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

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Outline

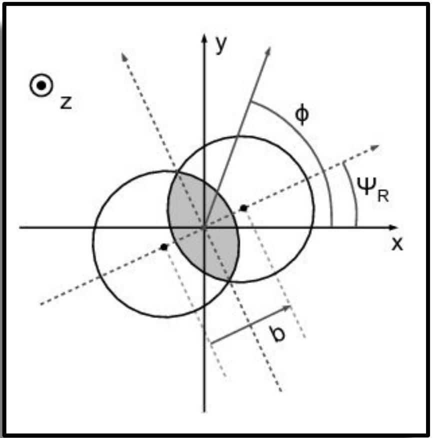
- Motivation
- STAR Detector
- Analysis Technique
- Results and Discussion
  - Directed Flow (v_1)
  - Triangular Flow (v_3)
- Summary

Anisotropic Flow

- 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, PRC 87 014902 (2013)

Directed flow

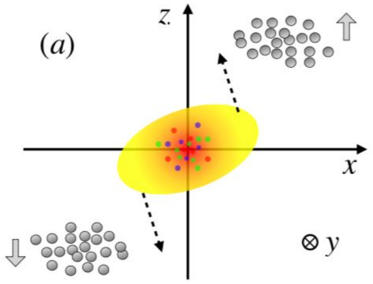
$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

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

Triangular flow

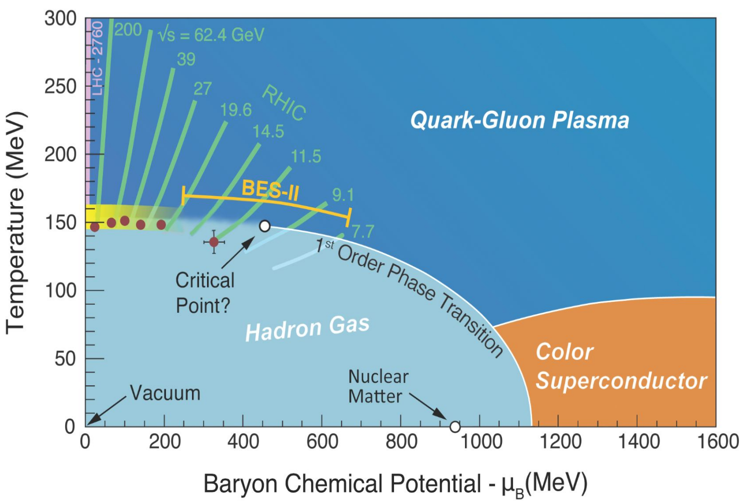
$$v_3 = \langle \cos 3(\phi - \Psi_1) \rangle$$

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

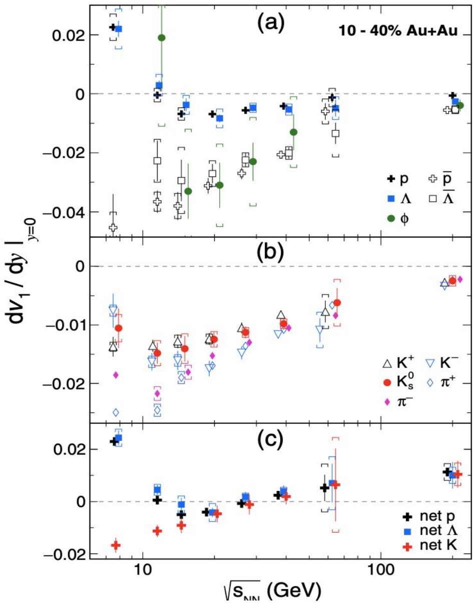


R. Snellings New J. Phys. 13 055008 (2011)

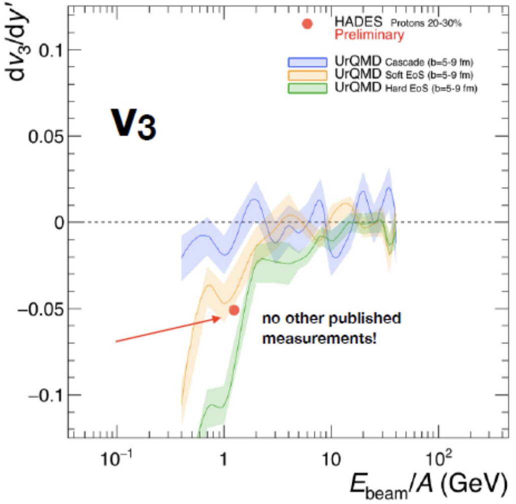
Motivation



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



Phys. Rev Lett. 120, 062301 (2018)

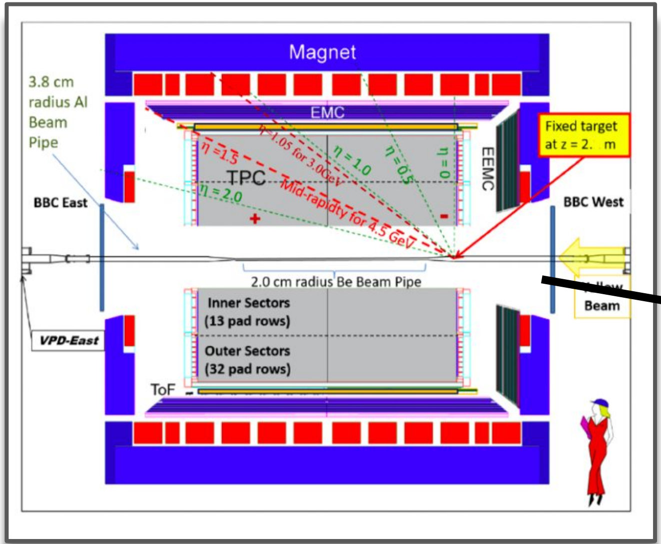


J. Phys. G: Nucl. Part. Phys. 45 085101 (2018)

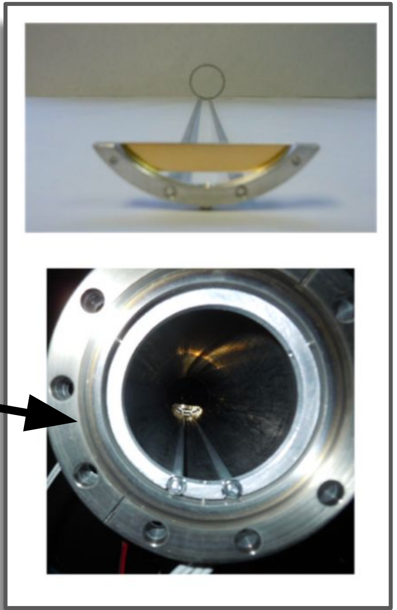
- The primary aim of relativistic heavy-ion collisions → Understand the properties and the evolution of strongly interacting matter, **Q**uark–**G**luon **P**lasma (**QGP**)
- Minimum in baryon's dv_1/dy predicted to be sensitive to softening of EoS → Signature of a 1st-order phase transition between hadronic matter and QGP
- At high energies, v_3 → uncorrelated with the 1st order event plane, contrary to observation at lower energy

STAR Experiment

Schematic of fixed target setup

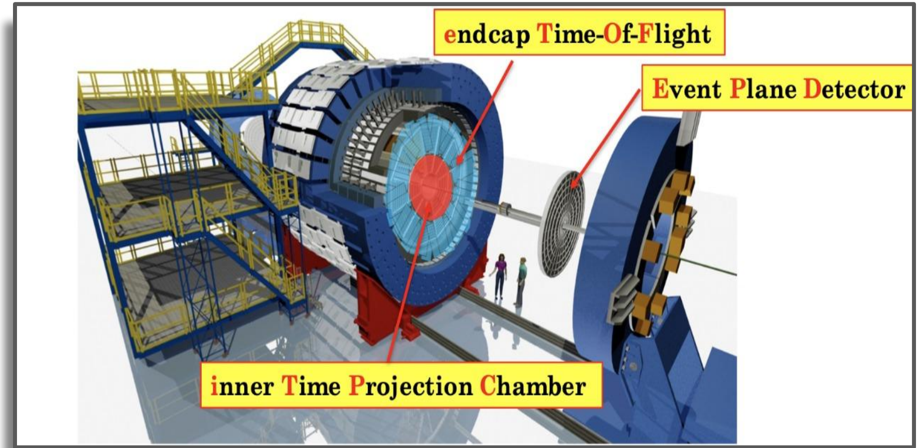


Nuclear Phy A 808-811 (2017)



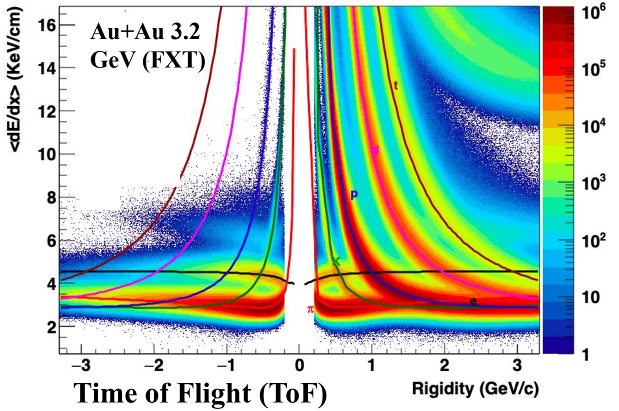
- ❑ **Fixed-Target (FXT)** program at **S**olenoidal **T**racker **A**t **R**HIC (**STAR**) → low center-of-mass energies and high baryon density region
- ❑ **BES-II FXT mode**: Au+Au collisions at $\sqrt{s_{NN}}$ = 3, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2, and 7.7 GeV.

Particle Identification

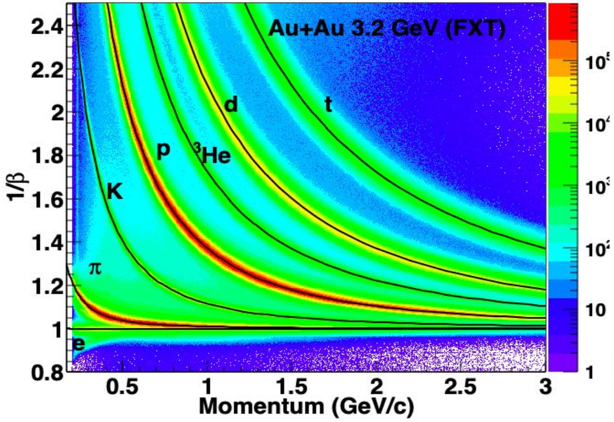


https://www.star.bnl.gov/

Time Projection Chamber (TPC)



Time of Flight (ToF)



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

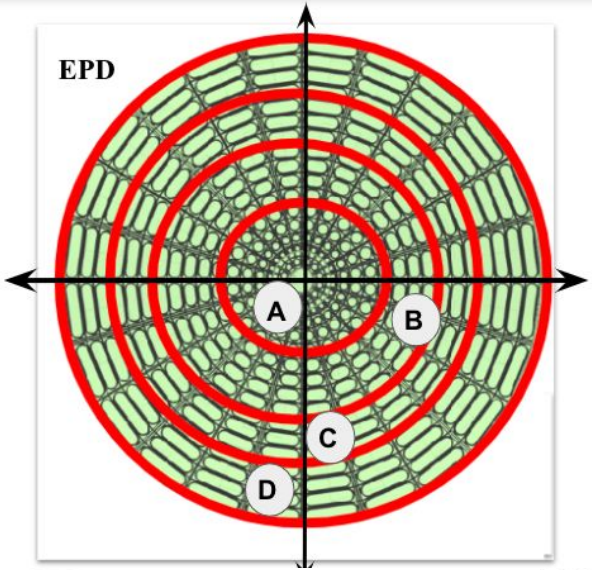
- Time Projection Chamber (**TPC**)

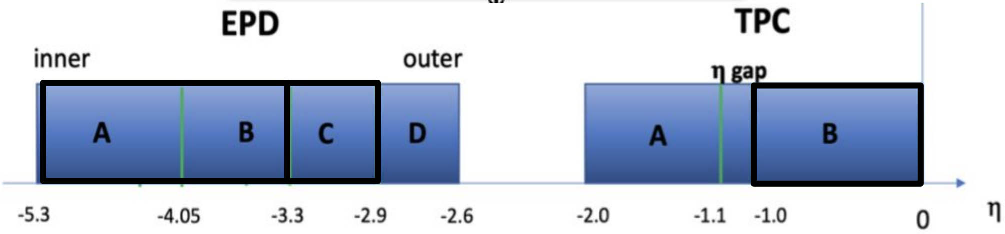
$$z_X = \ln\left(\frac{\langle dE/dx\rangle}{\langle dE/dx\rangle^B_X}\right)$$

- 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)

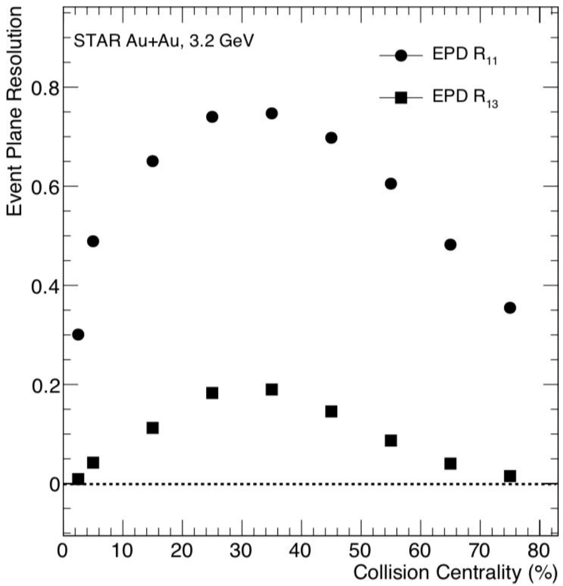
- ➔ **Event Plane Detector (EPD)** → Measures charged particles emitted in the forward and backward directions
- ➔ TPC and EPD are divided into 2 and 4 regions ,respectively, based on their pseudorapidity (η) coverage

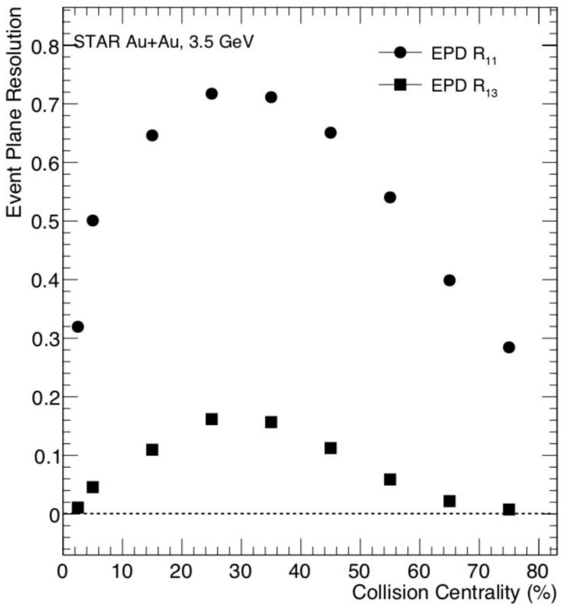
$$\vec{Q} = \begin{pmatrix} Q_y \\ Q_x \end{pmatrix} = \begin{pmatrix} \sum_i w_i sin(\phi) \\ \sum_i w_i cos(\phi) \end{pmatrix}$$

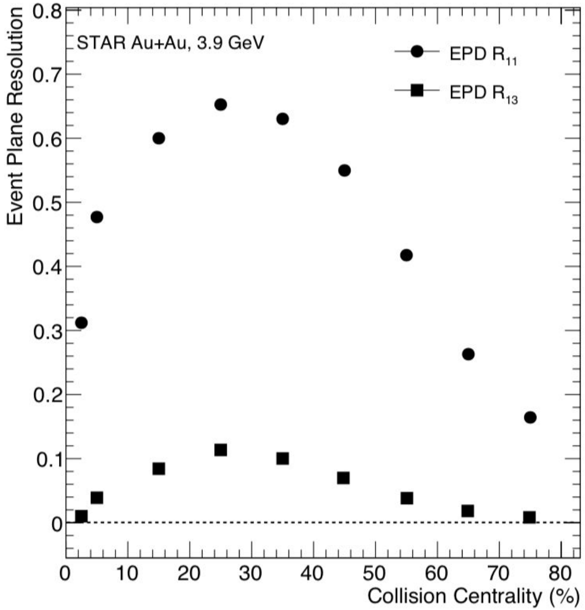
$$\Psi_1 = tan^{-1}\left(\frac{\sum_i w_i sin(\phi)}{\sum_i w_i cos(\phi)}\right)$$

where ϕ 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







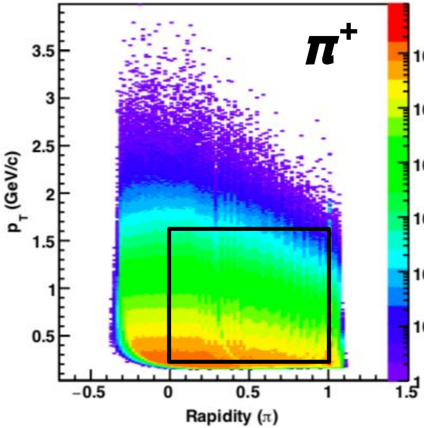
- In FXT mode collision, 3-sub event method was used to determine the EPD first order event plane resolution.

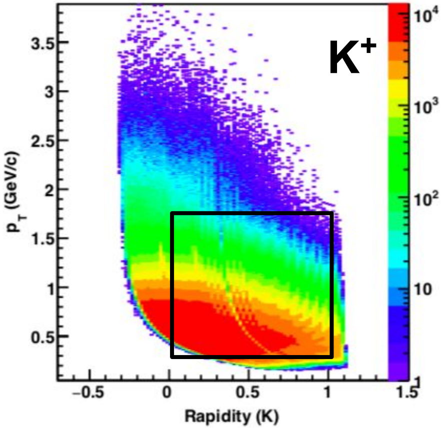
$$\langle cos(\Psi_1^a - \Psi_r)\rangle = \sqrt{\frac{\langle cos(\Psi_1^a - \Psi_1^b)\rangle \langle cos(\Psi_1^a - \Psi_1^c)\rangle}{\langle cos(\Psi_1^b - \Psi_1^c)\rangle}}$$

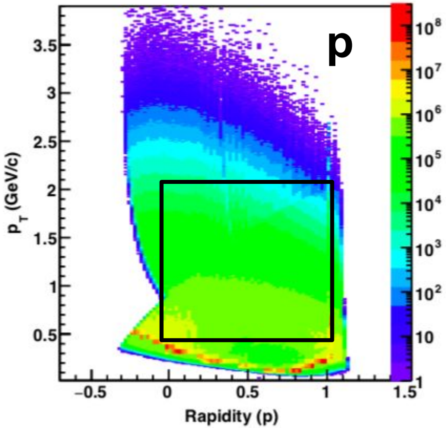
a → EPD-AB (-5.3 < η < 3.3)
b → EPD-C (-3.3 < η < 2.9)
c → TPC B (-1.0 < η < 0)

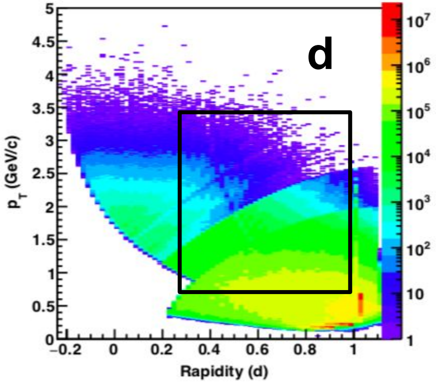
Phase Space Distribution

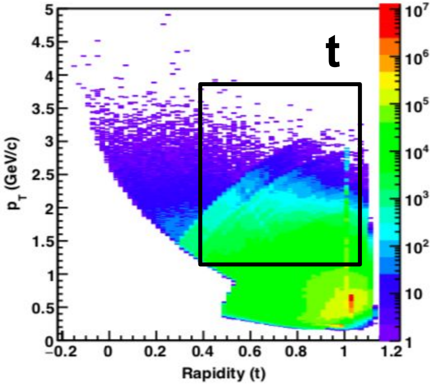
Au+Au 3.2 GeV









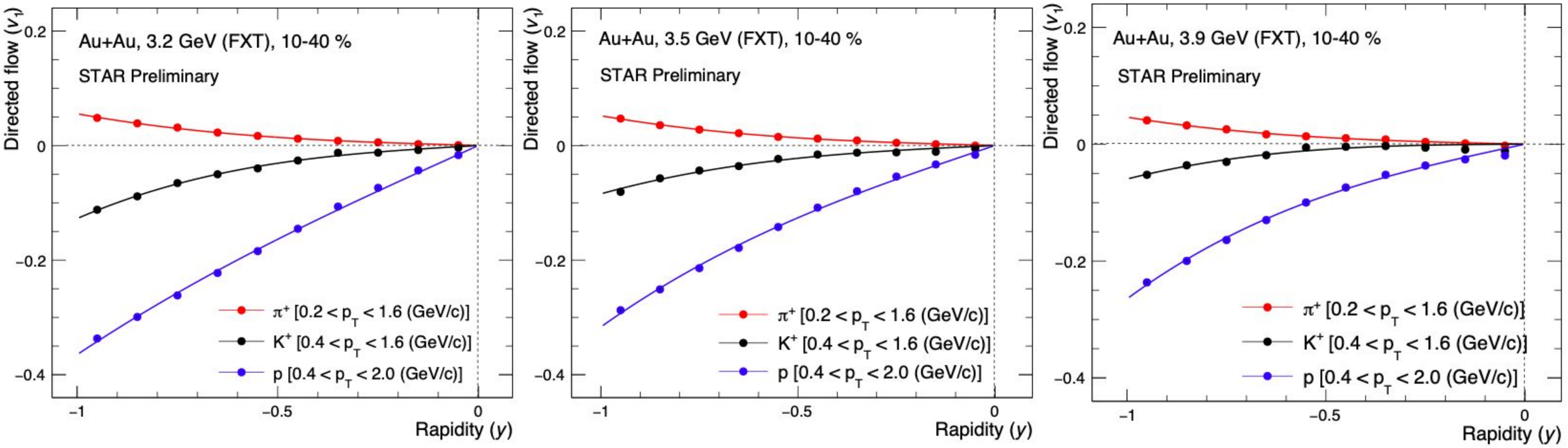


- Rapidity: $y_{cms} = y + |y_{mid}|$, for FXT 3.2 GeV, $y_{|mid|} = -1.127$

➢ 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)

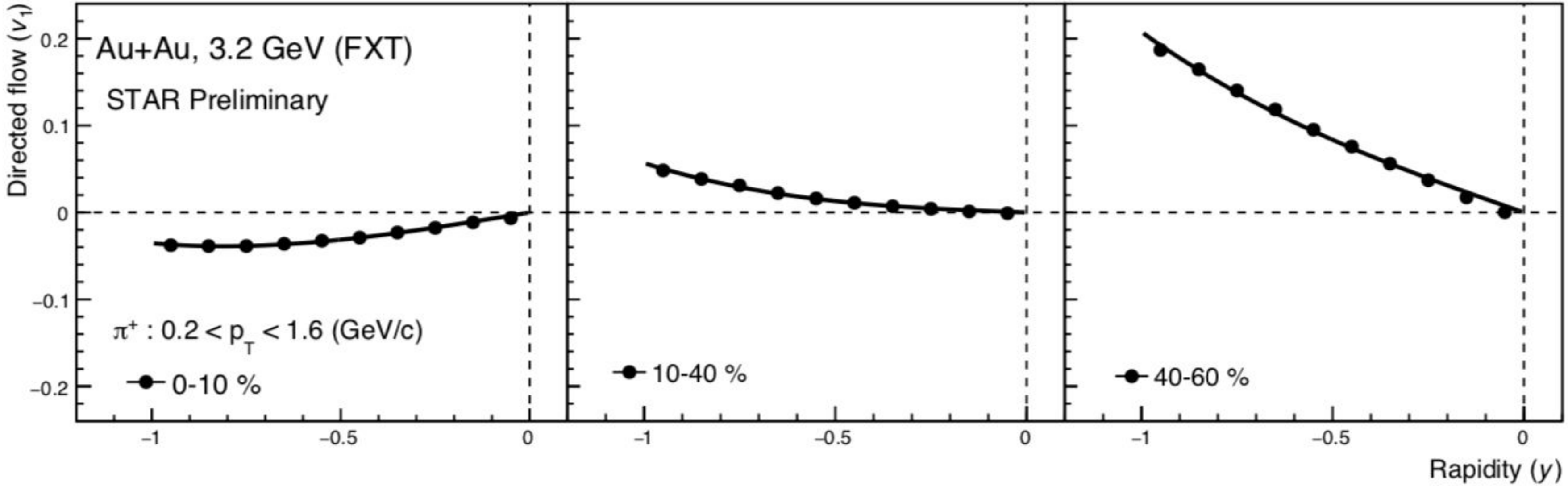
Directed Flow (v_1) Results

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



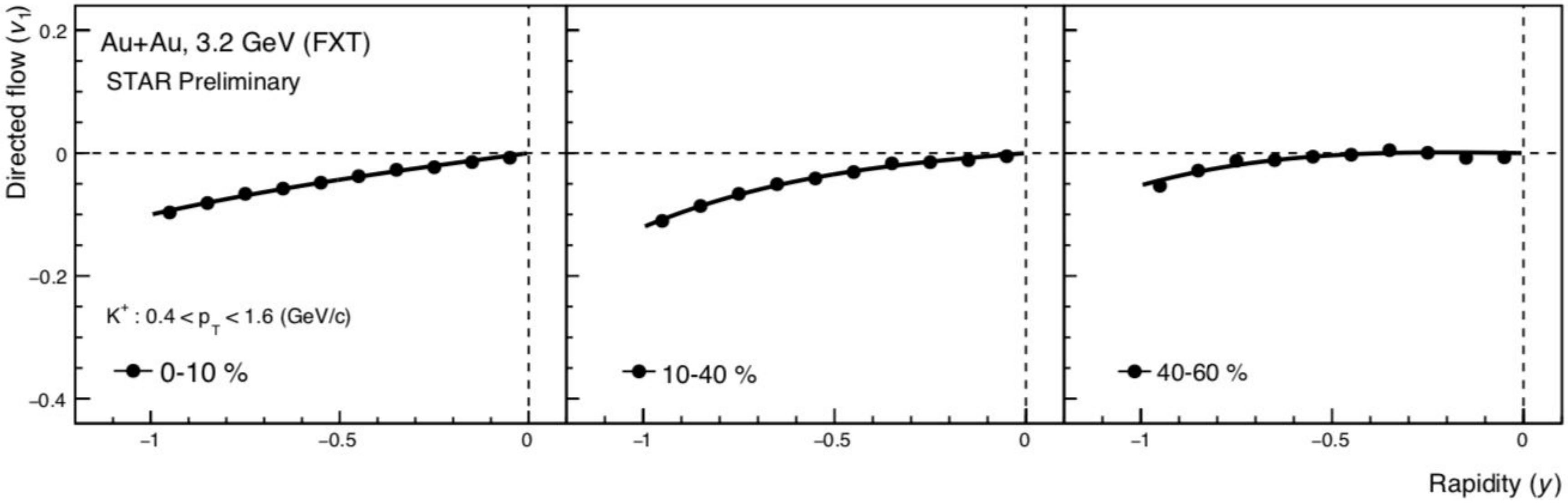
- Magnitude of v_1 increases with increasing rapidity
- Magnitude of v_1 increases with increasing mass of the particle (p > K^+ > π^+)

Centrality dependence of v_1 (π^+)



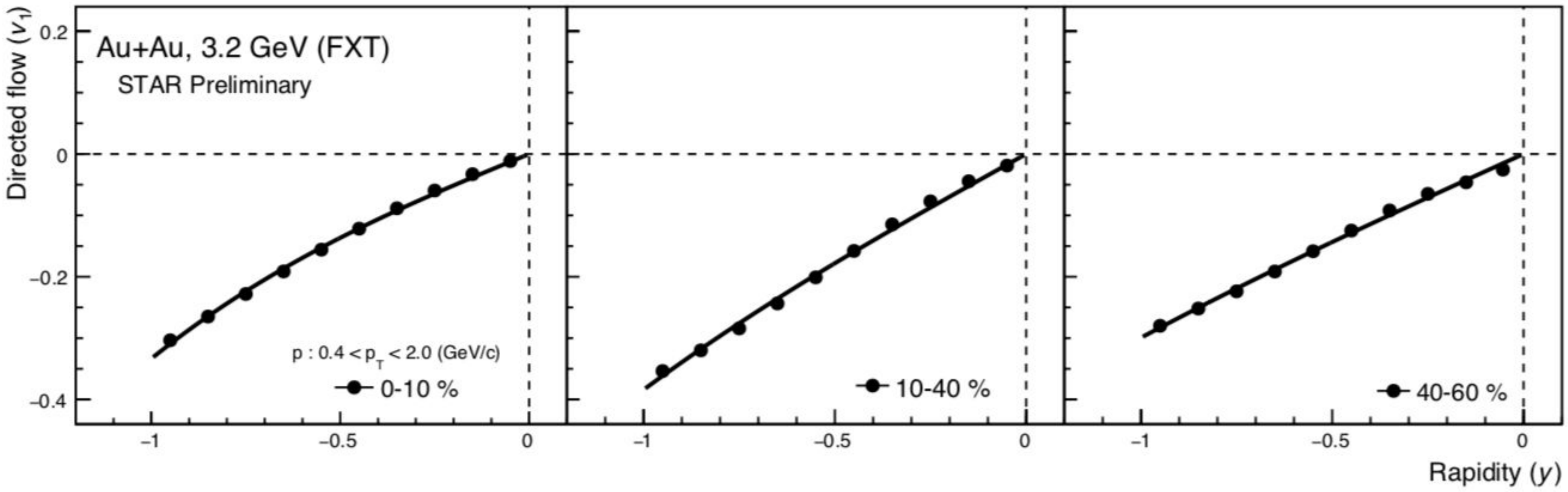
- v_1 changes sign moving from central to peripheral collision
- v_1 slope is maximum for peripheral collision

Centrality dependence of v_1 (K^+)



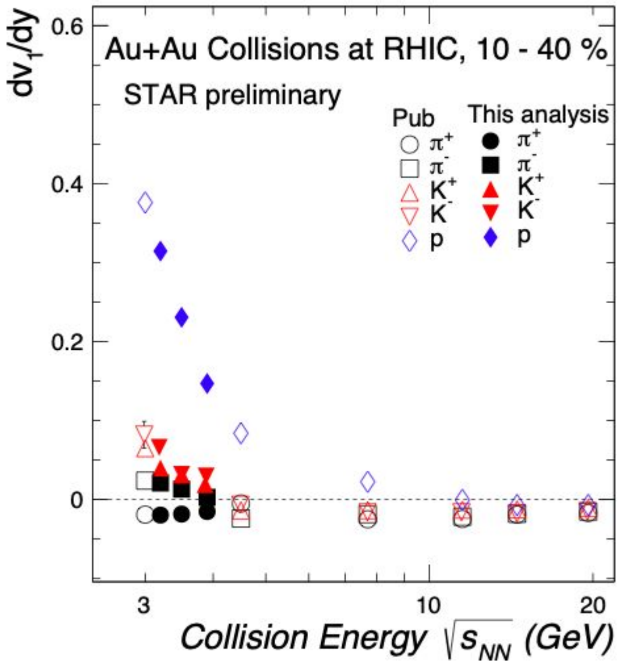
- v_1 has weak centrality dependence for kaon
- v_1 slope is maximum for mid-central collision

Centrality dependence of v_1 (p)



- 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)



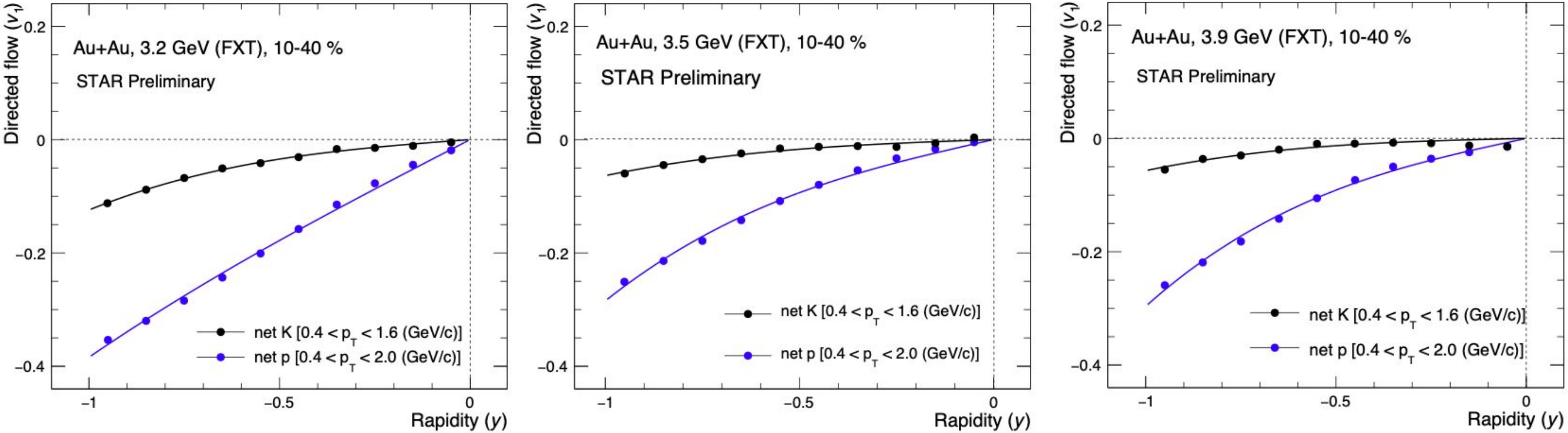
- $v_1(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_1/dy$)

  $v_1(y) = by + cy^3$
- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing v_1 slope
- Mass ordering in slope: $dv_1/dy|_p > dv_1/dy|_K > dv_1/dy|_\pi$

The slope for published collider data was extracted using 1st order polynomial

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

Rapidity dependence of v_1 (net p and net K)



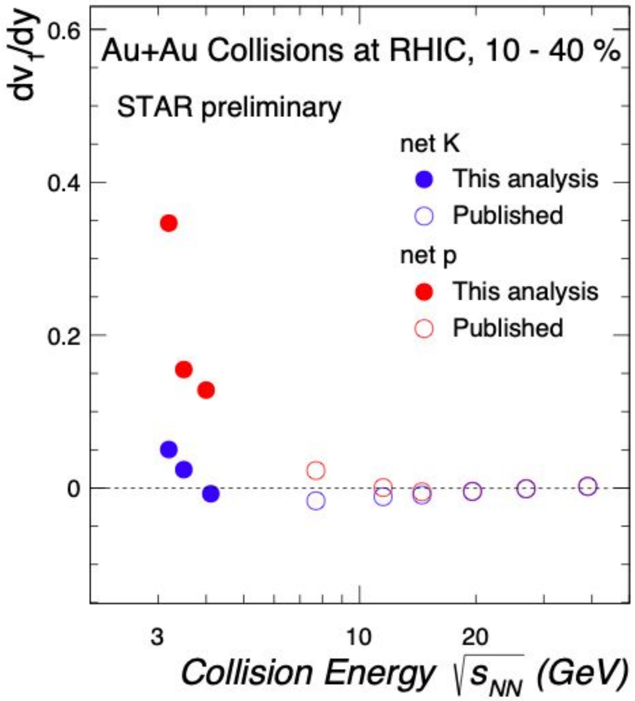
- Net particle v_1 is defined as

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

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)



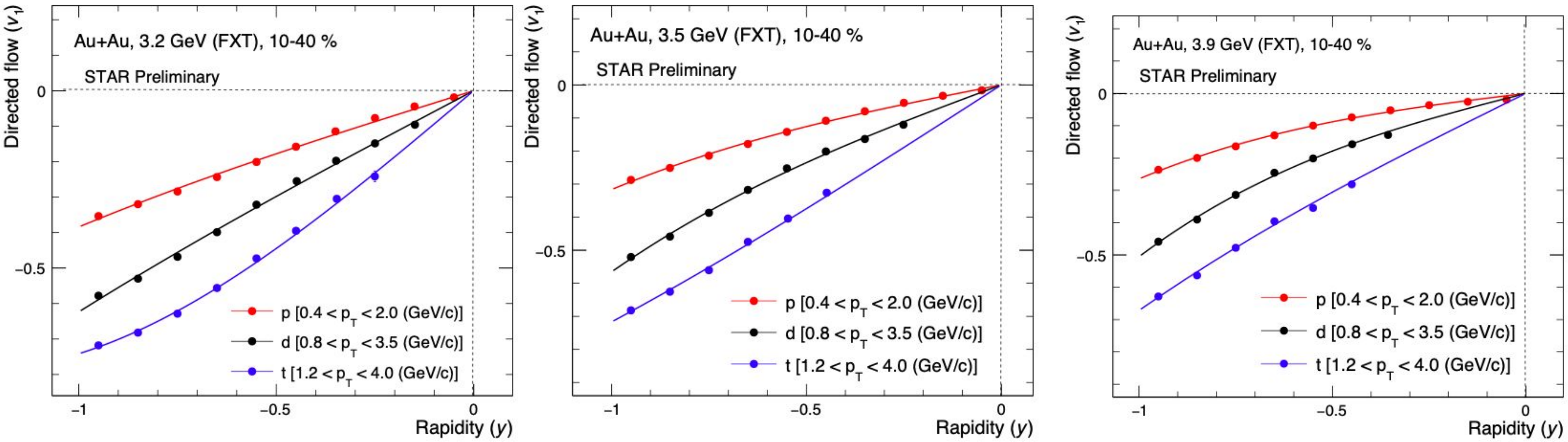
- $v_1(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_1/dy$)

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

The slope for published data was extracted using 1st order polynomial

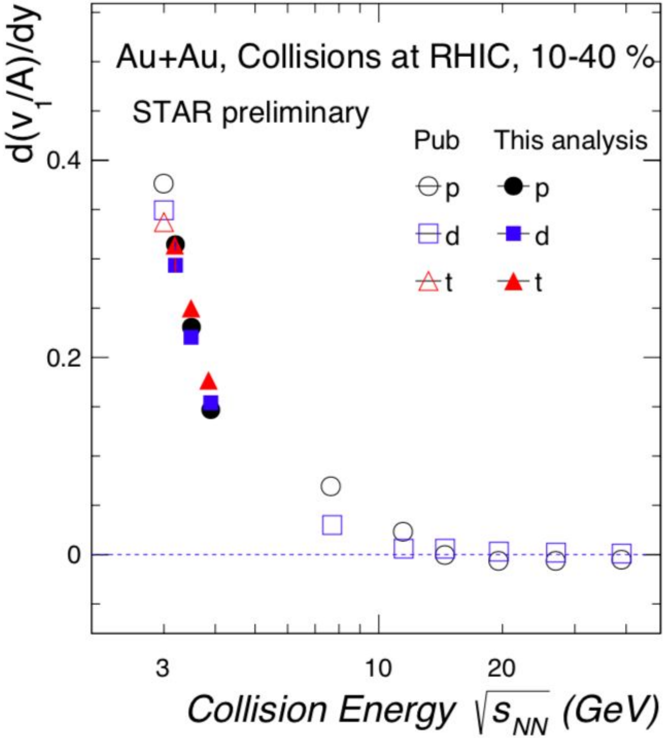
Phys. Rev. Lett. 120, 062301 (2018)

Rapidity dependence of v_1 (p, d, t)



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

Collision energy dependence of v_1 slope (p, d, t)



The slope for published data was extracted using 1st order polynomial

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

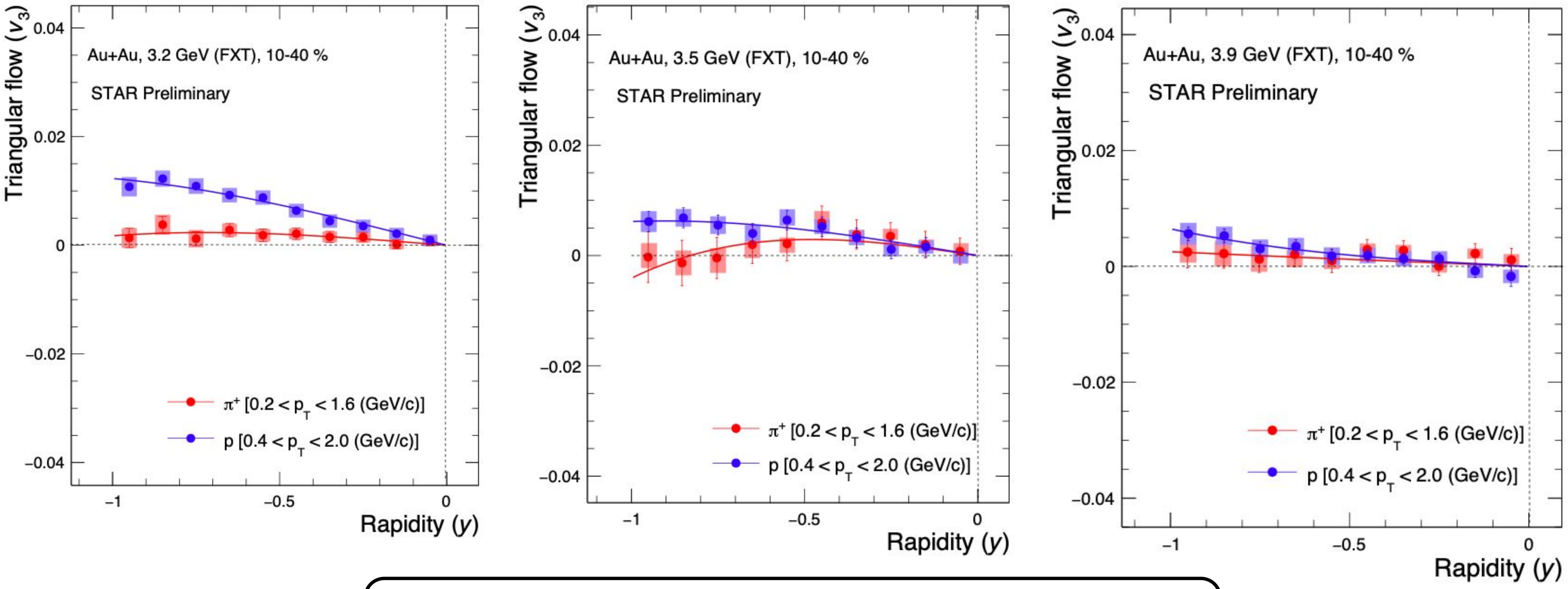
  $v_1(y) = by + cy^3$

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

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

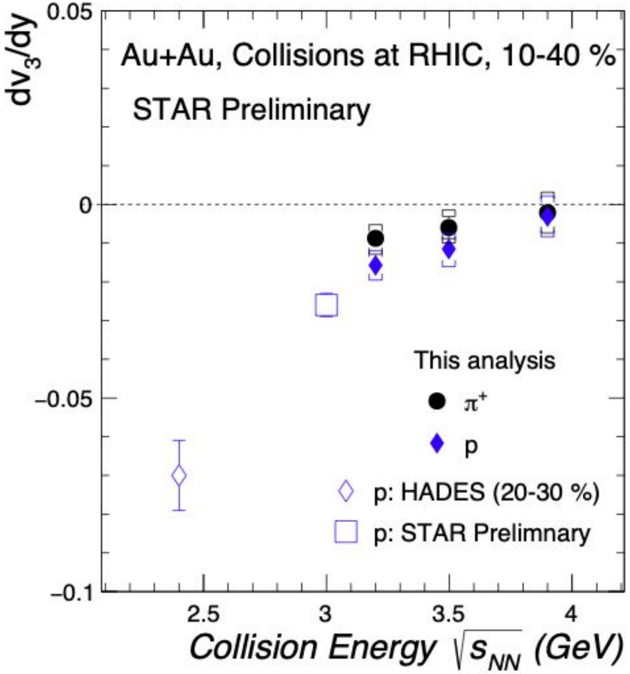
Triangular Flow (v_3) Results

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



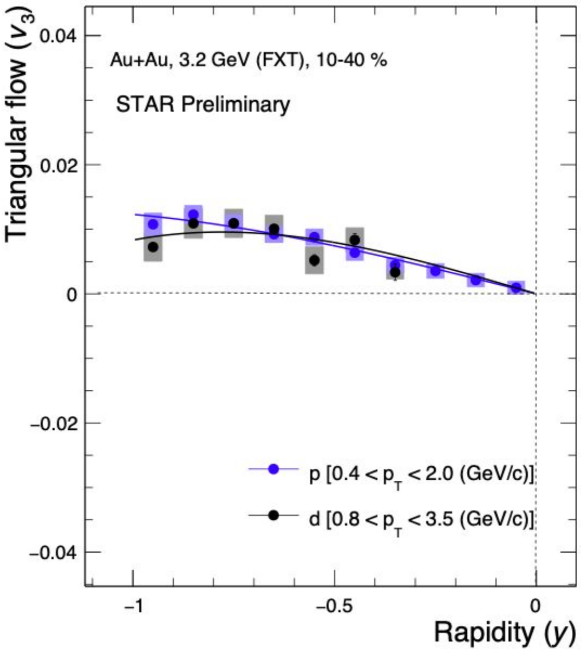
HADES→ p (20-30 %): 0.6 < p_T < 0.9 GeV/c

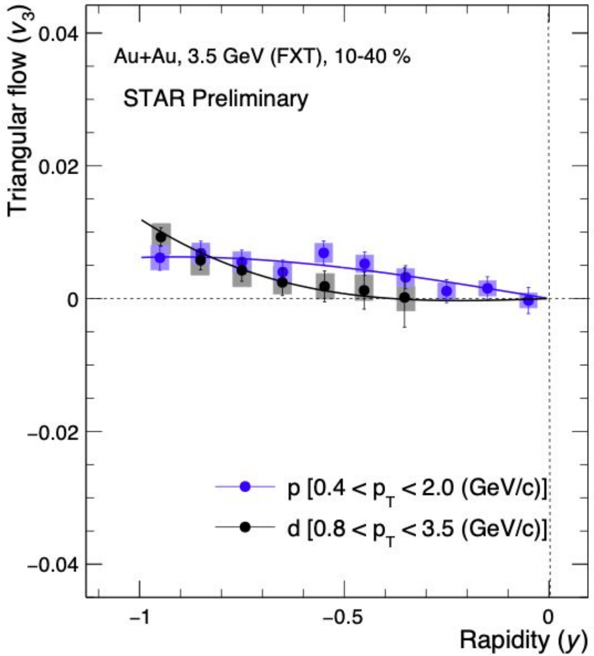
- $v_3(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_3/dy$)

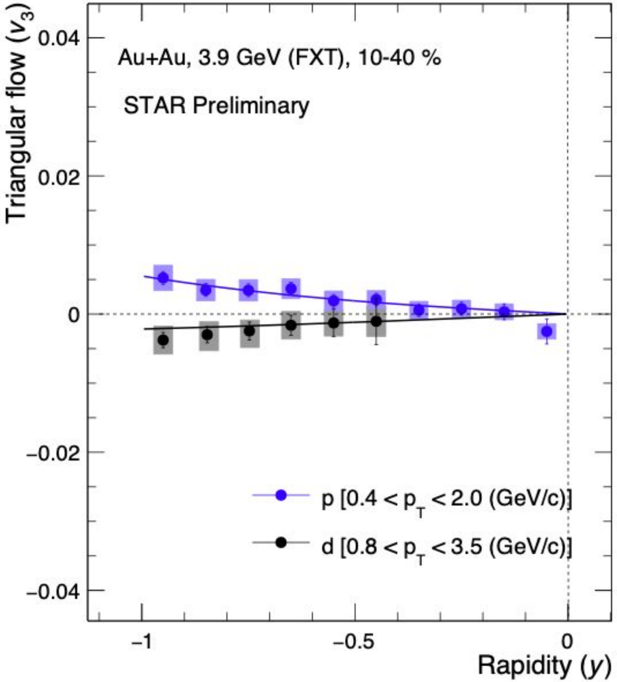
  $v_3(y) = by + cy^3$
- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing magnitude of v_3 slope

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

Rapidity dependence of v_3

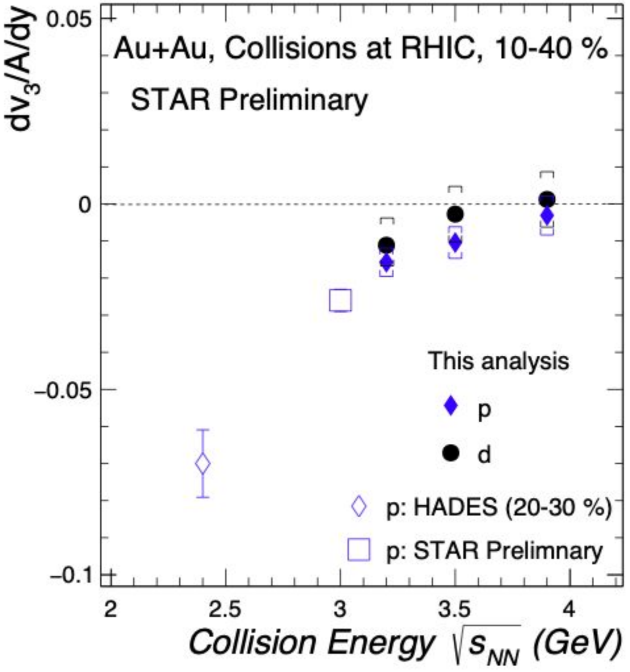






- Weak rapidity dependence of v_3 observed for deuteron compared to proton

Collision energy dependence of v_3 slope



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)

Summary

- 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
- dv_1/dy for both net-kaon and net-proton shows a non monotonic behaviour at lower collision energies
- Magnitude of v_3 slope (dv_3/dy) decreases with increasing collision energy for all particles and light nuclei

Thank you for your attention!