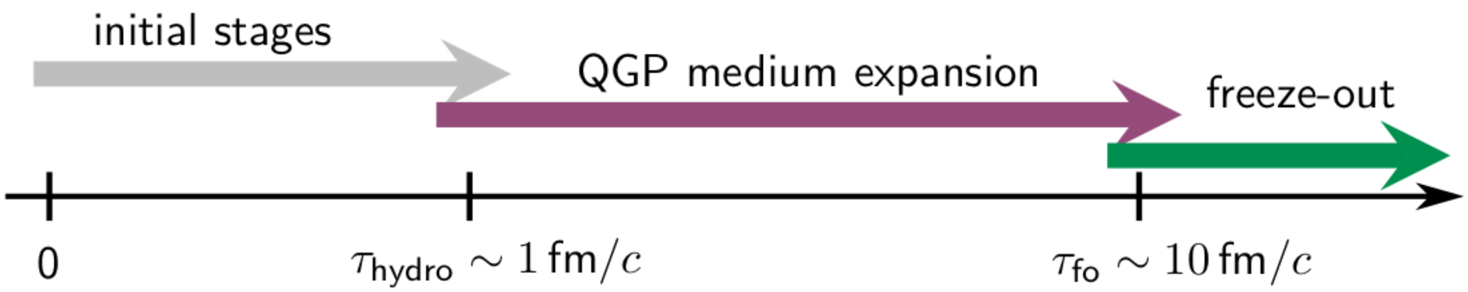
Stony Brook University | The State University of New York

Challenges and opportunities in flow studies

Jiangyong Jia

- Introduction
- Challenges
- Opportunities

Dynamics and properties of QGP



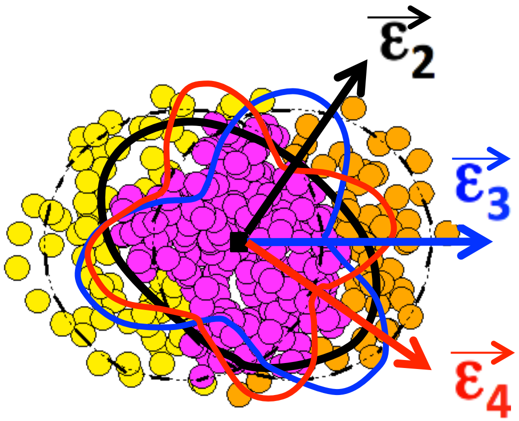
Challenge: simultaneous determination of two unknowns

Dynamics ⟺ Properties

- Properties drives the dynamics of the medium
- Extraction of properties require good knowledge of dynamics

Connecting the initial and final state

Initial state

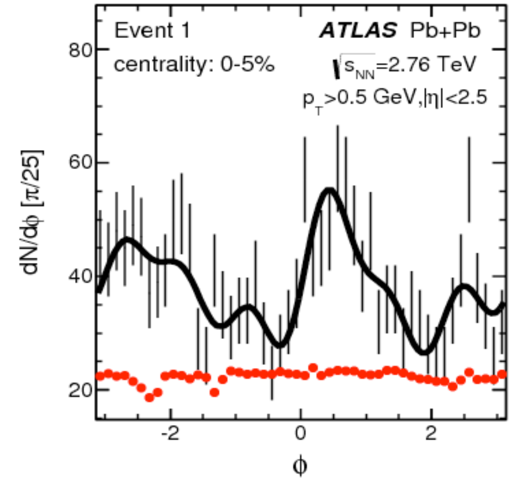


$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} \equiv -\frac{\langle r^n e^{in\phi} \rangle}{\langle r^n \rangle}$$

Hydro-response

Space-time dynamics

Particle flow

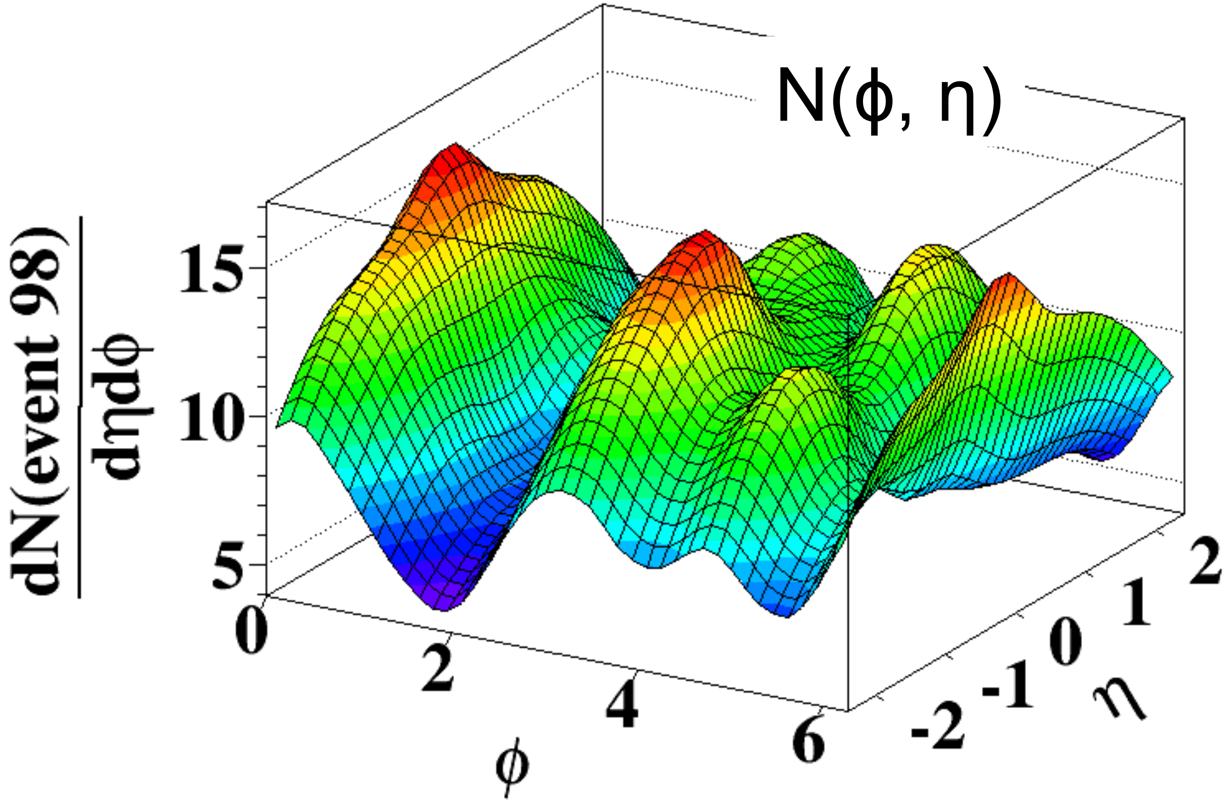


$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

Perturbing the system with different initial state fluctuations

Richness of flow fluctuations

Curtsey of L.Pang and X.N Wang, EbyE 3D hydro+AMPT condition



Fluctuation from event to event

Richness of flow fluctuations

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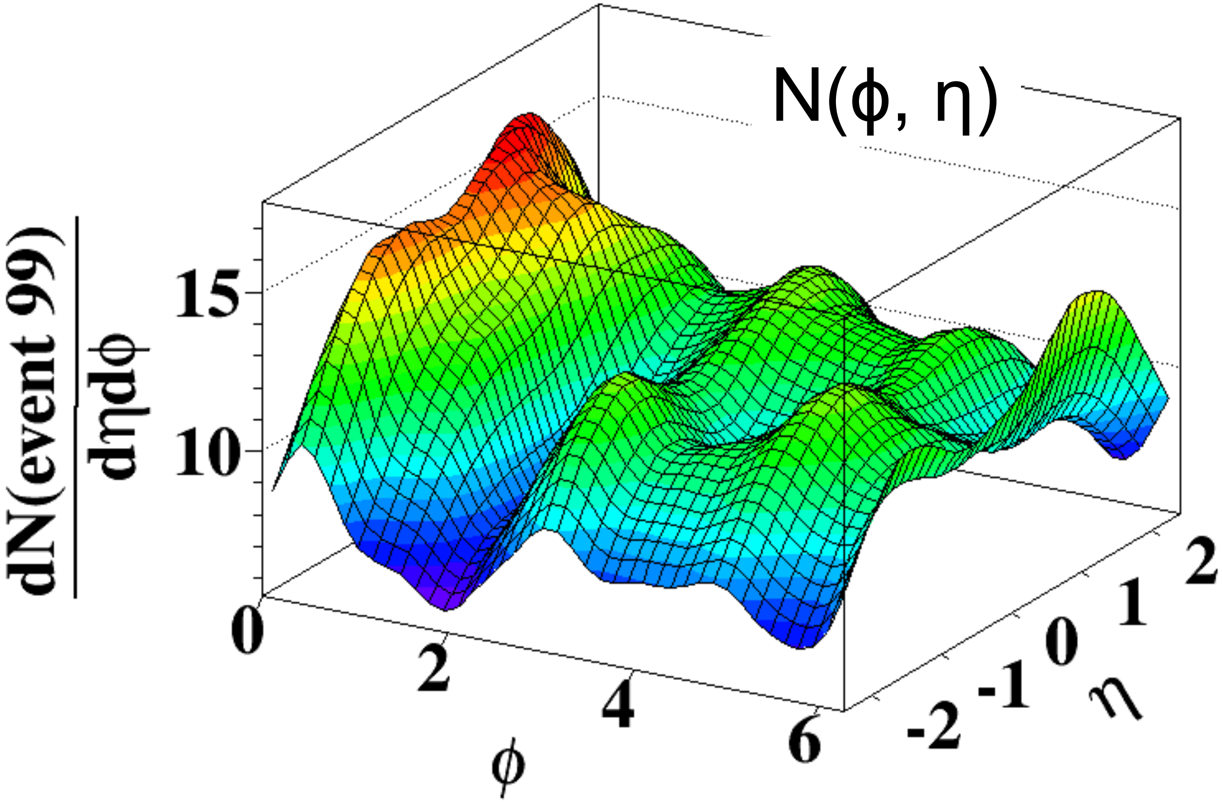
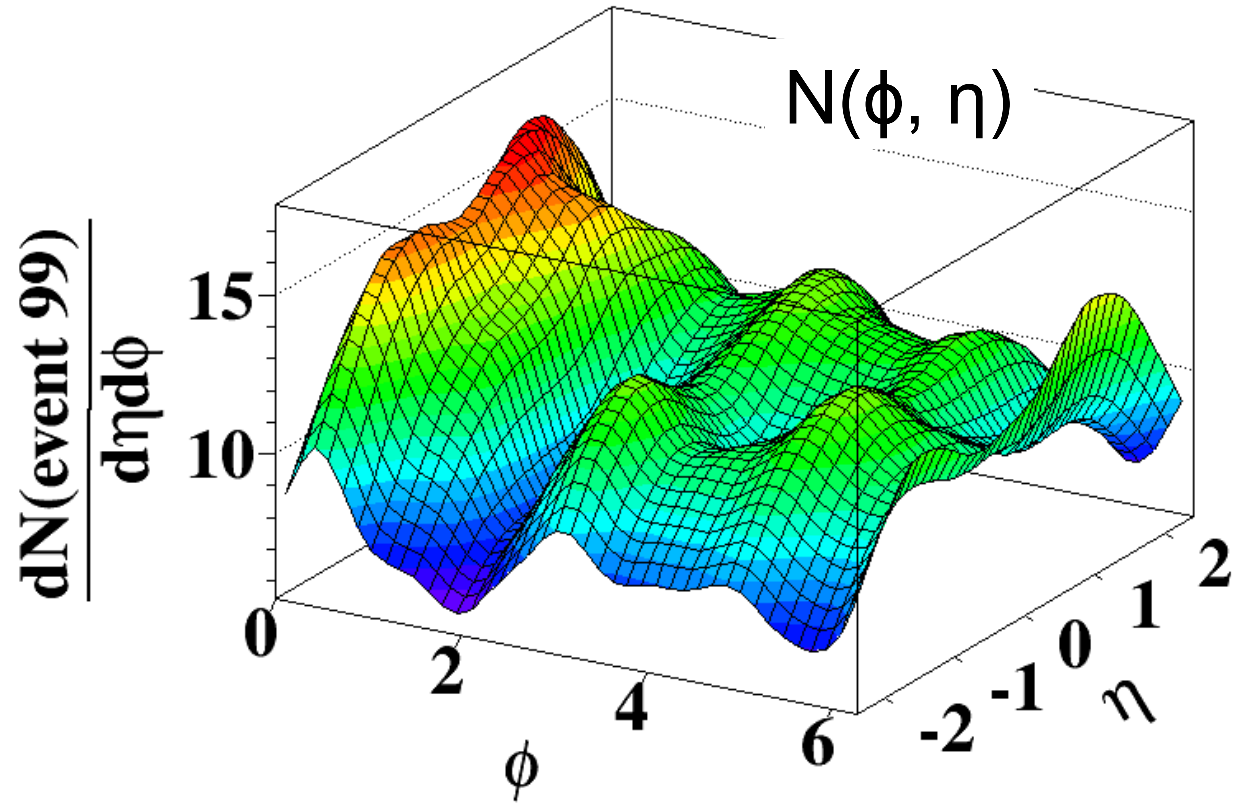


Fluctuation from event to event

Richness of flow fluctuations

Curtsey of L.Pang and X.N Wang, EbyE 3D hydro+AMPT condition



Fluctuation within a single event

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n} \mathrm{v}_{\mathrm{n}}(p_T, \eta, \ldots) \cos n\left(\phi - \Phi_n(p_T, \eta, \ldots)\right)$$

Flow observables

- Single particle distribution

Flow vector: $V_n = v_n e^{in\Phi_n}$

$$\frac{dN}{d\phi d\eta dp_T} = N(p_T,\eta)\left[1+2\sum_n \mathrm{v}_n(p_T,\eta)\cos n\left(\phi-\Phi_n(p_T,\eta)\right)\right]$$

$$= N(p_T,\eta)\left[\sum_{n=-\infty}^{\infty} V_n(p_T,\eta)e^{in\phi}\right]$$

Radial flow: $N(p_T,\eta) = V_0(p_T,\eta)$

Anisotropic flow: $V_n(p_T,\eta)$

- Two-particle correlation function

$$\left\langle \frac{dN_1}{d\phi d\eta dp_T}\frac{dN_2}{d\phi d\eta dp_T}\right\rangle \Rightarrow \left\langle V_n(p_{T1},\eta_1)V_n^*(p_{T2},\eta_2)\right\rangle$$

v_n from 2PC

- Multi-particle correlation function

$$\left\langle \frac{dN_1}{d\phi d\eta dp_T}..\frac{dN_m}{d\phi d\eta dp_T}\right\rangle \Rightarrow \left\langle V_{n_1}V_{n_2}...V_{n_m}\right\rangle \quad n_1+n_2+...+n_m=0$$

$$\downarrow$$

$$\langle v_{n_1}v_{n_2}...v_{n_m}\cos(n_1\Phi_{n_1}+n_2\Phi_{n_2}+...+n_m\Phi_{n_m})\rangle$$

Flow observables

- Single particle distribution

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v_n from 2PC

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$$\downarrow$$

$$p(v_n, v_m, \ldots., \Phi_n, \Phi_m, \ldots.) = \frac{1}{N_{\mathrm{evts}}}\frac{dN_{\mathrm{evts}}}{dv_n dv_m \ldots d\Phi_n d\Phi_m \ldots}$$

Examples

- Single-flow cumulants

$$c_n\{2\} = \langle v_n^2 \rangle$$
$$c_n\{4\} = \langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2$$
$$c_n\{6\} = \langle v_n^6 \rangle - 9\langle v_n^4 \rangle \langle v_n^2 \rangle + 12\langle v_n^2 \rangle^3$$
$$\cdots$$

n=1-7

- Symmetric cumulants

$$\mathrm{sc}_{n,m}\{4\} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$

(n,m)=(2,3), (2,4)…

- Asymmetric cumulants (Event plane correlator)

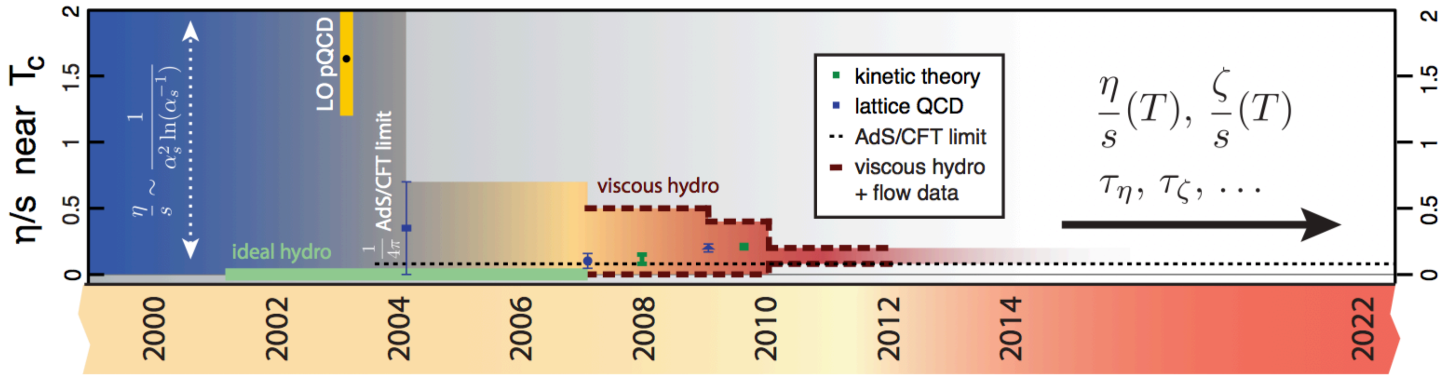
$$\langle v_2^2 v_4 \cos 4(\Psi_2 - \Psi_4) \rangle$$
$$\langle v_2^3 v_3^2 \cos 6(\Psi_2 - \Psi_3) \rangle$$
$$\langle v_2 v_3 v_5 \cos(2\Psi_2 + 3\Psi_3 - 5\Psi_5) \rangle$$
$$\cdots$$

- v_n-v_0 correlator

$$\langle v_n^2\, N \rangle,\ \langle v_n^2\, \delta p_{\mathrm{T}} \rangle\ \ldots$$
$$\langle \delta p_{\mathrm{T}} \delta p_{\mathrm{T}} \rangle, \langle \delta p_{\mathrm{T}} \delta p_{\mathrm{T}} \delta p_{\mathrm{T}} \rangle\ \ldots$$

Success of hydrodynamics

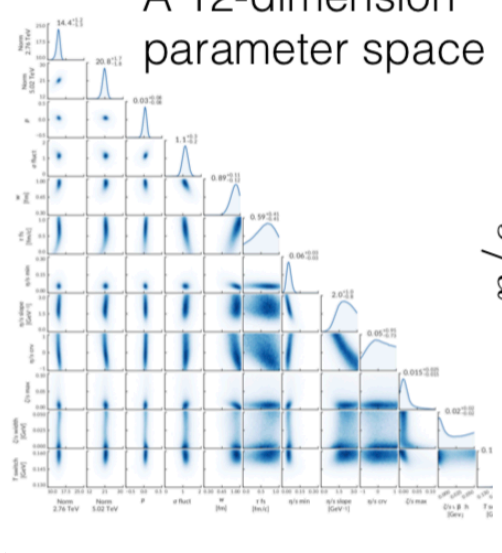
- Data-model comparison improves precision of transport parameters

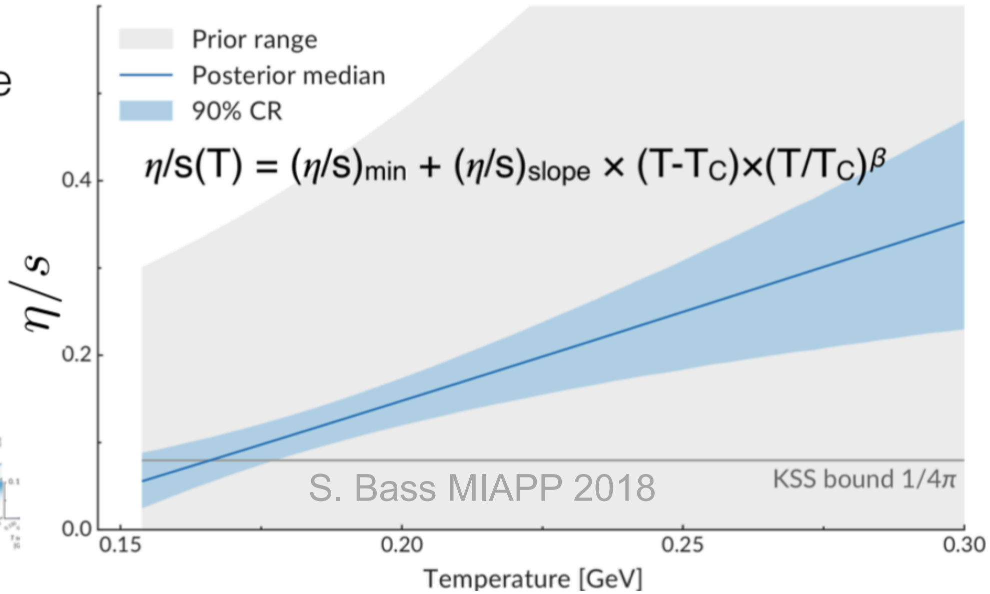


- Multi-parameter adaptive fitting optimizes constraining power.
  - Differential information in the parameter space

…within a given model

A 12-dimension parameter space





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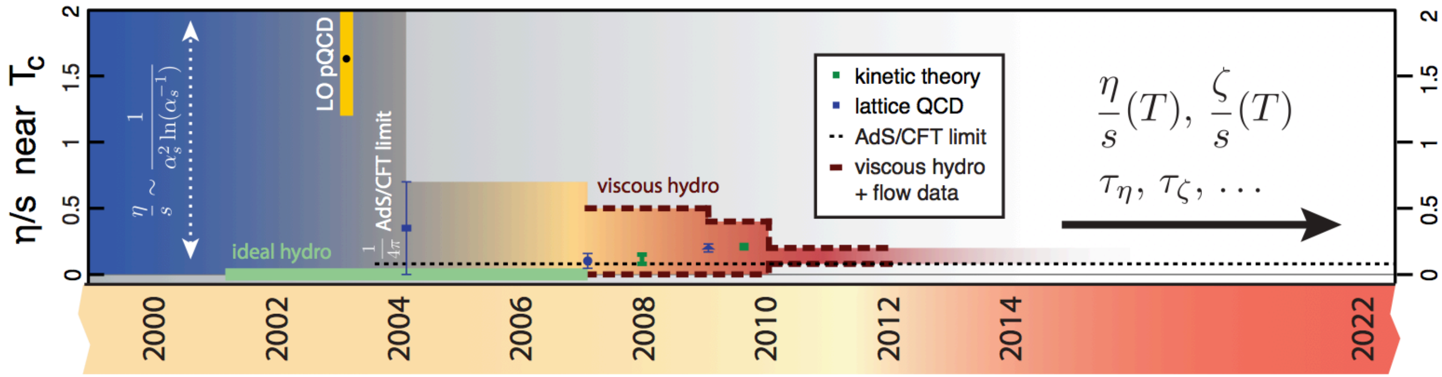
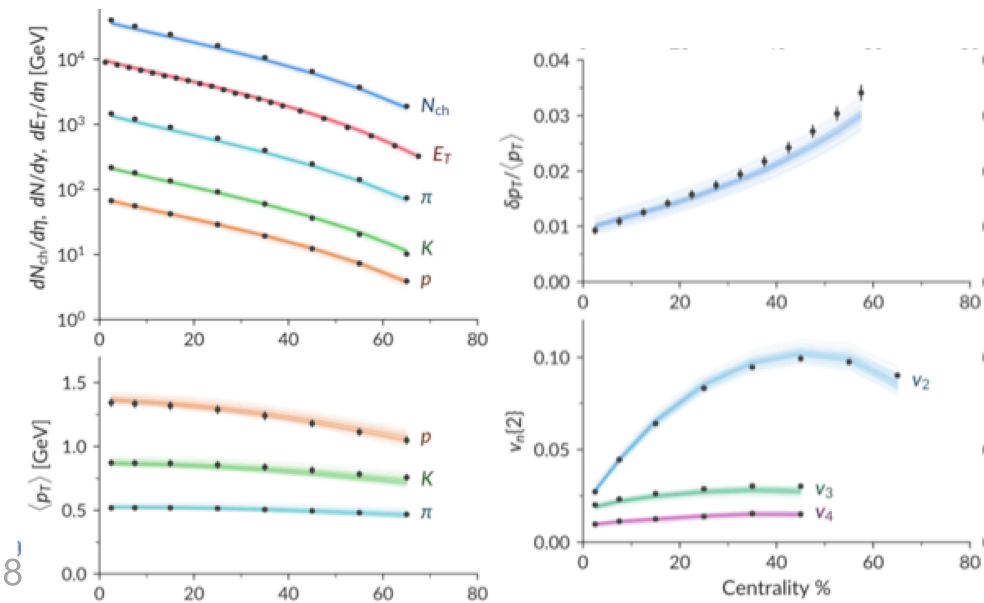


- Multi-parameter adaptive fitting optimizes constraining power.
  - Differential information in the parameter space …within a given model

Only utilize limited set of observables:
dN/dp_T, $\langle p_T \rangle$, $\langle \delta p_T \delta p_T \rangle$, $\langle v_n^2 \rangle$

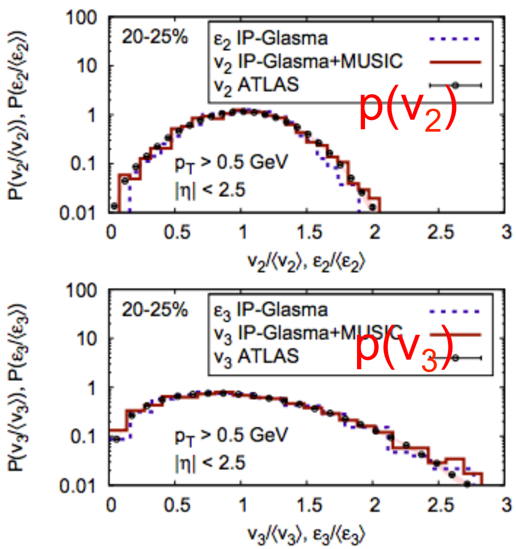
Limited by model uncertainties!
Initial state, QGP dynamics, freezeout/hadronic



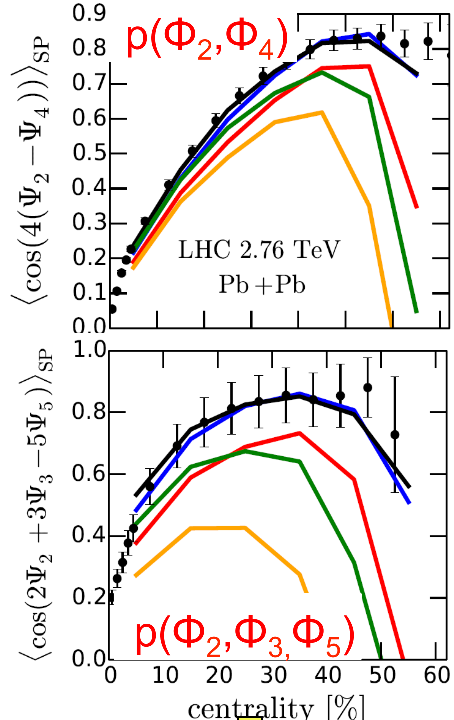
S. Bass MIAPP 2018

Power of flow fluctuations

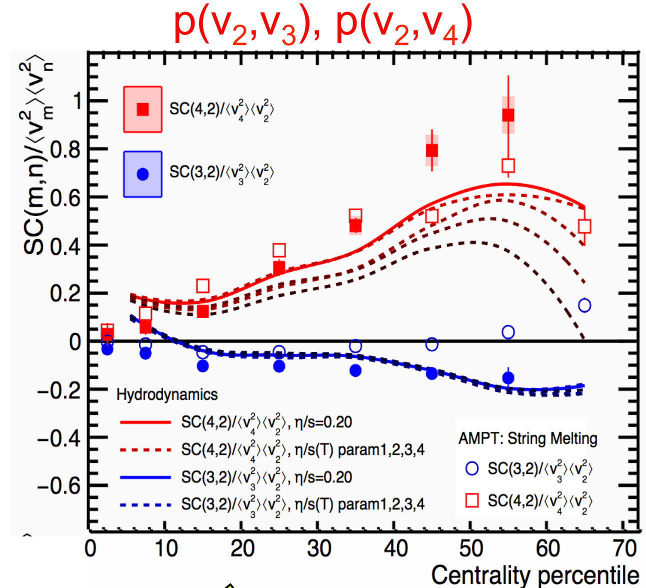
Gale, Jeon, Schenke, Tribedy, Venugopalan 1209.6330

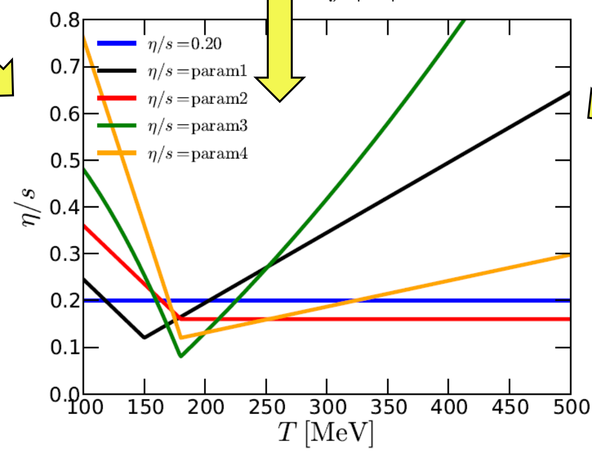


Niemi, Eskola, Paatelainen 1505.02677



ALICE 1604.07663



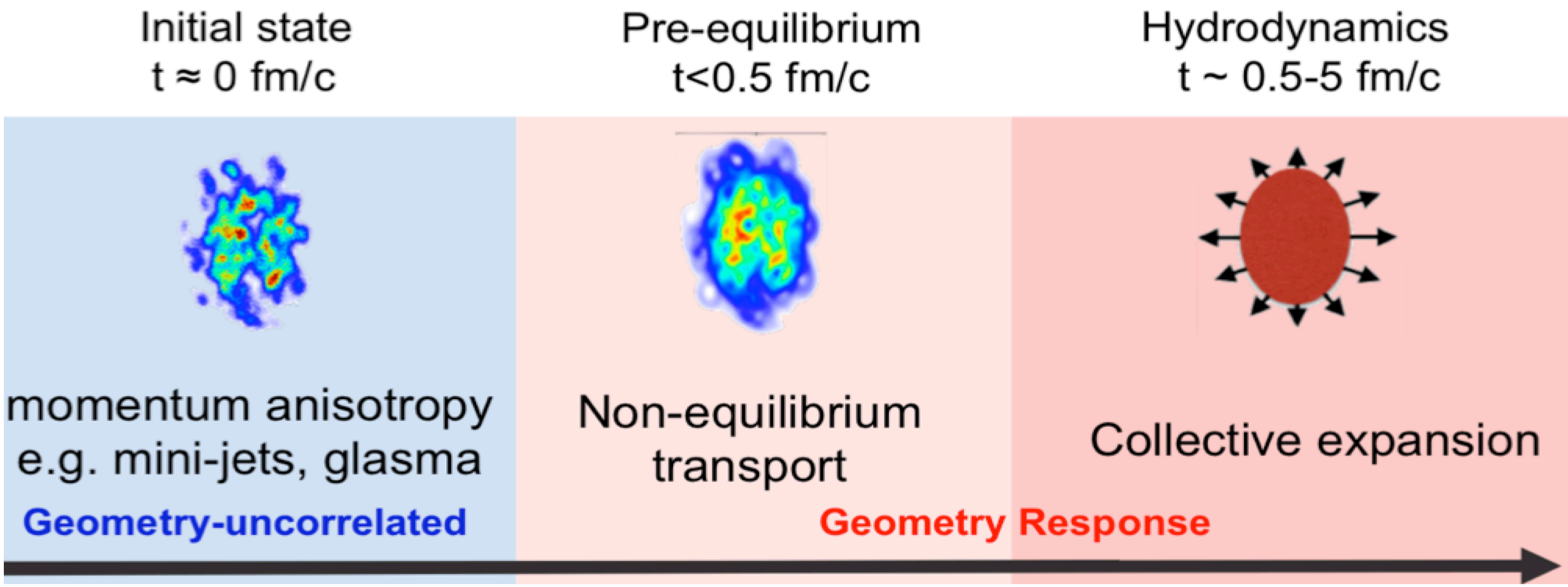


Probe the hydrodynamic response: $(\varepsilon_n,\Phi_n^*)\rightarrow(v_n, \Phi_n)$

Sensitive to detail of transport coeffis: η/s(T)

Potential to further reduce model uncertainties

Challenge for understanding

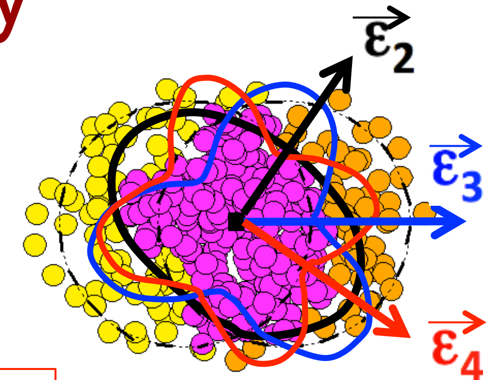


Contributions from different stages are difficult to disentangle

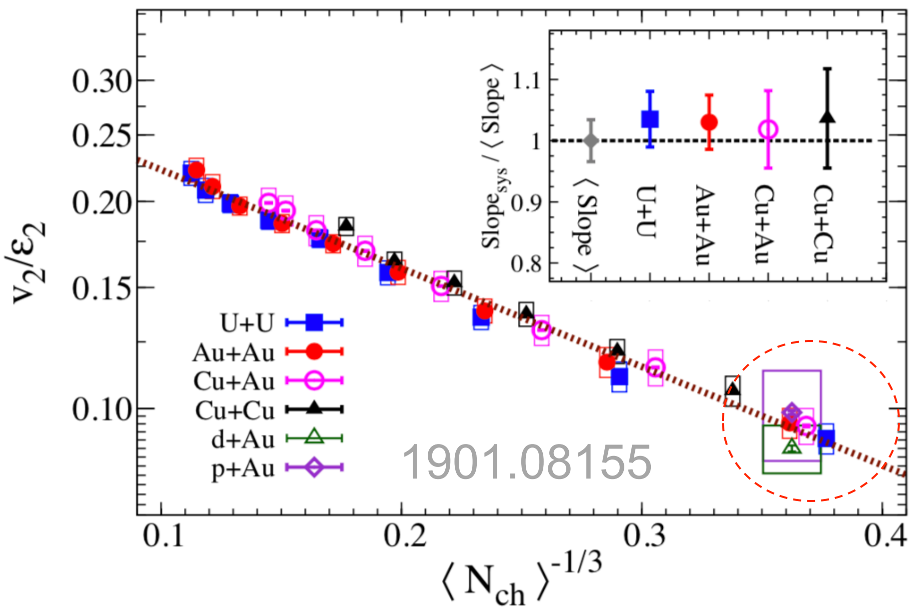
- Initial geometry and Initial momentum anisotropy
- pre-equilibrium dynamics and entropy production
- $\eta/s(T)$, $\zeta/s(T)$, EOS, non-equilibrium dynamics
- Phase transition and hadronization
- Hadronic transport and Freezeout

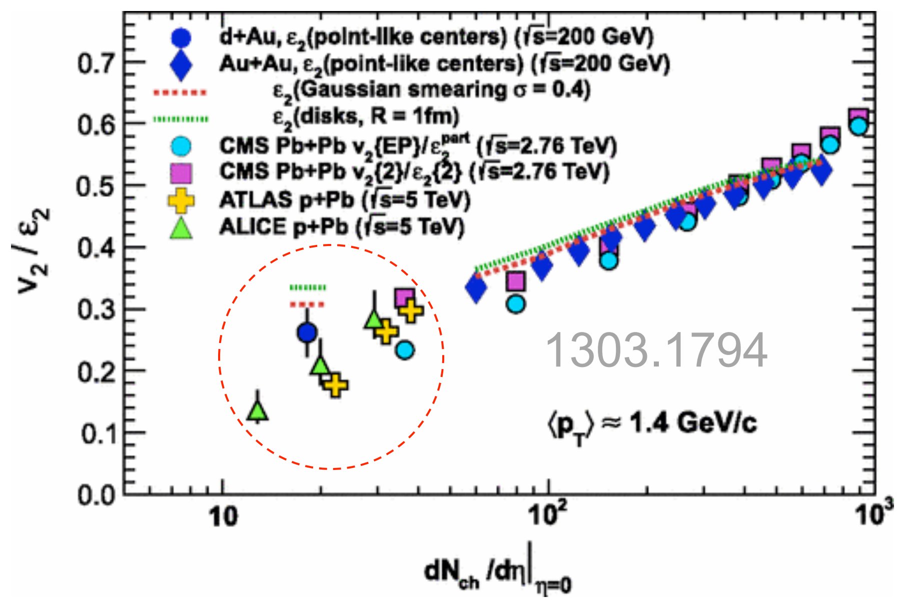
Hard to experimentally vary one ingredient at a time

Initial state geometry



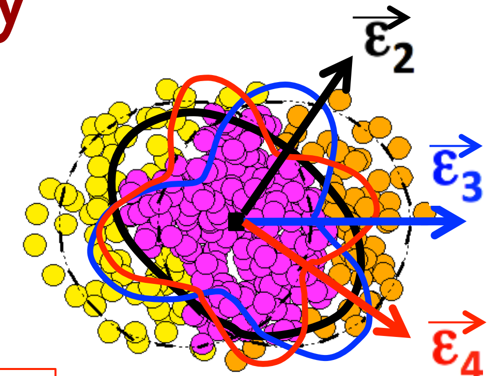
- By far the dominating source of fluctuations that we use to define the hydro response.
- Linear response works well on average $v_n \propto \epsilon_n$





Consists with geometry-driven hydrodynamic response

Initial state geometry



- By far the dominating source of fluctuations that we use to define the hydro response.
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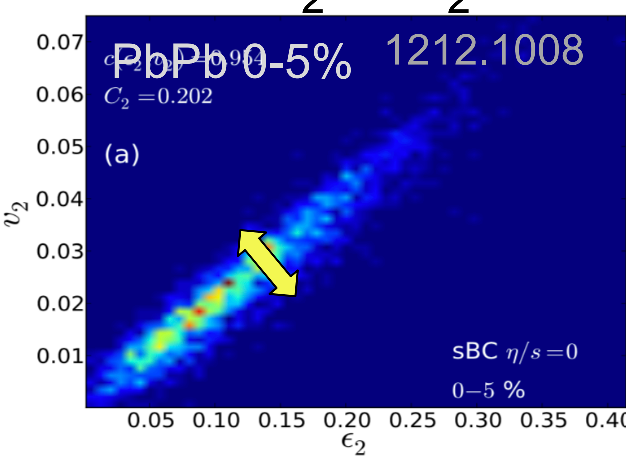
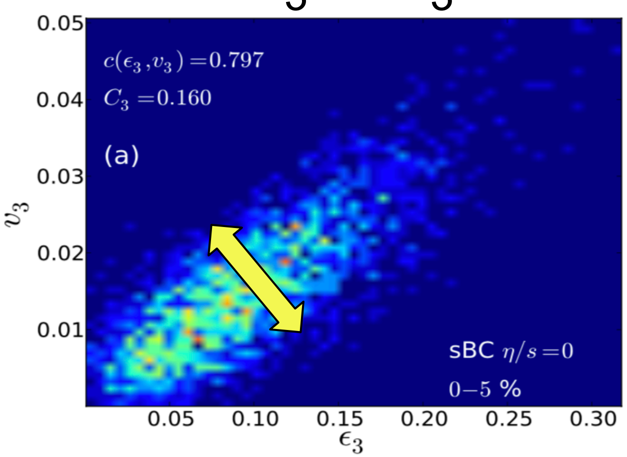
But significant EbyE spread remains

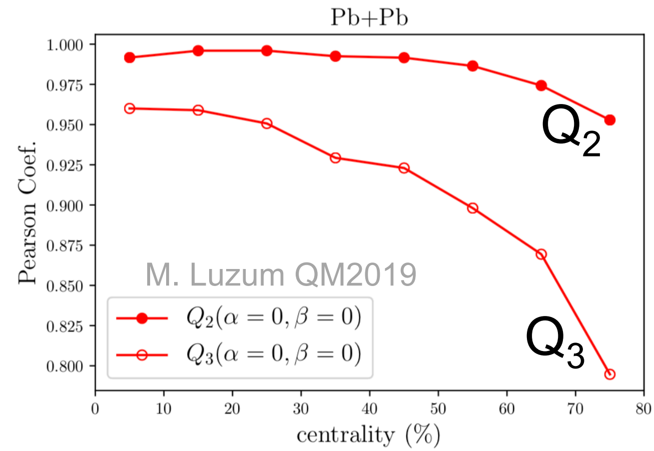
$$Q_n = \frac{\langle v_n \varepsilon_n \cos\left(n\left[\psi_n - \phi_n\right]\right)\rangle}{\sqrt{\langle|\varepsilon_n|^2\rangle\langle|v_n|^2\rangle}} \sim 1$$

v_2 vs ε_2



v_3 vs ε_3

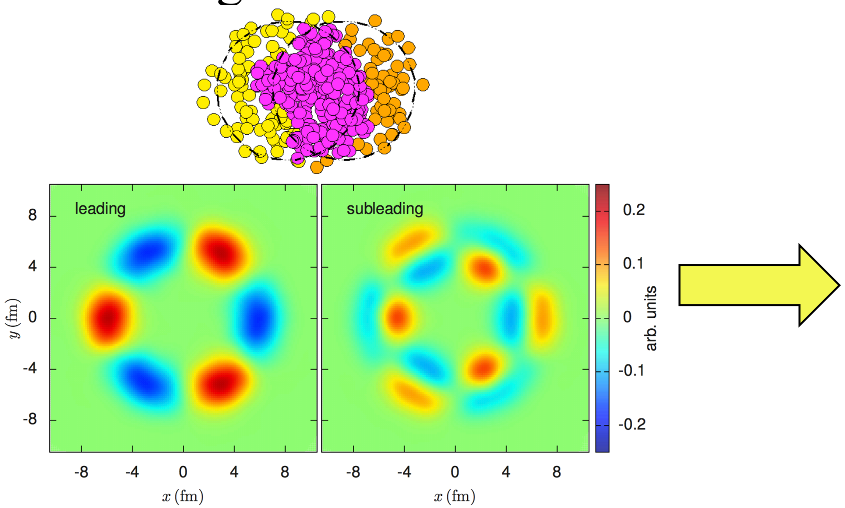




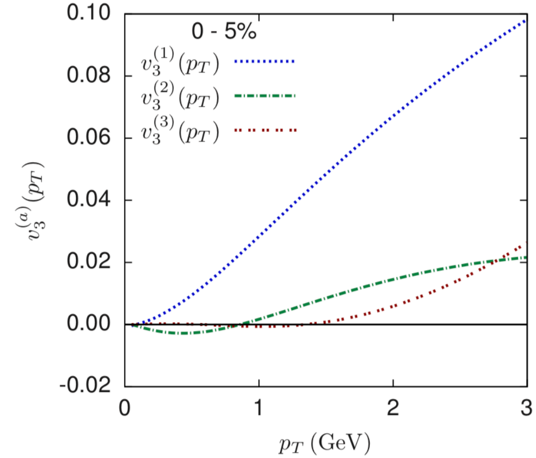
What is the origin of these spreads?

Dissecting the hydro response

- Leading ε_n does not capture everything about initial state
  - Subleading eccentricities from radial excitations

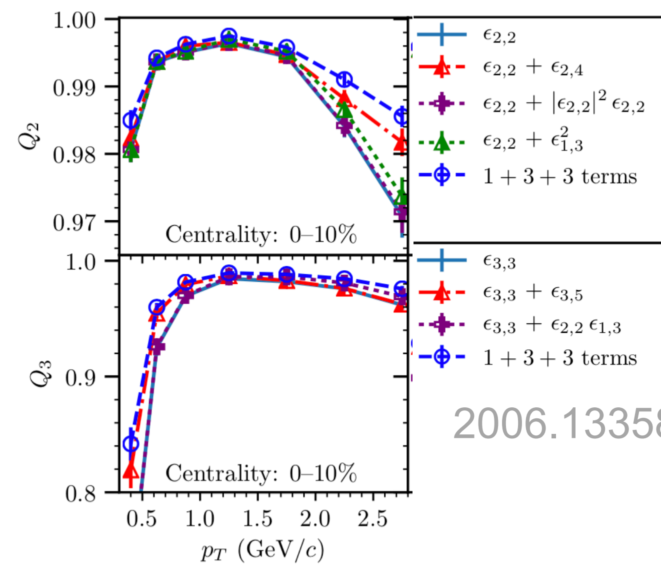


1509.07492



- Re-sum subleading ε_n and mode-mixing terms improves agreement

$$V_n(p_T) \approx \sum_{p=1}^{p_{\max}} \sum_{\{n',m'\}}^{\sum n'_i = n} \kappa^{(n)}_{\{n',m'\}}(p_T) \prod_{i=1}^{p} \epsilon_{n'_i,m'_i} + \\ + \mathcal{O}(\epsilon_{n,m_{\max}}) + \mathcal{O}(\epsilon^{p_{\max}+1})$$



2006.13358

How to characterize and understand the residual differences?

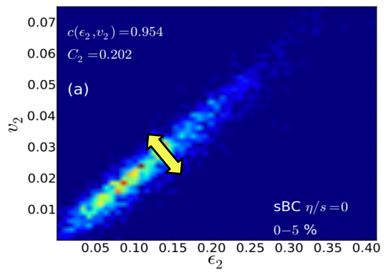
Understand the difference via flow fluctuations

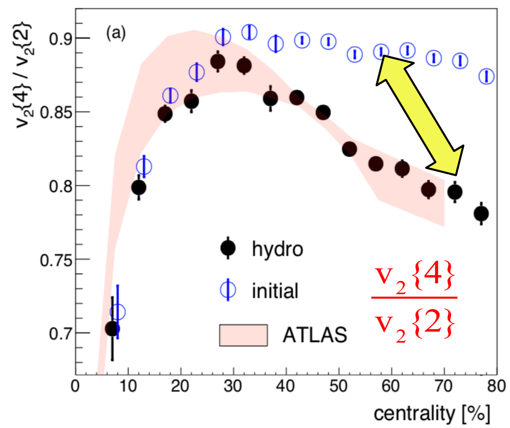
Often assumes:

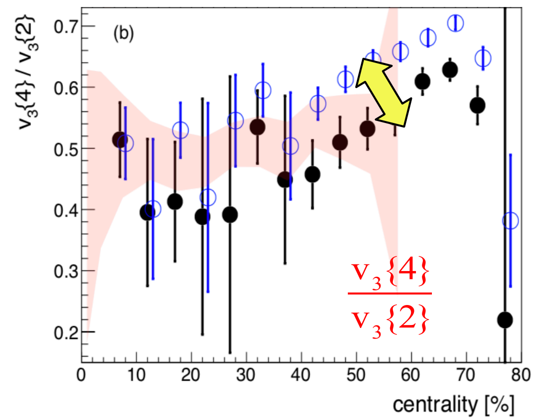
L. Yan, J. Ollitrault arXiv:1312.6555

Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.5, 054910

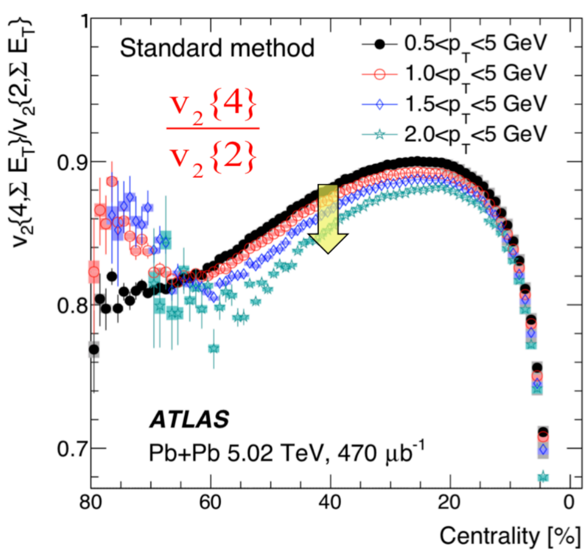
$$v_n \propto \varepsilon_n \Rightarrow \frac{v_n\{4\}}{v_n\{2\}} = \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}} \quad ✗$$



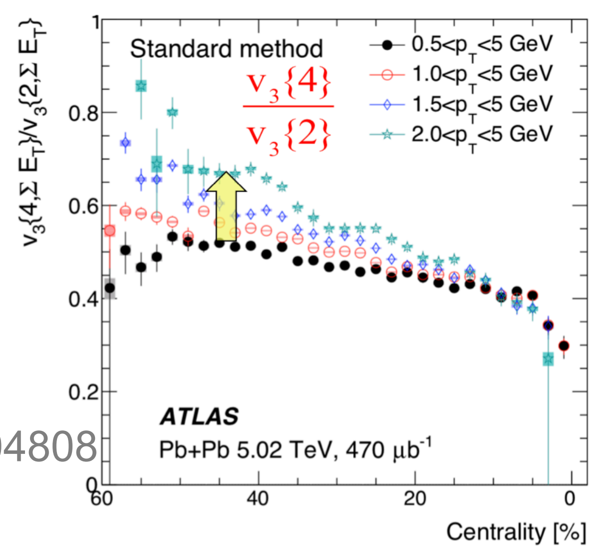




Also not supported by data:



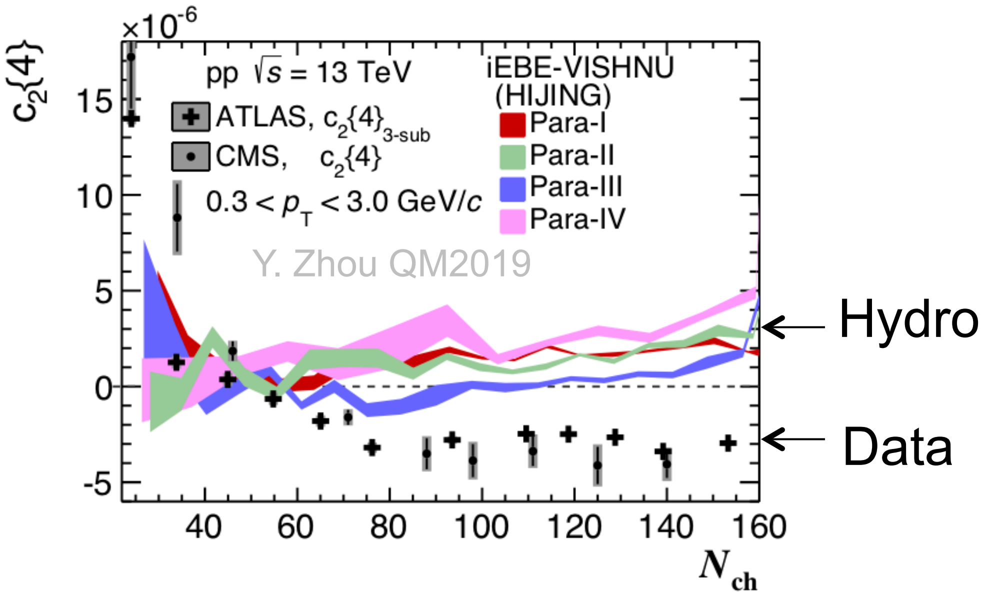
1904.04808



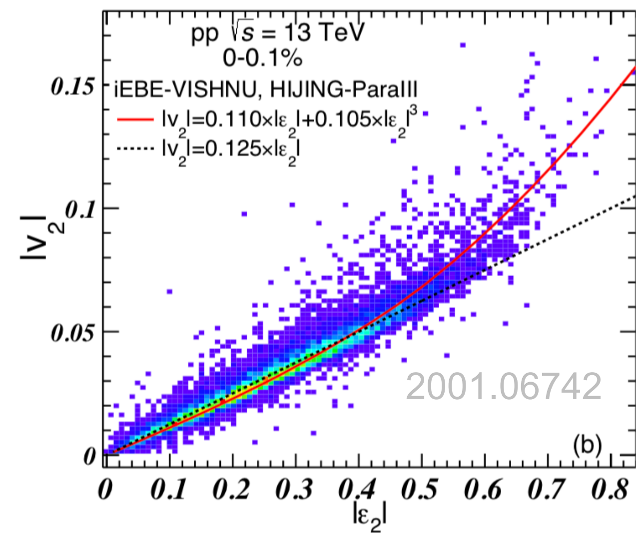
Role of initial-flow or final-state fluctuations?

Flow fluctuation in pp collisions

- Hydro calculation yields positive $c_2\{4\}$, opposite to data.



Also B. Schenke, C. Shen, and P. Tribedy, arXiv:1908.06212



Significant cubic response, responsible for $+c_2\{4\}$

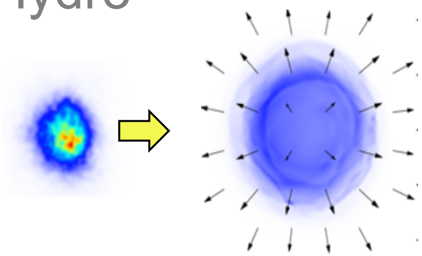
- Additional source of non-Gaussian fluctuations $$\frac{v_n\{4\}}{v_n\{2\}} \neq \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}}$$

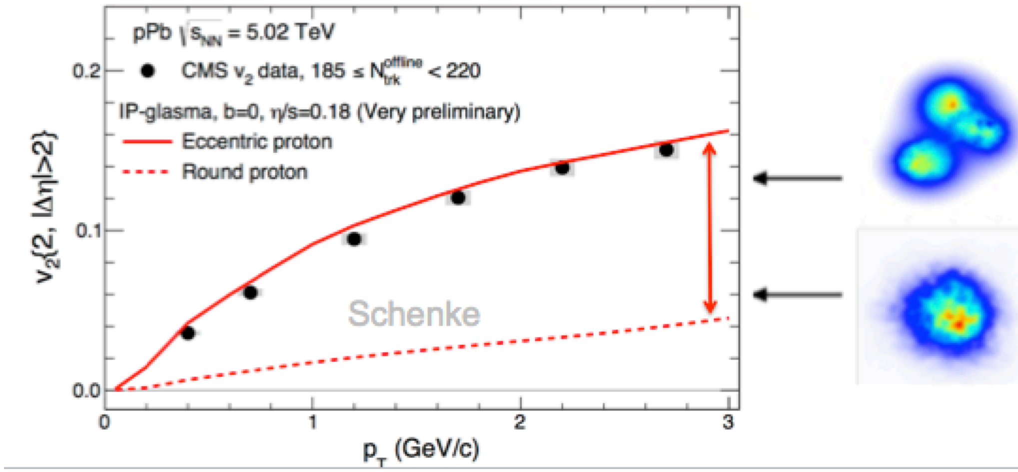
What is missing in this hydro simulation?

Role of initial-flow in pA collisions

Hydrodynamics with subnucleonic fluctuations describe the data

Hydro

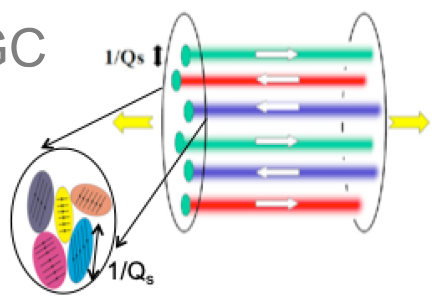


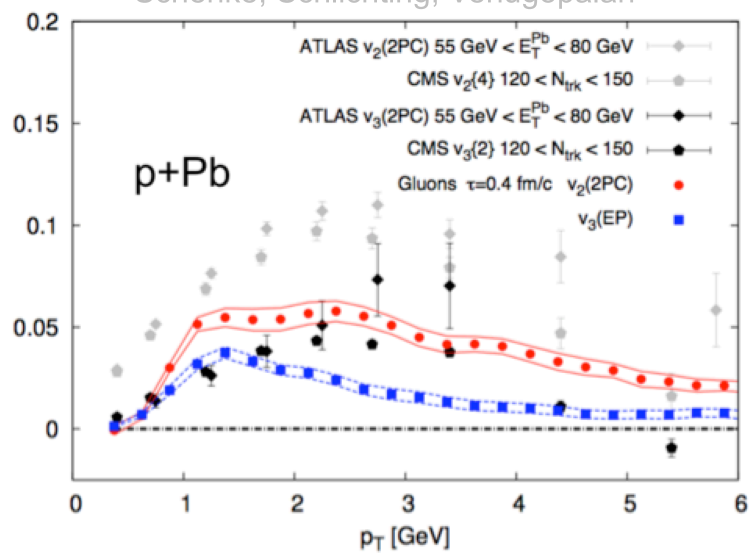


Initial momentum anisotropy contribution alone could be large

Schenke, Schlichting, Venugopalan

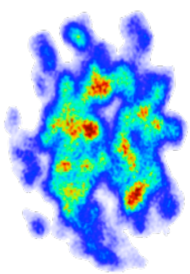
CGC





Role of initial-flow in pA collisions

Initial-state $T^{uv}(x,y)$ tensor contains large momentum T^{0i} and stress T^{ij}
→ source for initial flow

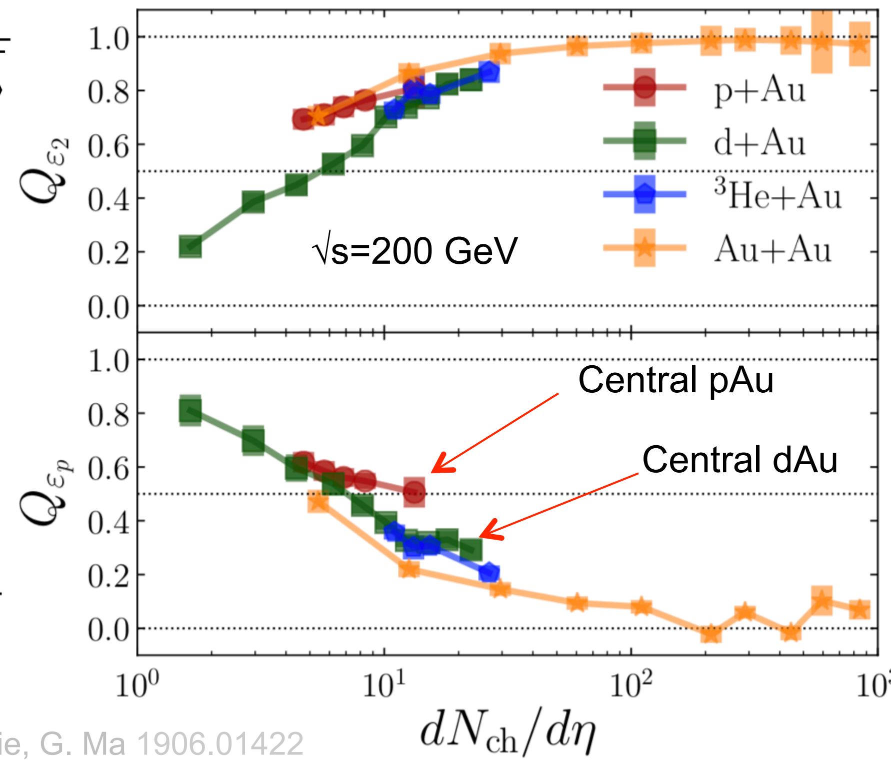


$$Q_{\varepsilon_2} = \frac{\mathrm{Re}\langle \vec{\mathscr{E}}_2 \cdot \vec{V}_2^* \rangle}{\sqrt{\langle |\vec{\mathscr{E}}_2|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$

$T^{00}(x,y)$
+
other $T^{\mu\nu}(x,y)$

$$Q_{\varepsilon_p} = \frac{\mathrm{Re}\langle \vec{\mathscr{E}}_p \cdot \vec{V}_2^* \rangle}{\sqrt{\langle |\vec{\mathscr{E}}_p|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$

B. Schenke, C. Shen, P. Tribedy, 1908.06212



Similar earlier study in J.Jia, M. Nie, G. Ma 1906.01422

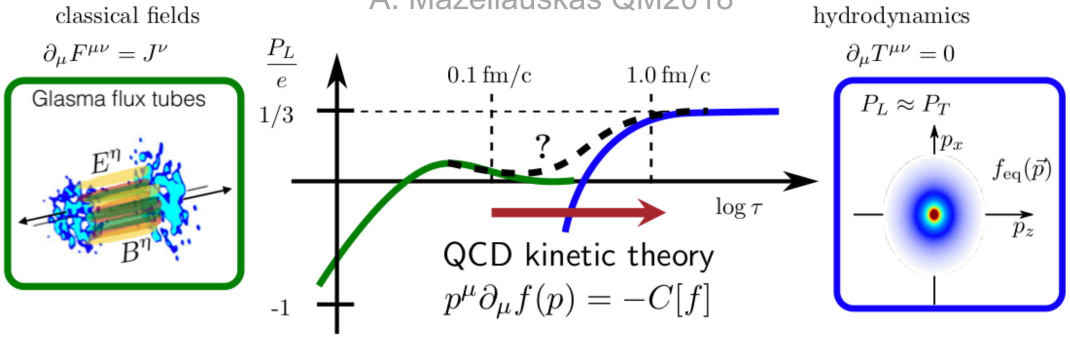
Geometry component of the T^{uv} dominates at large N_{ch}.
Momentum component of the T^{uv} dominates at low N_{ch}

Any direct experimental evidences for this ??

Pre-equilibrium dynamics in large system

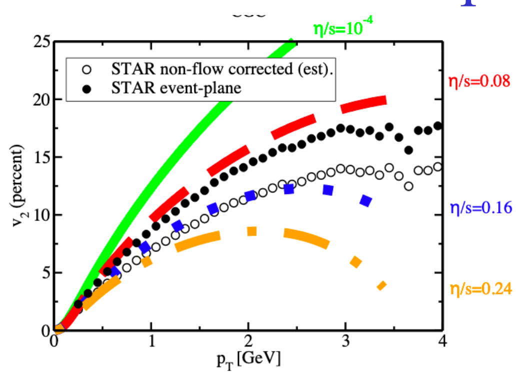
- Initial-flow is natural e.g. in bottom up thermalization 1506.06647 1605.04287
  - Interactions damp momentum-anisotropy, drive QGP towards local equilibrium
  - Necessary for rapid entropy production.

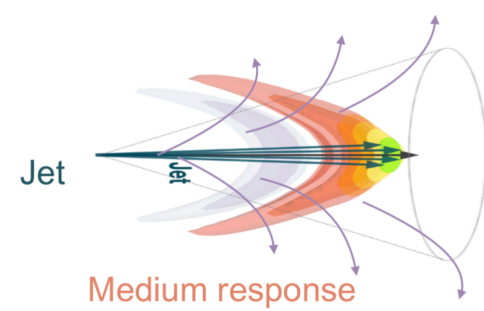
A. Mazeliauskas QM2018



quenching of mini-jets

- Non-equilibrium effects important for v_n and spectra at p_T>2-3GeV/c





How to identify and quantify non-equilibrium effects and understand their role for bulk physics?

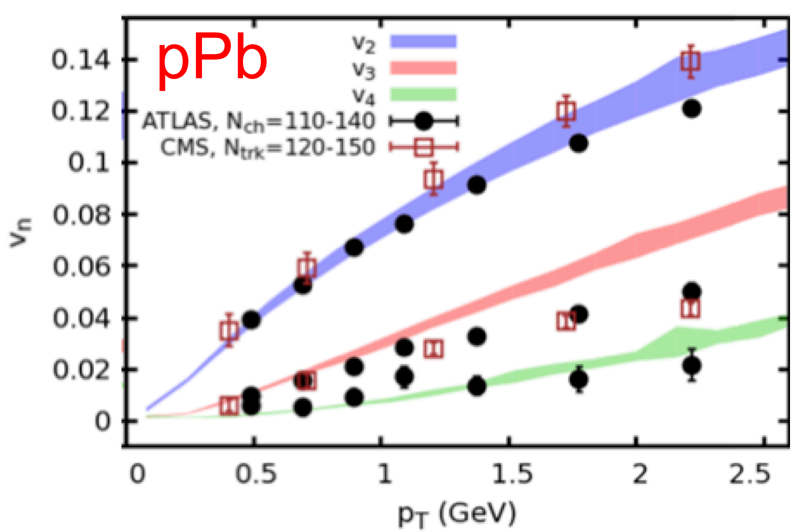
Hydro vs. non-equilibrium transport

- Non-equilibrium effects are naturally included in transport approach

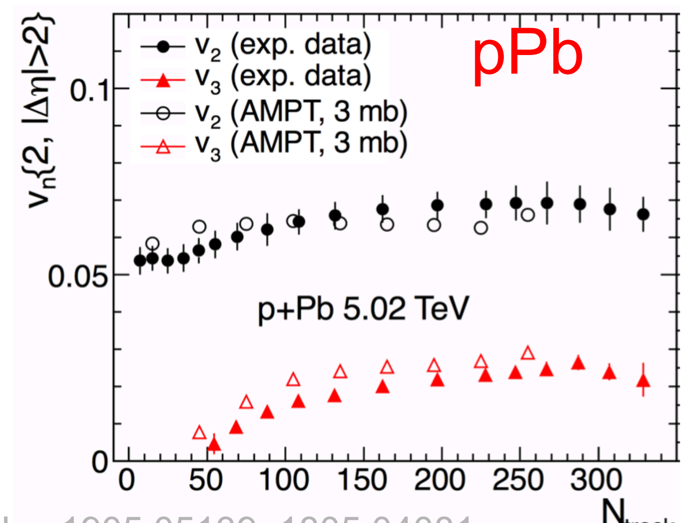
P. Romatschke, R. Weller 1701.07145

L.He, T.Edmonds, Z.Lin, F.Liu, D. Molnar and F. Wang 1502.05572, G. Ma and A Bzdak 1406.2804

Hydrodynamics

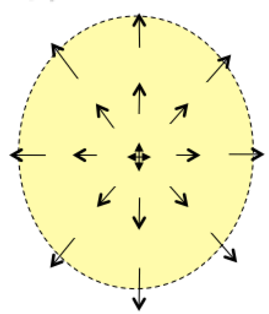


AMPT transport

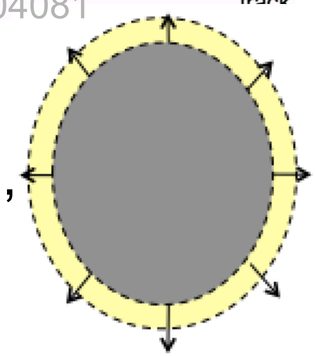


See also 1905.05139, 1805.04081

Pressure driven



Anistropic escape
Anistropic absorption,
surface emission
…



Both reflects final-state geometry response: $v_n=k_n\varepsilon_n$
but different space-time dynamics

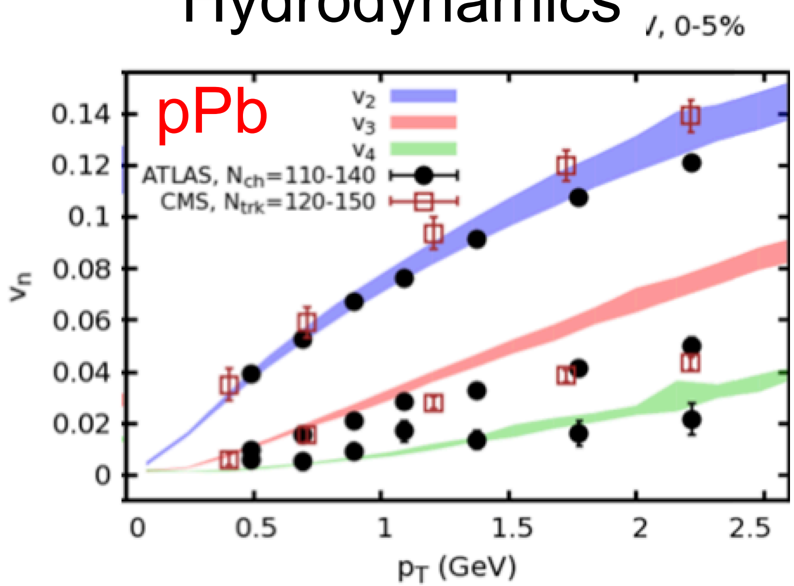
Hydro vs. non-equilibrium transport

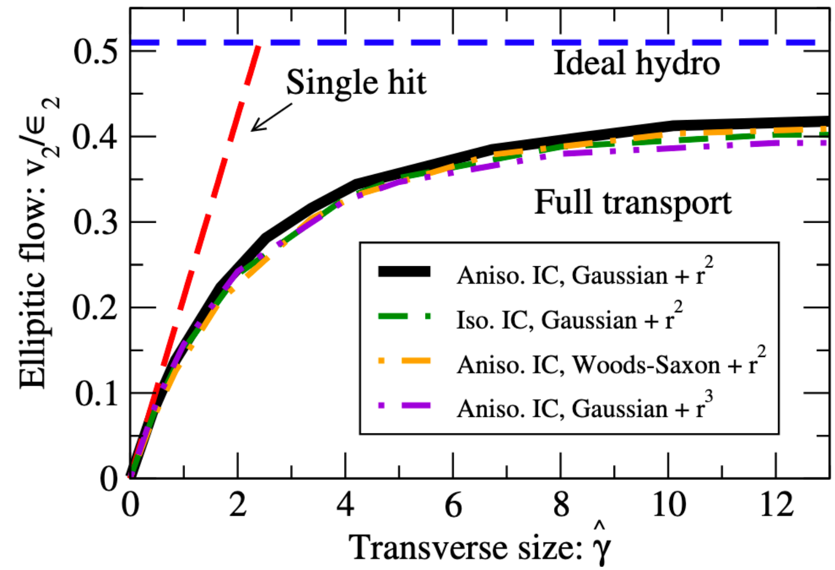
- Non-equilibrium effects are naturally included in transport approach

P. Romatschke, R. Weller 1701.07145

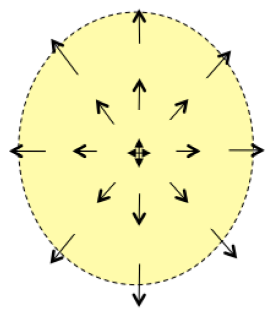
A Kurkela, U. Wiedemann, B.Wu 1905.05139, 1805.04081

Hydrodynamics

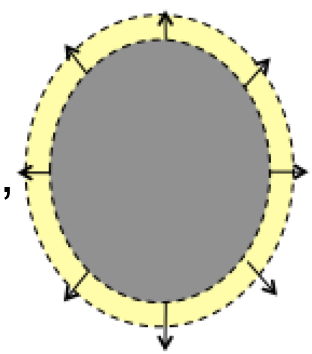




Pressure driven



Anistropic escape
Anistropic absorption,
surface emission
…



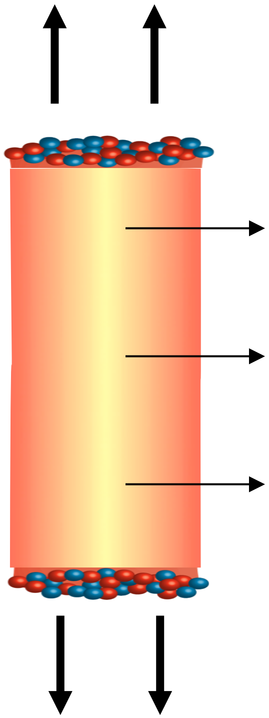
Expect response coefficients k_n is smaller in transport $v_n=k_n\varepsilon_n$

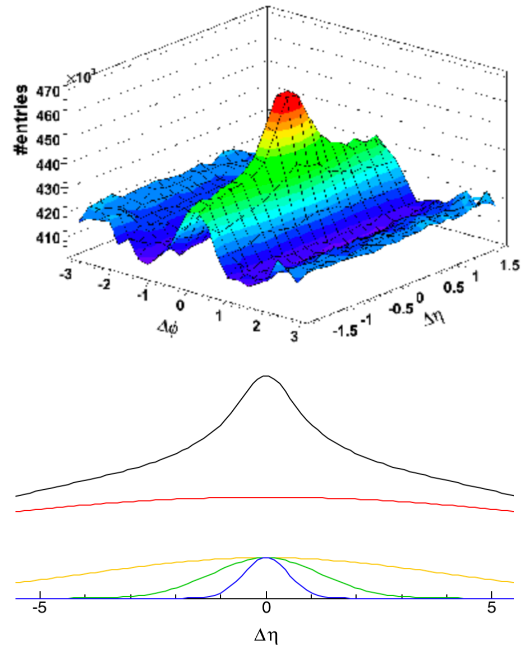
$$\partial_\mu T^{\mu\nu} = 0$$

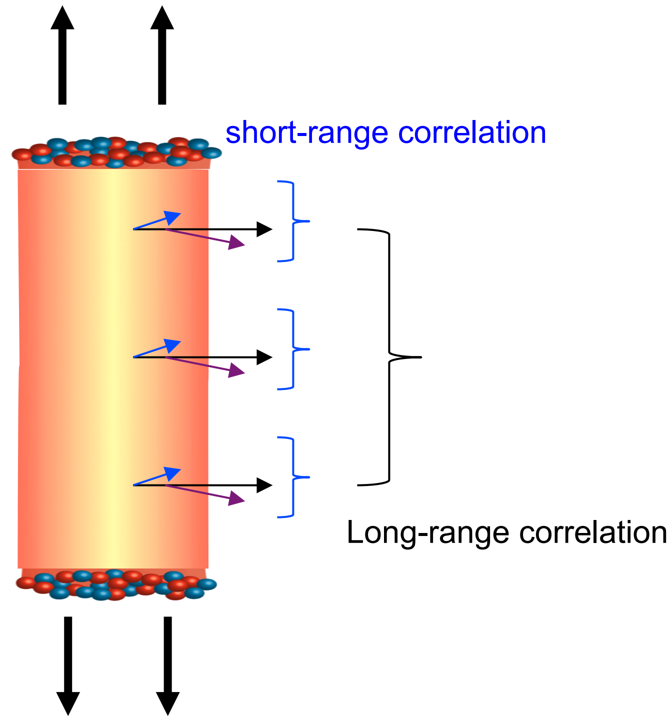
Flow from hydro is a single body distribution

$$p^\mu \partial_\mu f(p) = -C[f]$$

Flow from transport is n-body distribution





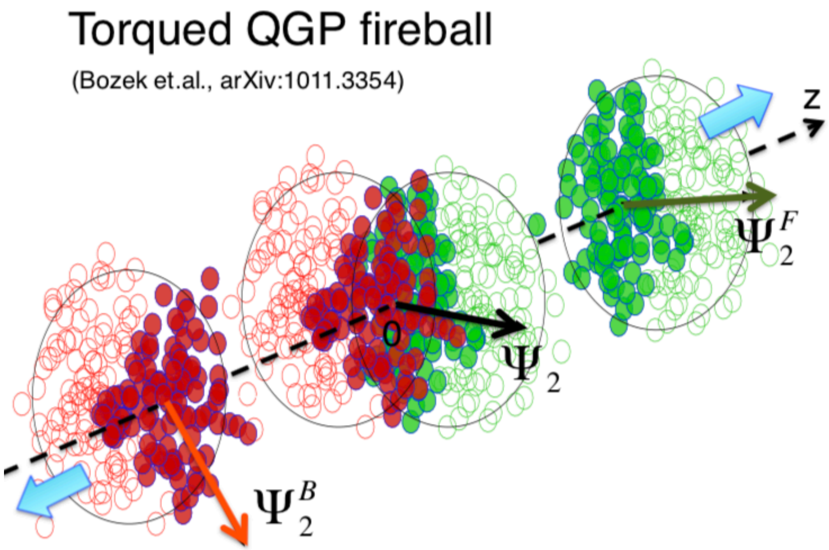


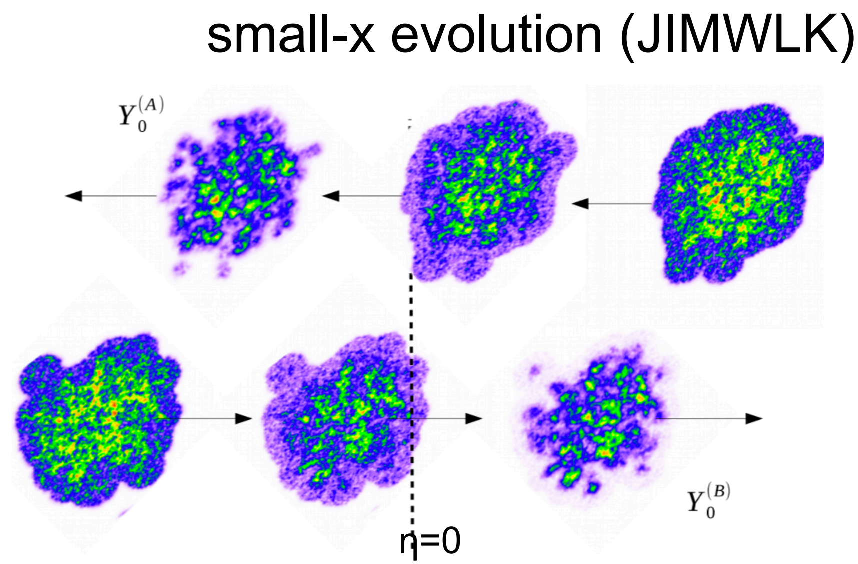
Focus on short-range correlations!

Long-range reflects geometry response, $v_n \propto \epsilon_n$, hard to distinguish
Short-range sensitive to the transport physics.

Break the boost-invariance

- The initial condition changes with rapidity



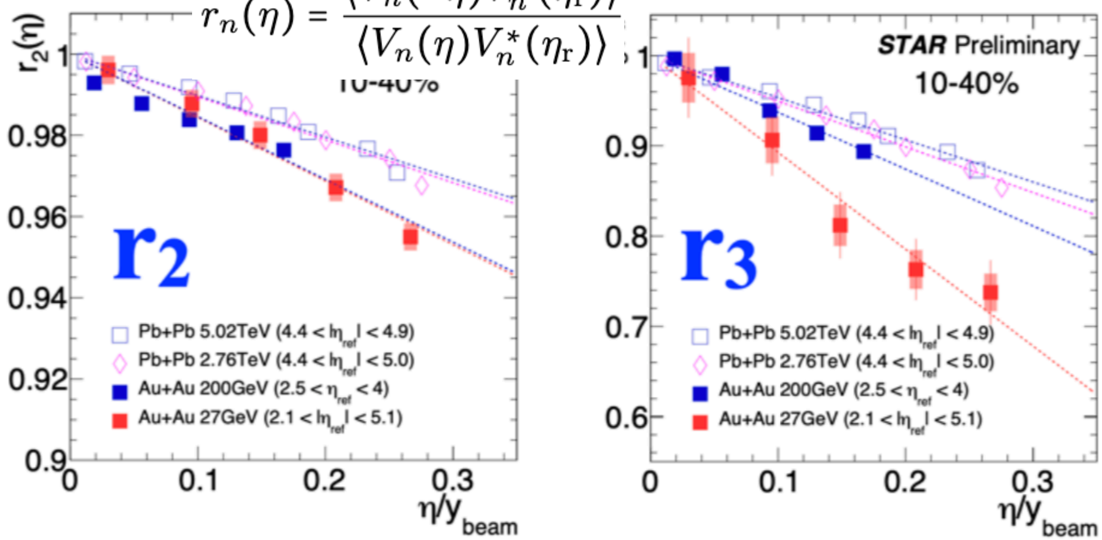


$\langle \vec{\varepsilon}_n(\boldsymbol{\eta}_1^s)\vec{\varepsilon}_n^{\,*}(\boldsymbol{\eta}_2^s)\rangle \Rightarrow \left\langle \vec{V}_n(\boldsymbol{\eta}_1)\vec{V}_n^{\,*}(\boldsymbol{\eta}_2)\right\rangle$ Flow decorrelation

$\langle \varepsilon_0(\boldsymbol{\eta}_1^s)\varepsilon_0(\boldsymbol{\eta}_2^s)\rangle \Rightarrow \langle N(\boldsymbol{\eta}_1)N(\boldsymbol{\eta}_2)\rangle$ Multiplicity/centrality decorrelation

Longitudinal flow decorrelations

$$r_n(\eta) = \frac{\langle V_n(-\eta) V_n^*(\eta_r) \rangle}{\langle V_n(\eta) V_n^*(\eta_r) \rangle}$$



- strong √s dependence
- sensitive to η/s, thermal fluctuation and stopping
- systematics not described by models

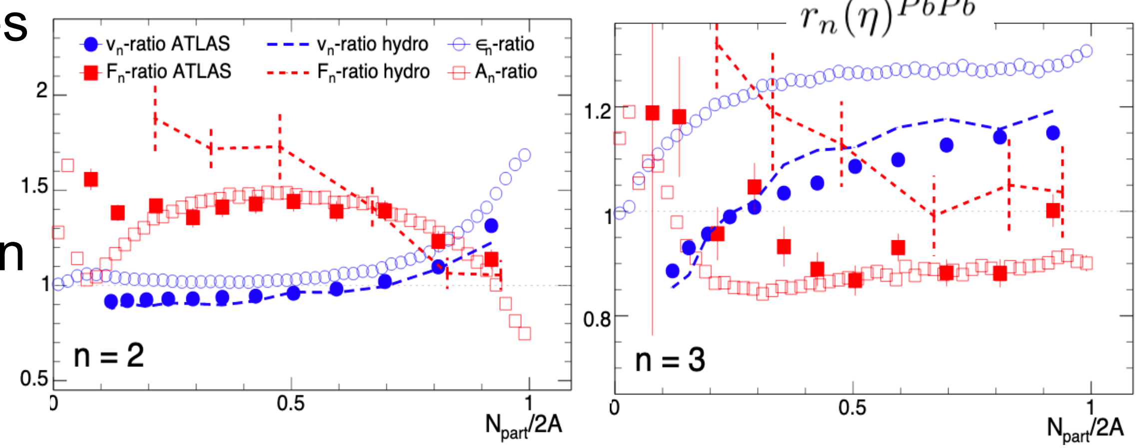
2003.13496

- system-size dependence scales with $N_{part}/2A$, reflects overall shape not the size
- sensitive to nuclear deformation
- systematics not fully described by models

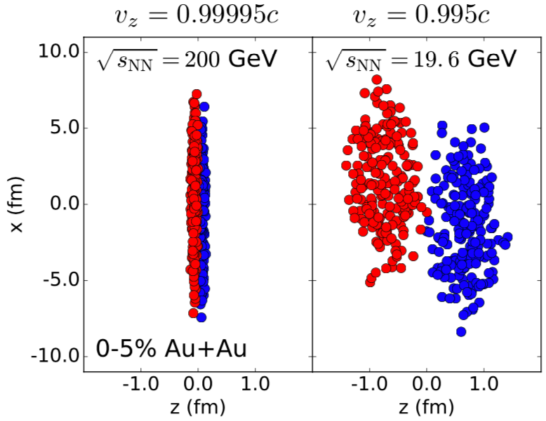
See 2003.04340

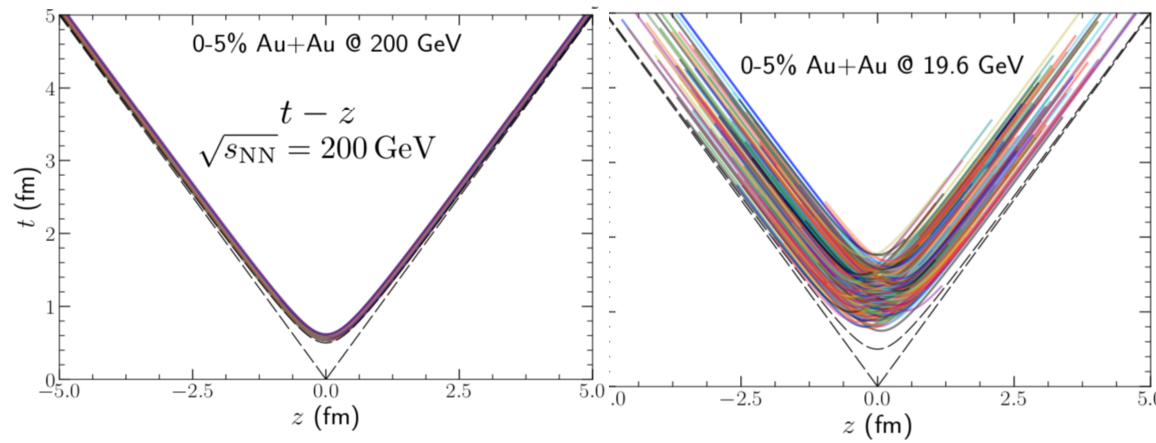
1709.02301 2001.04201

$$\frac{r_n(\eta)^{XeXe}}{r_n(\eta)^{PbPb}}$$



Beam-energy scan and longitudinal dynamics

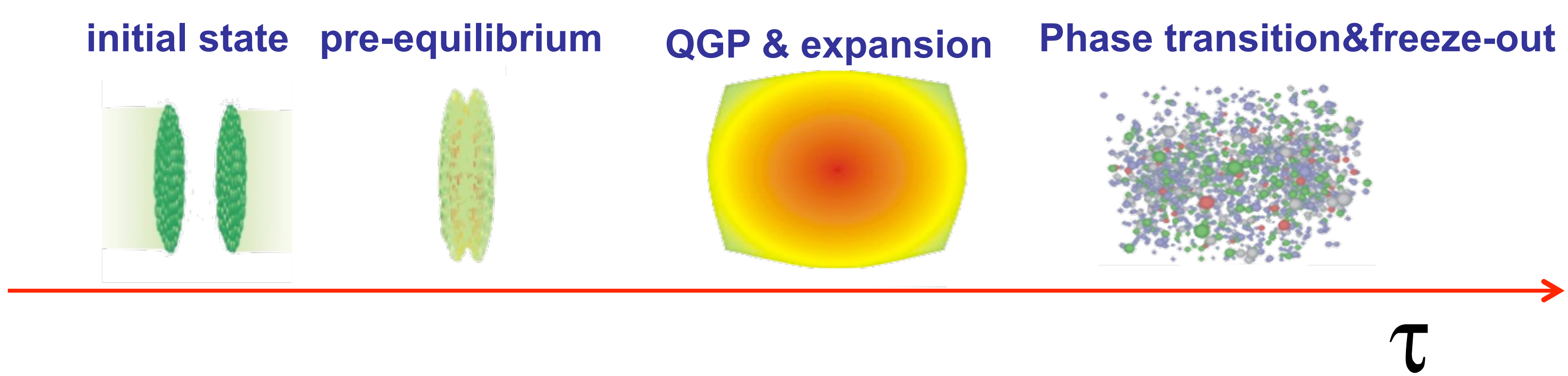




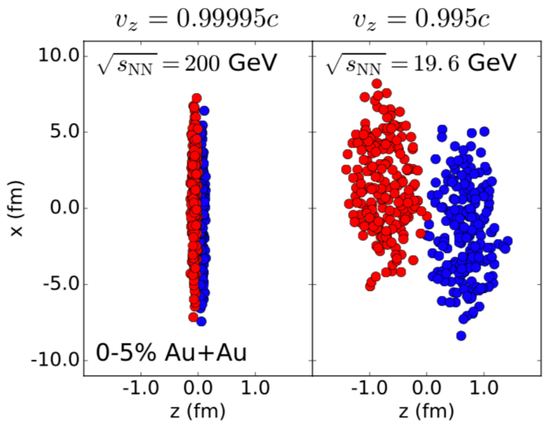
Nuclear overlap time becomes large at lower energies

Nucleons are decelerated with energy deposited over a larger space-time volume

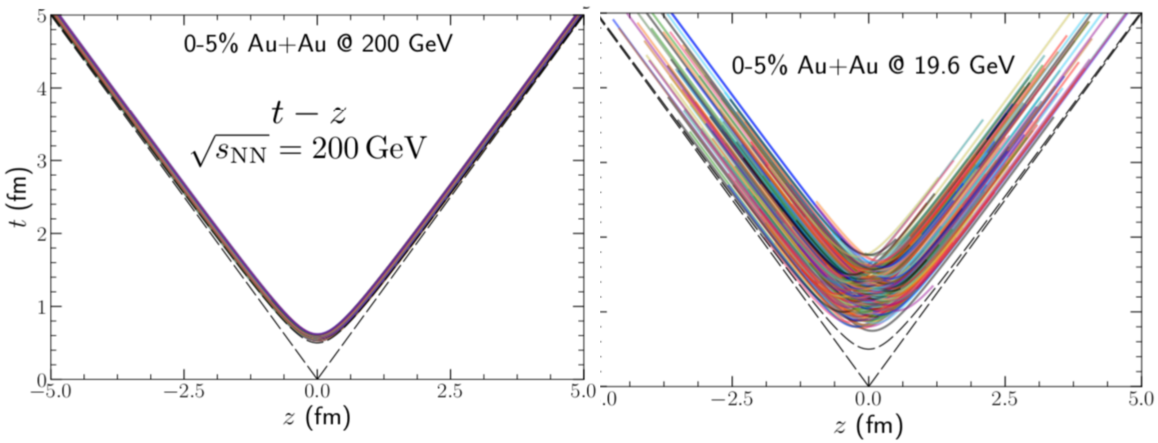
Different stages no longer separated



Beam-energy scan and longitudinal dynamics



Nuclear overlap time becomes large at lower energies



Nucleons are decelerated with energy deposited over a larger space-time volume

Longitudinal dynamics as important as transverse dynamics

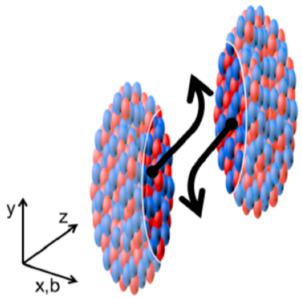
- Overlap between longitudinal stopping and transverse expansion
- Collective flow no-longer reflects only eccentricity.
- Nuclear stopping, baryon transport and importance of global vorticity
- EOS and transport properties are different
- Hadronic phase are more important

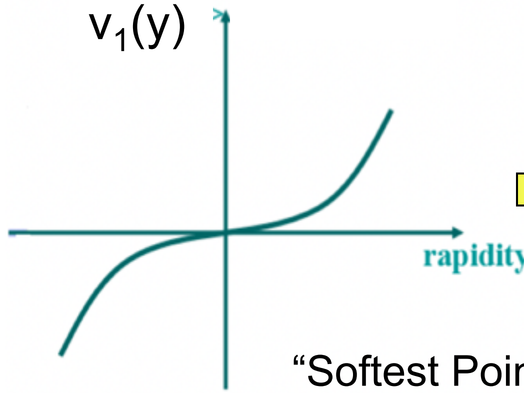
Description requires full 3+1D hydrodynamics or transport

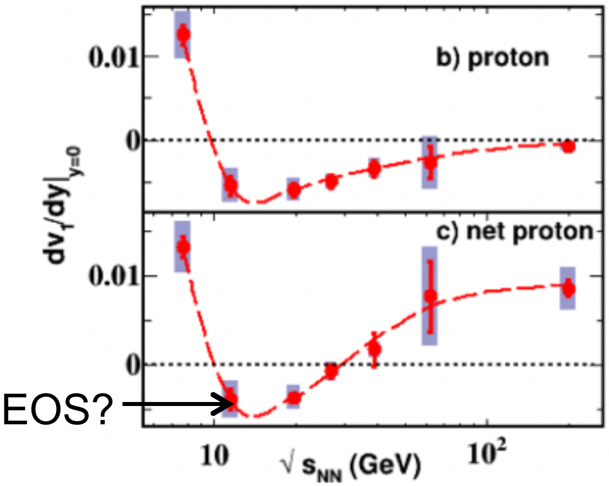
Collective flow at low √s

Interplay between nuclear stopping and final-state collective motion

Sideward flow

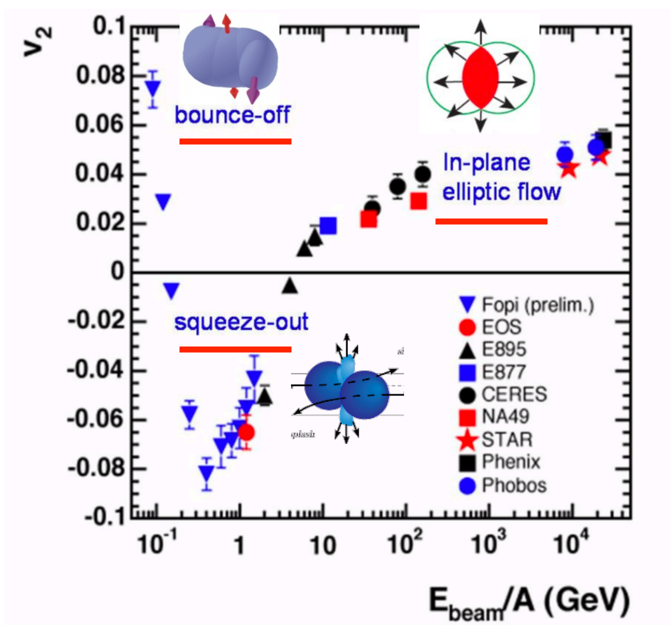






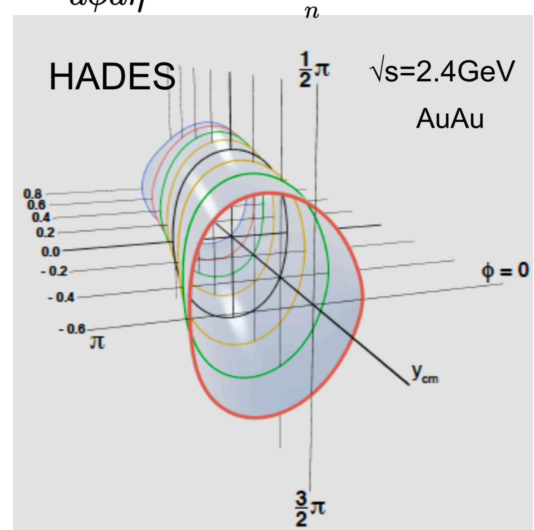
"Softest Point" in EOS?

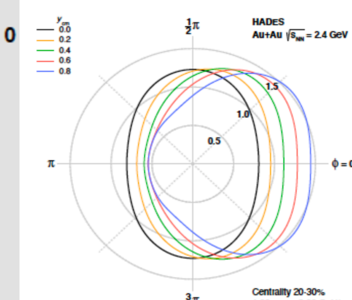
Elliptic flow



Higher-order flow harmonics

$$\frac{dN}{d\phi d\eta} \propto 1 + 2\sum_n v_n(\eta)\cos n(\phi - \Psi_{RP})$$



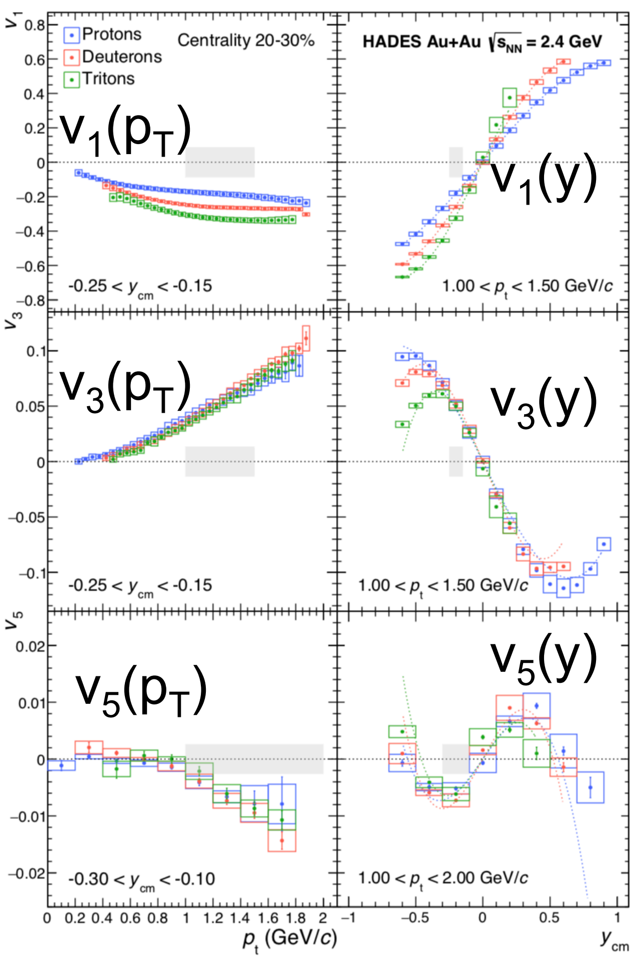


Flow results at HADES √s=2.4 GeV

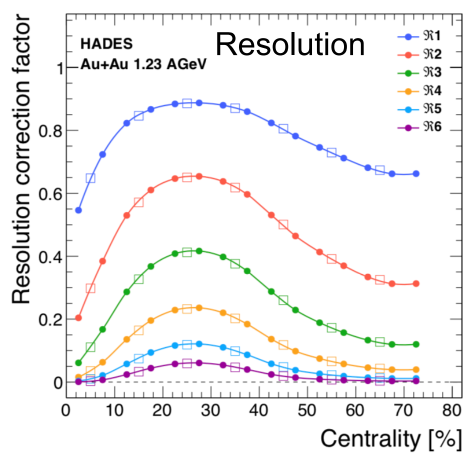
2005.12217

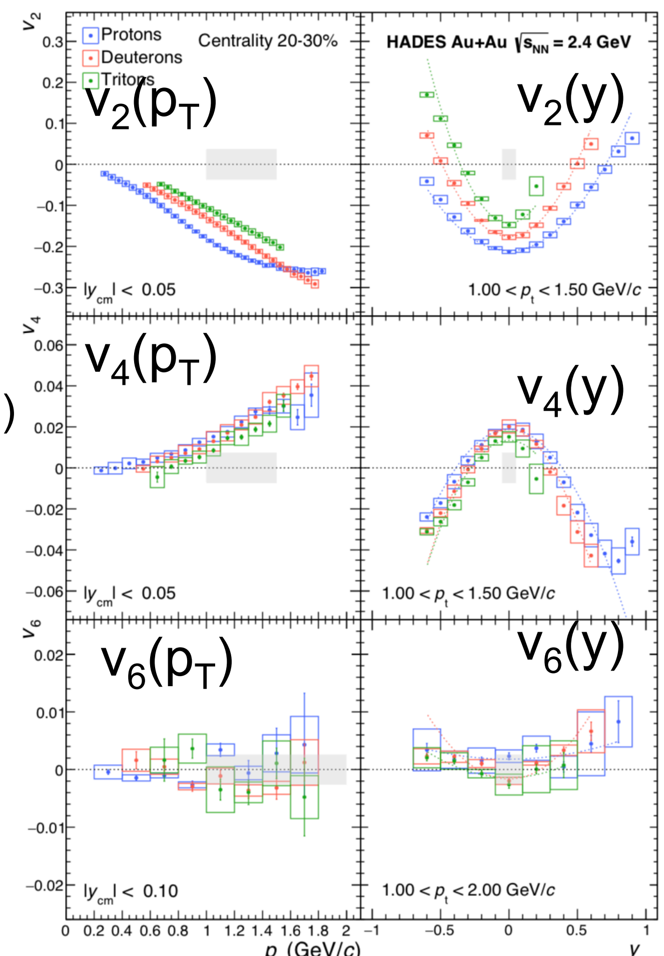
all light nuclei. Theory calculations within a hydrodynamic framework adapted to the description of baryon dominated matter are needed to investigate the question whether this kind of matter really exhibits a hydrodynamical behavior, at least in the last stages of the collision prior to freeze-out. The high precision information on higher order flow coefficients is a major step forward in constraining the EOS.

Challenge to theory



- Complex interplay between longitudinal and transverse dynamics.
- Measured in Ψ_1→Large mode-coupling terms between different harmonics
- Interesting to measure $v_n(\Psi_n)$ as well as EbyE fluctuations.





Look into the future

- Top $\sqrt{s}$: aim for precision in both dynamics and properties.
  - Easier with larger multiplicity and ~ boost invariance
- BES $\sqrt{s}$: more reliable modeling of the 3D dynamics
  - Identify observables with direct physics intuition
  - More measurements on flow fluctuations

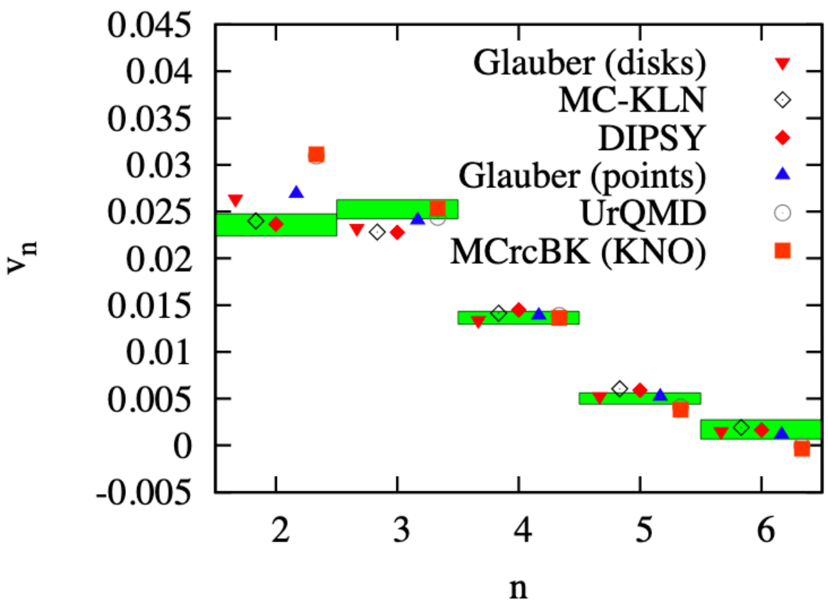
- Improve understanding in
  - Initial state geometry
  - Early time dynamics
  - Final state dynamics and properties

- New directions
  - Collision System scan
  - Rapidity scan

Flow in Ultra-central collisions

$v_2 \approx v_3 > v_4 > v_5$

$\varepsilon_2 \approx \varepsilon_3 \approx \varepsilon_4 \approx \varepsilon_5$



Volume fluctuation?

Goes opposite direction
See 1904.04808

Bulk/shear viscosity and EOS

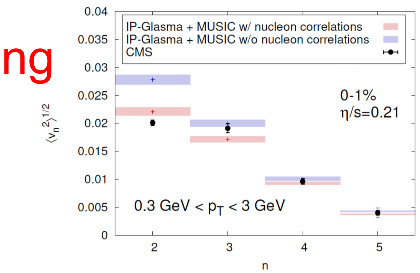
1408.0024,1502.04636, 1711.05207

May improves v_2 v_3 ordering
but not sufficient

Nucleon-nucleon correlation

1406.7792

Improves v_2 v_3 ordering
but not sufficient



Octupole deformation

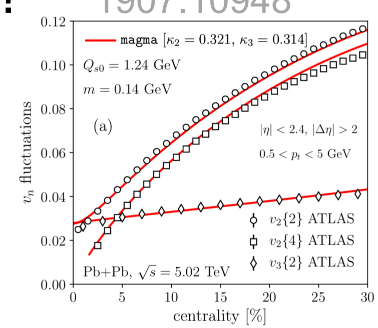
2007.00780

Improves v_2 v_3 ordering but worsening description of $v_3\{4\}/v_3\{2\}$

Subnucleon fluctuations?

1907.10948

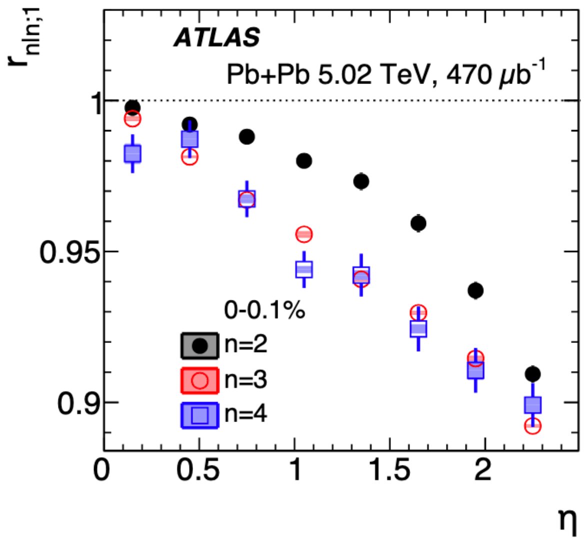
Produce v_2 v_3 ordering via fitting k_n in $v_n=k_n\varepsilon_n$ but $k_2 \approx k_3$?



Flow in Ultra-central collisions

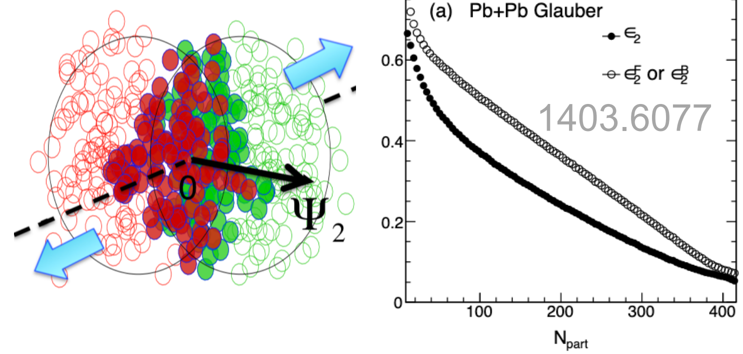
My bet: it is due to longitudinal dynamics

Large and non-linear decorrelation not yet reproduced by models



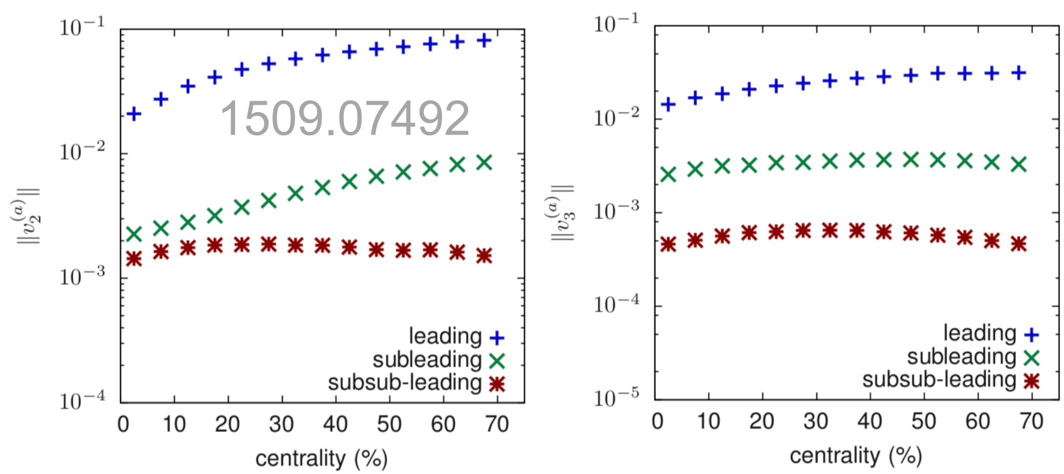
Non-trivial mixing between F/B

$\epsilon_2^F, \epsilon_2^B > \epsilon_2$



Analyze subleading flow including longitudinal fluctuations?

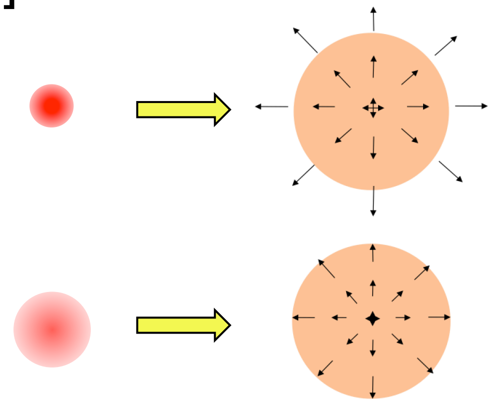
Likely some unknown 3D initial state effects amplified in UCC.



only transverse dynamics included so far

New handle on the initial state: v_n-p_T correlation

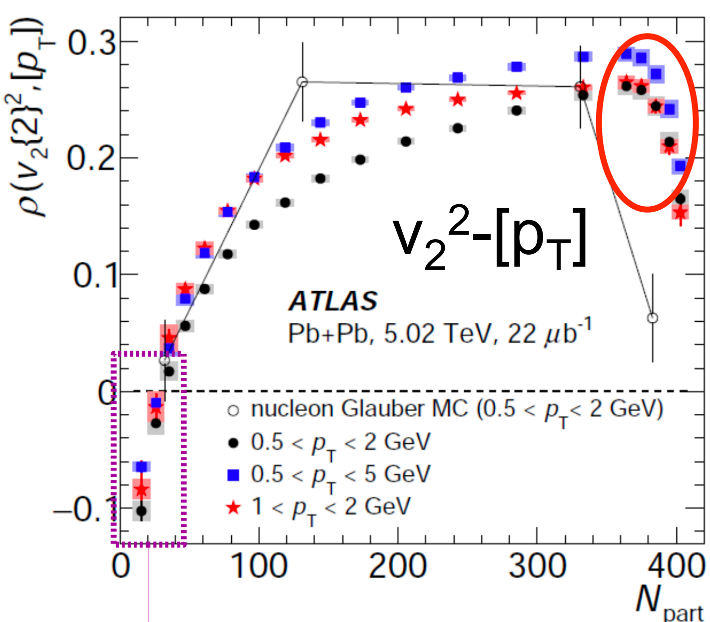
$[p_T]$ anti-correlates with size



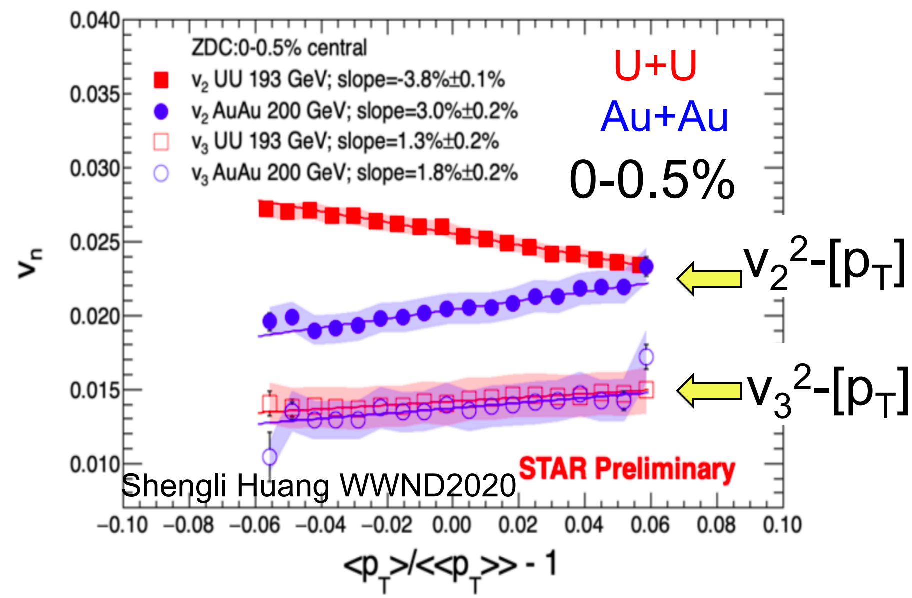
Fluctuation of radial size correlates with radial flow and harmonic flow

→ Strong v_n-p_T correlation, unique probe of the radial structures

sensitive to shape-size correlation



sensitive to nuclear deformation



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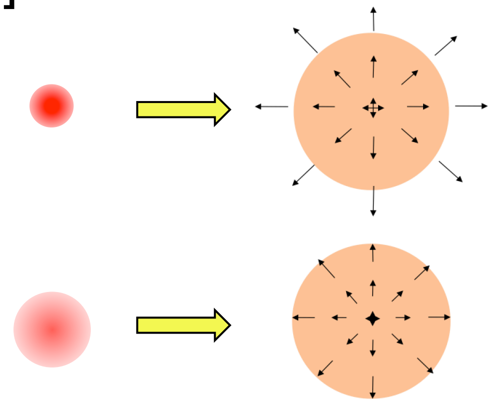

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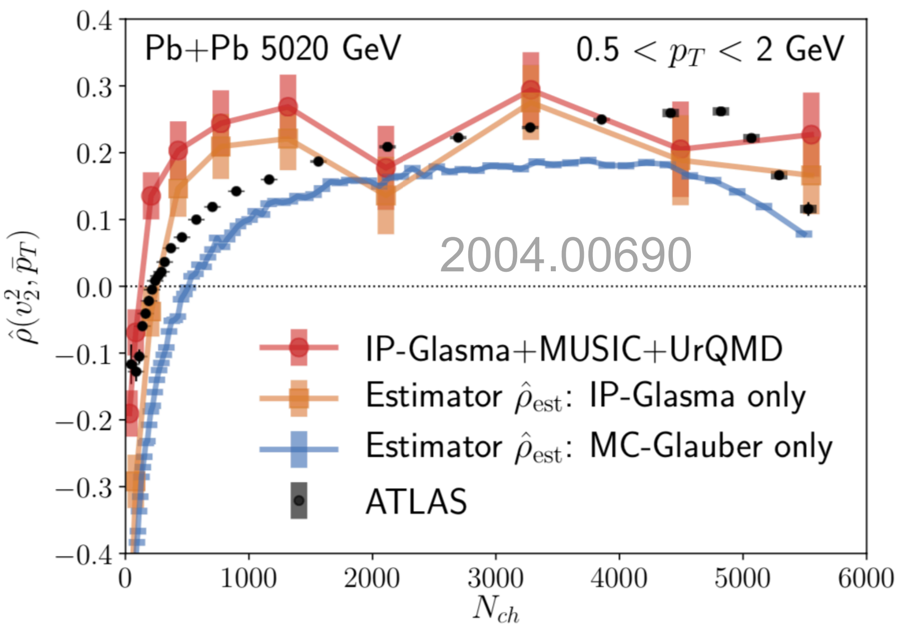

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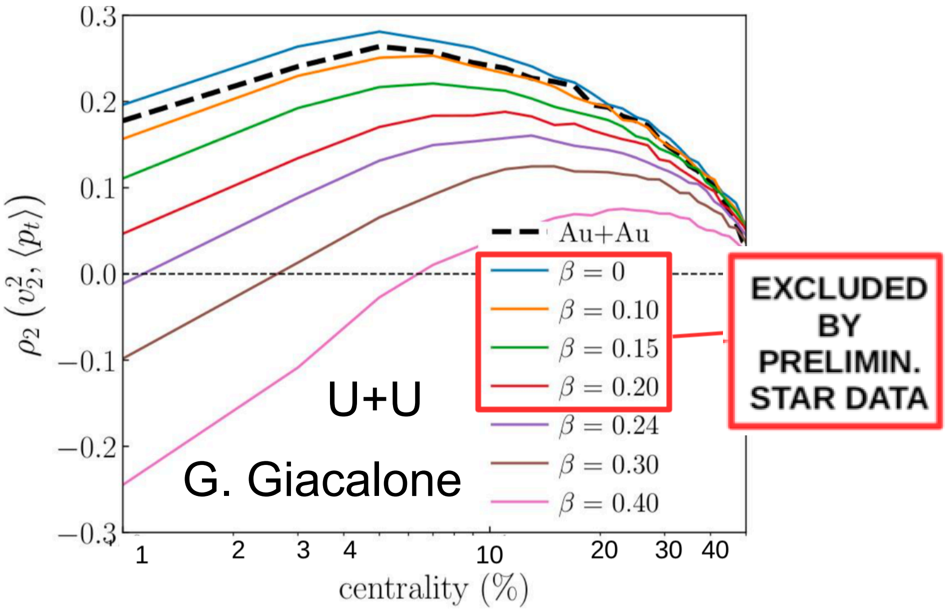
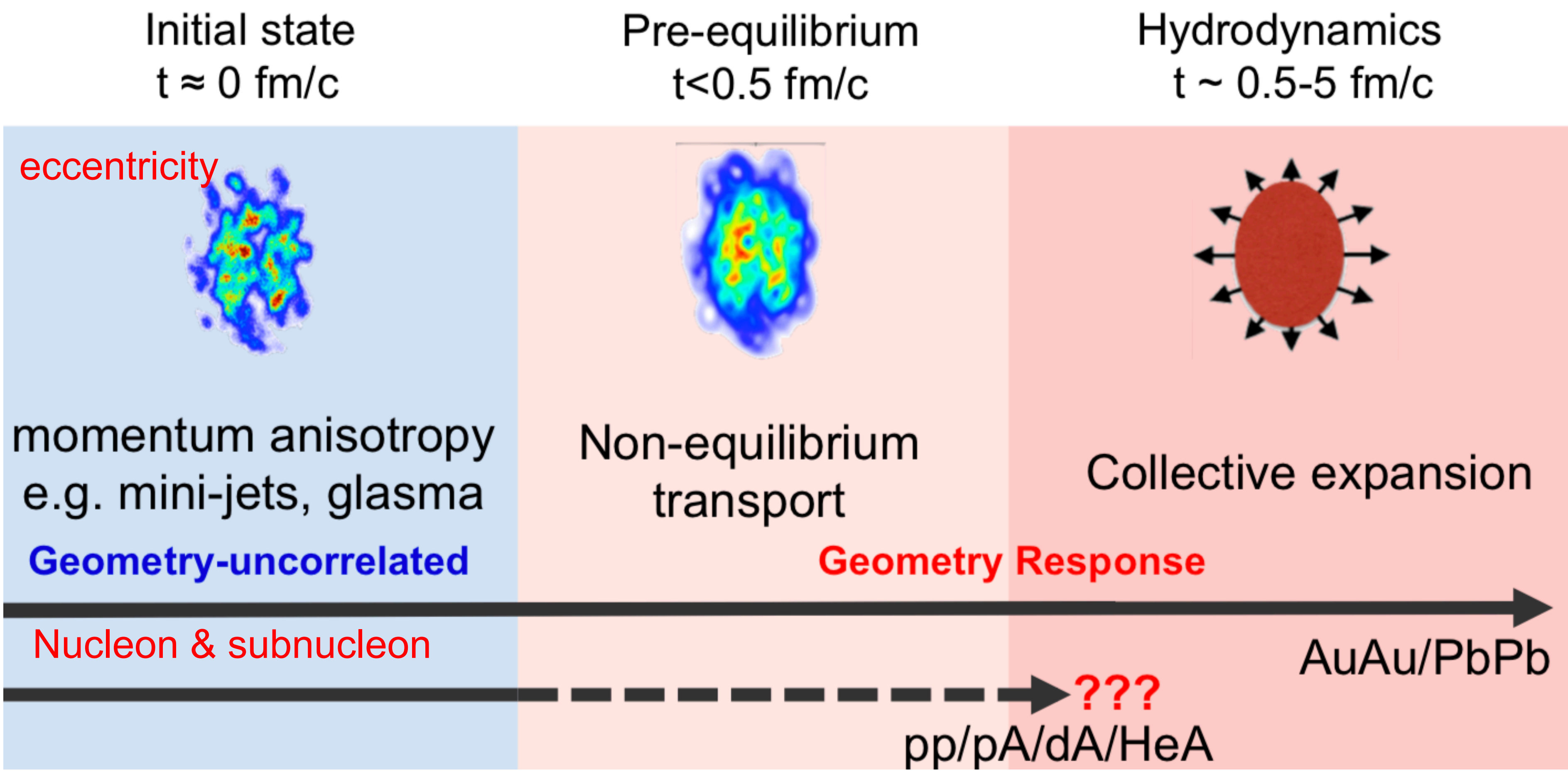


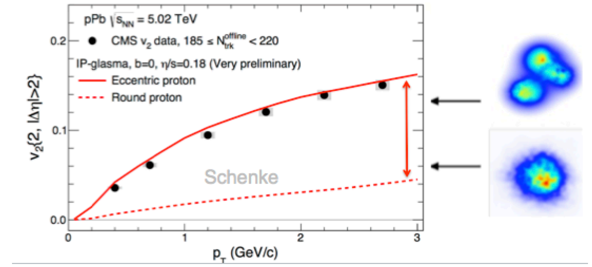
Disentangle early-time dynamics



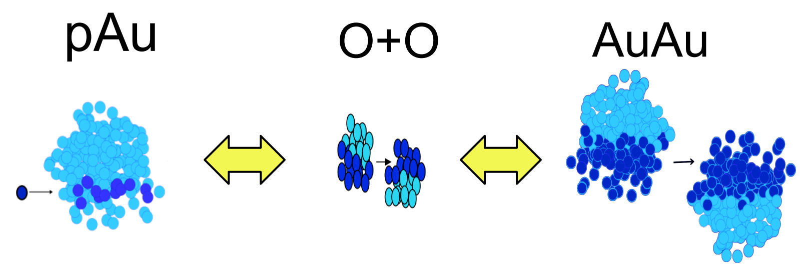
Extend lever-arm with symmetric small A+A collisions
to disentangle different contributions

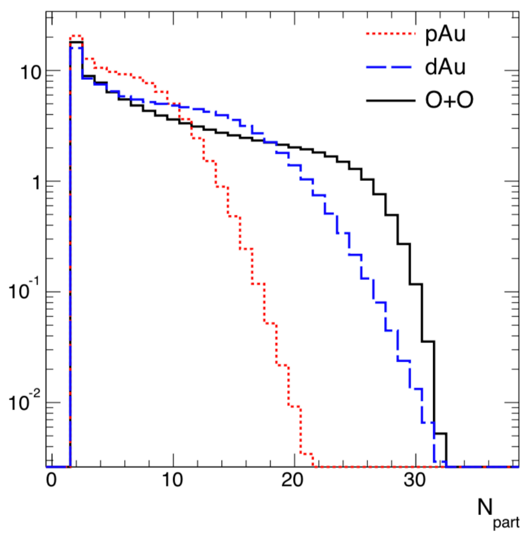
Why small A+A?

Subnucleon DOF is important for pAu ridge:



Nucleon & subnucleon DOF comparable in small A+A→ Bridging pAu and AuAu

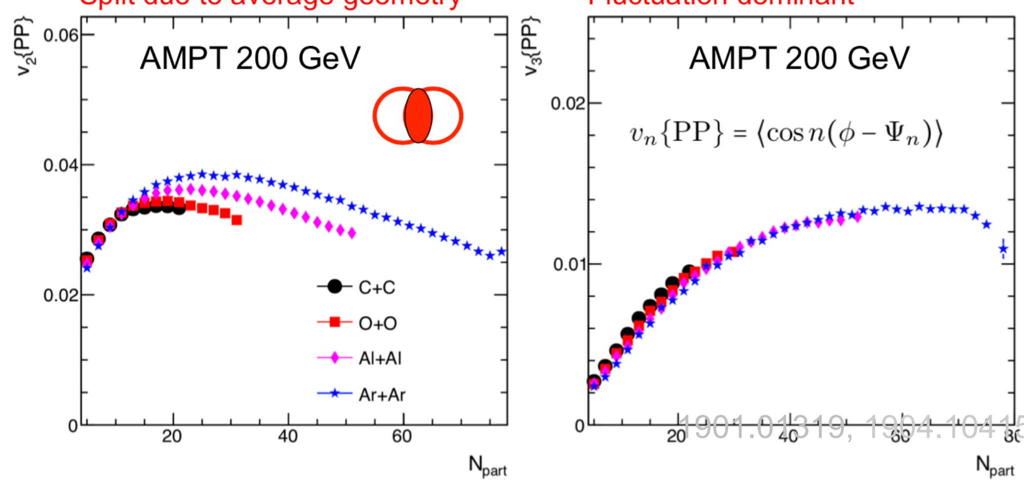




O+O a reasonable choice in terms of N_{part} coverage

	pAu	dAu	$^{16}O+^{16}O$
$\langle N_{part}\rangle$	5.8	8.8	9.5

Disentangle nucleon geometry vs fluctuations

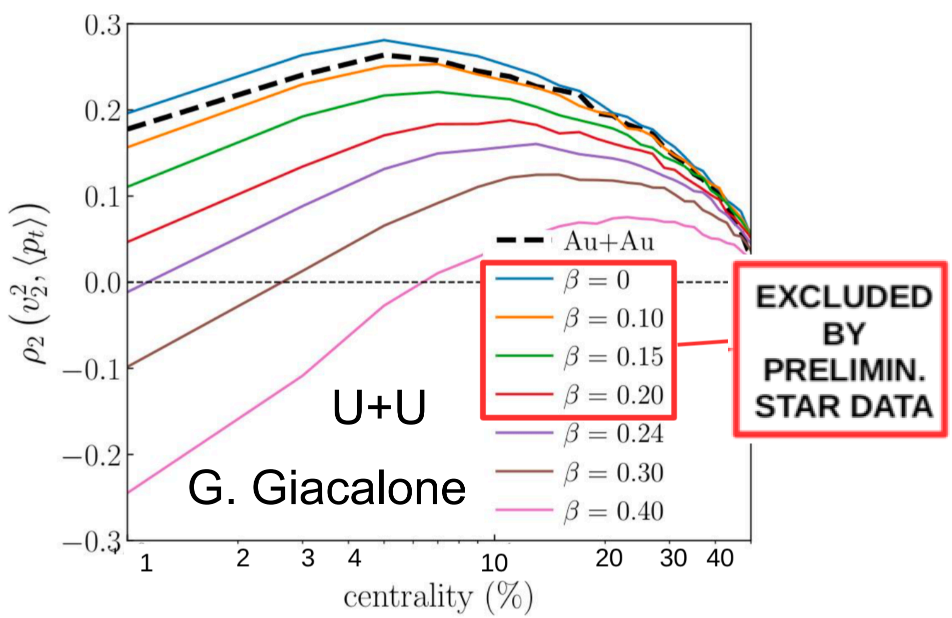


- STAR is pushing for a short O+O run in 2021
- Synergy with planned LHC O+O run in 2023: identical Glauber geometry, but different subnucleonic fluct. (Q_s).

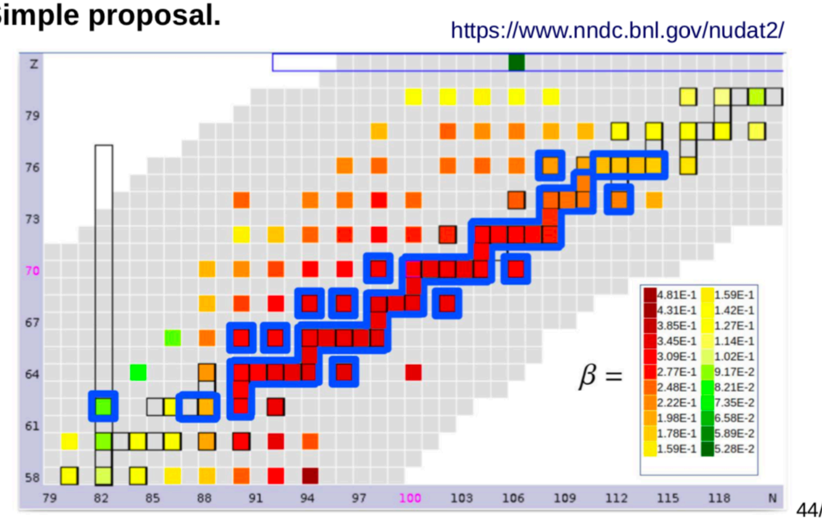
Collision System Scan

- Beam Energy Scan program has been vastly successful
  - Explore QCD Phase diagram
  - Bridge between high T and high μ_B frontiers
- An extensive system-size scan could be equally fruitful
  - Detailed exploration of the initial state via hydrodynamics $v_n = k_n \varepsilon_n$
  - New tool for nuclear structure physics via v_n-v_n, v_n-p_T, p_T-p_T correlations

Nuclear deformation



Region 144<A<190 populated by large well-deformed nuclei.
Systematic study of nuclear deformation at RHIC.
Simple proposal.



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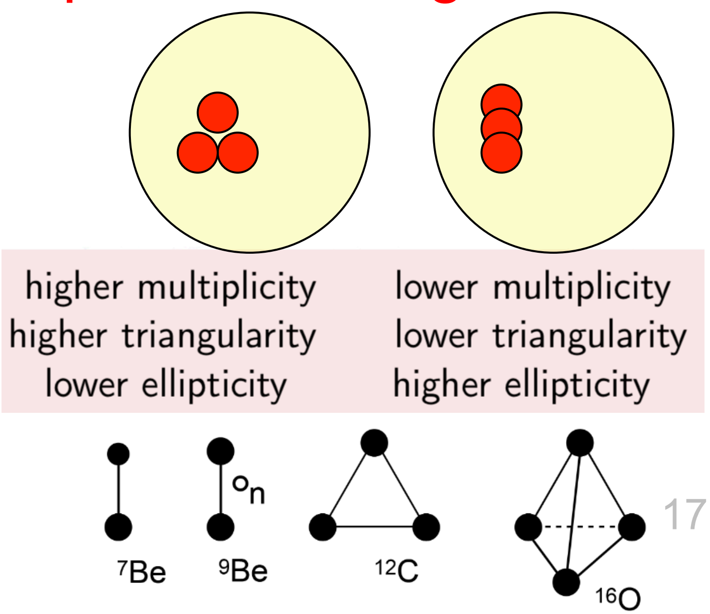
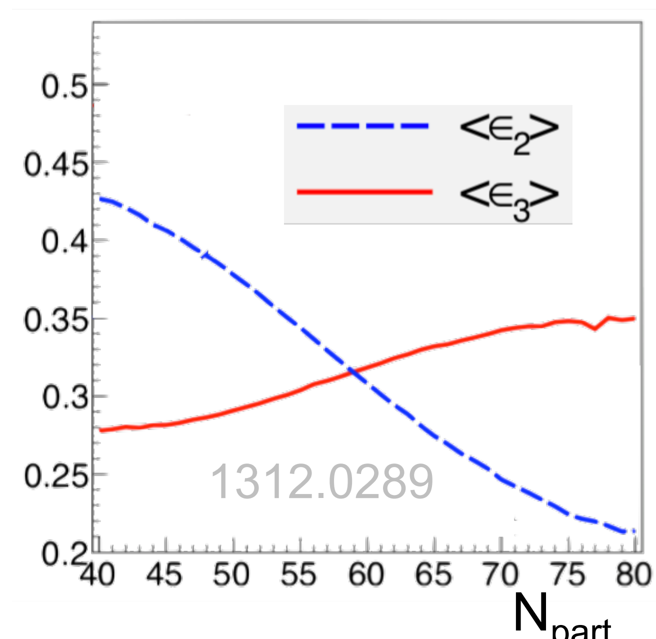
Alpha-clustering

Analyzing ^{12}C structure via collisions with a "disk" of Au:



1711.00438



Explore Be/C/O+Au collisions

Collision System Scan

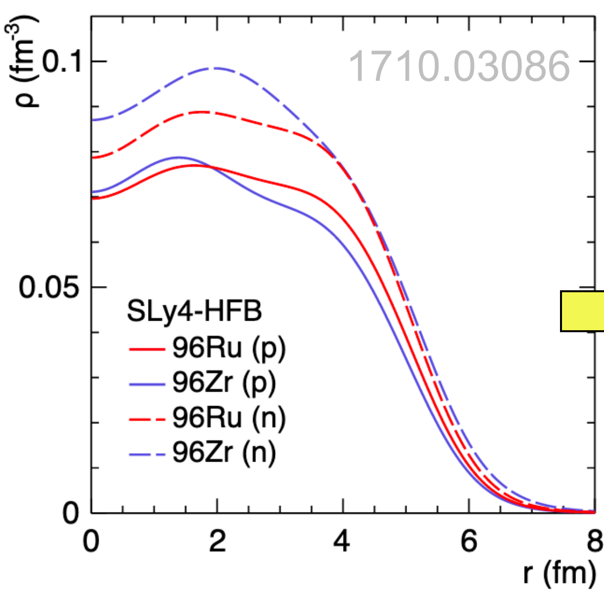
Scan doable during sPHENIX era 2023-2027!

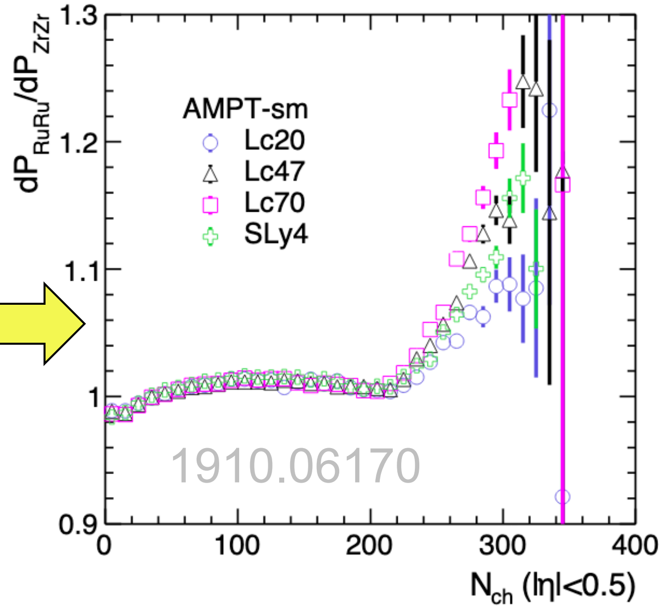
- Beam Energy Scan program has been vastly successful
  - Explore QCD Phase diagram
  - Bridge between high T and high μ_B frontiers
- An extensive system-size scan could be equally fruitful
  - Detailed exploration of the initial state via hydrodynamics $v_2 = \kappa_2 \varepsilon_2$
  - New tool for nuclear structure physics via v_n-v_n, v_n-p_T, p_T-p_T correlations

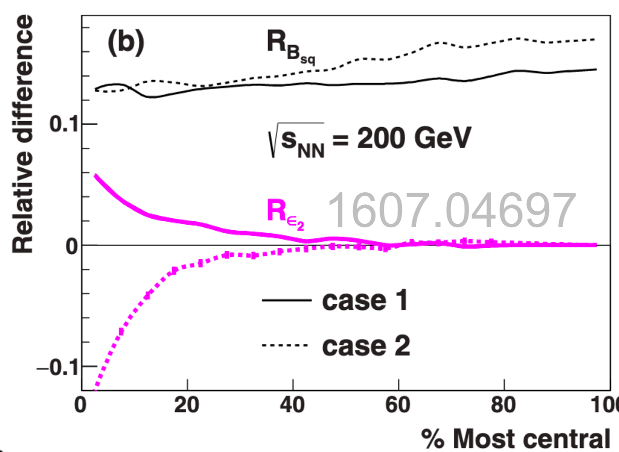
Neutron skin

Isobar-run demonstrates RHIC ability for controlled study of nuclei geometry

$^{96}_{44}\mathrm{Ru}+^{96}_{44}\mathrm{Ru}$ $^{96}_{40}\mathrm{Zr}+^{96}_{40}\mathrm{Zr}$

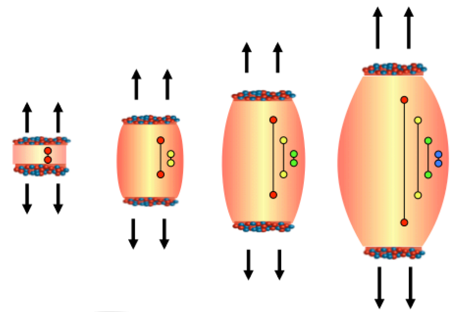




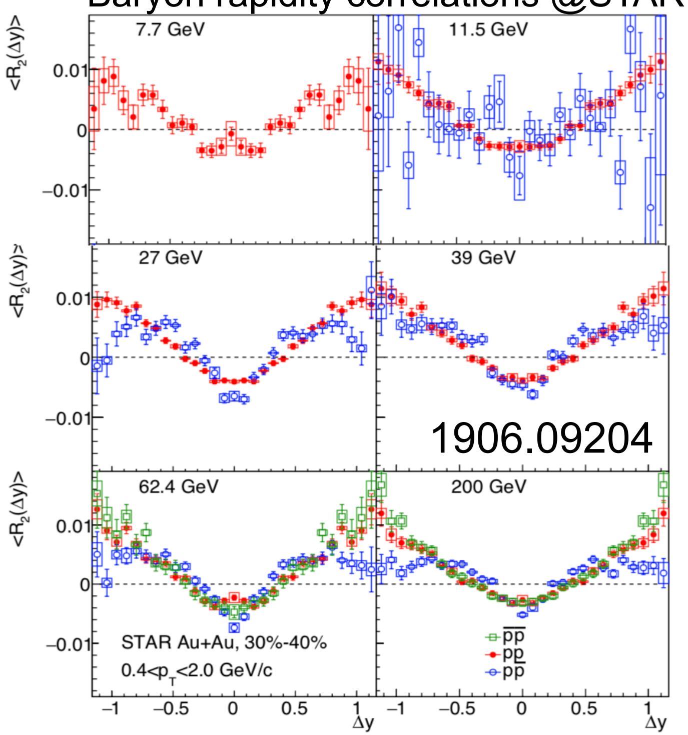


New frontier: Rapidity correlations

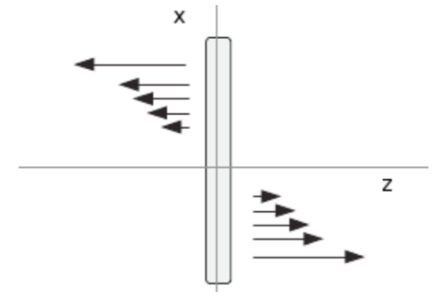
Many sources of fluctuations,
generated at different time, and
has different longitudinal/transverse dynamics



Baryon rapidity correlations @STAR

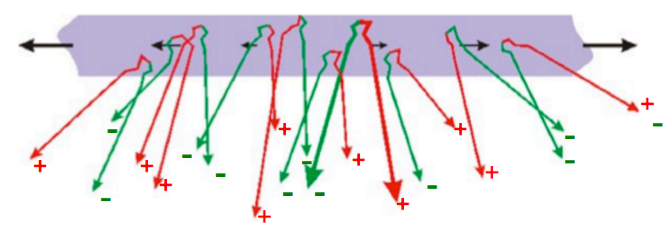


Longitudinal flow

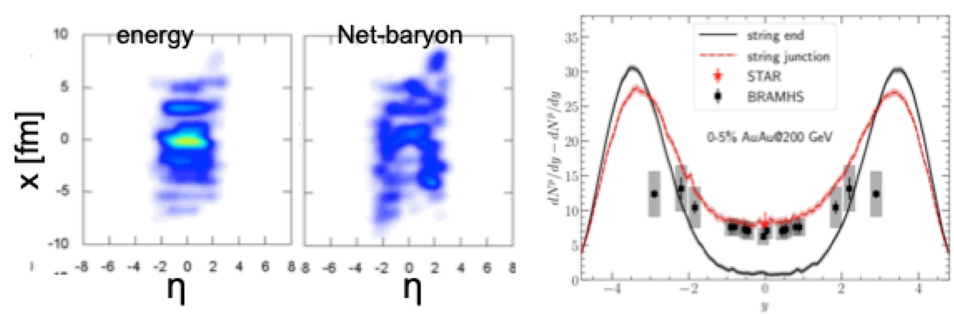


Charge transport

Balance function



Net-baryon transport



G. Denicol, C.Gale, S.Jeon, A.monnai, B.Schenke C.Shen 1804.10557

Rapidity Scan

- Rapidity scan at fixed √s ⇔ Beam-Energy scan within same event
  - Similar properties but very different dynamics
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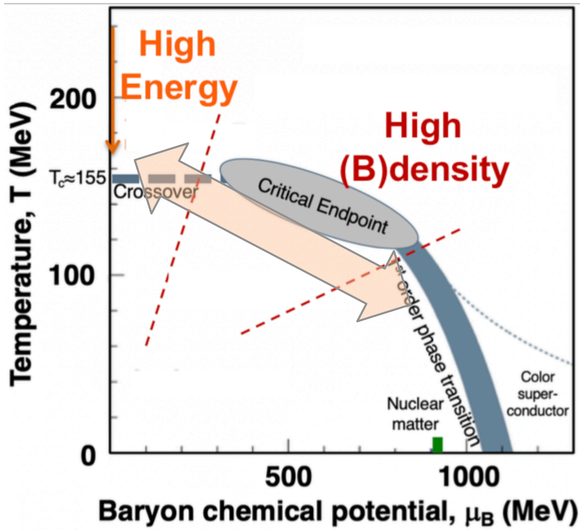
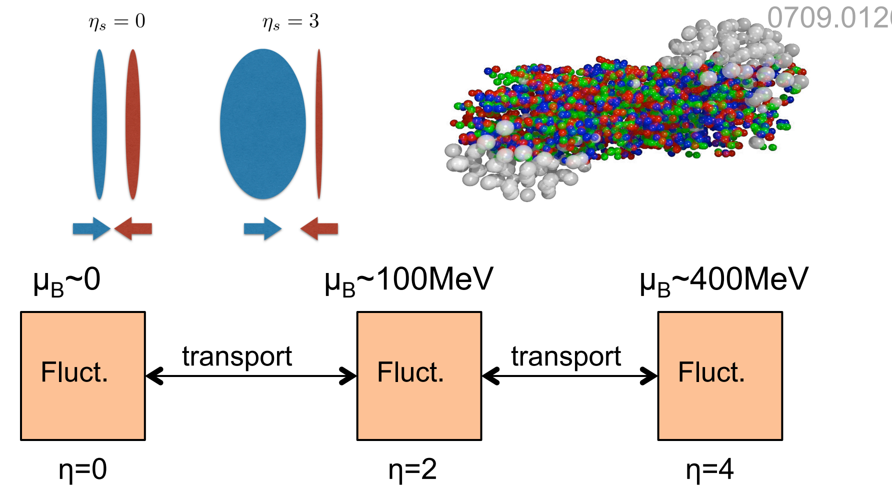
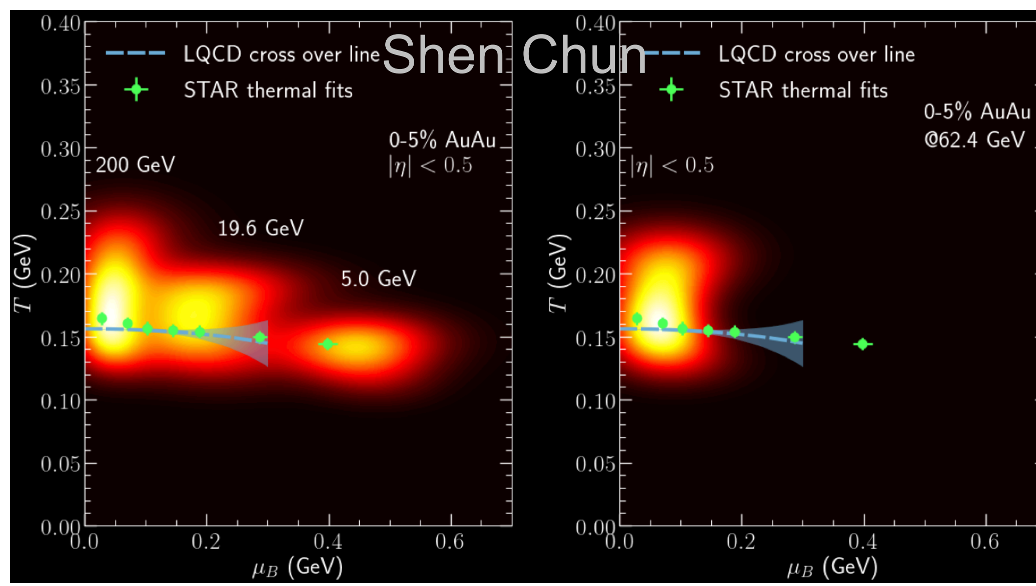




New handle on phase diagram, dynamics and properties



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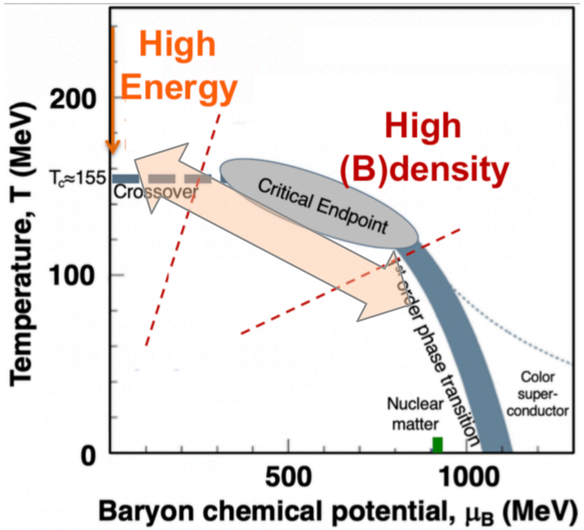

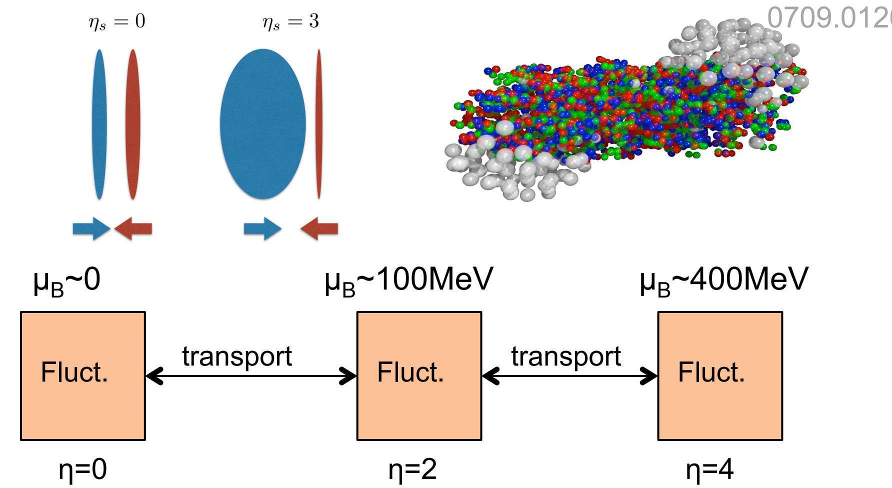

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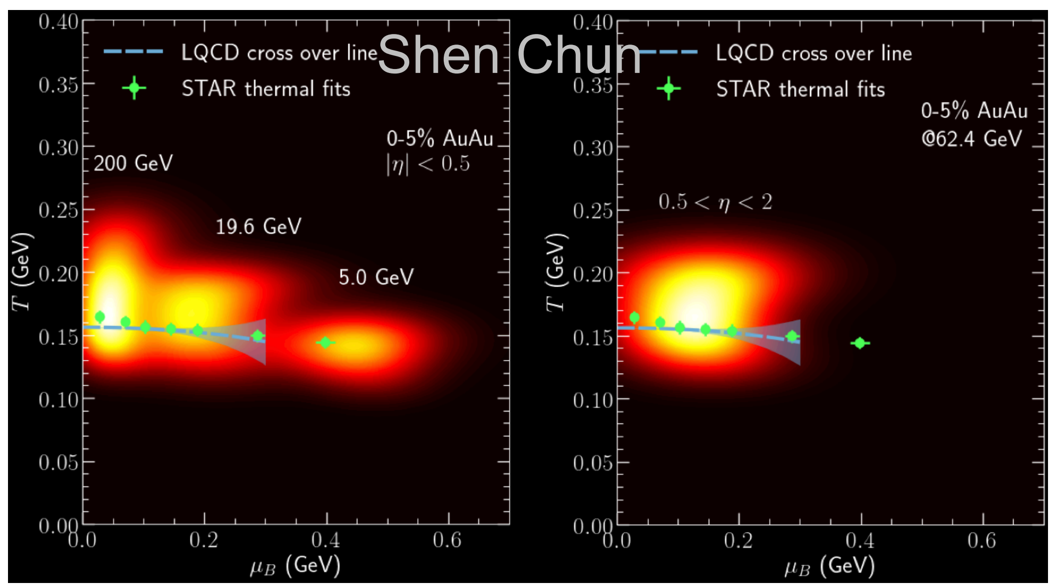

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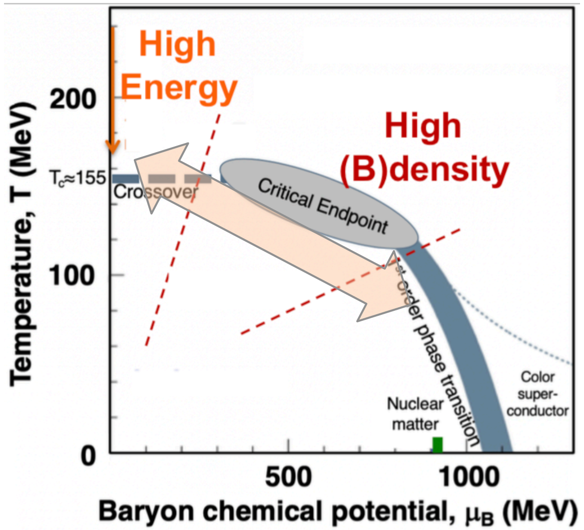

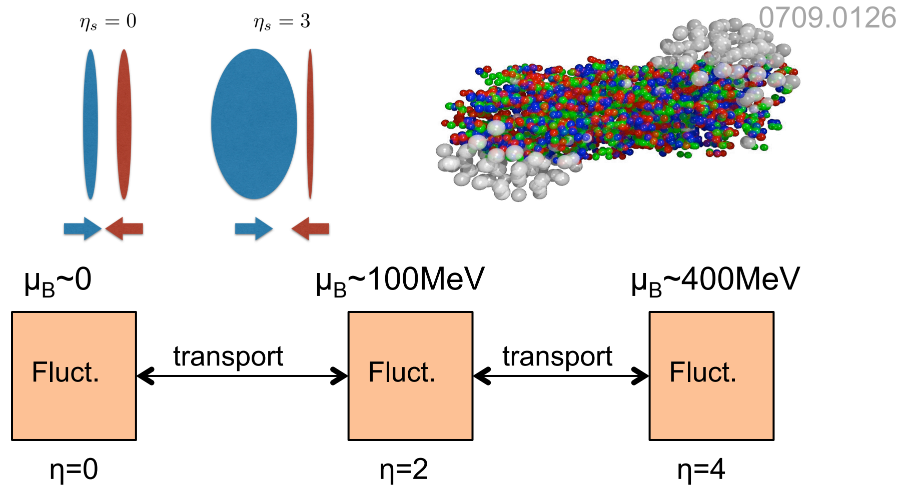

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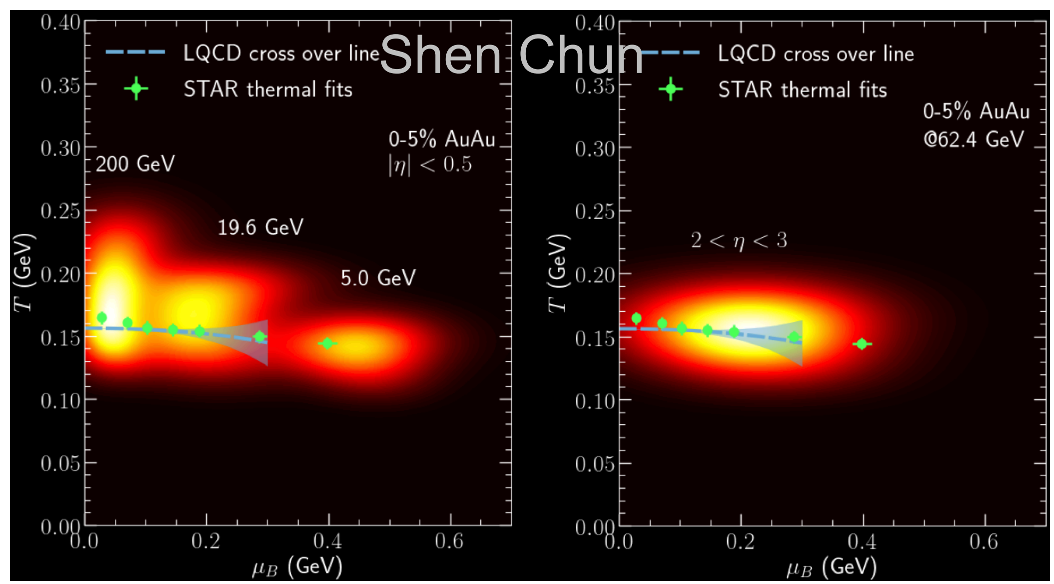

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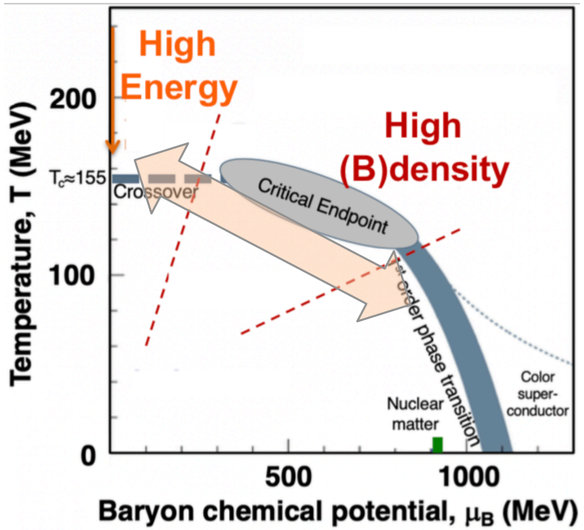

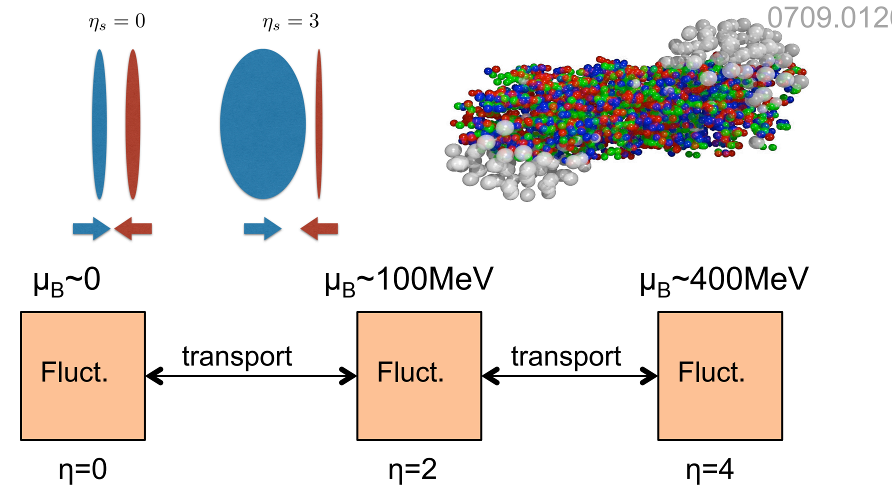

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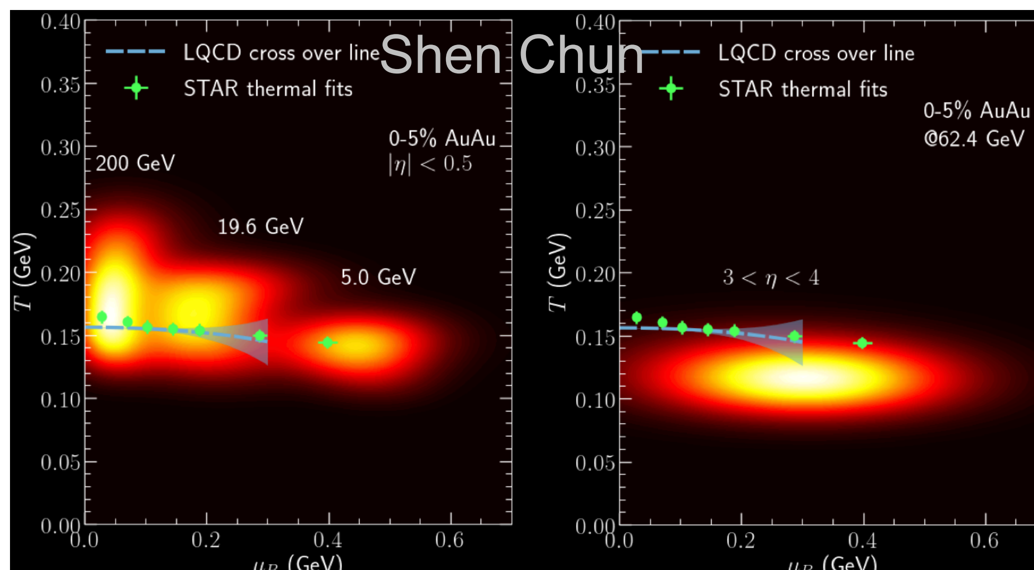
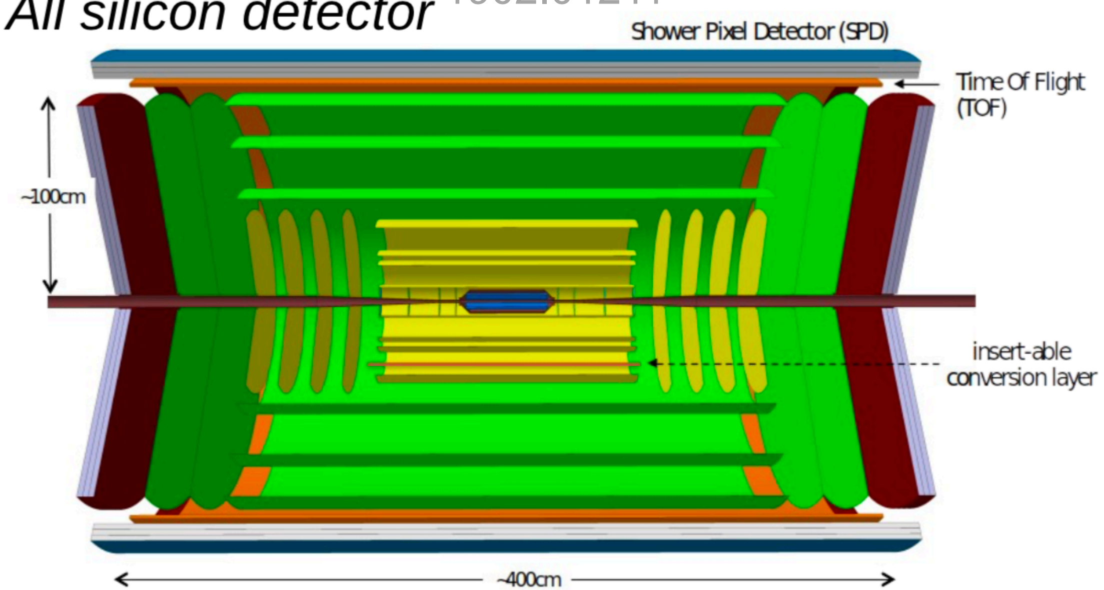


Rapidity Scan

- A possibility with future detector upgrades
  - STAR forward upgrade $2.5<\eta<4$ with p_T and maybe some PID information
  - ATLAS/CMS forward upgrades with some PID capability
  - New hermetic HI detector with PID and $|\eta|<4$
- LHC @ lower $\sqrt{s}$ and explore the rapidity correlations?

All silicon detector 1902.01211



Summary

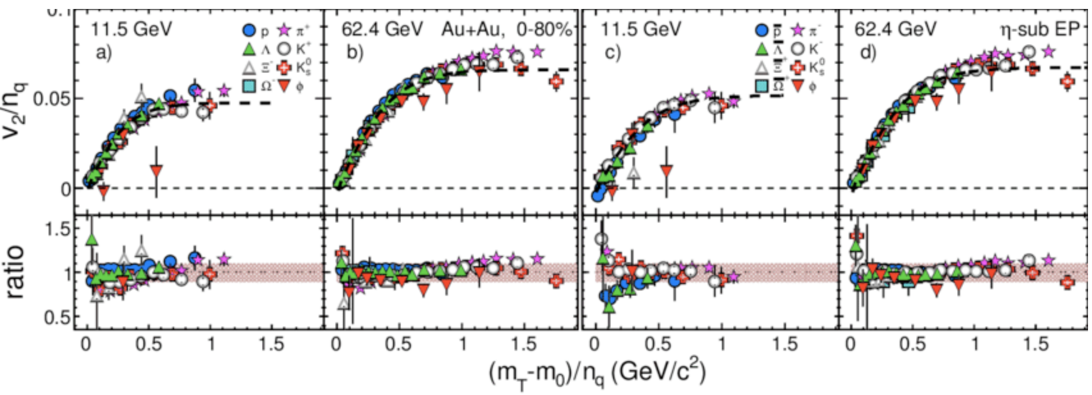
- Collective flow & hydrodynamics are most important tools to gain understanding on the dynamics and properties of HI

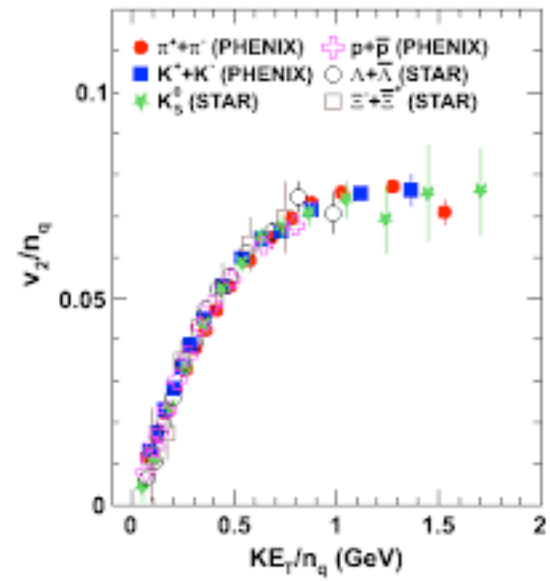
- Key challenge: how to disentangle different stages.
  - Initial geometry, initial flow and non-equilibrium dynamics
  - Longitudinal dynamics is crucial for BES
  - Comment: precision at high $\sqrt{s}$ as baseline for modeling the more complex physics at low $\sqrt{s}$.

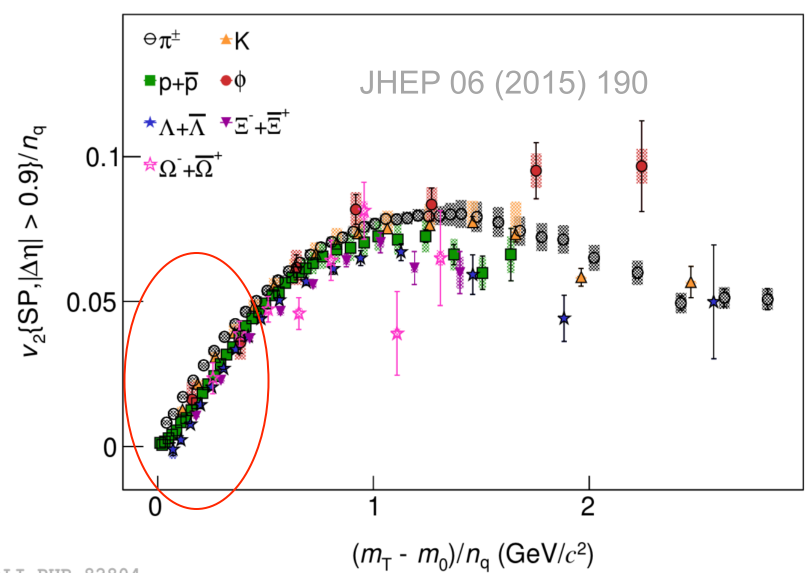
- Future opportunities
  - Need new approaches and observables to pinpoint initial state
  - Collision system scan to understand initial geometry and initial flow

    small A+A, deformation, alpha cluster
  - Rapidity scan as another handle on Phase diagram and longitudinal dynamics.

NCQ scaling


11.5 GeV
a)
62.4 GeV Au+Au, 0-80%
b)
11.5 GeV
c)
62.4 GeV η-sub EP
d)
v_2/n_q
ratio
$(m_T-m_0)/n_q$ (GeV/c^2)

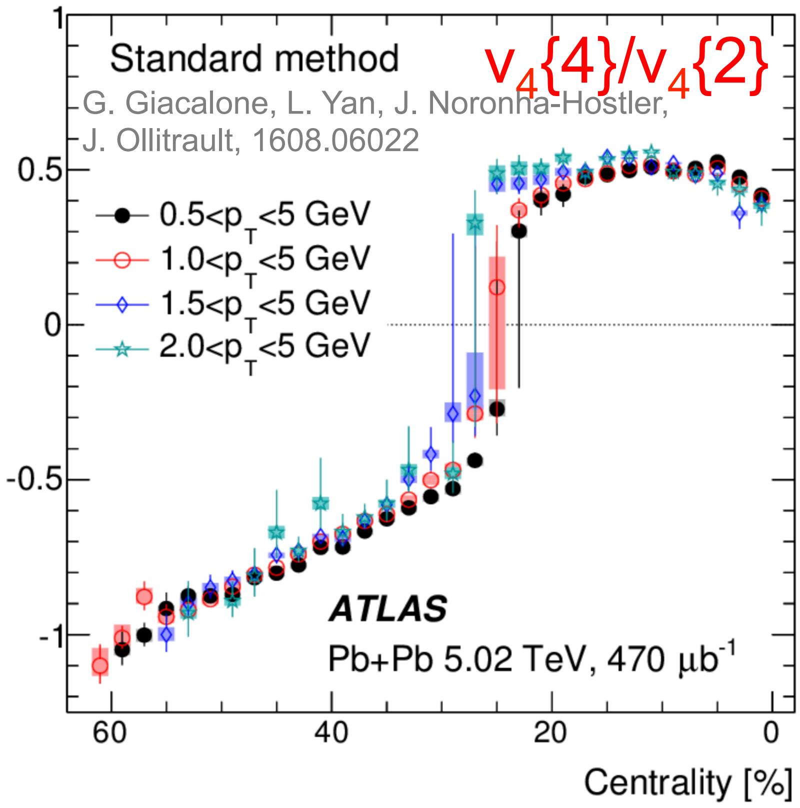

$\pi^++\pi^-$ (PHENIX)
$p+\bar{p}$ (PHENIX)
K^++K^- (PHENIX)
$\Lambda+\bar{\Lambda}$ (STAR)
K^0_S (STAR)
$\Xi^-+\bar{\Xi}^+$ (STAR)
v_2/n_q
KE_T/n_q (GeV)


$\pi^\pm$
K
$p+\bar{p}$
φ
$\Lambda+\bar{\Lambda}$
$\Xi^-+\bar{\Xi}^+$
$\Omega^-+\bar{\Omega}^+$
JHEP 06 (2015) 190
$v_2\{SP,|\Delta\eta|>0.9\}/n_q$
$(m_T - m_0)/n_q$ (GeV/c^2)

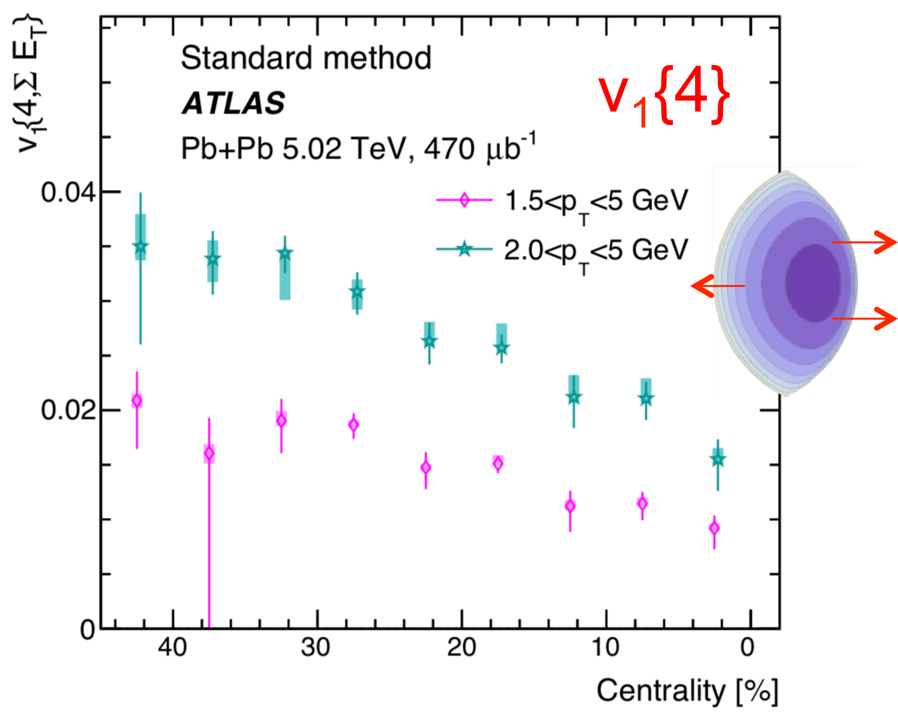
Higher-order flow fluctuations

$$(v_n\{4\})^4 \equiv 2\langle v_n^2\rangle^2 - \langle v_n^4\rangle$$

Peculiar sign change in v_4 fluctuations
→Not explained by non-linear effects



Significant dipolar flow fluctuations



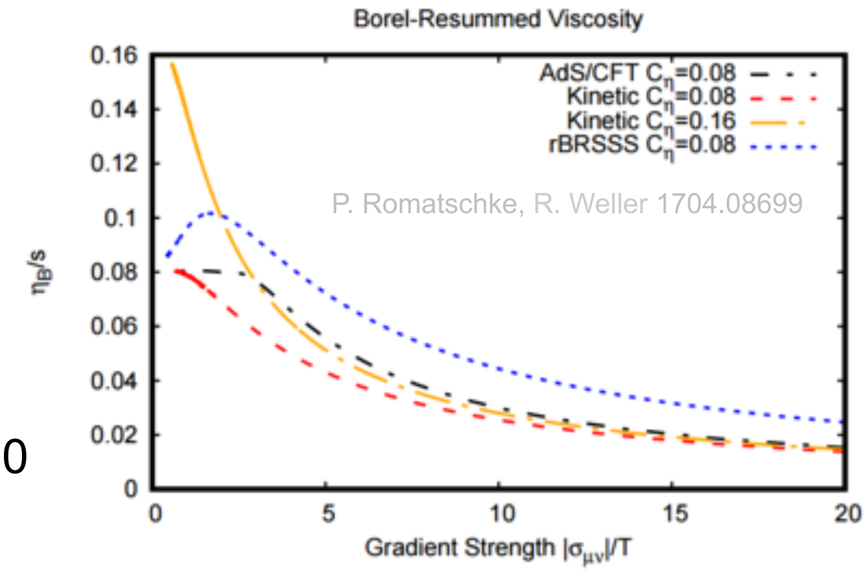
Unreasonable success of hydro?

- In far from equilibrium region, hydro still fit the data, but gives wrong viscosity

$$T^{\mu\nu}_{\text{hydro}} = (\epsilon + P_B)u^\mu u^\nu + P_B g^{\mu\nu} - \eta_B \sigma^{\mu\nu}$$

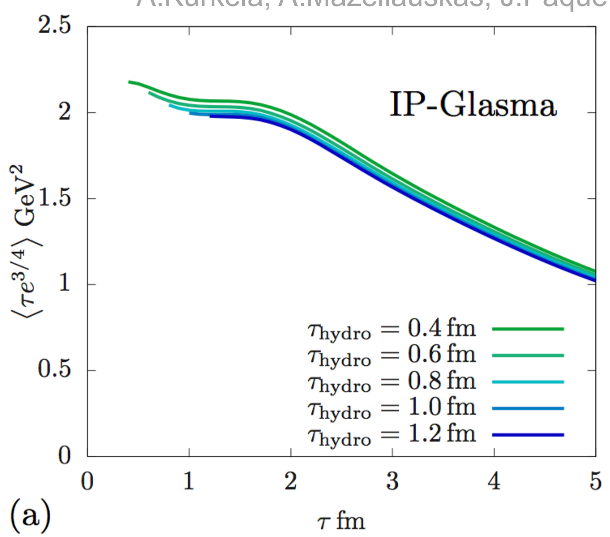
Small gradients $\eta_B \sim \eta$ Large gradients $\eta_B \to 0$

Also A.Kurkela, U.Wiedemann, B. Wu 1805.04081

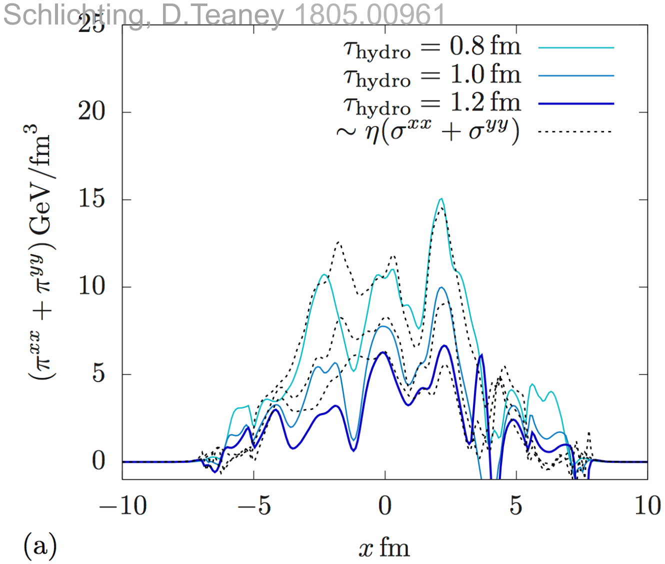


- Different models for early-time dynamics have similar average hydro-field, but different differential distri., e.g shear tensor $\pi^{\mu\nu}(\mathbf{x})$.

A.Kurkela, A.Mazeliauskas, J.Paquet, S.Schlichting, D.Teaney 1805.00961

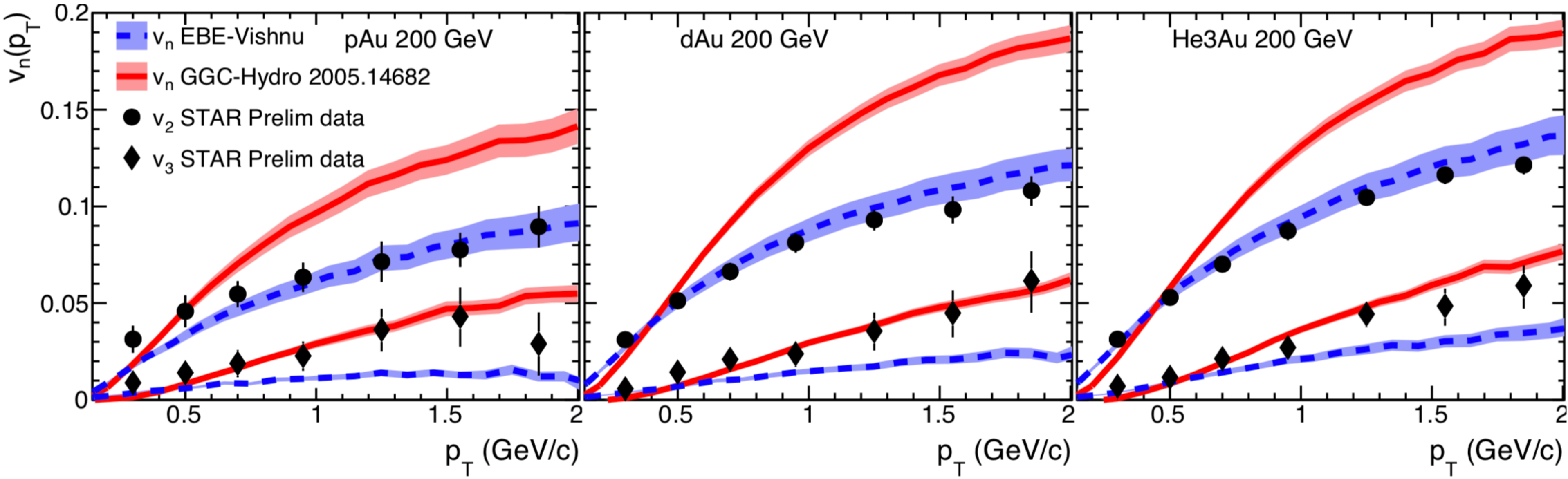


(a)



(a)

Small system

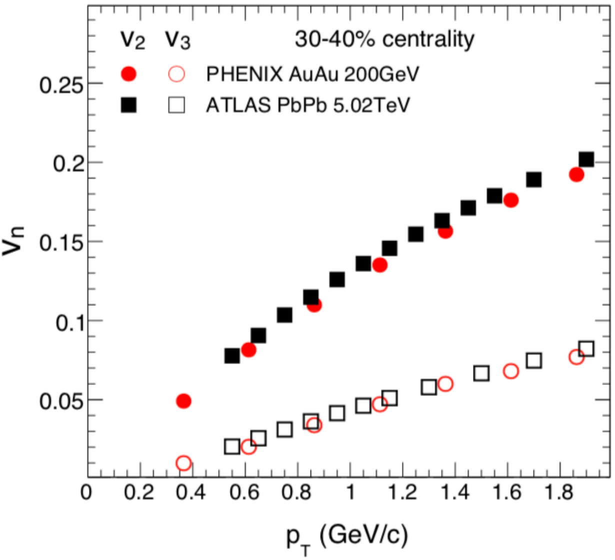


- Current models can't simultaneously describe v_2 and v_3
  - iEBE-Vishnu underestimate v_3
  - CGC-Hydro over-estimate v_2 (driven mainly by initial flow).

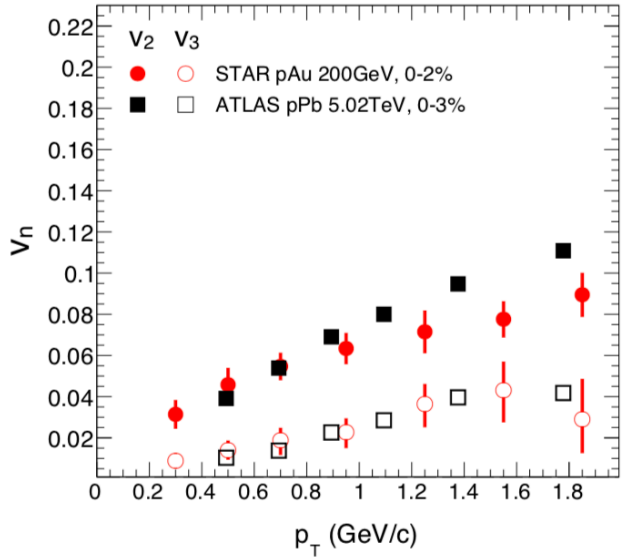
Bjoern Schenke,Chun Shen, Prithwish Tribedy, 1908.06212, 2005.14682,

Compare RHIC and LHC

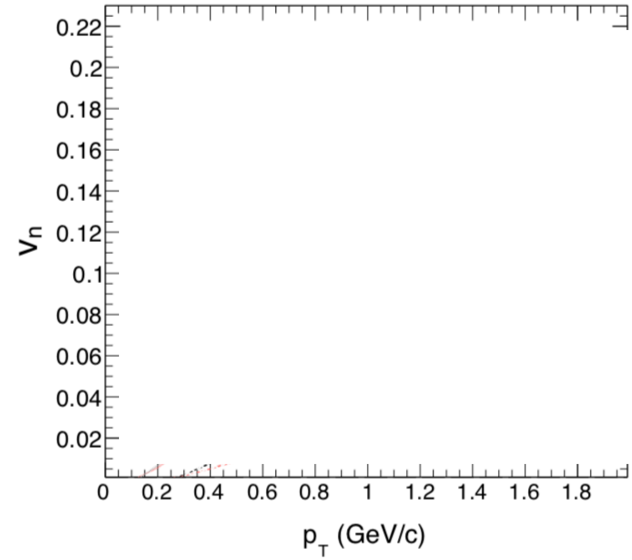
AuAu vs PbPb



pAu vs pPb



OO@RHIC vs OO@LHC?

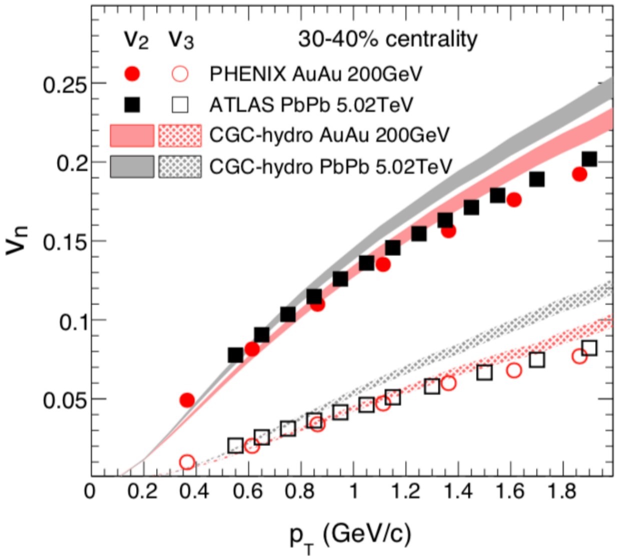


No difference between PbPb@LHC and AuAu@RHIC
No difference between pPb@LHC and pAu@RHIC
Will OO@LHC and OO@RHIC show consistent trend?

Agreement between two energies does not mean same viscous effects

Compare RHIC and LHC

AuAu vs PbPb



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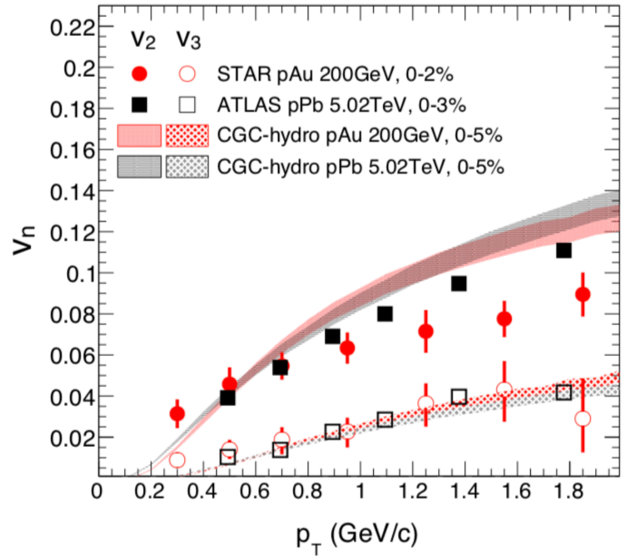

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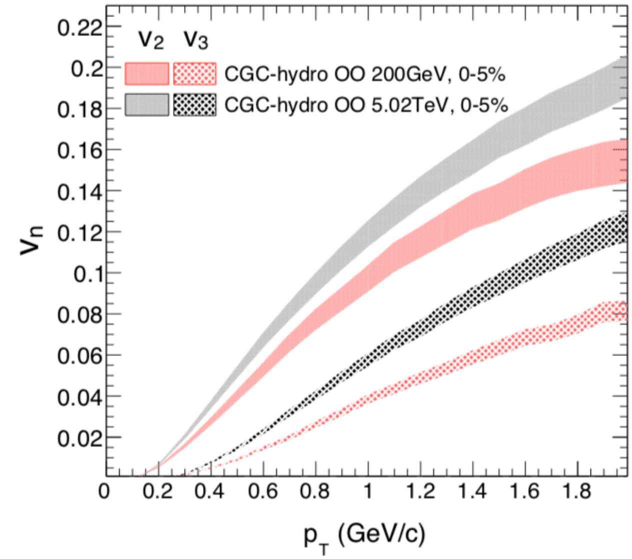

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Will OO@LHC and OO@RHIC show consistent trend?

What about model prediction?

- predict 30% difference for OO
- predict no difference for pA
- predict small difference for AA

The O+O comparison provides strong constraints on these models