Influence of fluctuating initial-state shape deformations in ultra-central collisions

Peifeng Liu (speaker)
Roy Lacey

Stony Brook University

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Puzzle: ultracentral $v_2$ in Pb+Pb

- Hydrodynamic calculations continue to predict higher $v_2$ than measured, for both 2.76 and 5.02 TeV.
- Can also be visualized with acoustic scaling (see eg. Liu & Lacey Phys. Rev. C 98, 031901 (2018)).

$$\log \frac{v_n}{\varepsilon_n} \propto -\frac{\eta}{s R T} \propto -M^{-1/3} \propto -N_{c_{\text{part}}}^{-1/3}$$

The drop of $v_2/\varepsilon_2$ suggests an initial stage issue.

- Eccentricities are calculated from a quark Glauber code as in the previous work.
- We use ATLAS 5.02 TeV Pb+Pb flow data (EPJC 78(2018) 997) for $p_T=0.5-0.8$ GeV. It contains $v_2$ for ultracentral bins 0-0.1% and 0-1%.
For U+U, deformation increases $e_2$ by 70% for the central 1%. Deformation is important for central collisions!

Investigate shape of Pb as sampled from single particle distribution and the effect on eccentricity.

Event by event we need an effective deformation $\beta$. We follow Gilbreth, Alhassid and Bertsch PRC 97, 014315 (2018) and use 2nd order spherical harmonics in the frame where

$$ \langle xy \rangle = \langle yz \rangle = \langle zx \rangle = 0 \text{ and, } \langle z^2 \rangle > \langle x^2 \rangle > \langle y^2 \rangle $$

then only there are only two nonzero components

$$ r^2 Y_{2,0} = \frac{1}{4} \sqrt{\frac{5}{\pi}} (-x^2 - y^2 + 2z^2) $$

$$ r^2 Y_{2,2} = \frac{1}{4} \sqrt{\frac{15}{\pi}} (x^2 - y^2) $$

Define $\beta_i = (4\pi/5) Y_{2,i}$ and take two-norm, $\beta = \sqrt{\sum \beta_i^2}$. Also define $\gamma = \arctan \beta_2 / \beta_0$

If we have a deformed Fermi dist, this gives the same $\beta$, in the limit of small $\beta$ and zero skin depth.

$\gamma = 0$ for perfectly prolate nucleus, 60° for oblate.
EbyE deformation: 2D $\beta$ distribution

- 2D $\beta$ distribution for Pb, U
- EbyE Pb can get sizable deformation (rms $\beta$ 0.12) from the sampling process
- Density is approximately $\beta^4 \sin 3\gamma \exp(-\beta^2 / C)$ for a spherical system when the 5 spherical harmonic components have gaussian distribution
EbyE deformation: 1D $\beta$ distribution

- Gaussian ansatz
  
  \[ \beta^4 \exp(-\beta^2/C) \]

  describes Pb well

- There is significant overlap between Pb and U

- NN correlation, even Pauli exclusion could modify these distributions!
Effect of deformation in central Pb+Pb

- Conditional mean of $\varepsilon_2$ is approximately linear in $\beta_A$ when selecting on one side, or $\beta_A + \beta_B$ when selecting on the sum

- Dependence is strong for central events
Reduction of deformation fluctuation

- In the frame $\langle xy \rangle = \langle yz \rangle = \langle zx \rangle = 0$
- Rescale x, y, z independently, so $Y_{2,i}$ is linear combination of original and “smooth” value $Y^*_{2,i}$
  \[ \tilde{Y}_{2,i} = R Y_{2,i} + (1 - R) Y^*_{2,i} \]
- RMS radius is fixed
- We find with $R=0.72$ we can achieve scaling in $v_2$ (next page) for Pb+Pb. $\varepsilon_3$ is not changed
- Similar to permanent deformation, the effect is mostly in 0-5% centrality
- If we do this for U+U the relative change is much smaller (-4% for 0-1%, vs -18% for Pb+Pb)

$\varepsilon_2\{2\}$ before and after deformation reduction

![Graphs showing deformation reduction](image-url)
Scaling with deformation reduction

- Scaling now holds for all measured centrality bins
Mean $p_T$ dependence of $v_2$ in Au+Au

- Observable proposed to show shape of nuclei (G. Giacalone, Phys. Rev. C 102, 024901 (2020))
- For example, in U+U body-body collisions has large $v_2$, large initial size $R$, small $<p_T>$ => anti-correlation between $v_2$ and $<p_T>$
- From AMPT we extract $<p_T>$ vs $R$ response and apply to Glauber events
Mean $p_T$ dependence of $v_2$ in Au+Au

- $\varepsilon_2\{2\}$ ordered as expected
- Reduction of fluctuation greatly reduces the mean $p_T$ dependence signal
- At track level for typical $p_T$, $v_2$ is roughly proportional to $p_T$. This would give a contribution of about 1 to normalized slope in all cases and is not included here.
Summary

• Event by event we calculated the deformation parameters $\beta$ and $\gamma$ for each nucleus from the nucleons
• By sampling from the single-body distribution we get a sizable rms $\beta=0.12$ for Pb
• Deformation drives $\varepsilon_2$ for spherical systems for central 5%
• Scaling down $\beta$ allows us to get a set of eccentricities that scales $v_2$. This suggests sampling from single-body distribution gives an unphysically wide $\beta$ distribution
• Shape fluctuation could be important for $v_2-<p_T>$ relationship, more important than the $\beta$ input in our Au+Au example