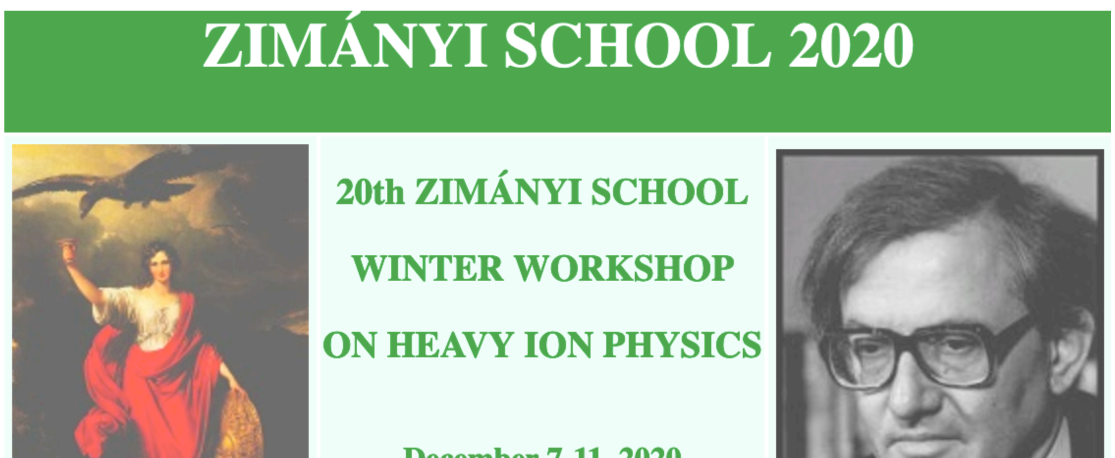
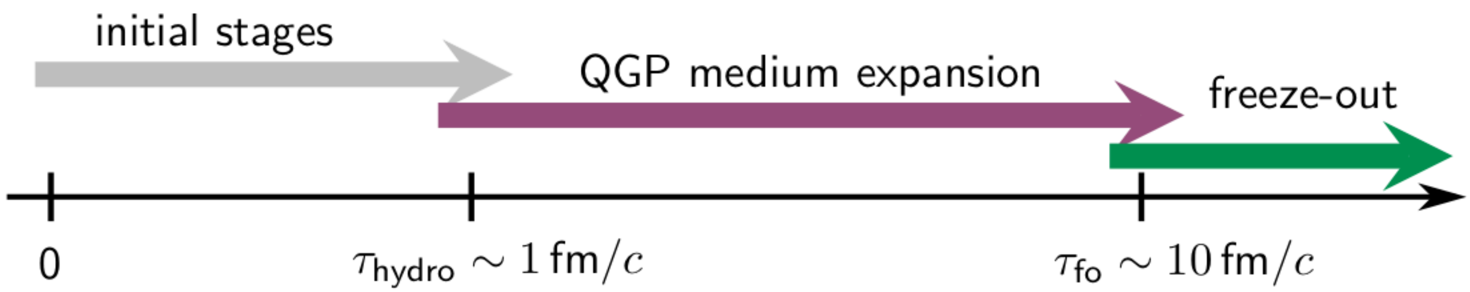
Stony Brook University | The State University of New York

Initial state and collective flow

Jiangyong Jia



Dynamics and properties of QGP

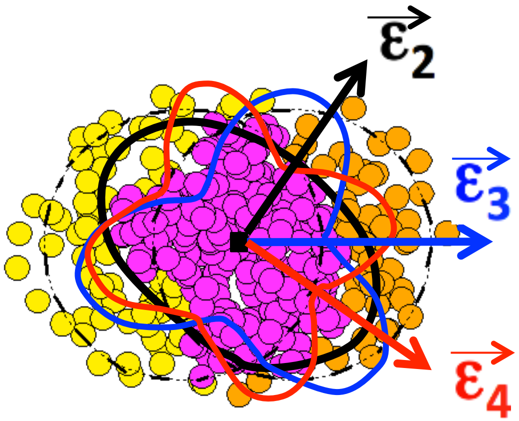


Challenge: simultaneous determination of two unknowns

Dynamics ⟺ Properties

Connecting the initial and final state

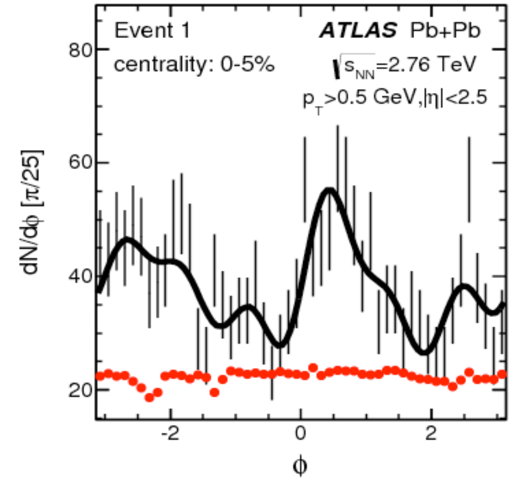
Initial state



Hydro-response

Space-time dynamics

Particle flow



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

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

Perturbing the system with different initial state fluctuations

Initial state structures in 3D

How fluctuations in x.y,z converted to fluctuations in p_x, p_y, p_z?

Cylindrical coordinate system: $\varphi, r, z \rightarrow \phi, p_T, \eta$

Fluctuations from event to event: consider only azimuthal modes

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n \mathrm{v}_n \cos n\left(\phi - \Phi_n\right)$$

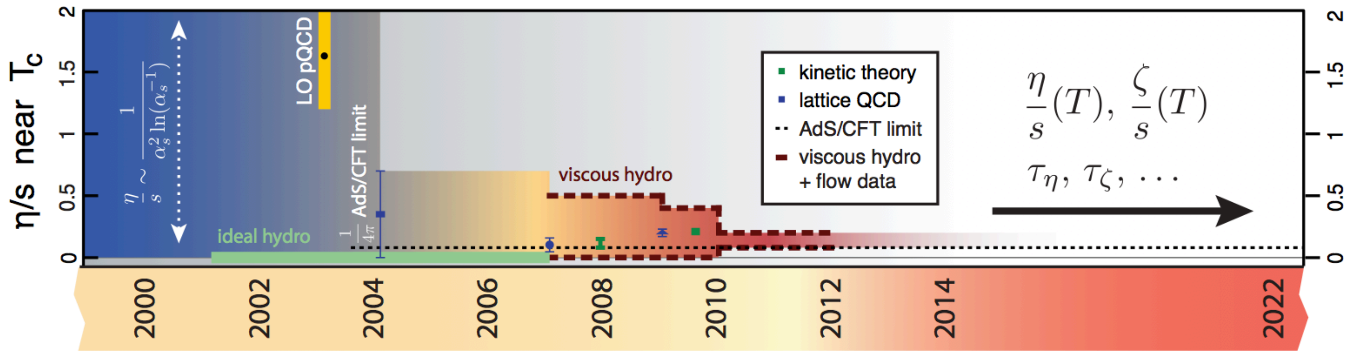
Fluctuations within a single event:

Radial modes → p_T space
Longitudinal modes → η space

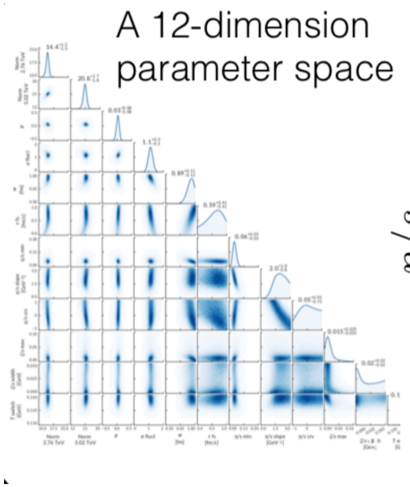
$$\frac{dN}{d\phi} \propto 1 + 2\sum_n \mathrm{v}_n(p_T, \eta, \ldots) \cos n\left(\phi - \Phi_n(p_T, \eta, \ldots)\right)$$

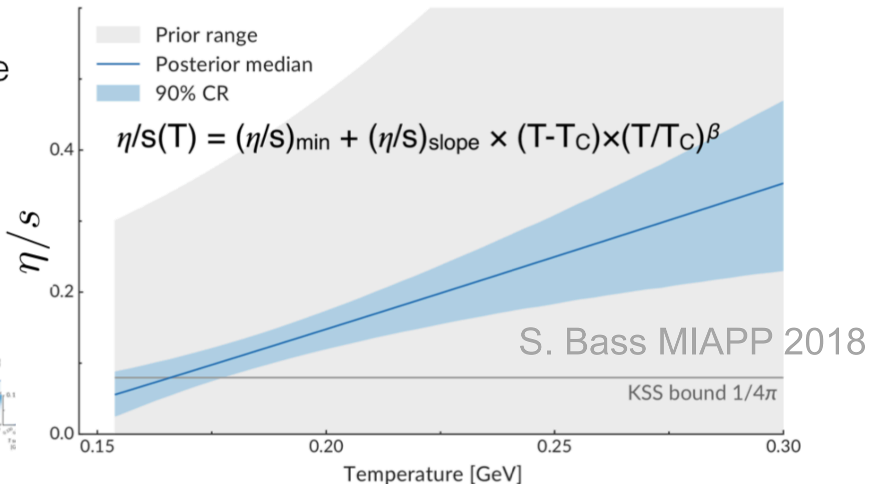
Success and challenges

- 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

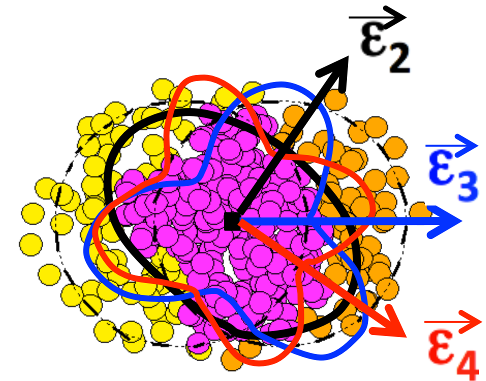




Hydrodynamics evolving into a precision tool for initial stages

Initial state: transverse

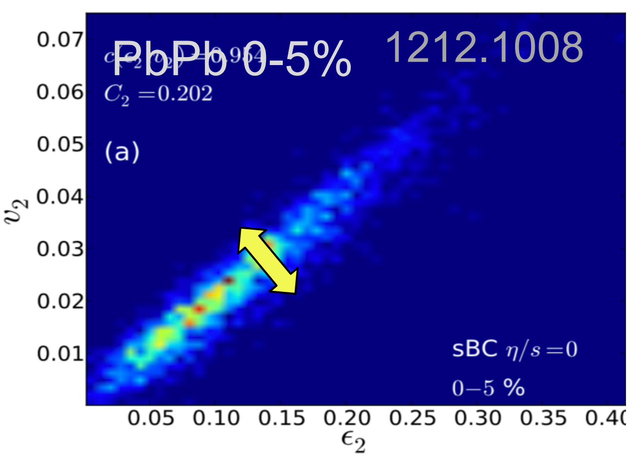
- EbyE overall shape fluctuations are by far the dominating modes
  - Linear response works well $v_n \propto \epsilon_n$

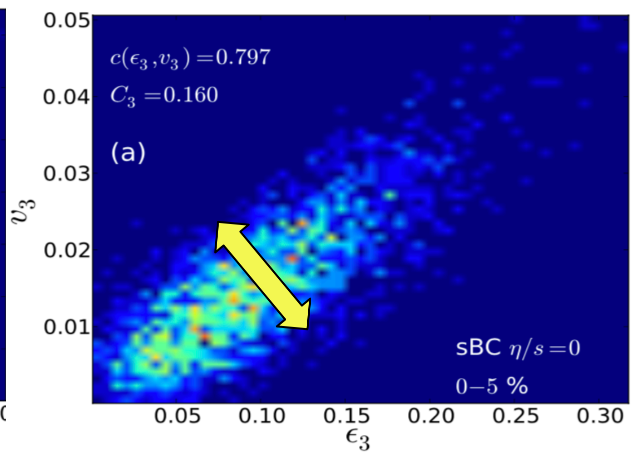


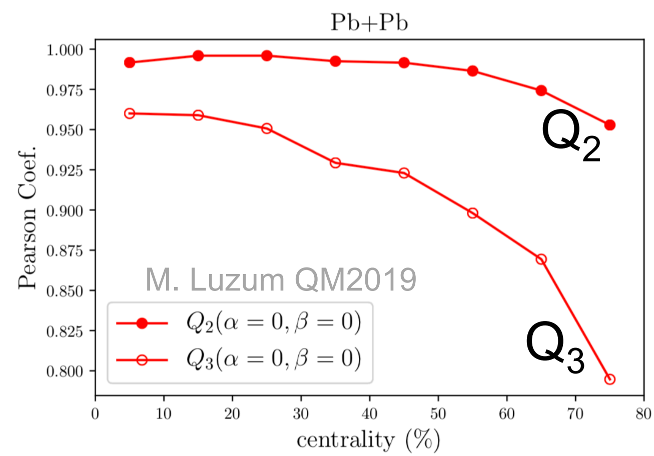
- But significant residual spreads observed

v_2 vs ε_2 v_3 vs ε_3

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



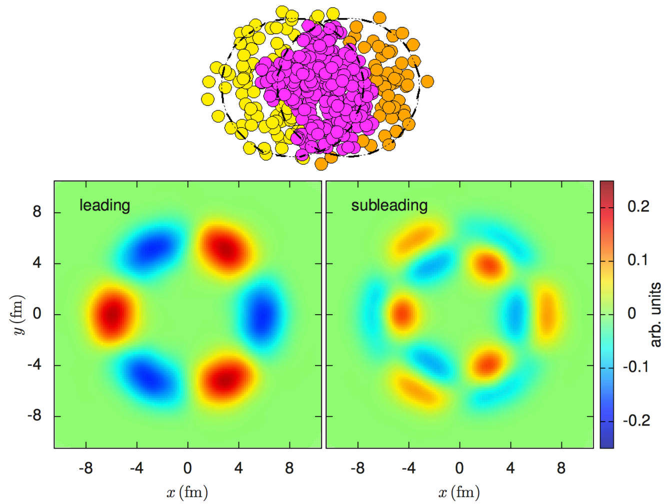




What is the origin of these spreads?

Dissecting the radial structures

- Leading ε_n do not capture radial fluctuations: subleading eccentricities



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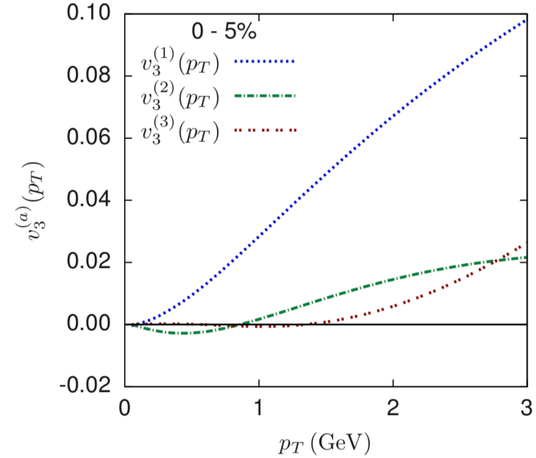
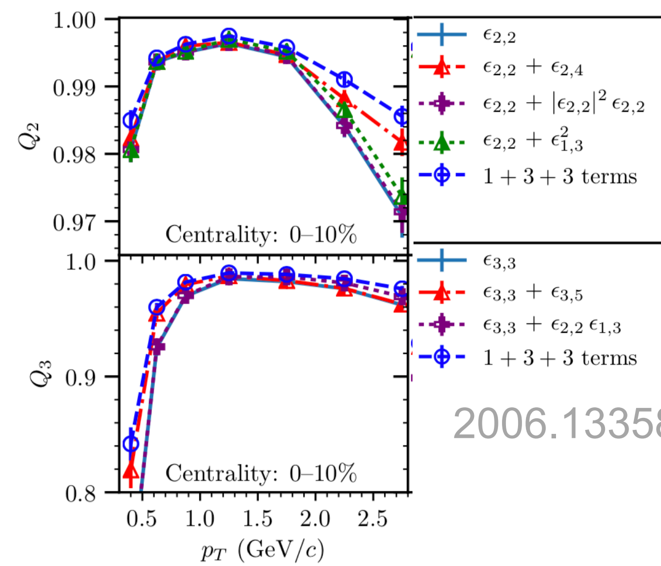


- Re-sum subleading ε_n and mode-mixing terms improves agreement

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



2006.13358

Significant residual still remain

Dissecting the radial structures

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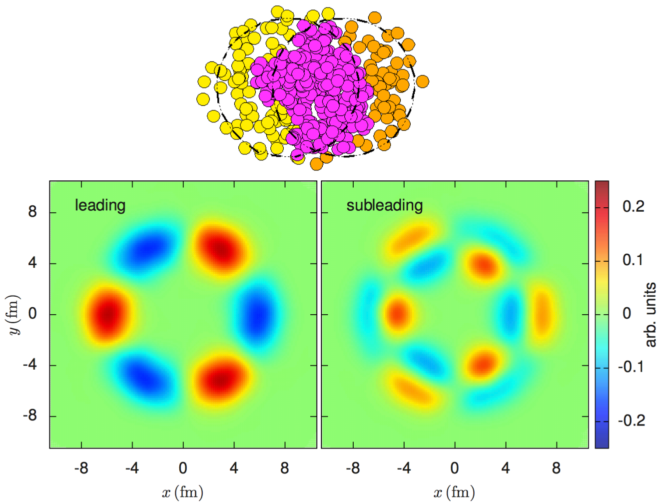

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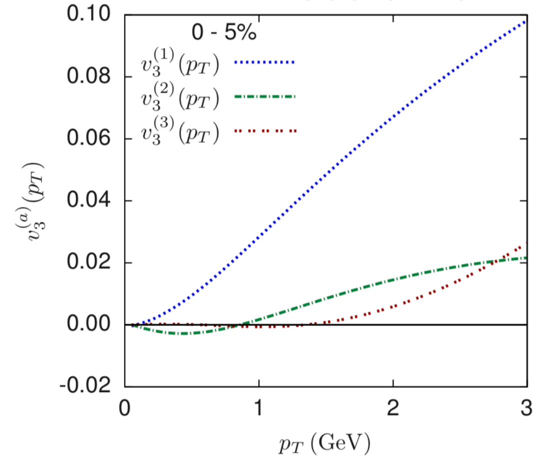
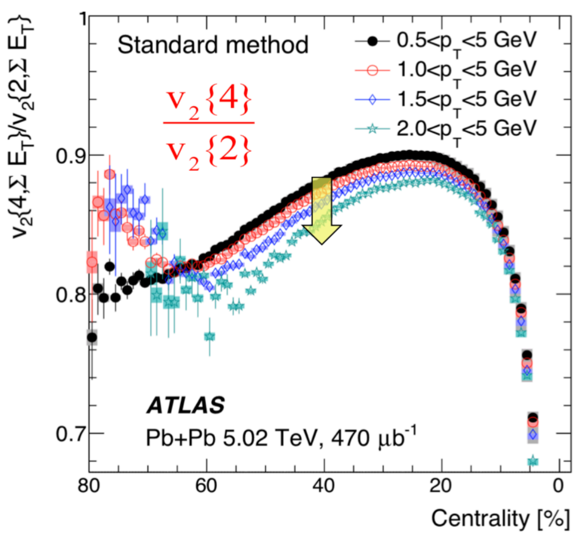


- Influence of subleading ε_n observed in multi-particle correlations

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

✗

Factorization breaking



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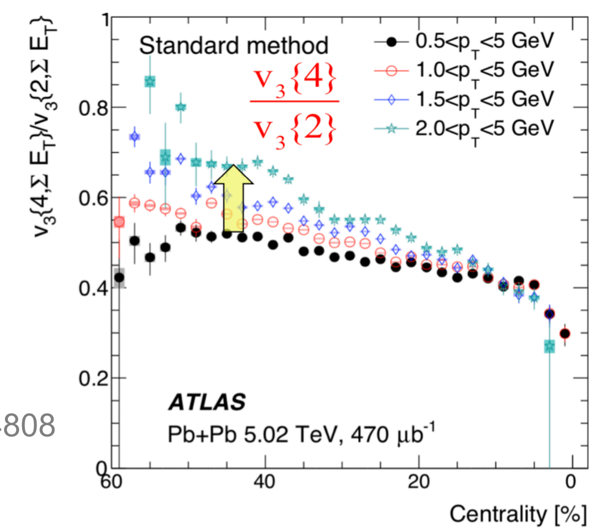
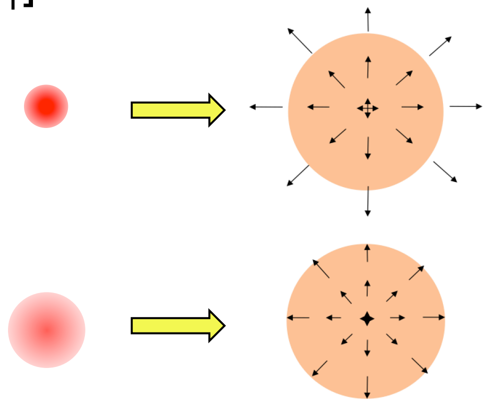


New handle on the initial state: v_n-p_T correlation

$[p_T]$ anti-correlates with size



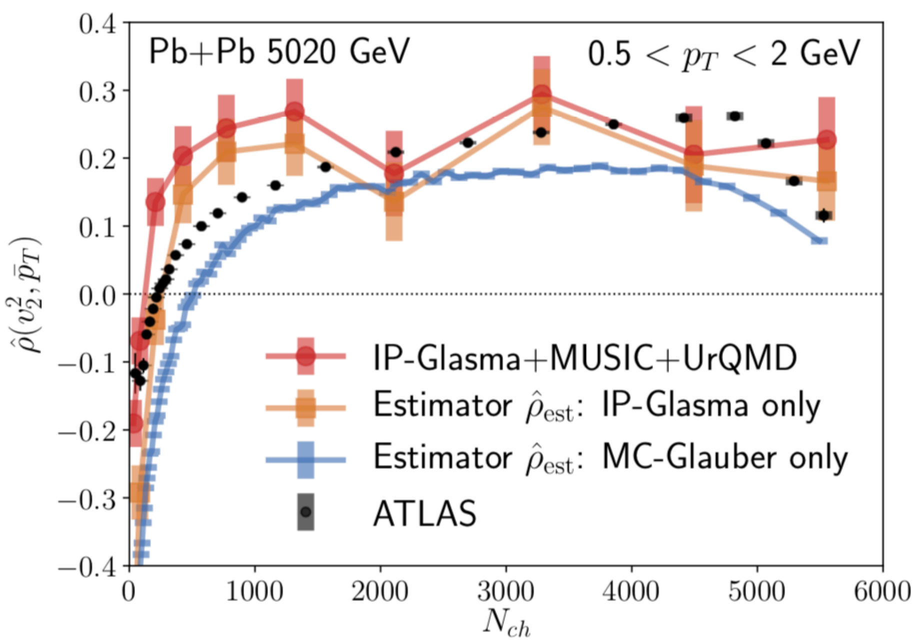
$$v_n \propto \epsilon_n \qquad \langle p_T \rangle \sim 1/R$$

Fluctuations in shape and size

→Correlations in azimuthal & radial flow

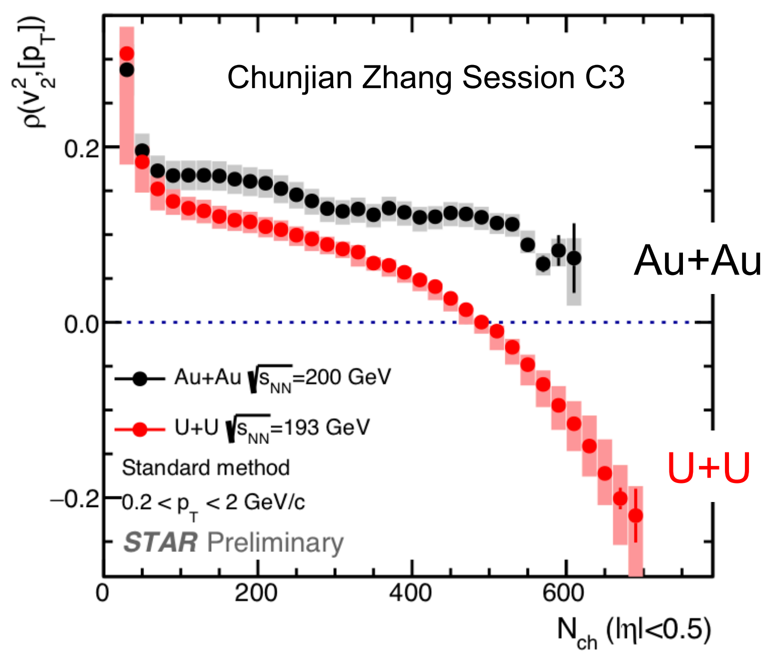
→Correlations in v_n-p_T

sensitive to shape-size correlation



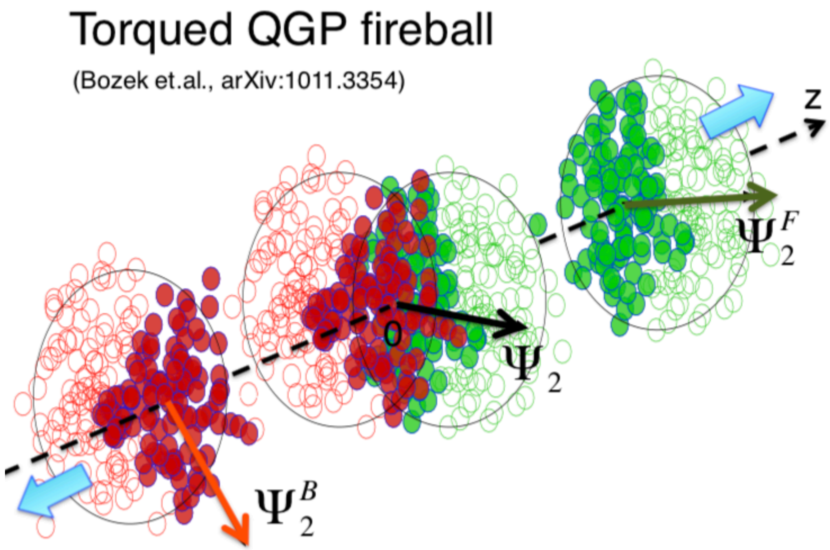
v_2^2-$[p_T]$

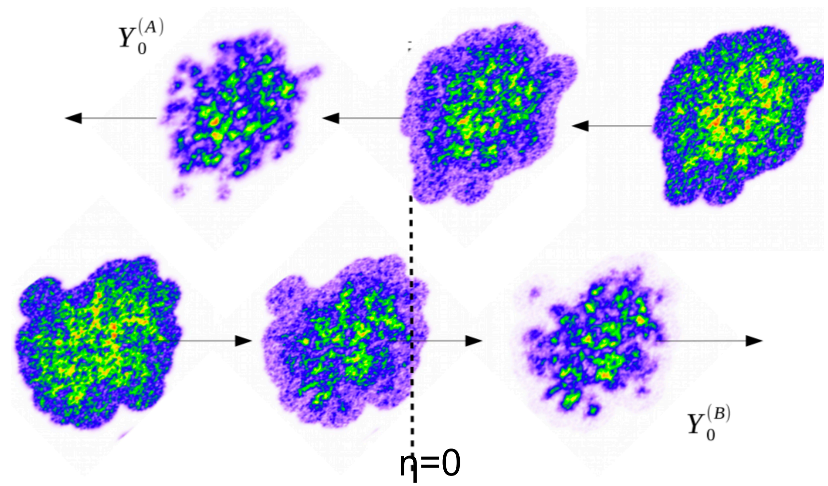
Probe nuclear deformation



Initial state: longitudinal

- The initial state of each event fluctuates longitudinally





$\langle \vec{\varepsilon}_n(\boldsymbol{\eta}_1^s)\vec{\varepsilon}_n^{\,*}(\boldsymbol{\eta}_2^s)\rangle \Rightarrow \left\langle \vec{V}_n(\boldsymbol{\eta}_1)\vec{V}_n^{\,*}(\boldsymbol{\eta}_2)\right\rangle$ Flow de-correlation 1011.3354

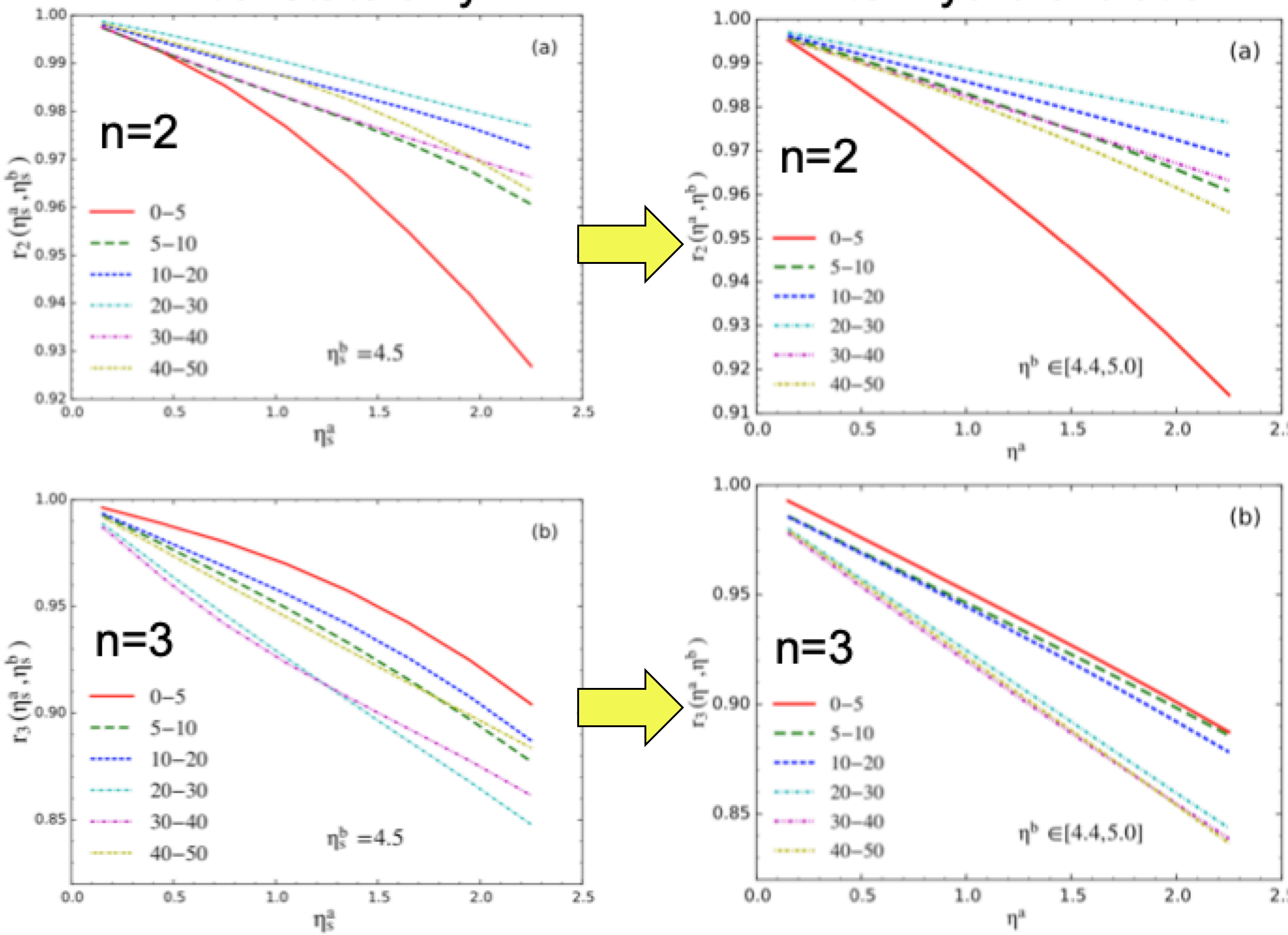
$\langle \varepsilon_0(\boldsymbol{\eta}_1^s)\varepsilon_0(\boldsymbol{\eta}_2^s)\rangle \Rightarrow \langle N(\boldsymbol{\eta}_1)N(\boldsymbol{\eta}_2)\rangle$ Multiplicity/centrality de-correlation

1803.01812, 2001.08602

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

Initial state only

After hydro evolution



Longgang Pang et.al . 1511.04131

Decorrelations dominated by initial stages

Compare Xe+Xe and Pb+Pb

- Consider Glauber model with parameterized longitudinal structure
  - Describe v_n-ratio vs N_{part} → viscous effects cancels at same N_{part}
  - Describe F_n-ratio vs $N_{part}/2A$ → FB asymmetry control by centrality

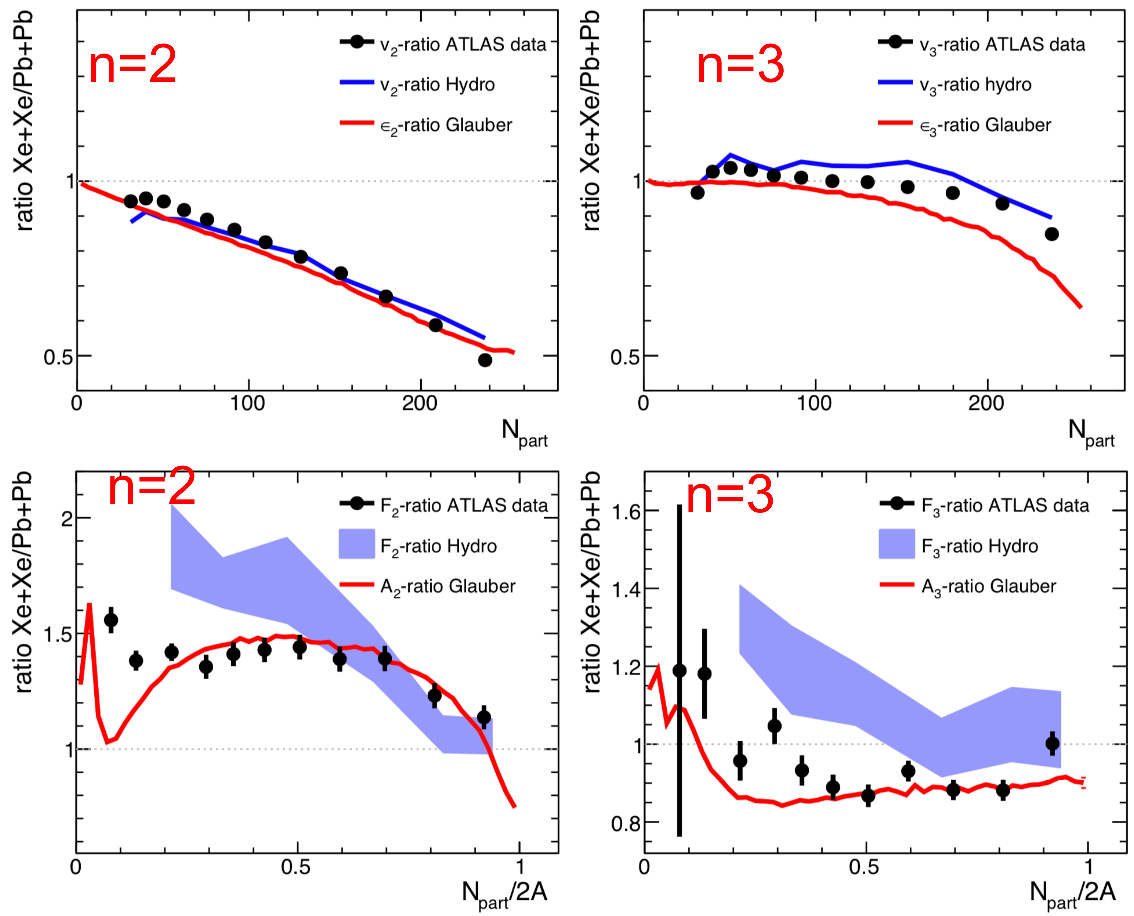
1709.02183
2001.04201

Ratio of inclusive flow

$$\frac{v_n(\eta)^{\rm XeXe}}{v_n(\eta)^{\rm PbPb}}$$

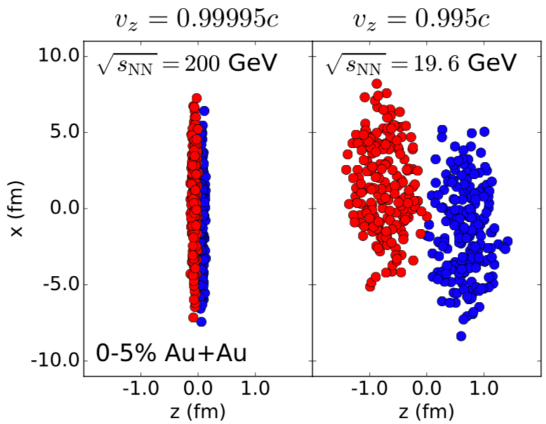
Ratio of flow decorrelation

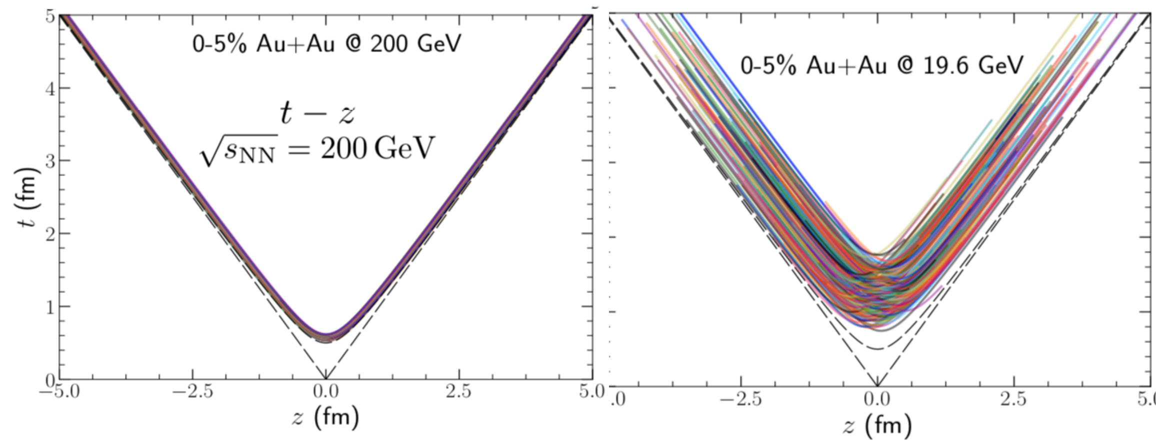
$$\frac{r_n(\eta)^{XeXe}}{r_n(\eta)^{PbPb}}$$



Better agreement than hydro → wrong longitudinal initial state?

Beam-energy scan: further break boost-invariance

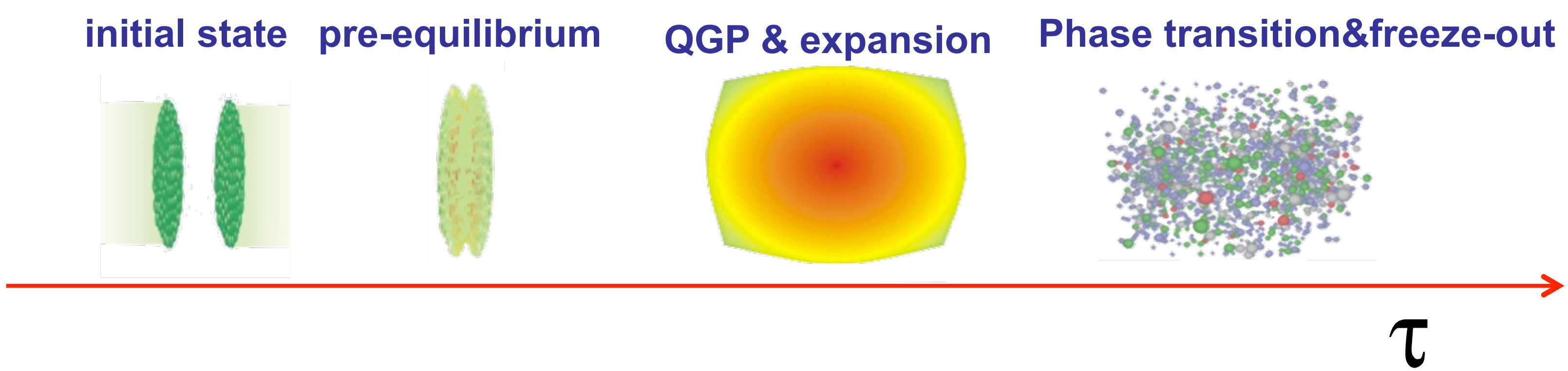




Nuclear overlap time becomes large at lower energies

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

Different stages no longer separated



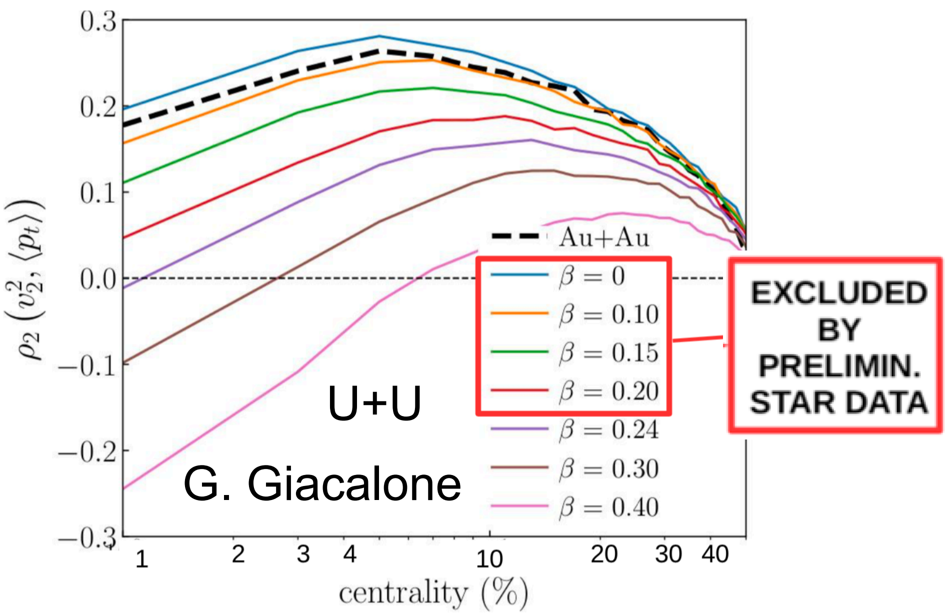
Longitudinal dynamics as important as transverse dynamics


Towards the future

Collision System Scan

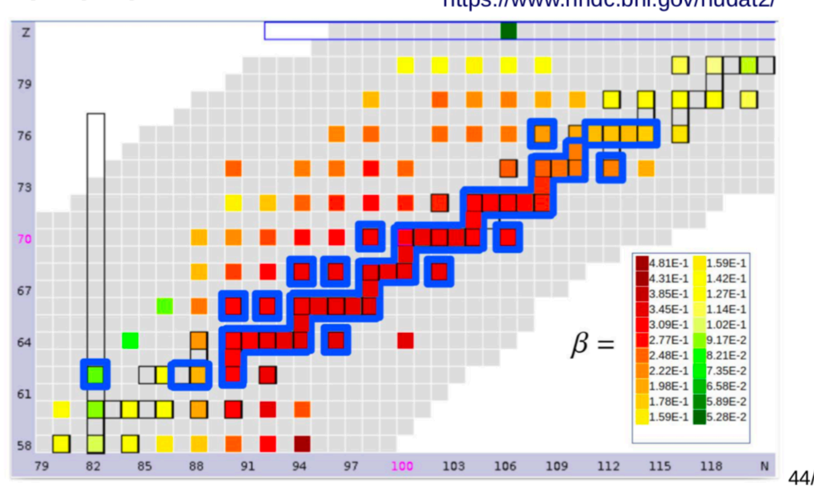
- Beam Energy Scan program has been vastly successful
  - Explore QCD Phase diagram
  - Bridge between high T and high μ_B frontiers
- A system-size scan could be equally fruitful
  - Detailed exploration of the initial state via hydrodynamics $v_n = k_n \varepsilon_n$
  - New tool for nuclear structure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

https://www.nndc.bnl.gov/nudat2/



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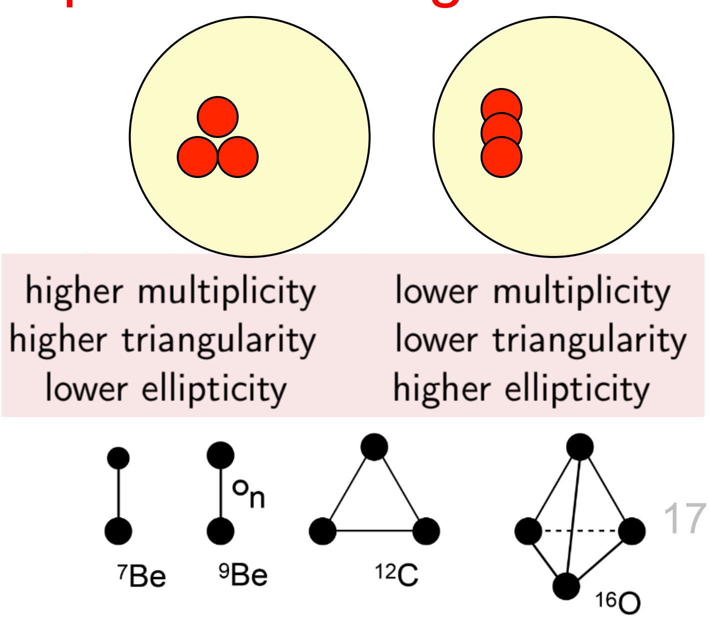
Alpha-clustering



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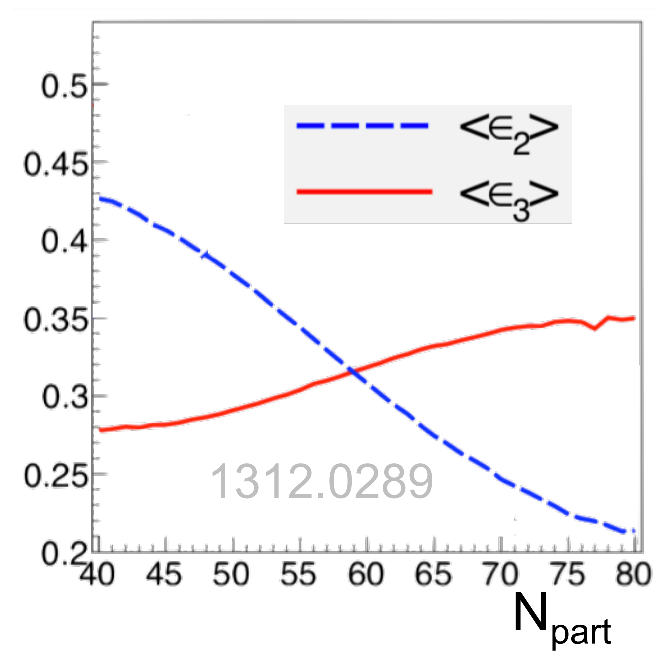
Analyzing ^{12}C via collisions with a "disk" of Au:



Explore Be/C/O+Au collisions

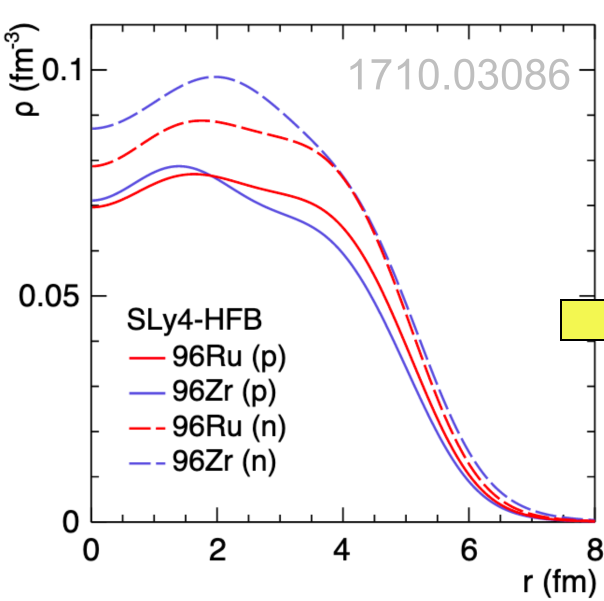
Collision System Scan

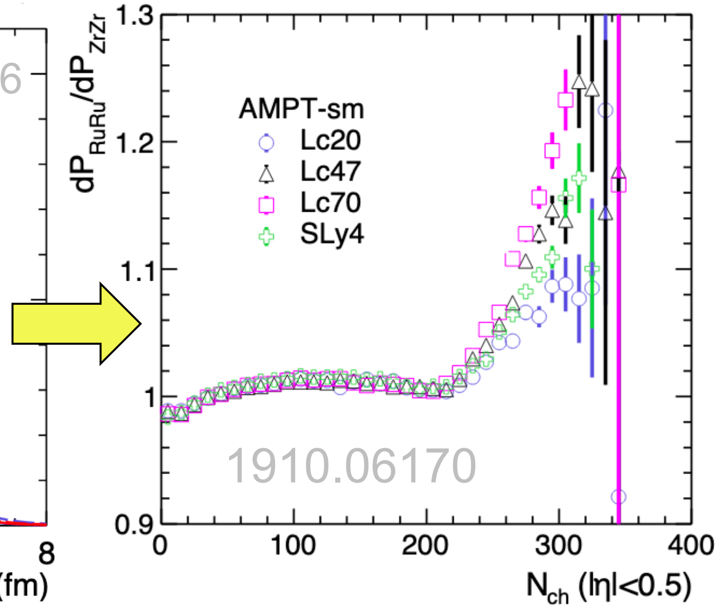
- Beam Energy Scan program has been vastly successful
  - Explore QCD Phase diagram Doable towards end of 2023-2027 era!
  - Bridge between high T and high μ_B frontiers
- A system-size scan could be equally fruitful
  - Detailed exploration of the initial state via hydrodynamics $v_2 = \kappa_2 \varepsilon_2$
  - New tool for nuclear structure physics via v_n-v_n, v_n-p_T, p_T-p_T correlations

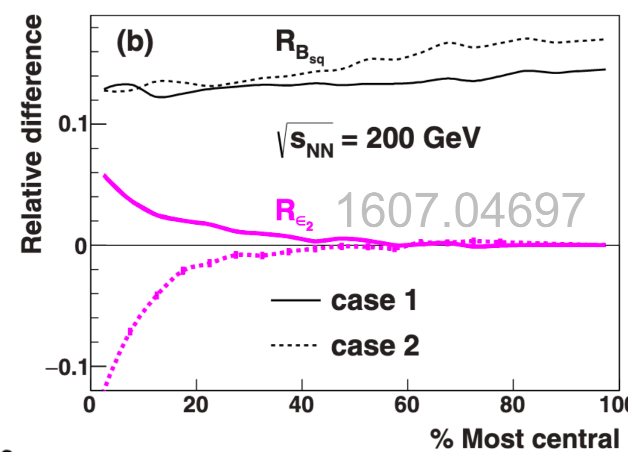
Neutron skin

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

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

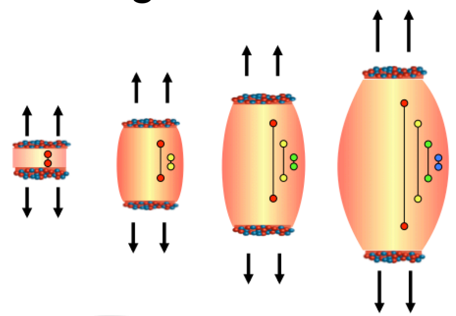




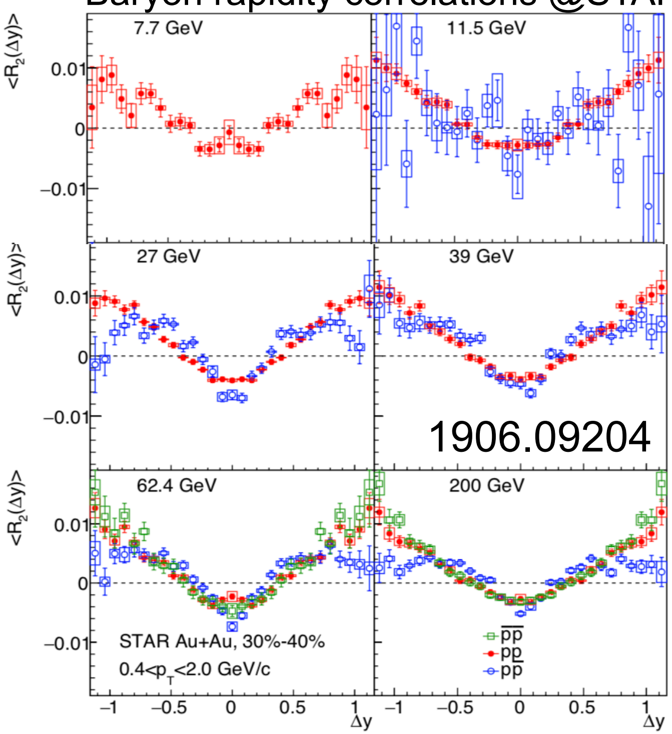


New frontier: Rapidity correlations

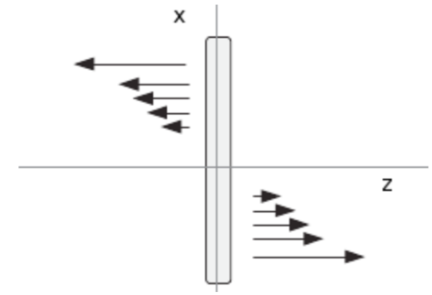
Many sources of fluctuations, generated at different time, and different longitudinal/transverse dynamics



Baryon rapidity correlations @STAR

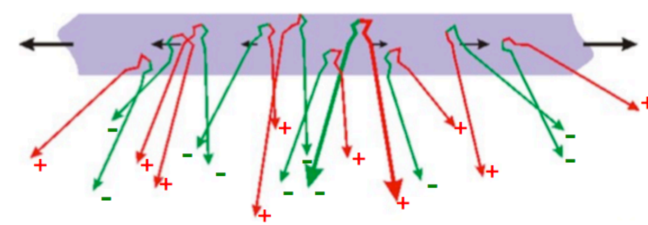


Longitudinal flow

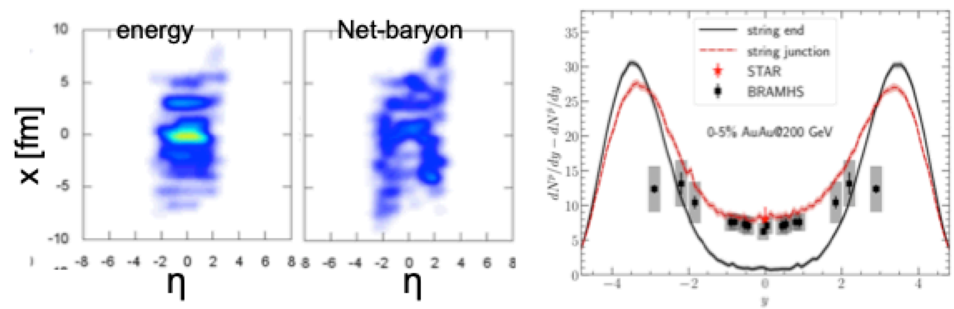


Charge transport

Balance function



Baryon transport

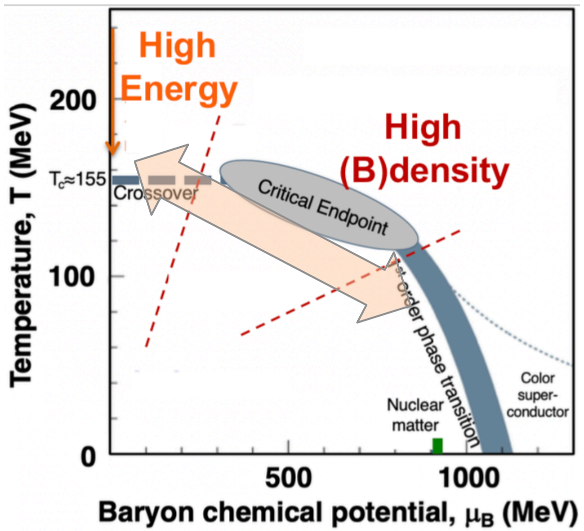


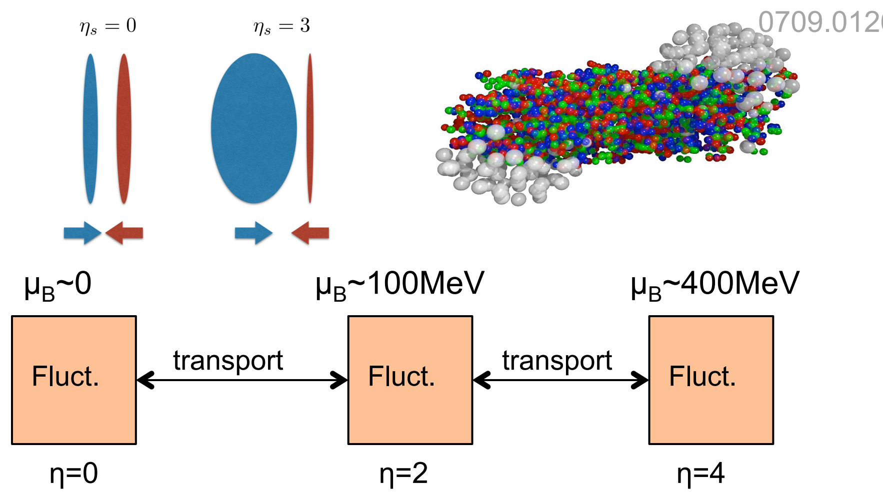
G. Denicol, C.Gale, S.Jeon, A.monnai, B.Schenke C.Shen 1804.10557

New handles on initial state

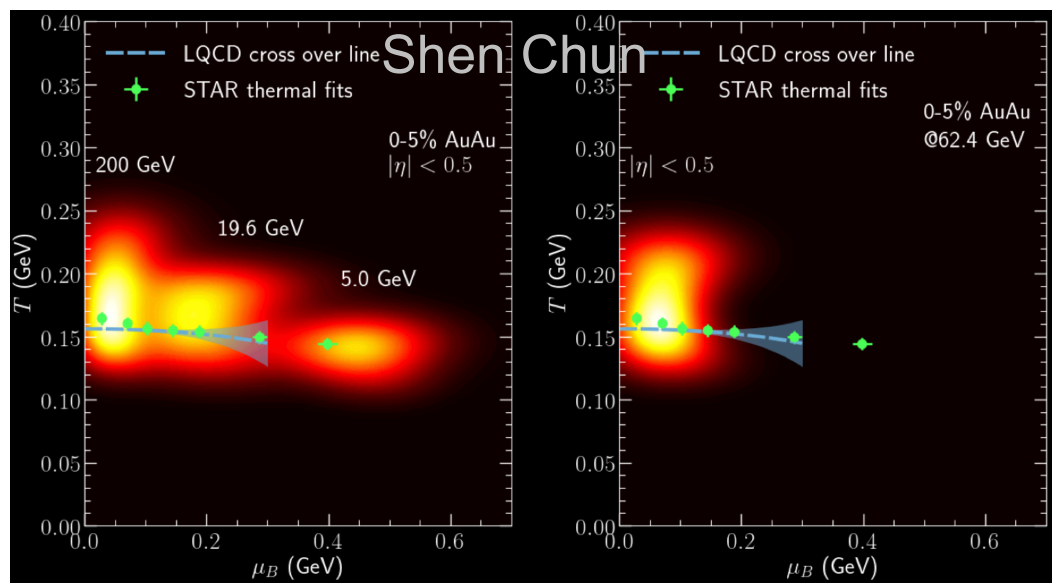
Rapidity Scan

- Rapidity scan at fixed √s ⟺ Beam-Energy scan within same event
  - Similar properties but very different dynamics
  - More information via fluctuations → more constrain on 3D hydrodynamics





New handle on phase diagram, dynamics and properties



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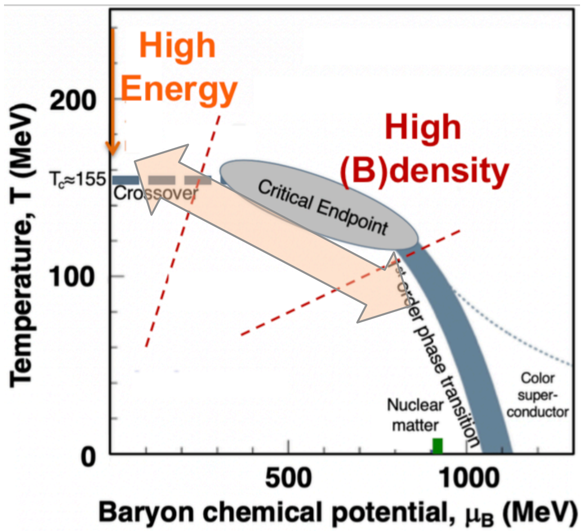

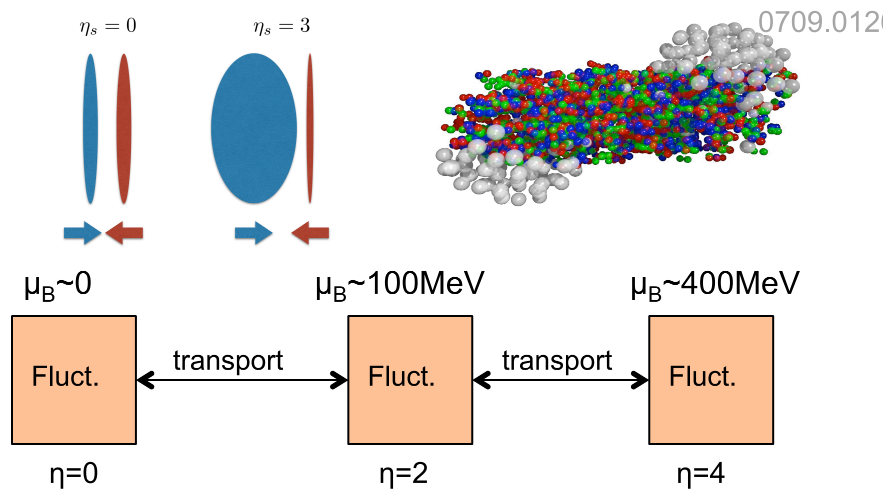

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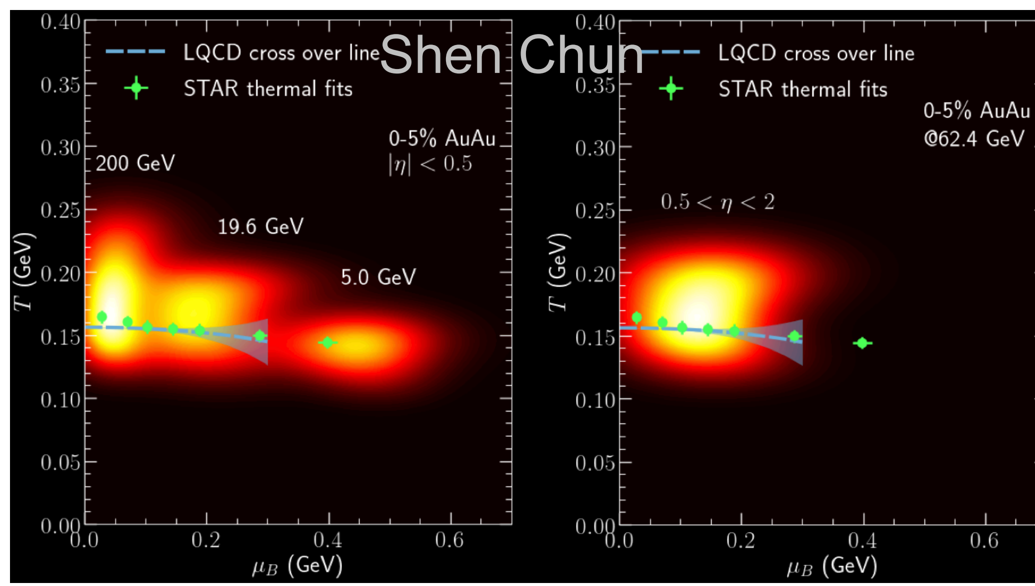

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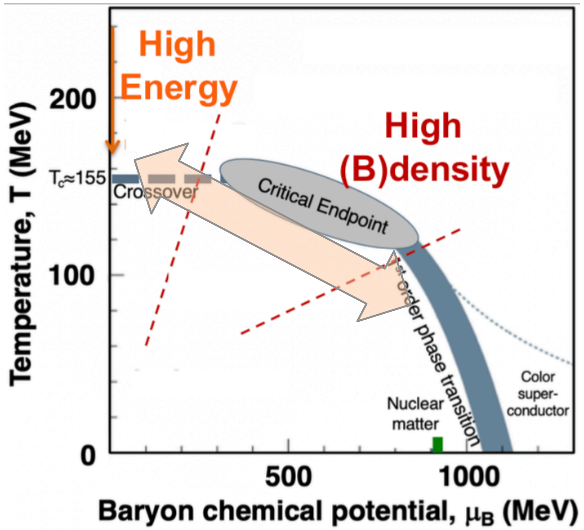

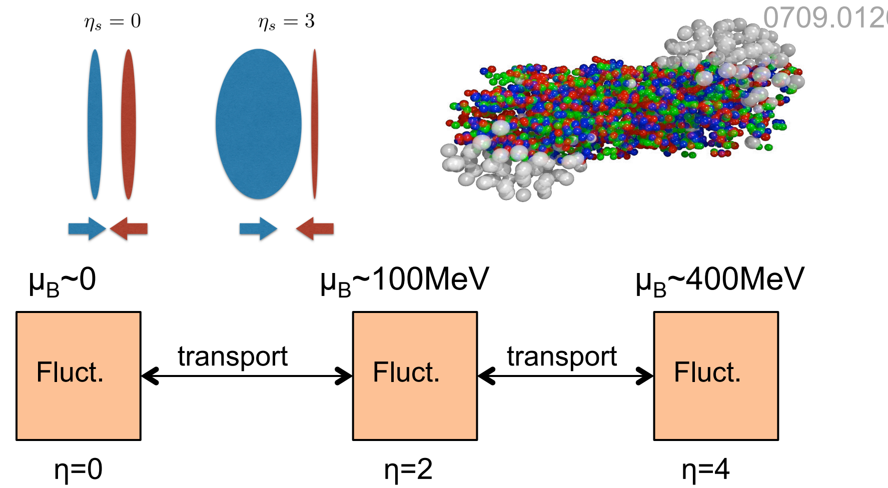

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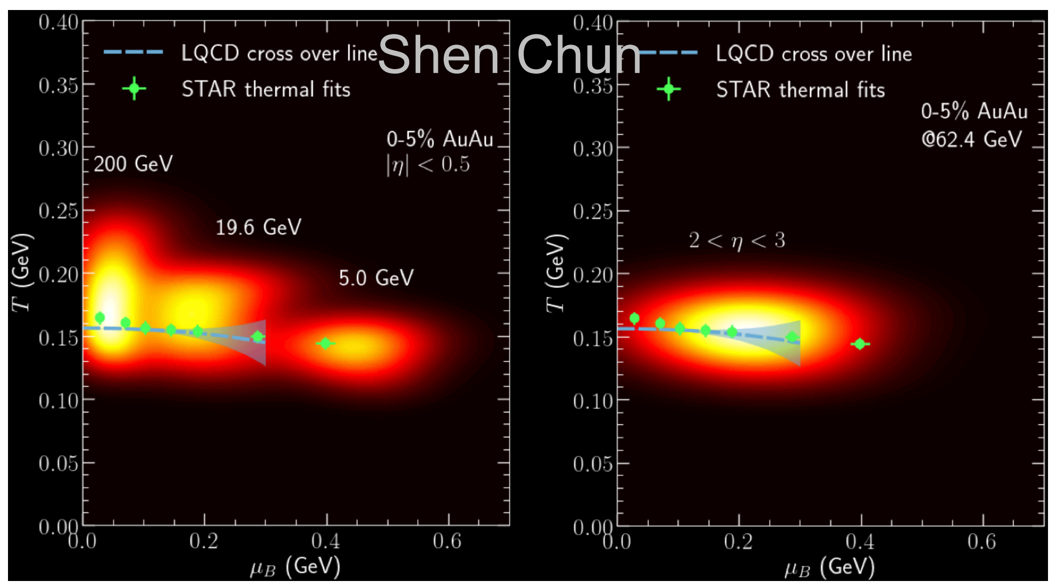

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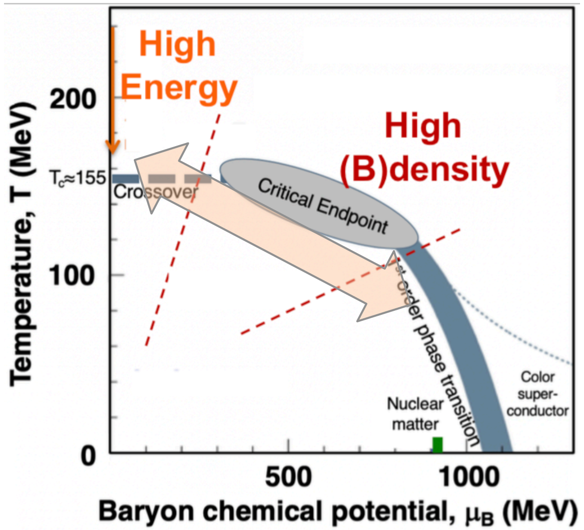

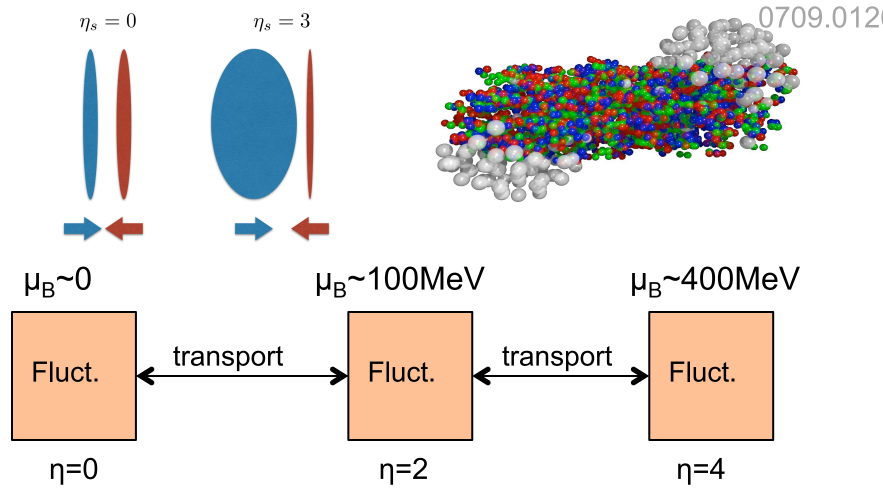

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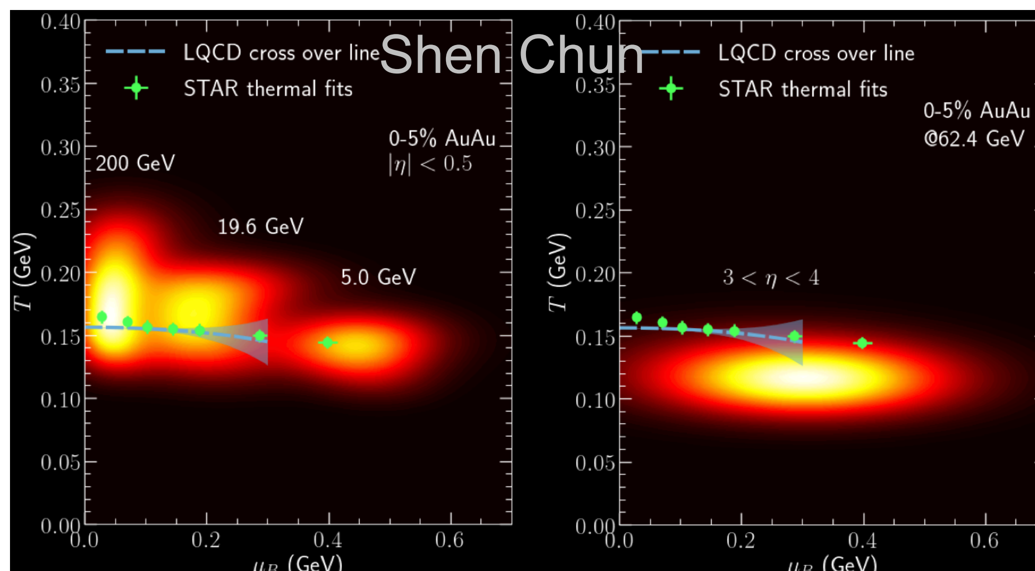
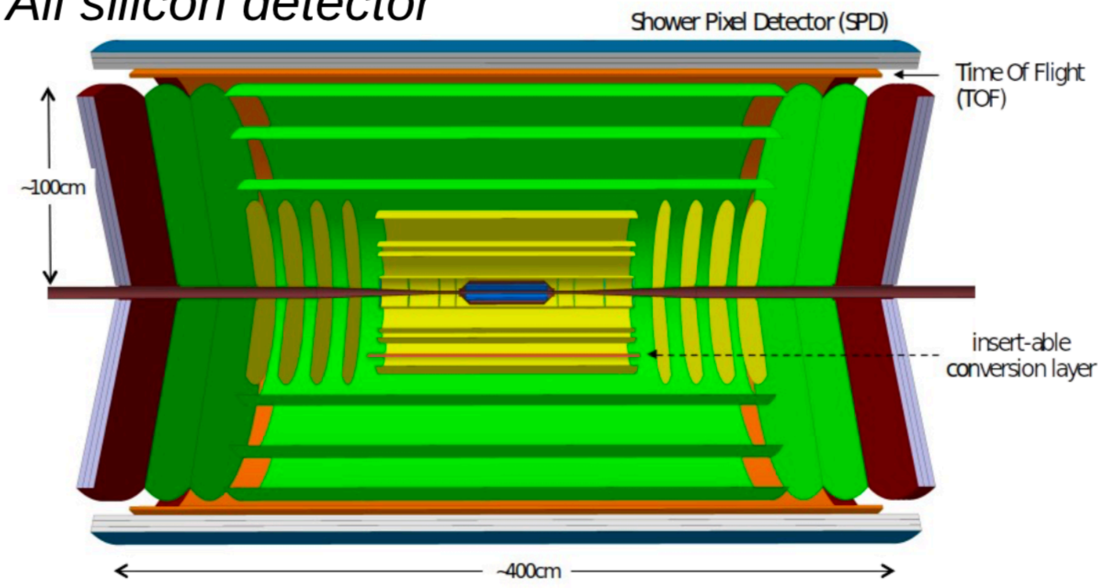


Rapidity Scan

- Possibilities 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 replaced ALICE detector with PID and $|\eta|<4$

All silicon detector 1902.01211



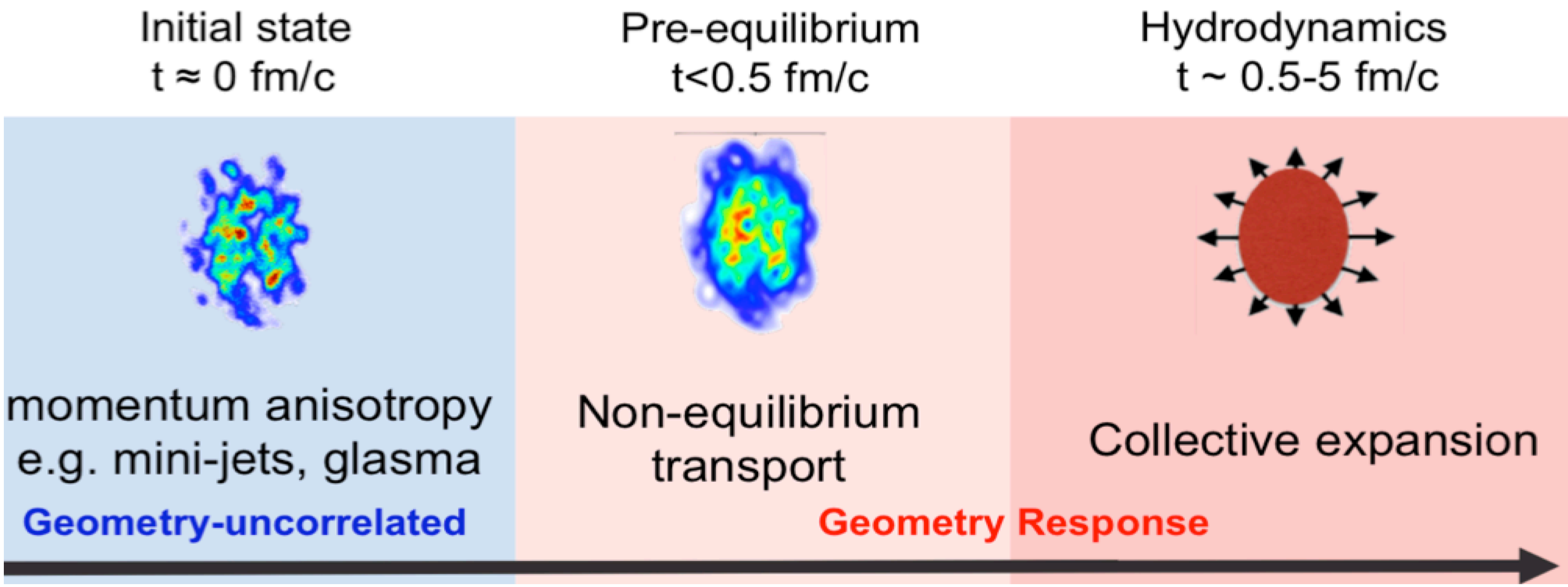
LHC @ lower $\sqrt{s}$ and explores rapidity correlations?

Summary

- Flow & hydrodynamics are precision tools to study the initial condition in 3D:
  - azimuthal, radial and longitudinal

- Future opportunities
  - Collision system scan as tool for nuclear structure physics
    - Also disentangle contributions from different stages (not discussed)
  - Rapidity scan as new handle on Phase diagram and longitudinal dynamics.

Challenge for understanding



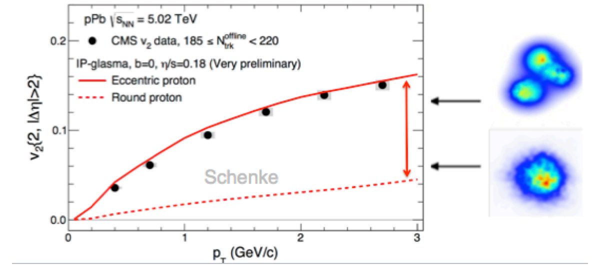
Contributions from different stages are difficult to disentangle

- 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

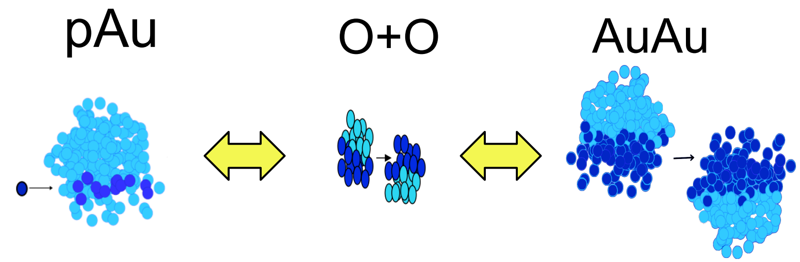
Hard to experimentally vary one ingredient at a time

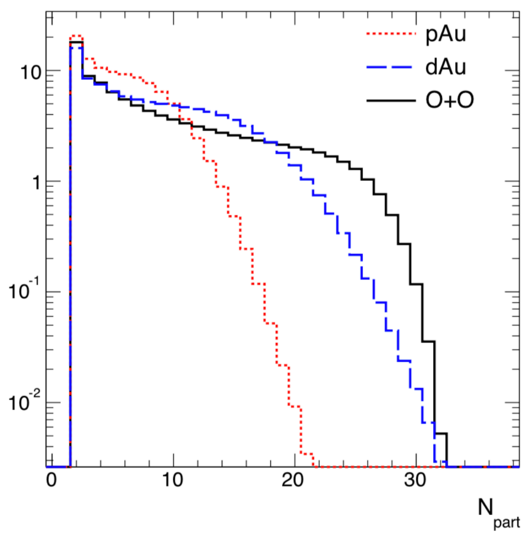
Why small A+A?

Subnucleon DOF is important for pAu ridge:



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

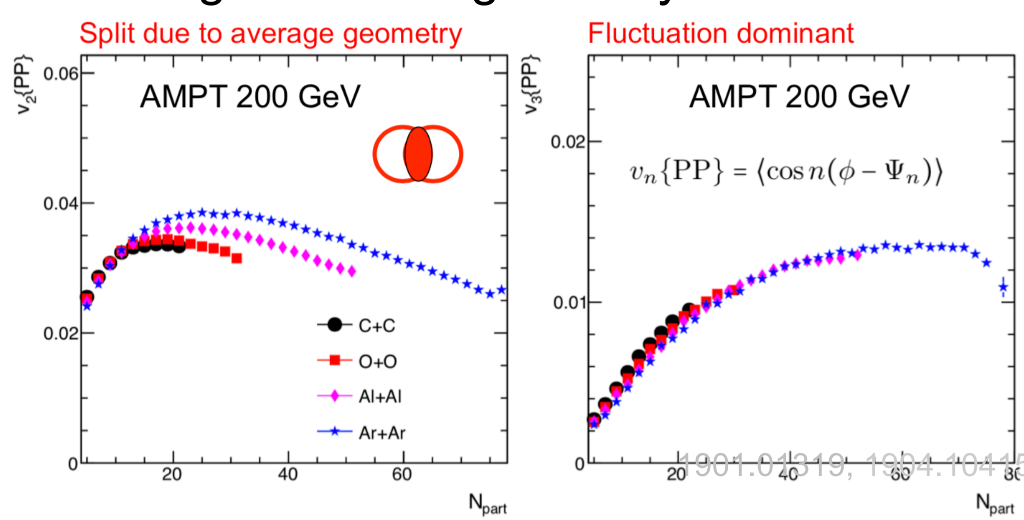




O+O a reasonable choice in terms of N_{part} coverage

	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).