Measurements of collectivity in the forward region at LHCb

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Outline

1. Introduction: Two-particle correlations and collectivity
2. LHCb capabilities
3. LHCb measurements:
   3.1. Two-particle angular correlations in pPb at $\sqrt{s_{NN}} = 5$ TeV
   3.2. Centrality dependence of two-particle angular correlations in PbPb at $\sqrt{s_{NN}} = 5$ TeV
   3.3. Multiplicity dependence of two-particle angular correlations in pPb at $\sqrt{s_{NN}} = 8$ TeV
   3.4. Study of the Bose-Einstein correlations of identical pions in pPb at $\sqrt{s_{NN}} = 5$ TeV
**Introduction**

**Initial state:** Energy density spatial asymmetry in non-central ion collisions

- **Moments and position asymmetry in the final state**

**Initial state**

<table>
<thead>
<tr>
<th>0 fm/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>b = 7 fm</td>
</tr>
<tr>
<td>( y (\text{fm}) )</td>
</tr>
<tr>
<td>( x (\text{fm}) )</td>
</tr>
<tr>
<td>( p_x )</td>
</tr>
<tr>
<td>( p_y )</td>
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Macropscopically described by **Energy-Momentum Tensor**

**Final state**

Access to initial state properties

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*Imanol Corredoira*

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SQM2022
Extraction Energy-Momentum tensor components from collective flow

Mainly Gluons

Shear viscosity $\eta$: anisotropic collective flow

$\langle T^{xy}(x, t)T^{xy}(0, 0) \rangle$

Bulk viscosity $\zeta$: transverse collective flow

$\langle T_{ij}(x, t)T_{ij}(0, 0) \rangle$

Experimentally


Radial flow $v_0$

Direct flow $v_1$

Elliptic flow $v_2$

Triangular flow $v_3$

Requires early thermalization of the medium

Caused by anisotropy of the overlap zone ($b \neq 0$)

$T_{xy} = 2\frac{\pi}{3} T_{xx} T_{yy} \sqrt{\frac{q}{T}}$

F. Bellini, Emergence of QGP phenomena

Hydrodynamics at play: flow

observable pressure gradients convert Anisotropic flow

Radial expansion of a medium in the vacuum under a thermal motion A collective motion of particles superimposed to the fluid $\$ anisotropy in azimuthal angle described by a Fourier series $n$

describe how initial fluctuations propagate in a viscous system as a medium - EPS spatial anisotropy - $27.07.2021$

Quantum bound results confirm that QGP is very close to the putative well controlled uncertainty, the specific shear viscosity in the system as a medium - $\eta/s$ - $\frac{4}{\pi}$ - $\frac{\pi}{3}$ - $\frac{3}{4}$ - $\frac{1}{s}$

If we focus on the parameters that are relevant for the shear viscosity they show that, with the viscosities [32]. If we focus on the parameters that are related to fundamental properties of the QGP, including the equation of state and properties from the experimental observables. Over the past Ph.D. thesis by Jonah Bernhard at Duke, who performed allows us to extract these QGP properties quantitatively from Ref. [35].

Measuring it with Fourier decomposition of particle correlations

Types of Collective Flow

- Radial flow $v_0$
- Direct flow $v_1$
- Elliptic flow $v_2$
- Triangular flow $v_3$

Measurments of collectivity in the forward region at LHCb
About LHCb

LHCb experiment

- Single-arm fully instrumented spectrometer in $\eta \in [2, 5]$
- pp, pPb, PbPb and fixed target modes
- Momentum resolution: $\Delta p/p = 0.5 - 1\%$, $p \in [2, 200]$ GeV/c
- Primary vertex resolution: $\in [10, 35] \mu$m
  $13.5\% / \sqrt{E/\text{GeV}} \oplus 5.2\% \oplus (0.32 \text{ GeV})/E$

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Accessing low-\(x\) phenomena

- \(Q^2\): exchanged moments between interacting partons
- \(x\): momentum fraction of the parton with respect to nucleus

\[
Q^2 \sim m^2 + p_T^2, \quad x \sim \frac{Q}{\sqrt{S_{NN}}} e^{-\eta}
\]

**LHCb coverage**
- Forward, \(10^{-6} \leq x \leq 10^{-4}\)
- Backward, \(10^{-3} \leq x \leq 10^{-1}\)

**LHCb particular capabilities**
- Charged and neutral hadron production at small-\(x\)
- Capability to study one system in a wide range of \(x\) values:
  - Forward/Backward comparison
  - Possible access to the saturation region → Non-linear dynamics
Two-particle angular correlations

Correlation function: \[ \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pairs}}}{d\Delta\phi d\Delta\eta} = B(0,0) \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)} \]

Where \( S(\Delta\eta, \Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{same \ pairs}}}{d\Delta\phi} \rightarrow \) Correlated pairs from the same events
\[ B(\Delta\eta, \Delta\phi) = \frac{1}{N_{\text{pairs}}(\Delta\phi = 0)} \frac{dN_{\text{mixed \ pairs}}}{d\Delta\phi} \rightarrow \) Uncorrelated pairs from mixed events

Background mixed events should have similar features with respect to signal

Fourier expansion
\[ \frac{dN_{\text{pairs}}}{d\Delta\phi} = A \left[ 1 + 2 \sum_{n=1}^{3} \langle V_n \rangle \cos(n \cdot \Delta\phi) \right] \]
Fitting we extract \( v_n(p_T^{\text{assoc}}) = \frac{V_n(p_T^{\text{assoc}}, p_T^{\text{trigg}})}{\sqrt{V_n(p_T^{\text{trigg}}, p_T^{\text{trigg}})}} \) \( v_1 \rightarrow \) Directed flow
\( v_2 \rightarrow \) Elliptic flow
\( v_3 \rightarrow \) Triangular flow
Two-particle angular correlations in pPb at 5 TeV

- Correlation function:
  \[ \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta\eta d\Delta\phi} = B(0, 0) \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)} \]
- \( \mathcal{L} = 95 \mu b^{-1} \)

Activity class definition based on percentiles of \( N_{\text{hit}}^{\text{VELO}} \) distribution:
- 50-100% (very low)
- 30-50% (low)
- 10-30% (medium)
- 0-10% (high)
- 0-3% (very high)
Two-particle angular correlations in pPb at 5 TeV

Quantitative analysis:

- 1-dimensional yield: 
  \[ Y(\Delta \phi) = \frac{1}{N_{\text{trig}}} \int d\Delta \phi \frac{dN_{\text{pair}}}{d\Delta \phi} = B(0, 0) \frac{S(\Delta \phi)}{B(\Delta \phi)} \]

- Integrating over \( 2 < |\Delta \eta| < 2.8 \) to avoid short range (jet etc) contributions
- Using zero-yield-at-minimum (ZYAM) condition to remove flat pedestal \( \rightarrow C_{\text{ZYAM}} \) from a second-order polynomial fit at \( \Delta \phi_{\text{min}} \)

![Graph showing angular correlations in pPb at 5 TeV](image)
Two-particle angular correlations in pPb at 5 TeV

Lower activity events (>30%)
- No near-side peak
- Pronounced away-side peaks

High activity events (<30%)
- Near-side peak emerge
- Near-side peaks are higher in PbP than in pPb
- $p_T$ dependence for both near and away-side peaks
Ongoing analyses

Charged hadrons $\nu_n$ in PbPb at $\sqrt{s_{NN}} = 5$ TeV
- Charge hadron $\nu_n$ in PbPb at 5TeV
- Centrality determination using calorimeter energy and MC Glauber
- Study direct flow in forward region
- $\mathcal{L} = 228 \, \mu$b$^{-1}$

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Charged hadrons and charm $\nu_n$ in pPb at $\sqrt{s_{NN}} = 8$ TeV
- Study initial effects at low-x
- $\mathcal{L} \sim 15$ nb$^{-1}$
- Multiplicity dependent measurement
- Multiplicity correction with response matrix
- Precise charmed mesons reconstruction→ High statistics

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$p$Pb forward, $D^0$

$\sqrt{s_{NN}} = 8.16$ TeV

arXiv:2205.03936 $M(K\pi)$ [MeV/c$^2$]

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Bose-Einstein correlations of identical pions in pPb

- Bose-Einstein correlations (BEC) → Enhanced production of identical particles with small momentum
- Measure scales that are referred to as lengths of homogeneity → Related with the geometrical size of the particle-emitting source
- Correlation radius scales universally with the cube root of the charge-particle multiplicity

Data sample: 2013 pPb/Pbp data at $\sqrt{s_{NN}} = 5.02$ TeV

1. Two-particle correlation function

$$C_2(Q) = \left( \frac{N_{\text{ref}}}{N_{\text{sig}}} \right) \left( \frac{dN_{\text{sig}}(Q)/dQ}{dN_{\text{ref}}(Q)/dQ} \right)$$

where $Q \equiv \sqrt{-q^2} = \sqrt{-(k_1 - k_2)^2}$

Where

\[
\begin{aligned}
N_{\text{sig}} &\rightarrow \text{Sample with BEC. Same-sign charged particles} \\
N_{\text{ref}} &\rightarrow \text{Sample free from BEC. Event-mixing method}
\end{aligned}
\]

2. Levy-type parametrization: $C_2(Q) = 1 + e^{-|RQ|}$ → Correlation radius, $R$

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In progress

In progress
LHCb at Run3

New tracking system:
- Silicon upstream detector (UT)
- Scintillating tracking fiber (SciFi)

New electronics for calorimeter and muon chambers

Upgrade for pp requirement
- 40 MHz collision rate
- Pile Up factor ~ 5

Full software trigger
- Remove L0 triggers.
- Read out full detector at 40 MHz.

Up to 30% centrality in PbPb

Many possibilities of flow studies in small systems
Summary

- Two-particle angular correlations $\Rightarrow$ Initial state properties

- LHCb can
  \[
  \begin{align*}
  &\text{Access low-}x\text{ physics in } pPb\text{ and } PbPb,\ 10^{-6} < x < 10^{-1} \\
  &\text{Measure two-particle correlations in a complementary pseudorapidity region to other experiments, } 2.0 < \eta < 4.9
  \end{align*}
  \]

Ongoing analysis:
- Centrality dependence of two-particle angular correlations in PbPb at $\sqrt{s_{NN}} = 5\text{ TeV}$
- Multiplicity dependence of two-particle angular correlations in pPb at $\sqrt{s_{NN}} = 8\text{ TeV}$
- Study of the Bose-Einstein correlations of identical pions in pPb at $\sqrt{s_{NN}} = 5\text{ TeV}$

More LHCb results will come in the future $\Rightarrow$ Stay tuned
Backup: Event activity classification

- Multiplicity of reconstructed VELO tracks assigned to a PV for the 2011 no-bias sample.
- Different colours indicate three activity classes defined as fractions of the full distribution.
- The minimum value of the track multiplicity to accept reconstructed PV is five

![Event activity classification diagram](image)

- Low activity (48%)
- Medium activity (37%)
- High activity (15%)

LHCb
\[ \sqrt{s} = 7 \text{ TeV} \]

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