Signatures of Primordial Momentum Anisotropy in Nuclear Collisions

by
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Based on: **Giacalone, Schenke, Shen**
arXiv:2006.15721 (to appear in PRL)

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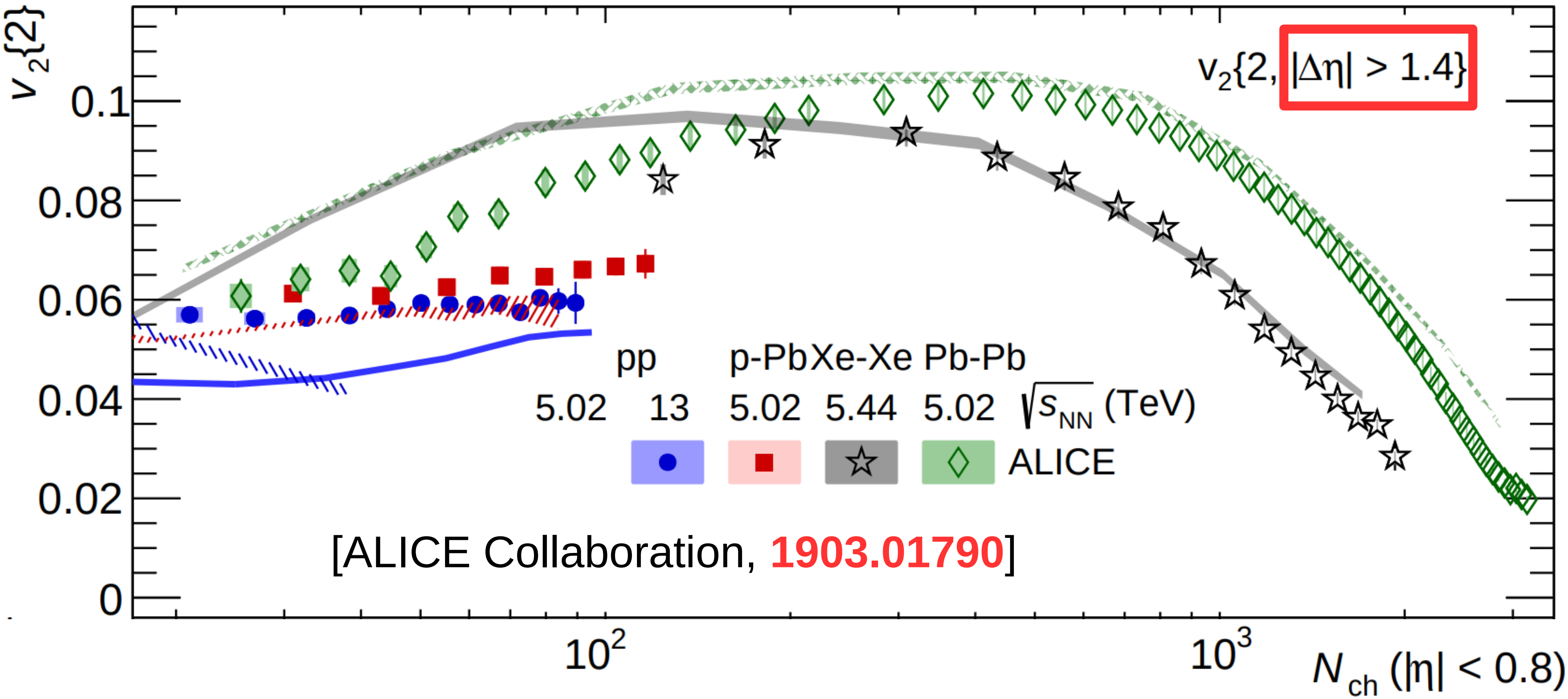
Elliptic flow all over the place!

$$\boxed{V_2} = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-i2\phi_p} \longrightarrow v_2\{2\}^2 \equiv \langle V_2 V_2^* \rangle$$



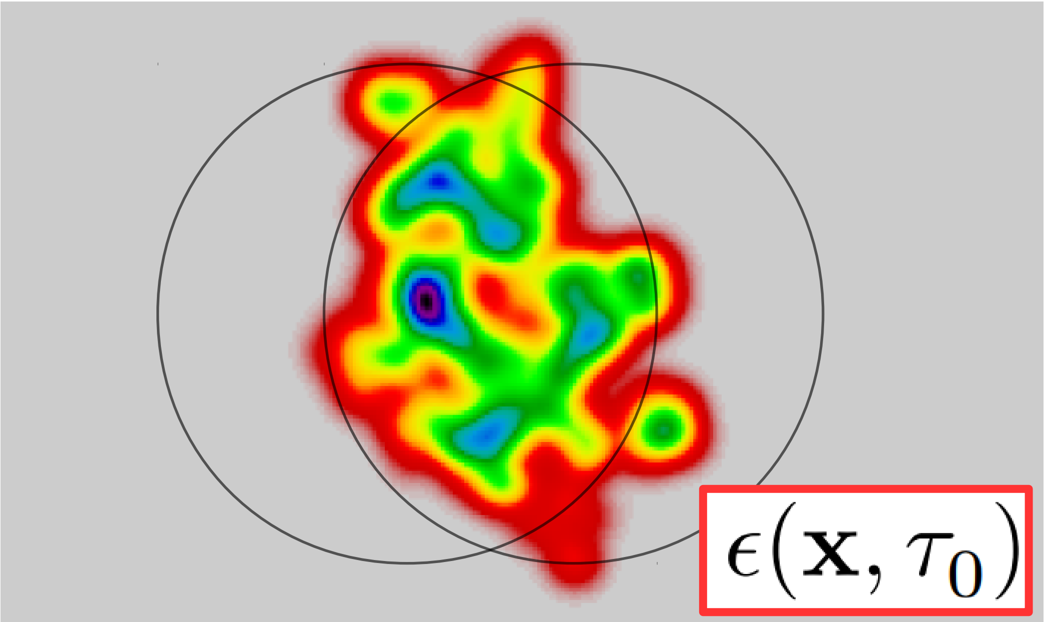
Within a hydro paradigm, what is its origin?

Simplest guess: $F = -\nabla P$. Response to the <u>ellipticity</u> of the large-scale structures.

$$T^{\mu\nu}(\tau_0) \approx \begin{pmatrix} \boxed{\epsilon} & 0 & 0 & 0 \\ 0 & P(\epsilon) & 0 & 0 \\ 0 & 0 & P(\epsilon) & 0 \\ 0 & 0 & 0 & P(\epsilon) \end{pmatrix}$$

onset of hydro

[Teaney, Yan, **1010.1876**]



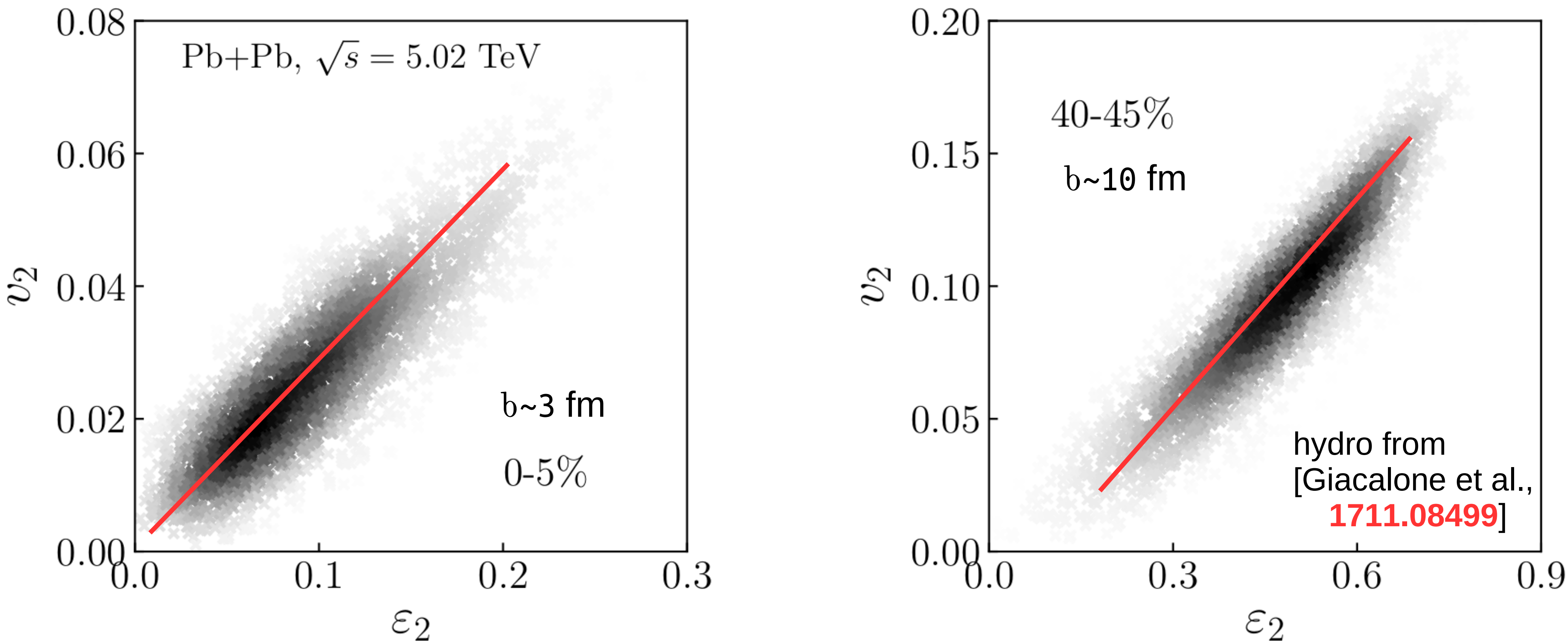
$\boxed{\epsilon(\mathbf{x}, \tau_0)}$

Quadrupole moment

$$\boxed{\mathcal{E}_2} = \frac{\boxed{\int_{\mathbf{x}} |\mathbf{x}|^2 e^{i2\phi} \epsilon(\tau_0, \mathbf{x})}}{\int_{\mathbf{x}} |\mathbf{x}|^2 \epsilon(\tau_0, \mathbf{x})}$$

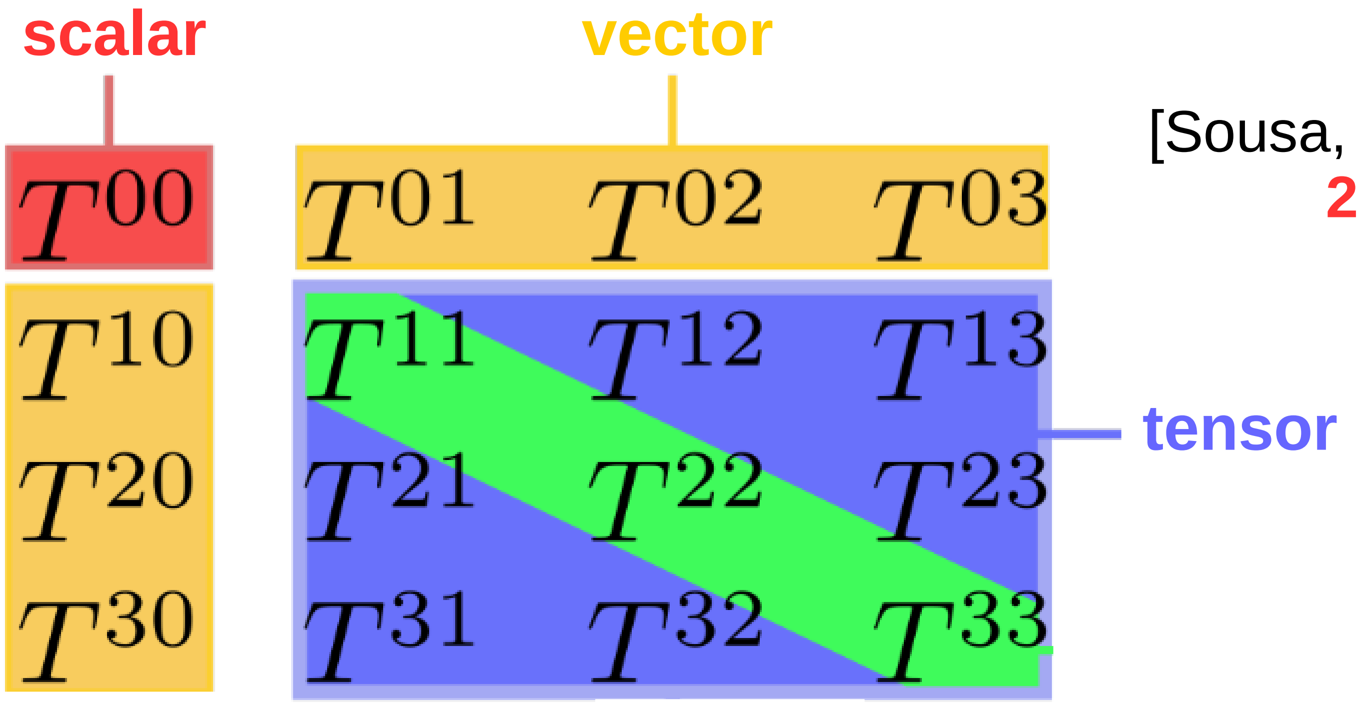
$$\boxed{V_2 \propto \mathcal{E}_2}$$

Excellent approximation. $\varepsilon_2 = |\mathcal{E}_2| \qquad v_2 = |V_2|$



Explains essentially all the phenomenology of anisotropic flow in large systems.

But more is needed for small or short-lived systems...



[Sousa, Luzum, Noronha, **2002.12735**]

Off-diagonal terms are filled by pre-equilibrium phase over the first fm/c. [Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, **1805.01604**]

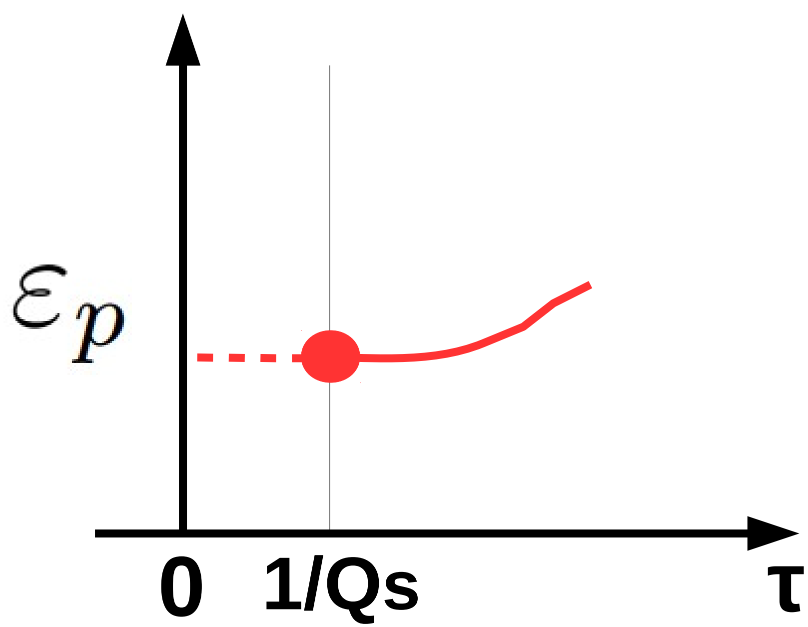
These terms are predicted by the IP-GLASMA framework based on the CGC effective theory.

[Schenke, Shen, Tribedy, **2005.14682**]

Large-scale ellipticity of the tensor modes.

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

In the CGC, it is encoded in the initial system.



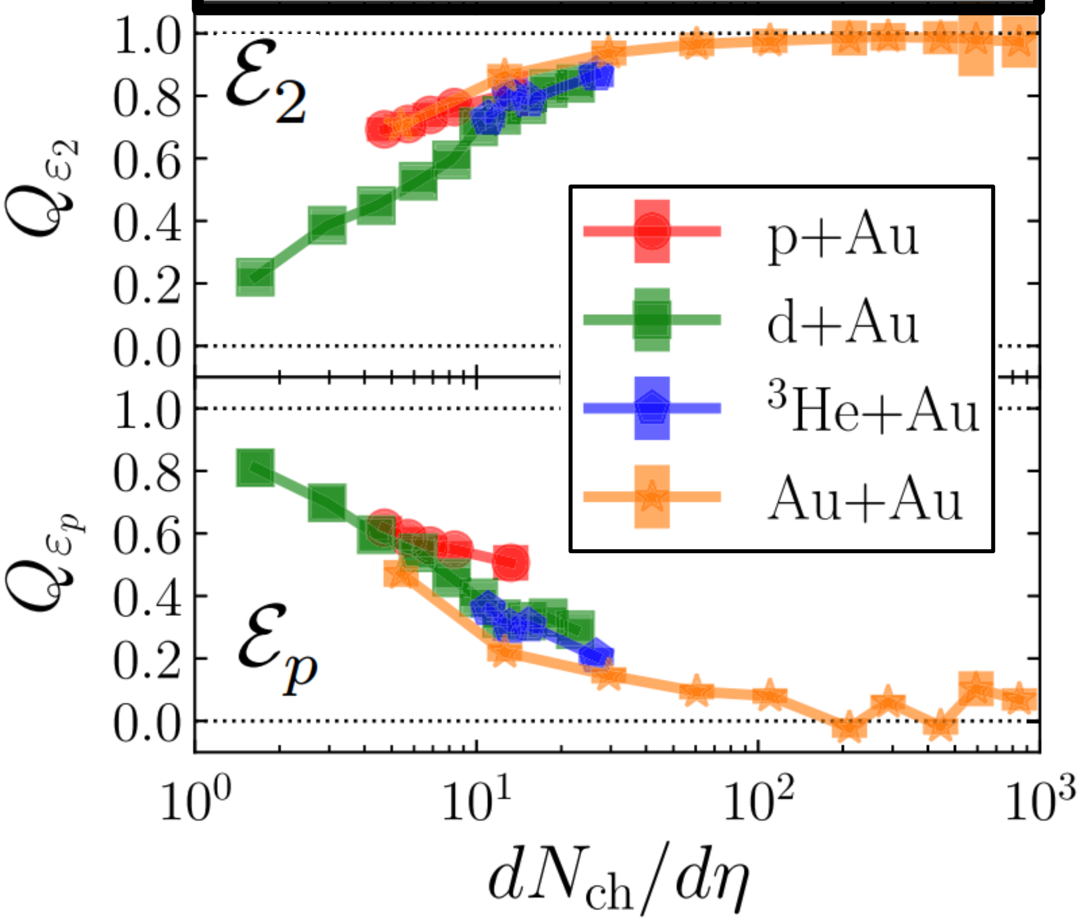
"primordial momentum anisotropy"

genuine CGC prediction

Does it impact the final anisotropy, V_2?

[Schenke, Shen, Tribedy, **1908.06212**]

$$Q_{\mathcal{E}} = \frac{\mathrm{Re}\langle \mathcal{E} V_2^* \rangle}{\sqrt{\langle |\mathcal{E}|^2 \rangle \langle |V_2|^2 \rangle}}$$



- Q coefficient of linear correlation.

- At low multiplicity, V_2 is in a stronger correlation with E_p than with E_2.

Can we see this effect in an observable quantity?

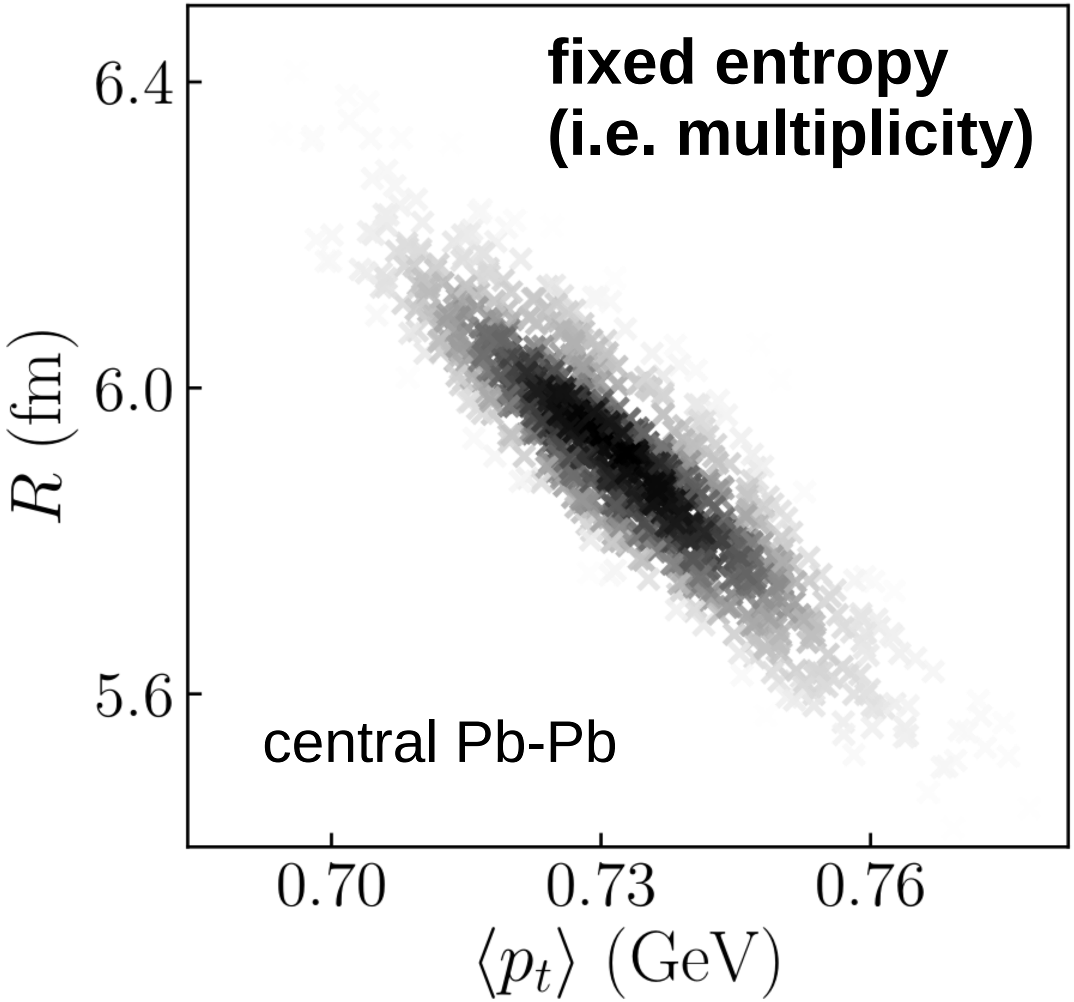
Yes, we can! The observable to study:

[Bozek, 1601.04513]

$$\boxed{\rho_2\left(v_2^2, \langle p_t\rangle\right) = \frac{\langle v_2^2 \langle p_t\rangle\rangle - \langle v_2^2\rangle\langle\langle p_t\rangle\rangle}{\sigma(v_2^2)\sigma(\langle p_t\rangle)}}$$

Statistical (Pearson) correlation between $(v_2)^2$ and <pT>.
It is evaluated at <u>fixed multiplicity</u>.

Elliptic flow correlated with a dimensionful quantity!
Physical meaning?



$$\langle p_t \rangle > \langle\langle p_t \rangle\rangle$$

$\downarrow$

Smaller system, hotter

$$\langle p_t \rangle < \langle\langle p_t \rangle\rangle$$

$\downarrow$

Larger system, colder

[Broniowski, Chojnacki, Obara, **0907.3216**] [Schenke, Shen, Teaney, **2004.00690**]

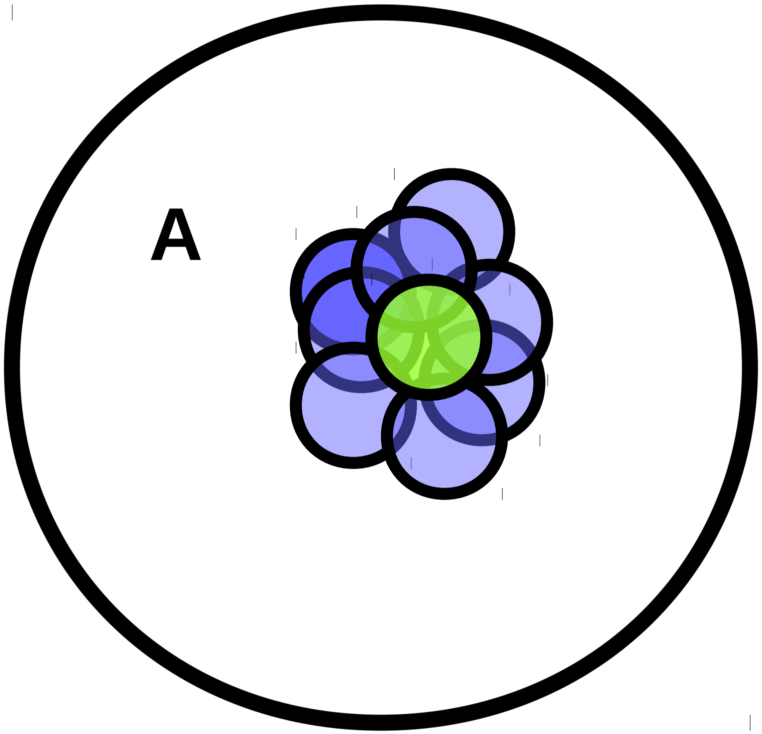
[Giacalone, Gardim, Noronha-Hostler, Ollitrault, **2004.01765**]

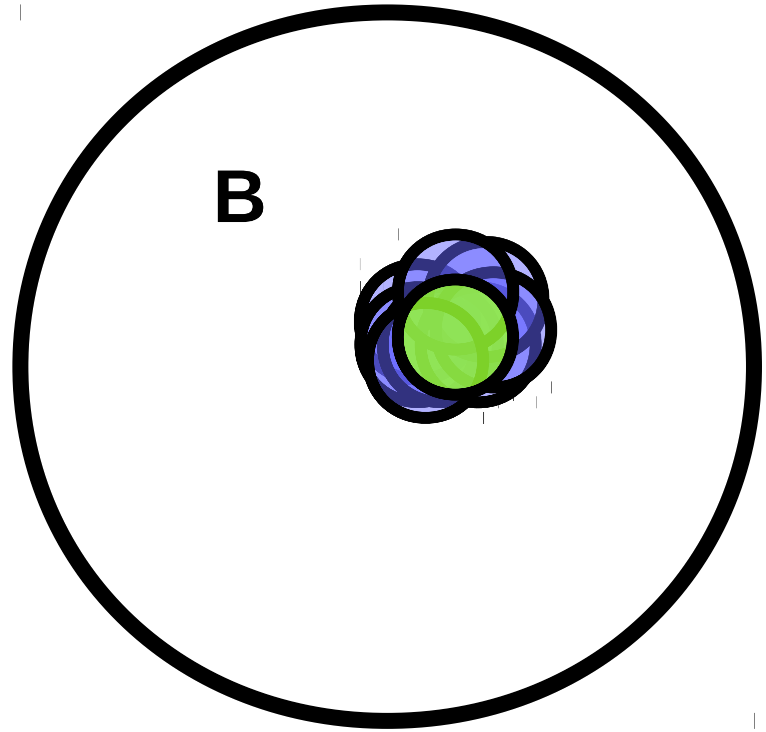
We correlate v_2 with system size/temperature!

We investigate both pA and AA collisions.

pA collisions

Behavior for pA collisions (fixed multiplicity):

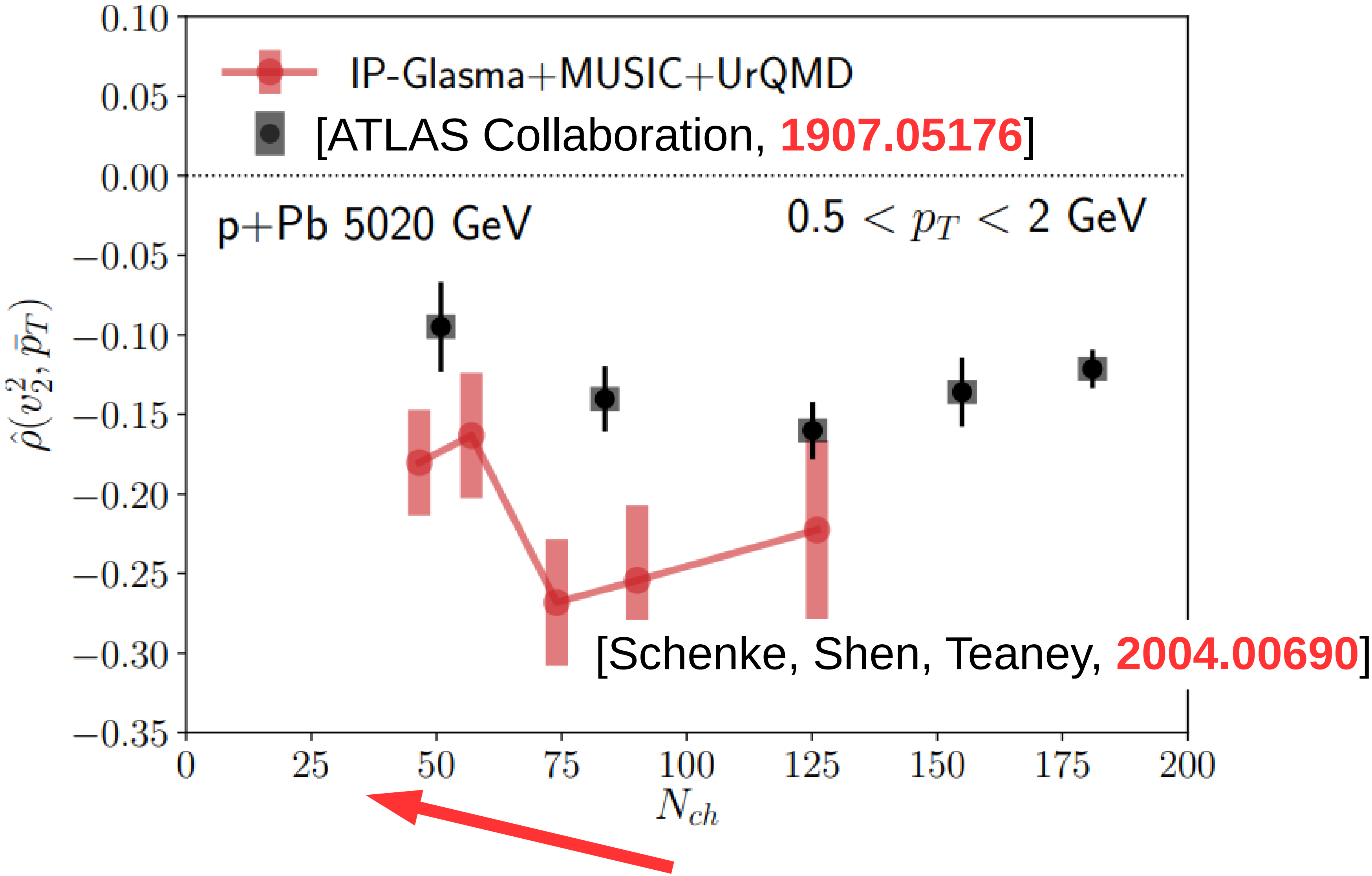




$$R\ (A) > R\ (B)$$
$$\langle p_t \rangle\ (A) < \langle p_t \rangle\ (B)$$
$$\varepsilon_2\ (A) > \varepsilon_2\ (B)$$

$\Longrightarrow$ **v_2 and $\langle p_t \rangle$ are anti-correlated!**

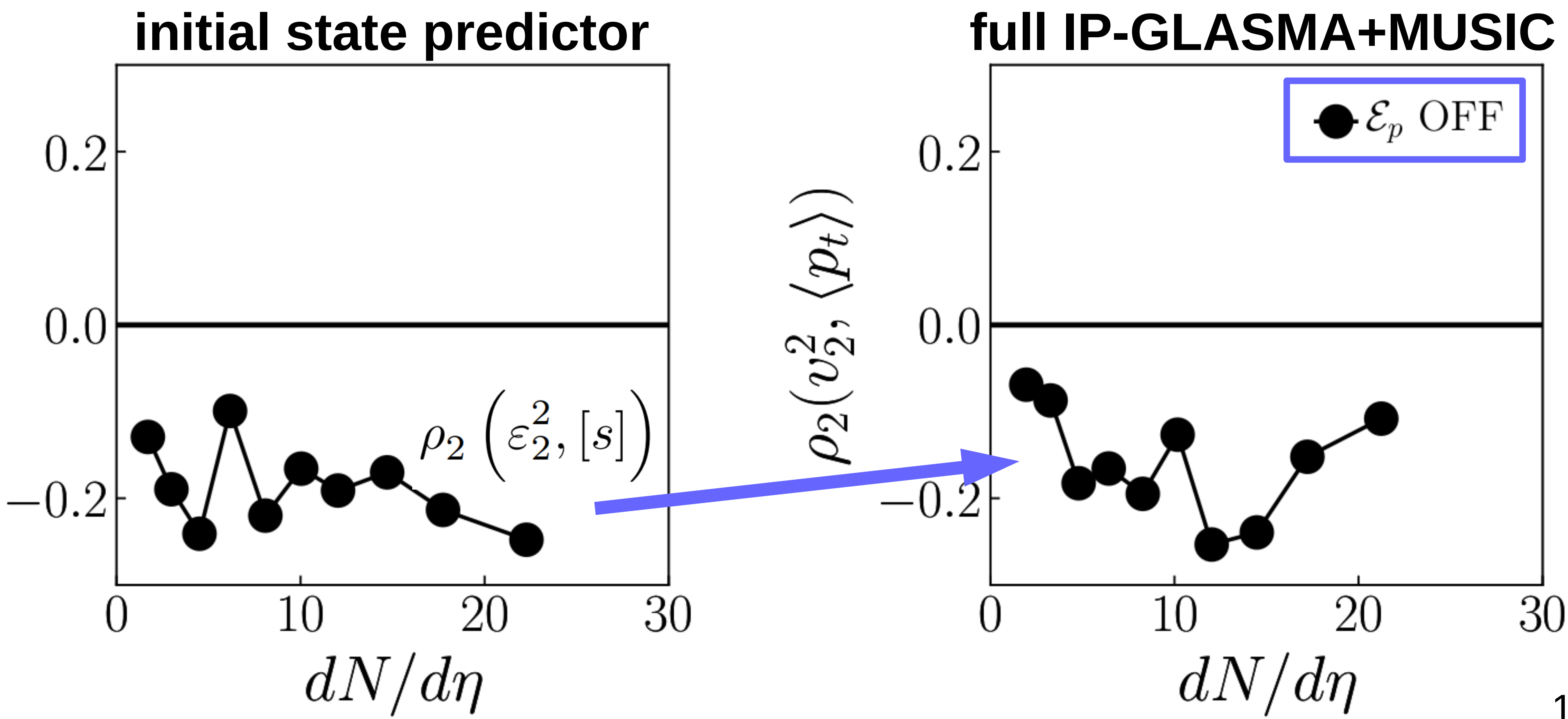
The correlation is indeed negative at moderate/high multiplicity.



What about lower multiplicity?

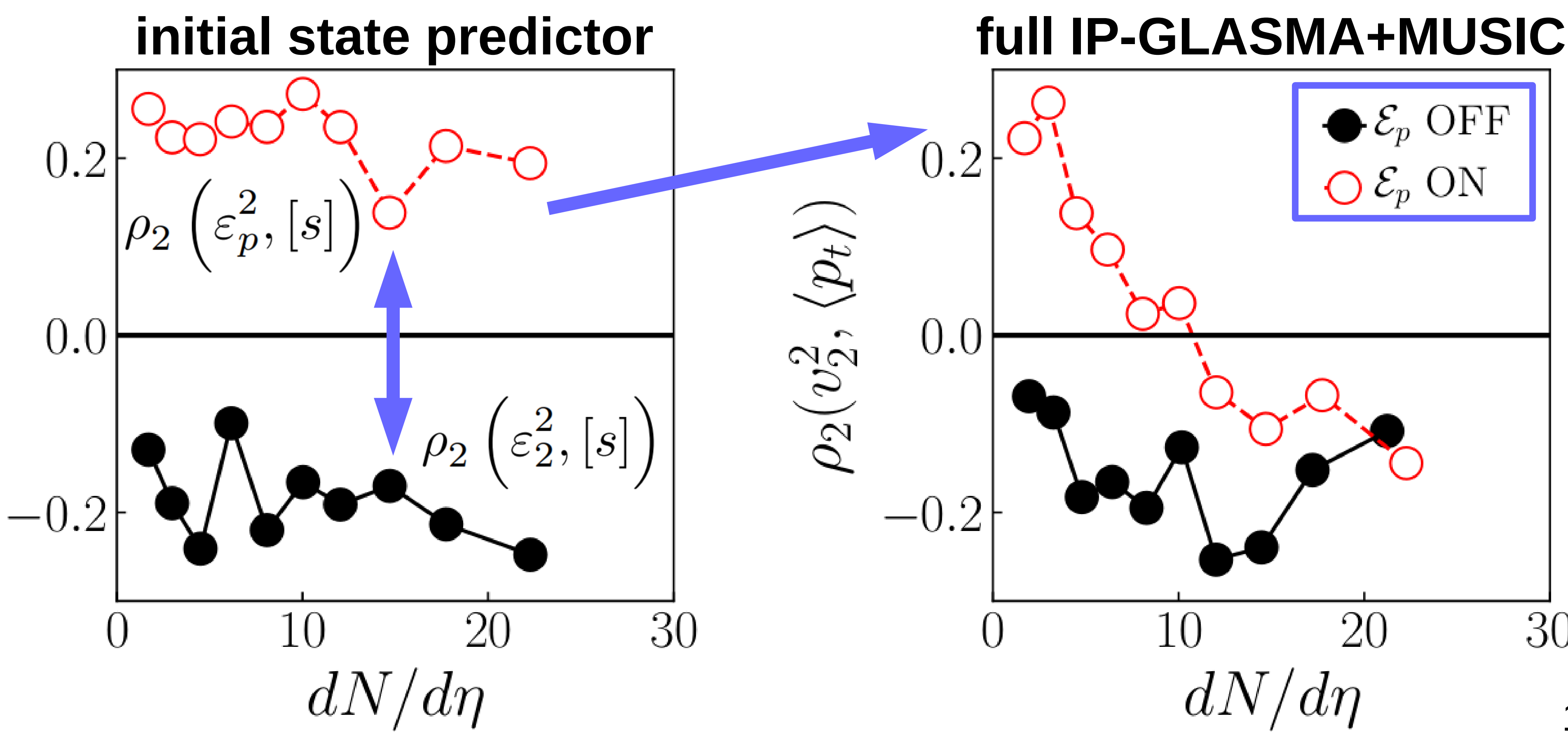
We consider $\langle p_t \rangle \propto [s]$ to understand the results of hydrodynamics.

- **d-Au collisions <u>without</u> initial anisotropy. geometry-based predictor matches full hydro.**

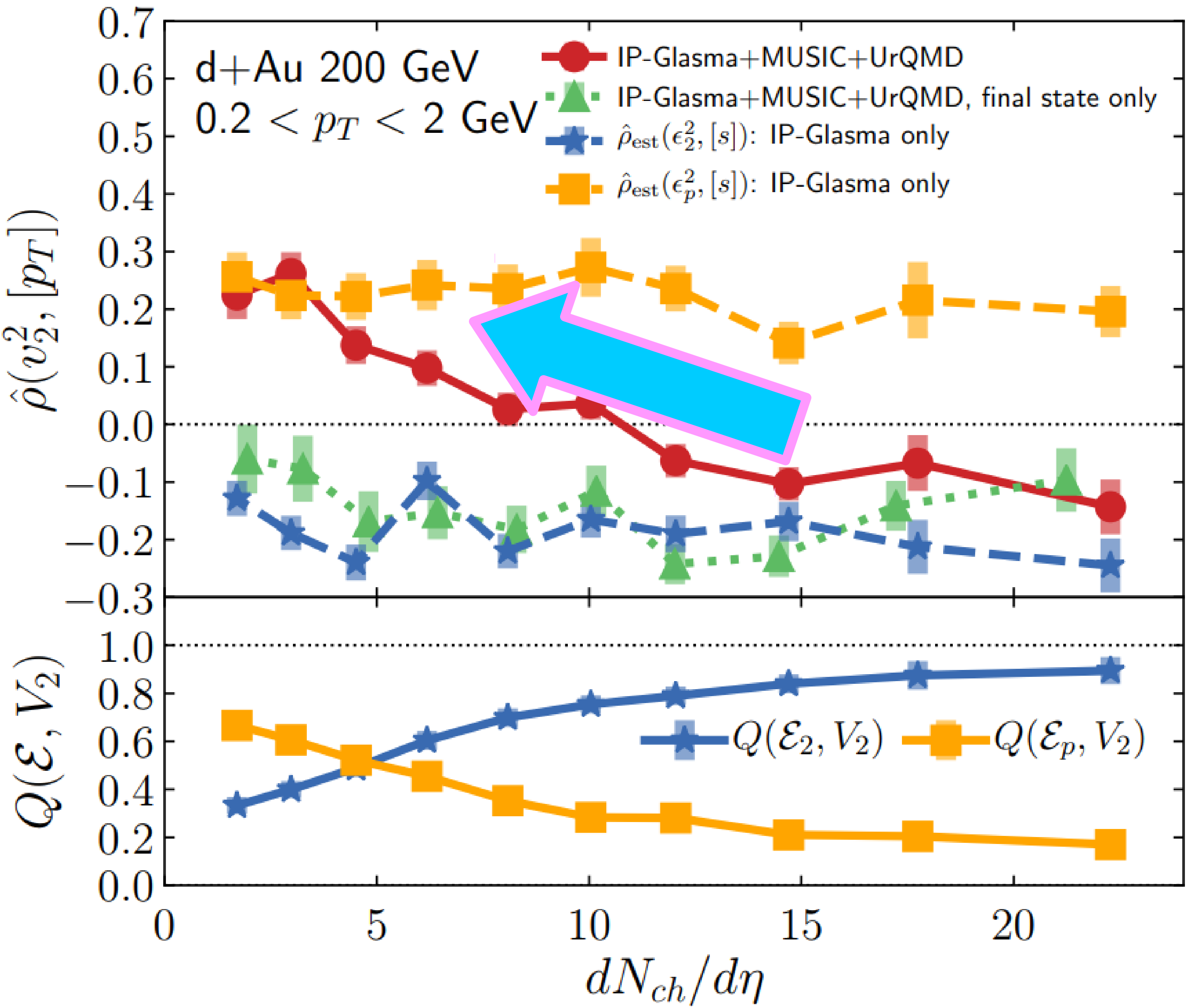


We consider $\langle p_t \rangle \propto [s]$ to understand the results of hydrodynamics.

- **d-Au collisions <u>without</u> initial anisotropy. geometry-based predictor matches full hydro.**
- **<u>with</u> the initial anisotropy the predictor is positive!! Sign change of the correlator at low dN/deta.**

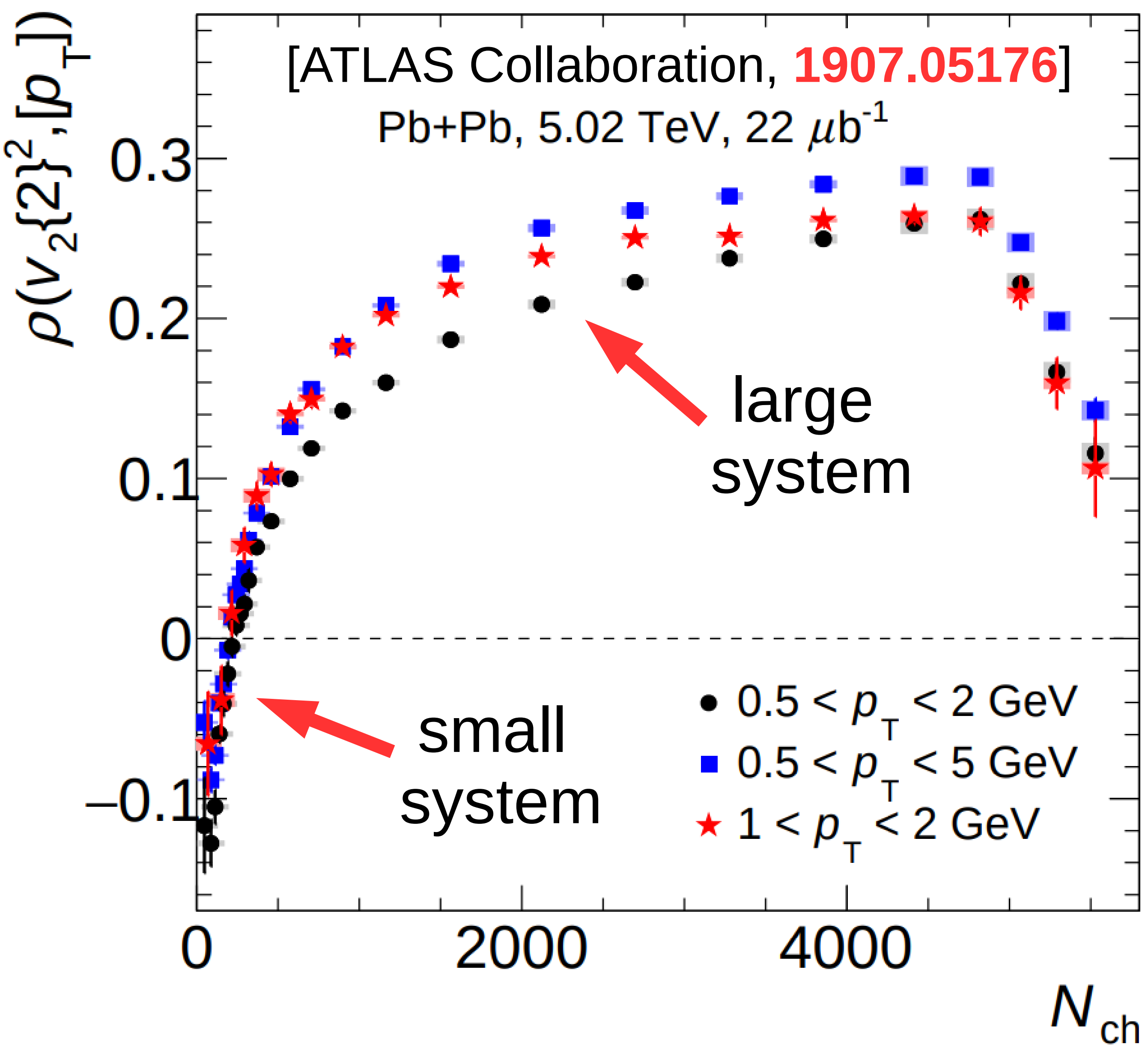


A sign change driven by the primordial momentum anisotropy. Clear prediction!

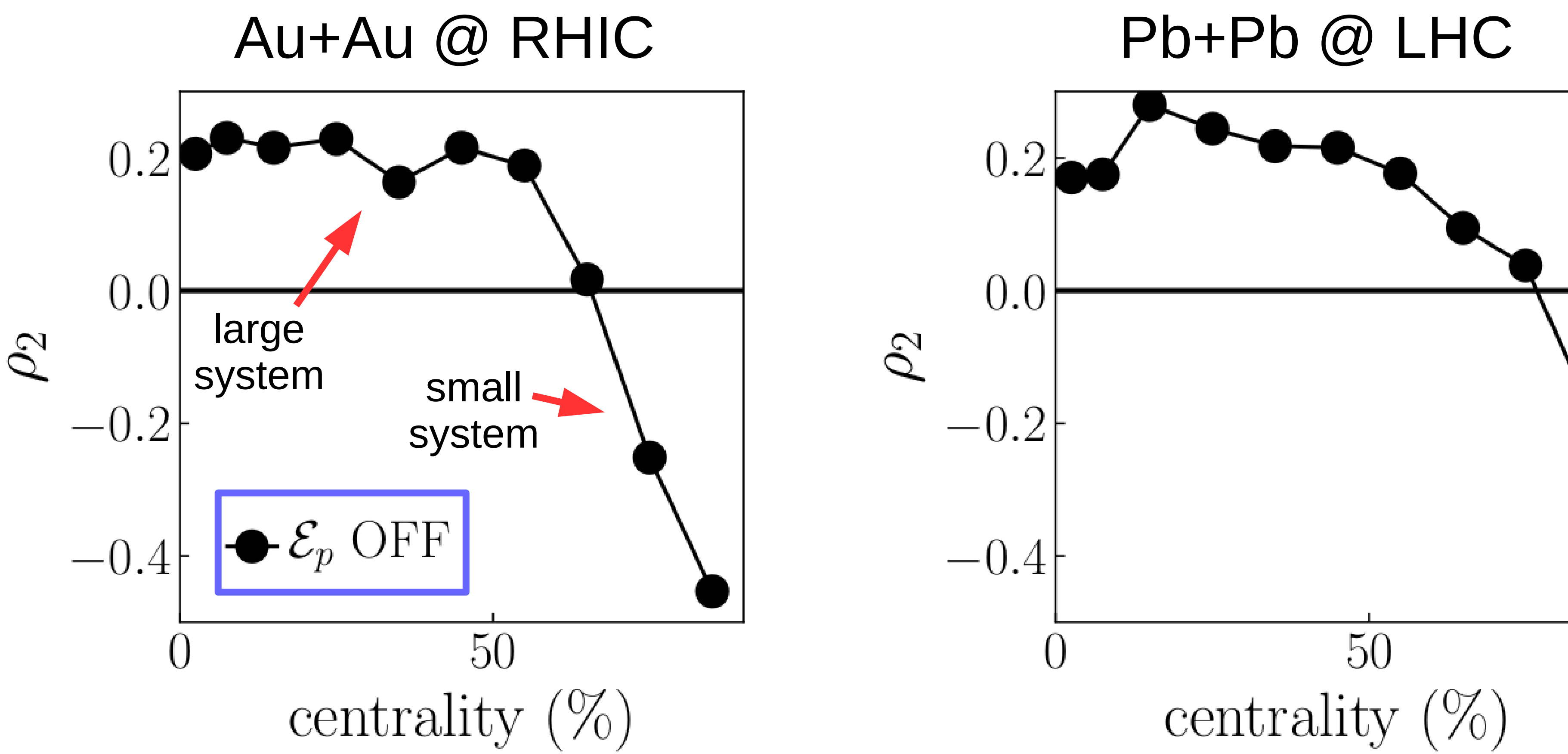


AA collisions

Correlation between v2 and <pT> measured by ATLAS. We understand the centrality dependence.

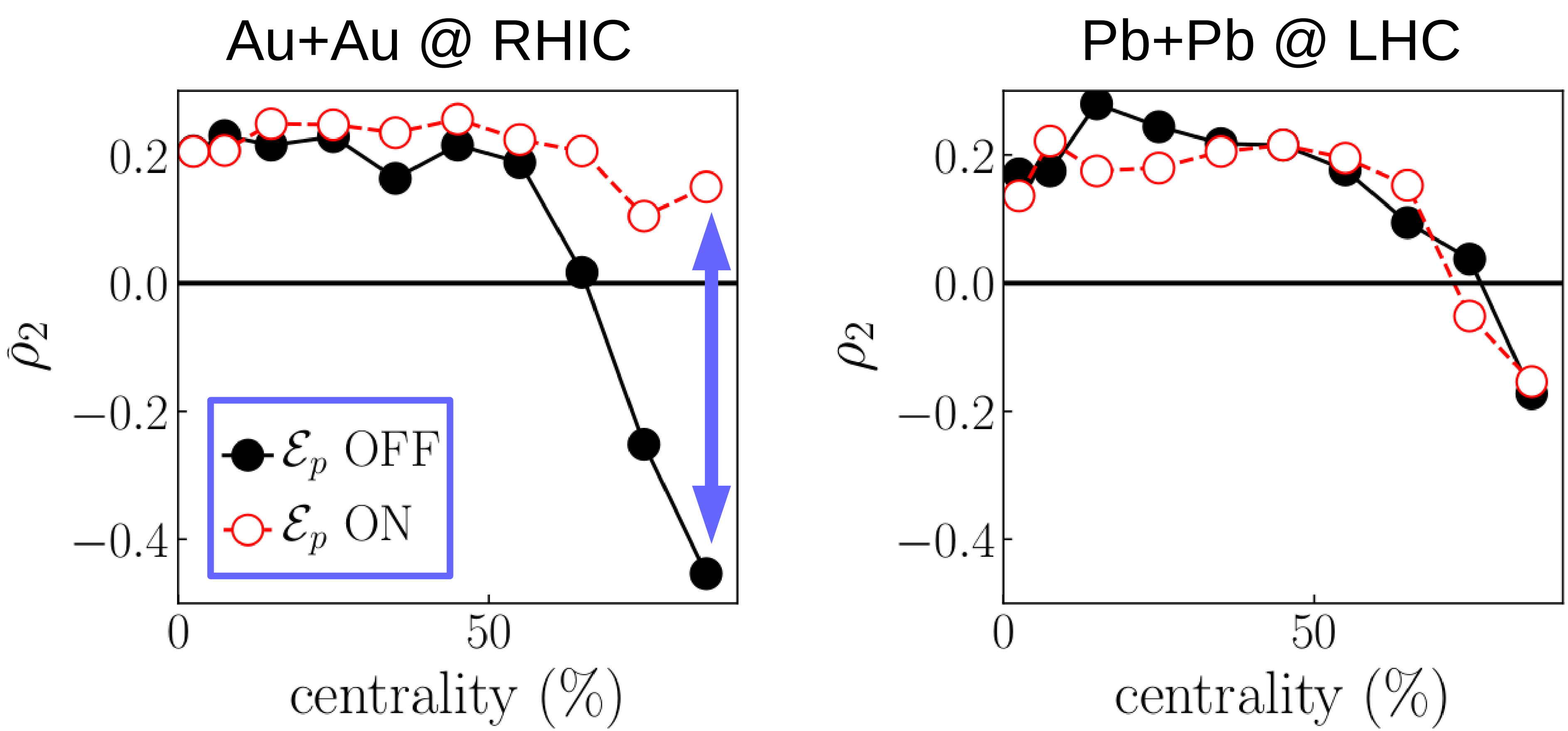


● **Same result in IP-GLASMA+MUSIC w/o off-diagonal terms.**

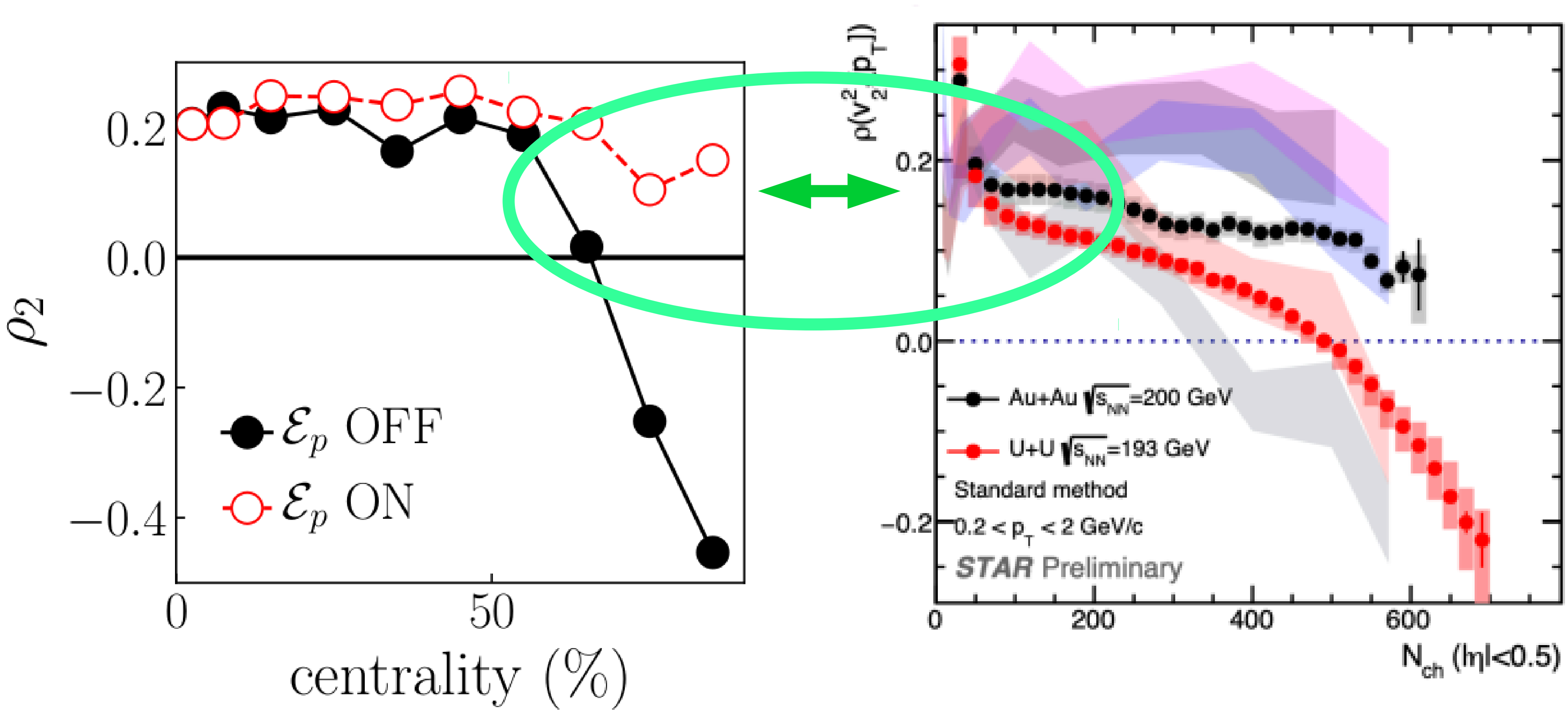


- Same result in IP-GLASMA+MUSIC w/o initial anisotropy.

- Sizable beam energy dependence w/ initial anisotropy!
Change of sign disappears at RHIC energy. A prediction!



Prediction verified at this workshop!



Poster by Chun-Jian Zhang, STAR Collaboration.

https://drive.google.com/file/d/1HukR5k023L1K7C0UT20g5QTg6dXXddgu/view?usp=sharing

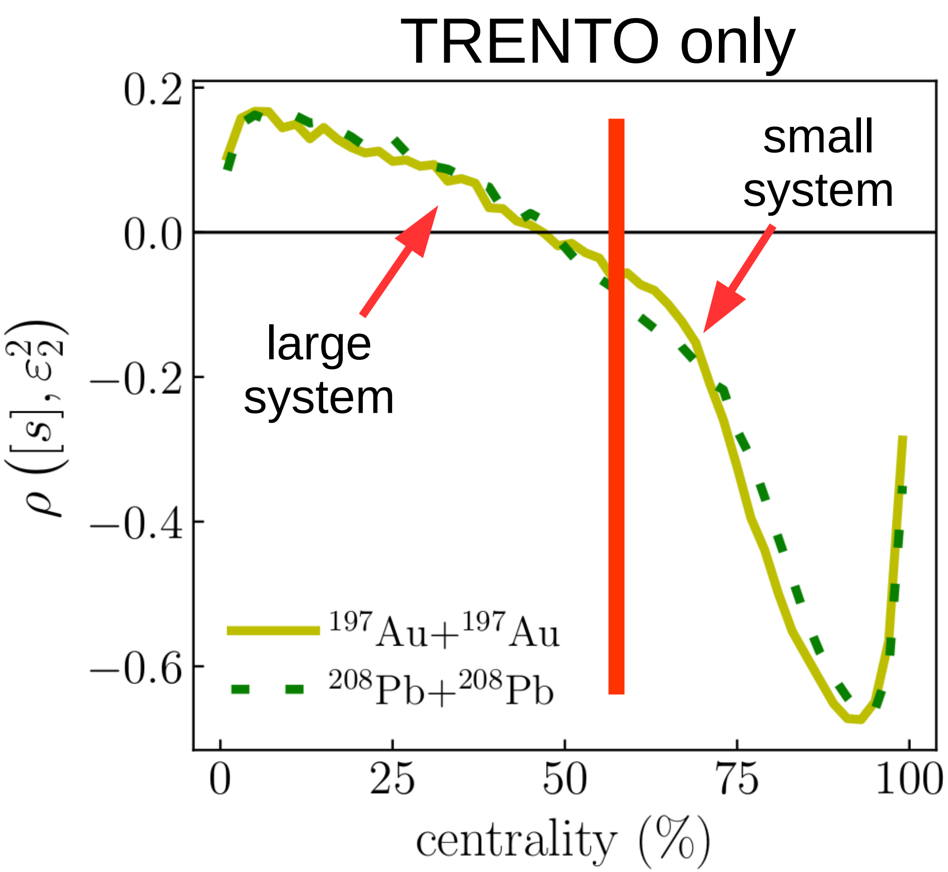
A potential discovery, or nonflow?

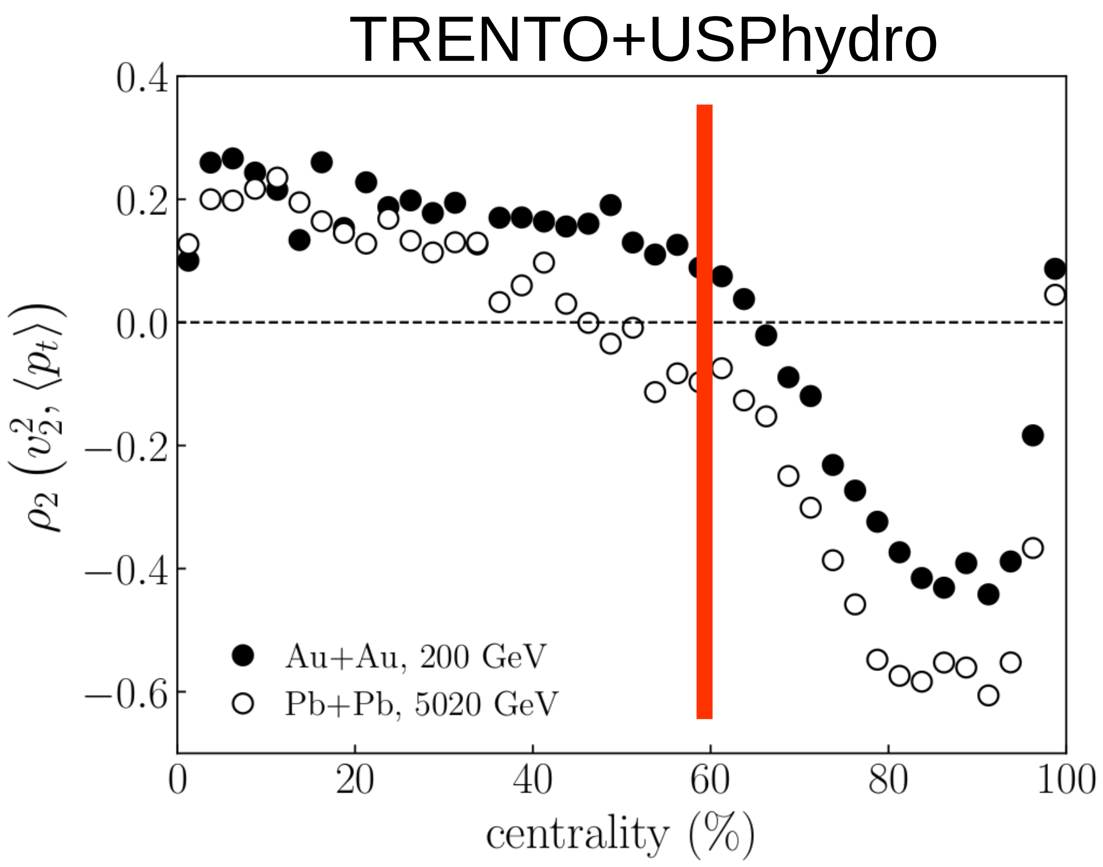
CONCLUSIONS

- Primordial momentum anisotropy predicted by the CGC.
- **Qualitative signatures to be searched for in data on v_2 - <pT> correlation.**
- Change of sign ***appears*** at low multiplicity in pA.
- Change of sign ***disappears*** in peripheral Au-Au.
- **Robust predictions set the basis for future phenomenology of the CGC anisotropy!**

BACKUP

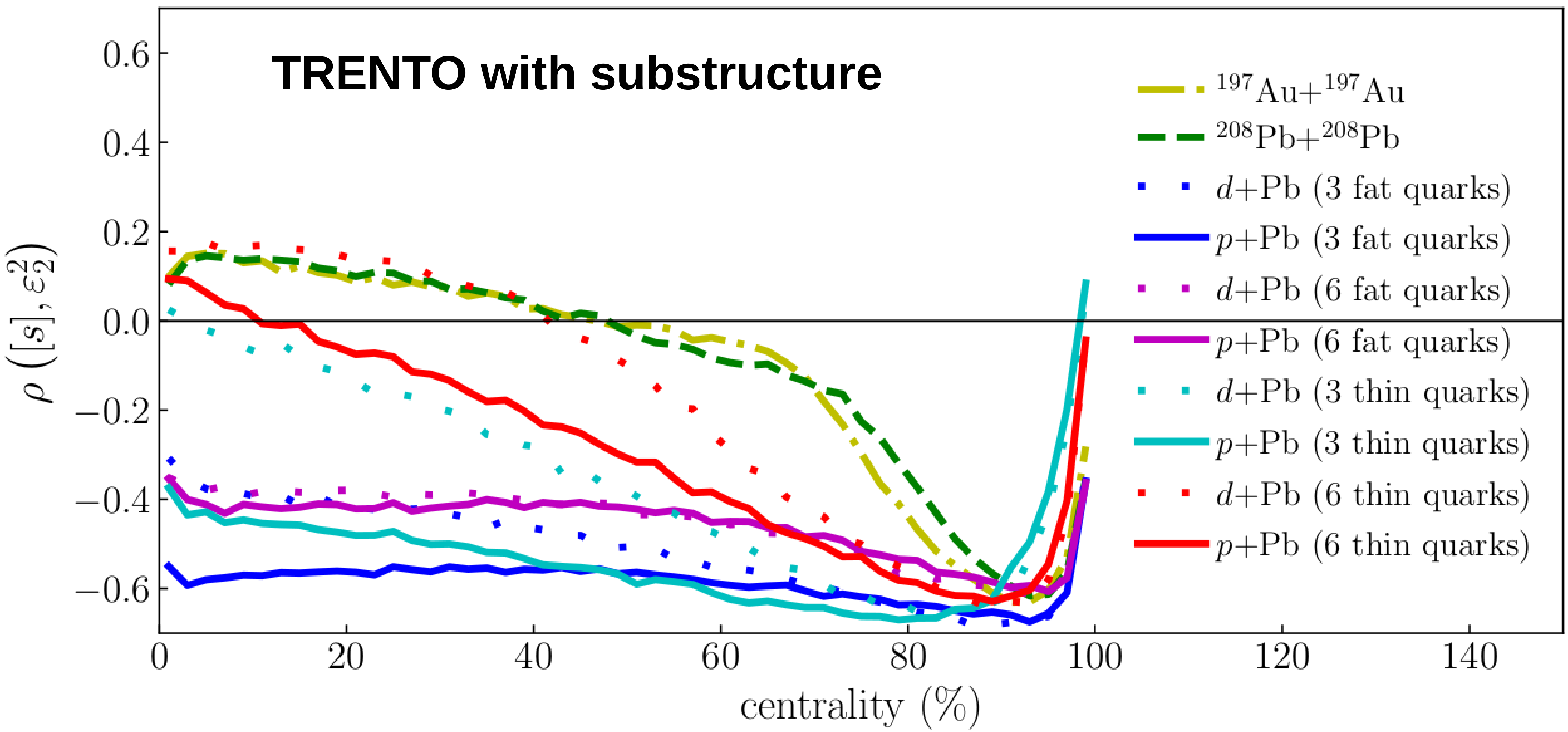
Clear predictions from hydrodynamics **without** initial momentum anisotropy. **NO** beam energy dependence!





[Alba, Mantovani Sarti, Noronha, Noronha-Hostler, Parotto, Portillo Velazquez, Ratti, **1711.05207**]

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



TRENTO with substructure
^{197}Au+^{197}Au
^{208}Pb+^{208}Pb
d+Pb (3 fat quarks)
p+Pb (3 fat quarks)
d+Pb (6 fat quarks)
p+Pb (6 fat quarks)
d+Pb (3 thin quarks)
p+Pb (3 thin quarks)
d+Pb (6 thin quarks)
p+Pb (6 thin quarks)
$\rho\left([s], \varepsilon_2^2\right)$
centrality (%)
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0
20
40
60
80
100
120
140