First-order event plane correlated directed and triangular flow from fixed-target energies at RHIC-STAR

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Outline

2023

- Motivation
- STAR Detector
- Analysis Technique
- Results and Discussion
  - Directed Flow (v_1)
  - Triangular Flow (v_3)
- Summary

Anisotropic Flow

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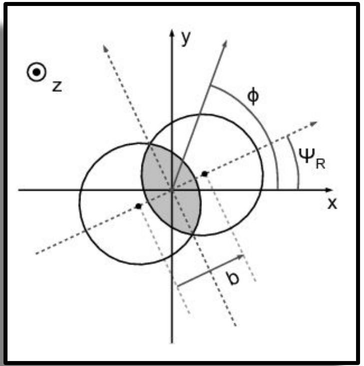
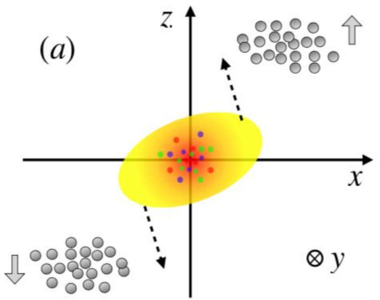
- **Flow** is the measure of azimuthal anisotropy
- Azimuthal distribution of particles

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

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





CMS, Phys. Rev. C 87 014902 (2013)

Directed flow

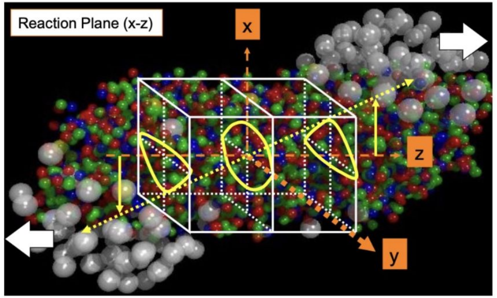
$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

$v_1 \rightarrow$ sideward motion of emitted hadrons with respect to collision reaction plane

Triangular flow

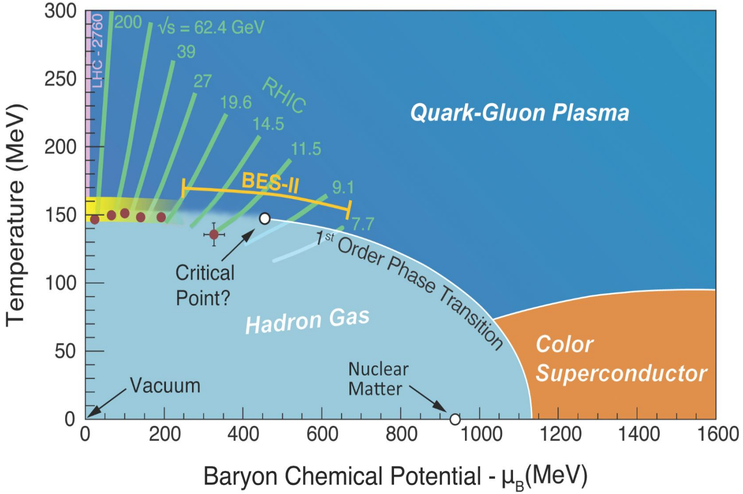
$$v_3 = \langle \cos 3(\phi - \Psi_1) \rangle$$

$v_3 \rightarrow$ driven by the shape of the initial collision geometry for lower collision energies

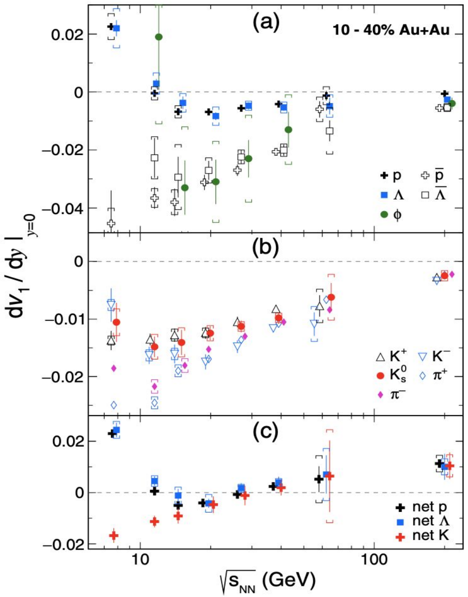


R. Snellings New J. Phys. 13 055008 (2011), 2309.12610 [nucl-ex]

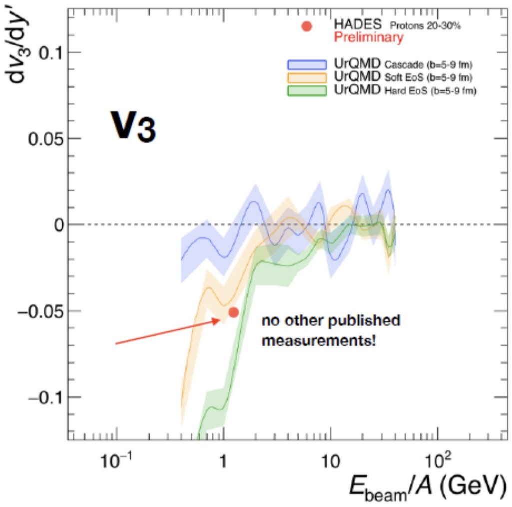
Motivation



A. Aprahamian et. al. DOE/NSF (NSAC) Report, (2015)



Phys. Rev Lett. 120, 062301 (2018)



J. Phys. G: Nucl. Part. Phys. 45 085101 (2018)
Phys. Rev. Lett. 125, 262301 (2020)
2309.12610 [nucl-ex]

- The primary aim of relativistic heavy-ion collisions → Understand the properties and the evolution of strongly interacting matter, **Quark–Gluon Plasma (QGP)**
- Minimum in baryons' dv_1/dy predicted to be sensitive to softening of EoS → **Signature of a 1st-order phase transition** between hadronic matter and QGP
- Contrary to observations at higher energy v_3 is correlated to first order reaction plane at 2.4 GeV (HADES) and 3 GeV (STAR)

STAR Experiment

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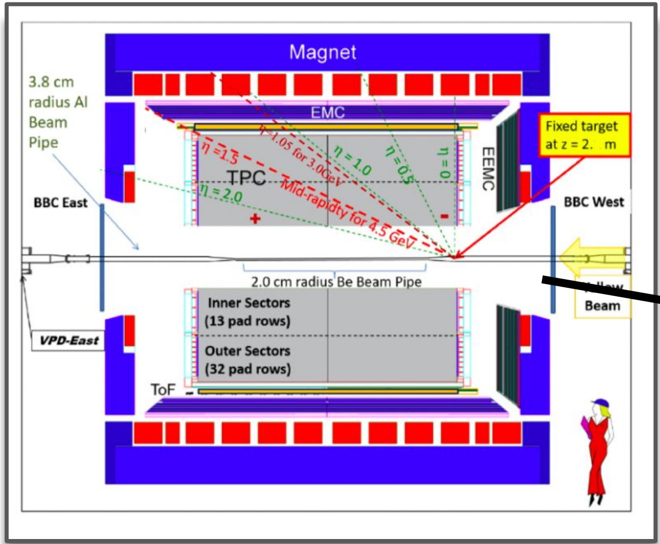
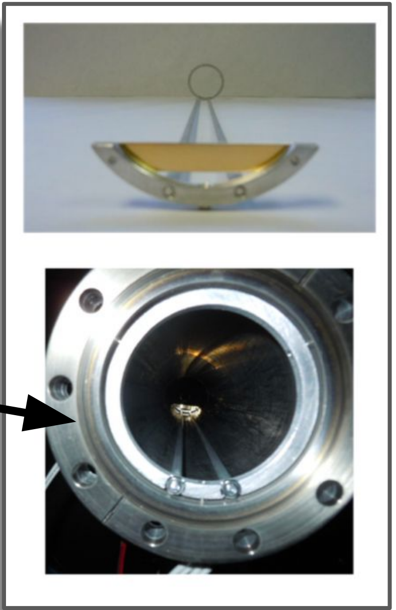
Schematic of fixed target setup

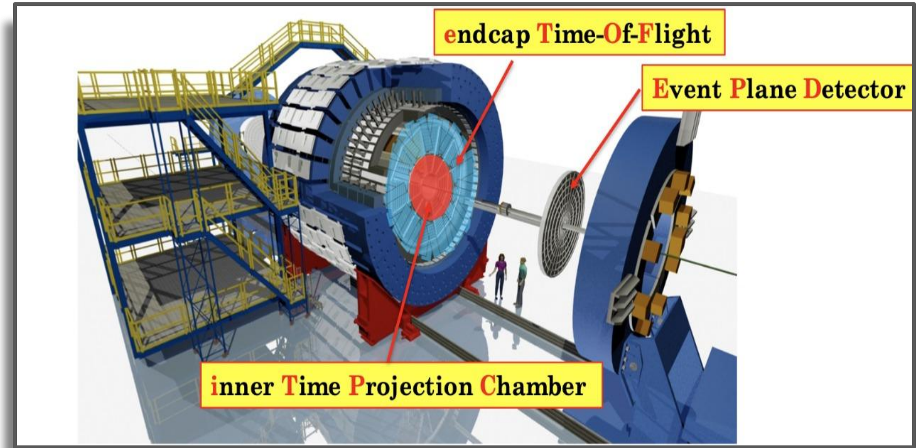


Nuclear Phy A 808-811 (2017)



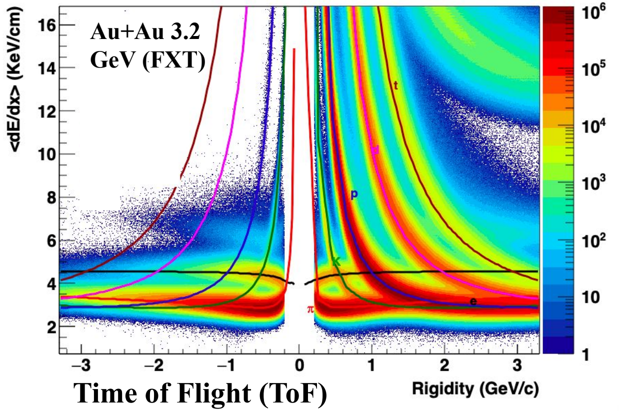
- **Fixed-Target (FXT)** program at **S**olenoidal **T**racker **A**t **R**HIC (**STAR**) → low center-of-mass energies and high baryon density region
- **BES-II FXT mode**: Au+Au collisions at $\sqrt{s_{NN}}$ = 3, **3.2, 3.5, 3.9**, 4.5, 5.2, 6.2, 7.2, and 7.7 GeV.

Particle Identification

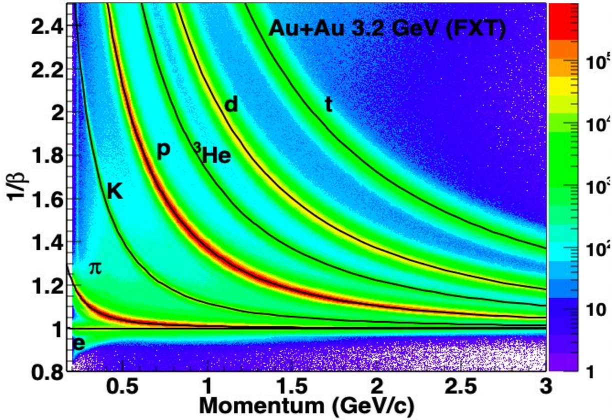


https://www.star.bnl.gov/

Time Projection Chamber (TPC)



Time of Flight (ToF)

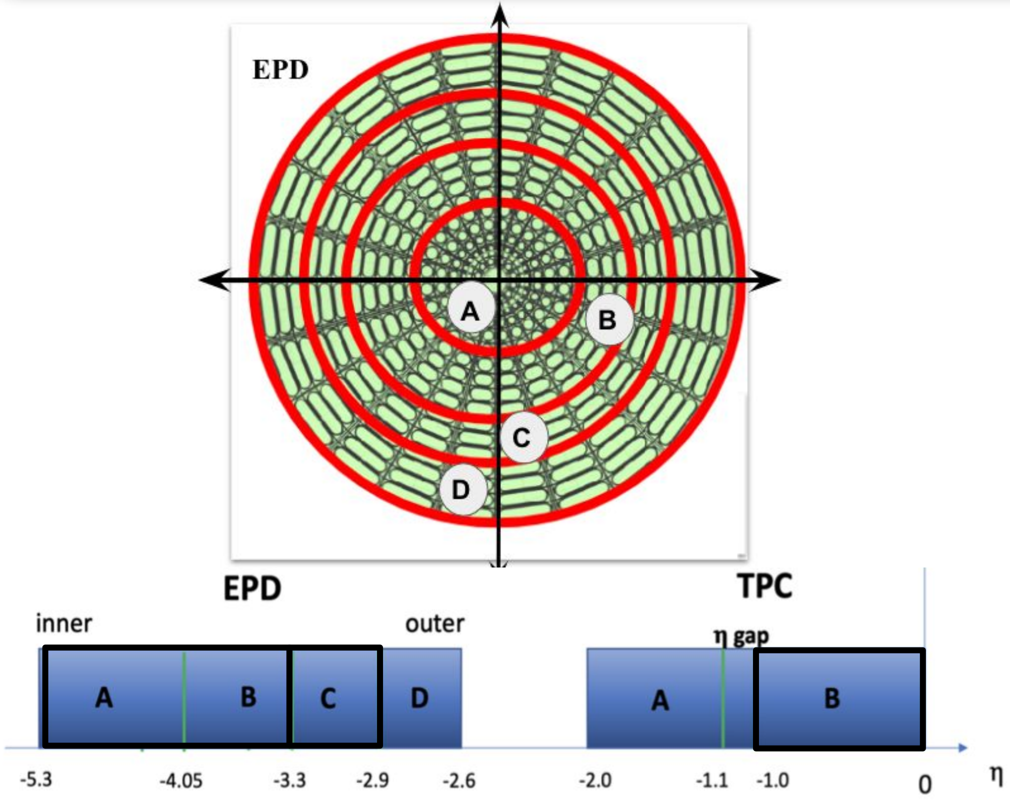


- Two main detectors are used for particle identification in **STAR**

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

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

Event Plane Reconstruction



Phys. Rev. C 58, 1671 (1998)

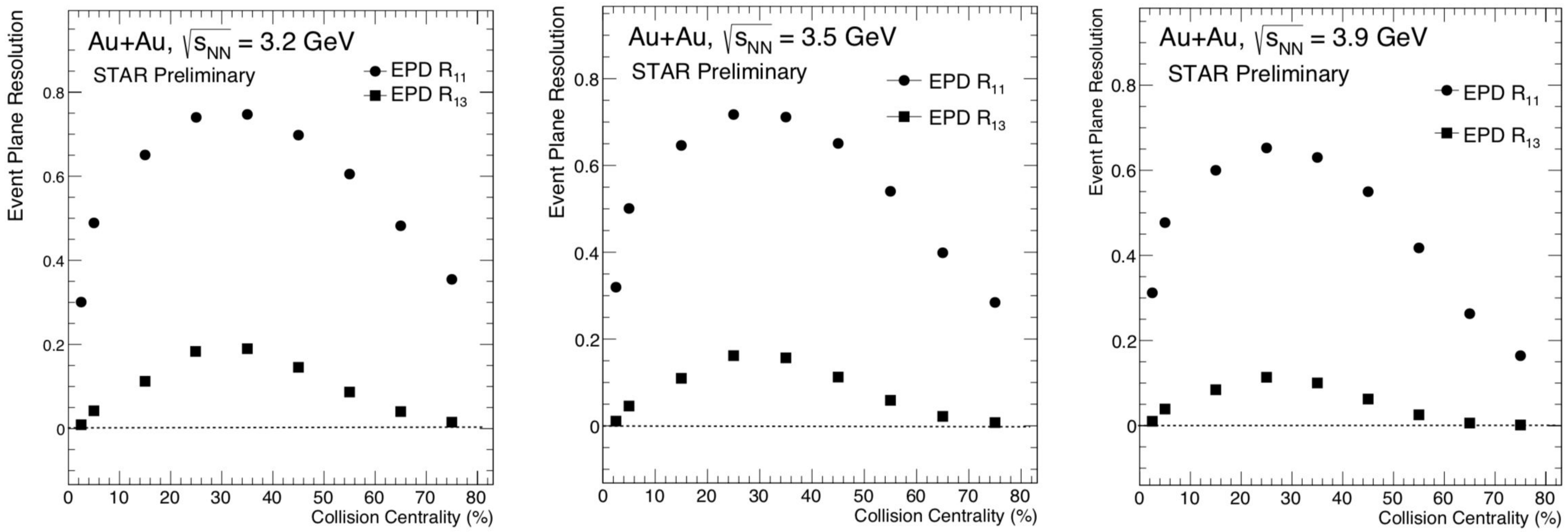
- ➔ **Event Plane Detector** (**EPD**) → Measures charged particles emitted in the forward and backward directions
- ➔ TPC and EPD are divided into 2 and 4 regions ,respectively, based on their pseudorapidity (η) coverage

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

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

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

Event Plane Resolution



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

$$\langle \cos[n(\Psi_m^a - \Psi_r)]\rangle = \sqrt{\frac{\langle \cos[n(\Psi_m^a - \Psi_m^b)]\rangle \langle \cos[n(\Psi_m^a - \Psi_m^c)]\rangle}{\langle \cos[n(\Psi_m^b - \Psi_m^c)]\rangle}}.$$

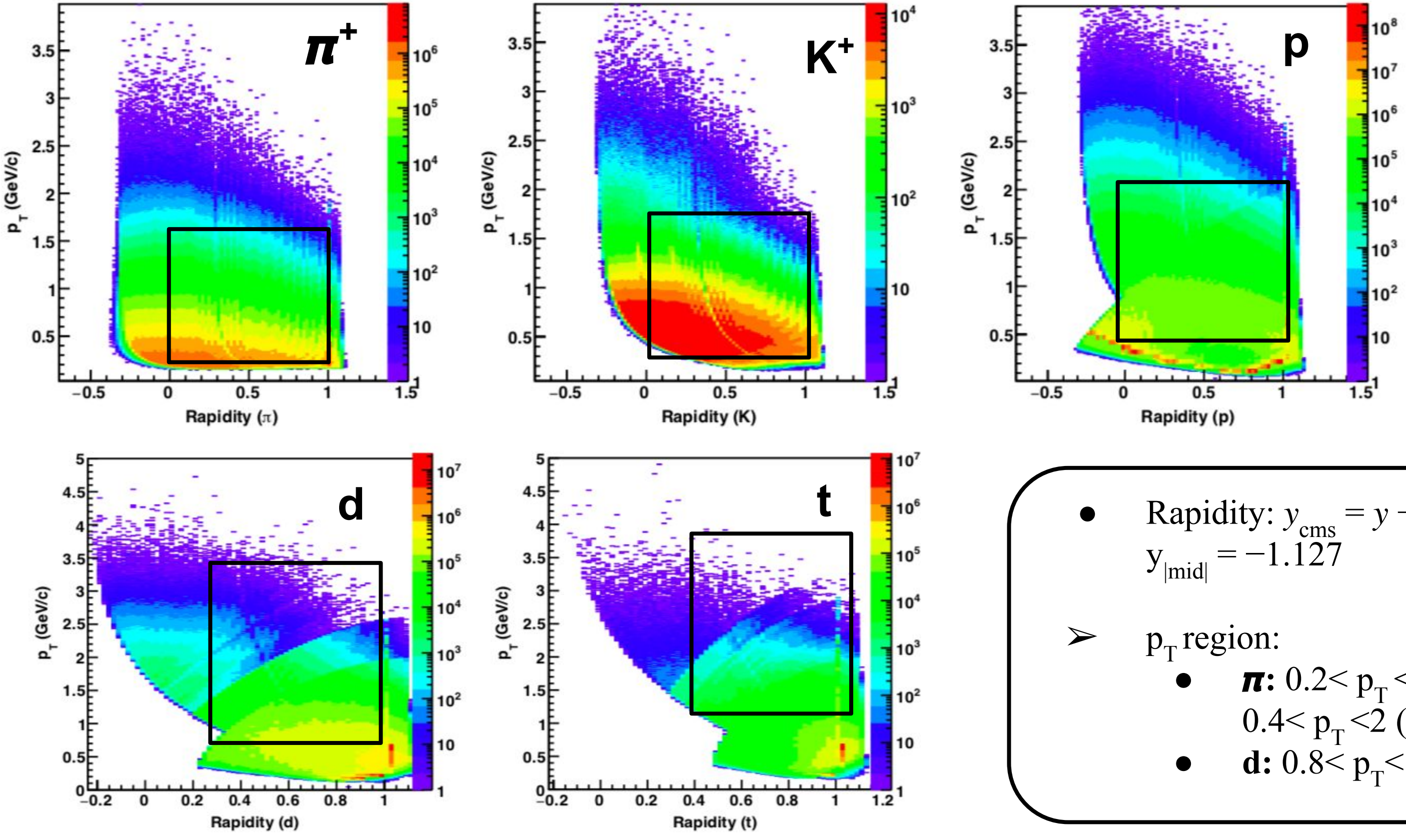
R_{11} (m=1, n=1)
R_{13} (m=1, n=3)

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

Phase Space Distribution

2023

Au+Au 3.2 GeV

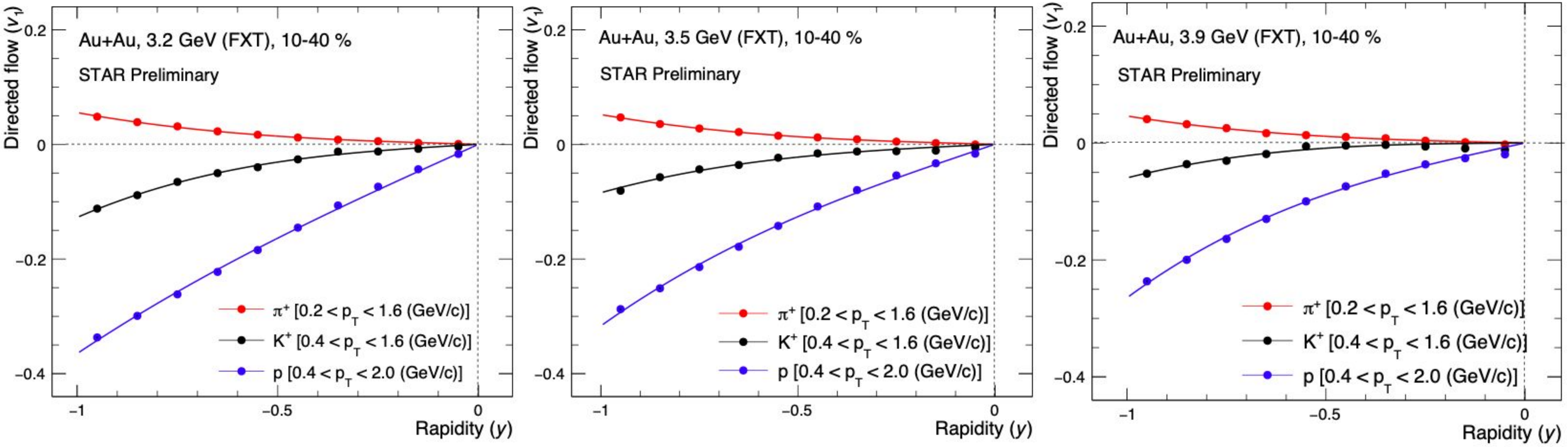


- Rapidity: $y_{cms} = y + |y_{mid}|$, for FXT 3.2 GeV, $y_{|mid|} = -1.127$

➢ p_T region:
- **π:** $0.2 < p_T < 1.6$, **K:** $0.4 < p_T < 1.6$, **p:** $0.4 < p_T < 2$ (GeV/c)
- **d:** $0.8 < p_T < 3.5$, **t:** $1.2 < p_T < 4$ (GeV/c)

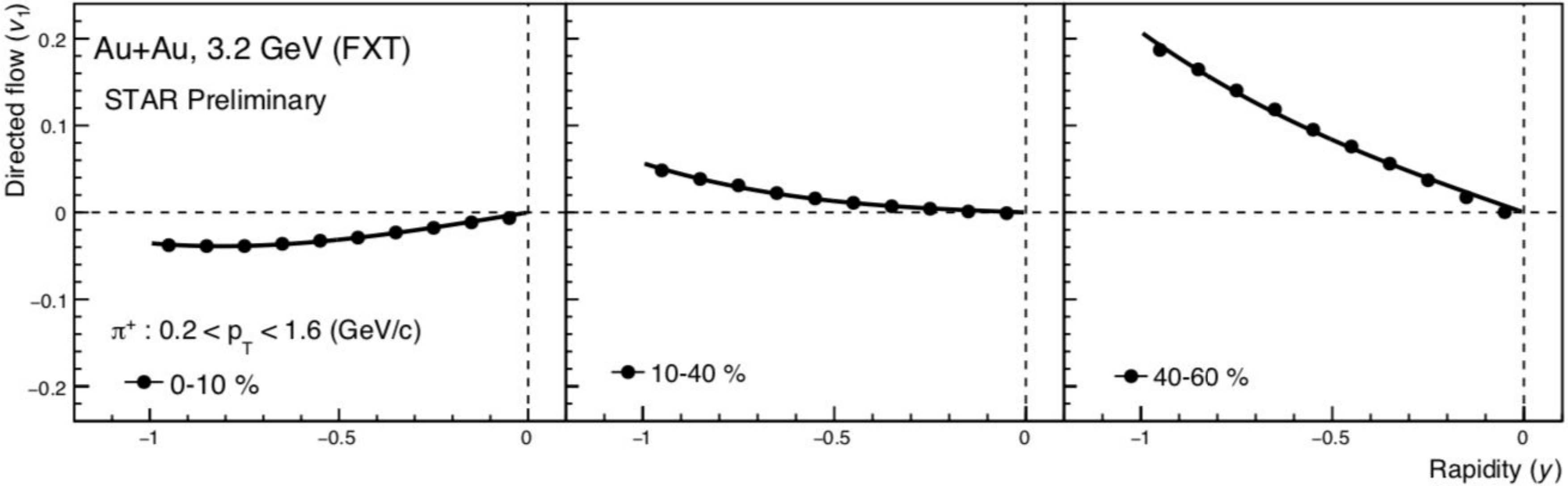
Directed Flow (v_1) Results

Rapidity dependence of v_1 (π^+, K^+, p)



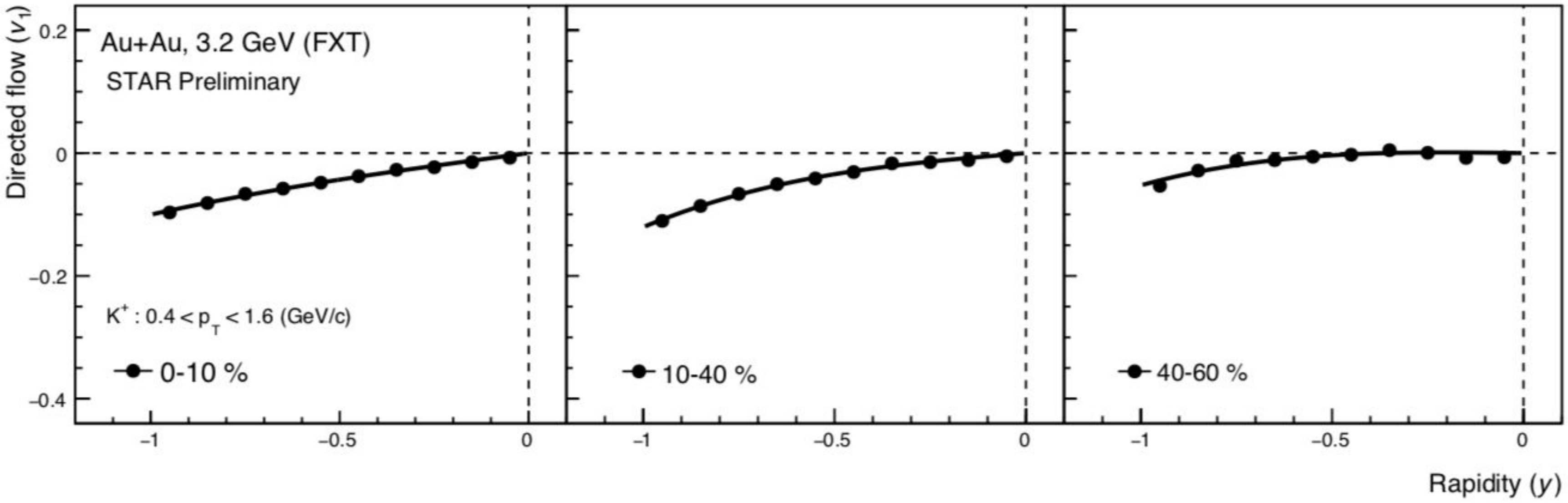
- Magnitude of v_1 increases with increasing rapidity
- Magnitude of v_1 increases with increasing mass of the particle (p > K^+ > π^+)

Centrality dependence of v_1 (π^+)



- v_1 changes sign moving from central to peripheral collision
- v_1 slope is maximum for peripheral collision

Centrality dependence of v_1 (K^+)



- v_1 has weak centrality dependence for kaon
- v_1 slope is maximum for mid-central collision

Centrality dependence of v_1 (p)

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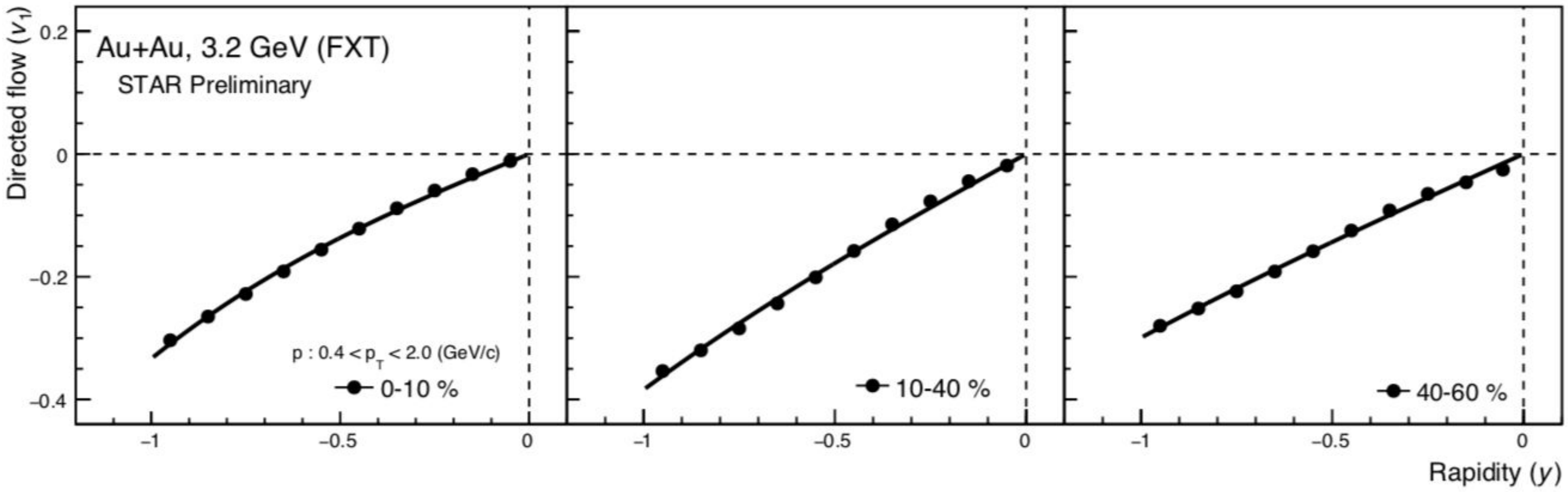
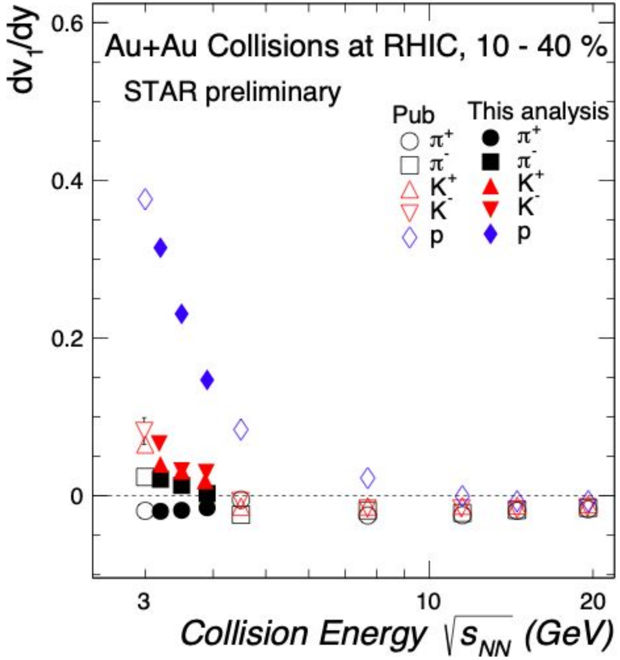


- v_1 has weak centrality dependence compared to pions
- v_1 slope is maximum for mid-central collision

Collision energy dependence of v_1 slope (π, K, p)



- $v_1(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_1/dy$)

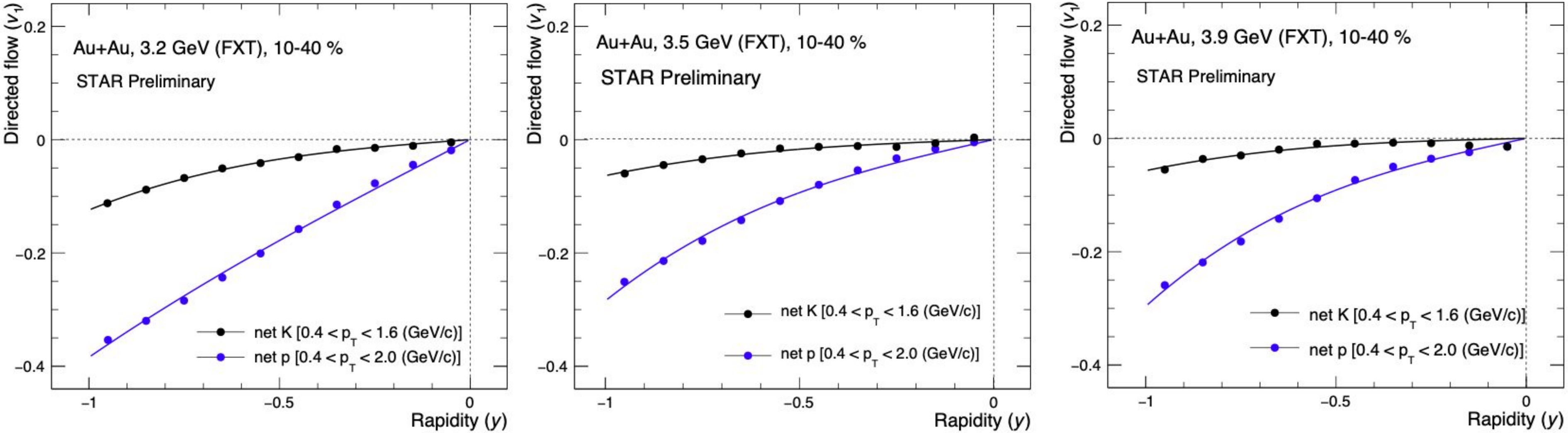
  $v_1(y) = by + cy^3$

- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing v_1 slope

dv_1/dy for collider energies was extracted using first-order polynomial fit

Phys. Rev. Lett. 120, 062301 (2018), Phys.Lett.B 827, 137003 (2022)

Rapidity dependence of v_1 (net p and net K)



- 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

- Magnitude of net particle v_1 increases with increasing rapidity

Collision energy dependence of v_1 slope (net p and net K)

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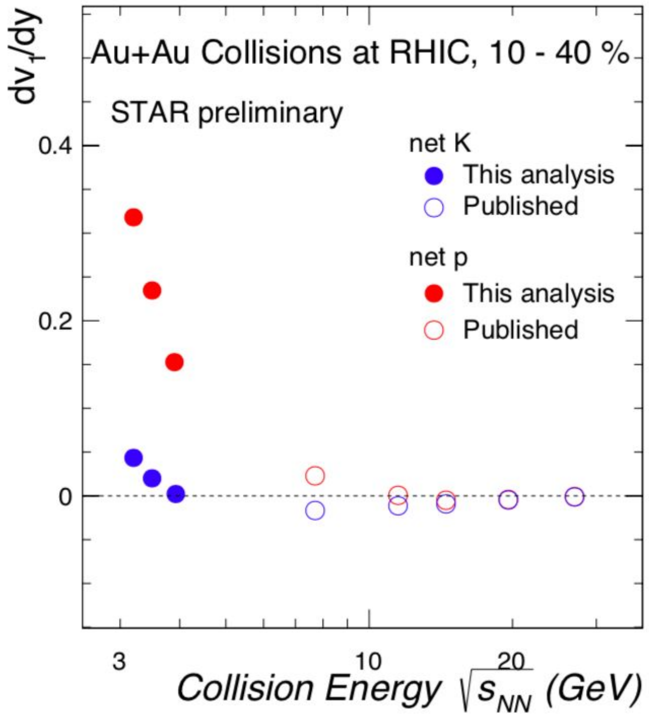

dv$_1$/dy for published data was extracted using first-order polynomial fit

- $v_1(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_1/dy$)

  $$v_1(y) = by + cy^3$$

- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing v_1 slope

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

Rapidity dependence of light nuclei v_1

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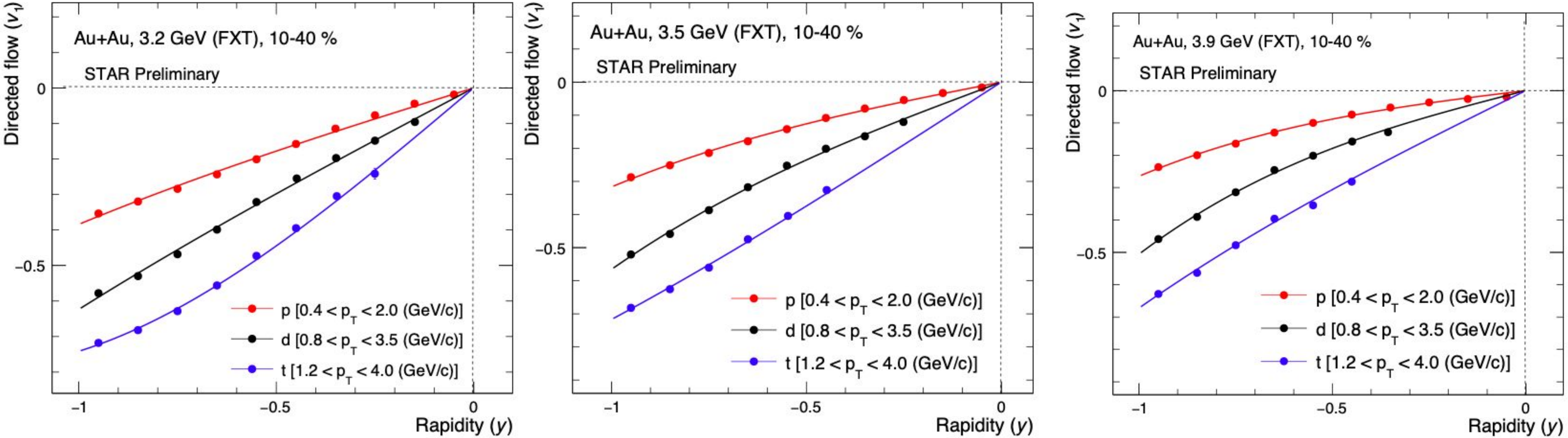
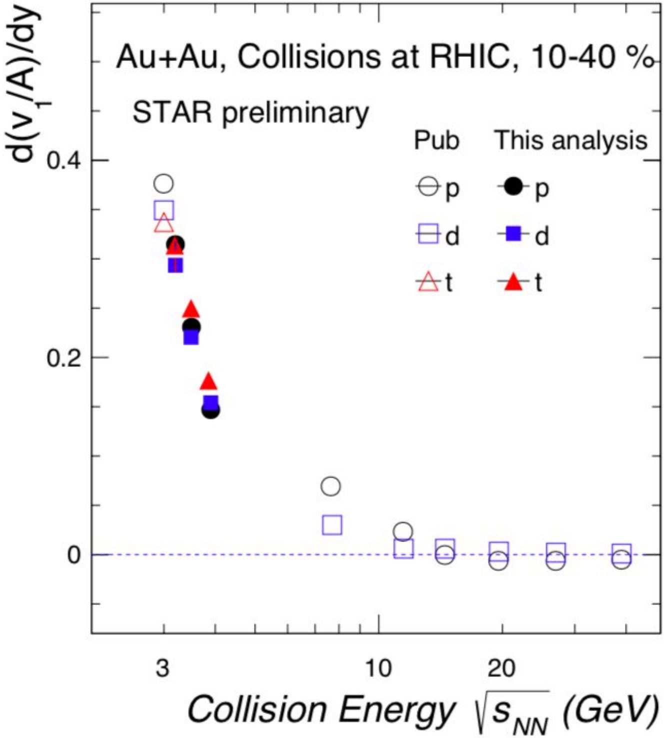


- Magnitude of v_1 increases with increasing rapidity
- Magnitude of v_1 increases with increasing mass of the particle

Collision energy dependence of light nuclei v_1 slope



dv_1/dy for published data was extracted using first-order polynomial fit

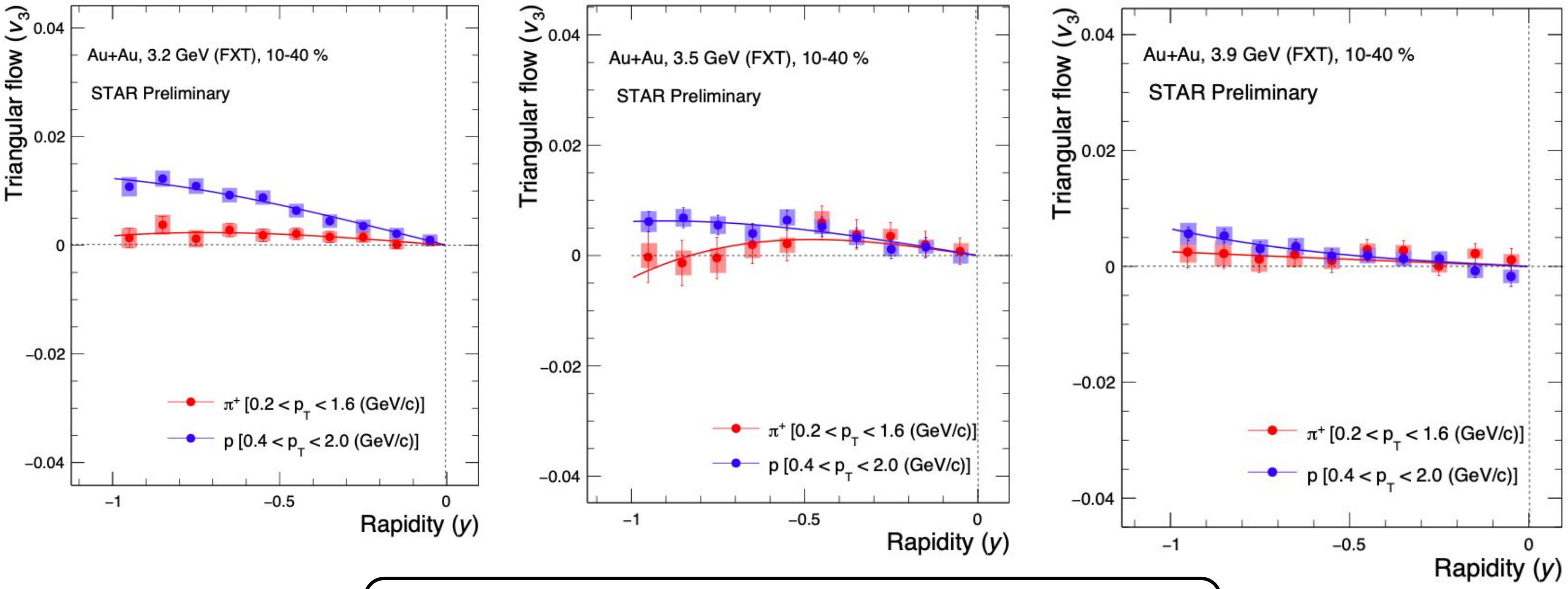
- $v_1(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_1/dy$)

  $v_1(y) = by + cy^3$
- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing v_1 slope

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

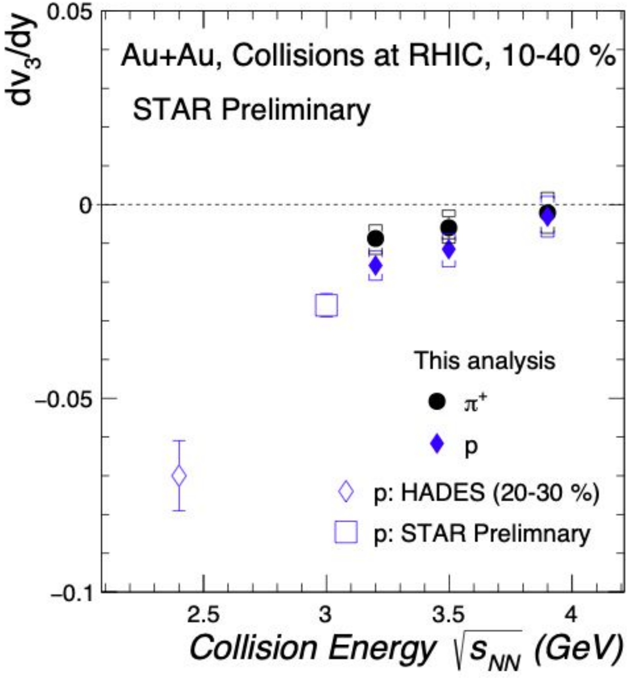
Triangular Flow (v_3) Results

Rapidity dependence of v_3



- Weak rapidity dependence of v_3 observed for pions
- Magnitude of proton v_3 increases with increasing rapidity

Collision energy dependence of v_3 slope



HADES→ p (20-30 %): $0.6 < p_T < 0.9$ GeV/c

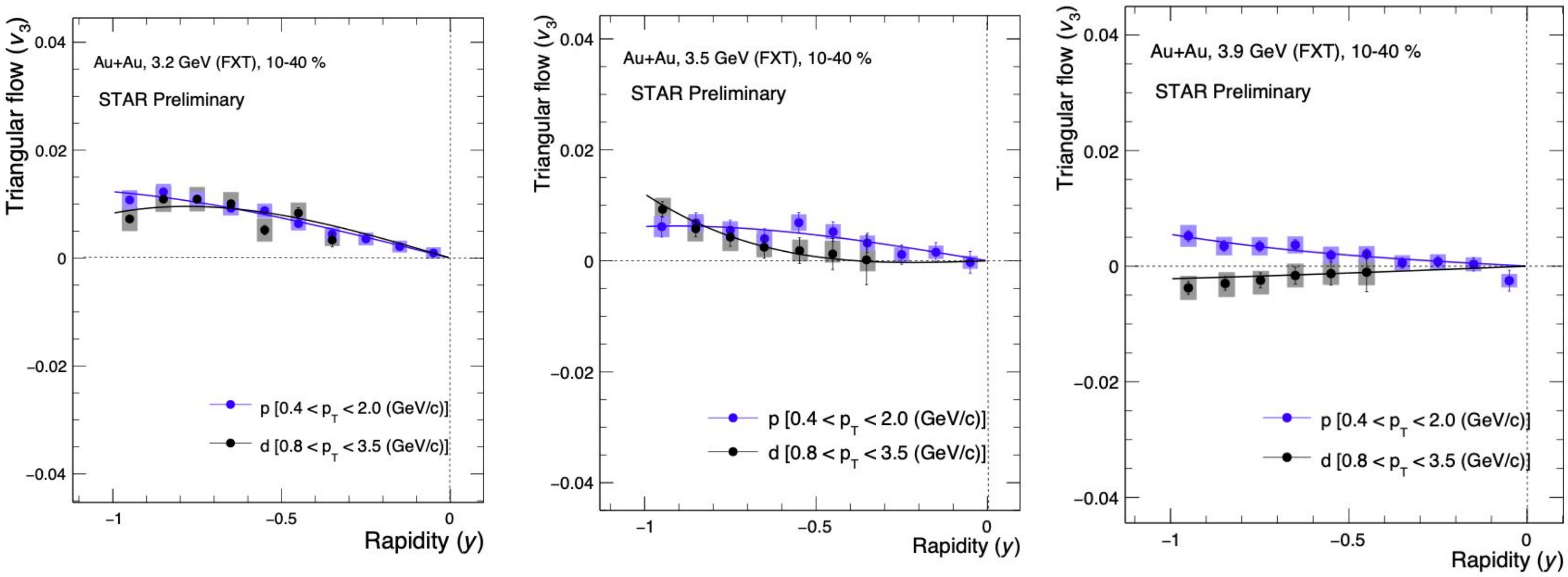
- $v_3(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_3/dy$)

  $v_3(y) = by + cy^3$

- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing magnitude of v_3 slope

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

Rapidity dependence of v_3



- Weak rapidity dependence of v_3 observed for deuteron compared to proton

Collision energy dependence of v_3 slope

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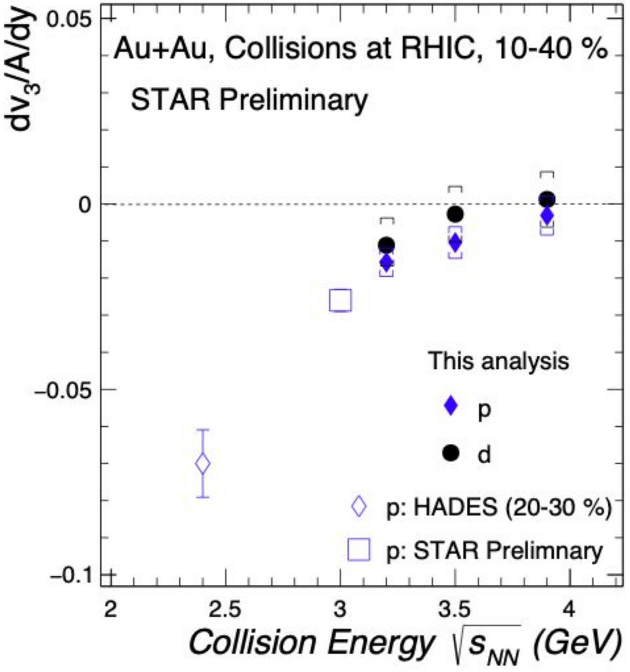

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  $v_3(y) = by + cy^3$
- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing magnitude of v_3 slope

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

Summary

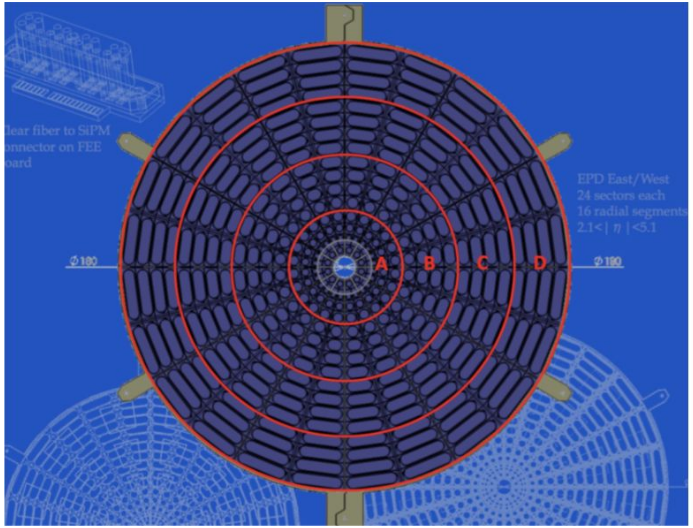
2023

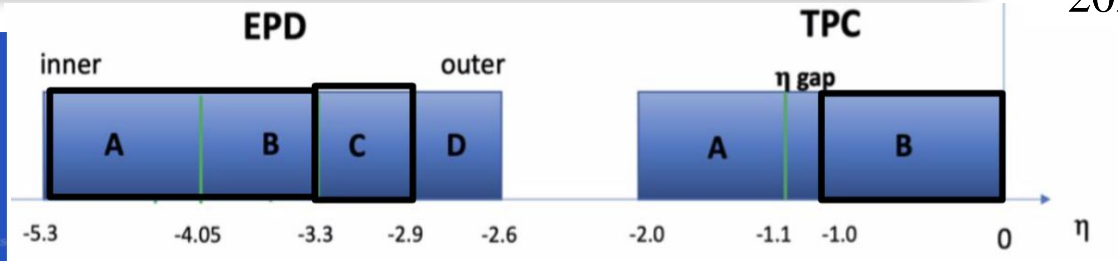
- The rapidity, centrality, and collision energy dependence of directed flow (v_1) and triangular flow (v_3) of identified hadrons, net particle, and light nuclei for Au+Au collisions at 3.2, 3.5, and 3.9 GeV are presented.
- Magnitude of v_1 and v_3 increases with increasing rapidity
- Slope of v_1 (dv_1/dy) decreases with increasing collision energy for all particles and light nuclei
- Approximate mass no. scaling for light nuclei is observed v_1
- dv_1/dy for both net-kaon and net-proton shows a non monotonic behaviour moving from high to low collision energies
- Magnitude of v_3 slope (dv_3/dy) decreases with increasing collision energy for pion, proton and deuteron

Thank you for your attention!

Backup slides

EPD groups





EPD group	Pseudorapidity	Ring
A	-5.3, -4.05	1-4
B	-4.05, -3.3	5-8
C	-3.3, -2.9	9-12
D	-2.9, -2.6	13-16

EPD has 16 rings, there are 24 sectors in each ring, while there are 12 sectors in the innermost ring, totally one side EPD has 372 sectors

Resolution comparison 3.2, 3.5, 3.9 GeV