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Centrality dependent correlations between anisotropic flow harmonics in Xe-Xe collisions at 5.44 TeV

Saraswati Pandey

Department of Physics

Institute of Science

Banaras Hindu University(BHU)

Varanasi, India.

Outline

Introduction

- Heavy-ion collision at LHC
- Collision systems
- Model employed
- Anisotropic flow production in the model employed

Aims and Objectives

- Centrality dependence of the anisotropic flow coefficients upto fourth order.
- Visualization of the elliptic flow in various geometrical configurations as function of transverse momentum and collision centrality.
- Correlations between anisotropic flow harmonics and their significance.

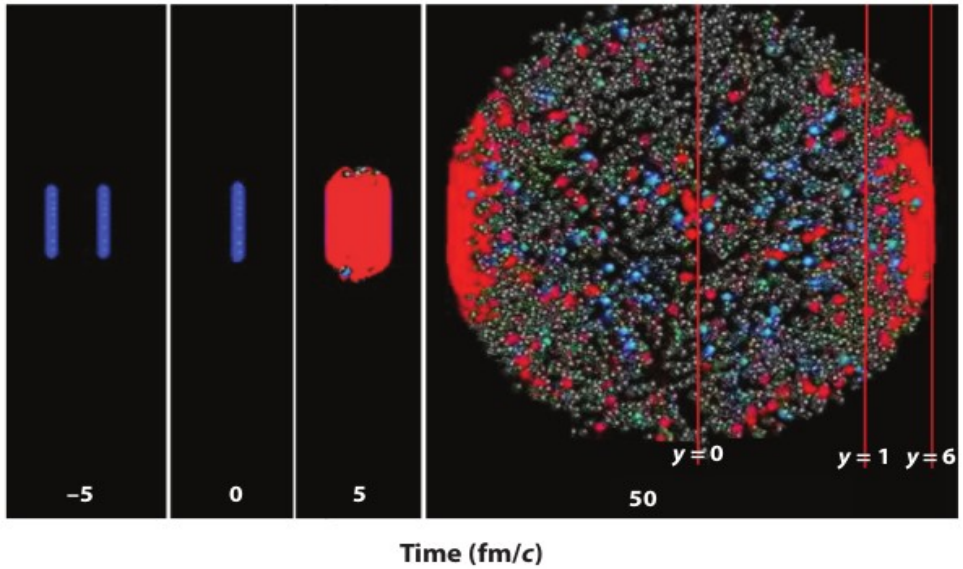
Research Output

Summary

Introduction

Heavy-ion collision at LHC

- Study the properties of a state where quarks and gluons are deconfined, Quark-Gluon Plasma (QGP).
- similar to the QGP in the early universe
- quarks and gluons produced here are not free
- very strongly coupled to one another
  - forming a collective medium that expands,
  - flows as a relativistic hydrodynamic fluid,
  - low ratio of shear viscosity to entropy density (η/S).

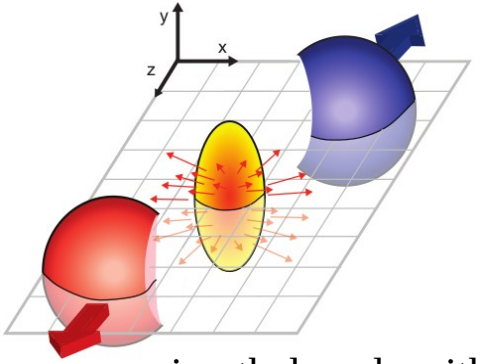


Snapshots of a central 2.76 TeV Pb-Pb collision at different times with hadrons (blue and gray spheres) as well as quark–gluon plasma (red). At a given time, the hottest regions can be found at high rapidity close to the outgoing remnants of the nuclei. (***Busza W, Rajagopal K, van der Schee, Wilke, Annu. Rev. Nucl. Part. Sci. 68, 1, 339-376 (2018).***)

Flow observables

In non-central collisions, the spatial anisotropy is converted to momentum anisotropy,

- ➔ initial properties measured with final-state particles
- ➔ assess the transport properties of the Quark-Gluon Plasma
- ➔ validate models of bulk evolution that are used in the computation of other observables
- ➔ constrain the initial state



Anisotropy in azimuthal angle described by a Fourier series:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \psi_n))$$

$$v_n = \langle \cos[n(\phi - \psi_{RP})] \rangle$$

- φ = azimuthal angle with respect to the reaction plane ψ_n of the produced particle,
- Reaction plane contains the beam direction and the centers of the colliding nuclei.

Collision systems used

- Several collision systems are chosen such as p+p, Au+Au, Cu+Cu, U+U, Pb+Pb, Xe+Xe, etc.
- We aim to perform our study on Xe-Xe collision systems.
- Why such nucleus?
  - Xenon is a moderately deformed nucleus, (prolate).
  - has mass number roughly in mid-between proton and Pb^{208} nuclei.
- So, colliding xenon will be a good way to bridge the multiplicity gap between smaller systems like p+p and p+Pb and larger Pb-ion systems.
- Hydrodynamical models predict an increase in elliptic flow (v_2) by 10% for a deformed Xe nucleus compared to the spherical Xe nucleus in central collisions.

Parameters	Value
A	129
β_2	0.162
β_4	-0.003
a	0.59

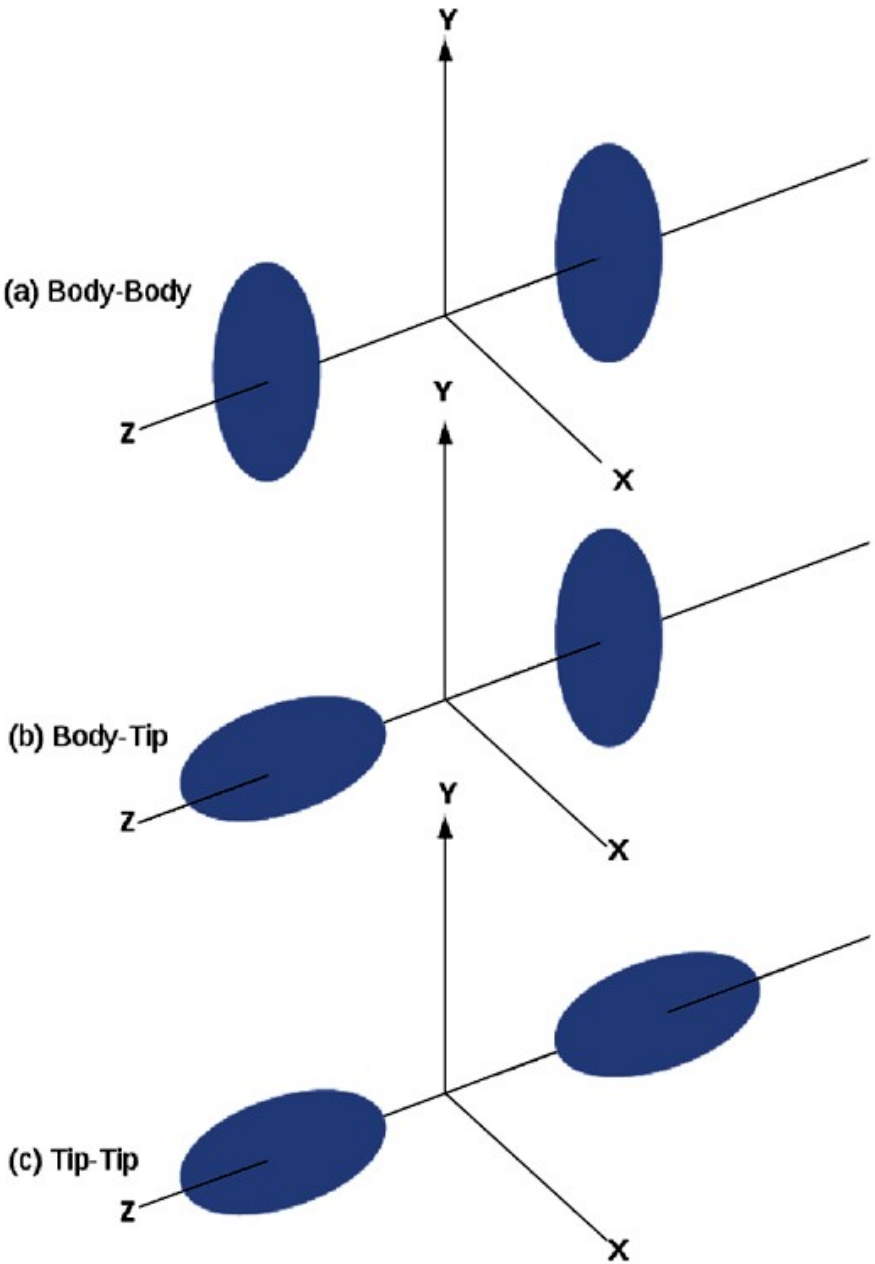
- The deformed Woods-Saxon nuclear density profile function for xenon nucleus in cylindrical polar coordinates is expressed as:-

$$\rho'(\rho,\theta,z) = \frac{\rho'_0}{1+\exp\frac{[r-R(1+\beta_2 Y_{20}+\beta_4 Y_{40})]}{a}}$$

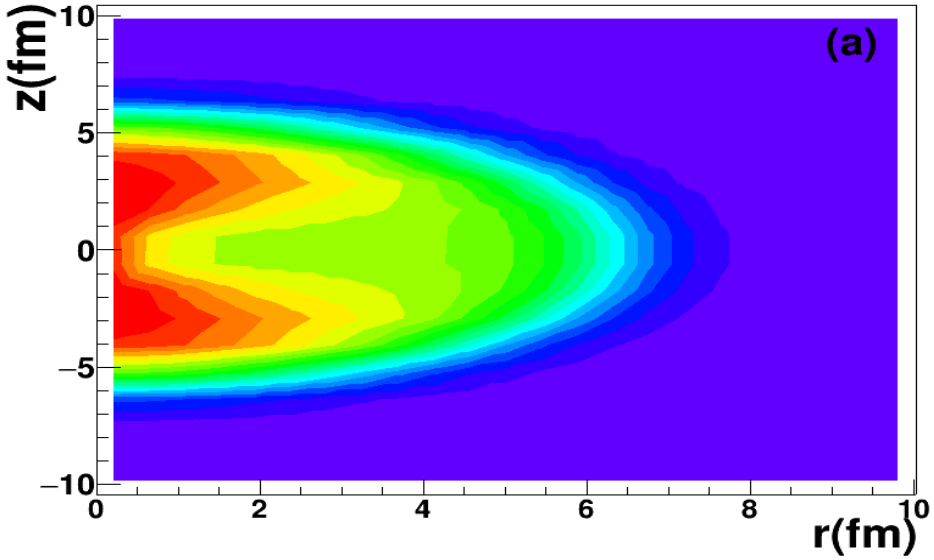
where,

- $R=R_0A^{1/3}$, $R_0 = 1.15$ fm,
- β_2 and β_4 are the deformation parameters,
- Y_{20} and Y_{40} are the spherical harmonics.

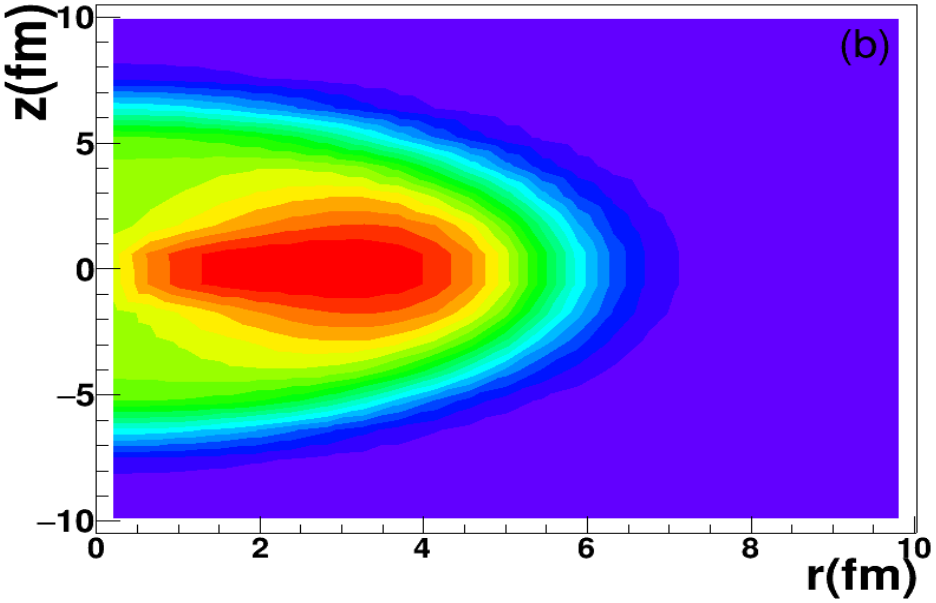
Deformed Xenon geometrical configurations



➔ *(a) Body type*



➔ *(b) Tip type*



Model or framework Used

- The simulation model chosen for study must have the following features:-
  - can handle collision systems at both RHIC and LHC energies.
  - such model works well for spherical, deformed, symmetic and asymmetric collision systems.
  - models should be successful in producing experimental results both quantitatively as well as qualitatively.

HYDJET++ (HYDrodynamics plus JETs) Model

Soft part

- FASTMC statistical model in which particles are produced on thermal or chemical freeze-out hypersurfaces.
- A scenario with different chemical and thermal freeze-outs is implemented ($T_{ch} \geq T_{th}$).
- In between these two freeze-outs, the system is expected to expand hydrodynamically, followed by cooling and then the hadrons stream freely as thermal freeze-out temperature is reached.

Hard part

- It incorporates PYQUEN model in which a jet actually produced by PYTHIA is modified.
- Event-by-event simulation procedure in PYQUEN.
- PYTHIA is used here for simulation of NN collisions, including only those events whose generated total transverse momentum is greater than p_T^{min} value.

(I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, I. Arsene, K. Tywoniuk, Comput.Phys.Commun. 180 (2008) 779.)

Anisotropic flow generation in HYDJET++(soft component)

Elliptic flow v_2 :

- Spatial modulation of freeze-out surface;
- Fluid velocity modulation.

Spatial anisotropy

$$\varepsilon(b) = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}$$

R(b) – surface radius

Momentum anisotropy

$$\tan\varphi_u = \sqrt{\frac{1-\delta(b)}{1+\delta(b)}}\tan\varphi$$

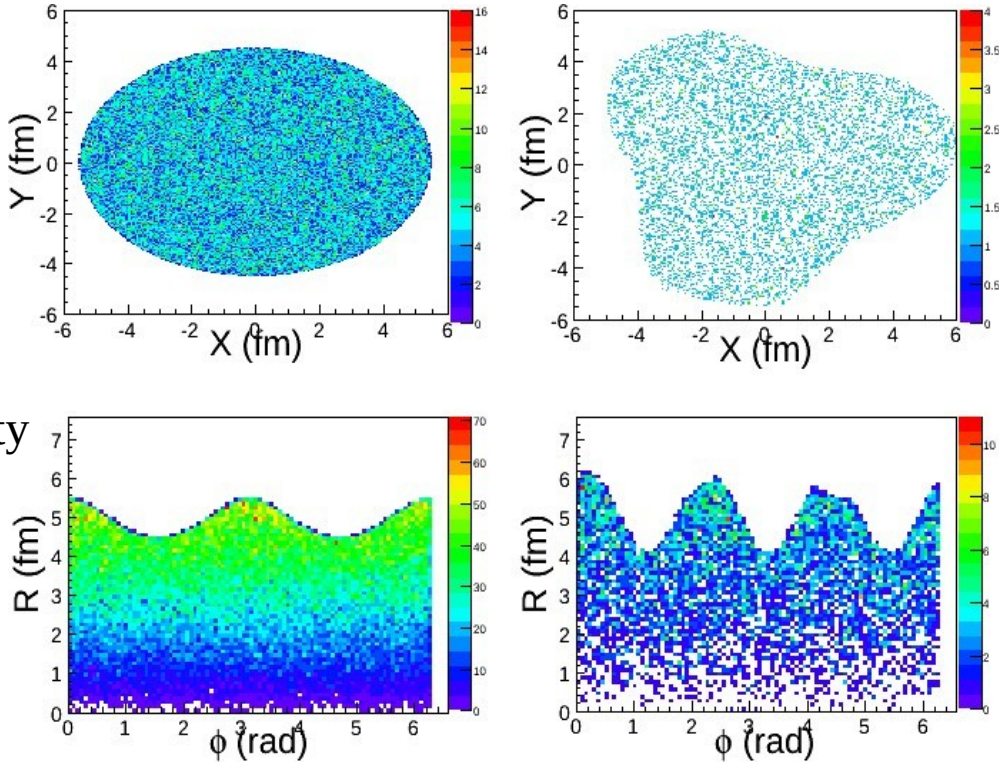
φ_u - azimuthal angle of fluid velocity

φ - spatial azimuthal angle

$$v_2 \propto \frac{2(\delta-\epsilon)}{(1-\delta^2)(1-\epsilon^2)}$$

ε-spatial anisotropy parameter

δ-momentum anisotropy parameter



Triangular flow v_3 :

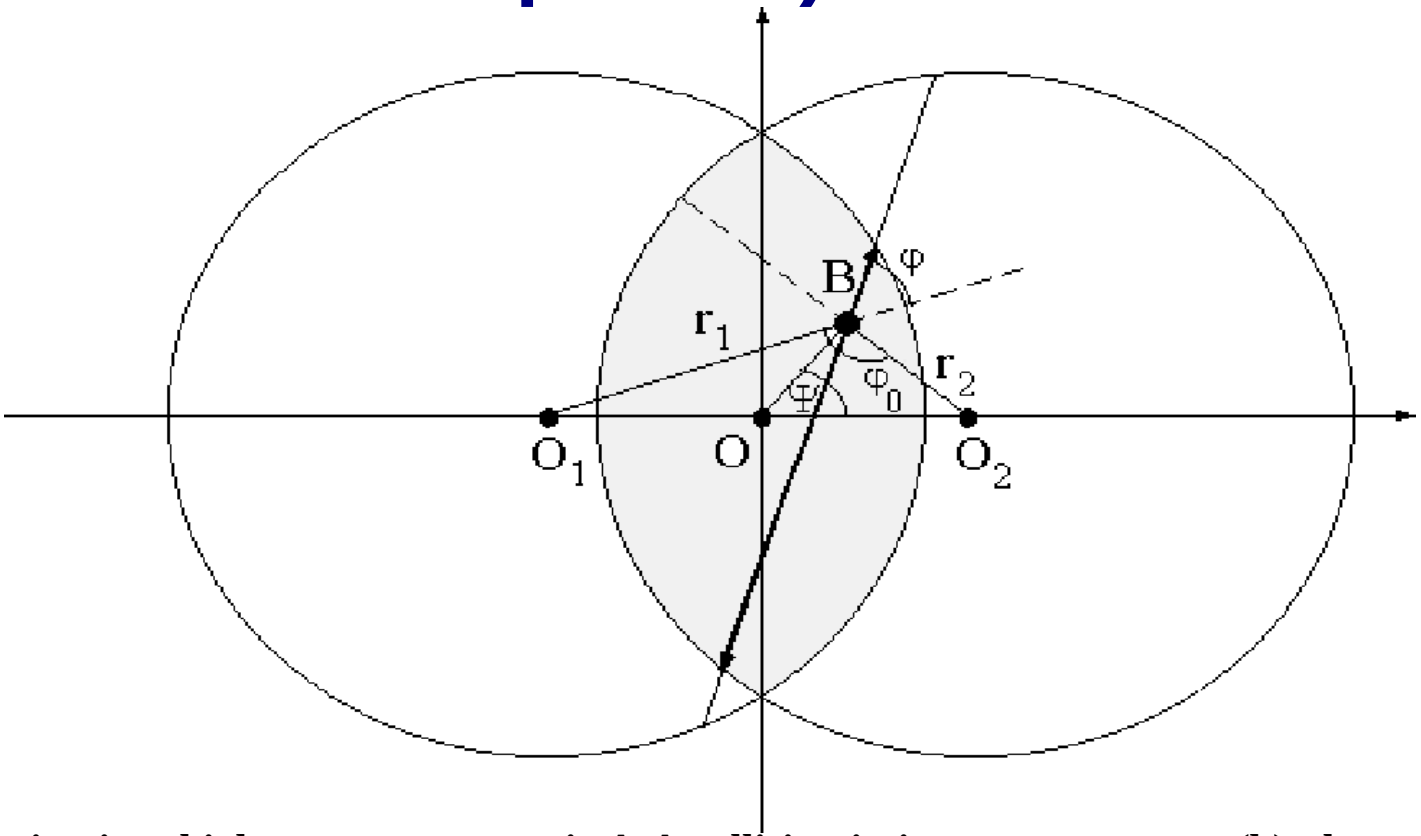
Spatial modulation of freeze-out surface as cos(3φ) with independent phase Ψ_3 and parameter ε_3

Three parameters $\varepsilon(b_0)$, $\varepsilon_3(b_0)$ & $\delta(b_0)$ are tuned to fit the data.

$$R(b,\phi) = R_f(b)\frac{\sqrt{1-\epsilon^2(b)}}{\sqrt{1+\epsilon(b)\cos 2\phi}}[1+\epsilon_3(b)\cos 3(\phi-\Psi_3^{RP})]$$

The simple modification of the HYDJET++ via introducing the distribution over spatial anisotropy parameters permits model to reproduce both elliptic and triangular flow fluctuations in heavy ion collisions at the LHC energy.

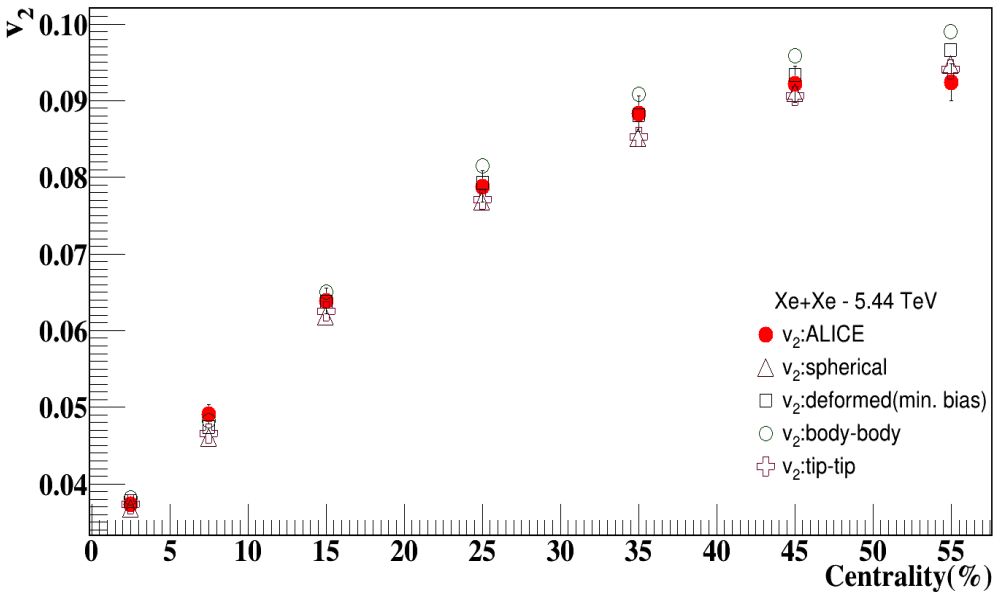
Anisotropic flow generation in HYDJET+(hard component)

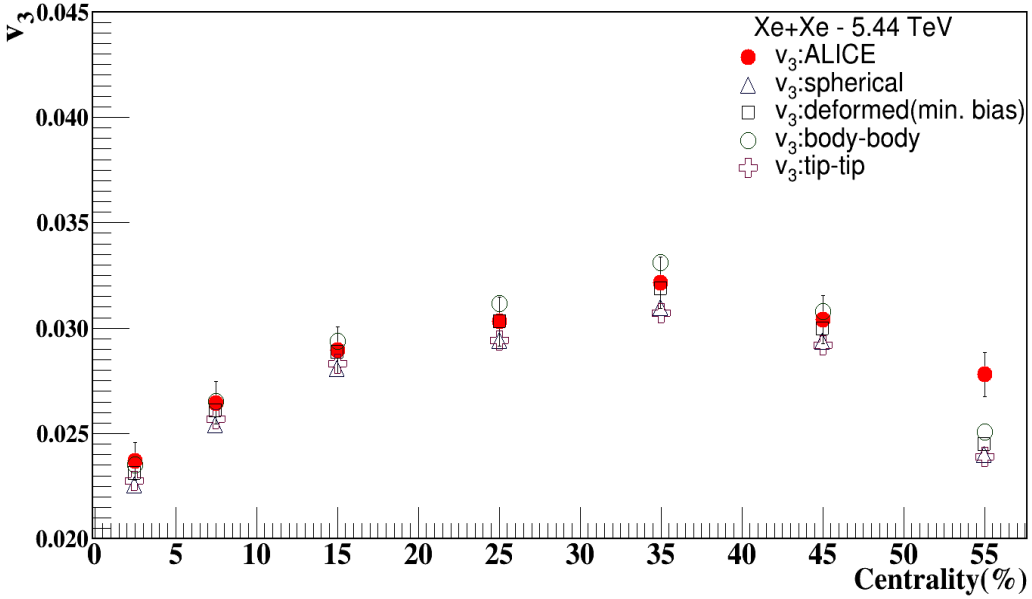


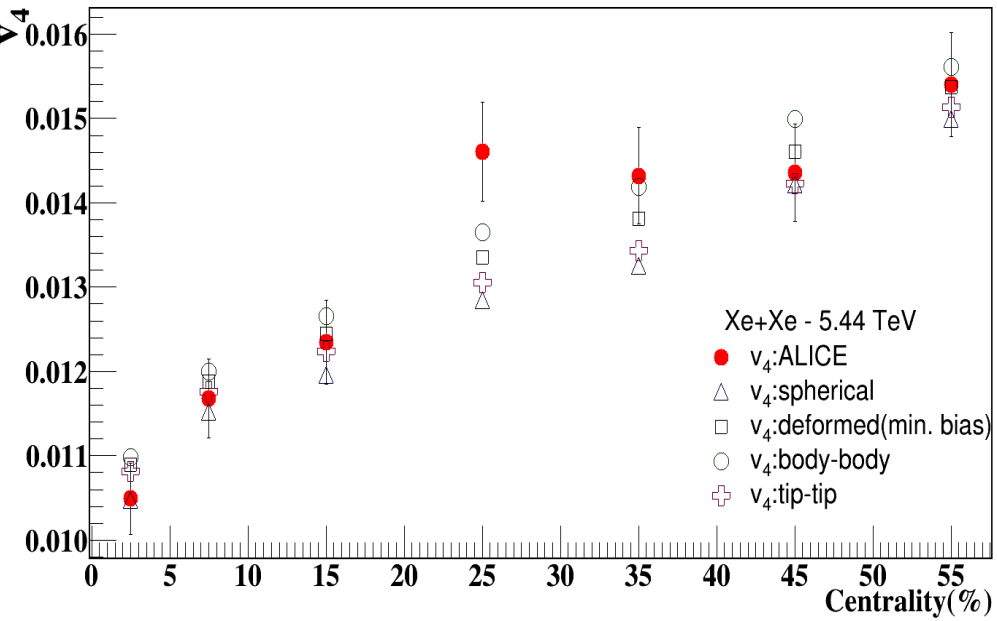
Jet production in a high energy symmetric A-A collision in impact parameter (b) plane. O_1 and O_2 are the nucleus centers, $OO_2 = O_1O = b/2$. B(rcos ψ, rsin ψ) is the jet (dijet) production vertex, r is the distance from the nuclear collision axis to B, r_1, r_2 are the distances between the nucleus centers (O_1,O_2) and B; φ is the jet azimuthal angle, and φ_0 is the azimuthal angle between the vectors r_1 and r_2.

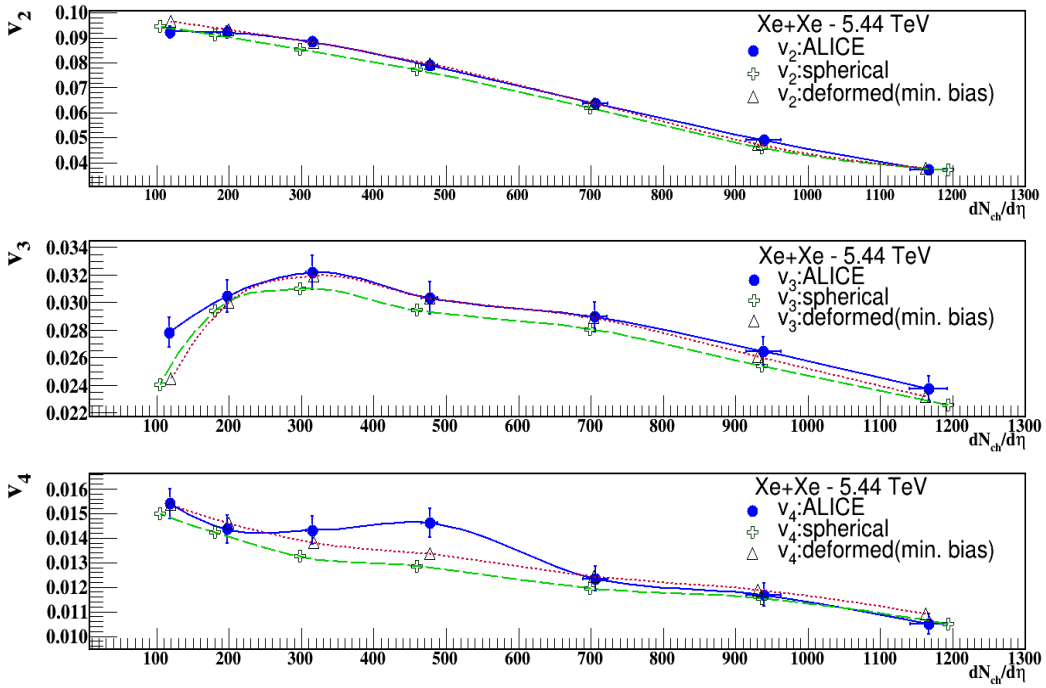
Some anisotropic flow for hard component (elliptic flow and higher even harmonics at high transverse momenta) is generated due to partonic rescattering and energy loss in azimuthally asymmetric volume of the medium.

Results and discussions









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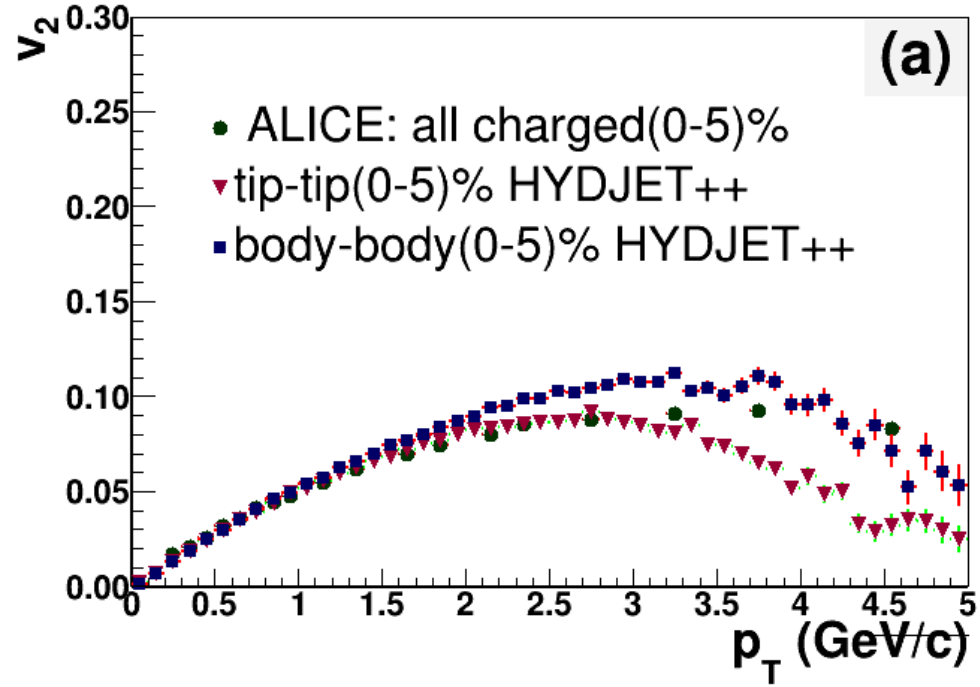
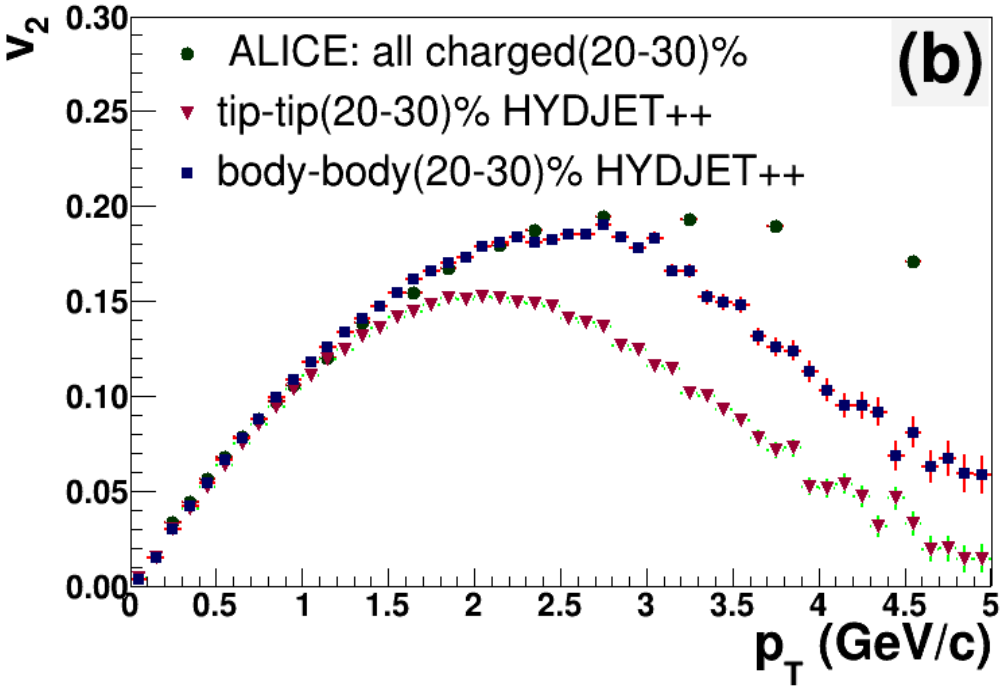
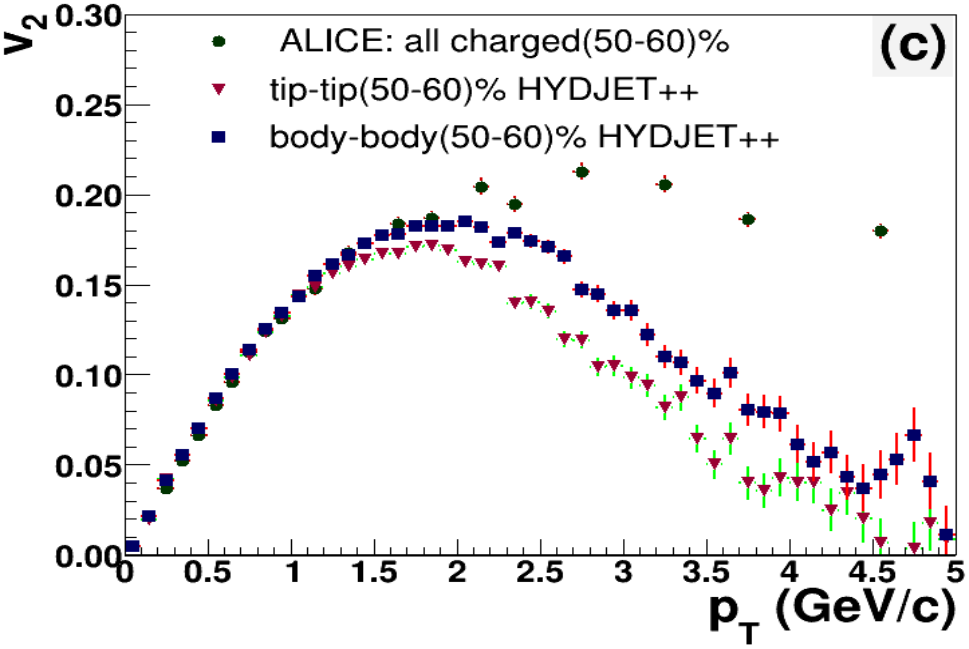
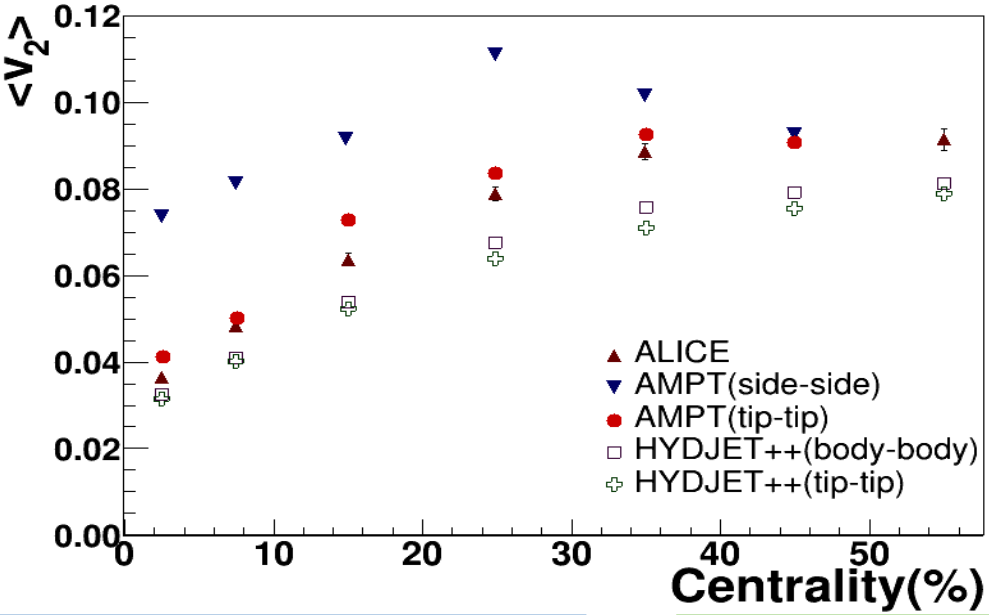

(a)
ALICE: all charged(0-5)%
tip-tip(0-5)% HYDJET++
body-body(0-5)% HYDJET++
v_2
p_T (GeV/c)


(b)
ALICE: all charged(20-30)%
tip-tip(20-30)% HYDJET++
body-body(20-30)% HYDJET++
v_2
p_T (GeV/c)


(c)
ALICE: all charged(50-60)%
tip-tip(50-60)% HYDJET++
body-body(50-60)% HYDJET++
v_2
p_T (GeV/c)


ALICE
AMPT(side-side)
AMPT(tip-tip)
HYDJET++(body-body)
HYDJET++(tip-tip)
$\langle v_2 \rangle$
Centrality(%)

conti...

- HYDJET++ model shows suitable match with ALICE experiment both qualitatively as well as quantitatively within error bars.
- Strong centrality dependence of elliptic flow is observed whereas triangular and quadrangular flows, comparatively, are weakly dependent on collision centrality.
- v_n increases from most central to peripheral collisions, then falls in most peripheral collisions.
- As a function of centrality $v_2 > v_3 > v_4$.
- Anisotropic flow for spherical xenon collision systems is smaller and underpredicts the experimental data.
  - conclusion: due to nuclear deformation, there is an increase in anisotropic flow.
- Body-body collisions produce higher anisotropic flow than minimum bias and tip-tip collisions.
- Spherical xenon collisions produce anisotropic flow similar to the flow from tip-tip collisions.
- v_4 in body–body and tip–tip collisions shows a qualitative match with the experimental data.
- v_n decreases gradually as charged-hadron pseudorapidity density increases.
  - anisotropic flow decreases as collision system-size increases.
- As a function of p_T the two geometrical configurations show the same behavior qualitatively.
  - $v_2^{body\text{-}body} > v_2^{tip\text{-}tip}$
- In each class of centrality, the difference between the elliptic flow of the body-body and tip-tip configurations increase as we move towards larger p_T .
- As we move from the most central to the most peripheral collisions, the value of p_T at which maxima are obtained decreases.

Importance of flow correlations

- Azimuthal correlations, exhibit a well-defined and rich structure.
- Extensively studied as a function of
  - centrality of collision,
  - transverse momentum p_T ,
  - produced particle type,
  - rapidity, and
  - expected event-by-event geometrical fluctuations of the nuclei.

- Azimuthal correlations provide valuable information about the relativistic hydrodynamic nature of the medium, about its transport coefficients, and also about the fluctuations in the initial state from which the medium formed.

- Detailed shape of centrality dependent $v_n - v_m$ correlation is actually cognizant to the shear viscosity of the expanding fluid and also to the fluctuation spectrum of the expanding fireball.

- Such correlations can be very useful in future to constrain the transport coefficients of the QGP formed.

Centrality dependent correlations between anisotropic flow harmonics in Xe-Xe collisions at 5.44 TeV

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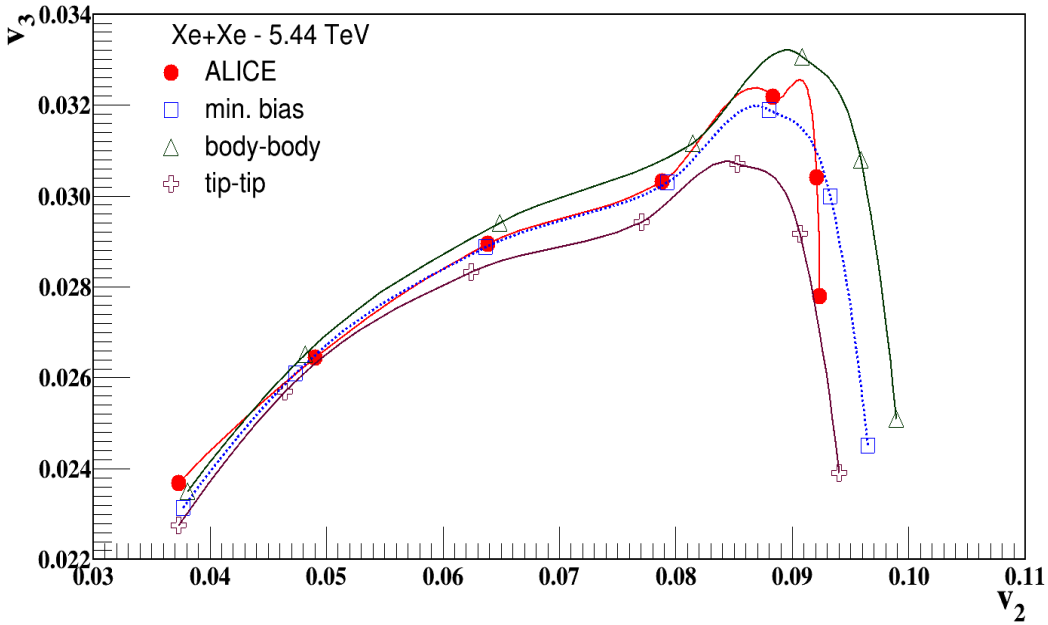
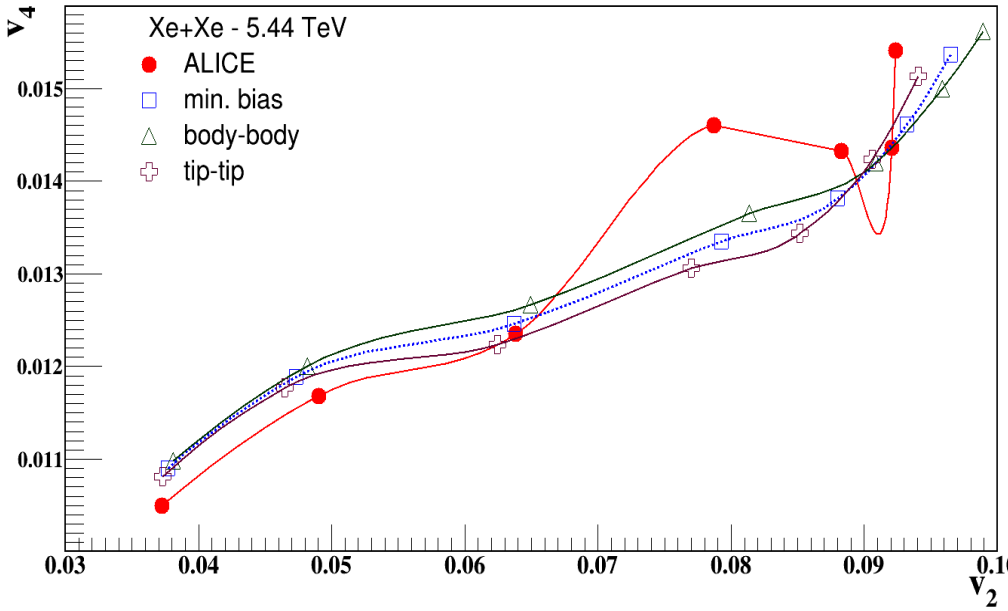
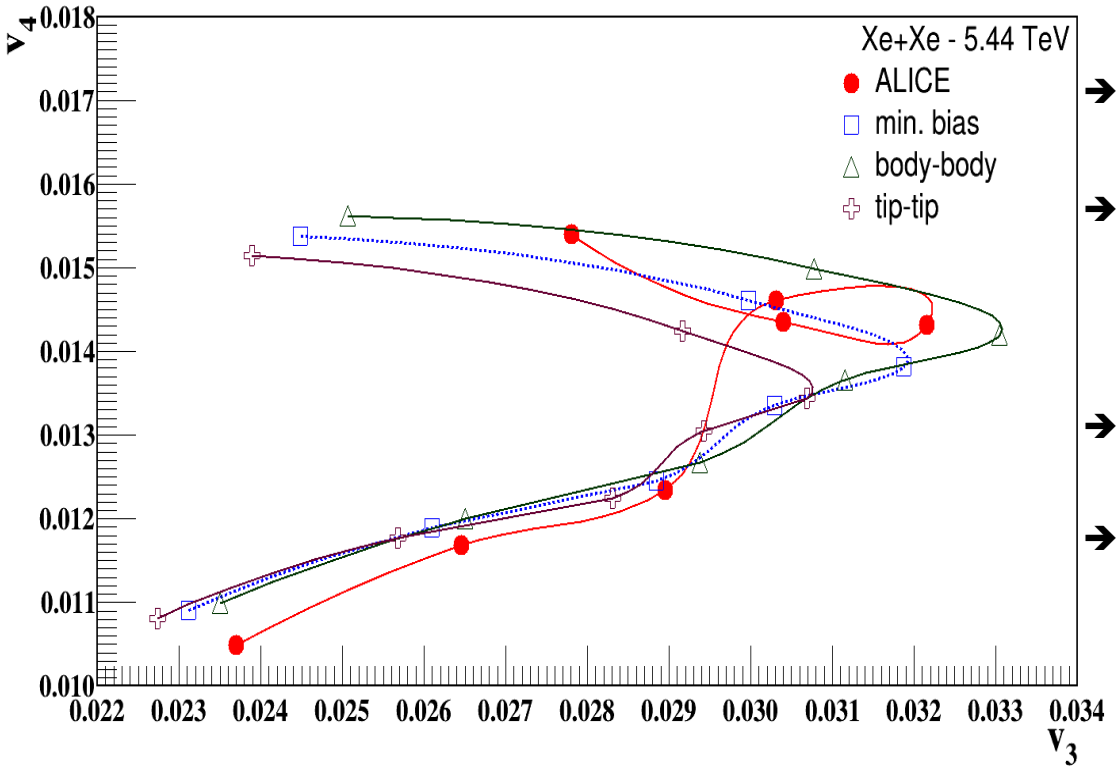




- ➔ Quantitatively, flow correlations show deviation from experiment in various classes of centrality.
- ➔ v_3–v_2 correlations underestimate ALICE experiment in most central and most peripheral class of collisions.
- ➔ There exists a linear positive correlation between v_3–v_2 at smaller impact parameter.
- ➔ At larger impact parameter, boomerang like behaviour is present.
- ➔ v_4–v_2 predict a sort a non-linear positive correlation throughout centrality, no boomerang observed.
- ➔ This may be due to the independent treatment of the fourth order anisotropy determiner and not depending on lower order fourier coefficients.
- ➔ Notable two points: first, we have not implemented fourth-order spatial and momentum anisotropies in the body of the model; second, v_4 is not measured by the dependence on lower order Fourier harmonics (mode-mixing).
- ➔ In central collisions, body–body and tip–tip collision results are indistinguishable and overestimate the ALICE experimental
- ➔ Data.
- ➔ As we move towards peripheral collisions, the two geometrical configurations can be distinguished and underestimate the experimental data.
- ➔ Quantitatively, body–body results are higher than tip–tip collision results.

results and discussions(cont...)



- ➔ Min. bias HYDJET++ model results overpredict the data quantitatively in central collisions.
- ➔ Positive linear correlation is observed between v_4 and v_3 in central collisions.
- ➔ Model underestimate experimental data at higher centralities.
  - ➔ because HYDJET++ v_3 underestimates experimental result in this region.
- ➔ v_4-v_3 correlation is a strong boomerang-like structure.
- ➔ strong agreement with the ALICE experimental data.
  - ➔ HYDJET++ model deals with the parameterized ideal hydrodynamics and does not include any dissipative effects.

- ➔ In peripheral collisions, strong boomerang structure is predicted.
- ➔ Body-body and tip-tip $v_n - v_m$ correlations predict their similar respective qualitative behaviour.
- ➔ Quantitatively, body-body correlations are higher than tip-tip correlations.
- ➔ Boomerang-like structure observed in peripheral collisions.
  - ➔ viscous damping is stronger in peripheral collisions than in central collisions where we have a linear positive correlation.
  - ➔ higher flow (body–body collisions) indicates lesser viscosity and lesser flow (tip–tip or spherical xenon collisions) indicates higher viscosity.
- ➔ Hence, the geometry of collision plays significant role in collective flow phenomenon and consequently on transport properties of QGP medium.

Summary

- We have made a scrupulous study of centrality dependence of anisotropic Fourier harmonic coefficients up to fourth-order for charged hadrons in Xe–Xe collision systems at 5.44 TeV LHC energies using the modified HYDJET++ model.
- Motivation to study whether the experimentally measured anisotropic flow correlations and their dependence on collision centrality can be affirmed under the HYDJET++ framework of relativistic heavy-ion collisions. ***Achieved!***
- Deformed Xe-Xe collisions show suitable match with ALICE experimental data.
- Anisotropic flow of charged hadrons have clear dependence on collision centrality and system-size.
- Spherical xenon collisions show suitable match with (deformed) tip-tip collision results.
- Body-body collisions produce higher flow in comparison to minimum bias and tip-tip collisions.
- We separated $v_n - v_m$ correlations into linear and non-linear (boomerang-like) contributions based on their dependence on collision centrality.
- At such stages, we are quite successful in disentangling the geometrical configurations.
- Strong centrality dependent correlation is observed between the flow harmonics (v_2, v_3, v_4).
- HYDJET++ model predicts a linear positive correlation in central collisions.
- Boomerang-like correlation structure exists in peripheral collisions as found in ALICE experiment.
- We find a strong dependence of the above observables on the geometry of collision.
  - Body–body and tip–tip $v_n - v_m$ correlations predict their similar qualitative behaviour.
  - Quantitatively, body–body correlations are higher than tip–tip correlations.

Thank you!