Collective flow from AA, pA to pp

— *Toward a unified paradigm*

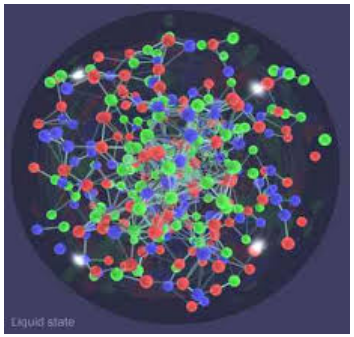
Wei Li
Rice University

Quark Matter 2017
Chicago, February 6 – 11

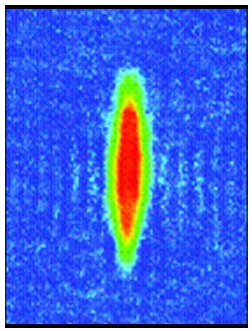
Collective phenomena

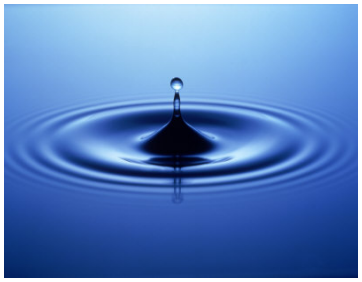
a central theme in the study of strongly correlated, **interacting** many-body systems

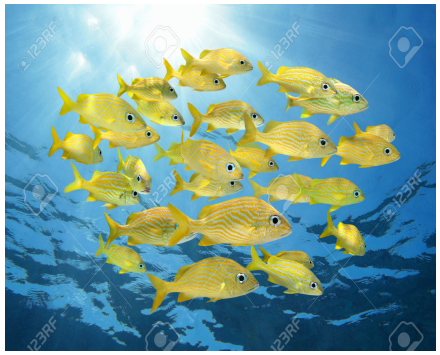
QGP



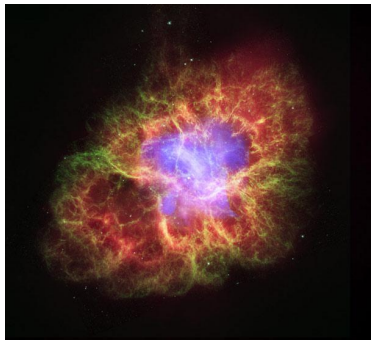
Ultra-cold Fermi gas







Neutron stars



small — large

Complex frontier – "Emergence"

Collective phenomena

a central theme in the study of strongly correlated, **interacting** many-body systems

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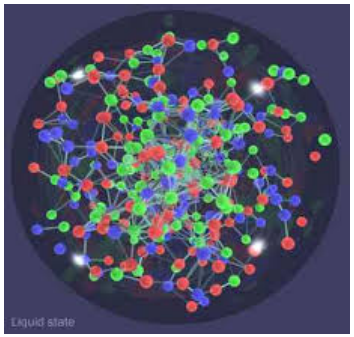

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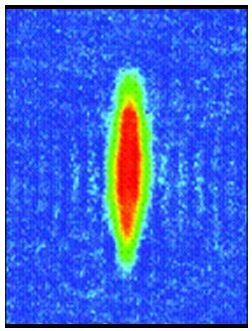

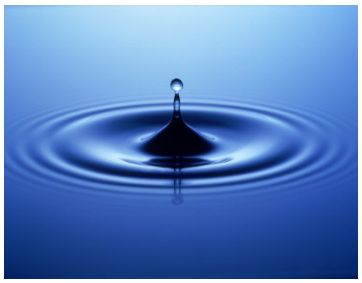

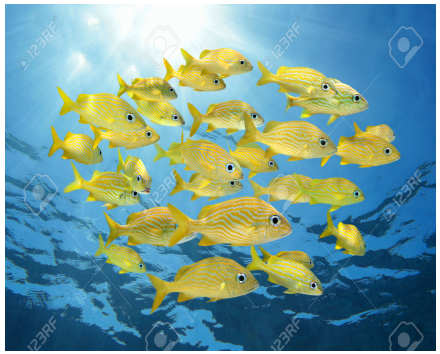

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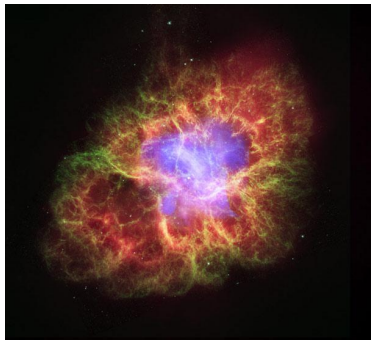


small — large

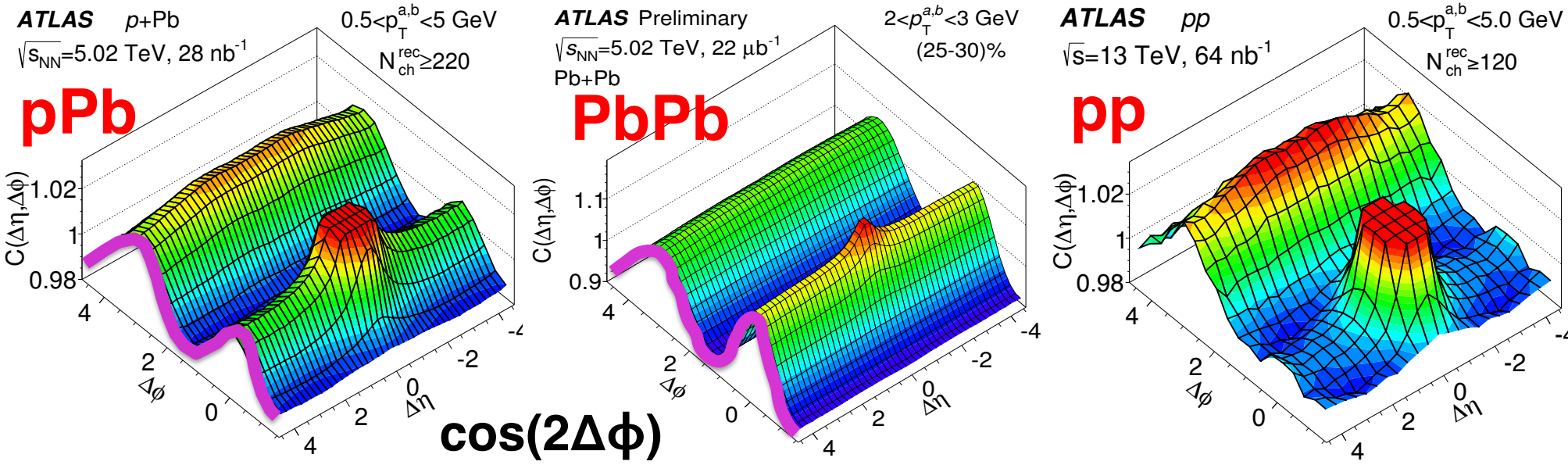
Complex frontier – "Emergence"

The key question:

- *What is the underlying mechanism to drive?*
- *Can be understood from fundamental forces?*

Emergent phenomena in pp, pA and AA

Novel azimuthal correlations



cos(2Δϕ)

Emergent phenomena in pp, pA and AA

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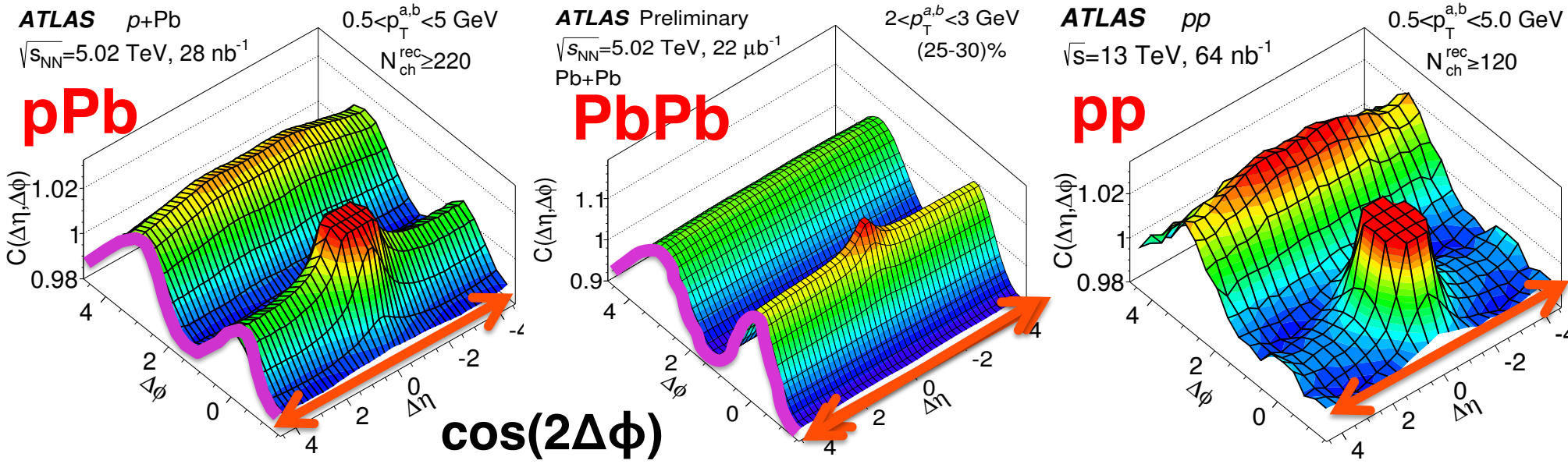

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✧ **Long-range in η**

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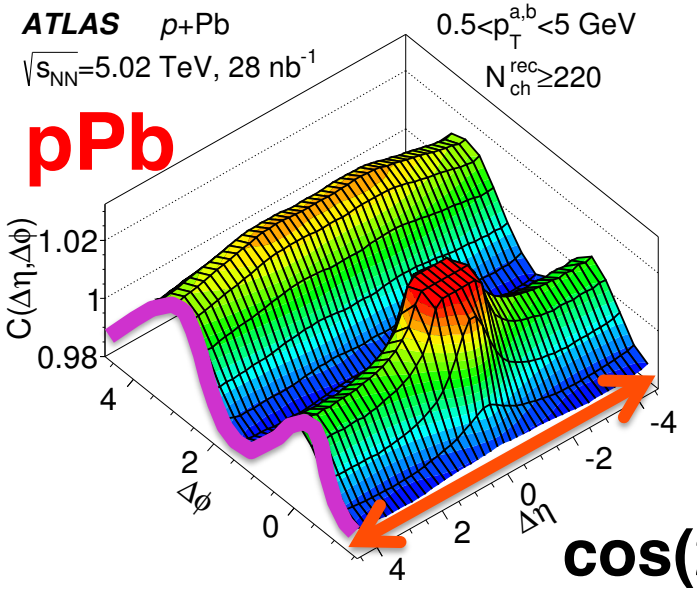

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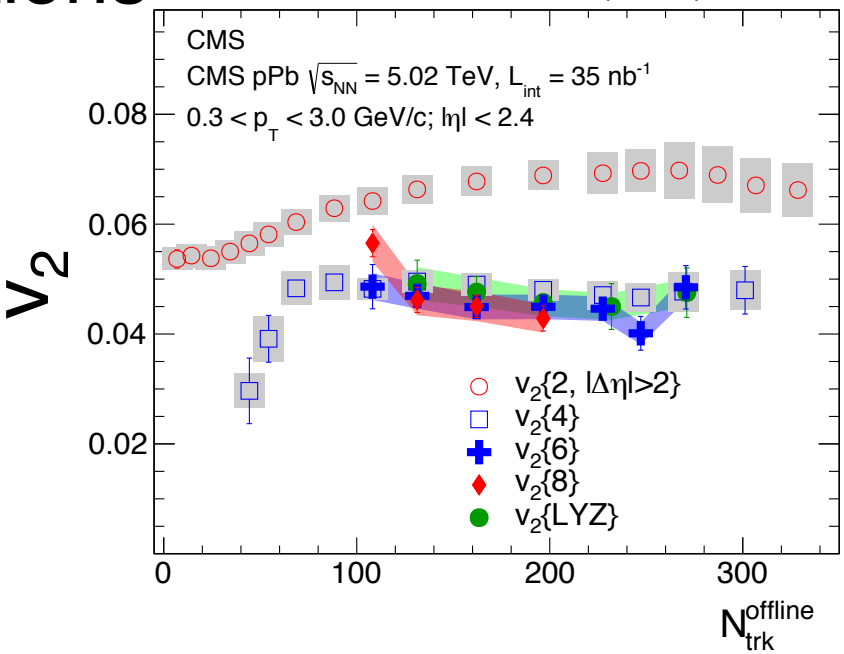
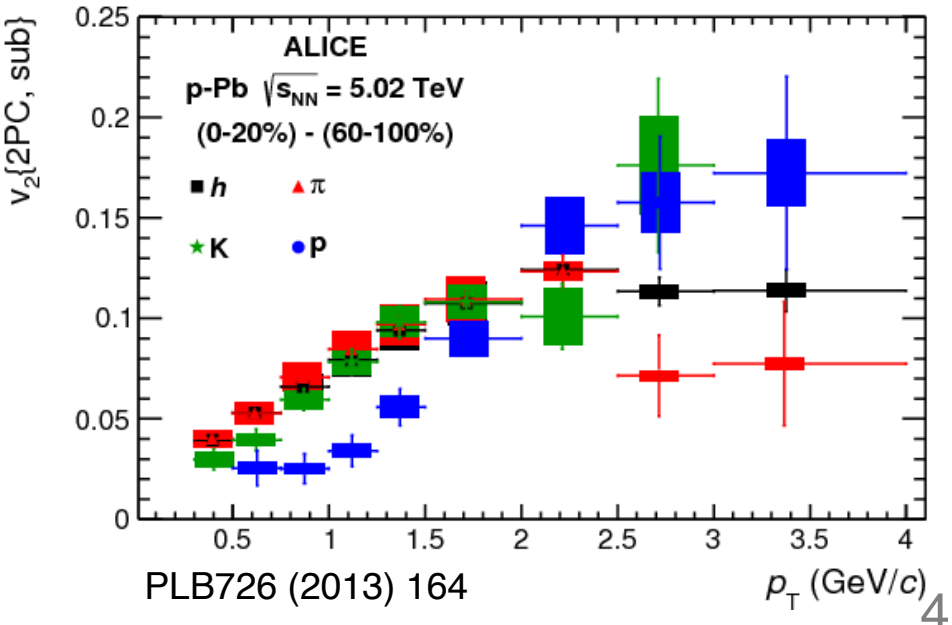
PRL 115 (2015) 012301



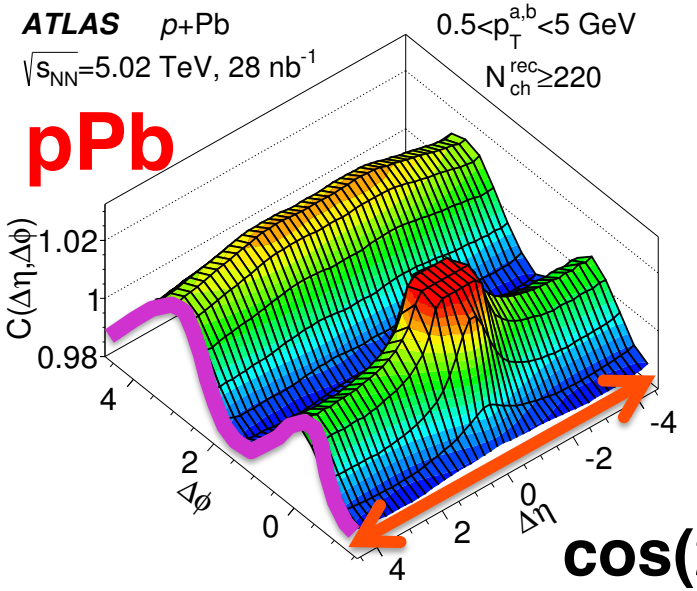
- ✧ **Long-range in η**
- ✧ **Collective**
  - ✓ $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$
  - ✓ Independent of N_{trk}
  - ✓ Mass ordering
  - …



PLB726 (2013) 164

Emergent phenomena in pp, pA and AA

Novel azimuthal correlations



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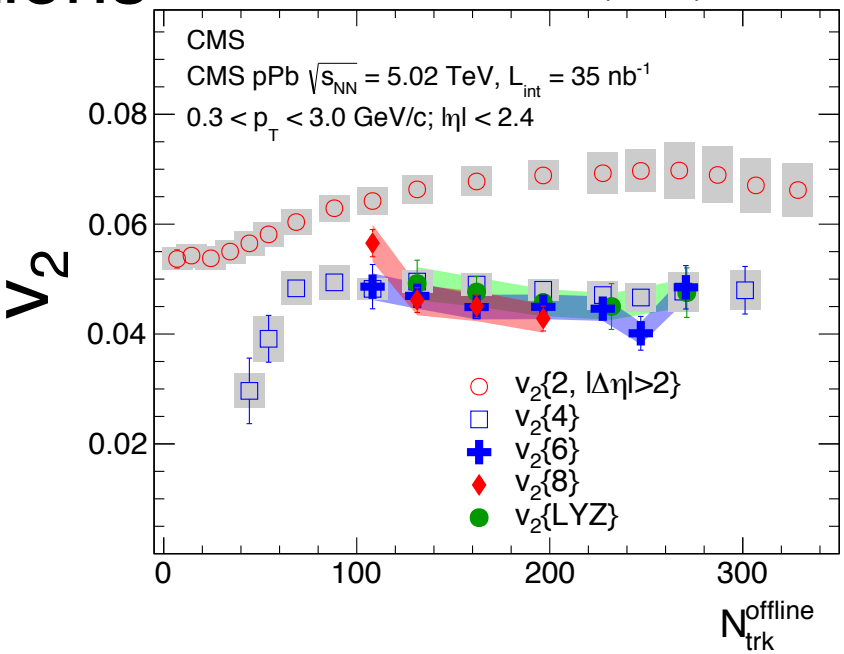

- ✧ **Long-range in η**
- ✧ **Collective** ⇨ *Interactions*
  - ✓ $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$
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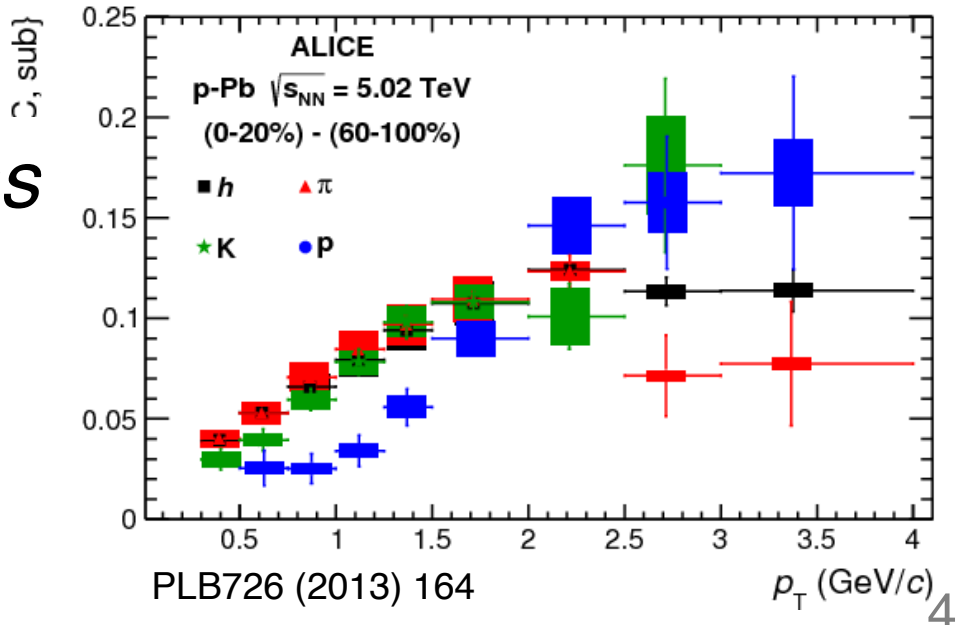


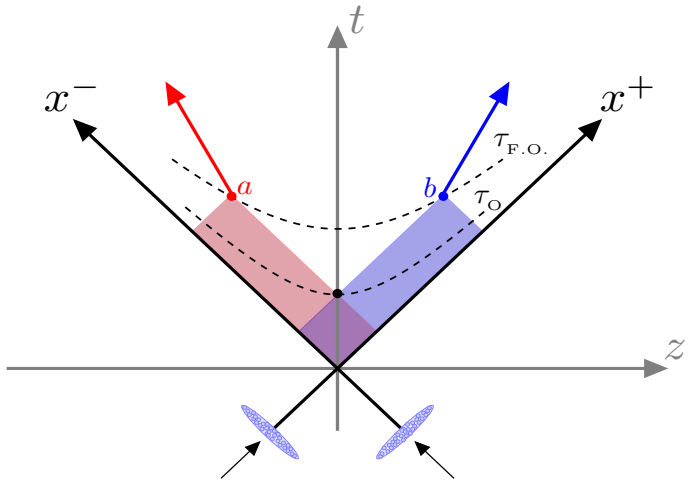
PLB726 (2013) 164

Emergent phenomena in pp, pA and AA

Long-range anisotropy in η

Rooted in **initial/early** stage

$$\tau_O \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right)$$



arXiv:1509.07939

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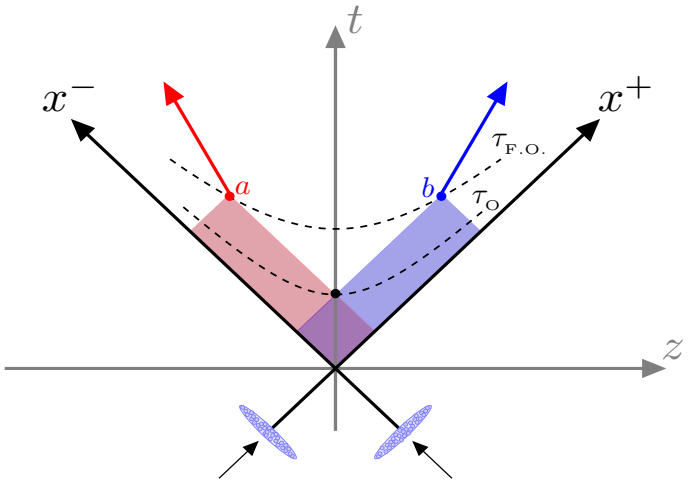

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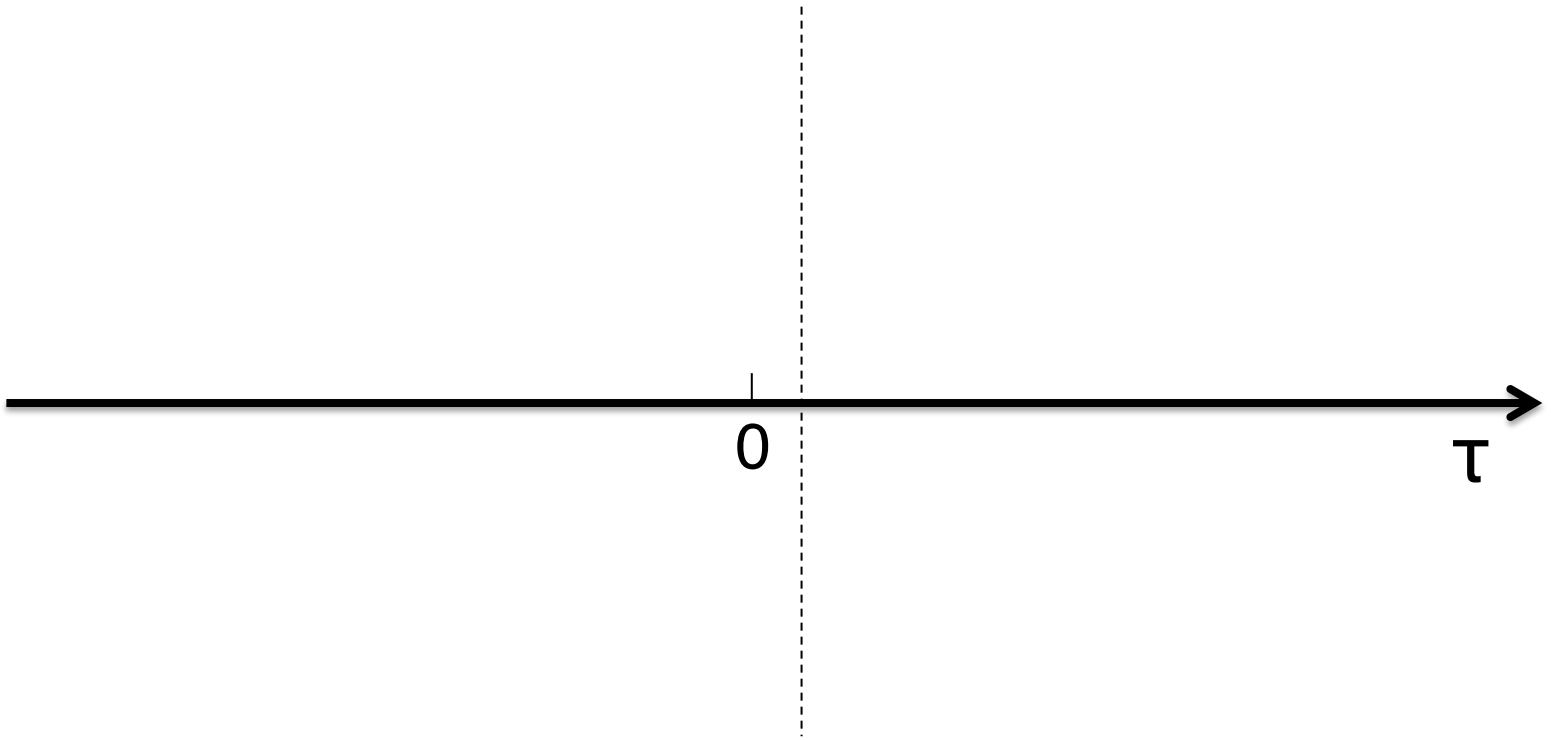

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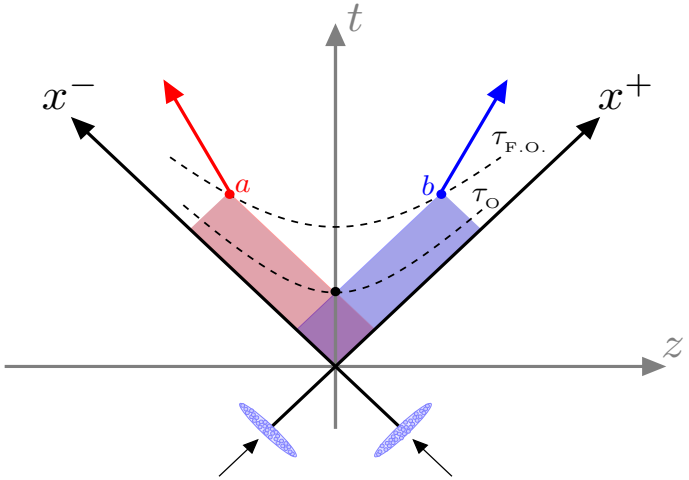

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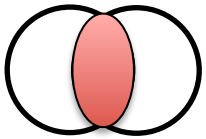
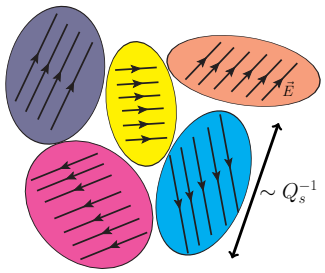


Initial spatial ε_s

0

τ

Initial momenta ε_p



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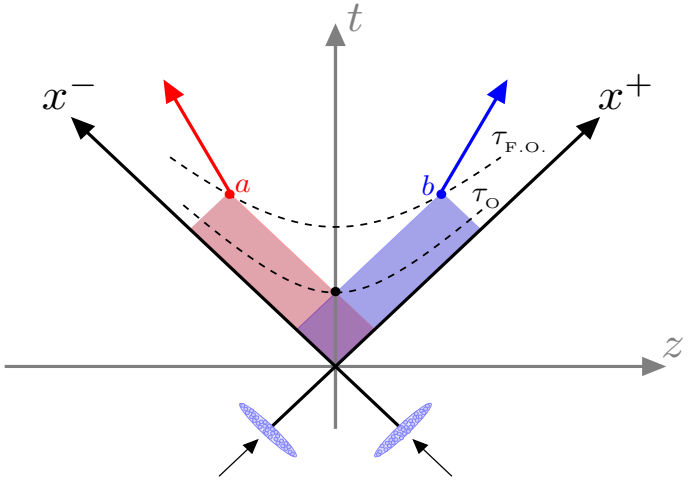

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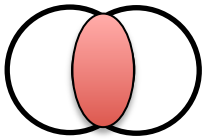
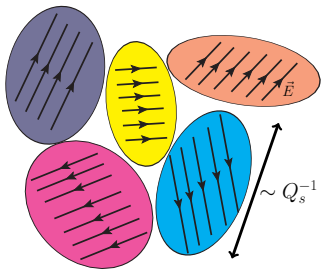


Initial spatial ε_s + **final** interactions

0 τ



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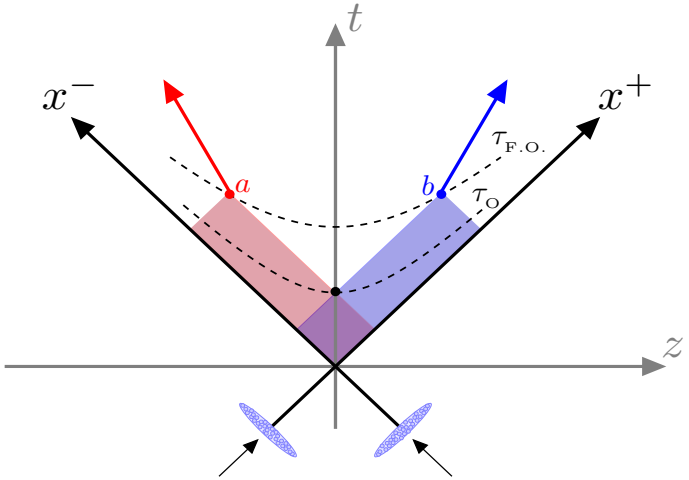

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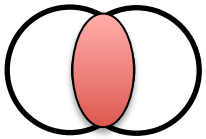
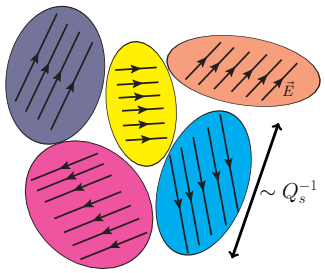


Hydrodynamics
Parton transport, escape

Initial spatial ε_s + **final** interactions

0 τ



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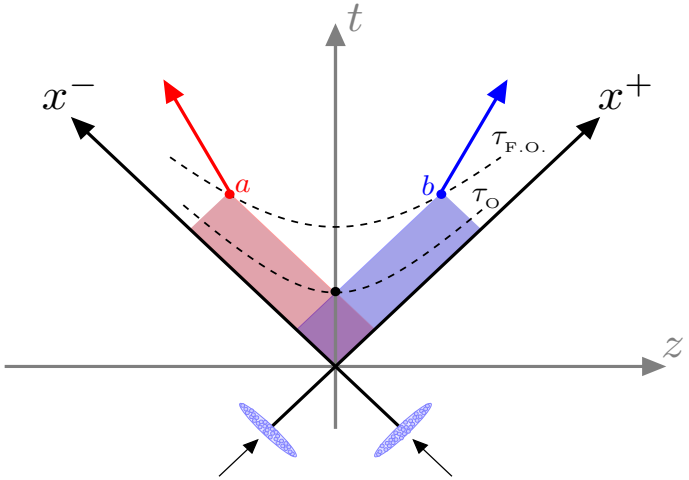

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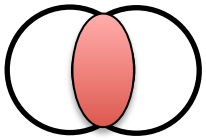

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Initial spatial ε_s + **final** interactions

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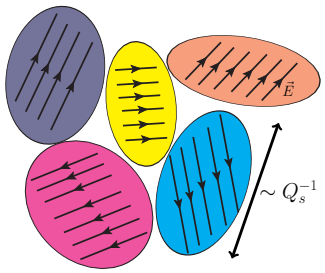

Initial momenta ε_p by **initial** interactions

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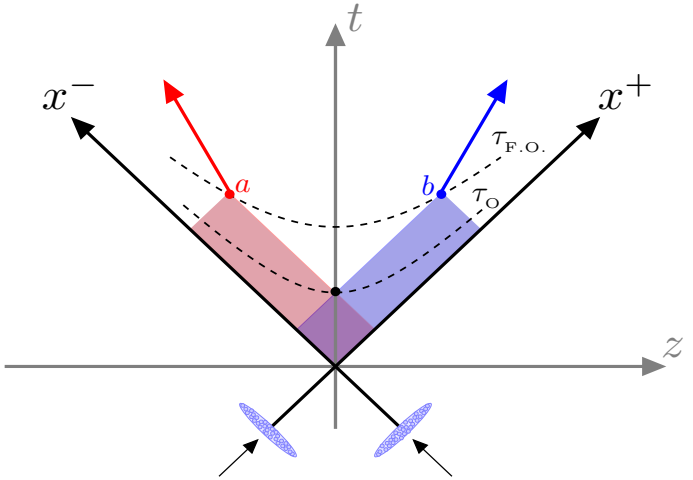

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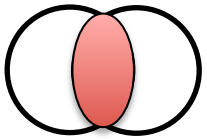

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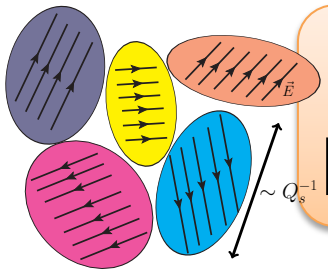
τ

Scenario #2



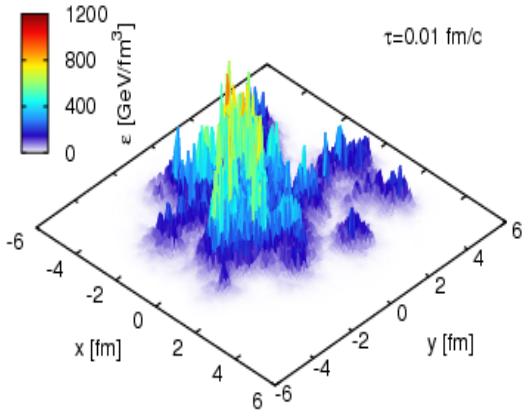
Initial momenta ε_p by **initial** interactions

CGC Glasma
Color-field domains, etc.

Perfect-liquid paradigm of AA collisions

Initial state:

$\varepsilon(x, y, \eta^s)$



Event-by-event

Pre-equilibrium

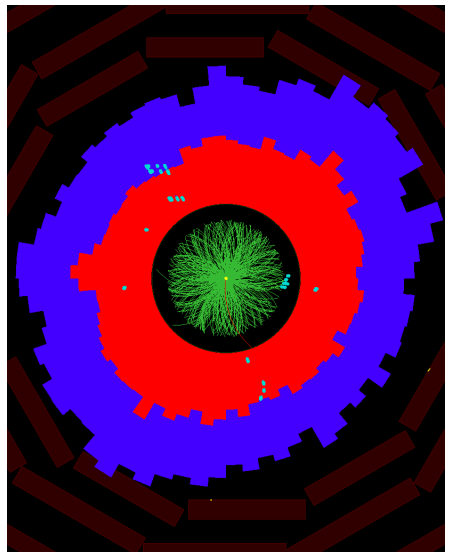
Hydrodynamics

$\partial_\mu T^{\mu\nu} = 0 + (\eta, \zeta, \ldots)$

Freeze-out;
Hadronic transport

Final state:

$f(p_T, \eta, \phi)$



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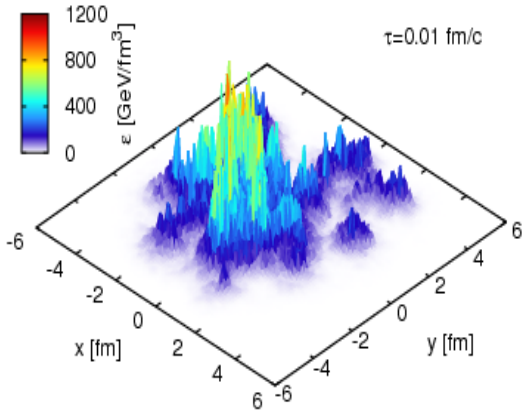

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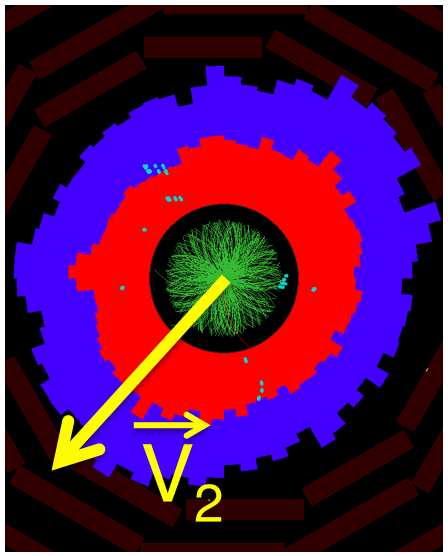

Fourier bases:

$$f(p_T, \eta, \phi) = N(p_T, \eta) \sum_{n=-\infty}^{+\infty} \vec{V}_n(p_T, \eta) \mathrm{e}^{-in\phi}$$

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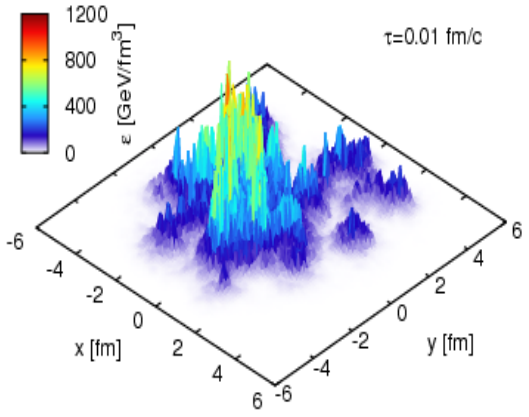

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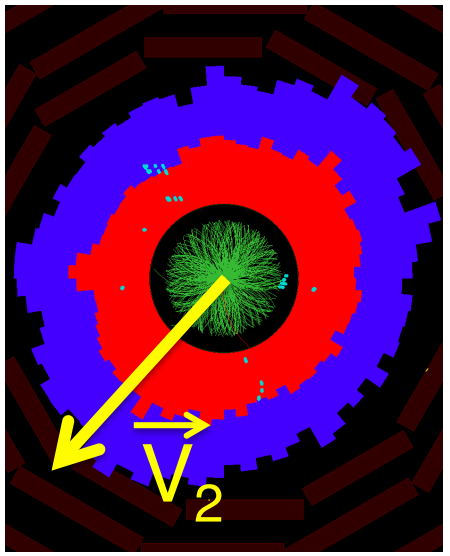

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Radial flow

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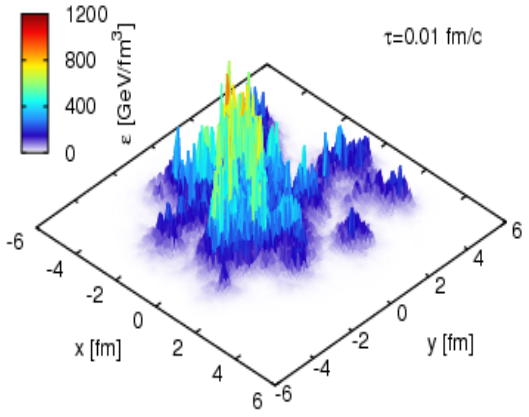

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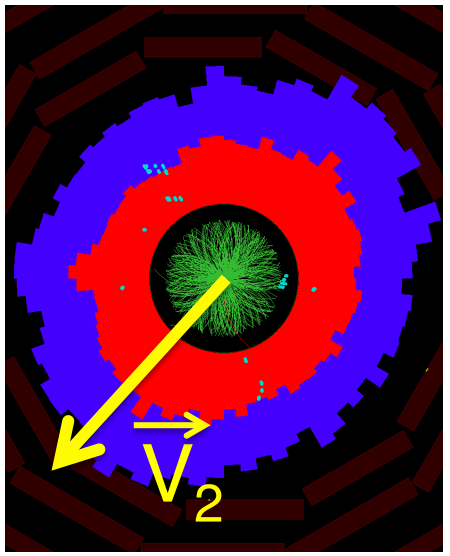

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Radial flow

Anisotropy flow
$\vec{V}_n = v_n e^{in\Psi_n}$

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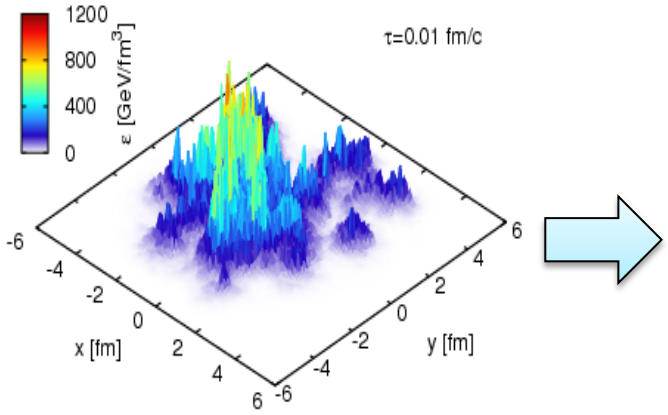
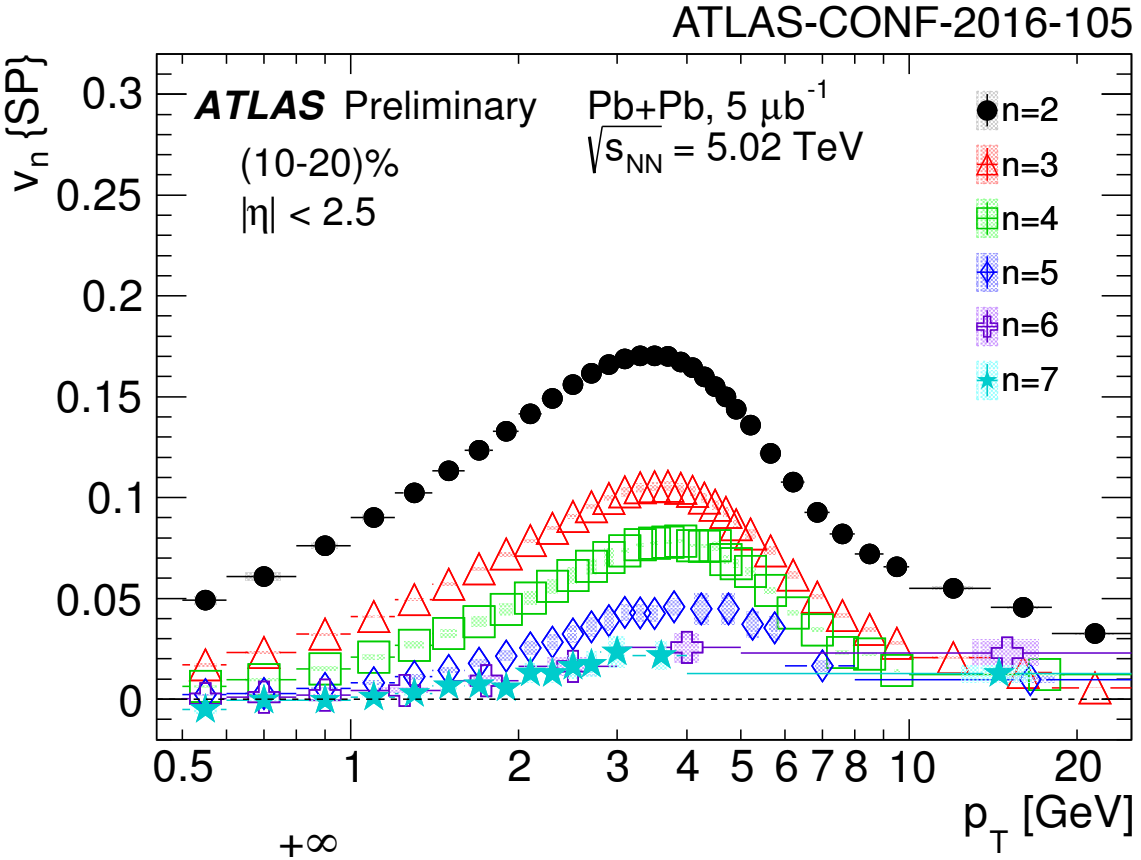
Initial state:

$$\varepsilon(x, y, \eta^s)$$





Fourier bases:

$$f(p_T, \eta, \phi) = N(p_T, \eta) \sum_{n=-\infty}^{+\infty} \vec{V}_n(p_T, \eta) e^{-in\phi}$$

Radial flow

Anisotropy flow

$$\vec{V}_n = v_n e^{in\Psi_n}$$

Perfect-liquid paradigm of AA collisions

A precision era with still open questions:

- Details of dynamics in **3+1D**:
  - **Initial state in 3D** – $\varepsilon(x,y,\eta^s)$
  - **Transport properties** – $\eta/s(T)$, $\zeta/s(T)$, …

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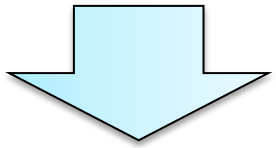

Toward extracting **full** final-state information

$$\mathrm{pdf}\left(N(p_{\mathrm{T}},\eta),\ \vec{V}_1(p_{\mathrm{T}},\eta),\ \vec{V}_2(p_{\mathrm{T}},\eta),\ \ldots\right)$$

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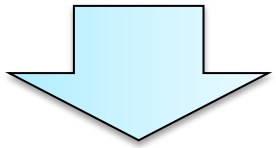
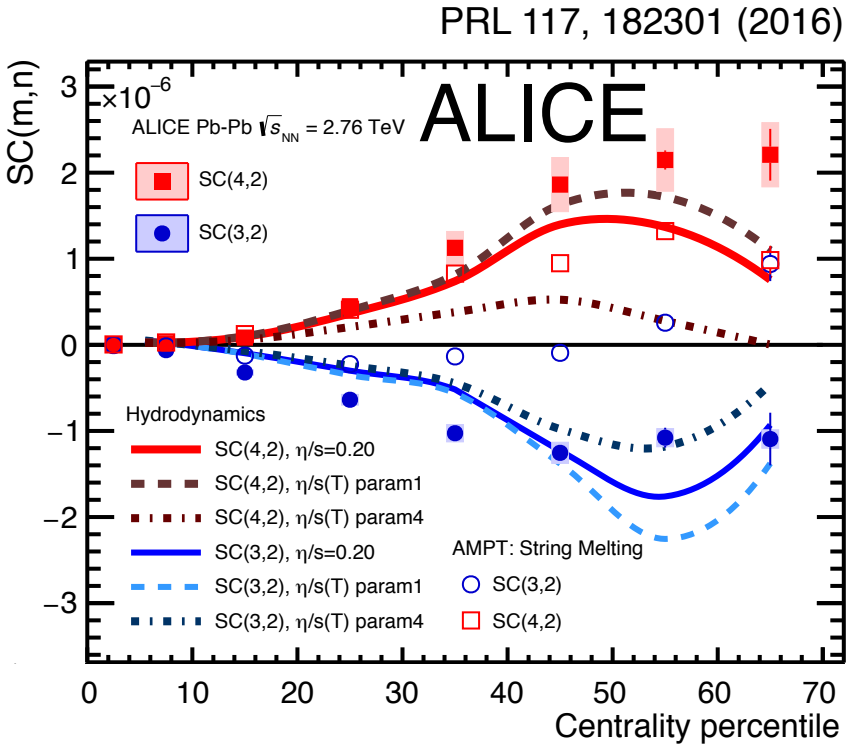


Practically, **"New"** flow observables:

1. $\{\vec{V}_n, \vec{V}_m\}$ — Mixed-order harmonics correlations
2. $\{\vec{V}_n(p_{T,1},\eta_1),\ \vec{V}_n(p_{T,2},\eta_2)\}$ / $\{N(p_{T,1},\eta_1),\ N(p_{T,2},\eta_2)\}$ — Details of initial states

Correlations of harmonics (V_n, V_m)



$v_n - v_m$ correlations

$$SC(n,m) = \left\langle v_n^2 v_m^2 \right\rangle - \left\langle v_n^2 \right\rangle \left\langle v_m^2 \right\rangle$$

⇒ **SC(2,3) < 0, SC(2,4) > 0**

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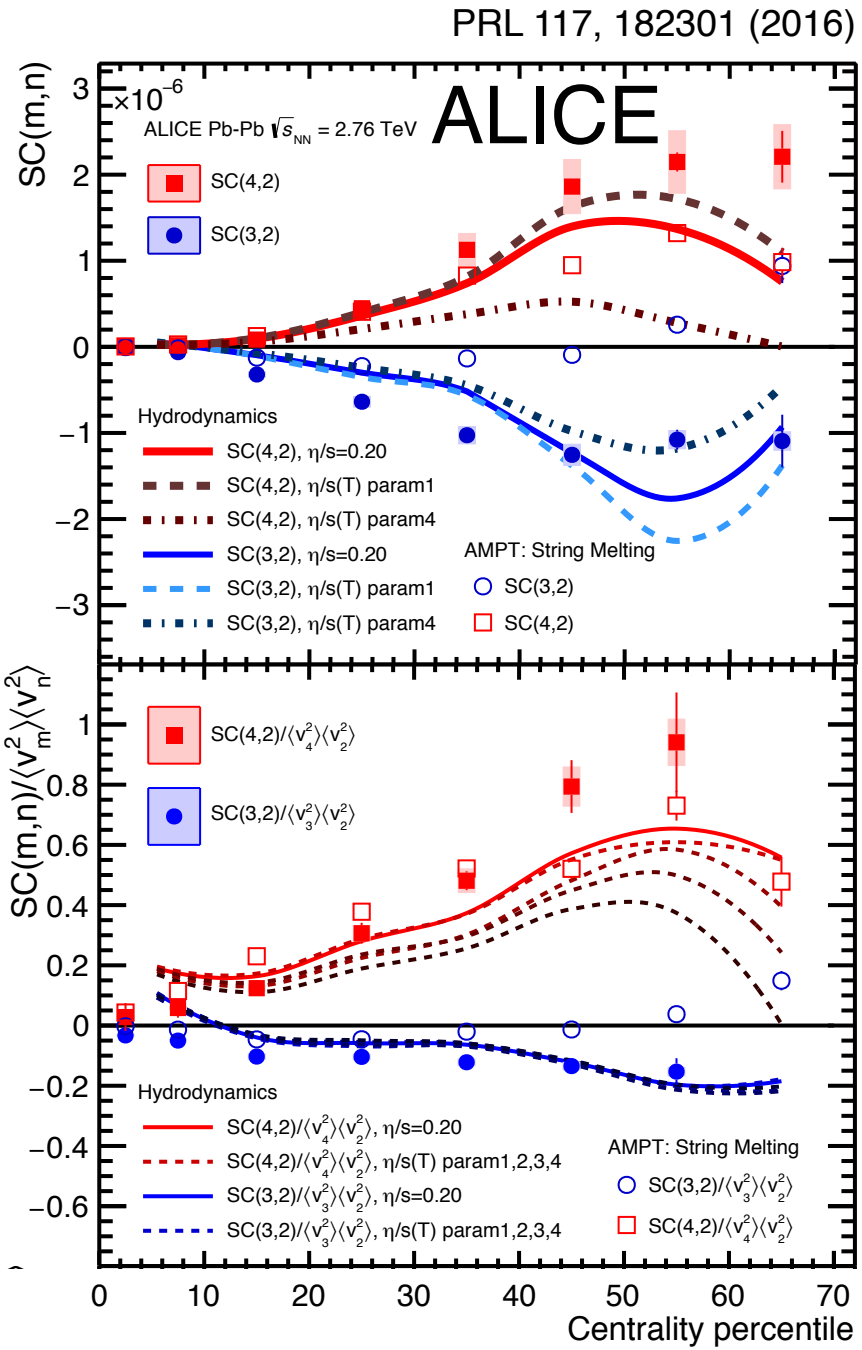

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As

$$v_2 = \kappa_2 \varepsilon_2$$

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SC(2,3) directly probes the initial state

– fluctuation granularities

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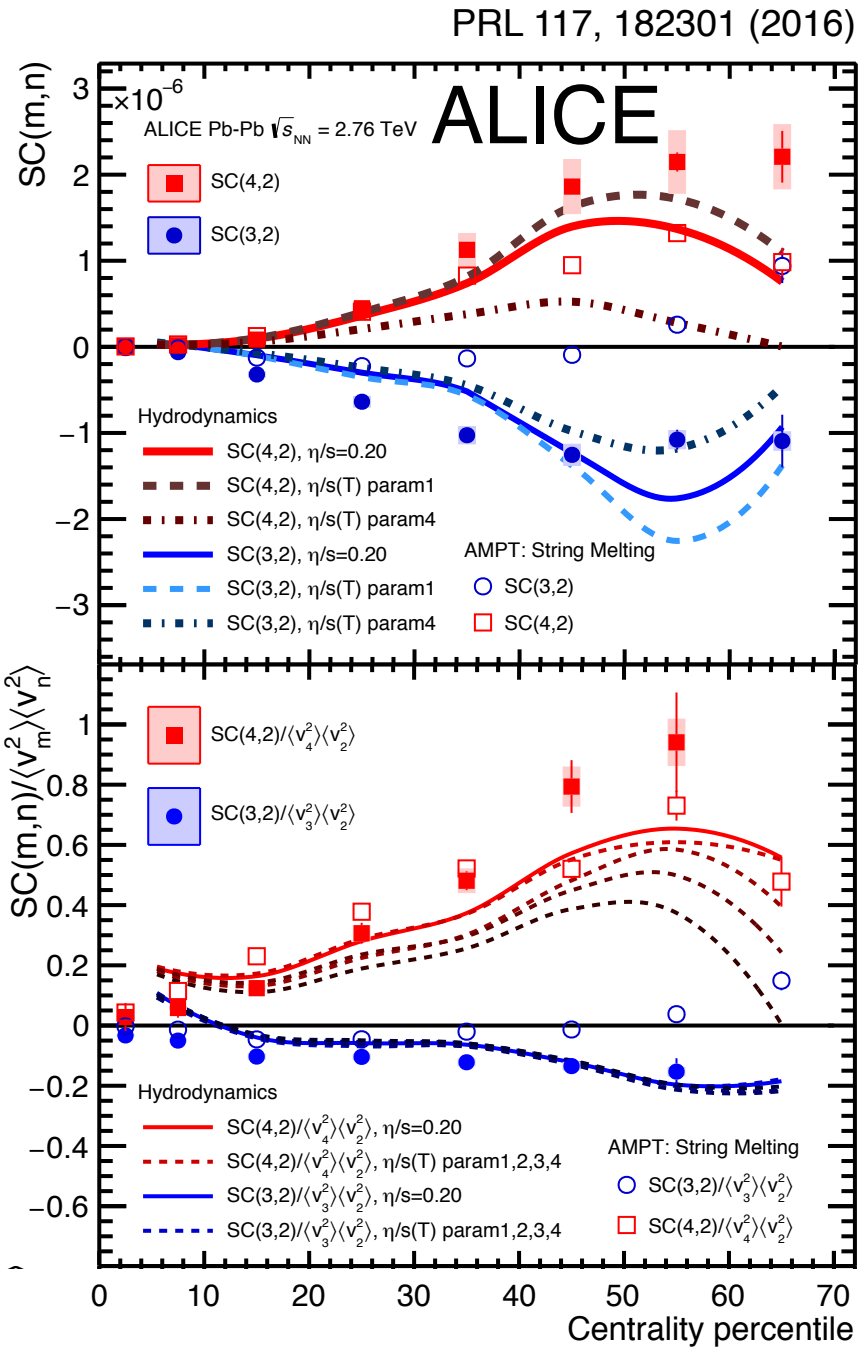

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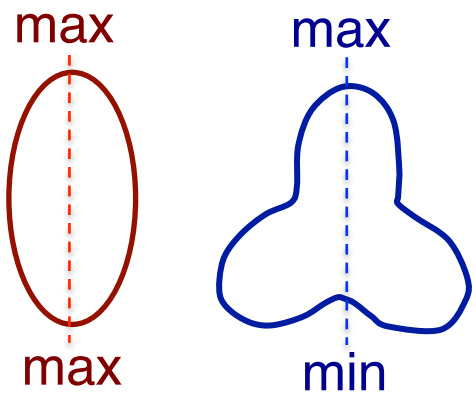

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Correlations of harmonics (V_n, V_m)

Moving to higher-order harmonics

$$v_4 \neq \kappa_4 \varepsilon_4$$
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Linear responses to initial geometry do not hold for n≥4

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Because of mixing with lower orders (v_2, v_3)

$$\vec{V}_4 = \vec{V}_{4L} + \chi_{422}\left(\vec{V}_2\right)^2$$
$$\vec{V}_5 = \vec{V}_{5L} + \chi_{523}\vec{V}_2\vec{V}_3$$
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$$\vdots$$

Nonlinear terms: sensitive to final-state dynamics

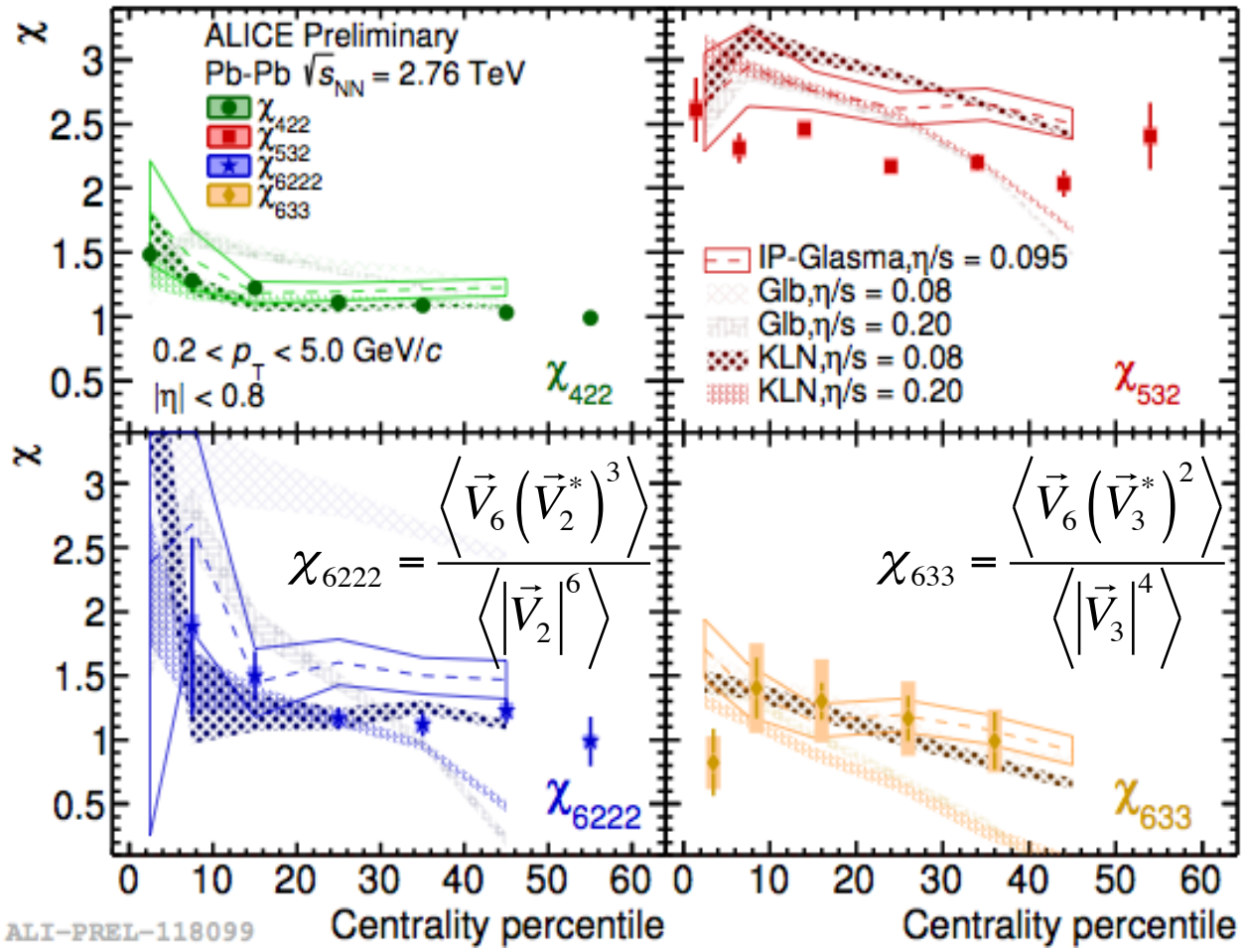
Leading terms: not exactly $\propto \varepsilon_n$ orthogonal

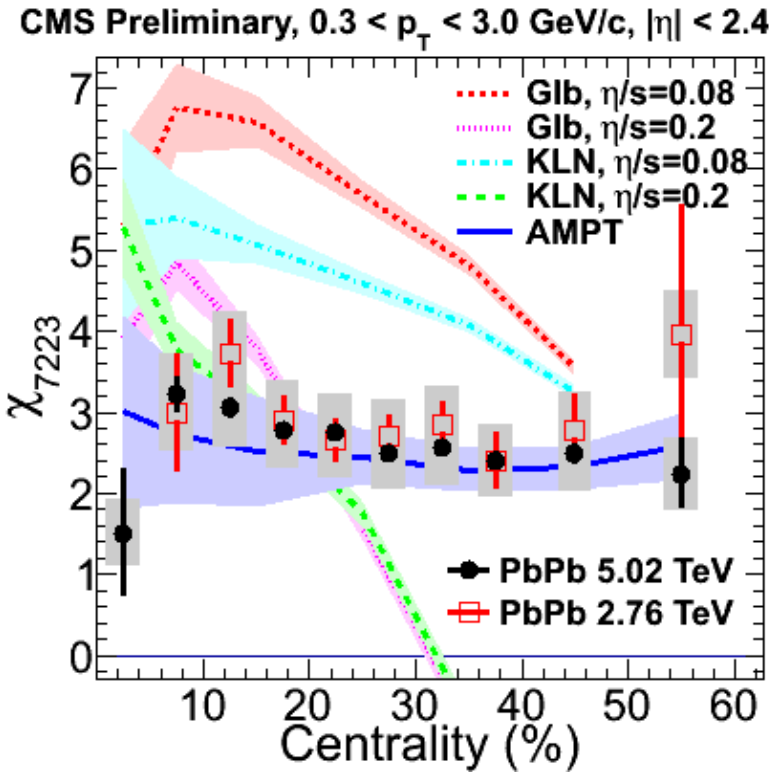
Correlations of harmonics (V_n, V_m)

Non-linear response coefficients

$$\chi_{422} = \frac{\left\langle \vec{V}_4 \left(\vec{V}_2^*\right)^2 \right\rangle}{\left\langle \left|\vec{V}_2\right|^4 \right\rangle} \qquad \chi_{523} = \frac{\left\langle \vec{V}_5 \vec{V}_2^* \vec{V}_3^* \right\rangle}{\left\langle \left|\vec{V}_2\right|^2 \left|\vec{V}_3\right|^2 \right\rangle}$$

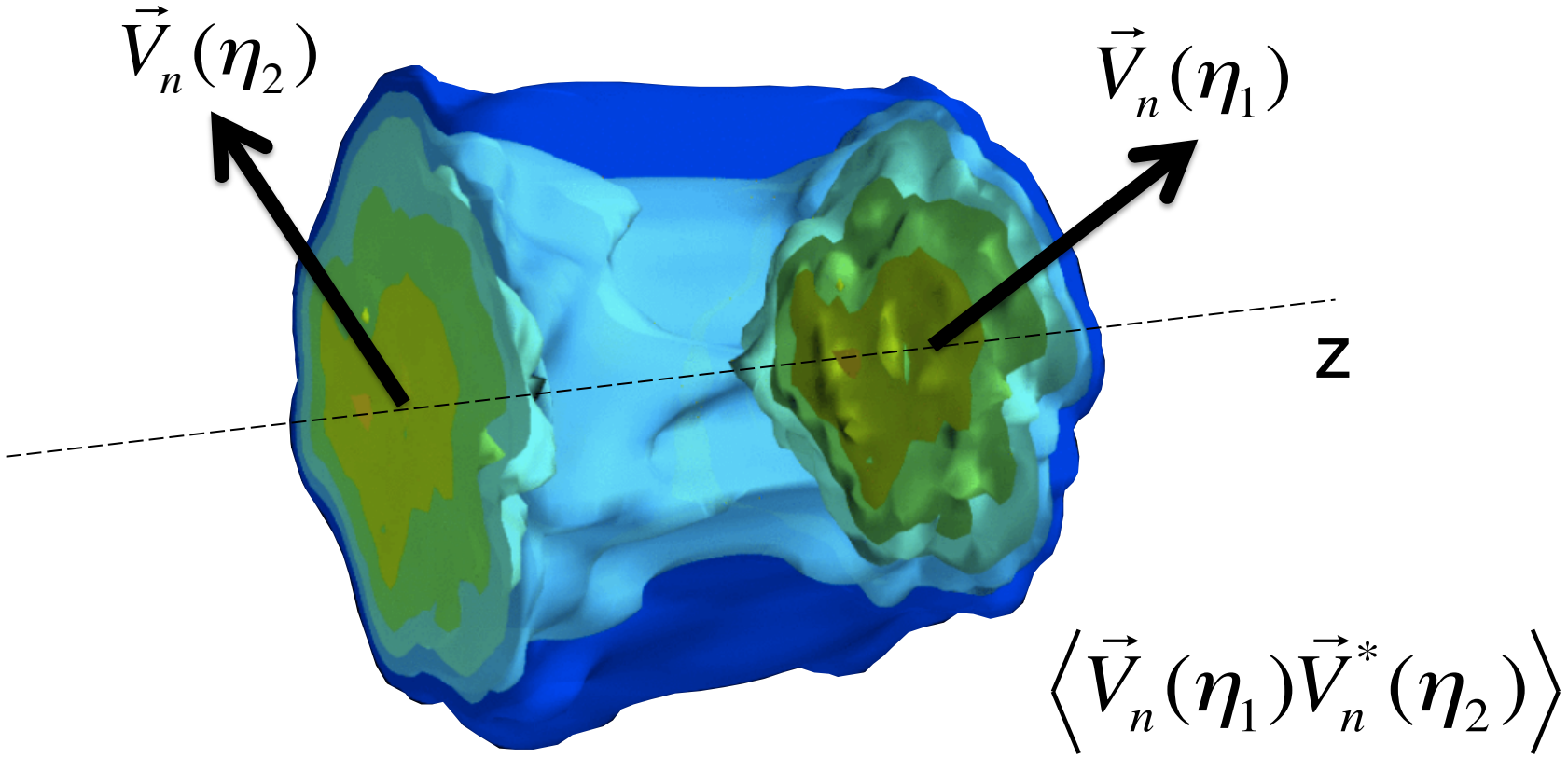
$$\chi_{7223} = \frac{\left\langle \vec{V}_7 \left(\vec{V}_2^*\right)^2 \vec{V}_3^* \right\rangle}{\left\langle \left|\vec{V}_2\right|^4 \left|\vec{V}_3\right|^2 \right\rangle}$$





New constraints to freeze-out dynamics

Evolution of the QGP in 3+1D



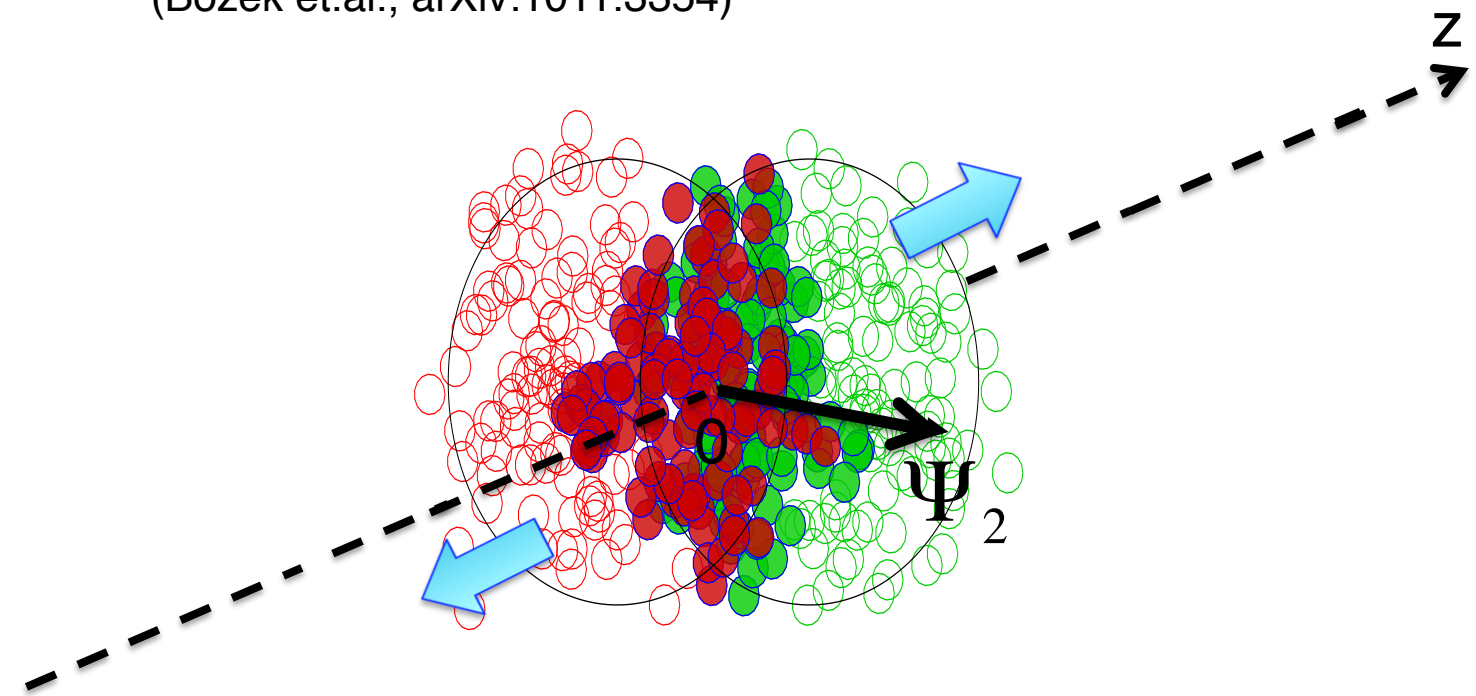
Longitudinal dynamics not fully explored yet

- How is the initial entropy deposited in 3D space? How it fluctuates event-by-event?
- What is the role of longitudinal pressure?

Initial states in 3D

Torqued QGP fireball

(Bozek et.al., arXiv:1011.3354)



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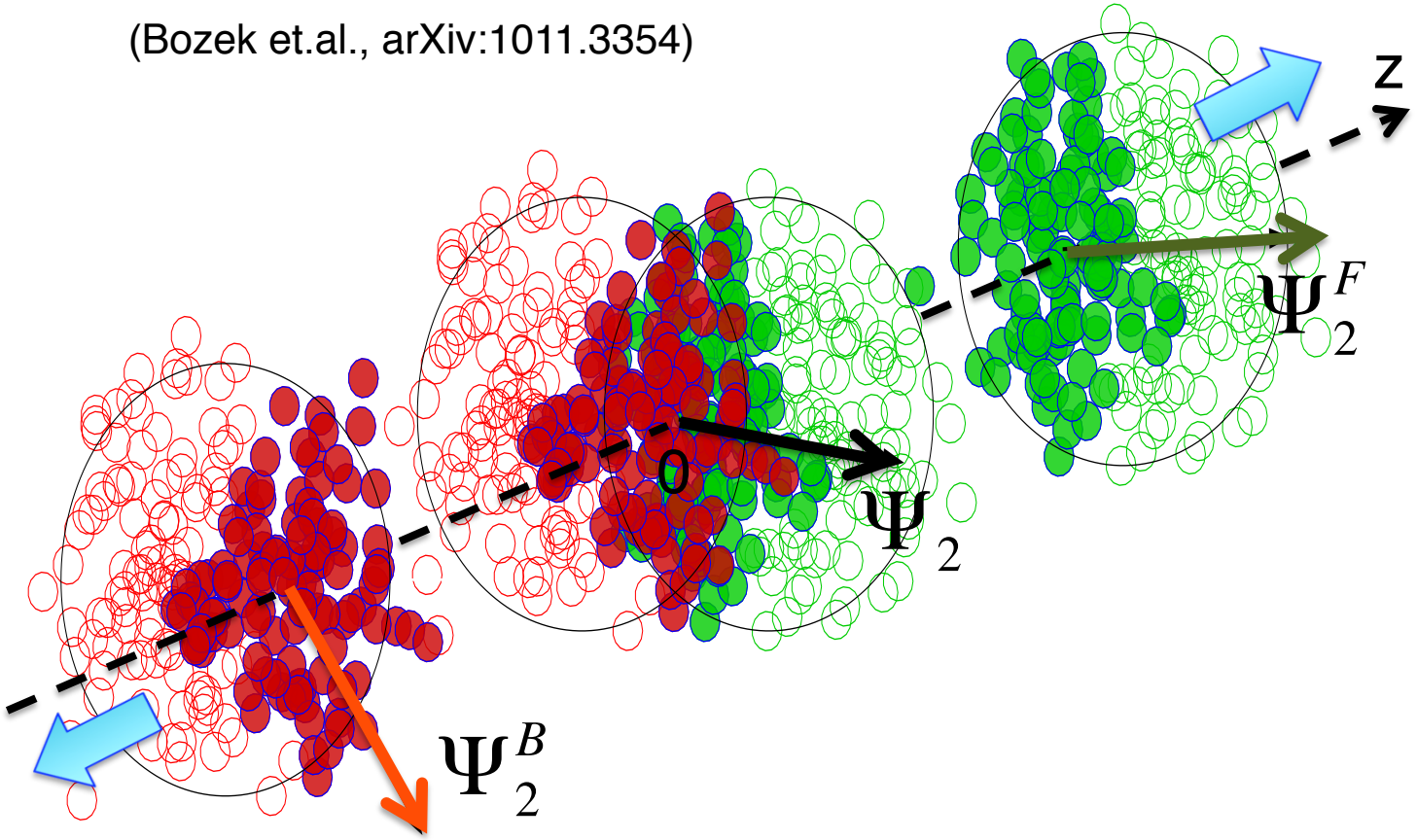

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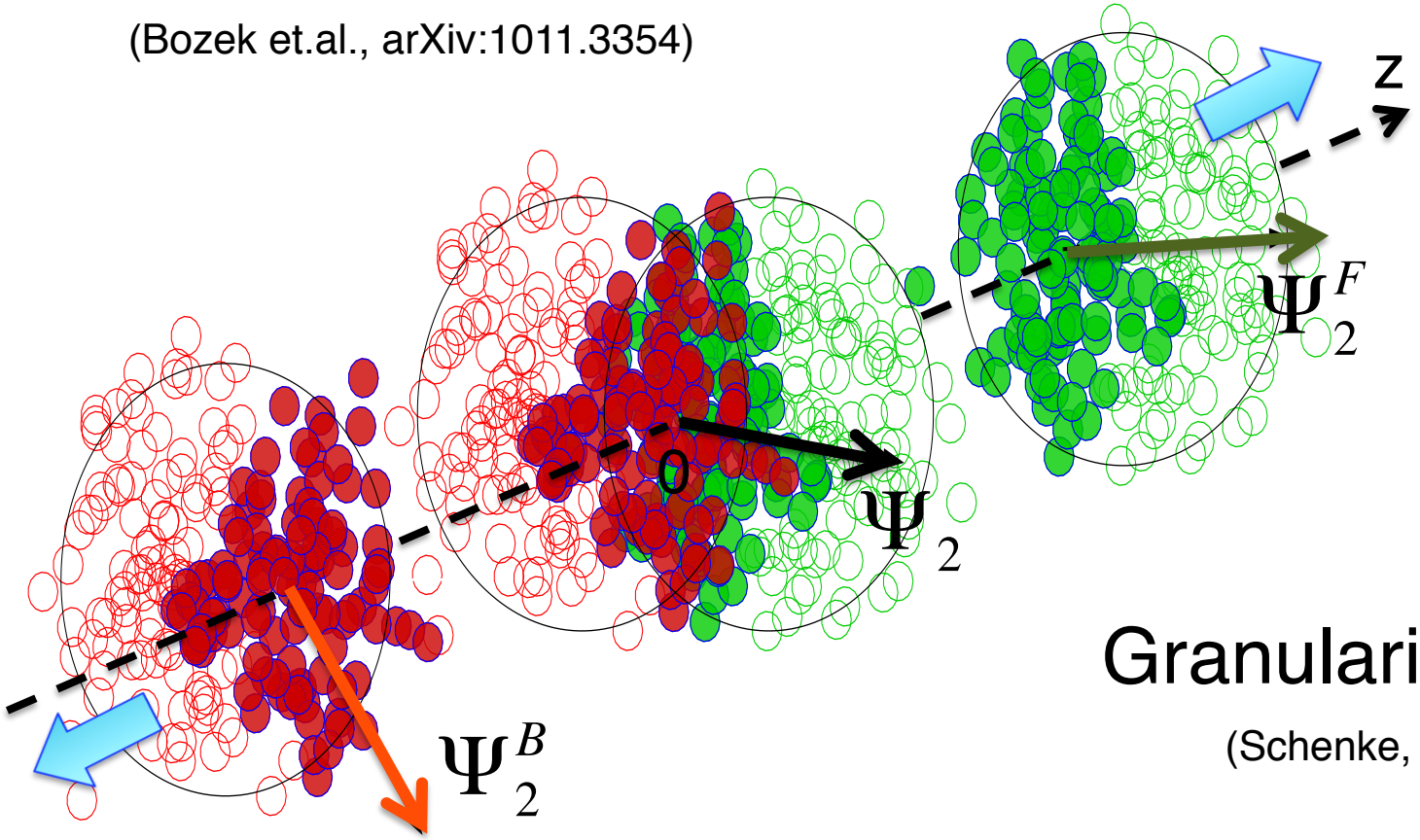
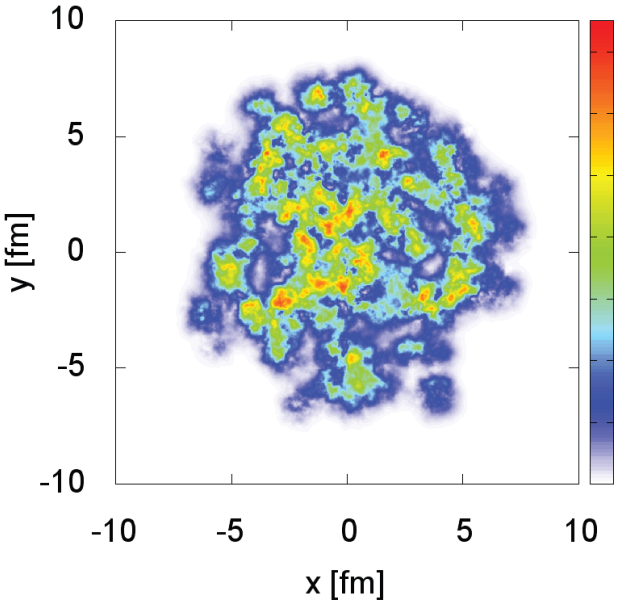


Y=-2.4 3D-glasma



Granularity of gluon fields

(Schenke, Schlichting, arXiv:1605.07158)

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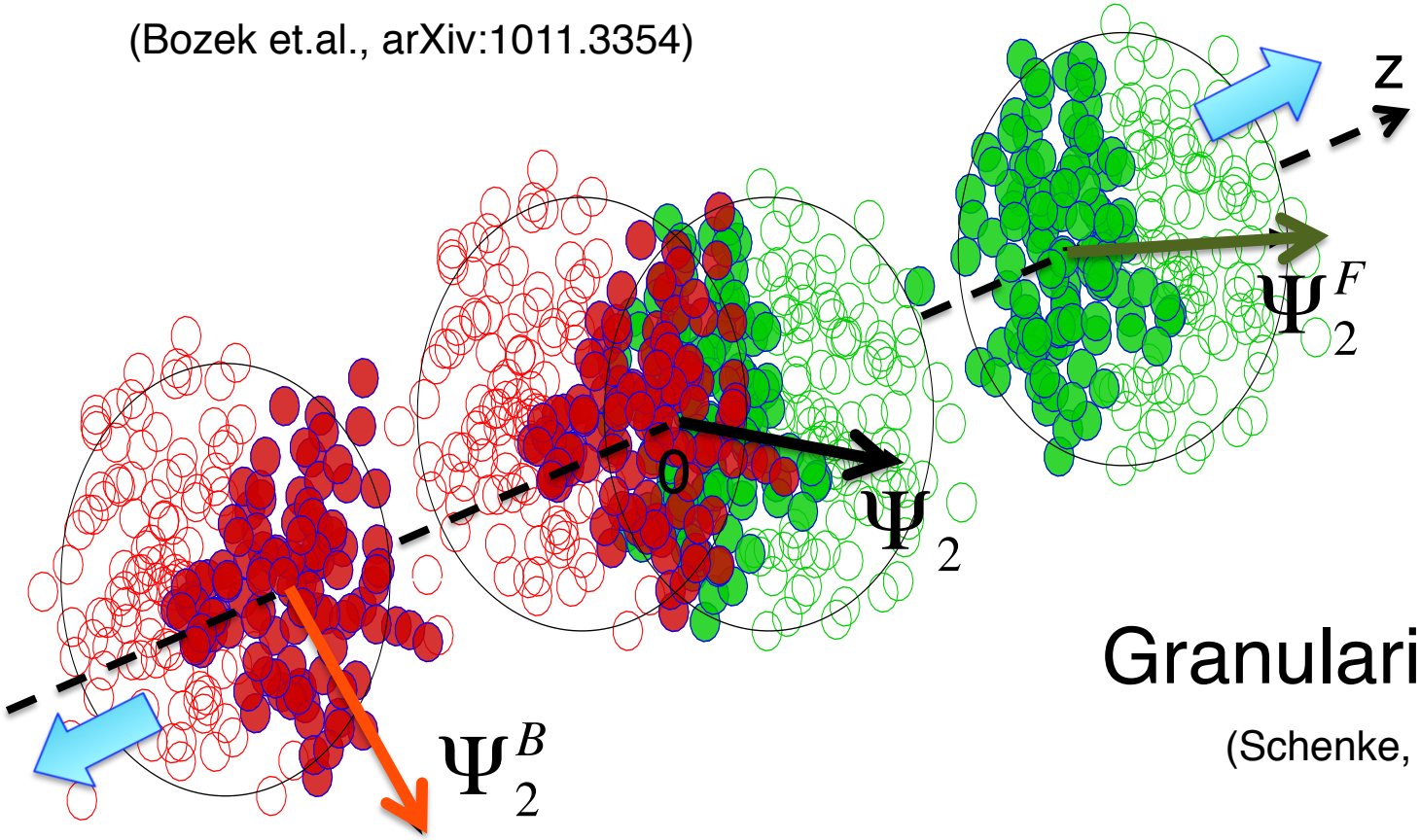

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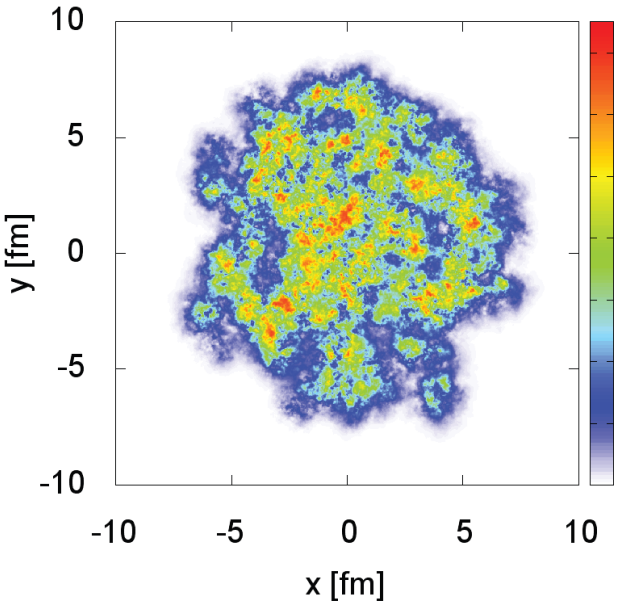

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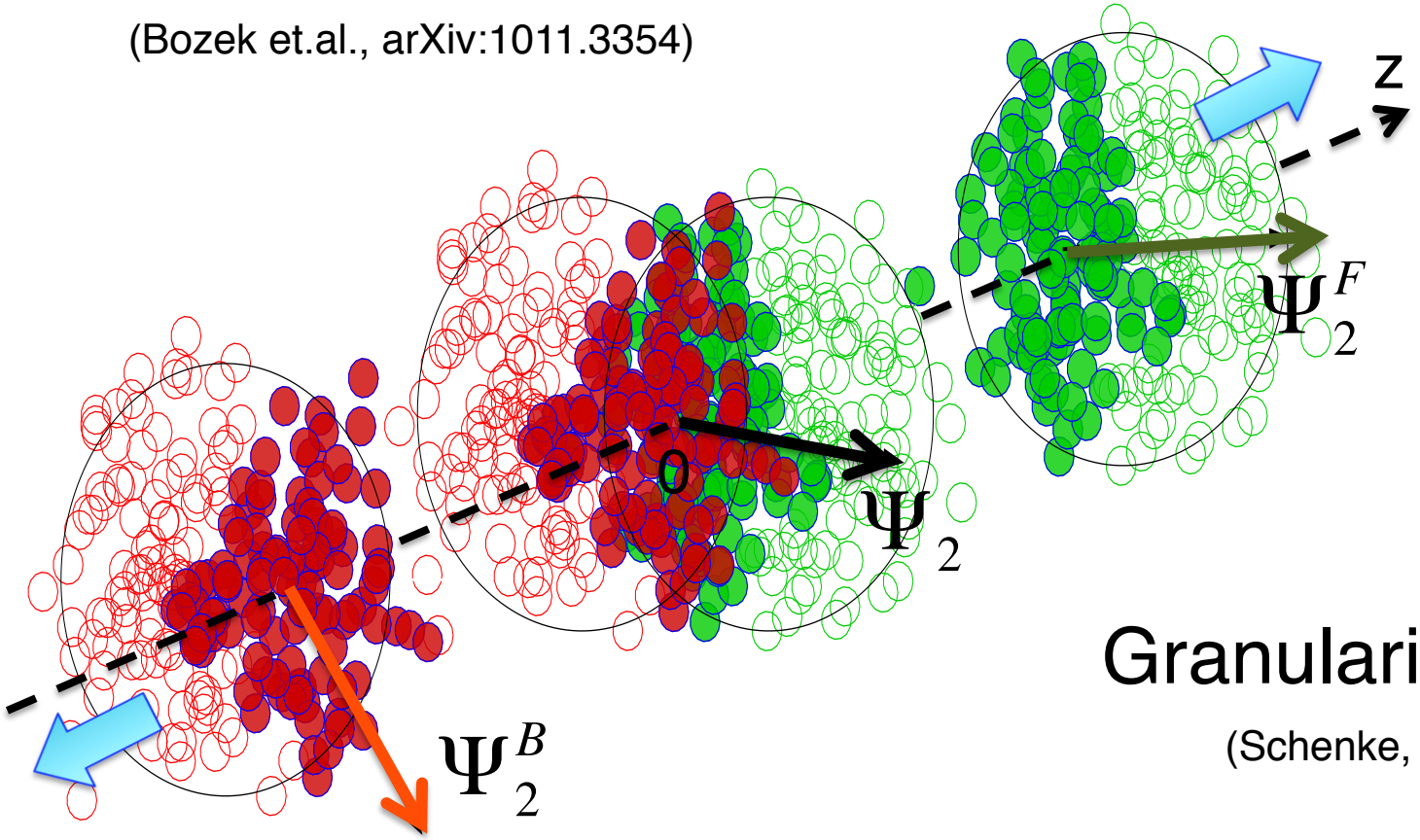

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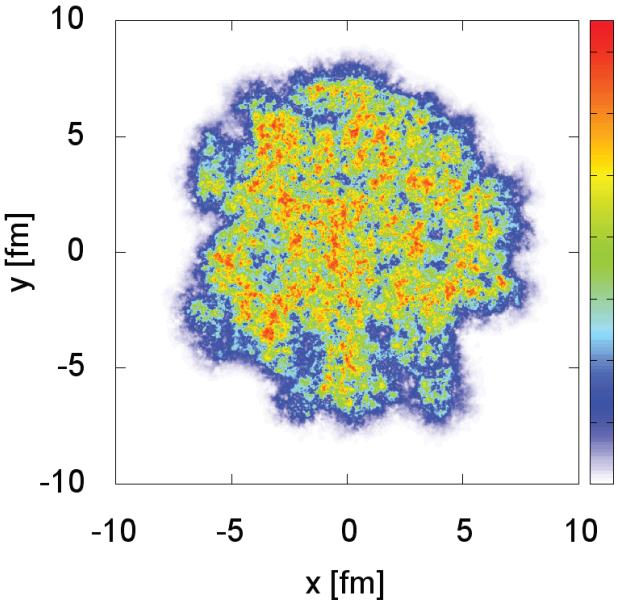

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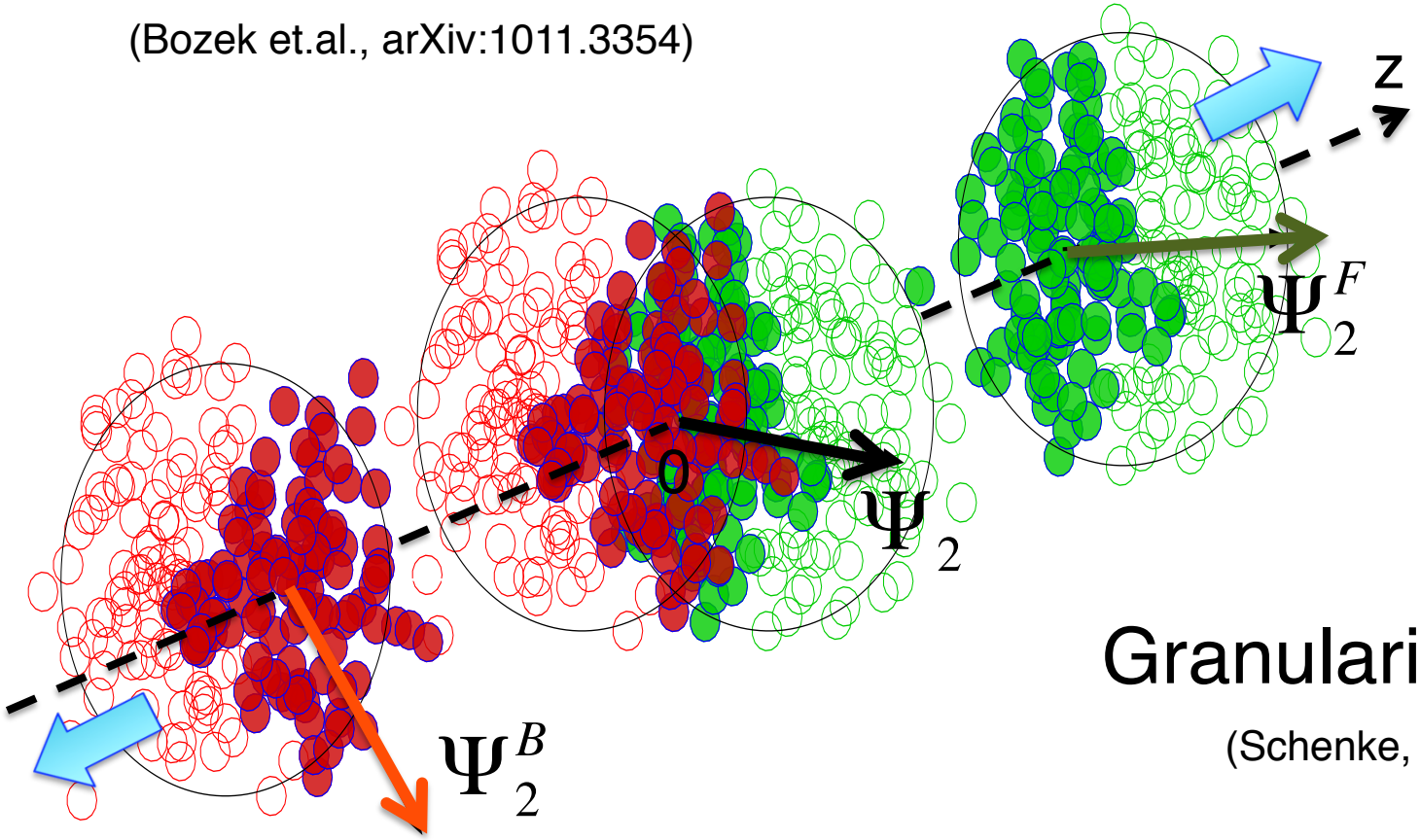

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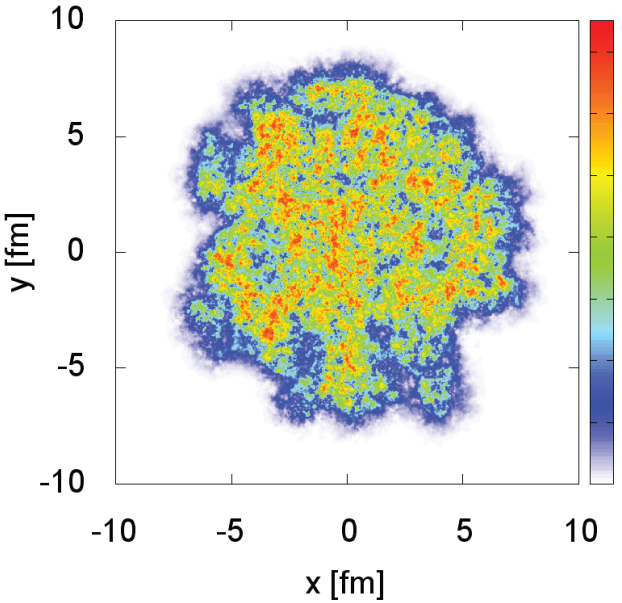


Granularity of gluon fields

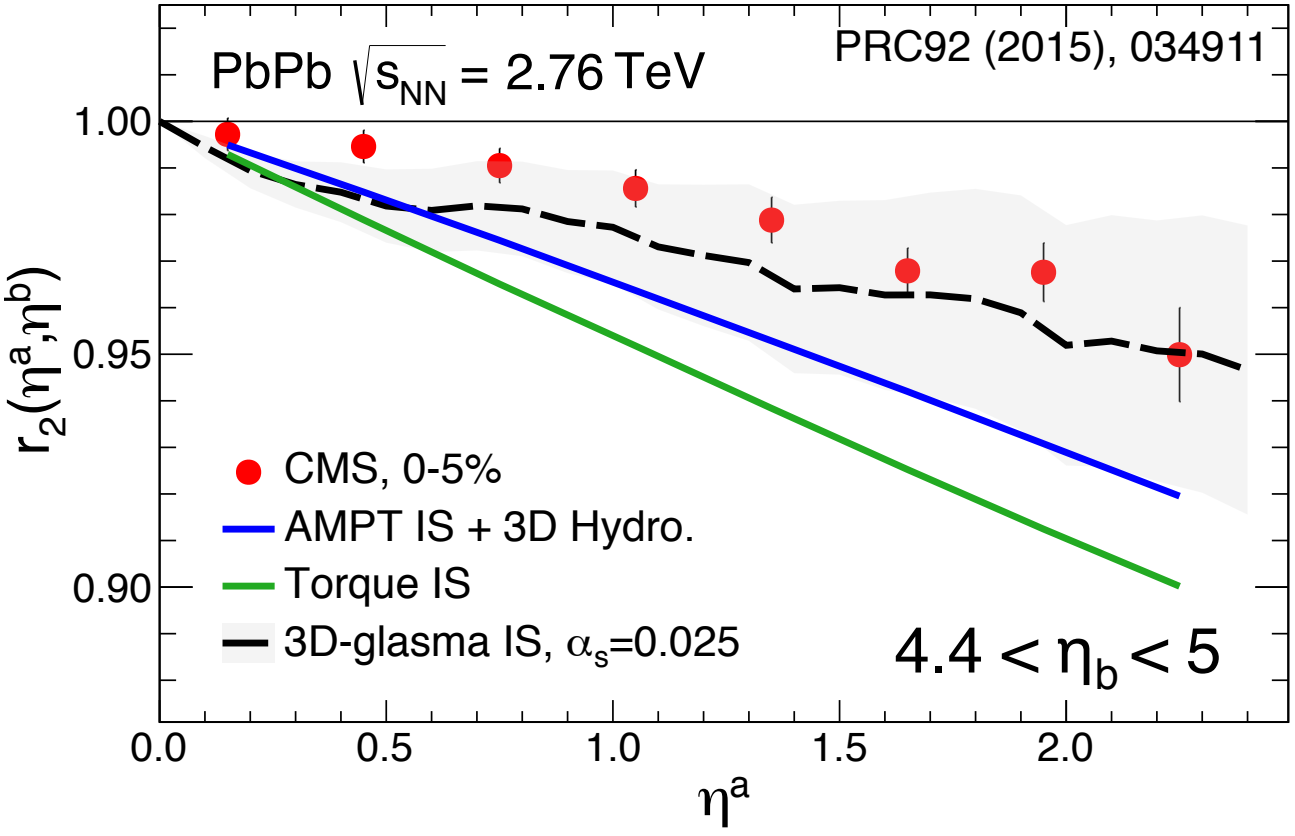
(Schenke, Schlichting, arXiv:1605.07158)

$$\left\langle \vec{\varepsilon}_n(\eta_1^s)\vec{\varepsilon}_n^*(\eta_2^s)\right\rangle \Rightarrow \left\langle \vec{V}_n(\eta_1)\vec{V}_n^*(\eta_2)\right\rangle$$

– rapidity-correlated flow fluctuations

Rapidity-correlated flow fluctuations

$$r_n \equiv \frac{\left\langle \vec{V}_n(-\eta^a)\vec{V}_n^*(\eta^b)\right\rangle}{\left\langle \vec{V}_n(\eta^a)\vec{V}_n^*(\eta^b)\right\rangle} \sim \left\langle \cos n\left[\Psi_n(\eta^a)-\Psi_n(-\eta^a)\right]\right\rangle$$ — "Event-plane decorrelations"



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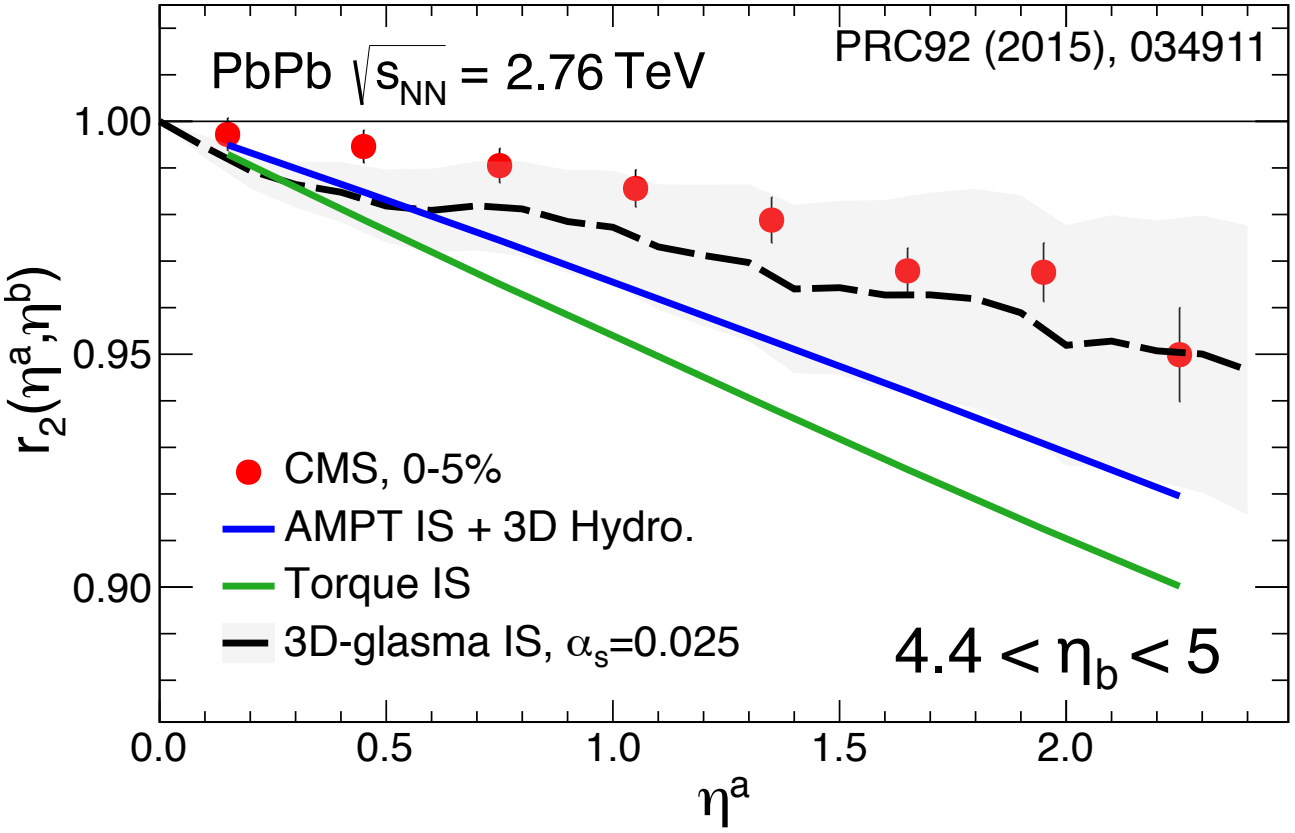

Transverse dynamics is approx. **boost invariant**, but **NOT** for the initial states (3D)

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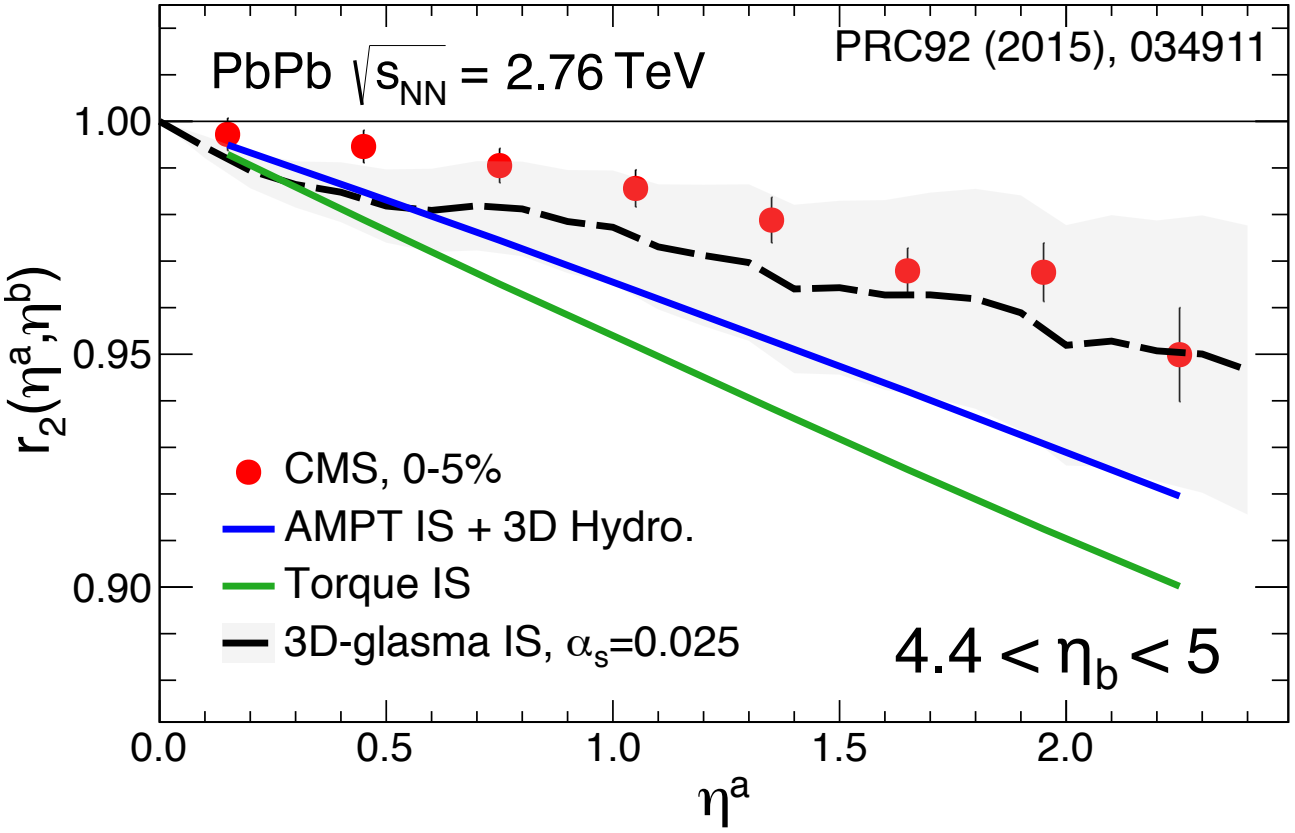

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Rapidity-correlated flow fluctuations

Minimize ε_n fluct. and single out EP twist

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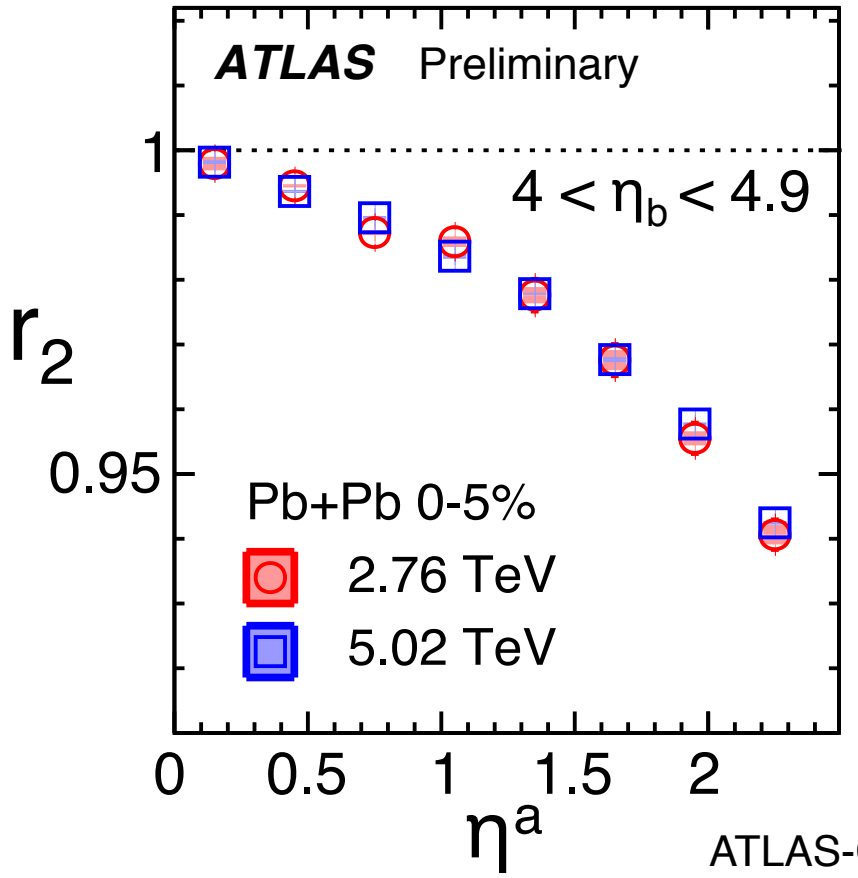

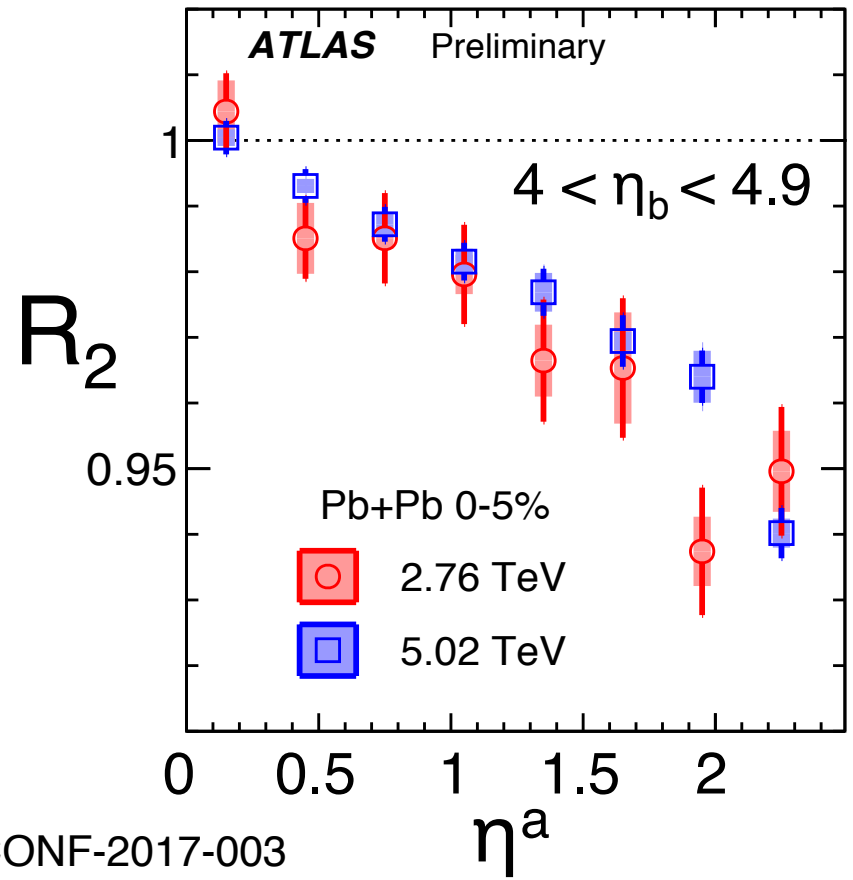

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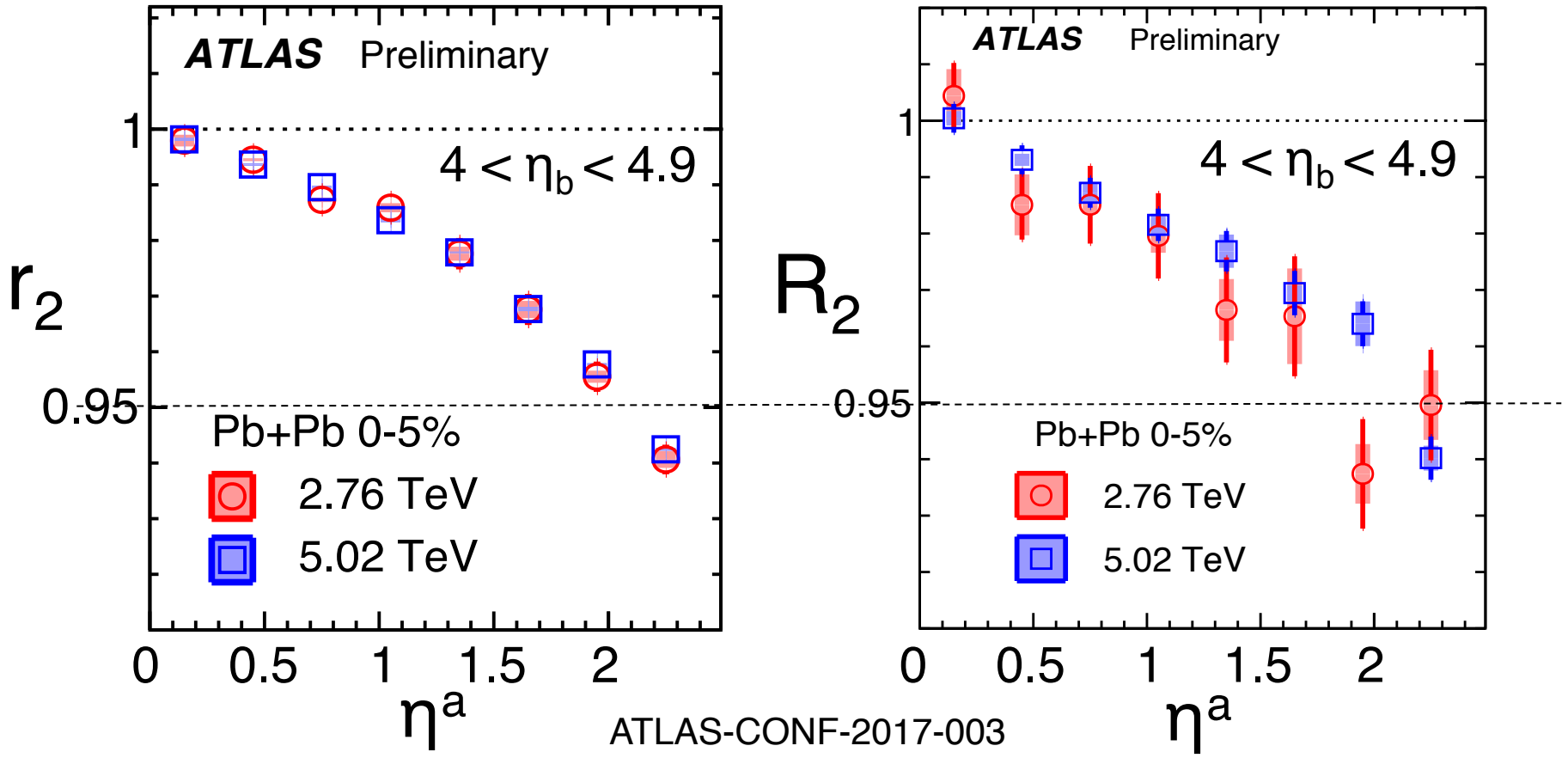
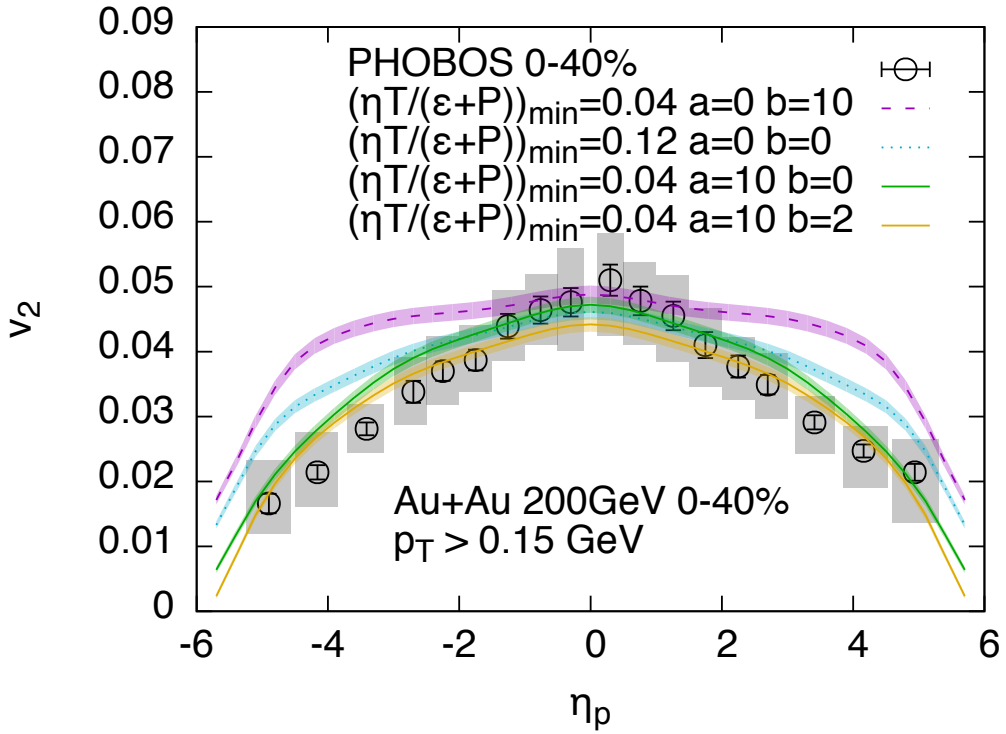
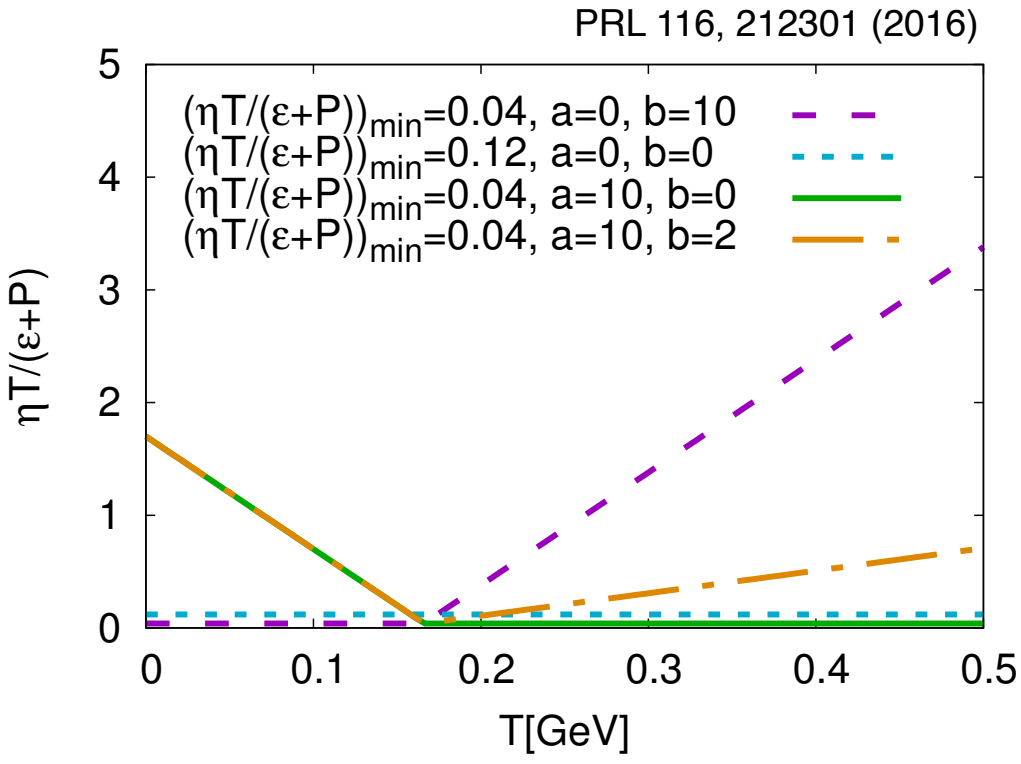


EP twist accounts for ~ 50% of r_2

Rapidity-correlated flow fluctuations

$v_2(\eta)$ proposed as a means of probing $\eta/s(T)$





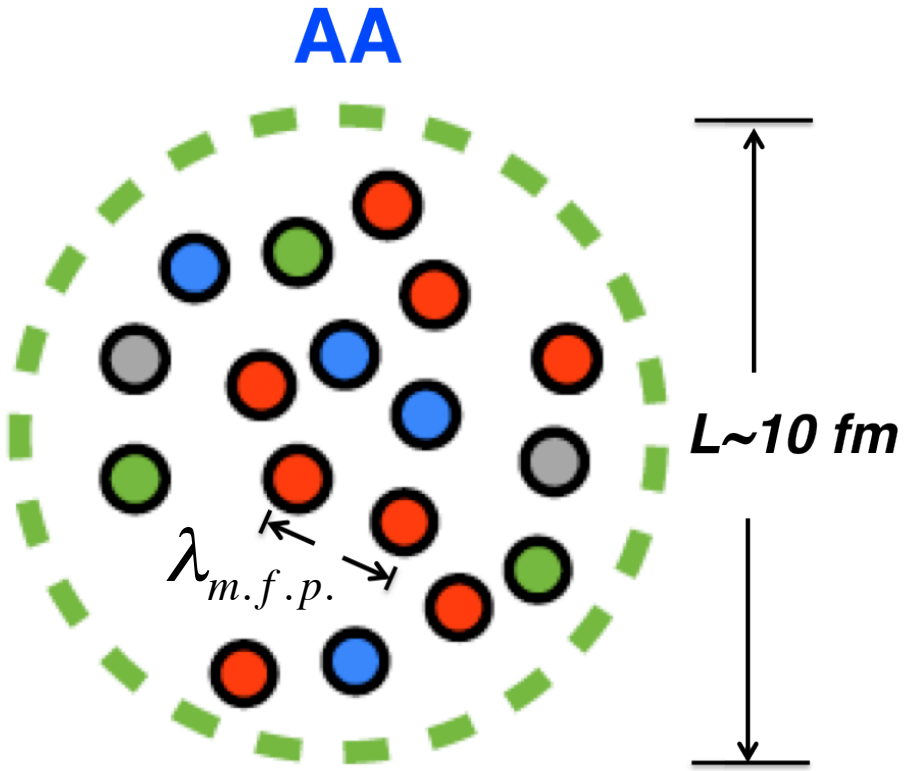
Crucial to understand the contribution of rapidity-correlated initial-state effects

How small a QGP fluid can be?

Hydrodynamics applies when:

$$L >> \lambda_{m.f.p.}$$

where $\lambda_{m.f.p.} \sim \frac{1}{g^4 T}$



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- For $g \sim 1$,

$\Rightarrow$ $LT >> 1$

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- For $g \sim 1$,

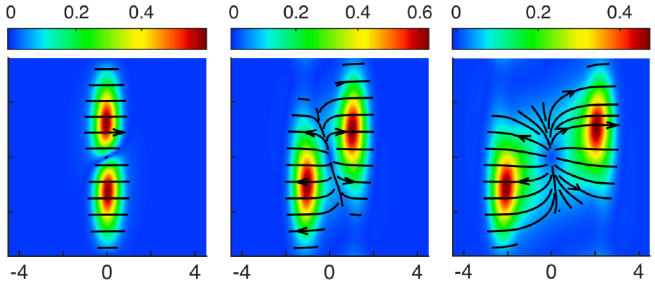
  ⇨ $LT >> 1$

OR

- In the limit of $g \to \infty$

  $LT \sim 1$

P. Chesler



QGP fluid in pp

How small a QGP fluid can be?

Hydrodynamics applies when:

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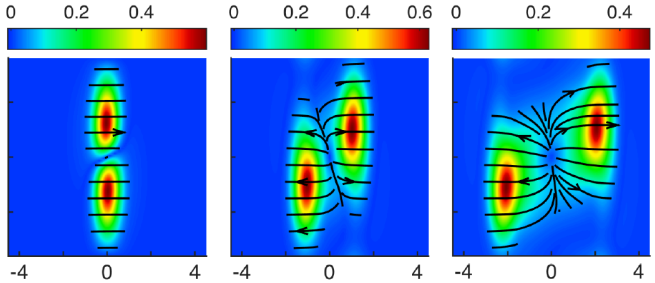

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Experimental condition

$$N_{trk} \sim (LT)^3 \qquad \left(N_{trk}/L^3 \sim s \sim T^3\right)$$

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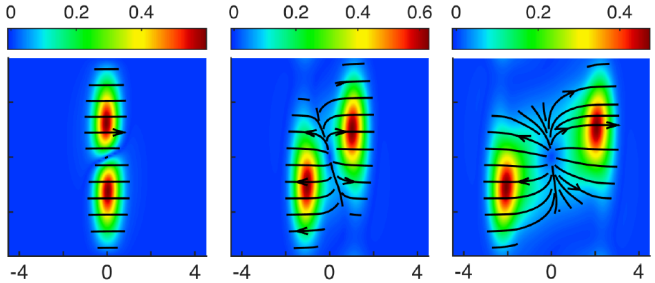

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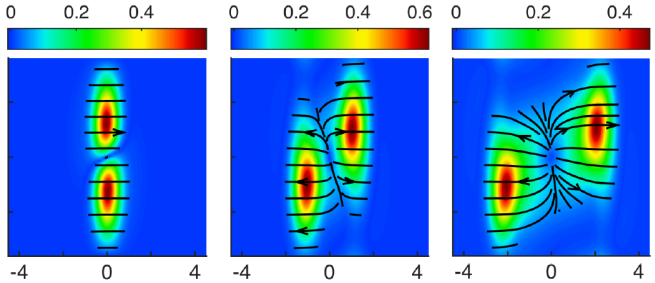

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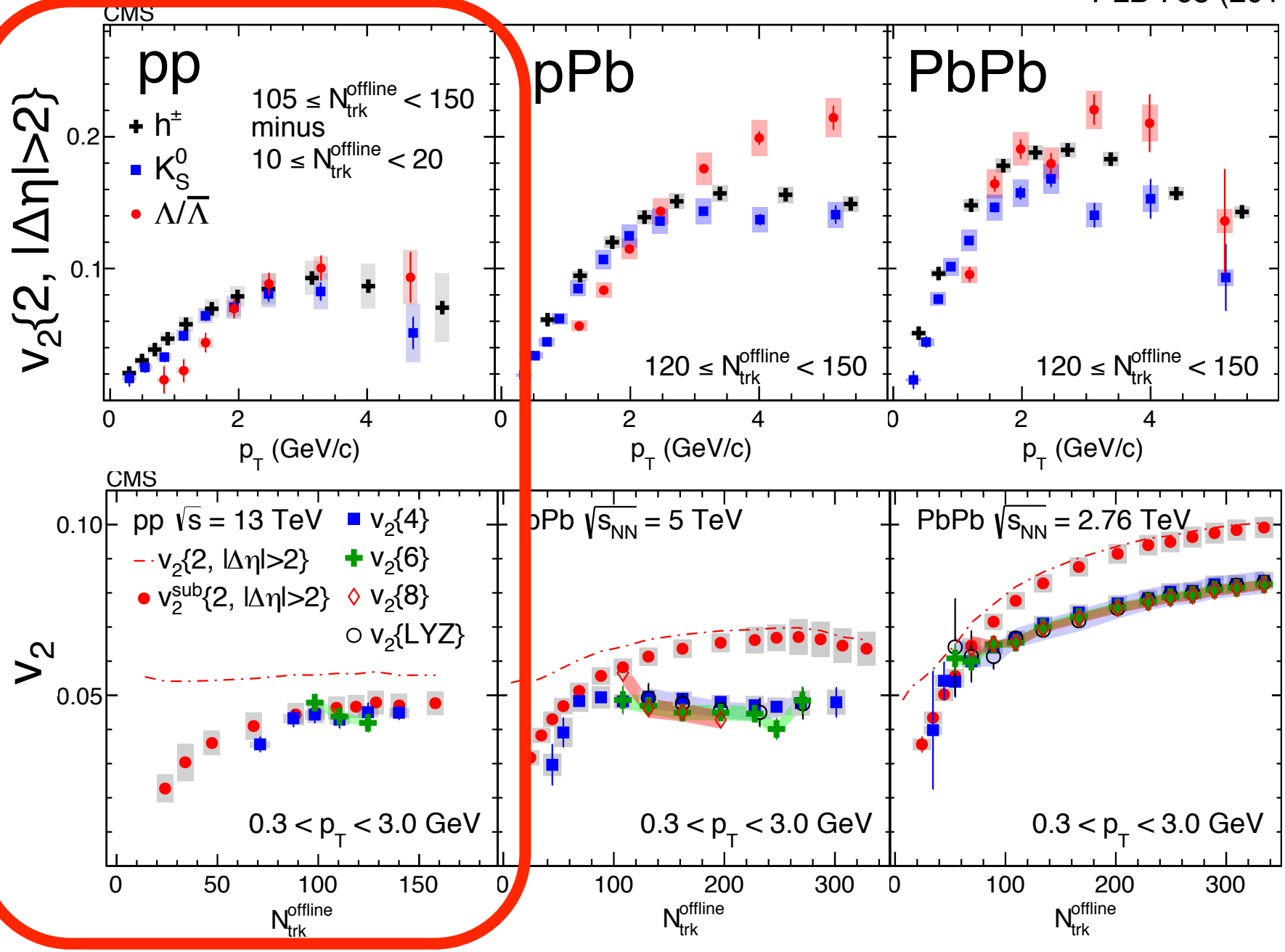
Multiplicity or entropy

What is the smallest ~~size~~ for a QGP fuild?

Collective flow in small systems (?)

Key features of collectivity seen in HM pp

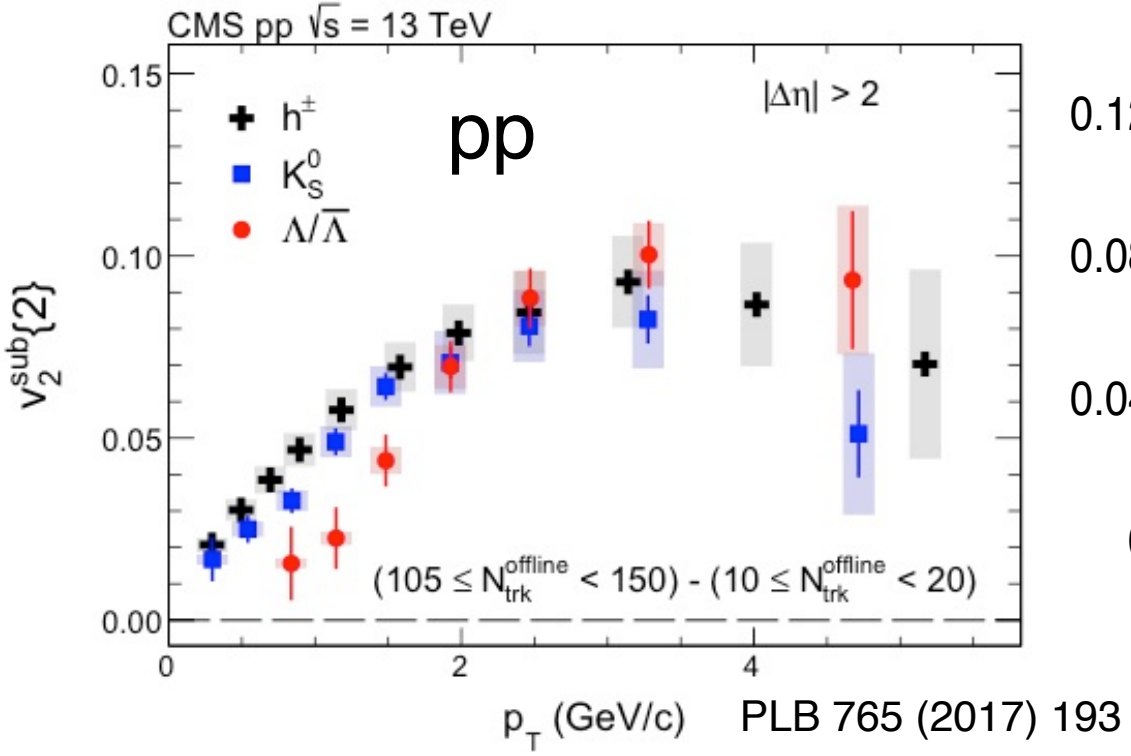
PLB 765 (2017) 193



Collective flow in small systems (?)

Initial interaction models confronting the data!

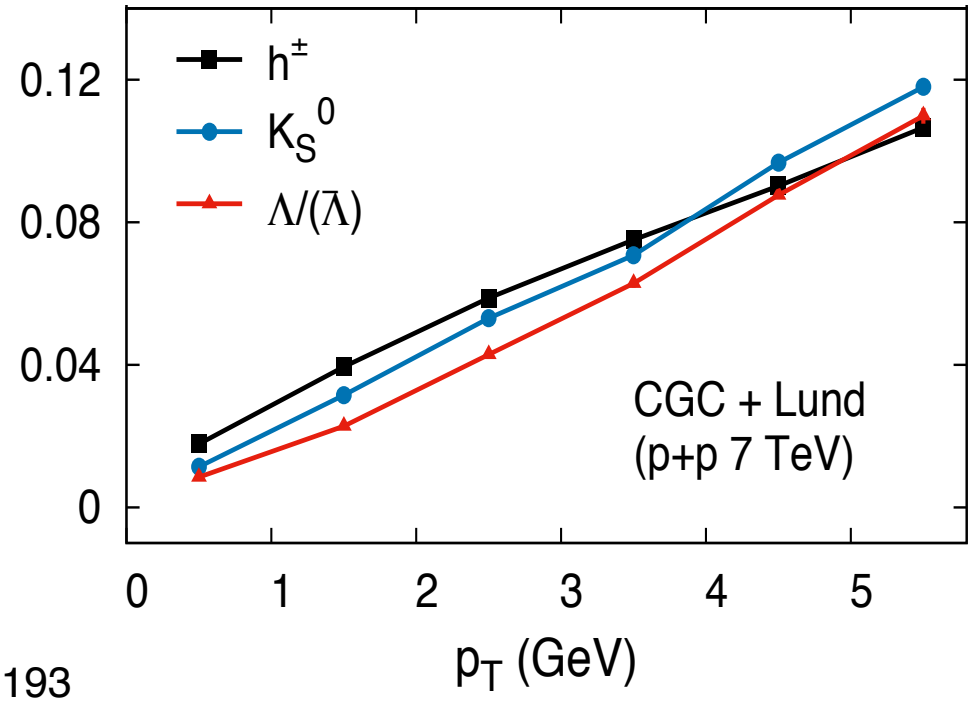
(scenario #2)



PLB 765 (2017) 193

CGC + Lund (PYTHIA)

Schenke et. al, PRL 117, 162301 (2016)



How about $v_2\{m\}$?

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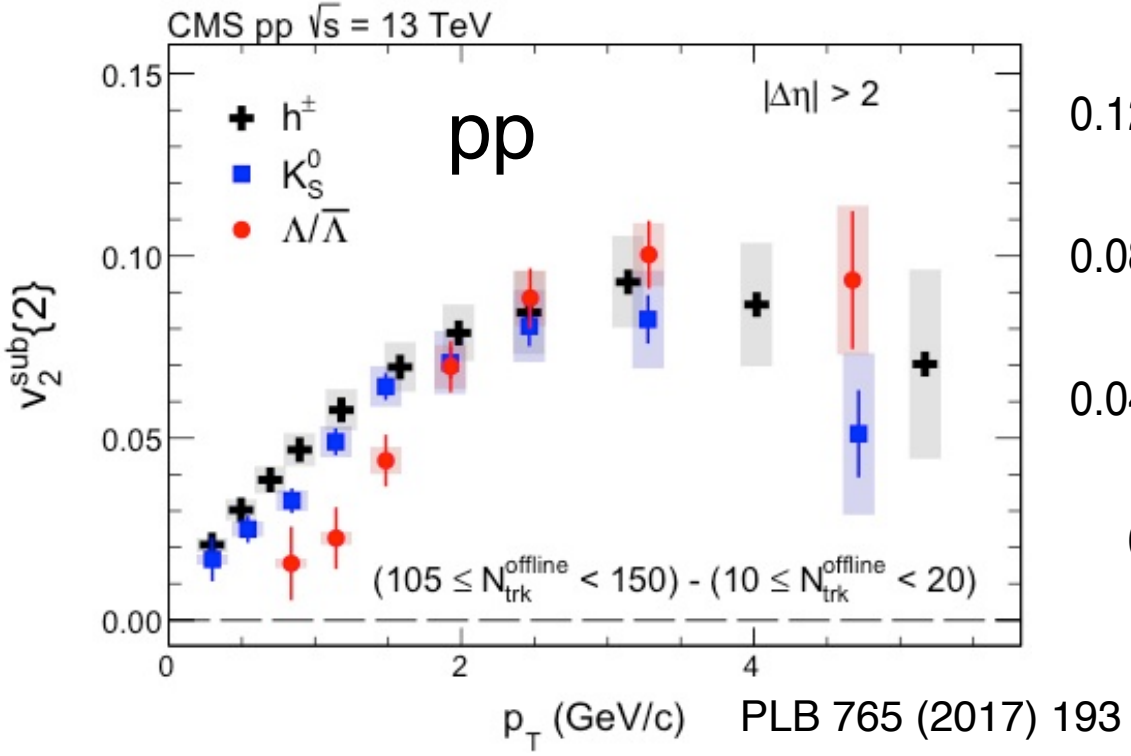

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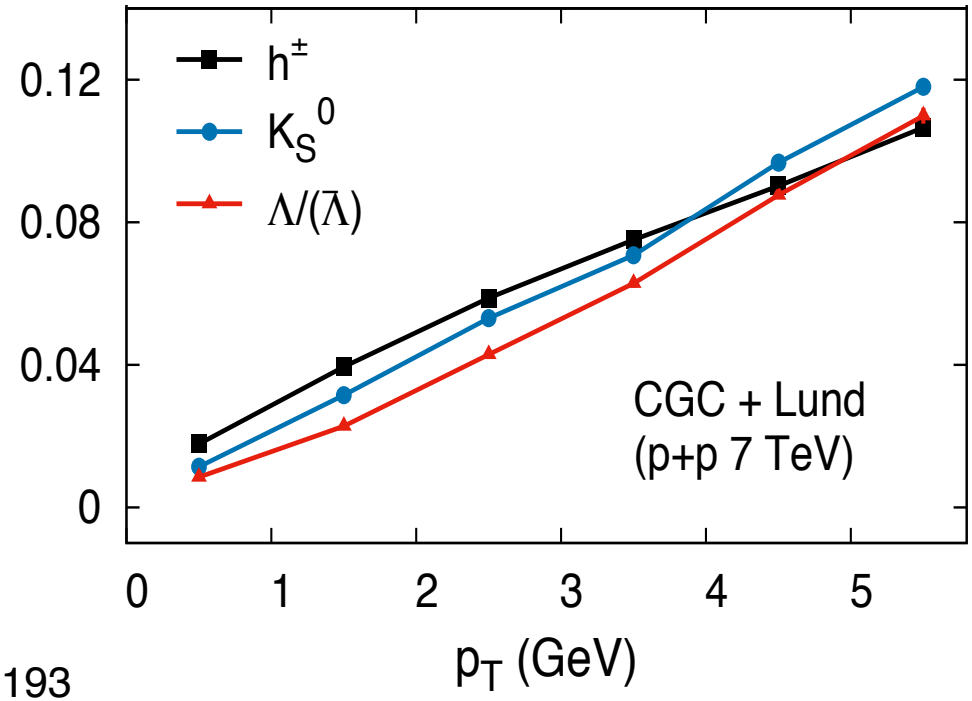
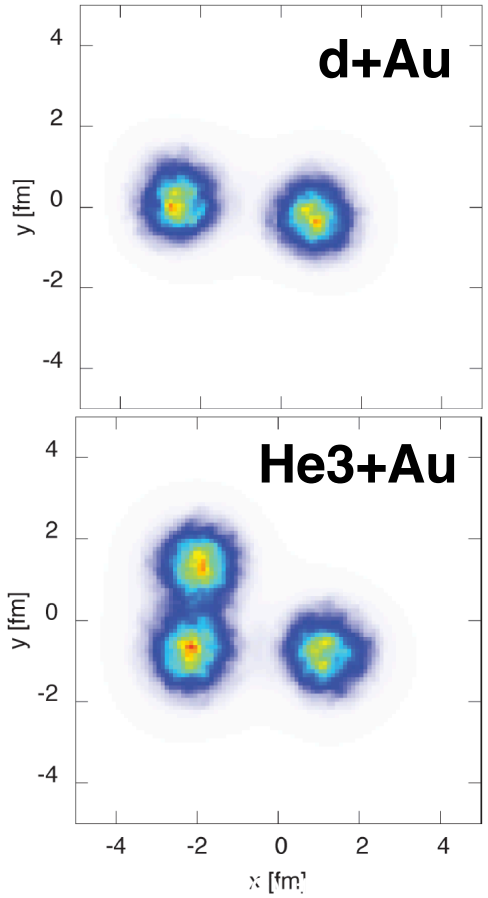


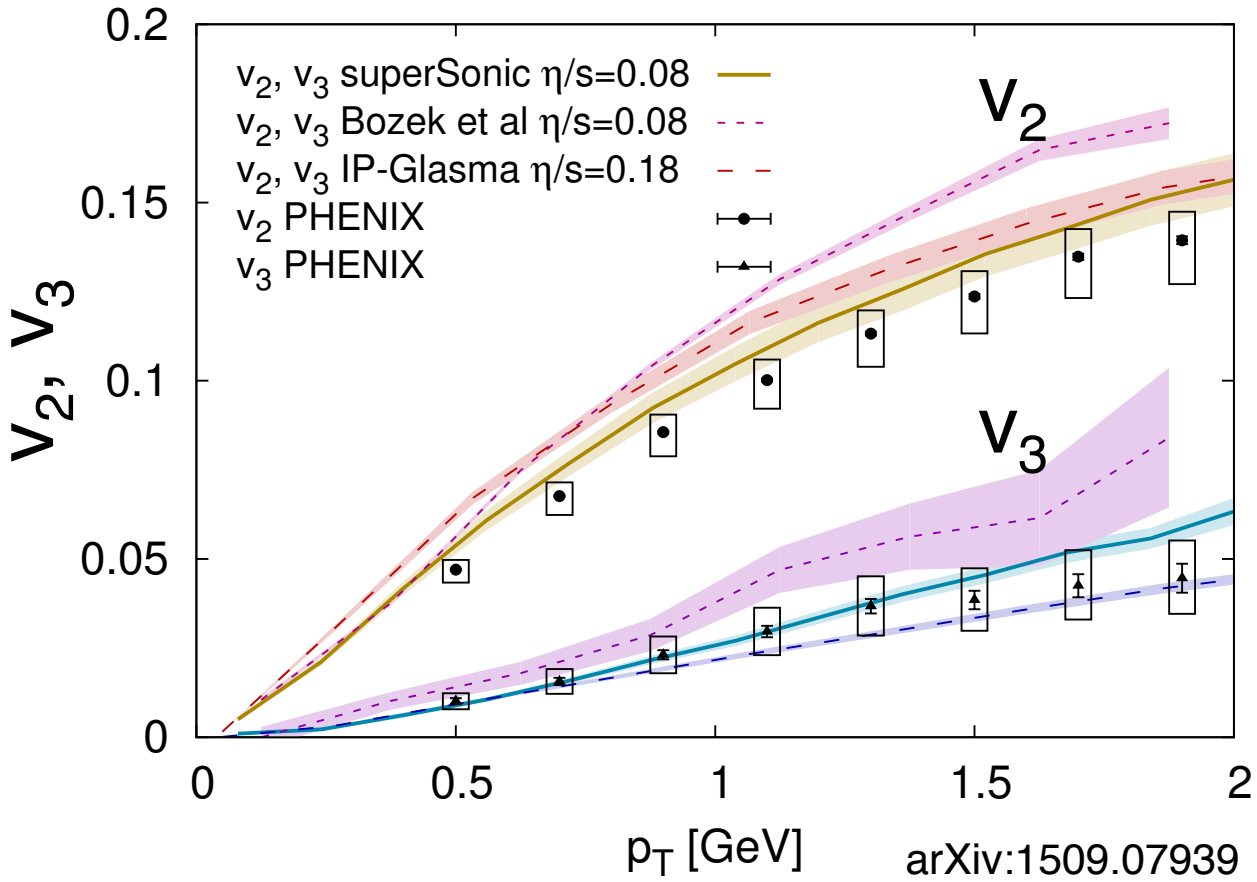
How about $v_2\{m\}$?

Connection to **initial-state geometry** is the key to further differentiate the two scenarios!

Geometry-controlled small systems

"Smallness" is not the limitation





For A_1 (A_2) ≥ 2, all hydro. models agree

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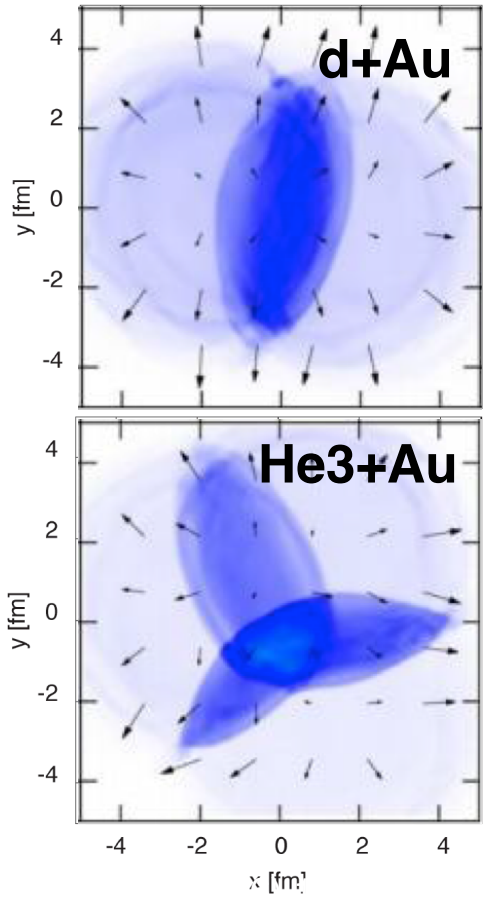

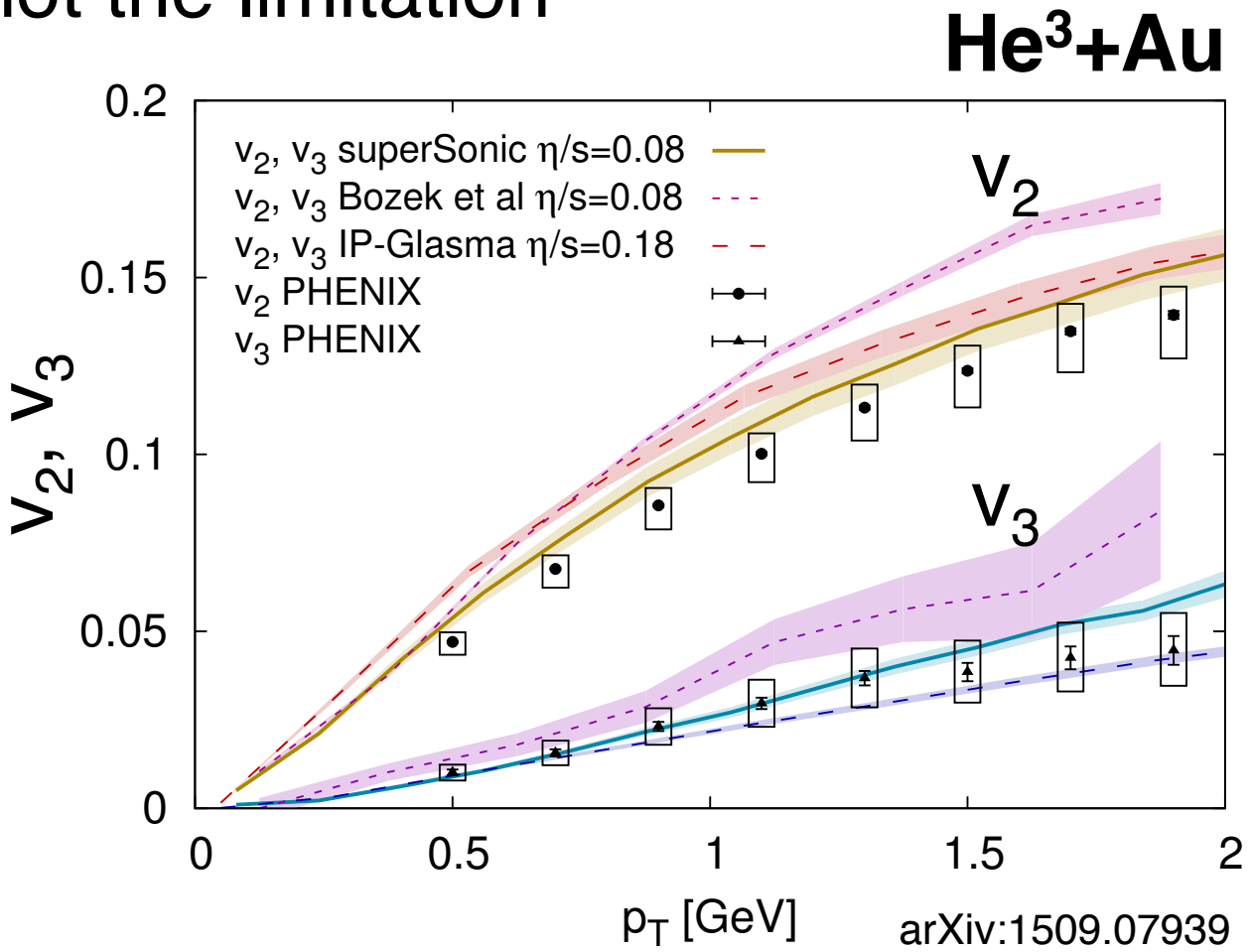

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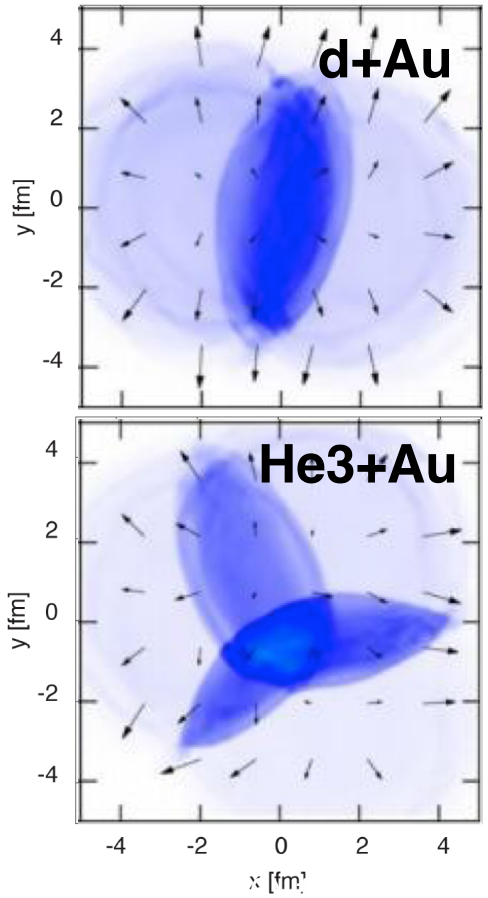

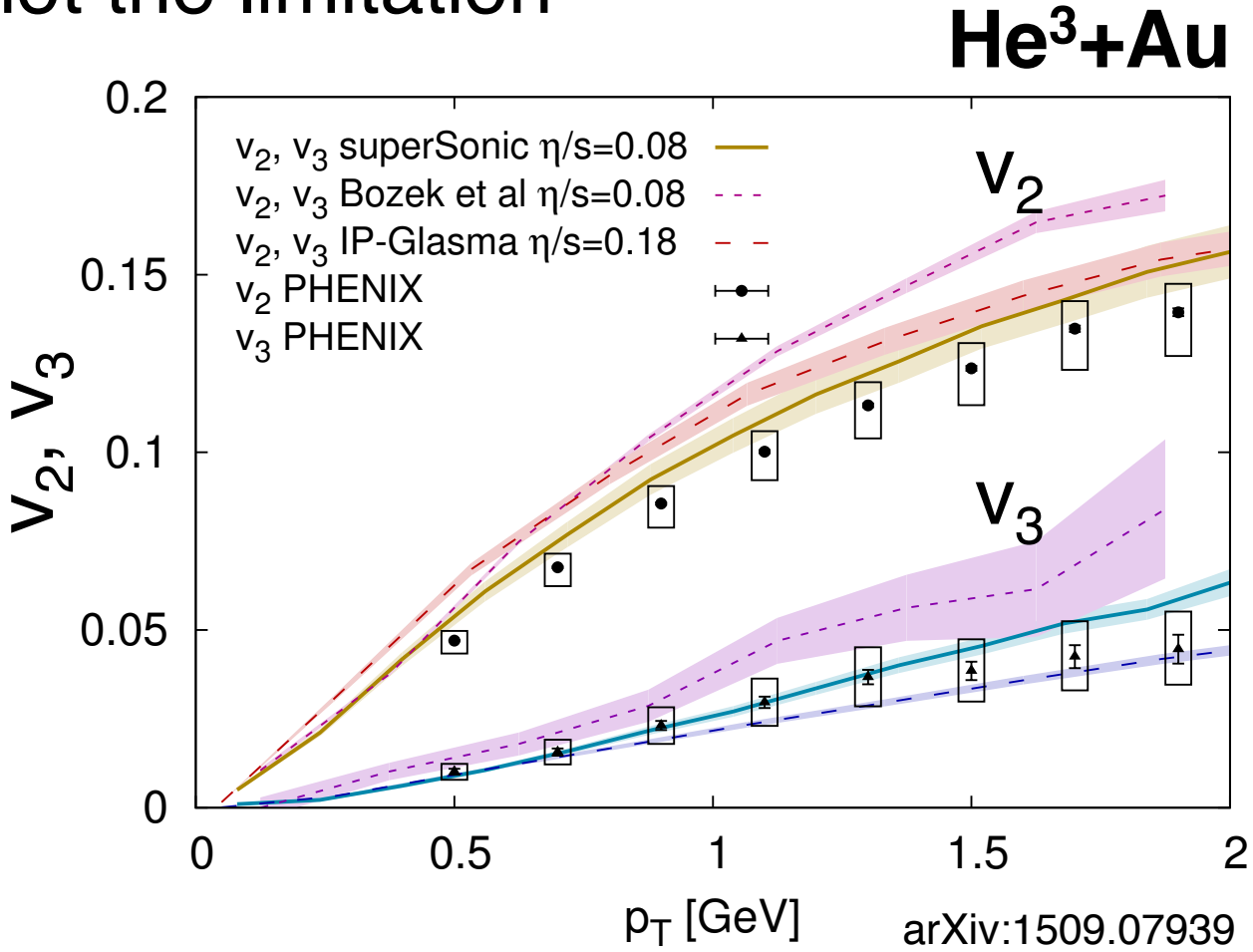

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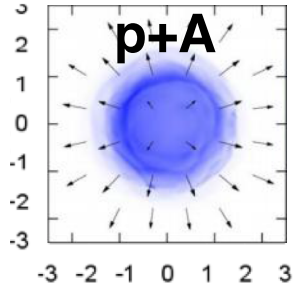
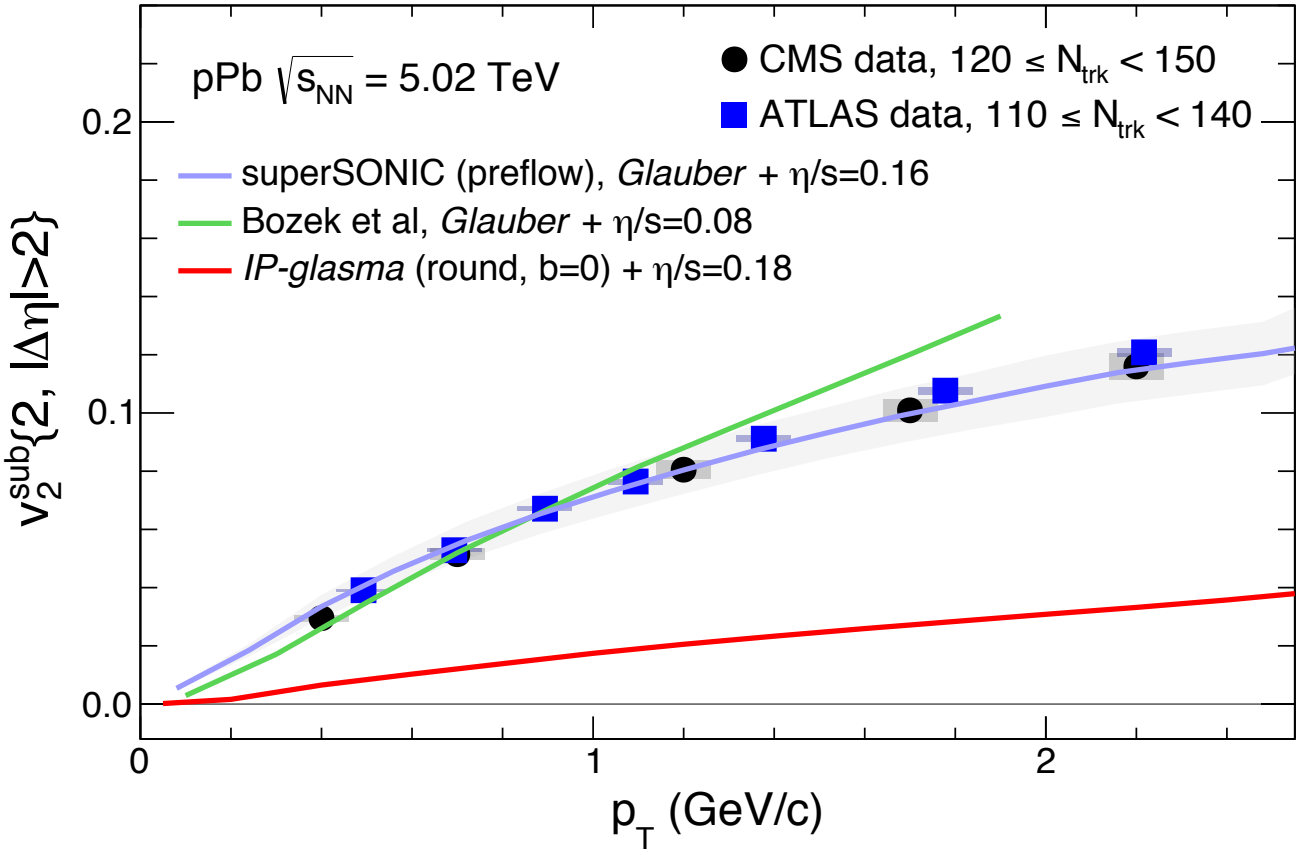
⇨ We know how to do hydro. in small systems!

Geometry "uncontrolled" in pA and pp

But if A_1 (A_2) = 1





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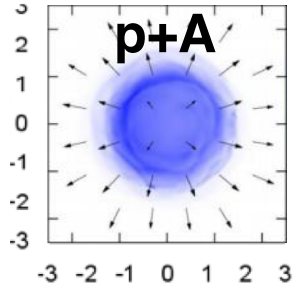
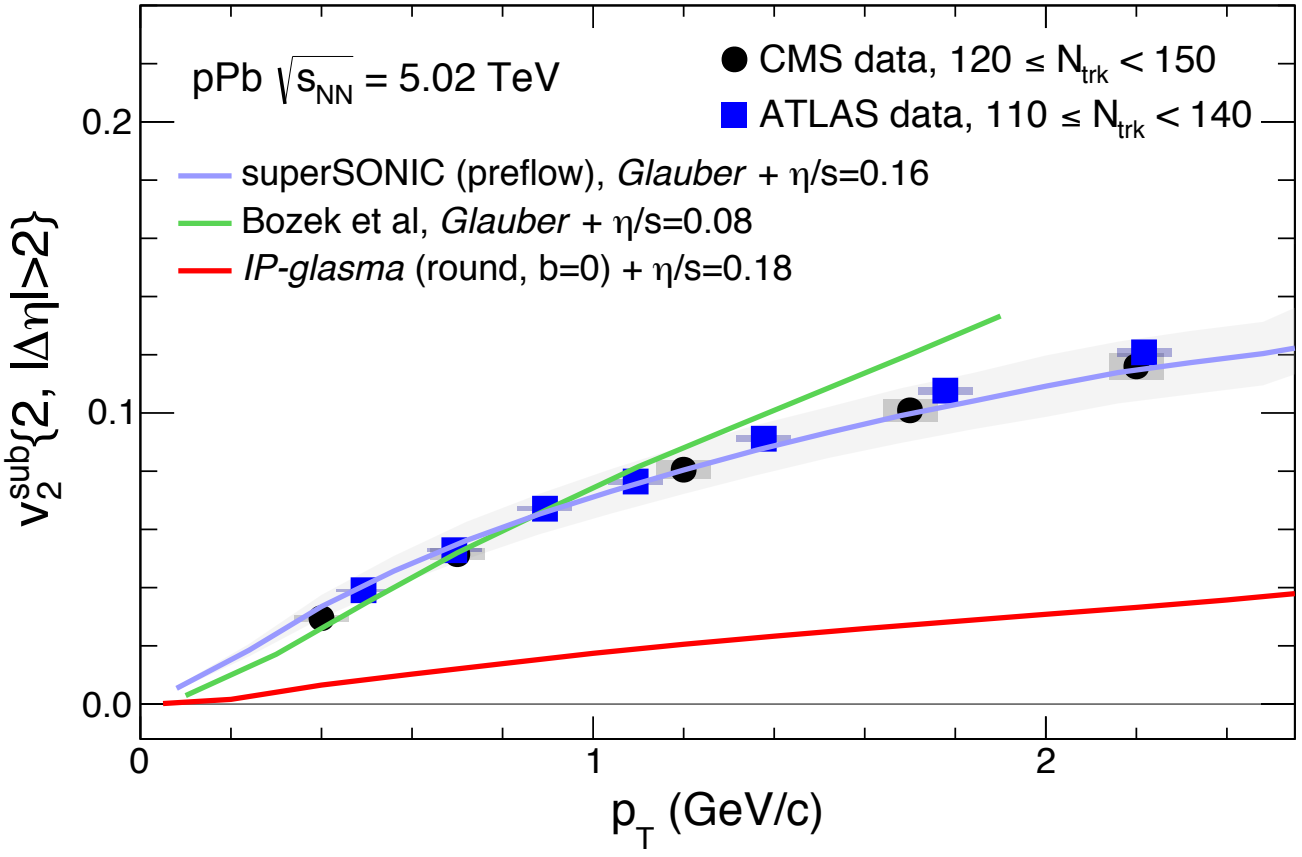
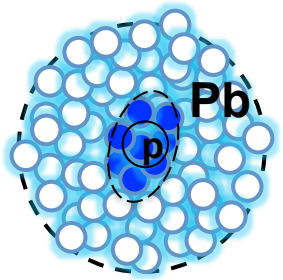
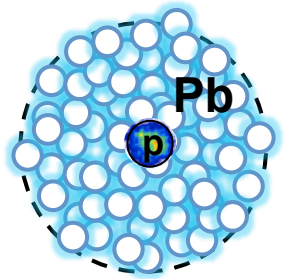




Glauber-like



IP-glasma



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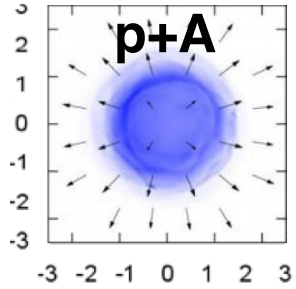
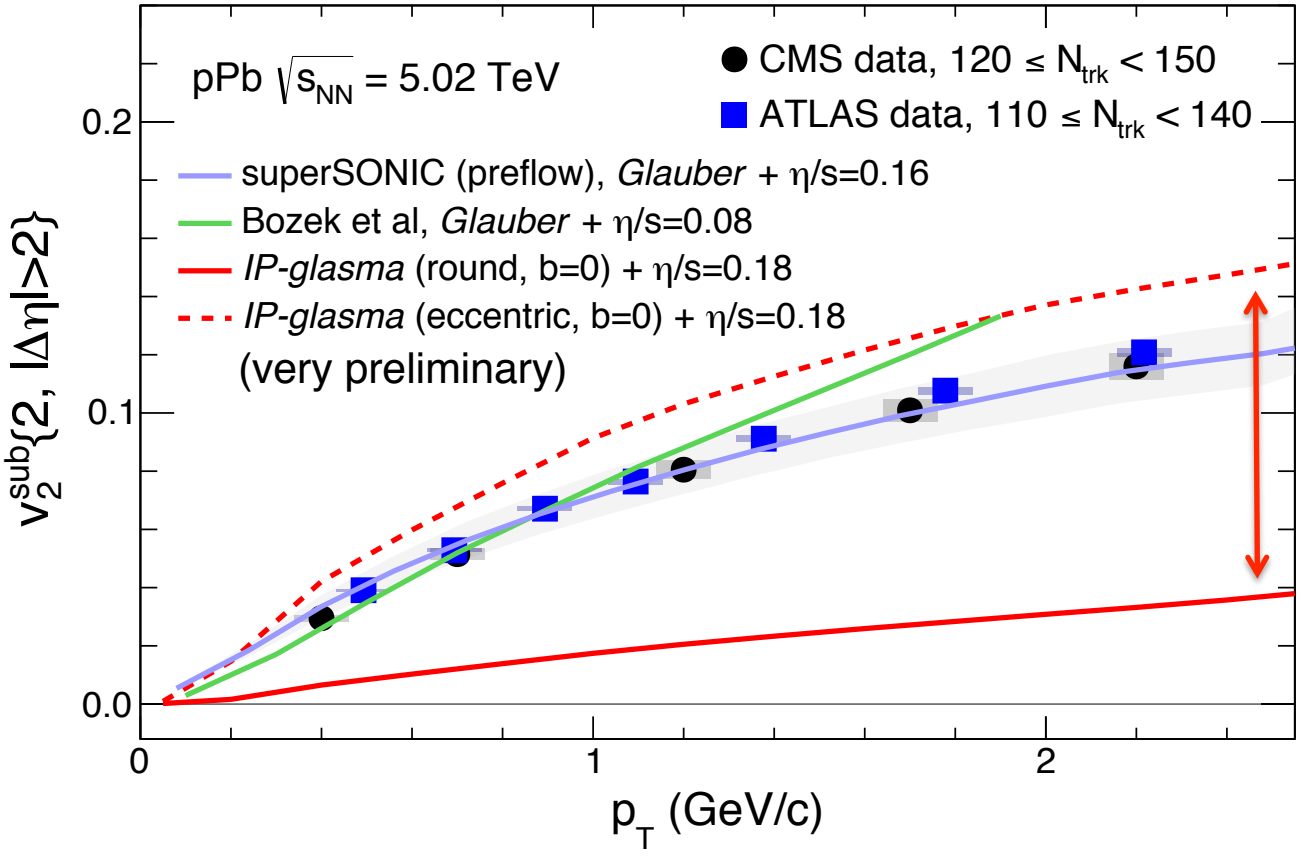
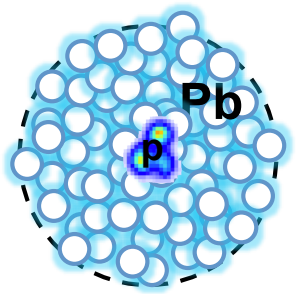




eccentric proton



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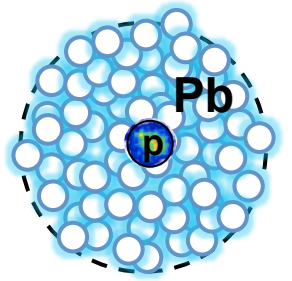

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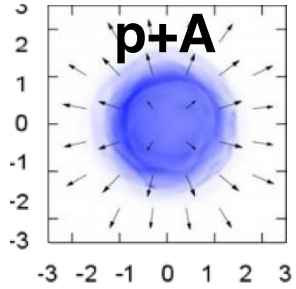
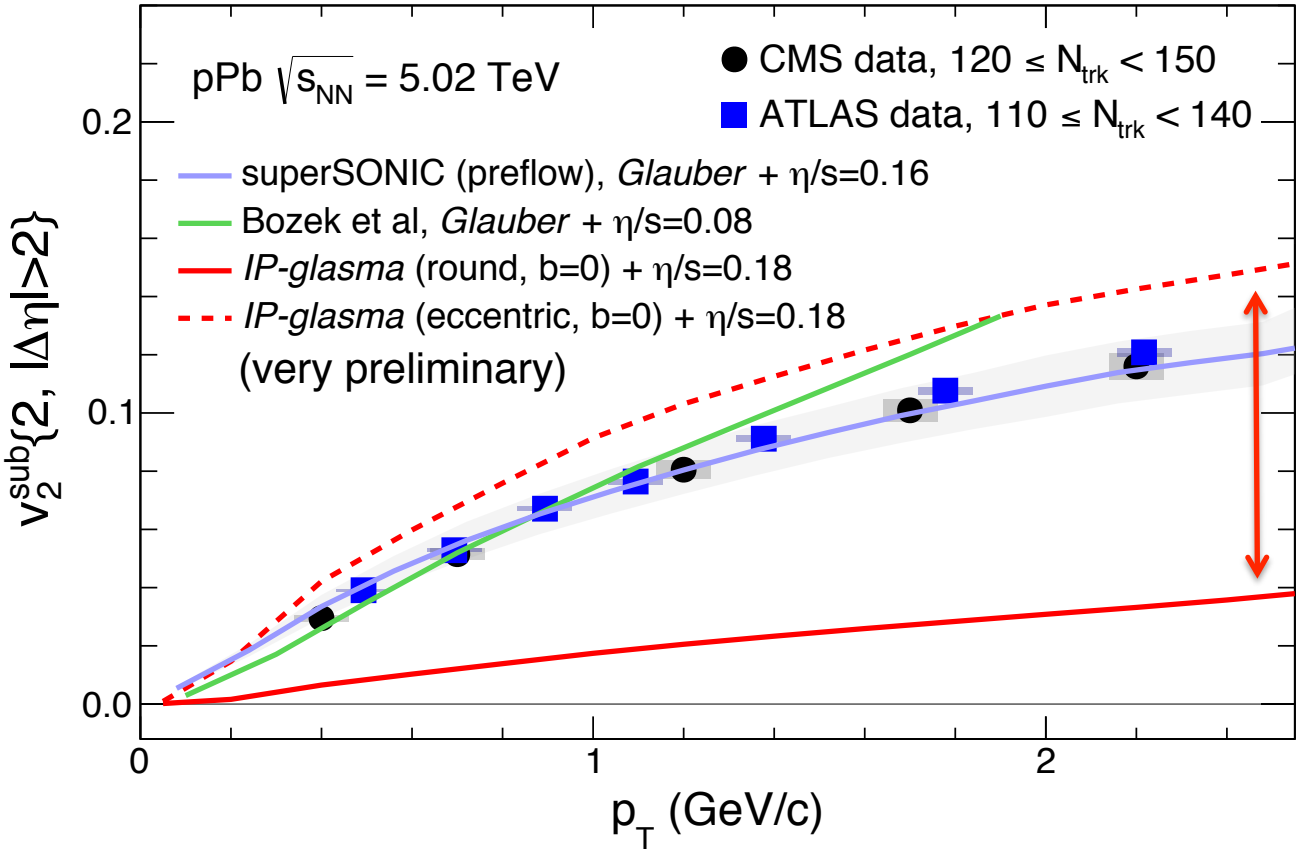
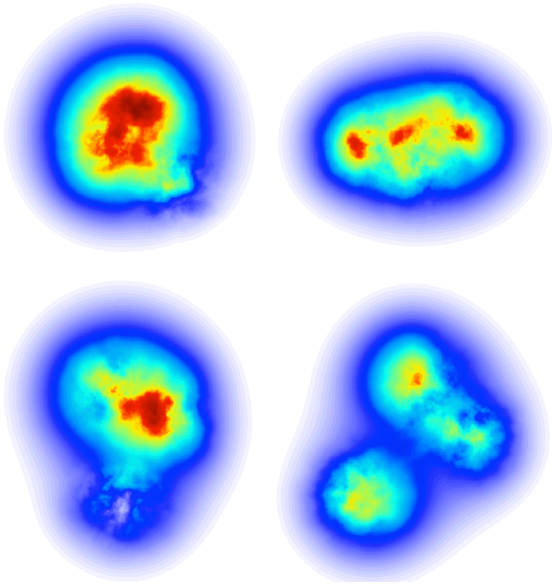






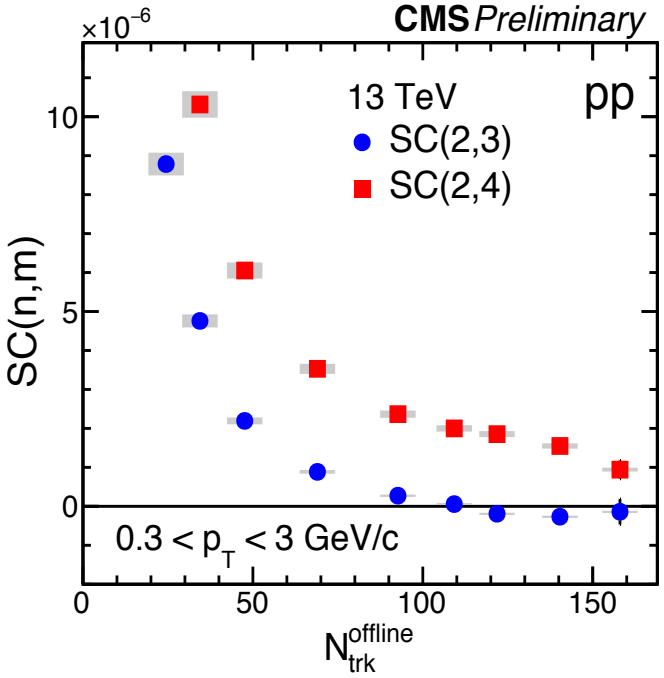
Mantysaari, Schenke,
PRL 117, 052301 (2016)

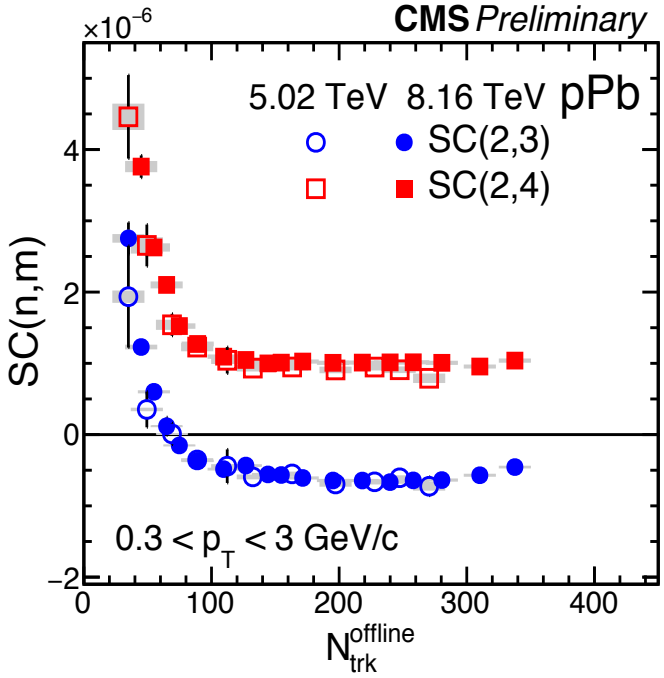
Unique opportunities for probing subnucleonic quantum fluctuations in yoctoseconds!

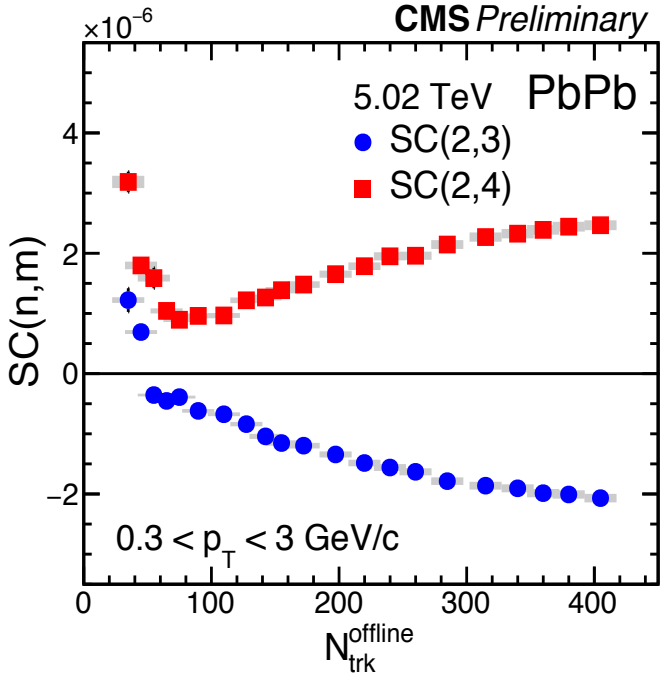
New insights to IS fluc. of pp and pA

$$SC(n,m) = \left\langle v_n^2 v_m^2 \right\rangle - \left\langle v_n^2 \right\rangle \left\langle v_m^2 \right\rangle$$ in small systems

2016 pPb data!







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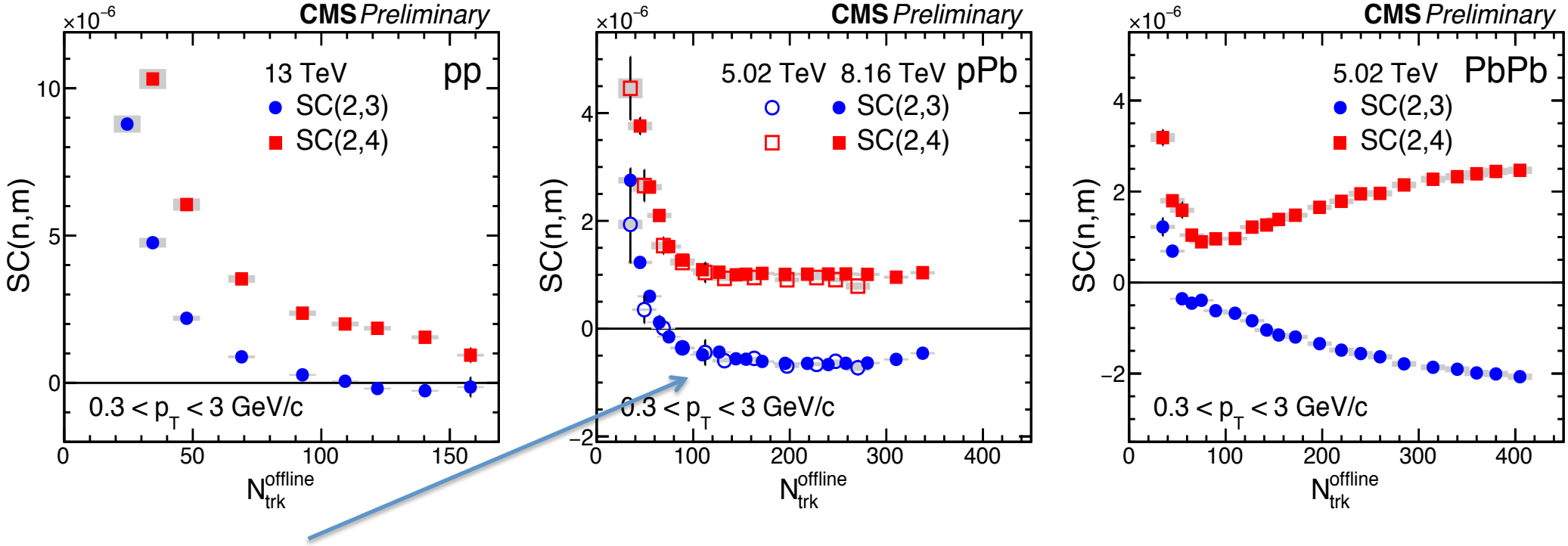

Anti-correlation of v_2 and v_3 in pPb, same as PbPb

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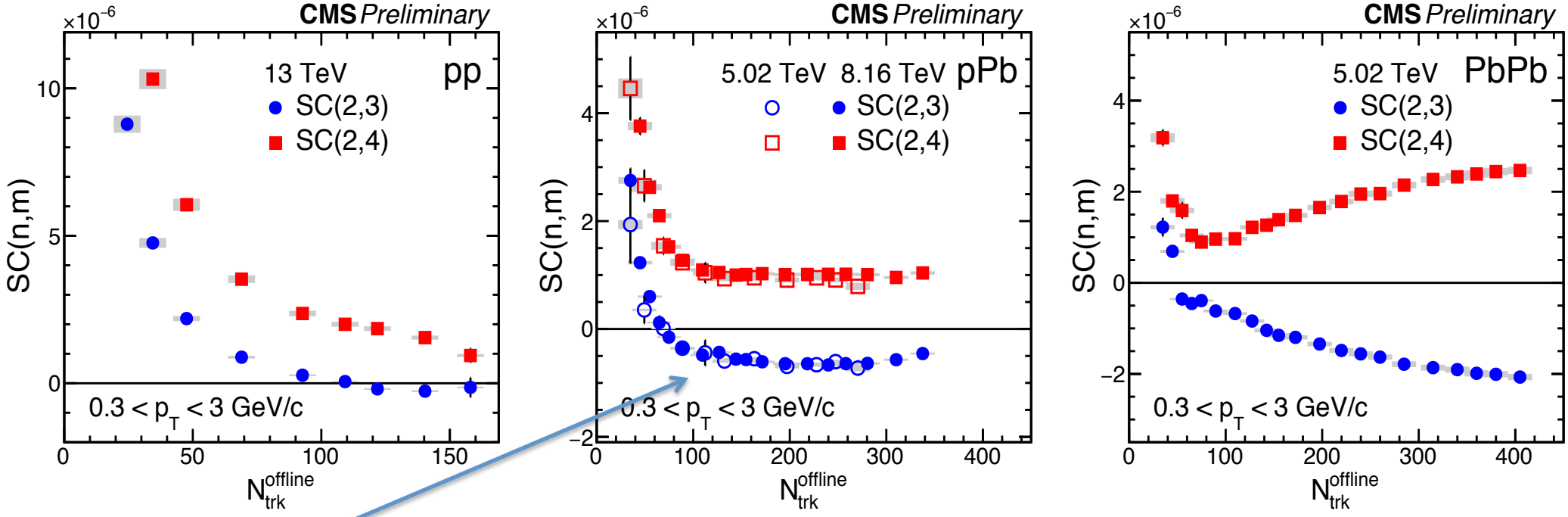
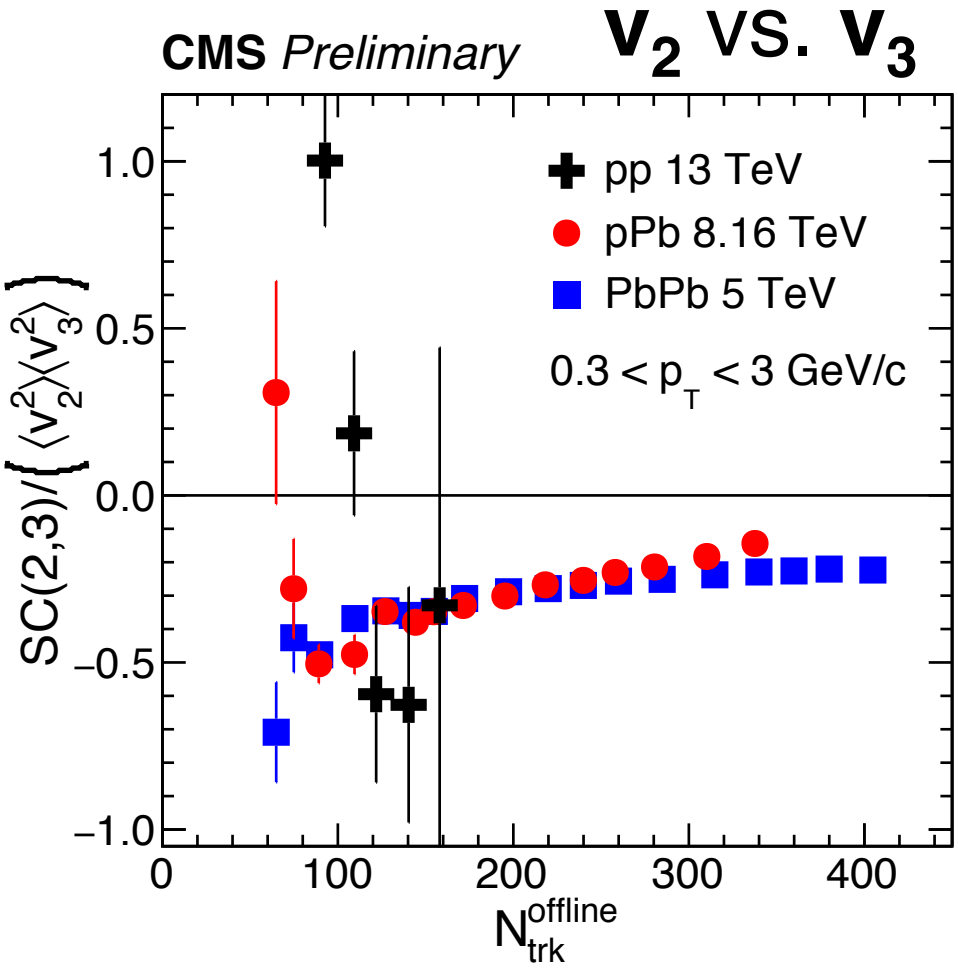


Anti-correlation of v_2 and v_3 in pPb, same as PbPb

- Naturally explained by initial geometry
- A new challenge to initial interaction models?

New insights to IS fluc. of pp and pA

Normalized by $\left\langle v_n^2 \right\rangle \left\langle v_m^2 \right\rangle$



Constraining the IS with “new” flow observables

New insights to IS fluc. of pp and pA

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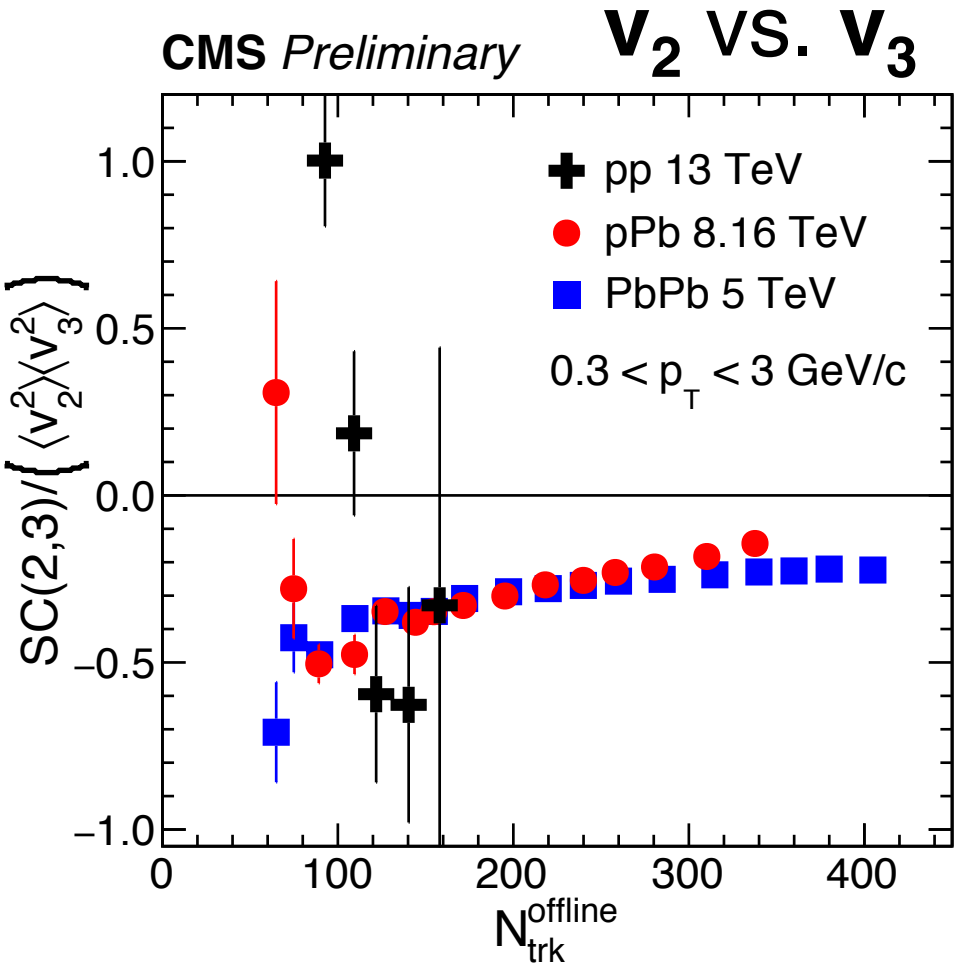
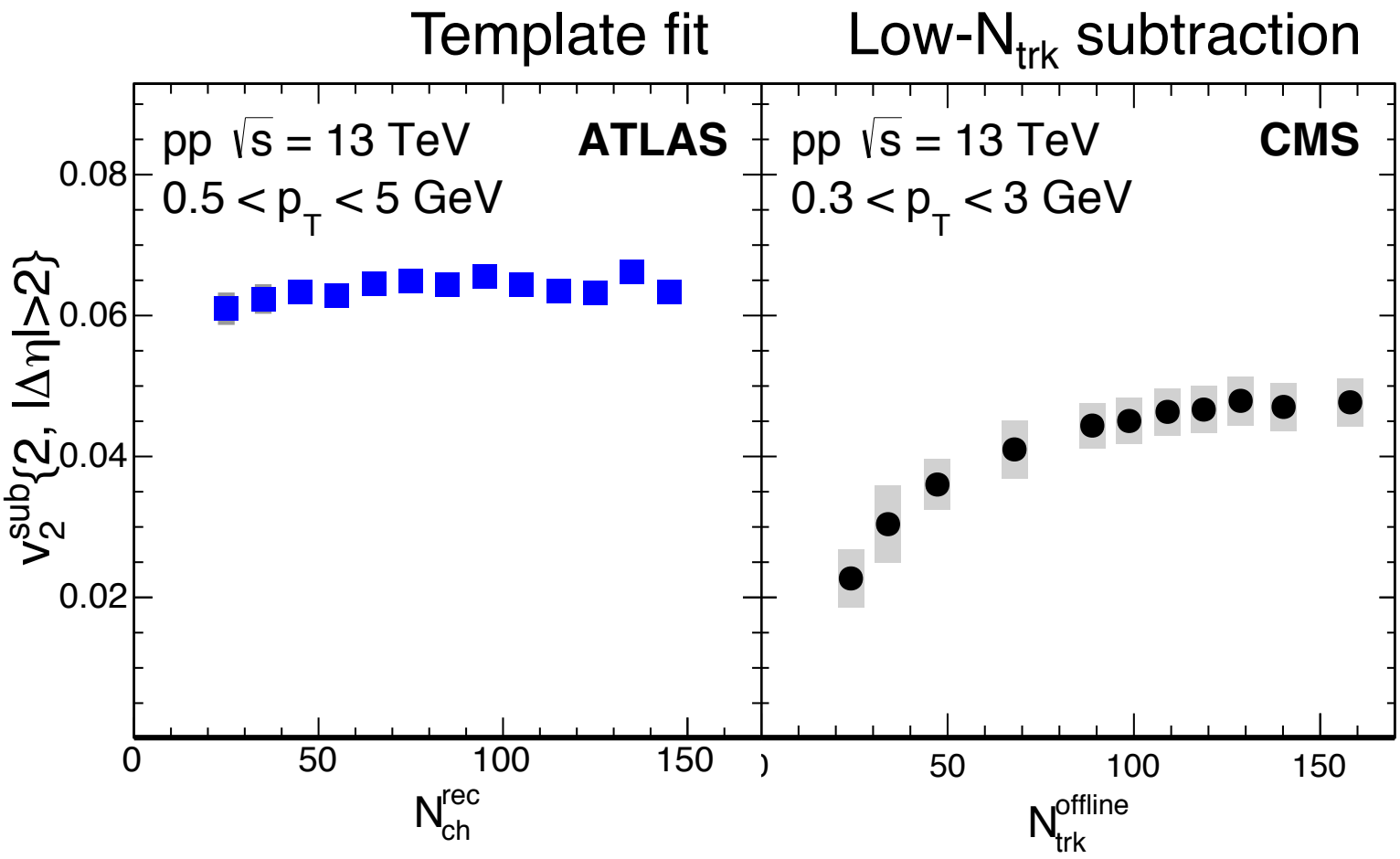


Constraining the IS with “new” flow observables

⇨ toward a **unified paradigm of pp, pA, AA**

Still open questions in small systems

Does collectivity turn off at low N_{trk}?



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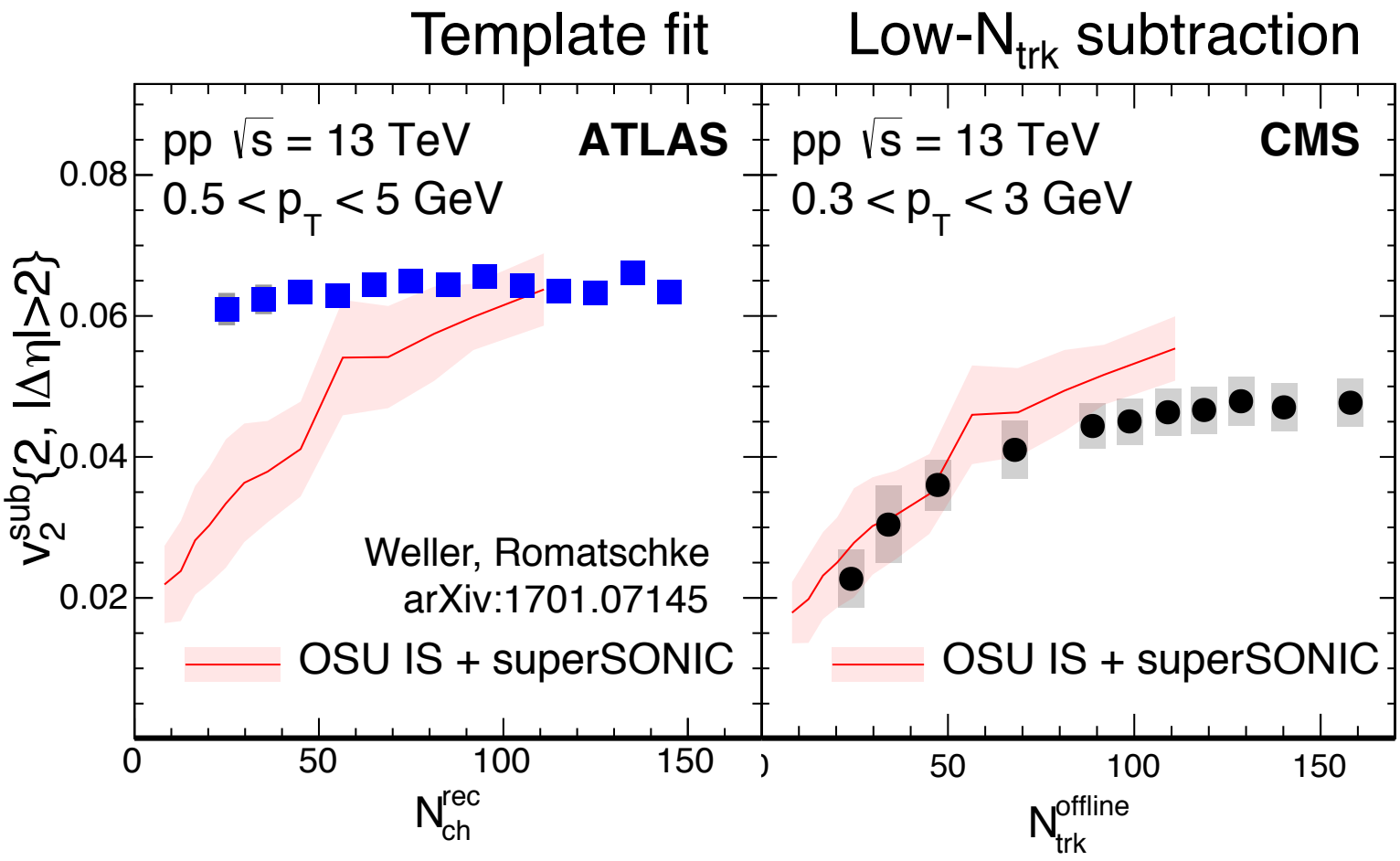

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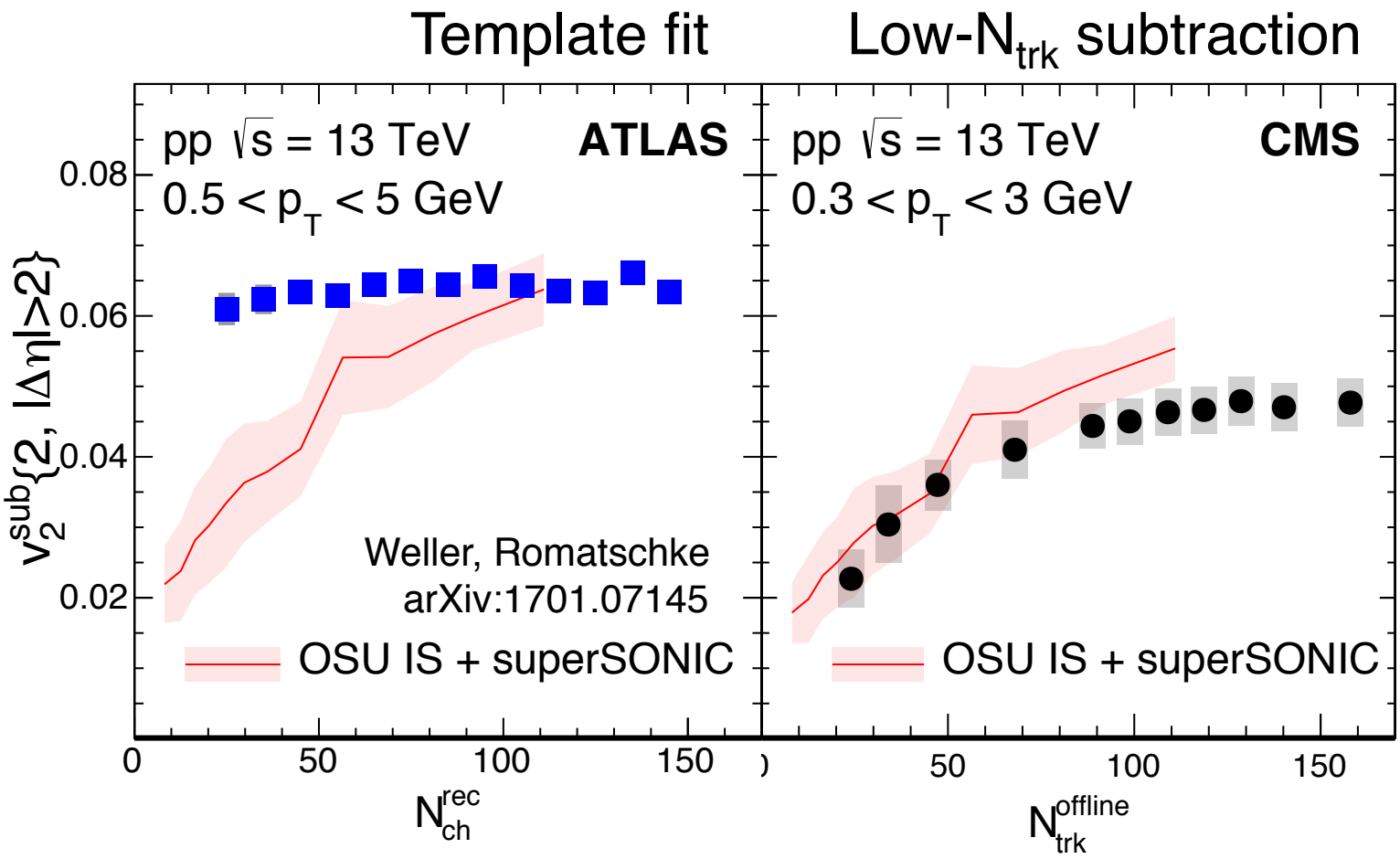

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Cumulants with η gap? arXiv:1612.05634, arXiv:1701.03830

Summary and outlook

Clear evidence of *long-range*, *collective* phenomena **universal** in all **high-multiplicity** hadronic collisions

Initial spatial ε_s + final interactions

OR

Initial momentum ε_p via initial interactions

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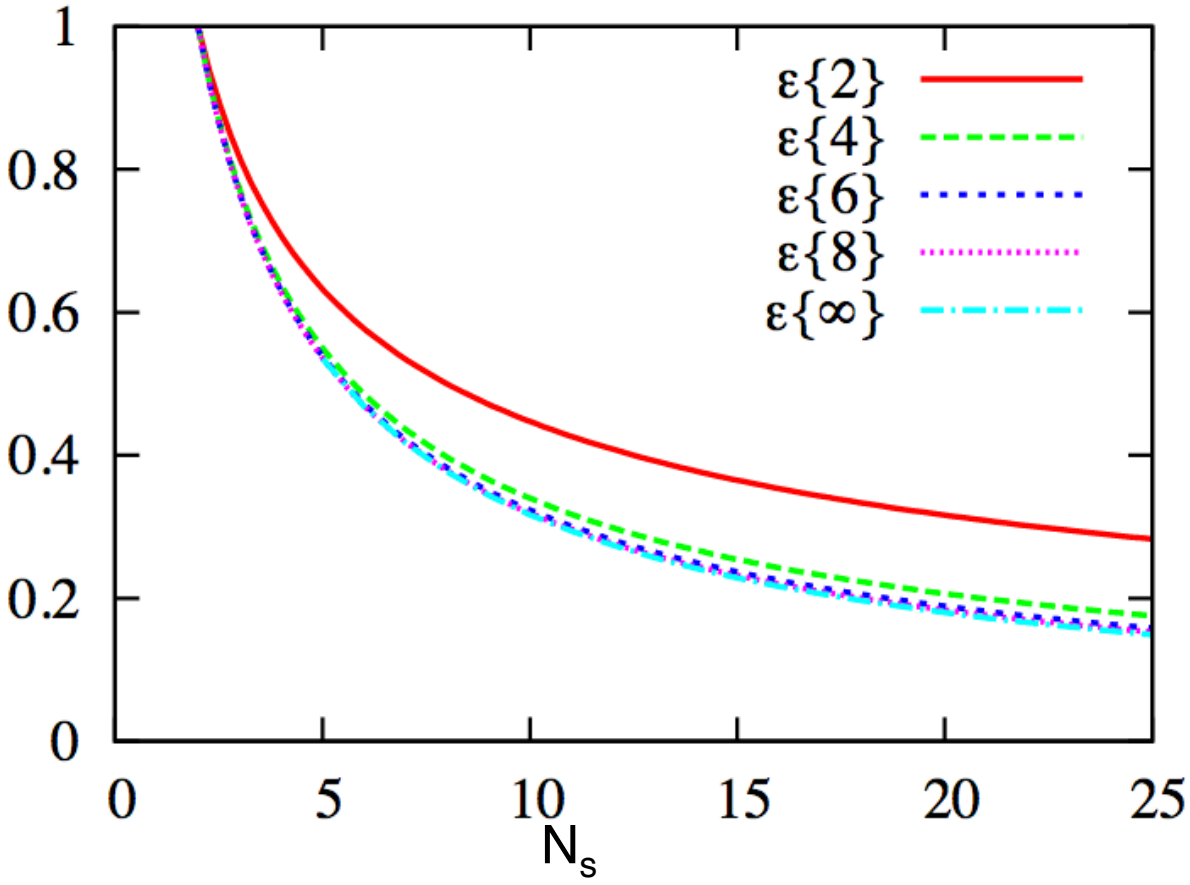
Universal collective behavior should even extend to **high-multiplicity** ep, eA (EIC), UPC, e^+e^-

Backup



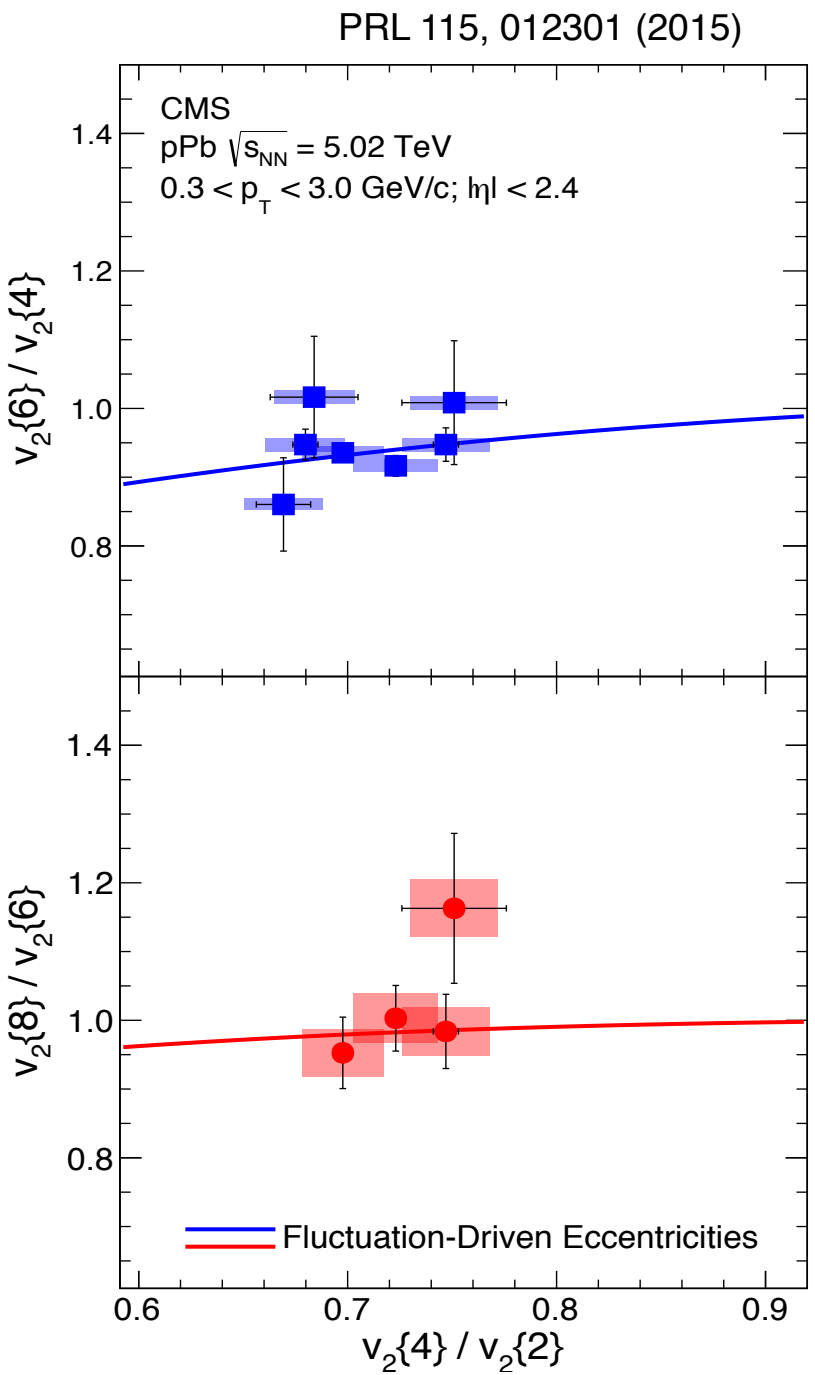
$$\frac{v_n\{4\}}{v_n\{2\}} = \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}} = \left(\frac{2}{1+N_s/2}\right)^{1/4}$$

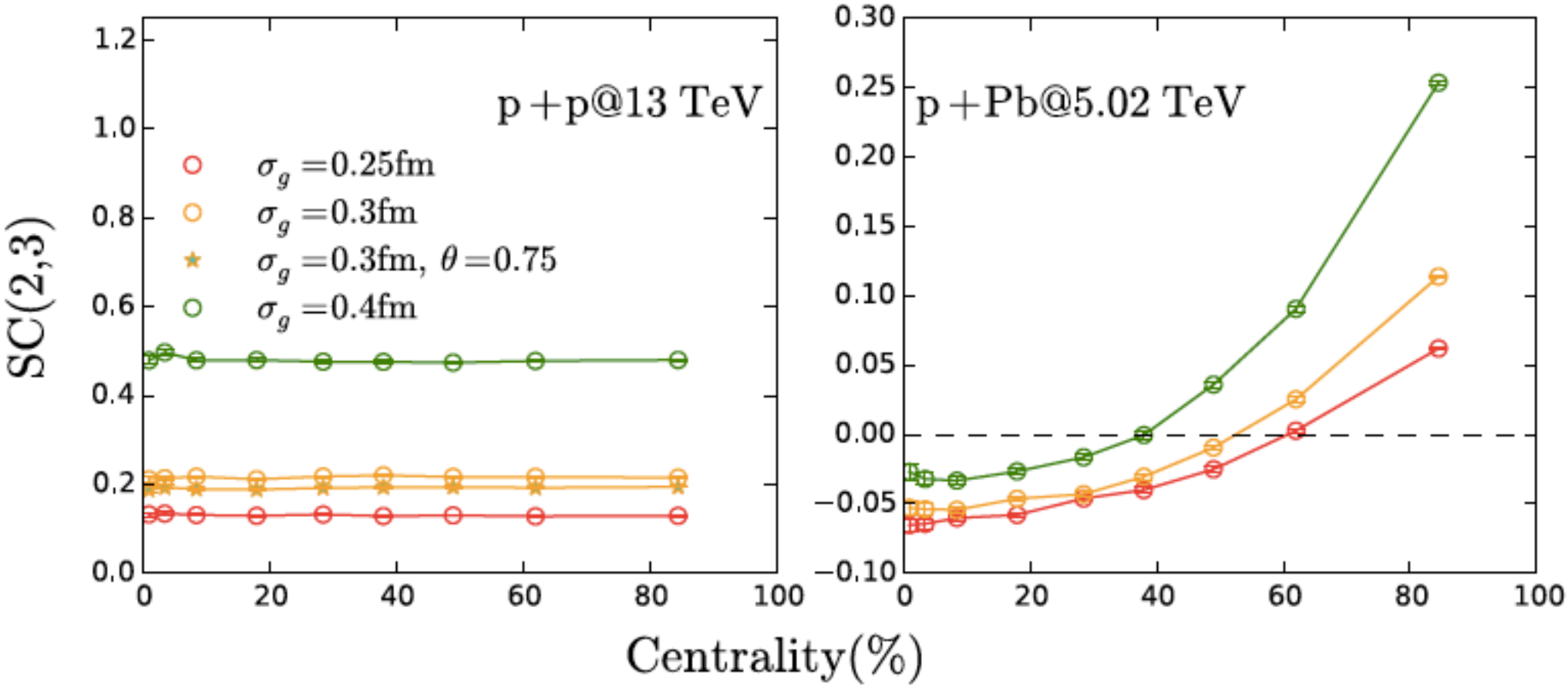
Higher-order cumulants

$$\varepsilon_2\{m\} \xrightarrow{\text{Hydro.}} v_2\{m\}$$

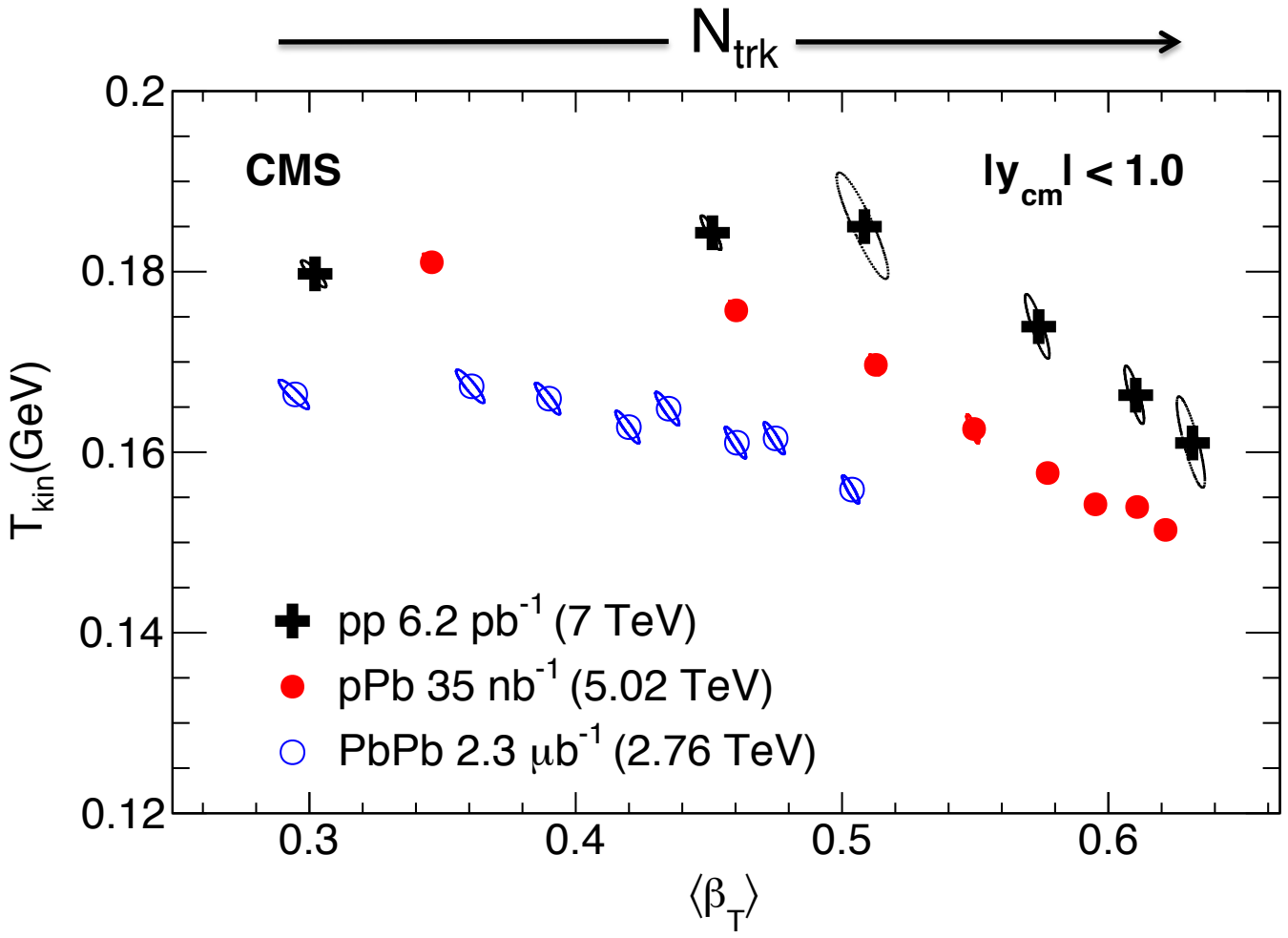
(m = 2, 4, 6, 8 …)

Very testable prediction from hydrodynamics

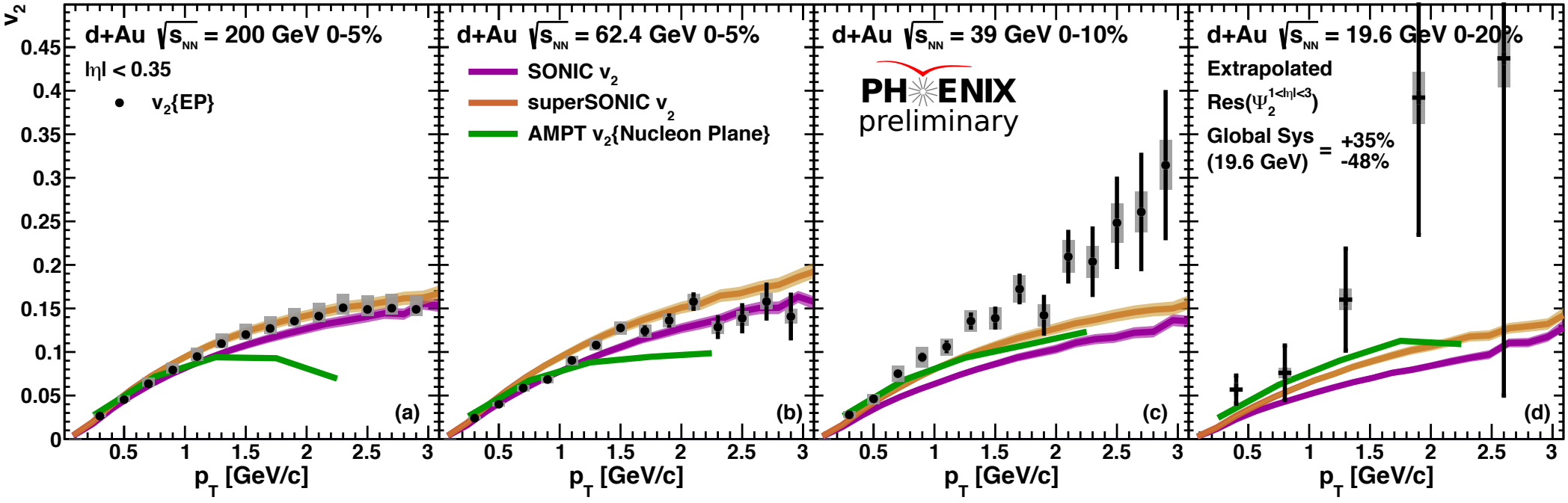



p+p@13 TeV
σ_g=0.25fm
σ_g=0.3fm
σ_g=0.3fm, θ=0.75
σ_g=0.4fm
p+Pb@5.02 TeV
SC(2,3)
Centrality(%)

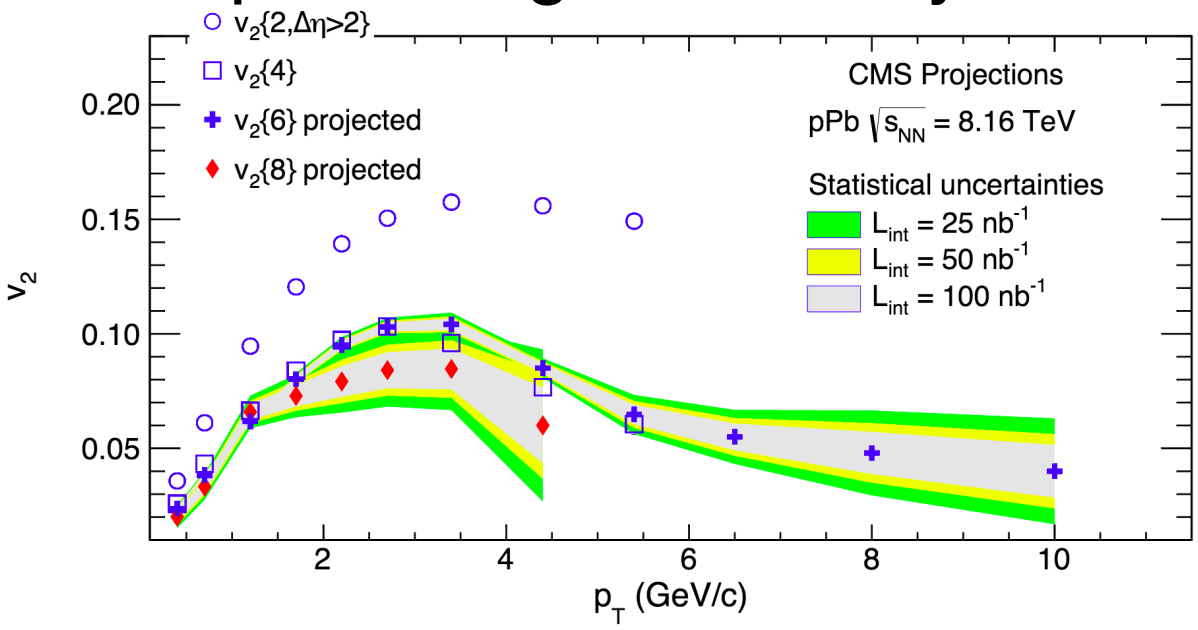
Blast-Wave fits to K_0^s, Λ and Ξ^-



$\langle\beta_T\rangle$ larger as N_{trk} increases


v2
d+Au √sNN = 200 GeV 0-5%
|η| < 0.35
v2{EP}
(a)
d+Au √sNN = 62.4 GeV 0-5%
SONIC v2
superSONIC v2
AMPT v2{Nucleon Plane}
(b)
d+Au √sNN = 39 GeV 0-10%
PHENIX
preliminary
(c)
d+Au √sNN = 19.6 GeV 0-20%
Extrapolated
Res(Ψ2 1<|η|<3)
Global Sys (19.6 GeV) = +35% -48%
(d)
pT [GeV/c]

Jet quenching in small system?



multiparticle v_2 at high p_T

L_{int} ~ 186 nb^{-1} collected in 2016