(\Phi) \cos(\Phi_{Glauber})\]
Event plane correlations

Centrality dependence of three-plane correlators in Pb+Pb (hep-ex/1403.0489):

\[
\langle \cos(4\phi_2) \rangle_{\text{part } N} \quad \langle \cos(8\phi_2) \rangle_{\text{part } N} \quad \langle \cos(12\phi_2) \rangle_{\text{part } N}
\]

\[
\langle \cos(6\phi_3) \rangle_{\text{part } N} \quad \langle \cos(6\phi_3) \rangle_{\text{part } N} \quad \langle \cos(6\phi_3) \rangle_{\text{part } N}
\]
Pseudorapidity dependence of elliptic flow integrated over $p_T$ in Pb+Pb (hep-ex/1405.3936):

\[
\begin{align*}
V_2 & \quad \text{method:} \\
\text{TKT } p_T > 0.07 \text{ GeV} & \quad \text{Pb+Pb } \sqrt{S_{\text{NN}}} = 2.76 \text{ TeV} \\
\text{PXT } p_T > 0.1 \text{ GeV} & \quad \text{IDT & PXT: } L_{\text{int}} = 0.5 \mu b^{-1} \\
\text{PXT } p_T > 0.5 \text{ GeV} & \quad \text{TKT: } L_{\text{int}} = 1 \mu b^{-1} \\
\text{IDT } p_T > 0.5 \text{ GeV} & \\
\end{align*}
\]
$v_2 - v_n$ correlations


![Graph showing $v_n$ versus centrality for different $p_T$ intervals. The graph is divided into four panels, each representing a different $p_T$ interval: 1-2 GeV, 2-3 GeV, 3-4 GeV, and 4-8 GeV. Each panel shows data for different $n$ values: 2, 3, 4, 5, and 6. The ATLAS experiment is labeled on the graph.](image-url)