Angular Correlations as a function of multiplicity in pp and p-Pb collisions in the ATLAS experiment

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Collective Behaviour in a small system

~30000 particles
~1000 particles
~100 particles

Reveal collective/flow like behaviour via the two particle correlation method
In high multiplicity events there is an enhancement in the particle production at $\Delta \phi \approx 0$ over wide range of $\Delta \eta$.
Extracting the Ridge

Observation: \( Y(\Delta \phi)_{\text{high-mult}} \approx F Y(\Delta \phi)_{\text{low-mult}} + A \cos 2\Delta \phi + C \)

Other harmonics much smaller
Suppress dijet system

Operational definition of ridge

\[ A \cos 2\Delta \phi + C = N(1 + 2 \nu_2 (p_T^a) \nu_2 (p_T^b) \cos 2\Delta \phi) \]
$40 < N_{\text{ch}} < 50$

Enhancement of the high $N_{\text{ch}}$ region due to a dedicated high-multiplicity track trigger
\[ 60 < N_{\text{ch}} < 70 \]
$N_{ch} > 90$

$Y(\Delta \phi)_{\text{Fit}} \equiv F Y(\Delta \phi)_{\text{low-mul}} + A \cos 2 \Delta \phi + C$

ATLAS
\begin{align*}
\sqrt{s} &= 13 \text{ TeV} \\
0.5 < p_T^{a,b} &< 5.0 \text{ GeV} \\
2.0 < |\Delta \eta| &< 5.0 \\
N_{\text{rec}}^{c_h} &\geq 90
\end{align*}

ATLAS
$Y(\Delta \phi)$
Narrowing of the distribution due to cosine component

\[ Y(\Delta \phi)_{\text{Fit}} \equiv F Y(\Delta \phi)_{\text{low-mult}} + A \cos 2\Delta \phi + C \]

\[ N_{\text{ch}} > 120 \]
In more Systems
Azimuthal Correlations

Characterized by Fourier coefficients to describe relative amplitudes of sinusoidal components

$\frac{dN}{d\phi} = \left< \frac{dN}{d\phi} \right> \left( 1 + \sum_n 2v_n \cos [n(\phi - \Psi_n)] \right)$

Measured by 2 pc:

$\frac{dN_{pair}}{d\Delta\phi} = \left< \frac{dN_{pair}}{d\Delta\phi} \right> \left[ 1 + \sum_n 2v_{n,n} \cos (n\Delta\phi) \right]$
Factorization?

While $v_{2,2}$ values vary, $v_2$ agrees quite well.

Similarly for p-Pb case.

$\langle v_{n,n}(p_T^a, p_T^b) \rangle = \langle v_n(p_T^a) \rangle \langle v_n(p_T^b) \rangle$
Multiparticle Cumulants

Useful tool to study the global nature of correlations

$$\langle\langle\text{corr}_2\{2\}\rangle\rangle = \langle\langle e^{i2(\phi_1-\phi_2)} \rangle\rangle$$
$$\langle\langle\text{corr}_2\{4\}\rangle\rangle = \langle\langle e^{i2(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle\rangle$$

where the brackets “$$\langle\langle \rangle\rangle$$” denote double averaging, performed first over particles in an event with a given multiplicity and then over all events with this multiplicity. For every event, the average is taken over all combinations of particle multiplets and each combination consists of different sets of $$2k$$ particles with azimuthal angles $$\phi_i (i = 1, \ldots, 4)$$.

Cumulants:

$$c_2\{4\} = \langle\langle\text{corr}_2\{4\}\rangle\rangle - 2\langle\langle\text{corr}_2\{2\}\rangle\rangle^2$$
$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}.$$
Results

$N_{\text{ref\_trk}}$: Ref particles: within a narrow $p_T$ range

Method 1: for a fixed $N_{\text{ref\_trk}}$

Method 2: fixed multiplicity for fluctuating $N_{\text{ref\_trk}}$

For lower ref $p_T$ range, method 2 gives smaller values, multiplicity fluctuations lead to negative contributions to cumulants

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Comparison with MC

As compared to the data, Pythia 8 overestimates the values of cumulants measured for events with high charged particle multiplicities.
Multiplicity Dependence

\[ \frac{1}{N} \frac{dN}{dN_{\text{rec}}^{\text{ch}}} \]

\[ p_T > 0.4 \text{ GeV}, |\eta| < 2.5 \]

\[ p+p \quad \sqrt{s}=13 \text{ TeV} \]
\[ p+Pb \quad \sqrt{s_{\text{NN}}}=5.02 \text{ TeV} \]
\[ Pb+Pb \quad \sqrt{s_{\text{NN}}}=2.76 \text{ TeV} \]
Observables

Disentangles statistical and dynamical fluctuations

2-D pseudorapidity correlation function

\[ C = \frac{\langle N(\eta_1)N(\eta_2) \rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} = \frac{\langle R_s(\eta_1)R_s(\eta_2) \rangle}{\langle R_s(\eta) \rangle^2} \]

<table>
<thead>
<tr>
<th>Oppositely charged pairs</th>
<th>Same charged pairs</th>
<th>Ratio</th>
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\[ R_s(\eta) = \frac{N(\eta)}{\langle N(\eta) \rangle} \]

Single particle distribution

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV, } p+\text{Pb, 28 nb}^{-1} \]

\[ 200 \leq N_{\text{ch}}^{\text{ec}} < 220 \]

\[ p_T > 0.2 \text{ GeV} \]

arXiv:1606.08170
Correlation function decomposed into Legendre Polynomials

Short Range Correlations
$\Delta \eta = \eta_1 - \eta_2 \approx 0$
Within same source

Long Range Correlations
large $|\Delta \eta|$
FB asymmetry of number of sources

SRC (decays, jet frag, BEC)

LRC
Legendre Spectra

More ±- pairs than ++− pairs in each source

No charge dependence, reflects global symmetry
Multiplicity vs Shape

Strong system dependance for SRC
Weak or no dependance for LRC
Summary

• Strong collectivity observed in high-multiplicity pp collisions, pp ridge described by $\cos 2\Delta \phi$, has (surprisingly) weak dependence on event activity and $\sqrt{s}$

• LRC controlled by $N_{ch}$, not by collision systems or charge combination, SRC depends strongly on collision system and charge combination

• $N_{ch}$ dependence of LRC and SRC follows power-law with an index close to 0.5 - information on the number of sources for particle production?

• $v_2$ from 2PC in pp is independent of $\sqrt{s}$ while $v_n$ are consistent with no $N_{ch}$ dependance in pp, but increase in p+Pb

• Multiplicity fluctuations are important and tend to shift cumulants to more negative values, as such, can mimic the collective-like effects