Collective phenomena at RHIC and LHC

Ilya Selyuzhenkov
(EMMI, GSI & FIAS)

Facets of Strong-Interaction Physics
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Non-central relativistic heavy-ion collision (HIC)

- Overlap area: non-uniform particle density and pressure gradient

- Large orbital angular momentum:
  \[ \mathbf{L} \sim 10^5 \hbar \]
  Liang, JPG34:323 (2007)

- Strong magnetic field:
  \[ \mathbf{B} \sim 10^{15} \text{T} \quad (e\mathbf{B} \sim 10^4 \text{MeV}^2) \]
  \[ (\mu_N \mathbf{B} \sim 100 \text{MeV}) \]
  Rafelski, Müller PRL36:517 (1976)

\[ \mathbf{B} - \text{magnetic field} \]
\[ \mathbf{L} - \text{orbital momentum} \]

\[ b - \text{impact parameter} \]

Colliding nuclei are moving out-of-plane
Anisotropic transverse flow

✓ What is anisotropic flow and why do we measure it?
✓ Measurement techniques: correlations and non-flow
✓ Elliptic flow at RHIC and LHC
✓ Flow fluctuations and higher harmonics
Colliding nuclei has a finite size

Peripheral collision (large $b$)

Overlap region is strongly asymmetric in the transverse plane

Central collision (small $b$)

Overlap region is close to be symmetric in the transverse plane

Asymmetry of the overlap region depends on the impact parameter

$b$ - impact parameter
Nucleon-nucleon collisions in the overlap region

Peripheral collision

- elementary nucleon-nucleon (NN) collision

Small number of nucleon-nucleon collisions: few particles produced

Central collision

Large number of NN collisions: abundant particle production

Number of produced particles is correlated with the impact parameter
Produced particles interact with each other

- Particle emitted out-of-plane
- Emitted in-plane

- Multiple interaction with medium
- Less interaction - small modification
Particle collectivity

Peripheral collision

Strong coordinate space asymmetry transforms into the azimuthal asymmetry in the momentum space

Central collision

Multiple interaction with medium but small initial spacial asymmetry: small asymmetry in the momentum space

Correlated particle production wrt. the collision plane of symmetry
Quantifying azimuthal asymmetry

Coordinate space asymmetry is ~ ellipsoidal quantified by eccentricity:

\[
\epsilon_s = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}
\]

\(x, y\) - position of each elementary NN interaction
Quantifying azimuthal asymmetry

Coordinate space asymmetry is \( \sim \) ellipsoidal quantified by eccentricity:

\[
\epsilon_s = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}
\]

\(x, y\) - position of each elementary NN interaction

Momentum space asymmetry:

\[
e_p \sim \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_y^2 + p_x^2 \rangle} \rightarrow \langle \cos(2 \Delta \phi) \rangle
\]

Second Fourier harmonic in momentum space

\(p_t\) - particle transverse momentum

\(\Delta \phi\) - azimuthal angle relative to the reaction plane
Time evolution of the spatial and momentum asymmetries

- Spatial asymmetry drops very fast
- Momentum asymmetry develops very early

Momentum asymmetry is sensitive to:
- Early times of the system evolution
- Equation of State

EoS I: massless ideal gas
EoS RHIC: matching Lattice QCD
Anisotropic transverse flow: Fourier harmonics

Fourier decomposition of the particle azimuthal distribution wrt. the reaction plane:

$$\frac{dN}{d(\Delta \phi)} \sim 1 + 2 \sum_{n=1} \nu_n(p_t, \eta) \cos(n \Delta \phi)$$

No “sin” terms because of the collision symmetry

$$\nu_n(p_t, \eta)$$ – anisotropic transverse flow coefficients

- $\nu_1$ - directed flow
- $\nu_2$ - elliptic flow
- $\nu_3$ - triangular flow
Experimental measurements of the anisotropic flow
Modern ultra-relativistic HI colliders

Relativistic Heavy Ion Collider

- RHIC
- PHOBOS
- BRAHMS
- PHENIX
- STAR
- AGS
- LINAC

Large Hadron Collider

- LHC
- CMS
- ALICE
- ATLAS
- LHCb
- SPS
- PS
- LINACs

<table>
<thead>
<tr>
<th></th>
<th>RHIC</th>
<th>LHC</th>
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<tbody>
<tr>
<td>Location</td>
<td>BNL (USA)</td>
<td>CERN (Europe)</td>
</tr>
<tr>
<td>Circumference</td>
<td>3.8 km</td>
<td>27 km</td>
</tr>
<tr>
<td>Species</td>
<td>p, d, Cu, Au, U polarized protons</td>
<td>p, Pb</td>
</tr>
<tr>
<td>Center of mass energy per nucleon pair</td>
<td>in GeV 7.7-38, 62, 200 500 (pp only)</td>
<td>in TeV 0.9, 2.76, 7 (pp) 2.76 (Pb)</td>
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Current heavy-ion experiments at RHIC and LHC

**STAR** (Solenoidal Tracker At RHIC)

**ALICE** (A Large Ion Collider Experiment)

**PHENIX** (Pioneering High Energy Nuclear Ion Experiment)

**ATLAS** (A Toroidal LHC Apparatus)

**CMS** (Compact Muon Solenoid)

Main capabilities for heavy-ion studies:
Charge particle tracking and identification: full azimuth, large rapidity coverage
wide $p_t$ range: $\sim 100$ MeV/c to $\sim 100$ GeV/c
Calorimetry and rare probes: neutral particles, photons, jets, heavy flavor
Anisotropic flow measurement techniques

\[ \frac{dN}{d(\phi_i - \Psi_{RP})} \sim 1 + 2 \sum_{n=1} v_n \cos[n(\phi_i - \Psi_{RP})] \]

\[ v_n = \langle \cos[n(\phi_i - \Psi_{RP})] \rangle \]

- directly calculable only in theory when the reaction plane orientation is known
Anisotropic flow measurement techniques

\[ \frac{dN}{d(\phi_i - \Psi_{RP})} \sim 1 + 2 \sum_{n=1} v_n \cos[n(\phi_i - \Psi_{RP})] \]

\[ v_n = \left\langle \cos[n(\phi_i - \Psi_{RP})] \right\rangle \]

- directly calculable only in theory when the reaction plane orientation is known

Event plane angle - experimental estimate of the reaction plane angle based on the measured azimuthal distribution of particles:

\[ \Psi_{RP} \rightarrow \Psi_{EP} \left\{ \sum_{\phi_j} g(\phi_j) \right\} \]

\[ v_{n}^{obs} = \left\langle \cos[n(\phi_i - \Psi_{EP})] \right\rangle \sim \left\langle \sum_{\phi_j \neq \phi_i} \cos n(\phi_i - \phi_j) \right\rangle \]

\[ c_n \{2\} = \left\langle \cos n(\phi_i - \phi_j) \right\rangle \]

- two particle correlations

Measure anisotropic flow with azimuthal correlations
Non-flow correlations

Non-flow: correlations among the particles unrelated to the reaction plane

In case of two particle correlations: \[
\langle \cos \left[ n \left( \phi_i - \phi_j \right) \right] \rangle = \langle v_n^2 \rangle + \delta_{2,n}
\]

Sources of non-flow correlations:
- Resonance decay
- Jet production
- In general - any cluster production
Non-flow correlations

Non-flow: correlations among the particles unrelated to the reaction plane

In case of two particle correlations: \( \langle \cos \left[ n \left( \phi_i - \phi_j \right) \right] \rangle = \langle v_n^2 \rangle + \delta_{2,n} \)

Sources of non-flow correlations:
- Resonance decay
- Jet production
- In general - any cluster production

Example: 2-particle decay

Collective flow: correlations between particles through the common plane of symmetry

Probability to be correlated for one particle with another out of \( M \)-particles is \( 1/(M-1) \):

\[
\delta_2 \sim \frac{1}{M - 1}
\]

To measure flow with 2-particle correlations:

\[
v_n \gg \frac{1}{\sqrt{M}}
\]

\( M = 200 \rightarrow v_n \gg 0.07 \)

For RHIC/LHC: \( v_n \approx 0.04 - 0.07 \)
Estimating flow with multi-particle cumulants

Rapidity separation between correlated particles suppress short-range non-flow:

\[ v_2^{(2)} > v_2^{(2, |\Delta \eta|)} \]

Large non-flow in peripheral collisions
Estimating flow with multi-particle cumulants

Rapidity separation between correlated particles suppress short-range non-flow:

\[ v_2\{2\} > v_2\{2,|\Delta \eta|\} \]

Large non-flow in peripheral collisions

Note: \( v_2\{2\} \) and \( v_2\{4\} \) differ not only because of non-flow, but also due to flow fluctuations (discussed later)

Multi-particle cumulants remove residual non-flow:

\[ v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \]
Elliptic flow:
the dominant flow component at the relativistic energies
Elliptic flow vs. collision energy

Experimental results covers about 4 decades of the collision energy

Data from GSI, AGS, SPS, RHIC, and LHC experiments

collision energy, $\sqrt{s_{NN}}$ (GeV)
Elliptic flow: RHIC vs. LHC

30% increase of $v_2$ from RHIC: stronger collectivity at LHC

But: measured $v_2$ vs. transverse momenta has similar shape and magnitude at RHIC and LHC

centrality 20-30%

collision energy, $\sqrt{s_{NN}}$ (GeV)
Identified particle spectra: LHC vs. RHIC

Spectra shapes changed significantly from RHIC to LHC

Radial expansion (flow):
Boost particles to higher $p_t$
(particles gain extra radial velocity)

From Blast wave spectra fits:
20% stronger radial flow at LHC
→ increase of integral $v_2$
Elliptic flow mass splitting

Similar to spectra:

- $v_2$ of heavier particles is pushed to higher $p_t$

Viscous hydrodynamics well describe flow of $\pi^\pm$ and $K^\pm$:

\[ \rightarrow \text{sensitivity to QGP viscosity} \]

Including hadronic rescattering with UrQMD model allows better reproduce proton $v_2$:

\[ \rightarrow \text{sensitivity to the evolution} \]

VISHNU: Heinz et. al, arxiv:1108.5323
Constituent number of quarks scaling

**Observe approximate number of quark scaling:**

Strong indication that system evolved through deconfined (QGP) phase
Flow fluctuations
Experimentally study many collisions

Three collisions with the same:
- magnitude of impact parameter
- reaction plane angle
Fluctuating initial energy density

Fluctuating spatial asymmetry results in the event-by-event fluctuations of anisotropic flow
How fluctuations affect the measured flow?

2-particle azimuthal correlation:

\[ c_n\{2\} = \langle \cos[2(\phi_i - \phi_j)] \rangle = \langle v_n^2 \rangle + \delta_{n,2} \]

\[ \langle v_n^2 \rangle \neq \langle v_n \rangle^2 \]

\[ \langle v_n^2 \rangle = \langle v_n \rangle^2 + \sigma_n^2 \]

\[ \langle \cos[n(\phi_i - \phi_j)] \rangle = \langle v_n \rangle^2 + \sigma_n^2 + \delta_{n,2} \]

flow  fluctuations  non-flow
Elliptic flow fluctuations

2-particle correlations affected by 3 effects: \[ v_2 \{2\} = \sqrt{\langle v_2 \rangle^2 + \sigma_2^2 + \delta_2^2} \]

Residual non-flow subtracted based on HIJING Monte-Carlo:

\[ v_2^{corr} \{2\} \approx \langle v_2 \rangle + \frac{\sigma_2^2}{2\langle v_2 \rangle} \]

Many-particle correlations free of non-flow:

\[ v_2 \{4\} \approx \langle v_2 \rangle - \frac{\sigma_2^2}{2\langle v_2 \rangle} \]

Fluctuations set the difference between \( v_2^{corr} \{2\} \) and \( v_2 \{4\} \)

Flow fluctuations are significant

Additional constraint on the initial condition
Triangular flow, $v_3$ - pure fluctuations

Non-zero correlations observed for $v_3^{corr}\{2\}$ and $v_3\{4\}$!

$$v_3^{corr}\{2\} = \sqrt{\langle v_3 \rangle^2 + \sigma_3^2} \neq 0$$

Due to collision symmetry the odd harmonic flow is asymmetric:

$$v_{2n+1}(-\eta) = -v_{2n+1}(\eta)$$

In the symmetric rapidity range:

$$\langle v_3 \rangle = 0$$

$$v_3^{corr}\{2\} = \sigma_3$$

Together with fluctuations in the 2nd harmonic provides strong constraints on the initial condition.
Two particle azimuthal correlations:

collective flow modulations
or ridge & mach cone?

\[ C(\phi_1 - \phi_2) \sim 1 + 2 \sum_{i=1} v_{n,1} v_{n,2} \cos(n[\phi_1 - \phi_2]) \]
Two particle correlations and higher harmonic flow

Azimuthal correlations are studied with large rapidity gap: \(0.8 < |\Delta \eta| < 1.8\)

**Correlations at small \(p_t\) (bulk)**

\(2 < p_T^b < 2.5\) GeV/c
\(1.5 < p_T^a < 2\) GeV/c
\(0.8 < |\Delta \eta| < 1.8\)

**Correlations at high \(p_t\) (away side jet)**

\(8 < p_T^b < 15\) GeV/c
\(6 < p_T^a < 8\) GeV/c
\(0.8 < |\Delta \eta| < 1.8\)

Gaussian fit:
\(\sigma_{\Delta \phi} = 0.34\)

“ridge” and “mach-cone” like structures are naturally described by the collective flow effects
Anisotropic flow: summary

- Anisotropic transverse flow is an important experimental observable to study the evolution of a heavy-ion collision and understand the properties of the quark-gluon plasma (QGP).

- It provides constraints on:
  - Equation of state of the created matter
  - Transport properties (i.e. viscosity) of the QGP matter
  - Shape of the initial conditions in a heavy-ion collision

- Helps to understand the origin of the correlations between produced particle
Probes of local parity violation in strong interactions

\[
\frac{dN_\pm}{d(\Delta \phi_\pm)} \sim 1 + 2a_\pm \sin \Delta \phi_\pm
\]
Charge asymmetry wrt. the reaction plane

Coordinate/momentum are vectors:
\[ \vec{r} \rightarrow -\vec{r} \quad \vec{p} \rightarrow -\vec{p} \]

Magnetic field (\( \mathbf{B} \)) is axial-vector:
\[ \vec{B} \rightarrow -\vec{B} \]

Charge asymmetry wrt. the \( \Psi_{RP} \) breaks the parity symmetry

Theoretical motivation for the local parity violation:

- T.D. Lee, PRD8:1226 (1973)
- Finch, Chikanian, Longacre,
  Sandweiss, Thomas, PRC65:014908(2002)
Observable to probe local parity violation

- Asymmetry fluctuates event by event. P-odd observable yields zero (no global violation of the symmetry):

\[
\langle a_\pm \rangle = \langle \sin(\phi_\pm - \Psi_{RP}) \rangle = 0
\]

- Study P-even correlations: \( \langle a_\alpha a_\beta \rangle \) \( (\alpha, \beta = \pm) \)

Measure the difference between in-plane and out-of-plane correlations:

\[
\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle = \langle \cos \Delta \phi_\alpha \cos \Delta \phi_\beta \rangle - \langle \sin \Delta \phi_\alpha \sin \Delta \phi_\beta \rangle =
\]

\[
= \left[ \langle v_{1,\alpha} v_{1,\beta} \rangle + Bg^{(in)} \right] - \left[ \langle a_\alpha a_\beta \rangle + Bg^{(out)} \right]
\]

\( \Delta \phi_{\alpha,\beta} = \phi_{\alpha,\beta} - \Psi_{RP} \)

- Large RP-independent background correlations cancel out in \( Bg^{(in)} - Bg^{(out)} \)

\( Bg^{(in)} (Bg^{(out)}) \) denotes in- (out-of) plane background correlations

- RP-dependent (P-even) backgrounds contribute:

\( \rightarrow Bg^{(in)} - Bg^{(out)} \) term

\( \rightarrow \langle v_{1,\alpha} v_{1,\beta} \rangle \): directed flow (zero in symmetric rapidity range) + flow fluctuations
Charge separation in Pb-Pb collisions at LHC

3-particle correlations measured with the reaction plane estimated from:

- Charge particle reconstructed with TPC
- Cumulants and mixed harmonics
- Particles counted with VZERO detectors
- Spectator deflection measured by ZDCs

Observe negative same sign and small/positive opposite sign correlations

- Very good agreement between results with different estimates of the reaction plane:
  → evidence for correlations wrt. to the reaction plane
- Charge separation observed in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Pb-Pb @ $\sqrt{s_{NN}} = 2.76$ TeV

same opp.

- TPC (cumulants)
- TPC (EP)
- ZDC (SP)
- VZERO (EP)

Preliminary

Ilya Selyuzhenkov, Hirschegg, 20/01/2012
Comparison with RHIC results

- RHIC and LHC observe charge separation
- Separation seems to disappear between 11.5 and 7.7 GeV energies

Note: RHIC data plotted inversely vs. centrality than the LHC data
Comparison with HIJING Monte-Carlo

HIJING reproduces the trends seen for opposite sign correlations.

Similar correlations for opposite and same sign pairs in HIJING.

Little/no charge dependence in HIJING

Other sources of background correlations:

- Charge conservation: S. Pratt, arXiv:1002.1758 [nucl-th]
Constraining backgrounds with two particle correlations

Similarity to RHIC:

- correlation strength between opposite sign pairs is larger than the same sign correlation

Difference from RHIC:

- Positive same sign correlation at LHC (while negative at RHIC)
- Magnitude of correlations is large than at RHIC

\[
\langle \cos(\phi_\alpha - \phi_\beta) \rangle = \langle \cos \Delta \phi_\alpha \cos \Delta \phi_\beta \rangle + \langle \sin \Delta \phi_\alpha \sin \Delta \phi_\beta \rangle = \\
\left[ \langle v_{1,\alpha} v_{1,\beta} \rangle + Bg^{(in)} \right] + \left[ \langle a_\alpha a_\beta \rangle + Bg^{(out)} \right]
\]

**Significant change in the correlation pattern for 2-particle correlations from RHIC to LHC**
Summary

Anisotropic transverse flow is an important experimental observable to study the evolution of a heavy-ion collision and understand the properties of the quark-gluon plasma (QGP).

- It provides constraints on:
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- Helps to understand the origin of the correlations between produced particle

Charge dependent azimuthal correlations are observed at RHIC and LHC:

- Correlations reflect collective effect
- Magnitude of the correlations is similar to that at RHIC energies
- Observe different behavior for the first harmonic two particle azimuthal correlations than at RHIC