Flow and correlations measurements in small and large systems
Highlights from ALICE, CMS, and ATLAS

Lucia Anna Tarasovičová
On behalf of ALICE, CMS, and ATLAS collaborations
Westfälische Wilhelms-Universität, Münster
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From large to small systems

Pb–Pb  →  p–Pb  →  pp  →  (e^+e^-)

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From large to small systems

Pb—Pb → p—Pb → pp → (\(e^+e^-\))

- What are the properties of the QGP medium, mechanisms of parton energy loss and hadronisation?
- What is the origin of collective-like behaviour in small collisions systems?
- What is the lower limit of the collective-like behaviour?
Correlation functions

Soft particles $p_T < 2$ GeV/c

Balance function

- Measure of balancing charges

$$R_2^{αβ} = \frac{ρ_2^{αβ}}{ρ_1^{α}ρ_1^{β}} - 1$$

$$B^{αβ} = \frac{1}{2}\left\{ ρ_1^{β−} [R_2^{α+β−} - R_2^{α−β−}] + ρ_1^{β+} [R_2^{α−β+} - R_2^{α+β+}] \right\}$$

$$G_2 = \frac{1}{⟨p_{T,1}⟩⟨p_{T,2}⟩} \left[ ∫_Ω p_{T,1} p_{T,2} ρ_1(p_1) dp_{T,1} dp_{T,2} - ⟨p_{T,1}⟩⟨p_{T,2}⟩ \right]$$

- Sensitive to momentum current correlations

- Charge independent:

$$G_2^{CI} = \frac{1}{2}(G_2^{US} + G_2^{LS})$$

- Charge dependent:

$$G_2^{CD} = \frac{1}{2}(G_2^{US} - G_2^{LS})$$

Like sign pairs (+ +) (- -)

Unlike sign pairs (+ -)

Measure of balancing charges

Soft particles $p_T < 2$ GeV/c

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Balance function: Identified hadrons

- Measure of balancing charges
- $BF_{\pi\pi}$ - narrow in central collision - coalescence?
Balance function: Identified hadrons

- Measure of balancing charges
- $BF_{pp}$ - wider than acceptance, no dependence on multiplicity
  - Early stage production?
Balance function: Identified hadrons

Pairing fractions not dependent on centrality, except $I_{\pi\pi} \Rightarrow$ quantitative characterisation of the hadronisation of the QGP
Balance function: Charged hadrons

- Narrowing of width of BF towards central collisions
- Radial flow, late particle production (coalescence)
- Similar behaviour in p—Pb collisions
Similar trends in p—Pb and Pb—Pb collisions

- Consistent with the delayed hadronisation, support collectivity in p—Pb collisions
- Models cannot describe data perfectly, though provide better description in $\Delta \varphi$
$G_2$ sensitive to momentum current correlations

- $G_2^{CI}$ - sensitive to momentum current correlations
- Affected by mini-jets, radial flow etc.
- $G_2^{CD}$ - driven by hadronic decays, radial flow

\[ G_2 = \frac{1}{\langle p_{T,1} \rangle \langle p_{T,2} \rangle} \left[ \int_\Omega p_{T,1} p_{T,2} \rho_{1} dp_{T,1} dp_{T,2} - \langle p_{T,1} \rangle \langle p_{T,2} \rangle \right] \]
\[ G_2 = \frac{1}{\langle p_{T,1} \rangle \langle p_{T,2} \rangle} \left[ \int_\Omega \rho_1(p_1) dp_{T,1} \int_\Omega \rho_2(p_2) dp_{T,2} - \langle p_{T,1} \rangle \langle p_{T,2} \rangle \right] \]
\[ G_2 = \frac{1}{\langle p_{T,1}\rangle \langle p_{T,2}\rangle} \left[ \int_{\Omega} \rho_{1}(p_{1}) dp_{T,1} \int_{\Omega} \rho_{2}(p_{2}) dp_{T,2} - \langle p_{T,1}\rangle \langle p_{T,2}\rangle \right] \]

- \( \Delta \eta \) CI - different for all three systems
- \( \text{Pb–Pb} \) - increase 24\% - viscous effects of long-lived QGP with small \( \eta/s \)

\[ G_2^{\text{CD}} \sigma_{\Delta \eta} \]

\[ G_2^{\text{CI}} \sigma_{\Delta \eta} \]

\[ G_2^{\text{CD}} \sigma_{\Delta \varphi} \]

\[ G_2^{\text{CI}} \sigma_{\Delta \varphi} \]

\[ p_{T} < 2 \text{ GeV/c} \]

\[ |\eta| < 0.8 \]

\[ \text{ALICE} \]

\[ \text{p–Pb } \bar{s}_{\text{NN}} = 5.02 \text{ TeV} \]

\[ \text{Pb–Pb } \bar{s}_{\text{NN}} = 2.76 \text{ TeV} \]

\[ \text{PLB 804, 135375 (2020)} \]

\[ \text{arXiv:2211.08979} \]
\[ G_2 = \frac{1}{\langle p_{T,1} \rangle \langle p_{T,2} \rangle} \left[ \int_{\Omega} \rho_1(p_1) dp_{T,1} \int_{\Omega} \rho_2(p_2) dp_{T,2} - \langle p_{T,1} \rangle \langle p_{T,2} \rangle \right] \]

- \( \Delta \eta \) CI - different for all three systems
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- pp - slight decrease, p—Pb slight increase
- Too small for viscous forces to equilibrate?
- Different explanations?

arXiv:2211.08979
\[ G_2 = \frac{1}{\langle p_{T,1}\rangle \langle p_{T,2}\rangle} \left[ \int_{\Omega} \rho_{T,1}(p_1)dp_{T,1} \int_{\Omega} \rho_{T,2}(p_2)dp_{T,2} - \langle p_{T,1}\rangle \langle p_{T,2}\rangle \right] \]

- $\Delta\eta$ CI - different for all three systems
- Pb–Pb - increase 24% - viscous effects of long-lived QGP with small $\eta/s$
- pp - slight decrease, p–Pb slight increase
- Too small for viscous forces to equilibrate?
- Different explanations
  - Models without collective effects do not describe data

arXiv:2211.08979
Anisotropic flow

- Reflects the conversion of the initial-state spatial anisotropy into final-state anisotropies in momentum space
- Anisotropy in distribution of final-state particles:

\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} \nu_n \cos n(\phi - \Psi_n)
\]

\[
\nu_n = \langle \cos(n(\phi - \psi_n)) \rangle
\]

- Initial conditions and transport properties of the created medium (low \(p_T\))
- Initial geometry affects energy loss of hard hadrons (high \(p_T\))
$v_n$ up to high $p_T$ in Pb—Pb

- First measurement of Fourier coefficients up to $p_T = 200$ GeV/c
- Compatible with previous measurements
- Decreased uncertainties
$\nu_n$ up to high $p_T$ in Pb–Pb

- Non-zero $\nu_2$ at high $p_T$
- Increasing towards semicentral collisions
- Hard hadrons influenced by initial geometry
$v_n$ up to high $p_T$ in Pb–Pb

- Non-zero $v_2$ at high $p_T$
  - Increasing towards semicentral collisions
  - Hard hadrons influenced by initial geometry
- $v_3$ at high $p_T$ compatible with zero
  - Hard hadrons not influenced by initial fluctuations
$\nu_n$ of dijets (Pb–Pb)

- Fourier coefficients of dijets measured with two-particle correlations

CMS

PbPb $\sqrt{s_{NN}} = 5.02$ TeV, $1.69$ nb$^{-1}$

Factorization region:
0.7 < Hadron $p_T$ < 3 GeV

$\nu_1$

- CMS charged hadron $\nu_2$
$p_T > 20$ GeV, $|\eta| < 1$

$\nu_3$

anti-$k_T$, $R = 0.4$

$|h_{\text{jet}}| < 1.3$
$p_{T,1} > 120$ GeV
$p_{T,2} > 50$ GeV
$|\Delta \phi_{1,2}| > \frac{5\pi}{6}$

$\nu_4$

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\( \nu_n \) of dijets (Pb—Pb)

- Fourier coefficients of dijets measured with two-particle correlations
- Non-zero \( \nu_2 \):
  - More jets observed coplanar with event plane
  - Less energy loss → higher chance to pass selection criteria

CMS charged hadron \( v_2 \)
\[ p_T > 20 \text{ GeV}, |\eta| < 1 \]

Anti-\( k_T \), \( R = 0.4 \)
\[ |h_{\text{jet}}| < 1.3 \]
\[ p_{T,1} > 120 \text{ GeV} \]
\[ p_{T,2} > 50 \text{ GeV} \]
\[ |\Delta \phi_{1,2}| > \frac{5\pi}{6} \]

CMS
\[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, 1.69 \text{ nb}^{-1} \]
\( \nu_n \) of dijets (Pb—Pb)

- Fourier coefficients of dijets measured with two-particle correlations
- Non-zero \( \nu_2 \):
  - More jets observed coplanar with event plane
  - Less energy loss \( \rightarrow \) higher chance to pass selection criteria
- \( \nu_3, \nu_4 \) compatible with zero:
  - The fluctuations in the initial state do not impact the azimuthal distributions of dijets
\( v_2 \) of particles in jets (\( p-\text{Pb}, \text{Pb}-\text{Pb} \))

- **Non-zero jet** \( v_2 \) in \( p-\text{Pb} \) and \( \text{Pb}-\text{Pb} \) collisions
  - Smaller magnitude than inclusive \( v_2 \)
  - No dependence on \( p_T^{\text{assoc}} \)
  - At high \( p_T \) - similar magnitude as in \( \text{Pb}-\text{Pb} \)
  - \( v_2 \) driven by the non-equilibrium anisotropic parton escape mechanism

arXiv:2212.12609
Study of influence of jets on inclusive $v_2$ and jet $v_2$ - origin of $v_n$ in pp?

- $h^{UE}$ separated by $\Delta \eta > 1$ from jet with $p_T > 15 \text{ GeV}/c$
- $h^J$ constituents of jets

arXiv:2303.17357
Presence of a jet with $p_T > 15$ GeV/c does not influence the $v_2$ of $h^{\text{UE}}$

- No multiplicity dependence
Presence of a jet with $p_T > 15$ GeV/c does not influence the $v_2$ of $h_{UE}$

No multiplicity dependence

$v_2$ of $h^J$ compatible with zero

The inclusive $v_2$ is not driven by jet fragmentation, but rather by bulk

The collective system is too small to influence jets - no energy loss

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Limit of collectivity in small systems

- Long-range two-particle correlations measured up to the smallest multiplicities
Limit of collectivity in small systems

Integrated ridge yield as a function of multiplicity calculated with great precision
Limit of collectivity in small systems

- Integrated ridge yield as a function of multiplicity calculated with great precision
- At $N_{ch} > 30$ compatible with CMS measurement
Limit of collectivity in small systems

- Integrated ridge yield as a function of multiplicity calculated with great precision
- At $N_{ch} > 30$ compatible with CMS measurement
- At lower multiplicities - increased precision

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Comparison with $e^+e^-$ collisions

- $Y_{pp} > Y_{ee}$ for $\langle N_{ch} \rangle \approx 15$ with 3σ
- First quantitative comparison between pp and $e^+e^-$ collisions
- New insight to processes contributing to the long-range ridge
Conclusion

- Large systems
  - Deconfined medium with small $\eta/s$
  - Late production of pions via coalescence, hint of early production of protons
  - $v_2$ of jets and jet particles induced by path length dependent energy loss

- Small systems
  - Collectivity supported by narrowing of the peak width of $BF$ and $G_2$ correlation functions of low $p_T$ hadrons and non-zero $v_2$
    - Viscous forces do not have time to equilibrated the system
  - $v_2$ in pp collisions not driven and not influenced by jet fragmentation
  - Significant ridge yield in pp down to $\langle N_{ch} \rangle \approx 10$, larger than in $e^+e^-$
Thank you for your attention!

Questions
More results
PID flow in Pb-Pb

- First $p_T$-differential $\nu_2$ measurements using four-particle cumulants for identified particles
- In the intermediate $p_T$ range, $-\nu_2\{4\}$ for baryons is larger than that for mesons by about 50%
- $F(\nu_2)$ - an apparent splitting between baryons and mesons for centrality above 30% ⇒ a significant role for final-state interactions in developing this observable

$$F(\nu_n) = \frac{\sigma_{\nu_n}}{\langle \nu_n \rangle}.$$
Back up
ALICE, charged particles
$|\eta| < 0.3, 0.15 < p_T < 10.0 \text{ GeV/c}$

- $pp \sqrt{s} = 7 \text{ TeV}$
- $p-Pb \sqrt{s_{NN}} = 5.02 \text{ TeV}$
- $Pb-Pb \sqrt{s_{NN}} = 2.76 \text{ TeV}$
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