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 $v_2$.

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 two nuclei) and quantum mechanical fluctuations in the nuclear positions. To model the initial condition we use the 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.

The “Knee” Structure

The shape of a temperature distribution in the $(r, \theta)$ transverse plane can be described by $r^2$-weighted eccentricity coefficients $e_n$.

$$e_n = \frac{\int dr d\theta r^2 \left( e_0 \cos n\theta + e_2 \sin n\theta \right)}{\int dr d\theta r^2}$$

where $(r, \theta)$ are the standard polar coordinates and $e_0, e_2$ is the initial energy density (so that $e_2$ is a measure of the fireball “ellipticity” and in general $e_n$ measures the $n$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 thepler tip-tip event. In the mixed model, this results in larger integrated entropy deposit (dS/dy) at these initial profiles. High dS/dy correlates to high final particle multiplicity $(N_{ch})$. We therefore expect a bias toward tip-tip events at high particle multiplicities as seen below in Figures 2, 3.

Zero Degree Calorimeters

Placed at zero degrees far from the collision pair, ZDCs catch information about the spectator neutrons. Selecting on the ZDCs allows us to reduce 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 $\theta$ 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:

$$\langle \cos \theta \rangle = \langle \cos 2\theta_1 + \cos 2\theta_2 \rangle / 2$$

We then make the requirement that for a tip-tip event $\langle \cos \theta \rangle \geq 0.86$; for a body-body event, $\langle \cos \theta \rangle \leq 0.31$. These values correspond to a maximumdeviating angle of $\pm 13^\circ$ 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 dS/dy. In the initial conditions these map to $v_2$ 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 $v_2$ (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.

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 dS/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 $v_2$, related in part to the discussion of the knee structure. Both $v_2$ and dS/dy provide >50% selection efficiency for body-body events.

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

References and Acknowledgements

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

For references:

2. ZEUS collaboration: https://github.com/zeus/19871658
3. Correspondence with Zhi Qiu.

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