68th DAE Symposium on Nuclear Physics

December 07 - 11, 2024

Indian Institute of Technology Roorkee, Uttarakhand, India

Measurement of directed flow in the high-baryon density region at RHIC-STAR

Sharang Rav Sharma (*for the STAR Collaboration*)

Indian Institute of Science Education and Research (IISER) Tirupati, India

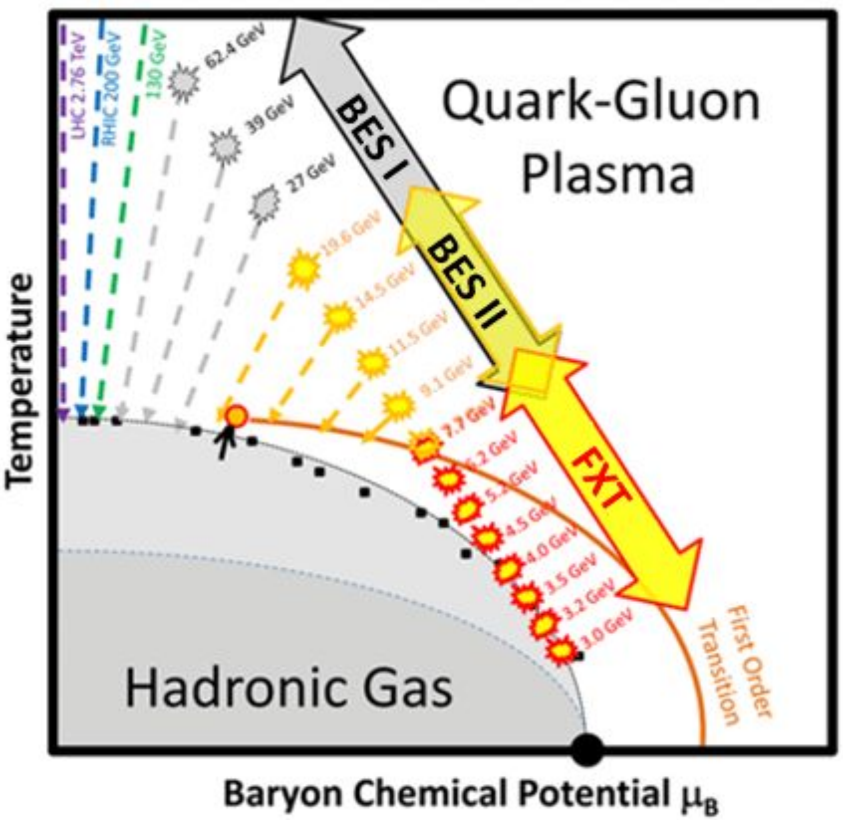
Supported in part by U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Introduction
- STAR Experiment
- Results and Discussion
    - Directed flow (v_1)
        - Experimental Measurements
        - Model Calculations
- 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:

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

Phase-I

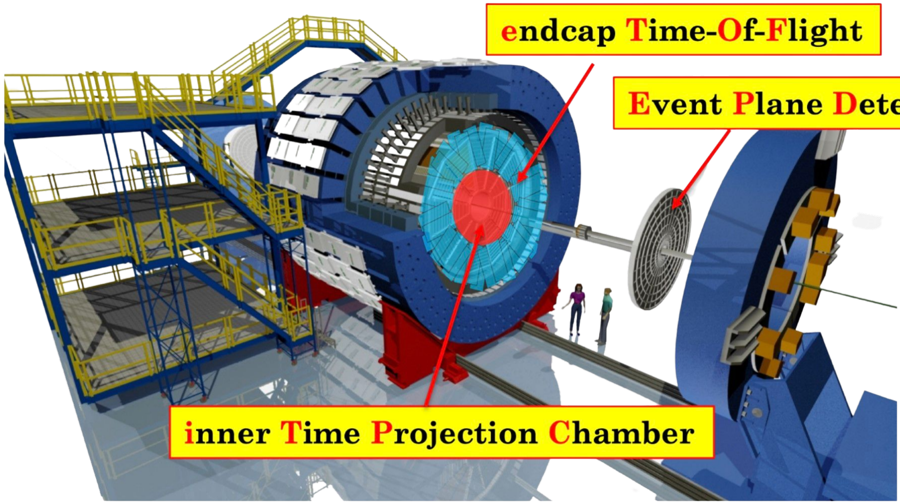
$\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, and 200 GeV **(COL)**

Phase-II

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

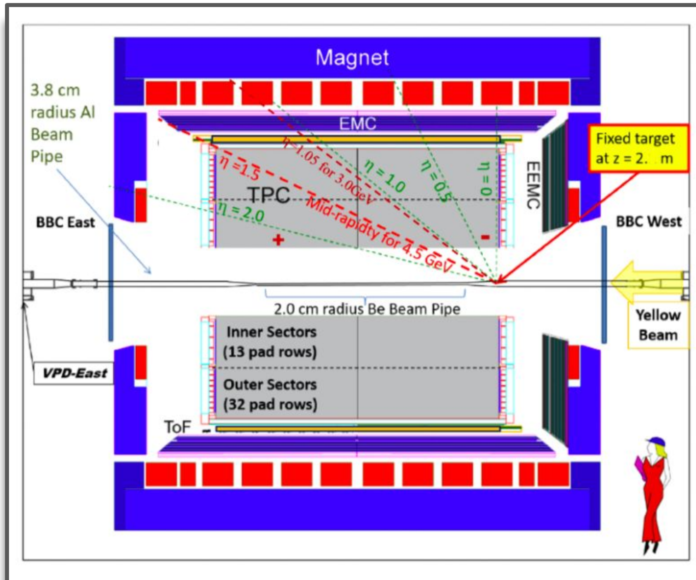
$\sqrt{s_{NN}}$ = **3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7**, 9.1, 11.5, and 13.7 GeV **(FXT)**

STAR Experiment



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

Fixed-target mode



Nuclear Phy A 808-811 (2017)

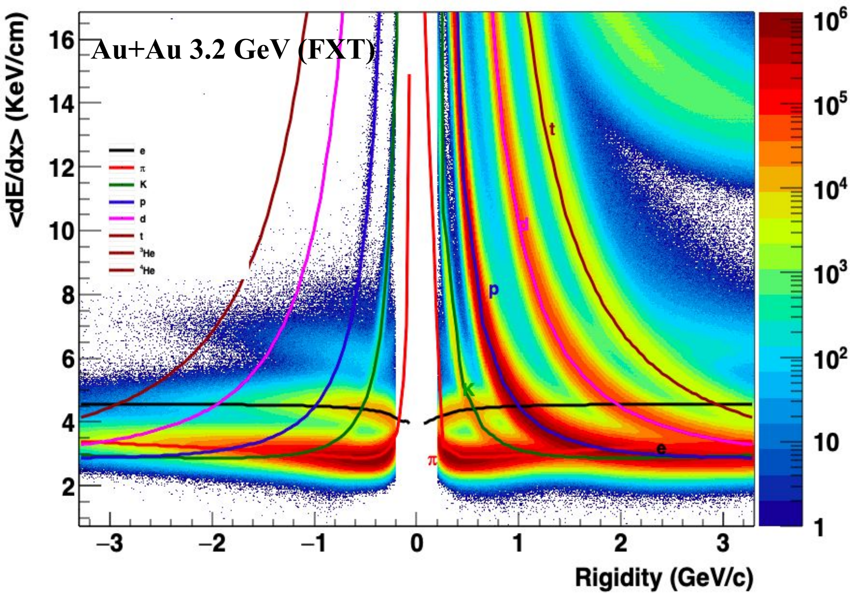
Solenoidal **T**racker **A**t **R**HIC (**STAR**) is one of the detector systems at RHIC consisting of several sub-detectors

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

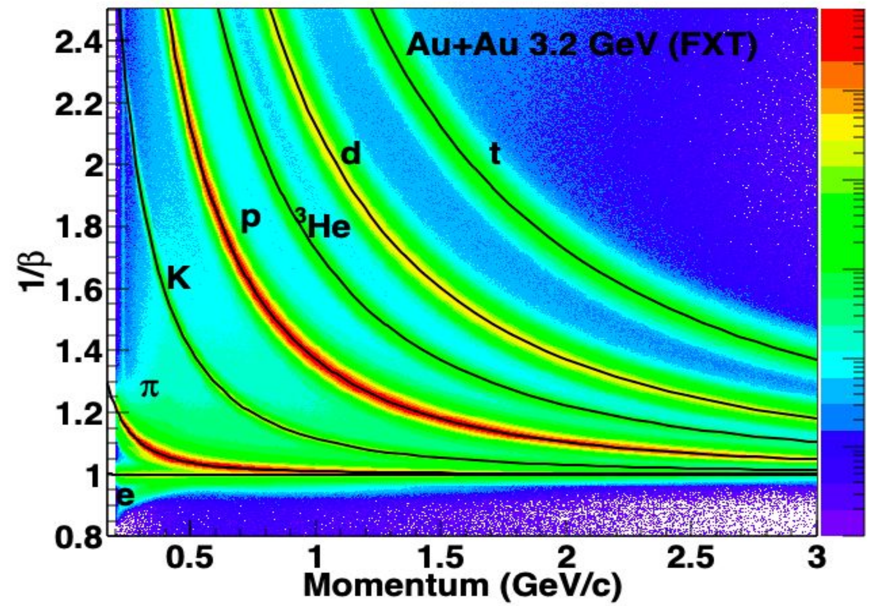
Collision energy	Events analyzed
3.2 GeV	220 M
3.5 GeV	110 M
3.9 GeV	110 M
4.5 GeV	100 M

Particle Identification

Time Projection Chamber (TPC)



Time of Flight (TOF)



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

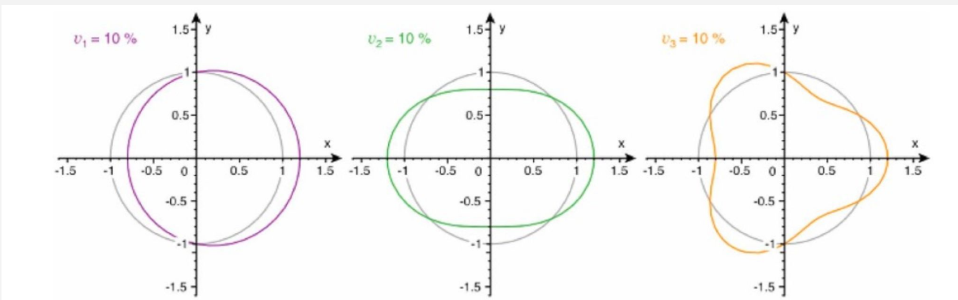
  - **Time Projection Chamber (TPC)** $z_X = \ln\left(\frac{\langle dE/dx\rangle}{\langle dE/dx\rangle_X^B}\right)$

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

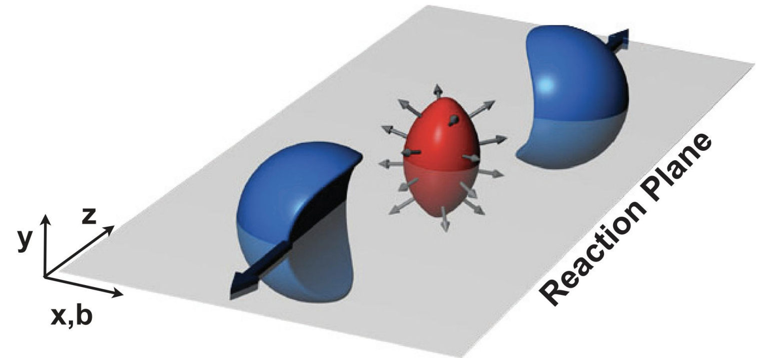
- **Flow** is the measure of azimuthal anisotropy of particles
- **Azimuthal distribution of particles**

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\{1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_R))\}$$

$$v_n = \langle \cos(n(\phi - \Psi_R)) \rangle$$



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

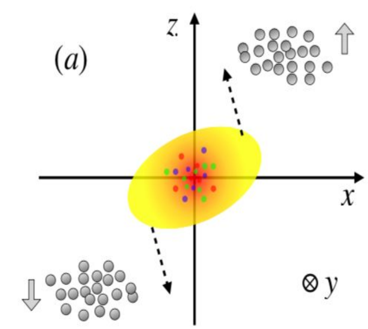


R. Snellings, New J.Phys.13:055008 (2011)

Directed flow

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

Sideward motion of emitted hadrons with respect to collision reaction plane

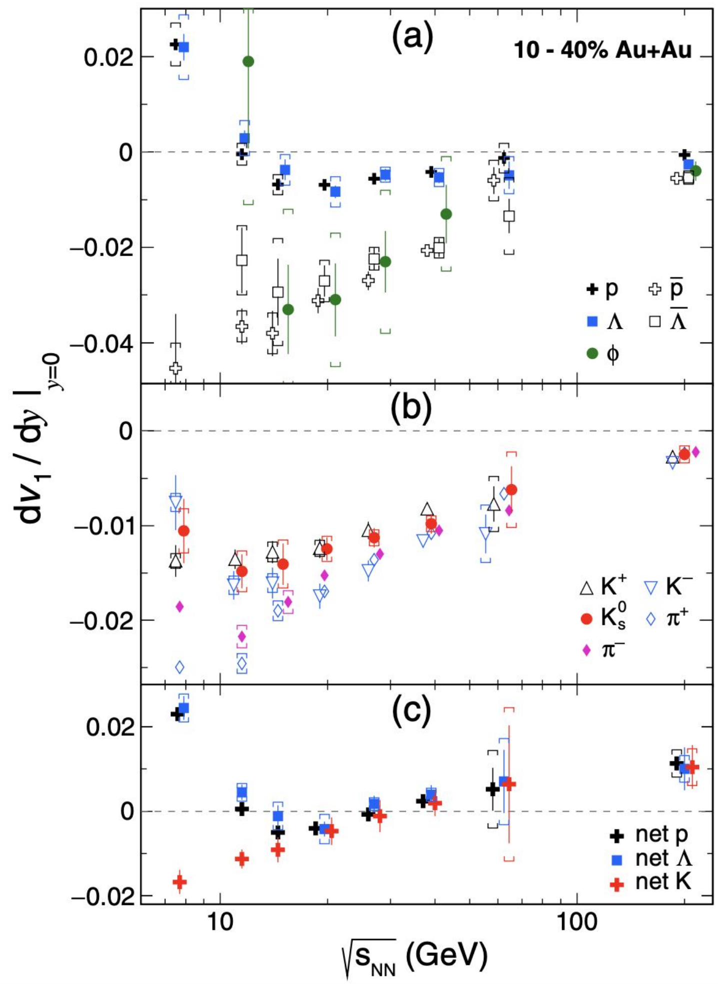


CMS, PRC 87 014902 2013)

Why v_n is important ?

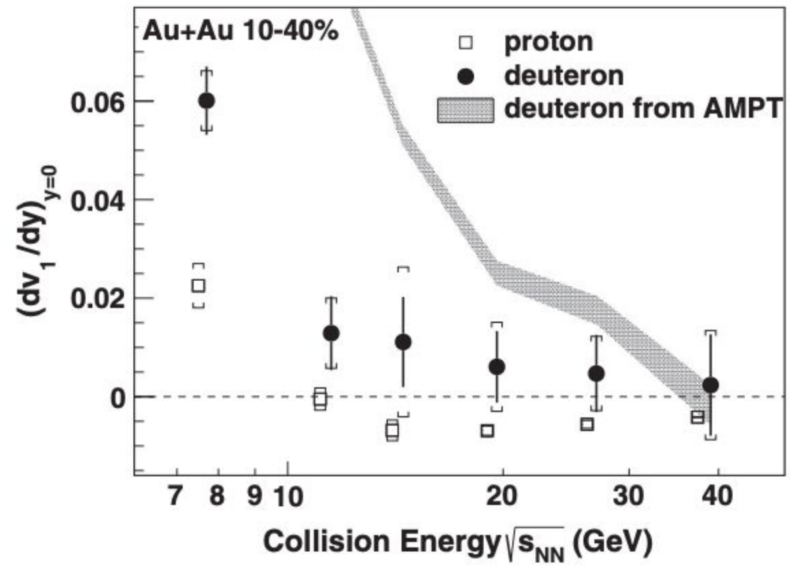
- Sensitive to the equation of state
- Sensitive to early times in the evolution of the system

Motivation for v_1 measurement



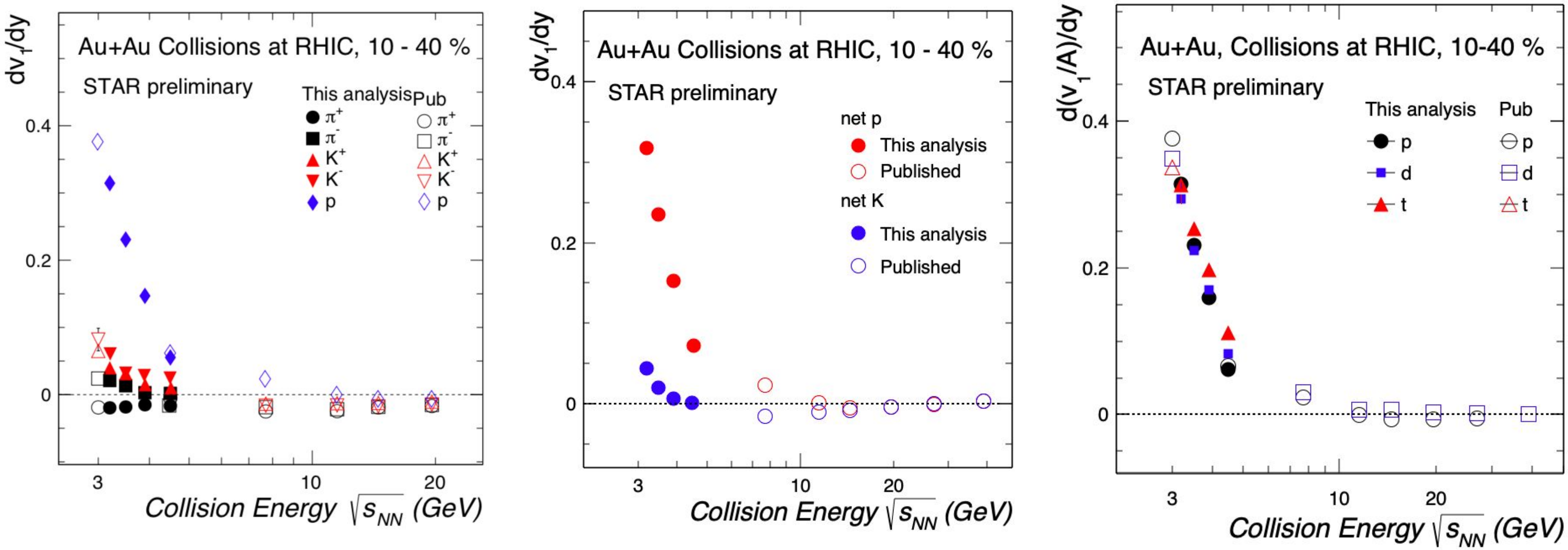
Phys. Rev. Lett. 120, 062301 (2018)

Phys. Rev. C 102, 044906 (2020)



- dv_1/dy for proton contrary to mesons showed a non-monotonic trend ➡ **Change of sign**
- **Net particle** → the excess of a particle over antiparticle → contribution of transported quarks w.r.t produced
- Minimum net-p at 11.5 - 19.6 GeV ➡ **Signature of 1st order phase transition**
  - **No minima for net-K**
- Light nuclei $d(v_1/A)/dy$ within systematic and statistical uncertainties ➡ **Approximate mass no. scaling**

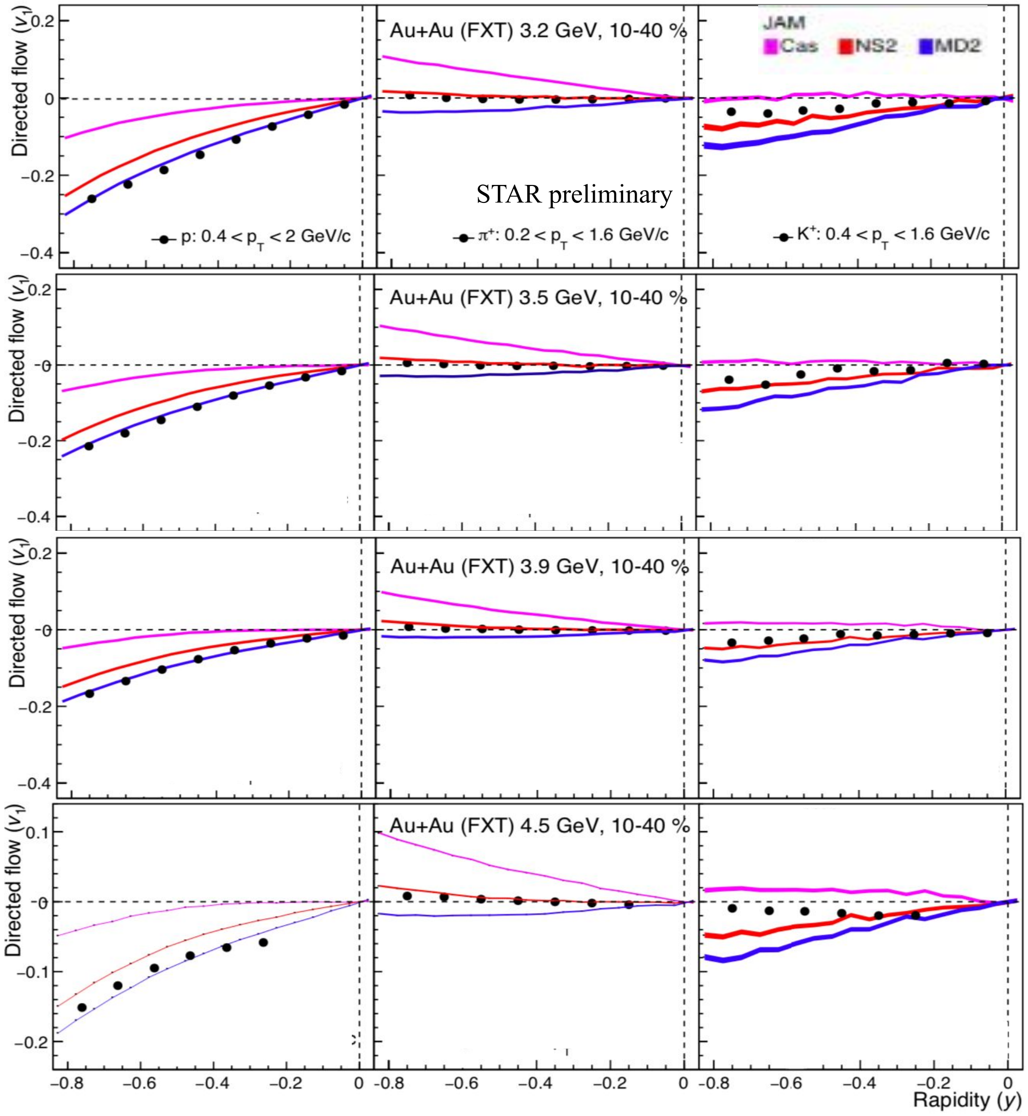
Collision energy dependence of dv_1/dy



- ❖ 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 coulombic 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 calculations

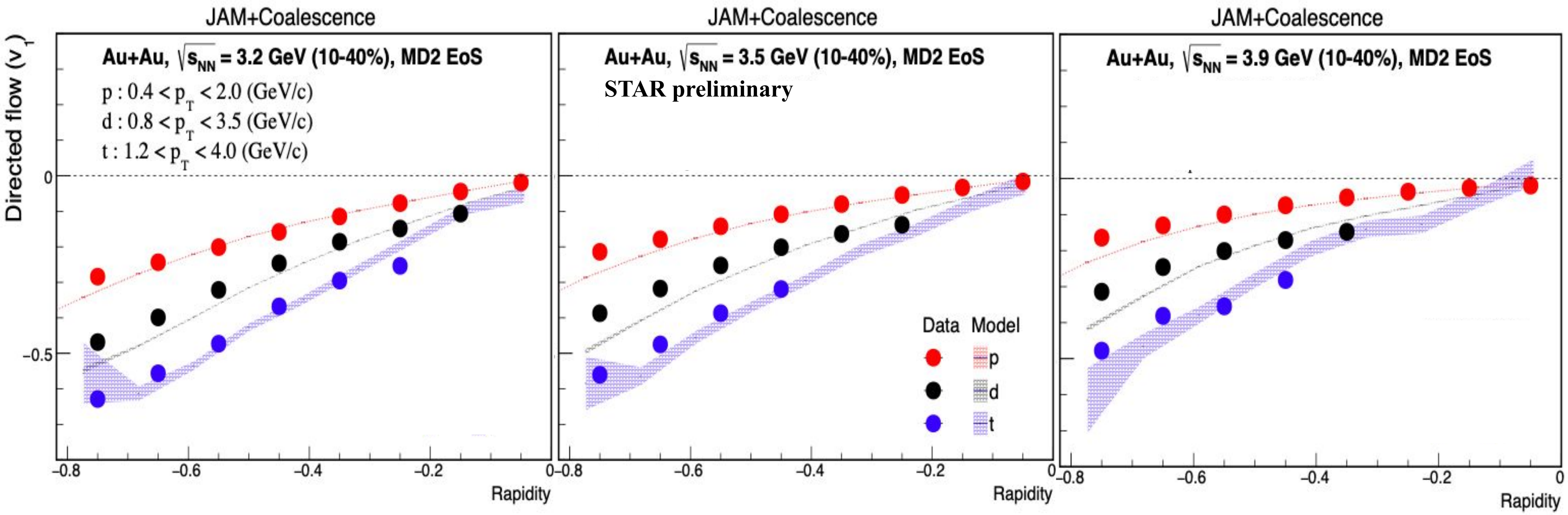


JET AA Microscopic Transportation Model (JAM2)

- **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 with mean-field gives better description to the experimental data

JAM model calculations

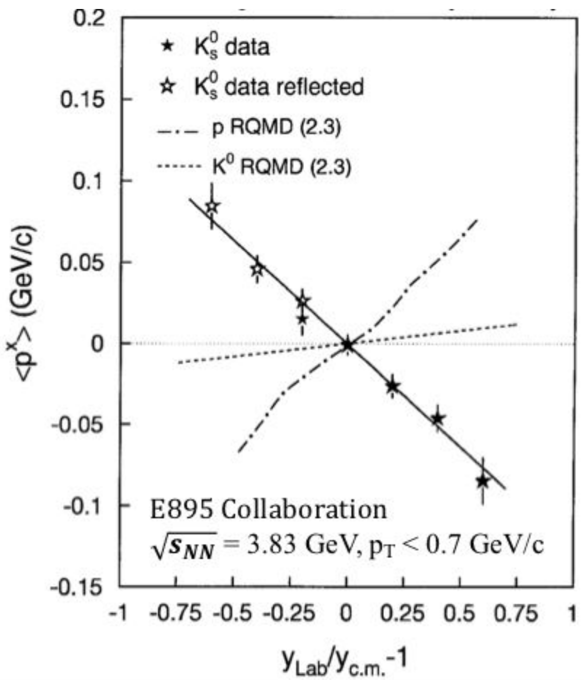


- Magnitude of v_1 increases with increasing rapidity
- **JAM MD2 with coalescence** provides good description of the data

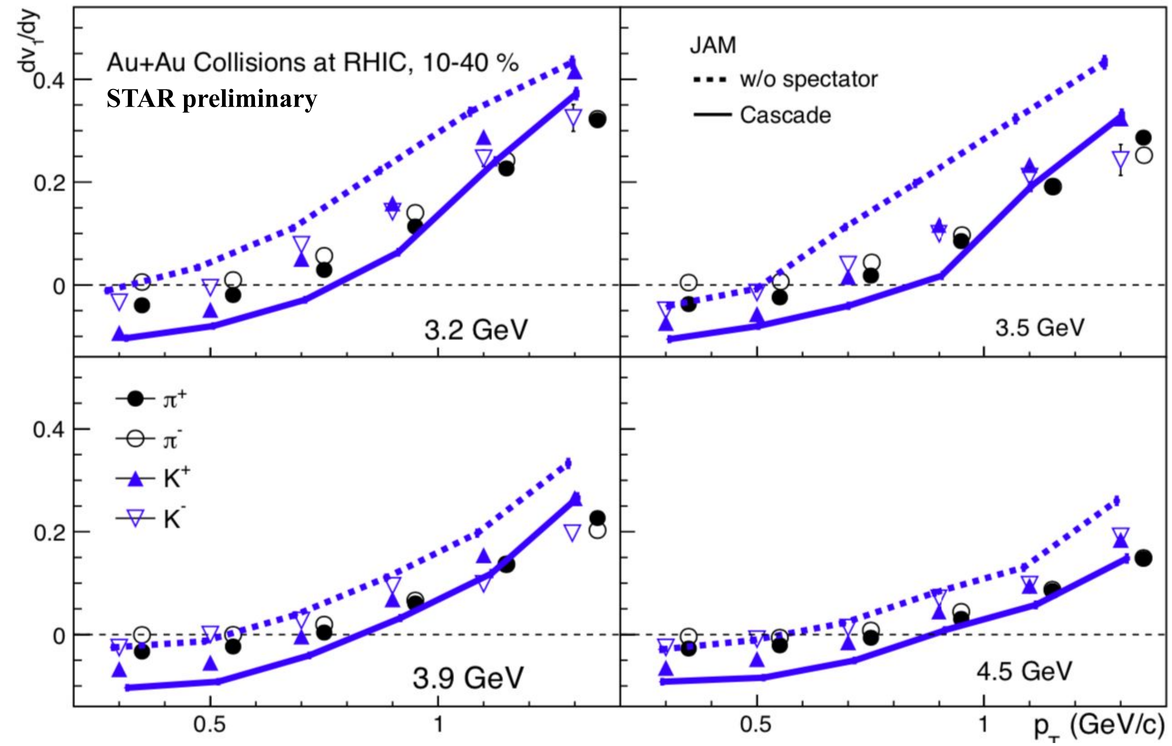
JET AA Microscopic Transportation Model (JAM2)

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 ➡ **No requirement of Kaon potential**

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

Summary

- The magnitude of the v_1 slope decreases with increasing collision energy
- $dv_1/dy|_{\pi+}$ is negative whereas $dv_1/dy|_{\pi-}$ is positive ➡ **Spectator shadowing and coulombic interactions**
- dv_1/dy for both net-kaon and net-proton shows a minimum ➡ **Might be a signature of 1st order phase transition**
- Approximate mass no. scaling is observed in the v_1 slope for light nuclei ➡ **Nucleon coalescence**
- JAM mean-field 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 anti-flow at low p_T ➡ **No requirement of Kaon potential**

Thank you for your attention!!