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

Peifeng Liu (speaker)
Roy Lacey

Stony Brook University

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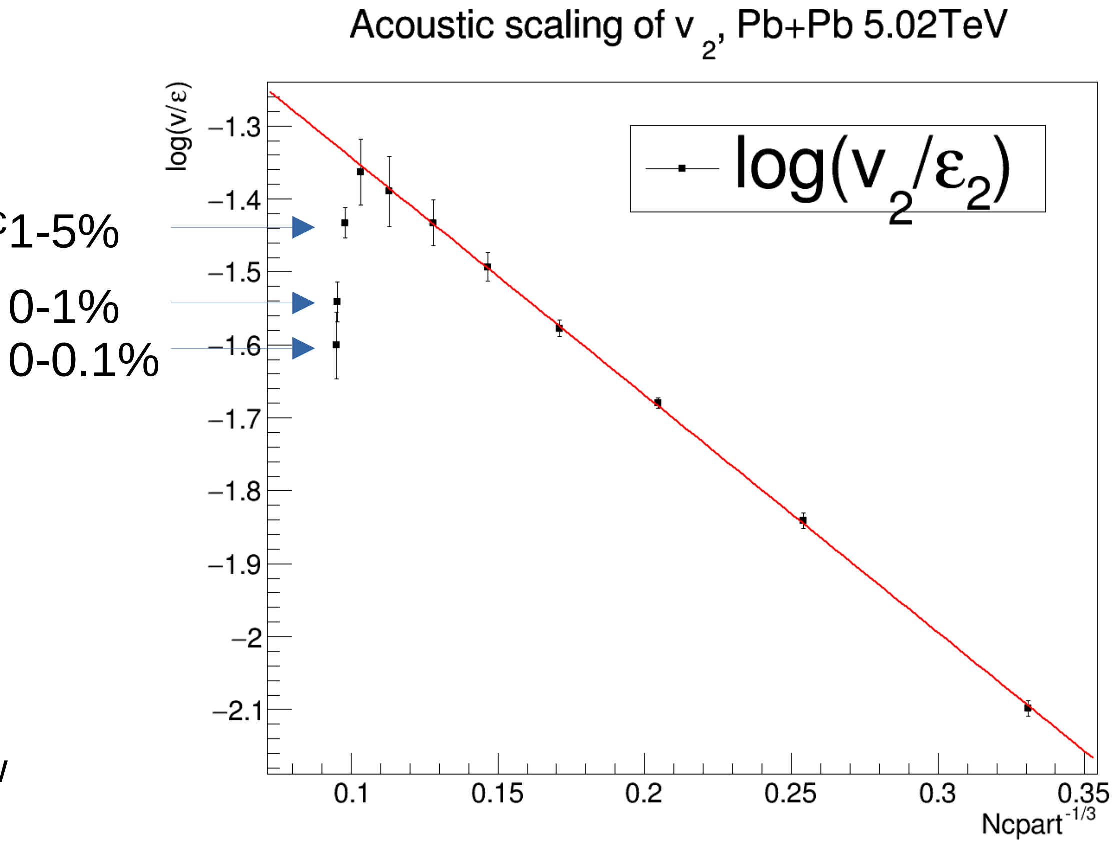
Puzzle: ultracentral v_2 in Pb+Pb

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

$$\log \frac{v_n}{\varepsilon_n} \propto -\frac{\eta}{s}\frac{n^2}{RT} \propto -M^{-1/3} \propto -N_{\mathrm{cpart}}^{-1/3}$$

The drop of v_2/ε_2 suggests an initial stage issue

- Eccentricities are calculated from a quark Glauber code as in the previous work
- We use ATLAS 5.02TeV Pb+Pb flow data (EPJC 78(2018) 997) for p_T=0.5-0.8GeV. It contains v_2 for ultracentral bins 0-0.1% and 0-1%.



EbyE deformation

- For U+U, deformation increases e2 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 β. We follow

  Gilbreth, Alhassid and Bertsch PRC 97, 014315 (2018) and use 2nd order spherical harmonics in the frame where

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

- then only there are only two nonzero components

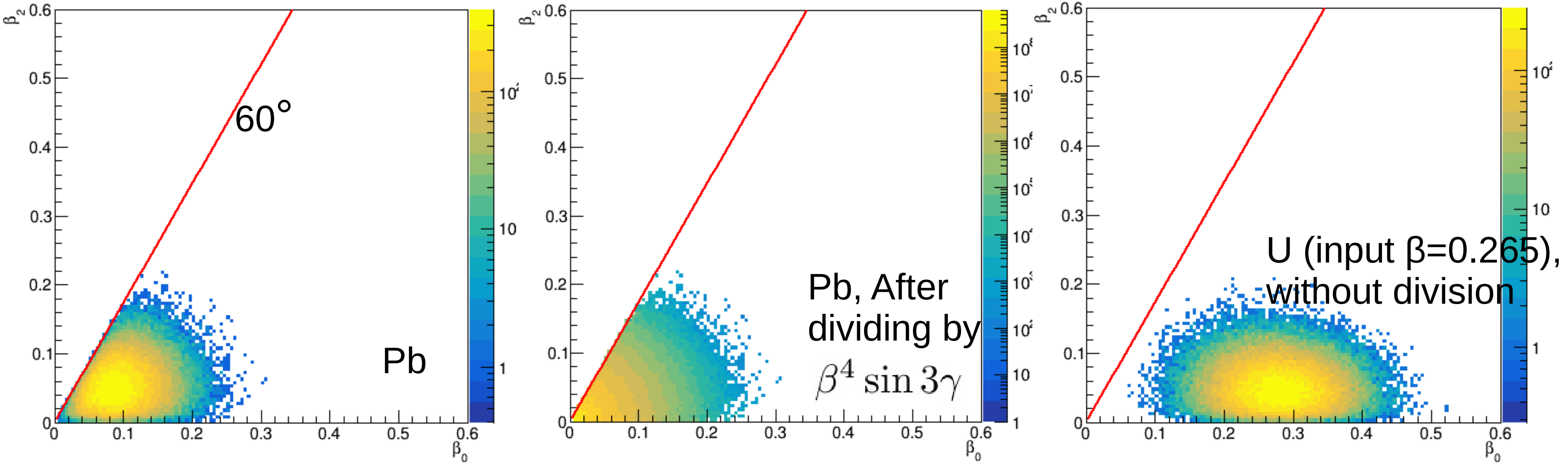
$$r^2 Y_{2,0} = \frac{1}{4}\sqrt{\frac{5}{\pi}}(-x^2 - y^2 + 2z^2)$$

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

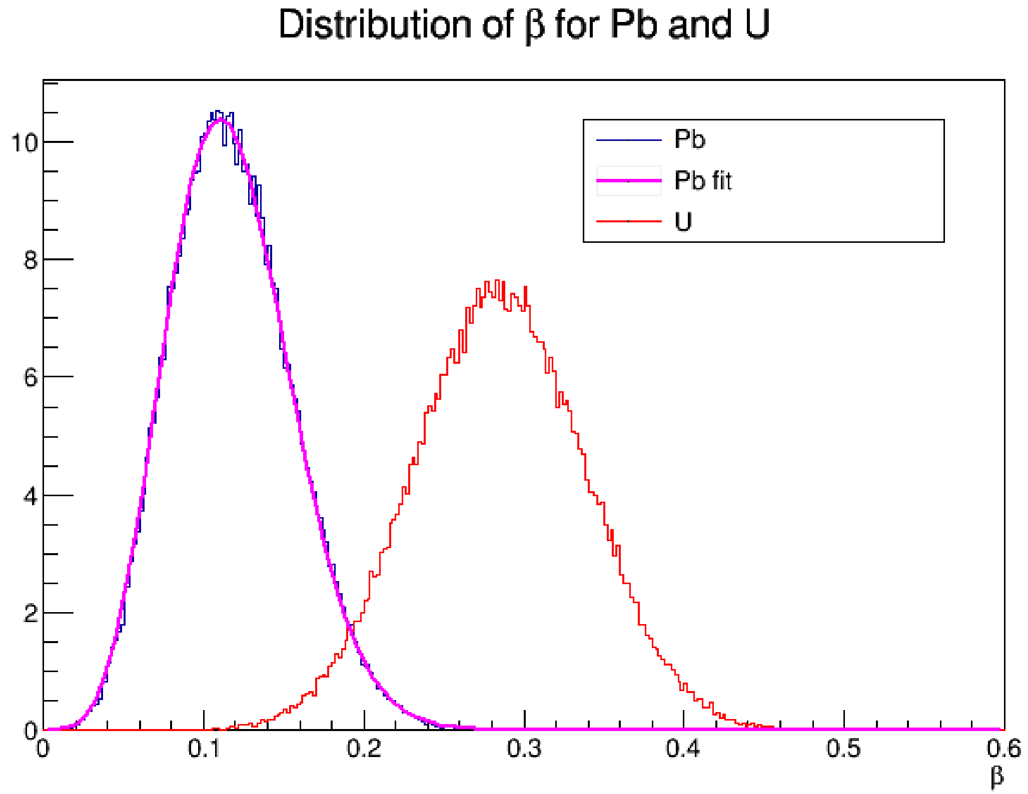
- Define $\beta_i = (4\pi/5) Y_{2,i}$ and take two-norm, $\beta = \sqrt{\sum \beta_i^2}$ Also define $\gamma = \arctan \beta_2/\beta_0$
- If we have a deformed Fermi dist, this gives the same β, in the limit of small β and zero skin depth
- γ=0 for perfectly prolate nucleus, 60° for oblate

EbyE deformation: 2D β distribution

- 2D β distribution for Pb, U
- EbyE Pb can get sizable deformation (rms β 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 β distribution



- Gaussian ansatz

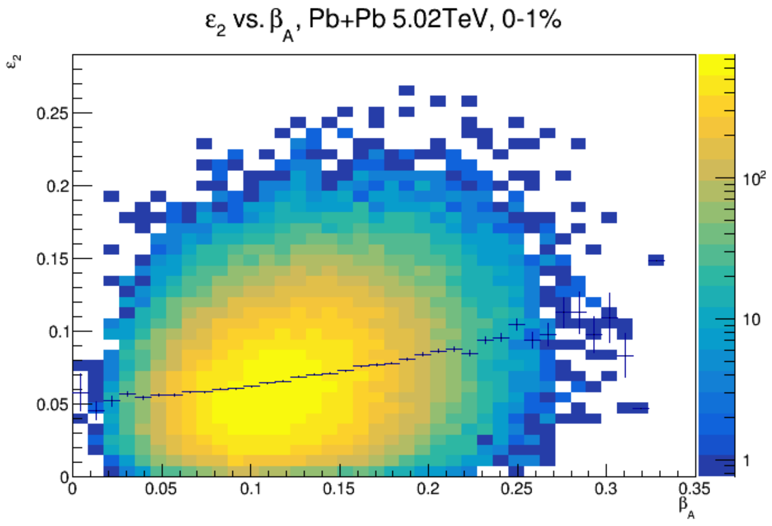
$$\beta^4 \exp(-\beta^2/C)$$

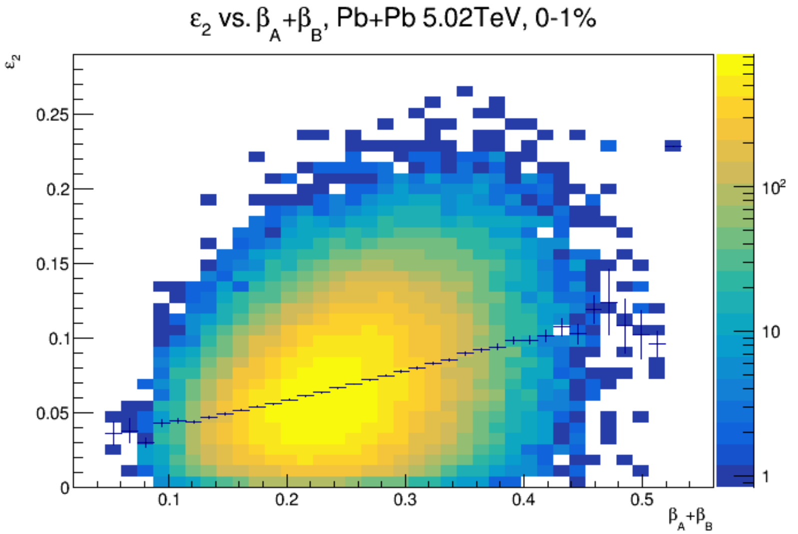
  describes Pb well
- There is significant overlap between Pb and U
- NN correlation, even Pauli exclusion could modify these distributions!

Effect of deformation in central Pb+Pb

- Conditional mean of ε_2 is approximately linear in β_A when selecting on one side, or $\beta_A+\beta_B$ when selecting on the sum

- Dependence is strong for central events

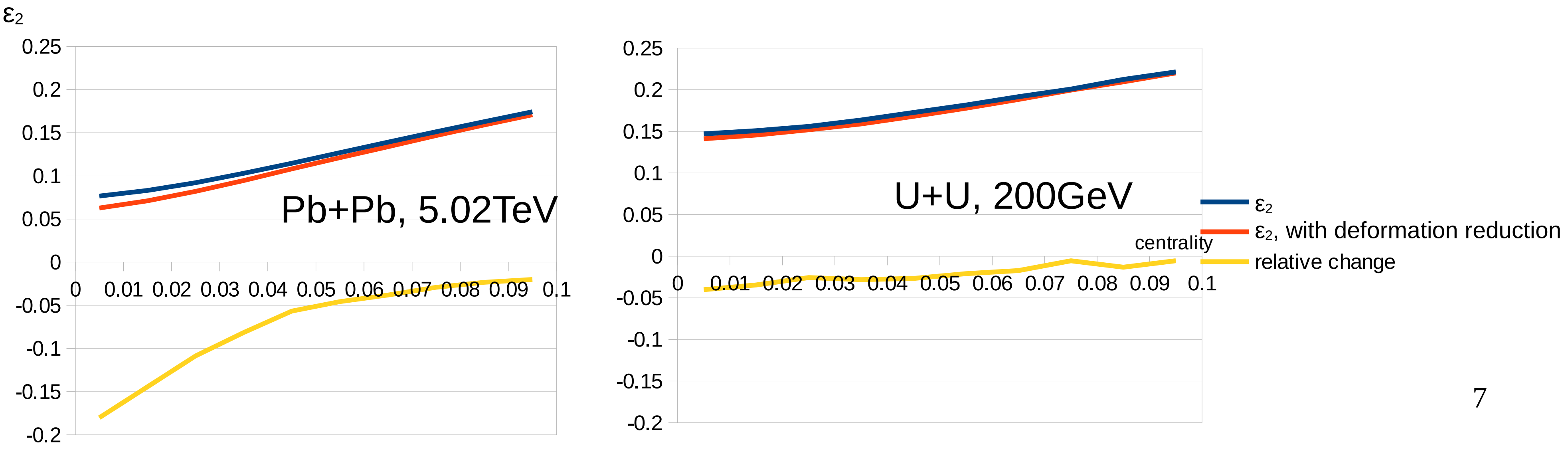




Reduction of deformation fluctuation

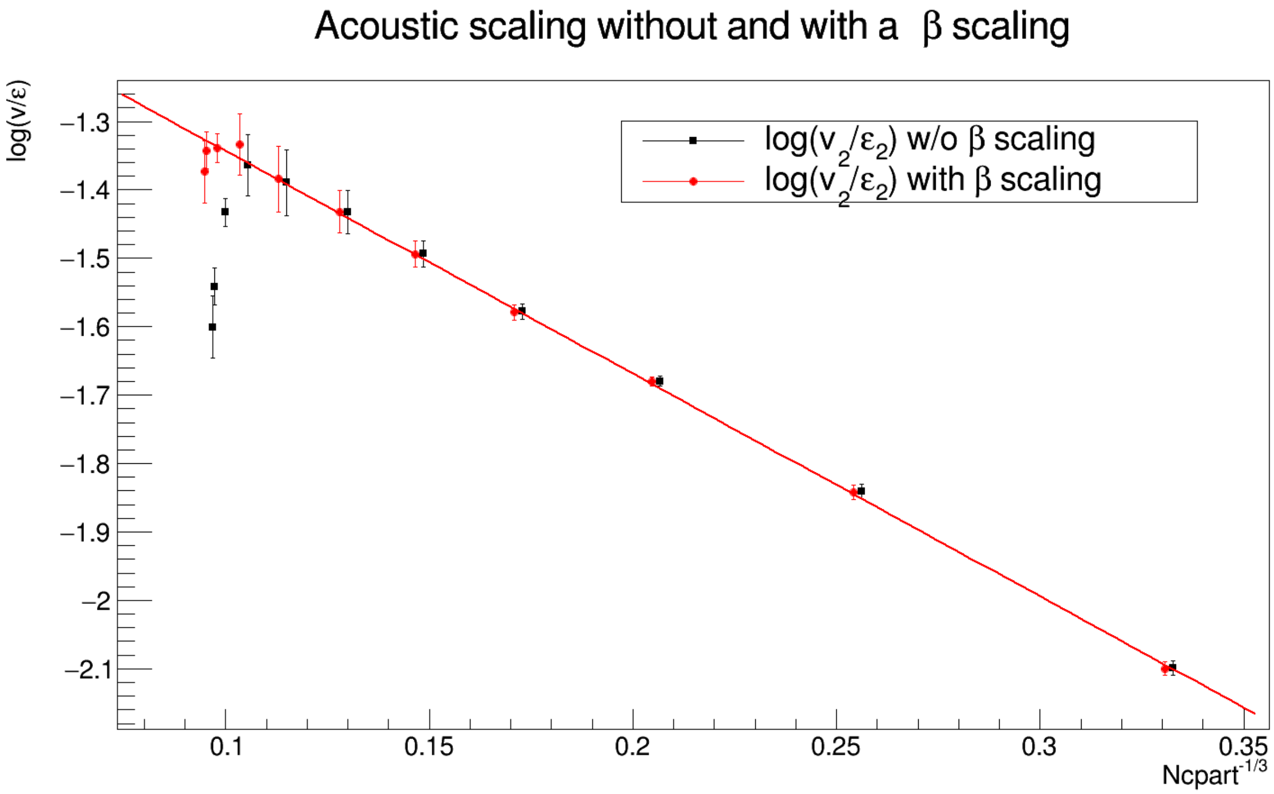
- In the frame $\langle xy\rangle = \langle yz\rangle = \langle zx\rangle = 0$
- Rescale x, y, z independently, so $Y_{2,i}$ is linear combination of original and “smooth” value $Y^*_{2,i}$
  $\tilde{Y}_{2,i} = RY_{2,i} + (1-R)Y^*_{2,i}$
- RMS radius is fixed
- We find with R=0.72 we can achieve scaling in v_2 (next page) for Pb+Pb. ε_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



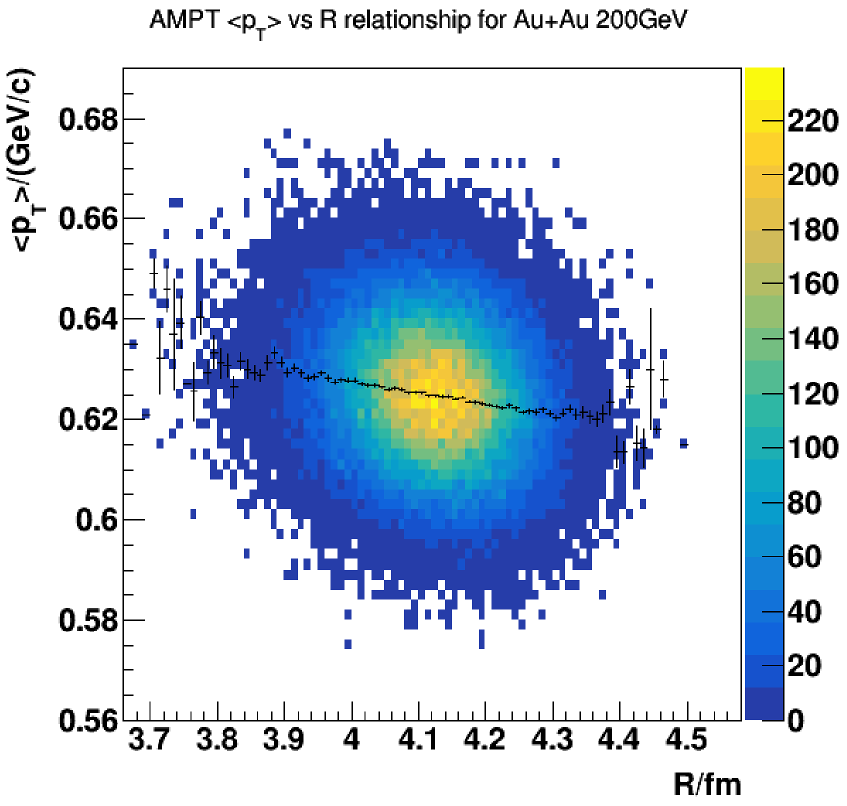
Scaling with deformation reduction

- Scaling now holds for all measured centrality bins



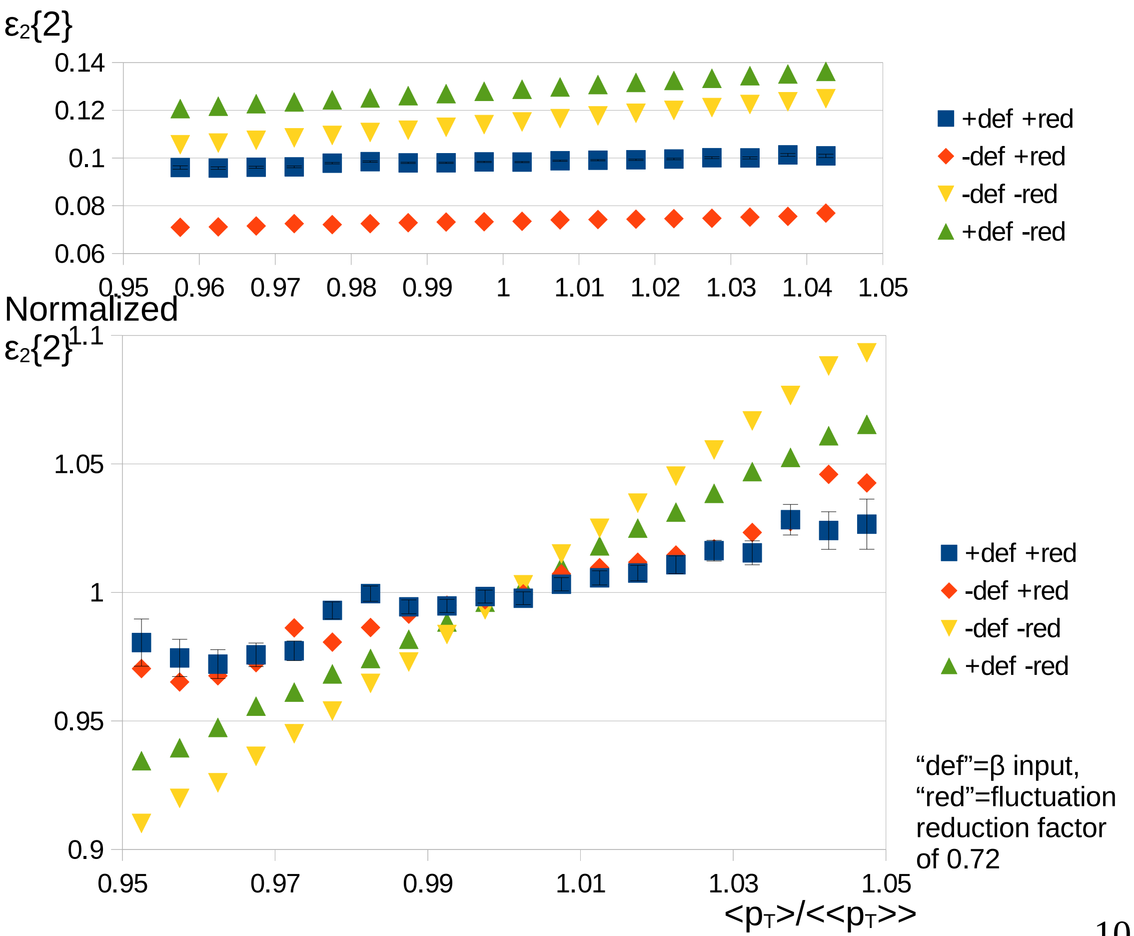
Mean p_T dependence of v_2 in Au+Au

- 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 $\langle p_T \rangle$ =>anti-correlation between v_2 and $\langle p_T \rangle$
- From AMPT we extract $\langle p_T \rangle$ 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.



"def"=β input, "red"=fluctuation reduction factor of 0.72

Summary

- Event by event we calculated the deformation parameters β and γ for each nucleus from the nucleons
- By sampling from the single-body distribution we get a sizable rms β=0.12 for Pb
- Deformation drives ε_2 for spherical systems for central 5%
- Scaling down β allows us to get a set of eccentricities that scales v_2. This suggests sampling from single-body distribution gives an unphysically wide β distribution
- Shape fluctuation could be important for v_2-$\langle p_T \rangle$ relationship, more important than the β input in our Au+Au example