Measurement of event plane correlated triangular flow in high baryon density region at RHIC-STAR

ALICE-STAR India collaboration meeting

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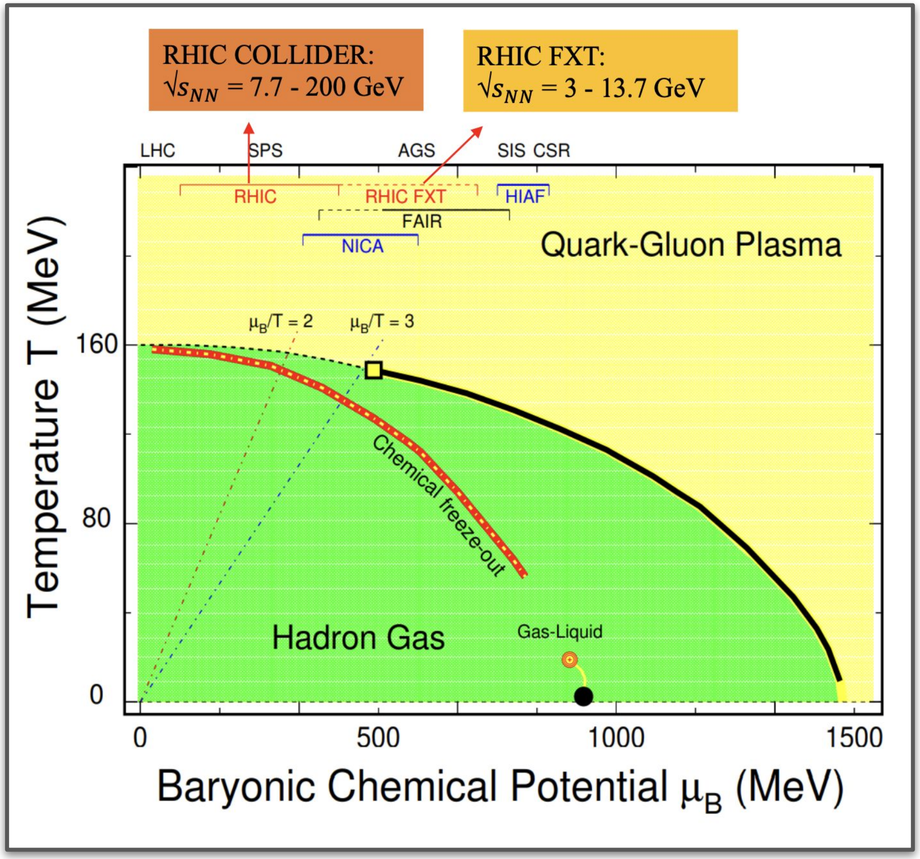
Outline

- ❖ Introduction
- ❖ STAR Detector
- ❖ Analysis Technique
- ❖ Results and Discussion
  - ❖ Triangular Flow (v_3)
- ❖ Summary and Outlook

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:

- To search for the predicted first-order phase transition
- To search for a critical end point
- To investigate the expected turn-off of QGP signatures

Phase I

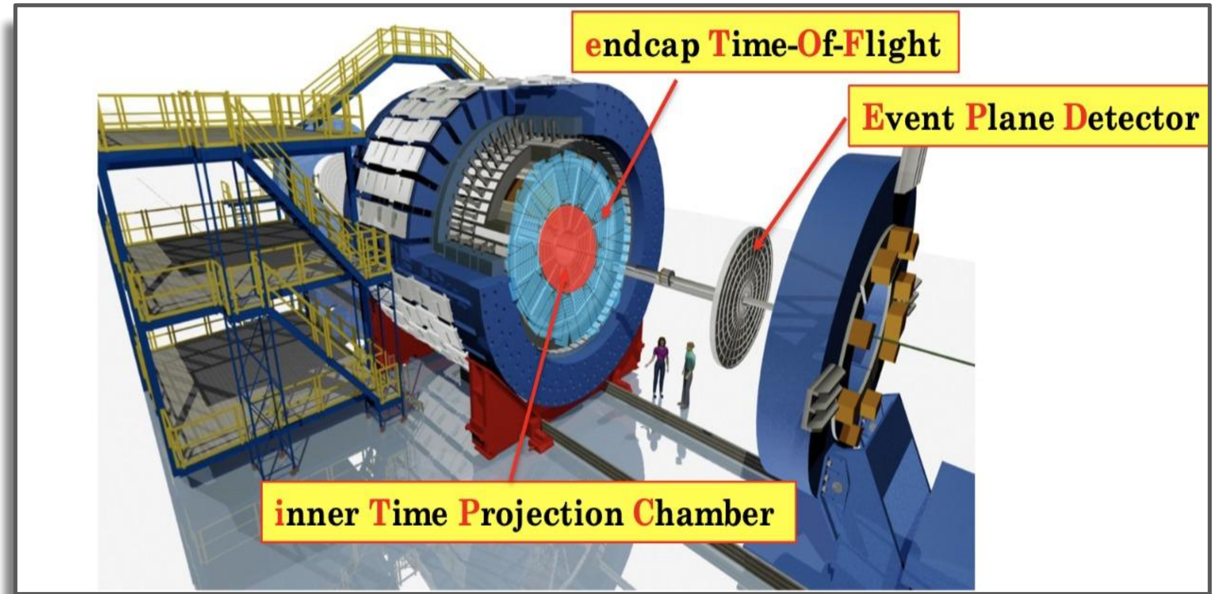
$\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, and 200 GeV **(COL)**

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 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
- ➢ Operational in 2019

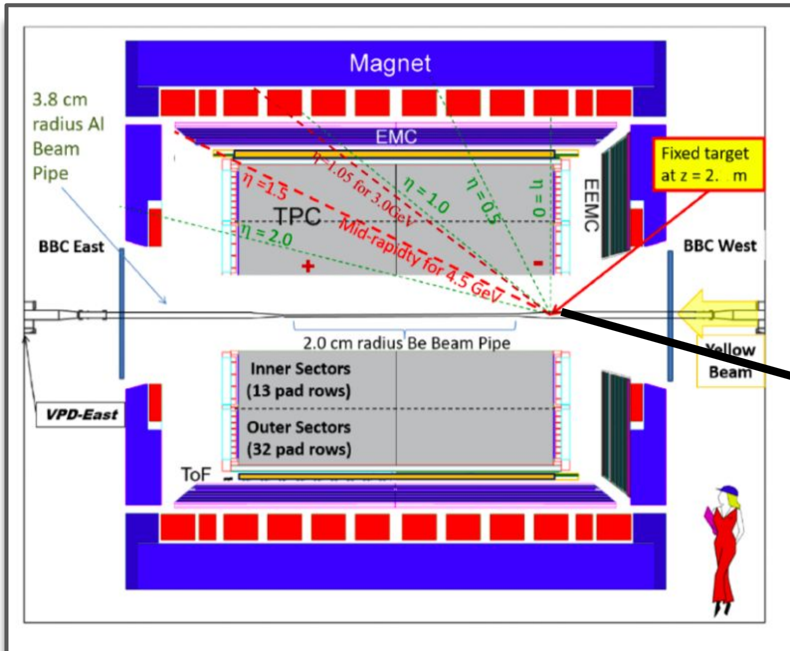
eTOF:
- ➢ Forward rapidity coverage
- ➢ PID at η = -1.1 to -1.6
- ➢ Operational in 2019

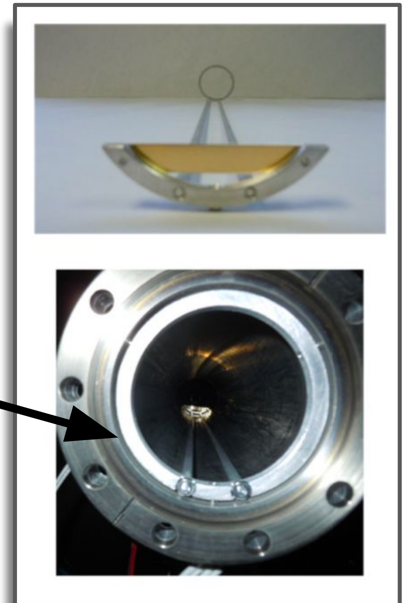
EPD:
- ➢ Improves trigger
- ➢ Event plane measurements
- ➢ Operational in 2018

[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 Experiment

Fixed-target mode





Nuclear Phy A 808-811 (2017)

- **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

Dataset Information

- **Au+Au $\sqrt{s_{NN}}$ = 3.2 GeV**
- **Trigger id:** 680000, 680001, 680002, 680003, 680004, 680006
- **Production**: P21id
- **Events analyzed:** 200 M
- **Bad Run List:** 20180005, 20180006, 20180019, 20180025, 20181016, 20182034, 20183001, 20183013, 20183014, 20183019

- **Au+Au $\sqrt{s_{NN}}$ = 3.5 GeV**
- **Trigger id:** 720000
- **Production**: P21id
- **Events analyzed**: 110 M
- **Bad Run List**: 20355020, 20355021, 21044023, 21045024, 21045025, 21044027, 21044035, 21045004

- **Au+Au $\sqrt{s_{NN}}$ = 3.9 GeV**
- **Trigger id**: 730000
- **Production**: P21id
- **Events analyzed**: 110 M
- **Bad Run List**: 20107029, 20113042, 20113043, 20169033, 20169043

- **Au+Au $\sqrt{s_{NN}}$ = 4.5 GeV**
- **Trigger id**: 740010
- **Production**: P21id
- **Events analyzed**: 100 M
- **Bad Run List**: 21032001

Events and Track selection cuts

Event Selection

Cut	Value
v_z	(198-202) cm
v_r	< 2 cm

Track Selection

Cut	Value
nHitsFit	≥ 25
nHitsRatio	≥ 0.52
DCA	<3 cm

PID

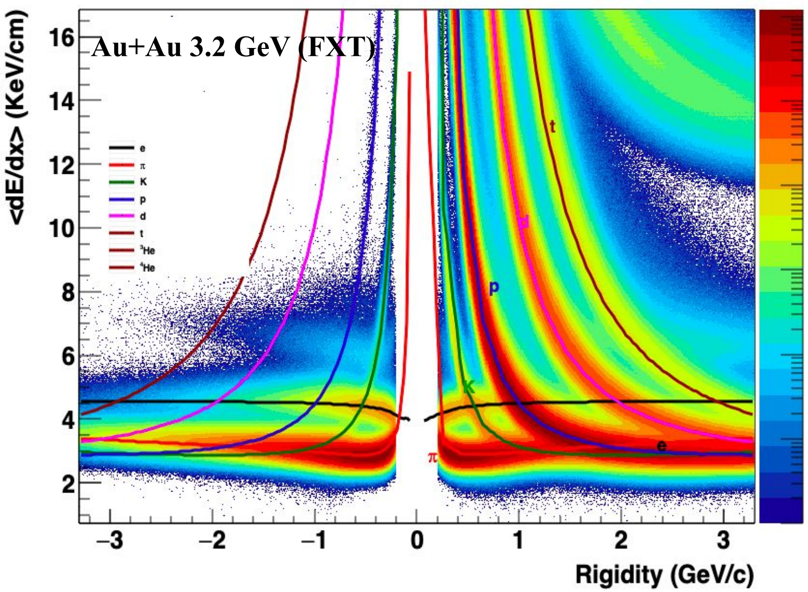
Cut	Value
$\|n\sigma_{\pi} - n\sigma_{\pi, mean}\|$	< 3
$\|n\sigma_{p} - n\sigma_{p, mean}\|$	< 2

Cut	Value (GeV^2/c^4)
m^2_{π}	(-0.1 - 0.15)
m^2_{p}	(0.6-1.2)

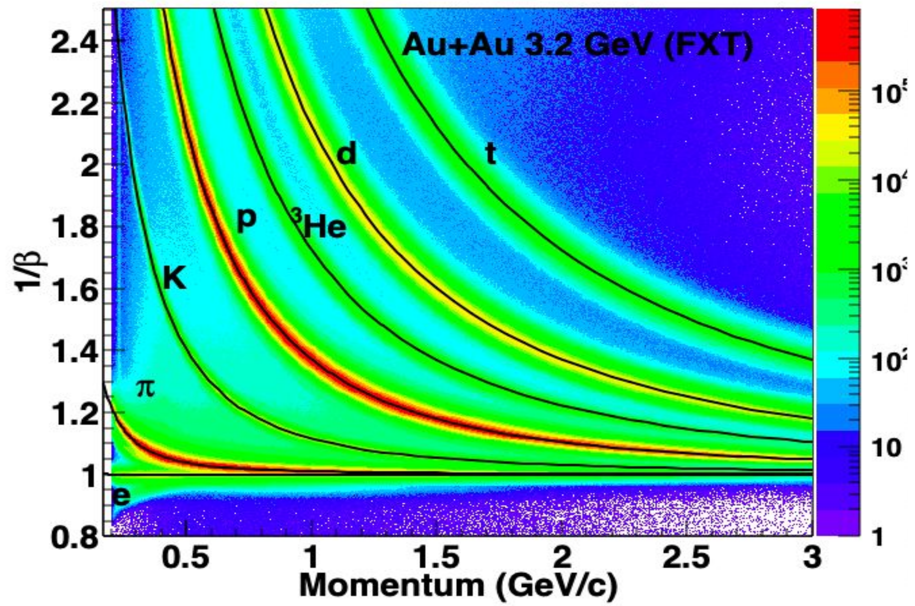
Momentum dependent z cut implemented for light nuclei identification

Particle Identification

Time Projection Chamber (TPC)



Time of Flight (ToF)



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

- **Time Projection Chamber** (**TPC**)

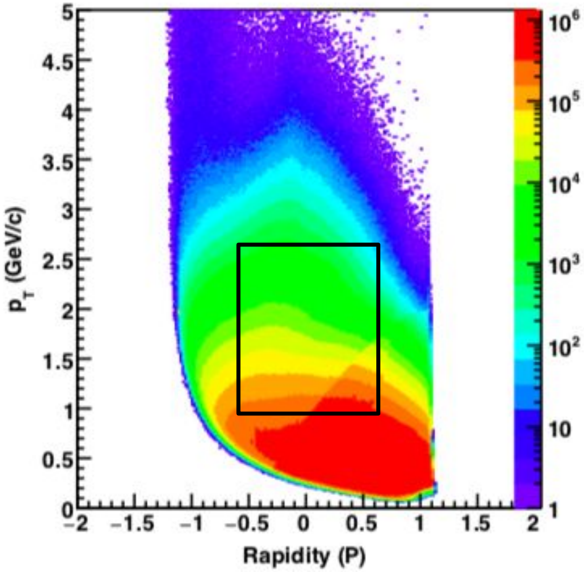
$$z_X = \ln\left(\frac{\langle dE/dx\rangle}{\langle dE/dx\rangle_X^B}\right)$$

- **Time of Flight** (**ToF**)

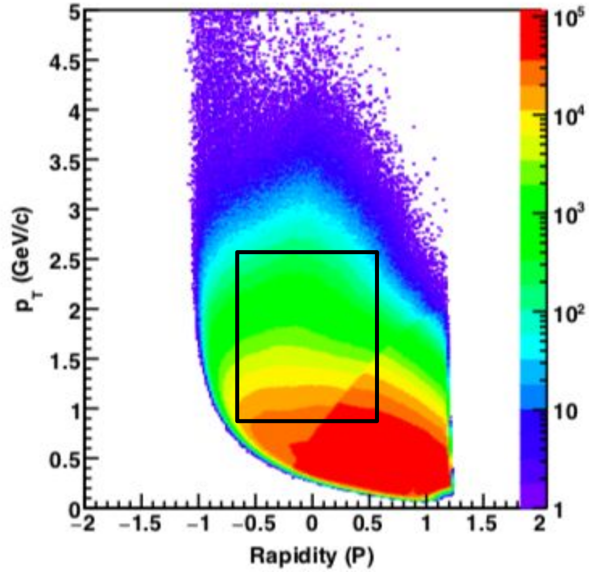
$$m^2 = p^2\left(\frac{c^2T^2}{L^2} - 1\right)$$

Phase Space Distribution

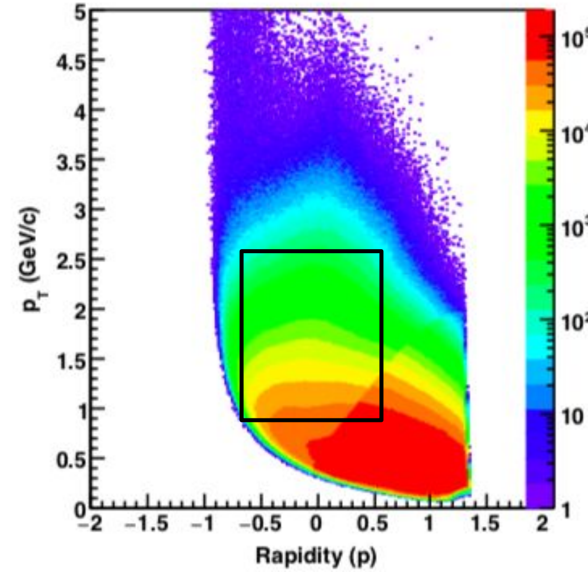
3.2 GeV



3.5 GeV



3.9 GeV

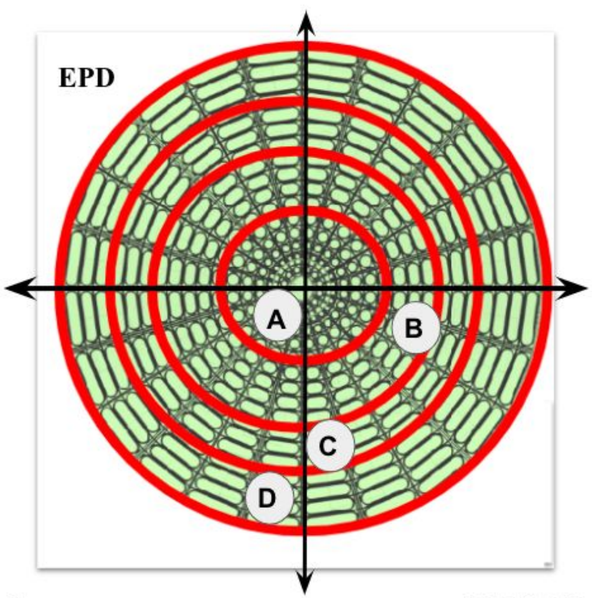


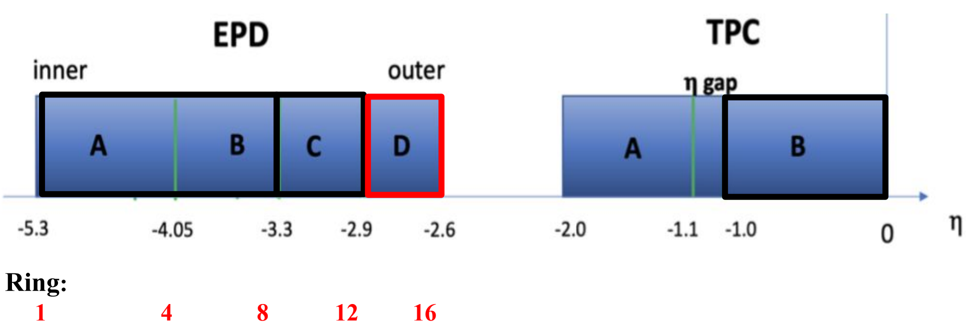
Rapidity

$$y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c};$$

$y_{cms} = y + |y_{mid}|$, for FXT 3.2 GeV, $y_{|mid|} = -1.127$

Event Plane Reconstruction





- ➔ **Event Plane Detector (EPD)** → Measures charged particles emitted in the forward and backward directions
- ➔ TPC and EPD are divided into 2 and 4 regions, respectively, based on their pseudorapidity (η) coverage

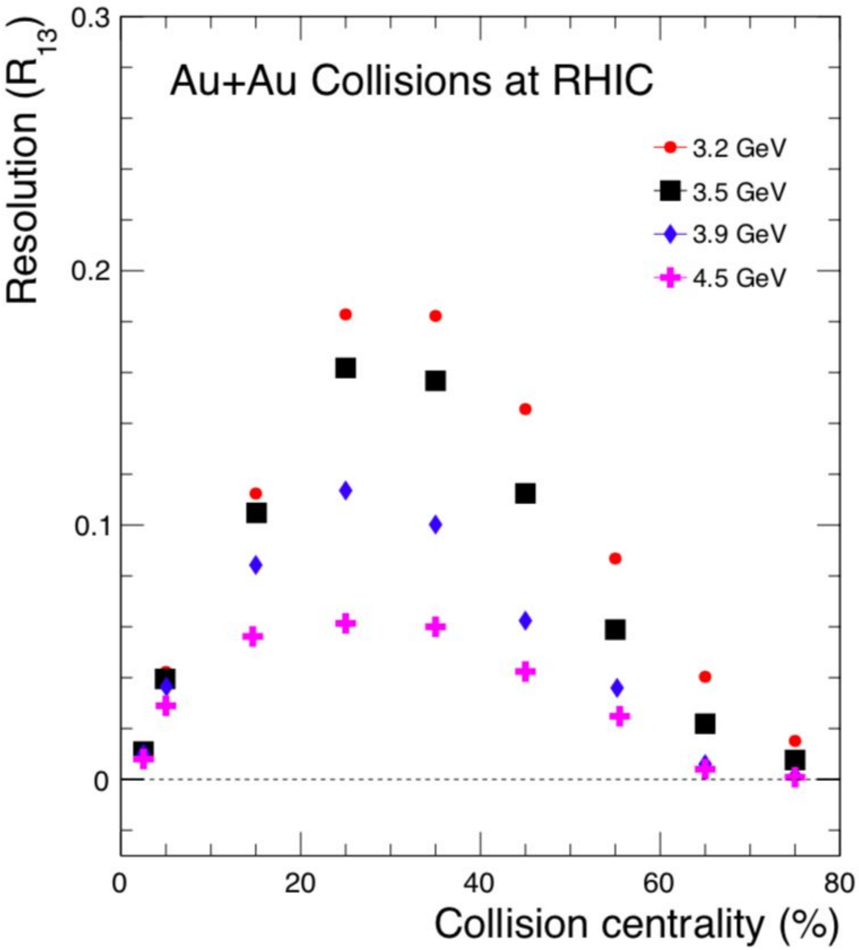
$$\vec{Q} = (Q_x, Q_y) = \left(\sum_i w_i \cos(\phi_i), \sum_i w_i \sin(\phi_i)\right)$$

$$\psi_1 = \tan^{-1}(Q_y/Q_x)$$

where ϕ_i is azimuthal angle and w_i is the weight for the i^{th} hits, Ψ_1 is the first-order event plane angle

Phys. Rev. C 58, 1671 (1998)

Event Plane Resolution



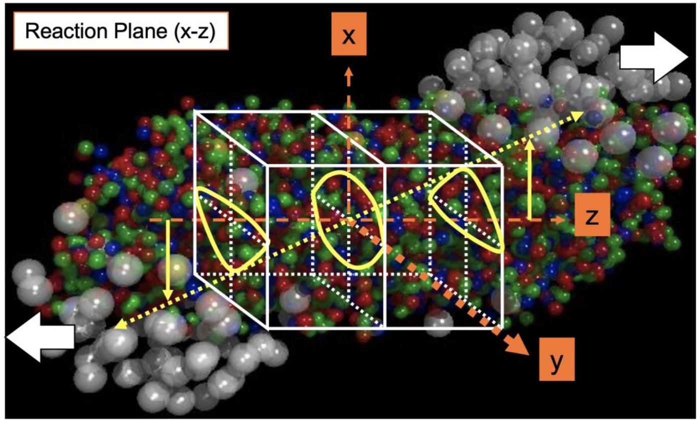
- In FXT mode collision, 3-sub event method was used to determine the EPD first order event plane resolution.

$$R_{31} = \sqrt{\frac{\langle \cos(3(\Psi_1^A - \Psi_1^B))\rangle \langle \cos(3(\Psi_1^A - \Psi_1^C))\rangle}{\langle \cos(3(\Psi_1^B - \Psi_1^C))\rangle}},$$

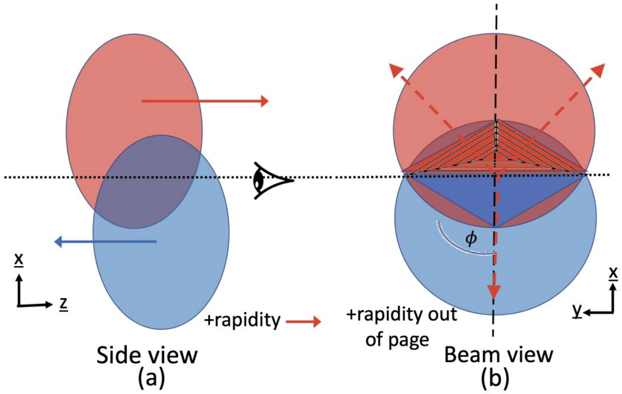
R_{13} (m=1, n=3)

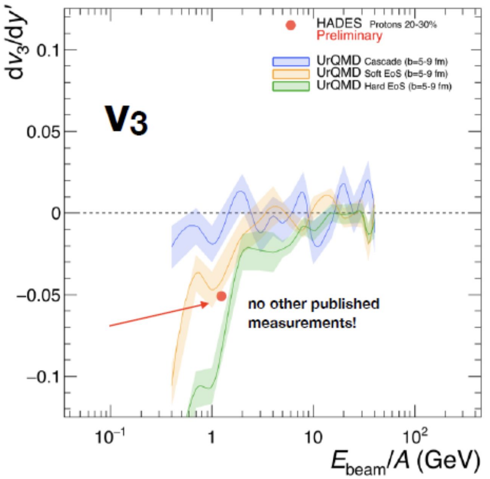
a → EPD-AB ($-5.3 < \eta < 3.3$)
b → EPD-C ($-3.3 < \eta < 2.9$)
c → TPC B ($-1.0 < \eta < 0$)

Triangular flow ($v_3(\Psi_1)$)



Phys. Rev. C 109, 044914 (2024)





J. Phys. G: Nucl. Part. Phys. 45 085101 (2018)
Phys. Rev. Lett. 125, 262301 (2020)

- **Azimuthal distribution of particles**

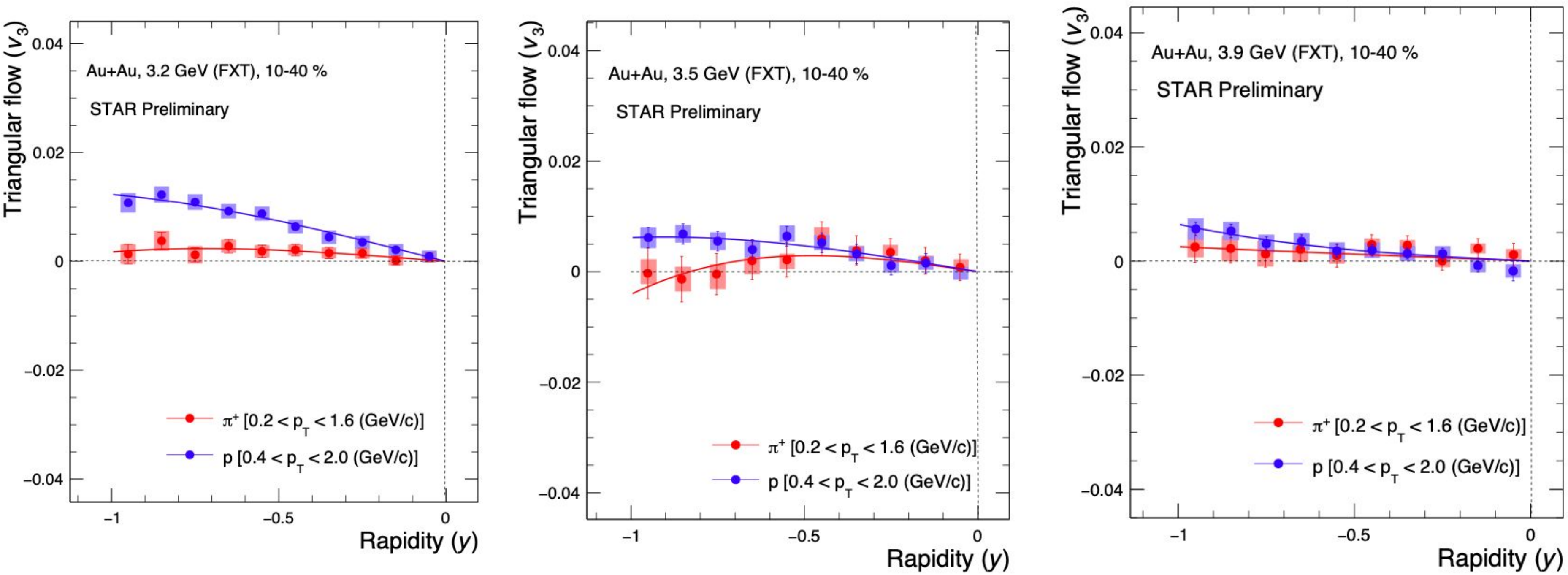
$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_n))\right)$$

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

- v_3 at higher energies → fluctuations in shape of the initial condition
- Contrary to observations at higher energy v_3 is correlated to first order reaction plane at 2.4 GeV (HADES) and 3 GeV (STAR)

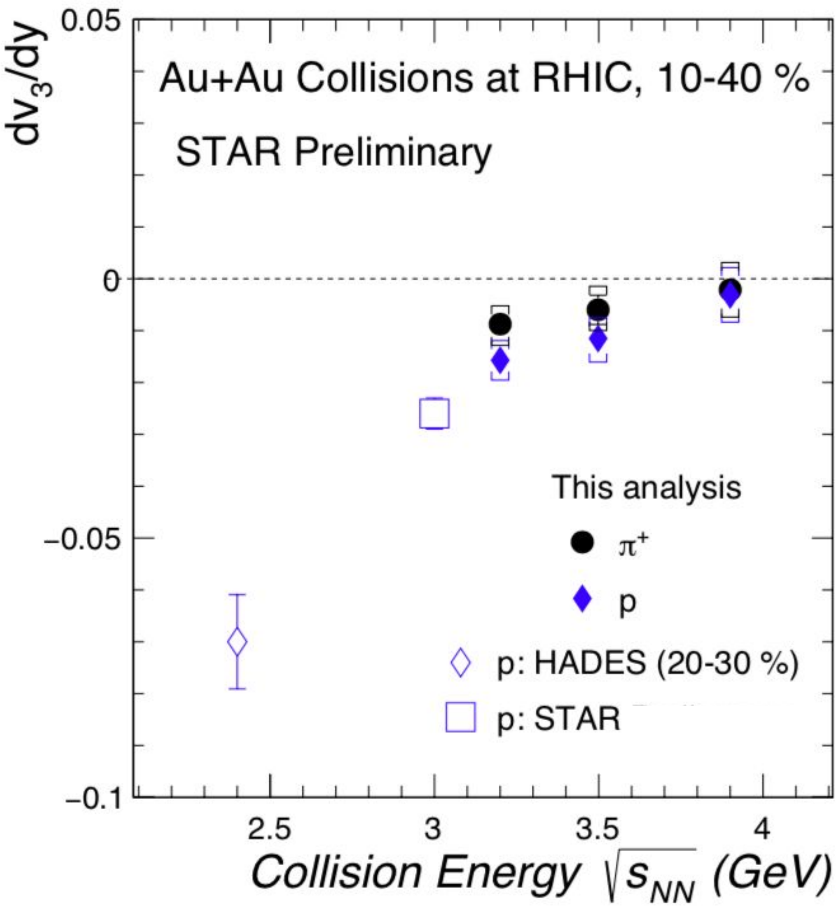
- $v_3(\Psi_1)$ at low collision energies is driven by
  - **Geometry** → baryon stopping
  - **Potential** in a responsive medium

Rapidity dependence of $v_3(\Psi_1)$



- Weak rapidity dependence of v_3 observed
- v_3(y) fitted with third order polynomial : $v_3(y) = by + cy^3$

Collision energy dependence of dv_3/dy

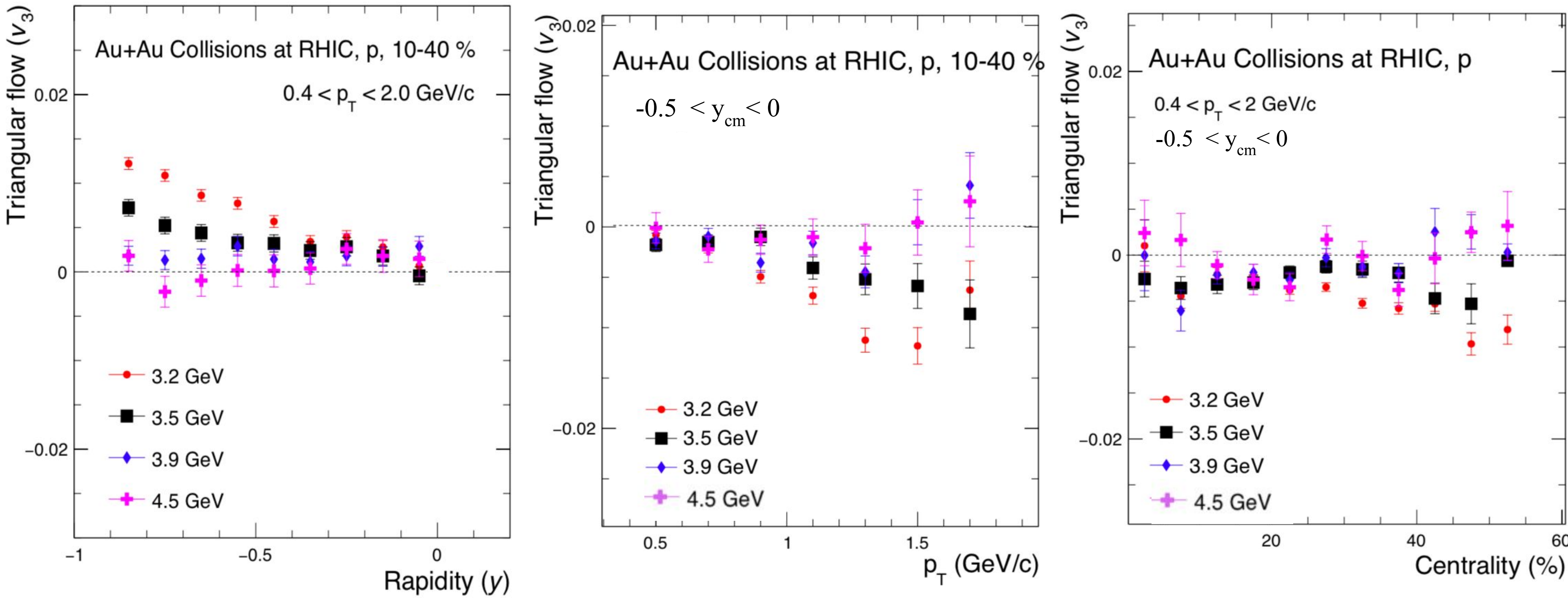


- $v_3(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_3/dy$)
  $v_3(y) = by + cy^3$
- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing magnitude of v_3 slope

(HADES) Phys. Rev. Lett. 125, 262301 (2020)

(STAR) Phys. Rev. C 109, 044914 (2024)

$v_3(\Psi_1)$ for proton

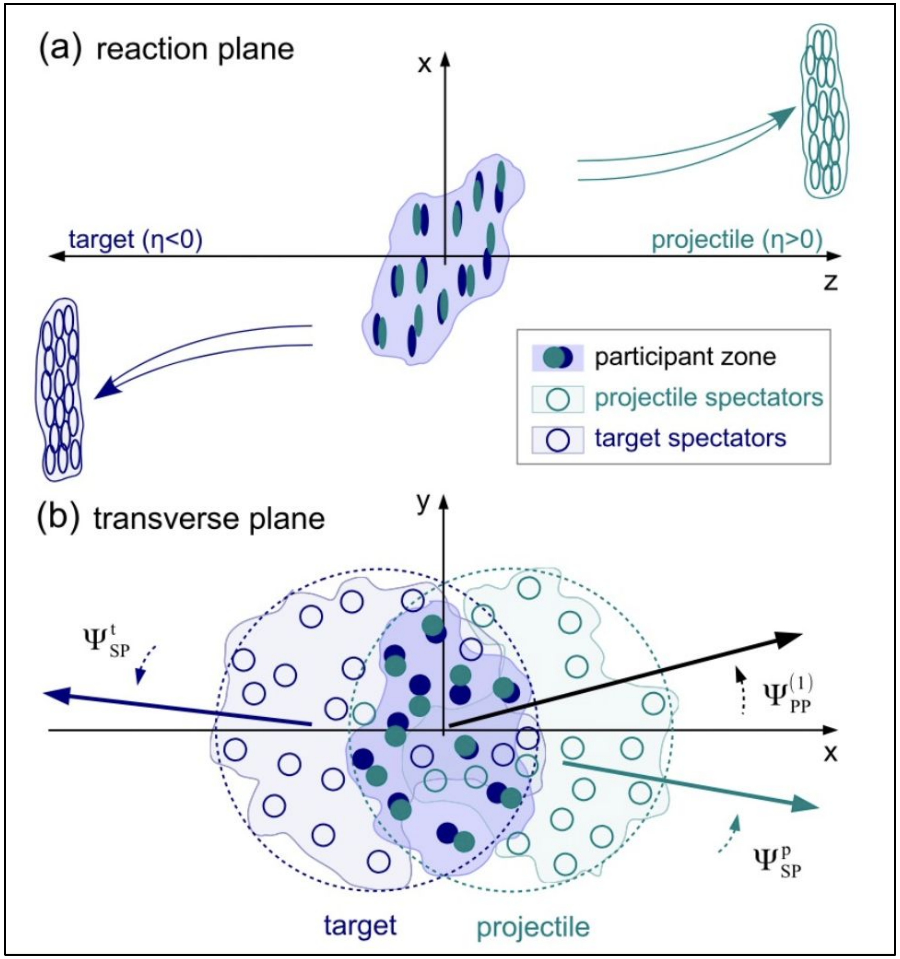


- Magnitude of proton $v_3\{\Psi_1\}$ increases with increasing rapidity, and p_T.
- $|v_3\{\Psi_1\}|$ increases towards peripheral collisions → strong geometric effect
- Magnitude of $v_3\{\Psi_1\}$ decreases with increasing collision energy

Separating v_3^{odd} and v_3^{even}

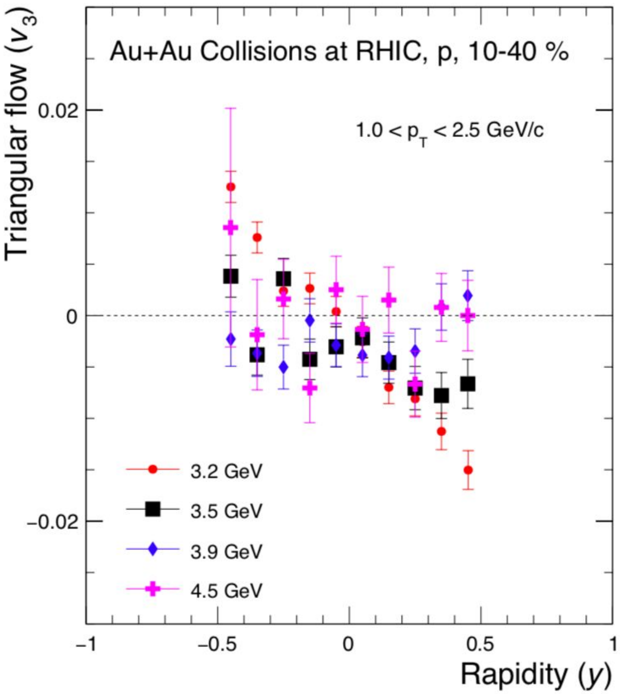
- ALICE has shown that v_1 can develop a rapidity-even contribution (v_1^{even}) even though it should be a completely odd function of rapidity.
- Since we are using Ψ_1 to calculate v_3, it's possible that our measurements are seeing the same effect and we can separate v_1^{even} and v_1^{odd}.

$$v_3^{odd} = \frac{1}{2}[v_3(y_{CM}) + \{-v_3(-y_{CM})\}]$$
$$v_3^{even} = \frac{1}{2}[v_3(y_{CM}) - \{-v_3(-y_{CM})\}]$$

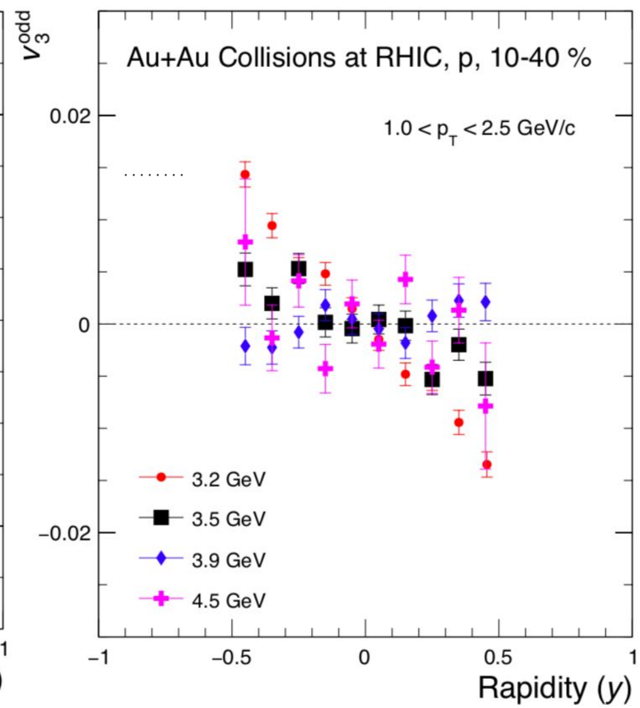


Phys. Rev. Lett. 111, 232302 (2013)

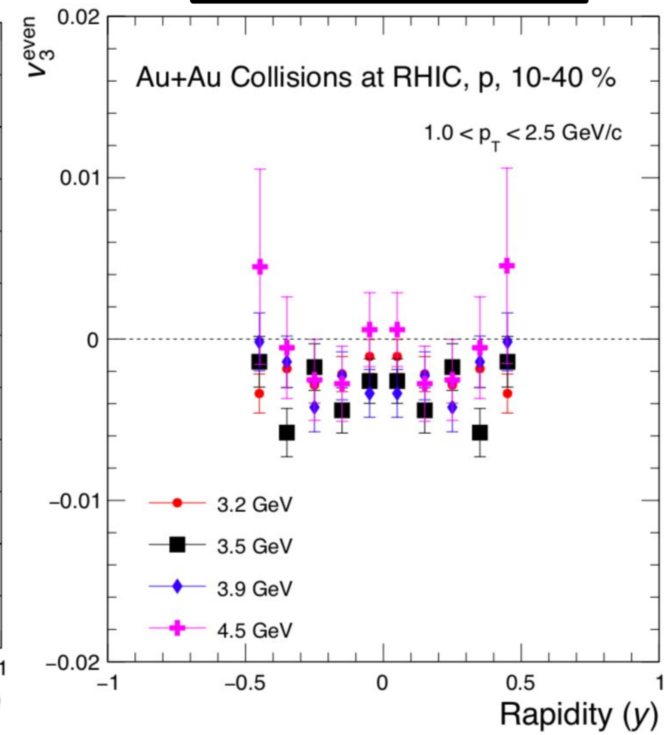
Separating v_3^{odd} and v_3^{even}



Odd component

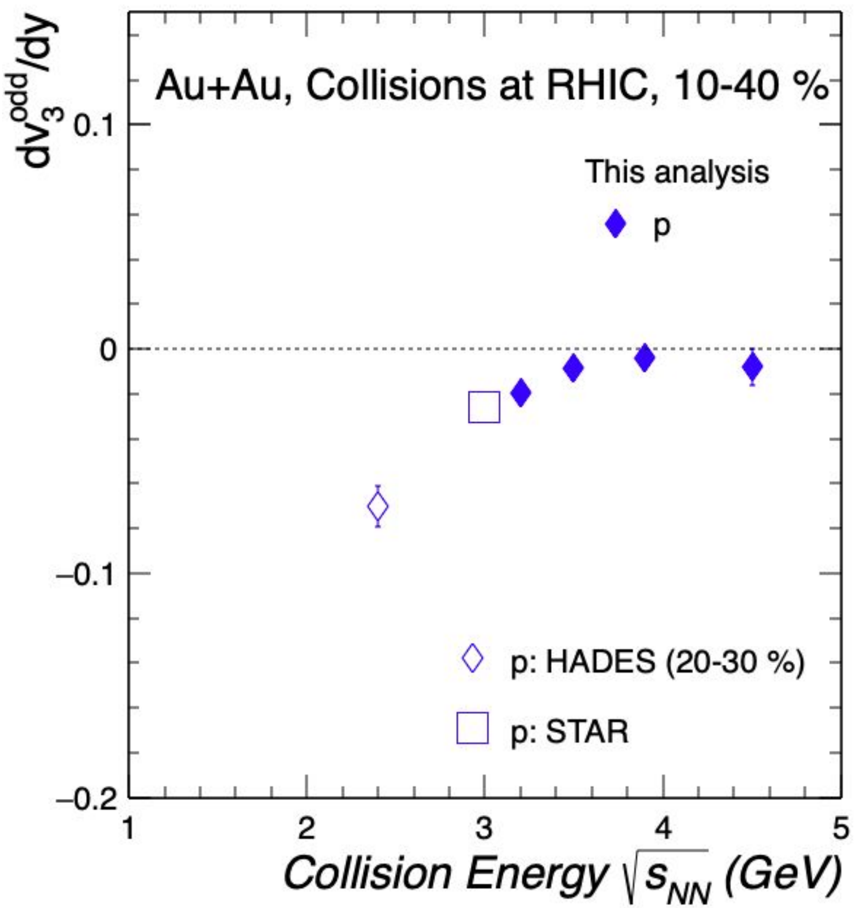


Even component



- v_1^{odd} appears consistent with zero at 3.9 and 4.5 GeV.
- v_1^{even} has large error bars and it is difficult to distinguish the shape

Collision energy dependence of dv_3^{odd}/dy

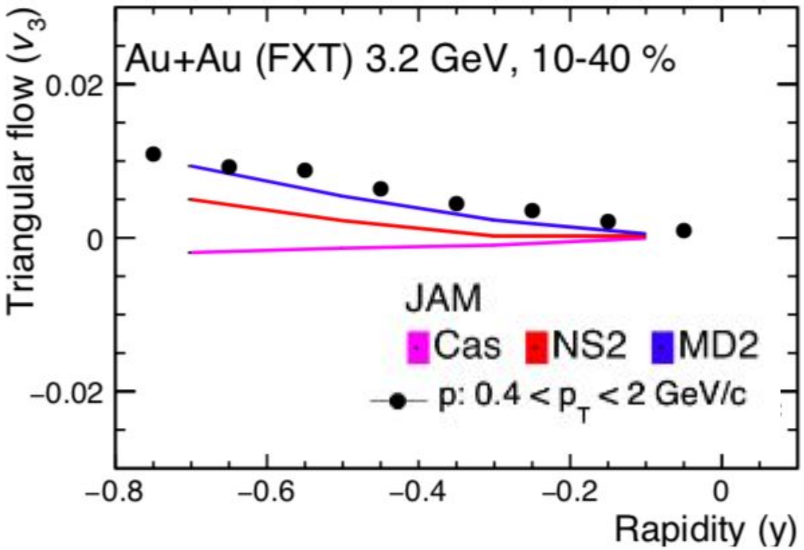


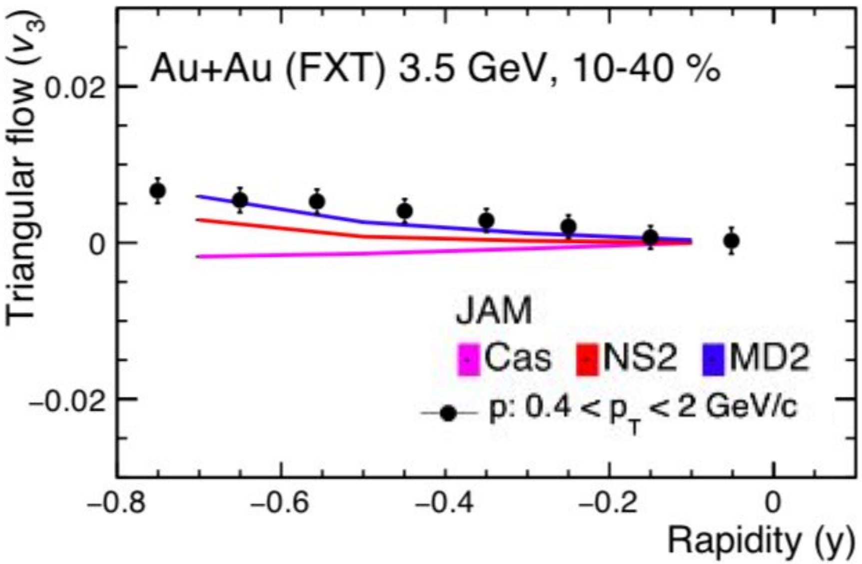
- $v_3(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_3/dy$)

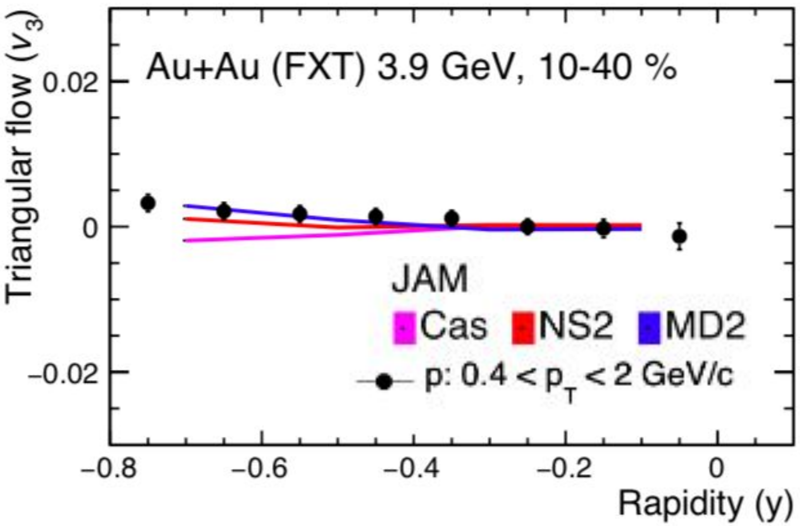
  $v_3(y) = by + cy^3$
- Fitting range → [y: -0.45, 0.45]
- Increasing collision energy → decreasing magnitude of v_3 slope

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

- Rapidity, p_T, centrality, and collision energy dependence of proton v_3, for 3.2, 3.5, 3.9, and 4.5 GeV is presented.
- v_3 and v_3^{odd} decreases with increasing collision energy and the signal is mostly consistent with zero by 4.5 GeV.
- v_3^{even} shows a weak dependence on rapidity and energy.
- JAM model with mean-field gives a better description to data → dominance of baryonic interactions at low collision energies.

Outlook

- Paper titled: "Energy dependence of reaction plane correlated triangular flow in Au+Au Collisions"is proposed in STAR FCV-PWG.

Thank you for your attention !!