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: ESTABLISHED QGP PICTURE**
  - Particle multiplicties (dN/dη).
  - Anisotropic flow (Vn).
  - Isotropic flow (<pt>)
  - Status of soft sector.

- **NUCLEAR PHENOMENOLOGY AT HIGH ENERGY BEYOND THE QGP**
  - Correlating Vn with <pt> (at fixed dN/dη).
  - Signatures of strong magnetic fields.
  - Nuclear deformation in heavy-ion collisions.
  - Primordial momentum anisotropies.

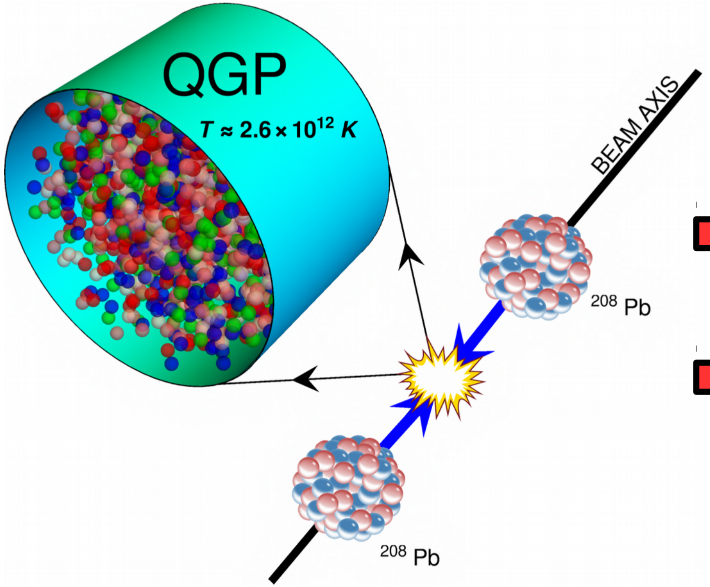
- **OUTLOOK**
  - The tip of the iceberg.

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

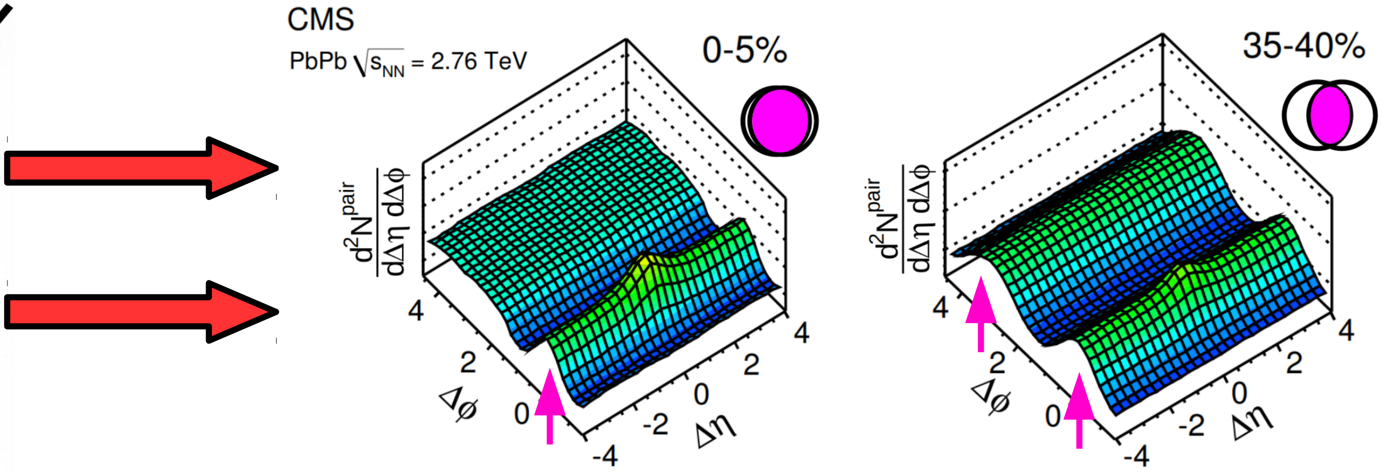
“More is different”
[Anderson, 1972]

- **Particle density in the overlap region is huge**: 1 to 10 fm^-3. Nuclear matter: 0.16 fm^-3.

- Regular structures in data: emergence of an **effective (collective) description**.



[Gardim, Giacalone, Luzum, Ollitrault, **1908.09728**]

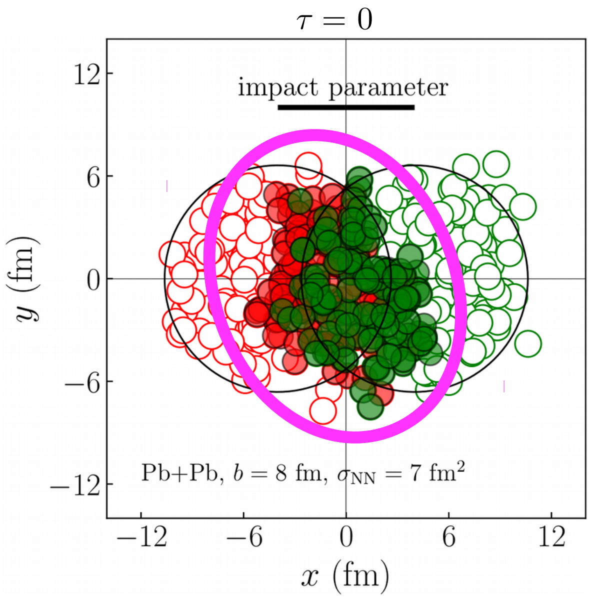


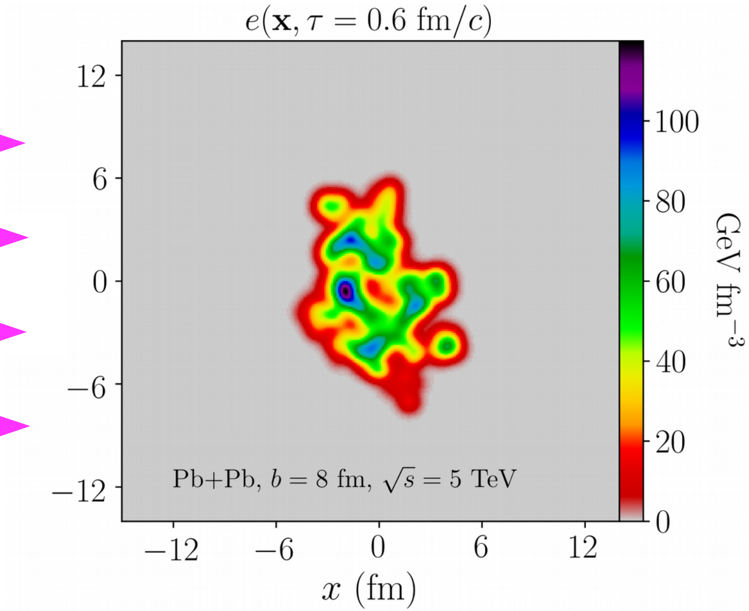
[CMS Collaboration, **1201.3158**]

System size much larger than "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 is that of a (relativistic) fluid.**





[Romatschke & Romatschke, 1712.05815]

Quasi-ideal dynamics:

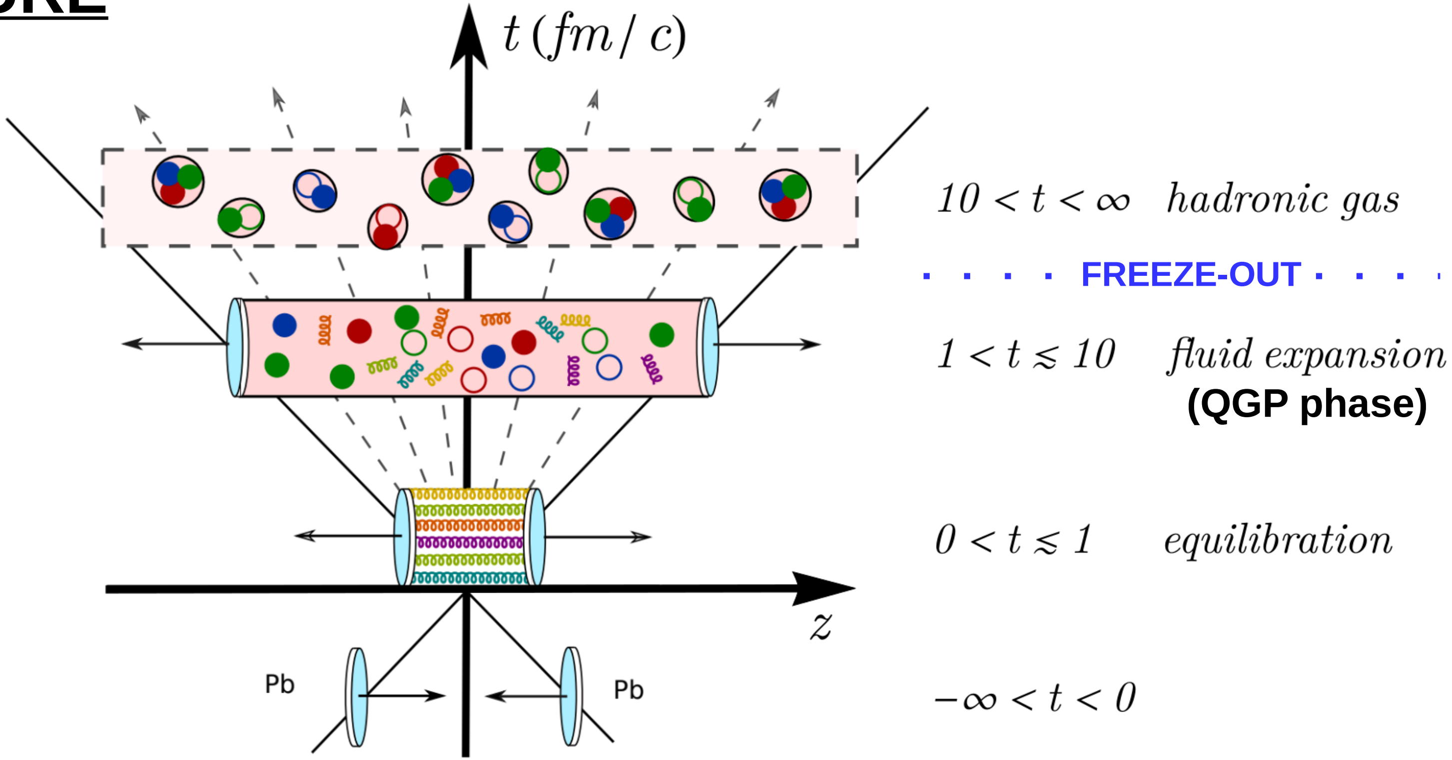
$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu} \text{ + small viscous corrections } (\eta/s, \zeta/s, \dots) \quad \mathbf{+} \quad \partial_\mu T^{\mu\nu} = 0$$

Equation of state of high-temperature QCD (T > Tc ~ 156 MeV). [HotQCD collaboration, 1407.6387]

Large number of DOF (~40) due to parton liberation: Quark-Gluon Plasma (QGP).

BIG PICTURE

(courtesy A. Mazeliauskas)



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, **p_t < 2 GeV**.

At ultrarelativistic energy, **particle yields are nearly independent of rapidity**.
Focus on the midrapidity slice:

$$\frac{dN}{dy\,d^2\mathbf{p}_t} \longrightarrow \frac{dN}{d^2\mathbf{p}_t} = \frac{dN}{p_t dp_t d\phi_p}$$

Fundamental quantities in the soft sector:

event multiplicity	**anisotropic flow**	**average momentum**
$N = \int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t}$	$V_n = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-in\phi_p}$	$\langle p_t \rangle = \frac{1}{N}\int_{\mathbf{p}_t} p_t \frac{dN}{d^2\mathbf{p}_t}$

Basics of QGP phenomenology: understanding these quantities.

[Giacalone, 2101.00168]

1 - event multiplicity.

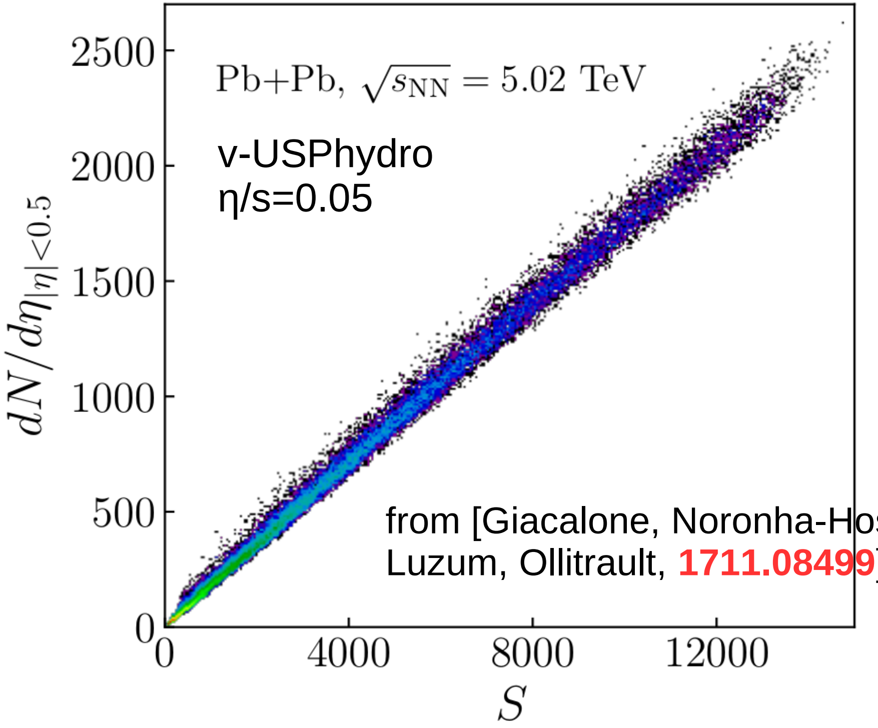
Underlying physics is that of an ideal gas of massless particles.

The number of particles determines the entropy. The QGP expansion is nearly isentropic.

Entropy, S, should thus be proportional to number of detected hadrons:

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

Confirmed by full hydro calculations.
(including viscosity, freeze-out, etc.)



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

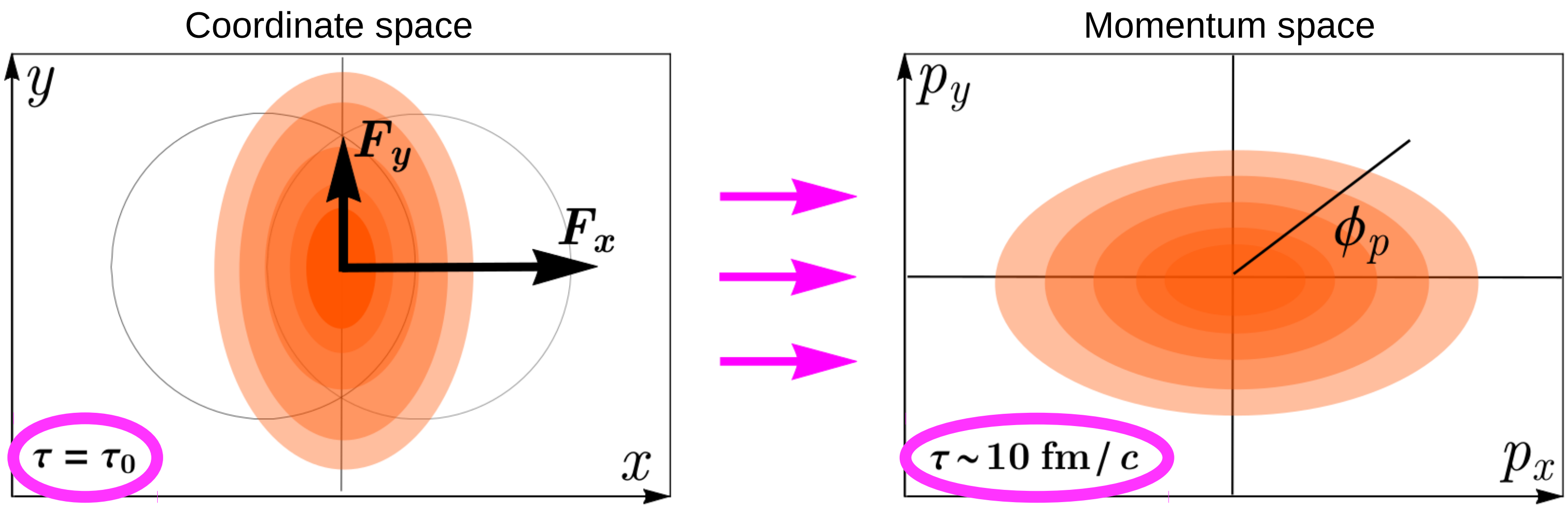
The event multiplicity is a measure of the entropy of the system.

2 - anisotropic flow.

Azimuthal anisotropy of particle emission.
The most famous is **elliptic flow**, the 2nd harmonic. $\longrightarrow$ $V_2 = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-i2\phi_p}$

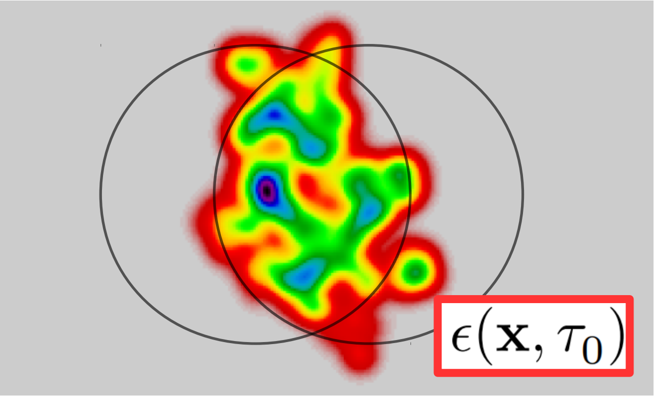
Geometric origin: imbalance of forces in anisotropic medium.
Shape-flow transmutation at finite impact parameter. $\vec{F} = -\vec{\nabla} P$

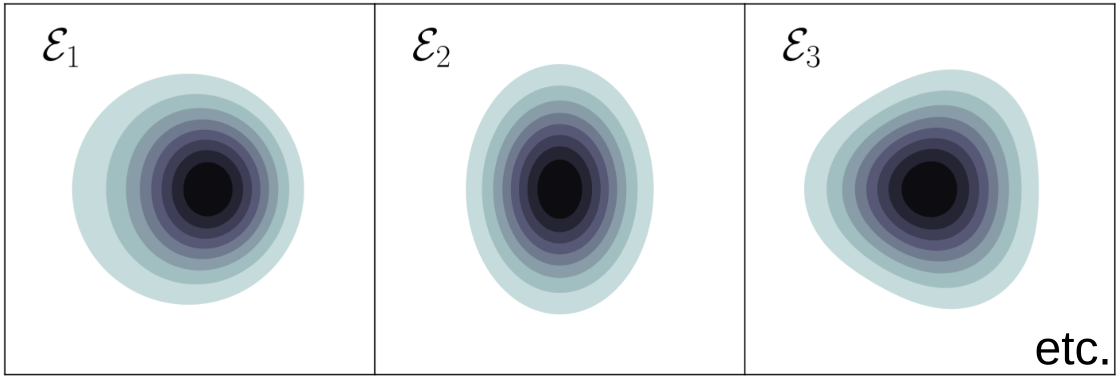
[Ollitrault, 1992]



Momentum anisotropy from spatial anisotropy.

More than ellipse: due to fluctuations (nucleon positions), all multipole moments are nonzero.





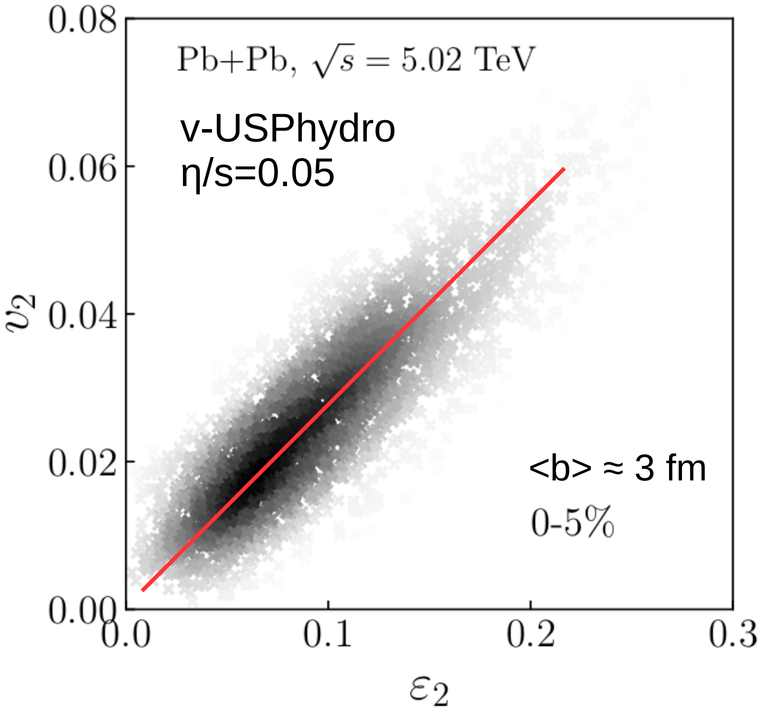
Multipole moments in two dimensions identified by [Teaney, Yan, 1010.1876].
For n=2 or n=3, they read:

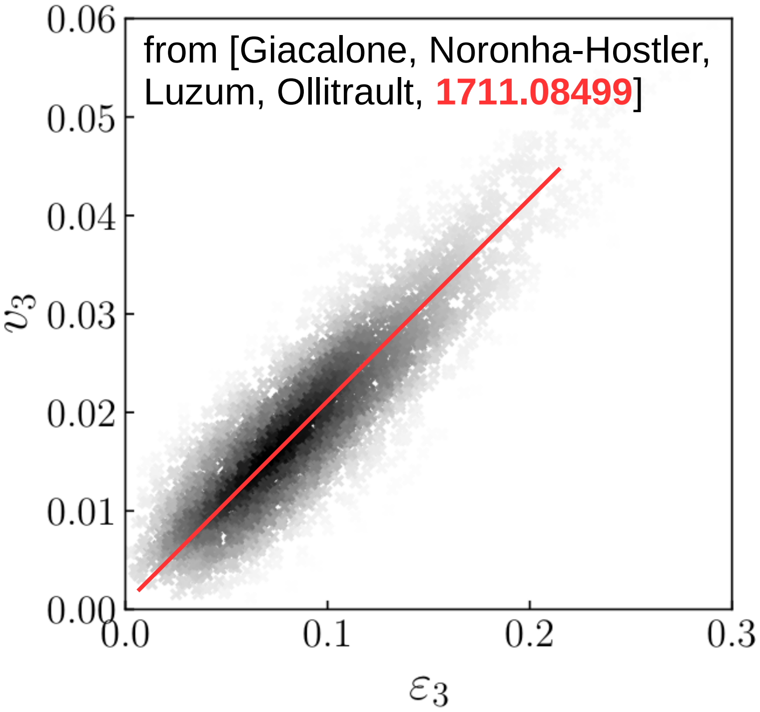
$$\mathcal{E}_n = -\frac{\int r dr d\phi \; r^n e^{in\phi} \epsilon(r,\phi)}{\int r dr d\phi \; r^n \epsilon(r,\phi)}$$

But recall: $\vec{F} = -\vec{\nabla} P$. Each E_n in the initial state leads to V_n in the final state.

Simple relation: $V_n \propto \mathcal{E}_n$

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]

3 – average momentum (isotropic flow)

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

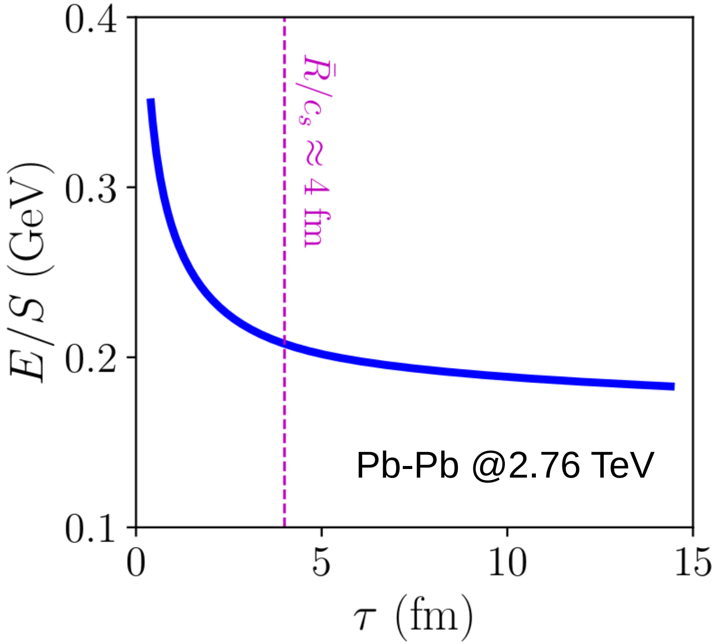
Energy per particle in the QGP is nontrivial:

$$E/S$$

Evolution is quasi-isentropic, but the energy is not constant!

Longitudinal cooling in QGP: [Björken, 1982]

$$dE = -PdV$$



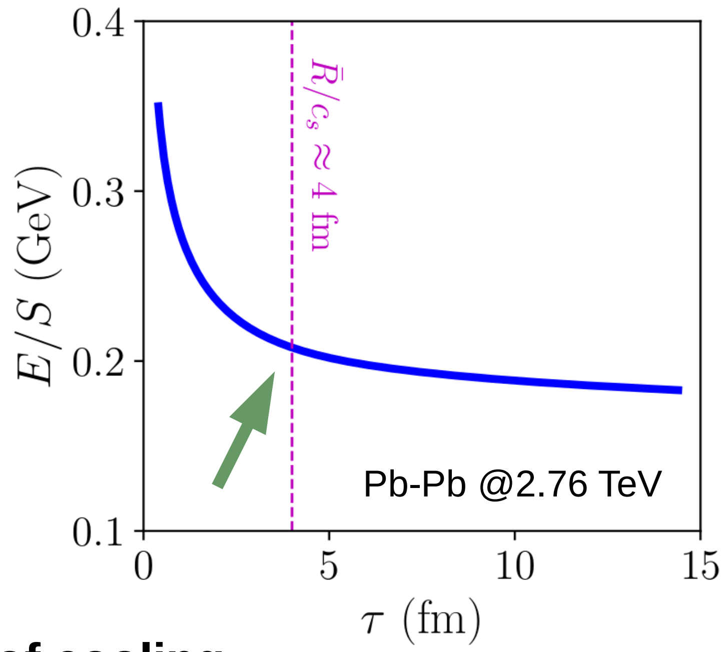
Energy per particle is fixed only at the end of cooling.

Back to the ideal gas. Energy per particle:

$$p \simeq E = 3T$$

Therefore in a heavy-ion collision we expect:

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



where T is the temperature of the system at the end of cooling.
This has been verified in hydrodynamic simulations. [Gardim, Giacalone, Luzum, Ollitrault, **1908.09728**]

Application:

Understanding <pt> measured by the ALICE collaboration in 0-5% Pb+Pb.
They measure **<pt>≈680MeV.** The temperature is then **<pt>/3≈226MeV ~ 2.6** x **10^{12} K**.

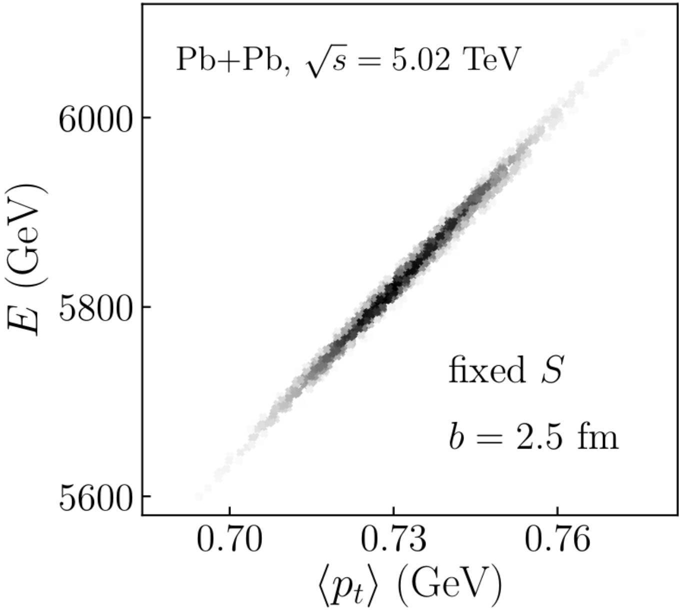
<pt> fluctuations. Consider that <pt> is proportional to the initial temperature, T.
A few relations follow (E=initial energy, R=initial rms radius):

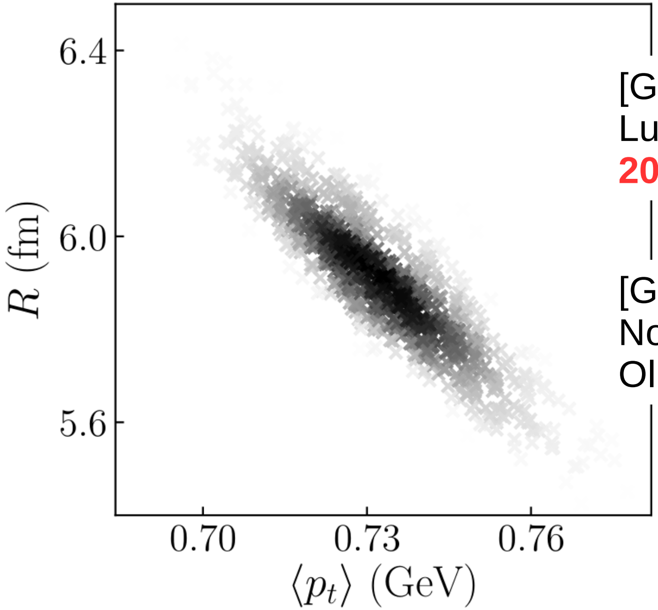
$$c_s^2 = \frac{dP}{d\epsilon} = \frac{d\ln T}{d\ln s} \xrightarrow{\langle p_t\rangle \sim T} \frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto \frac{dE}{E} \qquad \frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto -\frac{dR}{R}$$

The proportionality factors depend on the equation of state.

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

Verified in full hydrodynamic simulations at fixed entropy (multiplicity).





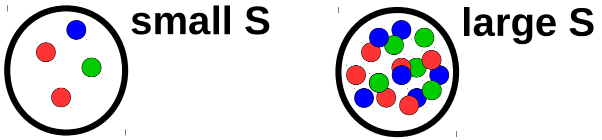
[Gardim, Giacalone, Luzum, Ollitrault, 2002.07008]

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

<u>SUMMARY</u>: basics of the soft sector of heavy-ion collisions.

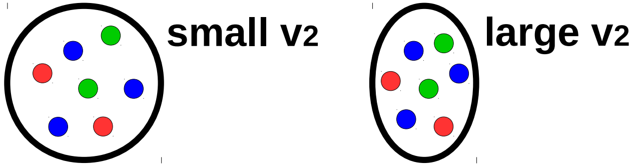
- The **number of detected hadrons** (N or dN/dη) is a measure of the **entropy** of the QGP.

$$S \propto N$$



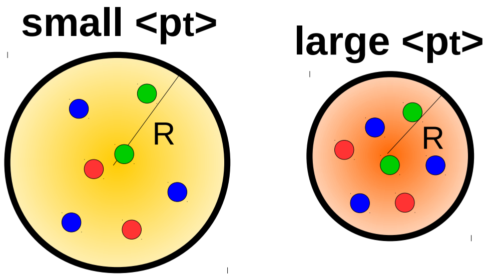
- **Anisotropic flow coefficients** (V_n) are a hydrodynamic response of the system to its **initial spatial anisotropies** (E_n).

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



- **Momentum** of the outgoing hadrons, $<p_t>$, depends on the temperature reached in the QGP. Its **fluctuations probe the thermodynamics** of the system (energy, volume).

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



Current <u>status of the field</u>. I think there are three main directions:

- **Clarifying the origin and limits of applicability of this picture.** How does thermalization occur? How small can a QGP be? When can you talk about 'hydro'?

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

- **Refining the picture and challenging current descriptions.** Values of transport coefficients, medium properties, initial conditions, freeze-out, etc.

[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 study new phenomena at high energy.** Popular topics: chiral magnetic effect, color glass condensate, hydrodynamics with spin, nuclear structure.

THIS TALK

Revealing nuclear phenomena at high energy with multi-particle correlations.

So far we have built observables from fluctuations of anisotropic flow:

$$\langle v_n^2 \rangle = \left\langle \frac{\int_{\mathbf{p}_1,\mathbf{p}_2} e^{in(\phi_1-\phi_2)} \frac{dN}{d^2\mathbf{p}_1 d^2\mathbf{p}_2}}{\int_{\mathbf{p}_1,\mathbf{p}_2} \frac{dN}{d^2\mathbf{p}_1 d^2\mathbf{p}_2}} \right\rangle$$

Or fluctuations of the average transverse momentum, **which I also dub [p_t]**:

$$\langle [p_t]^2 \rangle - \langle [p_t] \rangle^2 = \left\langle \frac{\int_{\mathbf{p}_1,\mathbf{p}_2} (p_1 - \langle\langle p \rangle\rangle)(p_2 - \langle\langle p \rangle\rangle) \frac{dN}{d^2\mathbf{p}_1 d^2\mathbf{p}_2}}{\int_{\mathbf{p}_1,\mathbf{p}_2} \frac{dN}{d^2\mathbf{p}_1 d^2\mathbf{p}_2}} \right\rangle$$

Revealing nuclear phenomena at high energy with multi-particle correlations.

Breakthrough idea: Mix the previous two!

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

First apparition as a byproduct of a principal component analysis.

[Mazeliauskas, Teaney, 1509.07492]

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

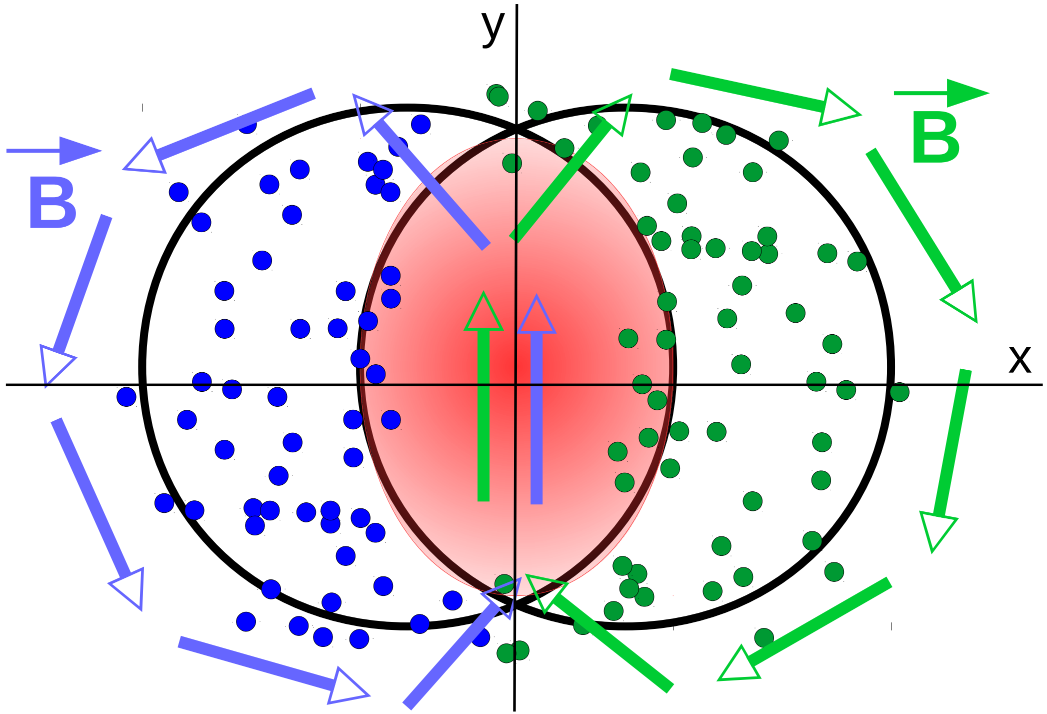
[Bożek, 1601.04513]

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

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

I show that this observable appears naturally in the study of several phenomena.

#1 – Electromagnetic fields.



– Magnetic field of **spectator protons** sum up coherently in the region of overlap.

– The strongest field ever produced in the laboratory. **|B| ~ 10¹⁴ T**

– Typically probed by **charge-dependent dipolar flows** (very small effects).

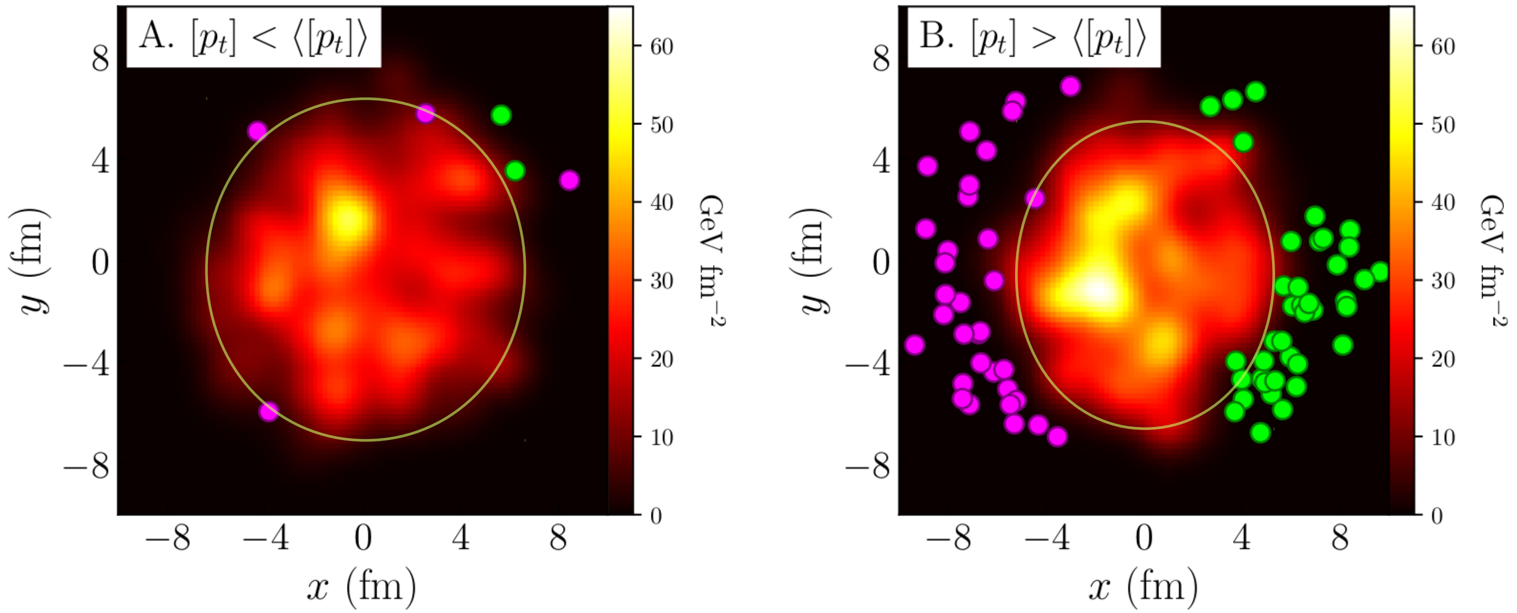
[Oliva, 2007.00560] $\langle \cos(\phi_1^{\pm} - \phi_2^{\pm}) \rangle$

Motivation
– Strong fields.
– Parity violation (CME).
– Electric conductivity of QGP.

– Elusive. Clean experimental evidence still missing. But we can use <pt>!

Select two **central events** (2-3%) 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}	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

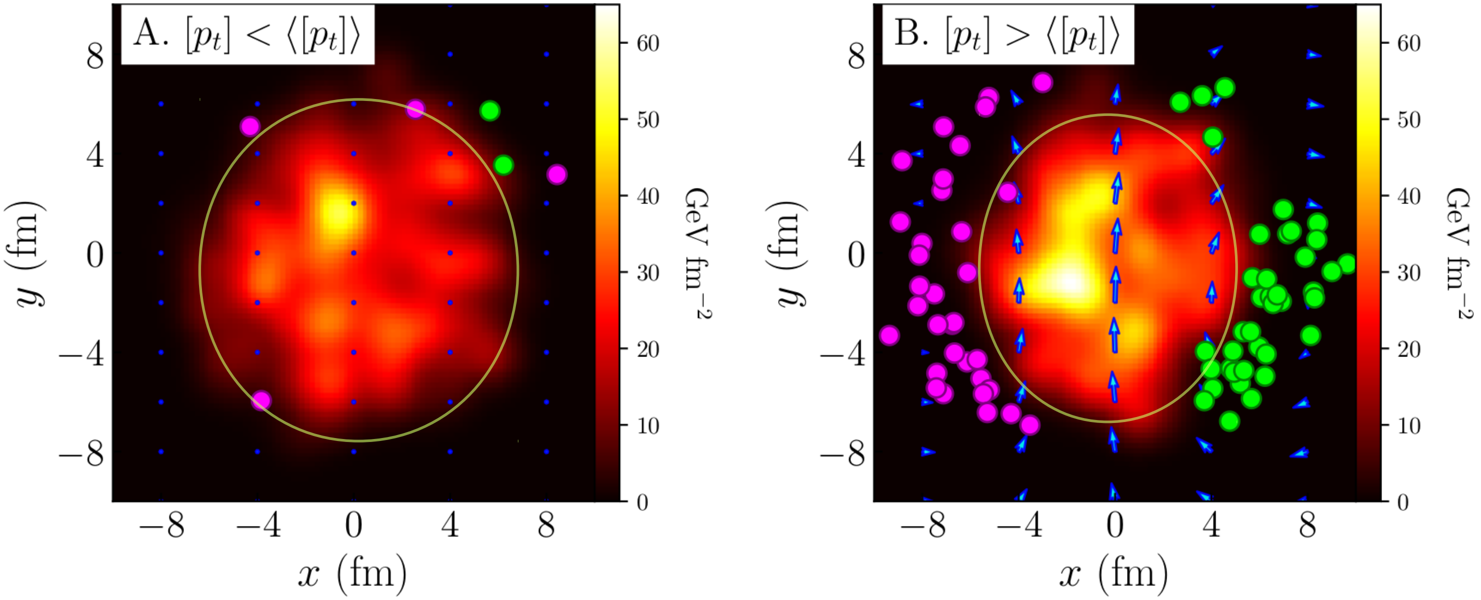
Finding of [Giacalone, 2006.06269]: **strong correlation between [pt] and <Ns>.**
<u>What about the magnetic field?</u>

[Gürsoy, Kharzeev, Rajagopal, 1401.3805]

Event-by-event calculation of <By> with the framework developed in:

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

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



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

[Giacalone, Shen, 2104.xxxxx]

AN OPTIMAL EVENT-SHAPE ENGINEERING (FOR CENTRAL COLLISIONS!)

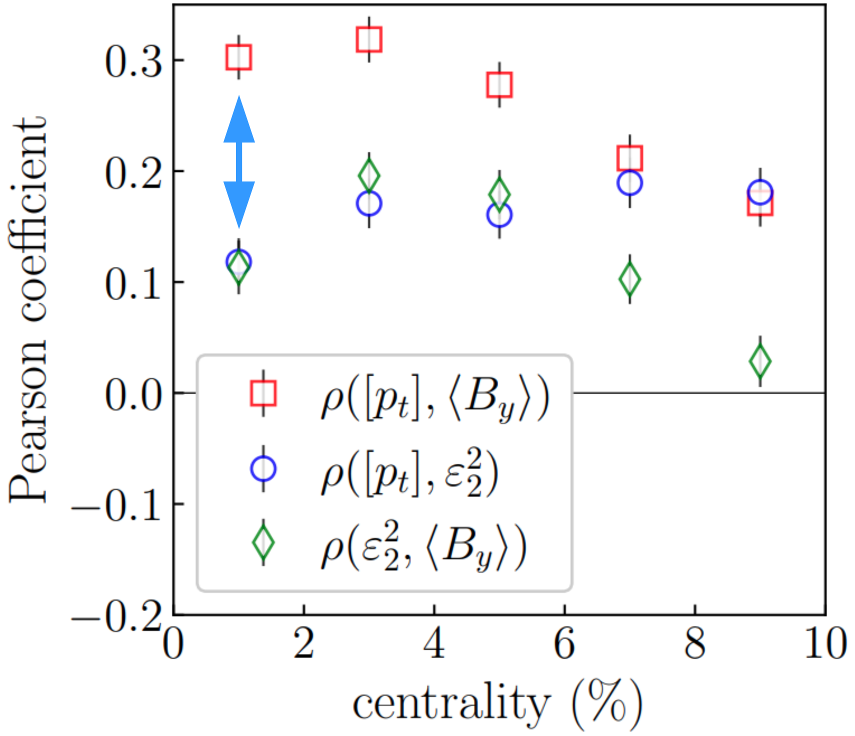
[Giacalone, Shen, **2104.xxxxx**]

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

Event selection based on $[p_t]$ provides a better handle on $\langle B_y \rangle$ than usual event selection based on q_2 vectors. ;-)

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

Event selection based on $[p_t]$ increases $\langle B_y \rangle$ more than v_2. Important for CME background.



NATURAL OBSERVABLE TO SEARCH FOR THE B FIELD (AND THE CME!)

[Giacalone, 2006.06269]
[Giacalone, Shen, 2104.xxxxx]

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

– **<u>Correlation between charge-dependent v_1 and <p_t> at fixed multiplicity.</u>**

– Can be turned into a Pearson (Bożek) coefficient:

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

Where one should use:

$$g^{\pm} = \left\langle \cos\left(\phi_1^{\pm} + \phi_2^{\pm} - 2\phi_3\right) \right\rangle = \left(v_1^{\pm}\right)^2 v_2$$

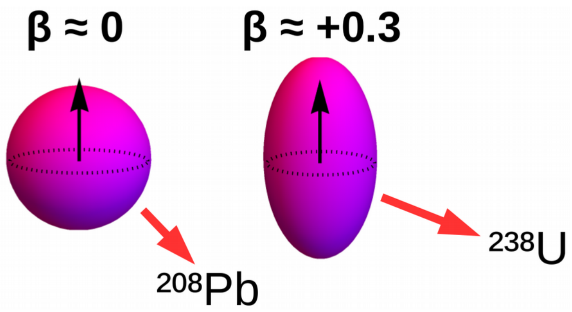
#2 – Nuclear structure: deformation.

Deformation: emergent property of nuclei (even for J=0). Nucleus as a deformed object. Quadrupole is the most important:

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

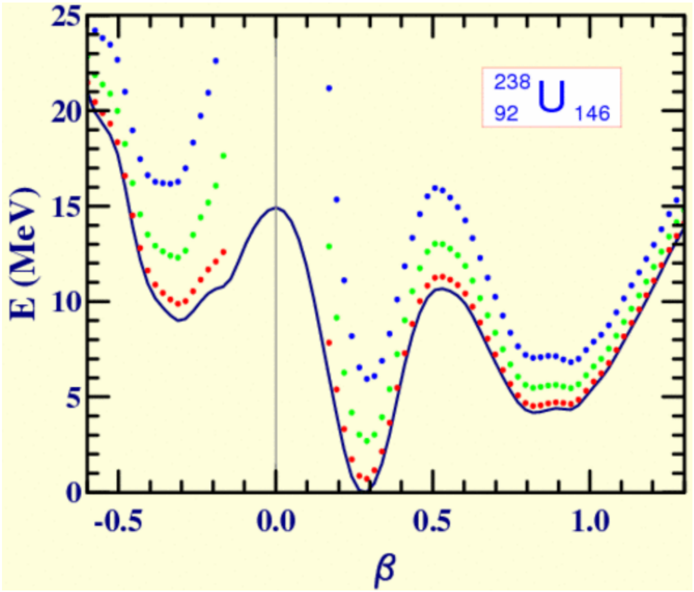
Quadrupole shape quantified by a coefficient:

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



(and ^{197}Au)

Hartree-Fock approach: in most nuclear systems, deformed configurations are energetically favored.

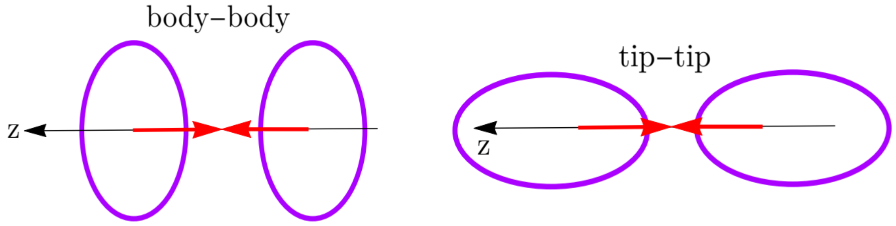


Rotational model: nucleus as an intrinsically deformed object with a random orientation.

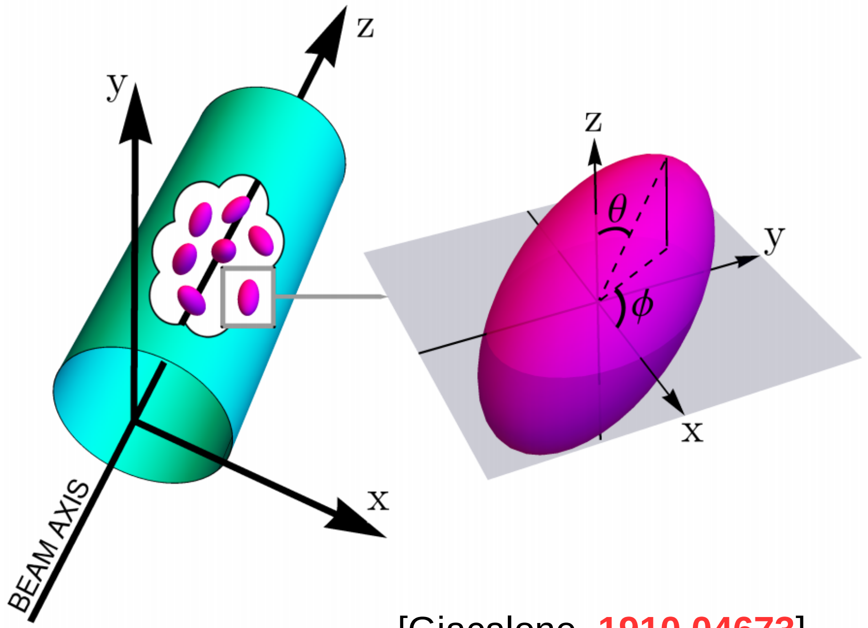
[Bohr, Mottelson 1957]

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

New overlap geometries:

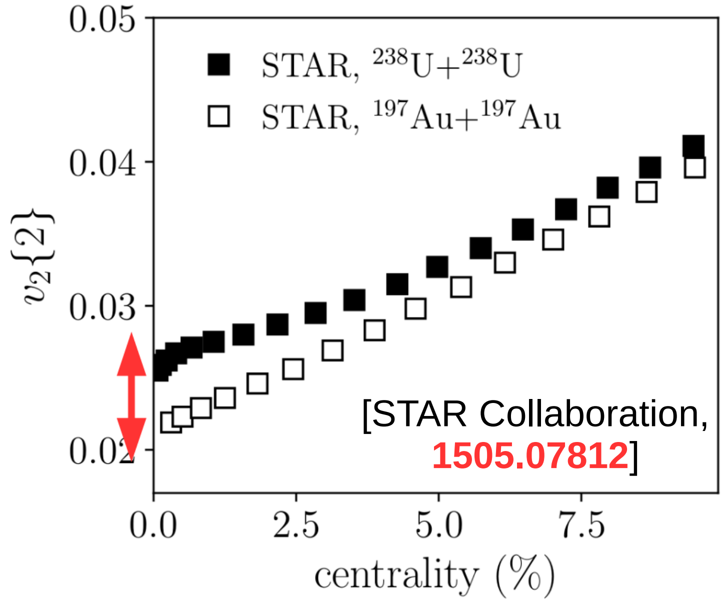


Deformed nuclei in the beampipe.



[Giacalone, 1910.04673]

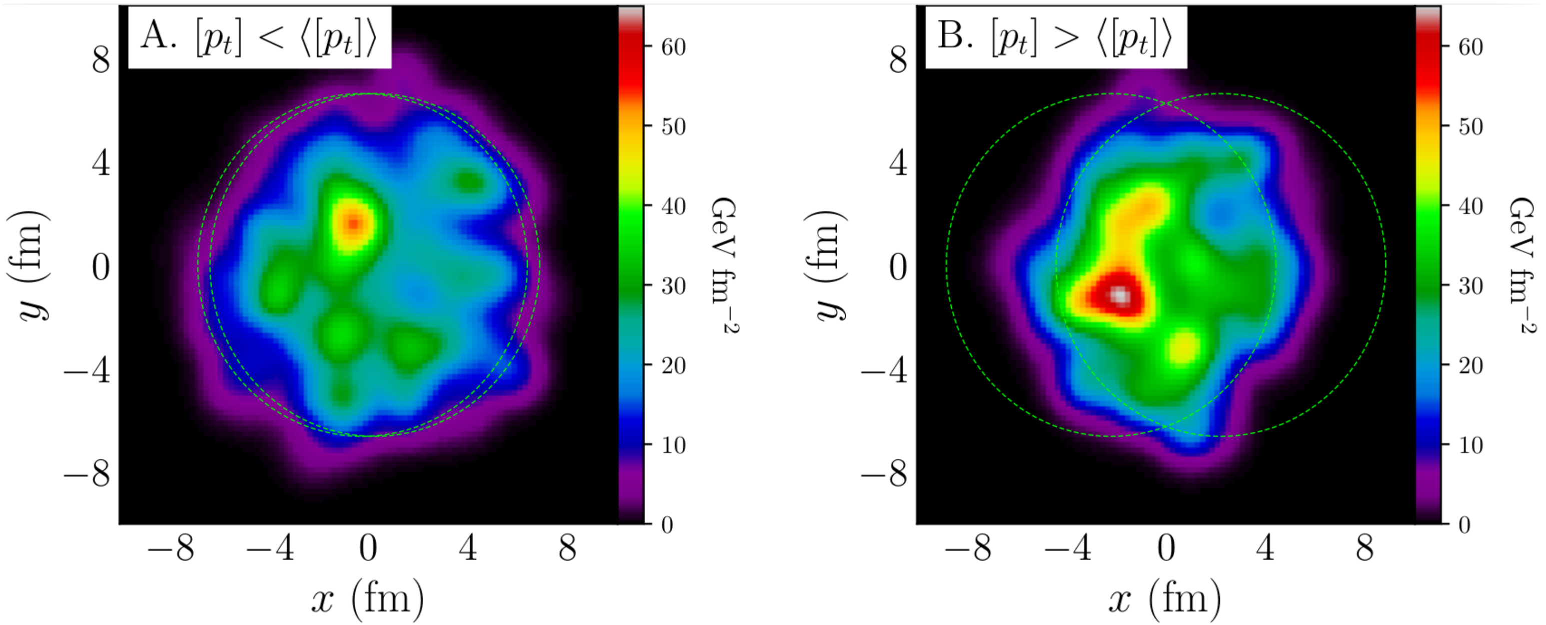
Prediction: contamination from body-body yields an excess v2 in central U+U collisions. Verified in RHIC data!



[STAR Collaboration, 1505.07812]

Back to spherical nuclei.

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



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

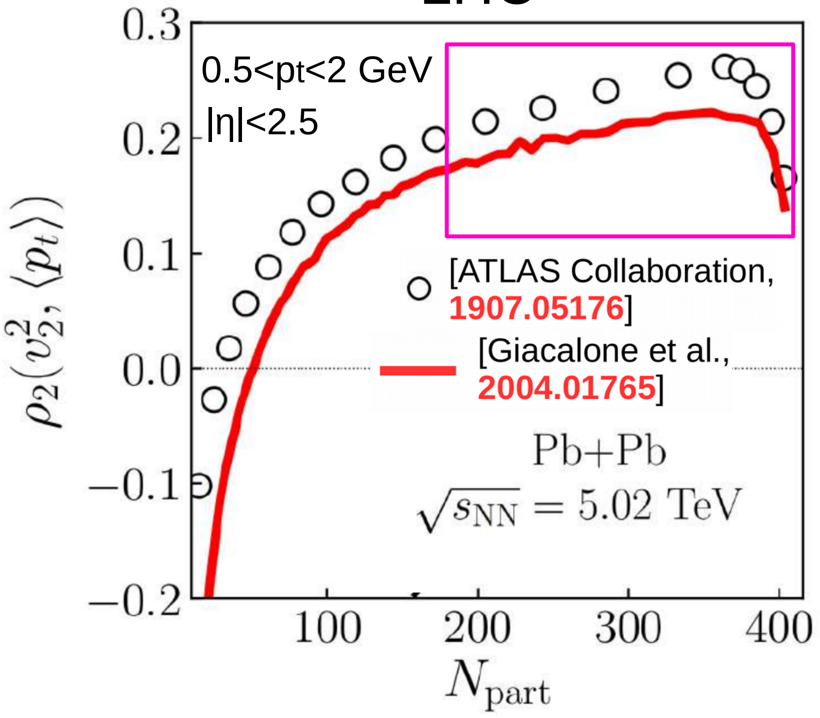
But also increases the impact parameter and eccentricity!

Prediction. In central heavy-ion collisions:

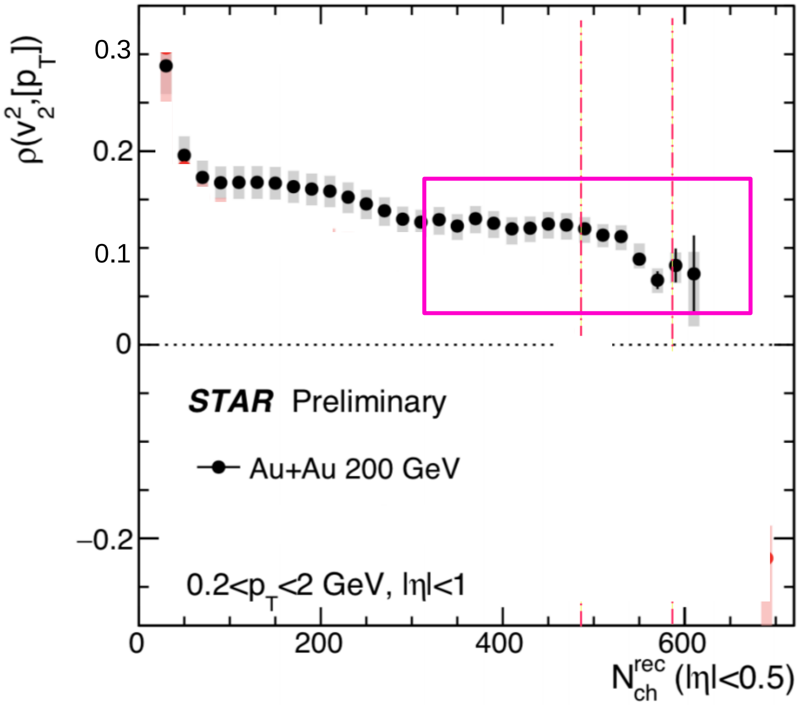
$$\boxed{\rho(v_2^2, [p_t]) > 0}$$

Prediction verified at LHC (Pb+Pb) and RHIC (Au+Au). Correlation is positive.

LHC



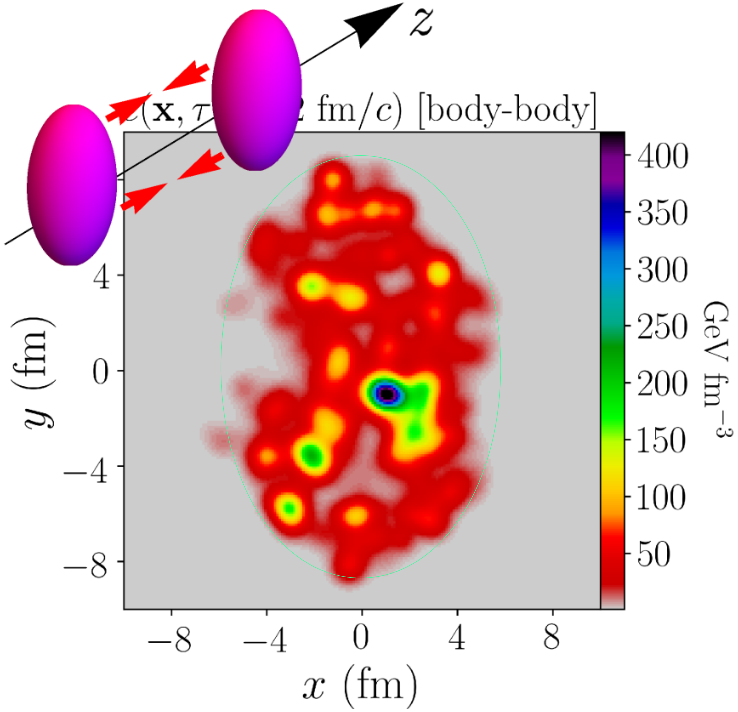
RHIC

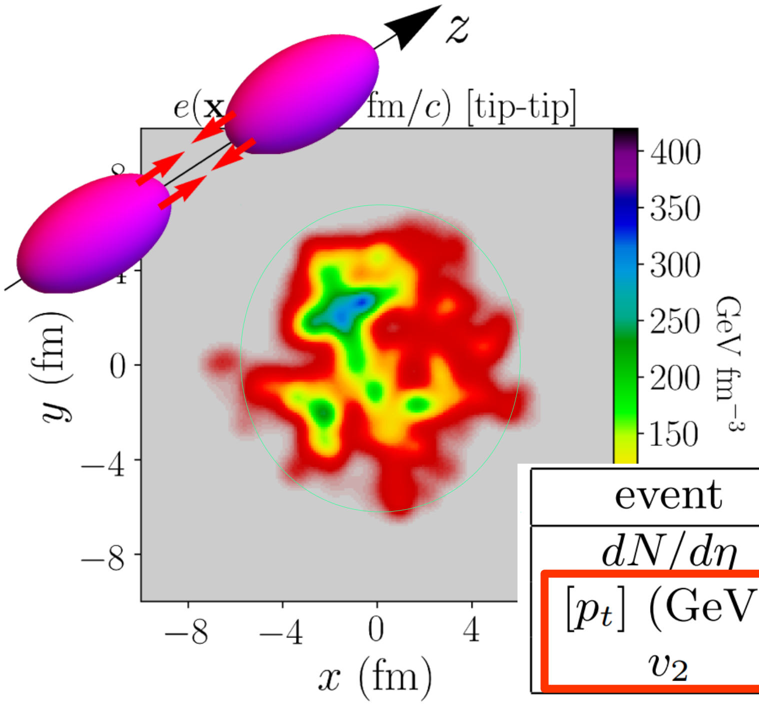


Insane differences between the two results… I'll get back to this.

WHAT IF THE COLLIDING NUCLEI ARE DEFORMED? ^{238}U + ^{238}U (β=0.3)

Select two **central events** (0.8-0.9%) at the **same multiplicity** but very **different [p_t].**





[Giacalone, 1910.04673]
[Giacalone, 2004.14463]

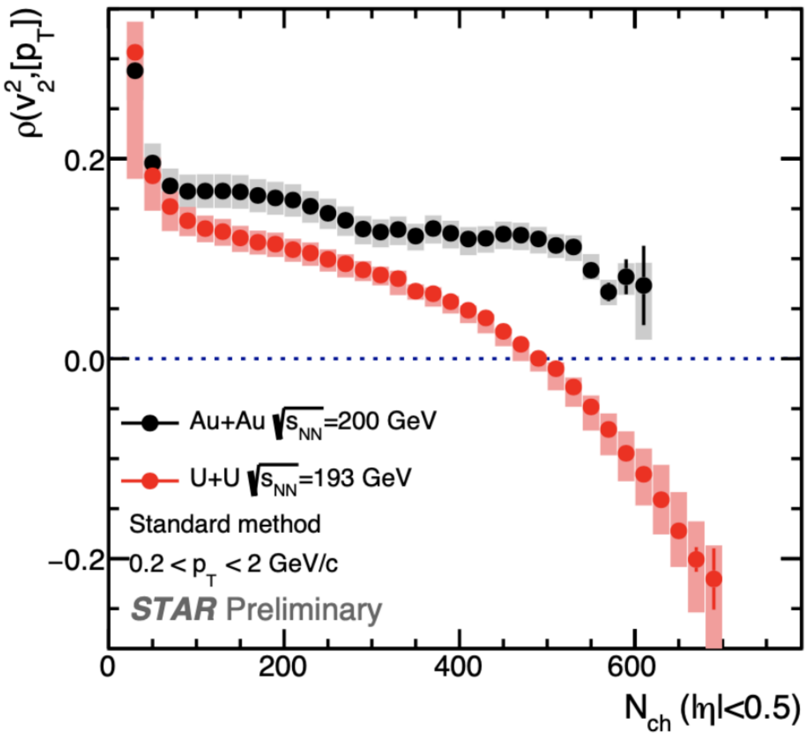
event	body-body	tip-tip
$dN/d\eta$	1296	1280
$[p_t]$ (GeV)	0.587	0.651
v_2	0.083	0.027

<u>Body-Body:</u> small <p_t>, large v_2. <u>Tip-tip:</u> large <p_t>, small v_2.

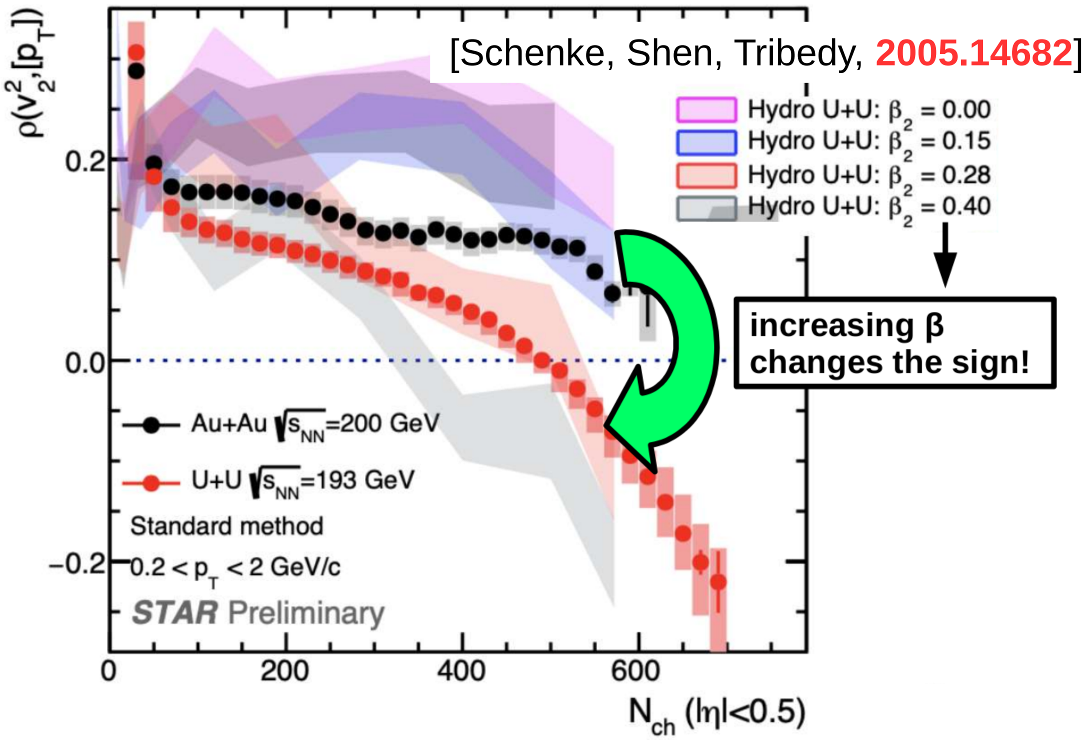
Prediction! In central collisions of <u>deformed</u> heavy ions: $\boxed{\rho(v_2^2, [p_t]) < 0}$

Spectacular confirmation at RHIC. Correlation is positive in Au+Au, and <u>negative in U+U</u>.

DATA



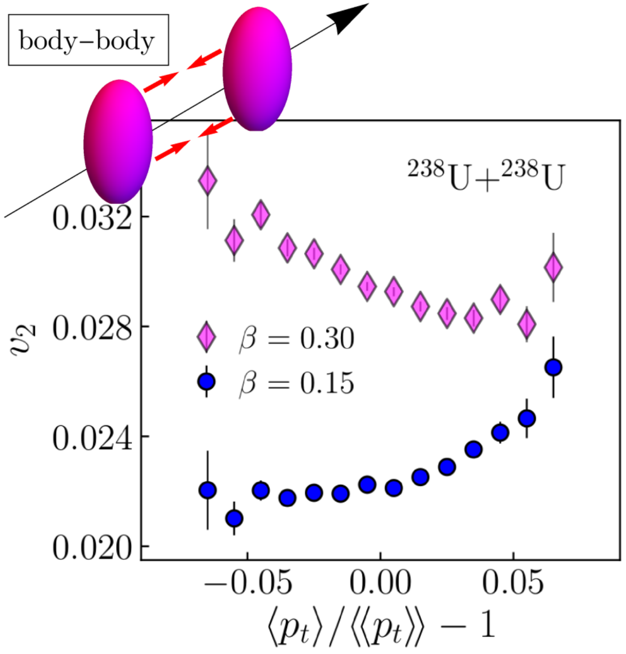
DATA + THEORY



Nuclear deformation interpretation confirmed by hydro calculations: β≈0.3

<u>Brings consistency with low-energy nuclear structure theory.</u>

We have isolated body-body collisions. A nontrivial result in nuclear physics.



PRACTICAL APPLICATION

– Ultra-sensitive to the value of β. High-energy experiments as a new probe of the low-energy structure.

DEFORMATION: INTERPRETATION

– Quantum nature of nuclei:

“Body-body collisions” are only a simplification: the nucleus is J=0 (spherical!)
Exact wavefunction in any basis of (non-deformed) states, should give the same results.

But the QGP and its eccentricity are real entities! Can you get the right <ε2>-R correlations without deformed densities?

#3 – Primordial momentum anisotropies.

So far I have considered $V_n \propto \mathcal{E}_n$, where En is the anisotropy of the energy density.

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

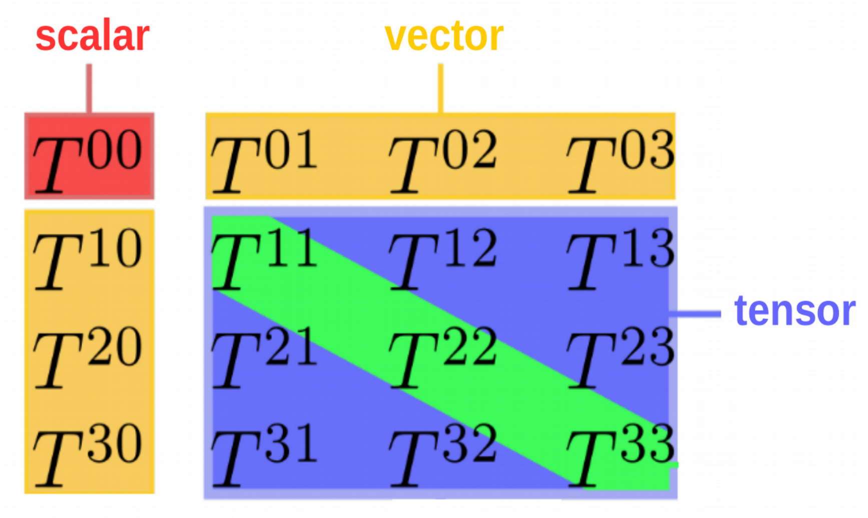
SCALAR

$$\mathcal{E}_2 = \frac{\langle x^2 - y^2 \rangle + i \langle 2xy \rangle}{\langle x^2 + y^2 \rangle}$$

TENSOR

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

(vector is less important)

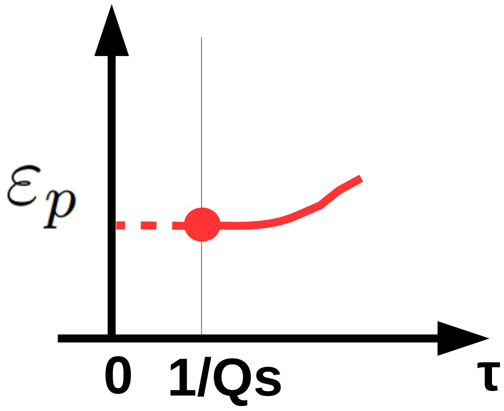


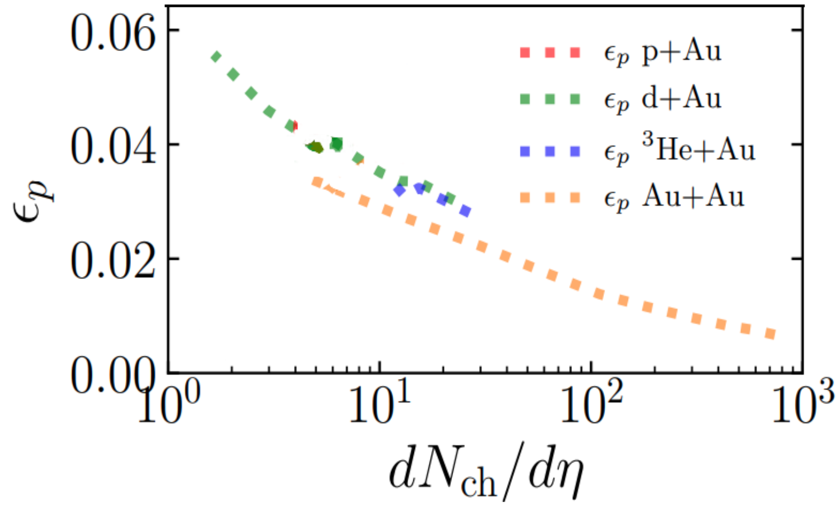
[Sousa, Luzum, Noronha, 2002.12735]

The color glass condensate predicts the 'off-diagonal' contribution.
Longstanding question in the field: <u>do we see initial-state CGC anisotropy in the data?</u>

[Altinoluk, Armesto, 2004.08185]

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





Assume now the following decomposition:

$$V_2 = \kappa_2 \mathcal{E}_2 + \kappa_p \mathcal{E}_p$$

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

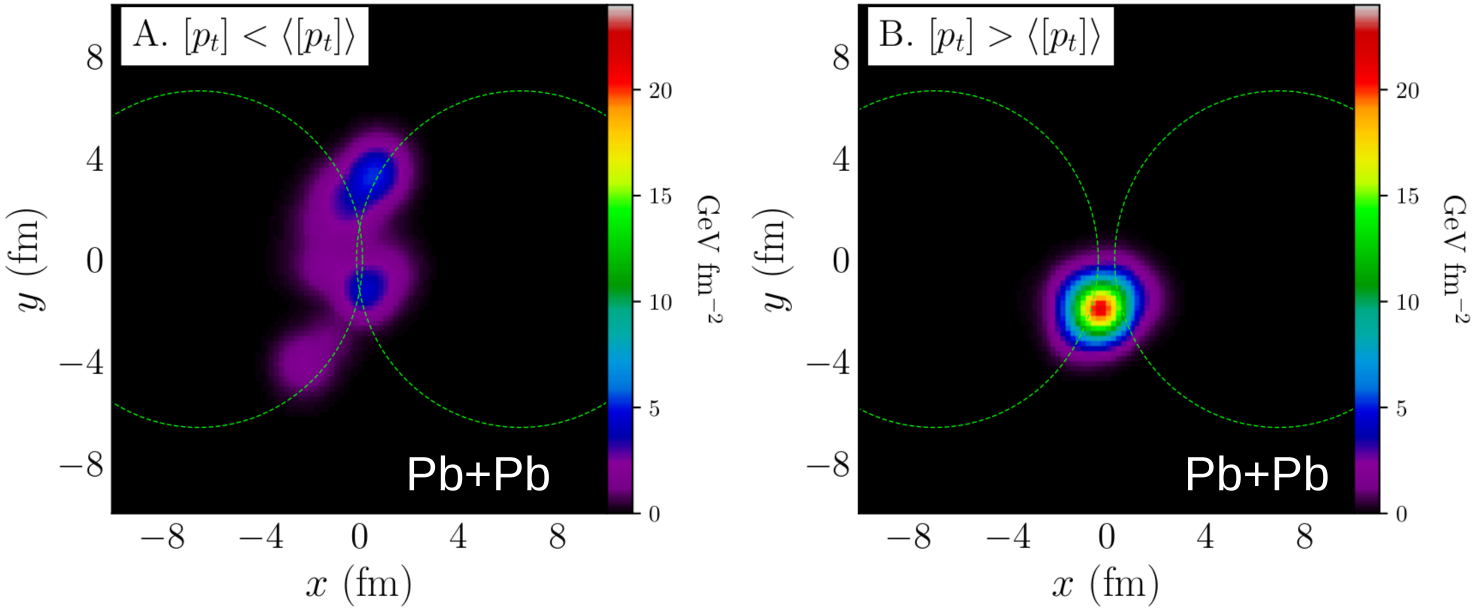
dominates for **dN/dη > 10**

dominates for **dN/dη < 10**

How to probe the new contribution at small dN/dη? … we can use <pT>!

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}	133.5	133.5
b (fm)	13.0	13.9
N_s	392	405
$[p_t]/\langle[p_t]\rangle$	0.907	1.143
R (fm)	2.97	1.34
ε_2	0.675	0.133

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

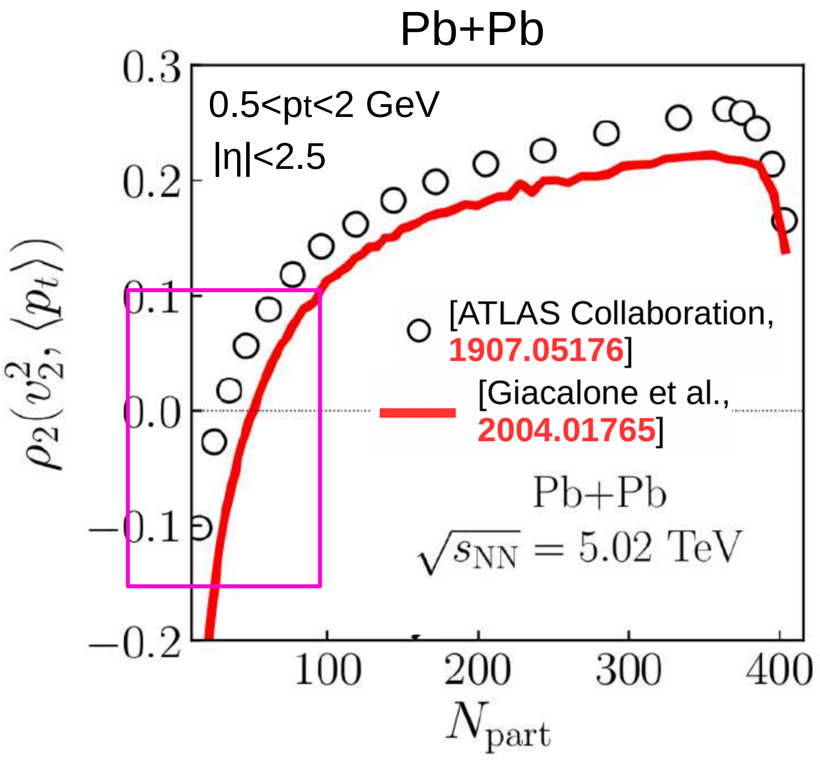
<u>**Prediction.**</u> In small systems:

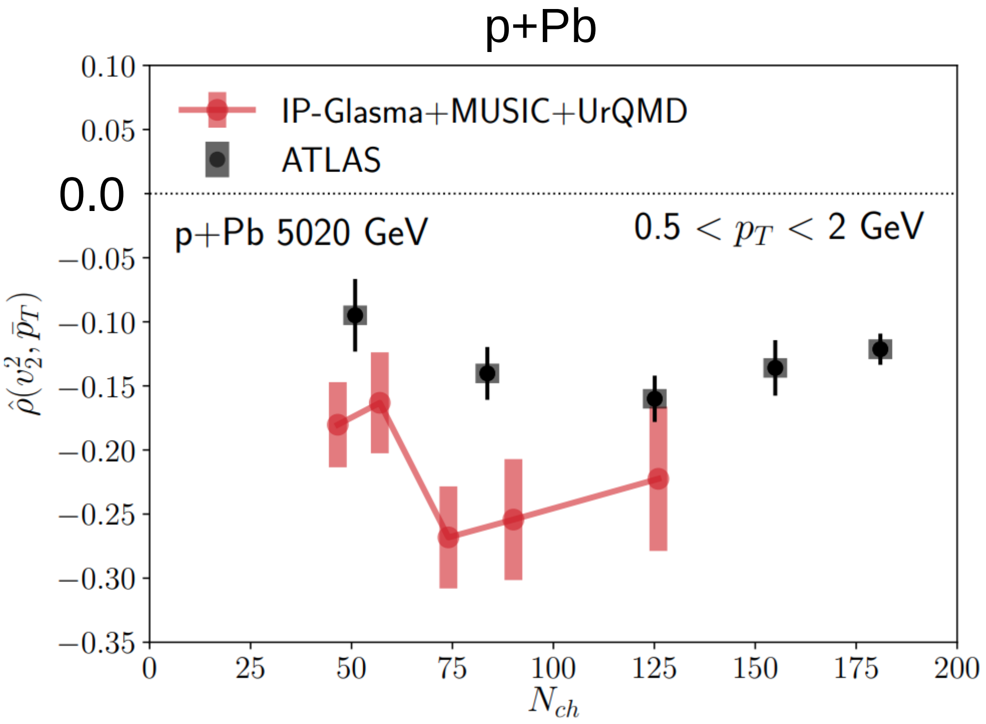
$$\boxed{\rho(v_2^2, [p_t]) < 0}$$

[Bożek, Mehrabpour, 2002.08832]

[Schenke, Shen, Teaney, 2004.00690]

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



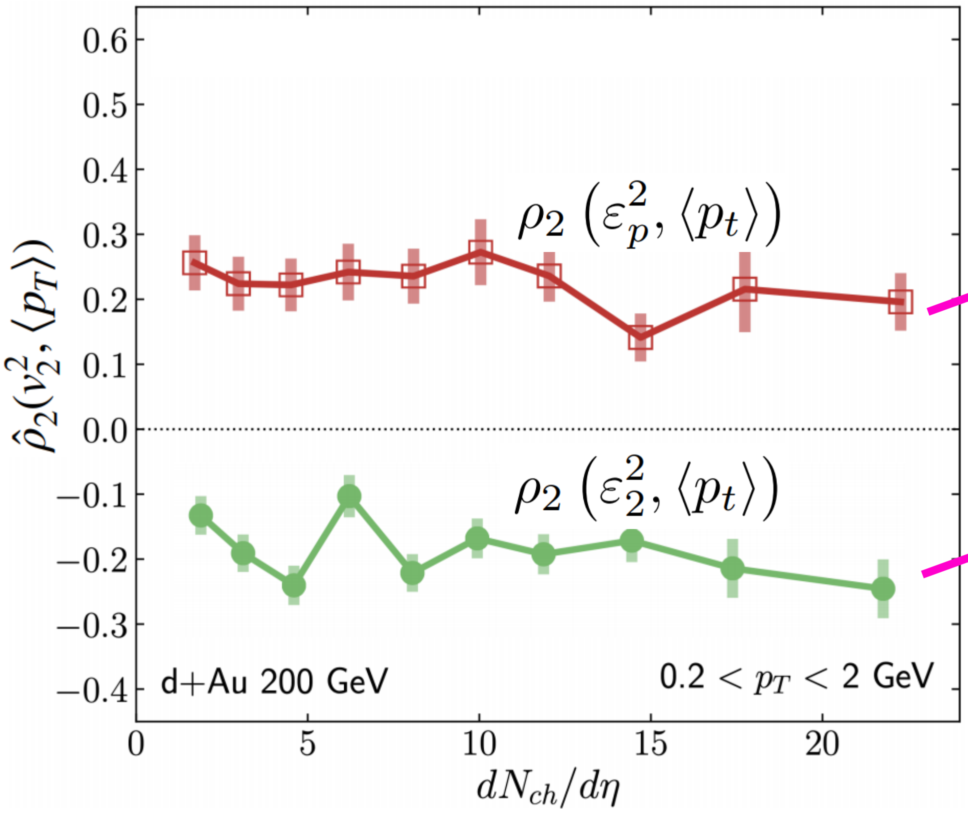


[Schenke, Shen, Teaney, 2004.00690]

What about Au+Au at RHIC? I'll get to that…

But if we 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!
A new feature of high-energy QCD.
(consistent with color-domain picture)

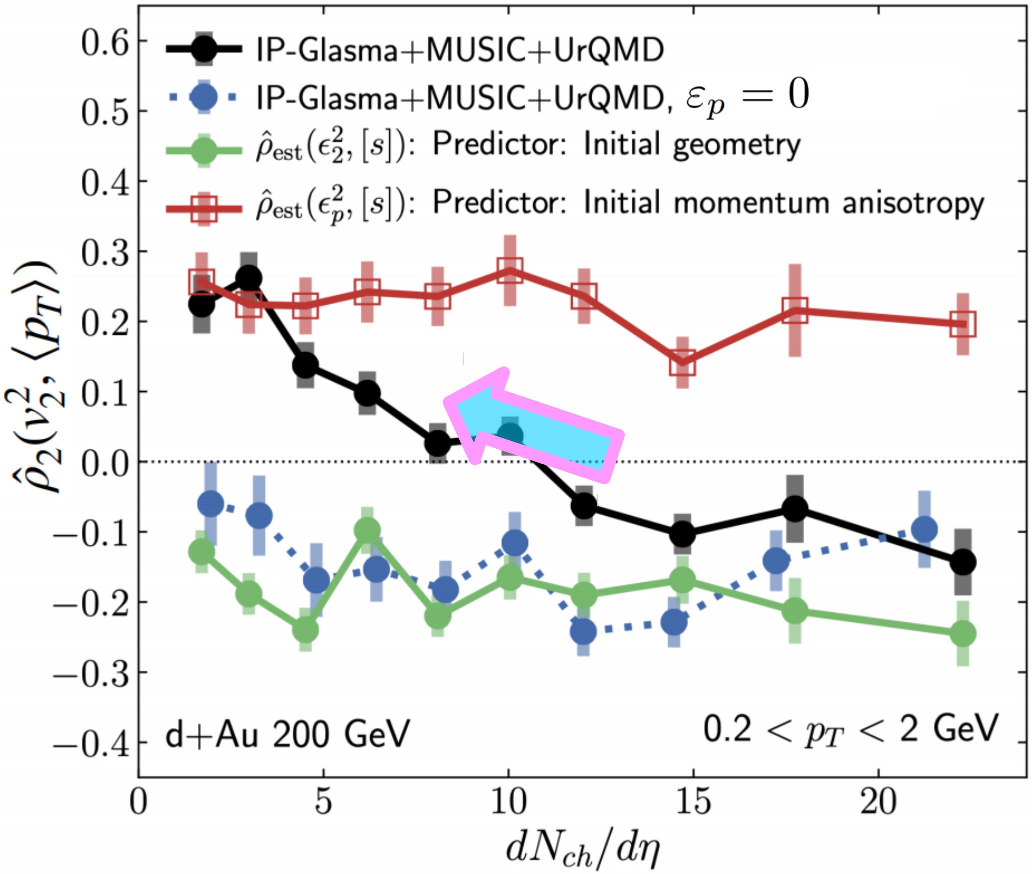
Negative. As expected.

The contributions are qualitatively different.

[Giacalone, Schenke, Shen, 2006.15721]

IP-Glasma+Hydro prediction for small systems.

[Giacalone, Schenke, Shen, 2006.15721]



– Sign change occurring as expected around dN/dη=10.
A neat prediction.

– No sign change if we set Ep=0.

– CGC result is solid, but non-flow mimics the signal, and has to be addressed carefully.

[Behera, Bhatta, Jia, Zhang, 2102.05200]

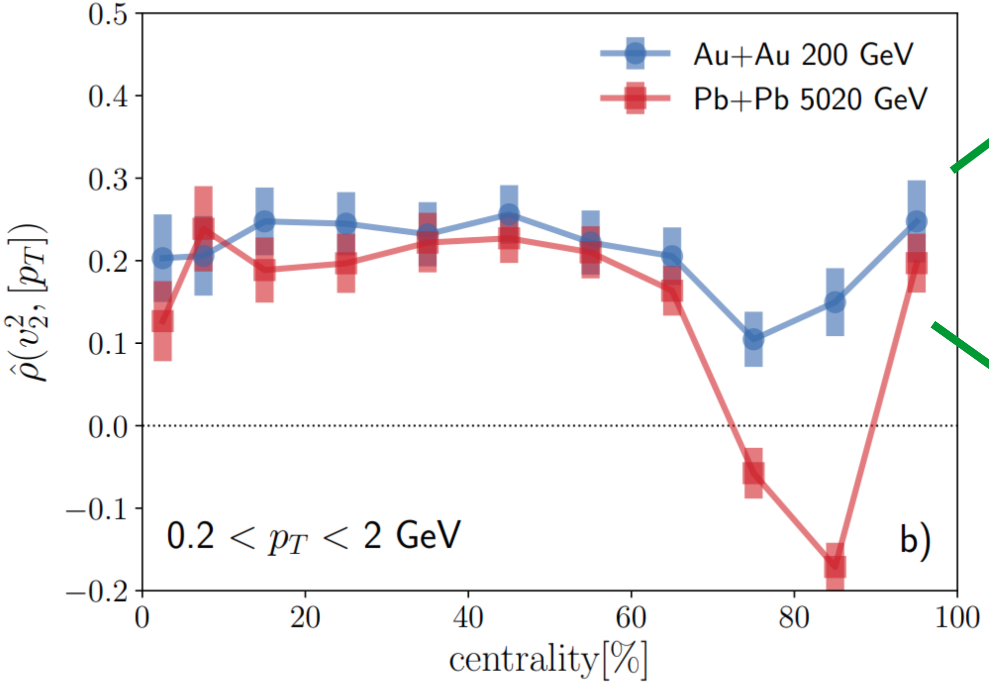
[Lim, Nagle, 2103.01348]

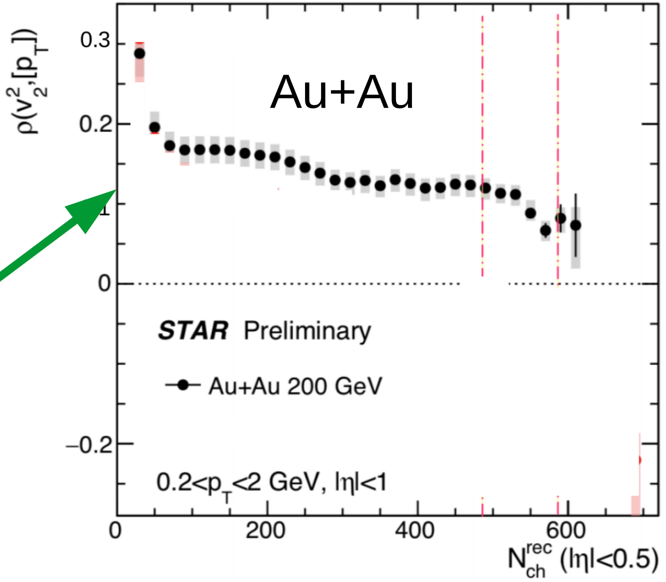
Prediction for peripheral large systems.

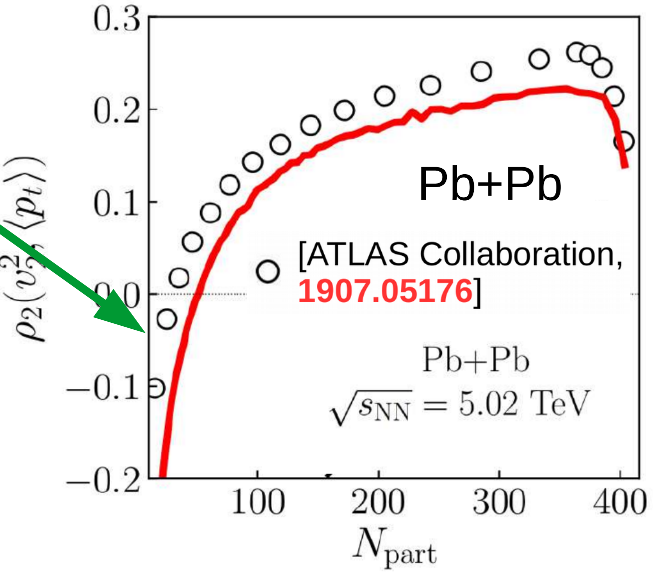
[Giacalone, Schenke, Shen, 2006.15721]

Shorter lifetime makes Ep more important at RHIC.

<u>Sign change does not occur at RHIC energy.</u>



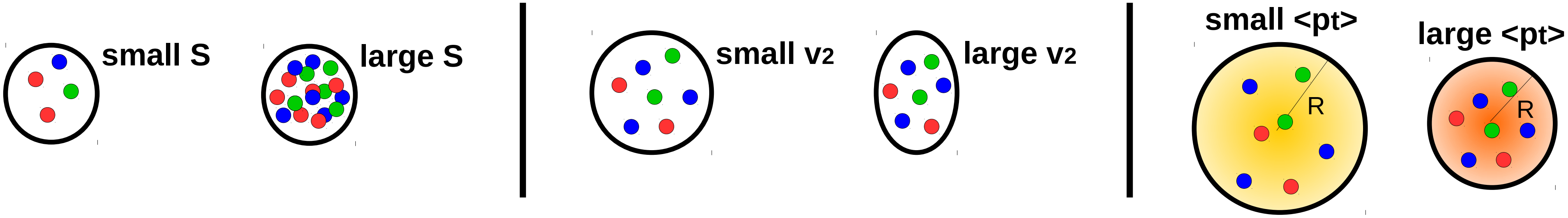




So far consistent with preliminary data.

SUMMARY

– Established picture of the QGP based on hydrodynamics.



– We can study nuclear phenomena beyond QGP by means of $[p_t]$-v_n correlations:

New probe of strong EM fields: $\rho^{\pm}\left(\langle p_t\rangle, v_1^{\pm}\right)$

Polarizing 'deformed' mass densities (body-body): $\rho(v_2^2, [p_t]) < 0$

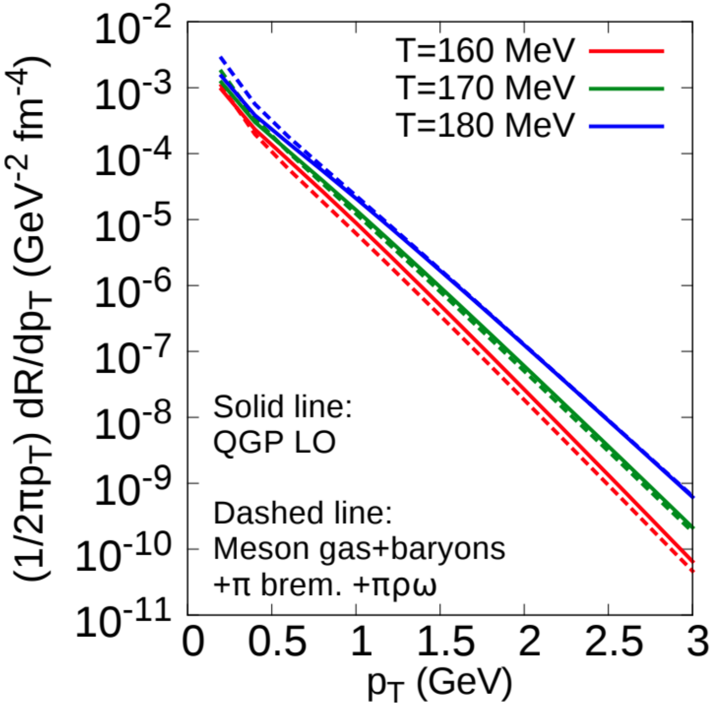
Manifestation of primordial momentum anisotropy: $\rho(\varepsilon_p^2, [p_t]) > 0$

But there is more…

OUTLOOK

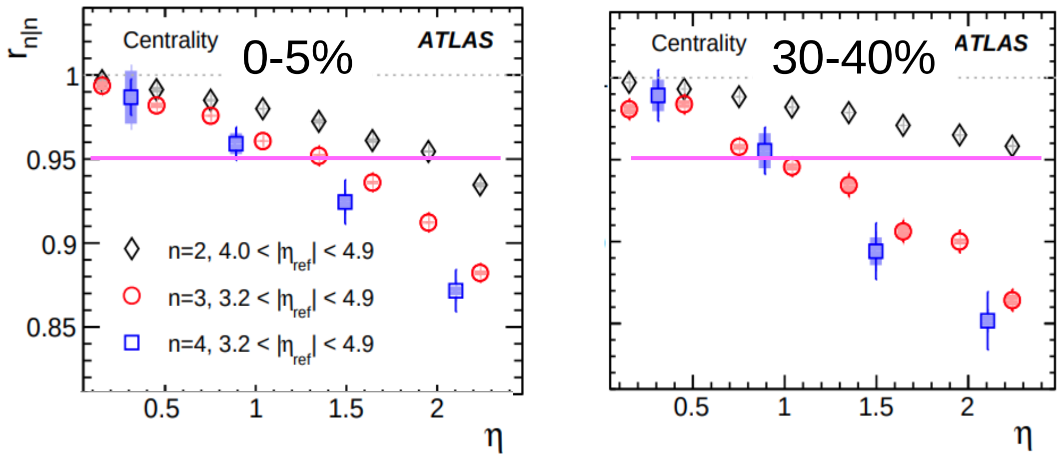
Thermal **photon yield**, N.
Depends on temperature.

prediction: $\rho(\langle p_T \rangle, N) > 0$.



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

Longitudinal de-correlations.
Smaller de-correlation at large impact parameters.



[ATLAS Collaboration, **2001.04201**]

prediction:
events with large $\langle p_T \rangle$ de-correlate less.

More candidates:
– vorticity?
– energy loss?
…
– any other ideas?

CORRELATIONS WITH $\langle p_t \rangle$: EXCITING PROSPECTS FOR THE NEXT DECADE.

THANK YOU!