Attributions of fluctuations in azimuthal anisotropies

by

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ANISOTROPY IN LARGE AND SMALL SYSTEMS

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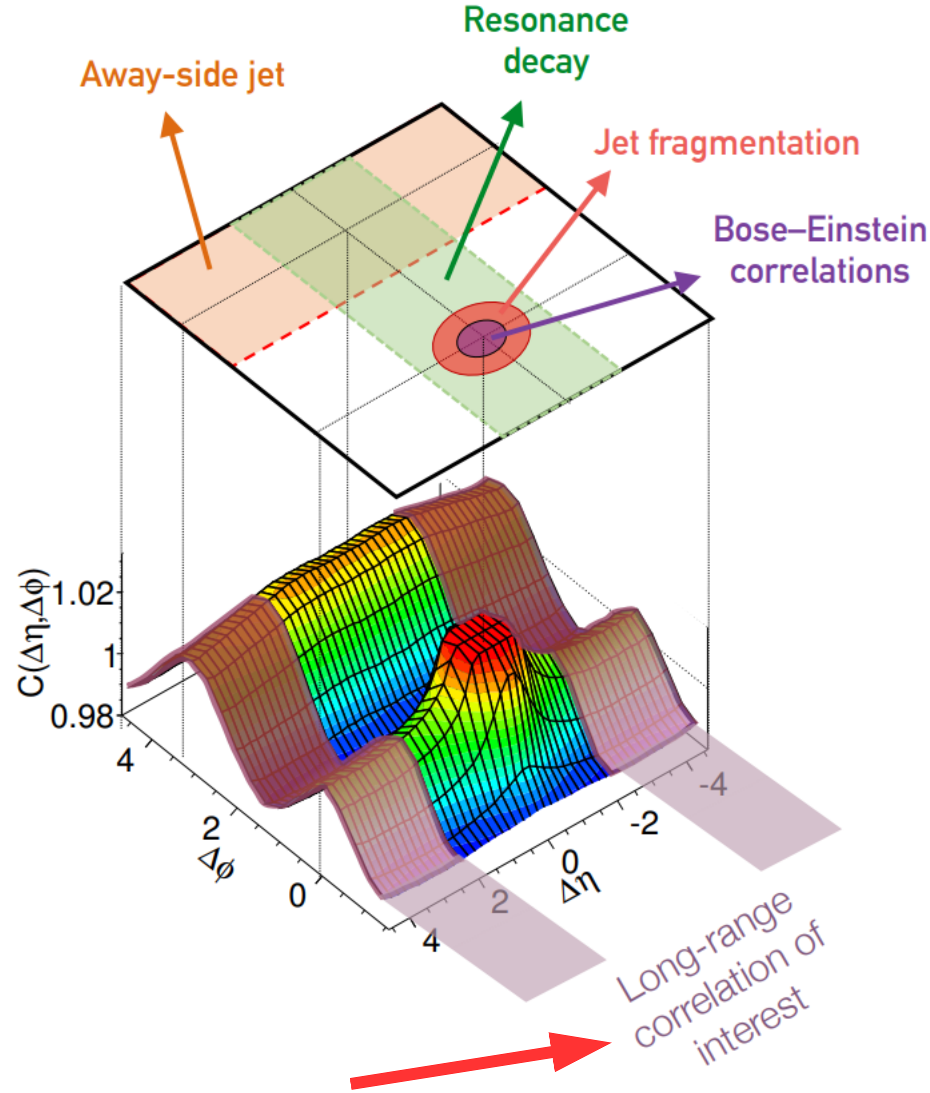
FLUCTUATIONS ON DIFFERENT SCALES



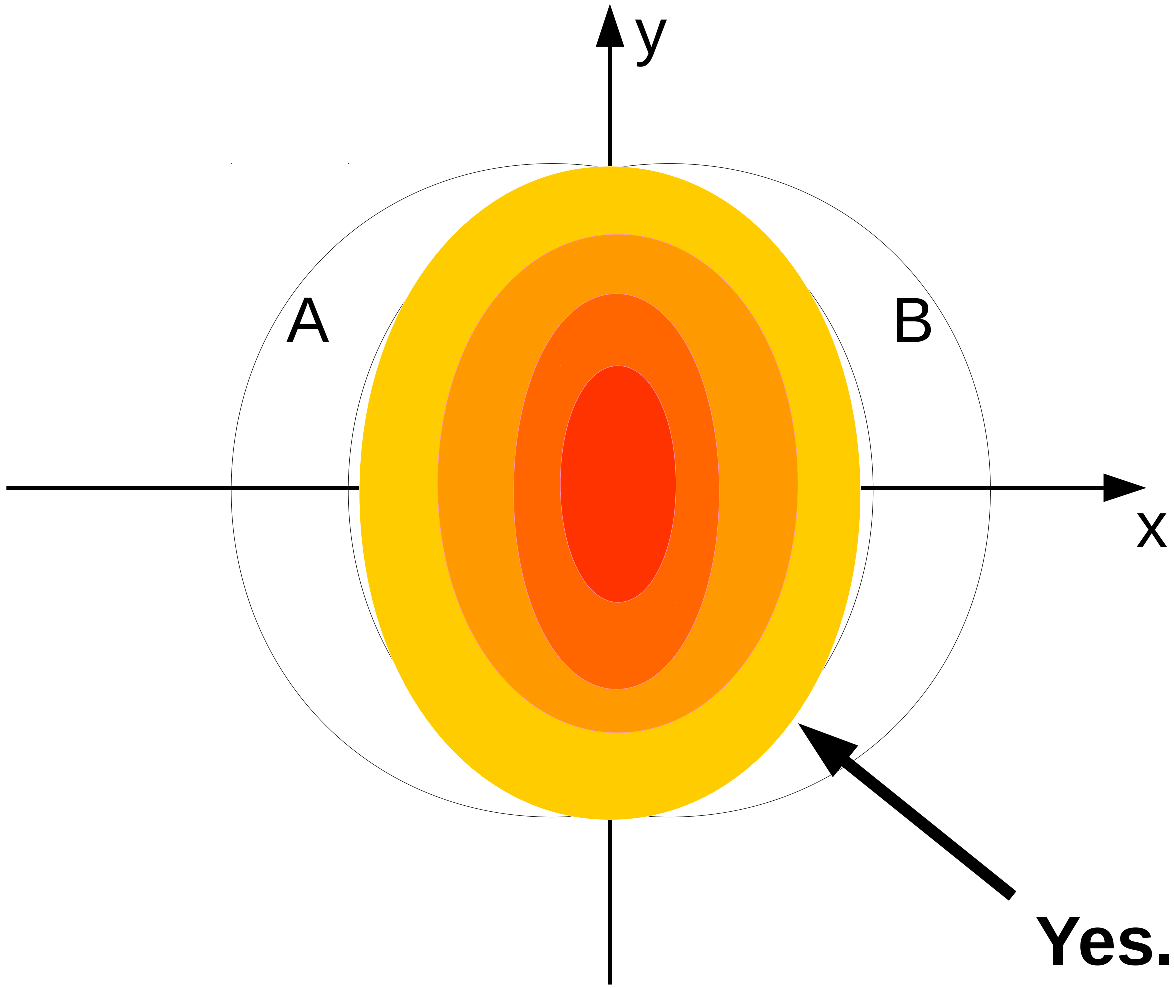
<u>IN THIS TALK:</u>

- Anisotropy is a collective long-range phenomenon.

- Fluctuations are dynamical (driven by initial-state physics).

- **Focus on questions driven by new data/developments.**

THE EXOTIC QUESTION
is there anisotropy without fluctuations?



[Ollitrault, 1992]

Eccentricity of the average energy density, <T^{00}>. → $$\varepsilon = \frac{\int dxdy(x^2 - y^2)\left\langle T^{00}(x,y)\right\rangle}{\int dxdy(x^2 + y^2)\left\langle T^{00}(x,y)\right\rangle}$$

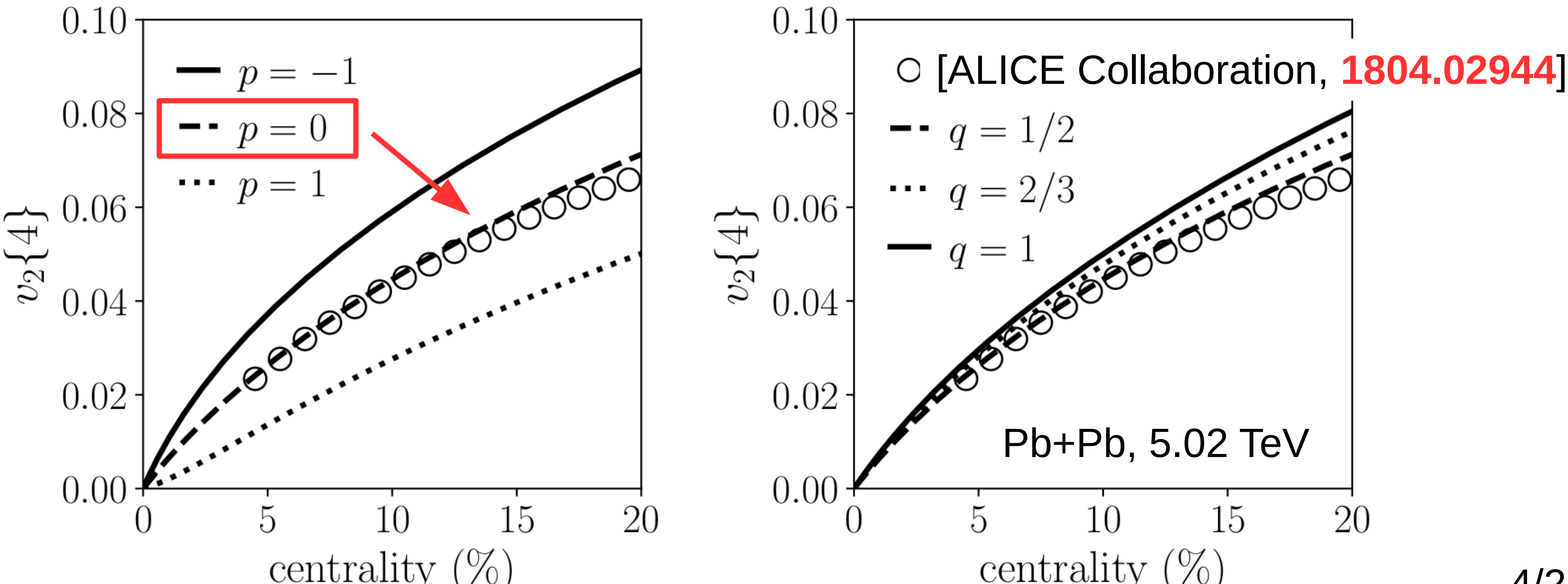
Central to mid-central collisions, one has:

$$v_2\{4\} \approx \kappa\ \varepsilon$$

κ ~ 0.25 with ALICE cuts

I dub T_A and T_B the optical participant densities.

$$\left\langle T^{00}(\mathbf{x})\right\rangle \propto \left(\frac{T_A^p(\mathbf{x}) + T_B^p(\mathbf{x})}{2}\right)^{1/p} \qquad \left\langle T^{00}(\mathbf{x})\right\rangle \propto \left(T_A(\mathbf{x})T_B(\mathbf{x})\right)^q$$



Experimental data suggests:

$$\left\langle T^{00}(\mathbf{x}, \tau = 0^{+}) \right\rangle \propto \Big(T_A(\mathbf{x}) T_B(\mathbf{x}) \Big)^{q}$$

q=1 → prediction of the color glass condensate (CGC).

[Lappi **hep-ph/0606207**]

q=1/2 → Only TRENTo parametrization of the form $T_A * T_B$. Strongly favored by Bayesian analyses.

[Bass, Bernhard, Moreland **1412.4708, 1605.03954, Nature Phys. 15 (2019)**]

Time evolution of **q** is known fairly well.

[Lappi, Venugopalan **nucl-th/0609021**]

[Giacalone, Mazeliauskas, Schlichting, **1908.02866**]

Average anistropy in data is consistent with a CGC-like model.

2005: Breakthrough discovery by the PHOBOS collaboration.

nucl-ex/0610037

At a given impact parameter:

$$\left\langle T^{00}(\mathbf{x})T^{00}(\mathbf{y})\right\rangle - \left\langle T^{00}(\mathbf{x})\right\rangle \left\langle T^{00}(\mathbf{y})\right\rangle \neq 0$$

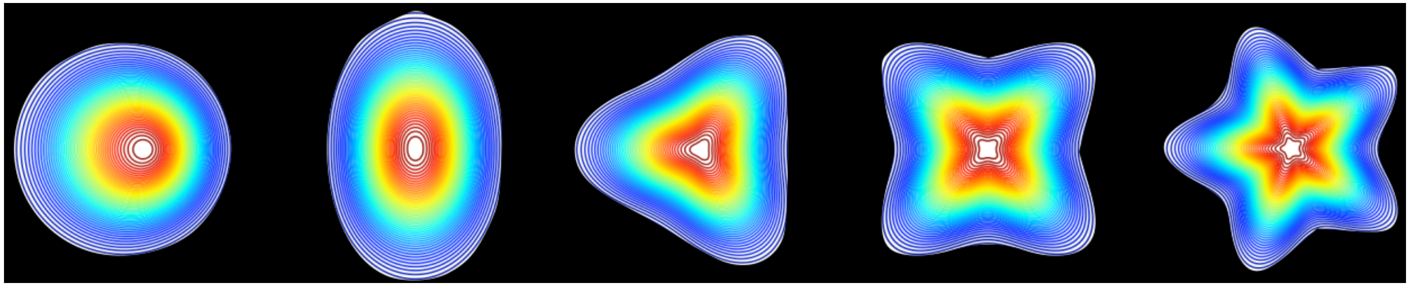
The initial condition fluctuates event-by-event!

Anisotropy is broken to all orders in the interaction region.
The energy density has **non-vanishing multipole moments**.

$$\mathcal{E} \propto \int r dr d\phi \; r^m e^{im\phi} T^{00}(r,\phi) \neq 0$$

[Alver, Roland **1003.0194**]
[Teaney, Yan **1010.1876**]

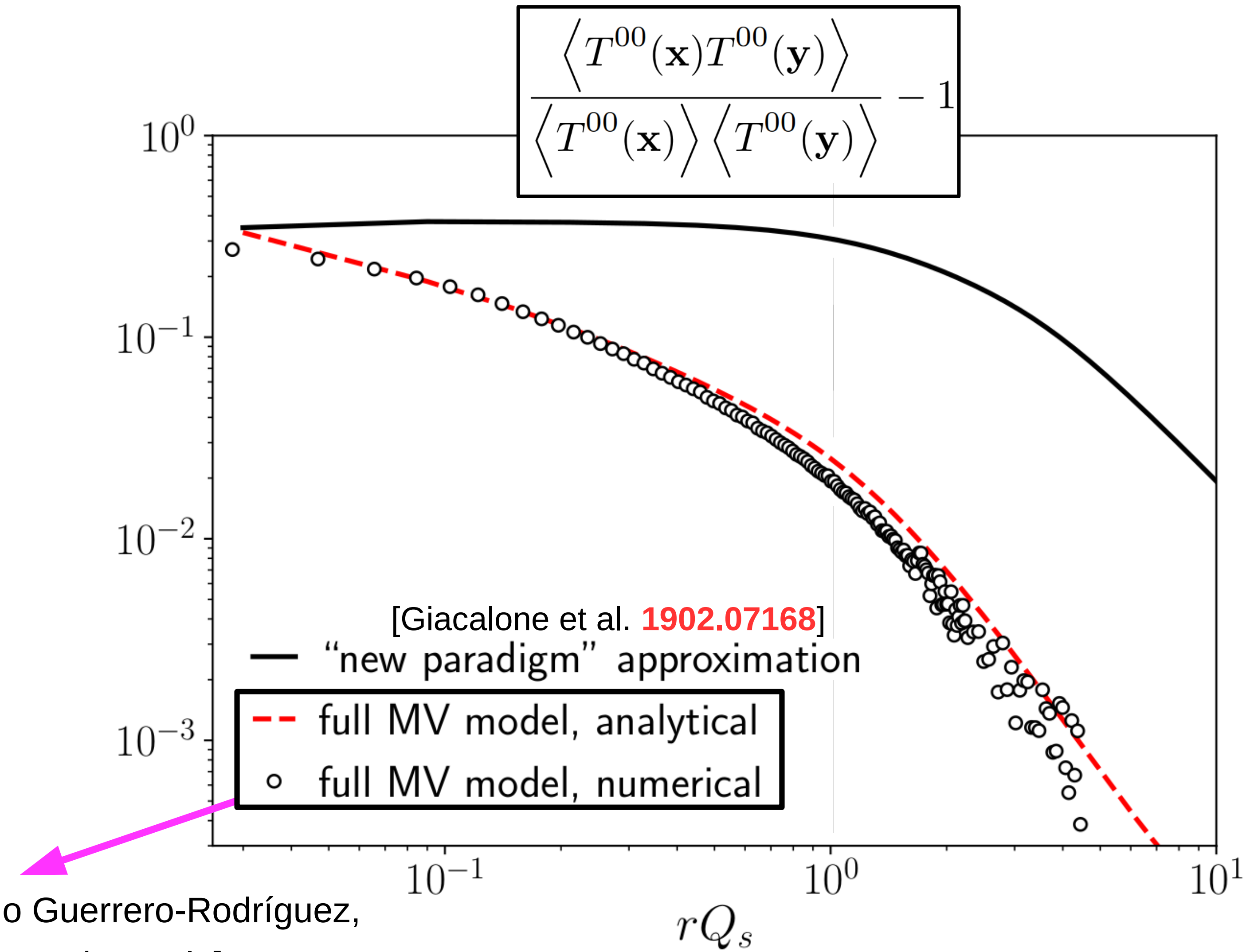
m=1 m=2 m=3



Does the CGC give us also the fluctuations?

Connected 2-point function in the CGC derived in:

[Albacete, Guerrero-Rodriguez, Marquet 1808.00795]



[courtesy: Pablo Guerrero-Rodríguez, Sanghoon Lim, Jamie Nagle]

Color-charge fluctuations are small, scale is ~1/Qs.

<u>We need additional fluctuations on nuclear/hadronic scales.</u>

ANISOTROPY #1 – nuclear structure: collective phenomena

Deformation: emergent property of nuclei.
Collective ‘organization’ of nucleons.

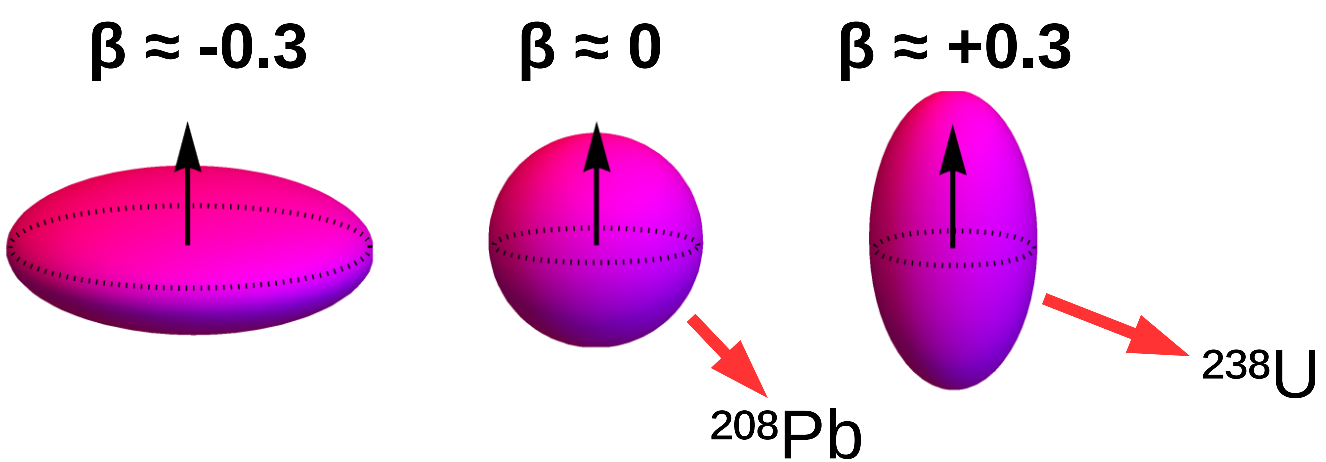
[Bohr, Mottelson 1957]

Rotational model: nuclei as ellipsoids with a random orientation.

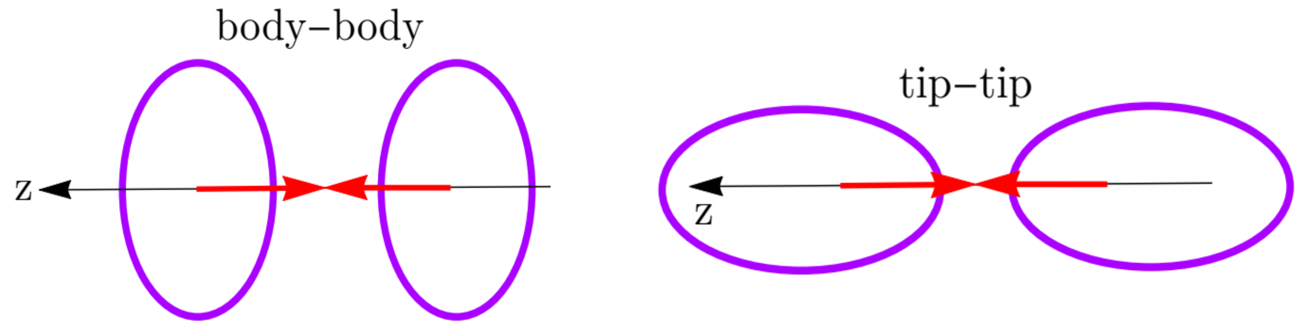
$$Q_2 \propto \langle Y_2^0(\Theta, \Phi) r^2 \rangle \neq 0$$

Dimensionless deformation parameter:

$$\beta \propto \frac{Q_2}{\langle r^2 \rangle}$$

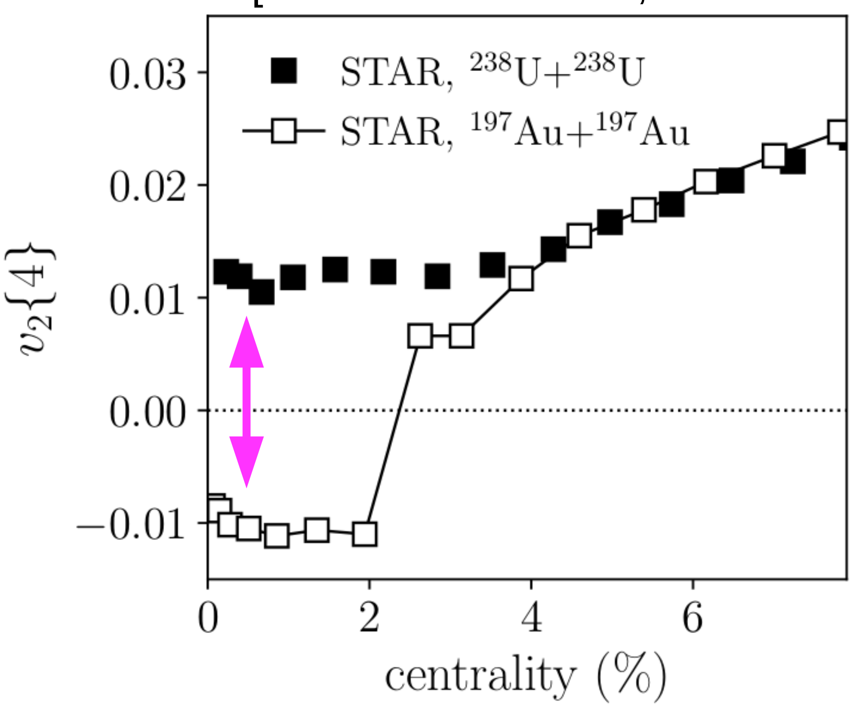


New source of fluctuations: the shape of the overlap area.

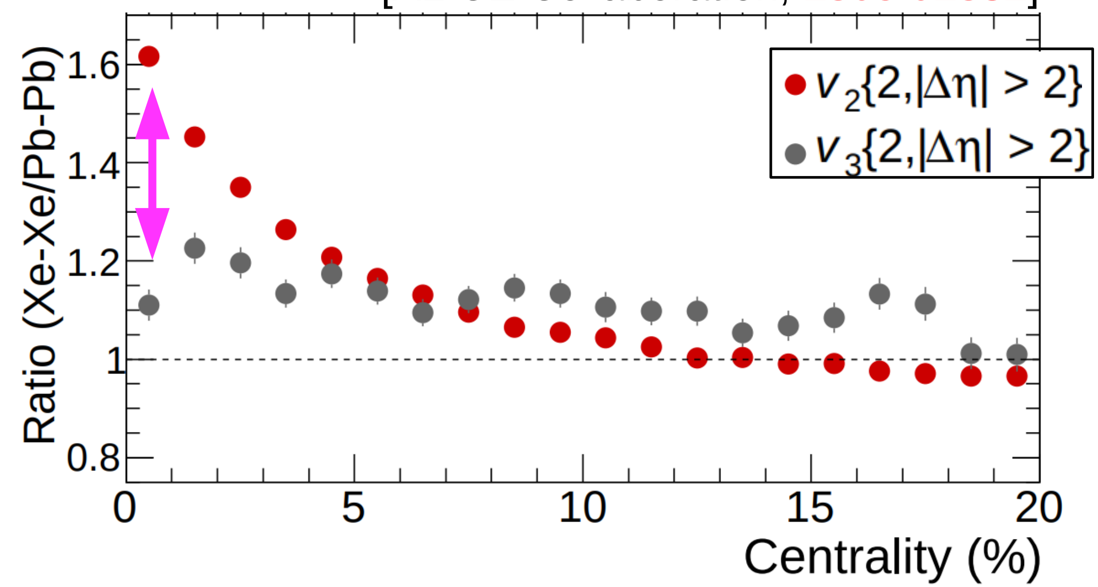


Manifestations observed in elliptic flow data.

[STAR Collaboration, **1505.07812**]



[ALICE Collaboration, **1805.01832**]



New spectacular signatures discovered at STAR this year.

[Talk by J. Jia, Thursday Jan 14th, contribution #55]

Soumya Mohapatra, IS2019:

“Can Xe-Xe @ LHC have the same impact as Cu-Cu @ RHIC?”

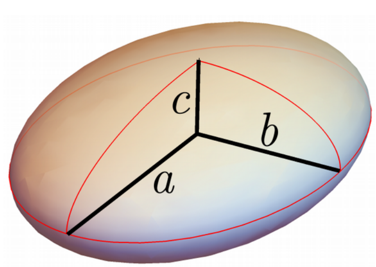
[potential energy for 130Xe, courtesy Benjamin Bally]

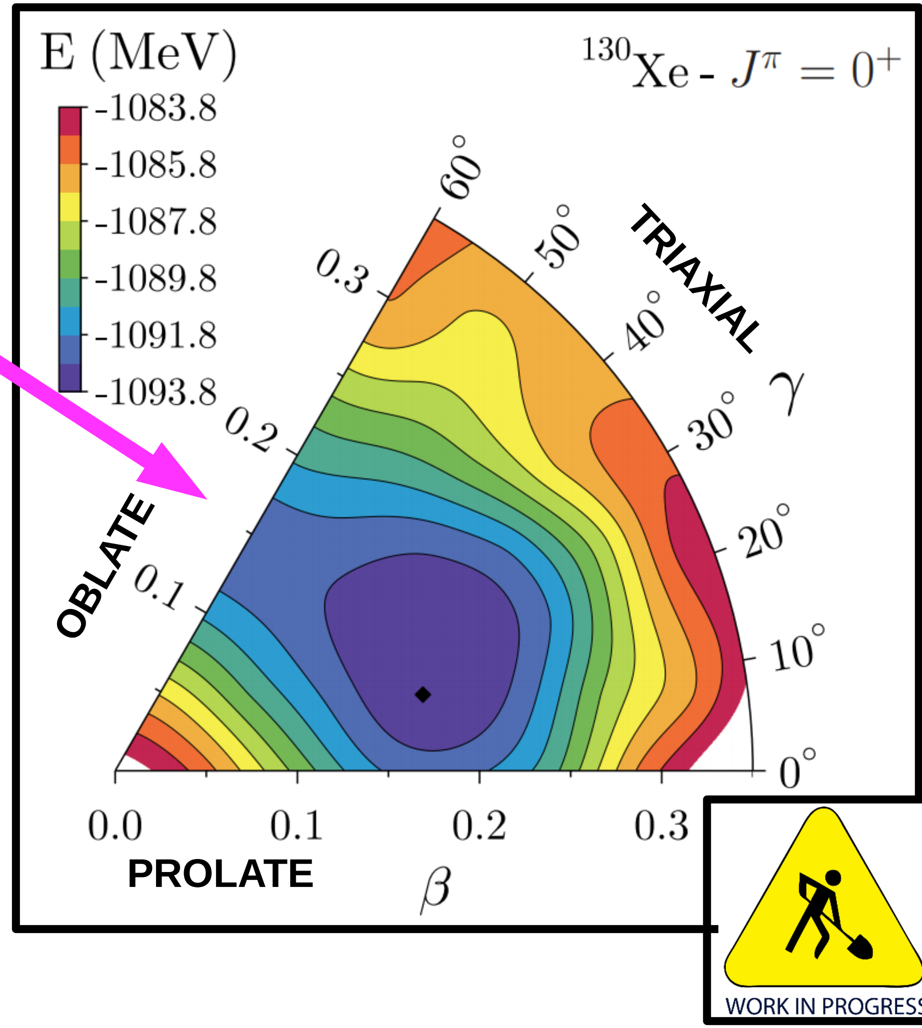
129Xe is not 238U.

Shape is not sharply defined.

Co-existence of prolate and oblate configurations.

Average geometry is triaxial.

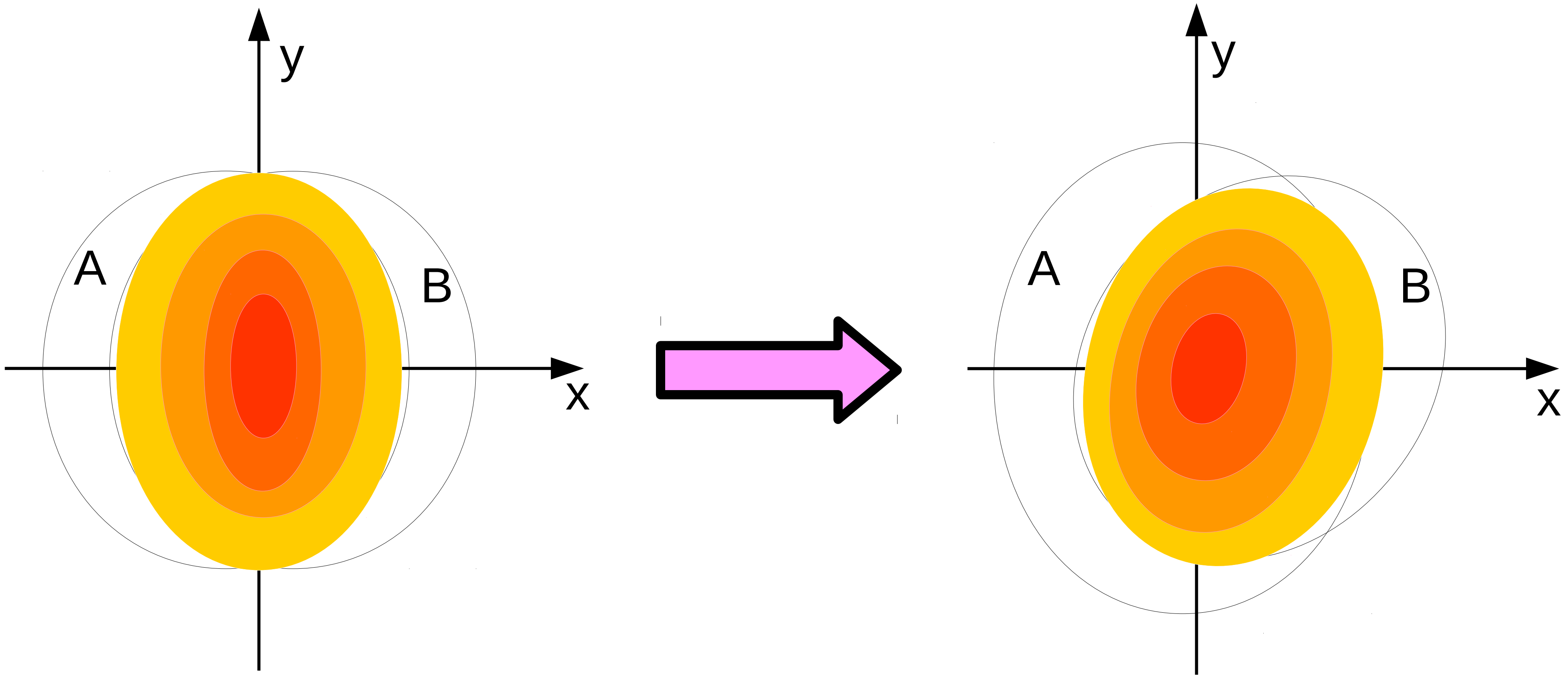




[Giacalone, 2101.00168]

Precision data on elliptic flow requires state-of-the-art nuclear theory.

NUCLEAR DEFORMATION **length scale ~ R_A**

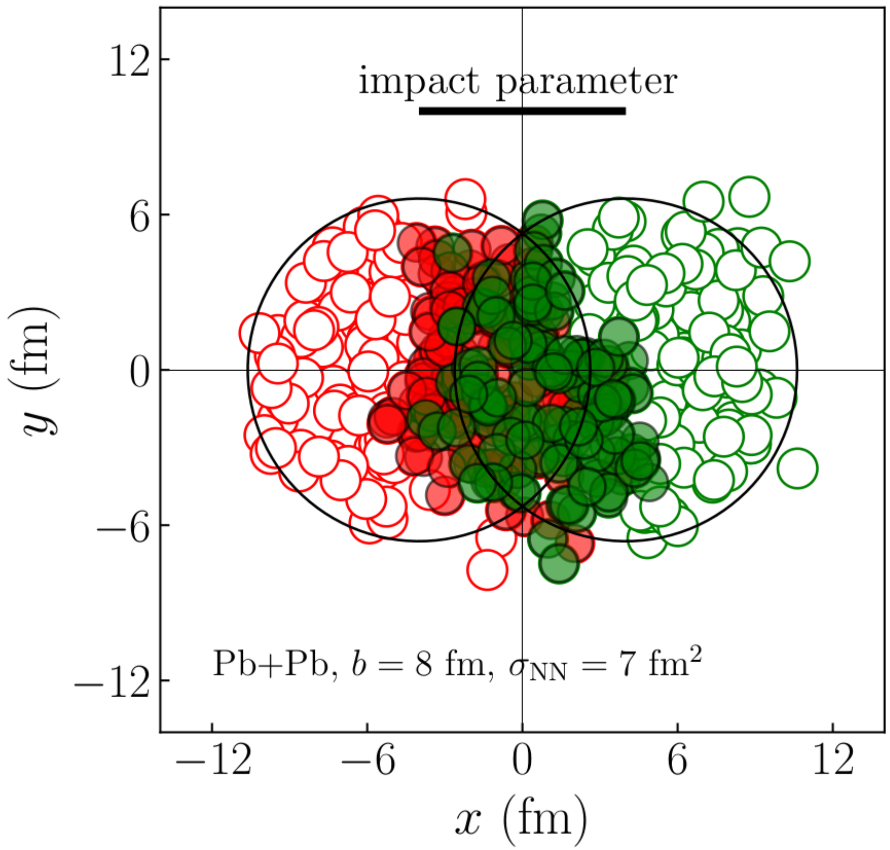


ANISOTROPY #2 – nuclear structure: individual nucleons

Nuclear structure on shorter scales: Quantum noise due to nucleons.
A mean-field approach: **Glauber Monte Carlo.**

[Miller, Reygers, Sanders, Steinberg
nucl-ex/0701025]

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$

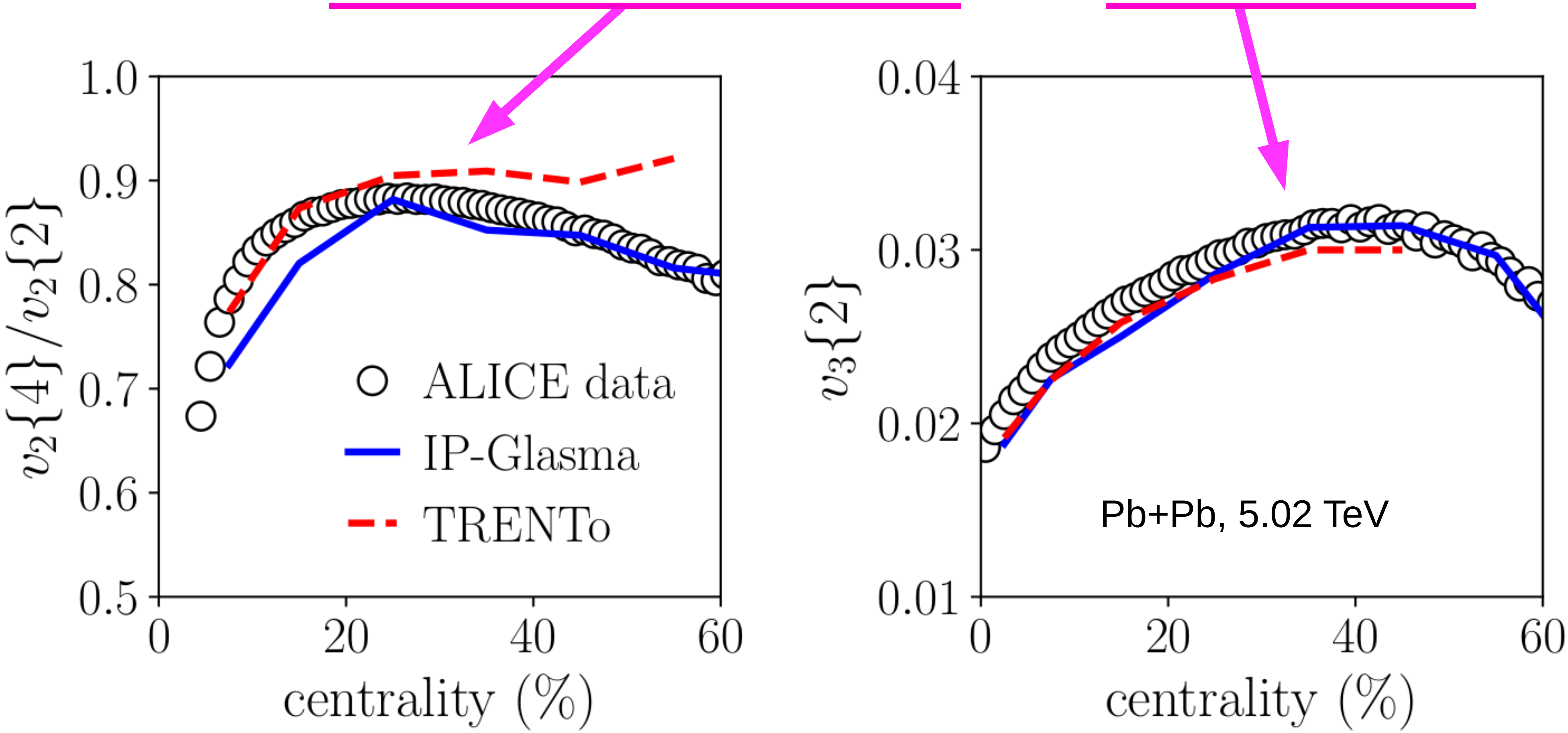


Energy density obtained from nucleon-nucleon interactions.

$$T_A(\mathbf{x}) T_B(\mathbf{x}) \longrightarrow \sum_{i,j} T_{A,i}(\mathbf{x}) T_{B,j}(\mathbf{x})$$

single nucleon

Explains elliptic flow fluctuations and triangular flow.



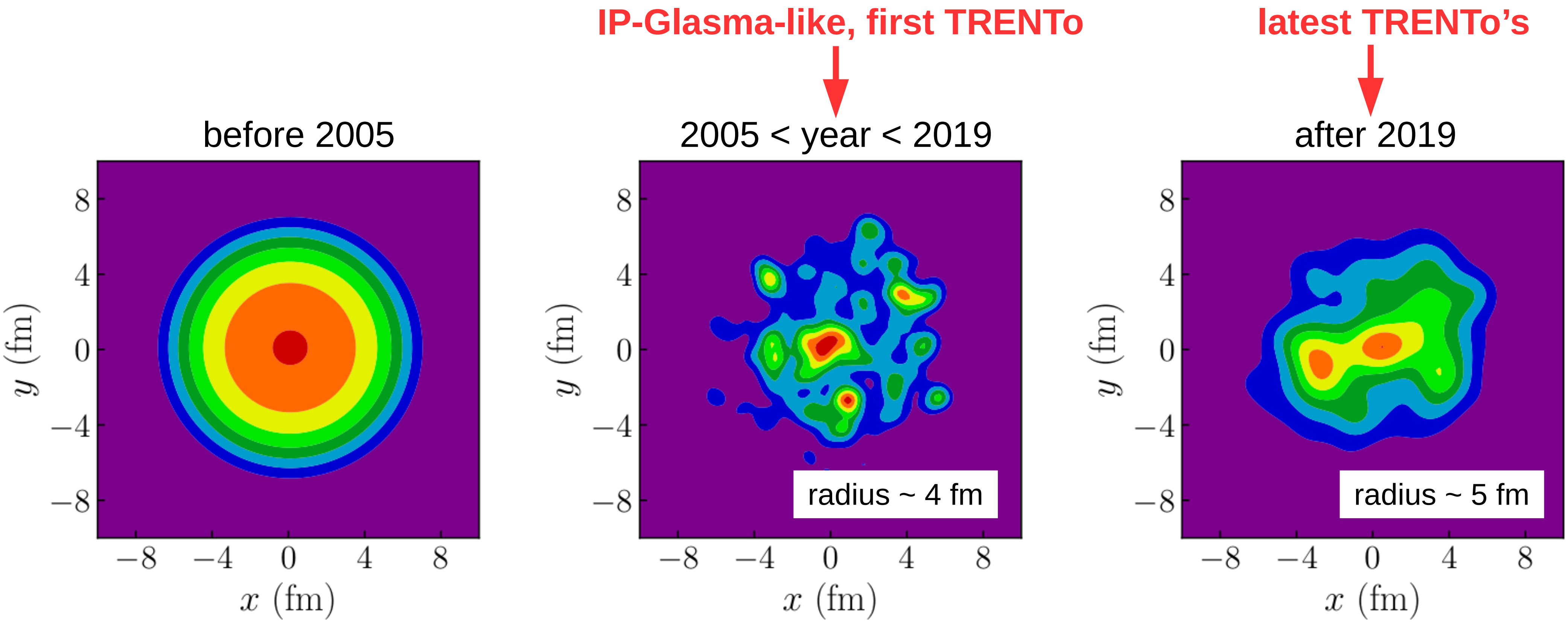
– [ALICE Collaboration, **1804.02944**]

– IP-Glasma+MUSIC+urQMD [Schenke, Shen, Tribedy **2005.14682**]

– TRENTo+hydro [Bass, Bernhard, Moreland **Nature Phys. 15 (2019)**]

But wait a minute…

… those models “look” fairly different.
Picture of the QGP over the years. (b=0, initial energy density)



- QGP has been rather spiky until 2019-2020.

- Latest Bayesian analyses return smoother medium.

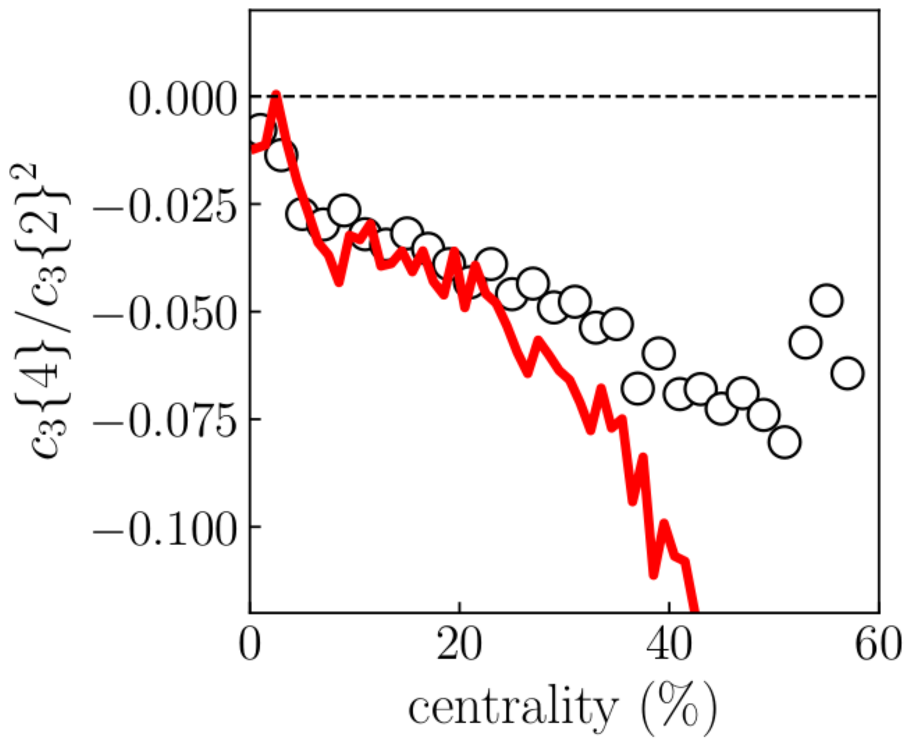
[Bass, Bernhard, Moreland **1808.02106**, **Nature Phys. 15 (2019)**]

[JETSCAPE Collaboration **2011.01430**, **2010.03928**] [Nijs, van der Schee, Gürsoy, Snellings **2010.15130**, **2010.15134**]

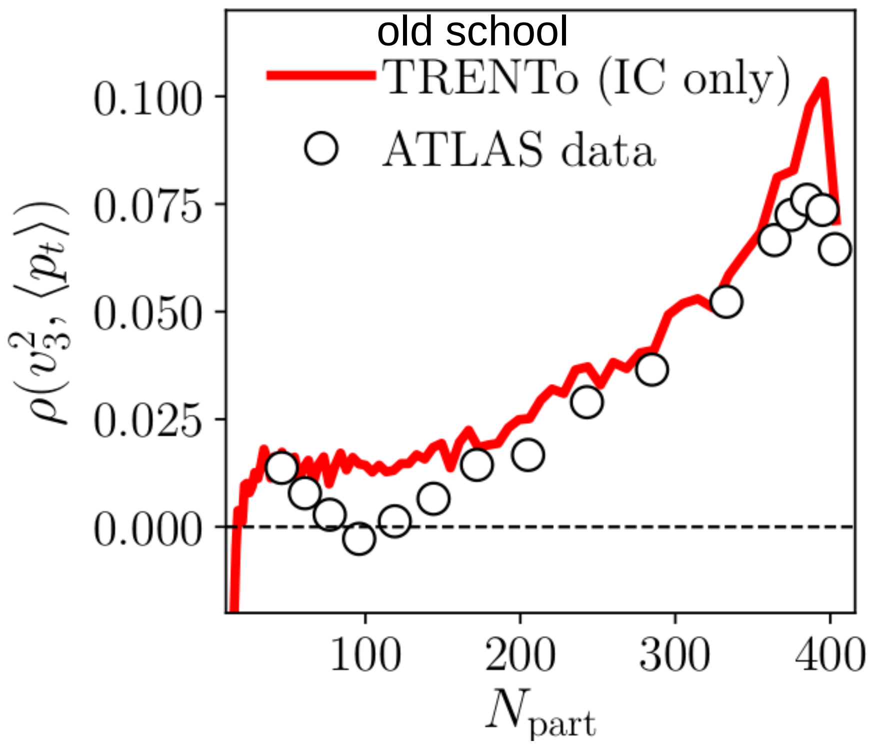
- Anisotropies $v_n\{2\}$ are roughly the same.

Can anisotropy discern spiky and smooth profiles?
Golden probes: do not involve the 1-point function! (i.e. v2)

[ATLAS Collaboration, 1904.04808]



[ATLAS Collaboration, 1907.05176]



Primordial non-Gaussianity (is negative!)

[Abbasi, Allahbakhshi, Davody, Taghavi 1704.06295]

[Bhalerao, Giacalone, Ollitrault, 1904.10350]

Ultra-sensitive to fluctuations

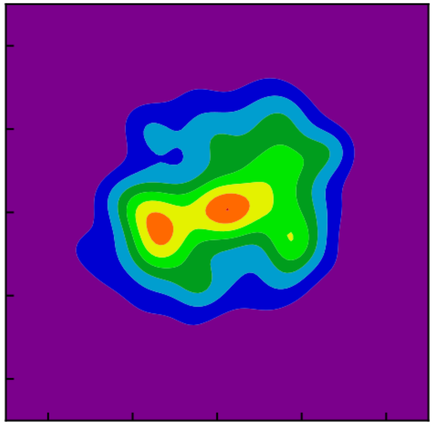
[Giacalone, Gardim, Noronha-Hostler, Ollitrault, 2004.01765]

[Giacalone, 2004.14463]

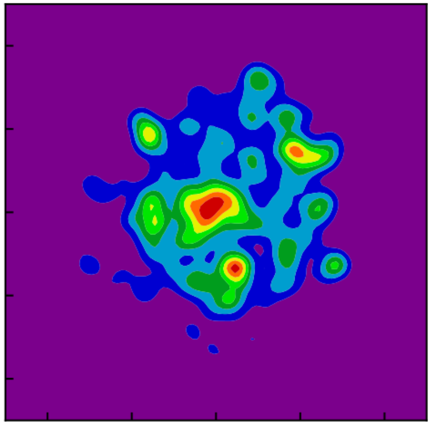
Simple IP-Glasma-like TRENTo calculation captures the data.

QUESTION ADDRESSED BY THESE COMPARISONS:

1 – Role of short-scale structures.

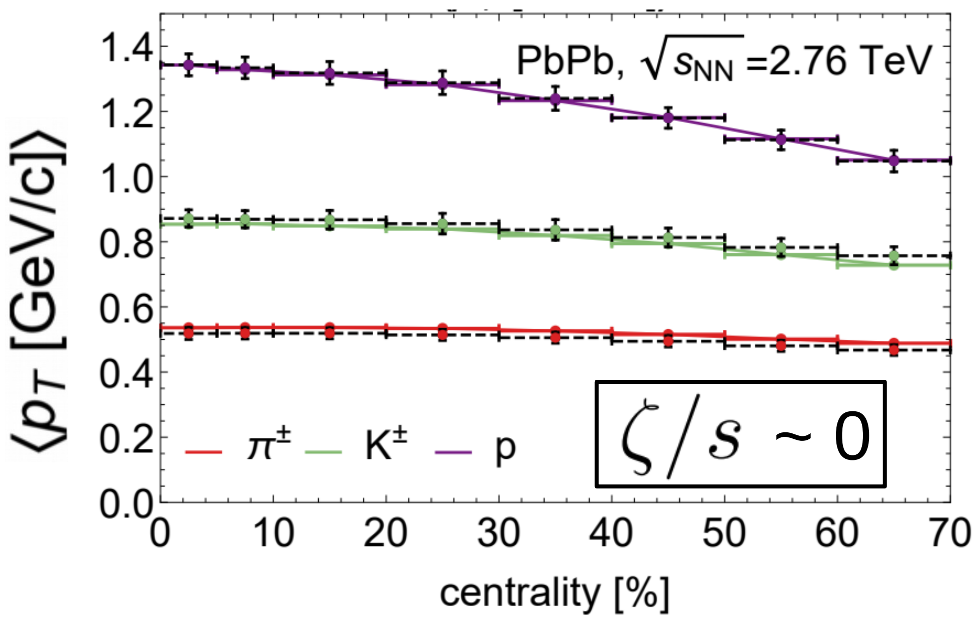


vs



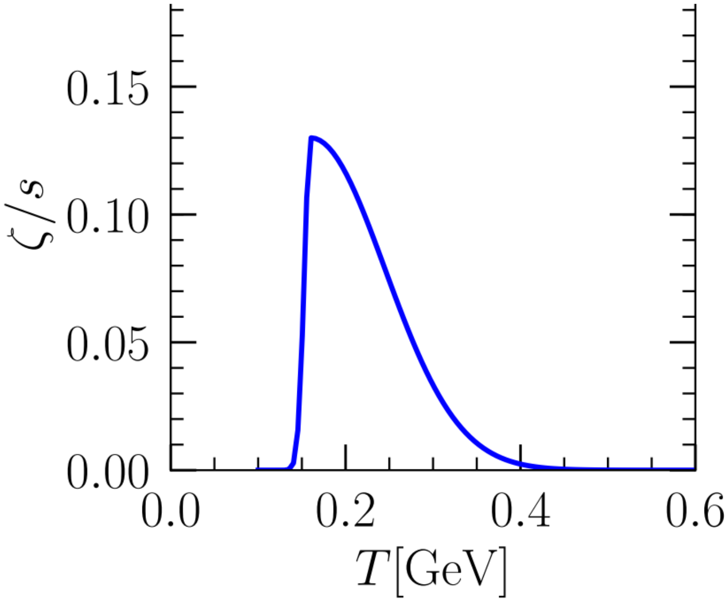
2 – The fate of the bulk viscosity. Tension in the literature?

[Trajectum, **2010.15134**]



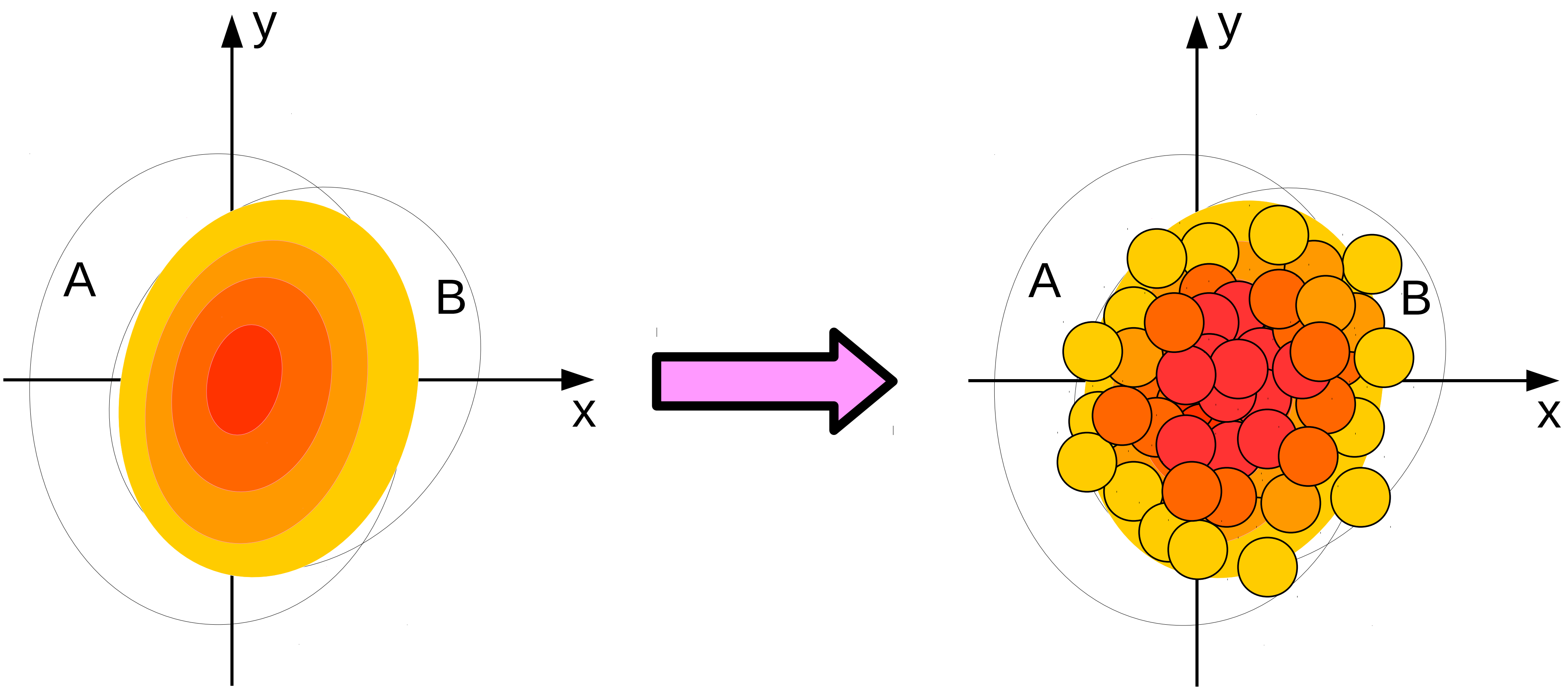
vs

[IP-Glasma+MUSIC, **2005.14682**]



NUCLEAR DEFORMATION — length scale ~ R_A

INDIVIDUAL NUCLEONS — length scale ~ $[\,1\ \mathrm{fm}\ ,\ R_A\,]$



ANISOTROPY #3 – nucleon structure

[talk by A. Soto-Ontoso, Friday Jan 15th, #233]

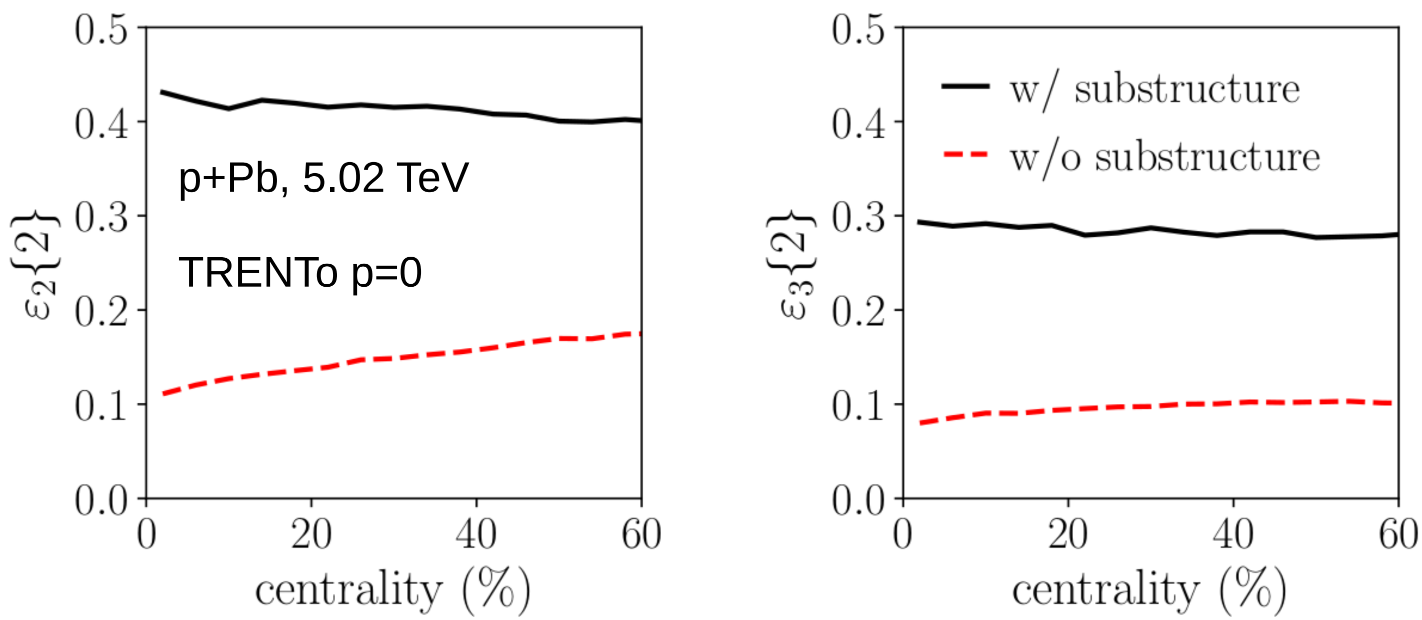
Anisotropy observed in pA (and pp).
The crucial question: **can we use the same 1-point function?**

$$\left\langle T^{00}(\mathbf{x},\tau=0^+)\right\rangle \propto \Big(T_A(\mathbf{x})T_B(\mathbf{x})\Big)^q$$

Yes, but you'll need more structures. [Schenke, Venugopalan 1405.3605]

IP-Glasma: Shape fluctuations in protons. [Mäntysaari, Schenke 1603.04349, 1607.01711]
[Mäntysaari, Schenke, Shen, Tribedy 1705.03177]

TRENTo: Combined analysis of p-Pb and Pb-Pb collisions
[Bass, Bernhard, Moreland 1808.02106]
[Nijs, van der Schee, Gürsoy, Snellings 2010.15130, 2010.15134]

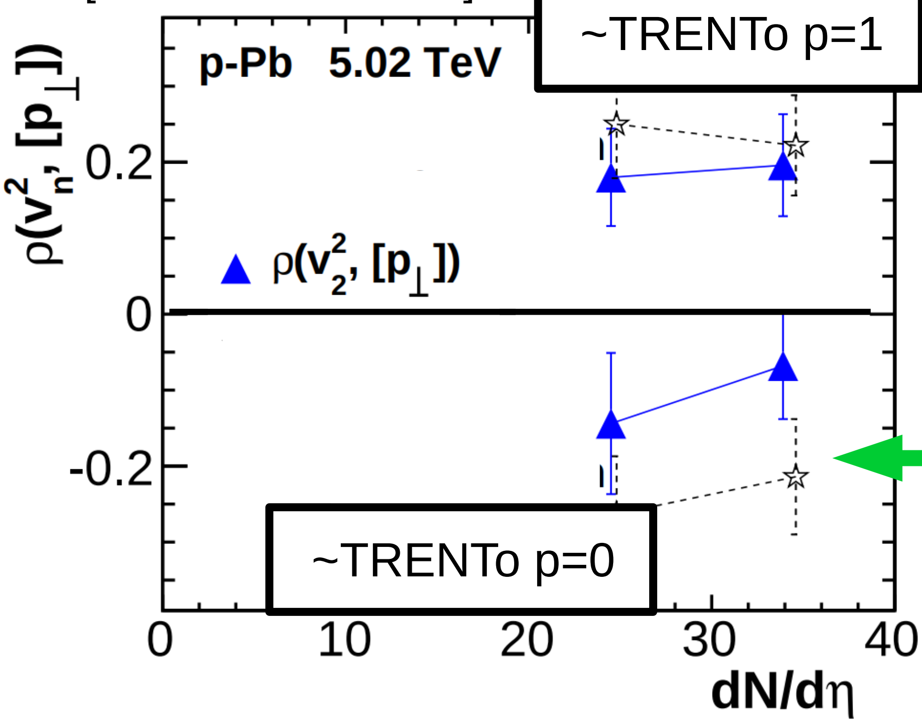


Is there experimental evidence of this behavior in small systems?

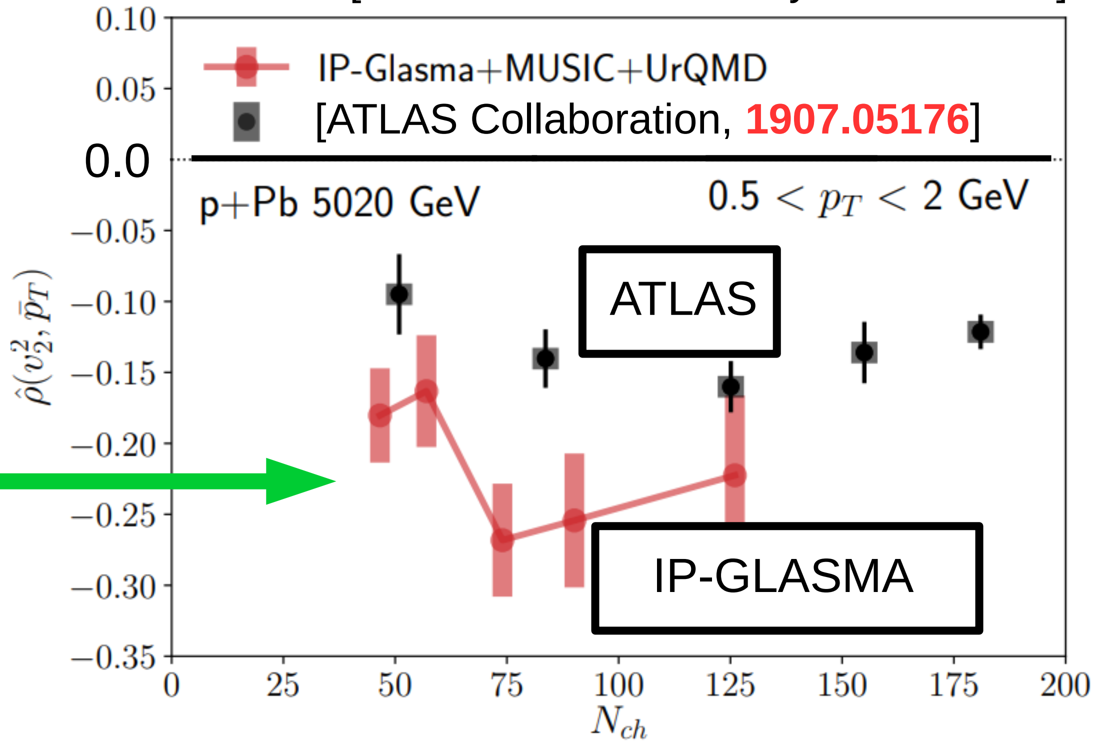
$$\left\langle T^{00}(\mathbf{x}, \tau = 0^{+}) \right\rangle \propto \Big(T_A(\mathbf{x}) T_B(\mathbf{x}) \Big)^q$$

Nontrivial information from vn-<pT> correlation.

[Bozek, 1601.04513]



[Schenke, Shen, Teaney, 2004.00690]



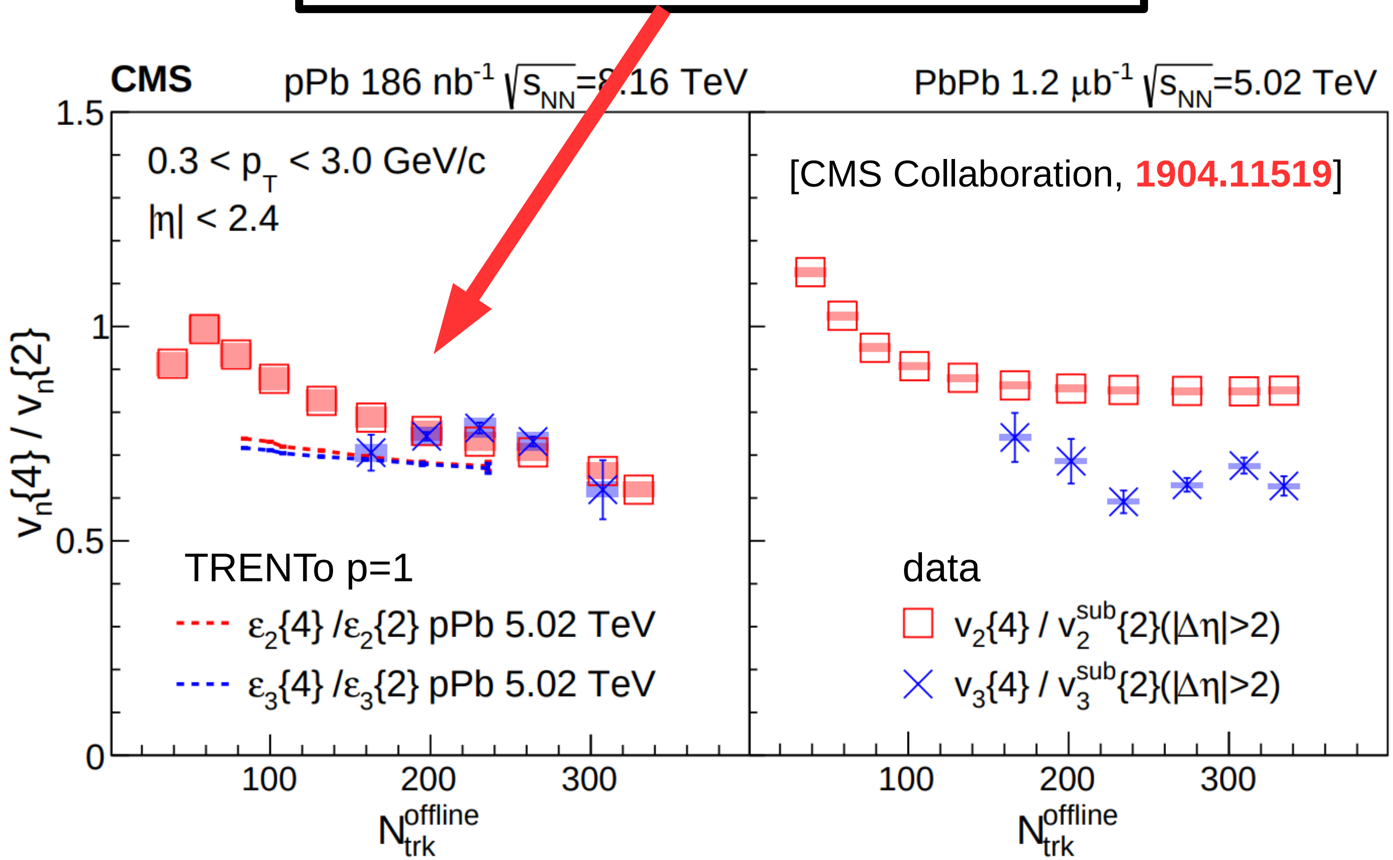
- Experimental ATLAS data is **negative** in high-multiplicity pA.

- Supports IP-Glasma or TRENTo p=0-like scaling.

DO WE HAVE THE RIGHT MODEL: OPEN QUESTIONS #1

Beautiful observation by CMS in p-Pb collisions:

$$v_2\{4\}/v_2\{2\} = v_3\{4\}/v_3\{2\}$$

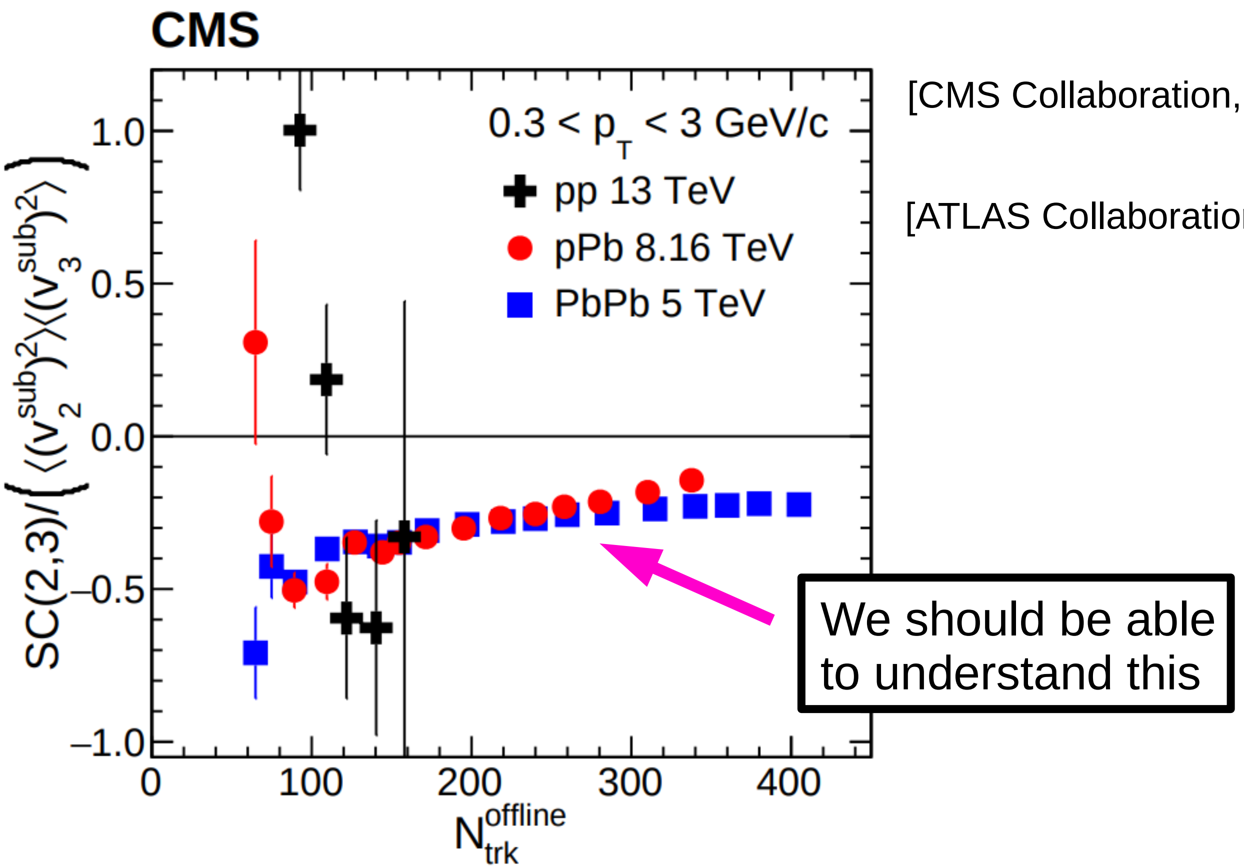


– Calculation with TRENTo p=1 (wounded nucleons) points to geometric origin of observables. [Giacalone, Noronha-Hostler, Ollitrault, 1702.01730]

– TRENTo p=1 is ruled out… <u>results from sub-structure models?</u>

DO WE HAVE THE RIGHT MODEL: OPEN QUESTIONS #2

Mixed correlations measured with great accuracy.



[CMS Collaboration, **1709.09189**, **1905.09935**]

[ATLAS Collaboration, **1807.02012**]

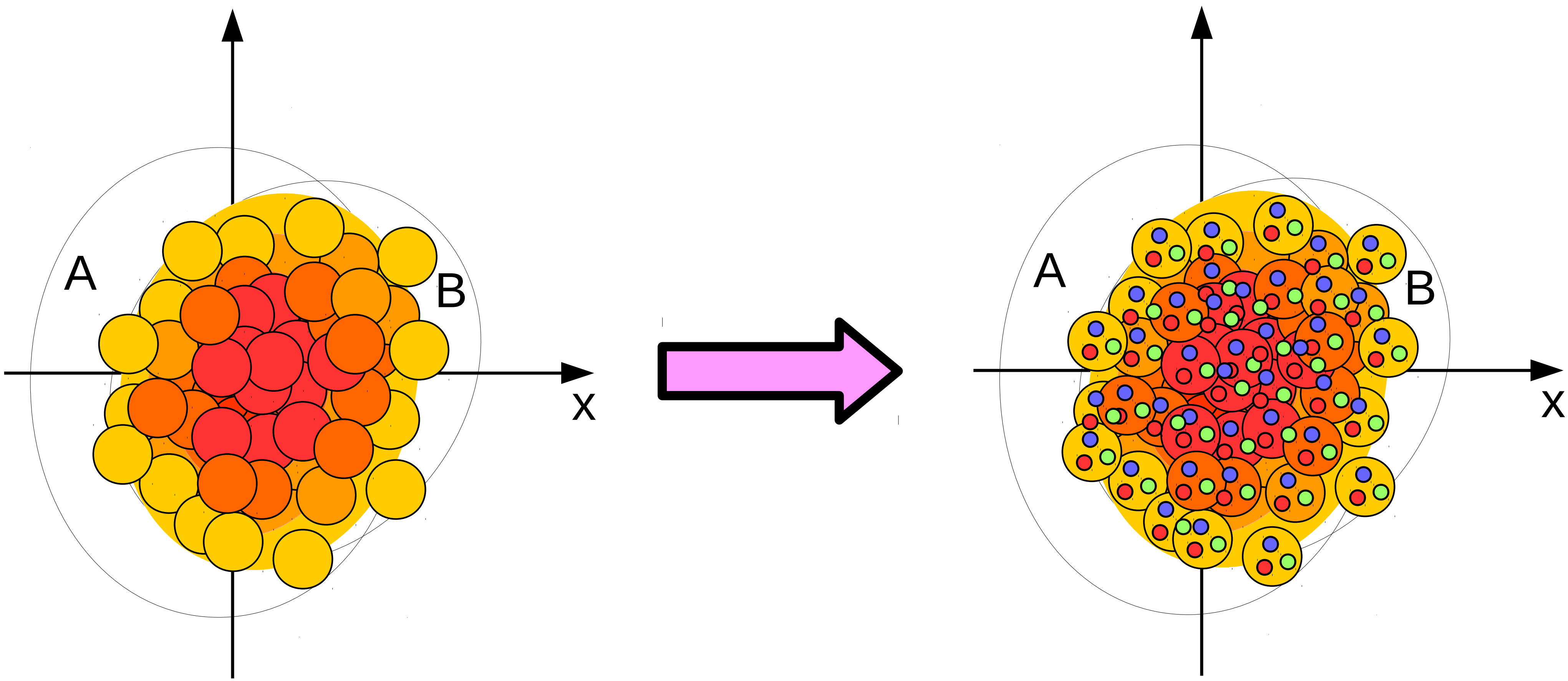
There are no results from recent sub-structure models.
I tried with the eccentricities and get the wrong sign. [NSC(3,2)>0]

[also observed in p-p: Zhao, Zhou, Murase, Song **2001.06742**]

Results for p-p (or Ntrk~100) sensitive to details of hot-spot deposition.

[Albacete, Elfner, Soto-Ontoso **1707.05592**]

- **NUCLEAR DEFORMATION** — **length scale ~ R_A**
- **INDIVIDUAL NUCLEONS** — **length scale ~ [1 fm , R_A]**
- **SUB-NUCLEONIC STRUCTURES** — **length scale ~ [$1/Q_s$, 1 fm]**

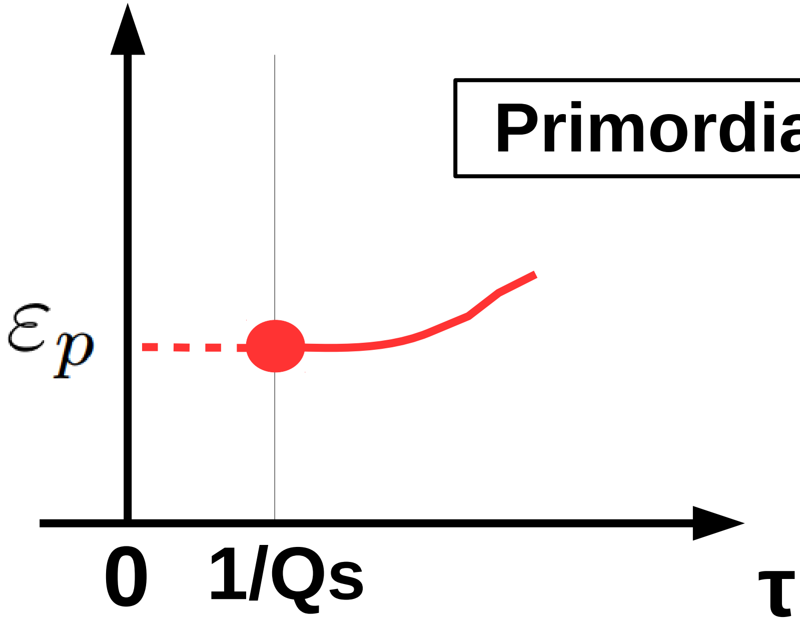


ANISOTROPY #4 – momentum space deformation

Vast literature describing long-range anisotropy in pp, pA collisions from initial-state effects in the CGC. [Altinoluk, Armesto **2004.08185**]

Address the question with IP-Glasma initial conditions.
Ellipticity of the tensor modes:

$$\boxed{\mathcal{E}_p} \equiv \varepsilon_p e^{i2\Psi_2^p} \equiv \frac{\langle T^{xx} - T^{yy}\rangle + i\langle 2T^{xy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$$



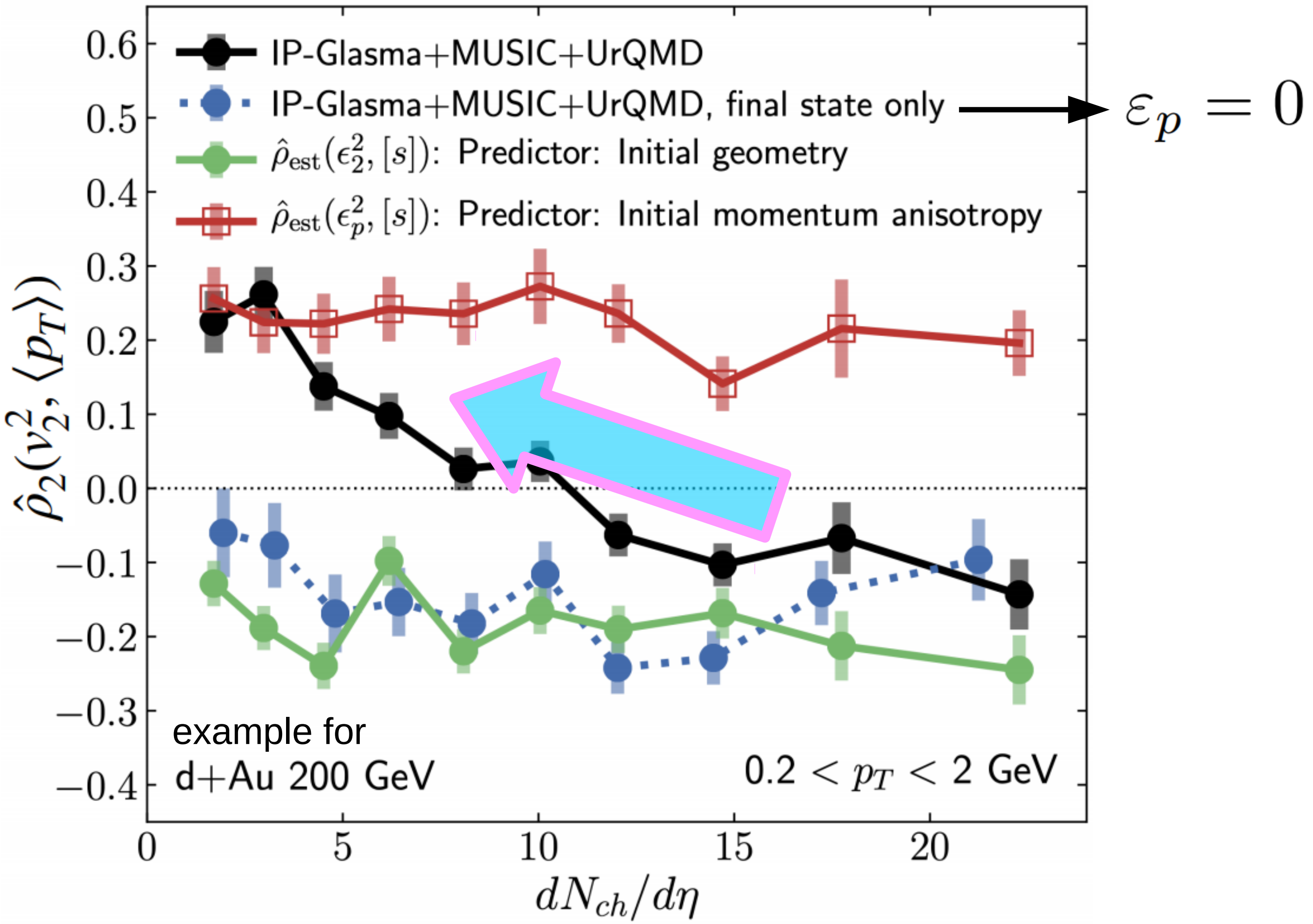
Primordial momentum anisotropy

For small multiplicities, ε_p is the dominant source of elliptic flow.

[Schenke, Shen, Tribedy, 1908.06212]

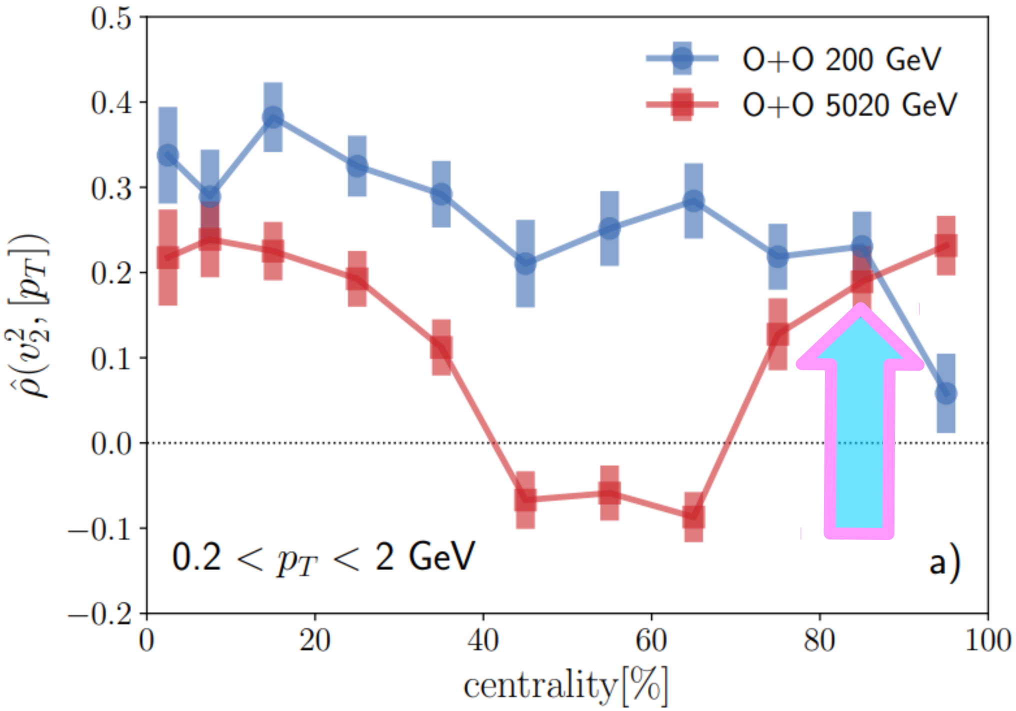
<u>OUR FINDING</u>: QUALITATIVE SIGNATURES IN SMALL SYSTEMS

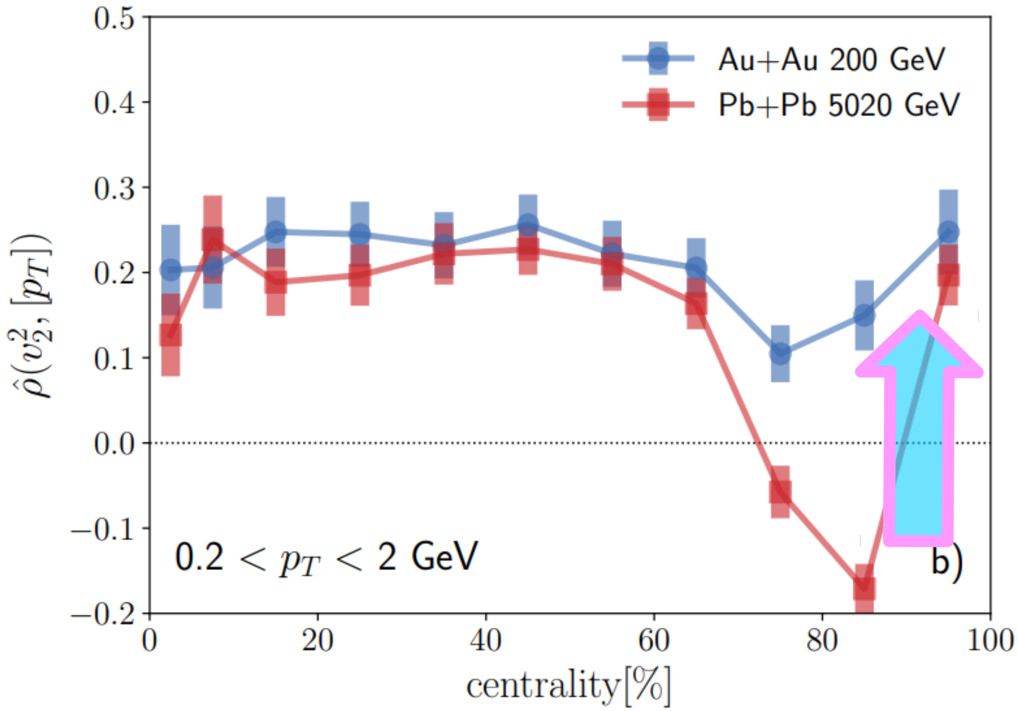
[Giacalone, Schenke, Shen, 2006.15721]



Correlator goes from negative to positive as we decrease dN/dη.

QUALITATIVE SIGNATURES IN PERIPHERAL A-A





- **Double sign change @ LHC**

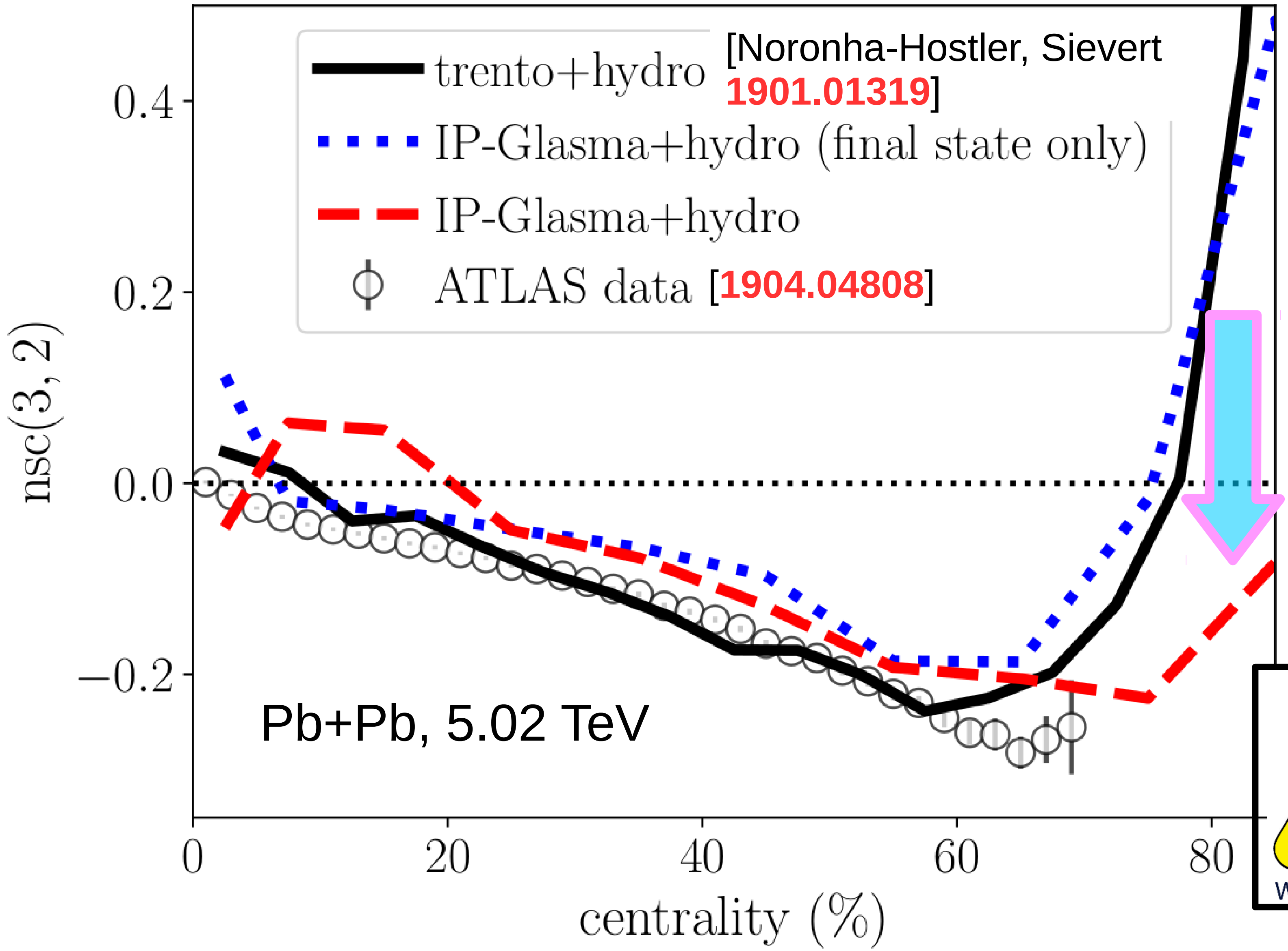
- **No sign change @ RHIC**

[consistent with preliminary STAR data]

NEW FOR IS21

[My poster contribution #47, tomorrow]

Normalized symmetric cumulant shows similar signatures.



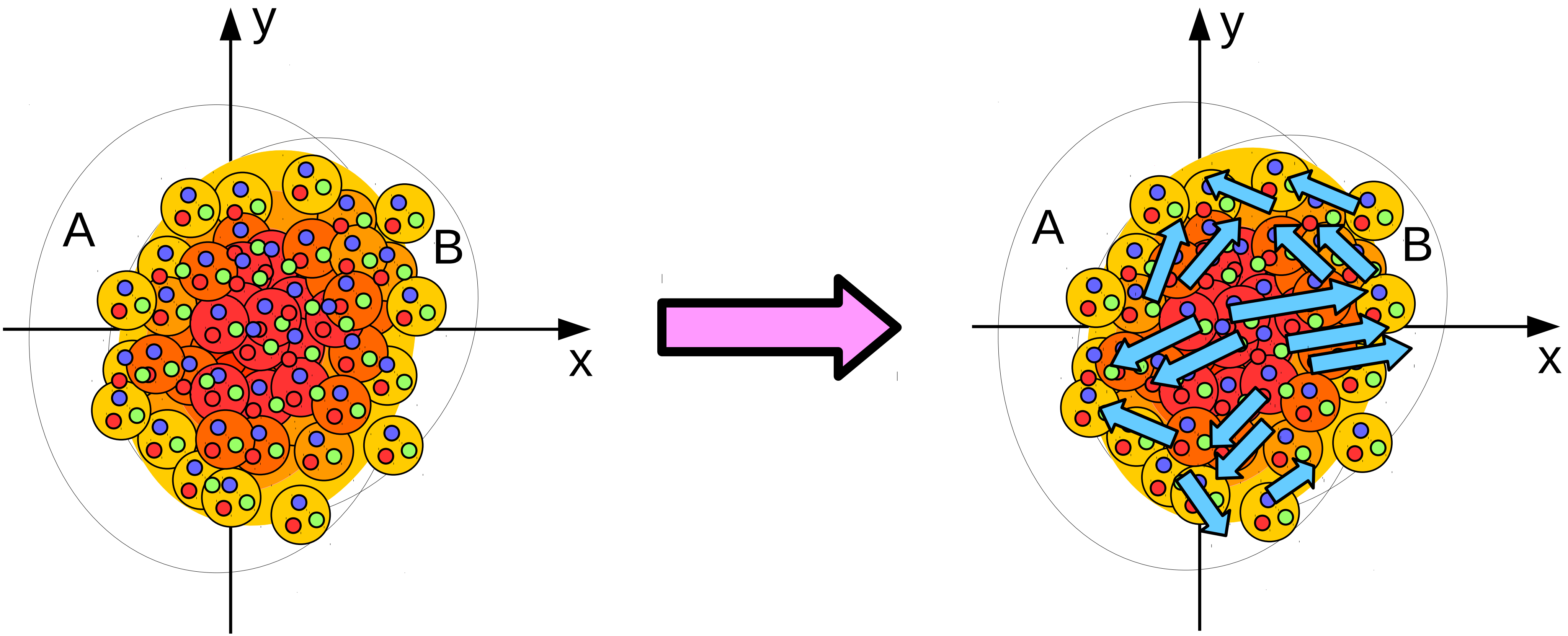
With initial momentum anisotropy the cumulant stays negative!

NUCLEAR DEFORMATION length scale ~ R_A

INDIVIDUAL NUCLEONS length scale ~ [1 fm , R_A]

SUB-NUCLEONIC STRUCTURES length scale ~ [1/Qs , 1 fm]

MOMENTUM SPACE ANISOTROPY



[Not covered: anisotropy from EM fields, longitudinal fluct, principal components]

ALL TOGETHER: "HEAVY-ION COLLISIONS 2.0"

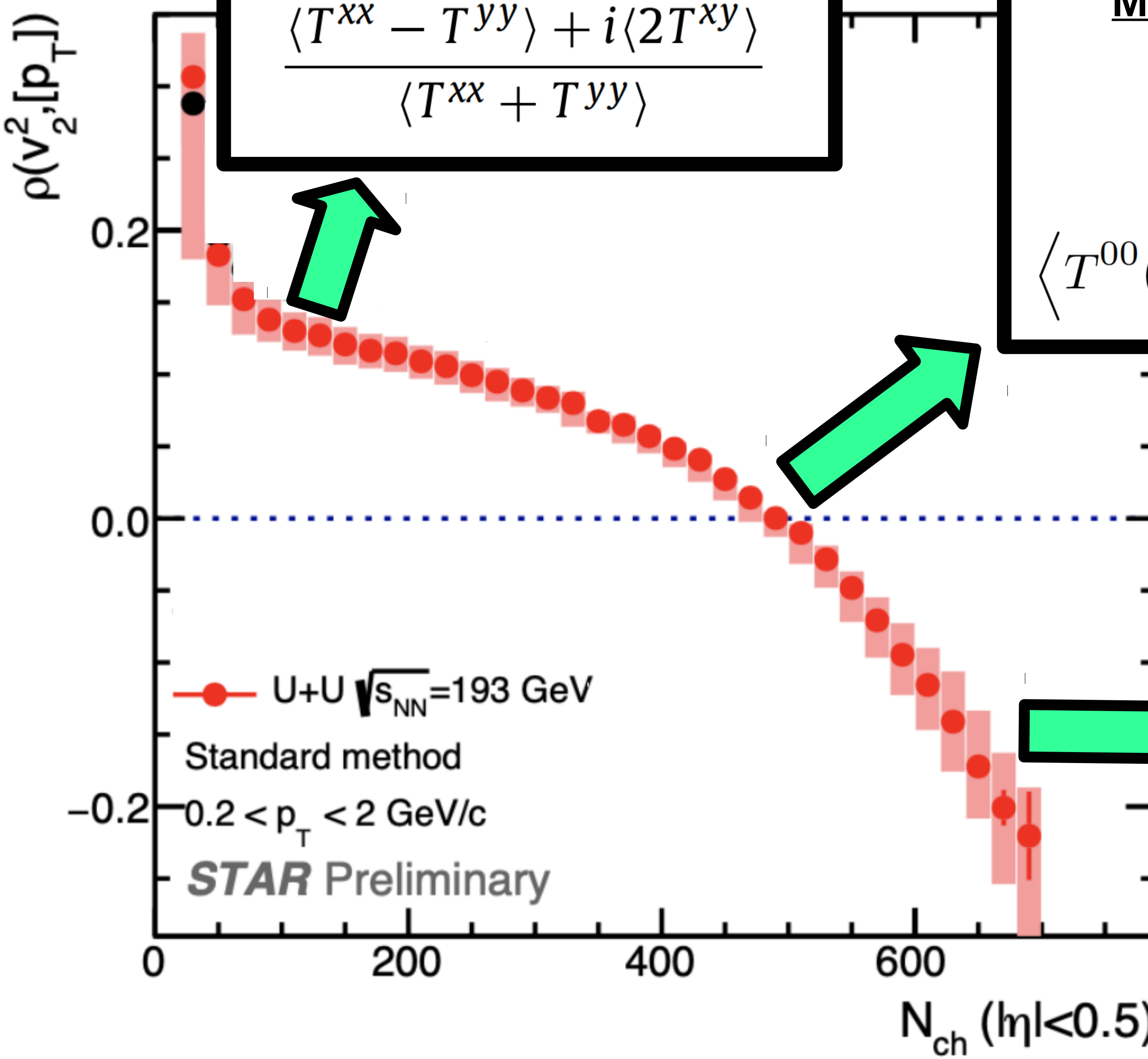
PERIPHERAL COLLISIONS
PRIMORDIAL MOMENTUM ANISOTROPY

$$\frac{\langle T^{xx} - T^{yy} \rangle + i \langle 2T^{xy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$

MULTIPLICITY DEPENDENCE
1-POINT AND 2-POINT FUNCTIONS OF T^{00}

$$\left\langle T^{00}(x) \right\rangle \propto (T_A T_B)^q$$

$$\left\langle T^{00}(\mathbf{x}) T^{00}(\mathbf{y}) \right\rangle - \left\langle T^{00}(\mathbf{x}) \right\rangle \left\langle T^{00}(\mathbf{y}) \right\rangle$$



CENTRAL COLLISIONS
NUCLEAR DEFORMATION

$\beta \approx 0.3$