Measurement of Anisotropic Flow for BES-II Energies at RHIC-STAR

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STAR 25 YEARS

QM 25

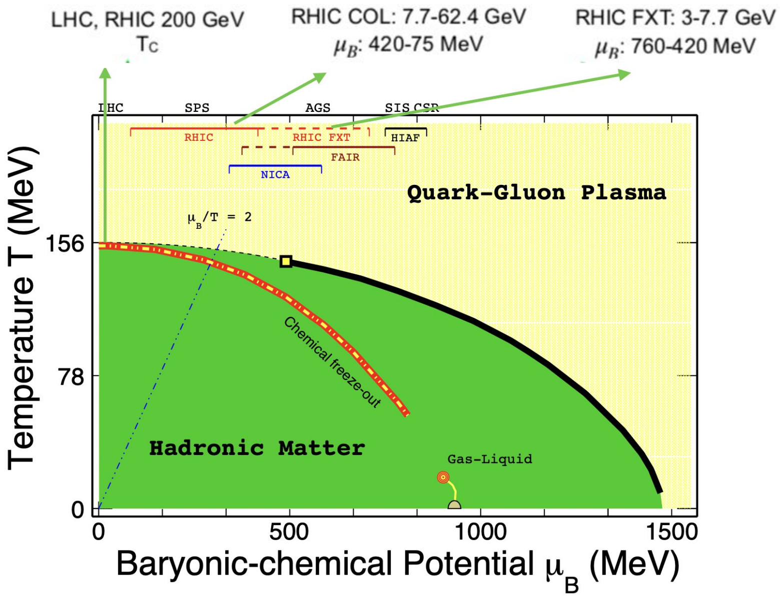
IISER TIRUPATI

STAR Collaboration

Outline

Introduction

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



RHIC Beam Energy Scan(BES) Program Searches for:

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

BES-I

$\sqrt{s_{NN}}$ = 7.7- 200 GeV (COL)

BES-II

$\sqrt{s_{NN}}$ = 7.7 - 54. 4 GeV (COL)
+
$\sqrt{s_{NN}}$ = 3.0 - 13.7 GeV (FXT)

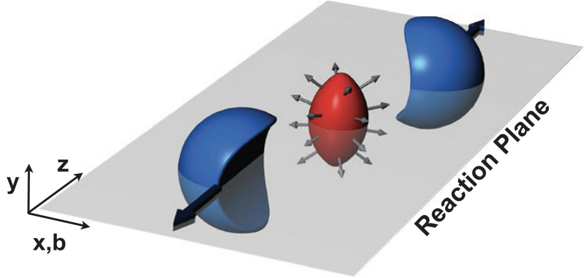
A. Bazavov et al., Phys. Rev. D 85, 054503 (2012); K. Fukushima and C. Sasaki, Prog. Part. Nucl. Phys, 72, 99 (2013)

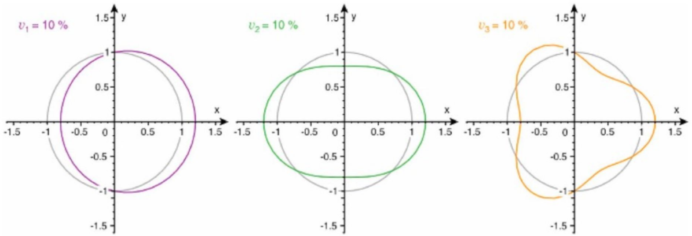
Anisotropic Flow

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

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

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





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

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

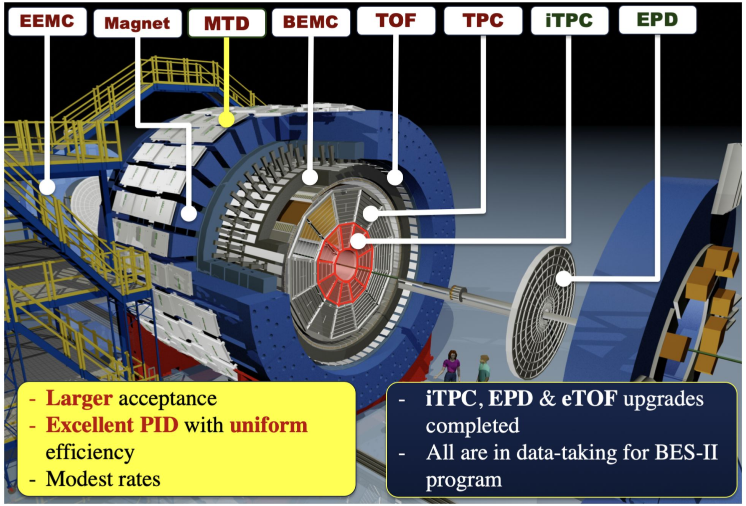
Driven by the shape of the initial collision geometry at low collision energies

Why is v_n an important observable?

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

R. Snellings, New J.Phys.13:055008 (2011) A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998)

STAR Experiment



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

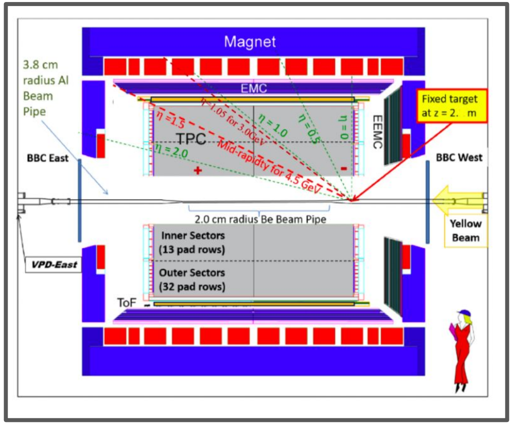
Major Upgrades in BES-II

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

STAR Fixed-target Setup

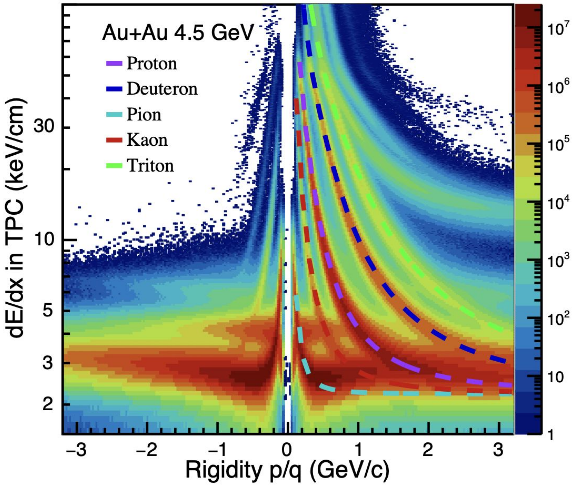


- **0.25 mm** Gold target at ***z* = 200 cm**, **2 cm** below beam axis.
- $\sqrt{s_{NN}}$ = **3.0 - 13.7 GeV (FXT)**

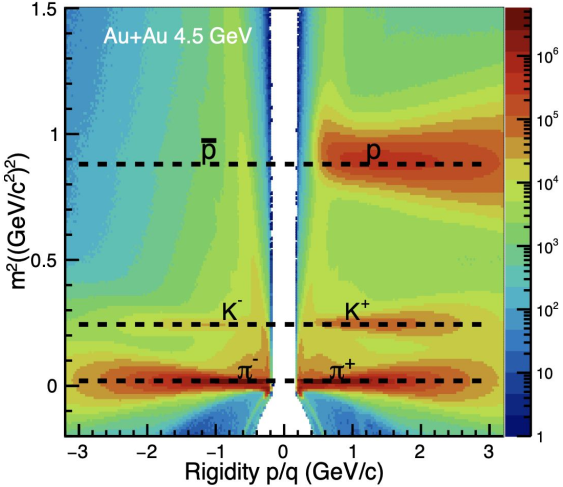
iTPC: https://drupal.star.bnl.gov/STAR/starnotes/. public/sn0619; **eTOF:** STAR and CBM eTOF group, arXiv: 1609.05102; **EPD:** J. Adams, et al. NIM A968, 163970 (2020)

Particle Identification

TPC



eTOF



Two main detectors are used for particle identification in **STAR**

Time Projection Chamber (TPC)

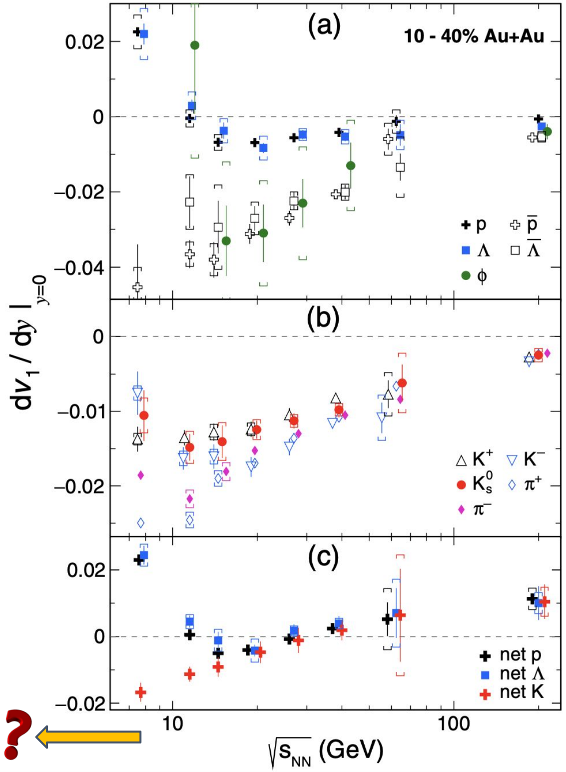
$$z_X = \ln\left(\frac{\langle dE/dx\rangle}{\langle dE/dx\rangle_X^B}\right)$$

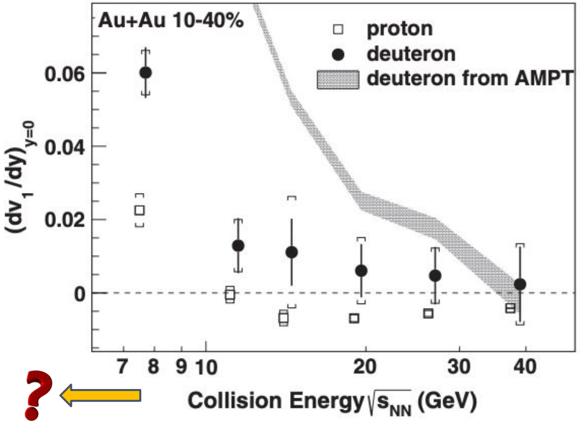
Time of Flight (TOF)

$$m^2 = p^2\left(\frac{c^2T^2}{L^2} - 1\right)$$

Good particle identification capability based on dE/dx and m^2 information from TPC and TOF respectively

Motivation: Directed flow (v_1)





Net particle v_1 is defined as

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

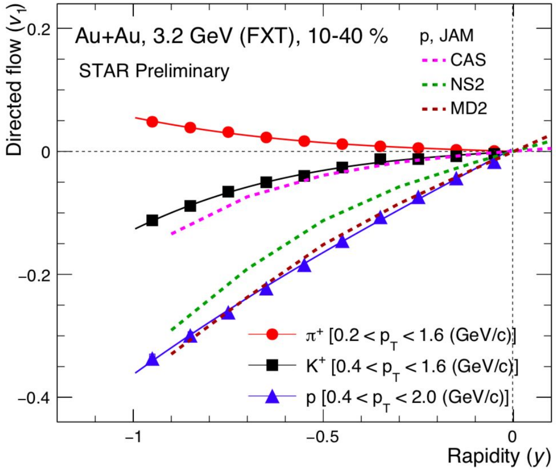
where $v_{1,p}$, $v_{1,\bar{p}}$ → particle and antiparticle v_1 and r is the ratio of anti-particles to particles

- 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**

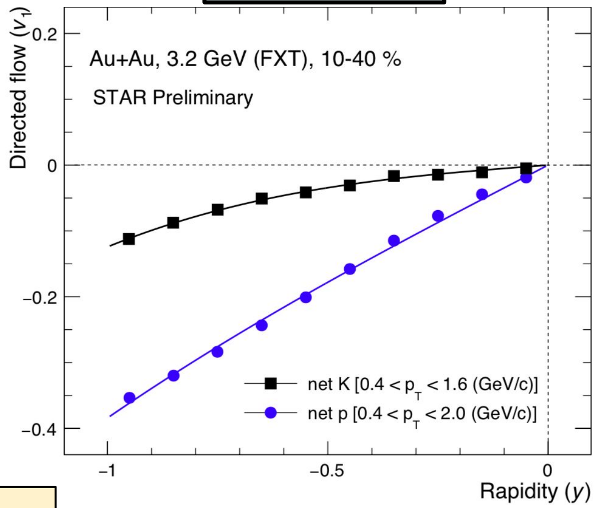
STAR: Phys. Rev. Lett. 120, 062301 (2018); STAR: Phys. Rev. C 102, 044906 (2020)

Directed flow vs y at 3.2 GeV

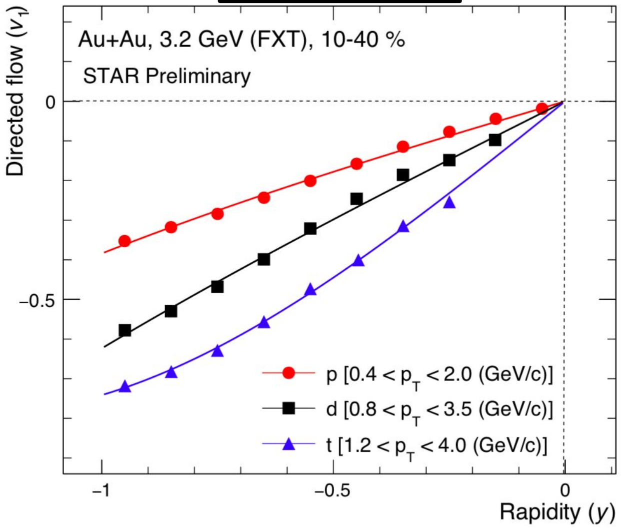
Identified hadrons



Net-particle



Light nuclei



JET AA Microscopic Transportation Model (JAM2)

Cas: no interactions among particles

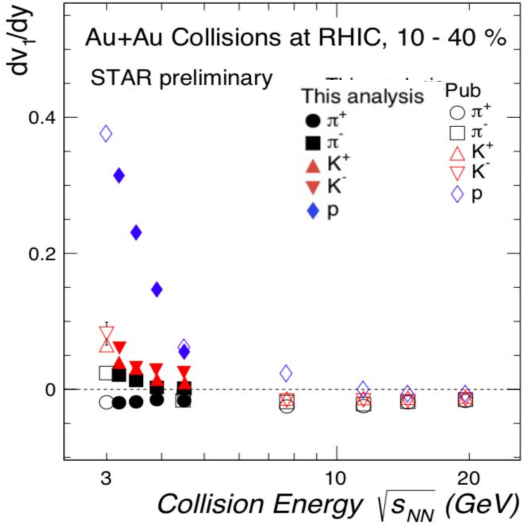
NS2: mean-field potential
Incompressibility constant: **κ** = 210 MeV

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

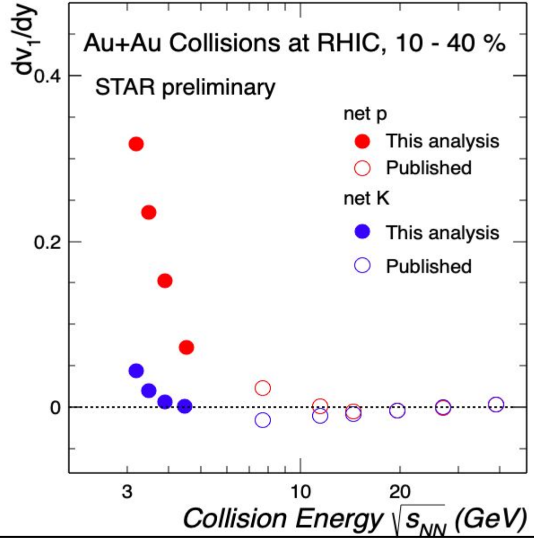
- ❖ Magnitude of v_1 increases with increasing rapidity
- ❖ Magnitude of v_1 increases with increasing mass of the particle
- ❖ JAM MD2 gives better description to the experimental data for baryons

Slope of directed flow

Identified hadrons



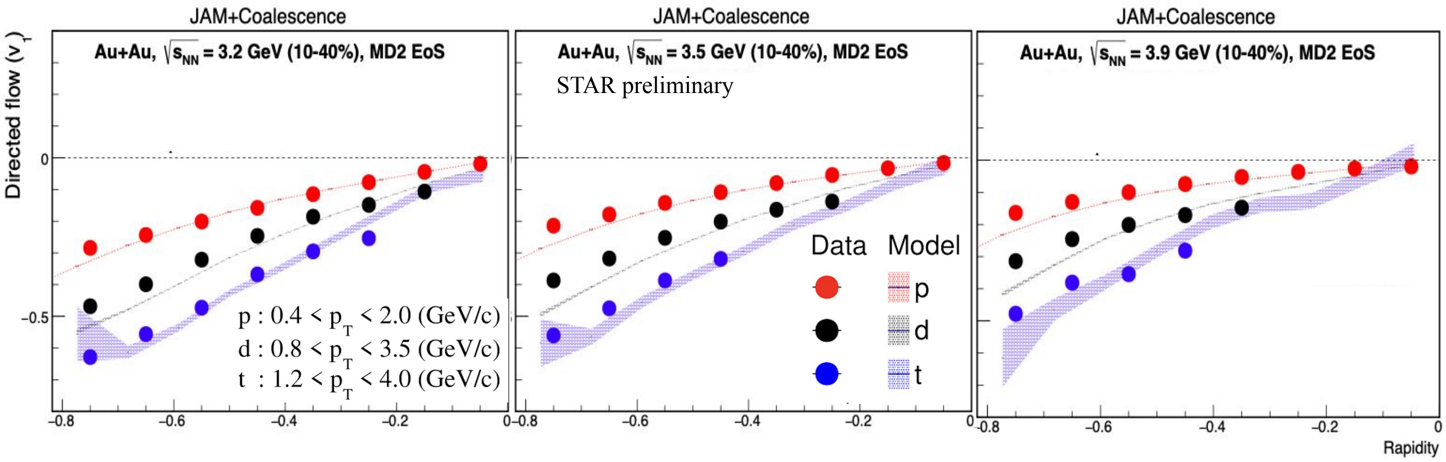
Net-particle



- 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)

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

Directed flow of light nuclei



JET AA Microscopic Transportation Model (JAM2)

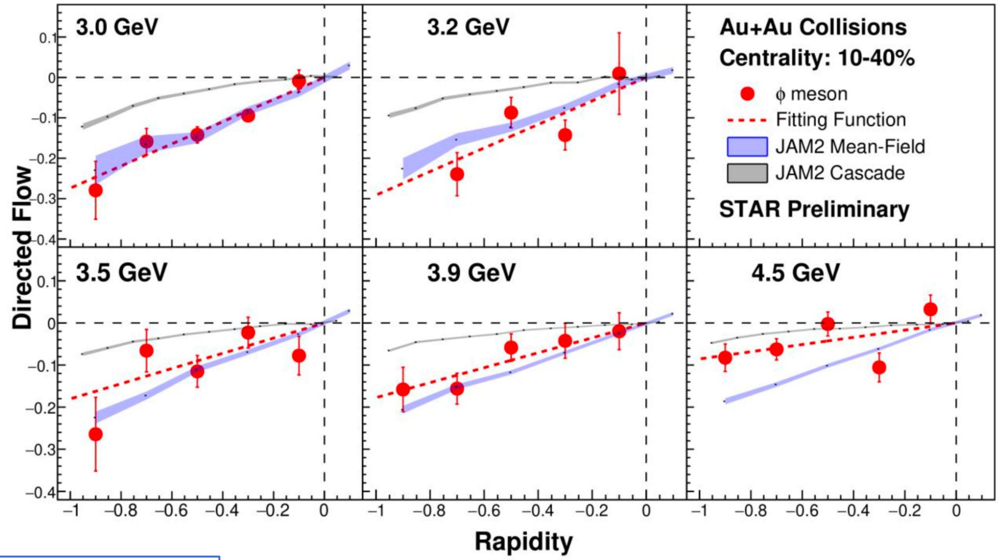
MD2: momentum dependent mean-field potential
Incompressibility constant: **κ** = 380 MeV

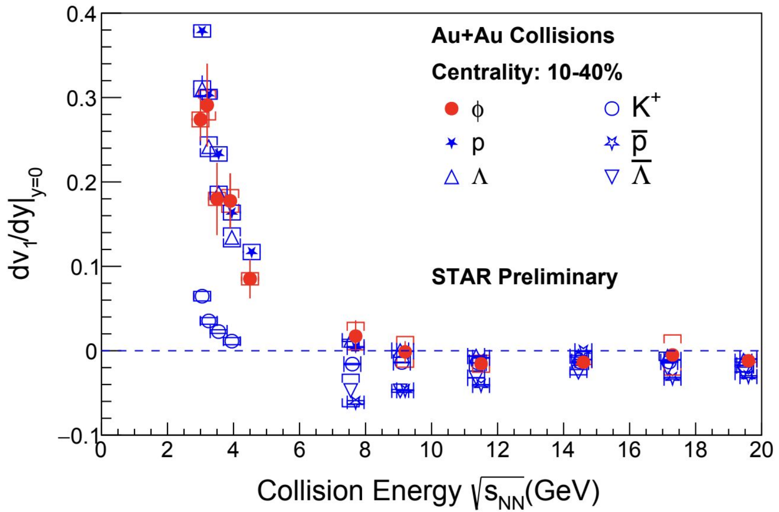
- ❖ Magnitude of v_1 increases with increasing rapidity
- ❖ **JAM MD2 with coalescence** provides good description of the data

Y. Nara et al. , Phys. Rev. C 61, 024901 (1999)

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



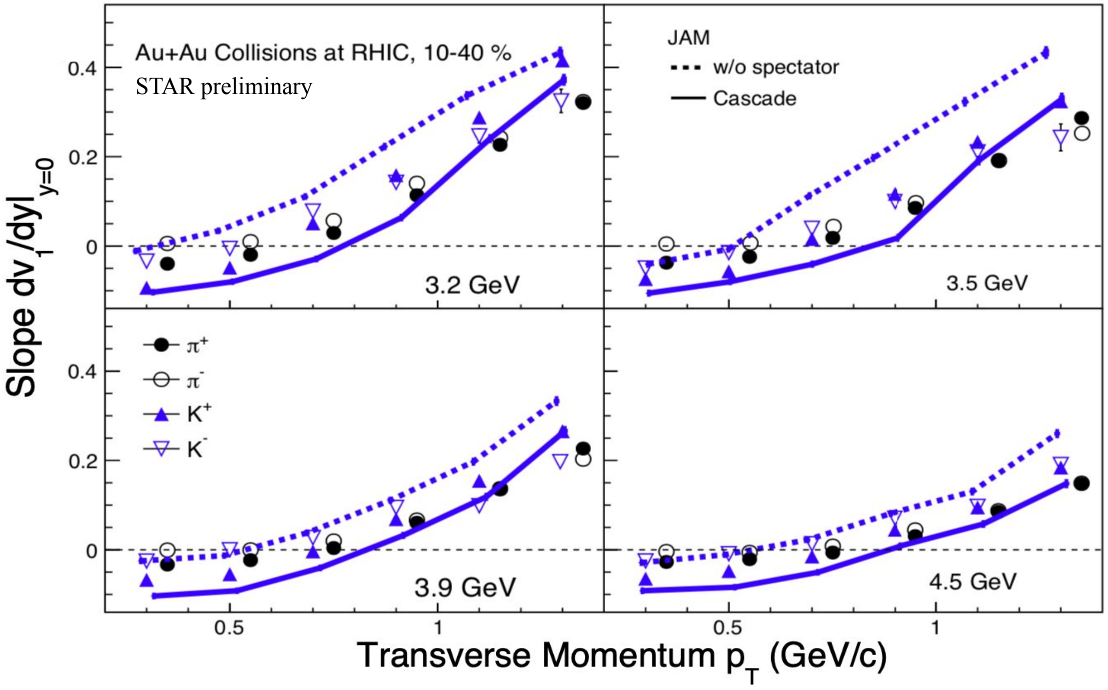


*Please refer to poster by **Guangyu Zheng** for more details*

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

STAR: Phys. Rev. Lett. 120, 062301 (2018)

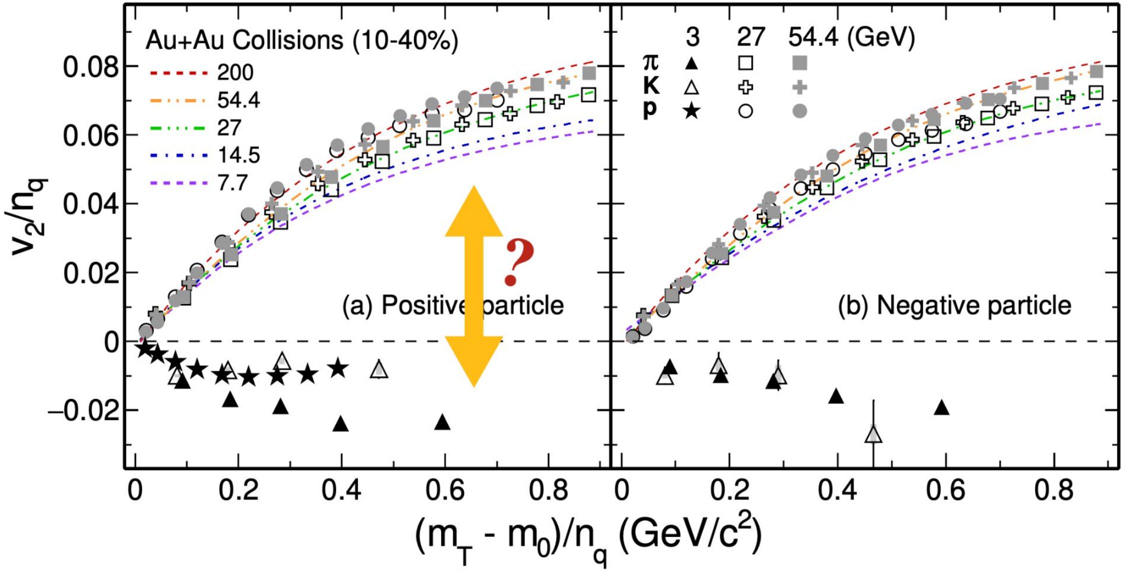
Anti-flow of mesons at low p_T



- It has been suggested that a **Kaon potential** is needed to explain kaon behavior in heavy ion collisions at low collision energies
- 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**

E895: Phys. Rev. Lett. 85, 940 (2000); Nucl. Phys. A 698, 495 (2002); C. M. Ko and G. Q. Li, J. Phys. G 22, 1673 (1996)

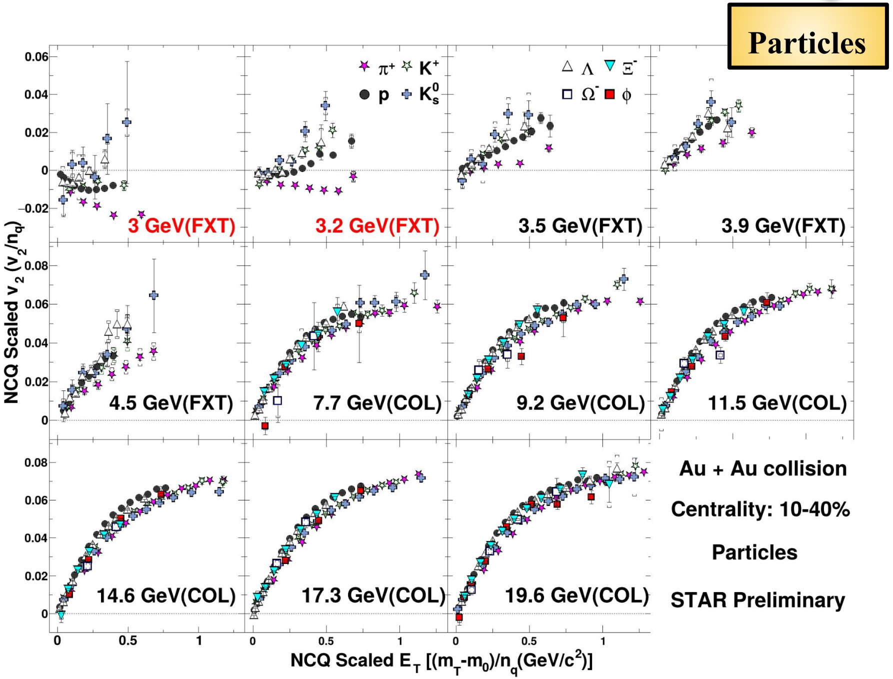
Motivation: Elliptic flow (v_2)

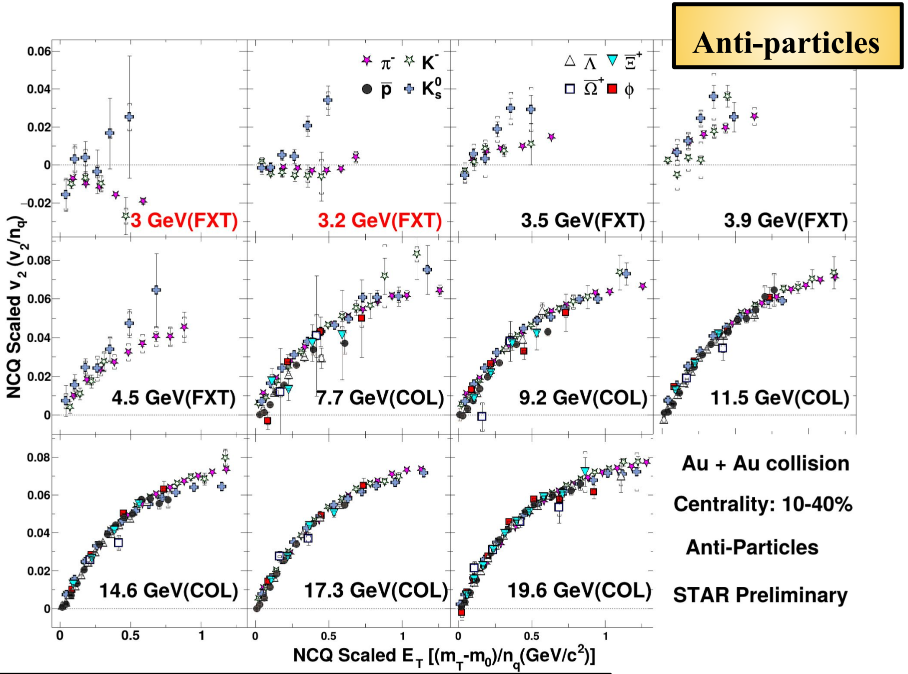


- ❖ At high energies, data follows **NCQ scaling**, indicating partonic collectivity
- ❖ At **3 GeV**, anti-flow from shadowing breaks **NCQ scaling**

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

NCQ scaled Elliptic flow



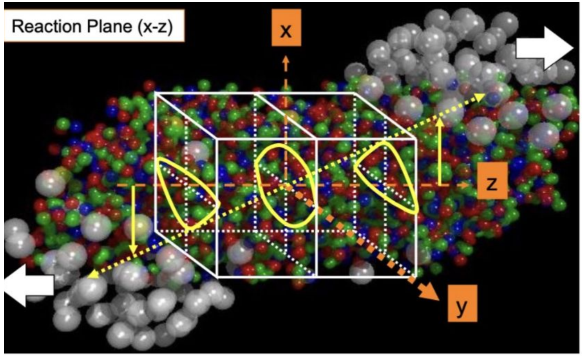


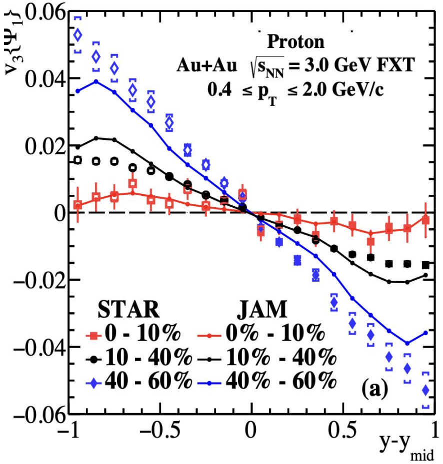
*Please refer to poster by **Guoping Wang** for more details*

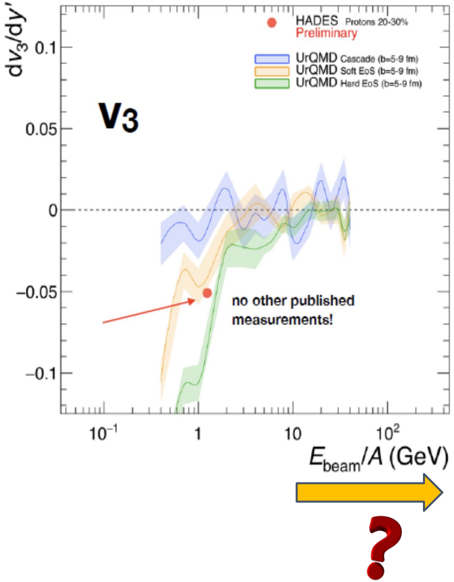
- ❖ **NCQ scaling** completely **breaks** below **3.2 GeV**
- ❖ NCQ scaling becomes better gradually with increasing collision energy after 4.5 GeV
- ❖ **Change of degree of freedom: 4.5 → 7.7 GeV ?**

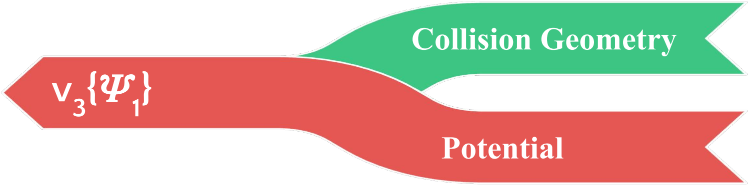
Motivation: Triangular flow ($v_3\{\Psi_1\}$)

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



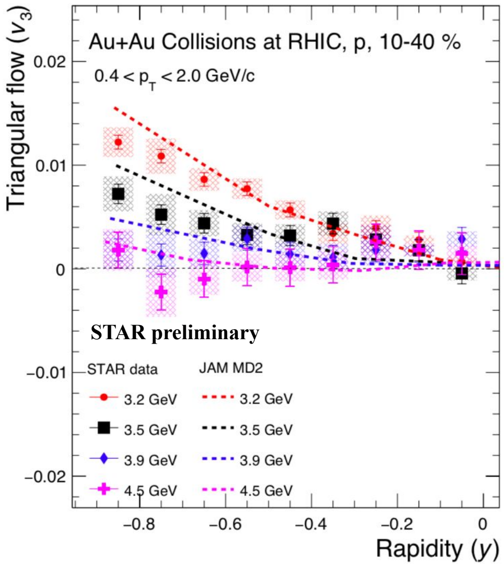


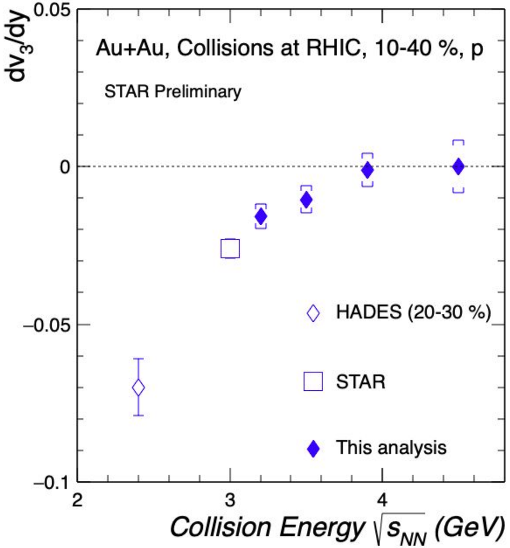


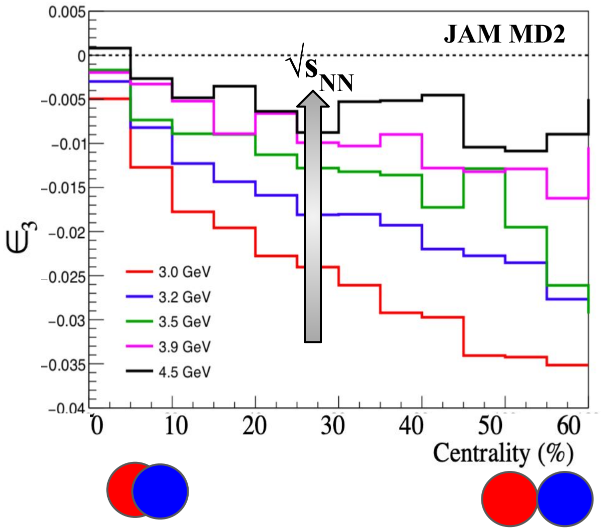


HADES: Eur. Phys .J. A 59 4, 80 (2023), STAR: Phys. Rev. C 109, 044914 (2024), J. Phys. G: Nucl. Part. Phys. 45 085101 (2018)

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

Directed flow (v_1)

- 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

Elliptic flow (v_2)

- NCQ scaling breaks at 3.0 and 3.2 GeV, and gradually restores from 3.2 to 4.5 GeV
  - Shadowing effect diminishes
  - Dominance of partonic interactions at 4.5 GeV and above

Triangular flow (v_3)

- 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 data

Thank you for your attention!!