Anisotropic flow measurements - highlights from STAR BES program

2025 RHIC/AGS Annual Users' Meeting
Brookhaven National Laboratory, USA

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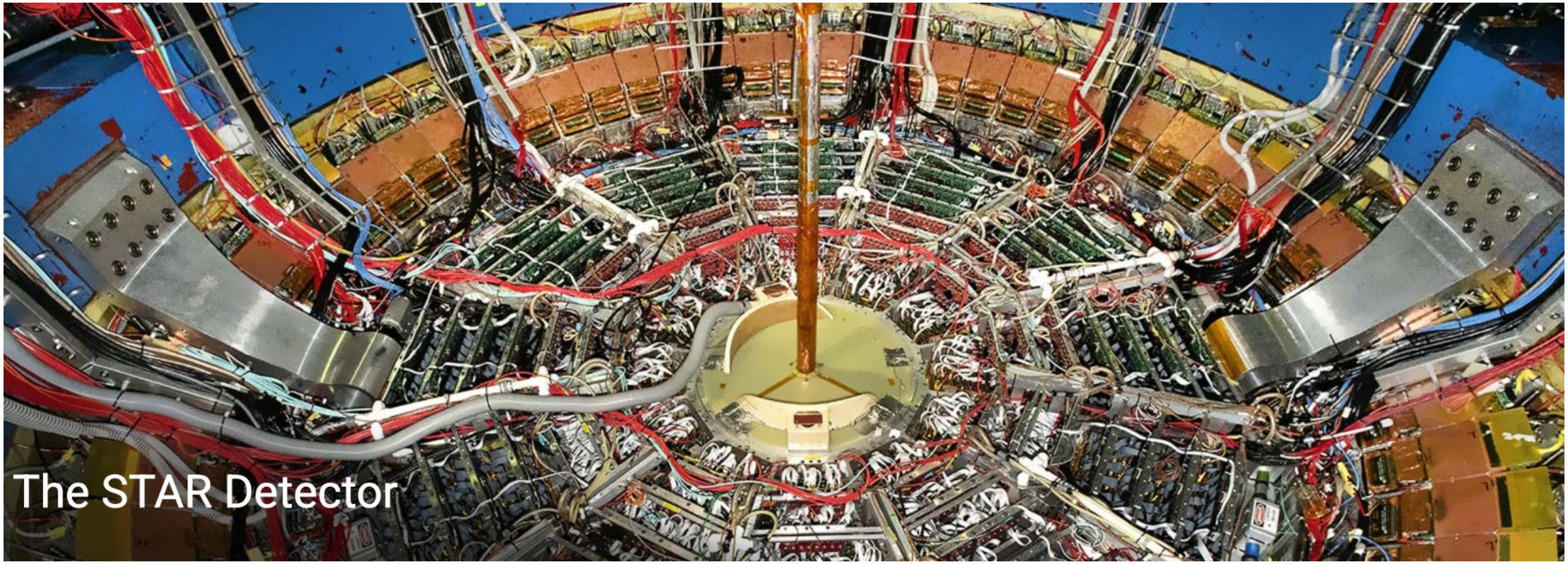
STAR 25 YEARS

IISER TIRUPATI

Date: May 21, 2025

Outline

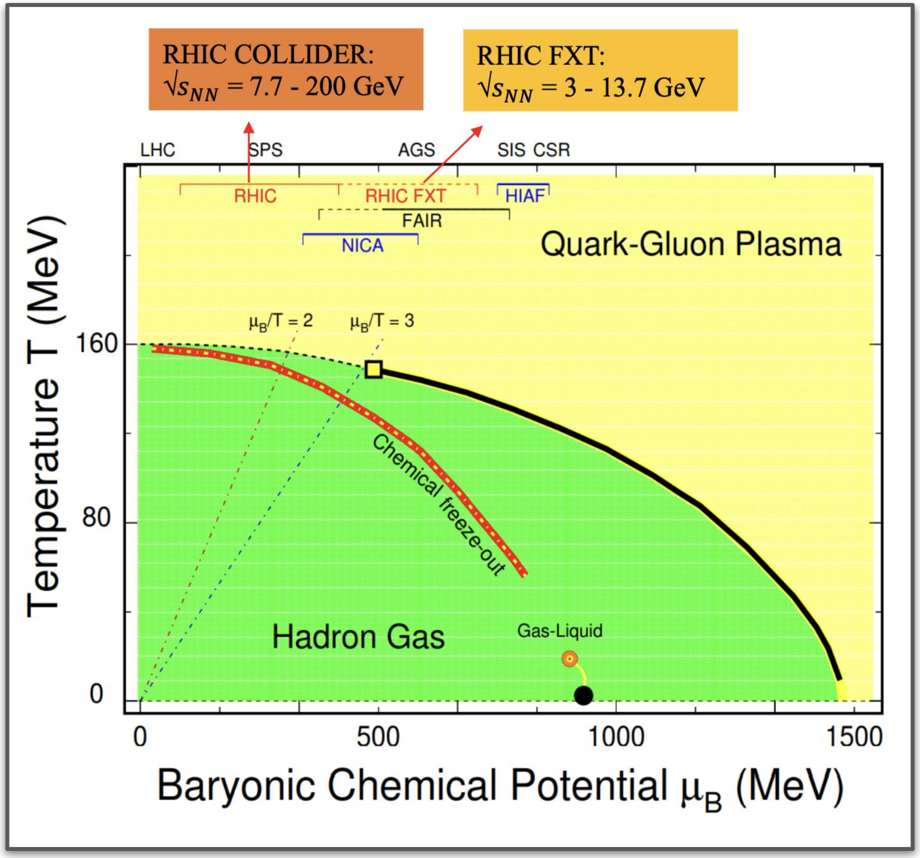


- Introduction
- STAR Experiment
- Results and Discussion
  - Directed flow (v_1)
  - Elliptic flow (v_2)
  - Triangular flow (v_3)
- Summary and Outlook

25 YEARS

Introduction

At very high temperature/energy density a deconfined phase of quarks and gluons is expected to form ➔ **Quark-Gluon Plasma (QGP)**



X.Luo, S.Shi, Nu Xu et al. Particle 3, 278 (2020)

RHIC BES Program:

- First-order phase transition
- QCD critical end point
- Turn-off of QGP signatures

Phase-I

$\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, and 200 GeV **(COL)**

Phase-II

$\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, 14.6, 19.6, 27 and 54. 4 GeV **(COL)**
$\sqrt{s_{NN}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7, 9.1, 11.5, and 13.7 GeV **(FXT)**

STAR Beam Energy Scan

Au+Au Collisions at RHIC

Collider Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	200	2000 M	25 MeV	5.3	Run-14, 16
2	62.4	46 M	75 MeV		Run-10
3	54.4	1200 M	85 MeV		Run-17
4	39	86 M	112 MeV		Run-10
5	27	585 M	156 MeV	3.36	Run-11, 18
6	19.6	595 M	206 MeV	3.1	Run-11, 19
7	17.3	256 M	230 MeV		Run-21
8	14.6	340 M	262 MeV		Run-14, 19
9	11.5	235 M	316 MeV		Run-10, 20
10	9.2	160 M	372 MeV		Run-10, 20
11	7.7	104 M	420 MeV		Run-21

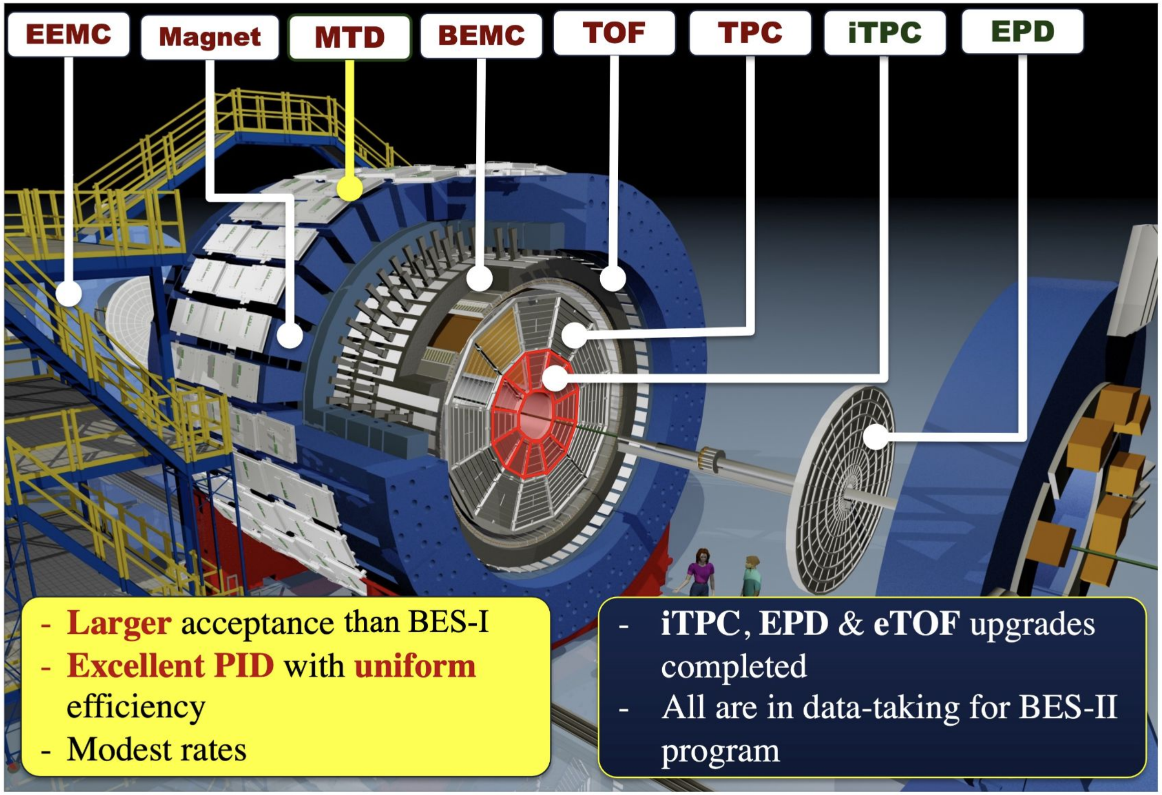
Fixed-Target Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
12	3.0 (3.85)	2000 M	760 MeV	-1.05	Run-18, 20

Extensive exploration of the QCD phase diagram

- Covers a wide range of collision energies: $\sqrt{s_{NN}}$ = 3 - 200 GeV
- Probes from low to high baryon densities: μ_B: 25 - 760 MeV

STAR Detector System



1) **Extended pseudorapidity acceptance**
2) **Improved particle identification**
3) **Enhanced event plane resolution**

Major Upgrades in BES-II

iTPC:
- ➢ Improves dE/dx
- ➢ Extends η coverage from ±1.0 to ±1.5
- ➢ Lowers p_T cut from 125 to 60 MeV/c
- ➢ Ready in 2019

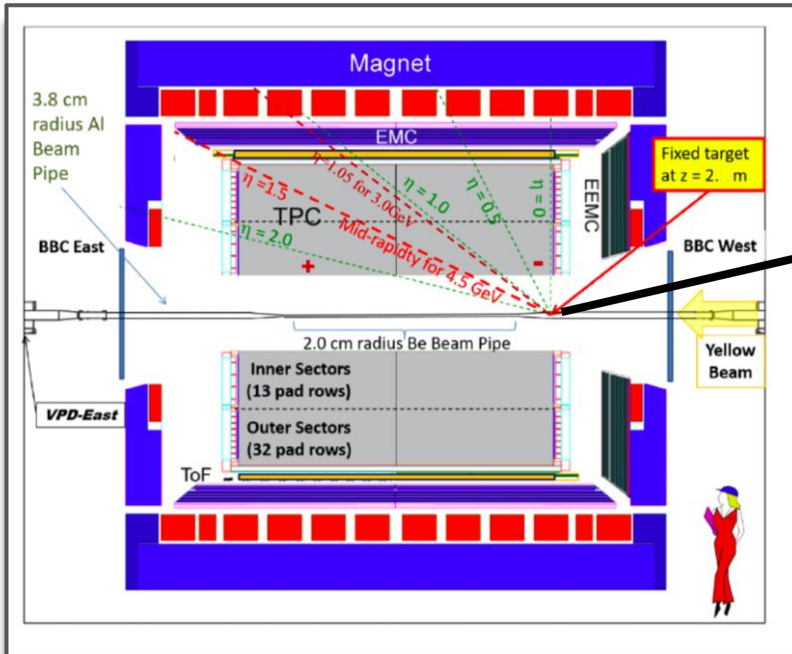
eTOF:
- ➢ Forward rapidity coverage
- ➢ PID at η = -1.1 to -1.6
- ➢ Ready in 2019

EPD:
- ➢ Improves trigger
- ➢ Event plane measurements
- ➢ Ready in 2018

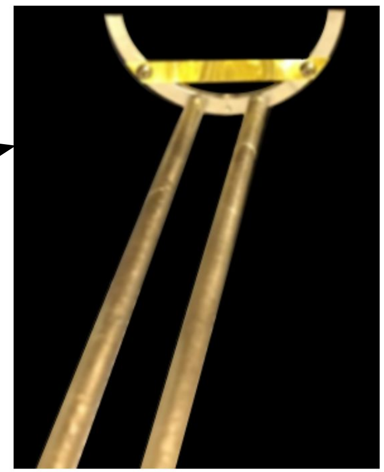
[1] iTPC: https://drupal.star.bnl.gov/STAR/starnotes/. public/sn0619.
[2] eTOF: STAR and CBM eTOF group, arXiv: 1609.05102.
[3] EPD: J. Adams, et al. NIM A968, 163970 (2020)

STAR Fixed-Target Setup

Fixed-target mode



Nuclear Phy A 808-811 (2017)



$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV) ≈
3.2	699
3.5	670
3.9	633
4.5 . . .	590 . . .

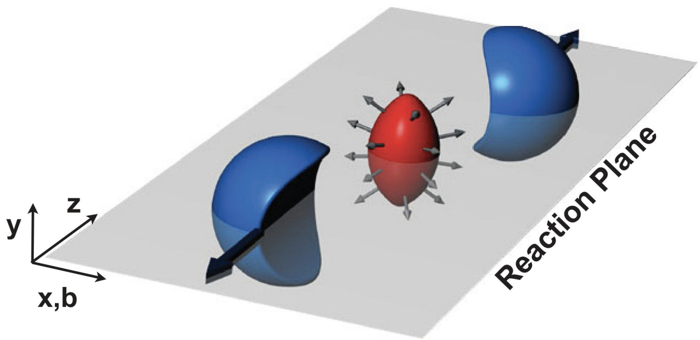
- **Fixed-Target (FXT)** program at **S**olenoidal **T**racker **A**t **R**HIC (**STAR**) → low center-of-mass energies and high baryon density region
  - Target located at **z = 200 cm**
  - Target is 0.25 mm thick (1% interaction probability) and held 2 cm below center of beam axis

Anisotropic Flow

- **Flow** is the measure of azimuthal anisotropy of particles
- **Azimuthal distribution of particles**

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy}\left\{1 + \sum_{n\geq 1} 2\,v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right\}$$

$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$



Why is v_n an important observable?

- Sensitive to the equation of state
- Sensitive to early times in the evolution of the system

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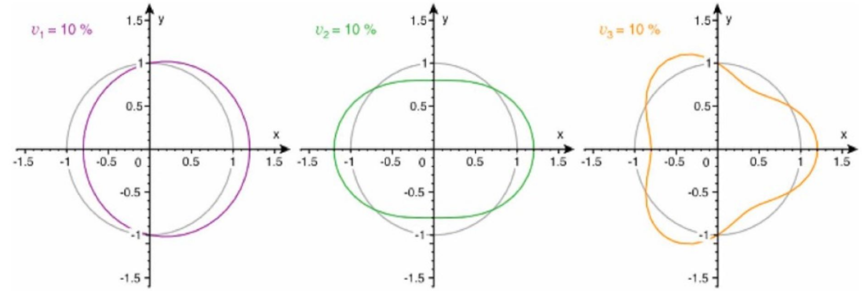
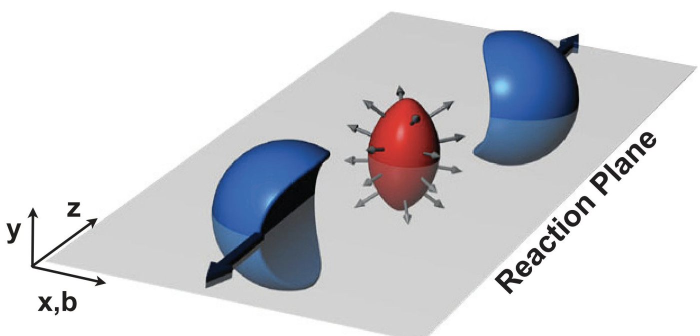


Directed flow(v_1) Elliptic flow(v_2) Triangular flow(v_3)



Directed flow

$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

Sideward motion of emitted hadrons with respect to collision reaction plane

Elliptic flow

$$v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$$

Driven by the initial spatial asymmetry of the overlap region

Triangular flow

$$v_3 = \langle \cos 3(\phi - \Psi_1) \rangle$$

Driven by the shape of the initial collision geometry at low collision energies

Why is v_n an important observable?

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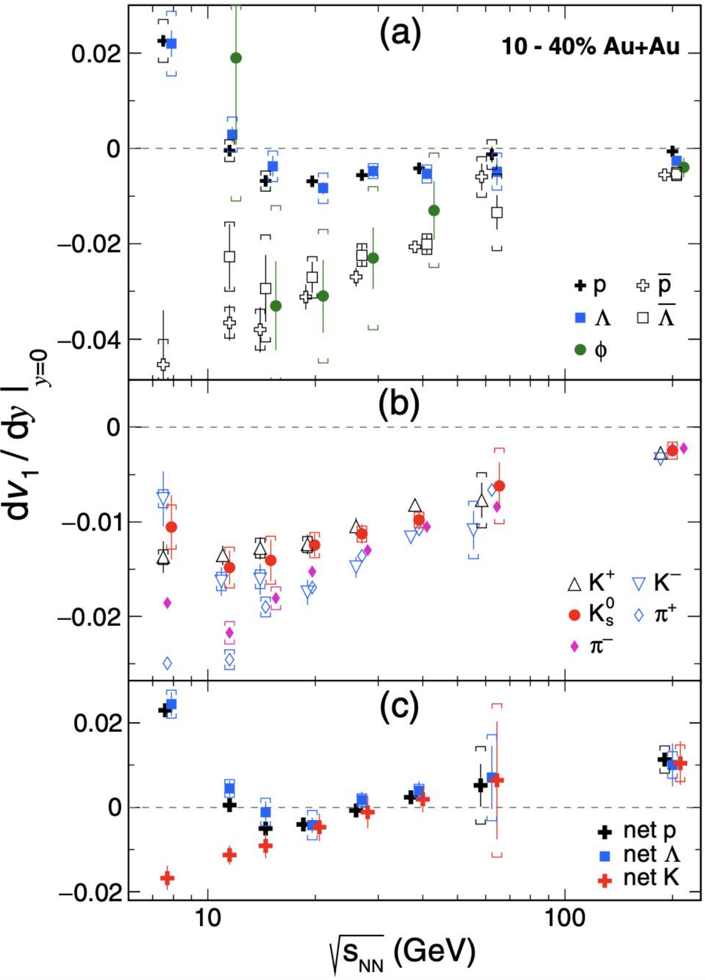
- Sensitive to early times in the evolution of the system

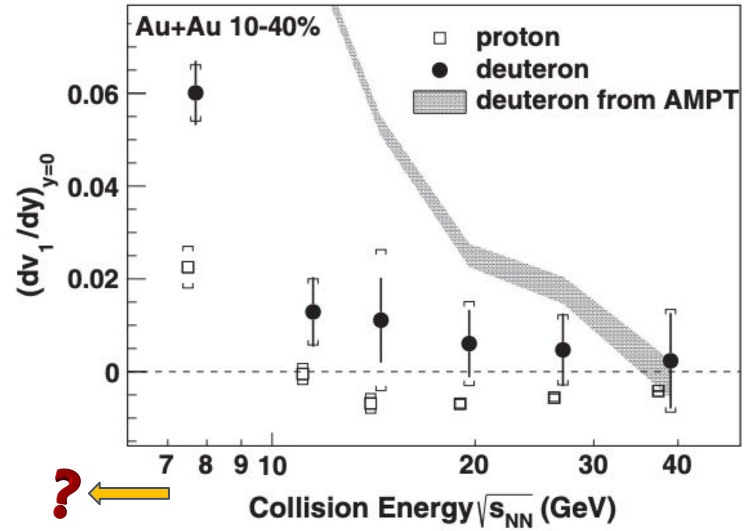
Motivation: Directed flow



Net particle v_1 is defined as

$$v_{1,net} = \frac{v_{1,p} - r v_{1,\bar{p}}}{1 - r}$$

where $v_{1,p}$, $v_{1,\bar{p}}$ → particle and antiparticle v_1 and r is the ratio of anti-particles to particles



- dv$_1$/dy for proton contrary to mesons showed a non-monotonic trend as function of collision energy ➡ **Change of sign**

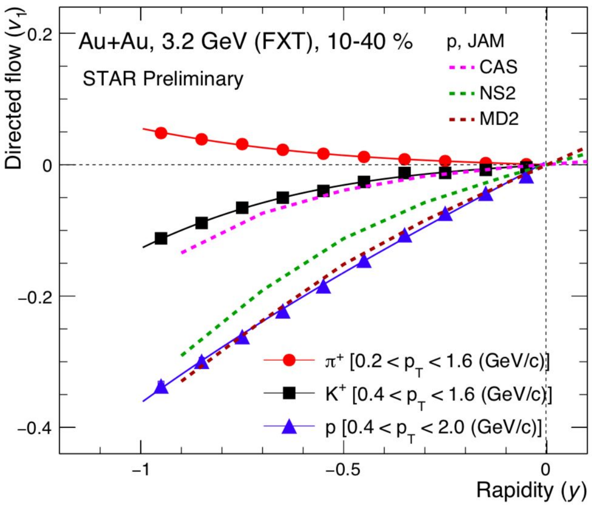
- **Net particle** (the excess of a particle over antiparticle) gives contribution of transported quarks w.r.t produced
- Observed minima in v$_1$ slope of net-p and net-**Λ** between **11.5 and 19.6 GeV**, ***no minima observed for net-K***

- Light nuclei d(v$_1$/A)/dy within systematic and statistical uncertainties ➡ **test for nucleon coalescence mechanism**

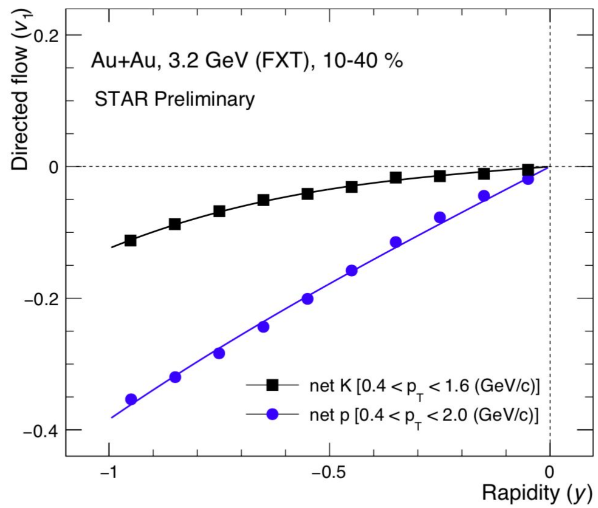
STAR: Phys. Rev. Lett. 120, 062301 (2018);
STAR: Phys. Rev. C 102, 044906 (2020)

Directed Flow at 3.2 GeV

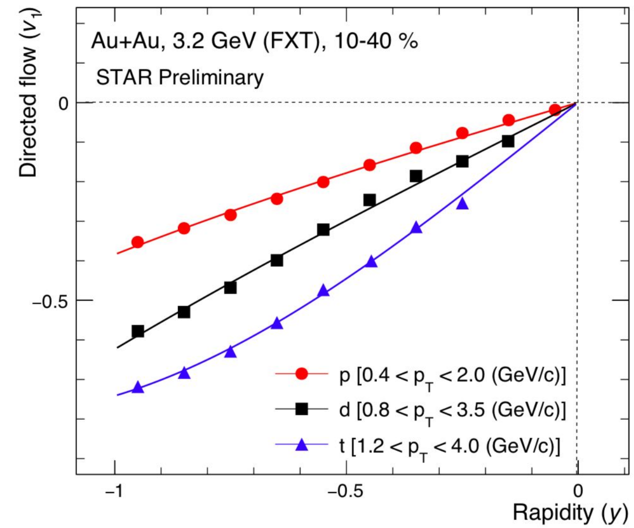
Identified hadrons



Net-particle



Light nuclei



JET AA Microscopic Transportation Model (JAM2)

Cas: no interactions among particles

NS2: mean-field potential

Incompressibility constant: **κ** = 210 MeV

MD2: momentum dependent mean-field potential

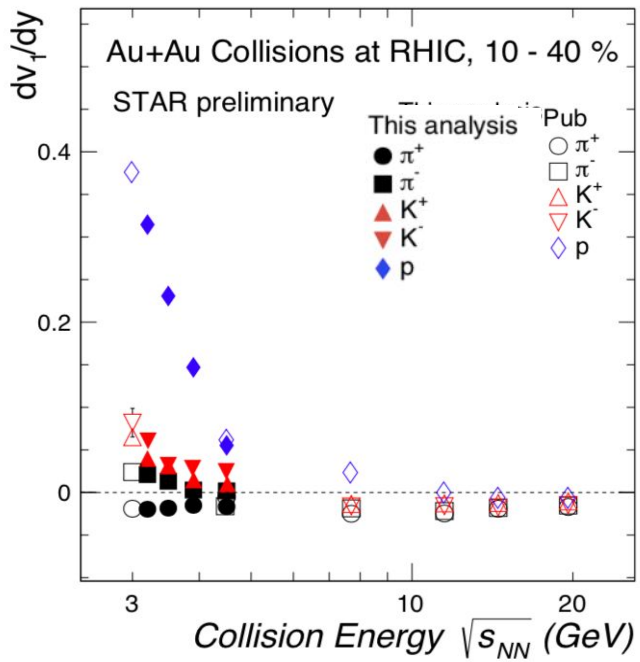
Incompressibility constant: **κ** = 380 MeV

Phys. Rev. C. 105, 014911(2022)

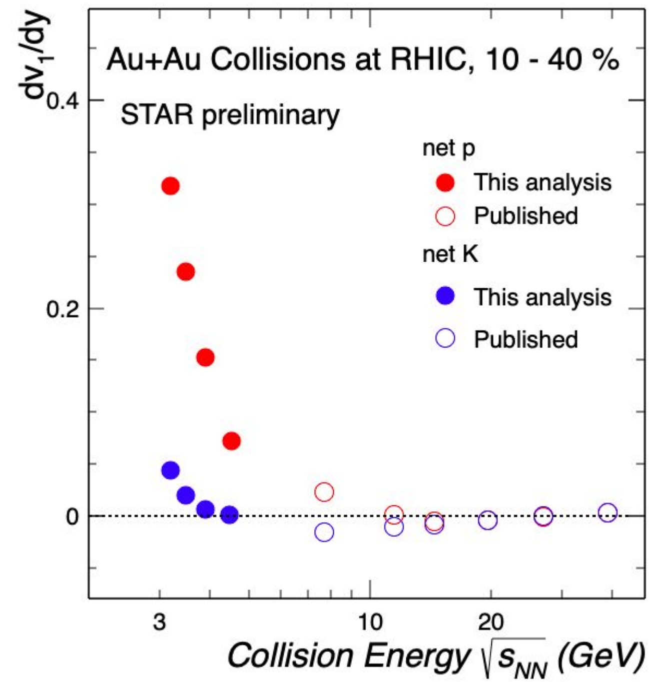
- ❖ Magnitude of v_1 increases with increasing rapidity
- ❖ Magnitude of v_1 increases with increasing mass of the particle
- ❖ JAM MD2 gives better description to the experimental data for baryons

Slope of Directed Flow

Identified hadrons

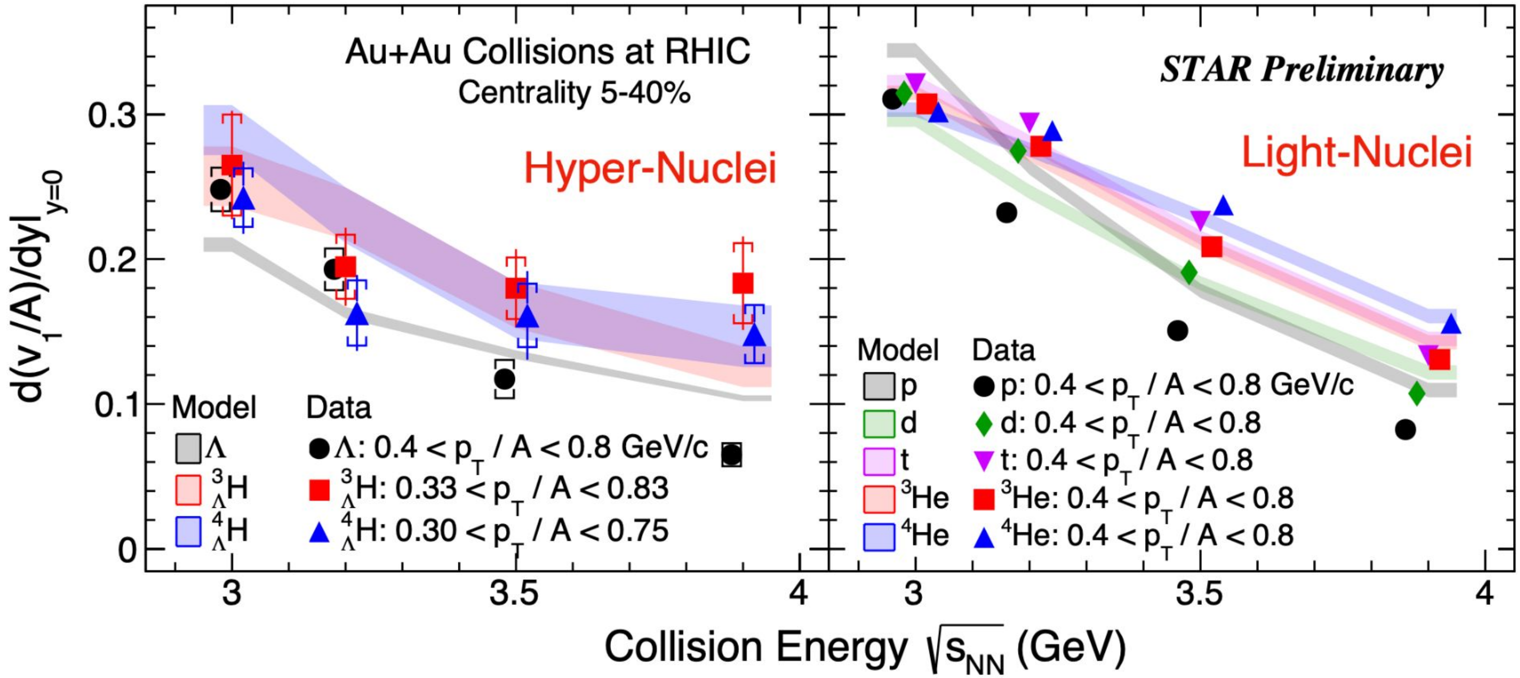


Net-particle



- Increasing collision energy → decreasing v_1 slope for the measured energies
  - $dv_1/dy|_{\pi+}$ is negative whereas $dv_1/dy|_{\pi-}$ is positive → **Spectator shadowing** **(3.0 - 4.5 GeV)**
- **Net-K** changes sign at ***lower collision energy*** (4.5 - 7.7 GeV) compared to **Net-p** (11.5 - 14.5 GeV)

Directed Flow of Light- And Hyper-Nuclei

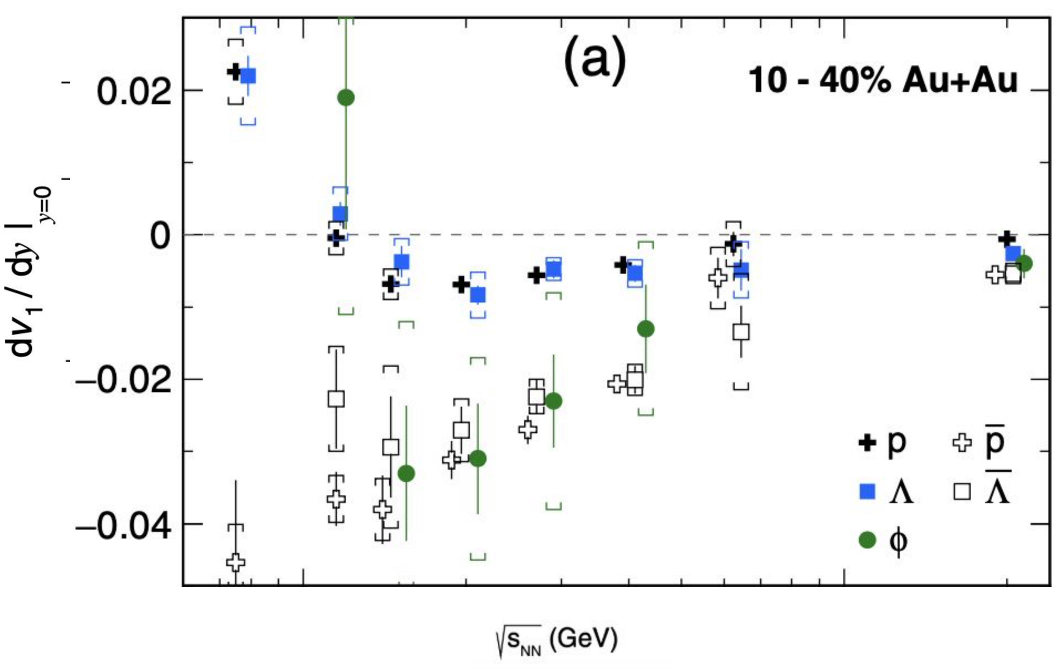


- As the collision energy increases, the v_1 slope of light- and hyper-nuclei decreases
- At given energy, for both light- and hyper-nuclei, it seems that the slopes of mid-rapidity v_1 are scaled with atomic mass number (A)
- Hadronic transport model (JAM2 mean field + Coalescence) calculations are consistent with observed energy dependence
- The results for light- and hyper-nuclei v_1 favor coalescence as their production mechanism

STAR: Phys. Lett. B 827, 136941 (2022); STAR: Phys. Rev. Lett. 130, 211301(2023); Phys. Rev. C. 105, 014911(2022)

Directed Flow of ϕ Meson

- **ϕ($s\bar{s}$)** is a unique particle as it is a **meson** with mass (*1020 MeV*) close to baryons



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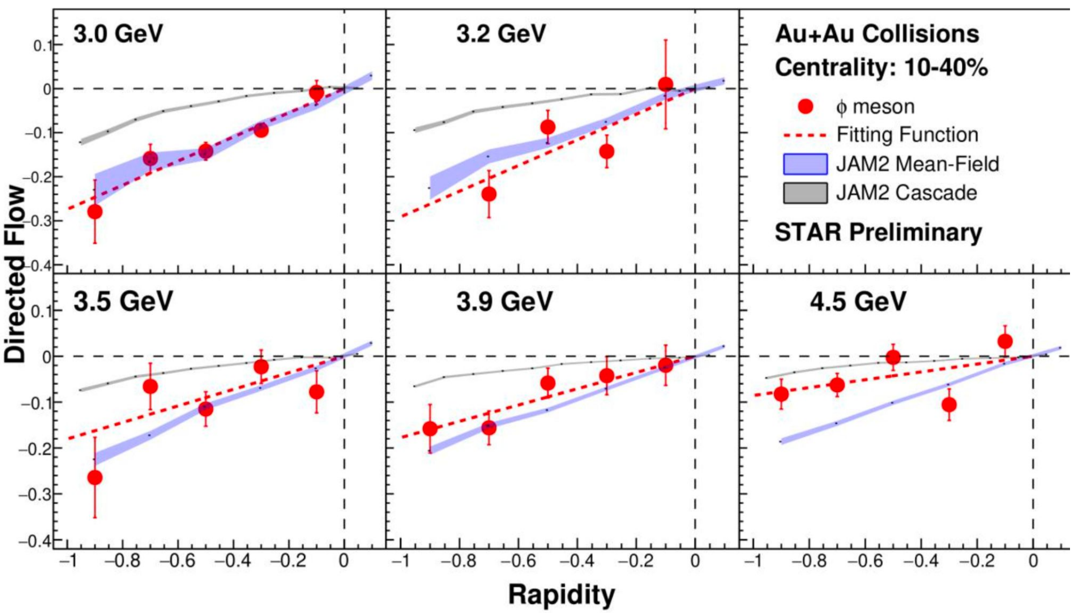
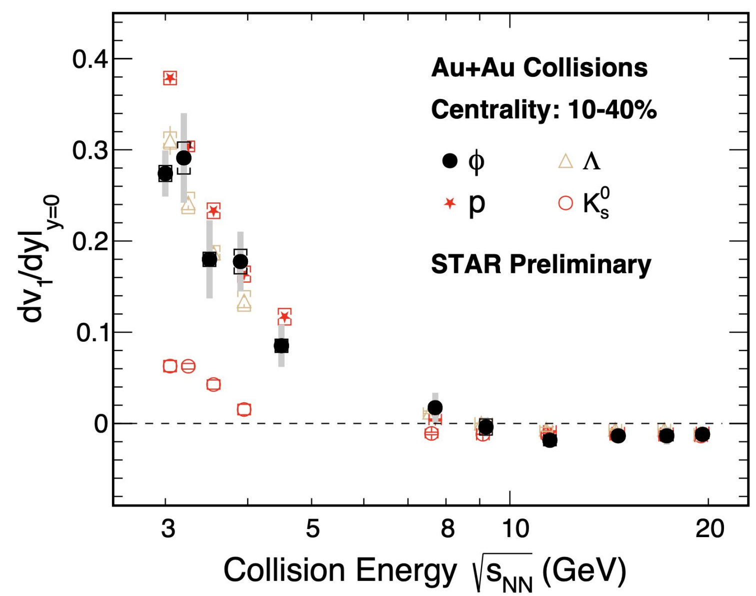
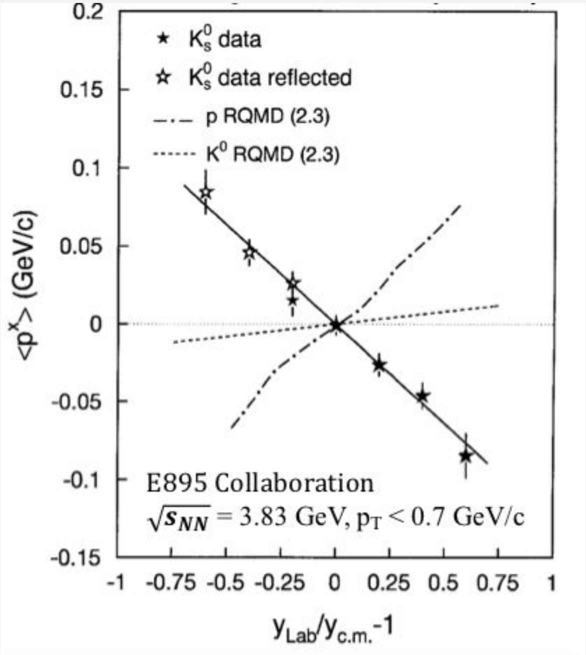




❖ The v_1 slope of ϕ meson shows similar trends to that of **p and Λ.**

Anti-flow of Mesons at Low p_T

Phys. Rev. Lett. 85, 940 (2000)

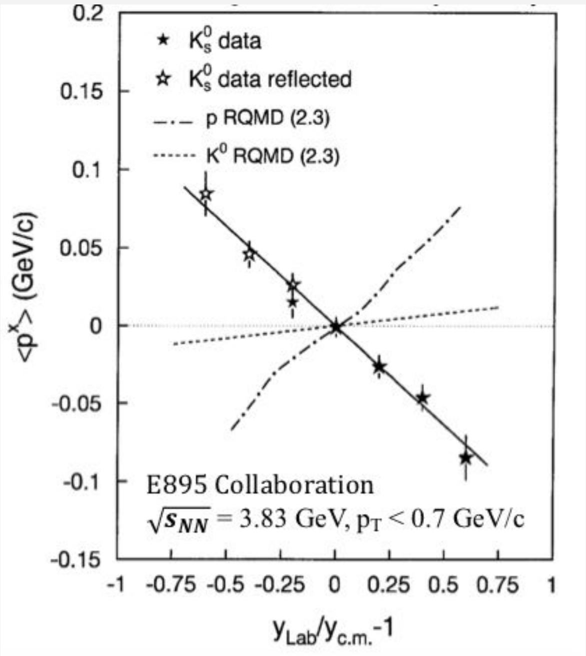


❖ E895: anti-flow of kaon at low p_T ➡ **Kaon potential?**

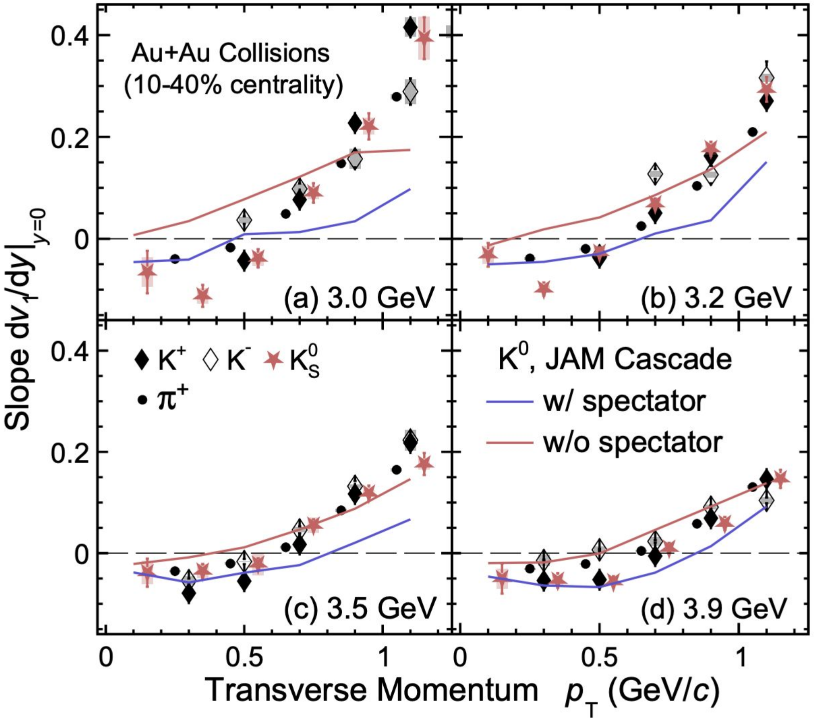
STAR: arXiv:2503.23665

Anti-flow of Mesons at Low p_T

Phys. Rev. Lett. 85, 940 (2000)



❖ E895: anti-flow of kaon at low p_T ➡ **Kaon potential?**

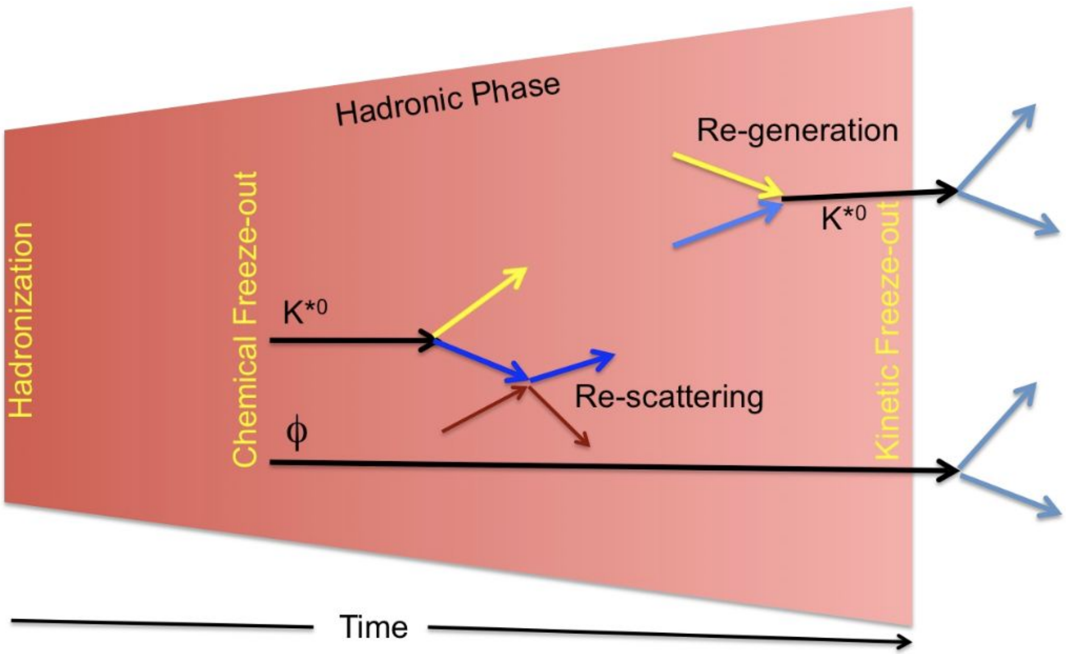


- Negative dv_1/dy at low p_T for mesons → **Anti-flow at low energies (3.0 - 4.5 GeV)**
- JAM Cascade model → with spectators able to reproduce the anti-flow at low p_T ➡ **Kaon potential is not necessary**

STAR: arXiv:2503.23665

Directed Flow of K^{*0} and ϕ Resonances

- Reconstructed K^{*0} yield can be affected by hadronic interaction suffered by its daughter particles between Chemical Freeze-out and Kinetic Freeze-out
- Asymmetric loss of K^{*0} yield in different sides of the p_x axis may lead slope change for K^{*0} v_1 as a function of rapidity



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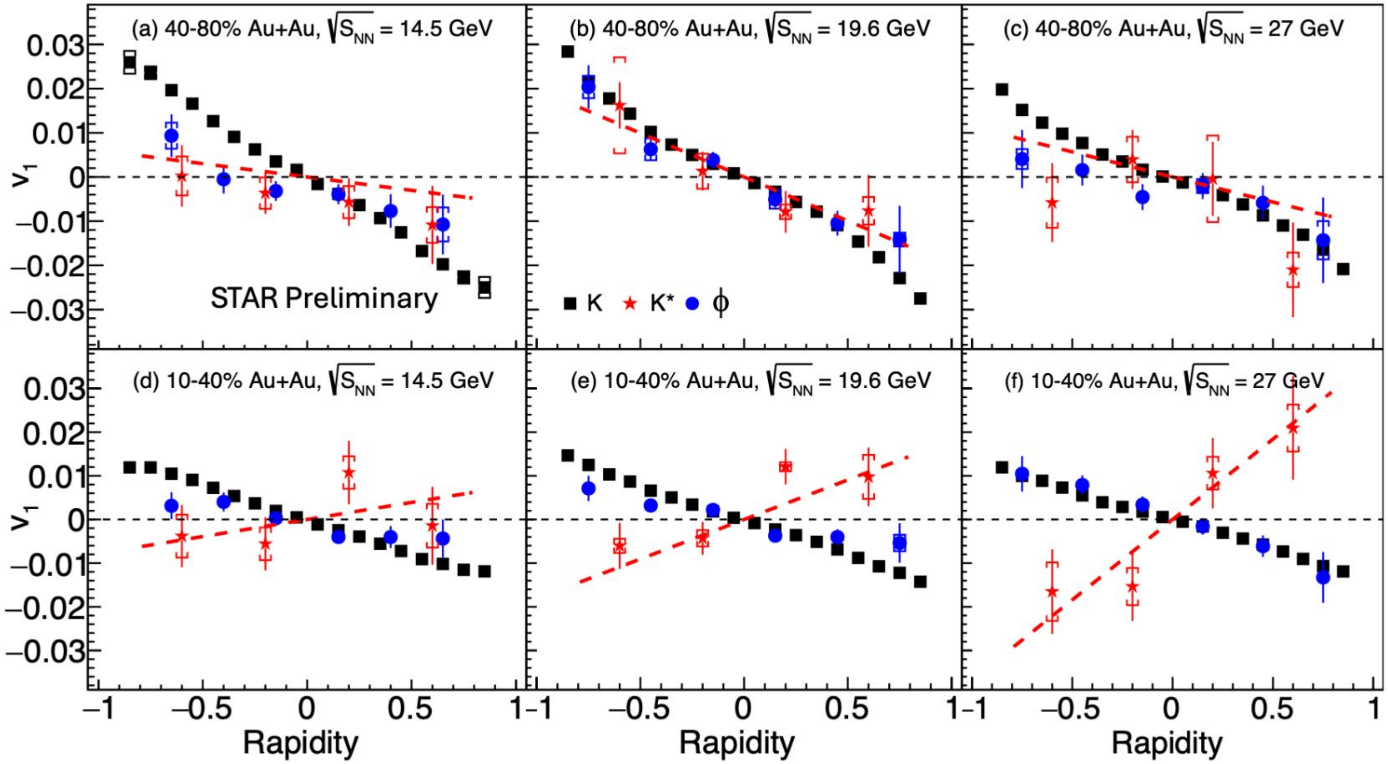
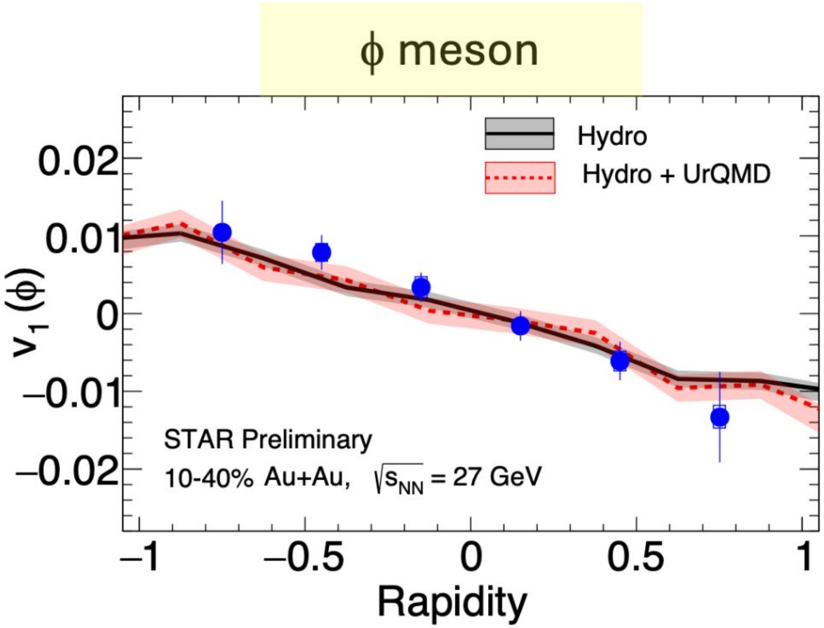


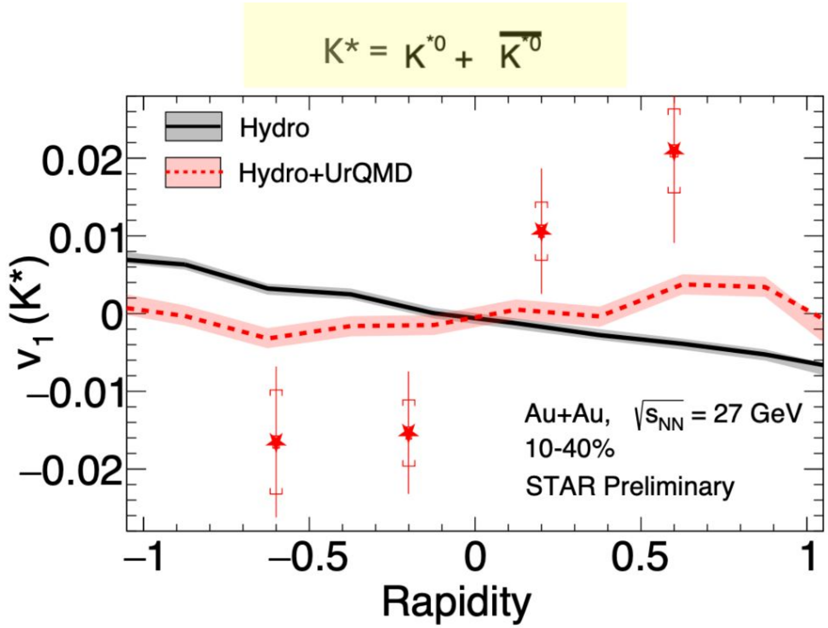
$K^* = K^{*0} + \overline{K^{*0}}$

$K = K^+ + K^-$

- Au+Au collisions **[40-80%]**: Negative v_1 slope for charged Kaon, ϕ and K^{*0} resonances
- Au+Au collisions **[10-40%]** : Opposite v_1 slope for K^{*0} resonances compared to peripheral

Directed Flow of K^{*0} and ϕ Resonances

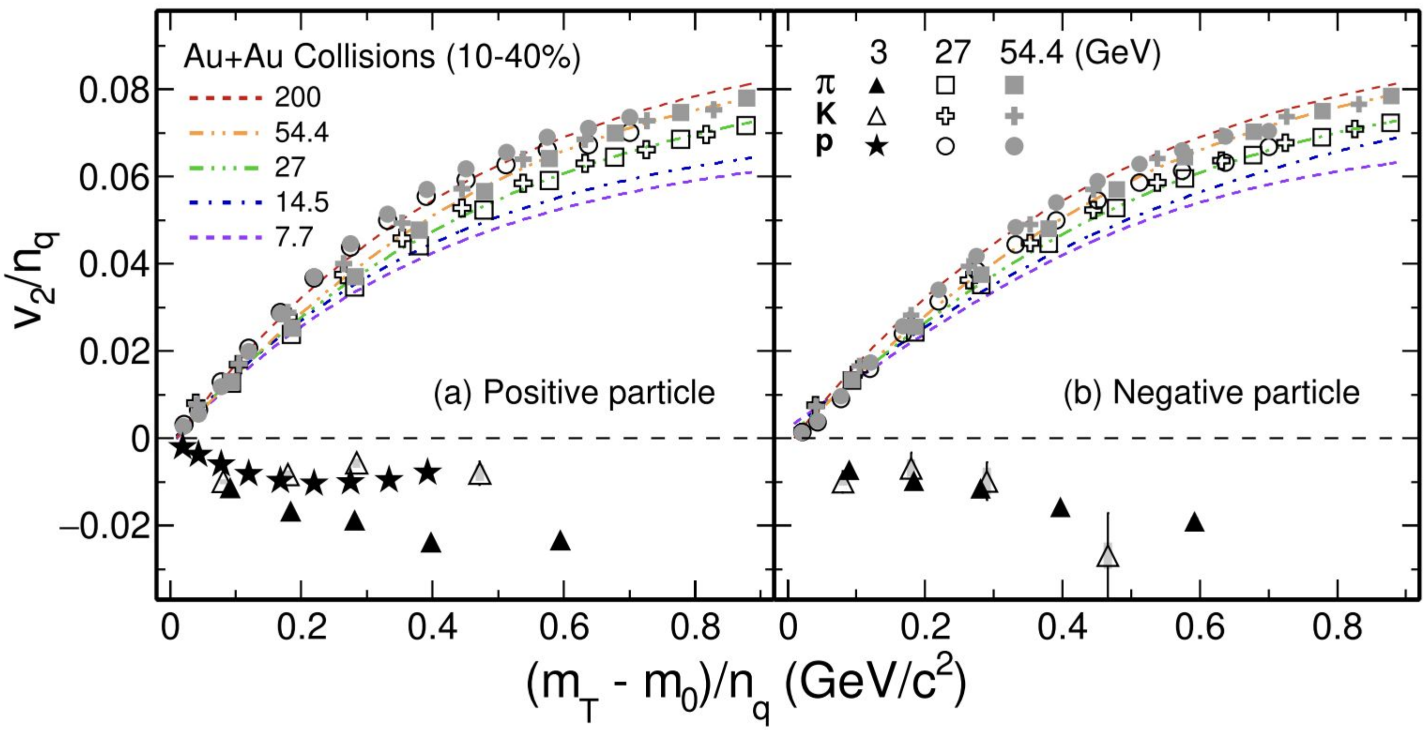




- Model calculation successfully reproduces measured f meson v_1 for **ϕ**
- Hydro model calculation shows opposite slope compared to data for $\mathbf{K^*}$
  - **Hydro+Hadronic afterburner** qualitatively explain the data.

Model: Phys. Rev. C 109, 044905 (2024)

Motivation: Elliptic flow (v_2)



- ❖ At high energies, data follows **NCQ scaling**, indicating partonic collectivity
- ❖ At **3 GeV**, anti-flow from shadowing breaks **NCQ scaling**

STAR: Phys. Rev. C 93, 14907 (2016), STAR: Phys. Lett. B 827, 137003 (2022)

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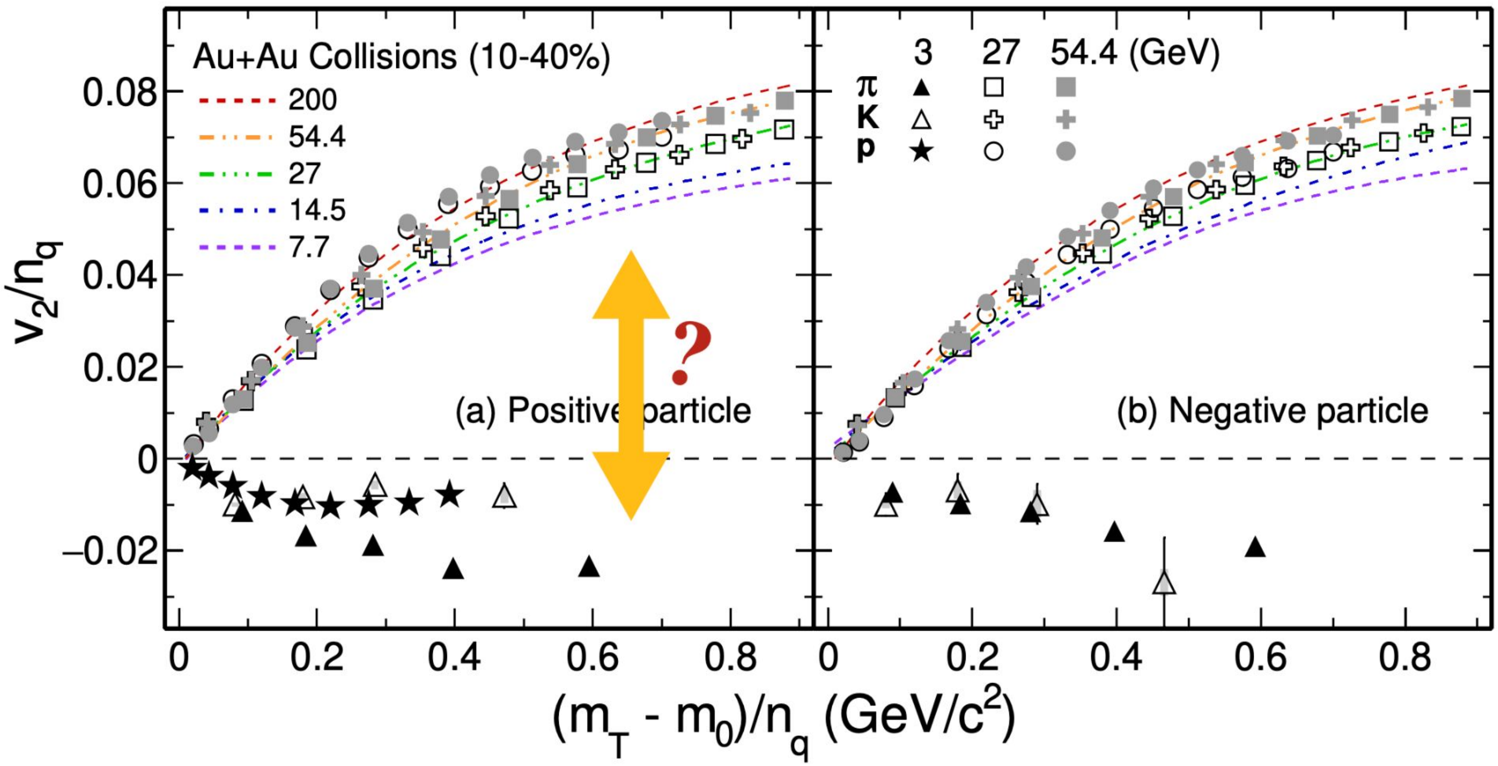

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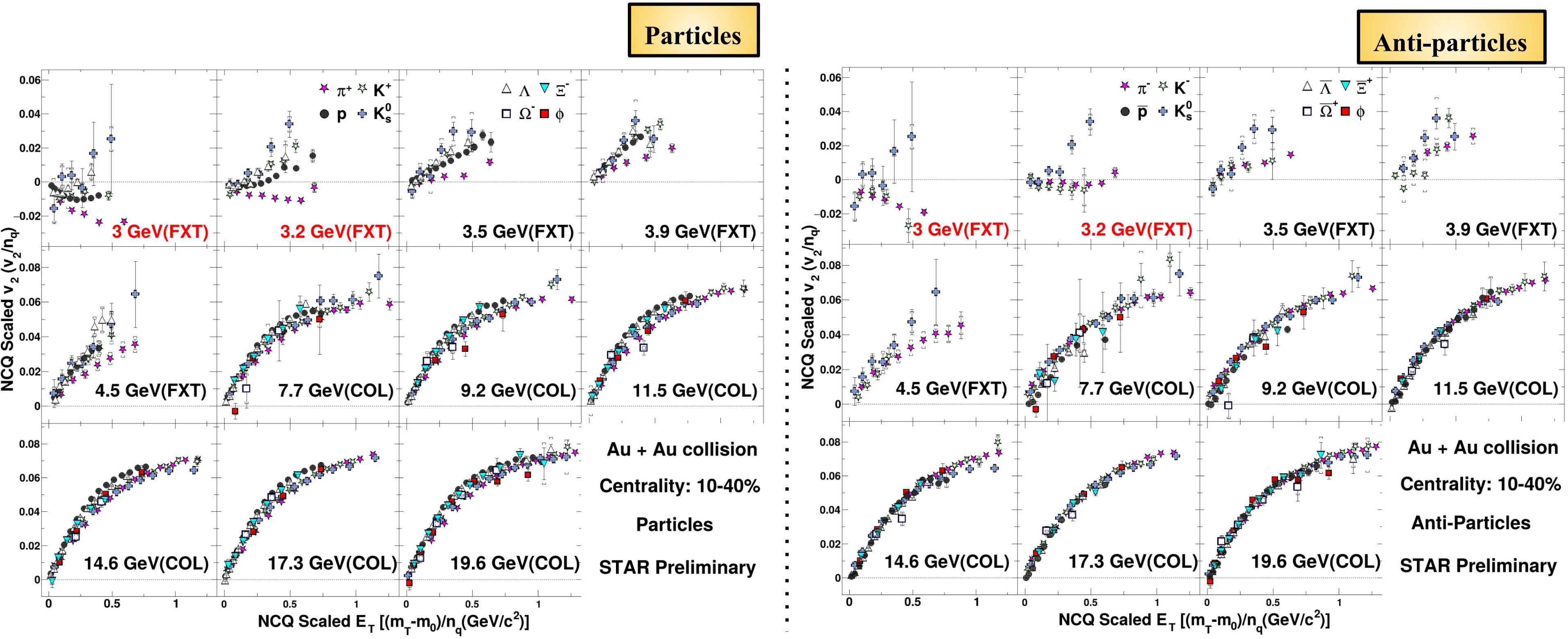
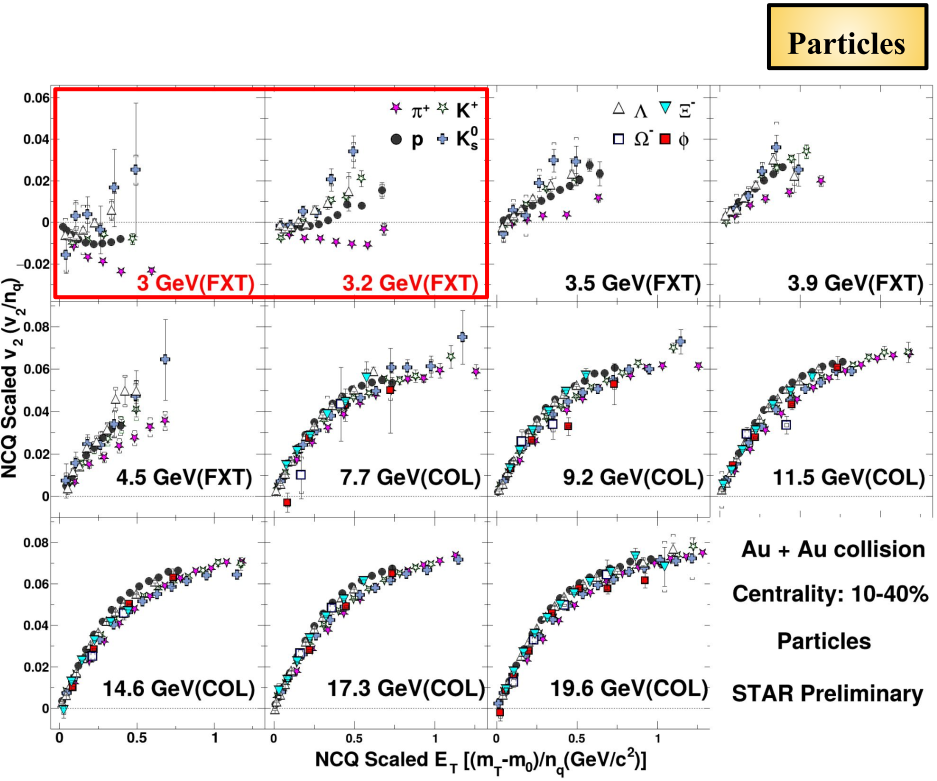
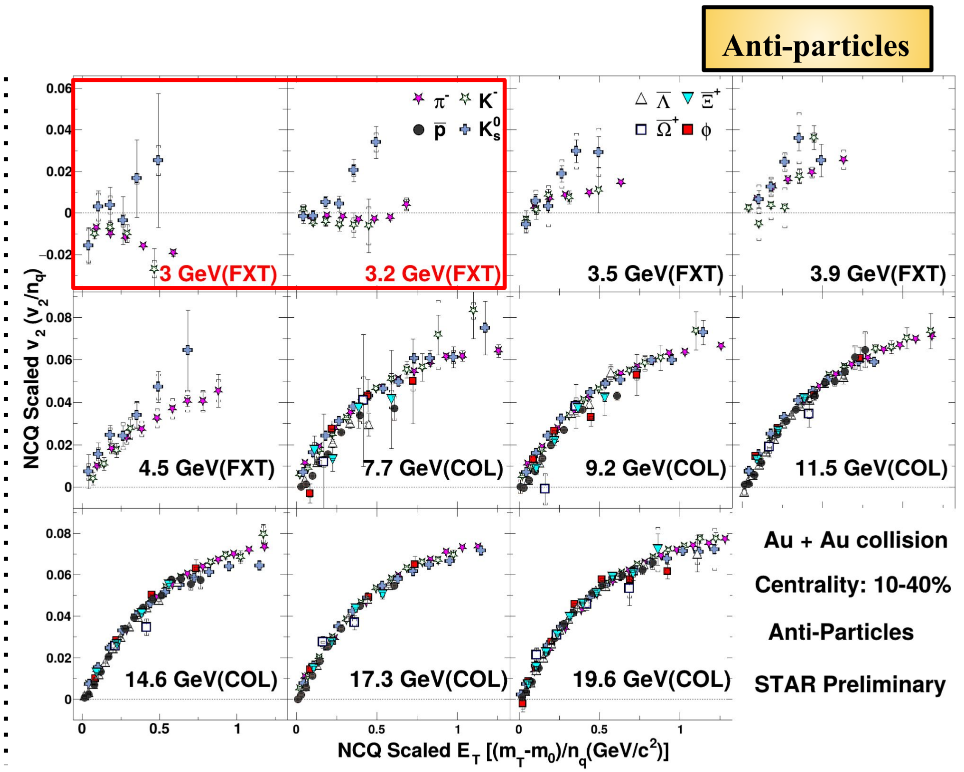
NCQ Scaling of Elliptic Flow



- **NCQ scaling** completely **breaks** below **3.2 GeV**
- NCQ scaling becomes better gradually with increasing collision energy after 4.5 GeV
- **Change of degree of freedom: 4.5 → 7.7 GeV ?**

NCQ Scaling of Elliptic Flow





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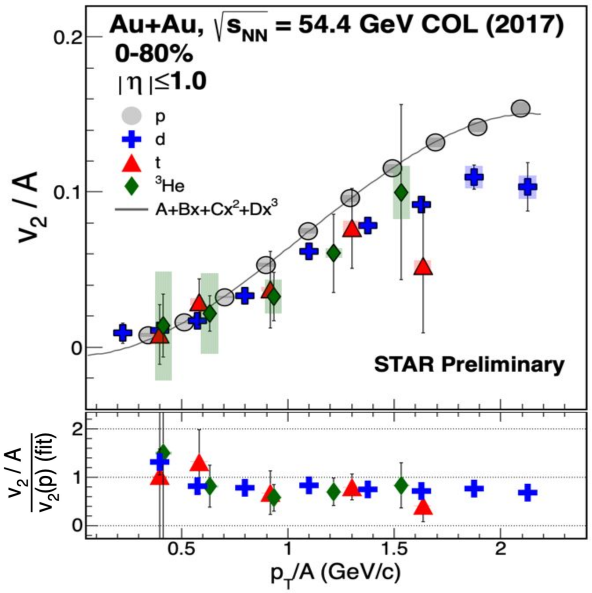
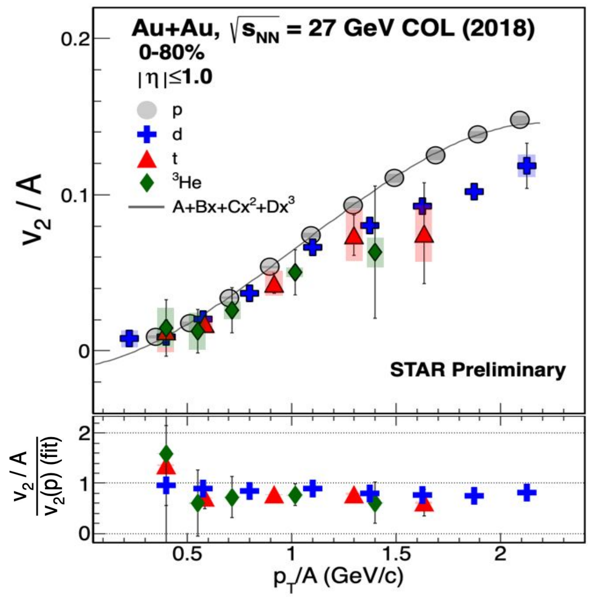
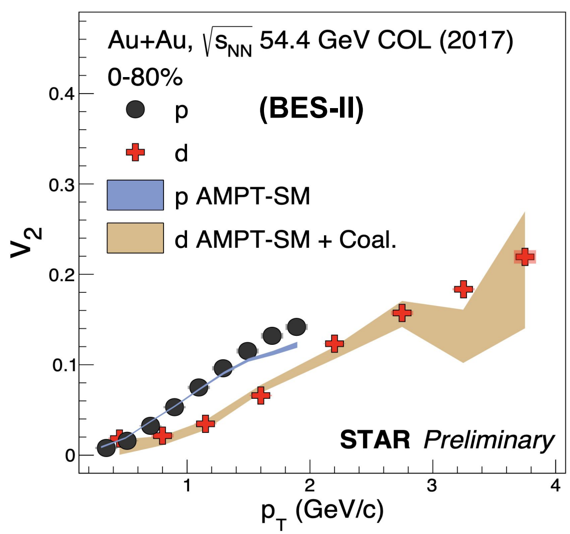
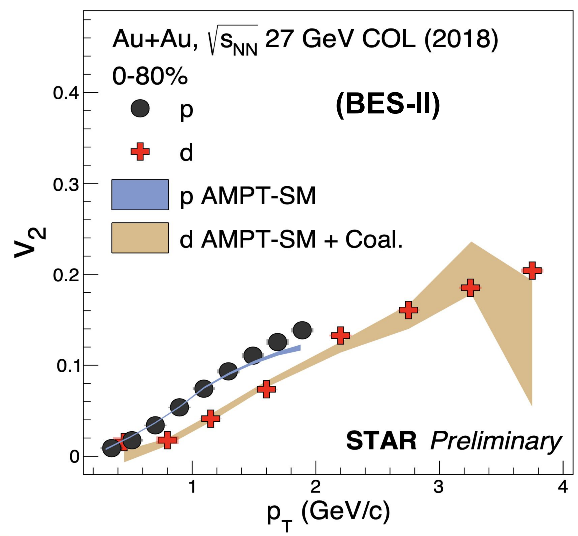
Elliptic Flow of Light Nuclei









- ❖ Systematic deviation of around 20-30% from mass number scaling is observed for all light nuclei in measured energies
- ❖ AMPT-SM model with a coalescence afterburner is in good agreement with $v_2(p_T)$ of d

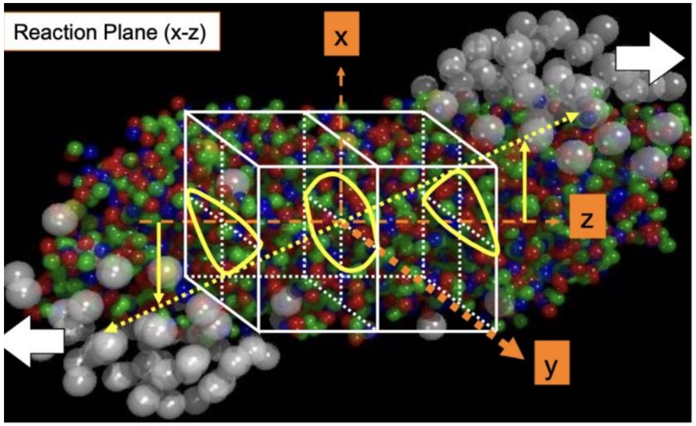
Phys. Rev. C 72, 064901 (2005)

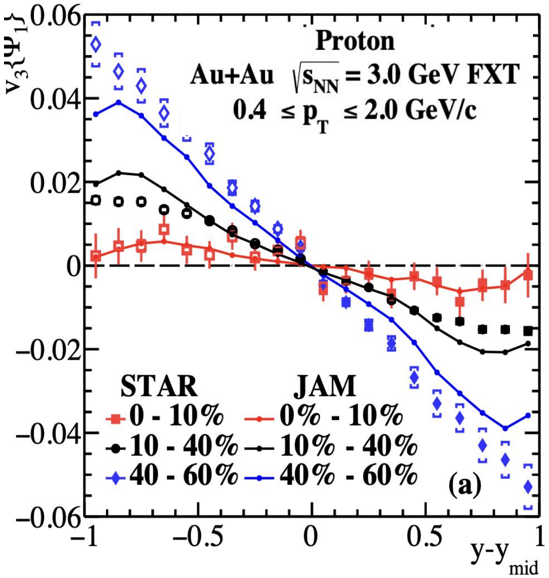
Nucl. Phys. A 729 (2003) 809–834

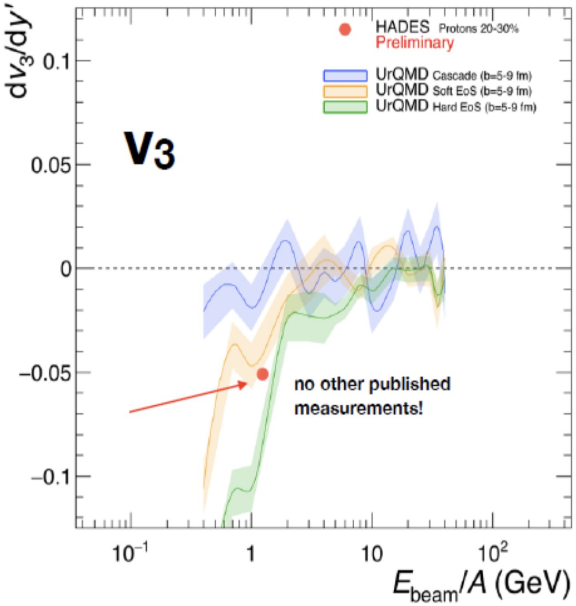
Proton v_2: Phys. Rev. C 93, 014907 (2016); Phys. Rev. C 88, 014902 (2013); Phys. Lett. B 827, 137003 (2022)

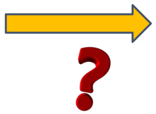
Motivation: Triangular flow (v_3)

At high energies, v_3 → uncorrelated with the 1st order event plane, contrary to observation at **2.4 GeV** by (***HADES***) and at **3 GeV** (***STAR***).





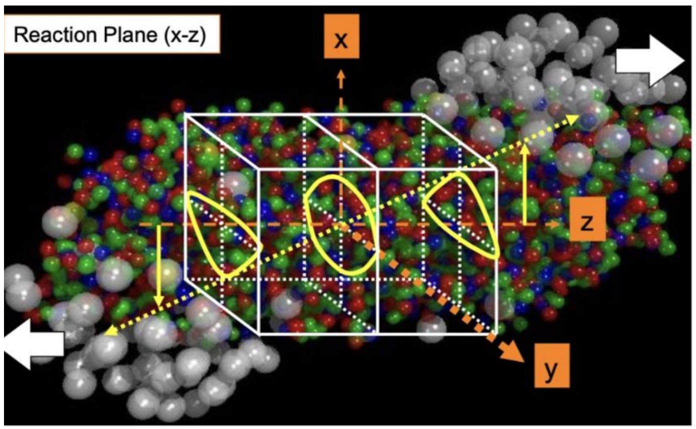


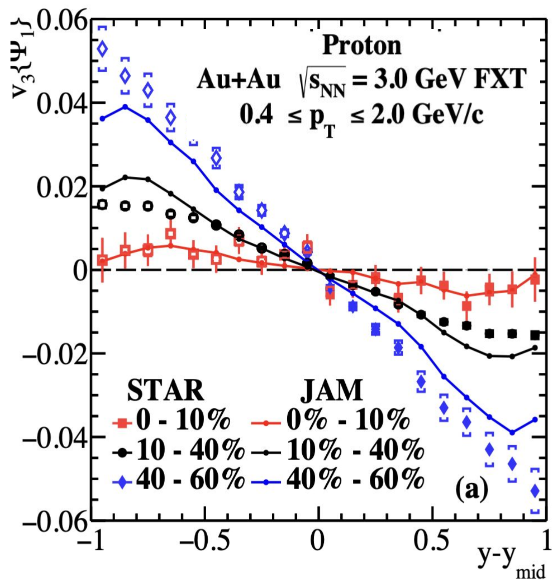


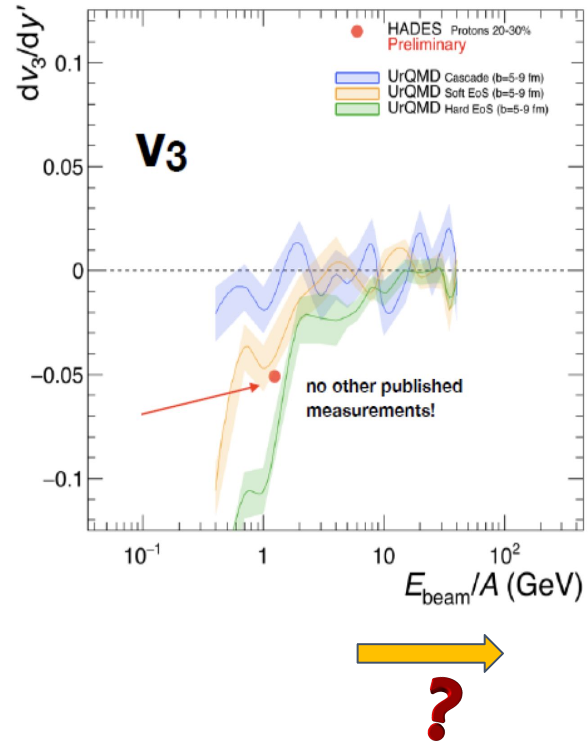
HADES: Eur. Phys .J. A 59 4, 80 (2023), STAR: Phys. Rev. C 109, 044914 (2024), J. Phys. G: Nucl. Part. Phys. 45 085101 (2018)

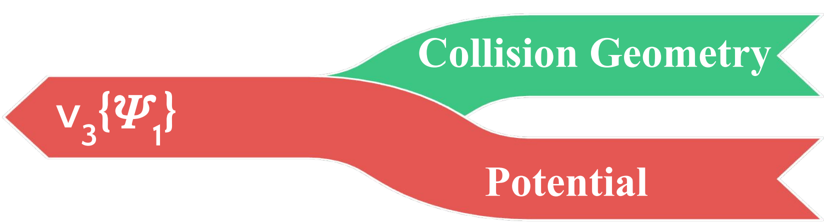
Motivation: Triangular flow (v_3)

At high energies, v_3 → uncorrelated with the 1st order event plane, contrary to observation at **2.4 GeV** by (***HADES***) and at **3 GeV** (***STAR***).



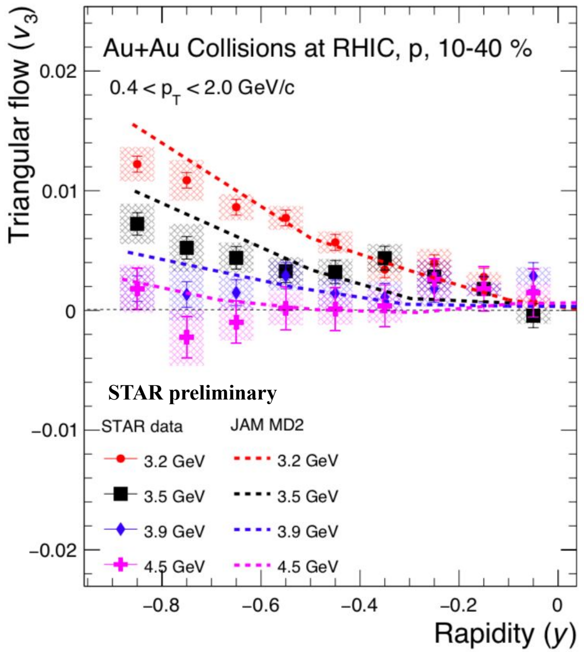


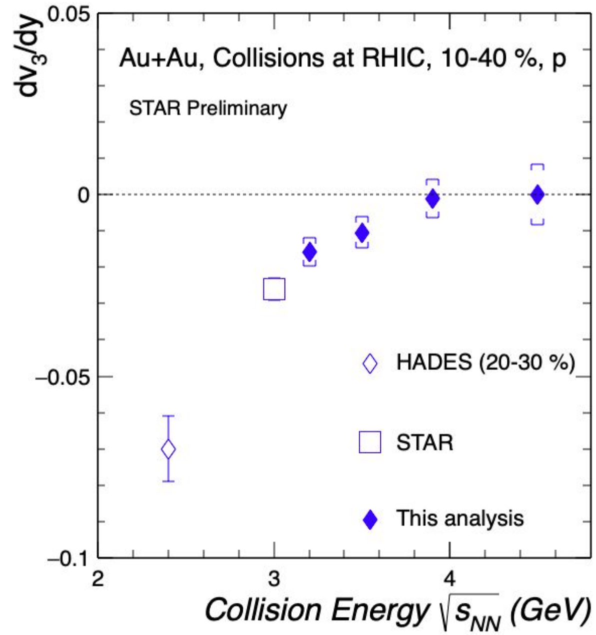


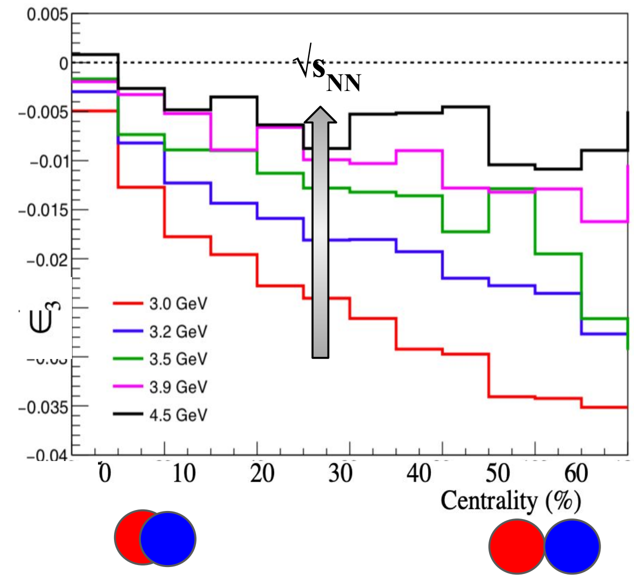


HADES: Eur. Phys .J. A 59 4, 80 (2023), STAR: Phys. Rev. C 109, 044914 (2024), J. Phys. G: Nucl. Part. Phys. 45 085101 (2018)

Triangular flow ($v_3\{\Psi_1\}$)







- Increasing collision energy → decreasing magnitude of $v_3\{\Psi_1\}$ slope
- JAM model with mean-field (MD2) describes the data ➡ Nuclear potential is essential for the development of $|v_3\{\Psi_1\}|$ ✅
- Triangularity (ϵ_3) decreases with increasing collision energy ➡ Strong geometric effect ✅

HADES: Eur. Phys .J. A 59 4, 80 (2023), STAR: Phys. Rev. C 109, 044914 (2024)

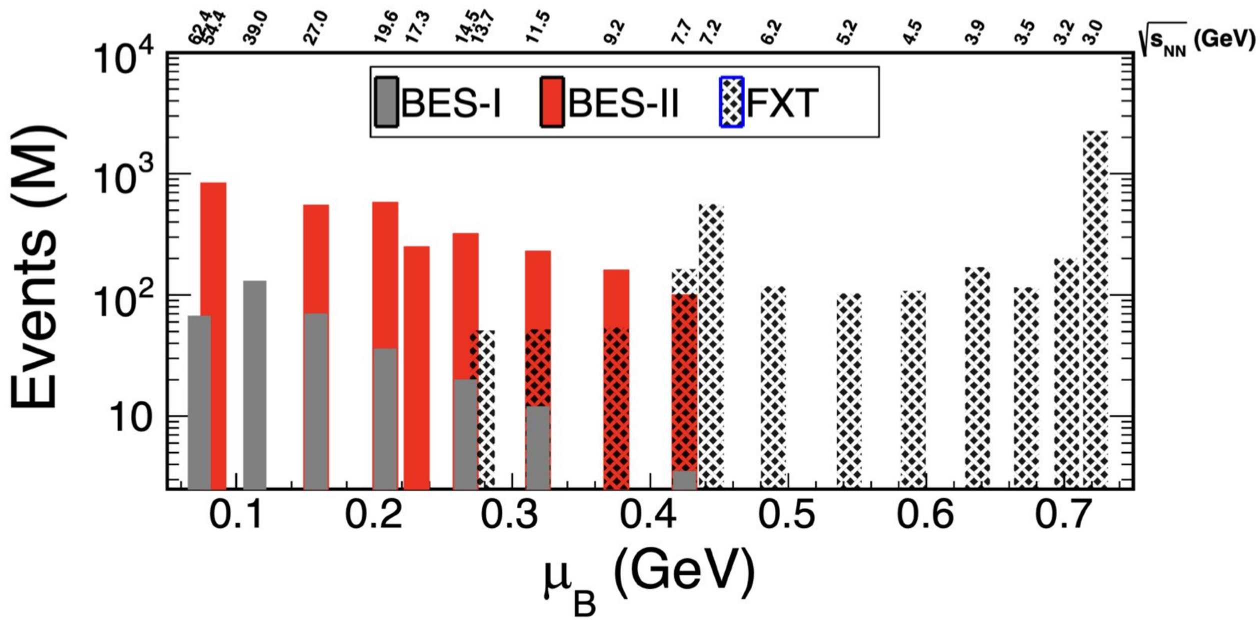
Summary

- Approximate mass no. scaling is observed in the v_1 slope for light nuclei ➡ Nucleon coalescence
- The v_1 slope of ϕ meson shows similar trends to that of baryons in 'in the high μ_B region
- In peripheral collisions, K^{*0} $v_1(y)$ shows a negative slope like ϕ and kaons, but a positive slope in mid-central collisions.

- NCQ scaling breaks at 3.0 and 3.2 GeV, and gradually restores from 3.2 to 4.5 GeV
  - Shadowing effect diminishes with increasing energy
  - Dominance of partonic interactions at 4.5 GeV and above
- AMPT-SM+Coal. seems to well describe the v_2 of d

- Magnitude of $d(v_3\{\Psi_1\})/dy$ decreases with increasing energy and approaches zero at 4.5 GeV
- JAM model with momentum dependent mean-field (κ = 380 MeV) describes the $v_3\{\Psi_1\}$ data

Outlook



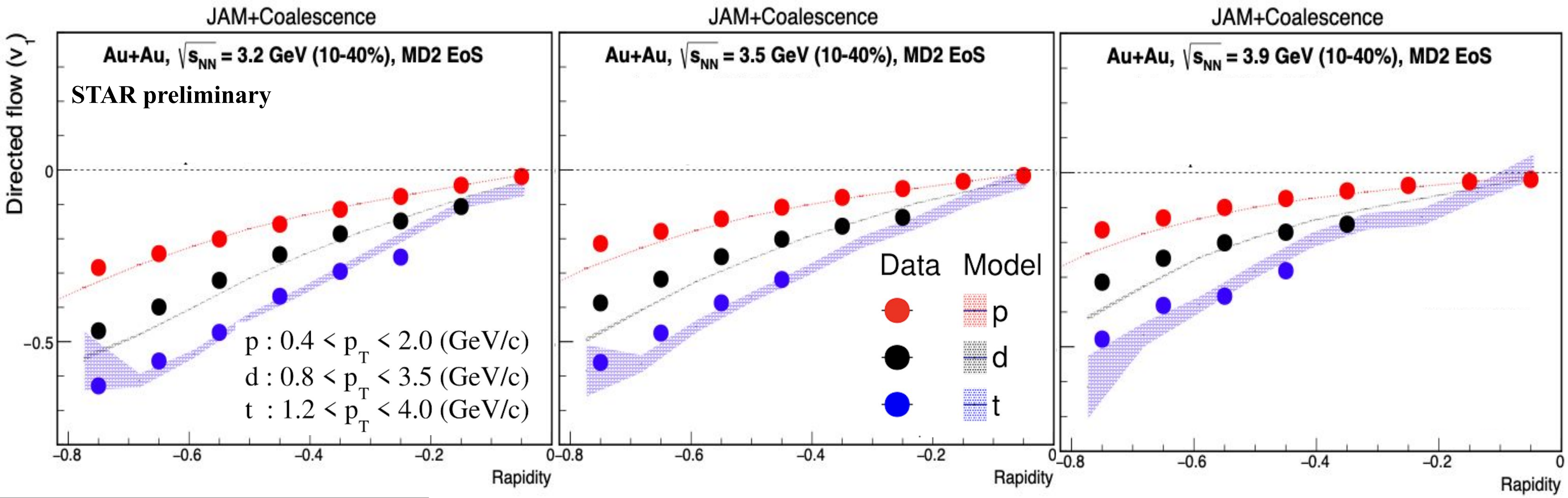
- **High-precision measurements** enabled by BES-II with improved statistics and upgraded detectors.
- **Deeper exploration of the QCD phase diagram**, targeting critical phenomena and phase transitions.
- **Stay tuned for more exciting results from BES-II and FXT runs at STAR!**

"With precision as our tool and curiosity as our guide, we move closer to unveiling the mysteries of the QCD phase diagram."

Thank you for your attention!

Backup slides

Directed Flow of Light Nuclei



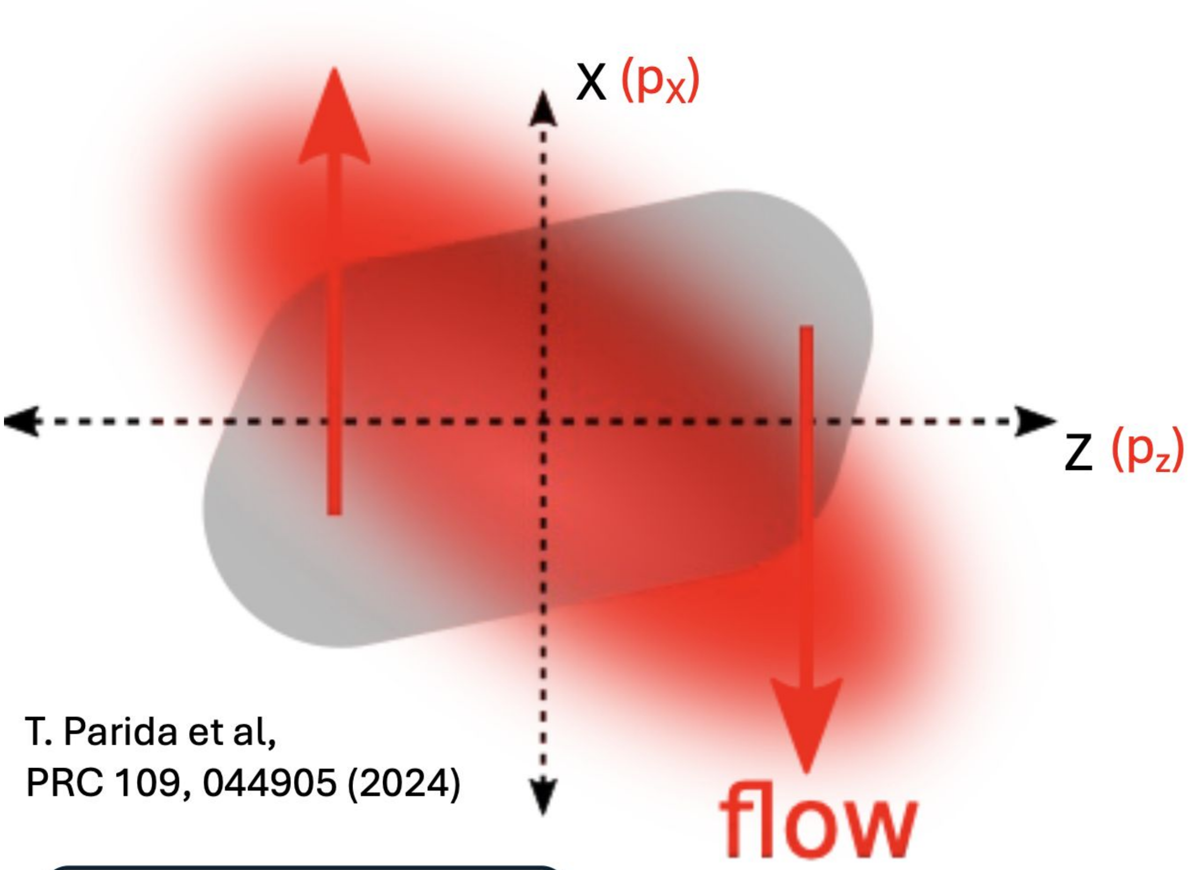
JET AA Microscopic Transportation Model (JAM2)

MD2: momentum dependent mean-field potential
Incompressibility constant: **κ** = 380 MeV

Phys. Rev. C. 105, 014911(2022)

- Magnitude of v_1 increases with increasing rapidity
- **JAM MD2 with coalescence** provides good description of the data

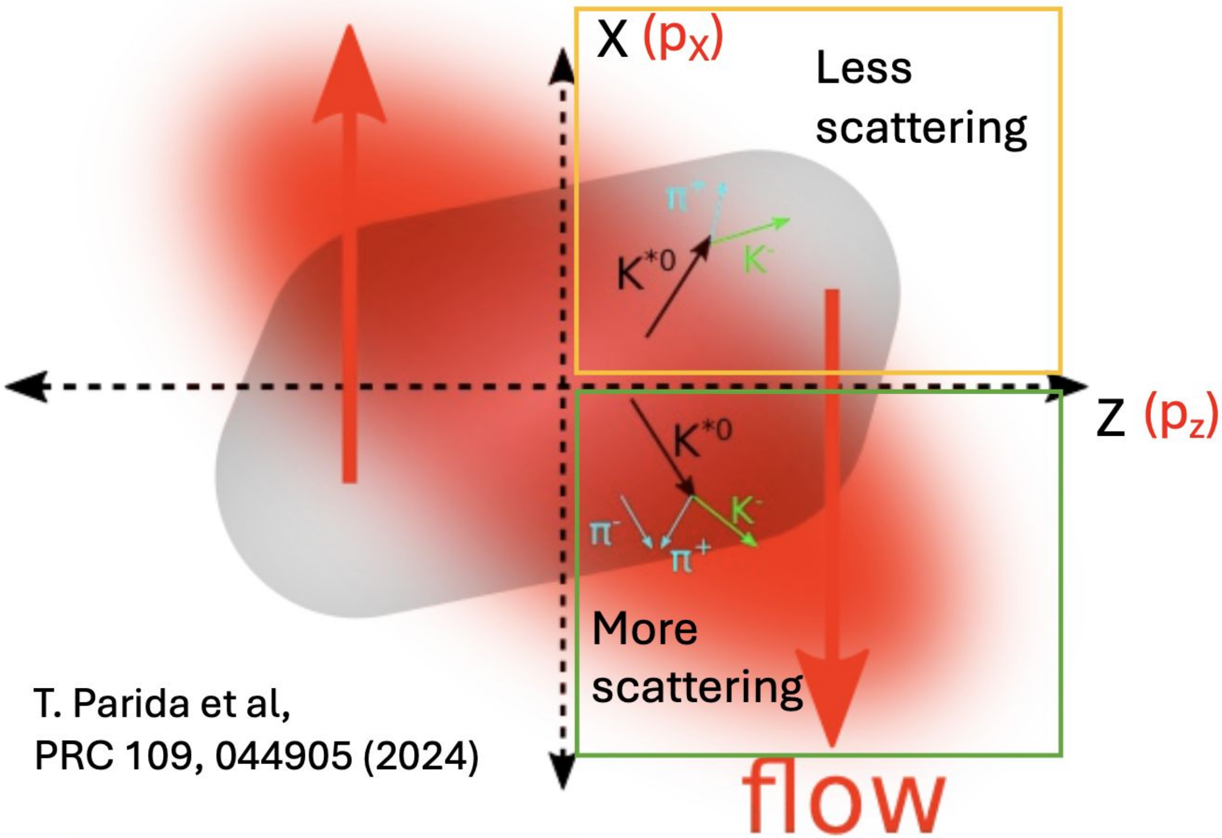
Directed flow of K^*



T. Parida et al,
PRC 109, 044905 (2024)

$$v_1 = \langle \cos(\phi - \psi_1) \rangle$$

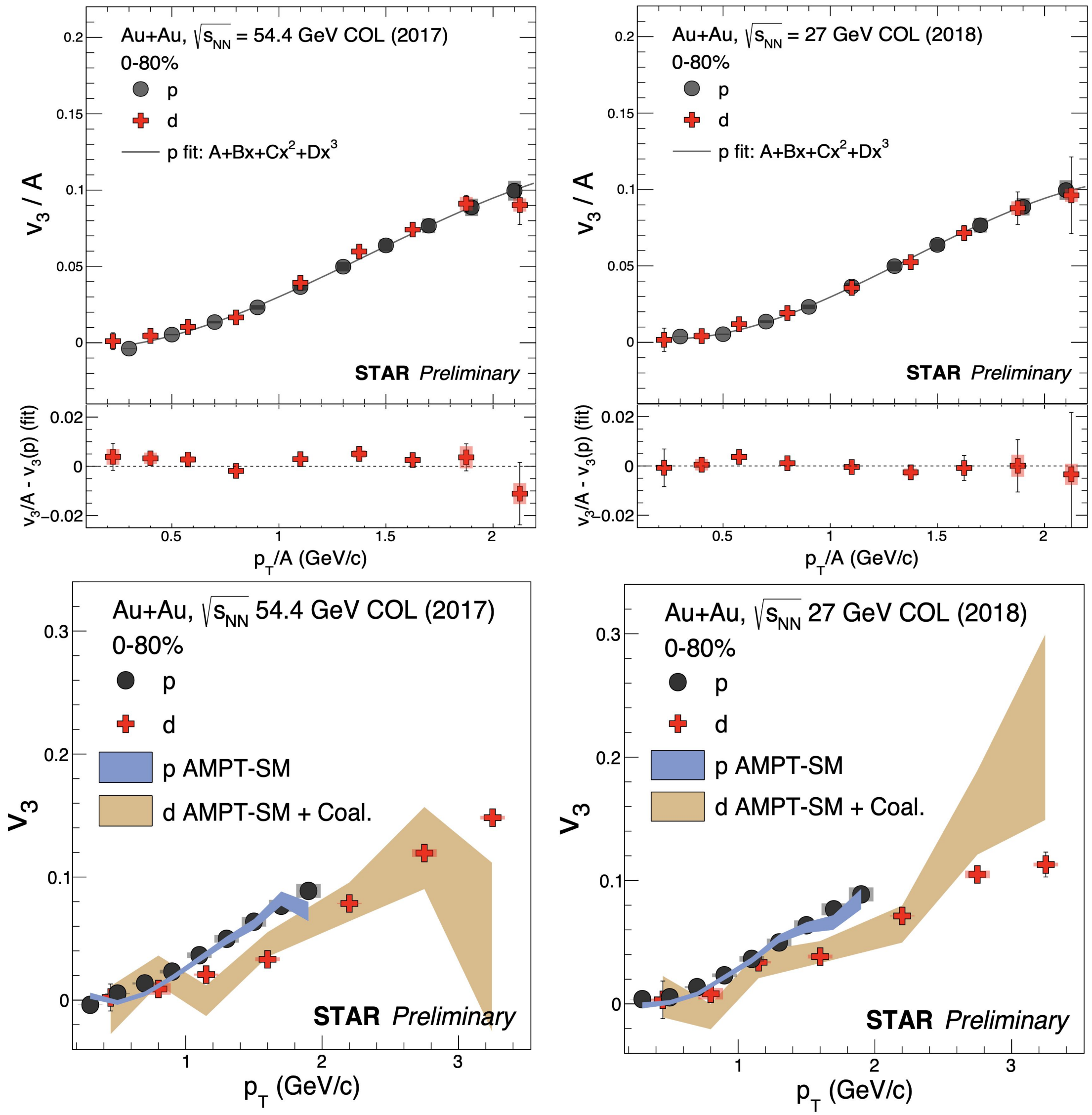
Directed flow of K^*



T. Parida et al,
PRC 109, 044905 (2024)

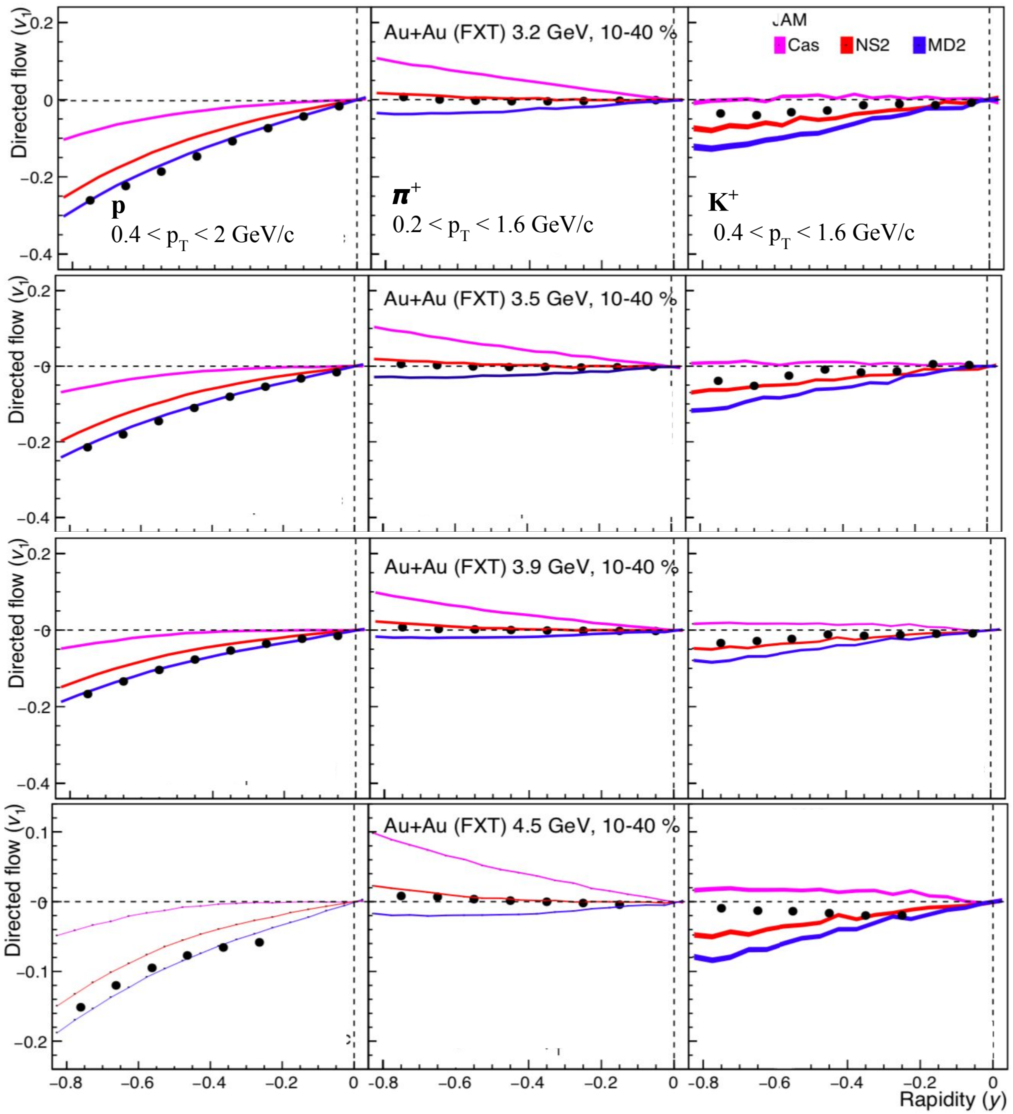
$$v_1 = \langle \cos(\phi - \psi_1) \rangle$$

Triangular Flow of Light Nuclei

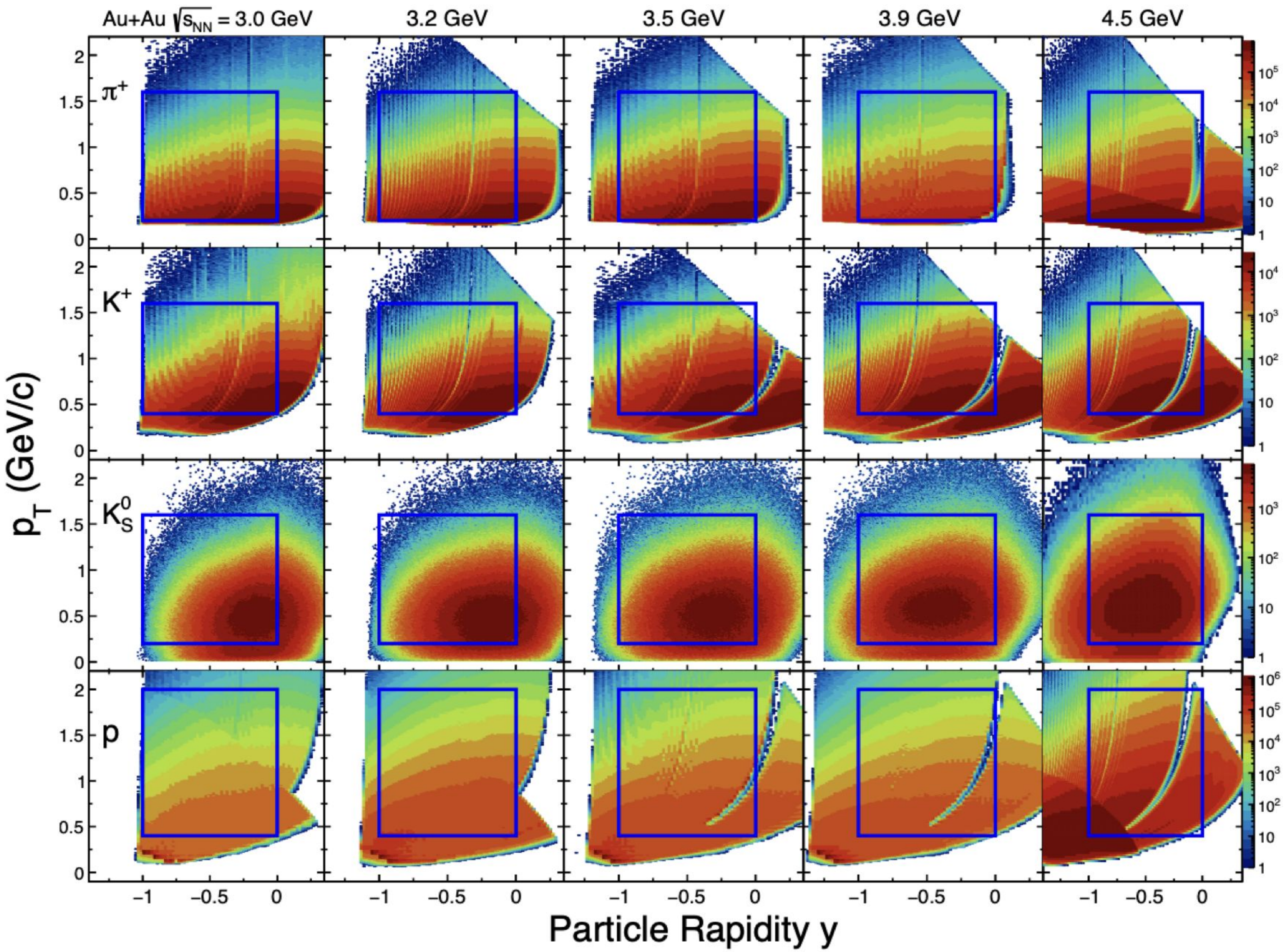


- $v_3(p_T)$ of *d* shows a good agreement with mass number scaling within ~10%
- AMPT-SM model with a coalescence afterburner is in good agreement with $v_3(p_T)$ of *d*

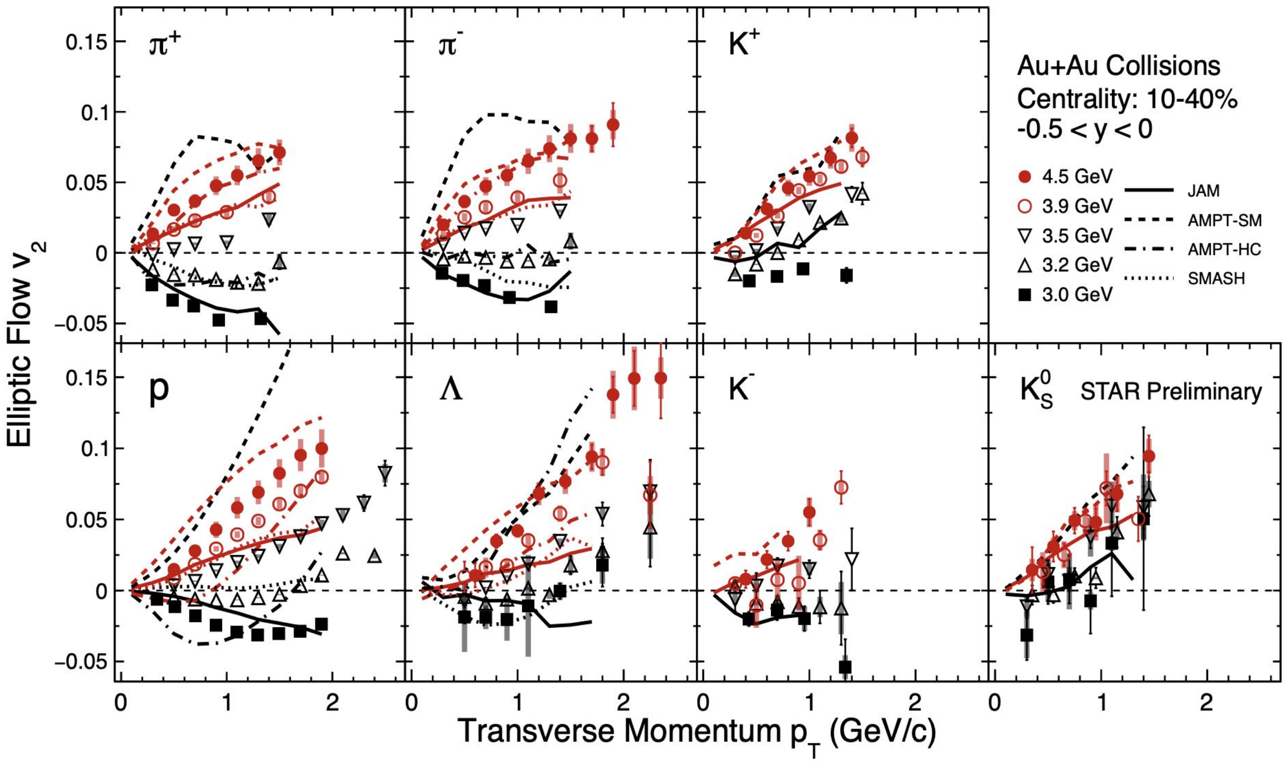
JAM Model Comparison



Phase Space Distribution

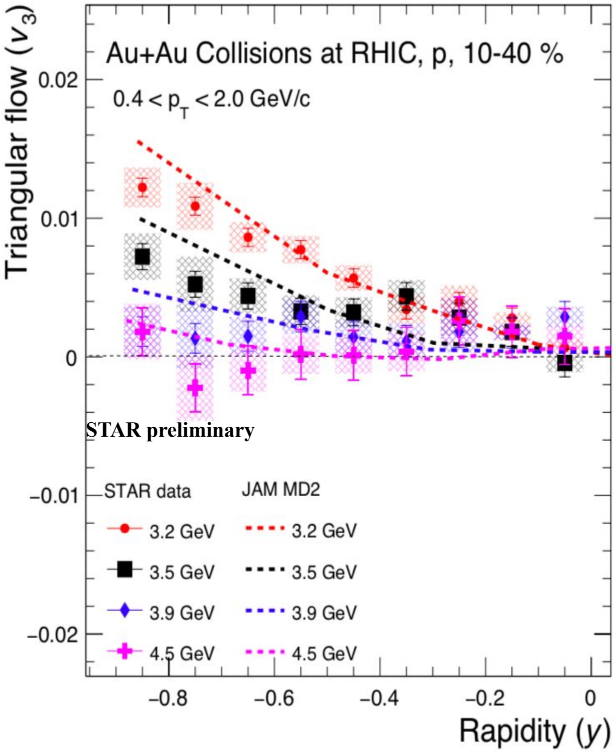


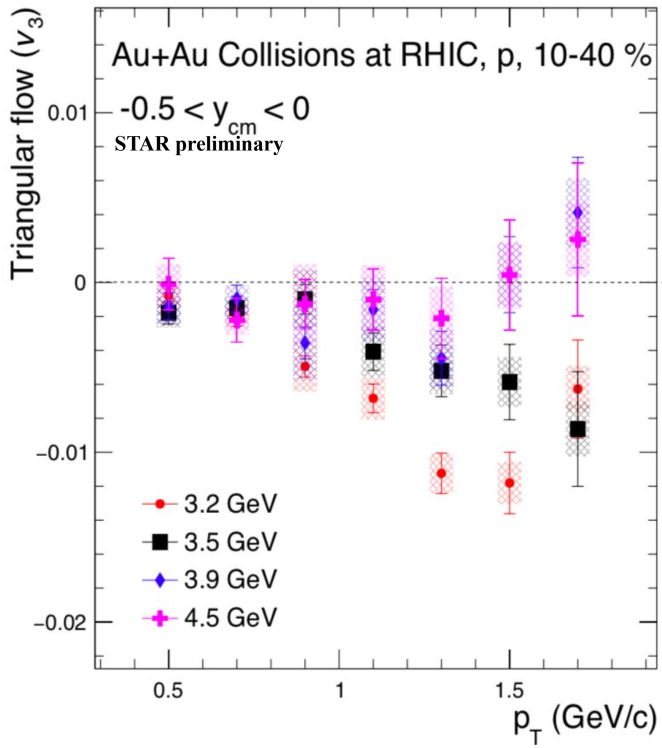
Elliptic flow (v_2)

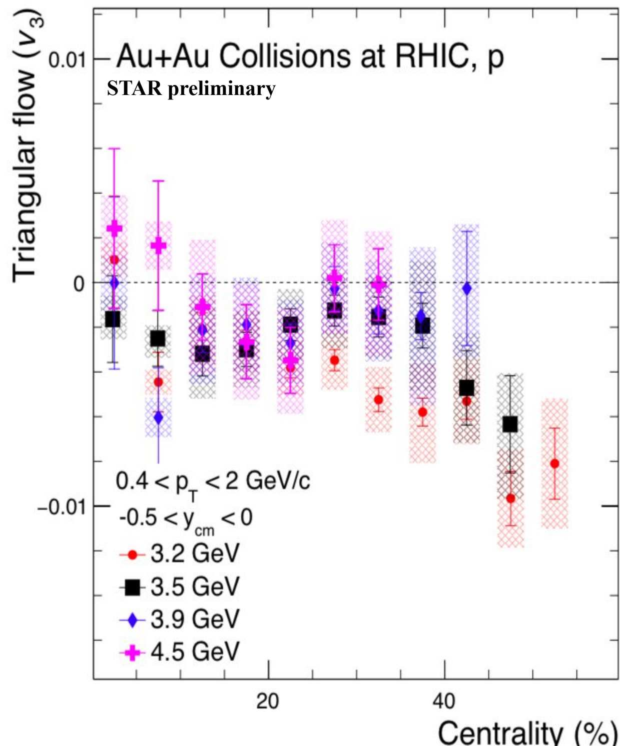


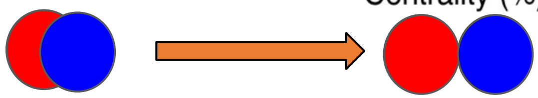
- As the collision energy increases, the passing time between nuclei decreases→ spectator shadowing is reduced.
- **Hadronic models** fit the experimental data well at 3.0 GeV, but the **AMPT-SM** model does not.
- At 4.5 GeV, the **AMPT-SM** model matches the data better, while hadronic models tend to underestimate the results.

Triangular flow









AMPT Model

- We have used the AMPT-SM **ampt-v1.26t9b-v2.26t9b** version
- String fragmentation parameters used:
  - **a = 0.55**
  - **b = 0.15 GeV/c^2**

Au+Au

↓

Initial Conditions
Obtained from **H**eavy-**I**on **J**et **IN**teraction **G**enerator (HIJING)

↓

Parton Interactions
Scatterings among partons are modeled by **Z**hang's **P**arton **C**ascade (ZPC)

↓

Hadronization
AMPT with string melting (AMPT-SM) uses quark coalescence to combine partons into hadrons

↓

Hadron Cascade
Dynamics of the hadronic matter is described by **A** **R**elativistic **T**ransport (ART) model

↓

Final Particle Spectra