Correlating anisotropic flow with isotropic flow in heavy-ion collisions

Nuclear phenomenology at high energy
beyond the quark-gluon plasma

by

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with J. Jia and Y. Zhou

- **HEAVY-ION COLLISIONS: QGP**
  - Particle multiplicties ($dN/d\eta$).
  - Anisotropic flow (Vn).
  - Isotropic flow (<pt>)
  - Status of soft sector.

- **PHENOMENOLOGY BEYOND THE QGP**
  - Correlating Vn with <pt> (at fixed $dN/d\eta$).
  - Strong magnetic fields.
  - Nuclear deformation.
  - Primordial momentum anisotropies.

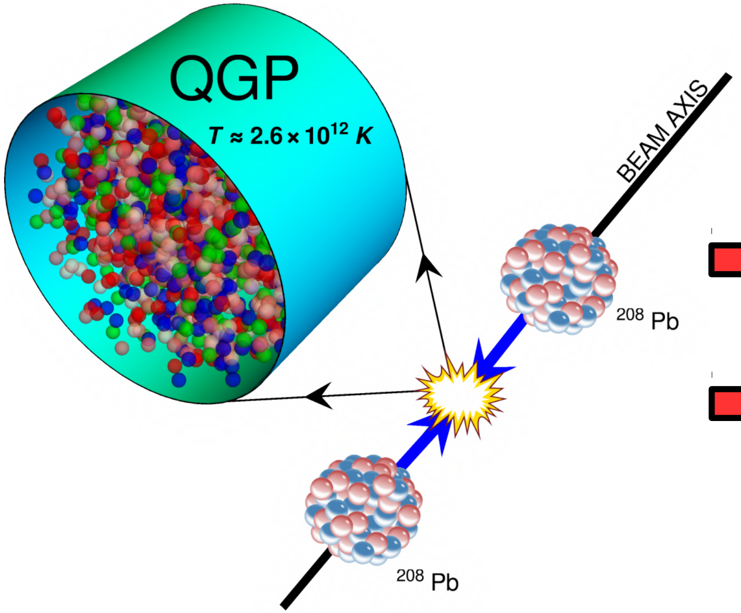
- **OUTLOOK**
  - The tip of the iceberg.

HEAVY-ION COLLISIONS: **EMERGENT PHENOMENA** AT HIGH ENERGY.

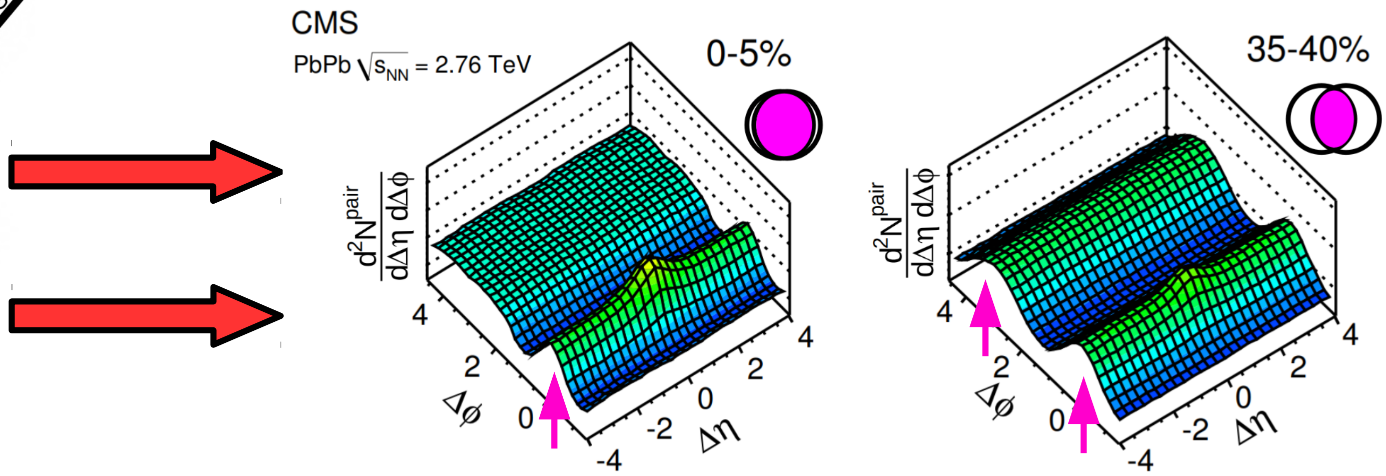
- Particle density is huge: 1 to 10 fm^-3. Nuclear matter: 0.16 fm^-3.

- Regular patterns in data: **collective phenomena**.

“More is different”
[Anderson, 1972]



[Gardim, Giacalone, Luzum, Ollitrault, 1908.09728]



[CMS Collaboration, 1201.3158]

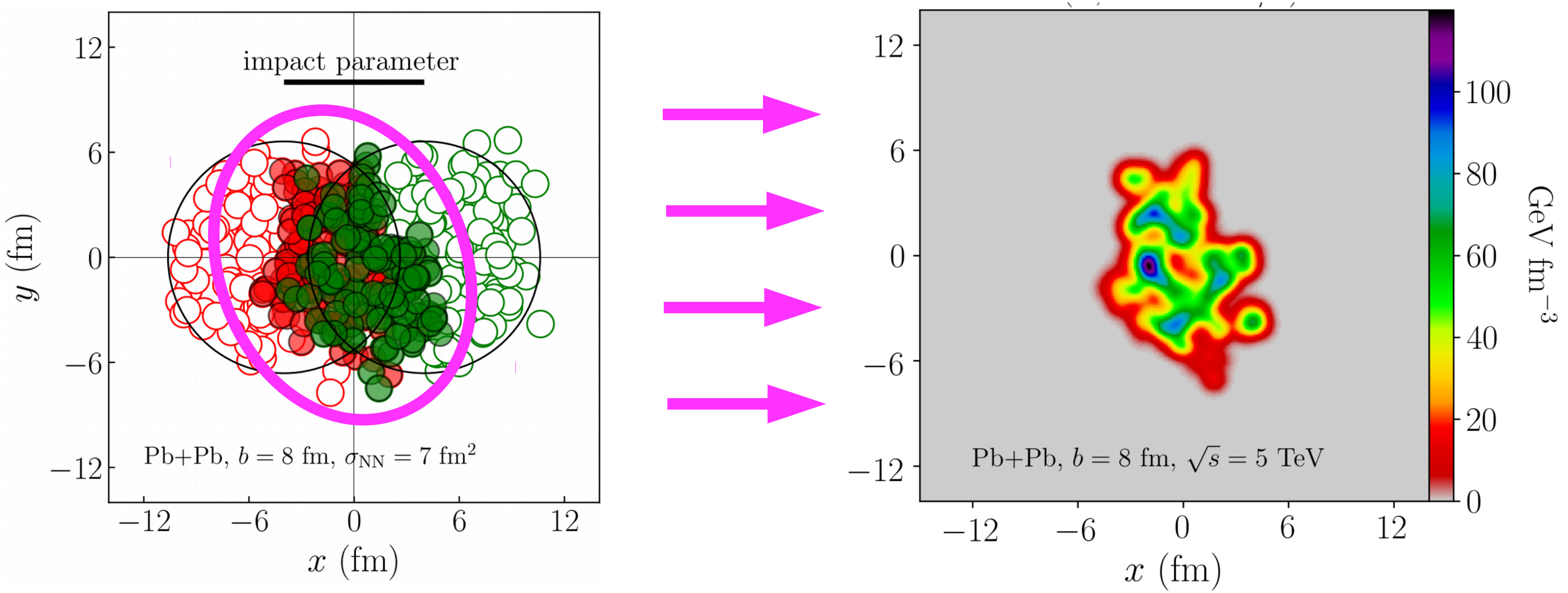
System size >> "mean free path". Equilibration on time scale of QCD, ~1 fm/c.

[Schlichting, Teaney, 1908.02113] [Berges, Mazeliauskas, Spaliński, Venugopalan, 2005.12299]

$\Longrightarrow$ Effective description: relativistic fluid.

[Romatschke & Romatschke, 1712.05815]

$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$ + small viscous corrections ($\eta/s, \zeta/s$, ...) **+** $\partial_\mu T^{\mu\nu} = 0$

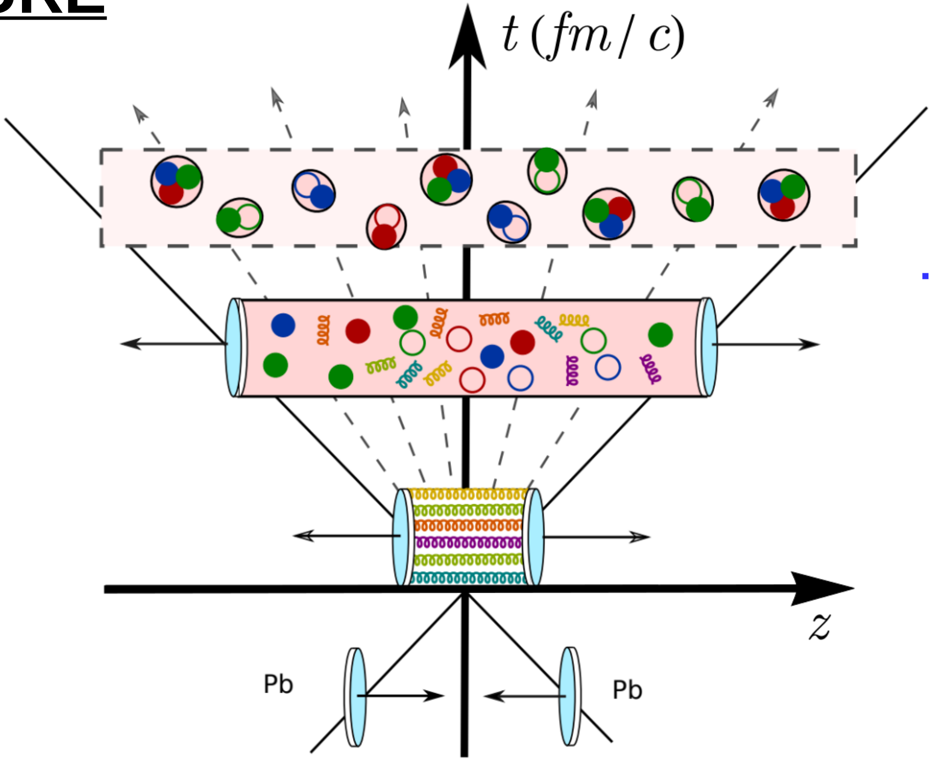


Equation of state from lattice QCD (T > 156 MeV). Large number of DOF (~40): QGP.

[HotQCD collaboration, 1407.6387]

BIG PICTURE

(courtesy A. Mazeliauskas)



$10 < t < \infty$ *hadronic gas*

FREEZE-OUT

$1 < t \lesssim 10$ *fluid expansion*
(QGP phase)

$0 < t \lesssim 1$ *equilibration*

$-\infty < t < 0$

---

t = ∞ → $\dfrac{dN}{d^3\mathbf{p}}$ **or** $\dfrac{dN}{dy\,d^2\mathbf{p}_t}$ **Hadron spectrum in momentum space.**

Bulk of produced O(10^3-10^4) particles is soft, **pt < 2 GeV**.

Particle yields are nearly independent of rapidity.

Fundamental quantities in the soft sector:

1 - event multiplicity

$$N = \int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t}$$

2 - anisotropic flow

$$V_n = \frac{1}{N} \int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-in\phi_p}$$

3 - average momentum

$$\langle p_t \rangle = \frac{1}{N} \int_{\mathbf{p}_t} p_t \frac{dN}{d^2\mathbf{p}_t}$$

Basics of QGP pheno: origin of these quantities.

[Giacalone, 2101.00168]

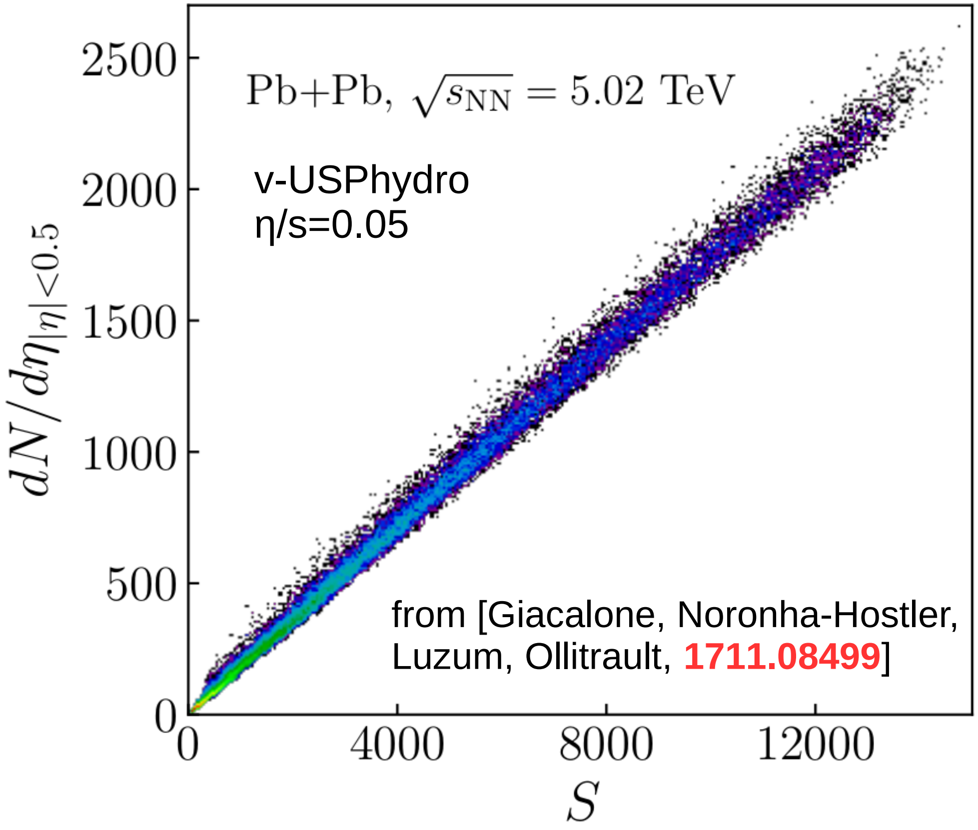
1 - event multiplicity.

Underlying physics is an ideal gas of massless particles.

The expansion is nearly isentropic.

Entropy, S, proportional to the number of detected hadrons:

$$S \propto N \quad \text{(dN/d}\eta\text{)}$$



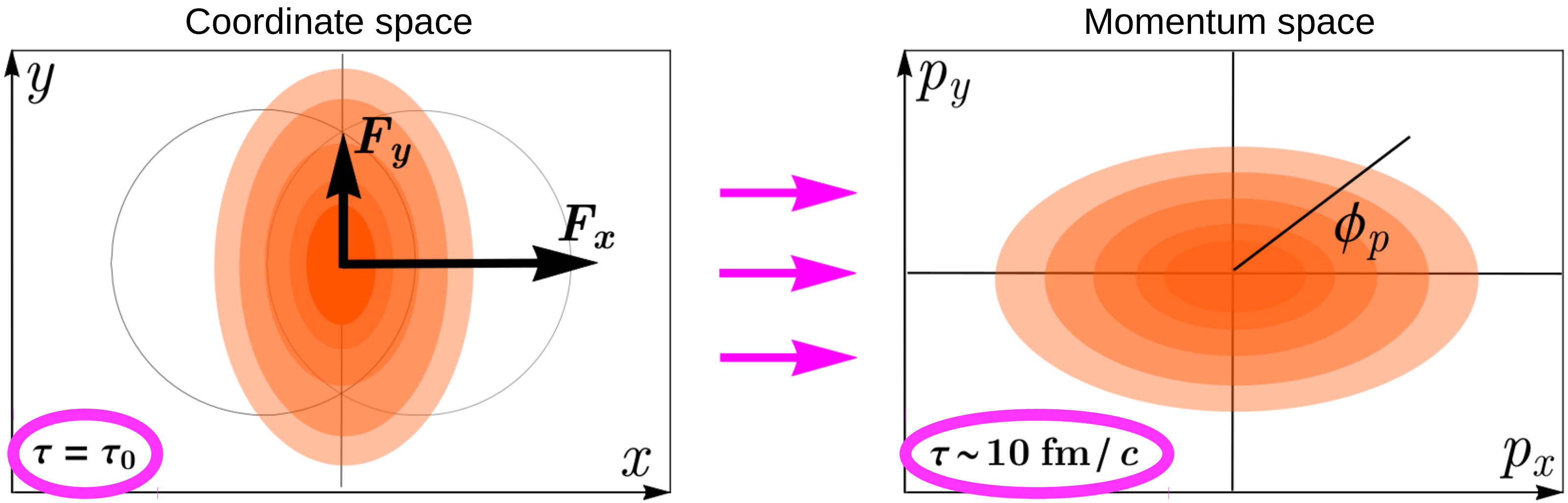
from [Giacalone, Noronha-Hostler, Luzum, Ollitrault, 1711.08499]

2 - anisotropic flow.

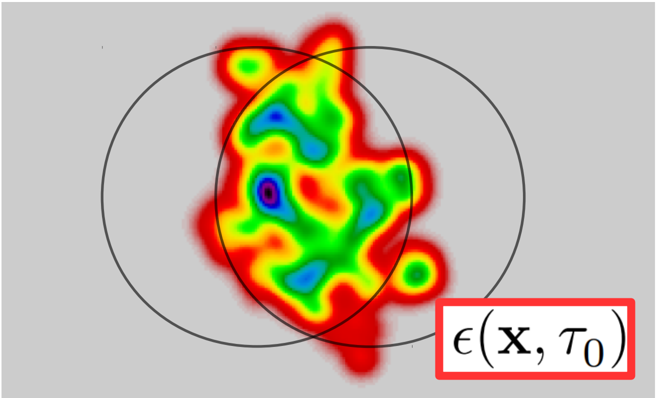
Azimuthal anisotropy of particle emission.
Elliptic flow, the 2nd harmonic. → $V_2 = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-i2\phi_p}$

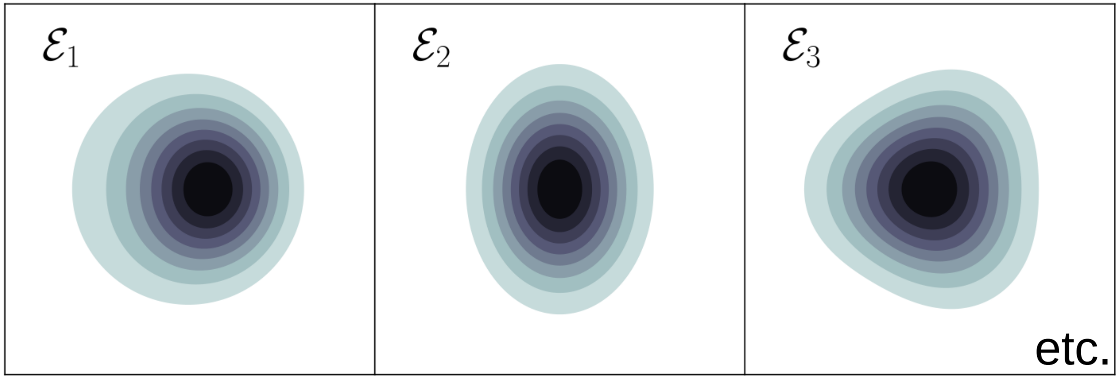
Geometric origin: shape-flow transmutation at finite impact parameter.

[Ollitrault, 1992]



More than ellipse: due to fluctuations, all multipoles are nonzero.



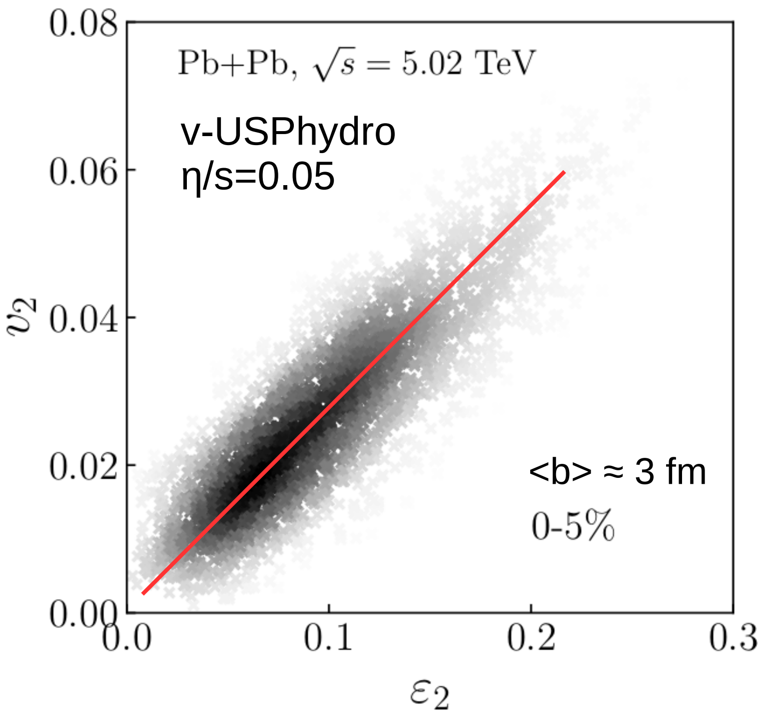


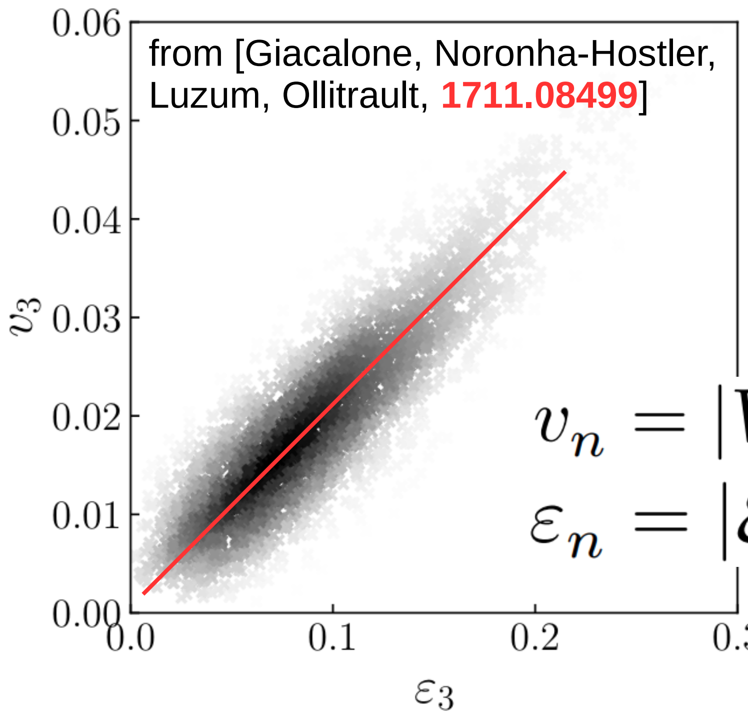
Deformations in two dimensions identified by [Teaney, Yan, 1010.1876]:

$$\mathcal{E}_n = -\frac{\int r dr d\phi \; r^n e^{in\phi} \epsilon(r,\phi)}{\int r dr d\phi \; r^n \epsilon(r,\phi)}$$

Each En in the initial state leads to Vn in the final state.

A simple relation: $V_n \propto \mathcal{E}_n$





$$v_n = |V_n|$$
$$\varepsilon_n = |\mathcal{E}_n|$$

Explains experimental data in both large and small systems.

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

3 – average momentum (isotropic flow)

Mean transverse momentum is the “energy per particle”. ⟶ $\langle p_t \rangle = \frac{1}{N} \int_{\mathbf{p}_t} p_t \frac{dN}{d^2\mathbf{p}_t}$

Energy per particle in the ideal gas:

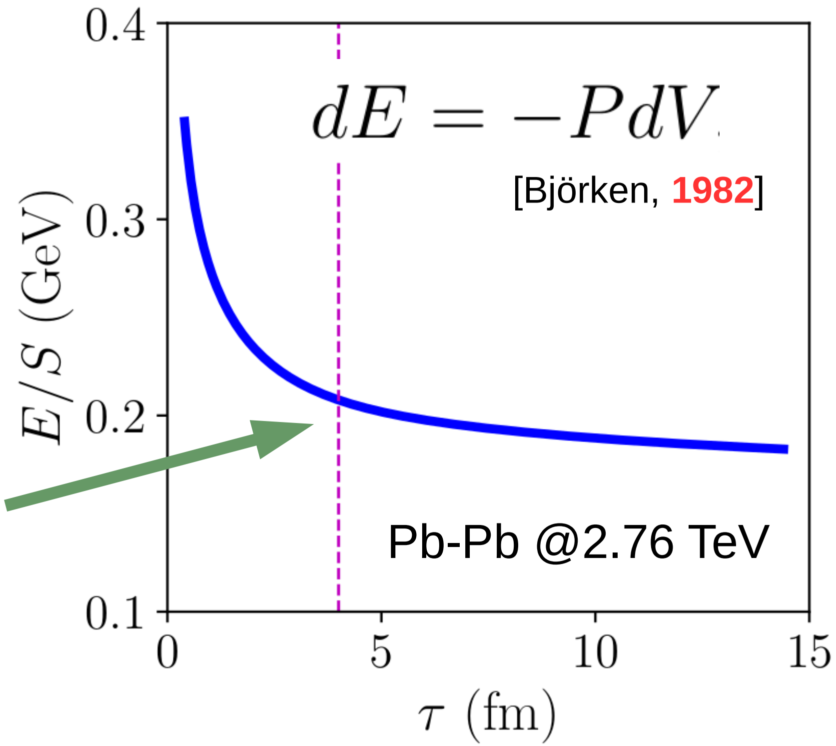
$$p \simeq E = 3T$$

Therefore in a heavy-ion collision we expect:

$$\langle p_t \rangle \simeq 3T$$

where T is the temperature at the end of cooling.
Verified in hydrodynamic simulations.

[Gardim, Giacalone, Luzum, Ollitrault, 1908.09728]



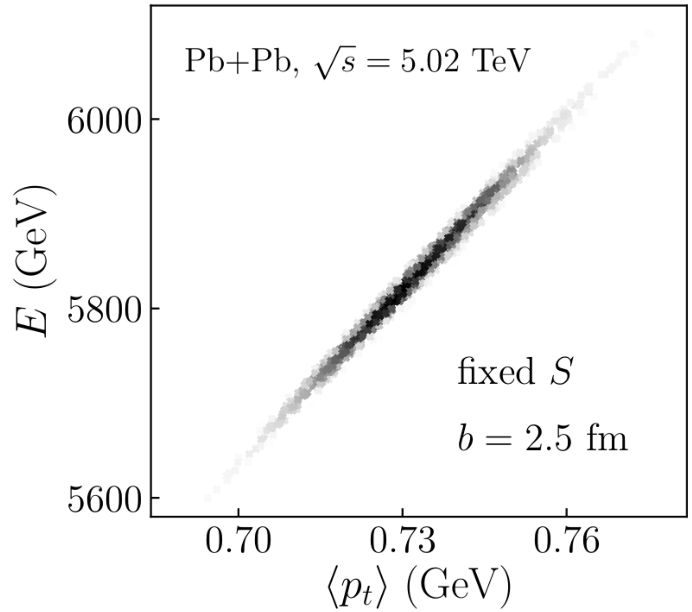
Application:

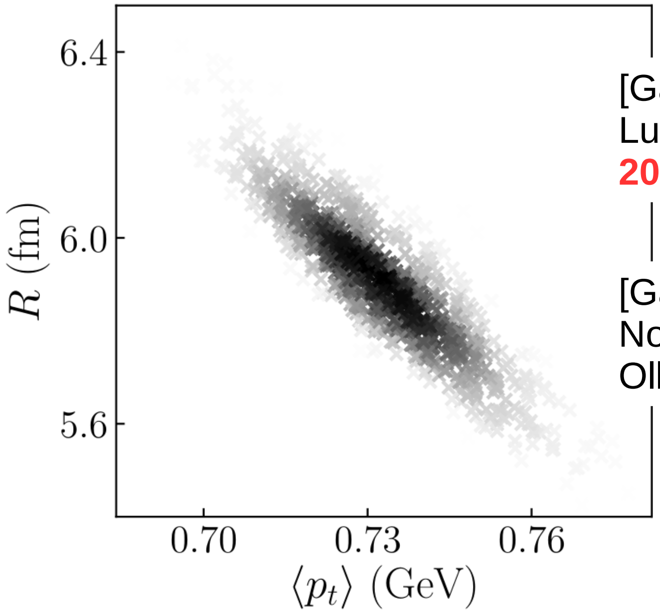
ALICE measures **<pt>≈680MeV** in 0-5%. The temperature is **<pt>/3≈226MeV ~ 2.6** x **10^{12} K**.

Origin of <pt> fluctuations (fixed multiplicity).

$$c_s^2 = \frac{dP}{d\epsilon} = \frac{d\ln T}{d\ln s} \xrightarrow{\langle p_t\rangle \sim T} \frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto \frac{dE}{E} \qquad \frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto -\frac{dR}{R}$$

(E=initial energy, R=initial radius)





[Gardim, Giacalone, Luzum, Ollitrault, **2002.07008**]

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

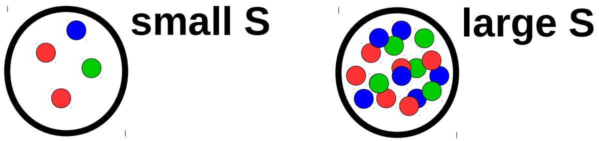
Proportionality factors depend on the equation of state.

[Gardim, Giacalone, Noronha-Hostler, Ollitrault, **2004.09799**]

SUMMARY OF INTRODUCTION: QGP BASICS

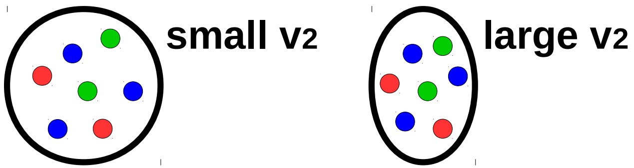
- The **number of detected hadrons** is a measure of the **entropy**.

$$S \propto N$$



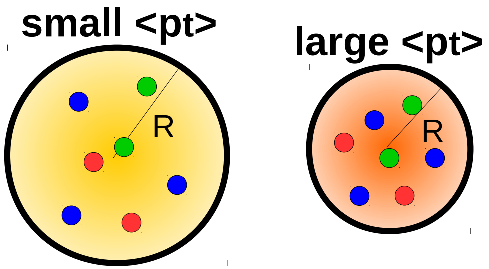
- **Anisotropic flow coefficients** (Vn) are a hydrodynamic response to the **initial spatial anisotropies** (En).

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



- **<pt>** depends on the temperature reached in the QGP. Its **fluctuations probe the thermodynamics**.

$$\frac{d\langle p_t \rangle}{\langle p_t \rangle} \propto \frac{dE}{E} \qquad \frac{d\langle p_t \rangle}{\langle p_t \rangle} \propto -\frac{dR}{R}$$



Status of the field. I think there are three main directions:

- **Clarifying the origin and limits of applicability of this picture.**

[Berges, Mazeliauskas, Spaliński, Venugopalan, **2005.12299**]

- **Refining the picture and pinning down viscosity/initial conditions/EOS.**

[Trajectum, **2010.15130, 2010.15134**] [JETSCAPE Collaboration, **2011.01430, 2010.03928**]

[Devetak, Dubla, Floerchinger, Grossi, Masciocchi, Mazeliauskas, Selyuzhenkov, **1909.10485**]

[Gardim, Giacalone, Ollitrault, **1909.11609**]

- **Use the established picture to reveal new phenomena at high energy.**
(e.g. chiral magnetic effect, CGC, hydrodynamics with spin, nuclear structure)

[Giacalone, Jia, Zhou, **2108.xxxxx**]

THIS TALK

Nuclear phenomena at high energy with multi-particle correlations.

Breakthrough idea:

$$\langle v_n^2 \delta[p_t] \rangle \equiv \left\langle \frac{\int_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3} (p_1 - \langle\langle p \rangle\rangle) e^{in(\phi_2 - \phi_3)} \frac{dN}{d^2\mathbf{p}_1 d^2\mathbf{p}_2 d^2\mathbf{p}_3}}{\int_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3} \frac{dN}{d^2\mathbf{p}_1 d^2\mathbf{p}_2 d^2\mathbf{p}_3}} \right\rangle$$

First apparition as a byproduct of a principal component analysis.

[Mazeliauskas, Teaney, **1509.07492**]

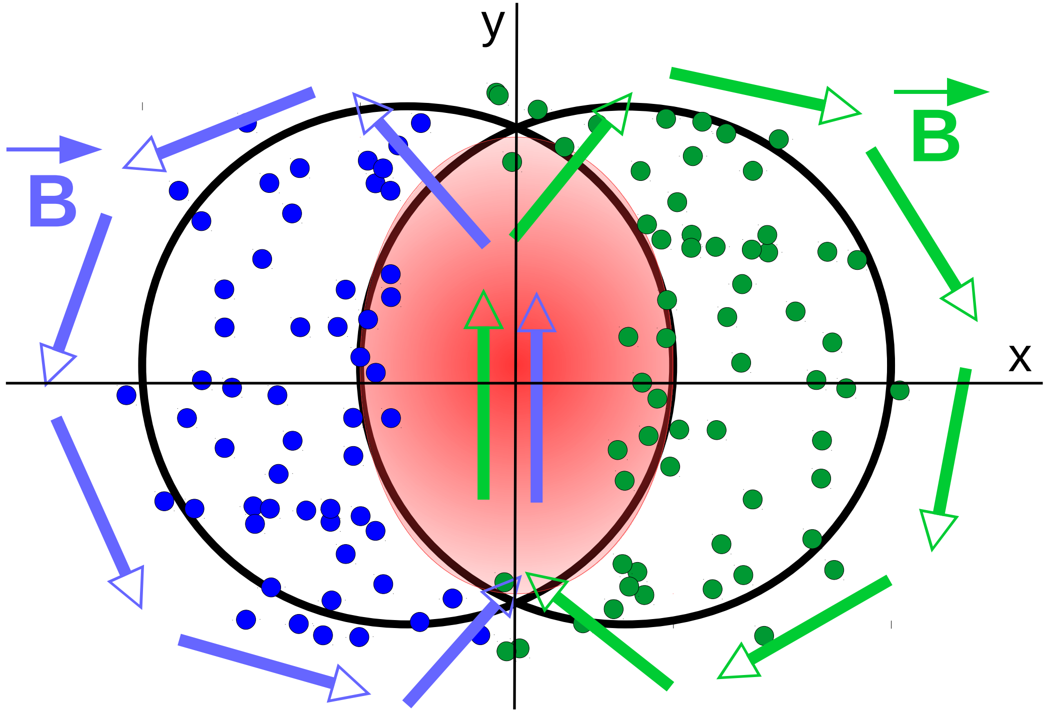
Bożek's formulation as a **Pearson correlation coefficient**:

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

[Bożek, **1601.04513**]

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

#1 – Electromagnetic fields.



– Coherent B field of **spectator protons** over interaction region.

– Strong field **|B| ~ 10^{14} T** may yield parity-violating effects (CME).

[Li, Wang, **2002.10397**]

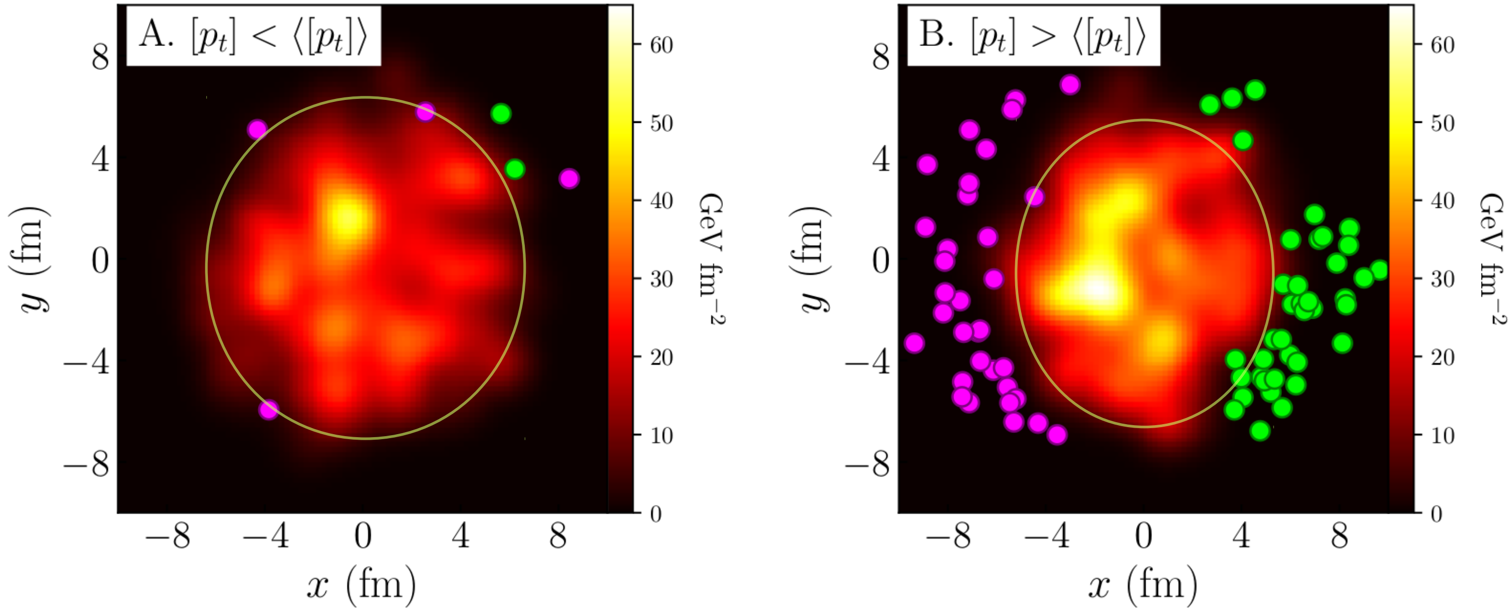
– Involves **charge-dependent dipolar flows.**

$$\left\langle \cos(\phi_1^{\pm} - \phi_2^{\pm}) \right\rangle$$ [Oliva, **2007.00560**]

– Experimental evidence missing.
<u>But we can use <pt>!</u>

Select two **central events** (2-3%) at the **same multiplicity** but **different [pt].**

Isentropic transformation of the QGP which increases T and reduces R**.**



event	A	B
N_{ch}	2813	2791
b (fm)	0.49	4.41
N_s	6	72
$[p_t]/\langle [p_t] \rangle$	0.976	1.028
[redacted]		
R (fm)	4.53	4.03
ε_2	0.073	0.153

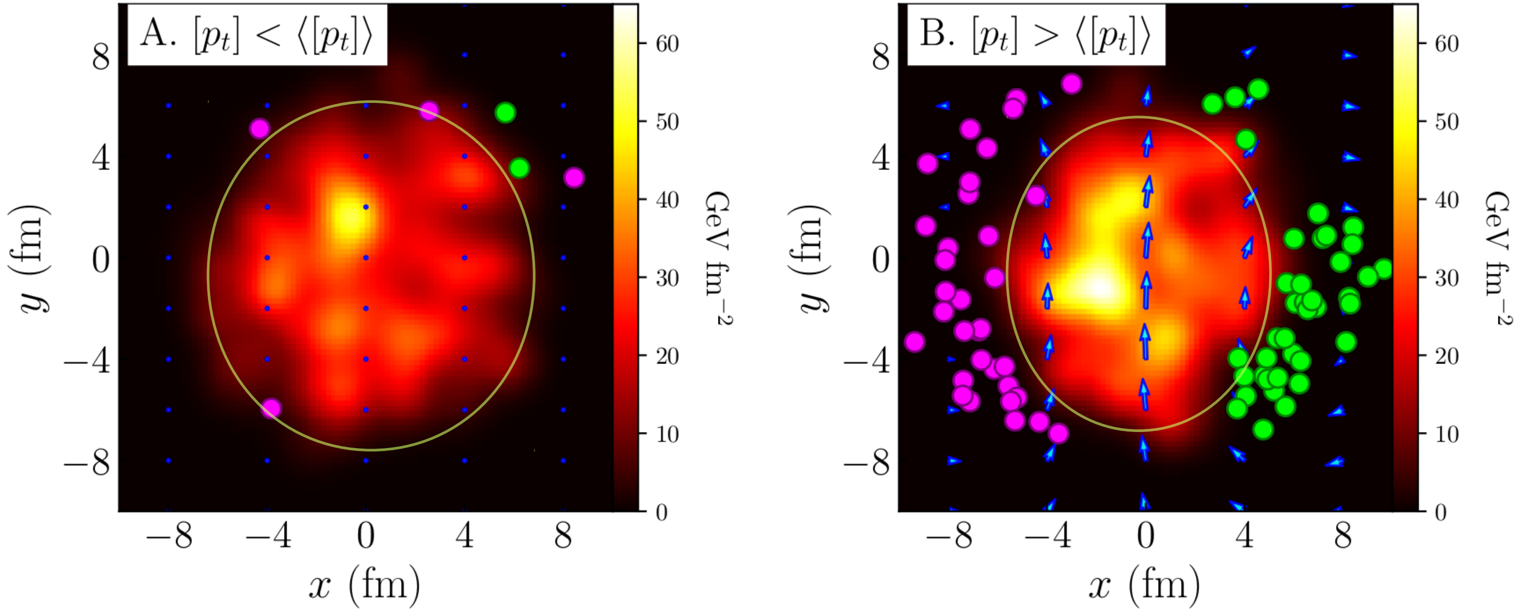
[Giacalone, 2006.06269]: **strong correlation between [pt] and <Ns>.**
<u>What about the magnetic field?</u>

Event-by-event calculation of <By> within the framework of:

[Gürsoy, Kharzeev, Rajagopal, **1401.3805**]

[Gürsoy, Kharzeev, Marcus, Rajagopal, Shen, **1806.05288**]

Consider only B field over overlap area: $\langle B_y \rangle = \dfrac{1}{E} \int d^2\mathbf{x}\; B_y(\mathbf{x}) e(\mathbf{x})$



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$\langle B_y \rangle / m_\pi^2$	0.013	0.151
R (fm)	4.53	4.03
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The idea works! Increase [pt] and the B field appears!

[Giacalone, Shen, **2104.01890**]

AN OPTIMAL EVENT-SHAPE ENGINEERING BASED ON [pt].

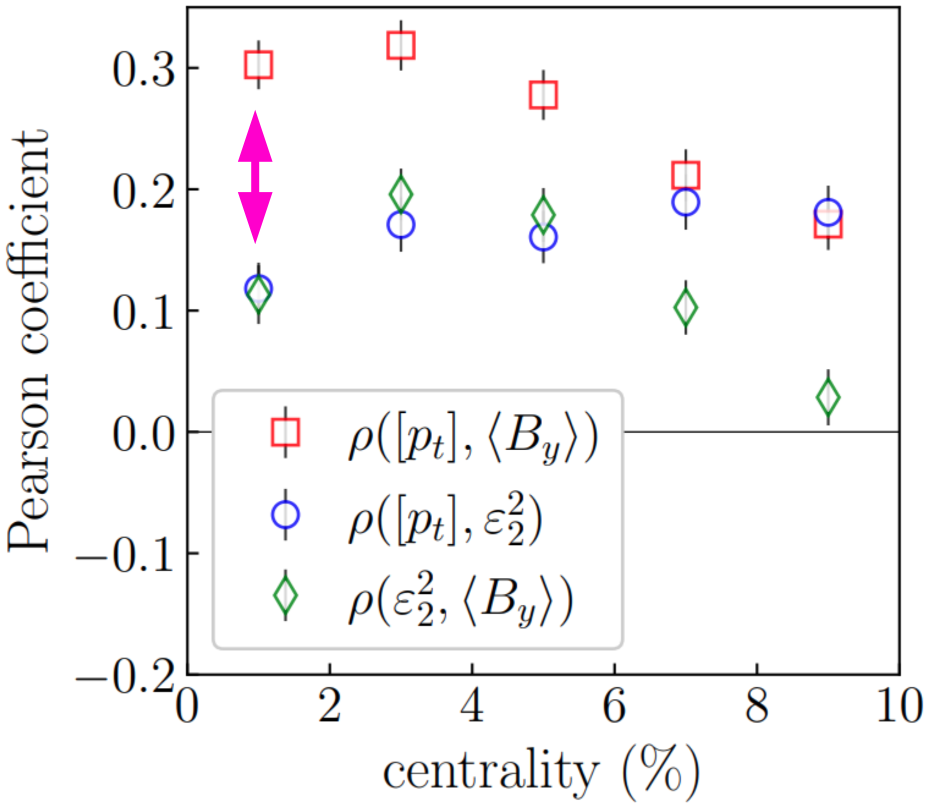
[Giacalone, Shen, 2104.01890]

- $\rho([p_t], \langle B_y \rangle) > \rho(\varepsilon_2^2, \langle B_y \rangle)$

Better handle on <By> than usual ESE based on q2 vectors. ;-)

- $\rho([p_t], \langle B_y \rangle) > \rho([p_t], \varepsilon_2^2)$

Increases <By> more than v2. Important for CME background.



OBSERVABLE NATURALLY SENSITIVE TO THE B FIELD:

$$\left\langle \delta\langle p_t\rangle \cos\left(\phi_1^{\pm} - \phi_2^{\pm}\right) \right\rangle$$

[Giacalone, 2006.06269]
[Giacalone, Shen, 2104.01890]

– **<u>Correlation between charge-dependent v1 and <pt> at fixed multiplicity.</u>**

– Can be turned into a Pearson coefficient:

$$\rho^{\pm}\left(\langle p_t\rangle, v_1^{\pm}\right) = \frac{\left\langle \delta\langle p_t\rangle \cos\left(\phi_1^{\pm} - \phi_2^{\pm}\right) \right\rangle}{\sqrt{\left\langle \left(\delta\langle p_t\rangle\right)^2 \right\rangle \left(g^{\pm}/v_2\right)}}$$

$$\left\langle \cos\left(\phi_1^{\pm} + \phi_2^{\pm} - 2\phi_3\right) \right\rangle$$

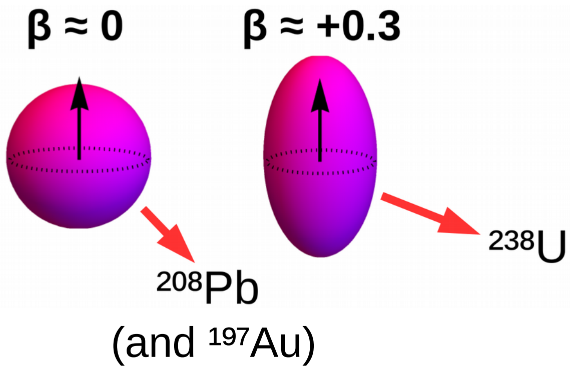
#2 – Nuclear structure: deformation.

Majority of nuclei have an intrinsic quadrupole moment:

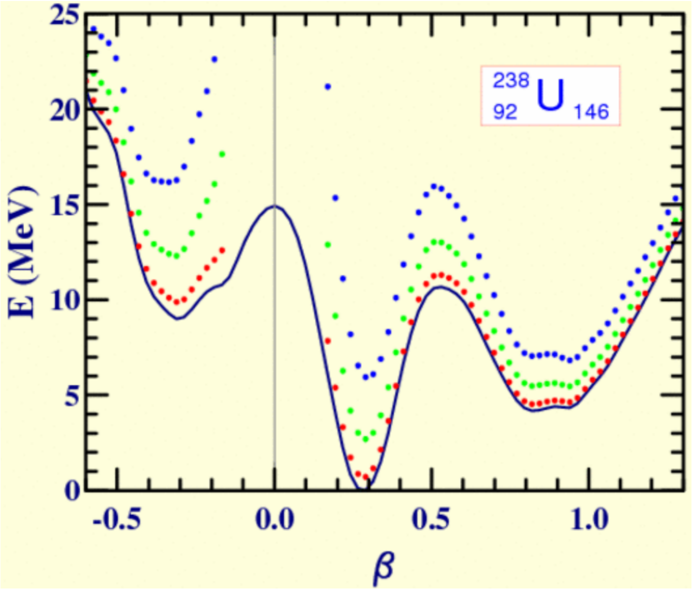
$$Q_2 \propto \langle Y_2^0(\Theta, \Phi) r^2 \rangle \neq 0$$

Deformation quantified by a coefficient:

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



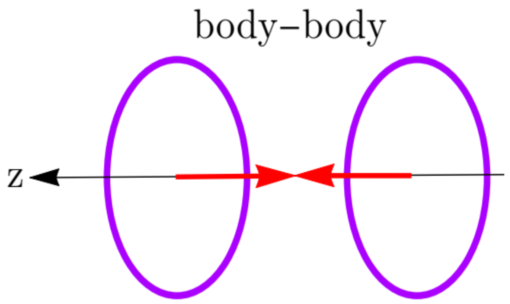
Hartree-Fock approach:
deformed configurations
are energetically favored.



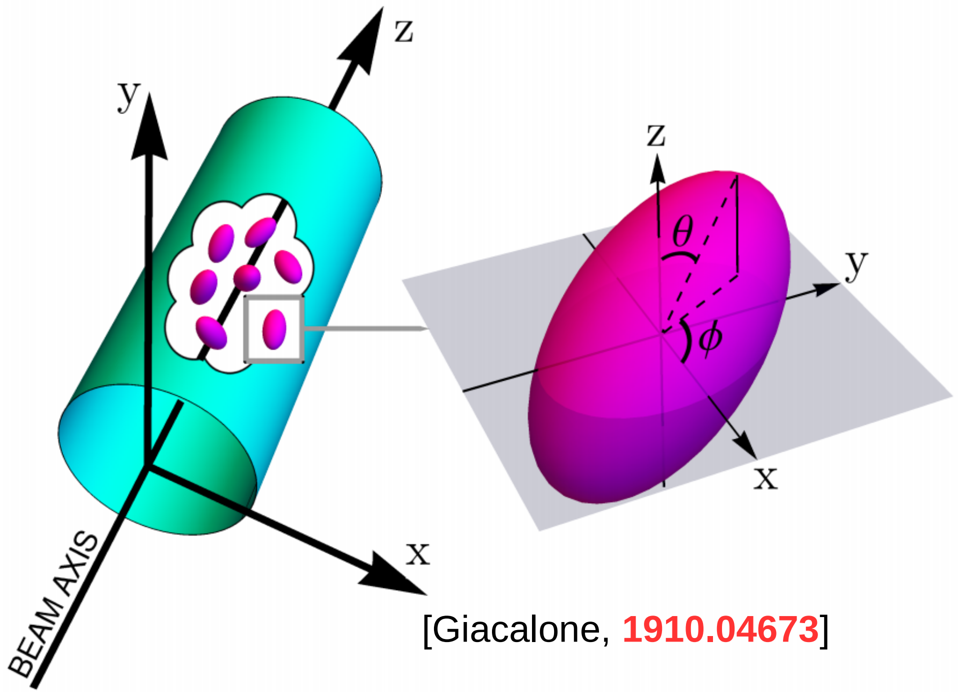
Rotational model:
intrinsically deformed object
with a random orientation.

[Bohr, Mottelson 1957]

Nuclear structure and heavy-ion collisions: an inevitable marriage.

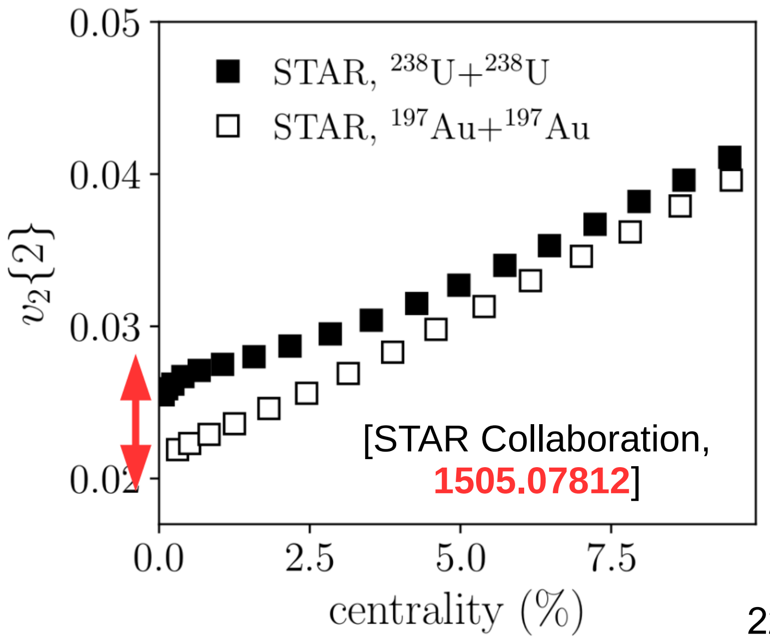


Deformed nuclei in the beampipe.



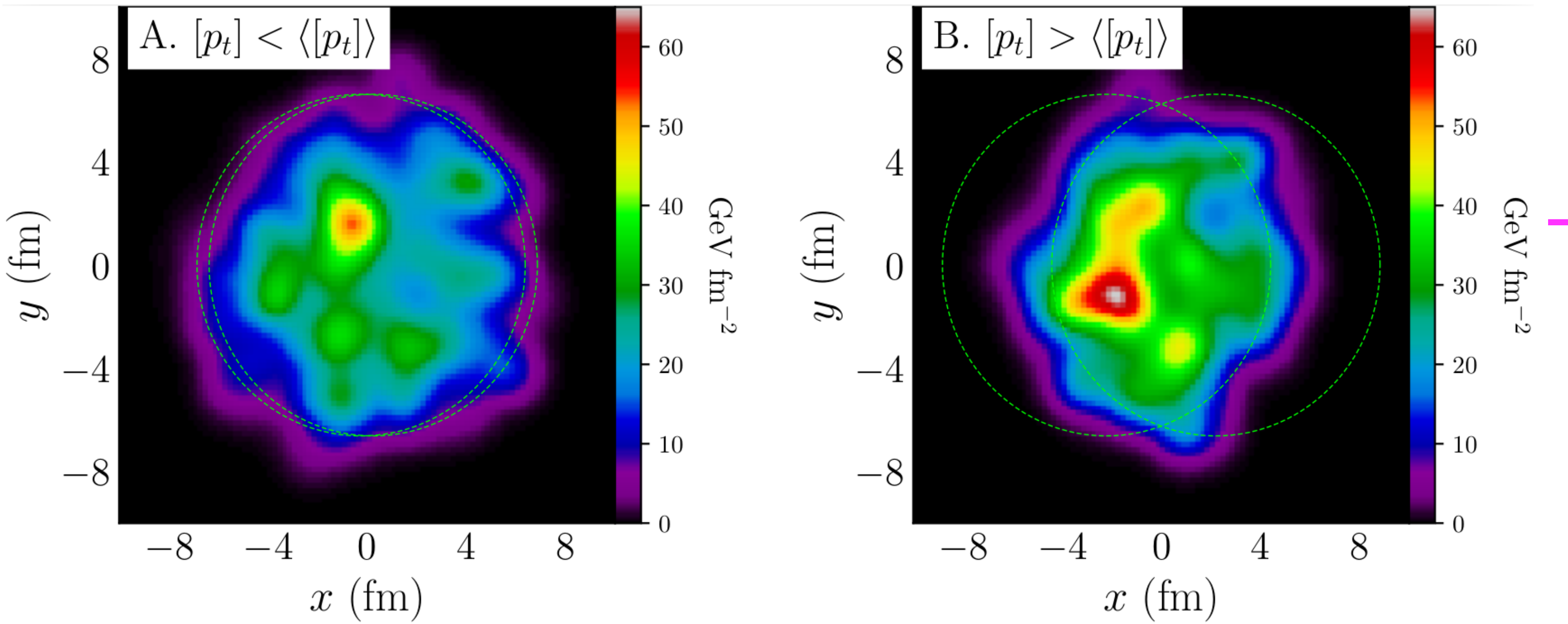
[Giacalone, 1910.04673]

Prediction: excess v2 in central U+U collisions. Observed at RHIC.



We can use <pt> to reveal nuclear deformation. Back to spherical nuclei.

Select two **central events** (2-3%) at the **same multiplicity** but **different [pt].**



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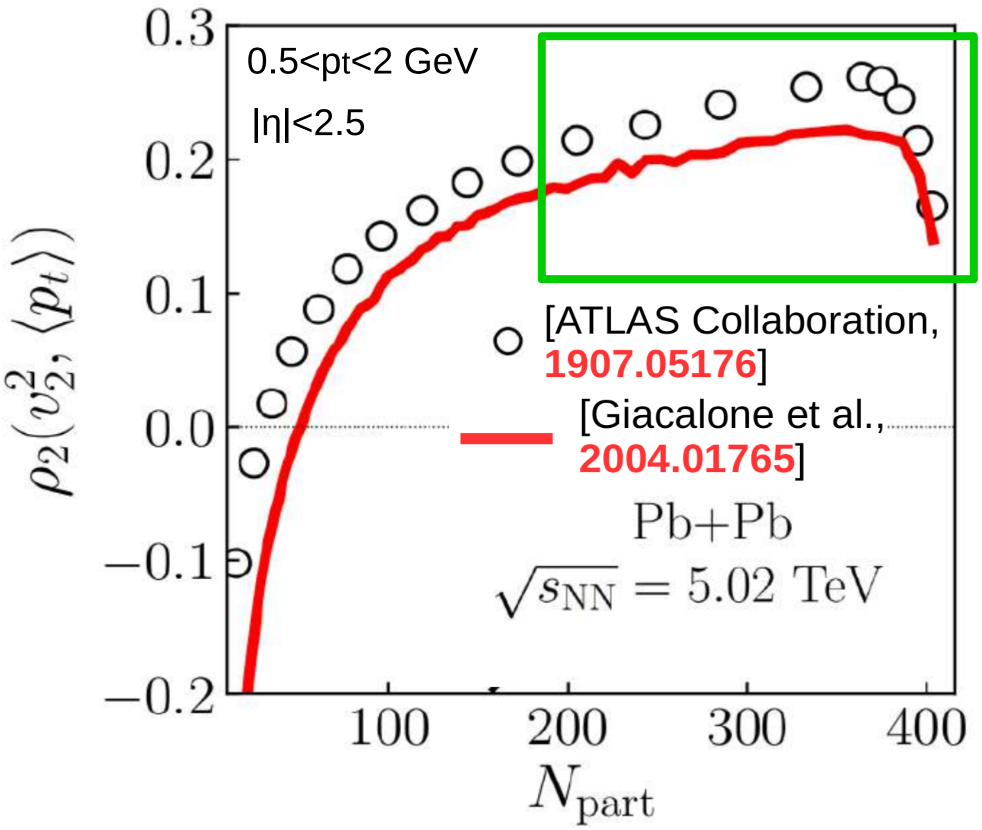
$[p_t]/\langle [p_t] \rangle$	0.976	1.028
$\langle B_y \rangle / m_\pi^2$	0.013	0.151
R (fm)	4.53	4.03
ε_2	0.073	0.153

Increasing <pt> increases the impact parameter and eccentricity!

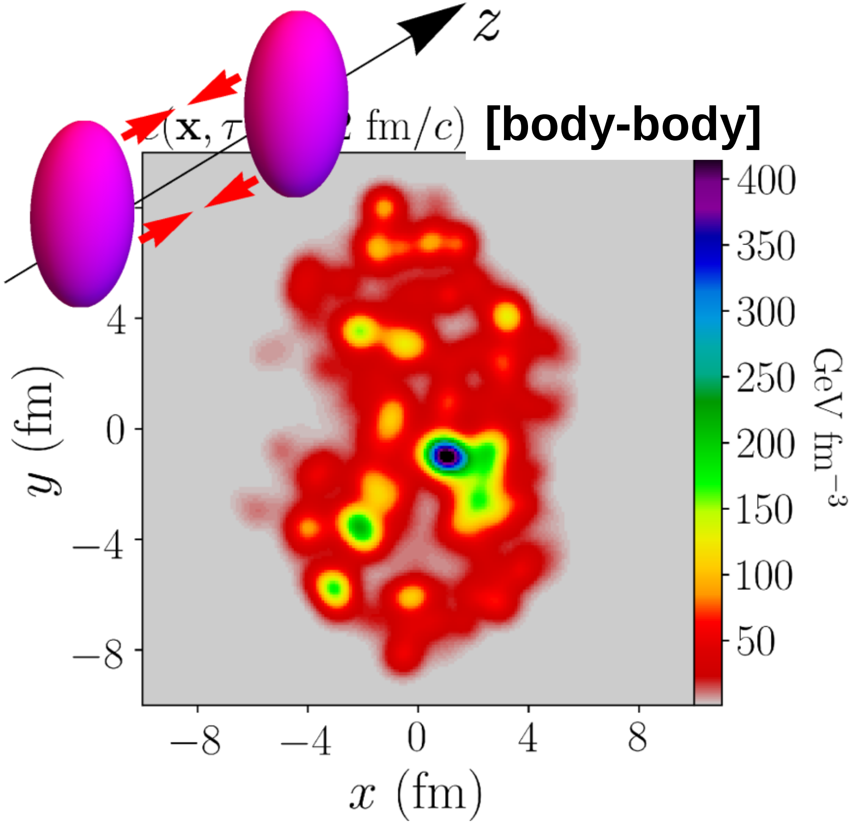
<u>Prediction.</u> In central heavy-ion collisions: $\boxed{\rho(v_2^2, [p_t]) > 0}$

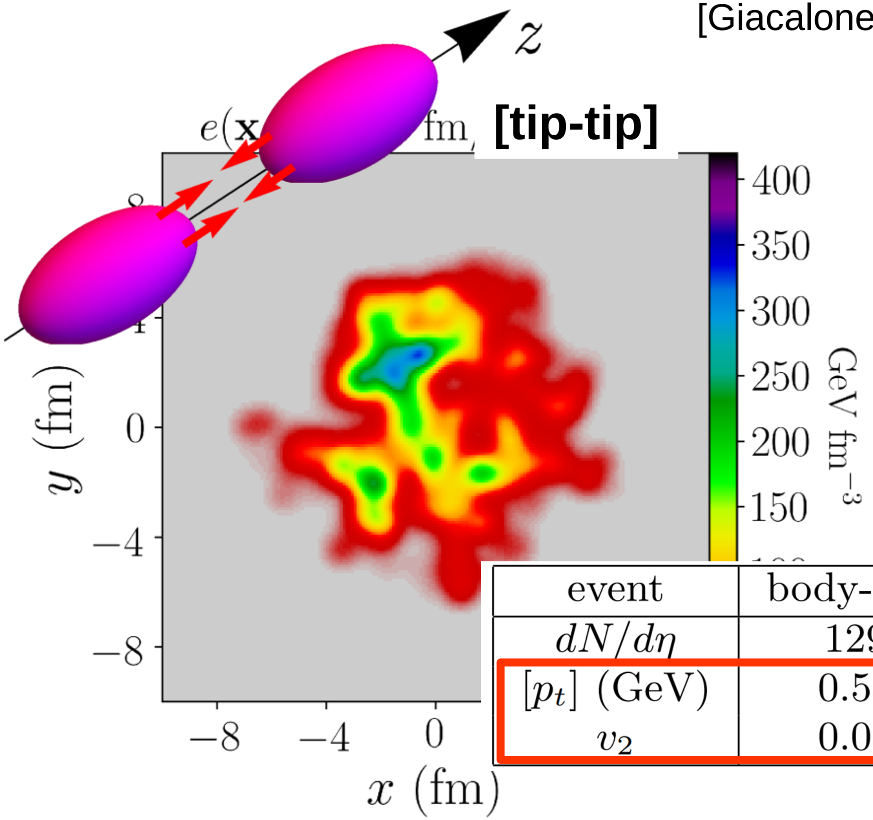
Prediction verified at LHC. Correlation is positive in central collisions.



WHAT IF THE COLLIDING NUCLEI ARE DEFORMED?

[Giacalone, 1910.04673]
[Giacalone, 2004.14463]





event	body-body	tip-tip
$dN/d\eta$	1296	1280
$[p_t]$ (GeV)	0.587	0.651
v_2	0.083	0.027

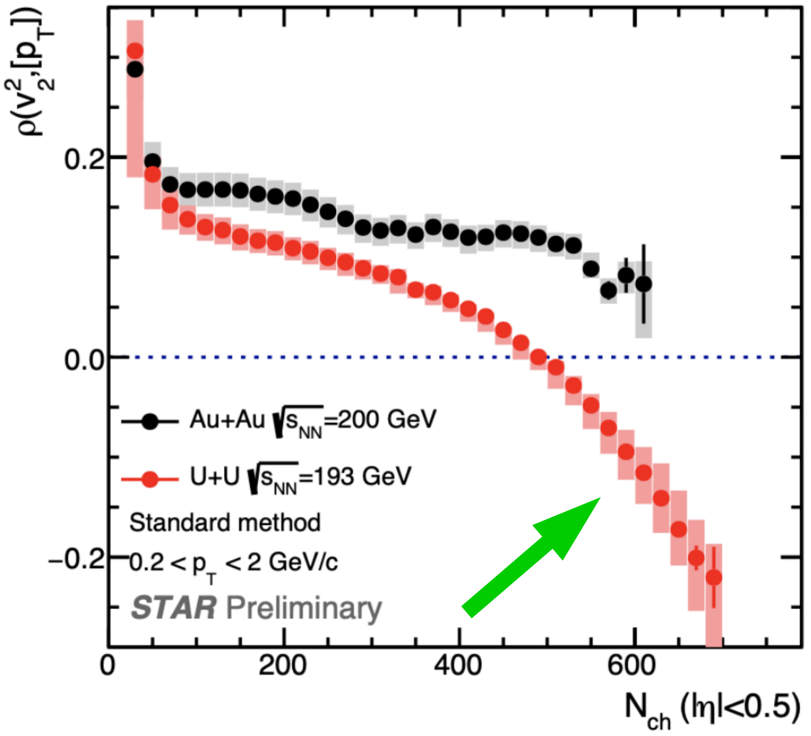
Body-Body: small <pt>, large v2. Tip-tip: large <pt>, small v2.

Prediction! In central collisions of deformed heavy ions: $\boxed{\rho(v_2^2, [p_t]) < 0}$

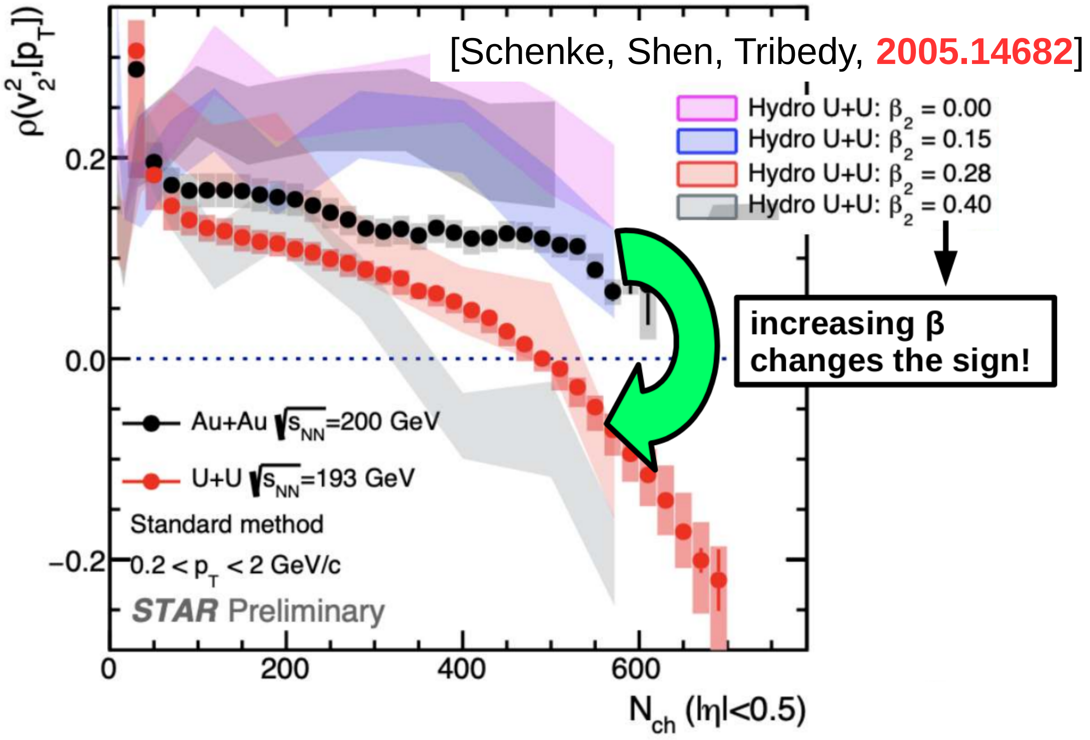
Spectacular confirmation at RHIC.

Correlation is positive in Au+Au, and negative in U+U.

DATA

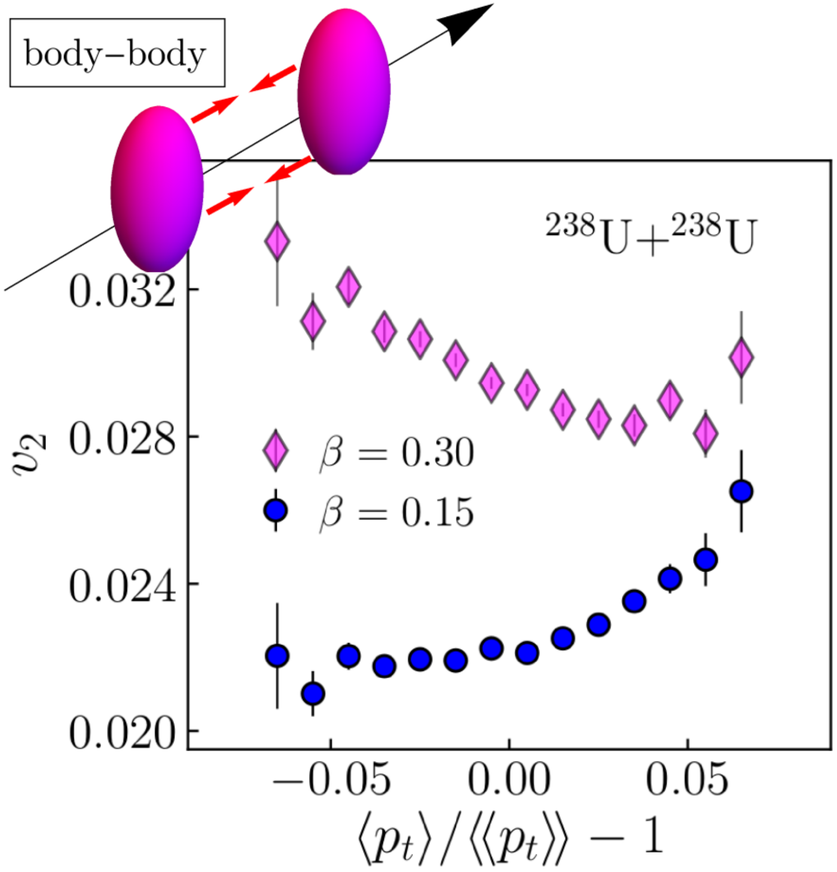


DATA + THEORY



Nuclear deformation interpretation confirmed by hydro calculations: β≈0.3

IMPLICATIONS



- NUCLEAR PHYSICS ACROSS ENERGY SCALES

High-energy experiments test the low-energy structure. Consistency for 238U. Inconsistent results for 197Au, 129Xe. New puzzles.

[Giacalone, Jia, Zhang **2105.01638**]

- BODY-BODY COLLISIONS?

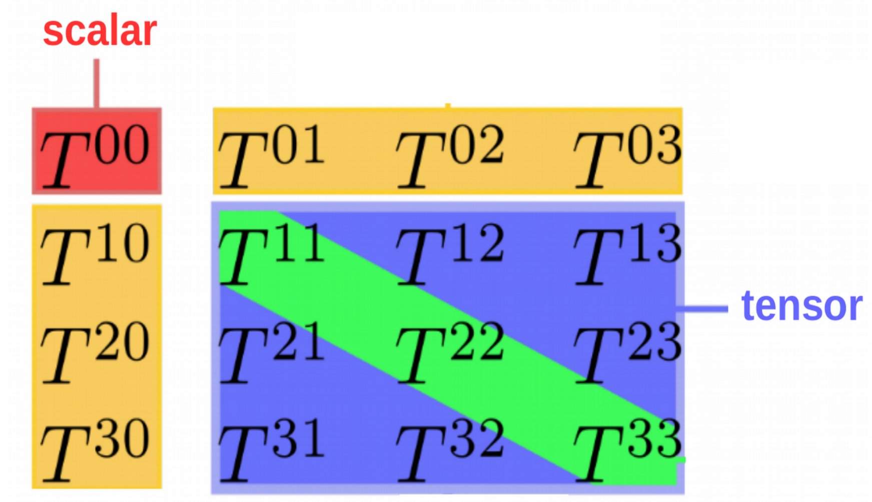
“Body-body collisions” only a useful simplification: the nucleus is J=0 (i.e. spherical!). We reveal long-range correlations in nuclei, not only for the charge density probed at low energies.

#3 – Primordial momentum anisotropies.

Going beyond F = - ∇P.

“MOMENTUM” ANISOTROPY

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



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

Engendered by pre-equilibrium phase.

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

Predicted by the color glass condensate (CGC).
Longstanding question in the field: <u>do we see initial-state CGC anisotropy?</u>

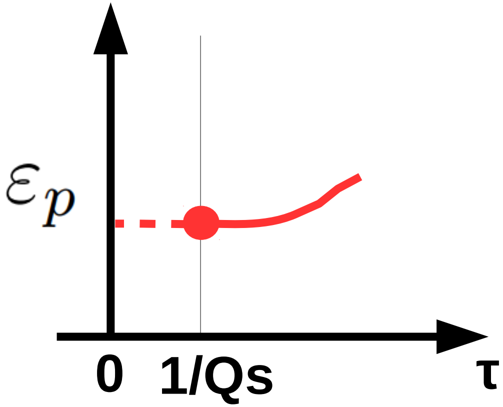
[Altinoluk, Armesto, **2004.08185**]

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

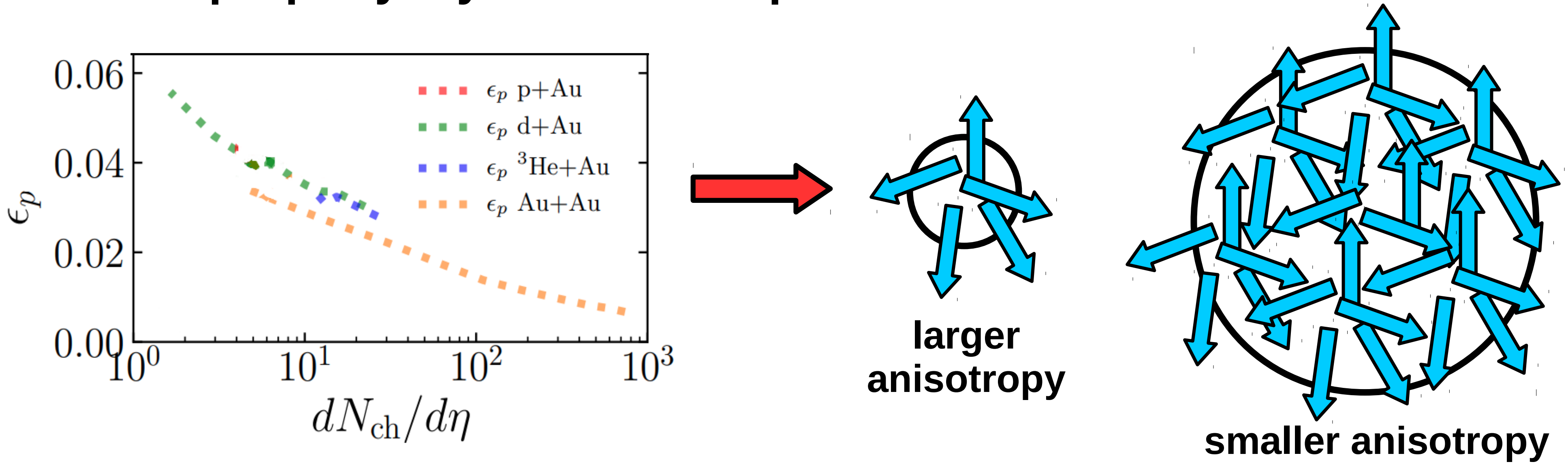
System is anisotropic (n=2) shortly after the collision.

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

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

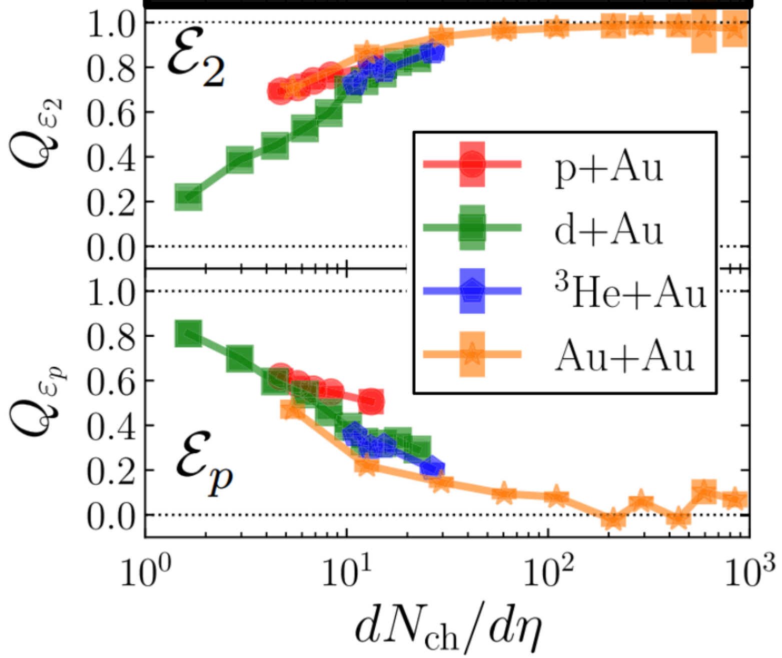


Salient property: system-size dependence.



Does the primordial anisotropy play a role?

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



– Q coefficient of linear correlation.

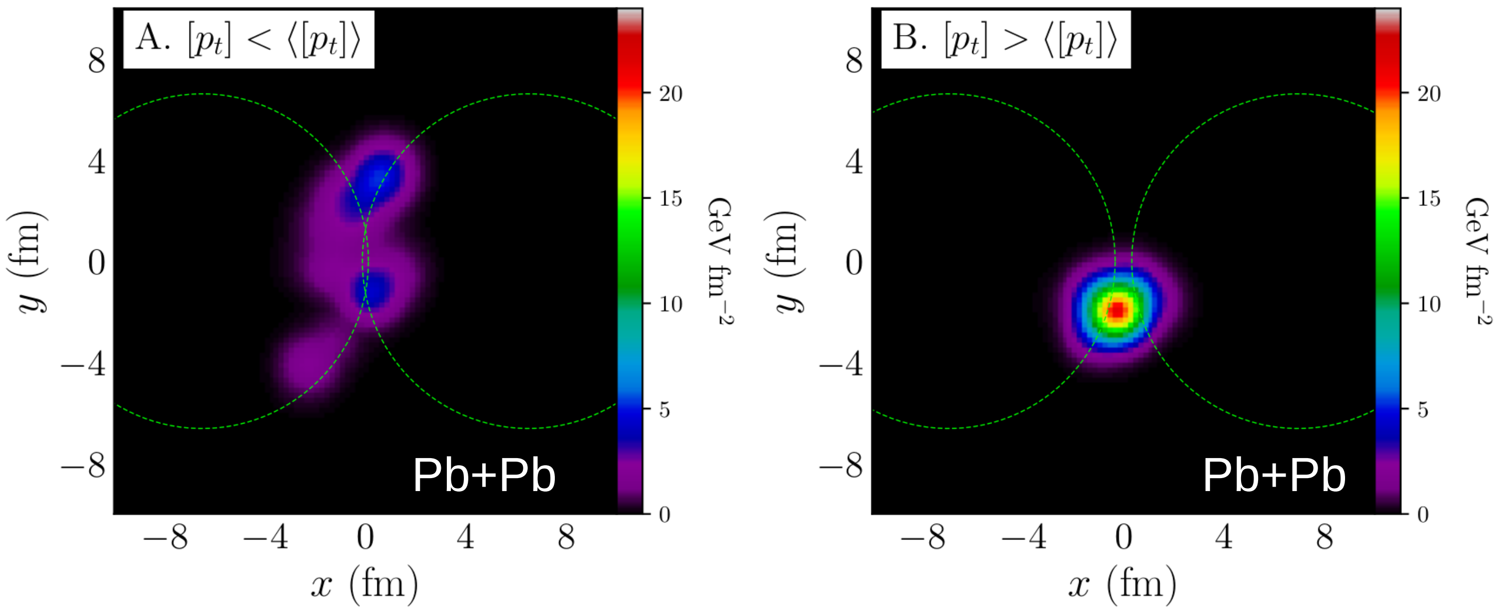
– E2 is the dominant contribution to V2 for dN/dη ≥ 20.

– At low multiplicity, V2 is instead in a stronger correlation with Ep.

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

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

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



event	A	B
$N_{\rm ch}$	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

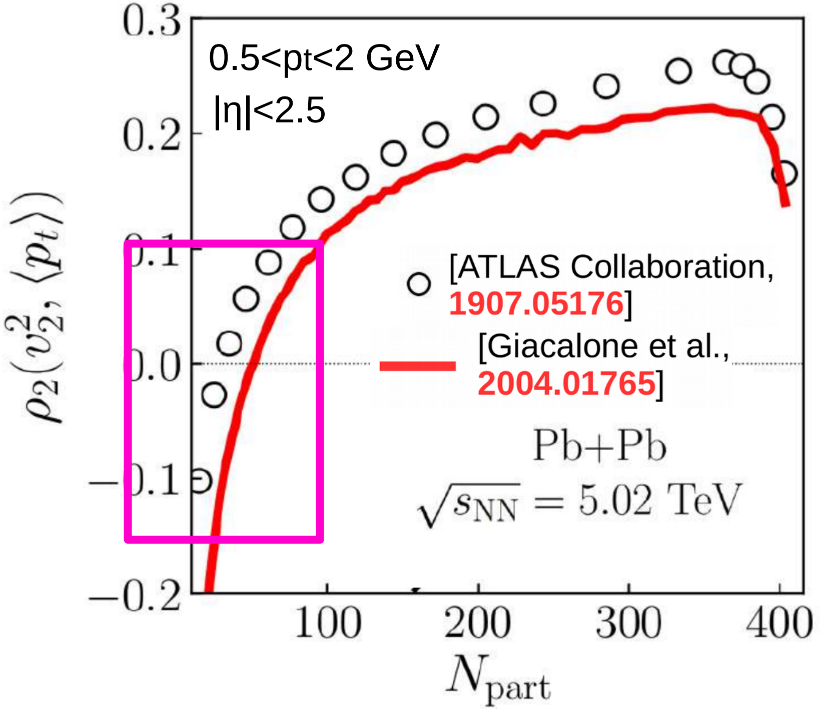
<u>@large [pt]:</u> hot spots clustered around one transverse point. Round system.

<u>Prediction.</u> In small systems: $\boxed{\rho(v_2^2, [p_t]) < 0}$

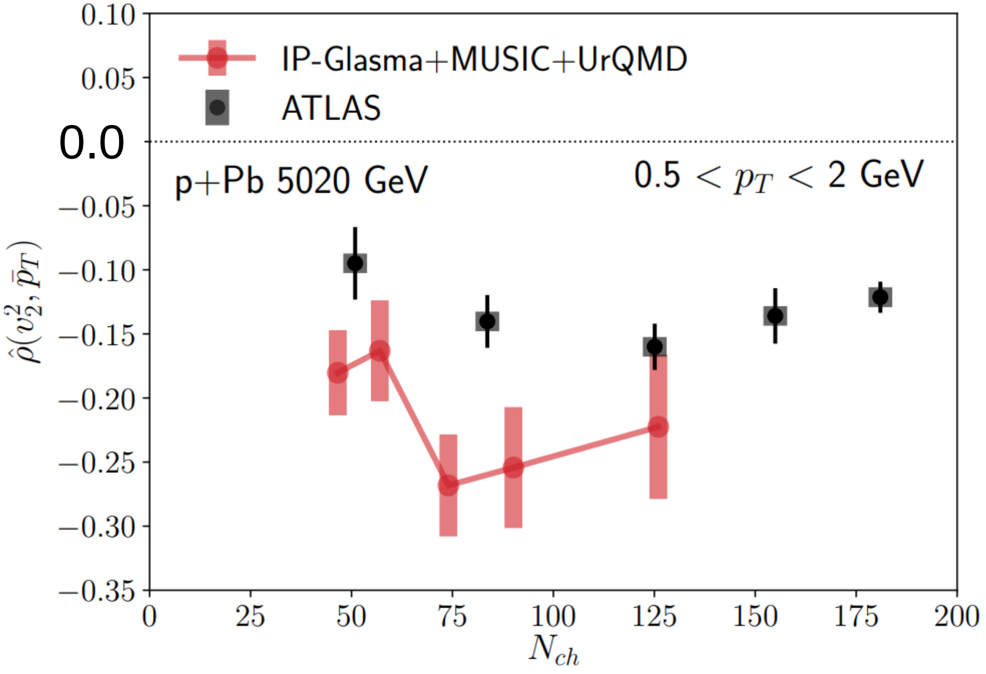
[Bożek, Mehrabpour, 2002.08832]
[Schenke, Shen, Teaney, 2004.00690]

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

Pb+Pb

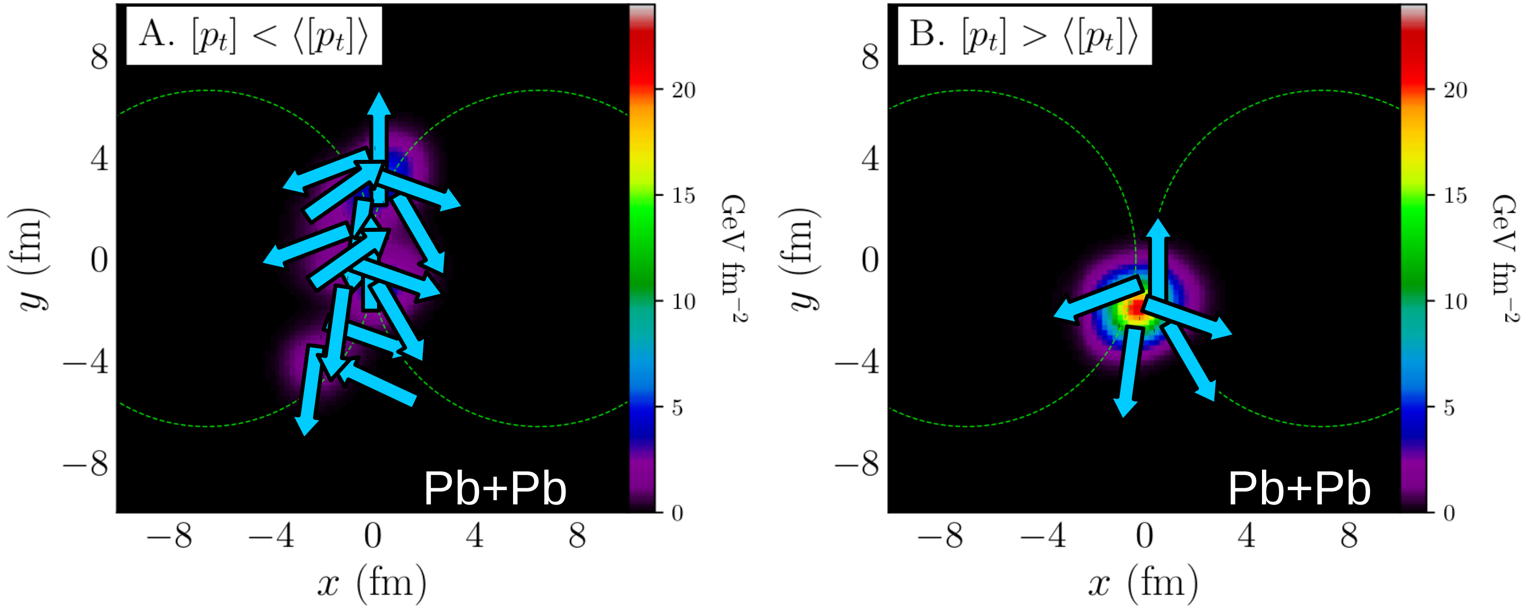


p+Pb



[Schenke, Shen, Teaney, 2004.00690]

What about the initial momentum anisotropy? Intuitive picture.



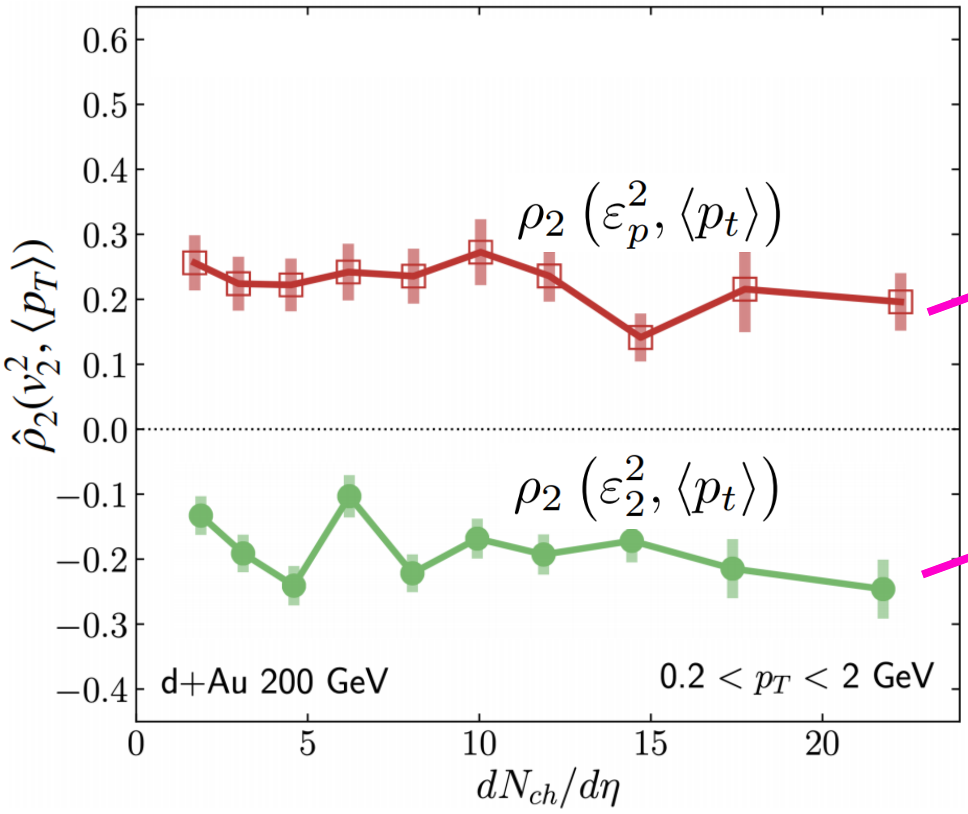
event	A	B
$N_{\rm ch}$	134	134
b (fm)	13.0	13.9
$[p_t]/\langle [p_t] \rangle$	0.907	1.143
R (fm)	2.97	1.34
ε_2	0.675	0.133
ε_3	0.229	0.067

<u>@large [pt]:</u> hot spots clustered around one point. Smaller size, more $\mathcal{E}_p$.

<u>**Prediction.**</u> 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:

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



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

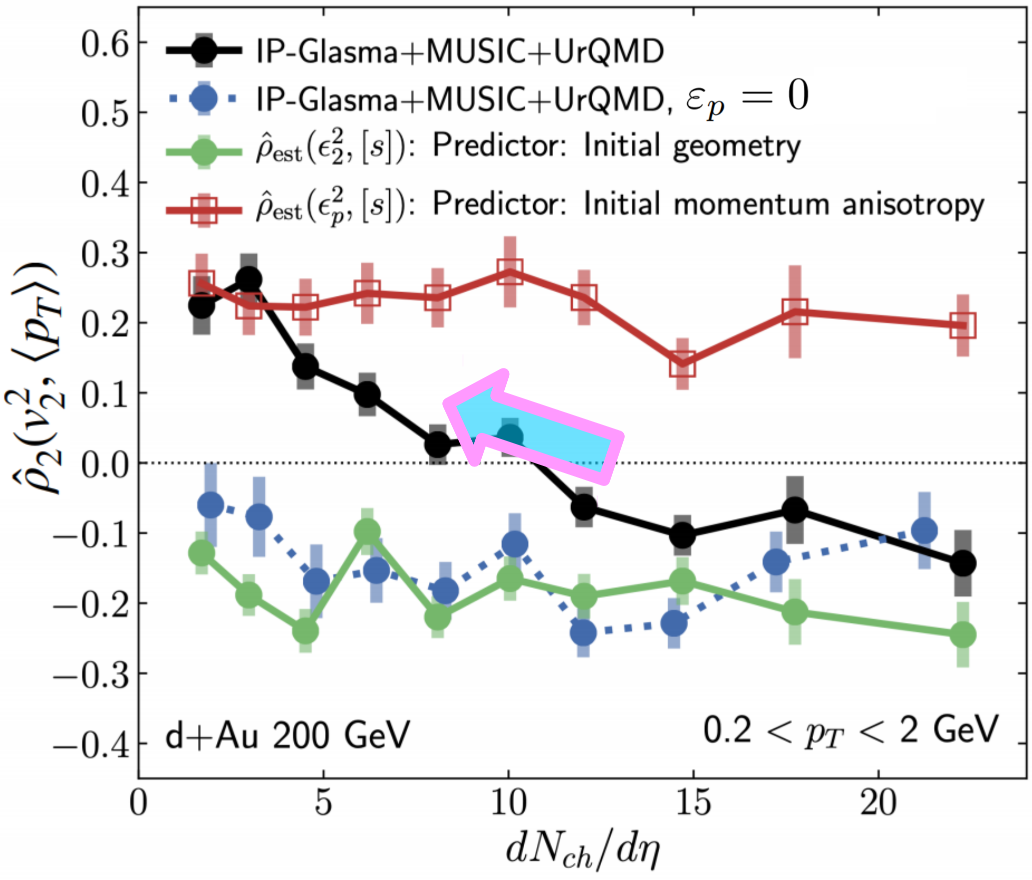
Negative. As expected.

They are qualitatively different.

[Giacalone, Schenke, Shen, **2006.15721**]

[Giacalone, Schenke, Shen, 2006.15721]

IP-Glasma+Hydro: full prediction.



– **Sign change** occurs as expected around dN/dη=10.
Neat prediction! (AA and pA).

– **No sign change if we set Ep=0.**

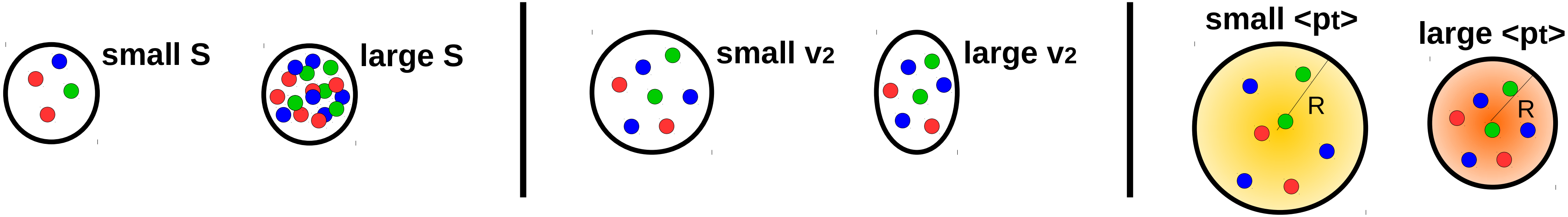
– **Non-flow mimics the signal.**
Must be carefully addressed.

[Behera, Bhatta, Jia, Zhang, 2102.05200]

[Lim, Nagle, 2103.01348]

SUMMARY

– Established picture of the soft sector in hydrodynamics:



– Nuclear phenomena through [pt]-vn correlations:

→ **Strong EM fields:** $\rho^{\pm}\left(\langle p_t \rangle, v_1^{\pm}\right)$

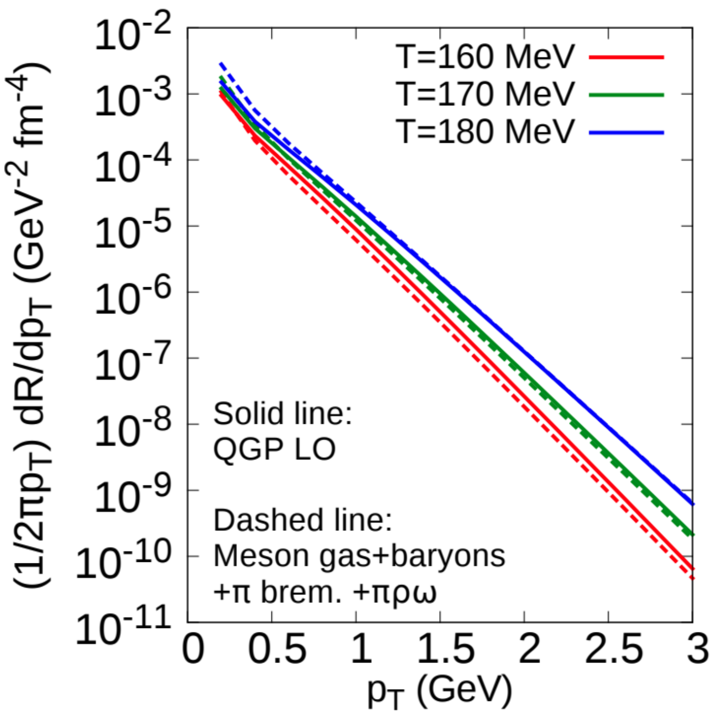
→ **Deformation in nuclei:** $\rho(v_2^2, [p_t]) < 0$

→ **Primordial momentum anisotropy:** $\rho(\varepsilon_p^2, [p_t]) > 0$

OUTLOOK

Thermal yields, N.
(photon, di-leptons)

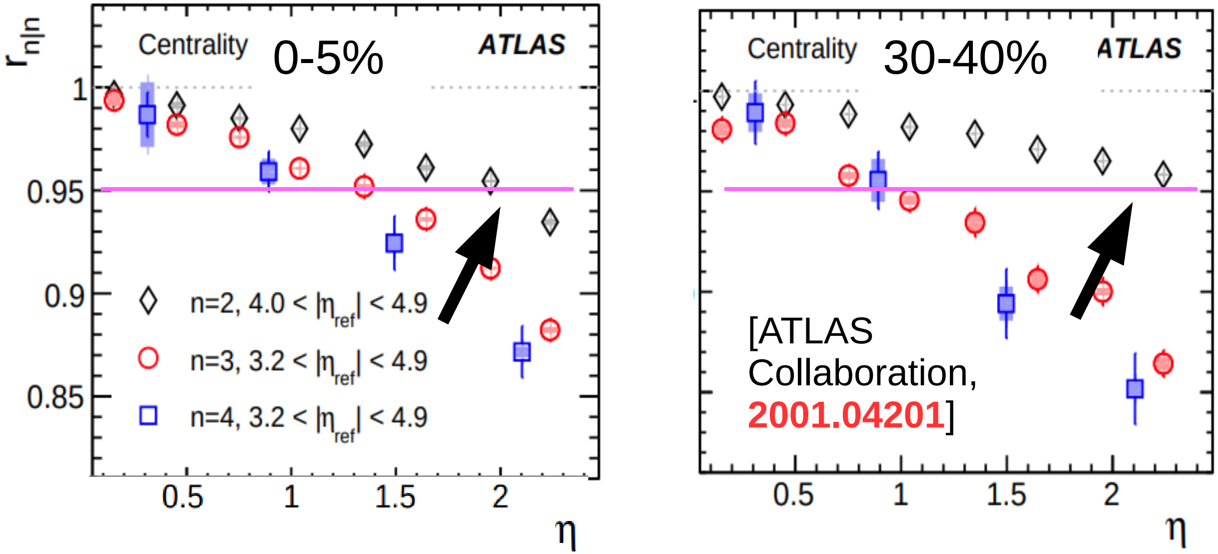
prediction: ρ(<pT>,N) > 0.



[Paquet, Shen, Denicol, Luzum, Schenke, Jeon, Gale, **1509.06738**]

Longitudinal de-correlations.

Smaller de-correlation at large impact parameters.



prediction: large-<pT> events de-correlate less.

More candidates:

– vorticity?
– energy loss?
…
– other ideas?

EXCITING PROSPECTS FOR THE NEXT DECADE

THANK YOU!