Knee structure in the elliptic flow in ultracentral U+U collisions

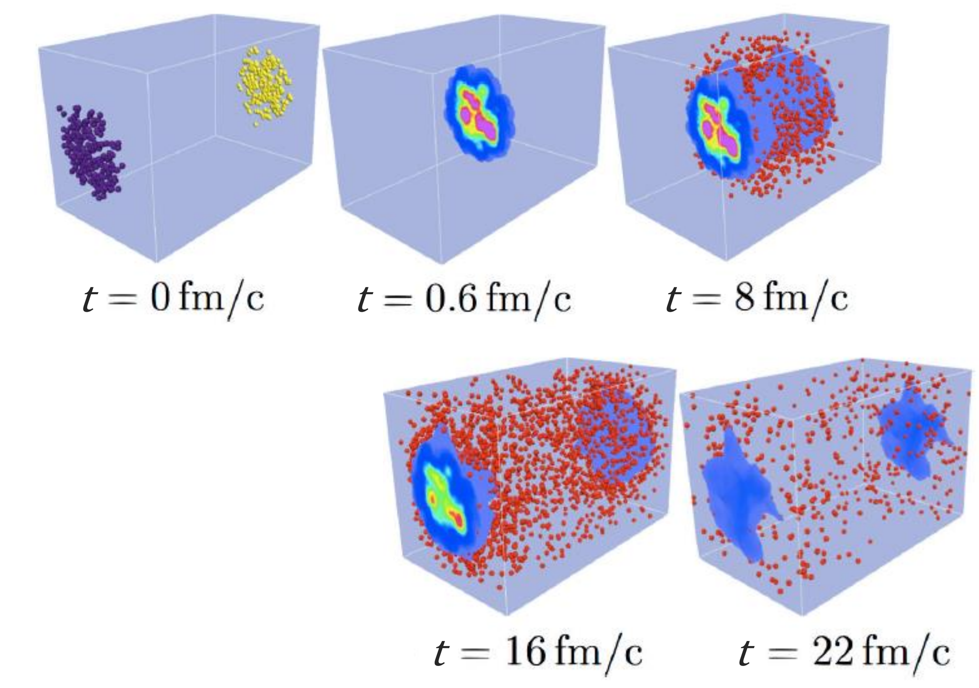
Andy Goldschmidt, Chun Shen, Ulrich Heinz

Abstract

Using event-by-event viscous fluid dynamics to evolve fluctuating initial density profiles for U+U collisions, we find a "knee"-like structure in the elliptic flow as a function of collision centrality, located around 0.5% centrality as measured by the final charged multiplicity. This knee is due to the preferential selection of tip-on-tip collision geometries by a high-multiplicity trigger. It arises from a similar knee in the ellipticity distribution in the initial states; hydrodynamic evolution translates the knee in the ellipticity vs. centrality into a knee of the elliptic flow in the final state.

No knee structure is seen in odd flow harmonics. A weaker knee structure in the centrality dependence of the 4th-order eccentricity is washed out by nonlinear hydrodynamic evolution effects and thus no longer visible in the centrality dependence of the final quadrangular flow v_4.

A deeper analysis of these structures is facilitated by additionally imposing a tight cut on complete nuclear overlap using the Zero Degree Calorimeters (ZDCs). We show results exploring the power of such cuts in selecting specific collision geometries and their impact on anisotropic collective flow.



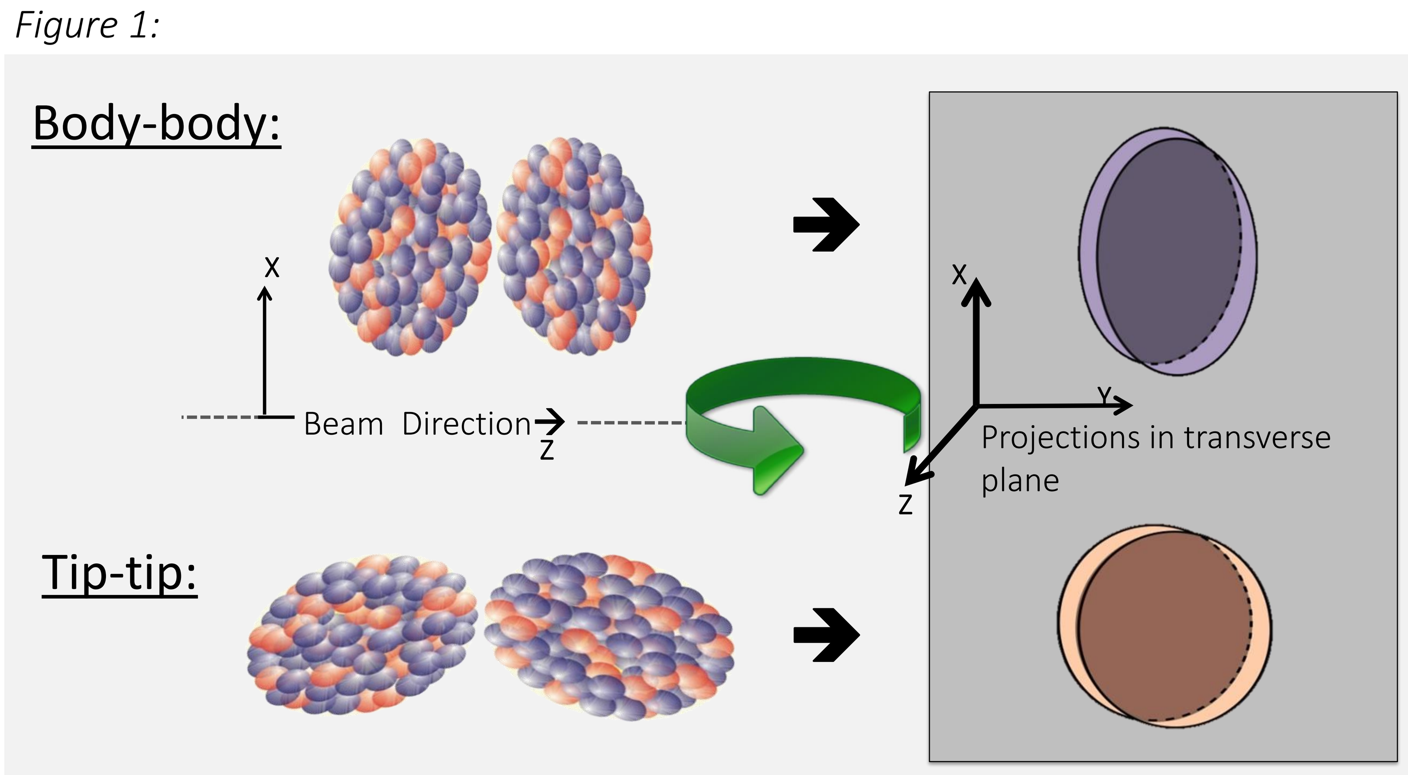
Collision Geometry

The initial temperature distribution of each ephemeral fireball is controlled by two main factors: deterministic collision geometry (i.e. the centrality and shape of the impact between two nuclei) and quantum mechanical fluctuations in the nucleon positions. To model the initial condition we use an MC-Glauber approach with Gaussian nucleons.

The uranium nucleus has a prolate deformation; the resulting deformed collision system implies the geometry of the initial temperature distribution depends on the orientation of the incoming nuclei.

We focus our attention on two extreme cases: tip-tip and body-body collisions. A tip-tip event occurs when the major axis of each nucleus is parallel to the beam direction. In a body-body event the major axis is perpendicular to the beam direction. The cartoon shown below (which ignores relativistic contractions for clarity) gives a visual representation of the colliding nuclei both along the beam direction and in the transverse plane.

Figure 1:

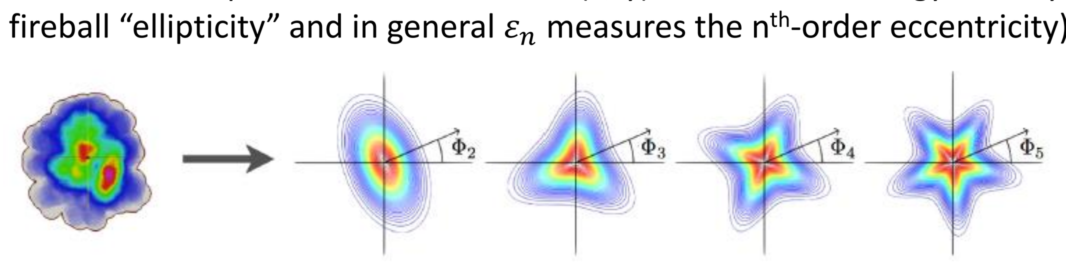


The "Knee" Structure

The shape of a temperature distribution in the (x, y) transverse plane can be described by r^2-weighted eccentricity coefficients ε_n:

$$\varepsilon_n e^{in\Phi_n} := -\frac{\int dxdy\, r^2 e^{in\varphi} e(x,y)}{\int dxdy\, r^2 e(x,y)}$$

where (r, φ) are the standard polar coordinates and e(x, y) is the initial energy density (so that ε_2 is a measure of the fireball "ellipticity" and in general ε_n measures the n$^{\text{th}}$-order eccentricity).



The ellipticity in the transverse plane for a tip-tip collision is small (as the overlap is approximately circular) while in a body-body collision the shape is deformed, implying a larger ellipticity (see Figure 1).

Although a fully overlapping tip-tip or body-body collision has the same number of participants, more binary collisions between nucleons can happen in the thicker tip-tip event. In the mixed model, this results in larger integrated entropy deposit (dS/dy) atop these initial profiles. High dS/dy corresponds to high final particle multiplicities (dN/dy). We therefore expect a bias toward tip-tip events at high particle multiplicities as seen below in Figures 2, 3.

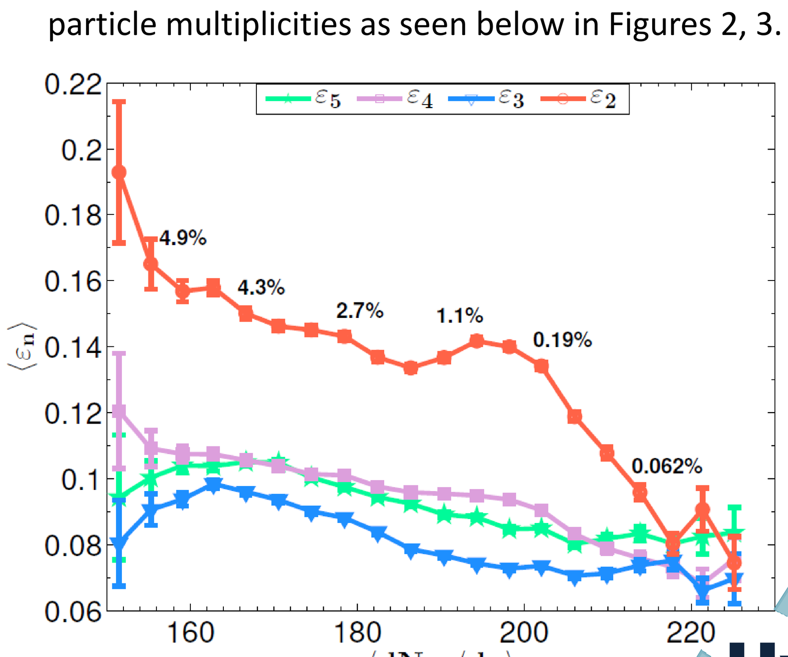


Figure 2: Here we have plotted as a function of final particle multiplicity for 0-5% centrality the decomposition of the initial energy density profile into the coefficients ε_2, ε_3, ε_4 and ε_5.

Note the presence of a knee feature correlated with the even harmonics 2 and 4. This is the discussed bias in central collisions of circular profiles from tip-tip collision events.

We then simulate the fireball evolution using viscous relativistic hydrodynamic simulations.

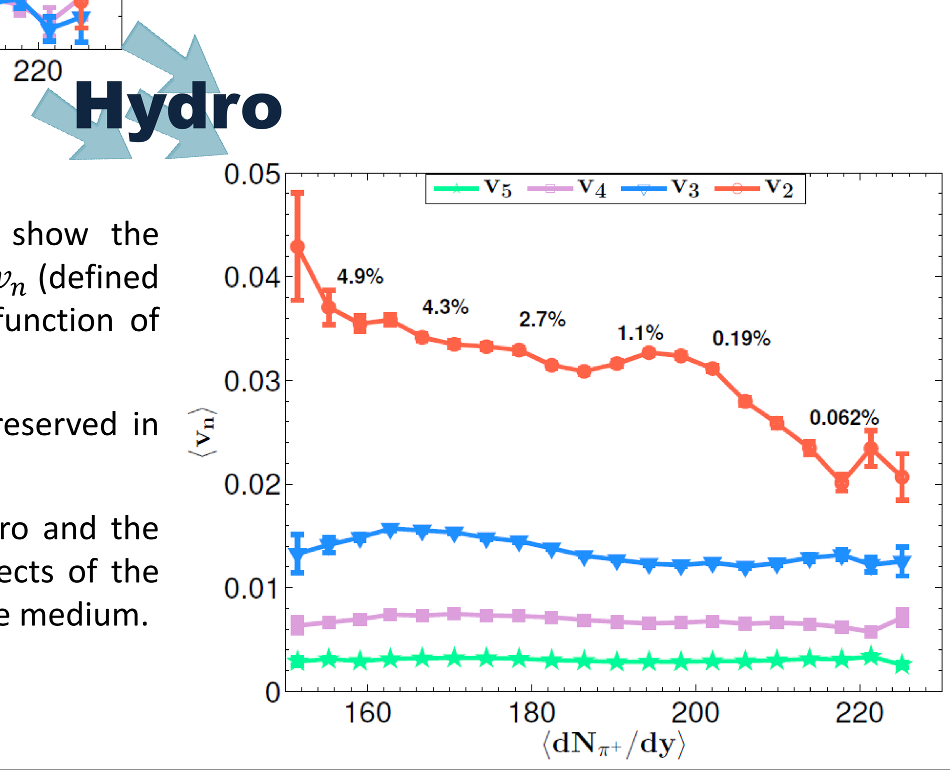


Figure 3: After hydro evolution, we show the decomposition of the final particle flows v_n (defined via the final particle distribution) as a function of final particle multiplicity.

We note the knee in the ellipticity is preserved in the final elliptic flow v_2.

The sorting of flow harmonics after hydro and the disappearance of structure in v_4 are effects of the assumed sheer viscosity $\eta/s = 0.08$ of the medium.

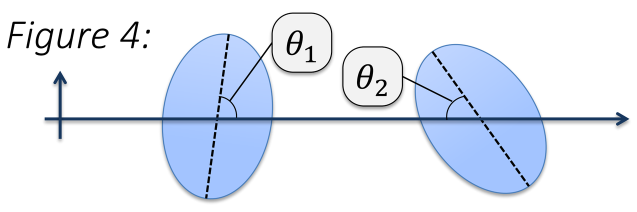
Zero Degree Calorimeters

Placed at zero degrees far from the collision pair, ZDCs catch information about the spectator neutrons. Selecting on the ZDC allows us to restrict to fully overlapping collisions, so that any initial geometric effects must come from the deformed shape of the uranium nucleus. We again appeal to body-body and tip-tip collisions as limiting cases to assist in discussion.

To be more explicit we define the angle θ between the major axis of the ellipsoidal uranium nucleus and the beam direction (Figure 4). Using the pair of angles from both incoming nuclei, let:

$$\|\cos\theta\| := \left(\sqrt{\cos^2\theta_1 + \cos^2\theta_2}\right)/\sqrt{2}$$

Figure 4:



We then make the requirement that for a tip-tip event $\|\cos\theta\| \geq 0.86$.; for a body-body event, $\|\cos\theta\| \leq 0.31$. These values correspond to a maximum deviating angle of $\frac{\pi}{10}$ for a colliding pair with equal angles (see Figure 5).

We study a cut of the 1% most participating ZDC events with the goal of distinguishing specific orientations. In experiment, there remain two further parameters we can use to discriminate between events: v_2 and dN/dy. In the initial conditions these map to ε_2 and dS/dy. However, theorists have the additional benefit of being able to record the angles under consideration.

Plotted in Figure 6 (7) is the probability distribution for ε_2 (dS/dy). Included is the distribution of tip-tip and body-body collisions scaled according to that part of the total population. Below this plot is the percent contribution for both extreme collision types. We can directly read off the likelihood of selecting a certain orientation based on a given eccentricity or multiplicity cut.

Figure 5:

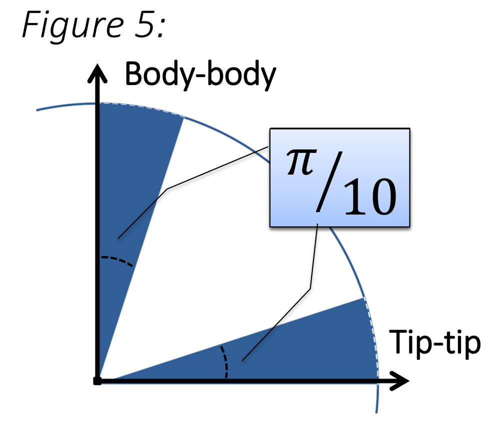


Figure 6:

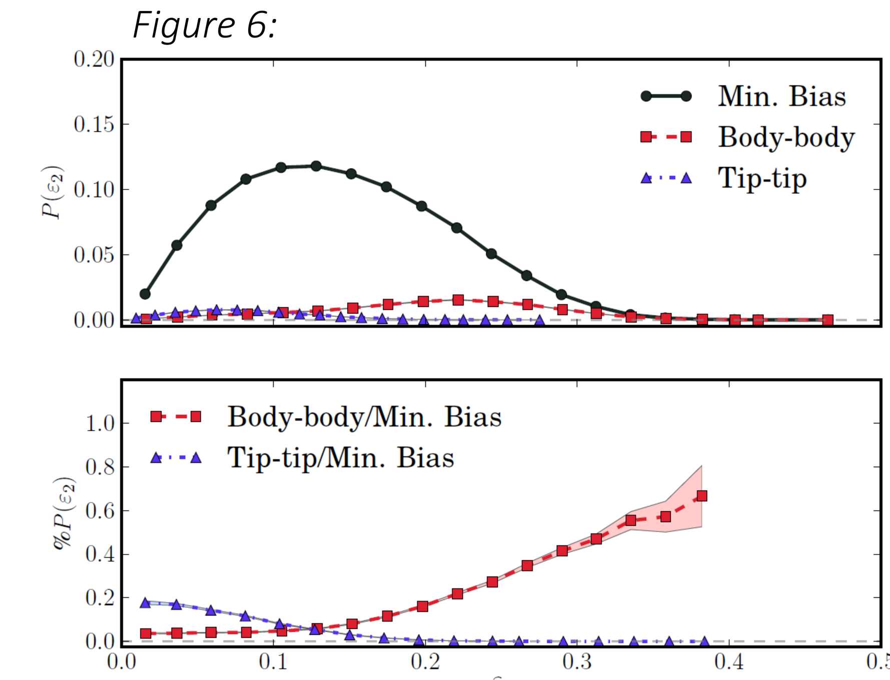
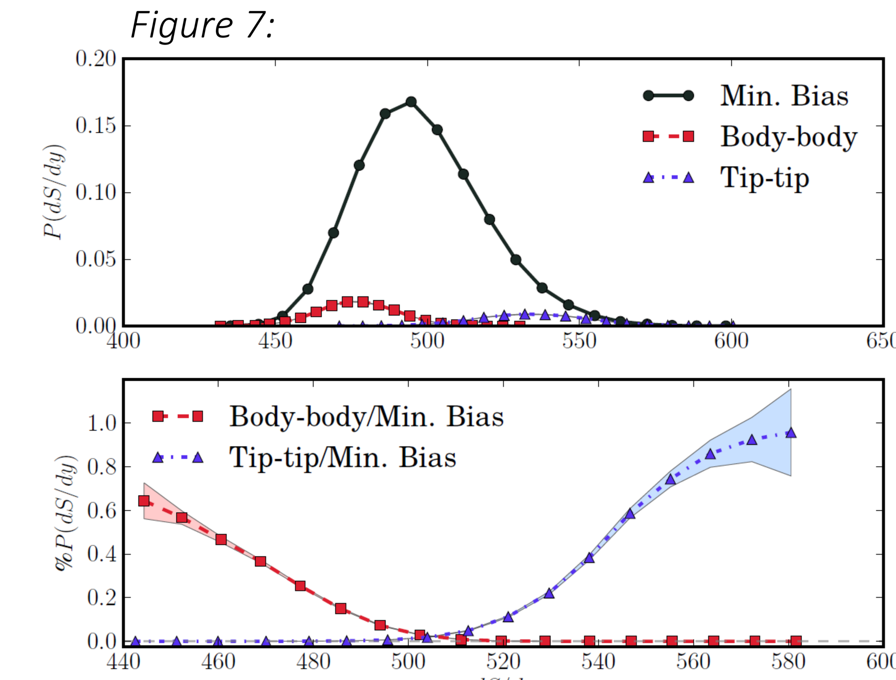


Figure 7:



Note that in our model, cuts on multiplicity are more effective than the cuts on eccentricity to select either case. However, this relies on the assumed nonlinear dependence on the number of participants. Cuts on eccentricity do not seem to provide sufficient discriminating power to effectively select tip-tip events; however, they may have use for selecting body-body systems.

Conclusion

- The prolate deformation of the uranium nucleus results in a "knee" structure in the ellipticity of the initial temperature distribution as a function of collision centrality.
- The knee structure remains preserved after relativistic viscous hydrodynamic evolution; however, to find the knee, we must look toward ultracentral (<0.5%) collision events.
- Cutting on ZDC allows us to select the fully overlapping collisions. By further cutting on elliptic flow v_2 and multiplicity dN/dy we may attempt to distinguish body-body and tip-tip events from the fold.
- By using dS/dy cuts we obtain better distinction of tip-tip events than with ε_2, related in part to the discussion of the knee structure. Both ε_2 and dS/dy provide >50% selection efficiency for body-body events.

The next step is to verify the correspondence of cuts on ε_2 and dS/dy with similar cuts on v_2 and dN/dy.

References and Acknowledgements

Thanks to Zhi Qiu, Chris Plumberg, Jia Liu, Dennis Bazow, and Amy Weisman for discussions.

For reference:
Event-by-event Hydrodynamic Simulations for Relativistic Heavy-ion Collisions Zhi Qiu (Ohio State U.). Aug 9, 2013. e-Print: arXiv:1308.2182 [nucl-th]

iEBE convenience package: *https://github.com/chunshen1987/iEBE*

Image sources:
www.bnl.gov/rhic/, jet.lbl.gov/

This work was supported in part by the U.S. Department of Energy and The Ohio State University Undergraduate Research Office.