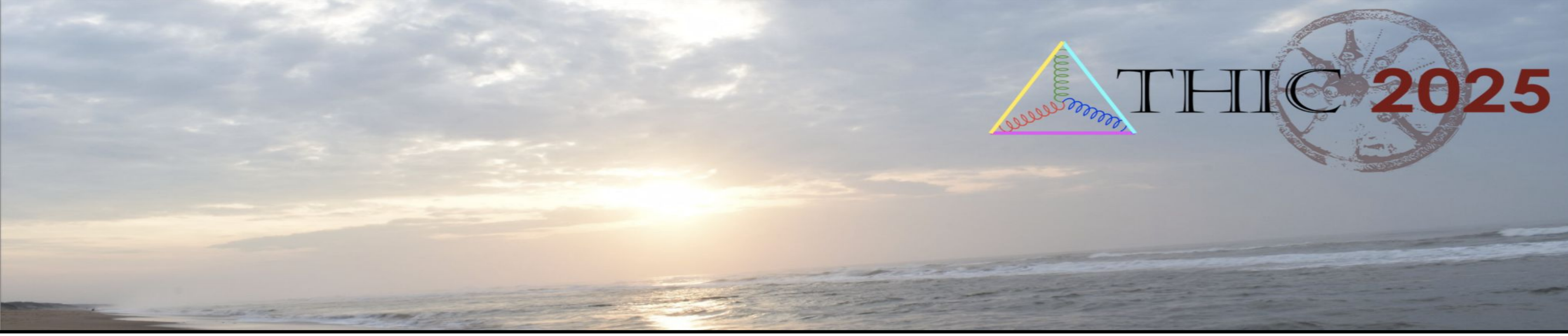

Study of first-order event plane correlated anisotropic flow in heavy-ion collisions at high baryon density region

10th Asian Triangle Heavy-Ion Conference (ATHIC 2025)
Indian Institute of Science Education and Research Berhampur

Sharang Rav Sharma (*for the STAR Collaboration*)
Indian Institute of Science Education and Research Tirupati

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STAR

IISER TIRUPATI

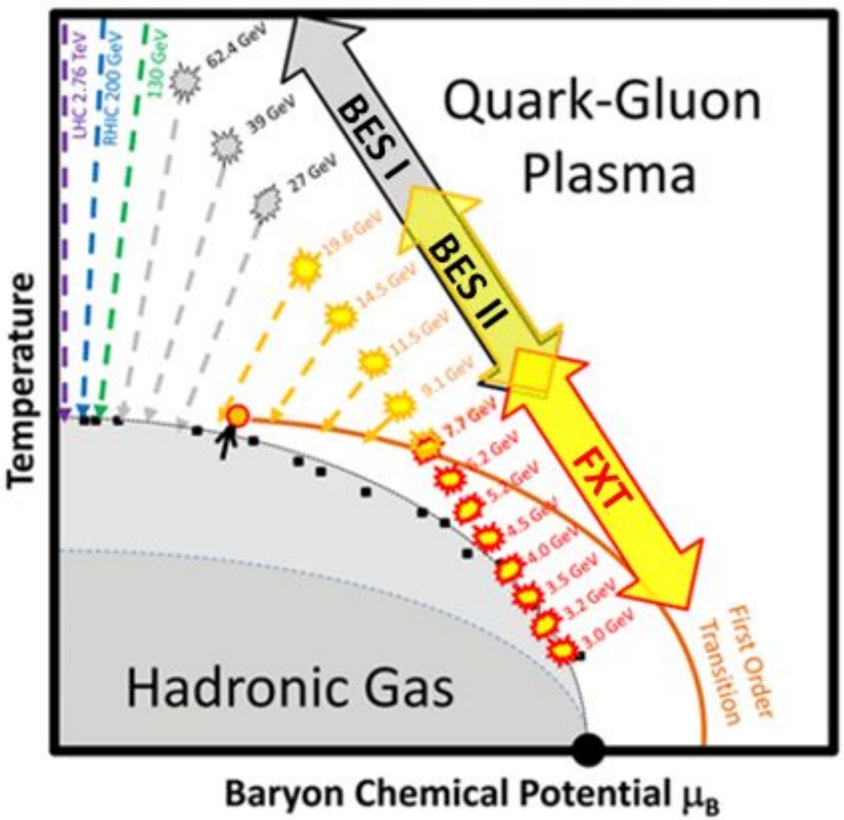
Date: January 14, 2025

Outline

- ❖ Introduction
- ❖ STAR Experiment
- ❖ Results and Discussion
  - ➢ Directed flow ($v_1\{\Psi_1\}$) and Triangular flow ($v_3\{\Psi_1\}$)
    - ■ Experimental Measurements
    - ■ Model Comparison
- ❖ Summary

Introduction

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



Nucl. Phys. A 967 808-811 (2017)

RHIC BES Program Searches for:

- 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)**

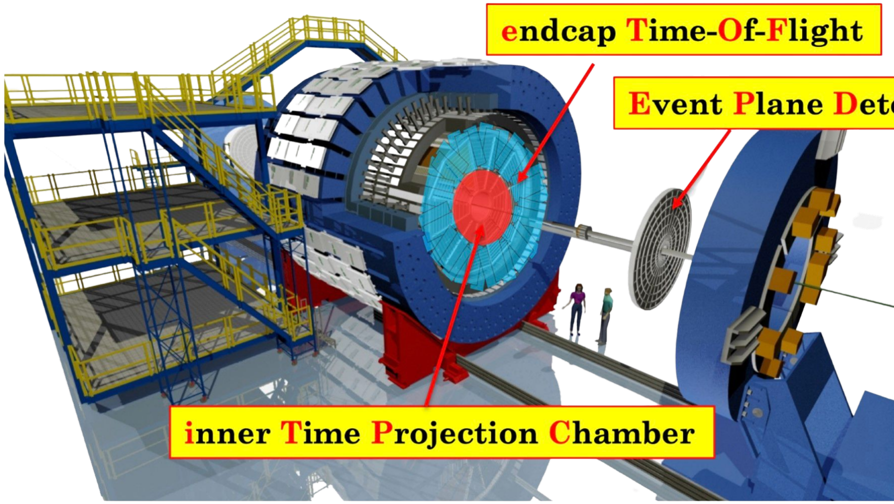
Phase-II

$\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, 14.6, 19.6, 27 and 54. 4 GeV **(COL)**

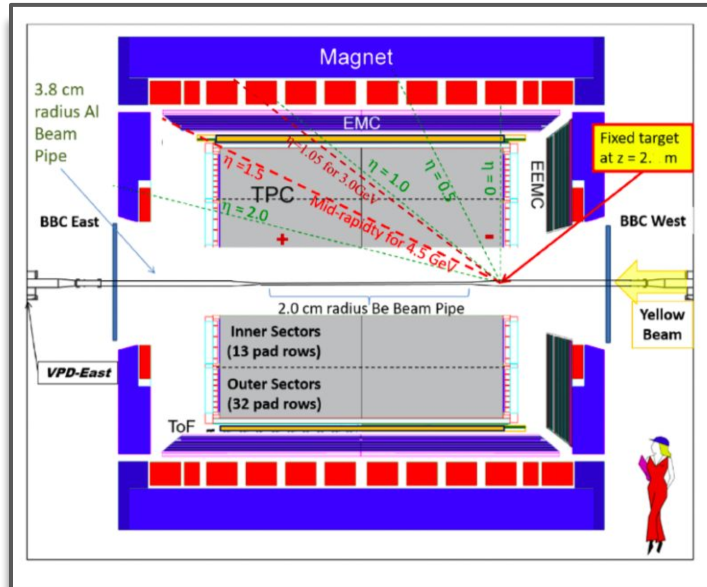
$\sqrt{s_{NN}}$ = **3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7**, 9.1, 11.5, and 13.7 GeV **(FXT)**

STAR Experiment

Fixed-target mode



C. Yang et al., JINST 15 C07040 (2020)



Nuclear Phy A 808-811 (2017)

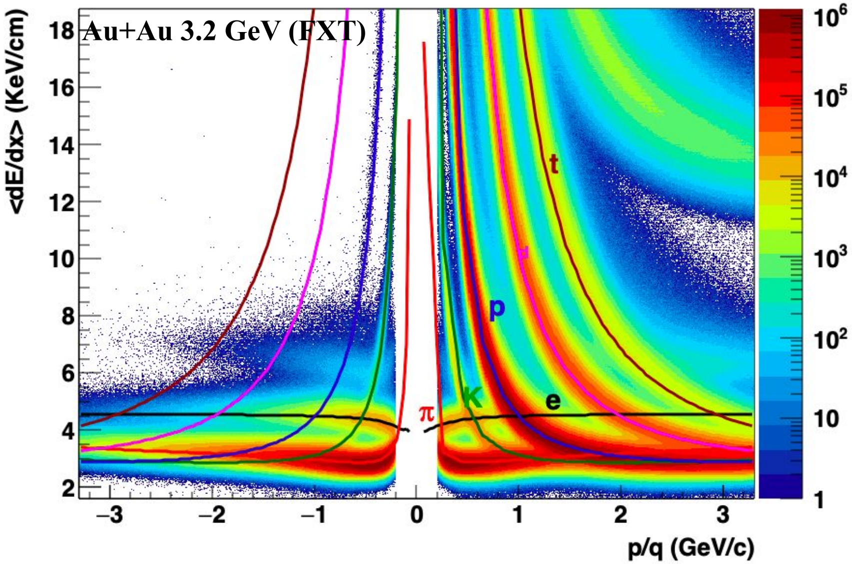
Solenoidal **T**racker **A**t **R**HIC (**STAR**) is one of the detector systems at RHIC consisting of several sub-detectors

Fixed-Target (FXT) program at STAR → low center-of-mass energies and high baryon density region

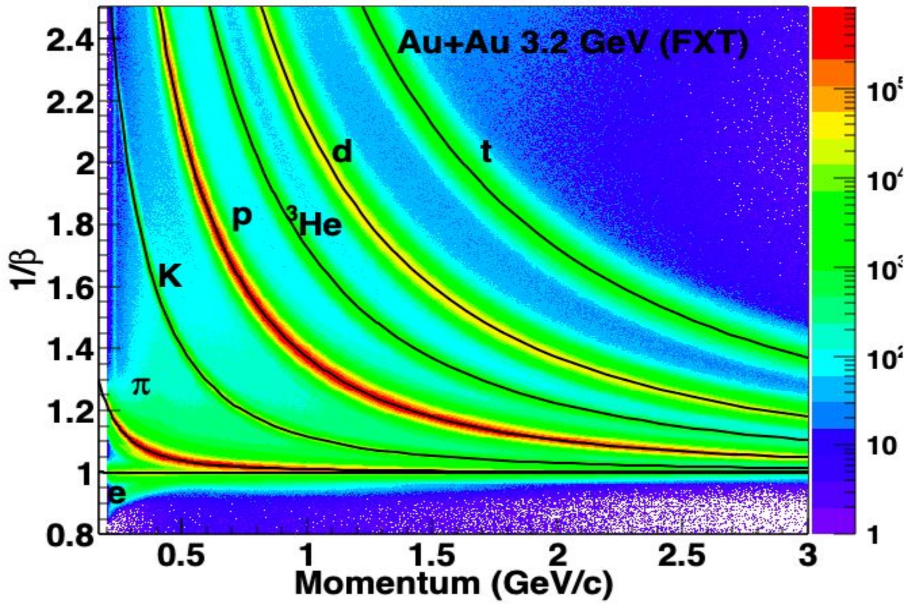
$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV) ≈	Events analyzed
3.2	679	220 M
3.5	649	110 M
3.9	614	110 M
4.5	568	100 M

Particle Identification

Time Projection Chamber (TPC)



Time of Flight (TOF)



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

  - **Time Projection Chamber (TPC)** $z_X = \ln\left(\frac{\langle dE/dx\rangle}{\langle dE/dx\rangle^B_X}\right)$

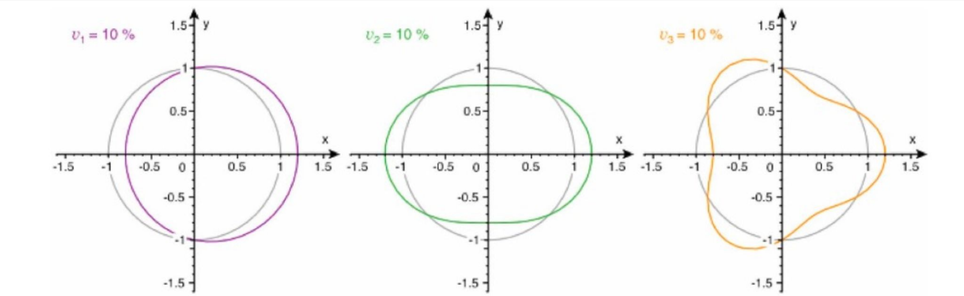
  - **Time of Flight (TOF)** $m^2 = p^2\left(\frac{c^2T^2}{L^2} - 1\right)$

Anisotropic Flow

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

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy}\left\{1 + \sum_{n\geq1} 2\, v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right\}$$

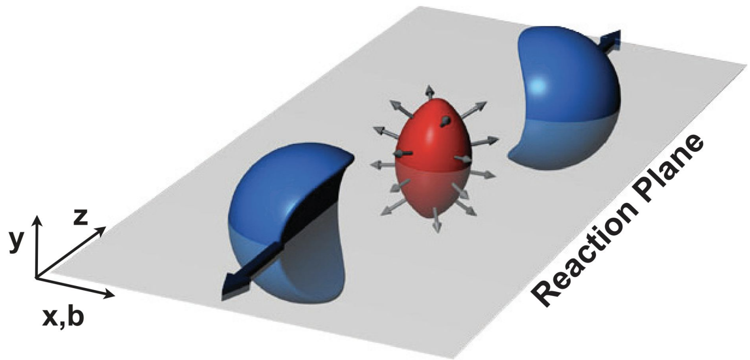
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$



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

Why v_n is important ?

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



R. Snellings, New J.Phys.13:055008 (2011)

Directed flow

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

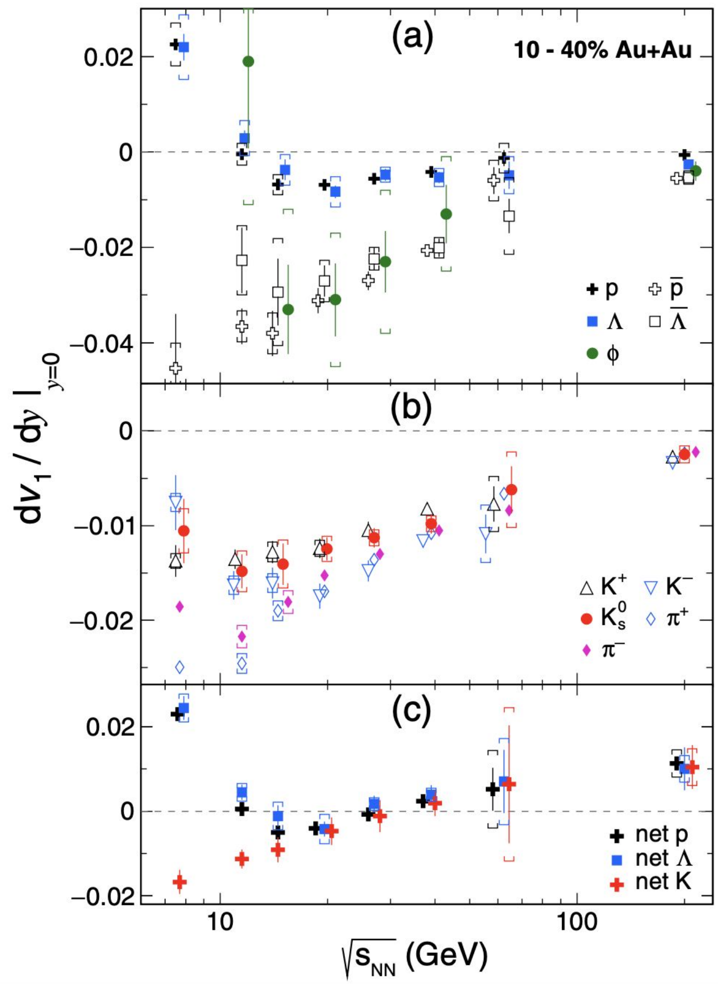
Sideward motion of emitted hadrons with respect to collision reaction plane

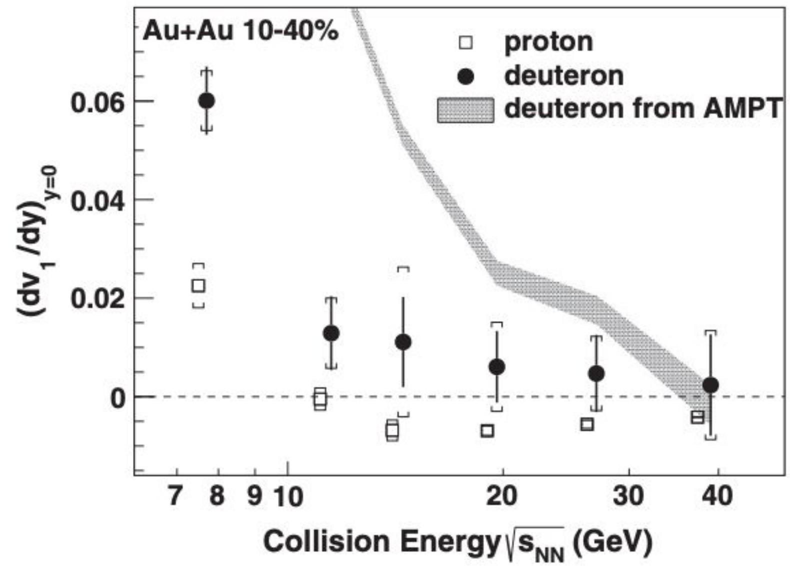
Triangular flow

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

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

Motivation for v_1 measurement



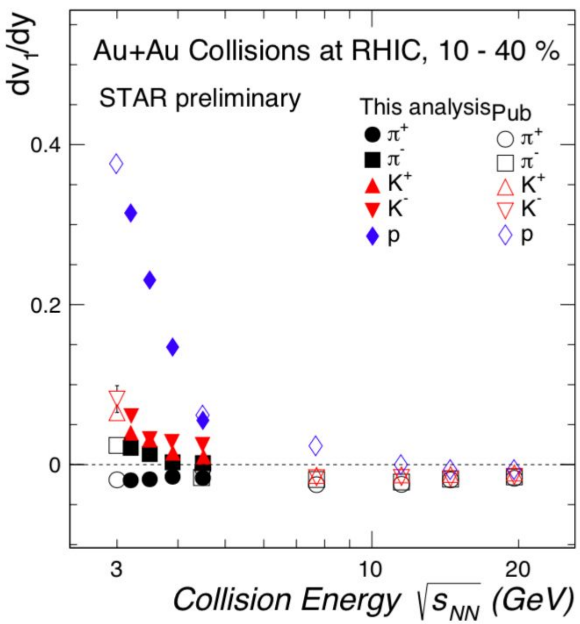


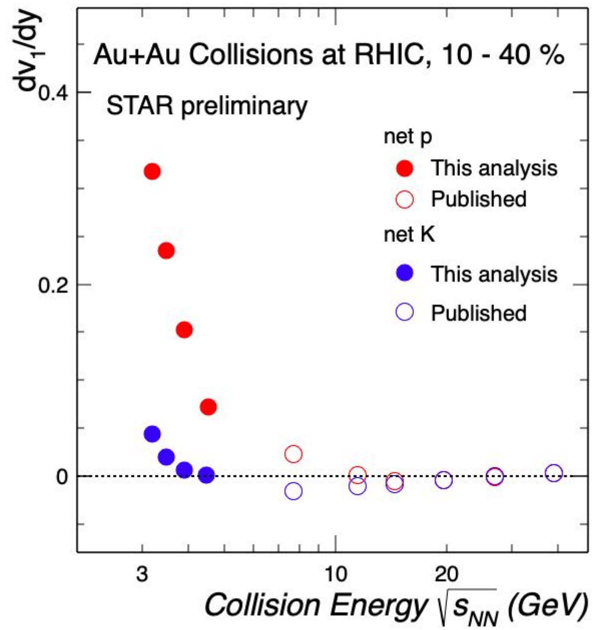
Phys. Rev. Lett. 120, 062301 (2018)
Phys. Rev. C 102, 044906 (2020)

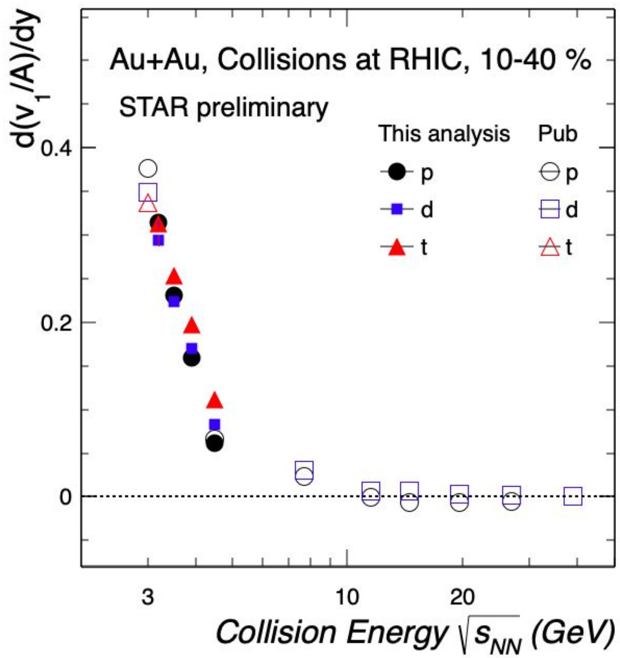
Nucl. Phys. A750, 121 (2005)

- 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 → contribution of transported quarks w.r.t produced
- **Softening of EoS** and a **minimum in v_1** predicted as a signature of first order phase transition.
- Observed minimum in net-p v_1 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 ➡ **Approximate mass no. scaling**

Collision energy dependence of dv_1/dy





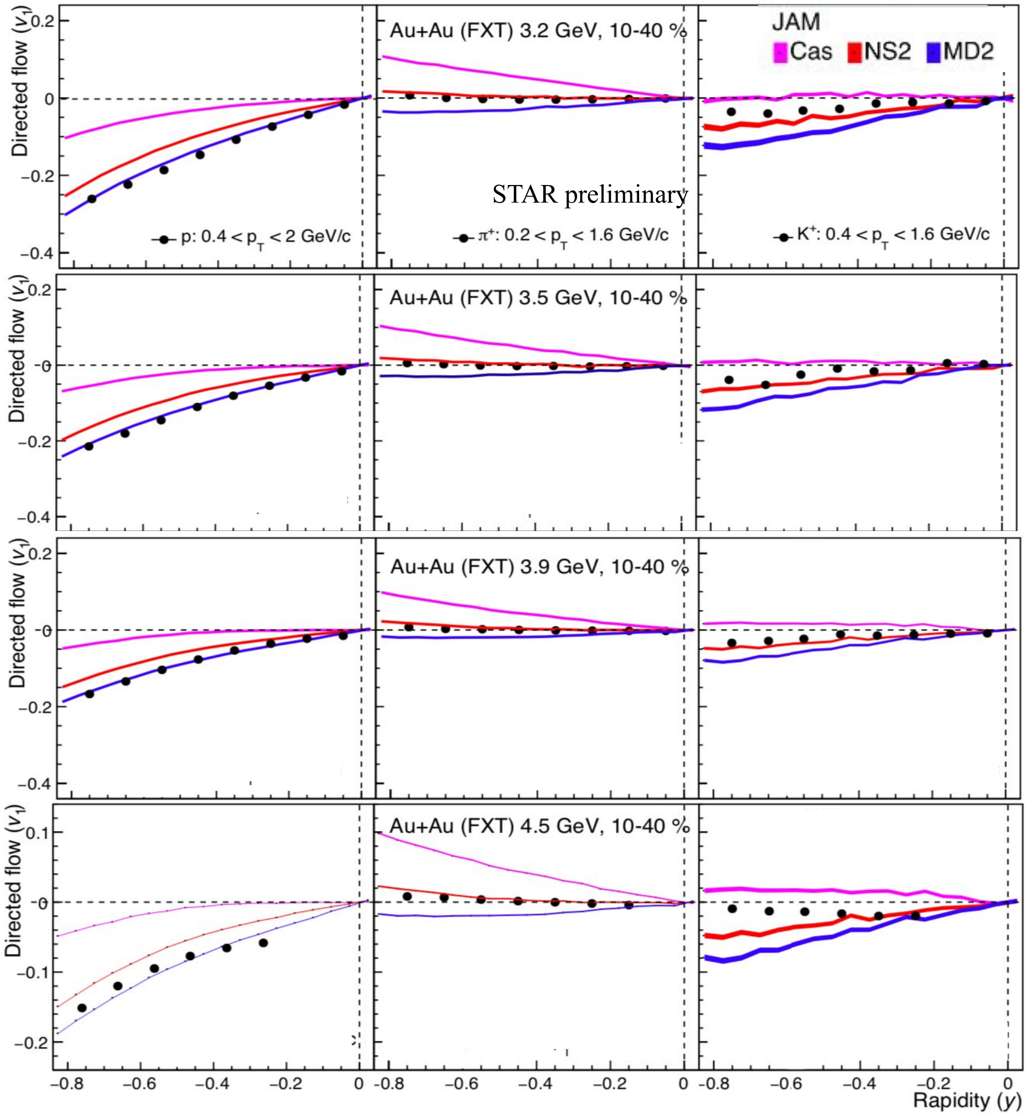


Studied energies: **Au+Au** collisions at $\sqrt{s_{NN}}$ **= 3.2, 3.5, 3.9, and 4.5 GeV (FXT)**

- ❖ Increasing collision energy → decreasing v_1 slope for the studied energies
  - ➢ $dv_1/dy|_{\pi+}$ is negative whereas $dv_1/dy|_{\pi-}$ is positive ➡**Spectator shadowing and Coulomb interactions**
- ❖ Minimum net-p at 11.5 - 19.6 GeV whereas **minimum net-K at 4.5 - 7.7 GeV**
- ❖ Approximate mass no. scaling is observed in the v_1 slope ➡**Nucleon coalescence**

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

JAM model comparison



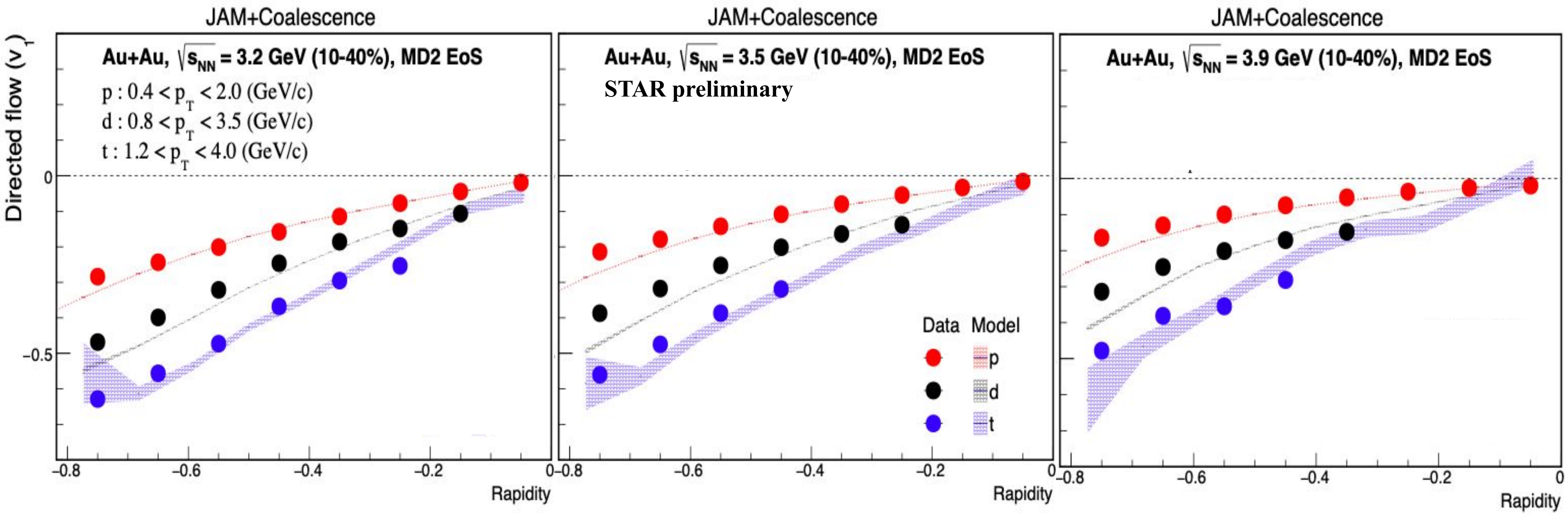
JET AA Microscopic Transportation Model (JAM2)

- **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

- JAM cascade mode fails to describe data
- **JAM MD2** gives better description to the experimental data for baryons

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

JAM model comparison

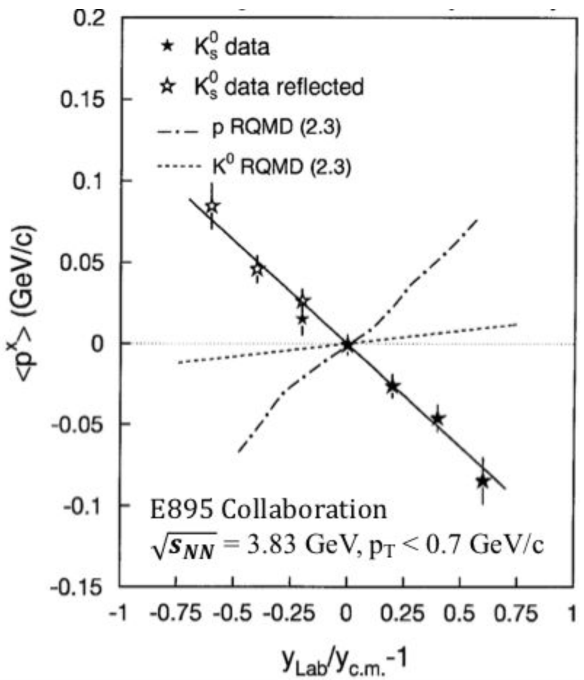


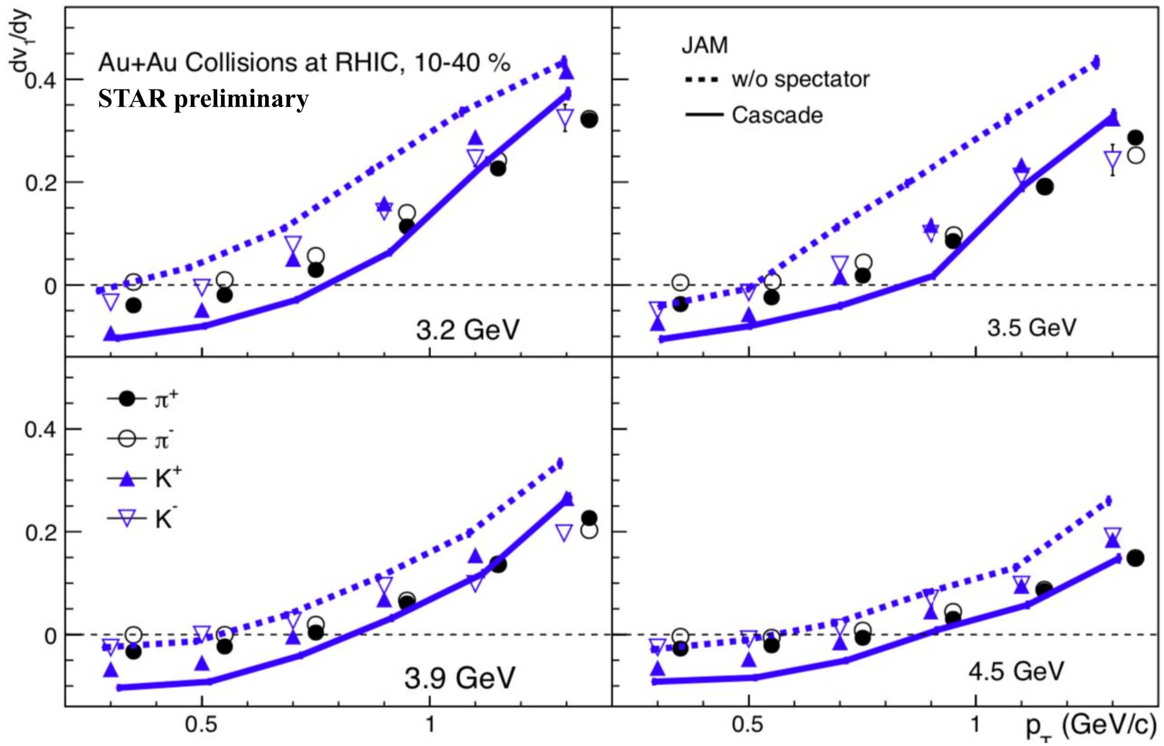
- Magnitude of v_1 increases with increasing rapidity
- **JAM MD2 with coalescence** provides good description of the data

JET AA Microscopic Transportation Model (JAM2)

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

Anti-flow of mesons at low p_T



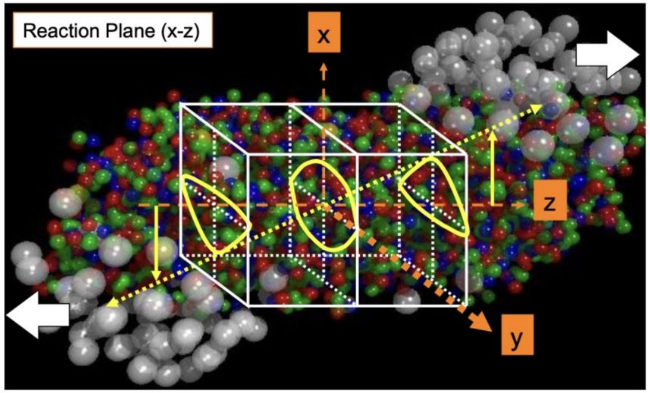


- ❖ E895: anti-flow of kaon at low p_T ➡ Kaon potential?

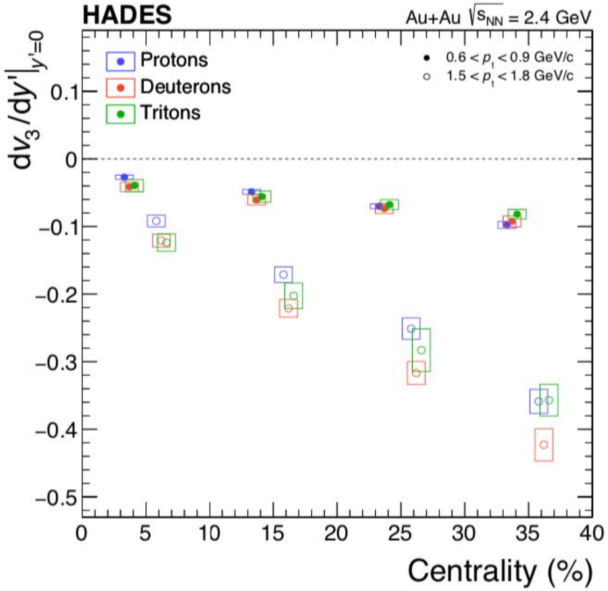
- Negative dv_1/dy at low p_T for mesons → **Anti-flow at low energies (3.0 - 4.5 GeV)**
- JAM Cascade model → with spectators able to reproduce the anti-flow at low p_T ➡ **Kaon potential is not necessary**

P. Chung et al. (E895 Collaboration), Phys. Rev. Lett. 85, 940 (2000)

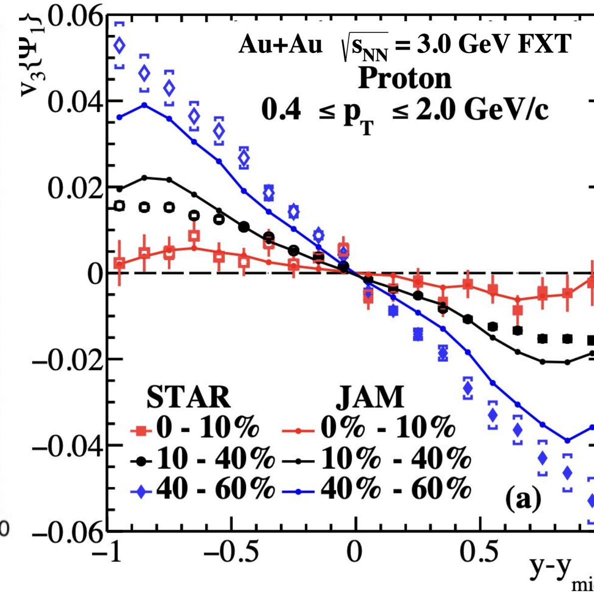
Motivation for $v_3\{\Psi_1\}$ measurement



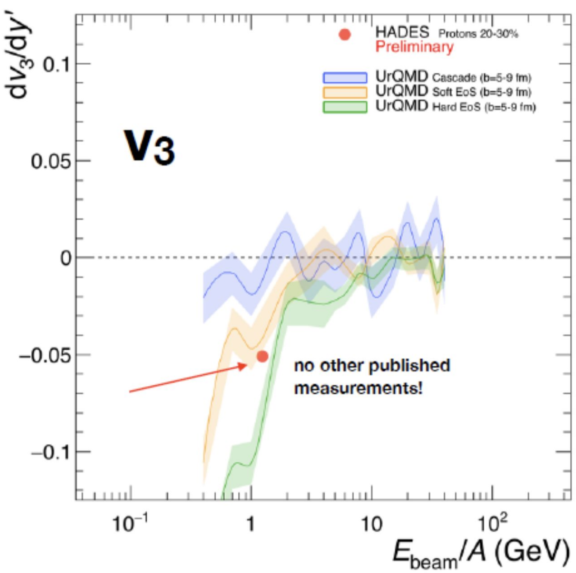
Phys. Rev. C 109, 044914 (2024)



(HADES) Eur. Phys .J. A 59 4, 80 (2023)



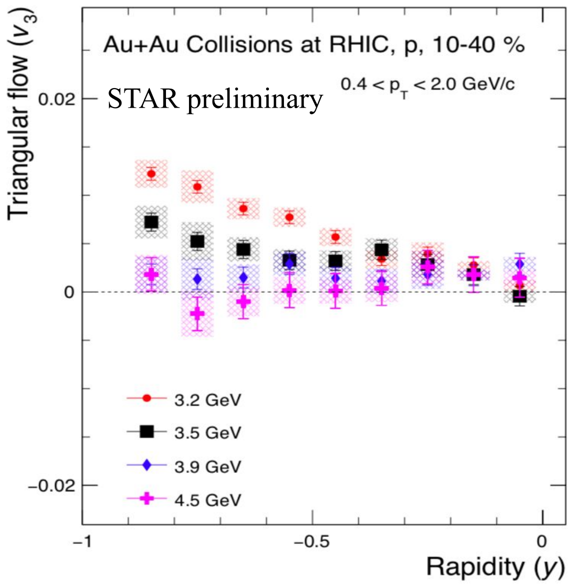
Phys. Rev. C 109, 044914 (2024)

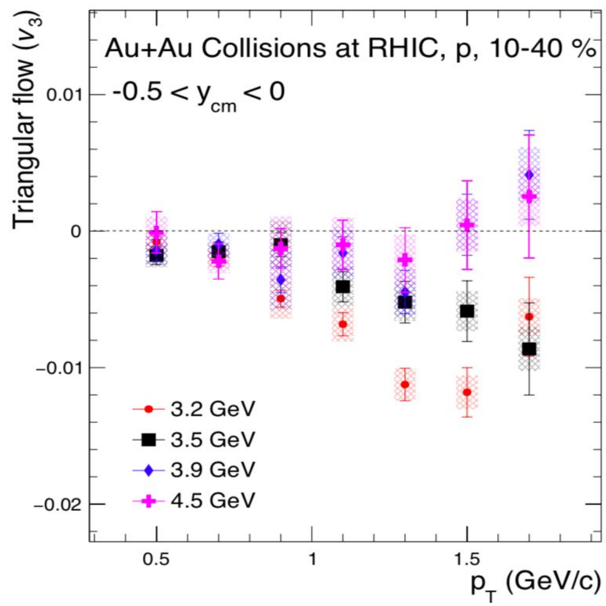


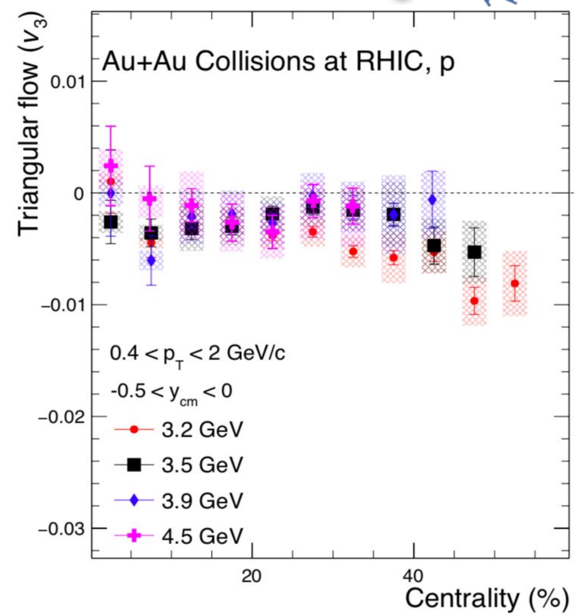
J. Phys. G: Nucl. Part. Phys. 45 085101 (2018)

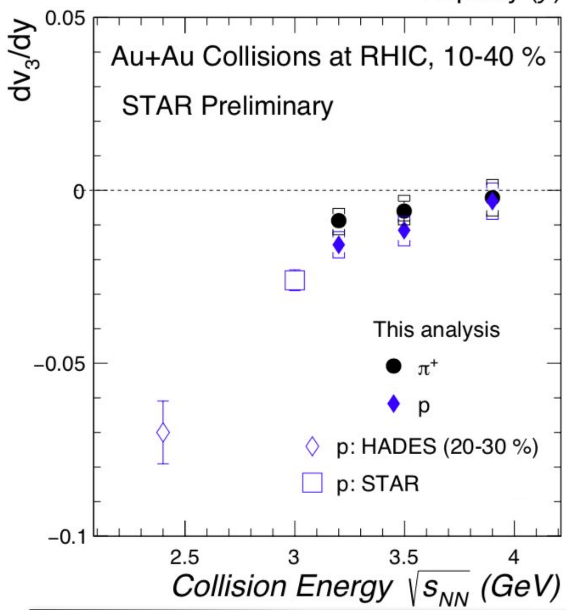
- At high energies, v_3 → uncorrelated with the 1st order event plane, contrary to observation at 2.4 GeV by HADES and at 3 GeV by STAR experiment.
- $v_3\{\Psi_1\}$ → two key ingredients ➡ **collision geometry** and **potential** in a responsive medium

$v_3\{\Psi_1\}$ for proton





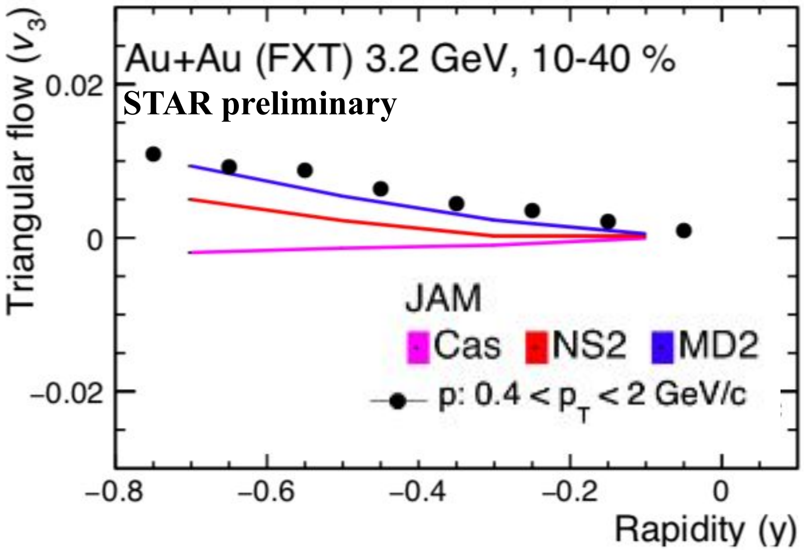


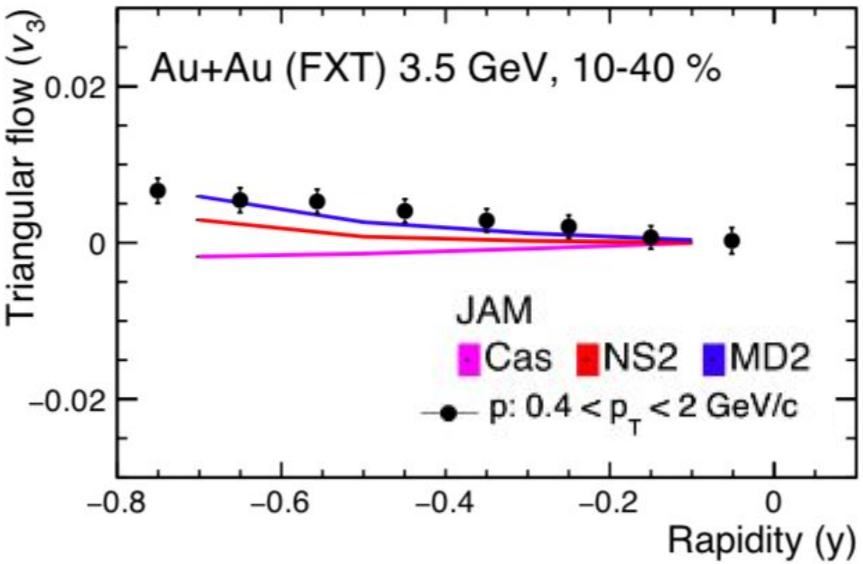


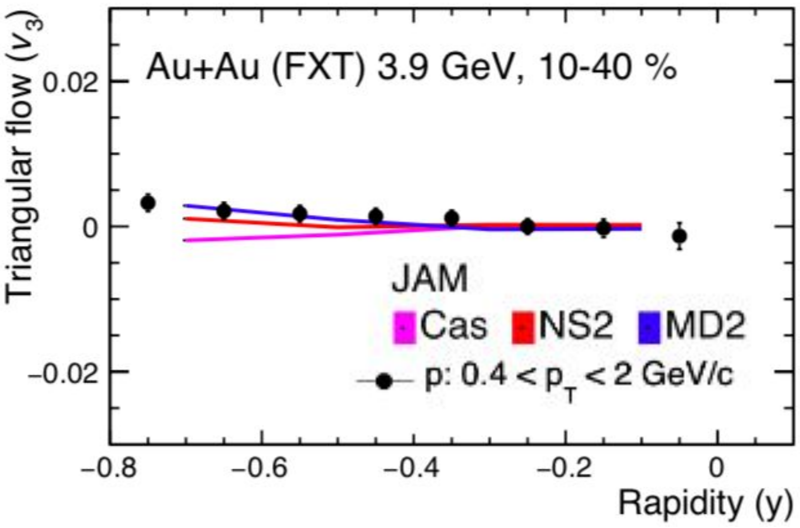
- Magnitude of proton $v_3\{\Psi_1\}$ increases with increasing rapidity and p_T.
- $|v_3\{\Psi_1\}|$ increases towards peripheral collisions ➡ **strong geometric effect**
- Increasing collision energy → decreasing magnitude of $v_3\{\Psi_1\}$ slope

(HADES) Phys. Rev. Lett. 125, 262301 (2020); (STAR) Phys. Rev. C 109, 044914 (2024)

JAM model comparison







- **JAM cascade** mode fails to describe data
- **JAM** model with **mean-field** describes the data ➡ **Nuclear potential** is essential for the development of $|v_3\{\Psi_1\}|$

Summary

- The magnitude of the v_1 slope decreases with increasing collision energy
- dv_1/dy (π^+) is negative whereas dv_1/dy (π^-) is positive ($\sqrt{s_{NN}}$ = 3.2 - 4.5 GeV) ➡ **Spectator shadowing and Coulomb interactions**
- dv_1/dy for both net-kaon and net-proton shows a minimum ➡ **Connection with changes in EoS is to be explored**
- Approximate mass no. scaling is observed in the v_1 slope for light nuclei ➡ **Nucleon coalescence**
- JAM mean-field with hard EoS gives a better description to the experimental data for identified hadrons as well as light nuclei (with coalescence afterburner)
- JAM-Cascade model with spectators able to reproduce the kaon anti-flow at low p_T ➡ **Kaon potential is not a necessary condition**

- Magnitude of $v_3\{\Psi_1\}$ decreases with increasing collision energy.
- $|v_3\{\Psi_1\}|$ increases in magnitude towards peripheral collisions ➡ **Strong geometric effect**
- **JAM** model with **mean-field** describes the data ➡ **Nuclear potential** is essential for the development of $|v_3\{\Psi_1\}|$

Thank you for your attention!!