Shrinking the Quark-Gluon Plasma

Matthew D. Sievert
With J. Noronha-Hostler and D. Wertepny
Rutgers University | New Brunswick

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Motivation: Turning Off the QGP in Small Systems

- **Hydrodynamics** successfully describes the bulk low-pT yields in heavy-ion collisions

- Its **basic assumptions should turn off** at lower energies and smaller collision systems

  - Does it really turn off?
  - Or do the signals of the QGP survive under the extreme conditions of a tiny droplet?

- Motivation for a **system size scan** in addition to a beam energy scan:
  - PbPb, XeXe, ArAr, OO

S.H. Lim et al., Phys. Rev. ***C99*** *(2019)*

Hydrodynamics ≈ Linear Response

$$\mathcal{E}_n \equiv -\frac{\langle \int r^n e^{in\phi} s(r,\phi) r dr d\phi \rangle}{\langle \int r^n s(r,\phi) r dr d\phi \rangle}$$

$$\xrightarrow{V_n \approx \kappa_n \mathcal{E}_n}$$

$$V_n = \frac{\left\langle \int d^2p\, dy\, e^{in\phi} \frac{dN_1}{d^2p\, dy} \right\rangle}{\langle N_{\text{tot}} \rangle}$$

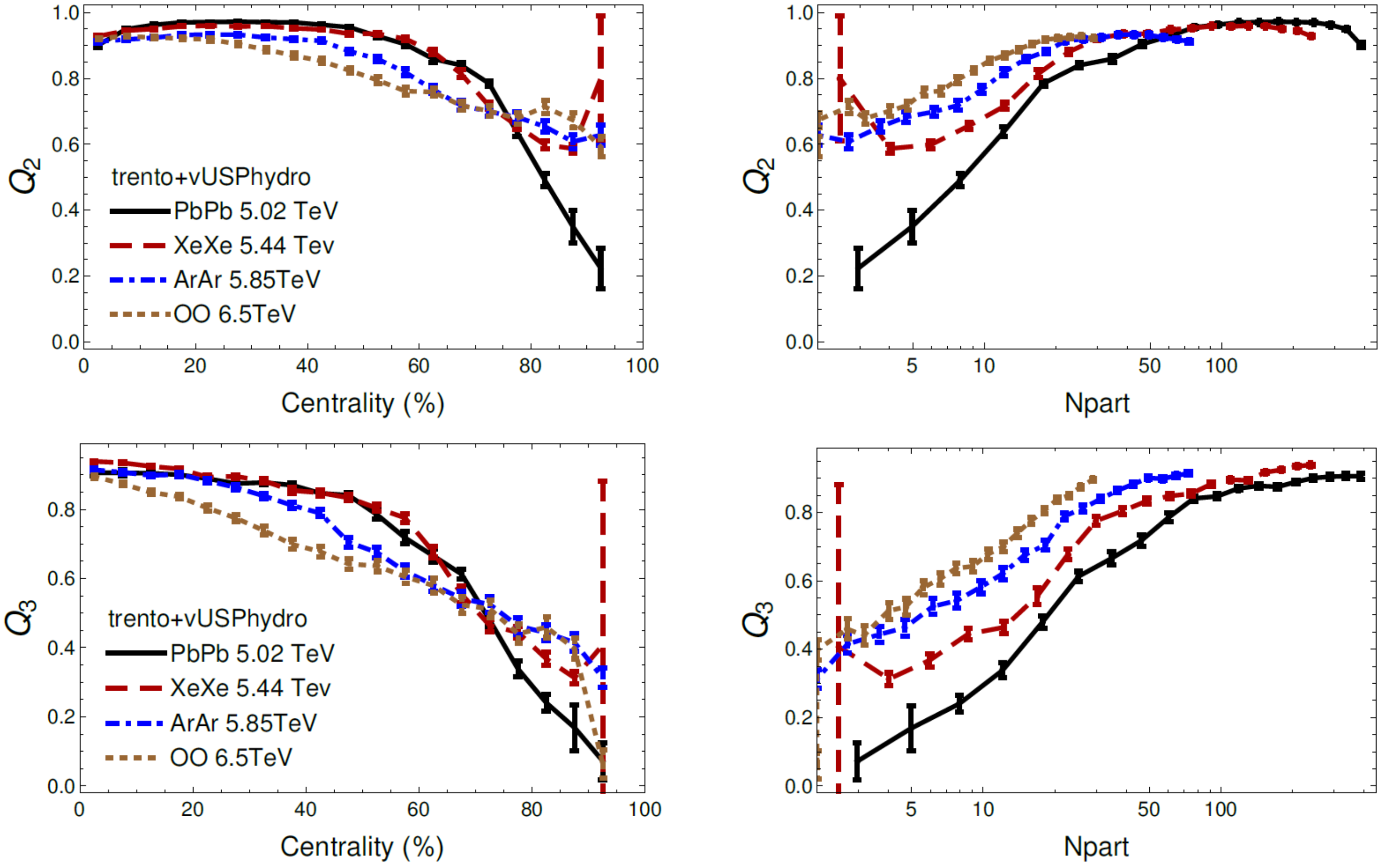
- Because of **perfect fluidity**, the QGP is **"Nature's Fourier Transform"**

T. Dore, Rutgers University

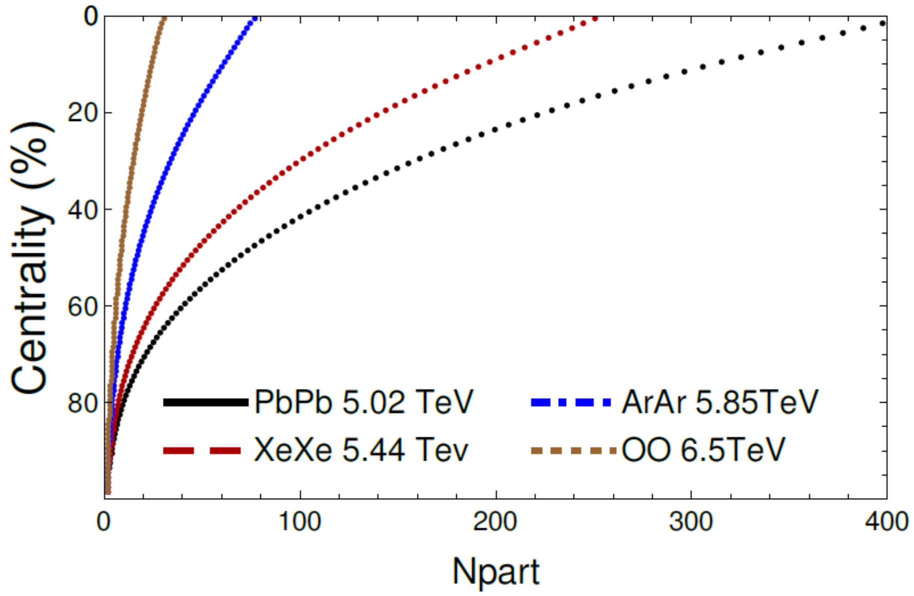
- Quantified by the **Pearson Coefficient**

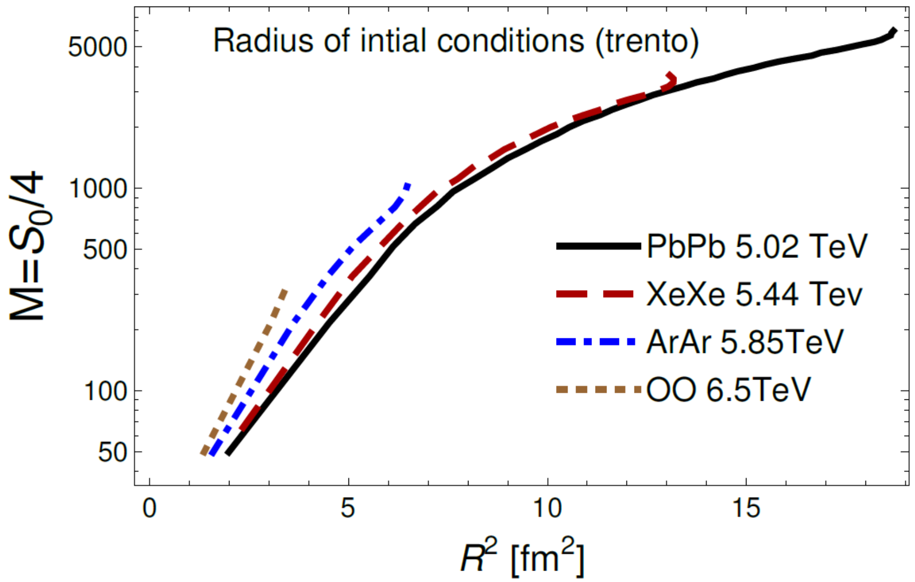
$$Q_n \equiv \frac{\langle V_n \mathcal{E}_n^* \rangle}{\sqrt{\langle |V_n|^2 \rangle} \sqrt{\langle |\mathcal{E}_n|^2 \rangle}} = \frac{\langle v_n \varepsilon_n \cos\left(n\left[\psi_n - \phi_n\right]\right)\rangle}{\sqrt{\langle |\varepsilon_n|^2 \rangle \langle |v_n|^2 \rangle}}$$

- **Linear response works well** in **central / mid-central** collisions across system size
- The visible trends depend significantly on **what is held fixed: centrality or Npart**
- For a **given Npart, smaller systems** are more central and have **better linear response**



Not All Small Droplets Are Created Equal

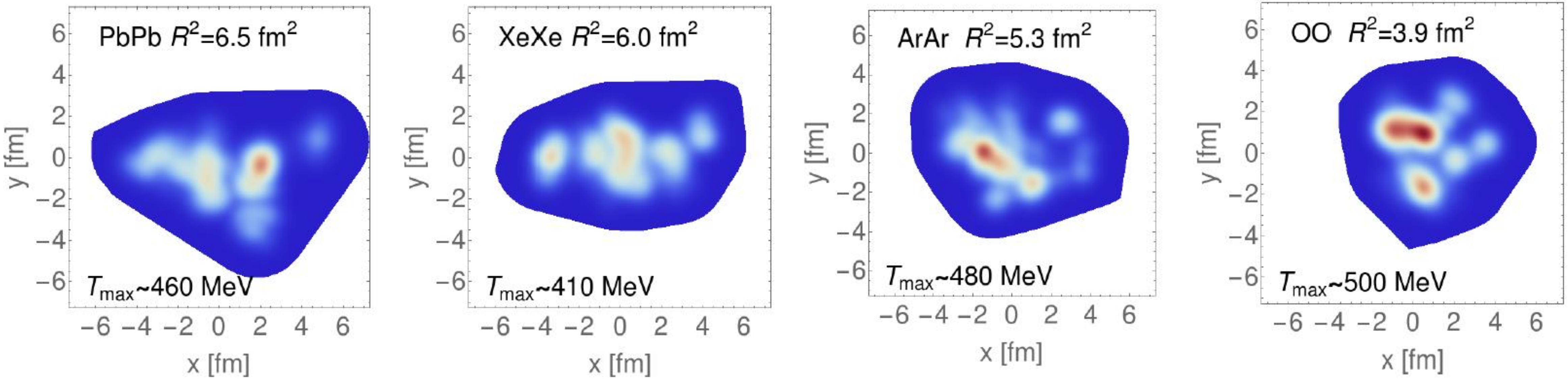




- **A "small droplet" in PbPb is very different from one in OO**
  - **More peripheral** in PbPb, more central in OO
  - **More elliptical** in PbPb, more round in OO
  - **Lower temperature** in PbPb, higher temperature in OO

Not All Small Droplets Are Created Equal

For fixed multiplicity



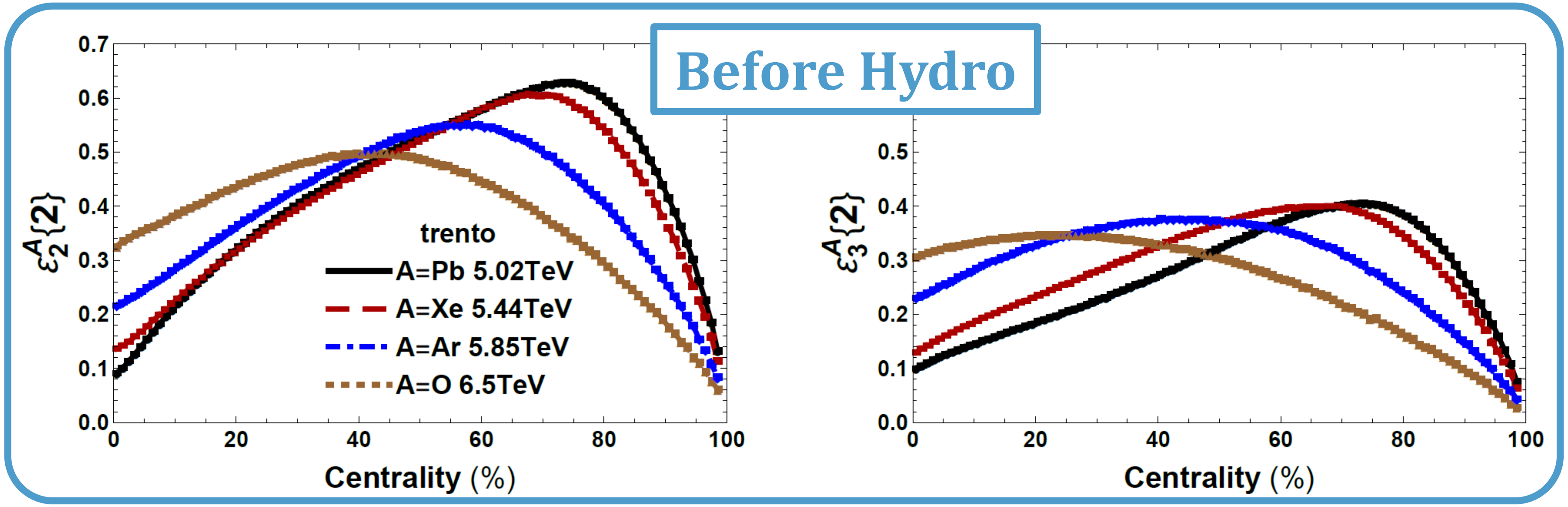
Larger System ←

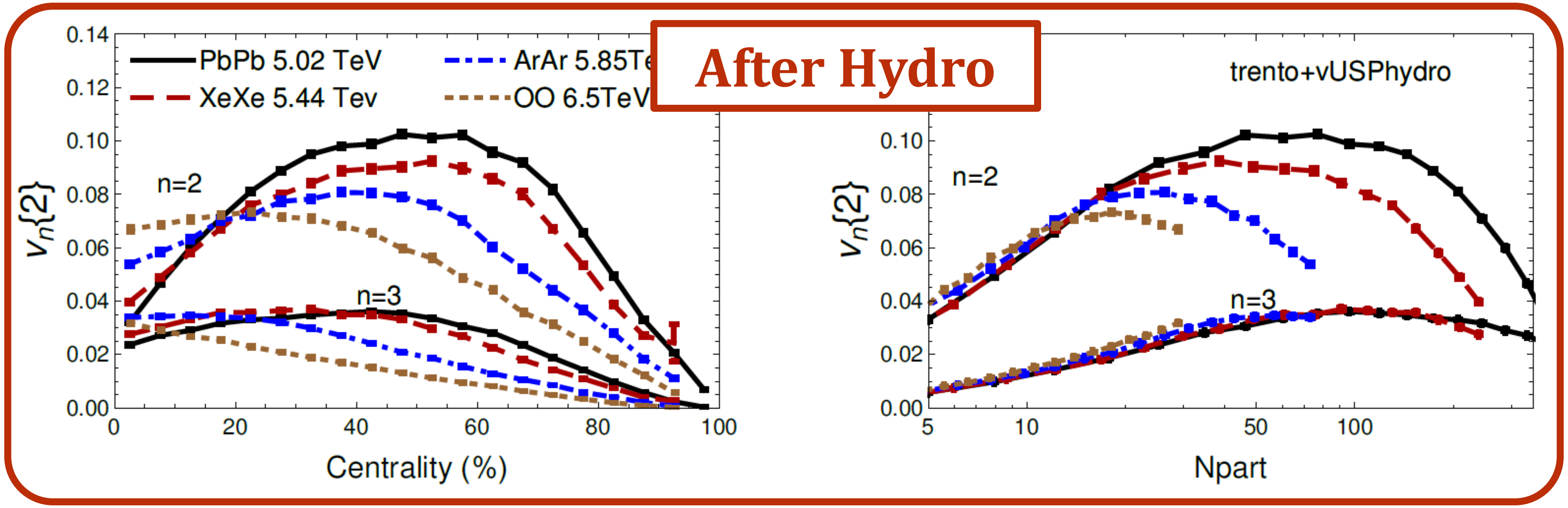
More Elliptical ←

Higher Temperature →

Initial Eccentricities and Final Flow Harmonics

- **System size hierarchy** exhibits a **crossing** in mid-central collisions
- **Linear response** a good qualitative predictor of vn
- **Npart dependence** better isolates system size effects





Cumulant Ratios: Measure of Fluctuations

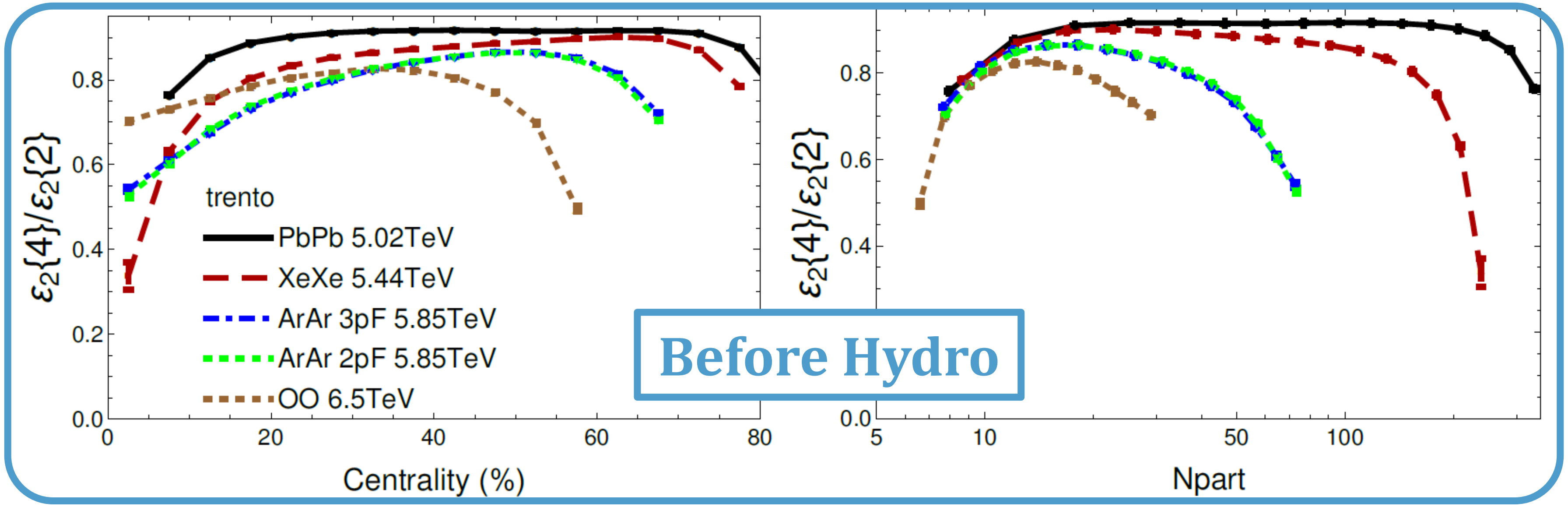
$$(v_n\{4\})^4 \overset{flow}{=} 2\langle v_n^2\rangle^2 - \langle v_n^4\rangle$$
$$= (v_n\{2\})^4 - \mathrm{Var}\left(v_n^2\right)$$

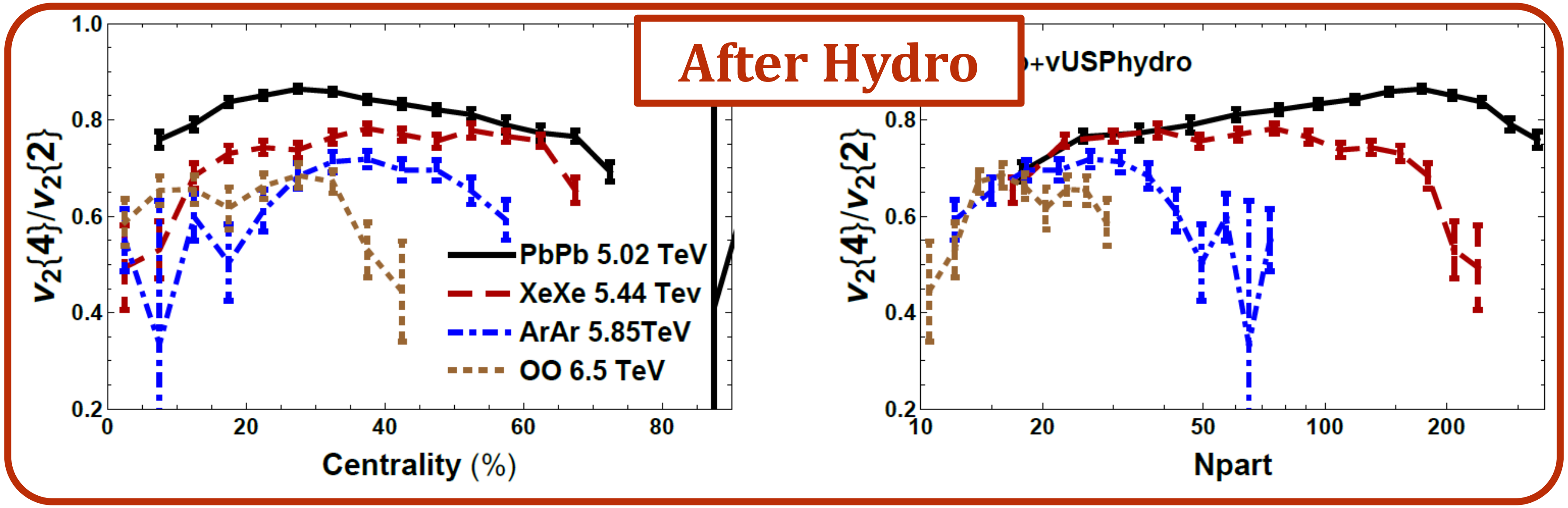
- If $\frac{v_n\{4\}}{v_n\{2\}} \approx 1$ then fluctuations are **small**
- If $\frac{v_n\{4\}}{v_n\{2\}} \ll 1$ then fluctuations are **large**

Initial state analog $\varepsilon_n\{m\}$ defined with averages of ε_n

Cumulant Ratios: Measure of Fluctuations

- **Smaller systems** tend to generate **more fluctuations**
- **Npart dependence** provides a better comparison than centrality
- **Linear response** is a reasonable estimate of fluctuations





Symmetric Cumulants

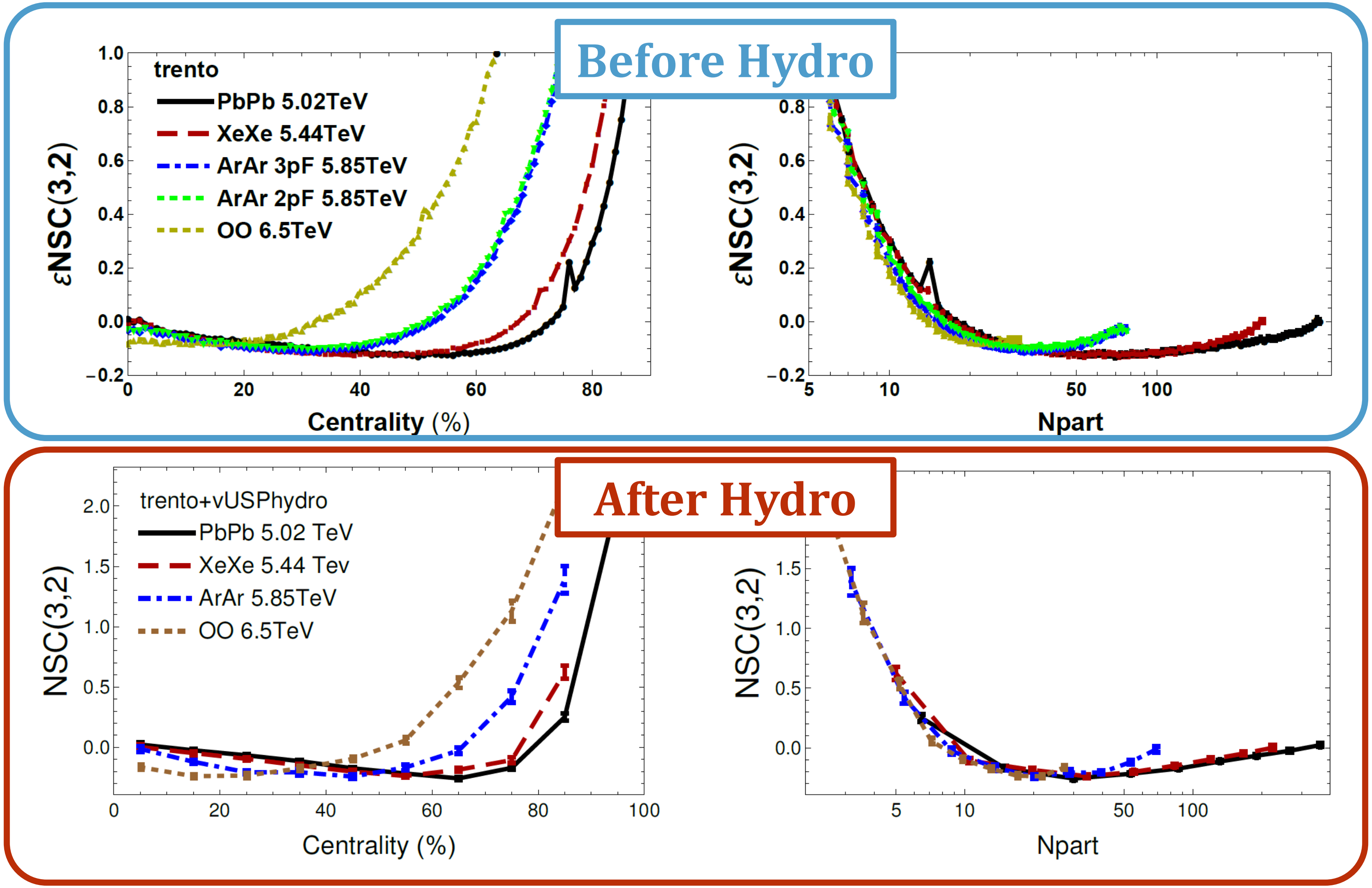
$$NSC(m,n) = \frac{\langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

- If $NSC(3,2) > 0$ then v_2 and v_3 are **positively correlated**
- If $NSC(3,2) < 0$ then v_2 and v_3 are **negatively correlated**
- If $NSC(3,2) = 0$ then v_2 and v_3 are **uncorrelated**

Initial state analog $\varepsilon NSC\{m\}$ defined with averages of ε_n

Symmetric Cumulants

- **Linear response** is a good qualitative predictor of correlations
- In very **central events**, NSC(3,2) is controlled by **centrality** (impact parameter)
- In **peripheral events**, NSC(3,2) is controlled by **small-number fluctuations**



Motivation: Using Deformed Nuclei as Model-Killers

- Very **central collisions** are **sensitive to deformation** of nuclei and other nuclear structure parameters

G. Giacalone et al., Phys. Rev. ***C97*** *(2018)*

- The **multiplicity dependence** of ultracentral collisions of deformed nuclei can be used to **tune collision geometries**

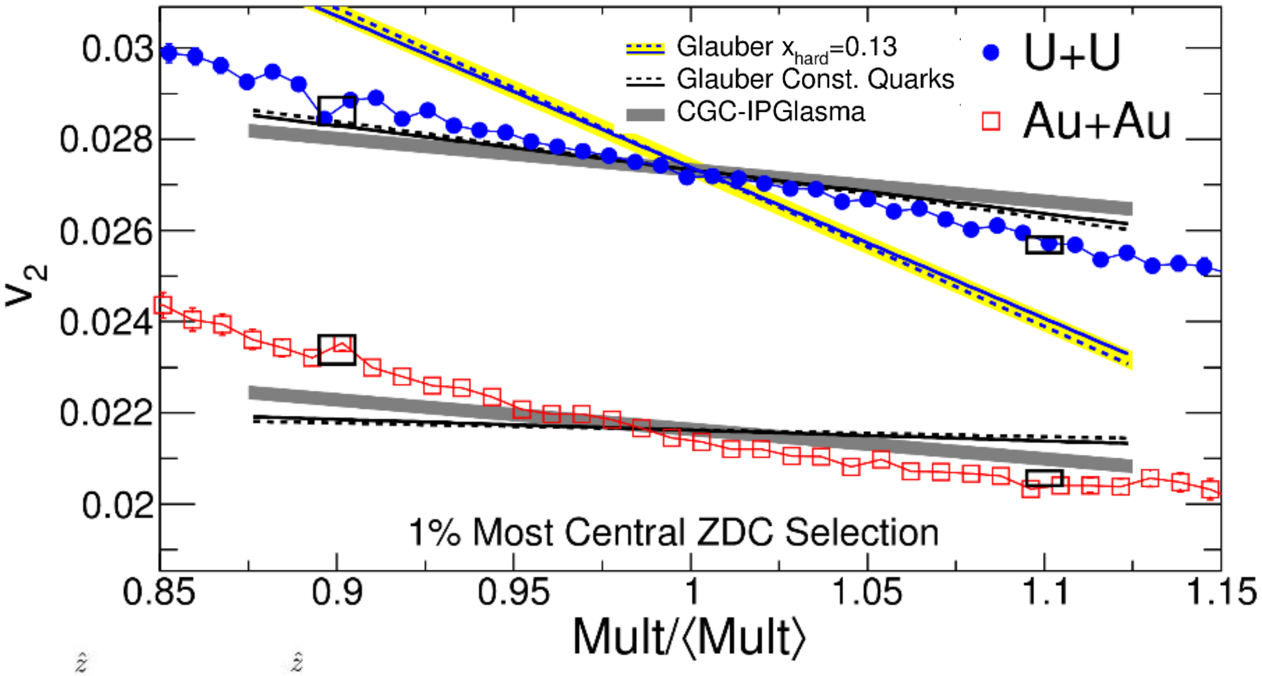
- Different models lead to **different multiplicity dependence**, which **couple to nuclear deformations differently**

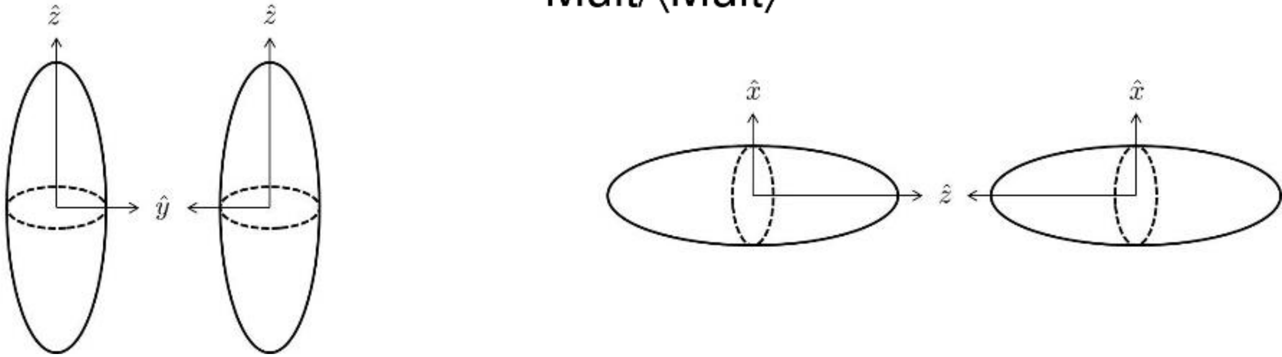
- Motivates a **deformed system size scan**
  - ➢ UU, ^{9}Be^{9}Be / ^{9}BeAu, ^{3}He^{3}He / ^{3}HeAu, dAu

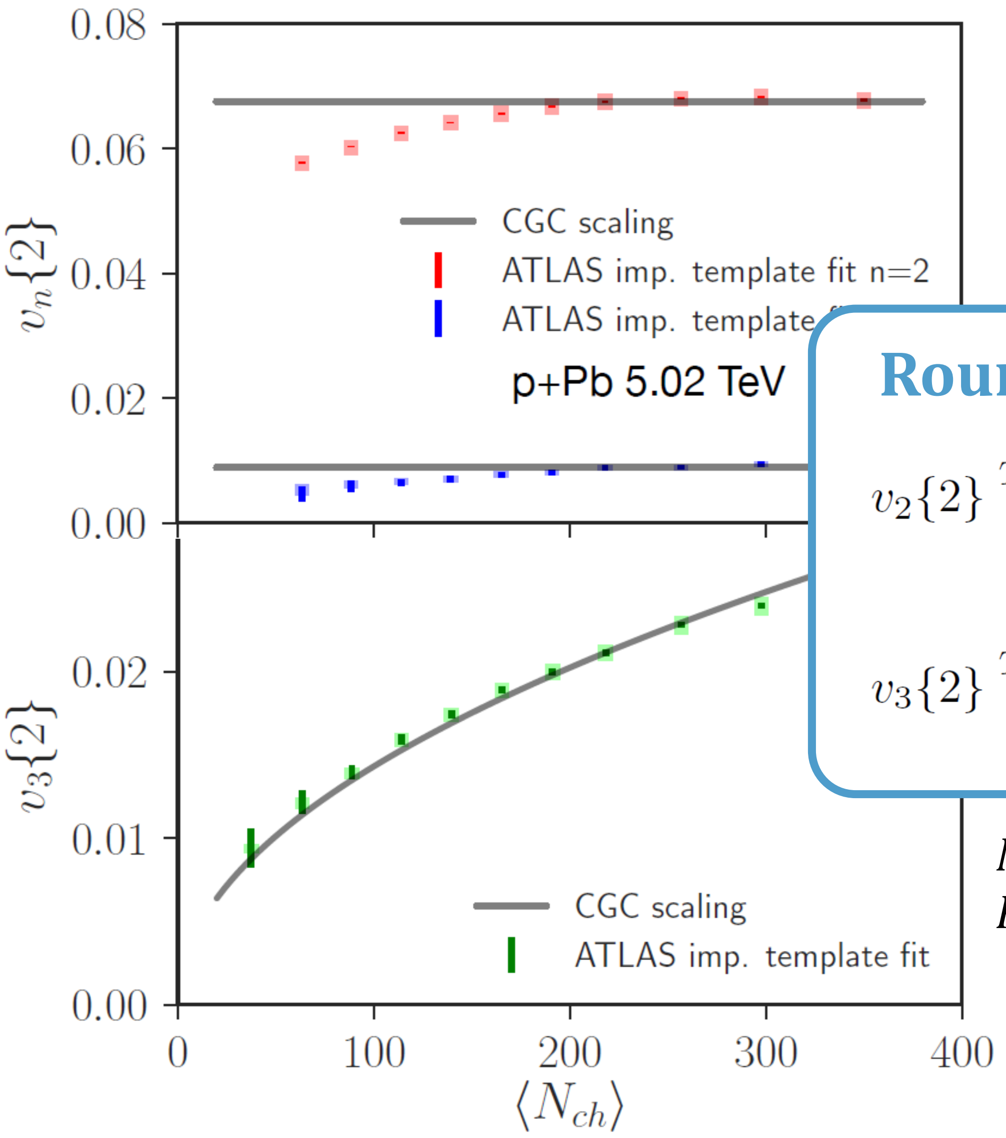
- STAR used a **novel centrality binning technique** for ultracentral collisions to select on **collision geometry**
- Used **ZDC cuts** to select on events with the **1% fewest spectators**
- Further **sub-binning by produced multiplicity** is sensitive to overall collision geometry

➢ Sensitive to the presence of **nucleonic substructure??**

L. Adamczyk et al., Phys. Rev. Lett. ***115*** *(2015)*







Round Nuclei

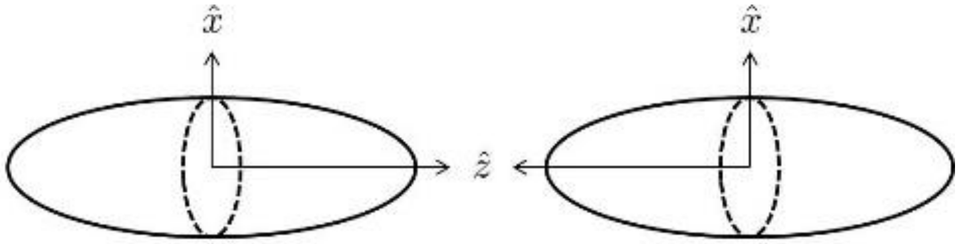
$$v_2\{2\} \overset{T_A T_B}{\sim} \text{const}$$

$$v_3\{2\} \overset{T_A T_B}{\sim} \sqrt{\frac{dN}{d^2x}}$$

M. Mace et al., Phys. Lett. ***B788*** *(2019)*

$$\frac{[v_2\{2\}]_{\text{tip}}}{[v_2\{2\}]_{\text{side}}} = \frac{1}{\lambda} > 1$$

Deformed Nuclei

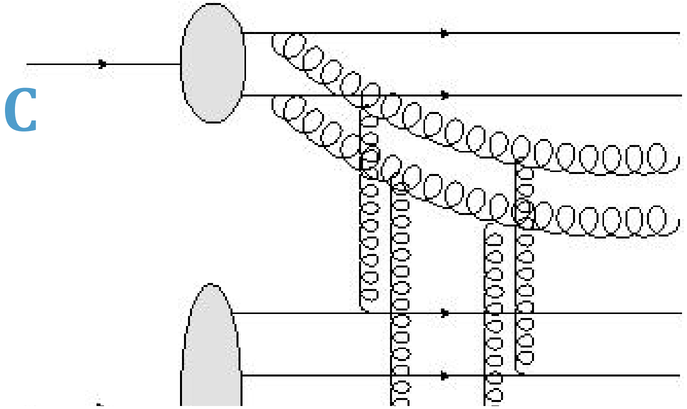


$$\rho(\vec{r}) = \rho_0 \exp\left[-\frac{x^2+y^2}{R^2} - \lambda^2 \frac{z^2}{R^2}\right]$$

Y. Kovchegov and D. Wertepny, Nucl. Phys. ***A925*** *(2014)*

Apples to Apples: CGC Correlations vs. Hydrodynamics

- In the "dilute / dilute" limit, the **gluon correlations in the CGC** can be expressed in terms of moments of the density profiles



LO: $v_2\{2\} \sim \frac{1}{N^2} \int T_A^2 T_B^2$

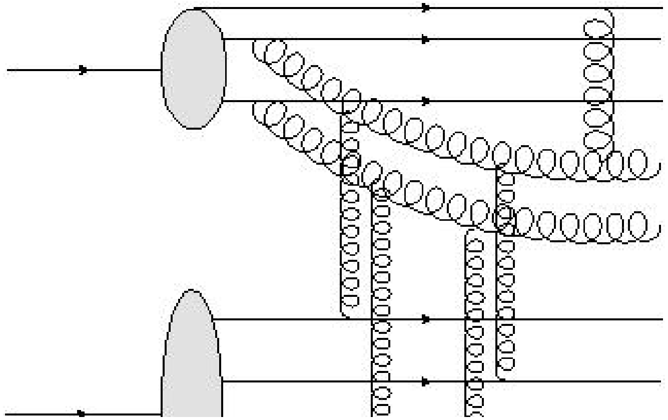
$$\frac{v_n^i\{2\}}{v_n\{2\}} = \sqrt{\frac{\left\langle N_{\text{tot}}^2 \right\rangle_{0-1\%}}{\left\langle N_{\text{tot}}^2 \right\rangle_i} \frac{\left\langle \mathcal{I}_{\nu_n} \right\rangle_i}{\left\langle \mathcal{I}_{\nu_n} \right\rangle_{0-1\%}}}$$

$$\mathcal{I}_\alpha \equiv \int d^2 x_\perp T_A^\alpha(\vec{x}_\perp) T_B^\alpha(\vec{x}_\perp)$$

$$\nu_n = \begin{cases} 2 & \text{if n = even} \\ 3 & \text{if n = odd} \end{cases}$$

$N_{tot} \propto T_A T_B$ (CGC)

$N_{tot} \propto \sqrt{T_A T_B}$ (Trento p=0)



NLO: $v_3\{2\} \sim \frac{1}{N^2} \int T_A^3 T_B^3$

Deformed Nuclei can Discriminate Models

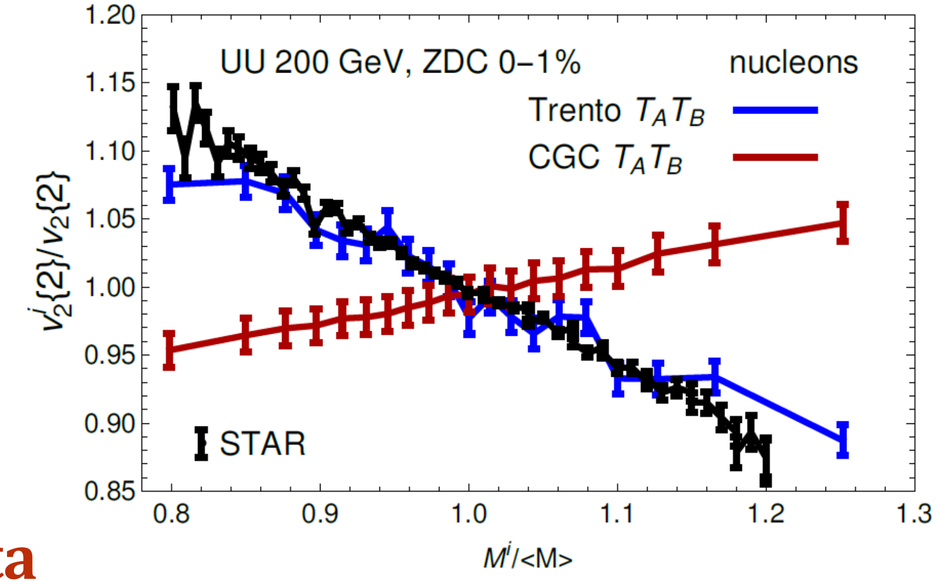
Using Trento + linear response to estimate final-state hydrodynamics

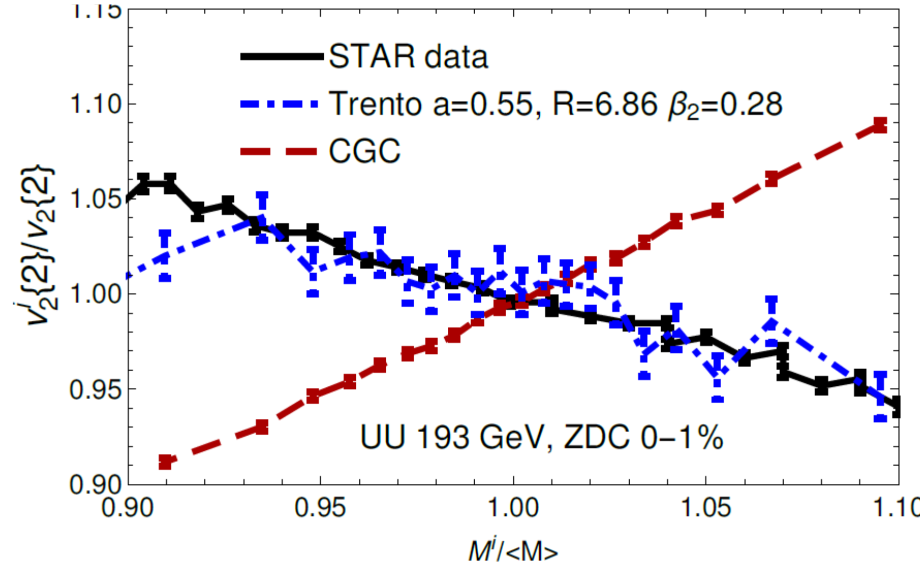
- As expected, CGC predicts **opposite multiplicity dependence** from hydro and STAR

➢ An initial-state only picture **cannot describe the data**

- Hydro is largely insensitive to choice of $T_A T_B$ vs $\sqrt{T_A T_B}$ scaling

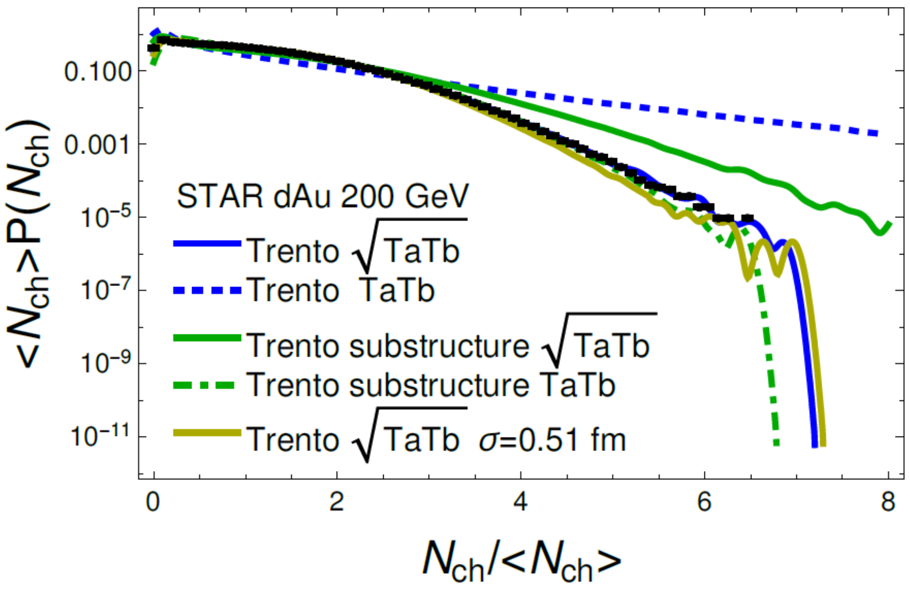
➢ CGC slope flattened significantly by linear $T_A T_B$ scaling

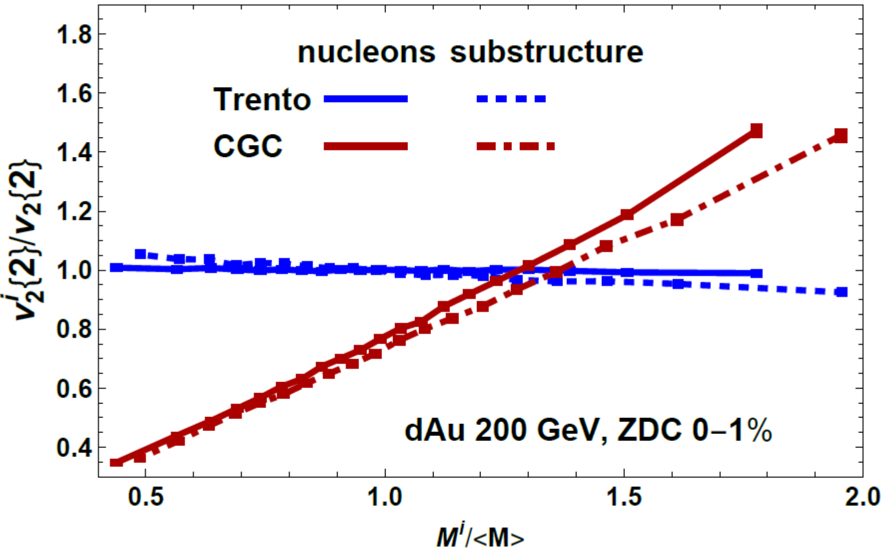


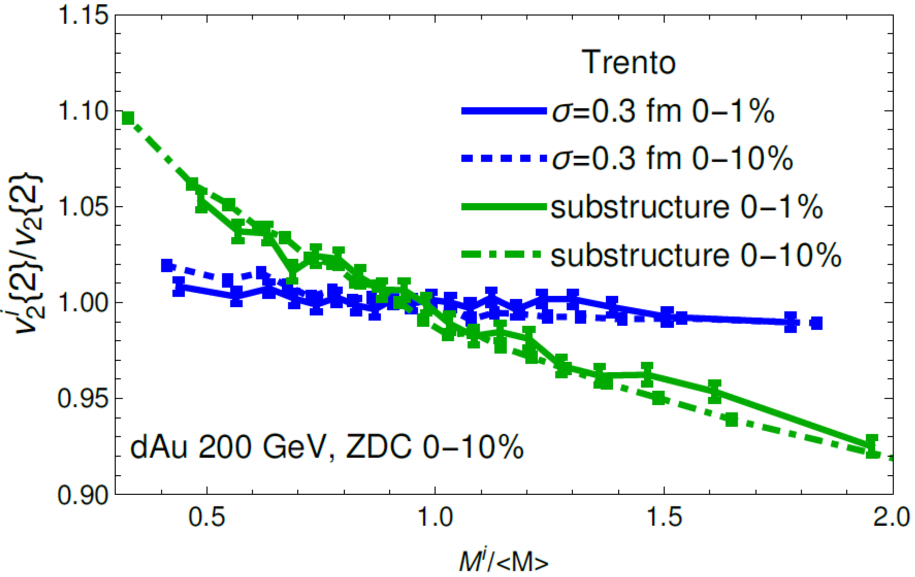


Small Deformed Systems: dAu

- Same qualitative trends remain in dAu
- Can study resolving power of **nucleonic substructure** in Trento 2.0



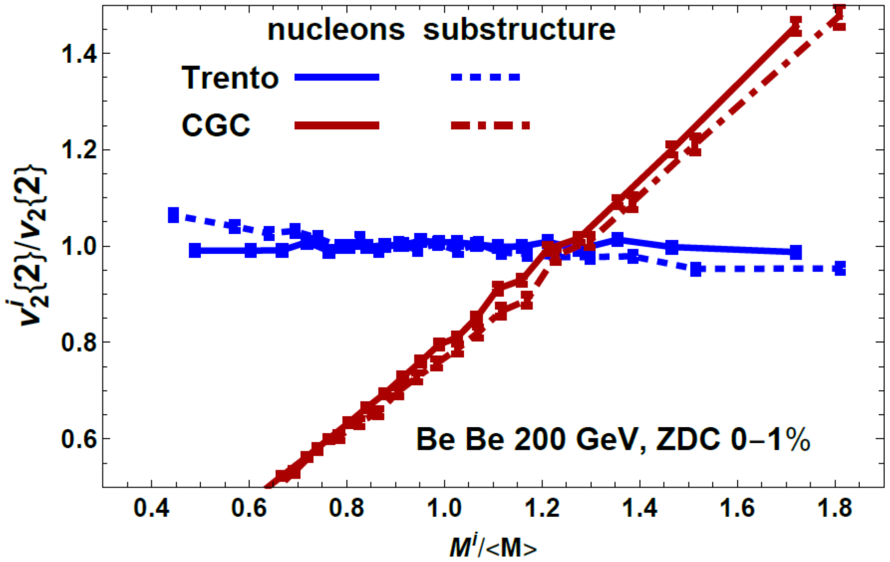


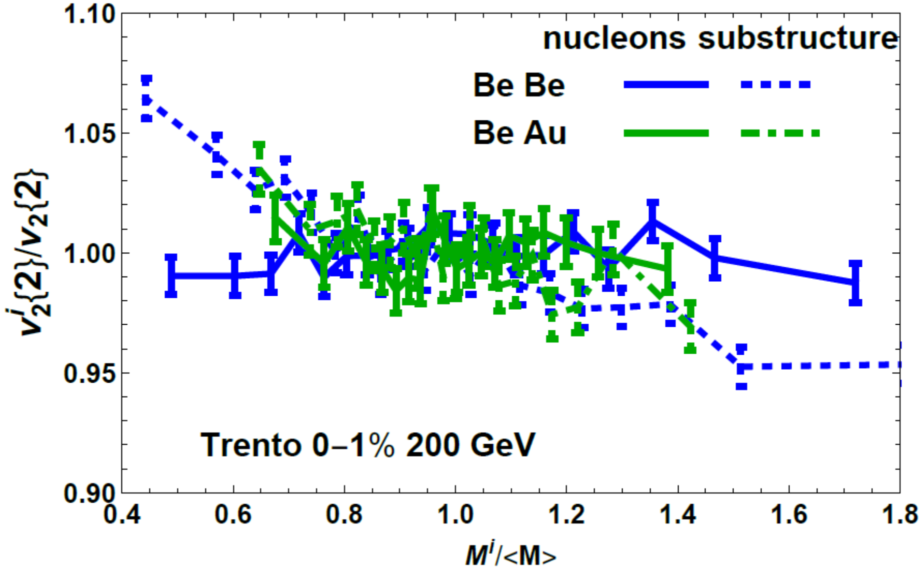


- Small **O(5%) sensitivity** to substructure (n=6)
- ➢ **Enhanced to O(10%)** sensitivity in 0-10% centrality
- $\sqrt{T_A T_B}$ **scaling** gets multiplicity distribution right

Small Deformed Systems: ^{9}Be^{9}Be and ^{9}BeAu

- ^{9}Be is a **highly deformed ion**: its quadrupole moment is more than **twice as large as uranium**
- Intermediate collision systems with large deformation: ^{9}Be ^{9}Be and ^{9}BeAu collisions
- Qualitative CGC vs hydro distinction persists
- Sensitive to nucleonic substructure at O(5%)
- **^{9}Be ^{9}Be collisions are better** than ^{9}BeAu collisions for identifying **sub-nucleonic fluctuations**





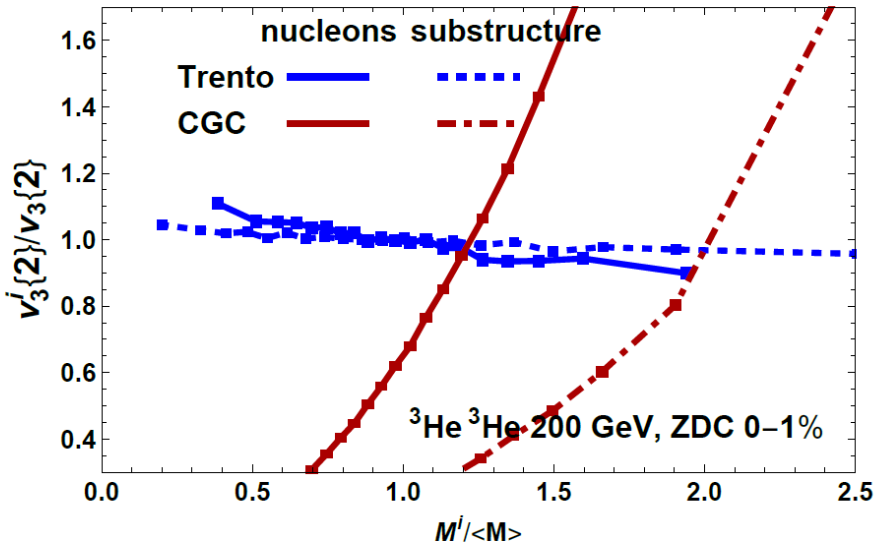
Small Deformed Systems: ^{3}He^{3}He and ^{3}HeAu

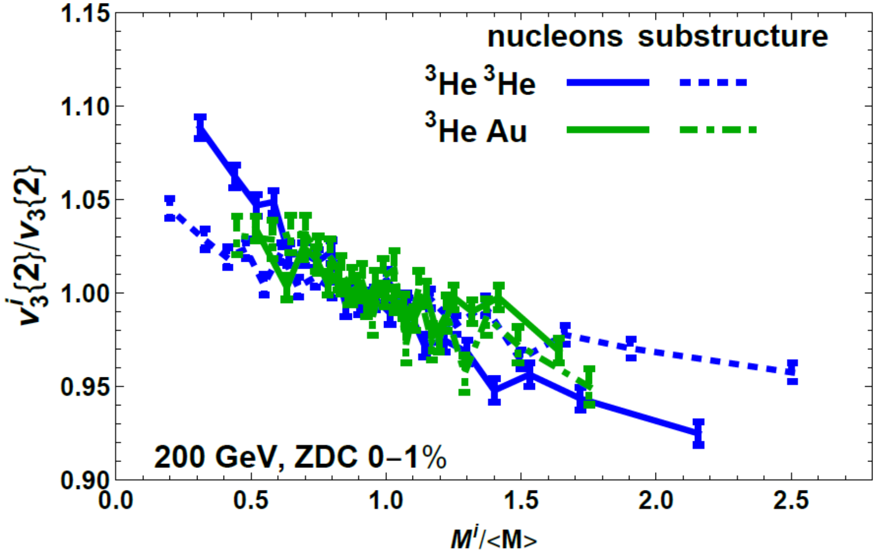
- **^{3}He possesses an innate triangularity** at the level of nucleons – more direct probe of v_3

- CGC multiplicity dependence is steeper than for v_2 due to entering at NLO in dilute / dense

- Still sensitive at **O(5%) to nucleonic substructure**, but this time due to a **flattening** of triangularity when turning on substructure

- **^{3}He ^{3}He collisions are better** than ^{3}He Au collisions for identifying **sub-nucleonic fluctuations**





Conclusions

- Drops of QGP created from smaller ions are **rounder** and **hotter** than comparable-multiplicity drops created from heavier ions.
- **Linear response** to initial eccentricities is a **good estimator for small collision systems**, with linear + cubic response improving quantitative control.
- Some features controlled by **universal small-number statistics in peripheral collisions**, others controlled by **impact parameter in more central collisions**.
- Collisions of **small, deformed systems** can **discriminate between models**, including **initial state CGC vs final state flow**, as well as nucleon vs **subnucleonic structure**.