Stony Brook University
FUDAN UNIVERSITY 復旦大學
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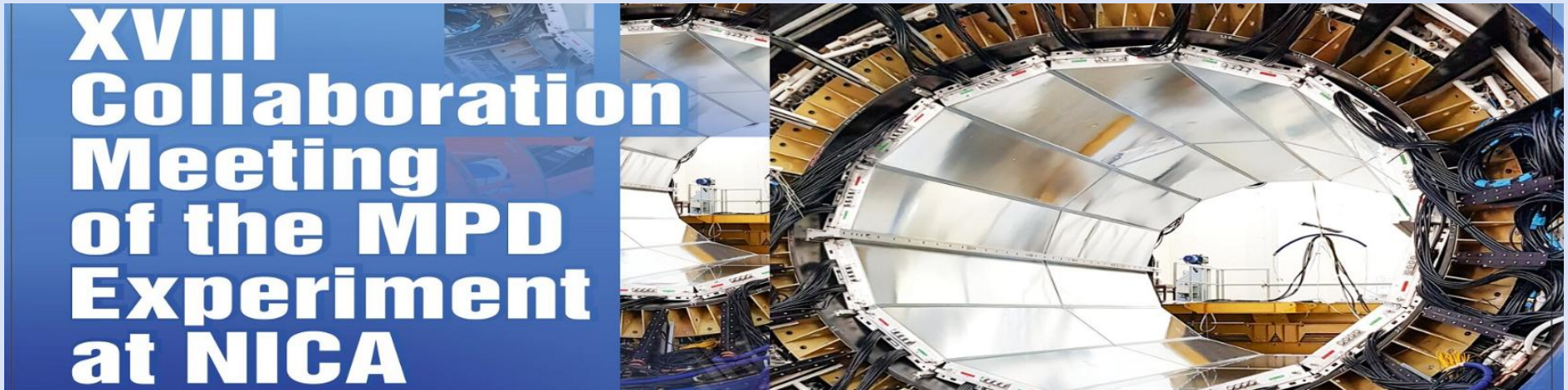
STAR collaboration
STAR 25 YEARS

Collision Energy and System Size Dependent Radial Flow Fluctuations at RHIC

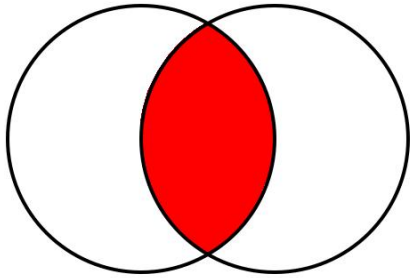
Zaining Wang

(for STAR Collaboration)



Evolution from initial to final

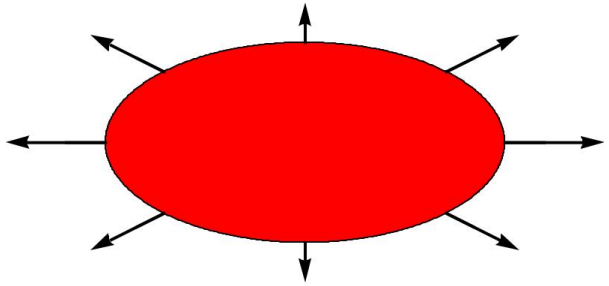
Initial



$F = -\nabla P(\epsilon)$

Hydro-response

Hydro flow: v_n^{Hydro}



Final

Shape $\varepsilon_n \propto \langle r_\perp^n e^{in\phi} \rangle$

Size $R_\perp^2 \propto \langle r_\perp^2 \rangle$

$$\frac{d^2N}{d\phi\, dp_T} = N(p_T)\left(1 + 2\sum_{n\geq 1} v_n \cos\left(n(\phi - \Psi_n)\right)\right)$$

Spectra shaped by radial flow

Anisotropic flow v_n

- Radial and anisotropic flow arise from the initial size and shape of the overlap region, and are transformed into final observables through collective hydrodynamic evolution;
- Sensitive to QGP transport properties and the equation of state:
  - Anisotropic flow is sensitive to shear viscosity and bulk viscosity;
  - Radial flow is mostly sensitive to bulk viscosity.

Establish a hydrodynamic picture of radial expansion

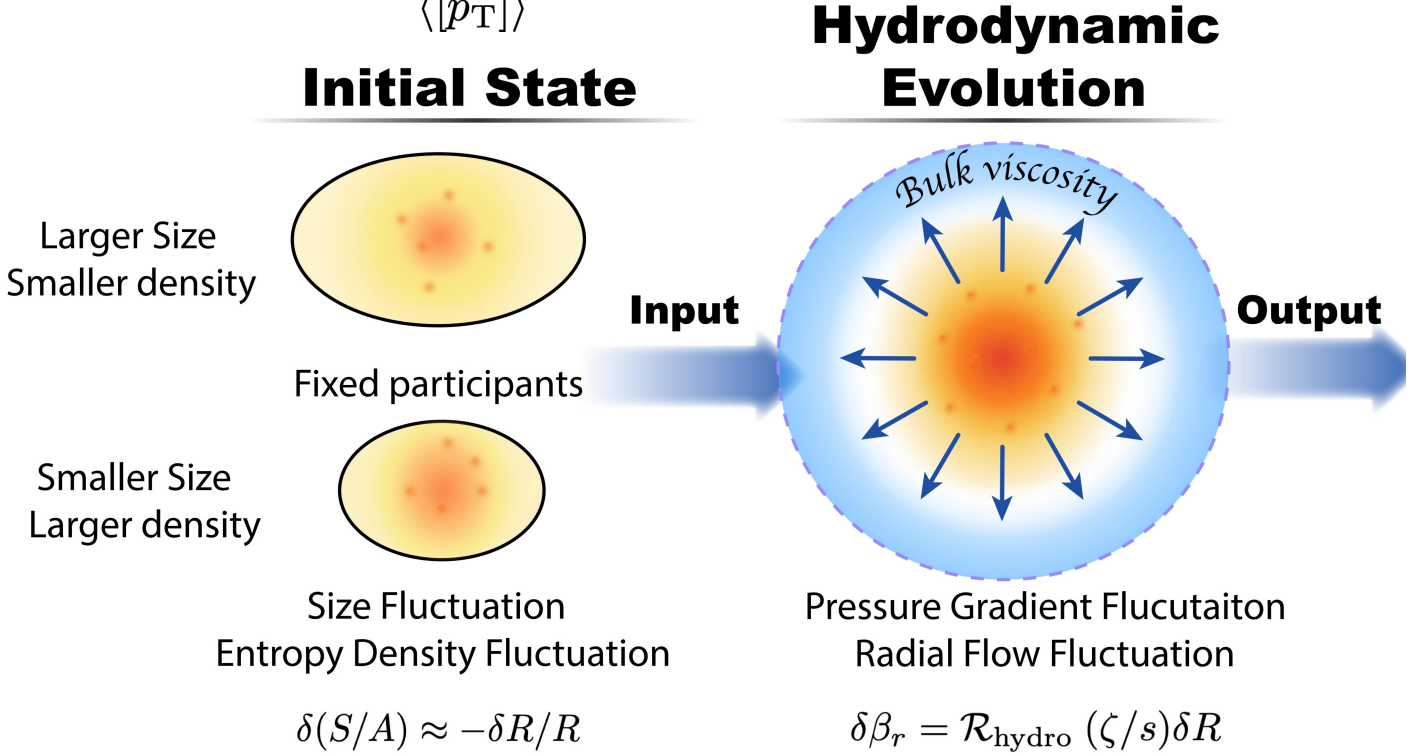
- Previous study on radial flow fluctuations:

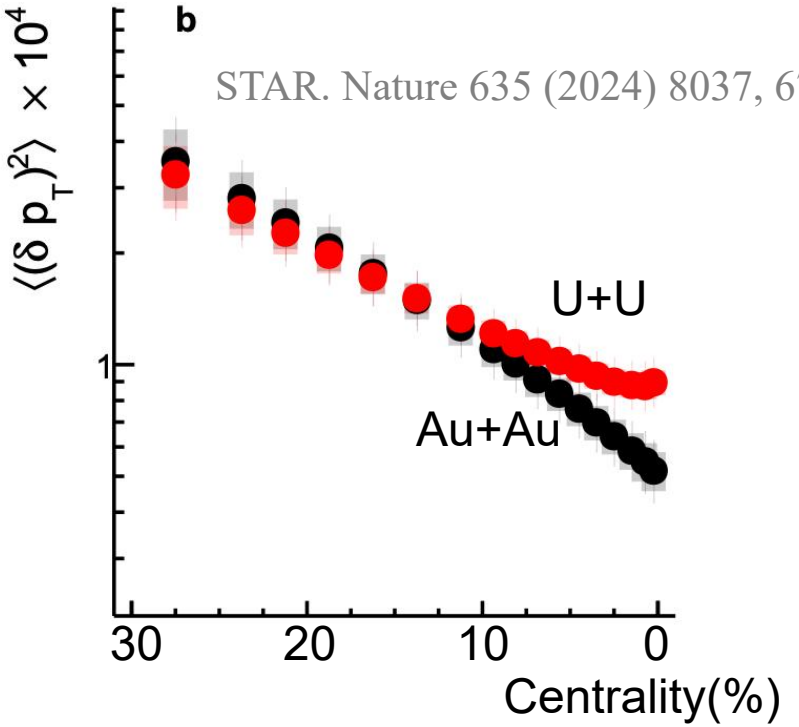
Integrated $[p_T]$ fluctuations v_0:

$$v_0 \equiv \frac{\sqrt{\langle \delta[p_T]\delta[p_T] \rangle}}{\langle [p_T] \rangle}$$

$$\frac{\delta[p_T]}{\langle [p_T] \rangle} \propto -\frac{\delta R}{R}$$

Linear response
linking final fluctuation
to the initial size fluctuation



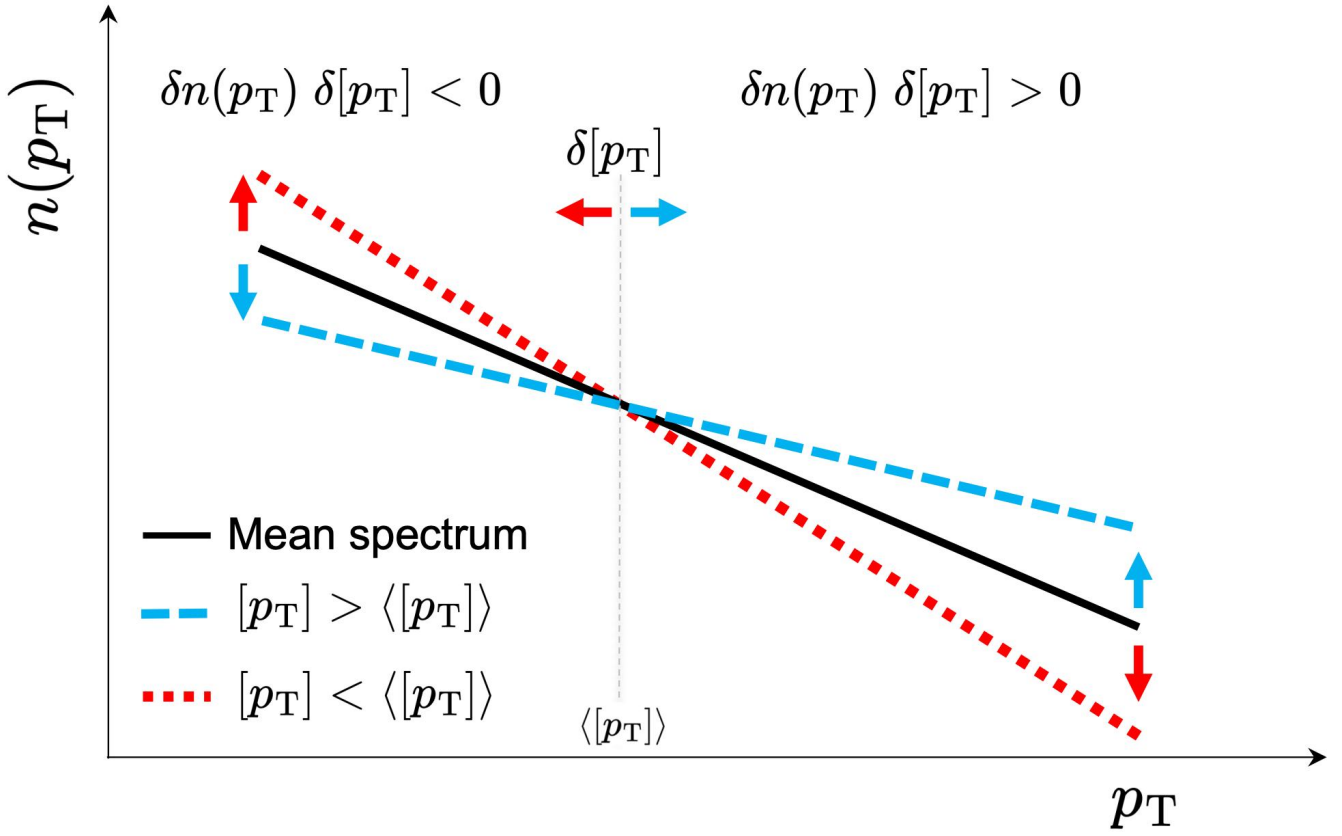


New probe to measure p_{T}-differential fluctuation

Construction: Capture the spectral fluctuation by correlating to $[p_{\mathrm{T}}]$ fluctuations.

$$v_0\left(p_{\mathrm{T}}\right) = \frac{\left\langle \delta n\left(p_{\mathrm{T}}\right) \delta\left[p_{\mathrm{T}}\right] \right\rangle}{\left\langle n\left(p_{\mathrm{T}}\right) \right\rangle \left\langle \left[p_{\mathrm{T}}\right] \right\rangle} \times \frac{1}{v_{0,\mathrm{int}}}$$

Normalized Covariance between local particle yield and mean p_{T}



Jiangyong Jia, Phys.Rev.Lett. 136 (2026) 11, 112301
Björn Schenke, et al., Phys.Rev.C 102 (2020), 034905
Tribhuban Parida, et al., Phys.Lett.B 857 (2024), 138985

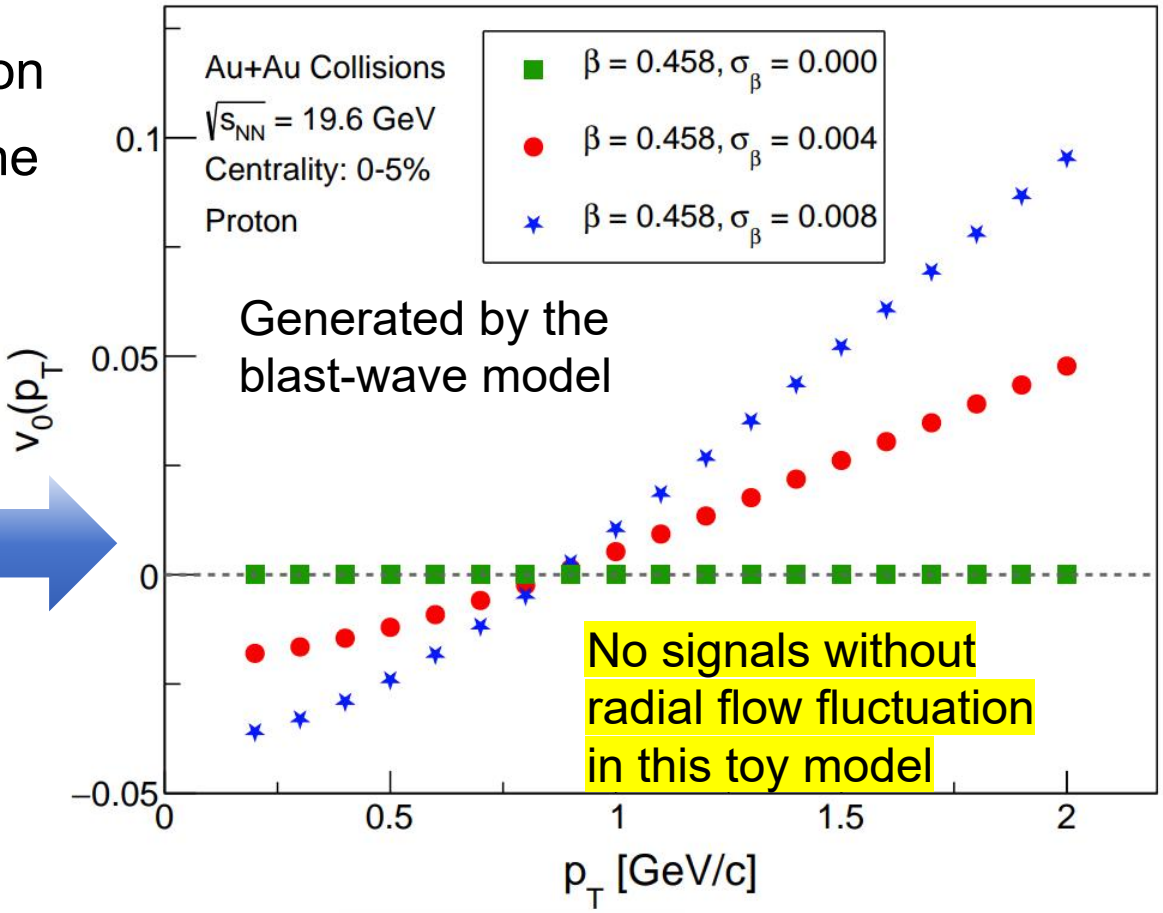
Capture the radial flow fluctuation

Blast-wave model

The blast-wave model is used to extract the average radial flow parameter β from the average spectrum.

- Starting from the average spectral shape, a fluctuation is introduced to the radial flow parameter, σ_β, and the resulting response is reflected in $v_0(p_\mathrm{T})$.

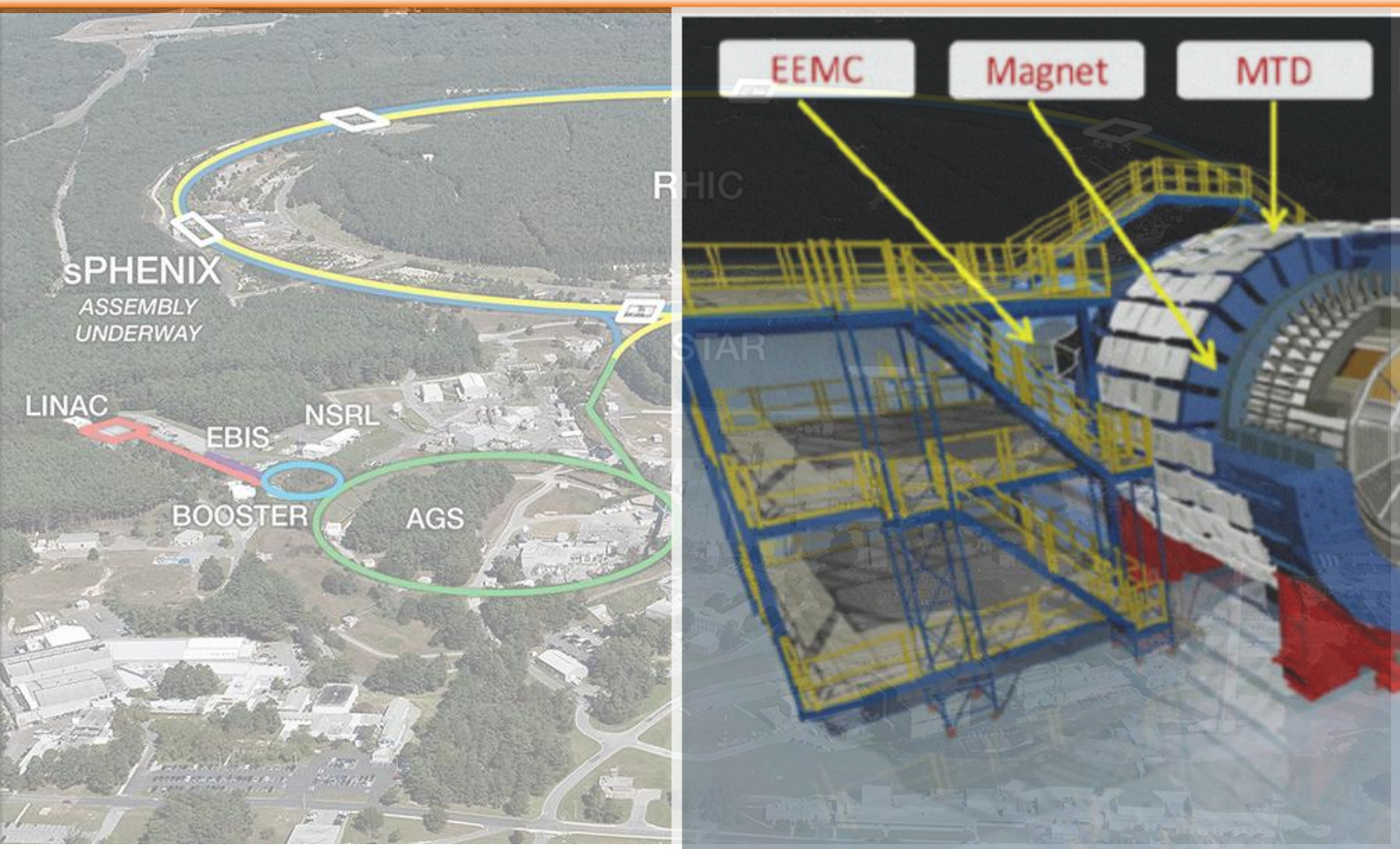
$$v_0\left(p_\mathrm{T}\right) = \frac{\left\langle \delta n\left(p_\mathrm{T}\right) \delta\left[p_\mathrm{T}\right]\right\rangle}{\left\langle n\left(p_\mathrm{T}\right)\right\rangle \left\langle\left[p_\mathrm{T}\right]\right\rangle} \times \frac{1}{v_{0,\mathrm{int}}}$$



Key point: Capture radial flow fluctuation confirmed by blast-wave model

Swati Saha, Ranbir Singh, and Bedangadas Mohanty. Phys. Rev. C(2025), 112:024902.

STAR Detector



STAR Detector

Systems from large to small

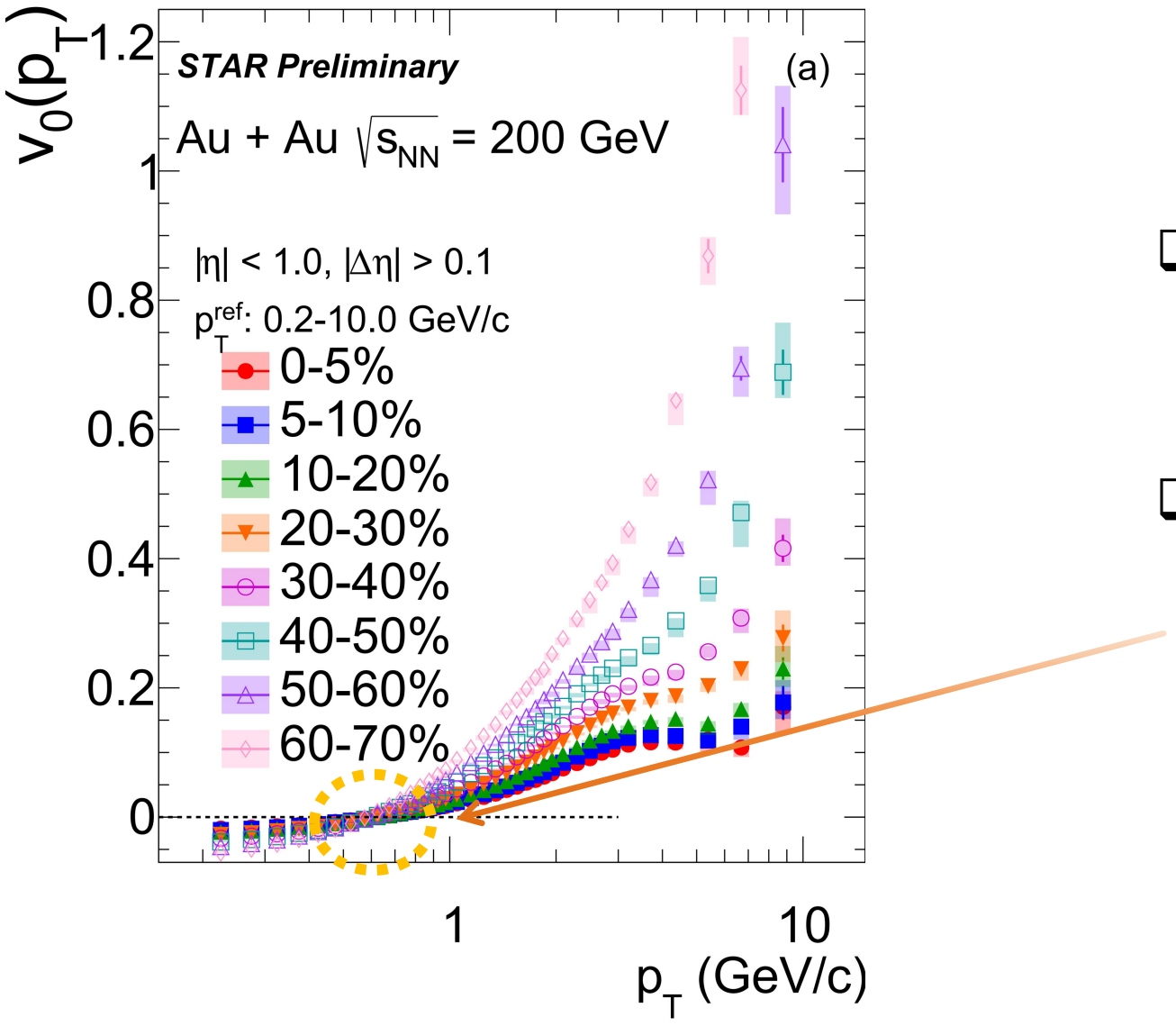
System Comparison	Number of events	
	HighMult	MinBias
Au+Au 200 GeV(2011)	/	397M
O+O 200 GeV(2021)	510M	470M

Beam energy scan

Energy Comparison
Au+Au Collisions
BES I: 7.7 - 200 GeV
BES II: 7.7 - 54.4 GeV

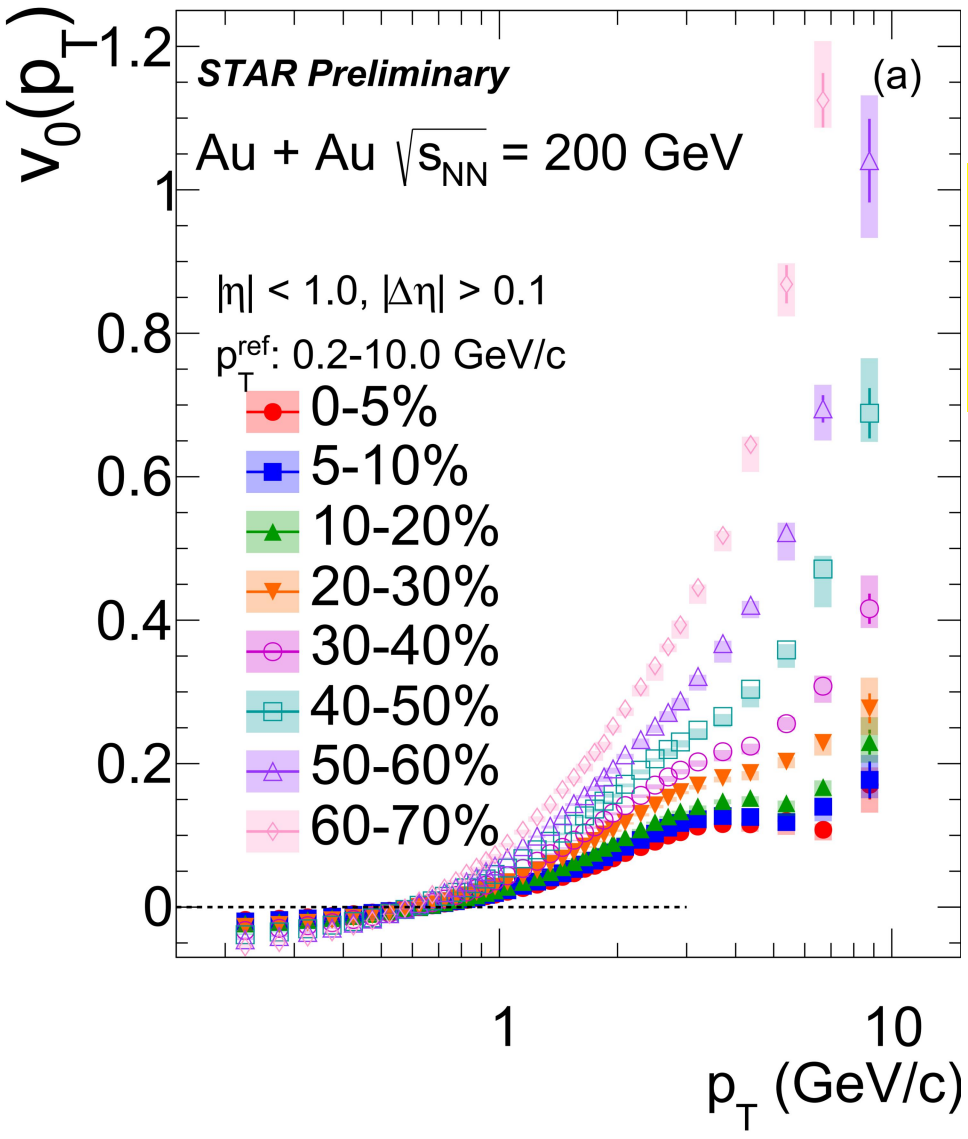
STAR performed this studies for different particle species, system sizes, and collision energies.

$v_0(p_T)$ in Au+Au collisions at 200 GeV



- Strong centrality-dependence: size-driven radial flow fluctuations;
- Cross at the same point (=$\langle [p_T] \rangle$).

Separate the initial size and medium response



Hydrodynamic linear response:

$$\frac{\delta[p_T]}{\langle[p_T]\rangle} = \kappa_0(-\frac{\delta R}{R})$$

Response coefficient (Size-independent)

Initial size (size-dependent)

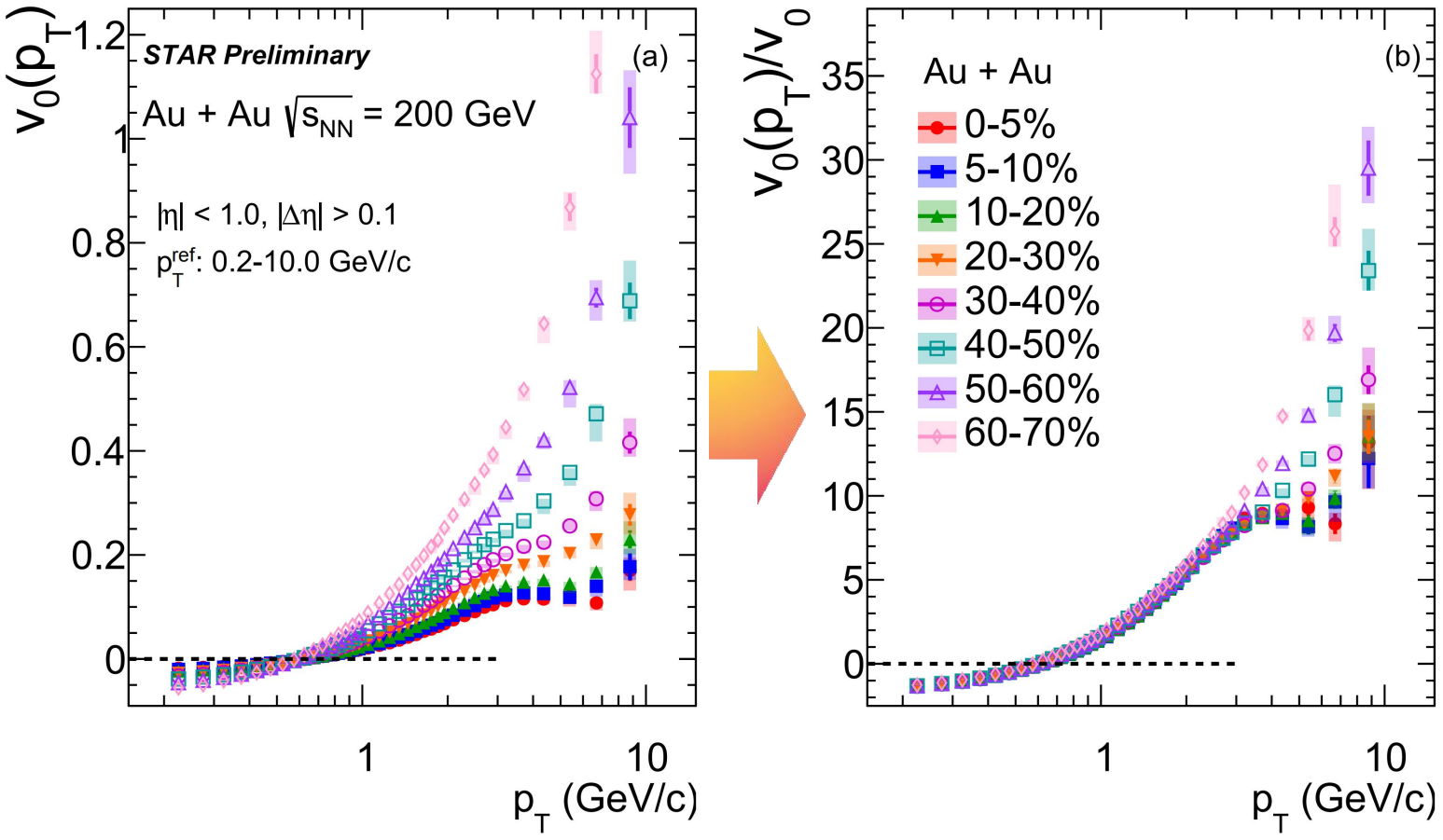
$$v_0(p_T) = \kappa_0(p_T)(-\frac{\delta R}{R})$$

$$v_0 = \kappa_0(-\frac{\delta R}{R})$$

$$\frac{v_0(p_T)}{v_0} = \frac{\kappa_0(p_T)}{\kappa_0}$$

Access medium properties

$v_0(p_T)/v_0$: Capture the hydrodynamic response



- **Common shape** at low-p_T(hydro-dominated region);
- **Breakdown** at high-p_T(jet-dominated region).

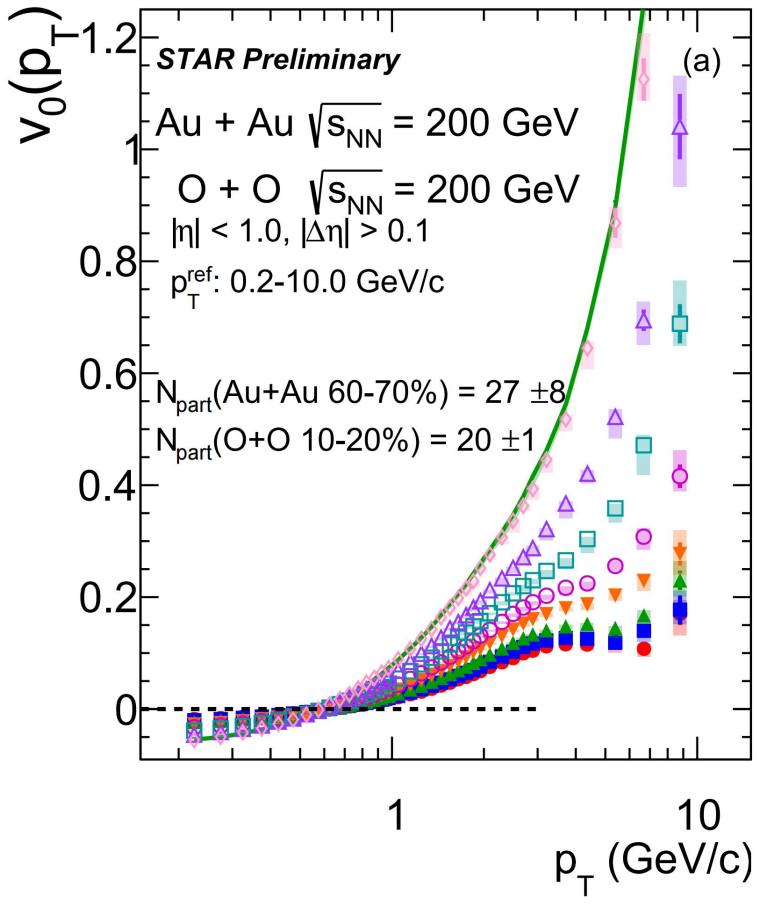
After normalizing by integrated v_0, we access the size-independent hydrodynamic response.

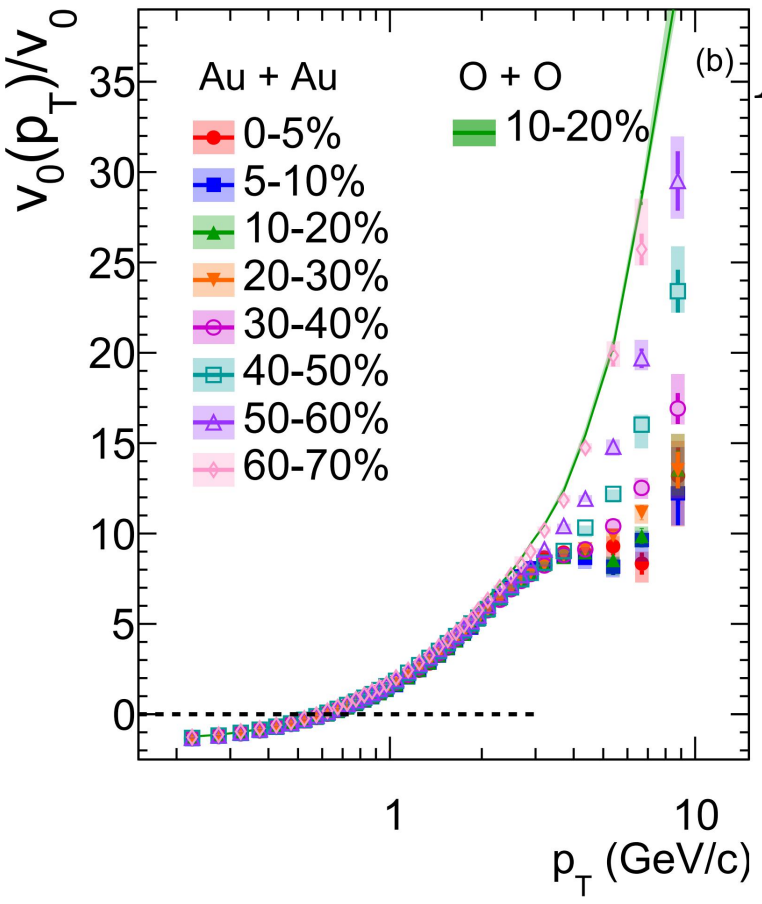
$$v_0(p_T) = \kappa_0(p_T)(-\frac{\delta R}{R})$$

$$v_0 = \kappa_0(-\frac{\delta R}{R})$$

$$\frac{v_0(p_T)}{v_0} = \frac{\kappa_0(p_T)}{\kappa_0}$$

System Comparison: Size dependence





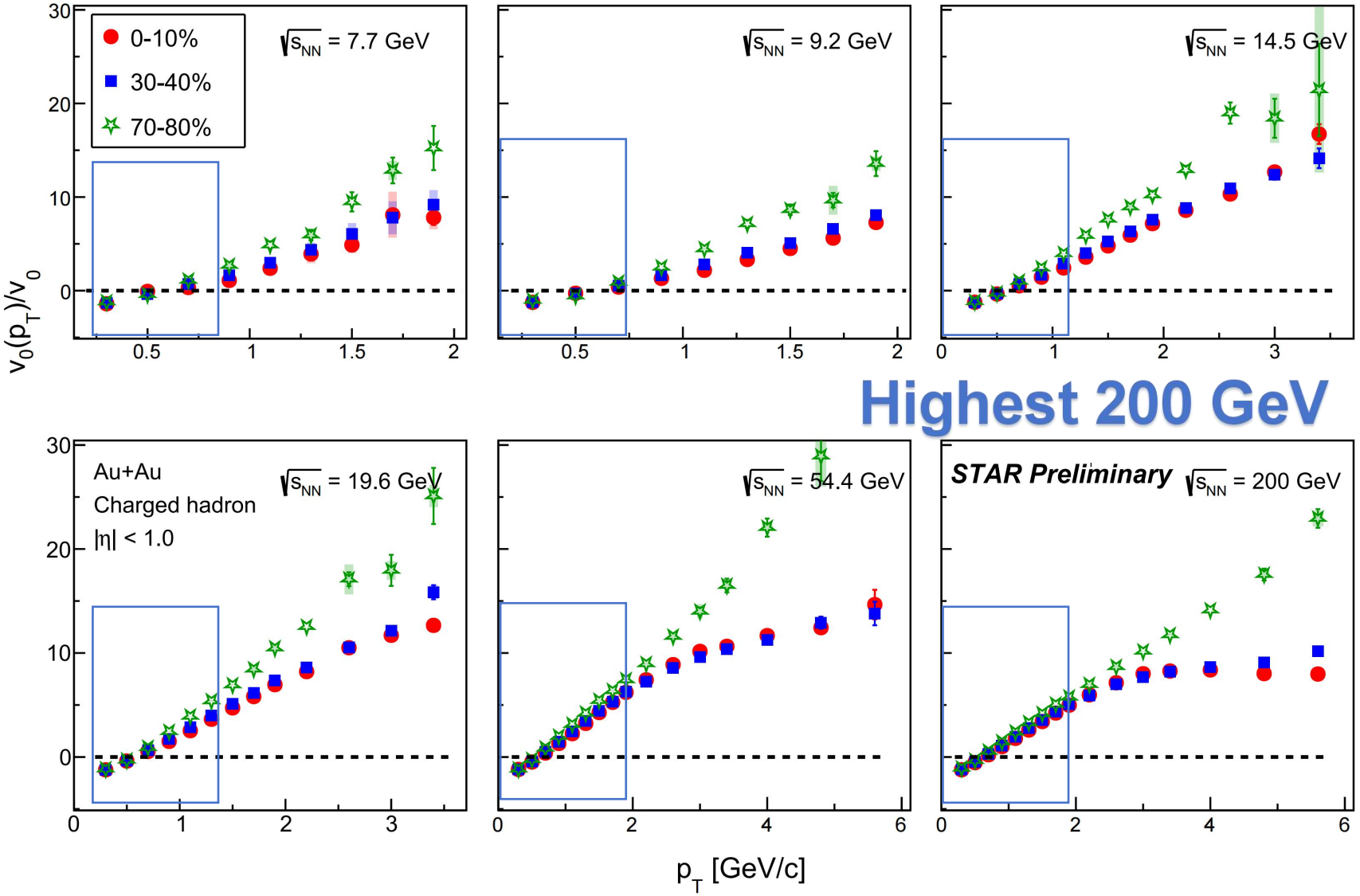
Similar system sizes

$$N_{\mathrm{part}}(\mathrm{Au+Au\ 60-70\%}) = 27 \pm 8$$
$$N_{\mathrm{part}}(\mathrm{O+O\ \ 10-20\%}) = 20 \pm 1$$

- $v_0(p_T)$ captures the **size-dependent** radial flow fluctuations while preserving a coherent hydrodynamic response in different systems.

Energy evolution of radial flow fluctuations

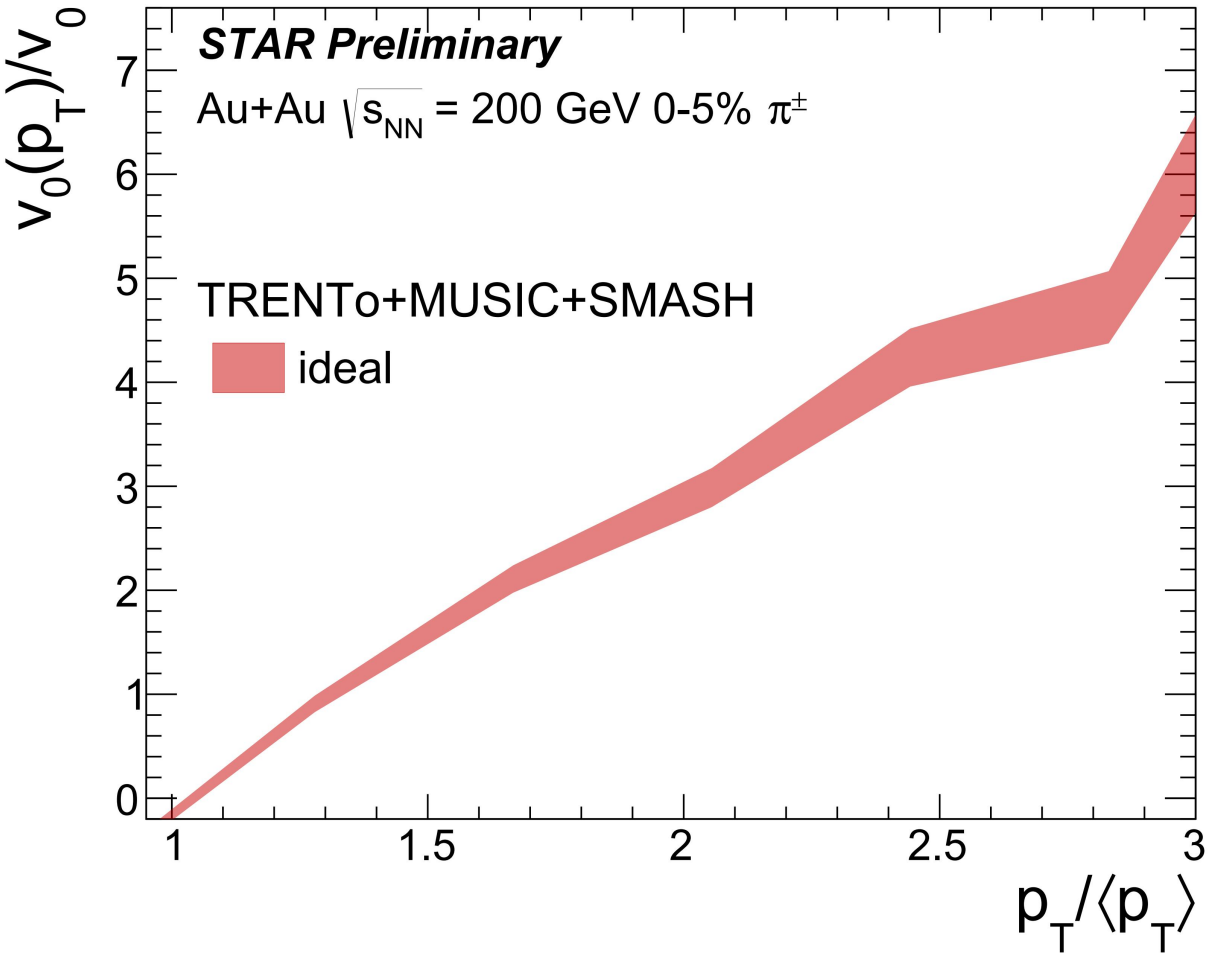
Lowest 7.7 GeV



Highest 200 GeV

- The reponse structure persists down to lower energies, with similar response coefficients.

Access the bulk properties with the model comparison

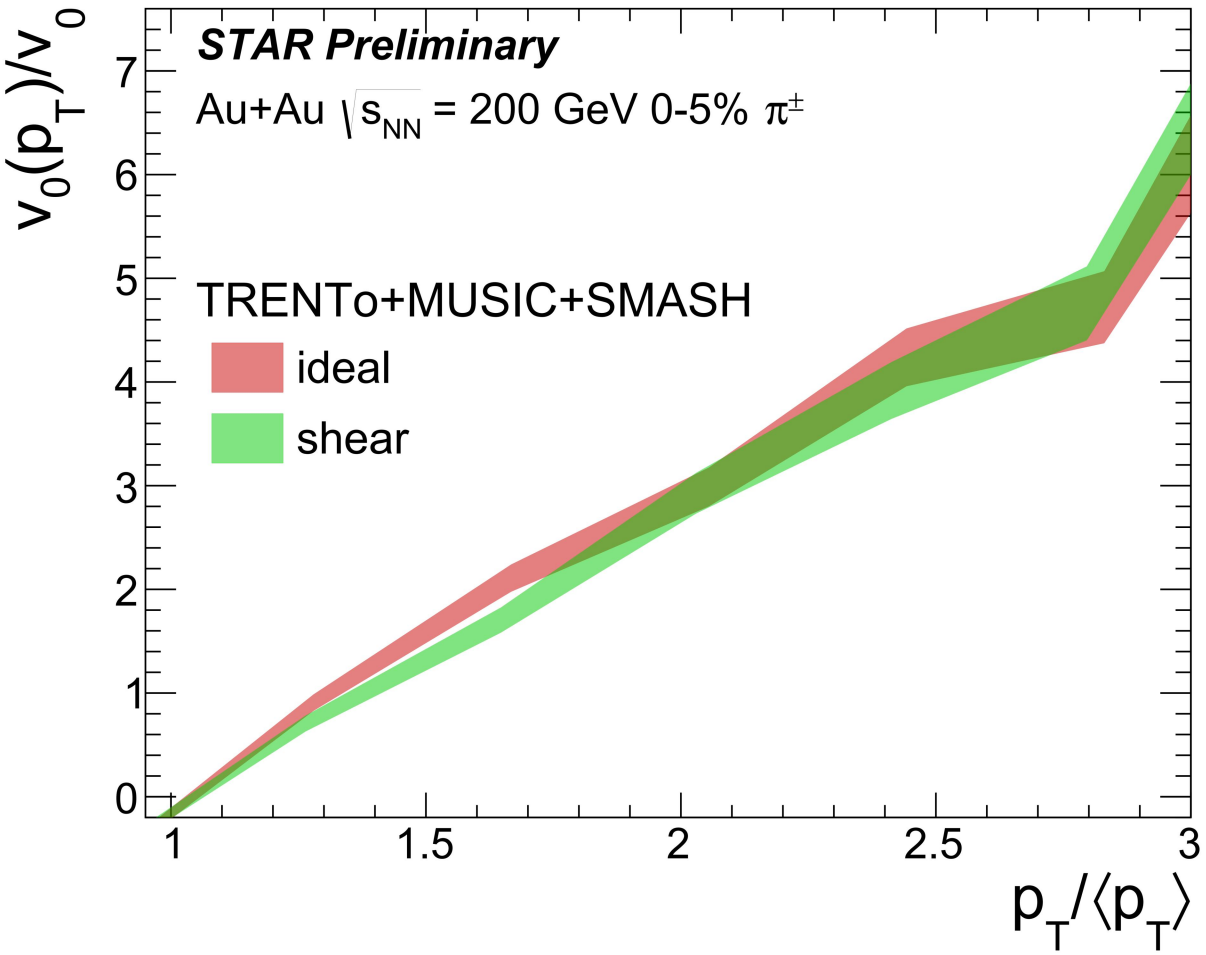


$$\frac{v_0(p_T)}{v_0}$$

: Access the medium properties without initial dependence.

Model calculation:
Lipei Du, Phys.Rev.C 113 (2026) 1, 014901

Access the bulk properties with the model comparison

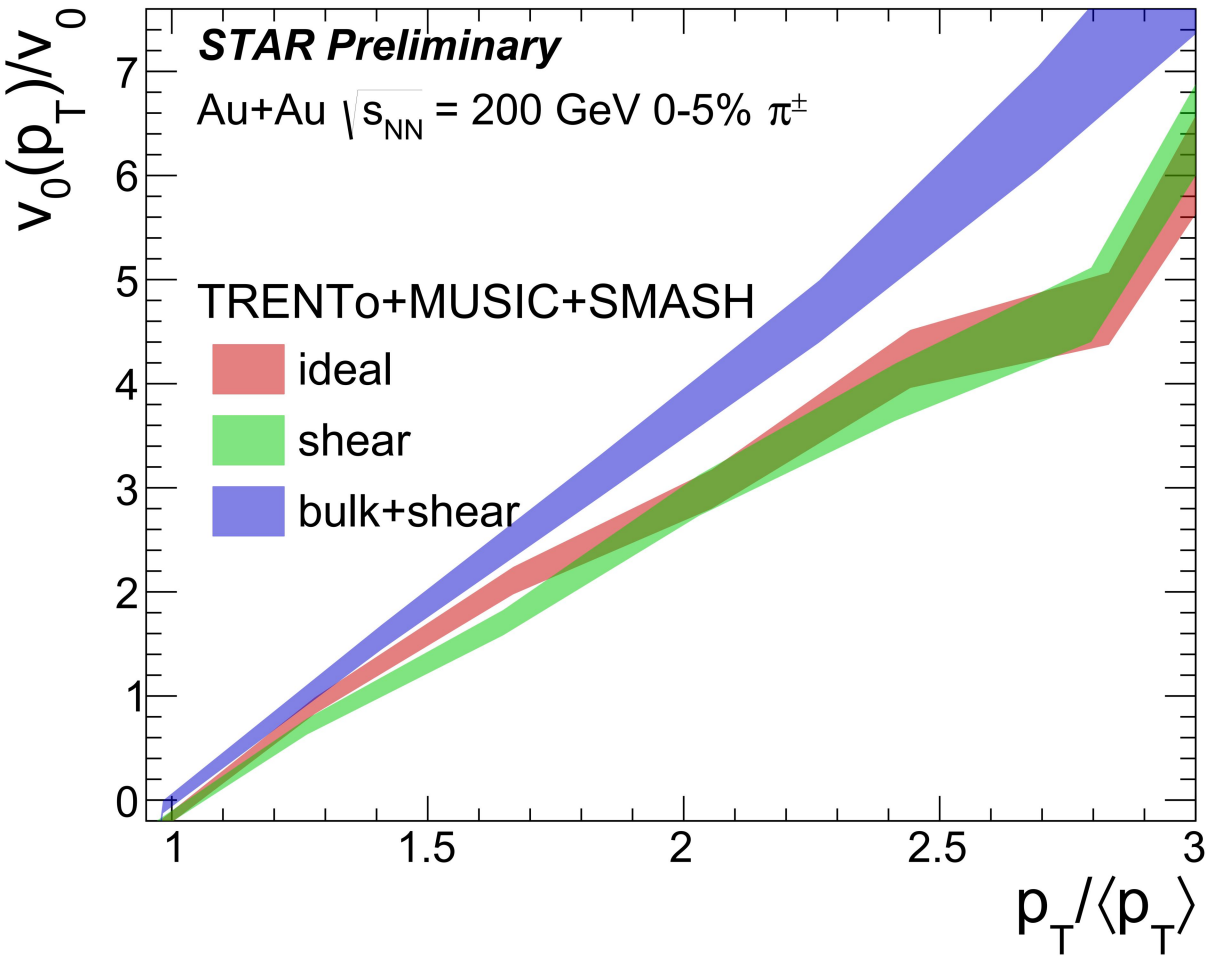


$$\frac{v_0(p_T)}{v_0}$$: Access the medium properties without initial dependence.

➢ $v_0(p_T)$ is weakly influenced by **shear viscosity**.

Model calculation:
Lipei Du, Phys.Rev.C 113 (2026) 1, 014901

Access the bulk properties with the model comparison

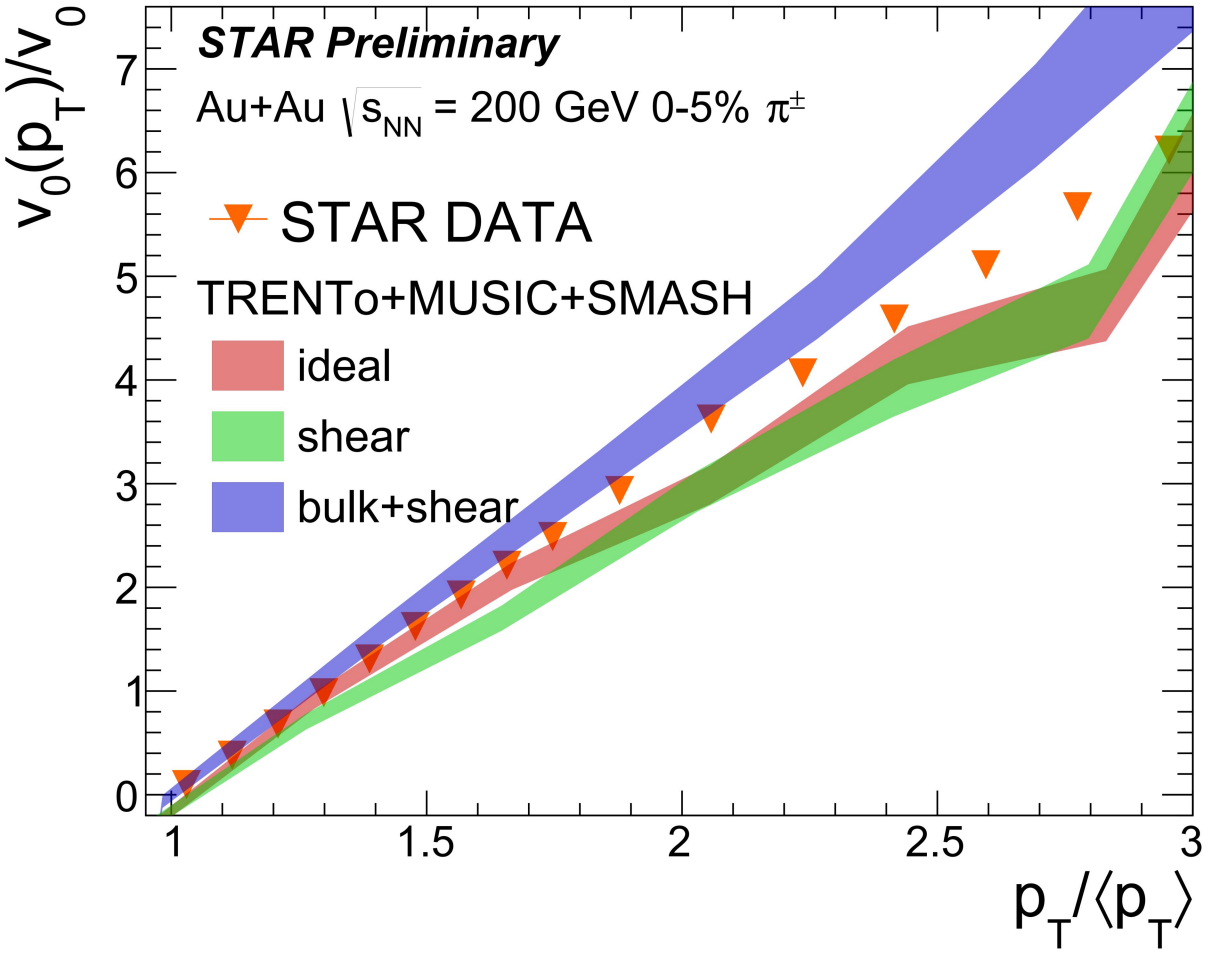


$$\frac{v_0(p_T)}{v_0}$$: Access the medium properties without initial dependence.

- Model calculations show that $v_0(p_T)$ has a visible **bulk viscosity** dependence while being weakly influenced by **shear viscosity**.

Model calculation:
Lipei Du, Phys.Rev.C 113 (2026) 1, 014901

Access the bulk properties with the model comparison



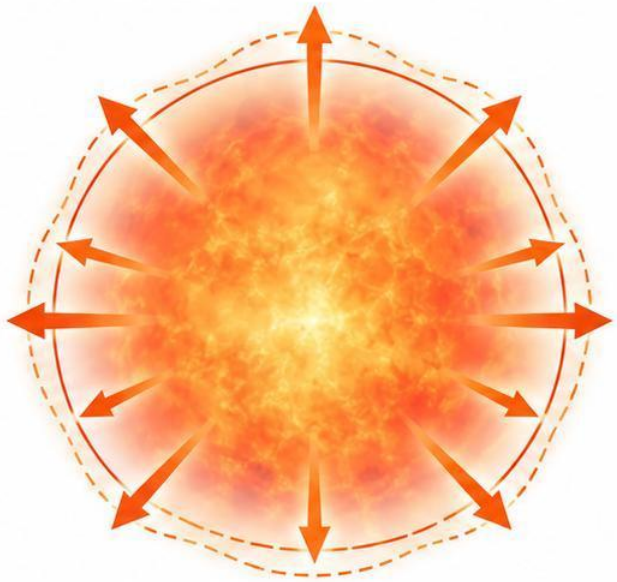
$$\frac{v_0(p_T)}{v_0}$$

: Access the medium properties without initial dependence.

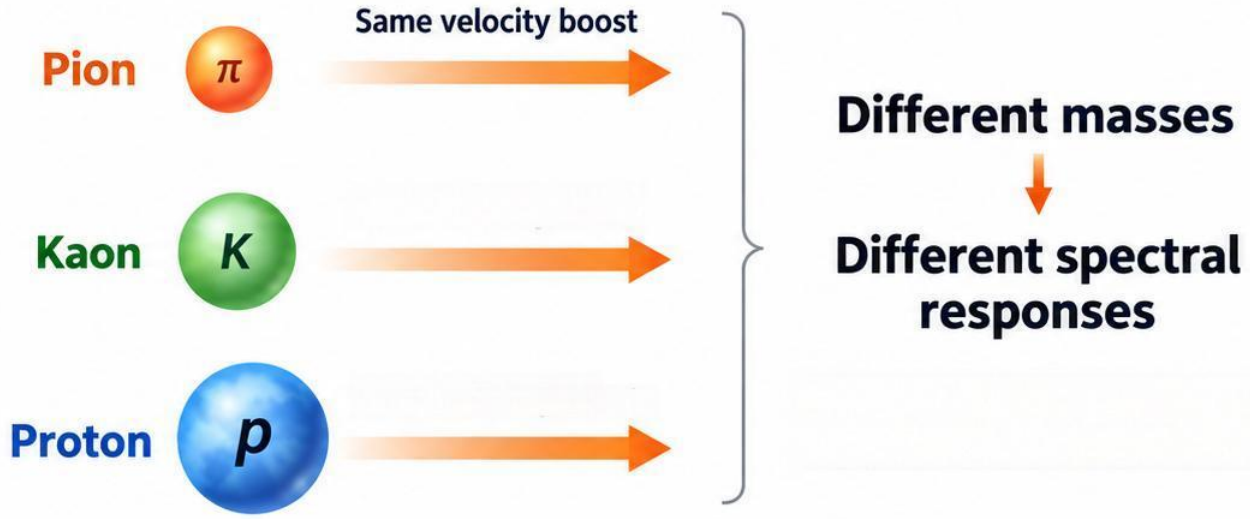
- The measurements of $v_0(p_T)/v_0$ in STAR experiments stay in between, providing a new approach to constrain bulk properties in hydrodynamic models.

Model calculation:
Lipei Du, Phys.Rev.C 113 (2026) 1, 014901

Impact on different particle speicies



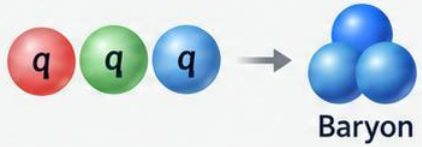
A common fluctuating radial velocity field



A common boost can produce species-dependent fluctuations.

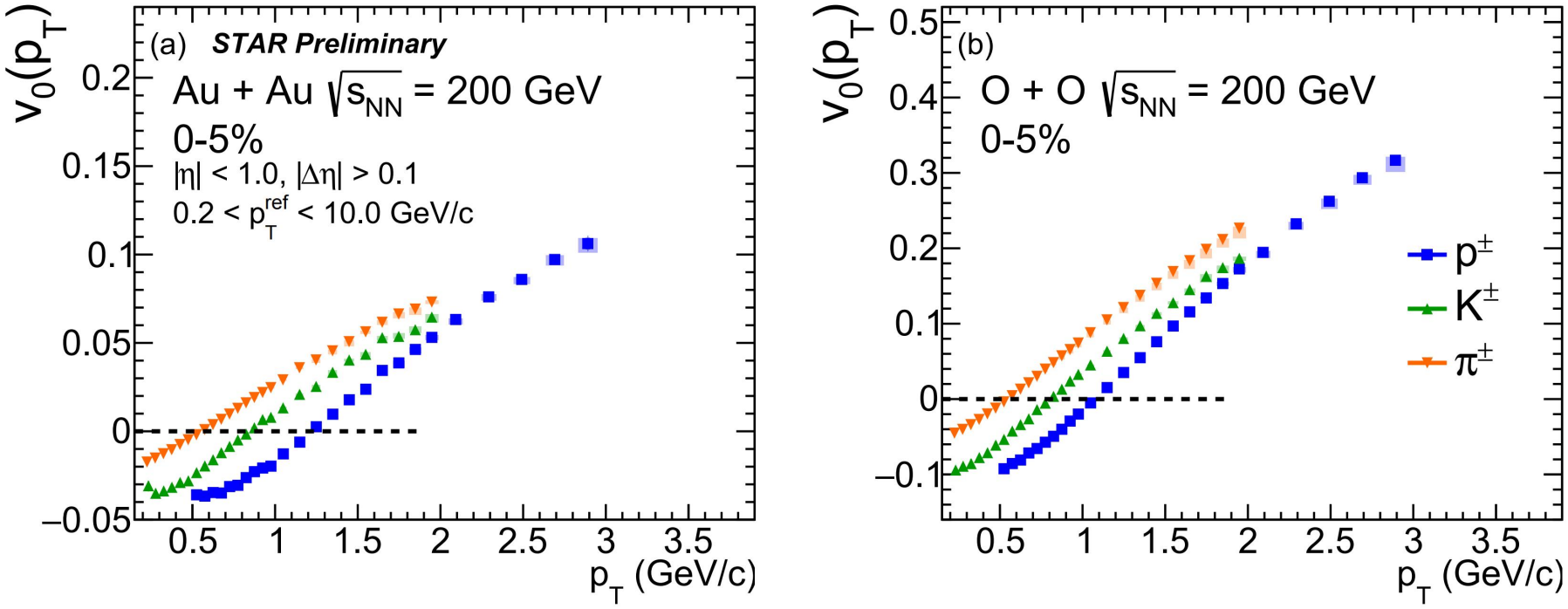
Possible hadronization effects





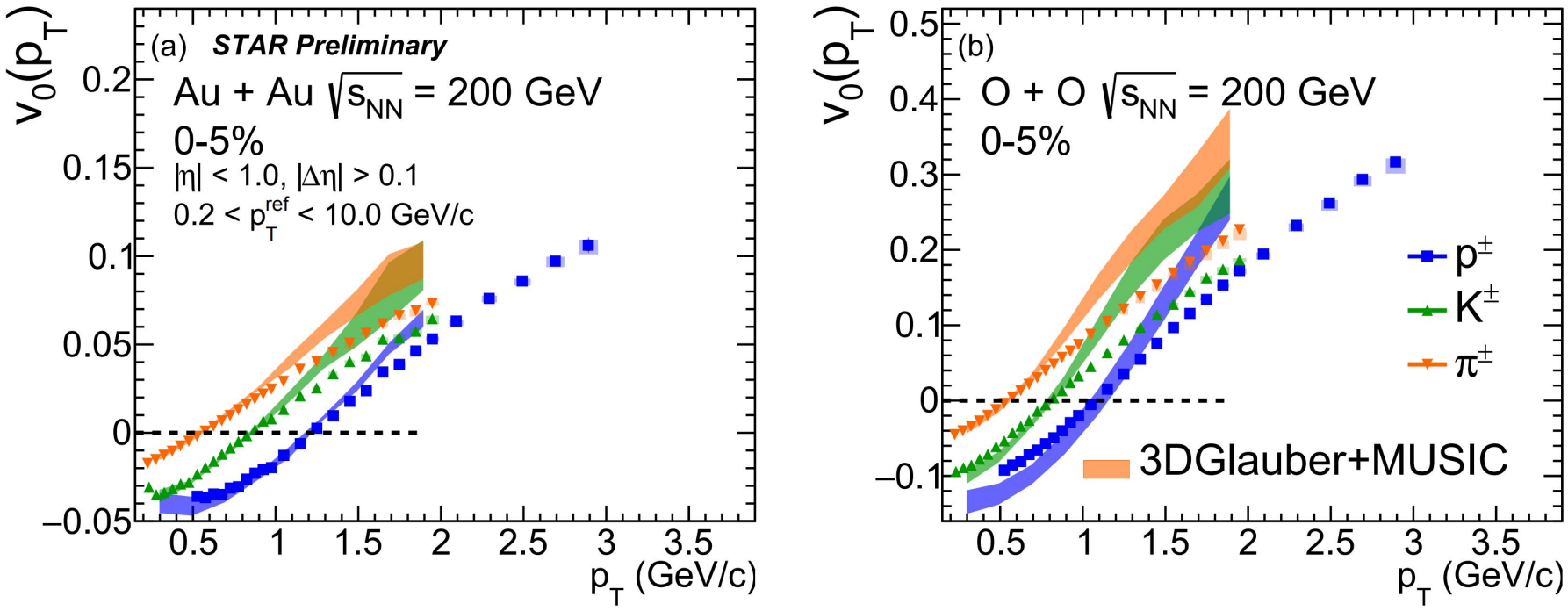
Quark coalescence may modify the intermediate-pT response.

$v_0(p_T)$ of different particle species



- Strong mass ordering at low p_T: different crossing points;

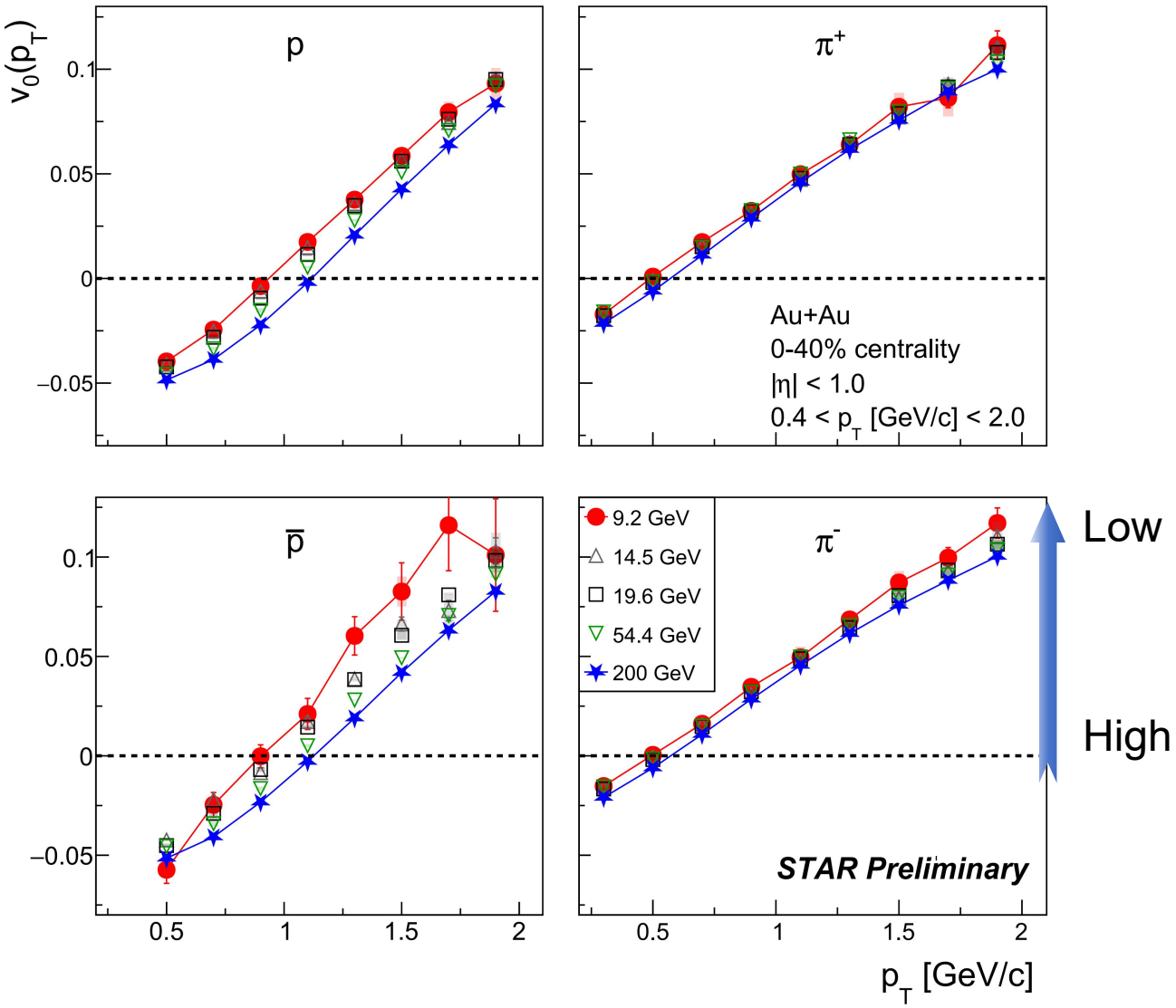
Mass ordering



Model calculations: Syed Afrid Jahan, Hendrik Roch, Chun Shen, Phys.Rev.C 113 (2026) 2, 024919

- Strong mass ordering at low p_T: different crossing points;
- Hydrodynamic calculations using 3D Glauber + MUSIC reproduce this feature well.

Energy evolution of different particles



- Shift of change of crossing points due to weaker radial flow from high to low energies.
- The energy dependence of the shape for different particle species indicates a larger influence for **protons** than for pions.

Integral v0: Amplitude of fluctuations

Differential shape: how does the spectrum fluctuate?

Integrated amplitude: how large are the correlated fluctuations?

- **Collision energy**
  Track the evolution of fluctuations and medium response.

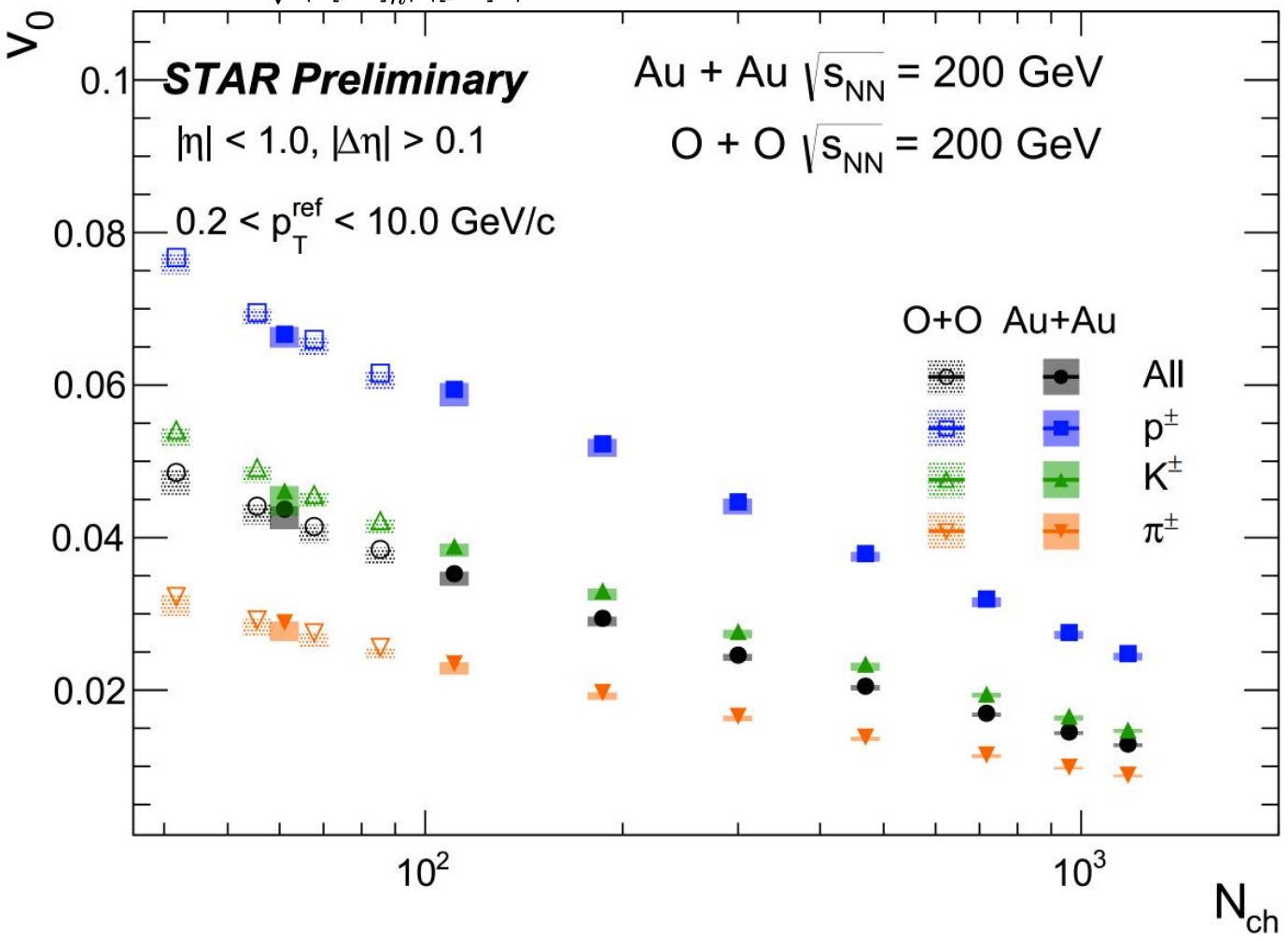
- **Particle species**
  Test a common boost through mass-dependent responses.

- **Multiplicity**
  Examine fluctuation dilution and compare collision systems.

Amplitude and differential shape provide complementary information.

Overall radial flow fluctuations from large to small systems

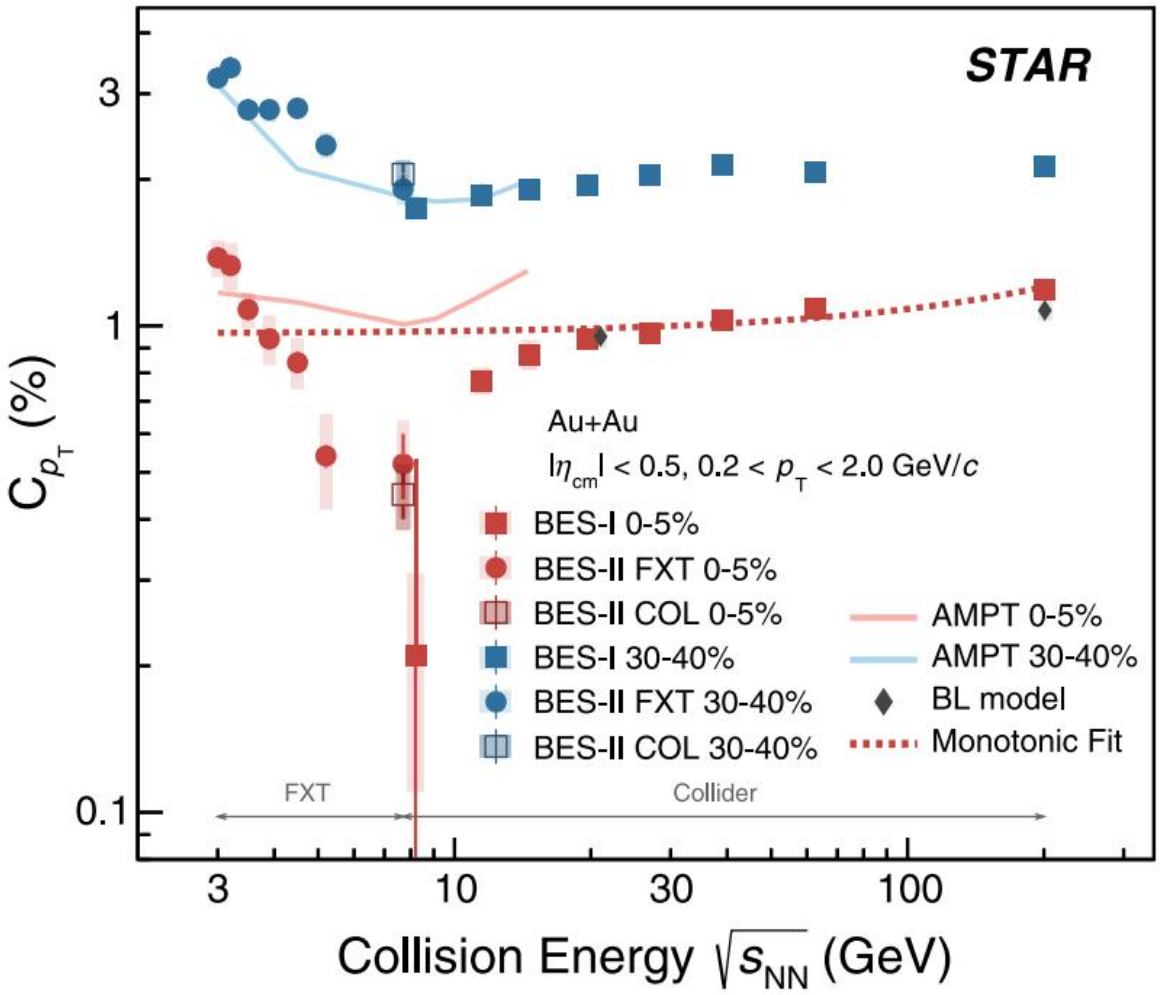
$$v_{0,\mathrm{PID}} = \frac{\langle \delta[p_\mathrm{T}]_\mathrm{PID}\, \delta[p_\mathrm{T}]_h \rangle}{\sqrt{\langle \delta[p_\mathrm{T}]_h^2 \rangle \langle [p_\mathrm{T}]_h \rangle}}$$



- Coherent scaling with N across different particles, suggesting that the sources are independent but share a common collective boost.
- Even in small systems, O+O still maintains this collective pattern of radial expansion fluctuations.

Overall radial flow fluctuations at low energies

$$C_{p_T} \equiv v_0 \equiv \frac{\langle \delta[p_T]\delta[p_T] \rangle}{\sqrt{\langle \delta[p_T]^2 \rangle \langle [p_T] \rangle}}$$



- The central and mid-central v0 both show a strong collision energy dependence.
- In the central collision, non-monotonic energy dependence: a dip shows up at ~7.7 GeV.
- Differential observables can help understand this trend.

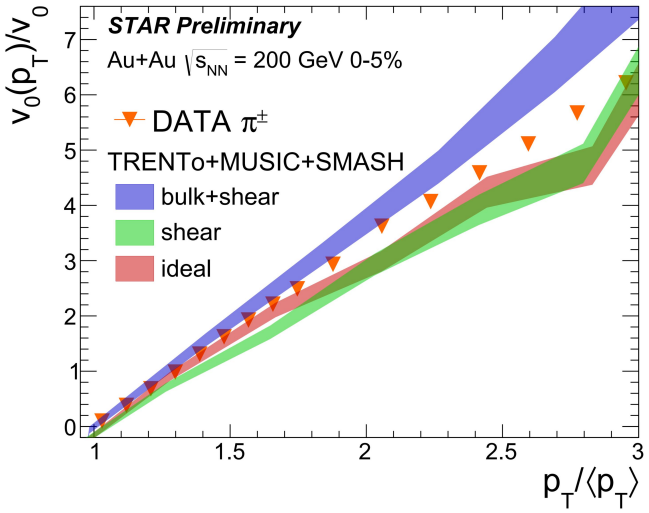
STAR Collaboration. Phys.Rev.Lett. 137, 132301 (2026)

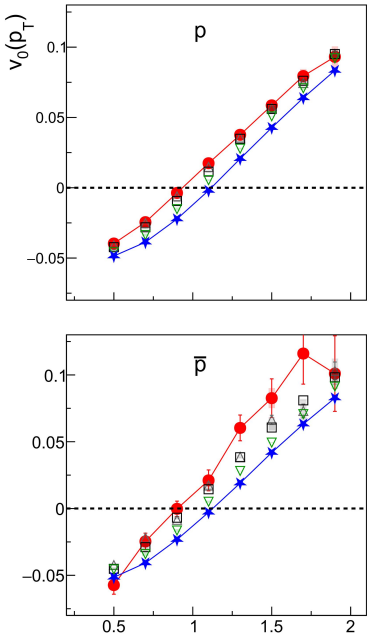
Summary

We measured the p_{T}-differential radial flow fluctuation with newly proposed observable $v_0(p_{\mathrm{T}})$ in Au+Au and O+O collisions at 200 GeV, and Au+Au collisions through Beam Energy Scan.

Access the medium by establishing response structure:

- Persists in the same pattern down to **O+O collisions**;
- A strong **bulk viscosity sensitivity** in model;
- The evolution of **energy-dependent** radial expansion.





A common response across systems with promising sensitivity to medium properties and the energy evolution .