Measurement of long range azimuthal correlations in proton-proton and proton-lead collisions with ATLAS

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Large vs Small system

- N+N - QGP formation and collective expansion
- Will the picture be same in small system???
- Relatively very small created medium in p+Pb and pp
- Expectation - No QGP and collective expansion in small system!!!
Long-range azimuthal correlation observed in both pp and p+Pb

- Both system show near-side and away-side ridge

Ridge in Small System

- ATLAS $p+Pb$
  - $|s_{NN}|=5.02$ TeV, 28 nb$^{-1}$
  - $0.5<p_T^{a,b}<5$ GeV
  - $N_{ch}^{rec} \geq 220$

- ATLAS pp
  - $|\sqrt{s}|=13$ TeV, 64 nb$^{-1}$
  - $0.5<p_T^{a,b}<5$ GeV
  - $N_{ch}^{rec} \geq 120$

- Near-side SRC (jets, HBT, ...)
- Away-side ridge (mainly from dijets)

• Long-range azimuthal correlation observed in both pp and p+Pb
• Both system show near-side and away-side ridge

Is QGP droplet present in small system? How to turn off QGP?
What’s the underlying physics?
Non-Flow in Ridge

- Non-Flow can contribute to both SRC (decays, single jets, HBT, etc.) and LRC (dijets).
- Detailed investigation of the correlation and non-flow is very important.

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ATLAS $p+Pb$
\[ \sqrt{s_{NN}}=5.02 \text{ TeV}, 28 \text{ nb}^{-1} \]
\[ N_{\text{rec}}^{\text{ch}} \geq 220 \]

ATLAS $pp$
\[ \sqrt{s}=13 \text{ TeV}, 64 \text{ nb}^{-1} \]
\[ N_{\text{rec}}^{\text{ch}} \geq 120 \]

Near-side ridge (jets, HBT, ...)
Non-flow in Ridge

- Non-Flow can contribute to both SRC (decays, single jets, HBT, etc) and LRC (dijets)
- Detailed investigation of the correlation and non-flow is very important

How to remove non-flow? Is there collectivity in small system?
Improved Template Fit


\( Y(\Delta \phi) \)

\( \text{ATLAS} \)

\( \sqrt{s} = 13 \text{ TeV} \)

0.5\( p_T \)\( ^{a,b} < 5.0 \text{ GeV} \)

2.0\( |\Delta \eta| \)\( < 5.0 \)

\( N_{\text{ch}} \geq 90 \)

\( Y(\Delta \phi) \)

\( G + F Y_{\text{trend}}(\Delta \phi) \)

\( Y_{\text{temp}}(\Delta \phi) \)

\( G + F Y_{\text{trend}}(0) \)

\( G + F Y_{\text{trend}}(0) \)
Improved Template Fit

**Template Fit**

**Phys. Rev. C 96 (2017) 024908**

![Graph showing data points and fitting curves](image)

- **ATLAS**
  - $\sqrt{s} = 13$ TeV
  - $0.5 < p_T^{a,b} < 5.0$ GeV
  - $2.0 < |\Delta \eta| < 5.0$
  - $N_{\text{ch}}^{\text{rec}} \geq 90$

**Data Points and Curves**

- $Y(\Delta \phi)$
- $G + FY^{\text{periph}}(\Delta \phi)$
- $Y^\text{templ}(\Delta \phi)$
- $G + FY^{\text{periph}}(0)$
- $Y^{\text{ridge}} + FY^{\text{periph}}(0)$

**Equation**

$$Y(\Delta \phi) = FY(\Delta \phi)^{\text{periph.}}$$
\[
Y(\Delta \phi) = G_{\text{templ.}} \left( 1 + 2 \sum_{n=2}^{\infty} v_n \{2, \text{templ.}\}^2 \cos n\Delta \phi \right) + F_Y(\Delta \phi)^{\text{periph.}}
\]
Improved Template Fit

**Physics Fit**

\[ Y(\Delta \phi) = FY(\Delta \phi)^{\text{periph.}} + G^{\text{templ.}} \left( 1 + 2 \sum_{n=2}^{\infty} v_n \{2, \text{templ.}\}^2 \cos n \Delta \phi \right) \]

- Bias - \( v_n \{2\}^2 \) can change with \( N_{ch} \)
  \[
  v_n \{2\}^2 = v_n \{2, \text{templ.}\}^2 - FG^{\text{periph.}} \frac{G^{\text{cent}}}{G^{\text{periph.}}} \left( v_n \{2, \text{templ.}\}^2 - v_n \{2, \text{periph.}\}^2 \right)
  \]

- Small impact on \( v_2 \{2\} \) - weak \( N_{ch} \) dependence
- Significant difference in \( v_3 \{2\} \) - strong \( N_{ch} \) dep.
Multi-particle Cumulants and Fluctuations

- Flow fluctuates from event to event -
  - Initial geometry
  - Hadronic interactions
  - Hydro-evolution
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  - Hadronic interactions

- Cumulants:
  - Global nature of correlation
  - Suppress non-flow
  - Measure $p(v_n)$
    \[
    c_n{4} = \langle \langle \{4\}_n \rangle \rangle - 2\langle \langle \{2\}_n \rangle \rangle^2
    \]
  - Reference flow:
    \[
    v_n\{4\} = \sqrt{-c_n\{4\}}
    \]
  - For Gaussian flow fluctuations:
    \[
    v_n\{2\} = \sqrt{\bar{v}_n + \sigma^2} \quad v_n\{4\} = \sqrt{\bar{v}_n - \sigma^2} = v_n\{6\} = v_n\{8\}, \ldots
    \]
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  - Suppress non-flow
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$$c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2$$

- Reference flow:

$$v_n\{4\} = \sqrt{-c_n\{4\}} \quad \text{Negatives}$$

- For Gaussian flow fluctuations:

$$v_n\{2\} = \sqrt{\bar{v}_n + \sigma^2} \quad v_n\{4\} = \sqrt{\bar{v}_n - \sigma^2} = v_n\{6\} = v_n\{8\}, \ldots$$

- Signature of Collectivity:

$$c_n\{4\} < 0 \quad \& \quad v_n\{2\} > v_n\{4\} \approx v_n\{6\} \approx v_n\{8\}$$
Cumulant Observables

- 4-particle cumulant: \( \langle \{4\}_n \rangle = \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle \quad c_n \{4\} = \langle \{4\}_n \rangle - 2\langle \{2\}_n \rangle^2 \)

- Mixed harmonics Correlation: correlation among different flow harmonics

**Symmetric Cumulant**

\[ \langle \{4\}_{n,m} \rangle = \langle e^{in(\phi_1-\phi_2)+im(\phi_3-\phi_4)} \rangle \]

\[ s_{c,n,m} \{4\} = \langle \langle \{4\}_{n,m} \rangle \rangle - \langle \langle \{2\}_n \rangle \langle \langle \{2\}_m \rangle \rangle \]

\[ s_{c,n,m} \{4\} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \]

**Asymmetric Cumulant**

\[ \langle \{3\}_n \rangle = \langle e^{i(n\phi_1+n\phi_2-2n\phi_3)} \rangle \]

\[ a_{c,n} \{3\} = \langle \langle \{3\}_n \rangle \rangle \]

\[ a_{c,n} \{3\} = \langle v_n^2 v_{2n} \cos 2n(\Phi_n - \Phi_{2n}) \rangle \]
Cumulant Observables

- **4-particle cumulant**: \( \langle \{4\}_n \rangle = \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle \)
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- **Mixed harmonics Correlation**: correlation among different flow harmonics

**Symmetric Cumulant**

\[
\langle \{4\}_{n,m} \rangle = \langle e^{in(\phi_1-\phi_2)+im(\phi_3-\phi_4)} \rangle
\]

\[
s_{c_{n,m}} \{4\} = \langle \langle \{4\}_{n,m} \rangle \rangle - \langle \langle \{2\}_n \rangle \rangle \langle \langle \{2\}_m \rangle \rangle
\]

\[
s_{c_{n,m}} \{4\} = \left\langle v_n^2 v_m^2 \right\rangle - \left\langle v_n^2 \right\rangle \left\langle v_m^2 \right\rangle
\]

**Asymmetric Cumulant**

\[
\langle \{3\}_n \rangle = \langle e^{i(n\phi_1+n\phi_2-2n\phi_3)} \rangle
\]

\[
a_{c_n} \{3\} = \langle \langle \{3\}_n \rangle \rangle
\]

\[
a_{c_n} \{3\} = \left\langle v_n^2 v_{2n} \cos 2n(\Phi_n - \Phi_{2n}) \right\rangle
\]

**Results**:

- **p+Pb low Nch** \( c_2 \{4\} \) has wrong sign
- **pp** \( c_2 \{4\} \) dominated by non-flow
- **No Collectivity in pp?**

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\( \text{ATLAS} \)

EvSel_M_{ref}

0.3 < \( p_T \) < 3 GeV

\( |\eta| < 2.5 \)

\( \langle N_{ch} | p_T > 0.4 \text{ GeV} \rangle \)

Subevent Method for Cumulants

- Subevents in pseudorapidity used to remove non-flow correlations

**Standard**

\[
\langle \{4\}_n \rangle = \langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle
\]

**3 Subevents**

\[
\langle \{4\}_n \rangle_{2a|b,c} = \langle e^{in(\phi_1^a + \phi_2^a - \phi_3^b - \phi_4^c)} \rangle
\]

- 2-subevent removes **intra-jet** and 3-subevent removes **inter-jet** correlations
Subevent Method for Cumulants

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**Standard**

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**3 Subevents**

\[ \langle \{4\}_n \rangle_{2a|b,c} = \langle e^{in(\phi_1^a + \phi_2^a - \phi_3^b - \phi_4^c)} \rangle \]

- 2-subevent removes intra-jet and 3-subevent removes inter-jet correlations

- Performance in Pythia - standard method fails to suppress non-flow

PHYSICAL REVIEW C 96, 034906 (2017)
• Standard cumulant has positive $c_2\{4\}$
  - residual non-flow

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3 Subevent has the highest non-flow suppression and measures 4% flow down to 70 tracks
Results: 4-Particle Cumulant

- Standard cumulant has positive $c_2\{4\}$ residual non-flow

**3 Subevent** has the highest non-flow suppression and measures 4% flow down to 70 tracks

- System comparison - 3-Subevent
  - Non-flow suppression in both pp and p+Pb
  - Correct sign both pp and p+Pb
  - Weak energy dependence for pp
**Results: 4-Particle Cumulant**

- **Standard cumulant** has positive $c_2\{4\}$
  - residual non-flow

**3 Subevent** has the highest non-flow suppression and measures 4% flow down to 70 tracks

**System comparison - 3-Subevent**

- Non-flow suppression in both pp and p+Pb
- Correct sign both pp and p+Pb
- Weak energy dependence for pp

pp also shows signs of collectivity
Symmetric Cumulant \((2,3)\)

\[
\text{sc}_{2,3}\{4\} = \langle v_2^2 v_3^2 \rangle - \langle v_2^2 \rangle \langle v_3^2 \rangle
\]

- At high \(N_{ch}\) - all consistent
- \(N_{ch} < 140\) - Standard method non-flow dominated
- Non-flow largely suppressed in sub-event method
- Anti-correlation of \(v_2\) and \(v_3\) in subevent method
Symmetric Cumulant (2,3)

\[ \text{sc}_{2,3}\{4\} = \langle v_2^2 v_3^2 \rangle - \langle v_2^2 \rangle \langle v_3^2 \rangle \]

- All \( N_{ch} \) - Standard method non-flow dominated
- Difference in 2SE and 3SE/4SE - Residual non-flow in 2SE
- 3SE and 4SE consistent
- Anti-correlation of \( v_2 \) and \( v_3 \) in subevent method

[Graph showing the relationship between \( N_{ch} \) and the symmetric cumulant (2,3)]

**ATLAS** Preliminary

0.3 \( < p_T < 3 \) GeV  pp 13 TeV, 0.9 pb\(^{-1}\)

ATLAS-CONF-2018-012
\[ \text{sc}_{2,3}\{4\} = \langle v_2^2 v_3^2 \rangle - \langle v_2^2 \rangle \langle v_3^2 \rangle \]

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3 Subevent method best choice for non-flow removal
Symmetric Cumulant (2,4)

\[ sc_{2,4}\{4\} = \langle v_2^2 v_4^2 \rangle - \langle v_2^2 \rangle \langle v_4^2 \rangle \]

- Positive correlation between \( v_2 \) and \( v_4 \) is observed in all methods.

- Standard method non-flow dominated.

- Residual non-flow in 2SE

- Manifestation of non-linear effects
  \[ v_4 = v_{4L} + \chi^2 v_2^2 \]
Symmetric Cumulant (2,4)

\[ sc_{2,4}\{4\} = \langle v_2^2 v_4^2 \rangle - \langle v_2^2 \rangle \langle v_4^2 \rangle \]

- Standard method non-flow dominated
- Positive correlation between \( v_2 \) and \( v_4 \) is observed in all methods
- Standard and subevent cumulants do not converge even at high Nch
- Possible flow decorrelation effects? \( v_4 \) shows stronger decorrelation than \( v_3 \)

Positive correlation is observed in all systems and all methods

Residual non-flow in 2SE
Asymmetric Cumulant

\[
ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle
\]

- Positive correlation is observed in all systems and all methods
- Residual non-flow in 2SE
- Standard and subevents don't converge even at high \(N_{ch}\) - Flow decorrelation? \[ \text{Eur. Phys. J. C 76 (2018) 142} \]
- Higher signal thus better statistical precision than symmetric cumulants
For $N_{ch} > 150$, $sc_{2,3}\{4\}$ and $sc_{2,4}\{4\}$ signals are larger for Pb+Pb than p+Pb.
System Size Dependence

\[ \text{sc}_{2,3}\{4\} \quad \text{sc}_{2,4}\{4\} \quad \text{ac}_{2}\{3\} \]

- Consistent results for symmetric cumulants \( N_{ch} \) range covered by pp
- For \( N_{ch} > 150 \), \( \text{sc}_{23}\{4\} \) and \( \text{sc}_{24}\{4\} \) signals are larger for Pb+Pb than p+Pb
- For \( N_{ch} > 100 \), \( \text{ac}_{2}\{3\} \) in the three systems deviate from each other
- Comparison not perfect - as different cumulants have different \( V_n \)
Normalized Cumulant

- Normalised cumulants - remove dependence on harmonics magnitude and focus only on correlation strength

\[ nsc_{2,3}\{4\} = \frac{sc_{2,3}\{4\}}{v_2\{2\}^2 v_3\{2\}^2} = \frac{\langle v_2^2 v_3^2 \rangle}{\langle v_2^2 \rangle \langle v_3^2 \rangle} - 1 \]

\[ nsc_{2,4}\{4\} = \frac{sc_{2,4}\{4\}}{v_2\{2\}^2 v_4\{2\}^2} = \frac{\langle v_2^2 v_4^2 \rangle}{\langle v_2^2 \rangle \langle v_4^2 \rangle} - 1 \]

\[ nac_{2}\{3\} = \frac{ac_{2}\{3\}}{v_2\{2\}^2 \sqrt{v_4\{2\}^2}} = \frac{\langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle}{\langle v_2^2 \rangle \sqrt{\langle v_4^2 \rangle}} \]

- "Improved" template fit method - To obtain \[ v_n\{2\}^2 \]

\[ nsc_{2,3}\{4\} \quad nsc_{2,4}\{4\} \quad nac_{2}\{3\} \]
Normalized Cumulant

- Normalization removes most of the $N_{ch}$ dependence at $N_{ch} > 100$!
- Signal strength similar in all systems at high $N_{ch}$ but 20-30% difference at low $N_{ch}$

$nsc_{2,3} \{4\}$

$nsc_{2,4} \{4\}$

$nac_{2} \{3\}$
Normalized Cumulant

- Normalization removes most of the $N_{ch}$ dependence at $N_{ch} > 100!$
- Signal strength similar in all systems at high $N_{ch}$ but 20-30% difference at low $N_{ch}$
- In pp $nsc_{23}\{4\}$ is very different than in p+Pb and Pb+Pb - $v_3^2\{2\}$ in template fit method underestimated significantly
- Normalization removes most of the $N_{ch}$ dependence at $N_{ch} > 100$!
- Signal strength similar in all systems at high $N_{ch}$ but 20-30% difference at low $N_{ch}$

In pp $n_{sc23}\{4\}$ is very different than in p+Pb and Pb+Pb - $v_{3}^{2}\{2\}$ in template fit method underestimated significantly

Behaviour of mixed harmonics correlation is similar in small systems and large systems

ATLAS-CONF-2018-012
Summary

- **Two-particle Flow:**
  - **Improved Template Fit** - corrects for fluctuating $u_n$ with $N_{ch}$
  - Significant $v_2 \{2\}$ for small system

- **Multi-particle Cumulants:**
  - Standard cumulant method dominated by non-flow
  - Three-subevent method removes non-flow
  - **Small system shows signs of collectivity**

- **Mixed Harmonics Correlation:**
  - Three-subevent method removes non-flow
  - Anticorrelation $(v_2, v_3)$ and correlated $(v_2, v_4)$
  - **Normalised cumulants - similar strength across all systems**
  - Behaviour of small and large systems are similar
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  - Behaviour of small and large systems are similar

Strong evidence for long-range correlation and collectivity in small system. Can help constrain theoretical models.
Backup

Improved Template Fit

ATLAS Preliminary

- pp 13 TeV, 0.9 pb
- $|\Delta \eta| > 2$

- $v_2^{(2)}$
- $v_3^{(2)}$
- $v_4^{(2)}$

- $p+Pb$ 5.02 TeV, 28 nb
- $|\Delta \eta| > 2$

- Direct Fourier
- Template fit
- Improved template fit
**p+Pb Collectivity**

*ATLAS*

EvSel$_{ref}$

p+Pb $\sqrt{s_{NN}} = 5.02$ TeV

$0.3 < p_T < 3$ GeV

$|\eta| < 2.5$

System dependence

ATLAS Preliminary

$0.3 < p_T < 3$ GeV
Three-subevent method

$0.5 < p_T < 5$ GeV
Three-subevent method
Normalised Cumulants

ATLAS Preliminary

- pp 13 TeV
- p+Pb 5.02 TeV
- Pb+Pb 2.76 TeV

0.3<p_t<3 GeV
Three-subevent method

0.5<p_t<5 GeV
Three-subevent method