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

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

Supervisor: Dr. Chitrasen Jena

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Outline

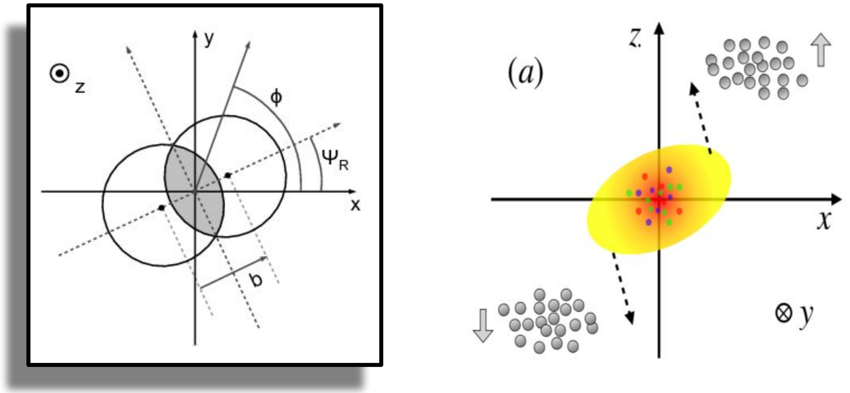
- ❖ Motivation
- ❖ STAR Detector
- ❖ Analysis Technique
- ❖ Results and Discussion
  - ❖ Directed Flow (v_1)
  - ❖ Triangular Flow (v_3)
- ❖ Summary

Anisotropic Flow

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

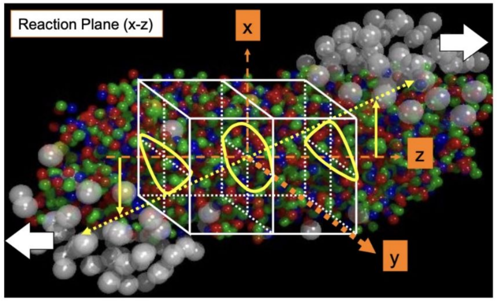
$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

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

Triangular flow

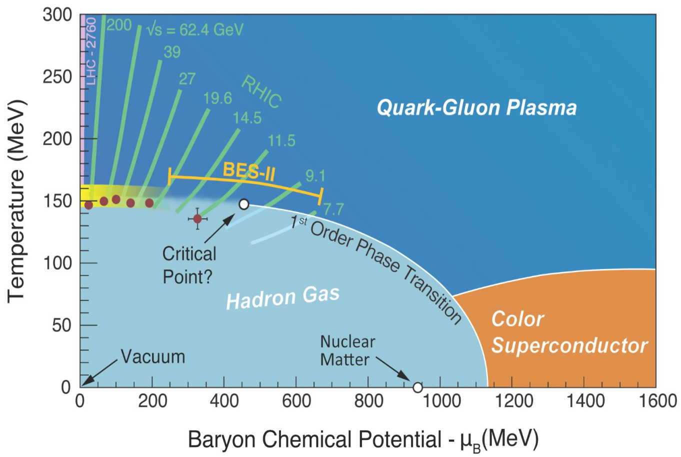
$$v_3 = \langle \cos 3(\phi - \Psi_1) \rangle$$

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

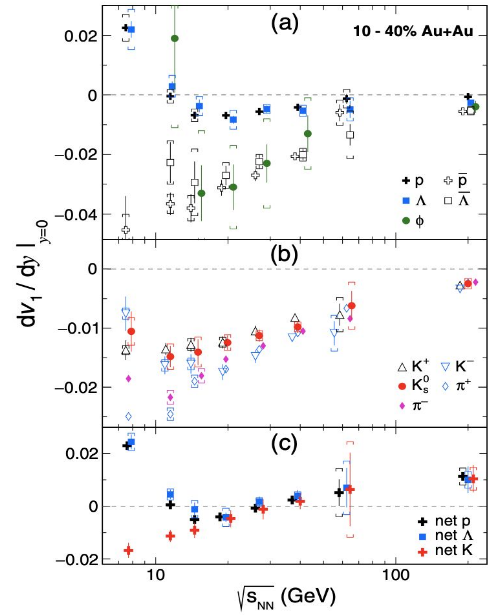


R. Snellings New J. Phys. 13 055008 (2011)
2309.12610 [nucl-ex]

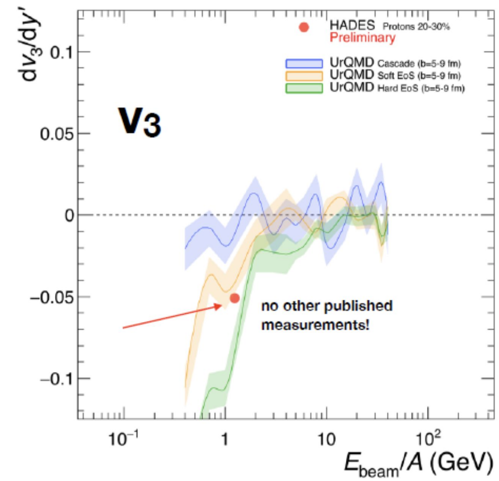
Motivation



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



Phys. Rev Lett. 120, 062301 (2018)

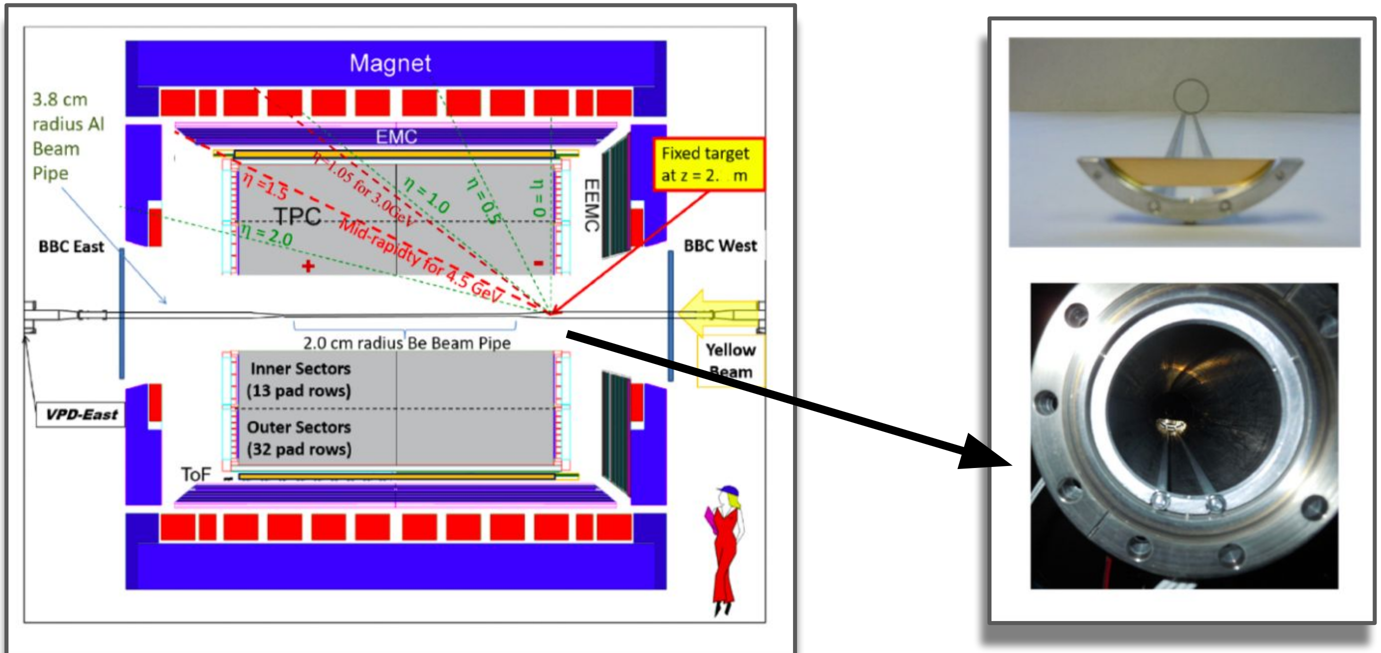


J. Phys. G: Nucl. Part. Phys. 45 085101 (2018)
Phys. Rev. Lett. 125, 262301 (2020)
2309.12610 [nucl-ex]

- ❑ The primary aim of relativistic heavy-ion collisions → Understand the properties and the evolution of strongly interacting matter, **Q**uark–**G**luon **P**lasma (**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

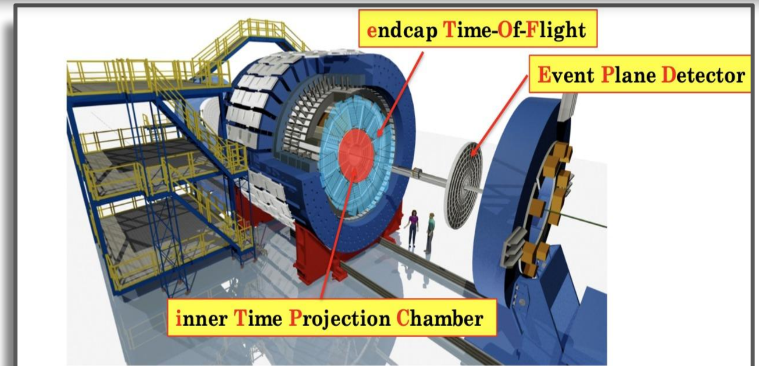
Schematic of fixed target setup



Nuclear Phy A 808-811 (2017)

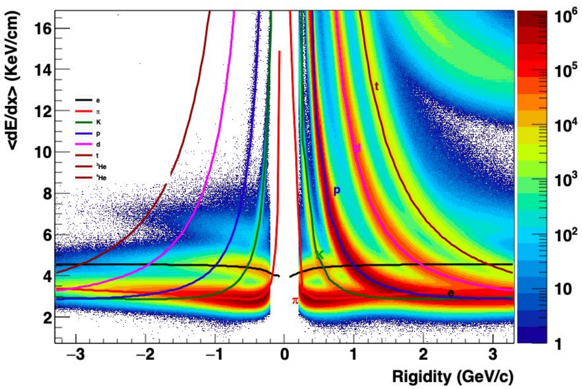
- ❑ **Fixed-Target (FXT)** program at **S**olenoidal **T**racker **A**t **R**HIC (**STAR**) → low center-of-mass energies and high baryon density region
- ❑ **BES-II FXT mode**: Au+Au collisions at $\sqrt{s_{NN}}$ = 3, **3.2, 3.5, 3.9, 4.5,** 5.2, 6.2, 7.2, and 7.7 GeV.

Particle Identification

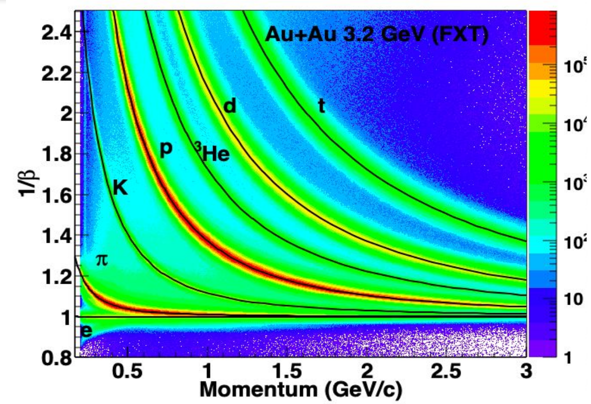


https://www.star.bnl.gov/

Time Projection Chamber (TPC)



Time of Flight (ToF)



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

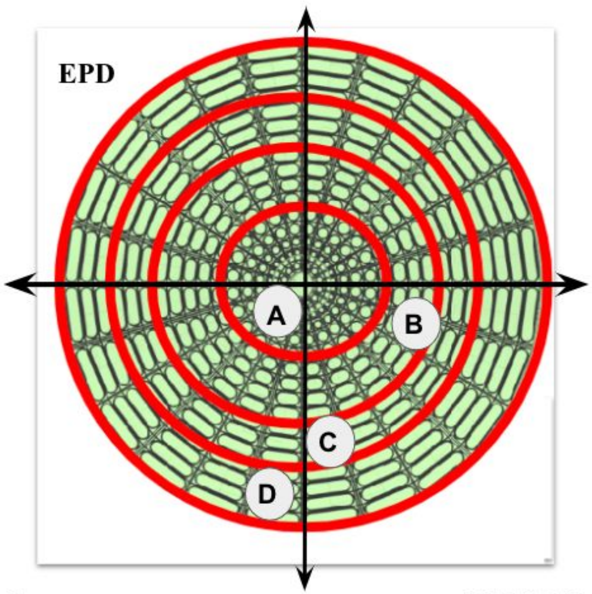
 - **Time Projection Chamber** (**TPC**)

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

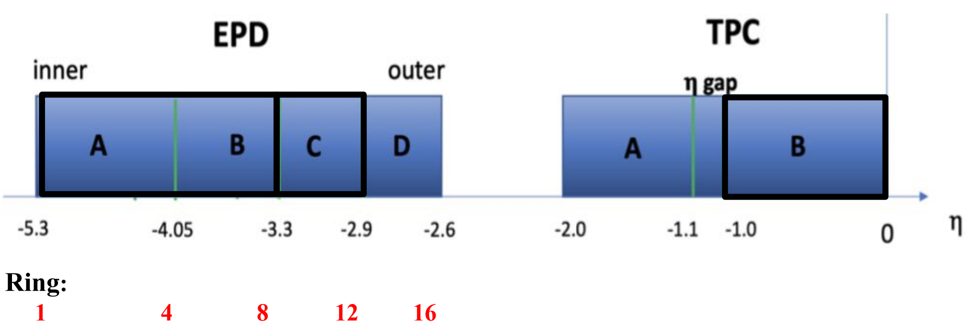
 - **Time of Flight** (**ToF**)

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

Event Plane Reconstruction



- **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



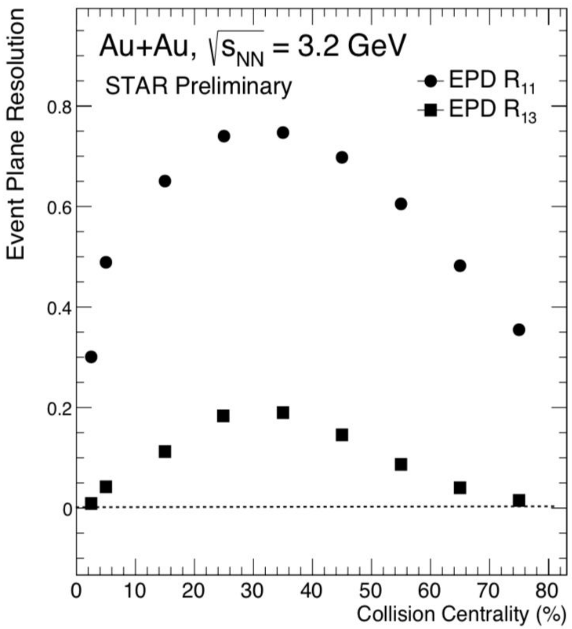
$$\vec{Q} = (Q_x, Q_y) = \left(\sum_i w_i \cos(\phi_i), \sum_i w_i \sin(\phi_i)\right)$$

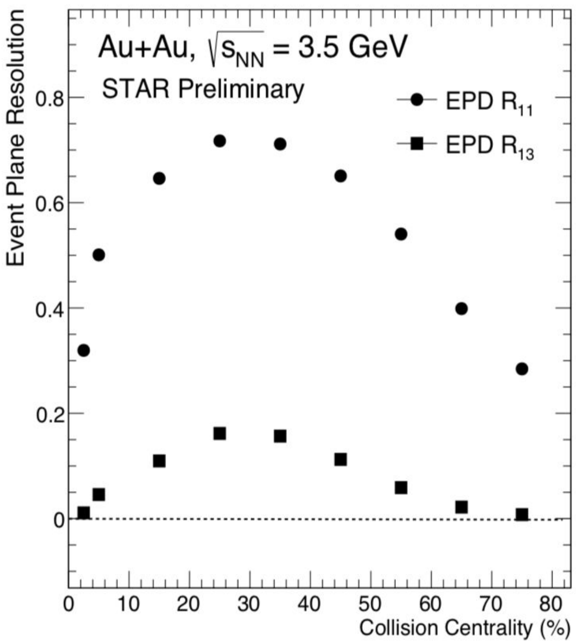
$$\psi_1 = \tan^{-1}(Q_y/Q_x)$$

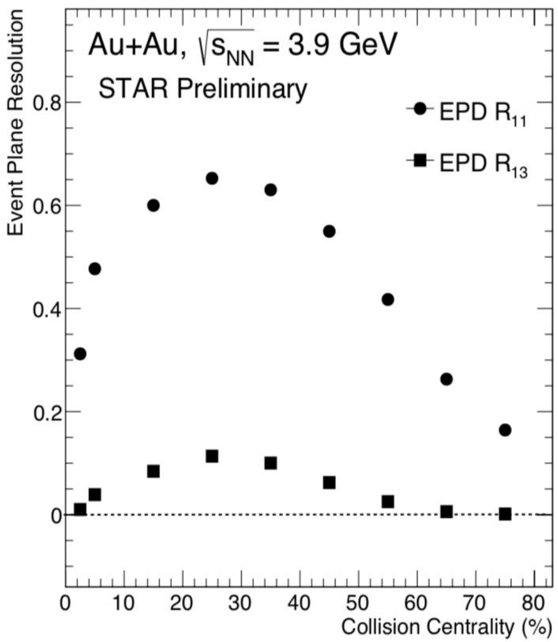
where ϕ_i is azimuthal angle and w_i is the weight for the i^{th} hits, Ψ_1 is the first-order event plane angle

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.

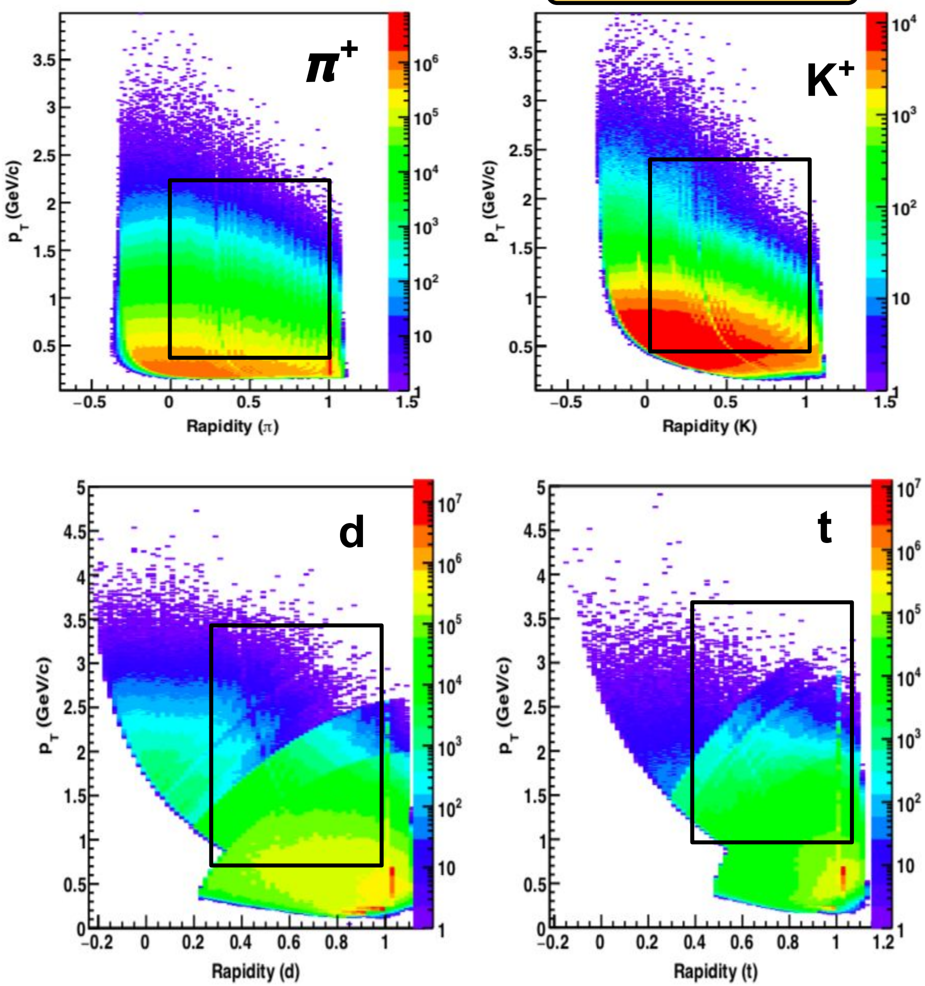
$$\langle\cos[n(\Psi_m^a-\Psi_r)]\rangle = \sqrt{\frac{\langle\cos[n(\Psi_m^a-\Psi_m^b)]\rangle\langle\cos[n(\Psi_m^a-\Psi_m^c)]\rangle}{\langle\cos[n(\Psi_m^b-\Psi_m^c)]\rangle}}.$$

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

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

Phase Space Distribution

Au+Au 3.2 GeV



Rapidity:

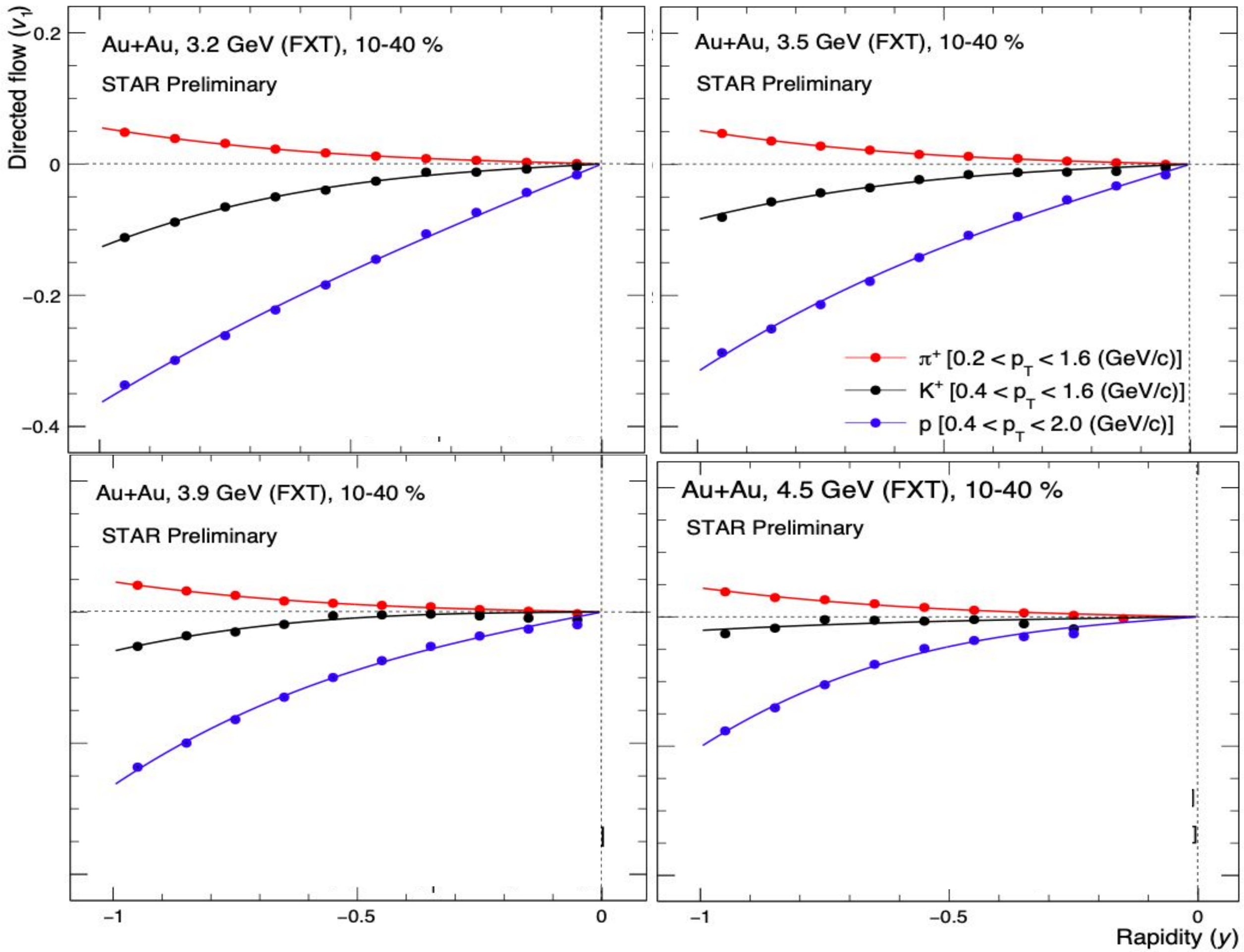
$$y = \frac{1}{2}\ln\frac{E + p_z c}{E - p_z c};$$

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

- 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)

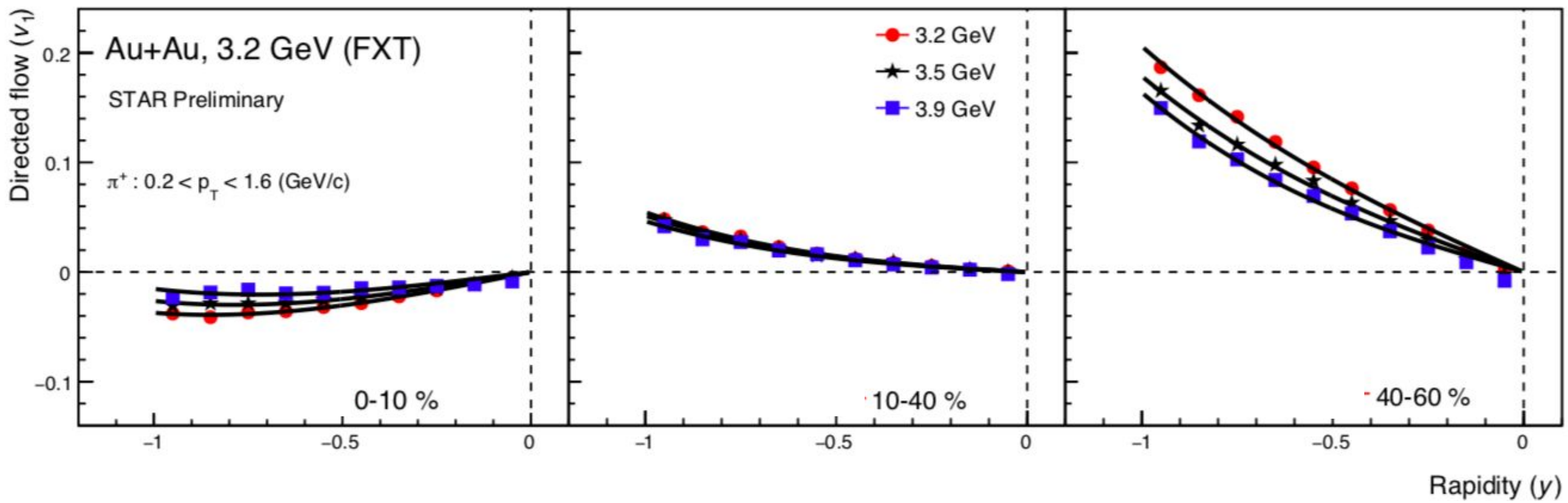
Directed Flow (v_1) Results

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^+)

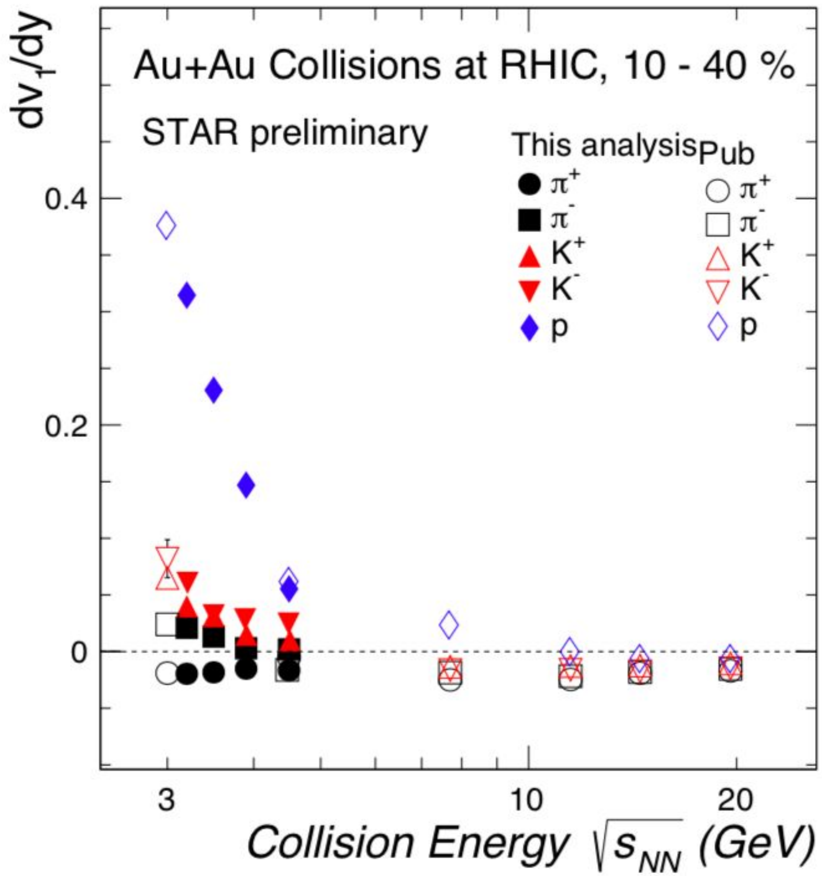
Centrality dependence of v_1 (π^+)



- v_1 changes sign moving from central to peripheral collisions due to spectator shadowing effect
- v_1 slope is maximum for peripheral collision

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

Presented in ISMD 2023, QM 2023, DQCD 2023



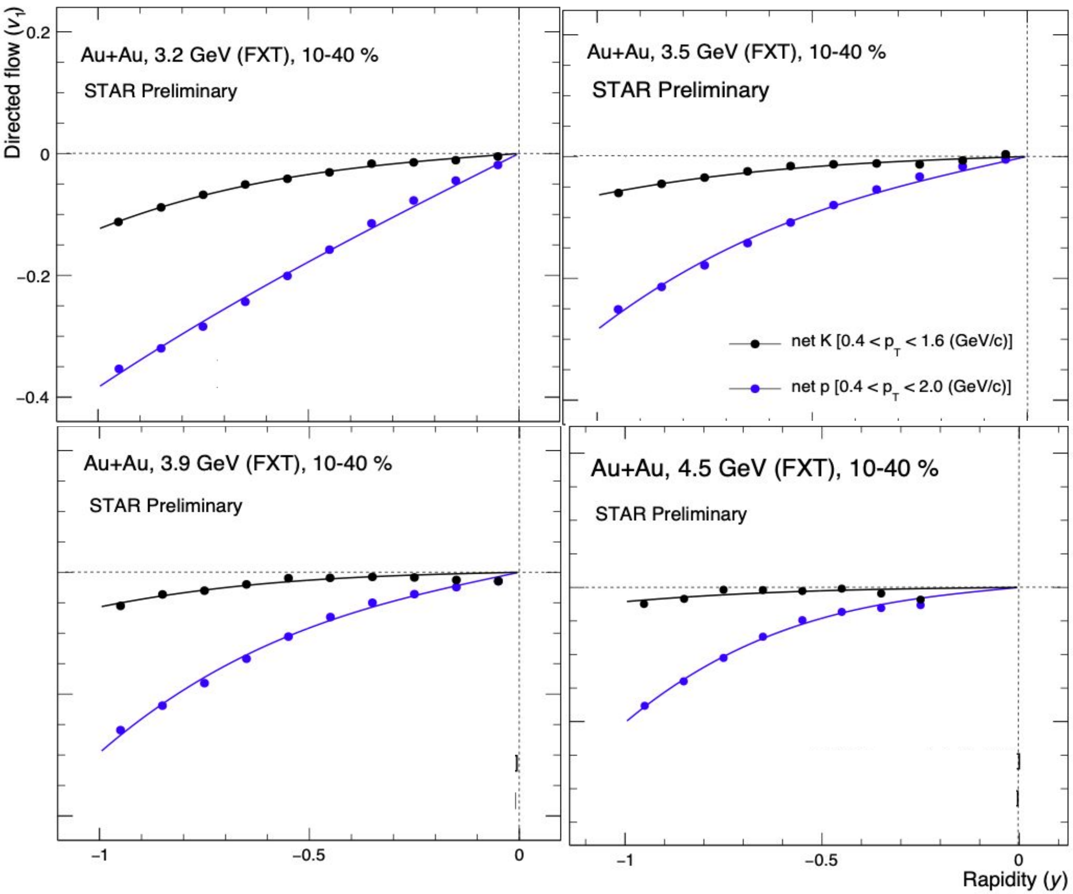
- $v_1(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_1/dy$)

  $v_1(y) = by + cy^3$
- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing v_1 slope
- $dv_1/dy|_{\pi+}$ → negative whereas $dv_1/dy|_{\pi-}$ → positive

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

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

Rapidity dependence of v_1 (net p and net K)



- Net particle v_1 is defined as

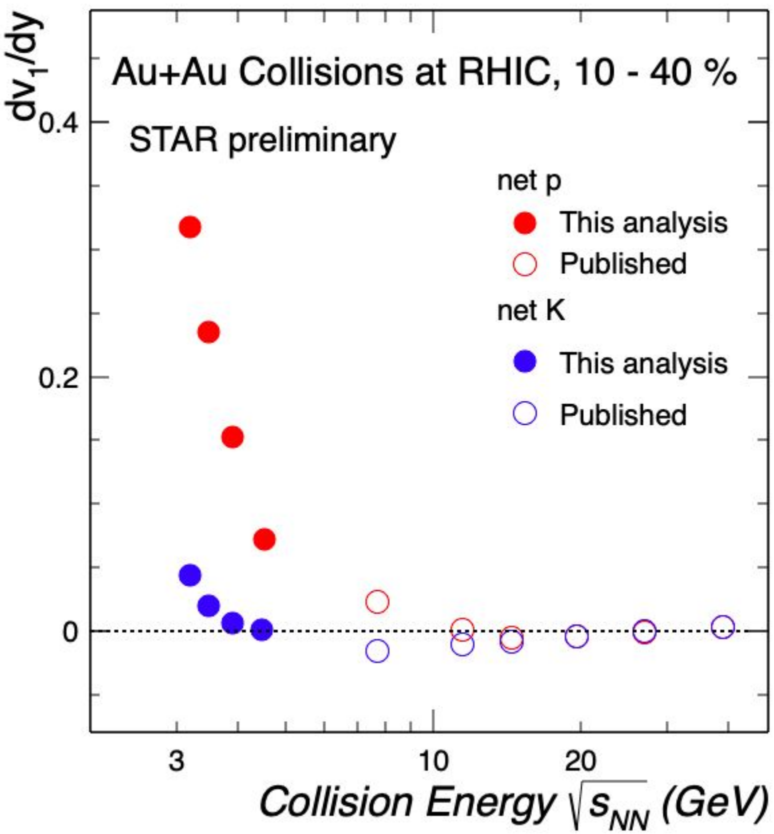
$$v_{1,net} = \frac{v_{1,p} - r v_{1,\bar{p}}}{1 - r}$$

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)

Presented in ISMD 2023, QM 2023, DQCD 2023



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

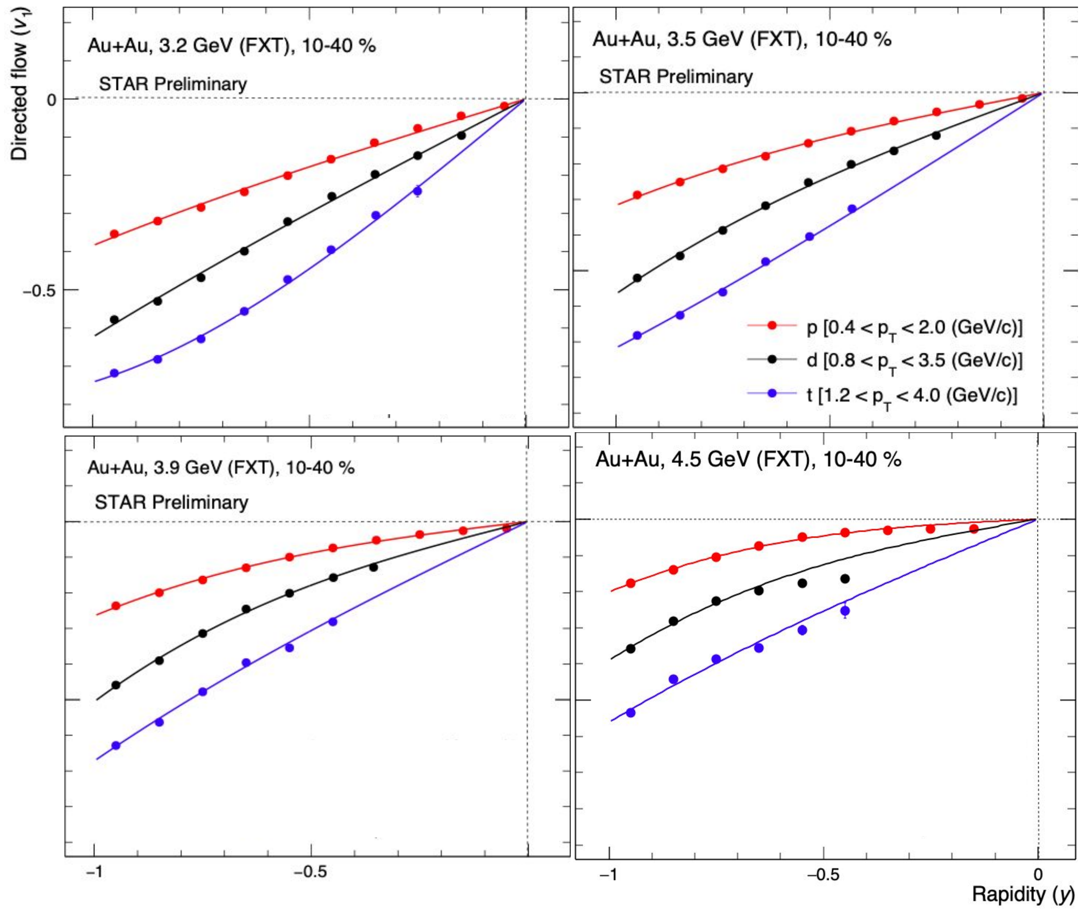
  $v_1(y) = by + cy^3$
- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing v_1 slope

- Minimum net-p → (11.5-19.6 GeV) whereas minimum net-K → (4.5-7.7 Gev)

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

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

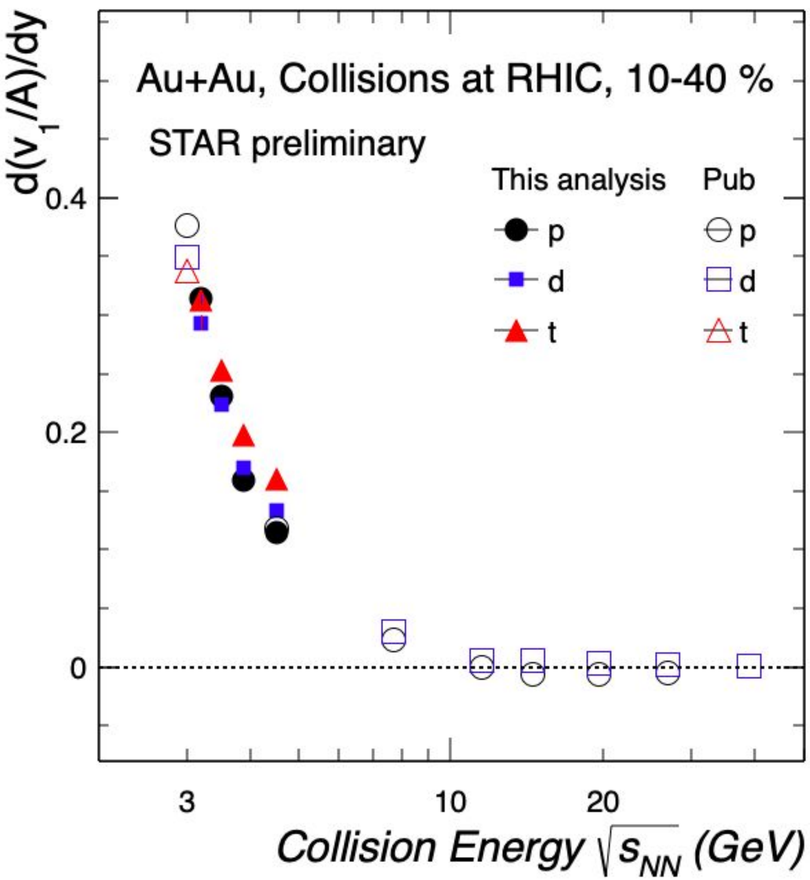
Rapidity dependence of light nuclei v_1



- 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

Presented in ISMD 2023, QM 2023, DQCD 2023



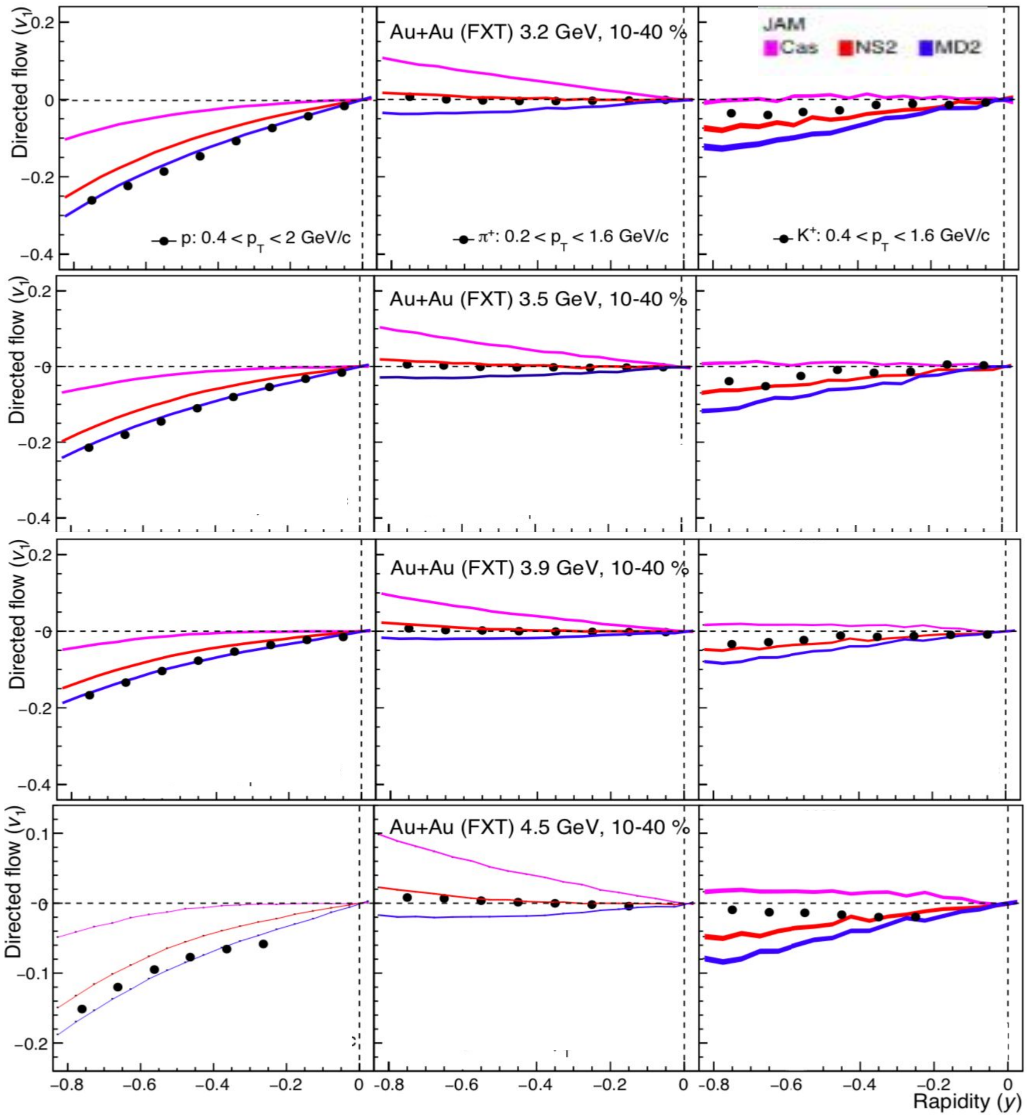
- $v_1(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_1/dy$)

  $v_1(y) = by + cy^3$
- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing v_1 slope
- Approximate mass no. scaling is observed in the v_1 slope

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

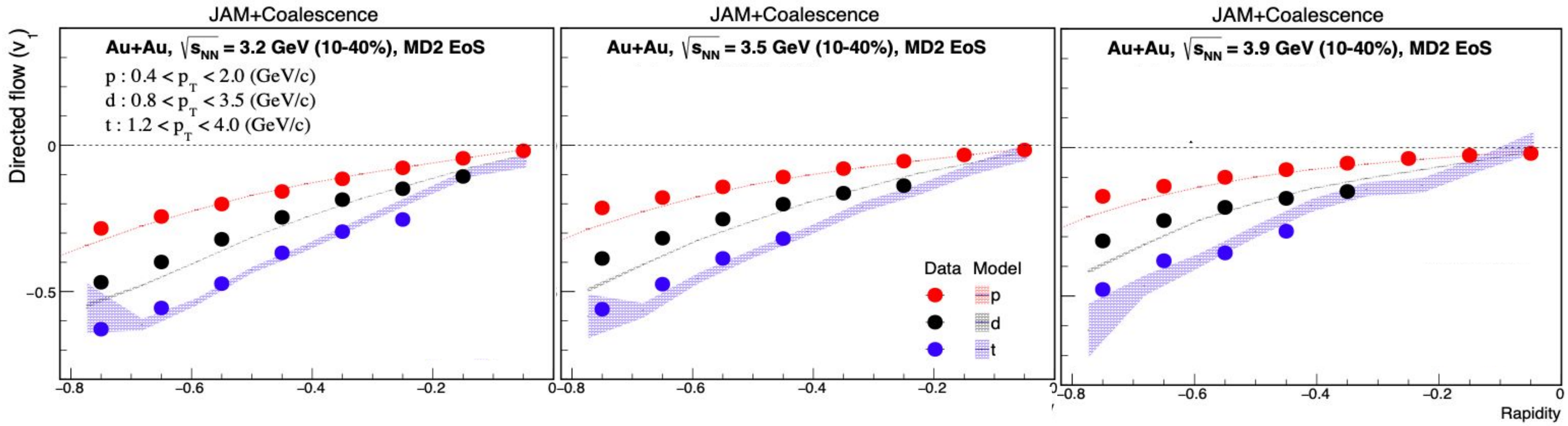
dv_1/dy for published data was extracted using first-order polynomial fit

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



- JAM cascade mode fails to describe data
- JAM mean field mode gives better description to the experimental data

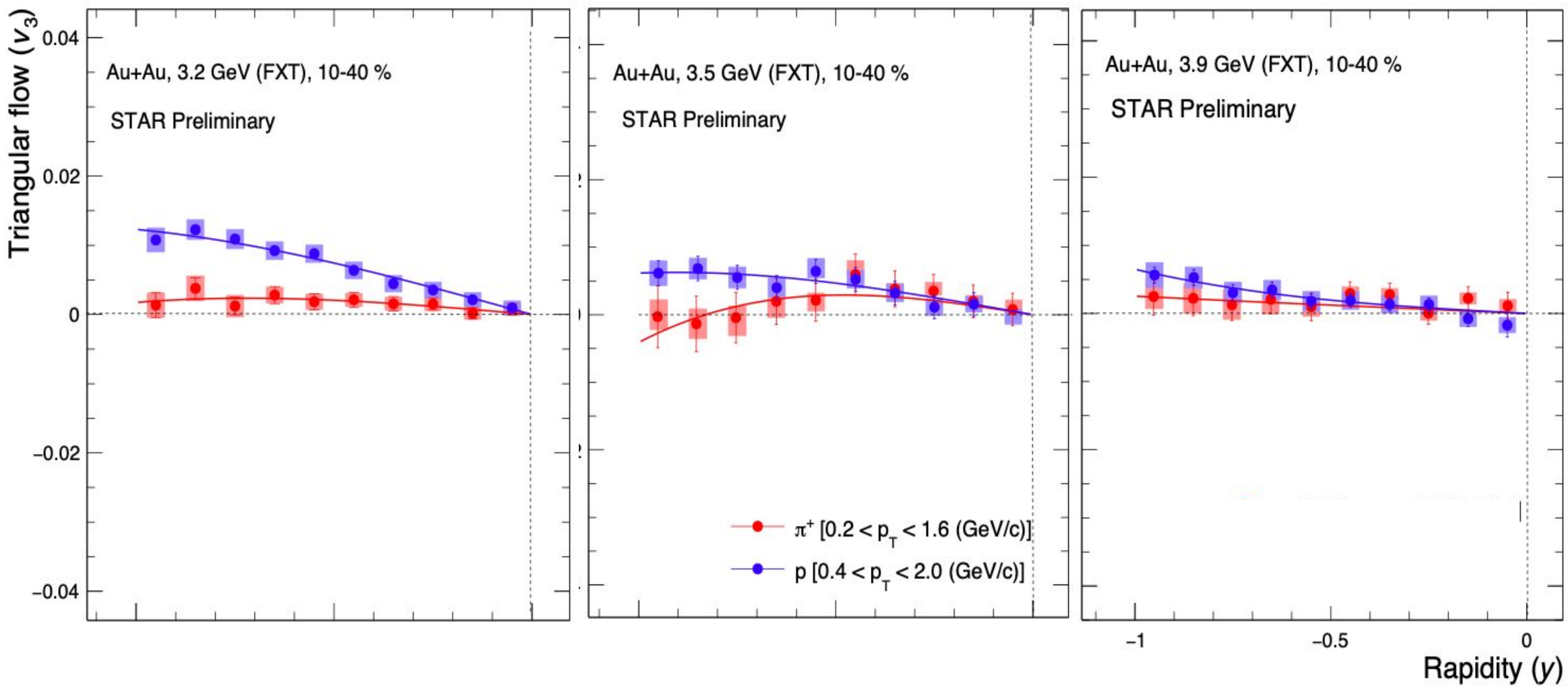
Rapidity dependence of v_1 (p,d, and t)



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

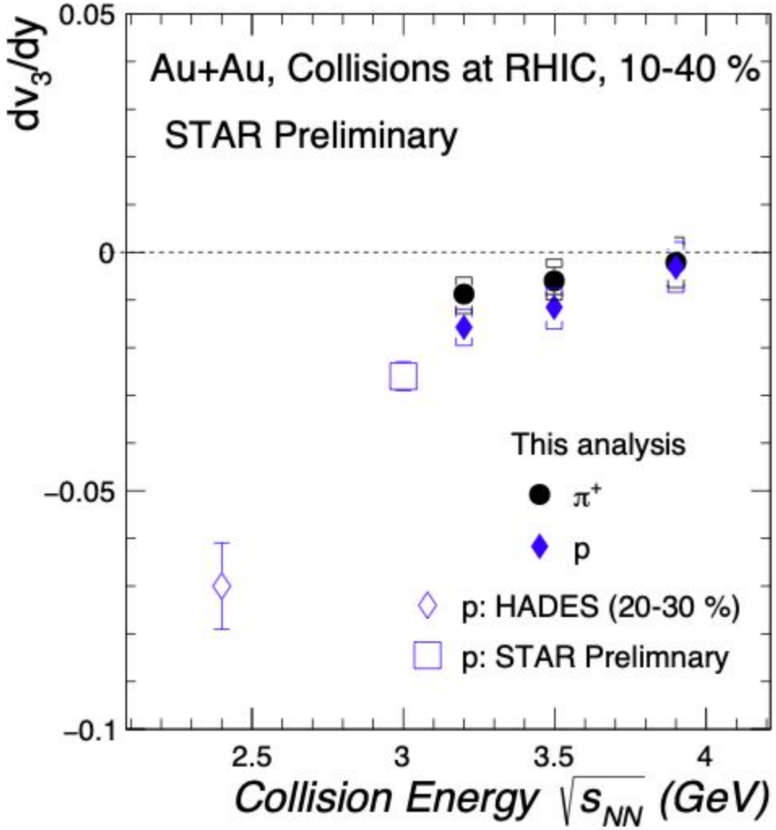
Triangular Flow (v_3) Results

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



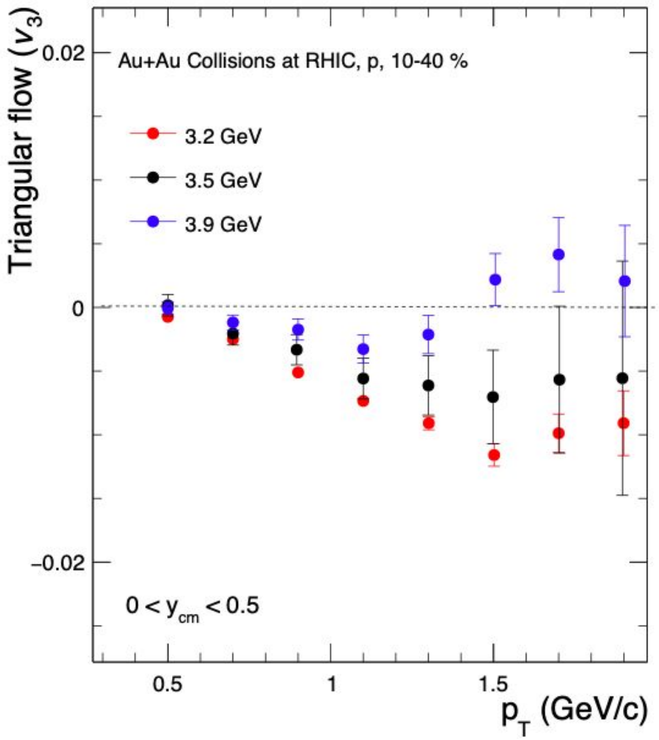
- $v_3(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_3/dy$)

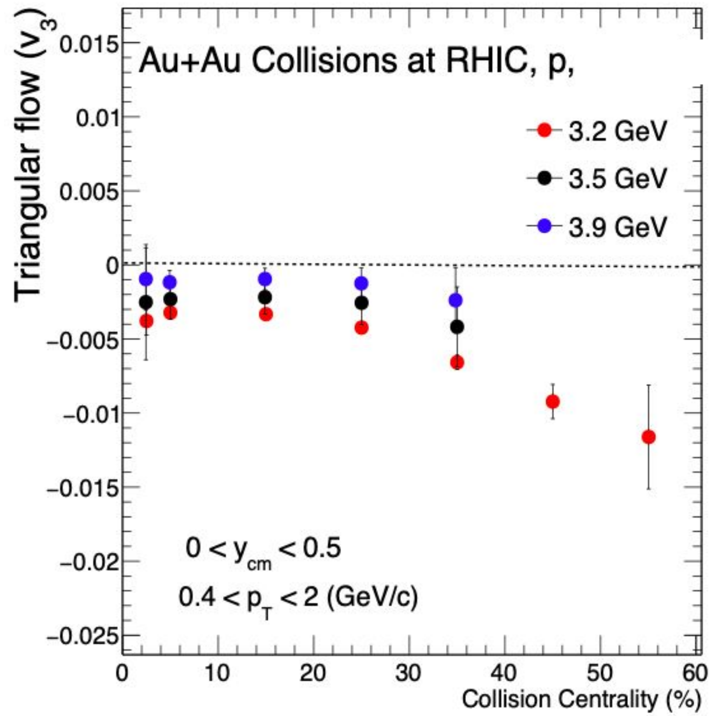
  $v_3(y) = by + cy^3$
- Fitting range → [y: -1, 0]
- Increasing collision energy → decreasing magnitude of v_3 slope

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

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

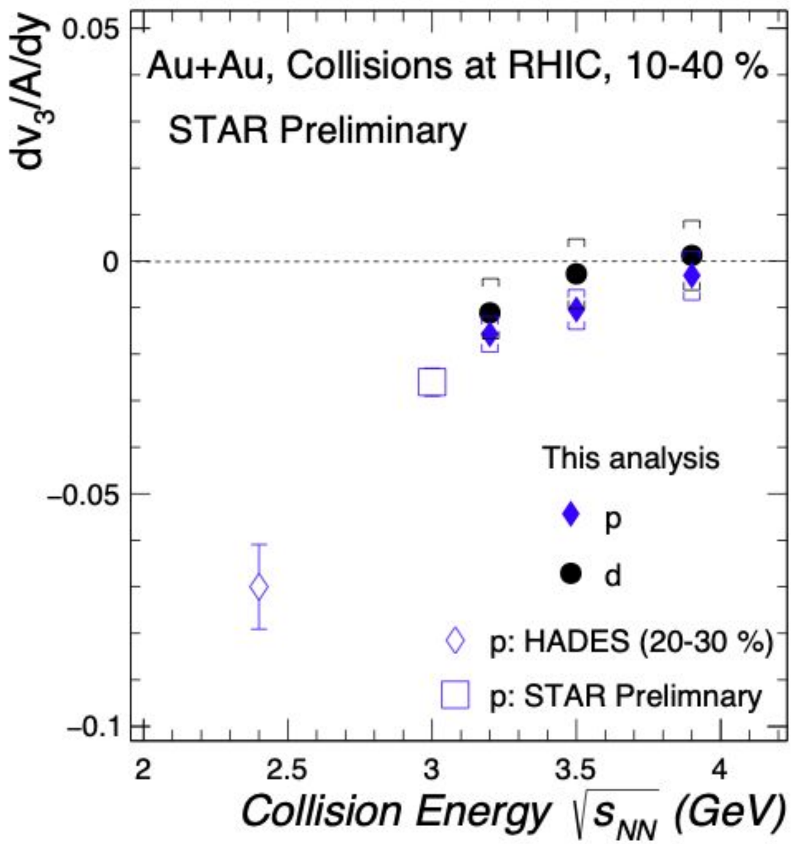
Proton v_3 dependence





- Magnitude of v_3 decreases with increasing collision energy

Collision energy dependence of v_3 slope



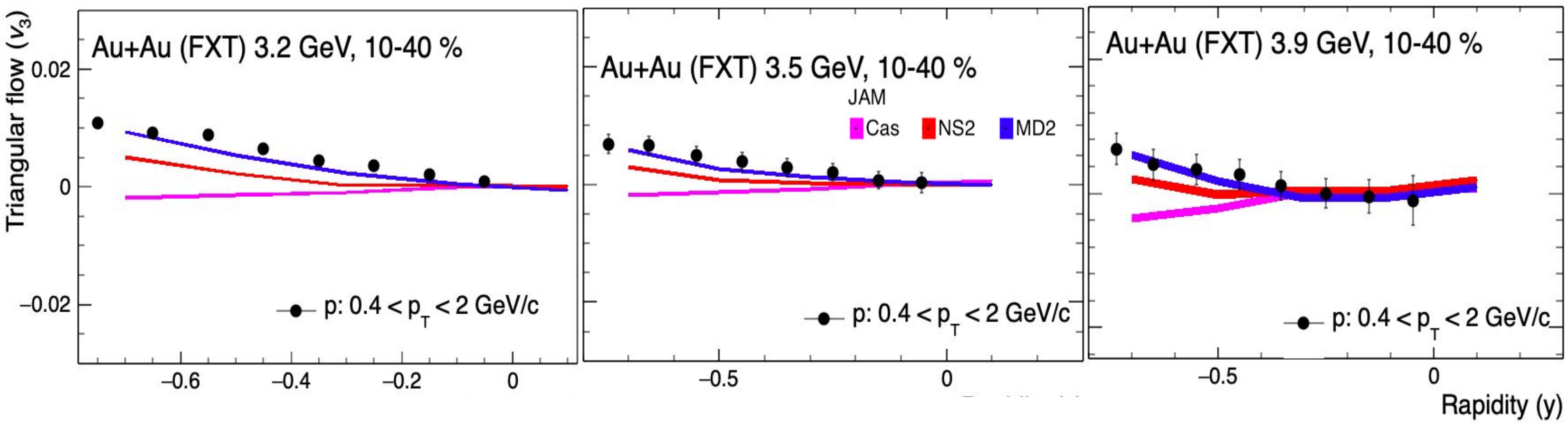
HADES→ p (20-30 %): 0.6 < p_T < 0.9 GeV/c

- $v_3(y)$ 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
- Approximate mass no. scaling is observed in the v_3 slope

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

Rapidity dependence of v_3



- JAM cascade mode fails to describe data
- JAM mean field mode with momentum dependent potential gives better description

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, 3.9, and 4.5 GeV are presented.
- The magnitude of the v_1 slope decreases with increasing collision energy, exhibiting a mass ordering.
- 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.
- Approximate mass no. scaling is observed in v_1 and v_3 slope for light nuclei.
- JAM mean-field gives a better description to the experimental data for identified hadrons as well as light nuclei.

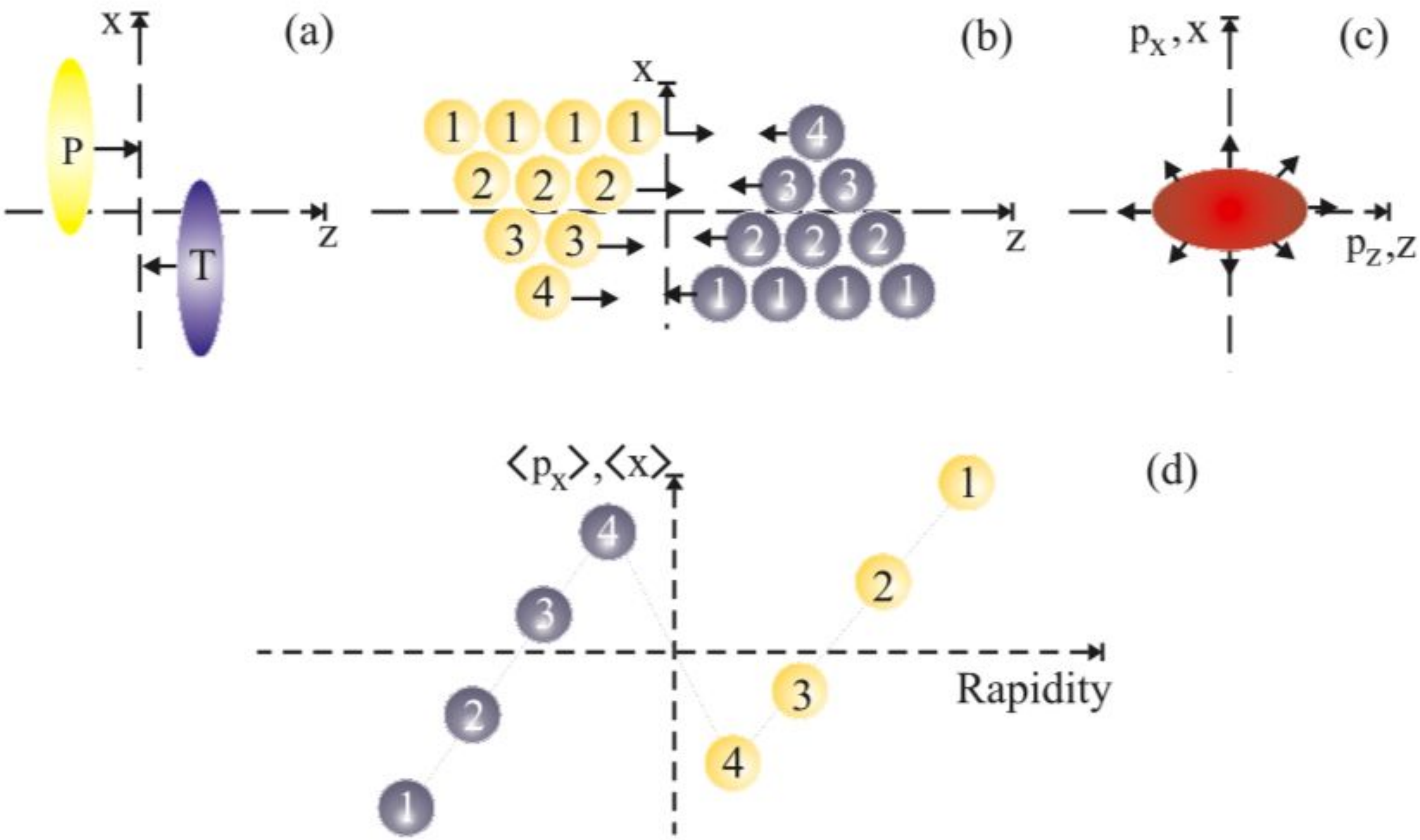
Outlook

- Paper proposal on ‘Directed flow of identified hadrons and light nuclei for fixed-target energies at RHIC-STAR’ is given in FCV-PWG. [Link]
- Finalize the v_3 measurements for FXT energies and proceed for the another paper proposal.
- Study the effect of EM field on the directed flow of particle and antiparticles in FXT energies.

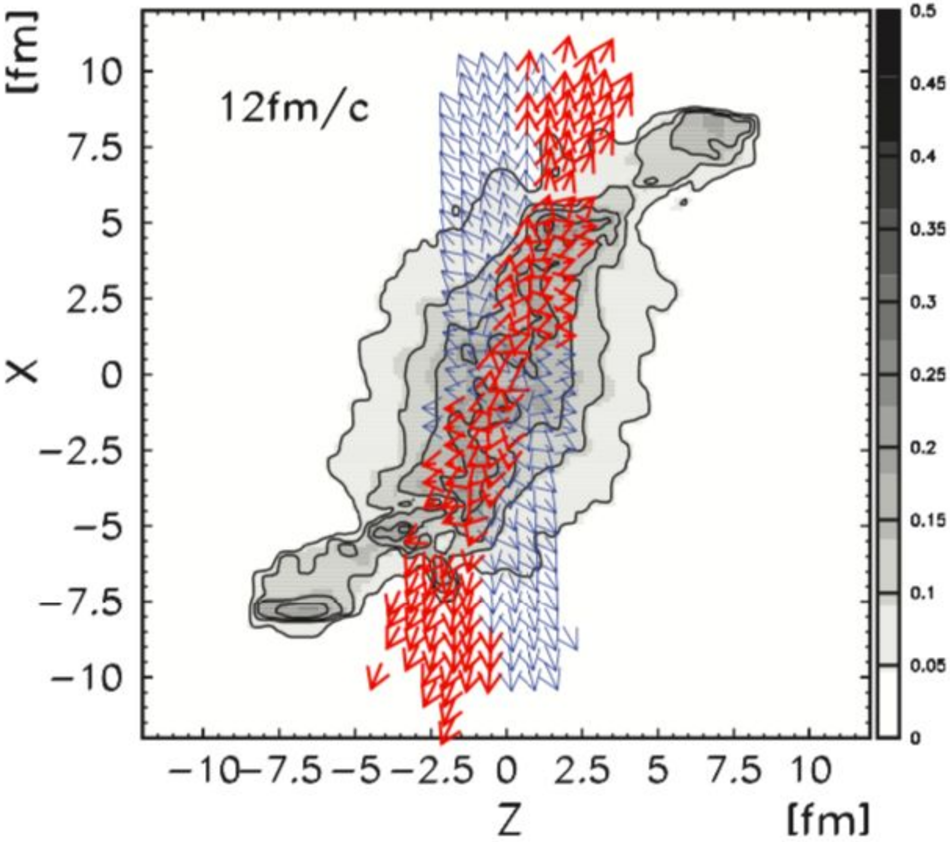
Thank you for your attention!

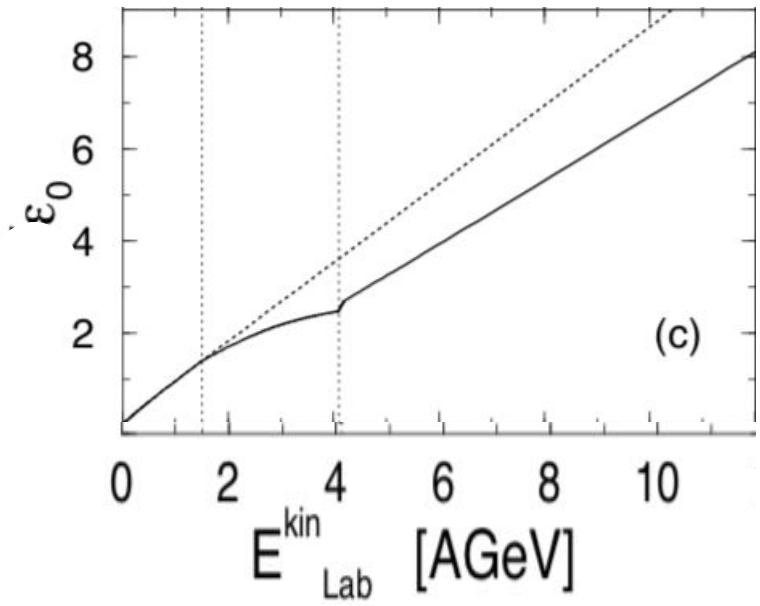
Backup slides

Directed flow (v_1)

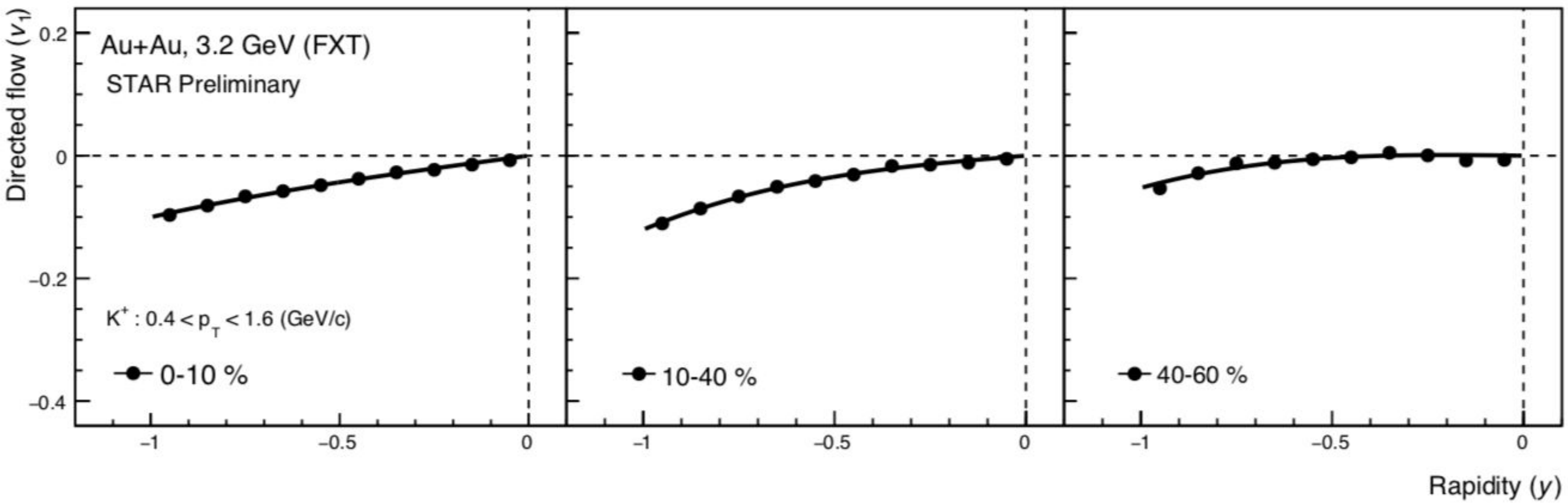


Directed flow (v_1)



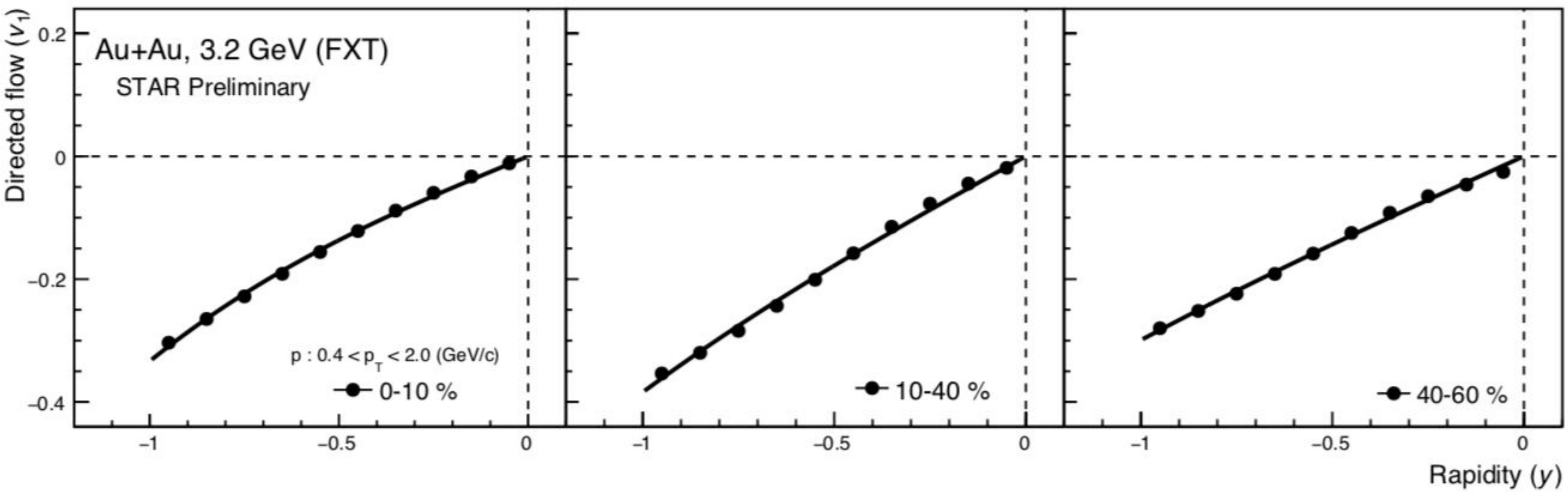


Centrality dependence of v_1 (K^+)



- 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

Triangular flow