Soft probes of the quark-gluon plasma in ATLAS

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Outline

Study of Quark-Gluon Plasma initial conditions and evolution

- Integrated elliptic flow
- Flow harmonics from multi-particle cumulants
- Event plane correlations
- Correlations between flow harmonics

- Long range pseudorapidity correlations
  More details were given in the earlier talk by Martin Spousta

Pb+Pb

p+Pb
The ATLAS detector

- Inner detector: $|\eta| < 2.5$
- Calorimeter: $|\eta| < 3.2$
- Forward Calorimeter: $3.1 < |\eta| < 4.9$

Detector characteristics:
- Width: 44m
- Diameter: 22m
- Weight: 7000t
Centrality of PbPb collisions

Distribution of the signals registered in the **Forward Calorimeter (FCal)** is divided into bins with appropriate percentage of events.

Fraction of the sampled non-Coulomb inelastic cross section after all trigger selection cuts is estimated to be $100\% \pm 2\%$
Azimuthal correlations decomposition - definitions

Event plane method

\[
\frac{dN}{d\phi} \sim 1 + 2 \sum_{n=1}^{\infty} v_n(p_T, \eta) \cos(n(\phi - \Phi_n))
\]

\[v_n = \langle \cos(n(\phi - \Phi_n)) \rangle\]

Two-particle correlations method

\[
\frac{dN}{d(\phi_a - \phi_b)} \sim 1 + 2 \sum_{n=1}^{\infty} v_{n,n}(p_T^a, p_T^b) \cos(n(\phi_a - \phi_b))
\]

\[v_{n,n} = \langle \cos(n(\phi_a - \phi_b)) \rangle\]

for flow: \[v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b)\]

Cumulants from 2k-particle correlations

\[\langle corr_n\{2k\}\rangle = \langle \exp(in(\phi_1 + \ldots + \phi_k - \phi_{k+1} + \ldots + \phi_{2k}))\rangle\]
Integrated elliptic flow:

- from reconstructed tracks with $p_T > p_T^{\text{min}}$, extrapolated to $p_T = 0$
- measured down-to very low $p_T$ ($p_T > 0.07$ GeV) [arXiv:1405.3936v2]

Using pixel tracklets (vertex+2 hits) and pixel tracks ATLAS is reconstructing low-$p_T$ charged primary particles with sufficient efficiency to measure integrated elliptic flow without model dependent corrections

ATLAS, arXiv:1405.3936v2
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Using pixel tracklets (vertex+2 hits) and pixel tracks ATLAS is measuring low-$p_T$ charged primary particles with sufficient efficiency.

Integrated flow is $\sim 20\%$ smaller than the flow calculated from tracks with $p_T > 0.5$ GeV
Integrated elliptic flow in Pb+Pb collisions

Elliptic flow for different $p_T$ cuts:
- $p_T > 0.3$ GeV
- $p_T > 0.2$ GeV
- $p_T > 0.1$ GeV
- $p_T > 0.07$ GeV

ATLAS and CMS results with the same $p_T$ cut agree very well

ATLAS, arXiv:1405.3936v2
Integrated elliptic flow - after transformation to the rest frame of one of colliding nuclei:

LHC results consistent with the extended longitudinal scaling observed at RHIC

ATLAS, arXiv:1405.3936v2
Flow harmonics with multi-particle cumulants in Pb+Pb collisions

Cumulants method results:
$v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$ values of elliptic flow obtained from 4, 6 and 8-particle correlations, in which effects from two-particle correlations are canceled, are significantly smaller than $v_2$ from two-particle correlations or from event plane method

$V_2\{2\} > V_2\{EP\} > V_2\{4\}$

$V_2\{4\} \approx V_2\{6\} \approx V_2\{8\}$

ATLAS, arXiv:1408.4342
Flow harmonics with multi-particle cumulants in Pb+Pb collisions

Even stronger relation for higher order harmonics:

\[ v_n^2 > v_n^{EP} >> v_n^4 \] for \( n > 2 \)

ATLAS, arXiv:1408.4342
Flow harmonics with multi-particle cumulants in Pb+Pb collisions

Weak pseudorapidity dependence of $v_3$ and $v_4$

ATLAS

Pb+Pb \( s_{NN} = 2.76 \text{ TeV} \)

\( L_{\text{int}} = 7 \mu b^{-1}, \ 0.5 < p_T < 20 \text{ GeV} \)

ATLAS, arXiv:1408.4342

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Flow harmonics with multi-particle cumulants in Pb+Pb collisions

Centrality dependence of $v_2$, $v_3$ and $v_4$

Harmonics measured using different methods have similar shape of centrality dependence, but with different magnitude:

$v_2^{(2)} > v_2^{(EP)} > v_2^{(EbyE)} > v_2^{(4)}$

Note:

$v_n^{(EbyE)}$ is calculated from the distribution of $v_n$ measured event-by-event

$$v_n(EbyE) = \sum v_n p(v_n)$$

$v_2^{(2)}$ - contains short range two particle correlations

$v_2^{(EP)}$ - increased by flow fluctuations

$v_2^{(EbyE)}$ - without these effects

$v_2^{(4)}$ - related to the "generic" initial flow effect

ATLAS, arXiv:1408.4342
Correlation between event planes $\Phi_n$ and $\Phi_m$

\[
\frac{dN_{\text{events}}}{d\left(k (\Phi_n - \Phi_m)\right)} \propto 1 + 2 \sum_{j=1}^{\infty} V_{n,m}^j \cos j k (\Phi_n - \Phi_m)
\]

\[V_{n,m}^j = \langle \cos j k (\Phi_n - \Phi_m) \rangle\]

Event plane angles $\Phi$ reconstructed in separated pseudorapidity intervals:

**2 planes**: (-4.8, -0.5) and (0.5, 4.8)

**3 planes**: (-2.7, -0.5), (0.5, 2.7) and (3.3, 4.8)

In the correlators combinations of angles $\Phi_2$ to $\Phi_6$ are used. Two methods of calculations are deployed:

**EP** - event plane method

**SP** - scalar product method - in which flow vector weights are used

For comparison unweighted or weighted correlators obtained from Glauber model are calculated.

**Correlators:**

\[\langle \cos 4 (\Phi_2 - \Phi_4) \rangle\]

\[\langle \cos 8 (\Phi_2 - \Phi_4) \rangle\]

\[\langle \cos 12 (\Phi_2 - \Phi_4) \rangle\]

\[\langle \cos 6 (\Phi_2 - \Phi_3) \rangle\]

\[\langle \cos 6 (\Phi_2 - \Phi_6) \rangle\]

\[\langle \cos 12 (\Phi_3 - \Phi_4) \rangle\]

\[\langle \cos 10 (\Phi_2 - \Phi_5) \rangle\]

\[\langle \cos (2 \Phi_2 + 3 \Phi_3 - 5 \Phi_5) \rangle\]

\[\langle \cos 4 (-8 \Phi_2 + 3 \Phi_3 + 5 \Phi_5) \rangle\]

\[\langle \cos 4 (2 \Phi_2 + 4 \Phi_4 - 6 \Phi_6) \rangle\]

\[\langle \cos 4 (-10 \Phi_2 + 4 \Phi_4 + 6 \Phi_6) \rangle\]

\[\langle \cos 4 (2 \Phi_2 - 6 \Phi_3 + 4 \Phi_4) \rangle\]

\[\langle \cos 4 (-10 \Phi_2 + 6 \Phi_3 + 4 \Phi_4) \rangle\]
Event plane correlations in Pb+Pb collisions

Correlation between two event planes $\Phi_n$ and $\Phi_m$

$$\frac{dN_{\text{events}}}{d\left(k\left(\Phi_n - \Phi_m\right)\right)} \propto 1 + 2 \sum_{j=1}^{\infty} V_{n,m}^j \cos jk\left(\Phi_n - \Phi_m\right), \quad V_{n,m}^j = \langle \cos jk\left(\Phi_n - \Phi_m\right) \rangle$$
Event plane correlations in Pb+Pb collisions

Glauber model does not describe these correlations

Event plane correlations in Pb+Pb collisions

Correlation between three event planes $\Phi_n$, $\Phi_m$ and $\Phi_h$

$$\langle \cos(c_n n\Phi_n + c_m m\Phi_m + c_h h\Phi_h) \rangle$$
Event plane correlations in Pb+Pb collisions

Comparison with AMPT model predictions

Reasonable agreement of AMPT model and the data

Event plane correlations are sensitive not only to initial conditions but also to later evolution of the system

Correlations between flow harmonics in Pb+Pb collisions

Studies of correlations between $v_2$ and $v_n$ (n=2-5), obtained from two-particle correlations:

- as a function of centrality
- as a function of $p_T$
- as a function of event shape, characterized by $q_2$ - flow vector magnitude, measured in $3.3 < |\eta| < 4.8$ interval

\[
\vec{q}_2 = \left( q_{x,2}^2, q_{y,2}^2 \right) = \frac{1}{\sum w_i} \left( \sum w_i \cos 2\phi_i, \sum w_i \cos 2\phi_i \right) - \left\langle \vec{q}_2 \right\rangle
\]

\[
q_2 = \sqrt{q_{x,2}^2 + q_{y,2}^2}
\]
Correlations between flow harmonics in Pb+Pb collisions

The "boomerang" shape is consistent with larger viscous-damping effects expected from hydrodynamic calculations.

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Correlations between flow harmonics in Pb+Pb collisions

Correlations between $v_2$ values for different $p_T$ ranges

When events in each centrality bin are divided into subsamples according to $q_2$ values, linear correlations are observed. For fixed centrality the viscous-damping changes very little with event ellipticity.

Viscous corrections are controlled by the overall system size.
Correlations between flow harmonics in Pb+Pb collisions

Centrality dependence of correlations between $v_2$ and $v_n$ (n=3-5) measured in the same range of $p_T$

Similar dependence also at higher $p_T$

ATLAS-CONF-2014-022
Correlations between flow harmonics in Pb+Pb collisions

Centrality and $q_2$ dependence of correlations between $v_2$ and $v_3$ or $v_4$

Negative correlation between $v_2$ and $v_3$ for changing $q_2$ within fixed centrality

Positive, non-linear correlation between $v_2$ and $v_4$ for changing $q_2$ within fixed centrality

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Correlations between flow harmonics in Pb+Pb collisions

Centrality and $q_2$ dependence of correlations between $v_2$ and $v_3$ or $v_4$

**fit:** $v_3 = k v_2 + v_0$

**fit:** $v_4 = \sqrt{c_0^2 + (c_1 v_2^2)^2}$

Parameters of the fit can be used to extract linear and non-linear component of $v_4$
Correlations between flow harmonics in Pb+Pb collisions

Linear and non-linear terms in $v_4$

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

Parameters of the fit can be used to extract linear and non-linear components of $v_4$

\[ v_4^L = c_0 \]
\[ v_4^{NL} = \sqrt{v_4^2 - c_0^2} \]

The same components can be calculated using the correlations between event planes

\[ v_4^{NL} = v_4 \langle \cos 4(\Phi_2 - \Phi_4) \rangle \]
\[ v_4^L = \sqrt{v_4^2 - (v_4^{NL})^2} \]

ATLAS-CONF-2014-022
Correlations between flow harmonics in Pb+Pb collisions

Centrality and $q_2$ dependence of correlations between $v_2$ and $v_5$

**Fit:**
\[ v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2} \]

**Linear and non-linear components of $v_5$ from event plane correlator:**
\[ v_5^L = c_0 \]
\[ v_5^{NL} = \sqrt{v_5^2 - c_0^2} \]

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Long-range pseudorapidity correlations in p+Pb collisions

To study long-range effects the yield from peripheral events needs to be subtracted:

Flow harmonics obtained from correlation function without subtraction ($v_n^{\text{unsub}}$) and after subtraction ($v_n$)

More details were given in the earlier talk by Martin Spousta

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Comparison of $v_n(p_T)$ in p+Pb and Pb+Pb collisions

Rescaling of Pb+Pb harmonics:
- change of $p_T$ by a factor $K=1.25$ (to account for different values of $<p_T>$)
- modification of the absolute magnitude of $v_2$ and $v_4$ by a common empirical factor 0.66

Similar shape of $v_n(p_T)$ is obtained

More details were given in the earlier talk by Martin Spousta

ATLAS-CONF-2014-021
Summary

Integrated elliptic flow
- measurement of elliptic flow down-to very low $p_T$ ($p_T > 0.07$ GeV)
- no need for model dependent extrapolations to $p_T=0$

Flow harmonics from multi-particle cumulants
- higher order cumulants insensitive to two-particle correlations
- harmonics obtained from cumulants better represent real flow
- confirmed significant non-flow contribution in $v_n$ from two-particle correlations
  - $v_2{2} > v_2{EP} > v_2{4} \approx v_2{6} \approx v_2{8}$
- strong centrality dependence of $v_2$ and a weak dependence of $v_n$ for $n>2$

Event plane correlations
- correlations between 2 or 3 event planes studied
- Glauber model inconsistent with the data, AMPT model including final state collective dynamics describes these correlations well

Correlations between flow harmonics
- presence of viscous-damping effects expected from hydrodynamic calculations
- negative correlation between $v_2$ and $v_3$ for changing ellipticity within fixed centrality
- positive, non linear correlation between $v_2$ and $v_4$ for changing $q_2$ within fixed centrality

Long range pseudorapidity correlations
- significant correlations extending to $|\Delta n| \approx 5$ present also in the away-side
- extracted $v_n(p_T)$ ($n=2-4$) in p+Pb collisions similar to those in Pb+Pb collisions after appropriate rescaling
Backup
The ATLAS detector

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The ATLAS detector

- **Inner detector**: $|\eta|<2.5$
- **Calorimeter**: $|\eta|<3.2$
- **Forward Calorimeter**: $3.2<|\eta|<4.9$
- **Muon spectrometer**: $|\eta|<2.7$

**Track reconstruction**

- **Jet reconstruction**
- **Centrality determination**
- **Muon reconstruction**
Integrated elliptic flow in Pb+Pb collisions

Integrated elliptic flow - $\eta$ dependence:

- Method:
  - TKT $p_T > 0.07$ GeV
  - PXT $p_T > 0.1$ GeV
  - PXT $p_T > 0.5$ GeV
  - IDT $p_T > 0.5$ GeV

- Pb+Pb $s_{NN}=2.76$ TeV
  - IDT & PXT: $L_{int} = 0.5 \mu$b$^{-1}$
  - TKT: $L_{int} = 1 \mu$b$^{-1}$

- ATLAS

- Centrality:
  - 0-10%
  - 10-20%
  - 20-30%
  - 30-40%
  - 40-50%
  - 50-60%
  - 60-70%
  - 70-80%

ATLAS, arXiv:1405.3936v2