Momentum anisotropies in the initial stages of heavy-ion collisions: the hunt is on

by

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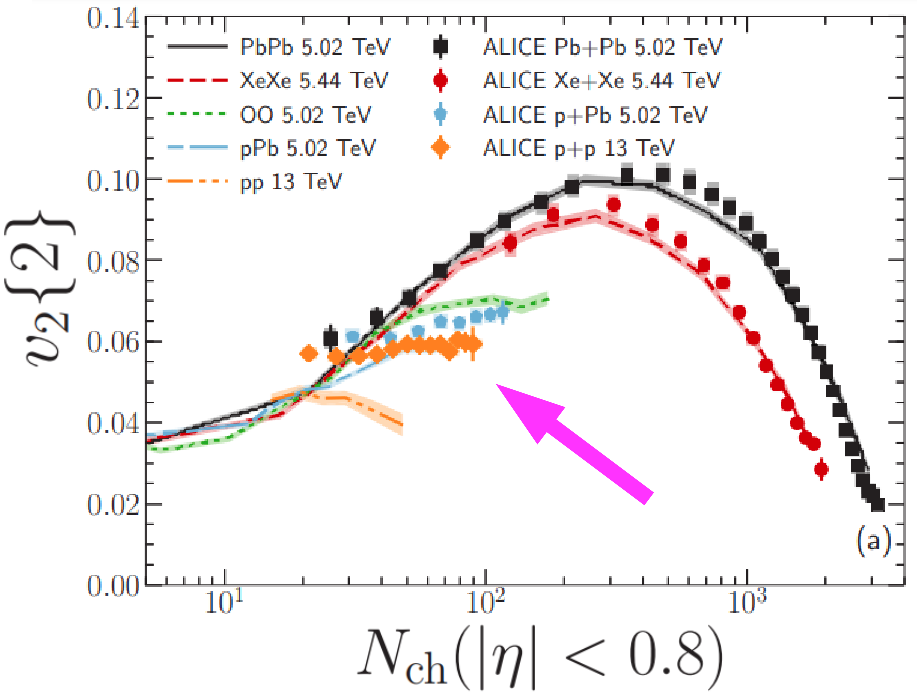
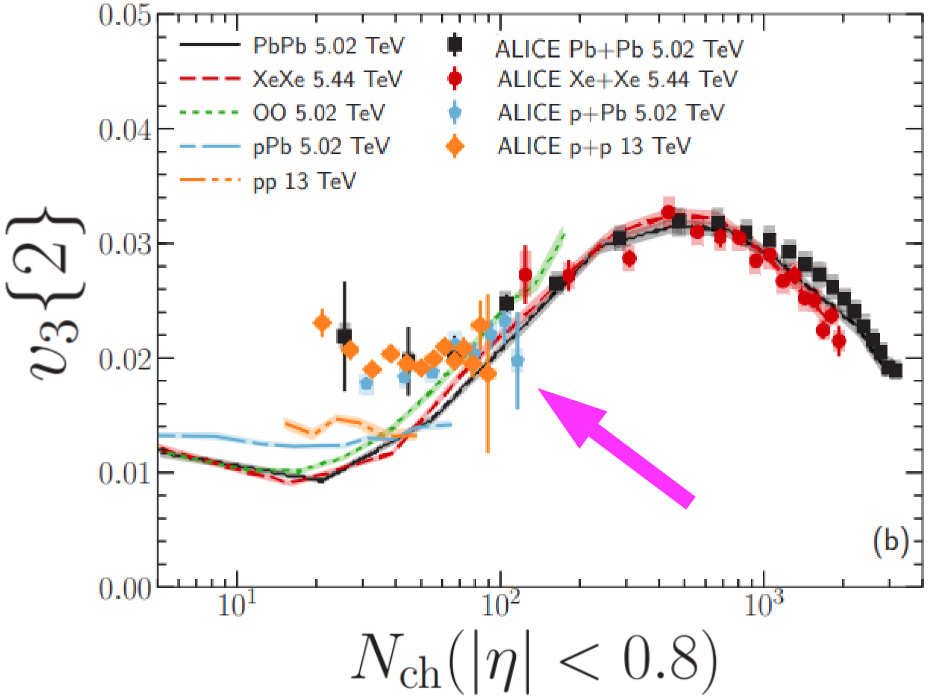
Anisotropic flow is all over the place!





[ALICE Collaboration, 1903.01790]

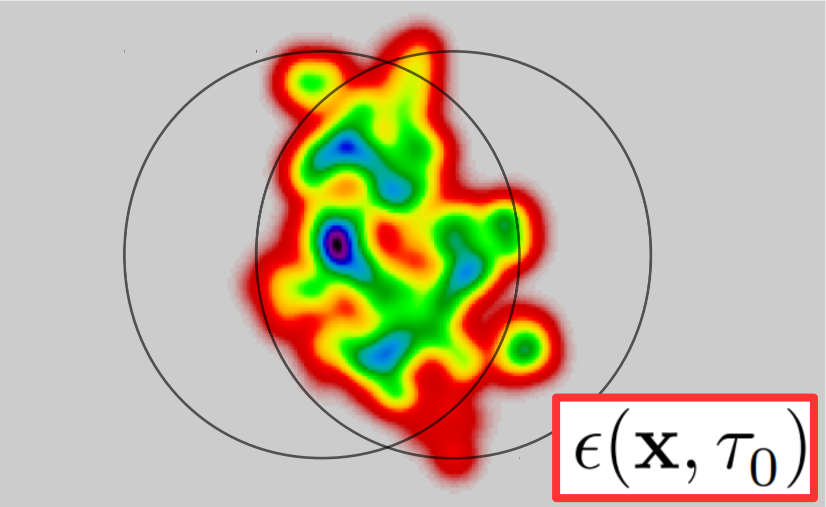
[Schenke, Shen, Tribedy, 2005.14682]

What is its origin?

Anisotropic flow from spatial anisotropies: $F = -\nabla P$

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

[Teaney, Yan, **1010.1876**]



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

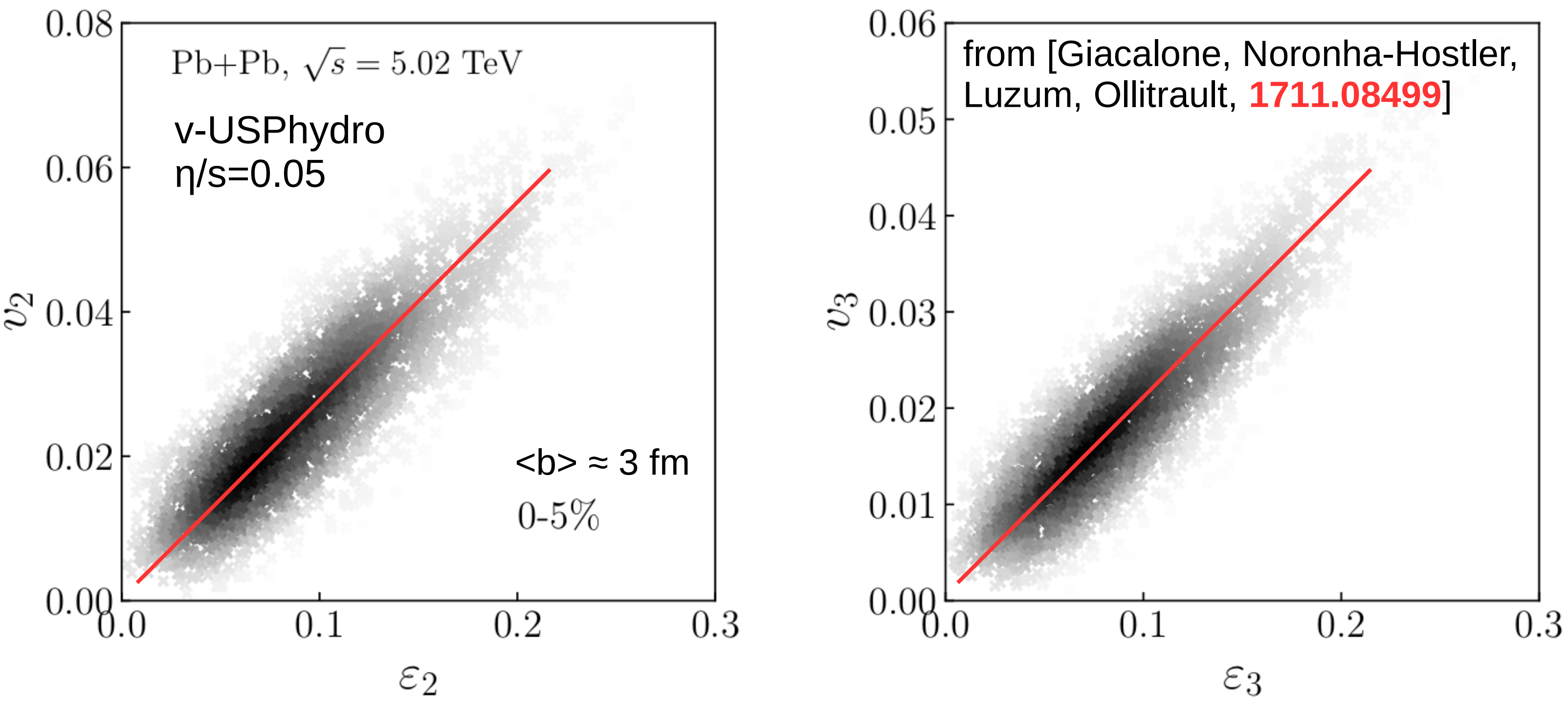
Profile has non-vanishing multipole moments.
They source anisotropic flow:

$$\mathcal{E}_n \propto \int r^n e^{in\phi} \epsilon(r, \phi)$$

$$V_n \propto \mathcal{E}_n$$

Relation is simple: $V_n \propto \mathcal{E}_n$

Verified in full hydrodynamic simulations ($\varepsilon_n = |\mathcal{E}_n|$, $v_n = |V_n|$)



Explains experimental data in both large and small systems.

The importance of initial conditions. [Giacalone, Noronha-Hostler, Ollitrault, 1702.01730]

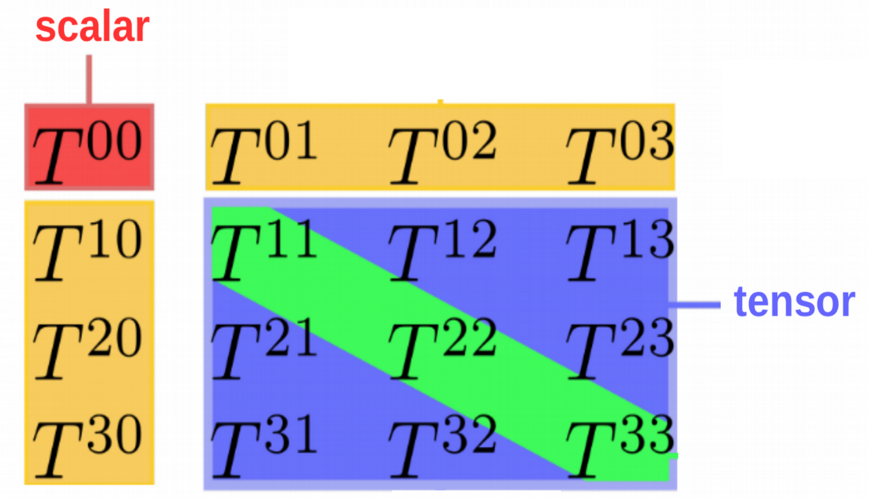
Going beyond F = - ∇P.

The **primordial** energy-momentum tensor contains more structures.

“MOMENTUM” ANISOTROPIES

$$\mathcal{E}_{2p} \propto \langle T^{xx} - T^{yy} + 2iT^{xy} \rangle$$

$$\mathcal{E}_{3p} \propto \left\langle r e^{i\phi} \left(T^{xx} - T^{yy} + 2iT^{xy} \right) \right\rangle$$



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

Off-diagonal terms are filled by pre-equilibrium phase over the first fm/c.

[Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, **1805.00961,1805.01604**]

[Schlichting, Teaney, **1908.02113**]

Only known theory that predicts these terms is the color glass condensate (CGC).
Longstanding question in the field: <u>do we see initial-state CGC anisotropy in the data?</u>

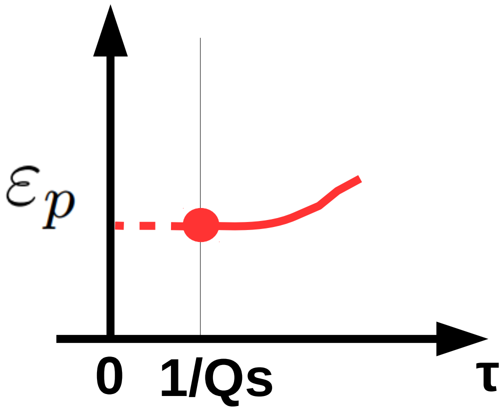
[Altinoluk, Armesto, **2004.08185**]

Evaluations in the IP-GLASMA+MUSIC+urQMD framework.

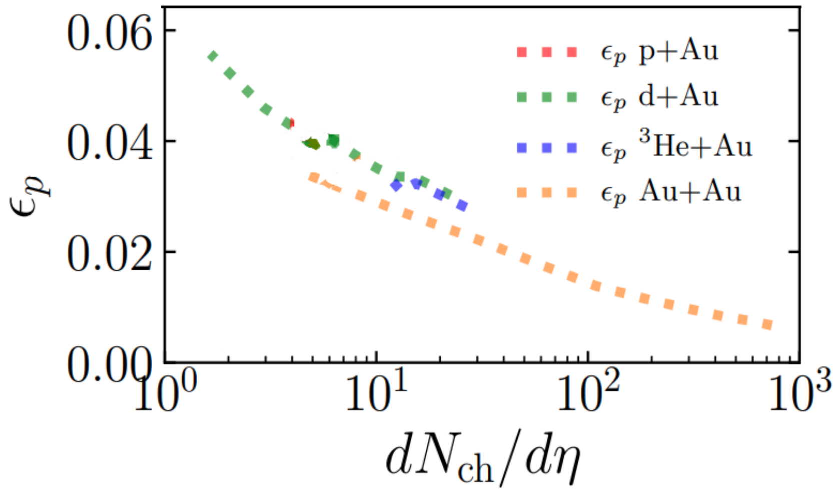
System is anisotropic (n=2) shortly after the collision.

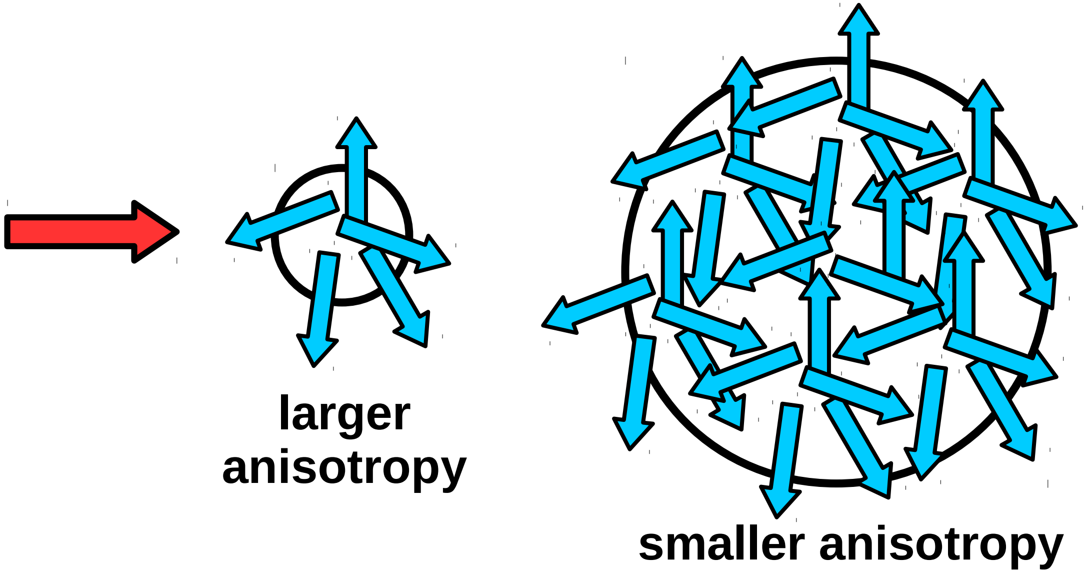
$$\mathcal{E}_p \equiv \varepsilon_p e^{i2\Psi_2^p} \equiv \frac{\langle T^{xx} - T^{yy}\rangle + i\langle 2T^{xy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$$

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



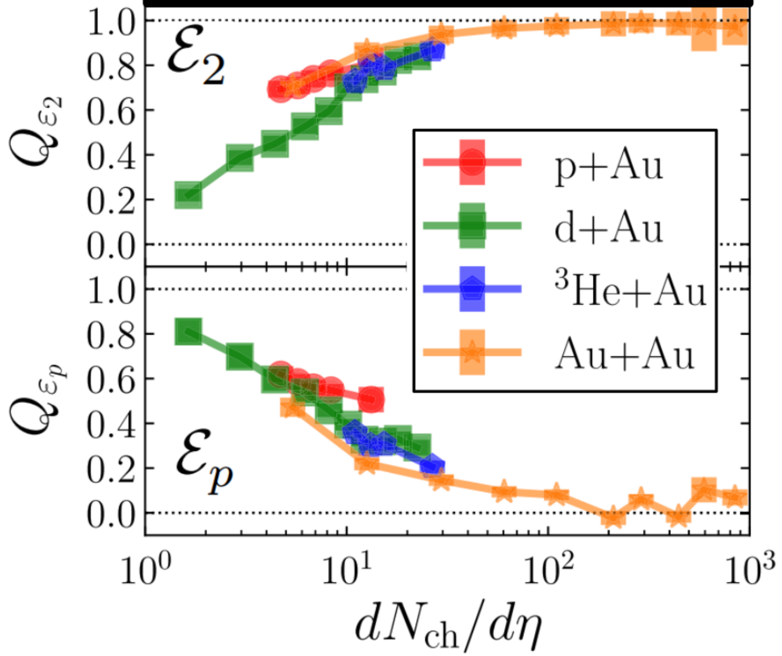
Salient property: system-size dependence.





Does the primordial anisotropy play a role?

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



– Q coefficient of linear correlation.

– E_2 is the dominant contribution to V_2 for $dN/d\eta \geq 20$.

– At low multiplicity, V_2 is instead in a stronger correlation with E_p.

[Schenke, Shen, Tribedy, 1908.06212]

What <u>observables</u> can reveal this transition and probe ε_p?

I use two observables in small systems.

– Bożek's correlation between <p_t> and v_n^2 :

[Bożek, 1601.04513]

1. $$\rho(v_n^2, [p_t]) = \frac{\langle \delta v_n^2 \delta [p_t] \rangle}{\sqrt{\langle (\delta v_n^2)^2 \rangle \langle (\delta [p_t])^2 \rangle}}$$

– ALICE's correlation between v_2^2 and v_3^2:

[ALICE collaboration, 1604.07663]

2. $$\mathrm{Nsc}(3,2) = \frac{\langle \delta v_2^2 \delta v_3^2 \rangle}{\sqrt{\langle (\delta v_2^2)^2 \rangle \langle (\delta v_3^2)^2 \rangle}}$$

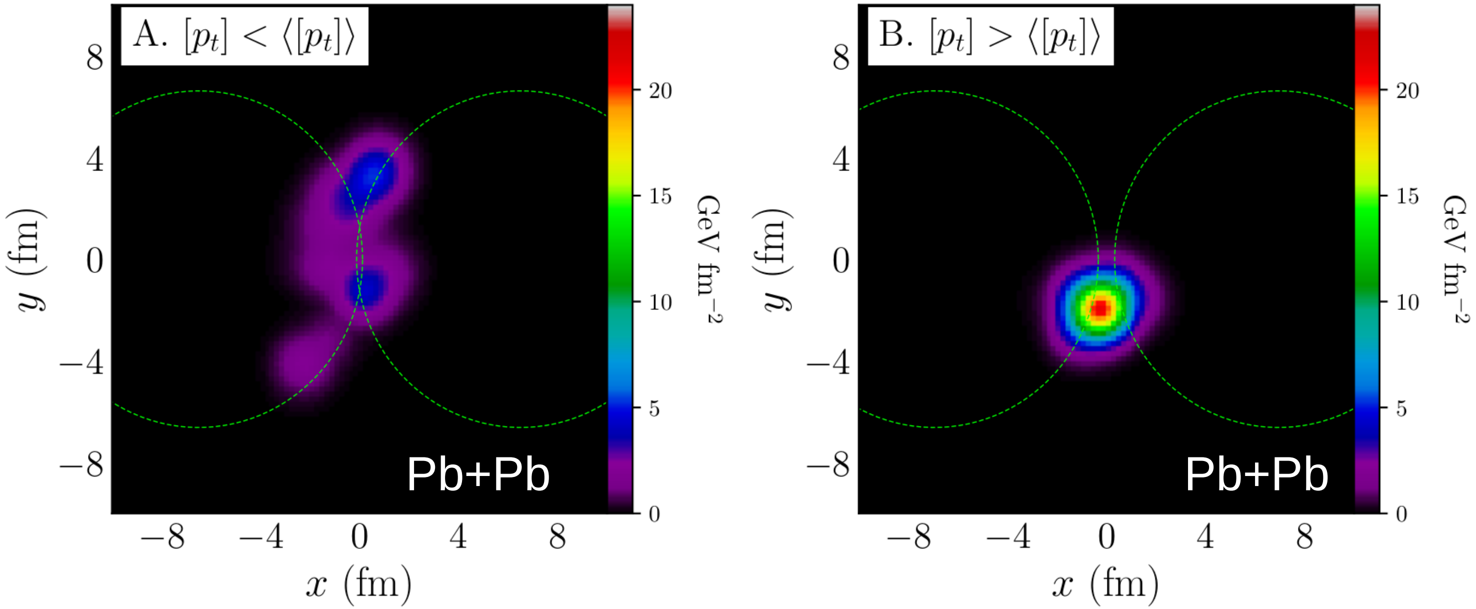
With $\delta o = o - \langle o \rangle$ at fixed multiplicity (entropy).

These are natural probes of the primordial momentum anisotropies.

1.

Select two **peripheral events** (69-70%) at the **same multiplicity** but very **different [pt].**

It is an “isentropic” transformation of the QGP which increases T and reduces R**.**



event	A	B
N_{ch}	134	134
b (fm)	13.0	13.9
$[p_t]/\langle [p_t] \rangle$	0.907	1.143
R (fm)	2.97	1.34
ε_2	0.675	0.133
ε_3	0.229	0.067

<u>@large [pt]:</u> hot spots clustered around one transverse point. Very round system.

<u>Prediction.</u> In small systems:

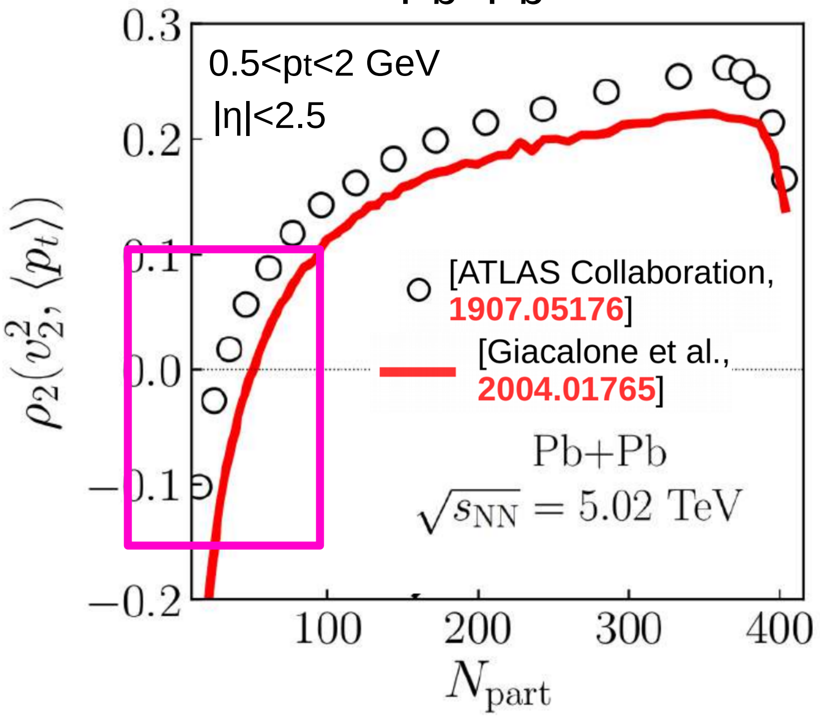
$$\boxed{\rho(v_2^2, [p_t]) < 0}$$

[Bożek, Mehrabpour, 2002.08832]

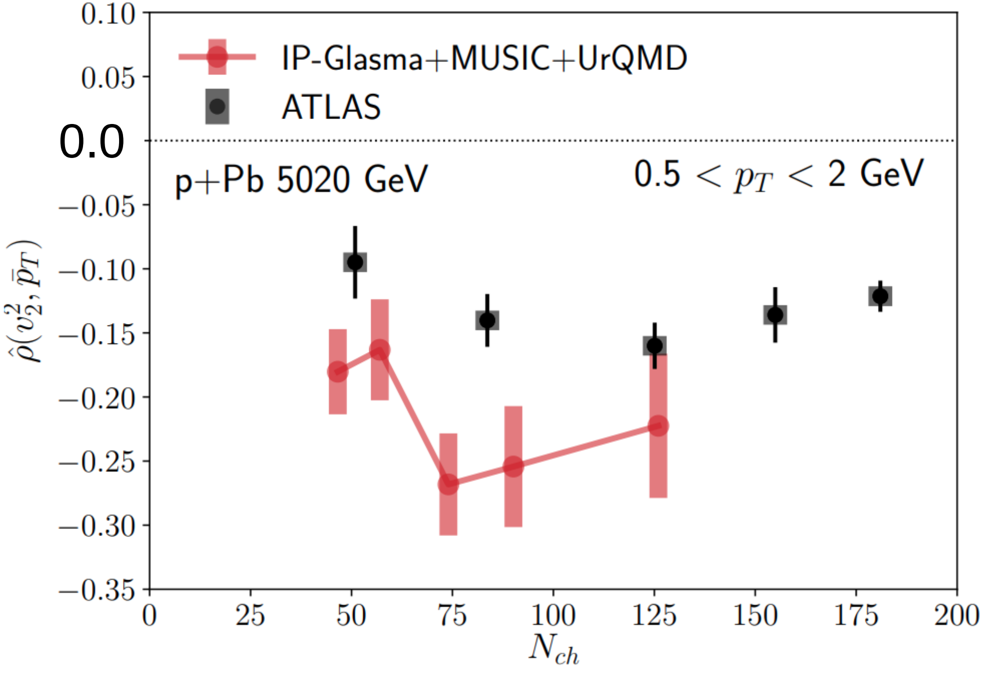
[Schenke, Shen, Teaney, 2004.00690]

Verified at LHC. Correlation is negative. Captured by hydrodynamic models.

Pb+Pb

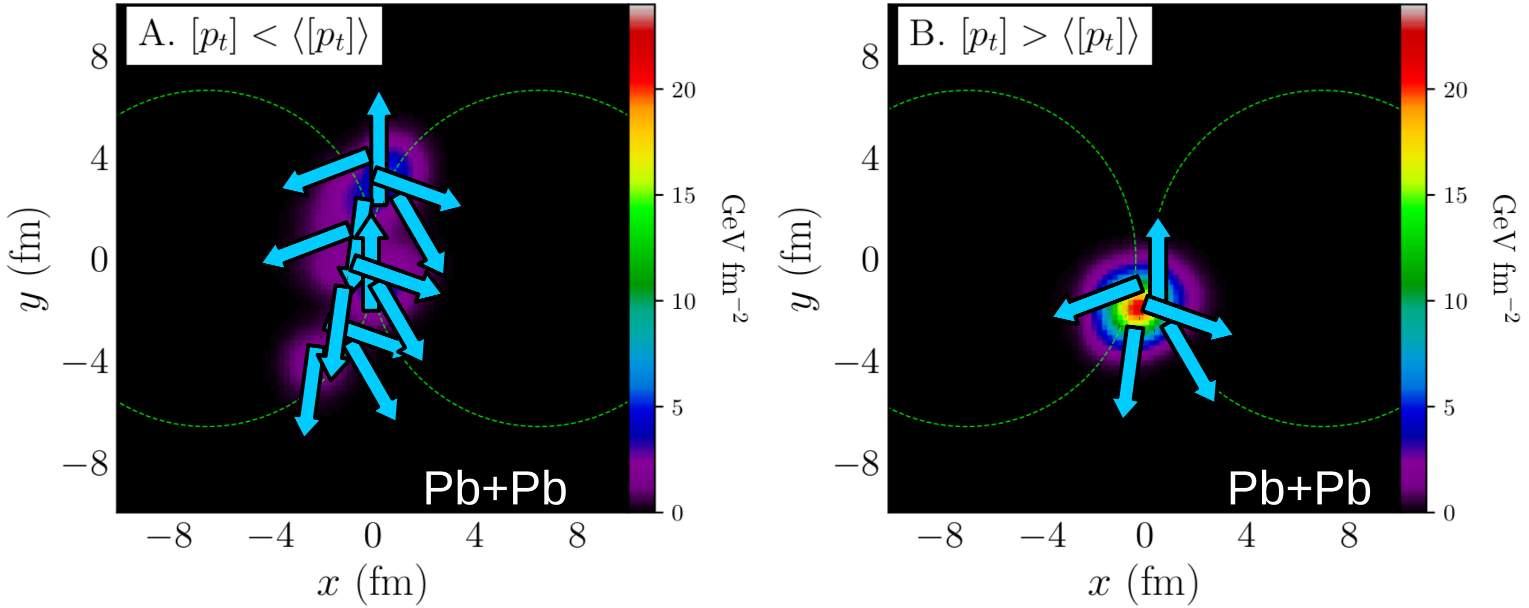


p+Pb



[Schenke, Shen, Teaney, 2004.00690]

What about the initial momentum anisotropy? Intuitive picture.



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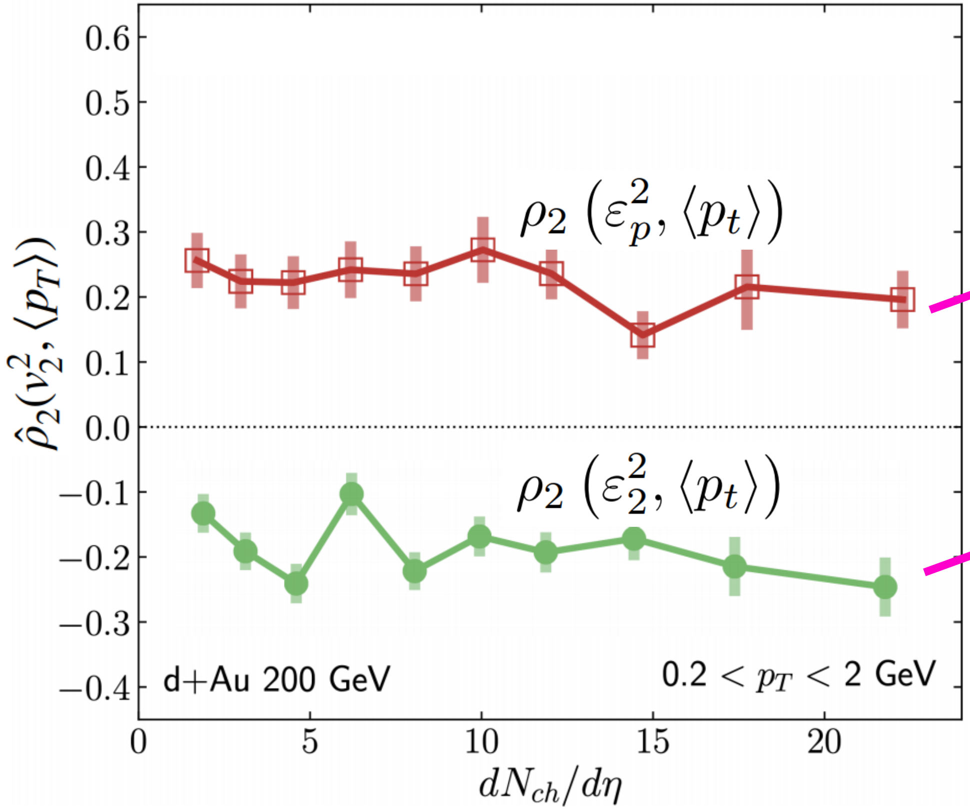
@large [pt]: hot spots clustered around one transverse point. Smaller size, more ε_p.

Prediction. In small systems: $\boxed{\rho(\varepsilon_p^2, \langle p_t \rangle) > 0}$

Consider $V_2 = \kappa_2 \mathcal{E}_2 + \kappa_p \mathcal{E}_p$, we expect:

$$\boxed{\rho(v_2^2, [p_t]) = \kappa_2^2 \rho(\varepsilon_2^2, [p_t]) + \kappa_p^2 \rho(\varepsilon_p^2, [p_t])}$$



Analyze the contributions separately:

Positive!
Confirms the intuitive picture.
<u>A new feature of high-energy QCD.</u>

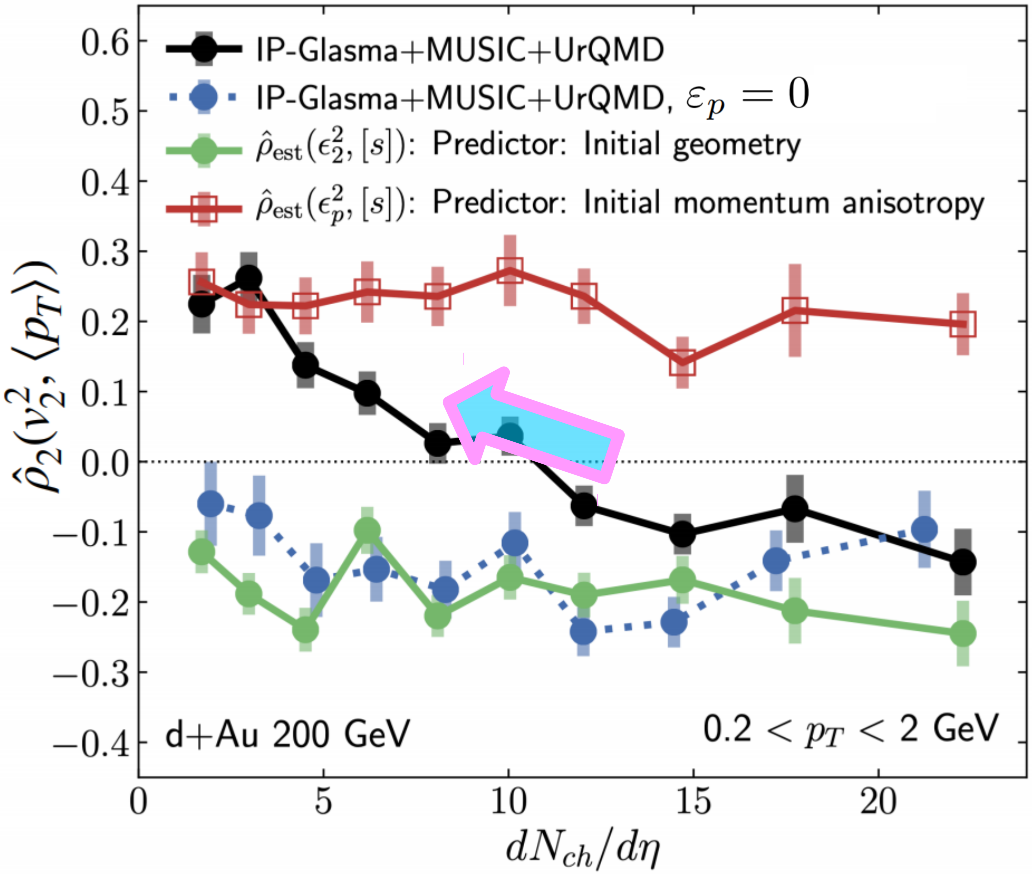
Negative. As expected.

The contributions are qualitatively different.

[Giacalone, Schenke, Shen, 2006.15721]

IP-Glasma+Hydro: full prediction.

[Giacalone, Schenke, Shen, 2006.15721]



– Sign change occurring as expected around dN/dη=10.
A neat prediction (both AA and pA).

– **No sign change if we set Ep=0.**

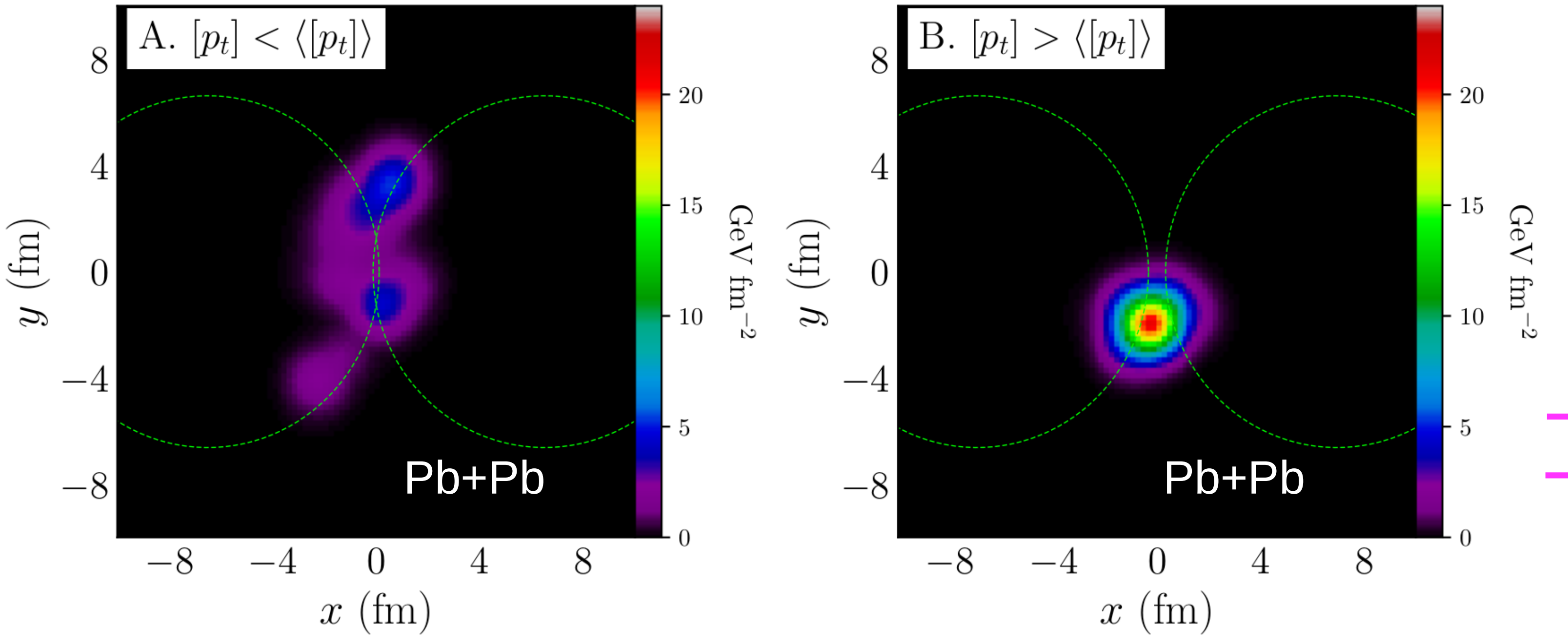
– **Non-flow has to be addressed carefully in future measurements.**

[Behera, Bhatta, Jia, Zhang, 2102.05200]

[Lim, Nagle, 2103.01348]

2.

Select two **peripheral events** (69-70%) at the **same multiplicity** but very **different [pt].**



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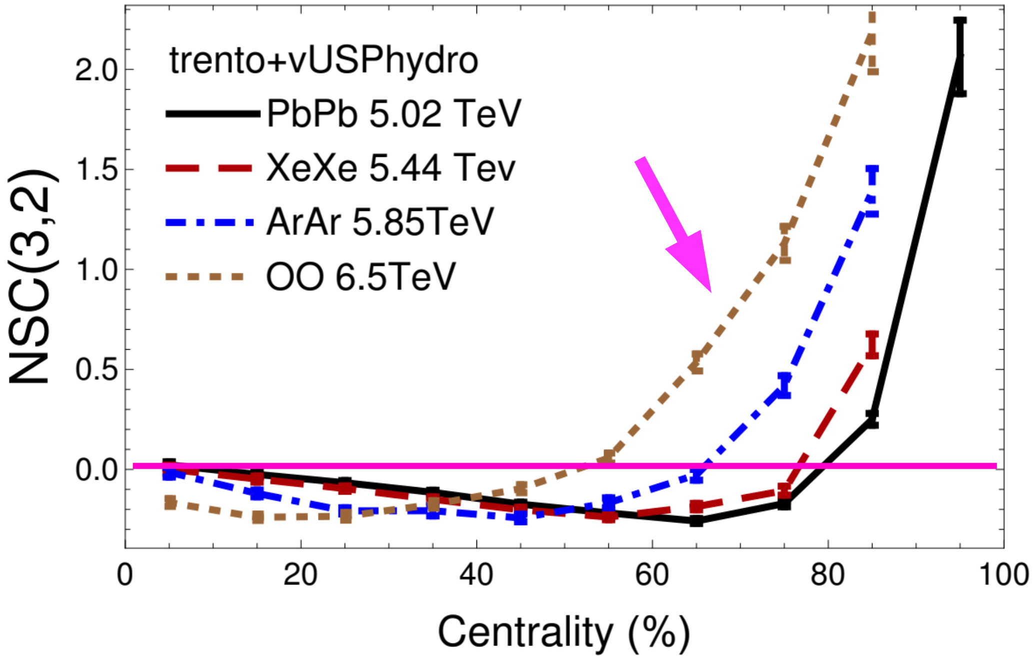
@large [pt]: hot spots clustered around one transverse point. **Both ε2 and ε3 decrease!**

Prediction. In small systems: $\boxed{\rho(v_2^2, v_3^2) > 0}$

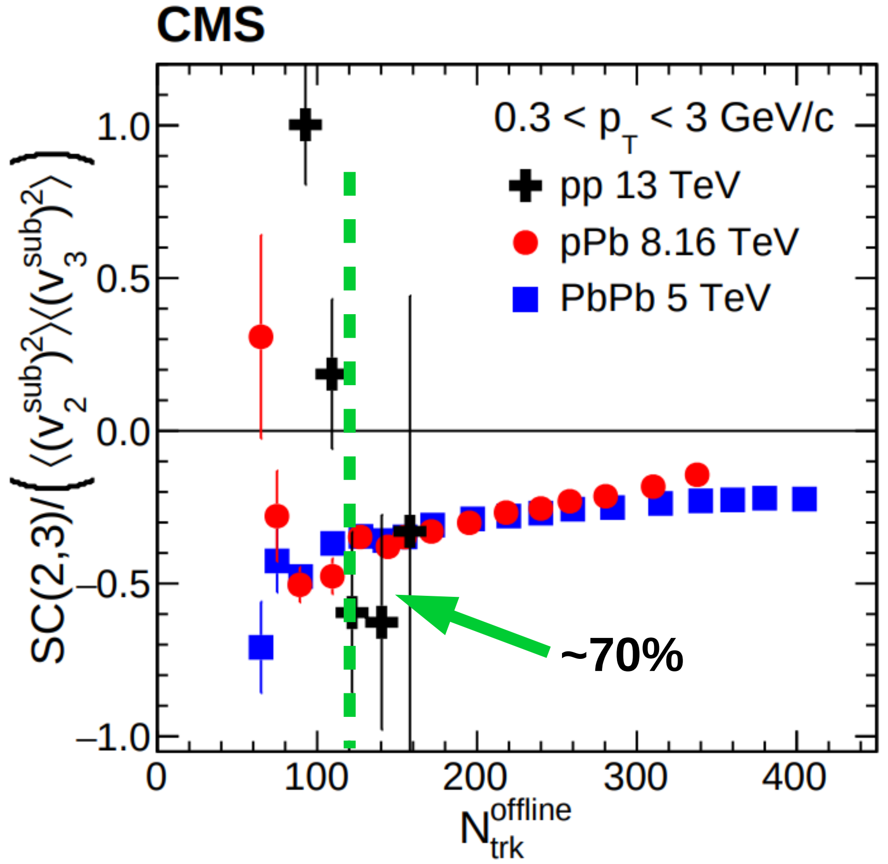
Confirmed in hydro…

[Noronha-Hostler, Sievert 1901.01319]



Include full Tμυ?

…but data?



[CMS Collaboration, 1709.09189, 1905.09935]

[ATLAS Collaboration, 1807.02012]

Consider now the correlation between V2 and V3. Very simple model:

$$V_2 = \kappa_2 \mathcal{E}_2 + \kappa_{2p} \mathcal{E}_{2p}$$
$$V_3 = \kappa_3 \mathcal{E}_3 + \kappa_{3p} \mathcal{E}_{3p}$$

Evaluate the symmetric cumulant. **Expectations from system size dependence:**

$$\langle V_2 V_2^* V_3 V_3^* \rangle - \langle V_2 V_2^* \rangle \langle V_3 V_3^* \rangle =$$

geometry-geometry | geometry-momentum | geometry-momentum | momentum-momentum

$$\boxed{\kappa_2^2 \kappa_3^2 \left(\langle \varepsilon_2^2 \varepsilon_3^2 \rangle - \langle \varepsilon_2^2 \rangle \langle \varepsilon_3^2 \rangle \right)} + \boxed{\kappa_2^2 \kappa_{3p}^2 \left(\langle \varepsilon_2^2 \varepsilon_{3p}^2 \rangle - \langle \varepsilon_2^2 \rangle \langle \varepsilon_{3p}^2 \rangle \right) + \kappa_{2p}^2 \kappa_3^2 \left(\langle \varepsilon_{2p}^2 \varepsilon_3^2 \rangle - \langle \varepsilon_{2p}^2 \rangle \langle \varepsilon_3^2 \rangle \right) + \kappa_{2p}^2 \kappa_{3p}^2 \left(\langle \varepsilon_{2p}^2 \varepsilon_{3p}^2 \rangle - \langle \varepsilon_{2p}^2 \rangle \langle \varepsilon_{3p}^2 \rangle \right)}$$

POSITIVE | **NEGATIVE** | **NEGATIVE** | POSITIVE (?)

Prediction: initial momentum anisotropies yield a negative contribution to sc(3,2).

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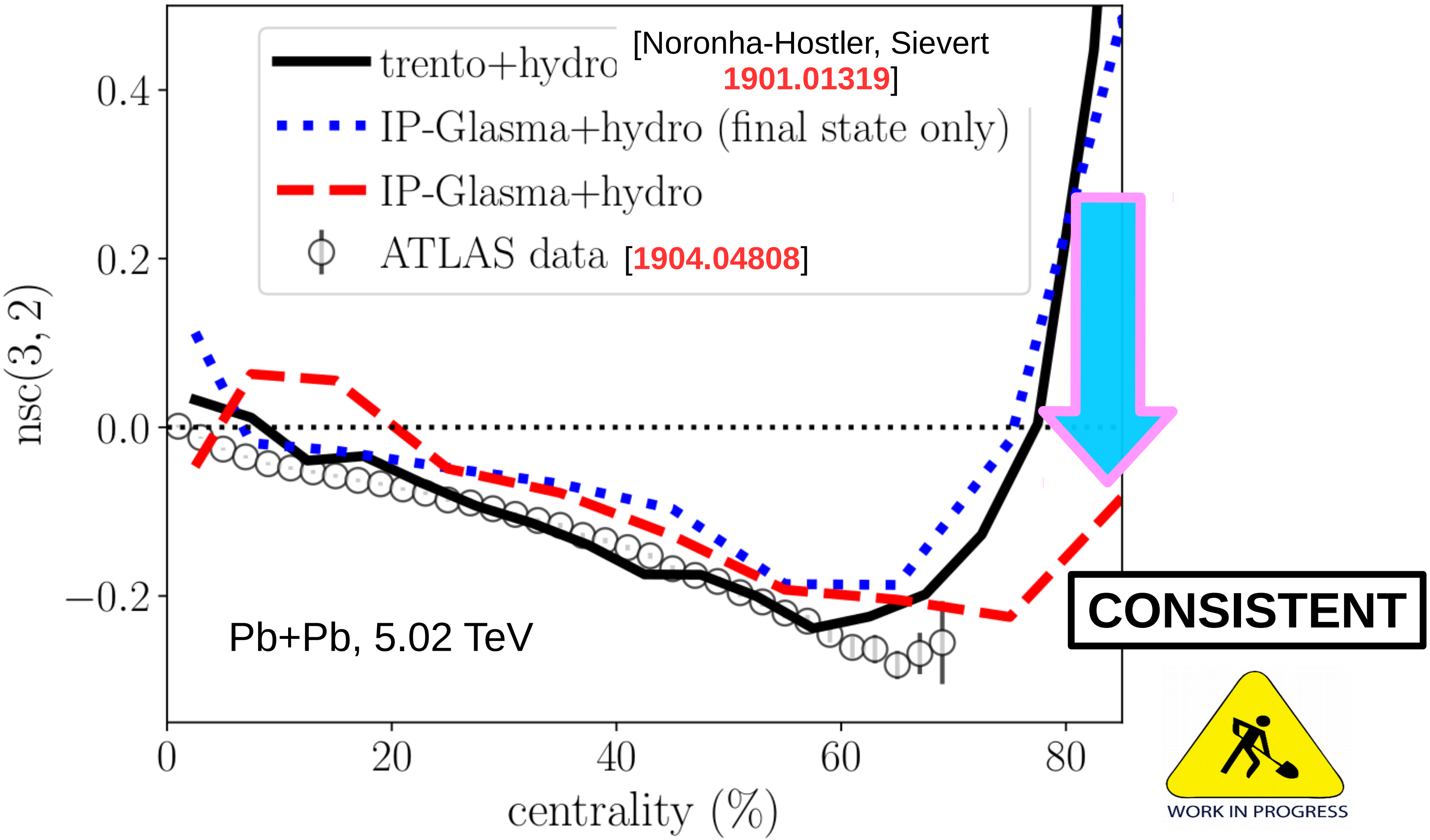


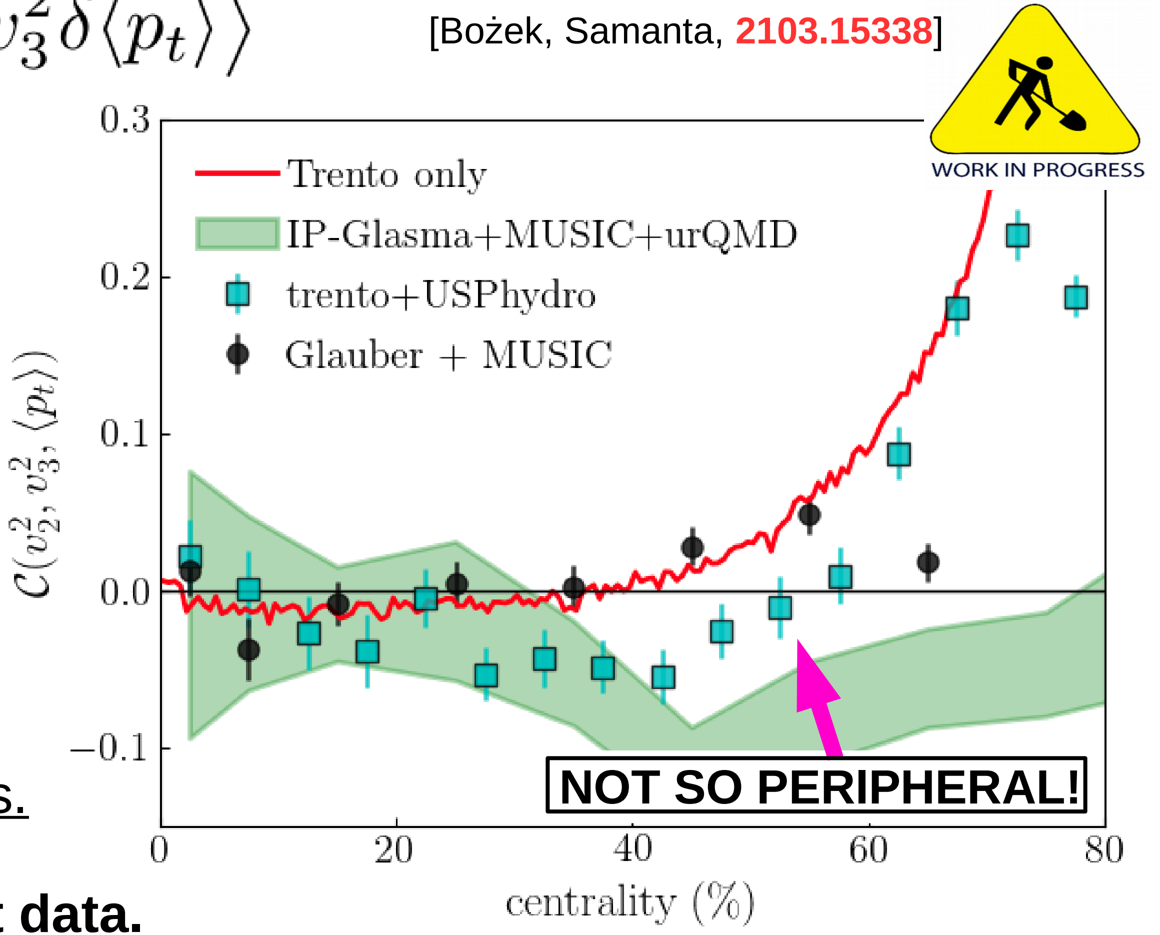
Ultra-recent developments. Cumulant of three variables (with <pt>):

$$\langle \delta v_2^2 \delta v_3^2 \delta \langle p_t \rangle \rangle$$

[ALICE Collaboration, **2101.02579**]
[Bożek, Samanta, **2103.15338**]

Involves the correlators:

- $\langle v_2^2 \langle p_t \rangle \rangle - \langle v_2^2 \rangle \langle\langle p_t \rangle\rangle$
- $\langle v_3^2 \langle p_t \rangle \rangle - \langle v_3^2 \rangle \langle\langle p_t \rangle\rangle$
- $\langle v_2^2 v_3^2 \langle p_t \rangle \rangle - \langle v_2^2 v_3^2 \rangle \langle\langle p_t \rangle\rangle$



<u>Naturally sensitive to initial anisotropies.</u>

Funny prospects for future high-stat data.

- “Geometry” paradigm explains anisotropic flow at large multiplicities.

- Beyond $F = -\nabla P$: initial momentum anisotropies at small multiplicity.

- Predicted by high-energy QCD.

- **Natural handle: vary system size with $\langle p_t \rangle$.**

- **Natural handle: correlation between v_2 and v_3.**

- **Hunt is ON**: more and more observables for a consistent picture that will lead to an unambiguous discovery.

THANK YOU!