Overview of fixed-target runs at RHIC-STAR

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GSI Helmholtzzentrum für Schwerionenforschung GmbH

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Outline

- ❖ Introduction
- ❖ STAR Detector and Fixed-target Setup
- ❖ Results and Discussion
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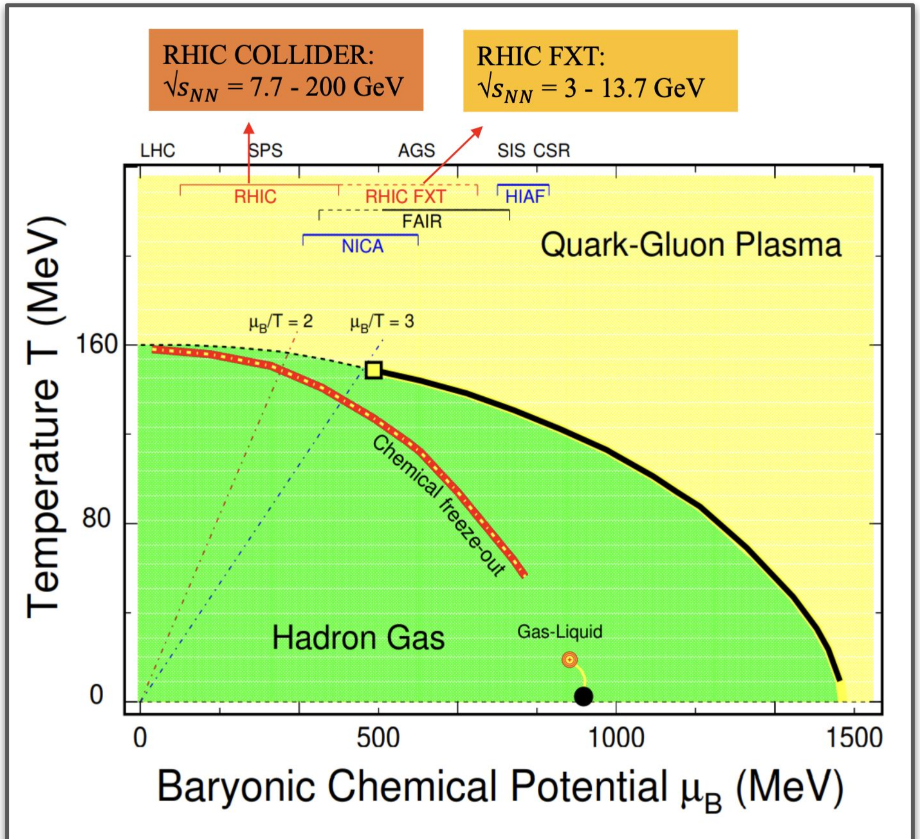
    - ➢ Elliptic Flow (v_2)
    - ➢ Triangular Flow (v_3)
  - ❖ Transverse Momentum Spectra
- ❖ Summary

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

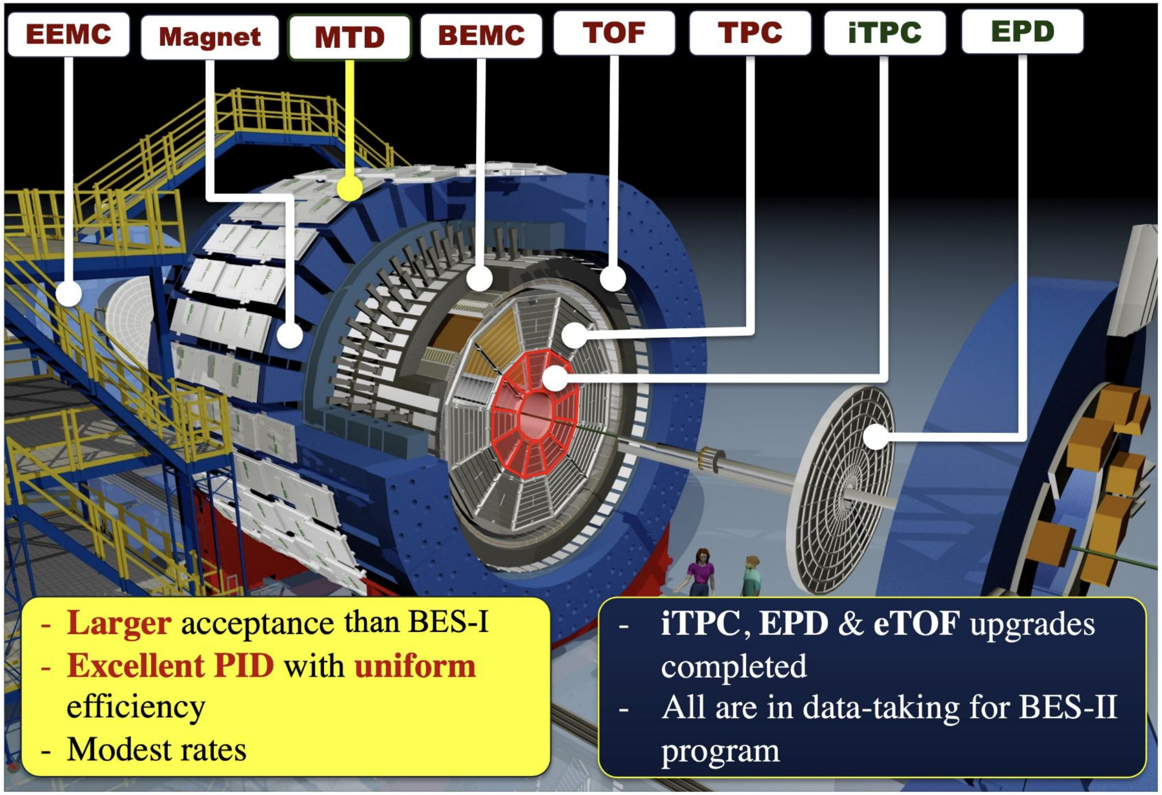
$\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, and 200 GeV **(COL)**

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
- ➢ Ready in 2019

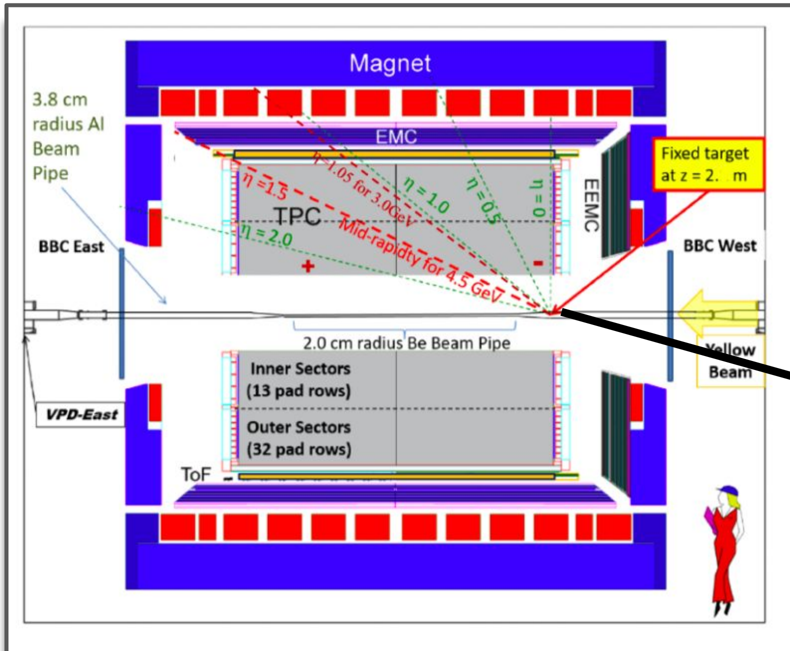
eTOF:
- ➢ Forward rapidity coverage
- ➢ PID at η = -1.1 to -1.6
- ➢ Ready in 2019

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

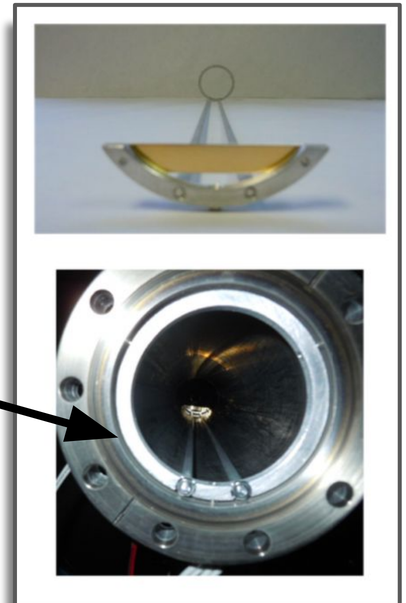
[1] iTPC: https://drupal.star.bnl.gov/STAR/starnotes/. public/sn0619.
[2] eTOF: STAR and CBM eTOF group, arXiv: 1609.05102.
[3] EPD: J. Adams, et al. NIM A968, 163970 (2020)

STAR Fixed-target Experiment

Fixed-target mode



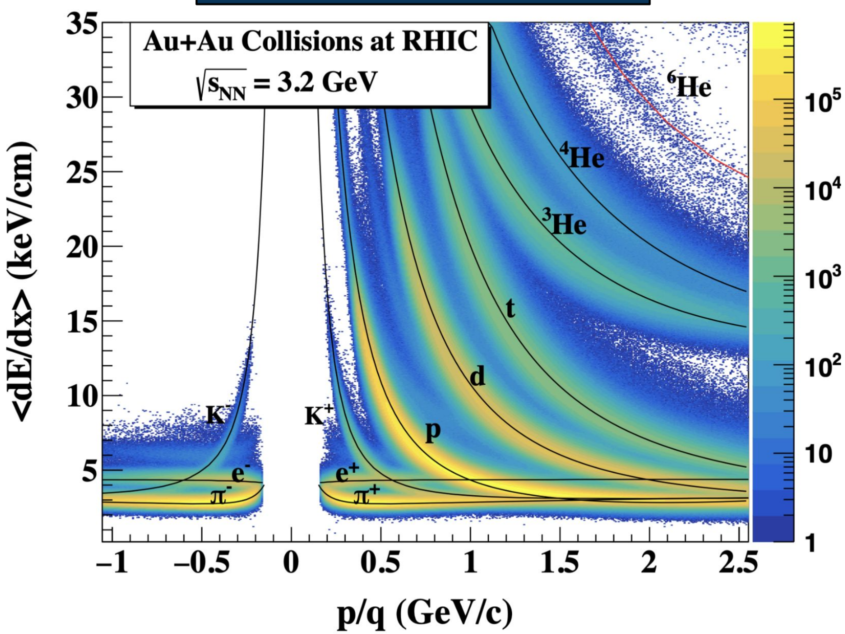
Nuclear Phy A 808-811 (2017)



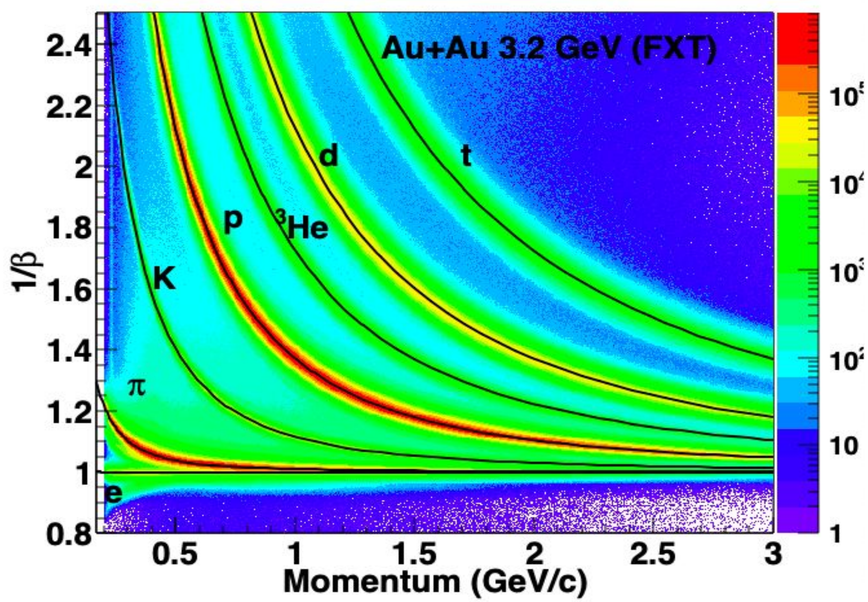
- **Fixed-Target (FXT)** program at **S**olenoidal **T**racker **A**t **R**HIC (**STAR**) → low center-of-mass energies and high baryon density region
  - Target located at **z = 200 cm**
  - Target is 0.25 mm thick (1% interaction probability) and held 2 cm below center of beam axis

Particle Identification

Time Projection Chamber (TPC)



Time of Flight (ToF)



Two detectors are used for particle identification in STAR

- **Time Projection Chamber (TPC)**

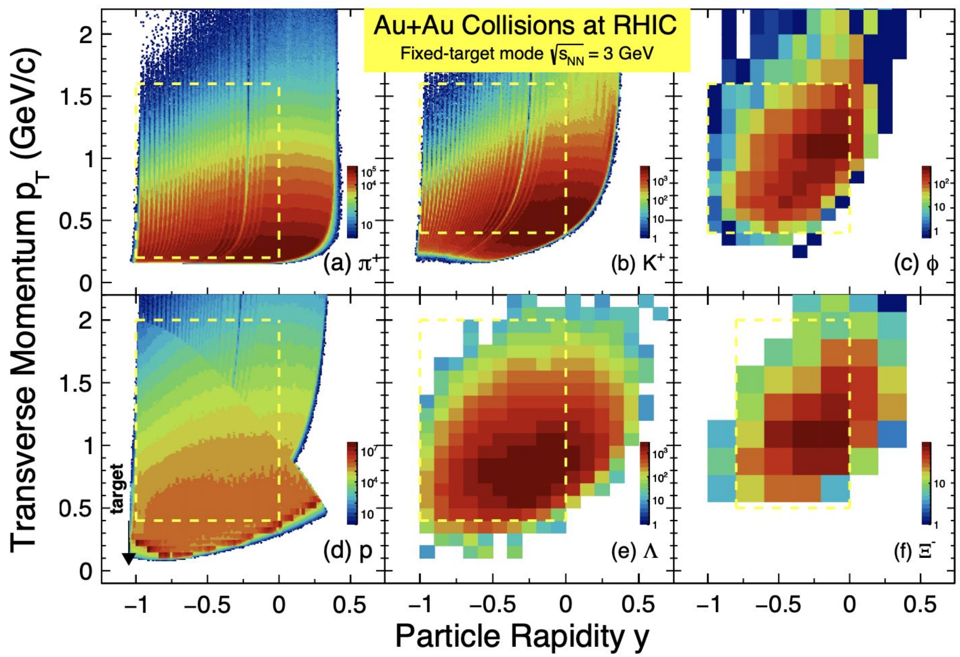
$$z_X = \ln\left(\frac{\langle dE/dx\rangle}{\langle dE/dx\rangle_X^B}\right)$$

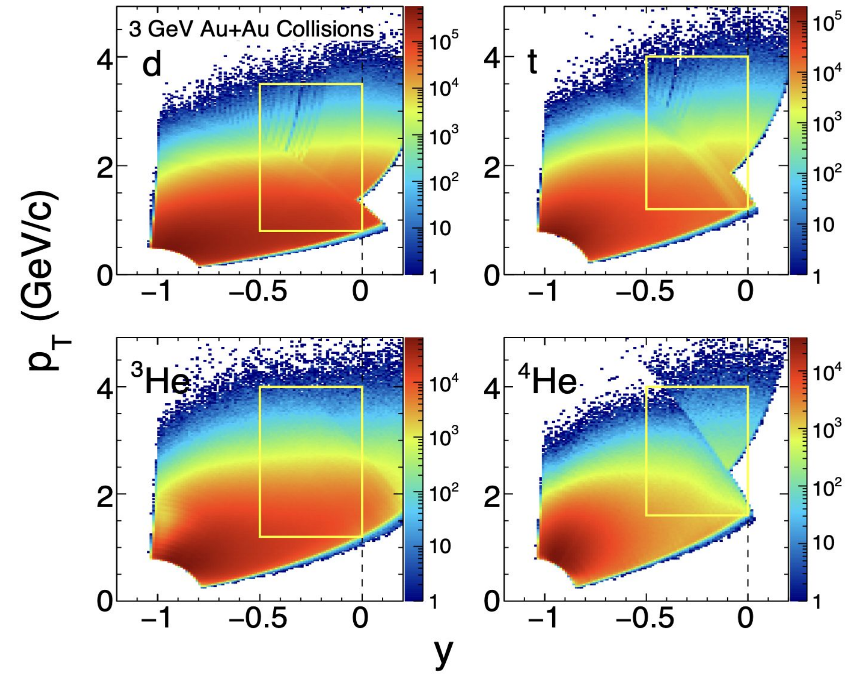
- **Time of Flight (ToF)**

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

H. Bichsel, Nucl. Instrum. Meth. A 562, 154 (2006)

Phase Space Distribution



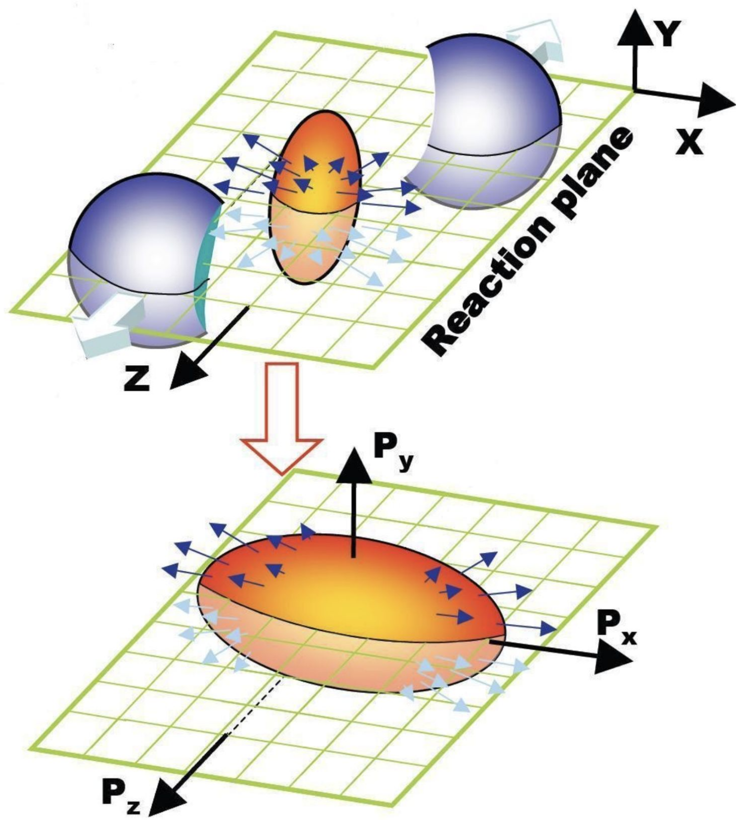


- Unlike collider mode collisions, the target is located at the edge of TPC, and the mid-rapidity is not zero in the FXT mode
- To convert the measured rapidity (y) in the coordinate system → y in the center of mass frame → boost the measured y by beam rapidity (y_b)

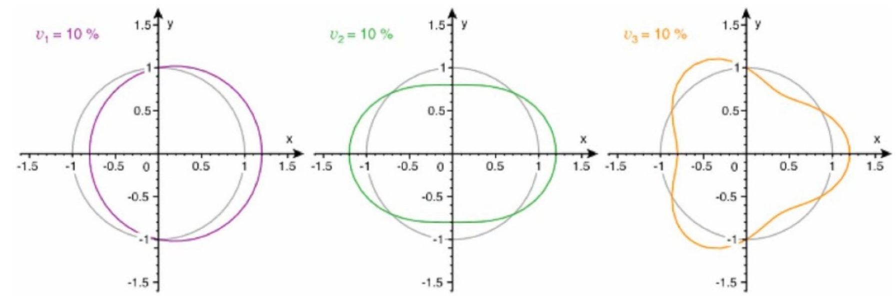
$$y_b = cosh^{-1}\left[\frac{\sqrt{s_{NN}}}{2 * m_p}\right]$$

y_{cms} = -(y_{lab} + y_b), for FXT 3 GeV, $y_b = -1.045$

Anisotropic Flow



$$\frac{dN}{d(\phi-\Psi)} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi))$$



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

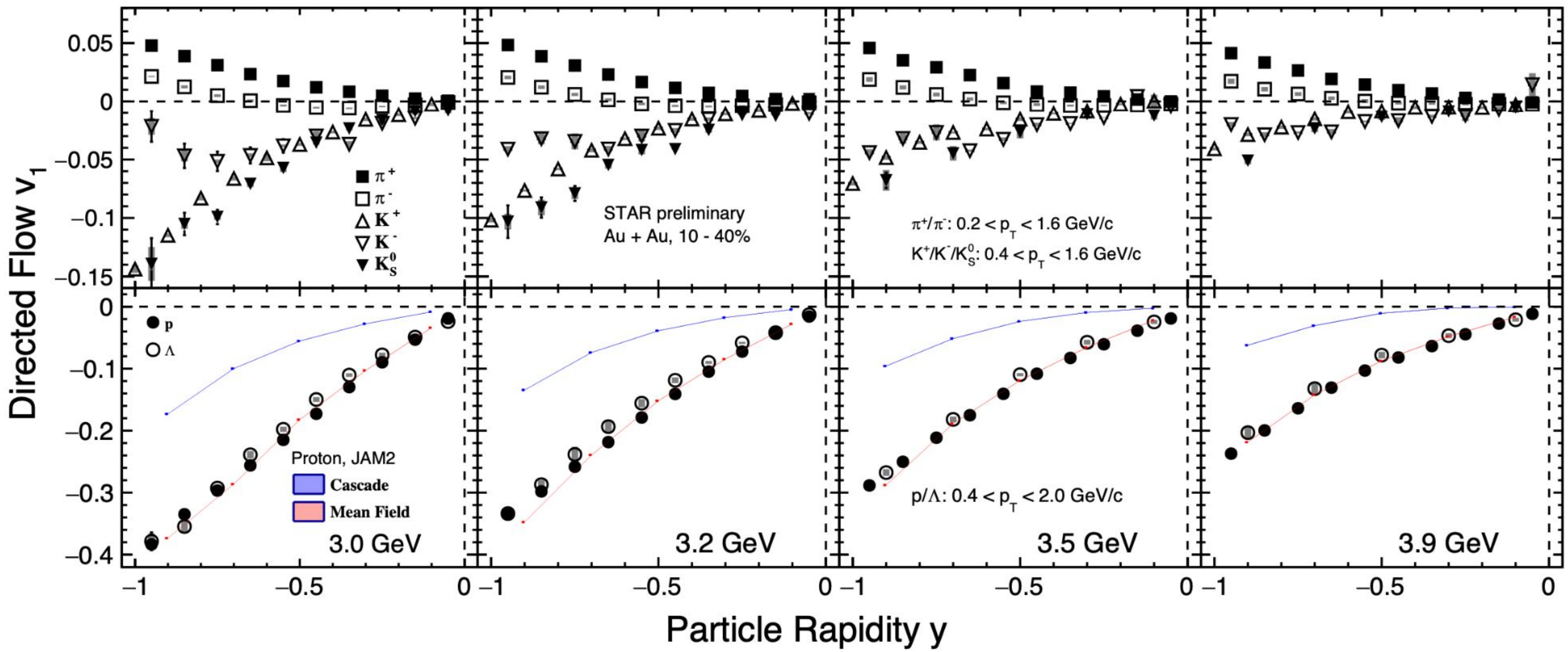
- $\mathbf{v_1}$ reveals the interplay between initial compression and tilted expansion.
- $\mathbf{v_2}$ and $\mathbf{v_3}$ are sensitive to event-by-event geometry and fluctuations, and provide insight on the constituent interactions and degree of freedom.

The initial pressure gradient of the collision system is directly related to the magnitude of v_n, and is a sensitive observable for studying equation of state.

[1] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998)
[2] L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 120, 062301 (2018)

Directed Flow (v_1) Results

Directed Flow Of Identified Hadrons At FXT Energies



- v_1 increases in magnitude with increasing rapidity for most particle species
- Magnitude of v_1 has a strong particle species dependence
- **JAM** model with baryonic mean-field describes the data well for baryons in comparison to cascade mode

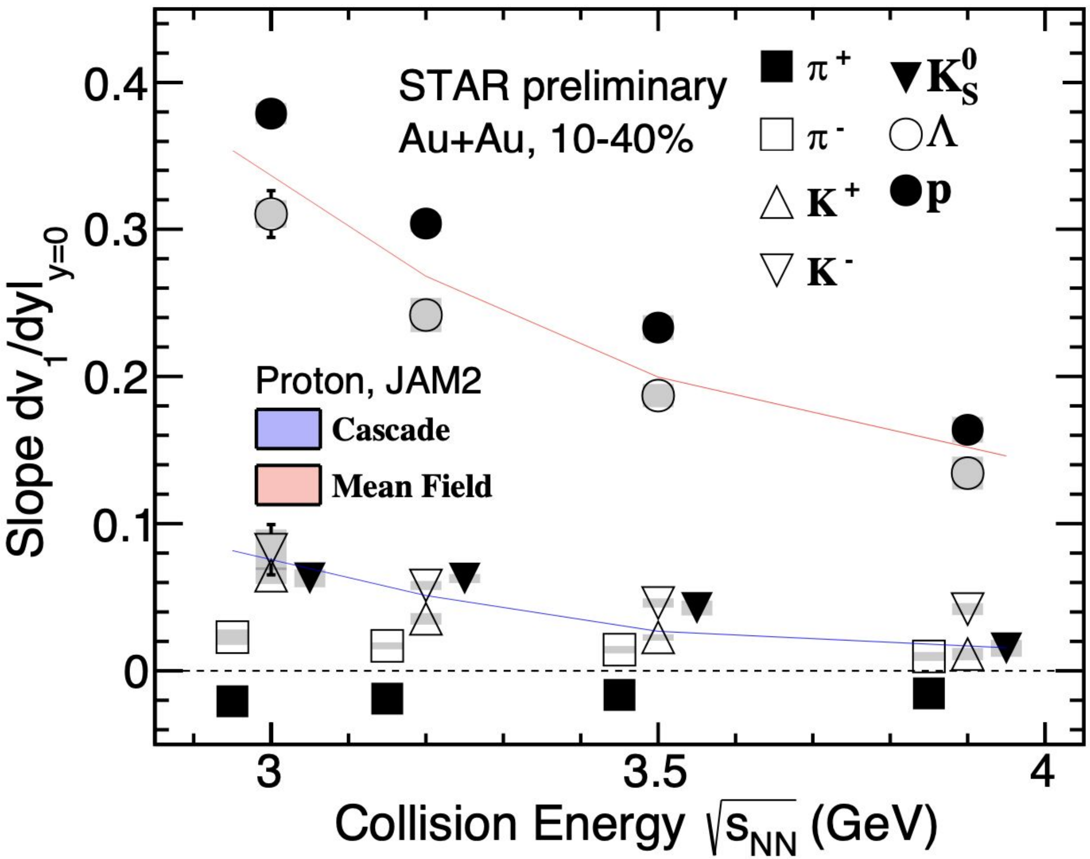
JET AA Microscopic Transportation Model (JAM2)

- **MD2**: momentum dependent mean-field potential
- Incompressibility constant **κ** = 380 MeV

Quark Matter 2023
https://indico.cern.ch/event/1139644/contributions/5502964/

M. S. Abdallah et al. (STAR Collaboration), Phys. Lett. B 827 137003 (2022)

Directed Flow Of Identified Hadrons At FXT Energies

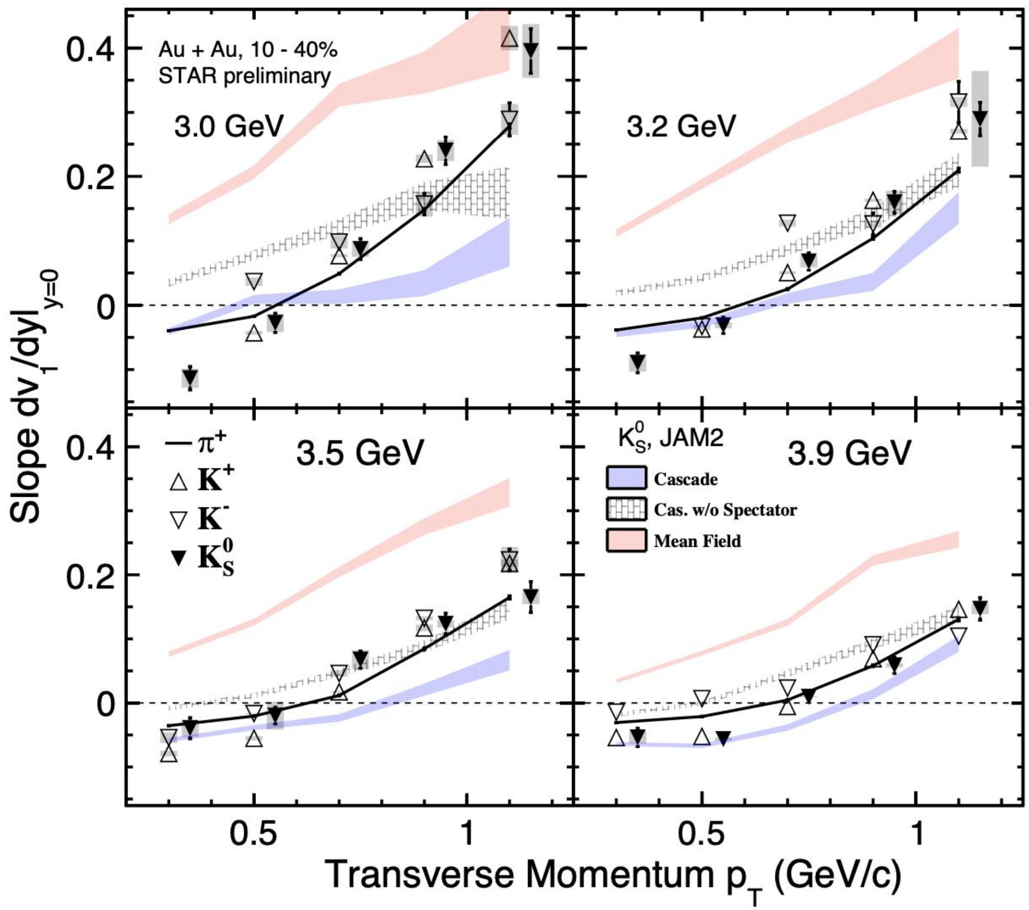


- v_1 slope decreases in magnitude as collision energy increases
- Baryonic mean field enhances v_1 slope.
  - Strong mean field at high baryon density region (at lower energies)
- $dv_1/dy|_{\pi+} \rightarrow$ negative whereas $dv_1/dy|_{\pi-} \rightarrow$ positive, suggesting dominant effect of bayon stopping and coulomb interactions at low collision energies

Quark Matter 2023
https://indico.cern.ch/event/1139644/contributions/5502964/

[1] M. S. Abdallah et al. (STAR Collaboration), Phys. Lett. B 827 137003 (2022)
[2] Yasushi Nara, Akira Ohnishi. Phys. Rev. C. 105, 014911(2022)

Directed Flow Of Identified Hadrons At FXT Energies

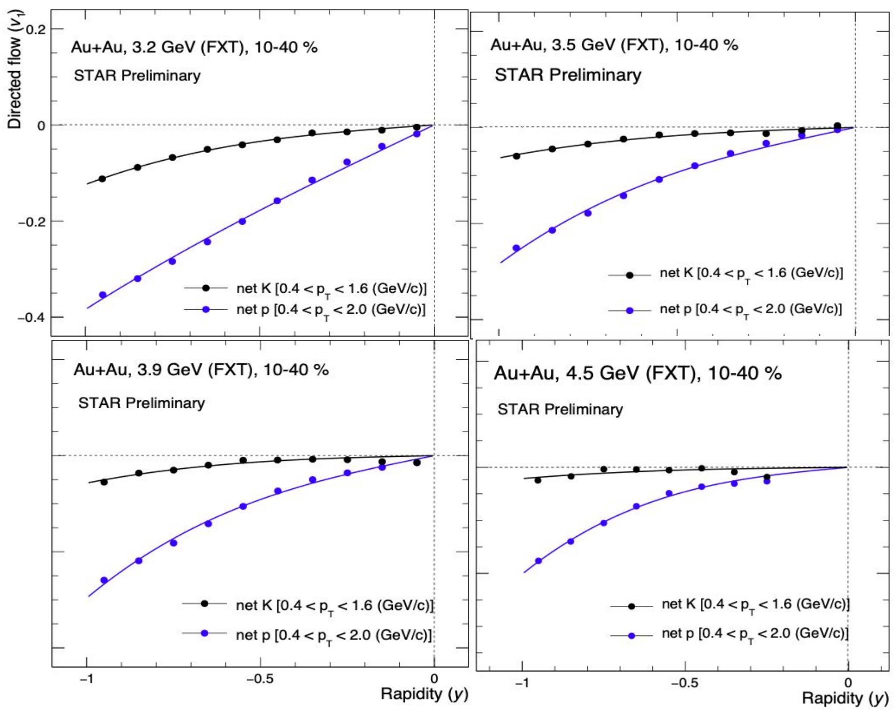


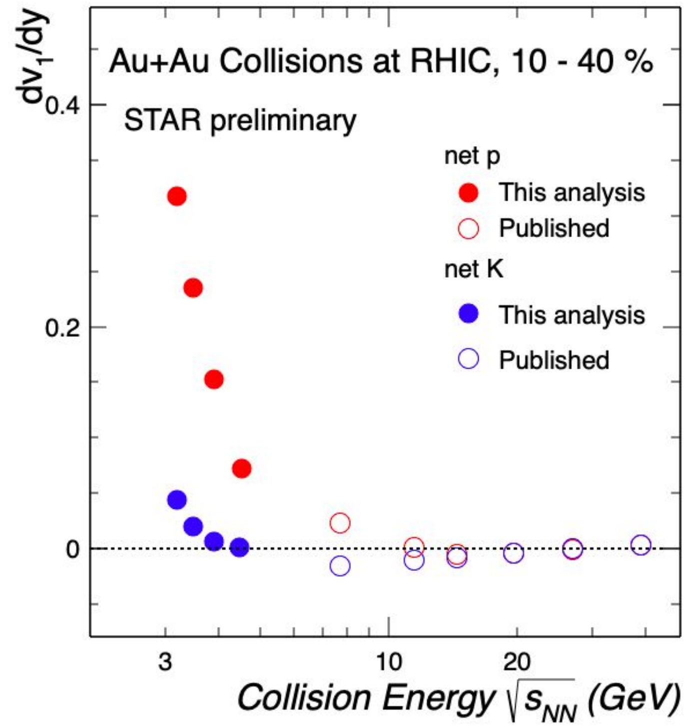
- **At low p_T**
  - $\pi^+(u\bar{d})$ and K^0_s $(d\bar{s})$ show negative v_1 slope
  - Anti-flow observed at 3 – 3.9 GeV
- **JAM** reproduces anti-flow at low p_T without incorporating kaon potential
- Anti-flow could be explained by shadowing effect from spectators

Quark Matter 2023
https://indico.cern.ch/event/1139644/contributions/5502964/

[1] M. S. Abdallah et al. (STAR Collaboration), Phys. Lett. B 827 137003 (2022)
[2] Yasushi Nara, Akira Ohnishi. Phys. Rev. C. 105, 014911(2022)

Directed Flow Of Net-particles At FXT Energies





- Net particle v_1 is defined as

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

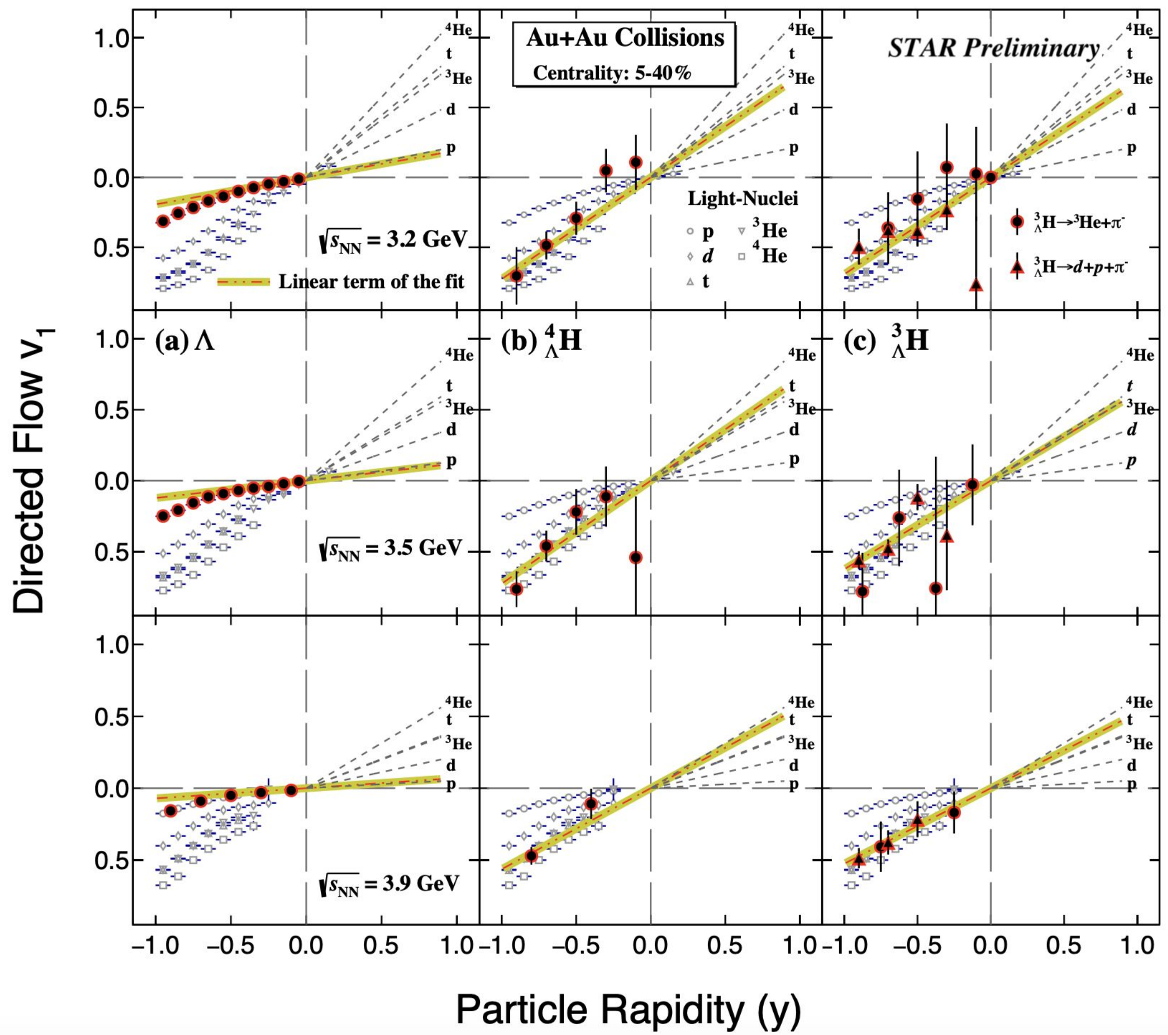
where $v_{1,p}$, $v_{1,\bar{p}}$ → particle and antiparticle v_1 and r is the ratio of anti-particles to particles

- Increasing collision energy → decreasing v_1 slope
- **Minimum net-p → (11.5-19.6 GeV) whereas minimum net-K → (4.5-7.7 Gev)**

L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 120, 062301 (2018)

ISMD 2023
https://indico.cern.ch/event/1258038/contributions/5535113/attachments/2700329/4686854/

Directed Flow Of Light- And Hyper-Nuclei At FXT Energies

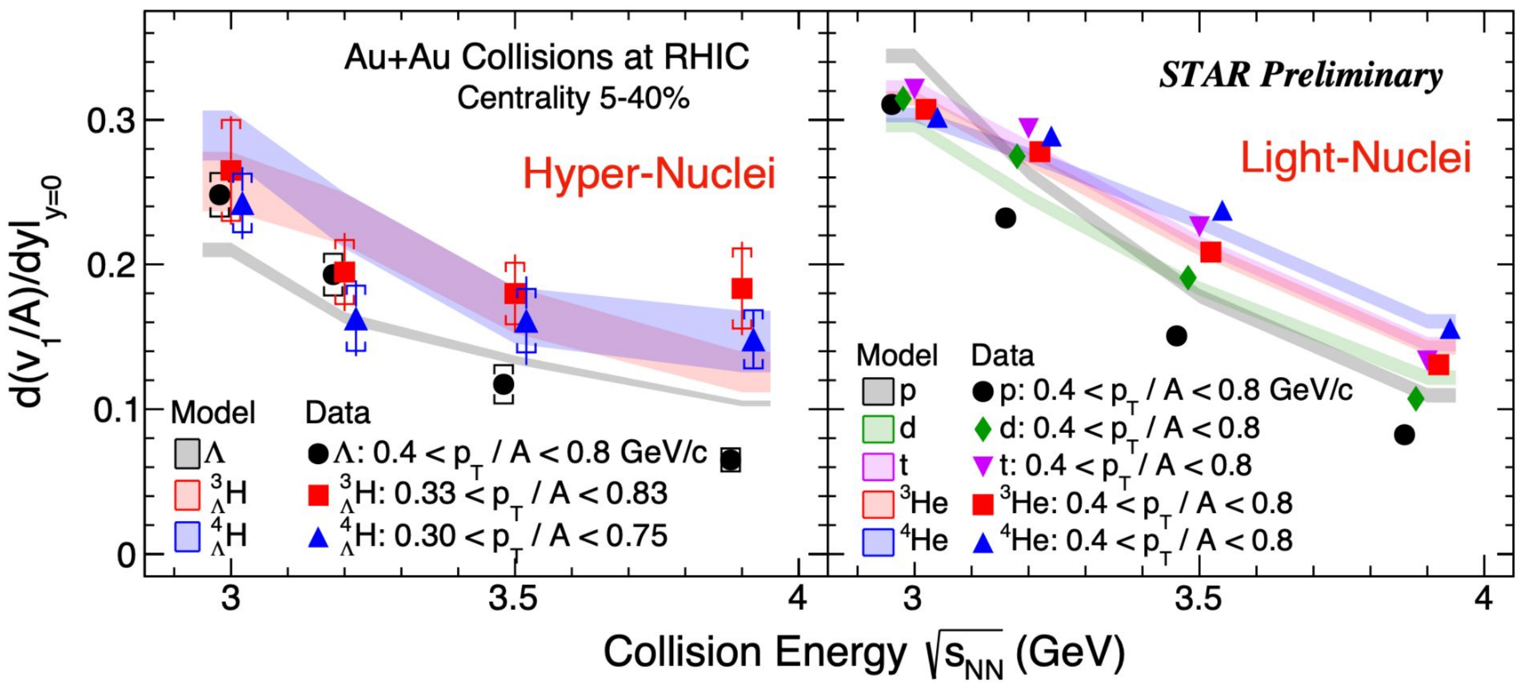


- v_1 increases in magnitude with increasing rapidity
- Magnitude of v_1 increases with increasing mass of the particle
- Hypernuclei v_1 follows similar trends as the light nuclei with the same mass number.

Quark Matter 2023
https://indico.cern.ch/event/1139644/contributions/5503055/

[1] M.S. Abdallah et al., (STAR Collaboration), Phys. Lett. B 827, 136941 (2022)
[2] B. E. Aboona et al., (STAR Collaboration), Phys. Rev. Lett. 130, 211301(2023)

Directed Flow Of Light- And Hyper-Nuclei At FXT Energies



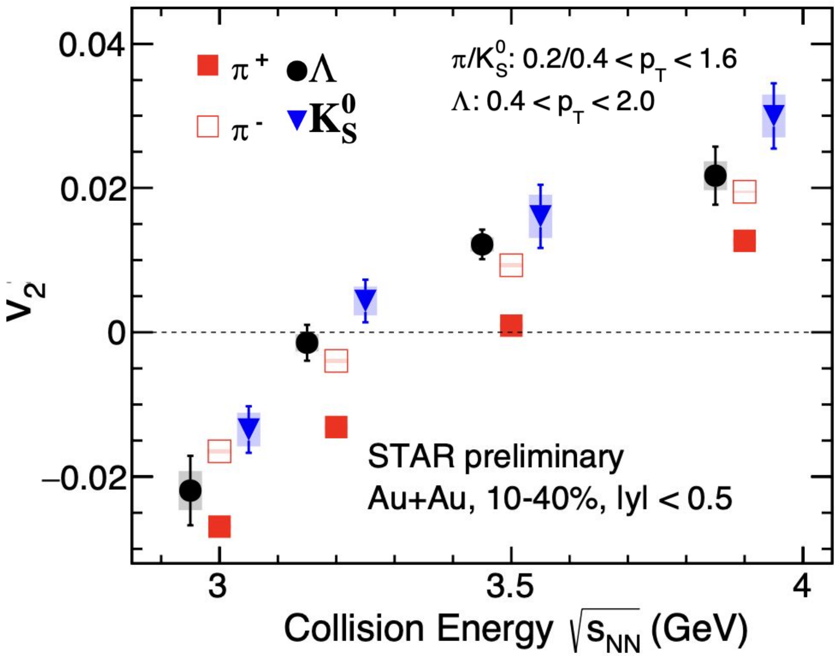
- As the collision energy increases, the v_1 slope of light- and hyper-nuclei decreases
- At given energy, for both light- and hyper-nuclei, it seems that the slopes of mid-rapidity v_1 are scaled with atomic mass number (A)
- Hadronic transport model (JAM2 mean field + Coalescence) calculations are consistent with observed energy dependence
- The results for light- and hyper-nuclei v_1 favor coalescence as their production mechanism

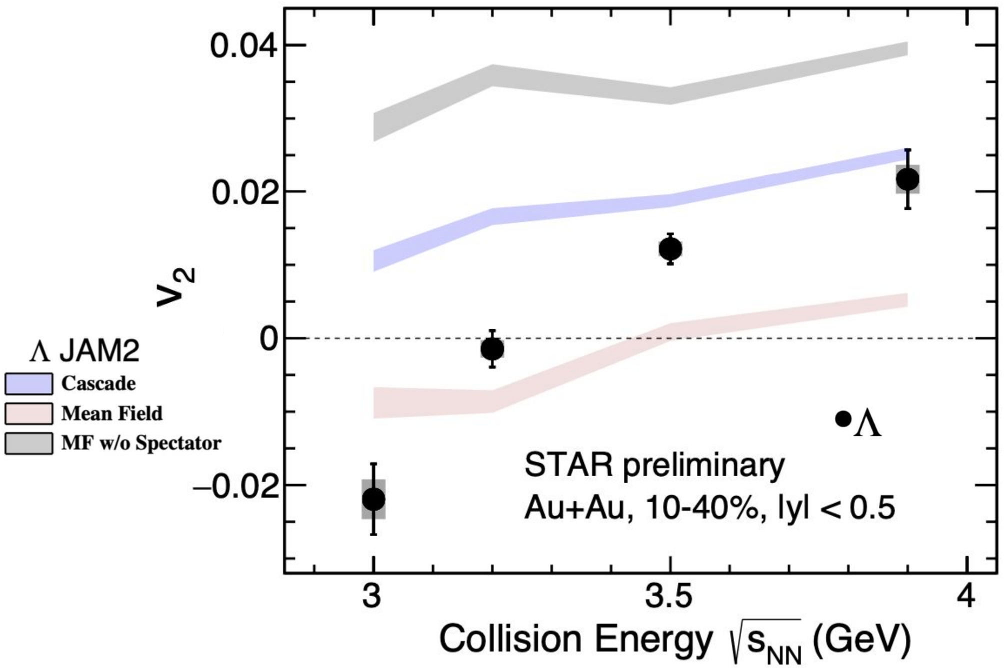
Quark Matter 2023
https://indico.cern.ch/event/1139644/contributions/5503055/

[1] M.S. Abdallah et al., (STAR Collaboration), Phys. Lett. B 827, 136941 (2022)
[2] B. E. Aboona et al., (STAR Collaboration), Phys. Rev. Lett. 130, 211301(2023)
[3] Yasushi Nara, Akira Ohnishi. Phys. Rev. C. 105, 014911(2022)

Elliptic Flow (v_2) Results

Elliptic Flow Of Identified Hadrons At FXT Energies





- Negative v_2 turns positive with collision energy
  - Out-of-plane flow (spectator effect) → in-plane flow
  - Shadowing effect decreases with increasing energy
- **JAM** baryonic mean-field with spectator shows sign change of v_2
  - Mean-field and spectator shadowing play important roles
  - Hadronic interaction dominate

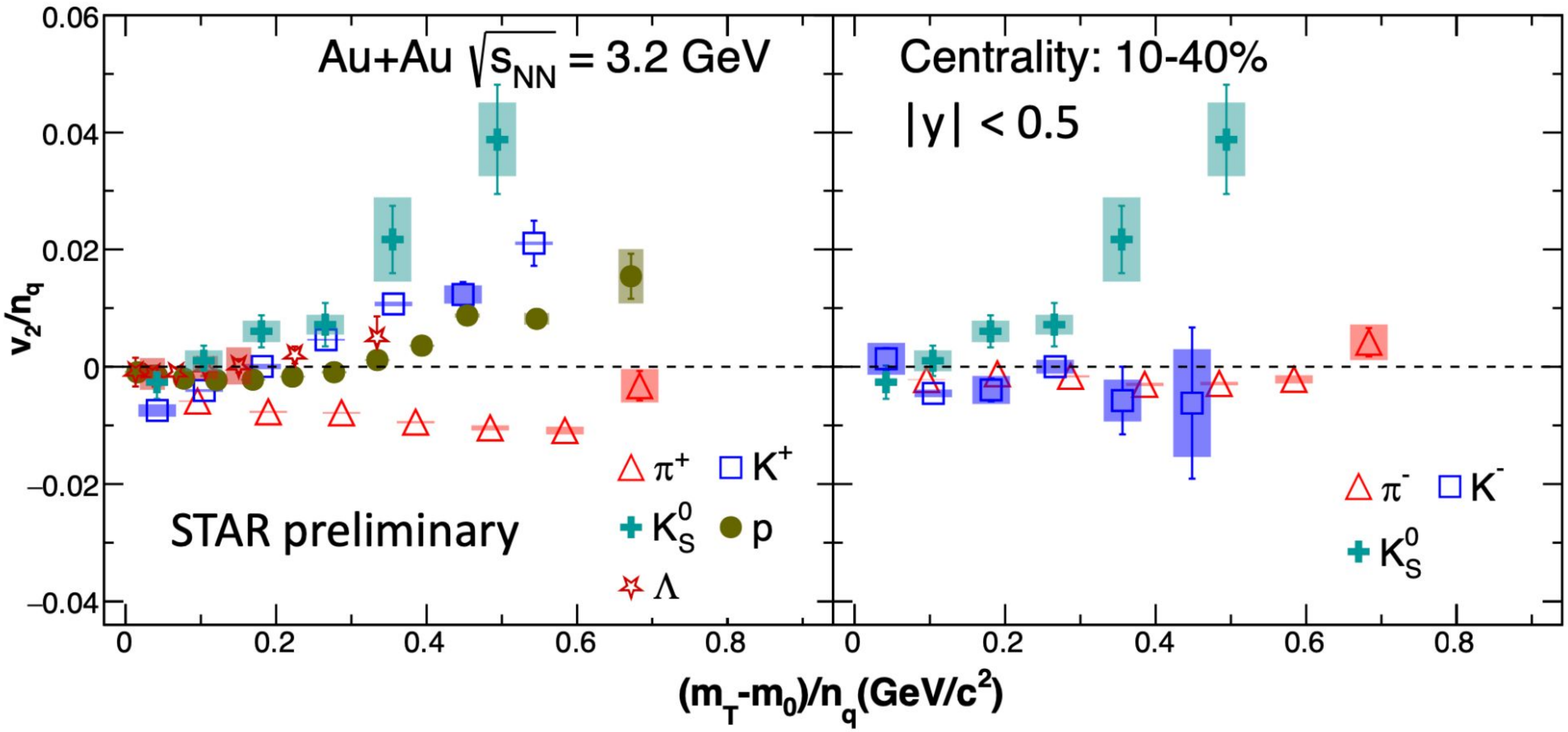
JET AA Microscopic Transportation Model (JAM2)

- **MD2**: momentum dependent mean-field potential
- Incompressibility constant **κ** = 380 MeV

Quark Matter 2023
https://indico.cern.ch/event/1139644/contributions/5502964/

[1] M. S. Abdallah et al. (STAR Collaboration), Phys. Lett. B 827 (2022) 137003
[2] Yasushi Nara, Akira Ohnishi. Phys. Rev. C. 105, 014911(2022)

Elliptic Flow Of Identified Hadrons At FXT Energies



- NCQ scaling broken completely at 3.2 GeV
  - Indication of the disappearance of partonic collectivity

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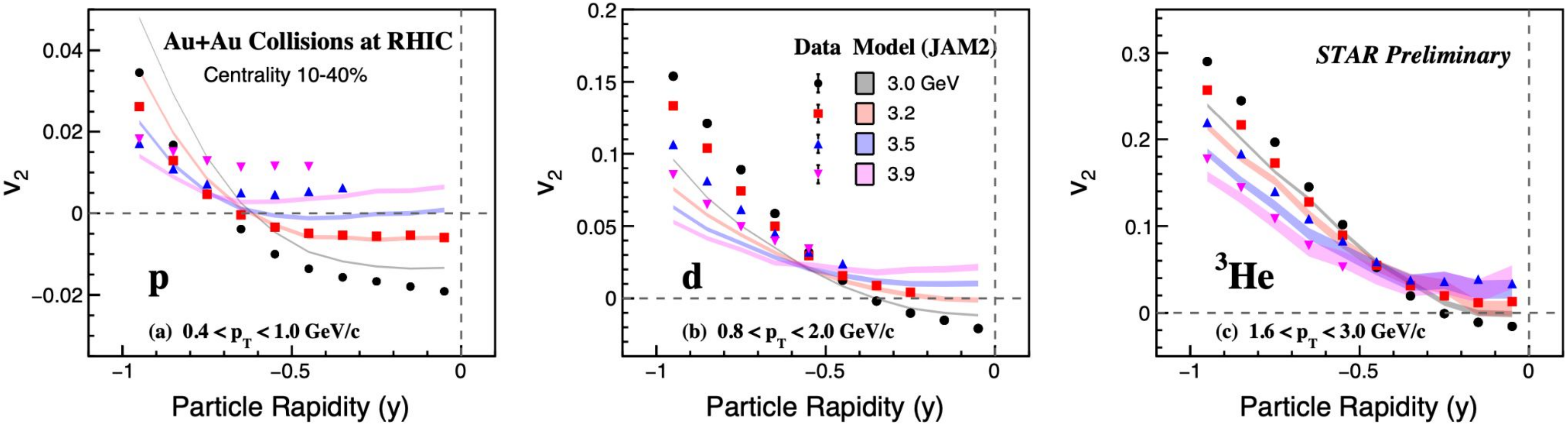
Elliptic Flow Of Light-Nuclei At FXT Energies



- Light-Nuclei elliptic flow (v_2) measurements in 10-40% mid-central Au+Au Collisions at $\sqrt{s_{NN}}$= 3.0, 3.2, 3.5, 3.9 GeV
- v_2 measurements at mid-rapidity indicate an out-of-plane expansion ($v_2 < 0$) at the lowest collision energy, whereas in-plane expansions ($v_2 > 0$) are evident at higher collision energies

JET AA Microscopic Transportation Model (JAM2)

- **MD2** (momentum dependent mean-field potential) + **Coalescence**
- Incompressibility constant κ = 380 MeV

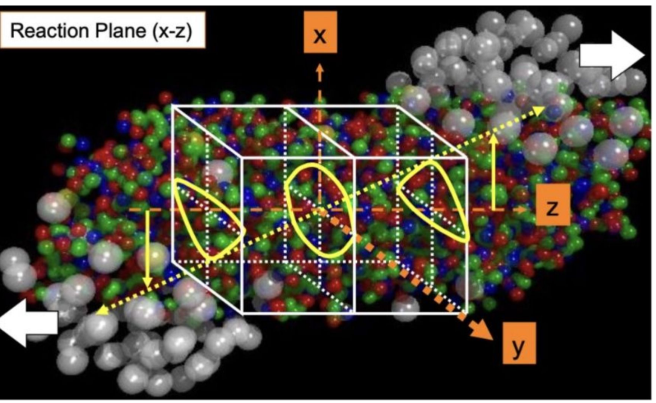
Quark Matter 2023
https://indico.cern.ch/event/1139644/contributions/5503055/

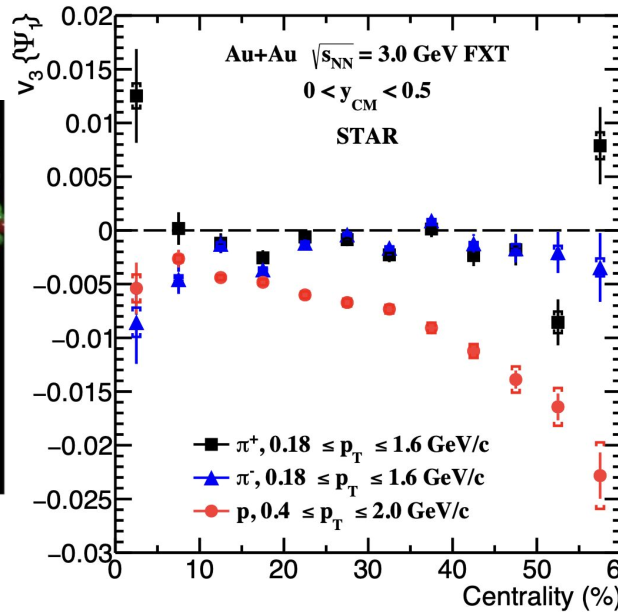
[1] M.S. Abdallah et al., (STAR Collaboration), Phys. Lett. B 827, 136941 (2022)
[2] Y. Nara *et al.*, Phys. Rev. C **106**, 044902 (2022)

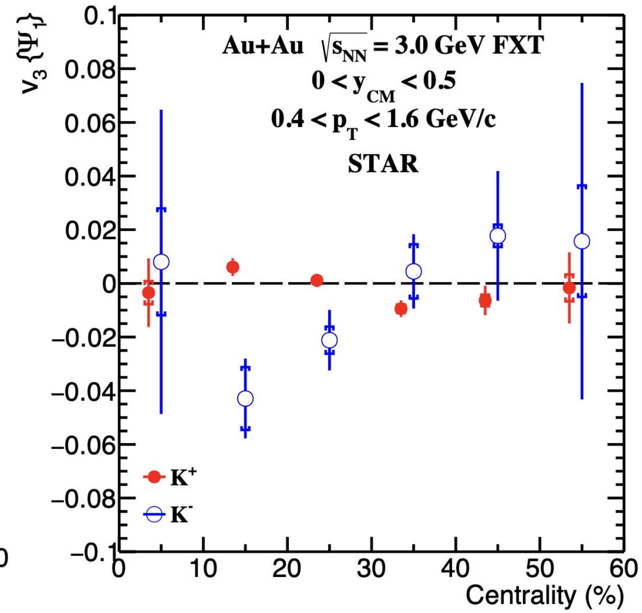
Triangular Flow (v_3) Results

Triangular Flow Of Identified Hadrons At FXT Energies

- v_3 at higher energies results from fluctuations in shape of the initial condition and is not correlated to the reaction plane
- Contrary to observations at higher energy v_3 is correlated to first order reaction plane at **2.4 GeV (HADES) and 3 GeV (STAR)**





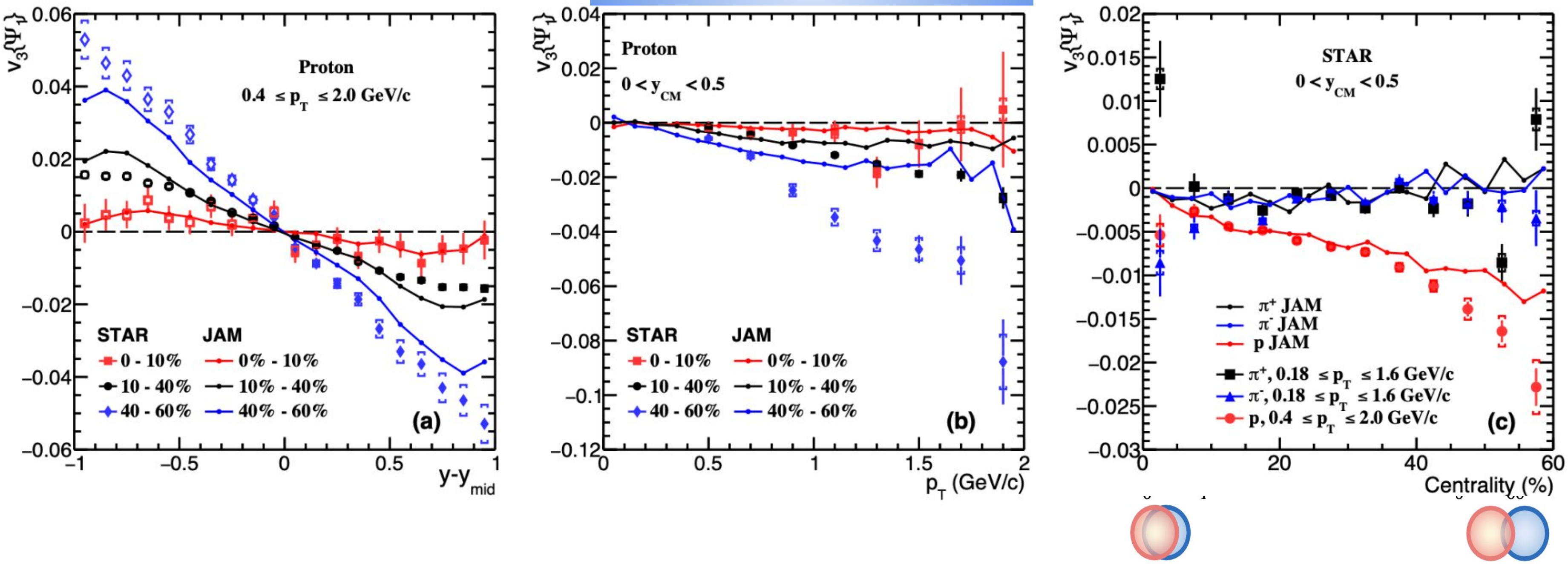


- $v_3\{\Psi_1\}$ for pions → slightly negative, protons exhibit a significant negative signal increasing with centrality.
- $v_3\{\Psi_1\}$ for K^+ is consistent with zero, while the available statistics for K^- do not allow for a definitive conclusion

(STAR Collaboration) arXiv: 2309.12610 [nucl-ex] (2023)

Triangular Flow Of Proton At FXT Energies

Au+Au $\sqrt{s_{NN}}$ = 3.0 GeV FXT



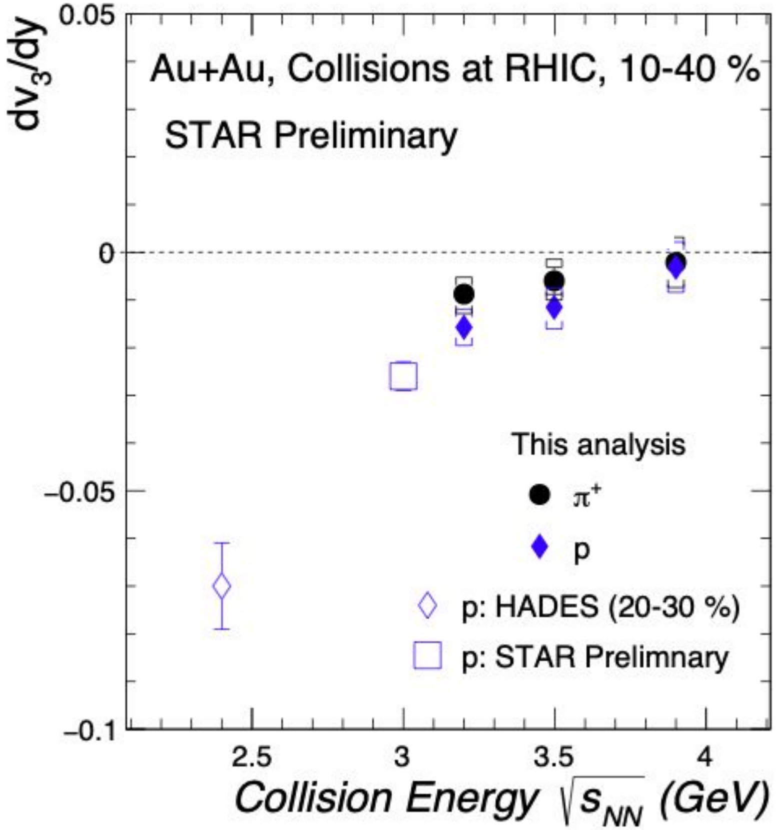
- $|v_3\{\Psi_1\}|$ increases with increasing rapidity and p_T
- $|v_3\{\Psi_1\}|$ increases towards peripheral collisions → strong geometric effect
- **JAM** model with mean-field describes the data → Nuclear potential is essential for the development of $|v_3\{\Psi_1\}|$

JET AA Microscopic Transportation Model (JAM2)

- **MD2**: momentum dependent mean-field potential
- Incompressibility constant **κ** = 380 MeV

(STAR Collaboration) arXiv: 2309.12610 [nucl-ex] (2023)

Collision Energy Dependence Of v_3 Slope At FXT Energies



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 ($b = dv_3/dy$)

  $v_3(y) = by + cy^3$
- Increasing collision energy → decreasing magnitude of v_3 slope

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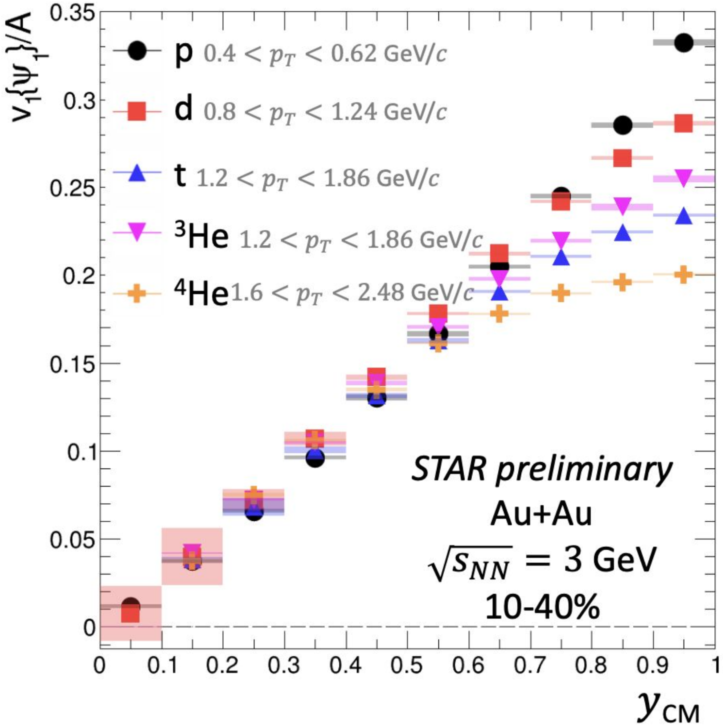
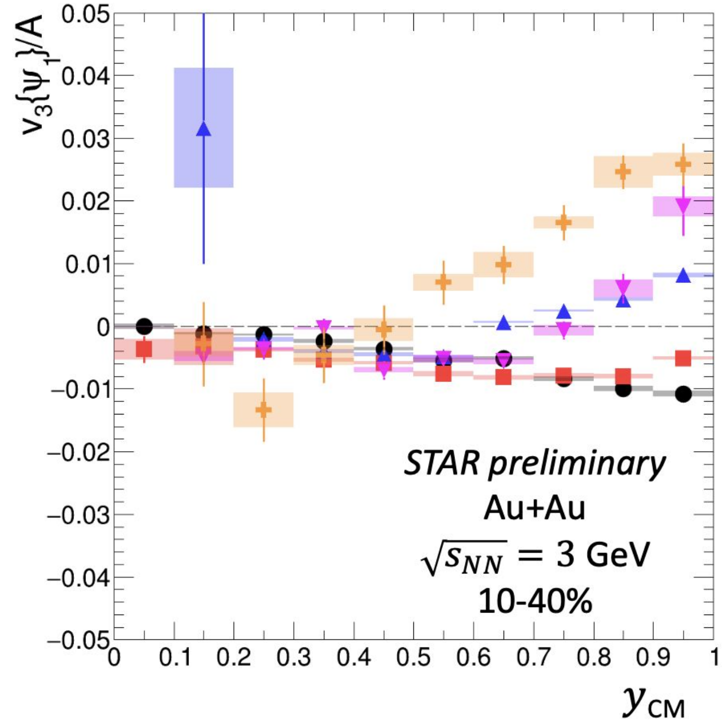
(HADES) Phys. Rev. Lett. 125, 262301 (2020)

Triangular Flow Of Light Nuclei At FXT Energies





- An approximate mass no. (A) scaling of $|v_3\{\Psi_1\}|$ holds at $y_{cm} < 0.5$ in 10 − 40% at $\sqrt{s_{NN}}$ =3 GeV → the production of light nuclei comes from coalescence of nucleons
- However, this A-scaling of v_1 and $|v_3\{\Psi_1\}|$ breaks for $y_{CM} > 0.5$.

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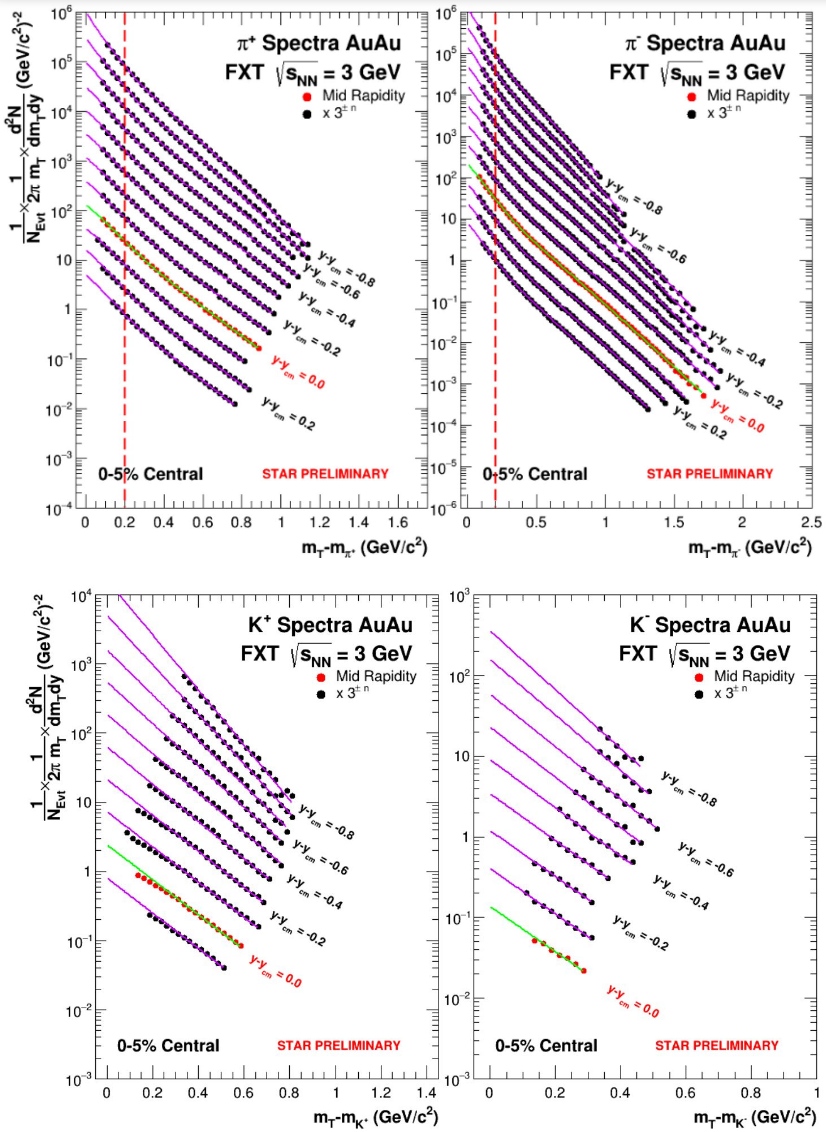
Transverse Momentum Spectra Results At FXT Energies

Identified Hadron Spectra



- Particle yields are extracted from fitting dE/dx from TPC and 1/β from ToF
- Pion spectra is well described by double thermal function, which describes thermal production at high $m_T - m_0$ and production from Δ resonance at low $m_T - m_0$
- Kaon spectra is fit with m_T exponential function since Bose-Einstein enhancement and radial flow effects mostly cancel

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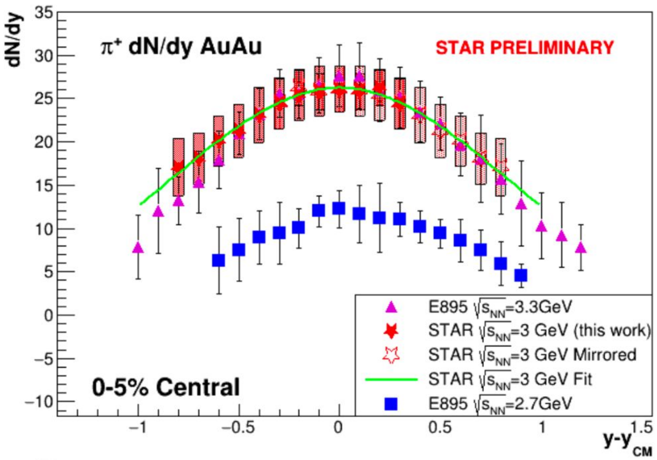
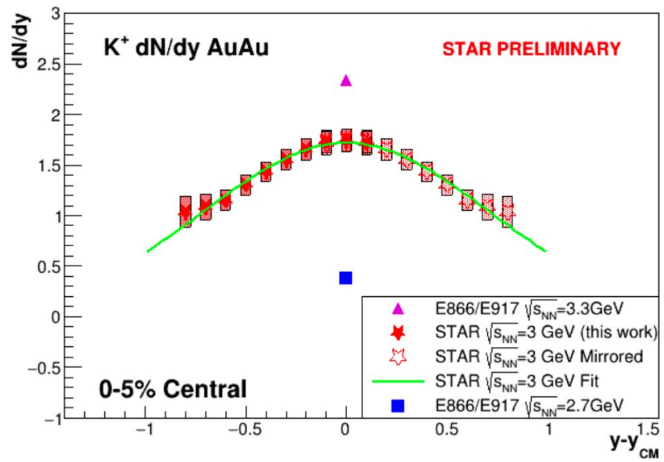
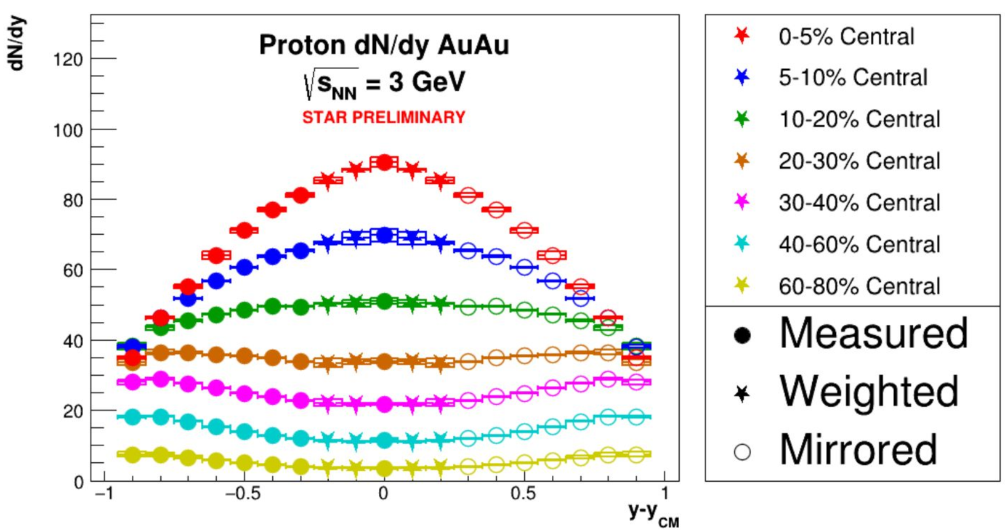
https://indico.cern.ch/event/895086/contributions/4717017/

J. Klay et al. (E895 Collaboration), Phys. Rev. C 68, 054905 (2003)

Rapidity Density Distributions (Identified Hadrons)





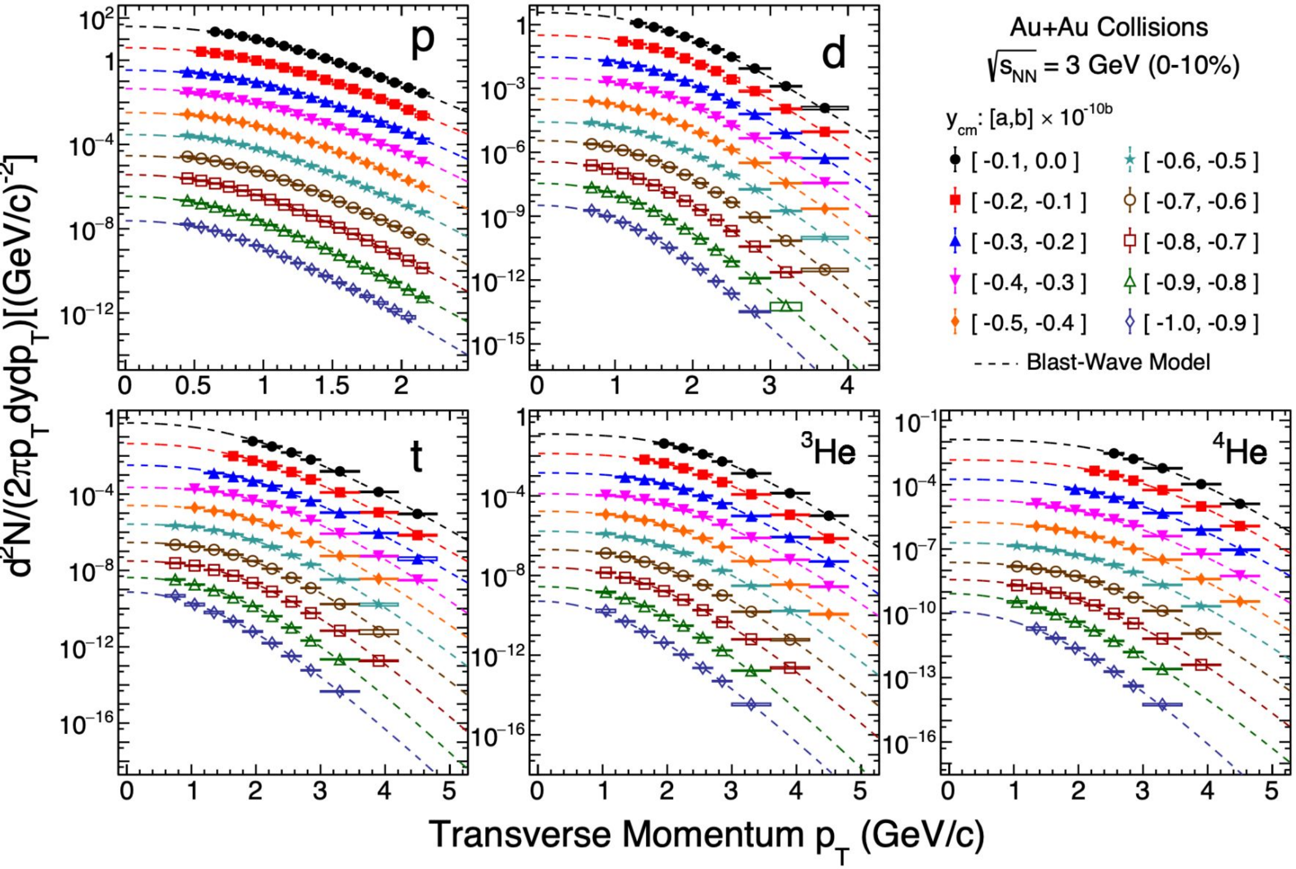


- Kaon yield follows the energy dependence, compared to E866/E917, while pion yields are close to E895 measurements at 3.3 GeV
- Centrality dependence for proton yield shows that the peak shifting away from mid-rapidity for more peripheral collisions, indicating less baryon stopping

[1] J. Klay et al. (E895 Collaboration), Phys. Rev. C 68, 054905 (2003)
[2] L. Ahle et al. (E866 and E917 Collaborations), Phys. Lett. B490, 53 (2000)

Quark Matter 2022
https://indico.cern.ch/event/895086/contributions/4717017/

Transverse Momentum Spectra Of Light Nuclei



➢ Transverse momentum spectra of *p*, *d*, *t*, ^{3}He, and ^{4}He with rapidity slices in central (0-10%) Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV

➢ Blast-Wave Function

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

$$\rho = \tanh^{-1}\beta_r, \quad \beta_r(r) = \beta_T\left(\frac{r}{R}\right)^n$$

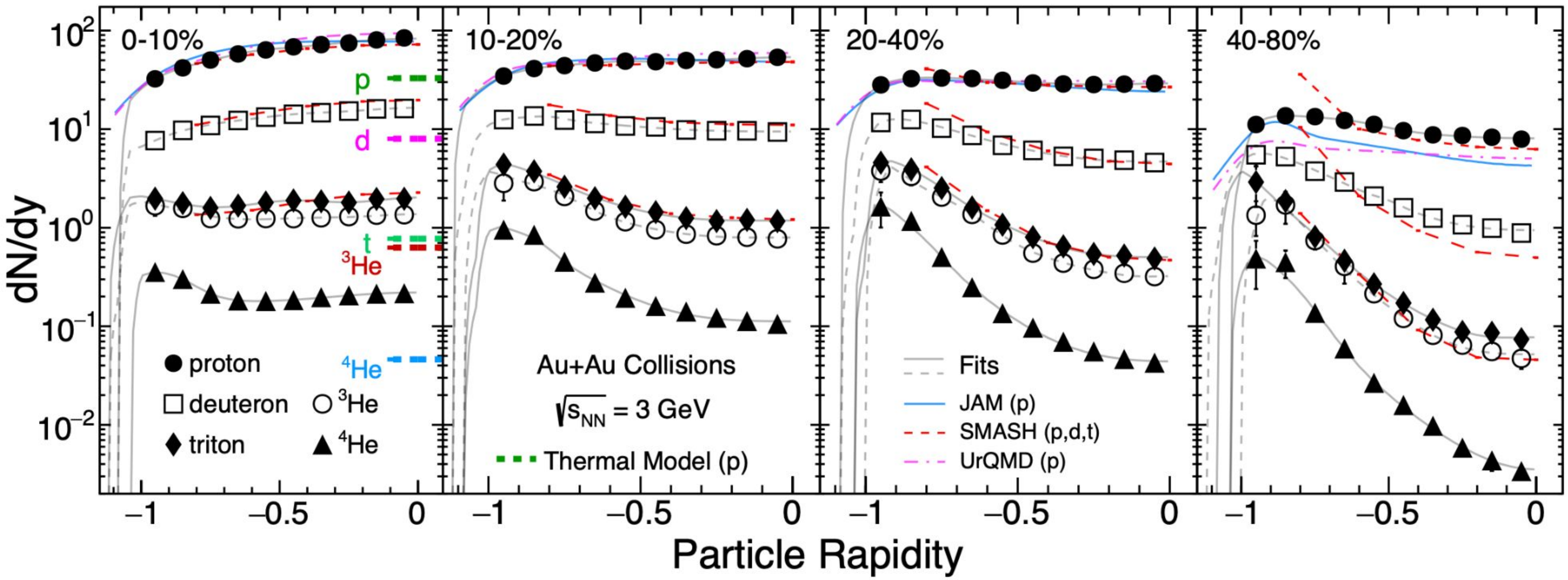
Freeze-out parameters:

T_{kin} : kinetic freeze-out temperature
$\langle\beta_T\rangle$: average radial flow velocity

n : n=1 (I_0 and K_1 are from Bjorken Hydrodynamic assumption)

(STAR Collaboration) arXiv:2311.11020 (2023)
E. Schnedermann et al. Phys.Rev.C 48 2462-2475 (1993)

Centrality & Rapidity Dependence of Yields



- dN/dy of protons and light nuclei show significant centrality and rapidity dependence
- Yields of *d* and *t* are described by the SMASH + Coal. model except the 40-80% centrality bin
- dN/dy of *p* is reproduced by the SMASH, JAM, and UrQMD models in centrality bins: 0-10%, 10-20%, and 20-40%

[1] (STAR Collaboration) arXiv:2311.11020 (2023)
[2] J. Weil et al. Phys.Rev.C 94 (2016) 5, 054905
[3] W. Zhao et al. Phys.Rev.C 98 (2018) 5, 054905

Summary

STAR

- Anti-flow observed for meson at low p_T in Au+Au collisions at 3 – 3.9 GeV possibly by shadowing effect from spectators
- Approximate mass no. scaling in v_n for light- and hyper-nuclei is observed favouring the nucleon coalescence
- Hadronic transport model gives a better description to the experimental data for identified hadrons as well as light nuclei.

- v_2 at mid-rapidity shows clear energy dependence → At higher collision energy, the effect of the spectator shadowing becomes weaker and expansion becomes in-plane ($v_2 > 0$)
- The NCQ scaling broken completely at 3.2 GeV
- The hadronic transported model JAM2 with mean field potential qualitatively describe the v_2 data

- Nonzero $v_3\{\Psi_1\}$, stronger in peripheral than central collisions → $v_3\{\Psi_1\}$ is driven by the geometry
- Comparison with JAM suggests potential is essential for the development of $v_3\{\Psi_1\}$

- Strong centrality and rapidity dependences observed for p_T spectra of identified hadrons and light nuclei
- Peak of dN/dy distribution for proton shifts away from mid-rapidity for more peripheral collisions, indicating indicating centrality-dependent baryon stopping
- Hadronic transport models (JAM, SMASH and UrQMD)+Coalescence reproduce the mid-rapidity (proton) light nuclei yields

Stay tuned for more exciting results from BES-II and FXT runs at STAR!

Thank you for your attention!