Anisotropic flow measurements at RHIC and LHC

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EMMI Days

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Introduction to the heavy-ion physics
History of the universe

Age ~ 13 billion years

Properties of matter during the 1st second are not well known

Early times ↔ short distances: interaction governed by QCD
Quantum Chromo-Dynamics (QCD)

$\alpha_s$, strong coupling constant

QCD is a theory of strong interactions

- Chiral symmetry: identical left & right handed quarks
- Asymptotic freedom & running coupling. Renormalization scale:
  $\Lambda_{QCD} \sim 200\text{MeV}$
- Perturbative regime: $Q^2 \gg \Lambda_{QCD}$
  Deconfined state of quark & gluons
- Non-perturbative regime: $Q^2 \sim \Lambda_{QCD}$
  Quark & gluons confined in hadrons
Main questions about QCD

• What are the forms of extended QCD matter?
  ▪ Properties of hadrons (confined quarks)
  ▪ Properties of deconfined quarks and gluons
  ▪ Relevant degrees of freedom for those states

• How & when the transition between different states of matter happens?

• What symmetries are preserved by QCD (chirality, Time, Parity, and C)
  Under what conditions they can be broken/restored?
Phase diagram: map of states and phase transitions

- Temperature, MeV
- Early universe
- Critical point?
- Deconfinement and chiral transition
- Neutron stars
- Color Superconductor
- Net baryon density

Quarks and Gluons

Hadrons

Nuclei
Experimental study of the phase diagram

Experimental study of QGP phase diagram by:
smashing nuclei in head-on collision and
converting cold nuclear matter into a fireball of partons
Evolution of the system created in HIC

$\tau \sim 0$

- Nuclei just before collision

Nuclei just before collision
Evolution of the system created in HIC

\[ \tau < 1 \text{ fm/c} \]

- Initial pre-equilibrium state
  hard parton scattering & jet production
gluonic fields (Color Glass Condensate)

Nuclei just before collision
Evolution of the system created in HIC

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- Quark-gluon plasma formation
  thermalization (hydrodynamics)

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- QGP expansion and decay
  phase transition of partons into hadrons
  - Hadronization

\[ \tau \sim 10 \text{ fm/c} \]
Evolution of the system created in HIC

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- QGP expansion and decay
  - phase transition of partons into hadrons
  - Hadronization
  - Rescattering & chemical freeze out
  - Kinetic freeze out (stop interacting)

\[ \tau > 10 \text{ fm/c} \]
Evolution of the system created in HIC

produced particles:
\[ p, \pi, K, \phi, \Lambda, \gamma, D, J/\Psi, \text{jets} \]

- Initial pre-equilibrium state
- Quark-gluon plasma formation
- QGP expansion and decay
- Experimentally access only hadronic state

Nuclei just before collision

Hard parton scattering & jet production
Gluonic fields (Color Glass Condensate)
Quark-gluon plasma formation
Thermalization (hydrodynamics)
Phase transition of partons into hadrons
- Hadronization
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\[ \tau \sim 10^{15} \text{ fm}/c \]
Evolution of the system created in HIC

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  - phase transition of partons into hadrons
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Many observables need to be studied to establish the properties of QGP
Anisotropic transverse flow

- Why measure flow?
- 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

Small number of nucleon-nucleon collisions:
- few particles produced

Central collision

Large number of NN collisions:
- abundant particle production

- elementary nucleon-nucleon (NN) collision

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

Particle emitted out-of-plane

Multiple interaction with medium

Emitted in-plane

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 \( \sim \) 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
Quantifying azimuthal asymmetry

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

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\( x, y \) - 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

Spacial 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 particles azimuthal distribution wrt. the reaction plane:

\[
\frac{dN}{d(\Delta \phi)} \sim 1 + 2 \sum_{n=1}^{\infty} v_n(p_t, \eta) \cos(n\Delta \phi)
\]

No “sin” terms because of the collision symmetry

\[v_n(p_t, \eta)\] – anisotropic transverse flow coefficients

- \(v_1\) - directed flow
- \(v_2\) - elliptic flow
- \(v_3\) - triangular flow
Experimental measurements of the anisotropic flow
Modern ultra-relativistic HI colliders

Relativistic Heavy Ion Collider

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

Large Hadron Collider

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

<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>
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<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

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

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

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

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

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

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- Resonance decay
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- 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:

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

For RHIC/LHC: \( v_n \approx 0.04 - 0.07 \)

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

elliptic flow vs. centrality

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:

$$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$$

ALICE Preliminary, Pb-Pb events at $$\sqrt{s_{NN}} = 2.76 \text{ TeV}$$
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
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
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 \( v_2 \):

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

$y_{lab}$

$\chi_{lab}$
Fluctuating initial energy density

Fluctuating spacial 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:

\[ v_2 \{2\} = \sqrt{\langle v_2^2 \rangle + \sigma_2^2 + \delta_2} \]

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
Summary

• Relativistic heavy-ion collisions provide a unique way to study the properties of the quark-gluon plasma (QGP) which is believed to be existed a few microseconds after the Big-Bang

• Anisotropic flow is a key experimental observable to study the evolution of a heavy-ion collision. 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

• Other important observables:
  ✓ Hard probes – see talk by Henner Büsching
  ✓ Heavy quarks – see talk by Yvonne Pachmayer

Looking forward for the upcoming heavy-ion run at LHC!