Recent results on correlations and fluctuations in $pp$, $p+Pb$, and $Pb+Pb$ collisions from the ATLAS experiment at the LHC

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(on behalf of the ATLAS Collaboration)
Recent ATLAS results to be reviewed in this talk

- Measurement of long-range multiparticle azimuthal correlations with the subevent cumulant method in \( pp \) and \( p+Pb \) collisions with the ATLAS detector at the LHC. Phys. Rev. C 97, 024904 (2018)
- Correlated long-range mixed-harmonic fluctuations in \( pp, p+Pb \) and low-multiplicity \( Pb+Pb \) collisions with the ATLAS detector. ATLAS-CONF-2018-012
- Measurement of long-range azimuthal correlations in \( Z \)-boson tagged \( pp \) collisions at \( \sqrt{s} = 8 \) TeV. ATLAS-CONF-2017-068
- \( D \) meson production and long-range azimuthal correlations in 8.16 TeV \( p+Pb \) collisions with ATLAS. ATLAS-CONF-2017-073
- Measurement of the \( v_n - \text{mean } p_T \) correlations in \( Pb+Pb \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV with the ATLAS detector. ATLAS-CONF-2018-008
- Measurement of azimuthal anisotropy of charged particle production in \( Xe+Xe \) collisions at \( \sqrt{s_{NN}} = 5.44 \) TeV with the ATLAS detector. ATLAS-CONF-2018-011
- More details and results from the heavy ion physics program realized by ATLAS are available in https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavylionsPublicResults
Introduction

- Immediately after an A+A collision, the overlap region defined by the nuclear geometry is almond shaped, with shortest axis along the impact parameter vector.
- Multiple interactions between particles in the evolving system change the initial coordinate space asymmetry into final momentum space asymmetry.

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

\( \Phi_n \) - azimuthal angle of the \( n \)-th order symmetry plane of the initial geometry.
Two-particle correlations and the template fitting method

- Two-particle correlation function (and focus on LRC):

\[
C(\Delta \eta, \Delta \phi) = \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)} \frac{\int_2^5 d|\Delta |}{\int_2^5 d|\Delta |} S(\Delta \phi) \equiv C(\Delta \phi)
\]

- \( S \) and \( B \) are pair distributions constructed from the same and from “mixed events” (similar \( N_{ch}^{rec} \) and \( z_{vtx} \)).
- Ratio \( S/B \) removes correlations due to detector effects.

- Per-trigger-particle yield - the average number of associated particles per trigger particle in a given \( \Delta \phi \) range:

\[
Y(\Delta \phi) = \frac{1}{2\pi N_{trig}} \left( \int_{-\pi/2}^{3\pi/2} B(\Delta \phi) d\Delta \phi \right) C(\Delta \phi)
\]

- Template fitting procedure is applied to separate ridge from other sources of angular correlations (e.g. dijets):

\[
Y_{\text{templ}}(\Delta \phi) = G \left( 1 + \sum_{n=2}^{\infty} 2v_{n,n} \cos(n\Delta \phi) \right) + F Y_{\text{periph}}(\Delta \phi)
\]

where \( Y_{\text{periph}}(\Delta \phi) \) is obtained from low-multiplicity events.

- Importance of higher order harmonics is also visualized.
Cumulants with the standard method

▶ The standard cumulant method is based on the $k$-particle azimuthal correlations, $\langle\{k\}\rangle$:

$$\langle\{2\}_n\rangle = \langle e^{in(\phi_1-\phi_2)} \rangle, \quad \langle\{3\}_n\rangle = \langle e^{in(\phi_1+\phi_2-2\phi_3)} \rangle, \quad \langle\{4\}_n,m\rangle = \langle e^{in(\phi_1-\phi_2)+im(\phi_3-\phi_4)} \rangle$$

▶ The 2- and 4-particle cumulants are then defined as:

$$c_n\{2\} = \langle\{2\}_n\rangle, \quad c_n\{4\} = \langle\{4\}_n\rangle - 2\langle\{2\}_n\rangle^2$$

where $\langle\{4\}_n\rangle \equiv \langle\{4\}_n,n\rangle$

▶ The multi-particle symmetric and asymmetric cumulants are obtained from $\langle\{k\}\rangle$ as:

$$ac_n\{3\} = \langle\{3\}_n\rangle, \quad sc_{n,m}\{4\} = \langle\{4\}_n,m\rangle - \langle\{2\}_n\rangle\langle\{2\}_m\rangle$$

▶ In the absence of non-flow correlations, $c_n\{2\}$, $c_n\{4\}$, $ac_n\{3\}$ and $sc_{n,m}\{4\}$ read:

$$c_n\{2\} = v^2_n, \quad c_n\{4\} = -v^4_n, \quad sc_{n,m}\{4\} = \langle v^2_nv^2_m \rangle - \langle v^2_n\rangle\langle v^2_m\rangle$$

$$ac_n\{3\} = \langle v^2_nv^2_m \rangle \cos 2n(\Phi_n - \Phi_{2n})$$

▶ Normalized cumulants:

$$ns_{n,m}\{4\} = \frac{sc_{n,m}\{4\}}{v_n\{2\}^2 v_m\{2\}^2} = \frac{\langle v^2_nv^2_m \rangle}{\langle v^2_n\rangle\langle v^2_m\rangle} - 1$$

$$nac_n\{3\} = \frac{ac_n\{3\}}{v_n\{2\}^2 \sqrt{v^2_{2n}} \{2\}^2} = \frac{\langle v^2_nv^2_{2n} \rangle \cos 2n(\Phi_n - \Phi_{2n})}{\langle v^2_n\rangle \sqrt{\langle v^2_{2n}\rangle}}$$

where the $v_n\{2\}^2 = \langle v^2_n \rangle$ are flow harmonics obtained using a 2-particle correlation method based on the template fitting method.
To suppress the non-flow correlations, that usually involve few particles within a localized region in $\eta$, the tracks are divided into several subevents, each covering a unique $\eta$ range. Multi-particle correlations are constructed by correlating tracks from different subevents.

**Two subevents (2SE) - removes intra-jet correlations**

\[
\langle \{2\} \rangle_{a|b} = e^{in(\phi^a_1 - \phi^b_2)}
\]

\[
sc^{2a|2b}_{n,m} \{4\} = \langle \{4\} \rangle_{a|b} - \langle \{2\} \rangle_{a|b} \langle \{2\} \rangle_{a|b}
\]

\[
\langle \{3\} \rangle_{2a|b} = e^{in(\phi^a_1 + \phi^a_2 - 2\phi^b_3)}
\]

\[
ac^{2a|b}_{n} \{3\} = \langle \{3\} \rangle_{2a|b}
\]

\[
\langle \{4\} \rangle_{2a|2b} = e^{in(\phi^a_1 - \phi^b_2) + im(\phi^a_3 - \phi^b_4)}
\]

\[
c^{2a|2b}_{n} \{4\} = \langle \{4\} \rangle_{2a|2b} - 2\langle \{2\} \rangle^2_{a|b}
\]

**Three subevents (3SE) - removes inter-jet correlations**

\[
\langle \{3\} \rangle_{a,b|c} = e^{in(\phi^a_1 + \phi^b_2 - 2\phi^c_3)}
\]

\[
s^{a,b|2c}_{n,m} \{4\} = \langle \{4\} \rangle_{a,b|c} - \langle \{2\} \rangle_{a|c} \langle \{2\} \rangle_{b|c}
\]

\[
\langle \{4\} \rangle_{a,b|2c} = e^{in(\phi^a_1 - \phi^b_2) + im(\phi^a_3 - \phi^b_4)}
\]

\[
ac^{a,b|c}_{n} \{3\} = \langle \{3\} \rangle_{a,b|c}
\]

\[
c^{a,b|c}_{n} \{4\} = \langle \{4\} \rangle_{a,b|2c} - \langle \{2\} \rangle_{a|c} \langle \{2\} \rangle_{b|c}
\]

**Four subevents (4SE) - removes partly inter-jet correlations also in case of jets belonging to two adjacent subevents**

\[
\langle \{4\} \rangle_{a,b|c,d} = e^{in(\phi^a_1 - \phi^b_2) + im(\phi^a_3 - \phi^b_4)}
\]

\[
s^{a,b|c,d}_{n,m} \{4\} = \langle \{4\} \rangle_{a,b|c,d} - \langle \{2\} \rangle_{a|c} \langle \{2\} \rangle_{b|d}
\]
\(c_2\{4\}\) cumulant and \(v_2\) in \(pp\) and \(p+Pb\) with SE method

- The \(c_2\{4\}\) values in \(pp\) collisions and in \(p+Pb\) collisions for \(\langle N_{ch} \rangle < 100\) are smallest for the 3SE method and largest for the standard method.

- In the \(p+Pb\) collisions the \(c_2\{4\}\) are consistent for all three methods for \(\langle N_{ch} \rangle > 100\) suggesting that non-flow effects in \(p+Pb\) collisions are much smaller than those in \(pp\) collisions at comparable \(\langle N_{ch} \rangle\).

- The 3SE method gives negative \(c_2\{4\}\) values in most of the measured \(\langle N_{ch} \rangle\) range.

- The \(v_2\{4\}\) values obtained from the 3SE method are smaller than \(v_2\{2\}\) extracted from 2PC, possibly due to EbyE flow fluctuations associated with the initial state (PRL 112, 082301 (2014)).
Symmetric cumulant \( sc_{2,3}\{4\} = \langle v_2^2 v_3^2 \rangle - \langle v_2^2 \rangle \langle v_3^2 \rangle \)

- Measured in two \( p_T \) intervals: \( 0.3 < p_T < 3 \text{ GeV} \) and \( 0.5 < p_T < 5 \text{ GeV} \).
- In \( pp \) and at low values of \( \langle N_{\text{ch}} \rangle \) in \( p+Pb \) the \( sc_{2,3}\{4\} \) obtained from the standard method are positive and significantly differ from SE.
- Non-flow is largely suppressed in SE; some residual non-flow in \( pp \) at low \( \langle N_{\text{ch}} \rangle \) in 2SE.
- For the \( p_T \) region of \( 0.5 < p_T < 5 \text{ GeV} \) results from 2SE are systematically lower than the 3SE/4SE, suggesting that the 2SE method may be affected by negative non-flow contribution (recently observed in PYTHIA, PLB777 (2018) 201).
- Anticorrelation between \( v_2 \) and \( v_3 \) in SE.
- In case of \( Pb+Pb \) collisions the measured \( sc_{2,3}\{4\} \) is consistent among all four methods across most of the \( \langle N_{\text{ch}} \rangle \) range.
- 3SE method seems to be good enough for non-flow removal.
Symmetric cumulant $s_{c_{2,4}}\{4\} = \langle v_2^2 v_4^2 \rangle - \langle v_2^2 \rangle \langle v_4^2 \rangle$

- Measured in two $p_T$ intervals: $0.3 < p_T < 3 \text{ GeV}$ and $0.5 < p_T < 5 \text{ GeV}$.
- In $pp$ and in $p+Pb$ the $s_{c_{2,4}}\{4\}$ obtained from the standard method are positive and significantly differ from SE methods.
- Non-flow is largely suppressed in SE; some residual non-flow in $pp$ at low $\langle N_{ch} \rangle$ in 2SE.
- Positive correlation between $v_2$ and $v_4$ is observed in all methods due to non-linear effect $v_4 = v_{4L} + \chi^2 v_2^2$.
- In case of Pb+Pb collisions the measured $s_{c_{2,4}}\{4\}$ is consistent among all SE methods while the standard method gives values systematically larger.
- 3SE method seems to be good enough for non-flow removal.
Asymmetric cumulant \( ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle \)

- Measured in two \( p_T \) intervals: 
  \( 0.3 < p_T < 3 \) GeV and \( 0.5 < p_T < 5 \) GeV.
- The \( ac_2\{3\} \) are positive for all methods.
- The standard method gives much larger results then the SE methods \( \Rightarrow \) standard method is dominated by non-flow effects.
- The \( ac_2\{3\} \) from the 3SE method in \( pp \) collisions show some increase at low \( \langle N_{ch} \rangle \), but are nearly constant at large \( \langle N_{ch} \rangle \). This suggest that 3SE method contains some non-flow contribution at \( \langle N_{ch} \rangle < 40 \) which is negligible at larger \( \langle N_{ch} \rangle \).
- In SE methods in both \( p+Pb \) and \( Pb+Pb \) collisions the influence of non-flow effects is very small for \( \langle N_{ch} \rangle > 60 \). The \( ac_2\{3\} \) from SE increase with \( \langle N_{ch} \rangle \) reflecting the \( \langle N_{ch} \rangle \) dependence of the \( v_2 \) and \( v_4 \).
- Difference between standard and SE methods at large \( \langle N_{ch} \rangle \) could be due to flow decorrelation (EPJC 78 (2018) 142).
System size dependence

- Use 3SE method as it is sufficient to suppress most of the non-flow effects.
- The results for $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ and $ac_{2}\{3\}$ support in small collision systems, an anti-correlation between $v_2$ and $v_3$ and a positive correlation between $v_2$ and $v_4$, the pattern observed previously in large collision systems.
- In the multiplicity range covered by the $pp$ collisions, $\langle N_{ch} \rangle < 150$, the $sc_{2,3}\{4\}$ and $sc_{2,4}\{4\}$ are similar among the three systems.
- For $\langle N_{ch} \rangle > 150$, $sc_{2,3}\{4\}$ and $sc_{2,4}\{4\}$ are larger in Pb+Pb than in $p+Pb$ collisions.
- The results for $ac_{2}\{3\}$ are similar among the three systems at $\langle N_{ch} \rangle < 100$, but they deviate from each other at higher $\langle N_{ch} \rangle$: $pp$ data are approximately constant, while $p+Pb$ and Pb+Pb data show significant increases as a function of $\langle N_{ch} \rangle$.  

![Graphs showing system size dependence](image-url)
System size dependence

▶ Use 3SE method as it is sufficient to suppress most of the non-flow effects.

▶ The results for $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ and $ac_{2}\{3\}$ support in small collision systems, an anti-correlation between $v_2$ and $v_3$ and a positive correlation between $v_2$ and $v_4$, the pattern observed previously in large collision systems.

▶ In the multiplicity range covered by the $pp$ collisions, $\langle N_{ch} \rangle < 150$, the $sc_{2,3}\{4\}$ and $sc_{2,4}\{4\}$ are similar among the three systems.

▶ For $\langle N_{ch} \rangle > 150$, $sc_{2,3}\{4\}$ and $sc_{2,4}\{4\}$ are larger in Pb+Pb than in $p+Pb$ collisions.

▶ The results for $ac_{2}\{3\}$ are similar among the three systems at $\langle N_{ch} \rangle < 100$, but they deviate from each other at higher $\langle N_{ch} \rangle$: $pp$ data are approximately constant, while $p+Pb$ and Pb+Pb data show significant increases as a function of $\langle N_{ch} \rangle$. 

![Graphs showing correlations and fluctuations with ATLAS Preliminary data for $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$, and $ac_{2}\{3\}$](attachment:image.png)
Normalized cumulants

- Remove dependence on harmonics magnitude and focus only on correlation strength.
- Normalization removes most of $\langle N_{\text{ch}} \rangle$ dependence at $\langle N_{\text{ch}} \rangle > 100$.
- Normalized cumulants are similar among different collision systems at large $\langle N_{\text{ch}} \rangle$, although some splitting at the level of 20 – 30% is observed for smaller $\langle N_{\text{ch}} \rangle$.
- Values of $nsc_{2,3}\{4\}$ in $pp$ collisions are very different from those in $p+Pb$ and $Pb+Pb$ collisions. This suggest that the $\langle v_3^2 \rangle$ values from the template fitting method may be significantly underestimated.
- Normalized cumulants are consistent between the two $p_T$ ranges. These results suggest that $p_T$ dependence of symmetric and asymmetric cumulants largely reflects the $p_T$ dependence of $v_n$ at the single-particle level.

![Graphs showing normalized cumulants for different collision systems and $p_T$ ranges.](ATLAS-CONF-2018-012)
Normalized cumulants

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- Normalization removes most of $\langle N_{ch} \rangle$ dependence at $\langle N_{ch} \rangle > 100$.
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- Values of $n_{sc2,3}\{4\}$ in $pp$ collisions are very different from those in $p+Pb$ and $Pb+Pb$ collisions. This suggests that the $\langle v_3^2 \rangle$ values from the template fitting method may be significantly underestimated.
- Normalized cumulants are consistent between the two $p_T$ ranges. These results suggest that $p_T$ dependence of symmetric and asymmetric cumulants largely reflects the $p_T$ dependence of $v_n$ at the single-particle level.
Two-particle correlations in $Z$-boson tagged $pp$ collisions

- Strong dependence of $v_2$ on $\langle N_{ch} \rangle$ in $p+Pb$ and $Pb+Pb$ collisions is attributed to the dependence on centrality.
- In $pp$ collisions $v_2$ is independent of event multiplicity.
- Try to control collision geometry in $pp$ by requiring presence of a $Z$ boson, produced in a hard scattering. $Z$-boson tagged events have smaller impact parameter $b$ and in consequence smaller $v_2$ then in inclusive events.
- A new technique was developed to subtract pileup contribution in 2PC measurements.
- A template fitting method was used to extract $v_2$
- Pileup subtraction changes $v_2$ by 20% on average.
- $Z$-tagged $v_2$ is $8 \pm 6\%$ higher than the inclusive one.
- No multiplicity dependence of $v_2$ in the $Z$-tagged data.

The plots show the distribution of $v_2$ for various $n_{trk}$, where $n_{trk}$ represents the number of tracks in the event. The plots also show the effect of pileup correction and the comparison with $8$ TeV $Z$-tagged data.
Longitudinal flow decorrelation in Pb+Pb collisions

- Both longitudinal & transverse fluctuation exist in EbyE particle distribution in \((\eta, \phi)\). The goal of this analysis is to study the longitudinal flow fluctuation.
- EbyE fluctuation in the magnitude and the phase of the harmonic flow vector:

\[
\tilde{v}_n(\eta) = v_n(\eta)e^{in\Phi_n(\eta)}
\]

is estimated from the observed flow vector \(\vec{q}_n \equiv \sum_i w_i e^{in\phi_i} \sum_i w_i\).

- The longitudinal flow fluctuations are studied using the correlation, \(r_{n|n;k}\), between the \(k\)-th-moment of the \(n\)-th-order flow vectors in two different \(\eta\) intervals, averaged over events in a given centrality interval (sensitive to twist and magnitude decorrelation).

- Another correlator, \(R_{n|n;2}\), involving flow vectors in four \(\eta\) intervals is also used to separate contributions of the asymmetry and twist effects.

\[
r_{n|n;k}(\eta) = \frac{\langle \tilde{q}_n^k(-\eta) \tilde{q}_n^{*k}(\eta) \rangle}{\langle \tilde{q}_n^k(\eta) \tilde{q}_n^{*k}(\eta) \rangle} \cdot \frac{q_n^k(\eta)q_n^{*k}(\eta)_{\text{ref}}}{q_n^k(-\eta)q_n^{*k}(\eta)_{\text{ref}}}
\]

\[
R_{n|n;2}(\eta) = \frac{\langle \tilde{q}_n(-\eta_{\text{ref}}) \tilde{q}_n^{*}(\eta) \tilde{q}_n(-\eta) \tilde{q}_n^{*}(\eta_{\text{ref}}) \rangle}{\langle \tilde{q}_n(-\eta_{\text{ref}}) \tilde{q}_n^{*}(\eta) \tilde{q}_n(-\eta) \tilde{q}_n^{*}(\eta_{\text{ref}}) \rangle} \cdot \frac{q_n(-\eta_{\text{ref}})q_n^{*}(\eta)}{q_n(-\eta_{\text{ref}})q_n^{*}(\eta_{\text{ref}})} \cdot \frac{q_n(-\eta)q_n^{*}(\eta_{\text{ref}})}{q_n(-\eta)q_n^{*}(\eta)}
\]
Longitudinal flow decorrelation in Pb+Pb collisions

- $r_{2|2;1}$ shows a linear decrease with $\eta$, except in the most central collisions.
- The decreasing trend is weakest around the $20 - 30\%$ centrality range, and is more pronounced in both more central and more peripheral collisions (related to a strong centrality dependence of the $v_2$ associated with the average elliptic geometry).
- The decreasing trend is slightly stronger at $\sqrt{s_{NN}} = 2.76$ TeV than at $\sqrt{s_{NN}} = 5.02$ TeV collisions (collision system less boosted at lower collision energy).
- Similar linear decrease of $r_{n|n;1}$ with $\eta$ also for $n = 3, 4$, which is almost independent of centrality ($v_n$, $n = 3, 4$ are mainly driven by fluctuations in the initial state).
- The decreasing trend of $r_{n|n;1}$ for $n = 2 - 4$ indicates significant breakdown of the factorisation of two-particle flow harmonics into those between different $\eta$ ranges.
Longitudinal flow decorrelation in Pb+Pb collisions

- $r_{n|n;k}(\eta)$ are expected to be approximately a linear function of $\eta$ (JPhysG 44, 075106 (2017)):

$$r_{n|n;k}(\eta) \approx 1 - 2F_{n;k}(\eta), \quad F_{n;k} = F_{n;k}^{\text{asy}} + F_{n;k}^{\text{twi}}$$

- Slope for $r_{2|2;1}$ first decrease and then increase as a function of $N_{\text{part}}$.

- Slopes for higher-order harmonics are larger.

- Decorrelation of $v_n$, ($n = 2, 3, 4$) is $10 - 20\%$ stronger in 2.76 TeV than in 5.02 TeV Pb+Pb collisions.
\( v_n \) — mean \( p_T \) correlations in Pb+Pb

- Correlations between magnitudes of the flow harmonics and other global event characteristics, e.g. mean \( p_T \), \([p_T]\), may provide insight into the properties of the QGP.

- Replace the standard Pearson’s \( R \) coefficient with a modified correlator to avoid additional broadening of \( v_n \{2\}^2 \) and \([p_T]\) distributions due to finite charged particle track multiplicity (PRC 93, 044908 (2016)):

\[
R = \frac{\text{cov}(v_n \{2\}^2, [p_T])}{\sqrt{\text{Var}(v_n \{2\}^2)} \sqrt{\text{Var}([p_T])}} \quad \Rightarrow \quad \rho = \frac{\text{cov}(v_n \{2\}^2, [p_T])}{\sqrt{\text{Var}(v_n \{2\}^2)_{\text{dyn}} \sqrt{c_k}}}
\]

- Multiplicity dependent variances are replaced by their dynamical counterparts (STAR PRC 72, 044902 (2005)):

\[
c_k = \left\langle \frac{1}{N_{\text{pair}}} \sum_{i,j \neq i} (p_{T,i} - \langle [p_T] \rangle) (p_{T,j} - \langle [p_T] \rangle) \right\rangle
\]

\[
\text{Var}(v_n \{2\}^2)_{\text{dyn}} = v_n \{2\}^4 - v_n \{4\}^4 = \langle \{4\}_n \rangle - \langle \{2\}_n \rangle^2
\]

\( c_k \) = 0.05 \( \rightarrow \) 0.1

\[\begin{array}{ccc}
-2.5 & -0.75 & -0.5 \\
0.5 & 0.75 & 2.5 \\
\end{array}\]

\( \eta \)

\( a \) \( b \) \( c \)
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\]

\[
\text{Var}(v_n\{2\}^2)_{\text{dyn}} = v_n\{2\}^4 - v_n\{4\}^4 = \langle\{4\}_n\rangle - \langle\{2\}_n\rangle^2
\]
\( v_n - \text{mean } p_T \) correlations in Pb+Pb

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\]
$v_n - \text{mean } p_T$ correlations in Pb+Pb

- $\rho(v_2\{2\}^2, [p_T])$
  - rapid increase with centrality for $N_{\text{part}} < 100$, starting from negative values at $N_{\text{part}} < 40$,
  - weaker increasing dependence is observed over the $N_{\text{part}}$ range $100 - 350$, and a fall in more central collisions,
  - significant correlation in midcentral events is attributed to stronger hydrodynamic response to the large initial state eccentricities (PRC 93, 024913 (2016)).

- $\rho(v_3\{2\}^2, [p_T])$
  - correlations for $v_3$ are smaller and have a weaker centrality dependence compared to $v_2$,
  - correlations are positive for all studied centralities except for $N_{\text{part}} < 100$ where they are negative or consistent with zero.

- $\rho(v_4\{2\}^2, [p_T])$
  - significant positive correlations over the full $N_{\text{part}}$ range,
  - largest values of $\rho$ are observed at low $N_{\text{part}} \approx 100$,
  - magnitude of $v_3$ and $v_4$ correlations are similar at $N_{\text{part}} > 270$

- Theoretical predictions are consistent with the data for $\rho(v_2\{2\}^2, [p_T])$ and $\rho(v_3\{2\}^2, [p_T])$ (PRC 93, 044908 (2016))
Azimuthal anisotropy in Xe+Xe collisions

Flow harmonics, $v_2 - v_5$, have been measured in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using 2PC, template fitting and SP methods as a function of $p_T$ and centrality.
Azimuthal anisotropy in Xe+Xe collisions

Flow harmonics, $v_2 - v_5$, have been measured in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using 2PC, template fitting and SP methods as a function of $p_T$ and centrality.

In the template fit $C_{\text{periph}}^{\Delta \phi}(\Delta \phi)$ is constructed using $\sqrt{s} = 5.02$ TeV $pp$ events with less than 20 reconstructed tracks.

ATLAS Preliminary
$\sqrt{s_{NN}} = 5.44$ TeV, 3 $\mu$b$^{-1}$
Xe+Xe

$2 < p_T^{ab} < 3$ GeV
(0-5)%

$2 < p_T^{ab} < 3$ GeV
(30-40)%

$2 < p_T^{ab} < 3$ GeV
(60-70)%

ATLAS Preliminary
$\sqrt{s_{NN}} = 5.44$ TeV, 3 $\mu$b$^{-1}$
Xe+Xe

$0.9 < \eta < 1.1$

ATLAS-CONF-2018-011

M. Przybycień (AGH UST)
Correlations and fluctuations with ATLAS
ICHEP 2018 4 - 11 July 2018 18 / 20
Event-by-event flow fluctuations in Xe+Xe collisions

- If flow fluctuations are 2D Gaussian in the transverse plane:
  \[ v_n\{2\text{PC}\} = \sqrt{\bar{v}_n^2 + \delta_n^2}, \quad v_n\{4\} = v_n\{6\} = \bar{v}_n \]

- Similar centrality dependence for different order flow cumulants, \( v_n\{2k\} \): largest in mid-central and decreasing towards both central and peripheral.

- \( v_n\{2\text{PC}\} > v_n\{4\} \approx v_n\{6\} \Rightarrow \) flow fluctuations close to Gaussian; also strong \( v_3 \) fluctuations: \( v_3\{2\text{PC}\} \approx 2 \cdot v_3\{4\} \)

- \( v_n\{4\}/v_n\{2\text{PC}\} \) - reflects the relative strength of flow fluctuations - flow fluctuations are larger in central collisions.

- \( v_n\{6\}/v_n\{4\} \lesssim 1 \Rightarrow \) in mid-central Xe+Xe collisions, the non-Gaussian component is slightly larger than in Pb+Pb.
ATLAS provided several new results on correlation and fluctuations in HI collisions:

- Standard, symmetric and asymmetric cumulants have been measured with standard and subevent methods in $pp$, $p+Pb$ and $Pb+Pb$ collisions.
- Results obtained with standard method are dominated by non-flow effects. Three subevent method removes most of non-flow effects.
- Normalized cumulants show similar strength of the correlations between flow harmonics across all systems.
- Within $(1\sim2)\sigma$ syst. uncertainties, the $Z$-tagged $v_2$ is consistent with the min-bias $v_2$.
- Evidence for long-range azimuthal correlations and collectivity in small systems is confirmed and supplemented by new ATLAS measurements.
- The factorisation of two-particle azimuthal correlations into single-particle flow harmonics was found to be broken, with the magnitude of decorrelation increasing linearly with the rapidity separation between two particles.
- Significant correlations of flow harmonics with event mean-$p_T$ in Pb+Pb collisions is observed.
- A comprehensive study of flow in Xe+Xe collisions at 5.44 TeV has been performed and compared to Pb+Pb at 5.02 TeV.

Thank you for your attention!
Backup slides
Heavy-ion data sets

▶ A+A collisions:

- **Pb+Pb @ 2.76 TeV** (2011), $L_{\text{int}} = 0.14 \text{ nb}^{-1}$
- **Pb+Pb @ 5.02 TeV** (2015), $L_{\text{int}} = 0.49 \text{ nb}^{-1}$
- **Xe+Xe @ 5.44 TeV** (2017), $L_{\text{int}} = 3 \mu\text{b}^{-1}$

▶ p + A collisions:

- **p+Pb @ 5.02 TeV** (2013), $L_{\text{int}} = 29 \text{ nb}^{-1}$
- **p+Pb @ 5.02 TeV** (2016), $L_{\text{int}} = 0.5 \text{ nb}^{-1}$
- **p+Pb @ 8.16 TeV** (2016), $L_{\text{int}} = 0.16 \text{ pb}^{-1}$

▶ Reference **pp** samples:

- **pp @ 8 TeV** (2012), $L_{\text{int}} = 19.4 \text{ fb}^{-1}$
- **pp @ 2.76 TeV** (2013), $L_{\text{int}} = 4 \text{ pb}^{-1}$
- **pp @ 5.02 TeV** (2015), $L_{\text{int}} = 28 \text{ pb}^{-1}$
- **pp @ 5.02 TeV** (2017), $L_{\text{int}} = 270 \text{ pb}^{-1}$
The ATLAS detector

Detector coverage:

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

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

Muon Spectrometer (MS):
\[ |\eta| < 2.7 \]

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

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

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

Identification of minimum-bias $p+Pb$ and $Pb+Pb$ collision measurement of spectator neutrons in ZDC and charged particle tracks (pulse height and arrival times) in MBTS.
Centrality determination in Pb+Pb and p+Pb

- Centrality is measured using forward calorimeters (3.2 < |η| < 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.
Tracks coming from pileup are partially rejected by requiring matching to the collision vertex where $Z$-boson is produced. Then the measured distributions are corrected for pileup on a statistical bases.

- **Direct** - tracks and track pairs that pass selection criteria and result from a single event.
- **Direct** contributions consist from Signal and from pileup interactions (Background).
- Use Mixed events constructed from tracks from different events, but with similar $\mu$ and $|z_{0}^\text{trk} - z_{\text{vtx}}^{Z\text{-boson}}| \sin \theta| < 0.75$ mm, to obtain Background distributions as functions of both $n_{\text{trk}}^\text{mixed}$ and $\nu \equiv \langle n_{\text{trk}}^\text{bkgd} \rangle$.

One can build transition matrices, which can be used in the unfolding to restore $n_{\text{trk}}^\text{signal}$:

$$ M(\nu, n_{\text{trk}}^\text{signal}, n_{\text{trk}}^\text{direct}) = P_{\text{Dir}}(\nu < 0.5, n_{\text{trk}}^\text{signal}) P_{\text{Mix}}(\nu, n_{\text{trk}}^\text{direct} - n_{\text{trk}}^\text{signal}) $$

**ATLAS-CONF-2017-068**
Pileup correction for the pair-distribution

- $D = \text{Direct}$, $S = \text{Signal}$, $B = \text{Bkgd}$

\[
D^a \times D^b \equiv \sum_{a \in D} \sum_{b \in D, b \neq a} (\phi^a - \phi^b)
\]

\[
D^a \times D^b = S^a \times S^b + S^a \times B^b + B^a \times S^b + B^a \times B^b
\]

- Averaging over many events:

\[
\langle S^a \times S^b \rangle = \langle D^a \times D^b \rangle - \langle B^a \times B^b \rangle - \langle B^a \times S^b \rangle - \langle S^a \times B^b \rangle
\]

- $S$ and $B$ are independent, and

\[
\langle S^a \rangle = \langle D^a \rangle - \langle B^a \rangle,
\]

hence

\[
\langle S^a \times S^b \rangle = \langle D^a \times D^b \rangle - \langle B^a \times B^b \rangle - \langle D^a \rangle \times \langle B^b \rangle - \langle B^a \rangle \times \langle D^b \rangle + 2 \langle B^a \rangle \times \langle B^b \rangle
\]

- Background events are statistically equivalent to $M = \text{Mixed}$ events at the same multiplicity.

\[
(S^a \times S^b) |_{n_{\text{trk}}^{\text{signal}}} = \sum_{\nu = 0}^{\nu_{\text{max}}} \sum_{n_{\text{trk}}^{\text{direct,max}}} \left( P(n_{\text{trk}}^{\text{signal}}) N_{\text{events}}^{\text{direct}} (S^a \times S^b) \right) |_{\nu} \cdot n_{\text{trk}}^{\text{direct}}
\]

\[
|_{\nu-0.5}
\]

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Correlations and fluctuations with ATLAS

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Heavy quarks are primarily produced at early stages of HI collisions in gluon-gluon fusion and can carry information about early stage properties of the QGP.

Compared with gluons and light quarks, heavy quarks lose less energy when traversing the medium due to the dead-cone effect (JPhys G17 (1991) 1481).

Reconstruction of $D^*$ mesons in “golden channel”:

$$D^*+ \rightarrow D^0 \pi^+_{\text{slow}} \rightarrow (K^- \pi^+) \pi^+_{\text{slow}} + C.C.$$  

$D^0$ candidates are constructed from opposite-sign pairs of tracks with $p_T > 1$ GeV each. Both combinations of kaon and pion masses are considered for the tracks, since no particle identification is applied. The invariant mass of the pair is required to be in the range $1.75 < m(K\pi) < 1.96$ GeV.

$D^*$ candidates are built by adding a soft pion track with $p_T > 250$ MeV to $D^0$ candidates.
Study of azimuthal angular correlations between charged particles and inclusive $D^*$ candidates with $3 < p_T < 30$ GeV and $-1.5 < y^* < 0.5$ in $p+Pb$ collisions.

$D^*$-hadron ($D^*-h$) correlations are quantified using the two-particle correlation function $C(\Delta \phi)$ obtained from all pairs of $D^*$ candidates and charged particle tracks, separated in pseudorapidity by $\Delta \eta > 1$.

A template fitting method is used to extract the harmonic coefficients associated with the long-range ridge contribution, using the shape of peripheral contribution obtained from events with low multiplicity of $10 < N_{ch} < 80$.

A finite $v_{2,2}$ is extracted from inclusive $D^*-h$ correlations with $(1 \sim 2)\sigma$ significance.
$v_n$ measured by the SP method in Xe+Xe collisions

- Scalar Product (SP) method for $v_n$ calculation:
  \[ v_n \{\text{SP}\} = \Re \frac{\langle q_n^{N} Q_{n}^{P*} \rangle}{\sqrt{\langle Q_{n}^{N} Q_{n}^{P*} \rangle}} \]

- For all centralities, $v_n \{\text{SP}\}(p_T)$ increase at low $p_T$, reach a maximum at $2 - 4$ GeV and then decrease.

- As a function of centrality, the $v_n$ values for all harmonics are comparable for Xe+Xe and Pb+Pb $\Rightarrow$ flow is related to the initial geometry rather than to the number of sources.

- Difference between $v_n$ as a function of $N_{\text{part}}$ may be related to the difference of sizes of $^{129}_{54}$Xe and $^{208}_{82}$Pb nuclei.

\[ v_n \{\text{SP}\} = \Re \langle q_n^{N} Q_{n}^{P*} \rangle / \sqrt{\langle Q_{n}^{N} Q_{n}^{P*} \rangle} \]
Symmetric and asymmetric cumulants in Xe+Xe collisions

- Differential flow cumulant, $v_n\{4\}(p_T)$, is calculated as:

$$v_n\{4\} = -\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}}, \quad d_n\{4\} = \langle d\{4\}_n \rangle - 2\langle d\{2\}_n \rangle \langle \{2\}_n \rangle$$

- For all centralities, $v_2\{4\}(p_T)$ and $v_3\{4\}(p_T)$ increase at low $p_T$, reach a maximum at $2 - 4$ GeV and then decrease.

- $sc_{2,3} \quad sc_{2,4} \quad \Rightarrow \quad v_2$ and $v_3$ are anti-correlated, and positive correlation between $v_2$ and linear component of $v_4$.

- $nsc_{n,m}$ and $nac_{n,m}$ keep increasing towards peripheral, i.e. their centrality dependence originates mainly form the $\langle v_n^2 \rangle$. 

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