Observation of Strong Directed Flow for ϕ meson in the High Baryon Density Region at RHIC

Guangyu ZHENG (for the STAR collaboration)

University of Chinese Academy of Sciences

October 24-28, 2025

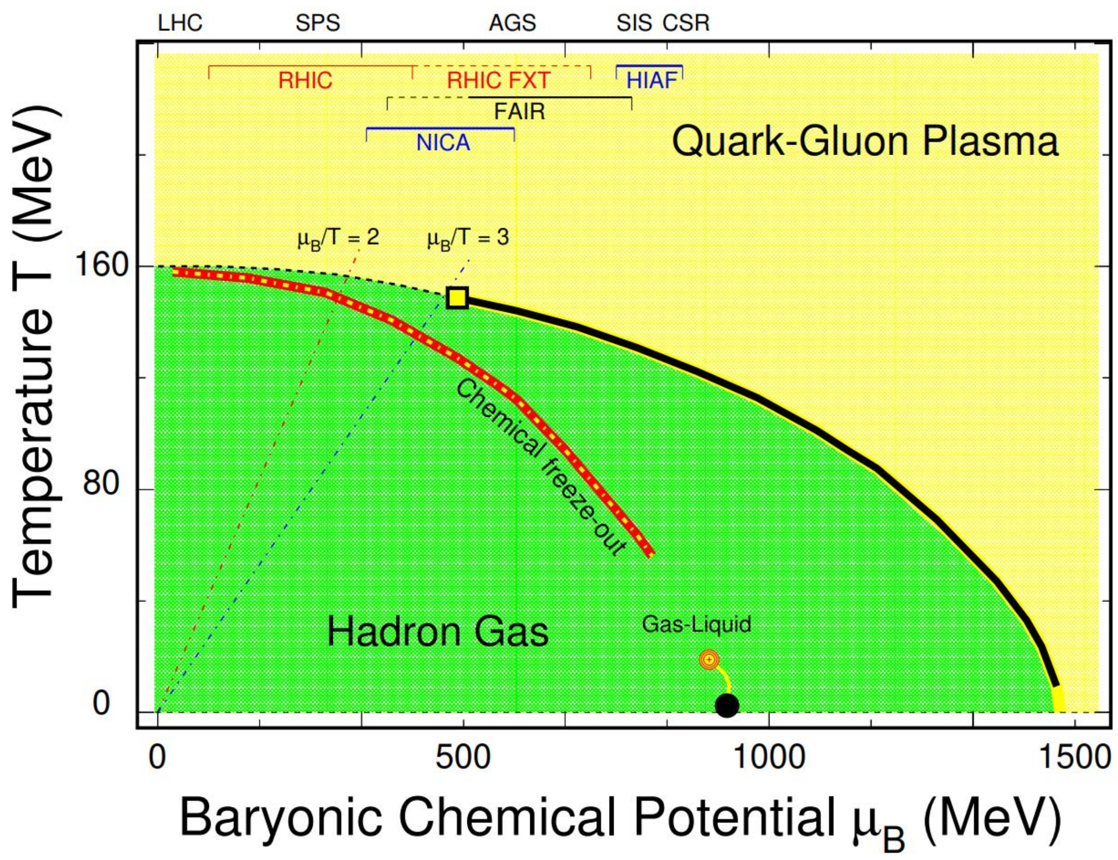
Supported in part by

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Introduction
- Experimental Setup
- Analysis Method
- Result and Discussion
- Summary

Introduction



A. Bzdak et al., Phys. Rept. 853, 1 (2020); X. Luo et al., Particles 3, 278 (2020)

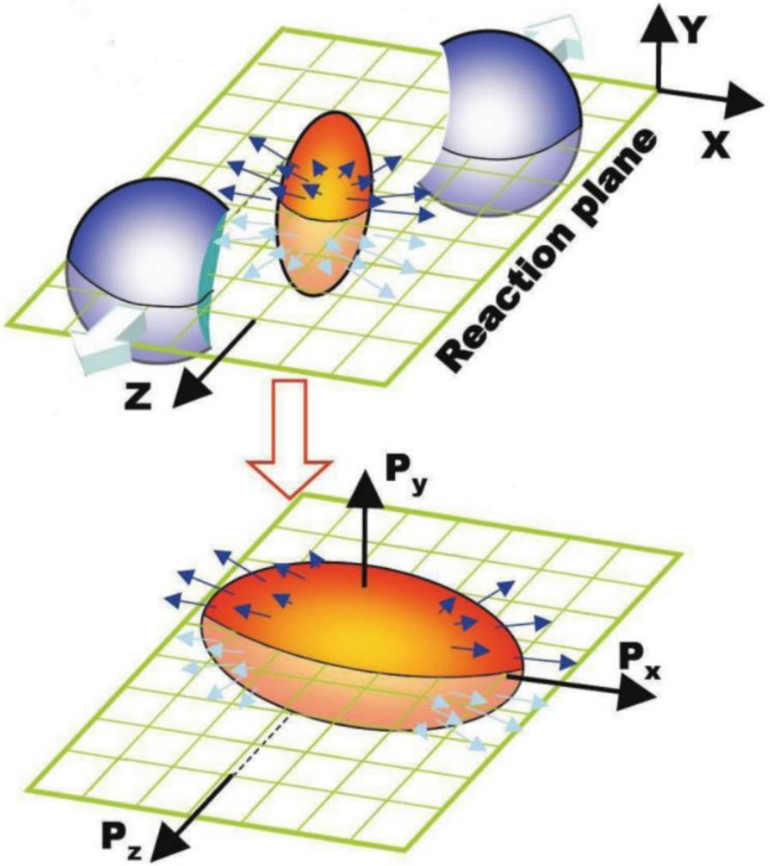
➢ Beam energy scan program

- Study properties of the QCD matter
- Locate possible QCD phase boundary

- Collider Runs(7.7-62.4 GeV, μ_B: 420-73 MeV)

- Fixed-Target Runs(3.0-13.7 GeV, μ_B: 750-270 MeV)

Anisotropic Flow



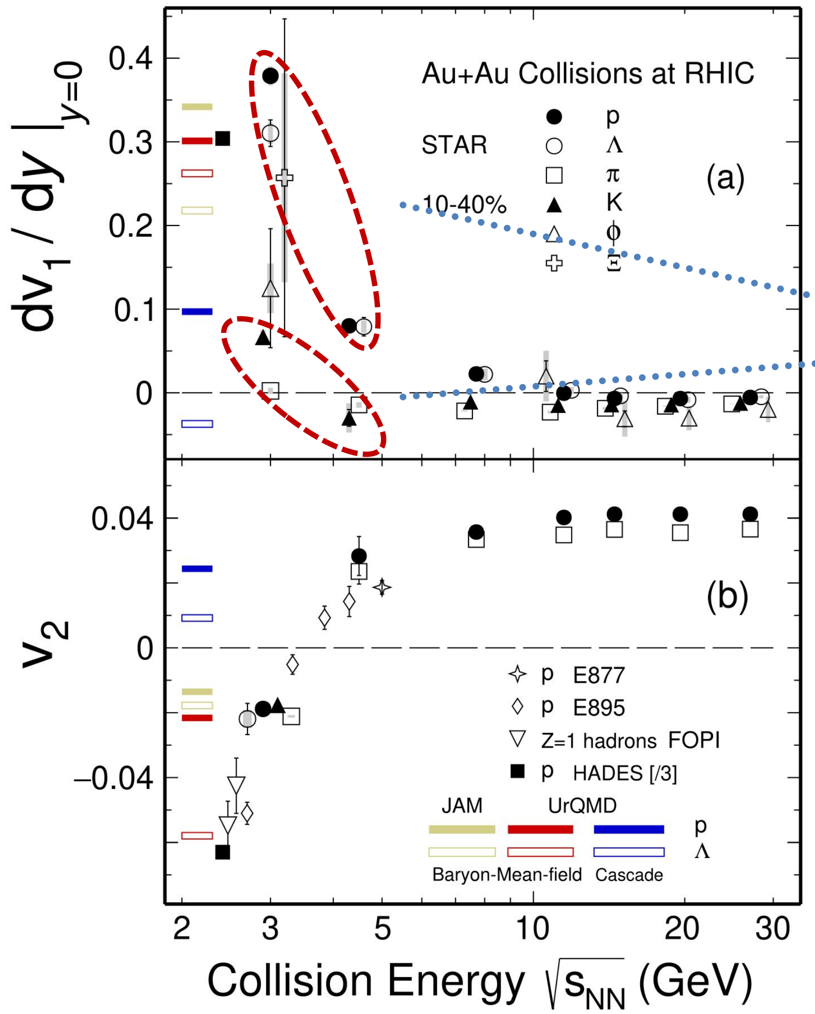
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1+\sum_1^{\infty} 2v_n \cos[n(\phi-\Psi_{RP})])$$

$$v_1 = \langle cos(\phi-\Psi_{RP})\rangle = \langle\frac{p_x}{p_T}\rangle$$ Directed flow

$$v_2 = \langle cos[2(\phi-\Psi_{RP})]\rangle = \langle\frac{p_x^2-p_y^2}{p_T^2}\rangle$$ Elliptic flow

- Directed flow originates mainly from the "sideward push" of compressed nuclear matter → sensitive to the compressibility of the system.
- A sensitive probe for:
  - Early-time dynamics
  - Equation of State (EoS) of the created medium.

v_1 Slope for Baryons and Mesons

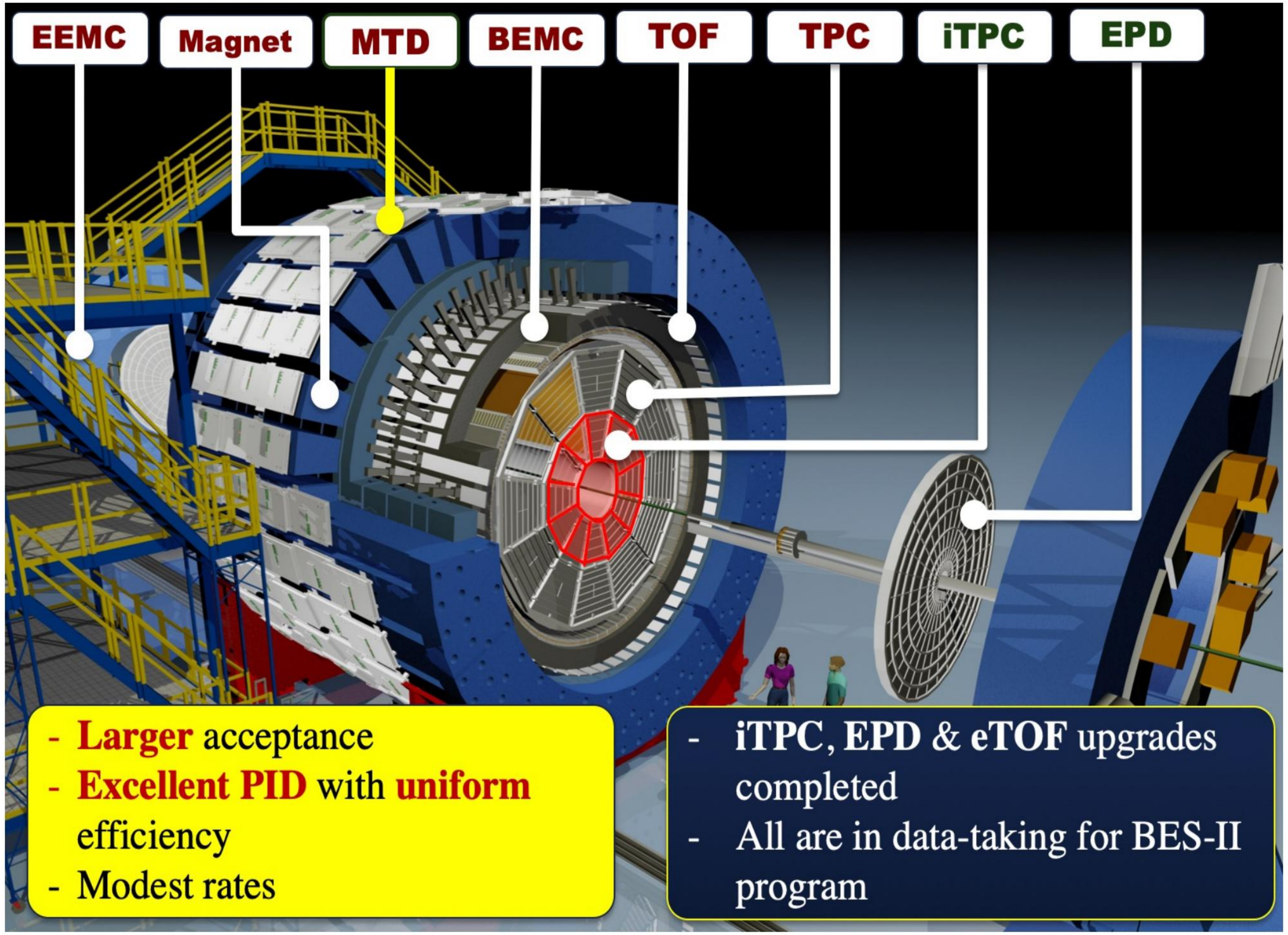


STAR, Phys.Lett.B 827 (2022) 137003

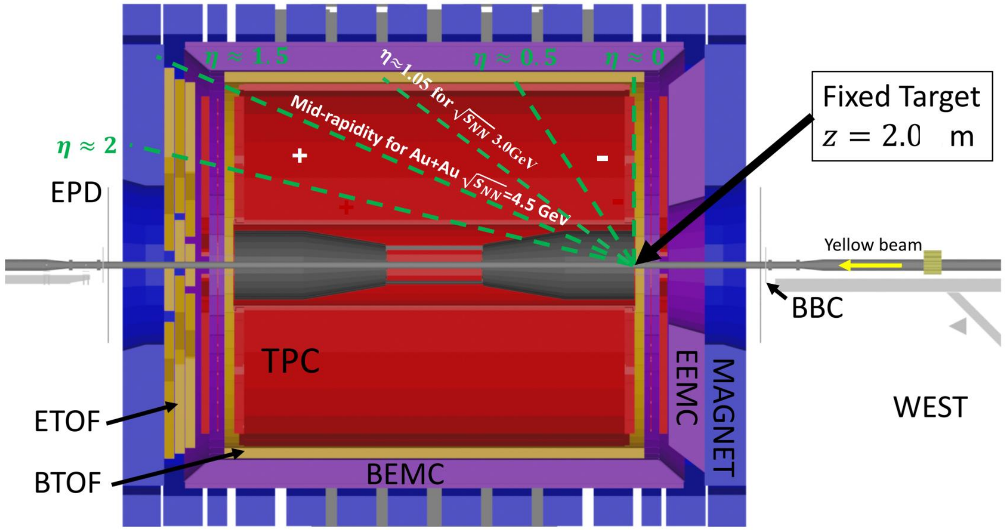
- BES-I (STAR) measured mid-rapidity v_1 for π, K , (anti-)protons, ϕ and (anti-) Λ over a wide energy range.
- Increasing difference in the v_1 slope below 4.5 GeV for baryons (proton, Λ) and mesons (π, K)
  - Baryonic mean field?
  - Mass ordering?
  - Different hadronic cross sections?
- ϕ meson is an ideal probe for early-stage dynamics
  - Meson with close mass to baryons(proton, Λ)
  - Small hadronic cross section and long lifetime(~46fm/c)

STAR, Phys. Rev. Lett. 118, 212301 (2017)
B. Mohanty, N. Xu, Journal of Physics G 36, 064022 (2009)

STAR Experimental Setup



- **STAR Detector Upgrade:**
  - Inner-Time Projection Chamber: Better track quality, Larger acceptance
  - Endcap Time Of Flight: Particle identification
  - Event Plane Detector: Event plane determination (2.1< |η| < 5.1)



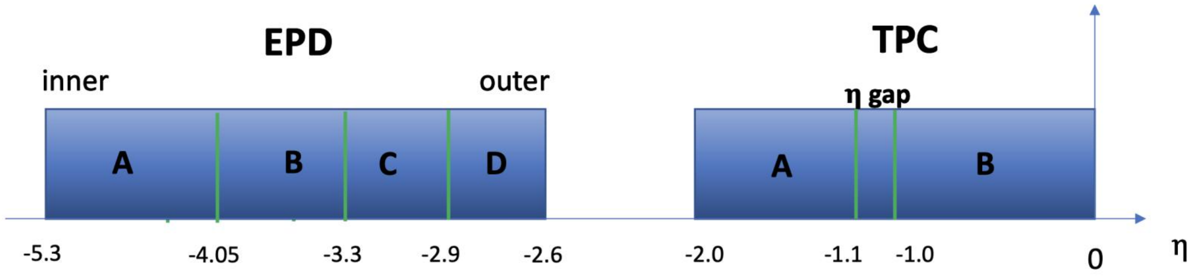
Event Plane Reconstruction

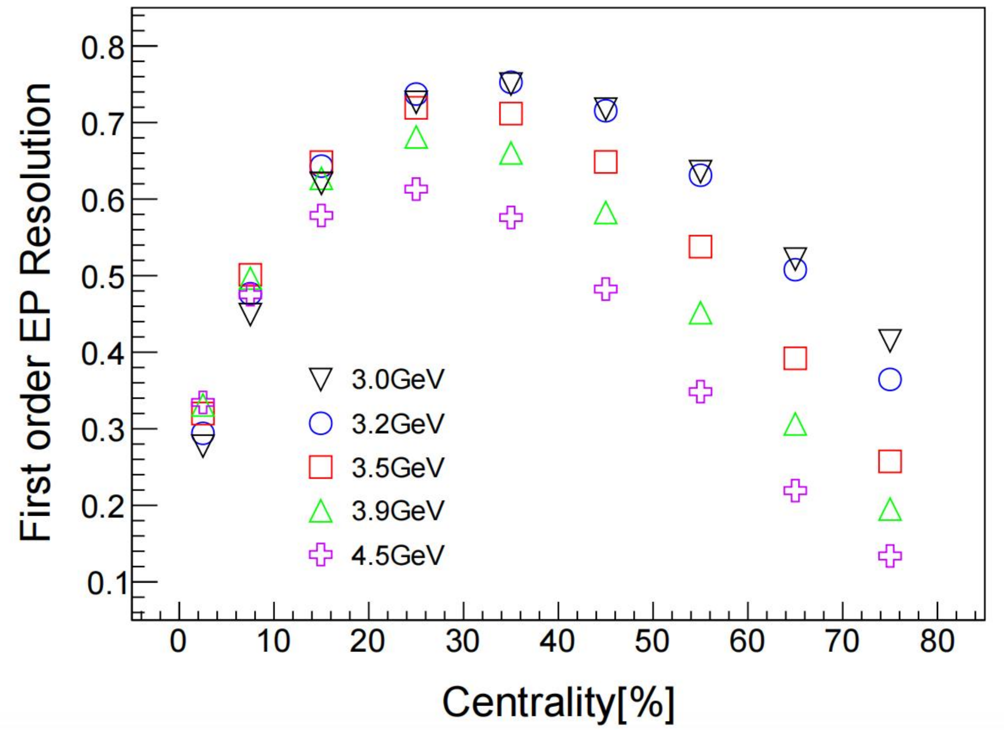
A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C58, 1671 (1998)

- The n^{th} harmonic event plane was calculated as:
- Due to the asymmetry of phase space acceptance in FXT, 3-sub event method is used for event plane resolution calculation.

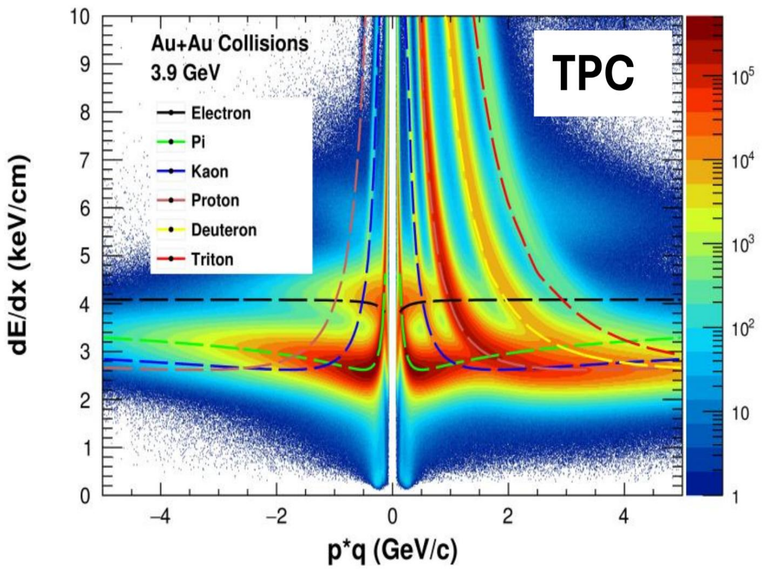
$$\vec{Q} = \begin{pmatrix} Q_y \\ Q_x \end{pmatrix} = \begin{pmatrix} \sum_i w_i \sin(n\phi_i) \\ \sum_i w_i \cos(n\phi_i) \end{pmatrix} \qquad \Psi_n = \tan^{-1}\left(\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}\right)/n$$

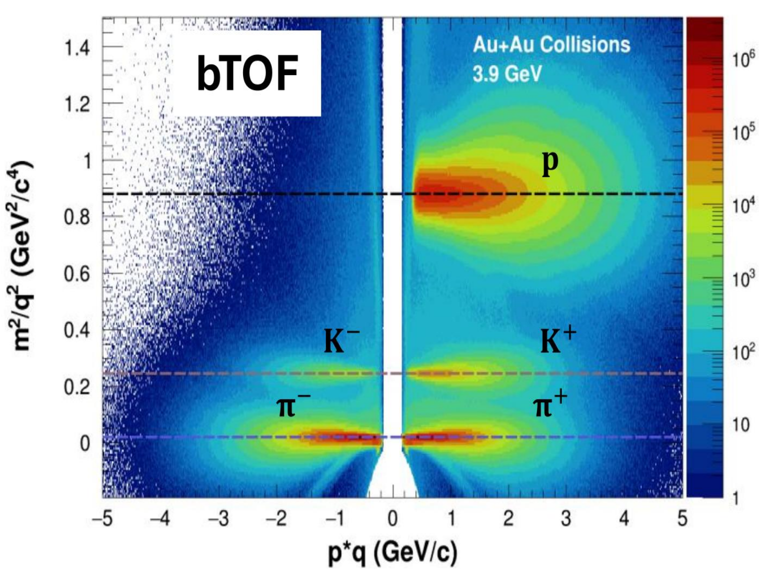
$$R_1 = \sqrt{\frac{\langle \cos(\Psi_1^a - \Psi_1^b)\rangle \langle \cos(\Psi_1^a - \Psi_1^c)\rangle}{\langle \cos(\Psi_1^b - \Psi_1^c)\rangle}} \qquad v_1 = \frac{v_1^{obs}}{R_1} = \frac{\langle cos(\phi - \Psi_1)\rangle}{\langle cos(\Psi_1 - \Psi_r)\rangle}$$

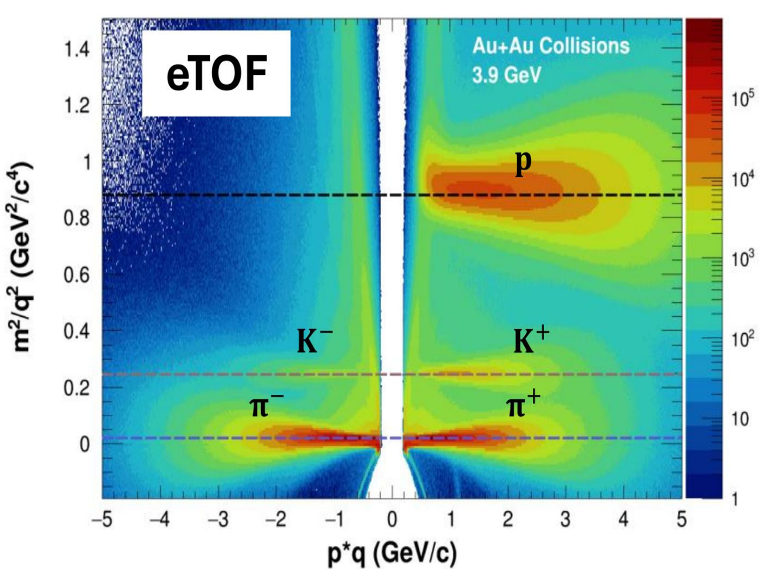




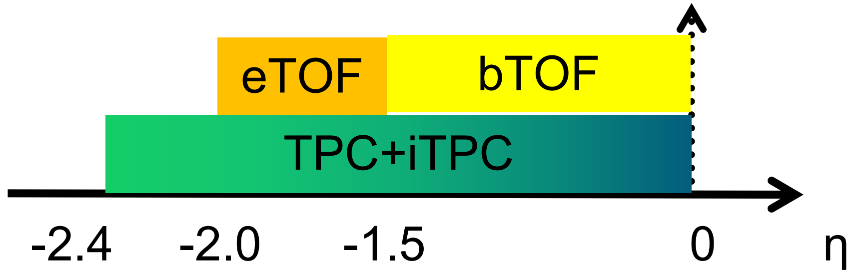
Particle Identification



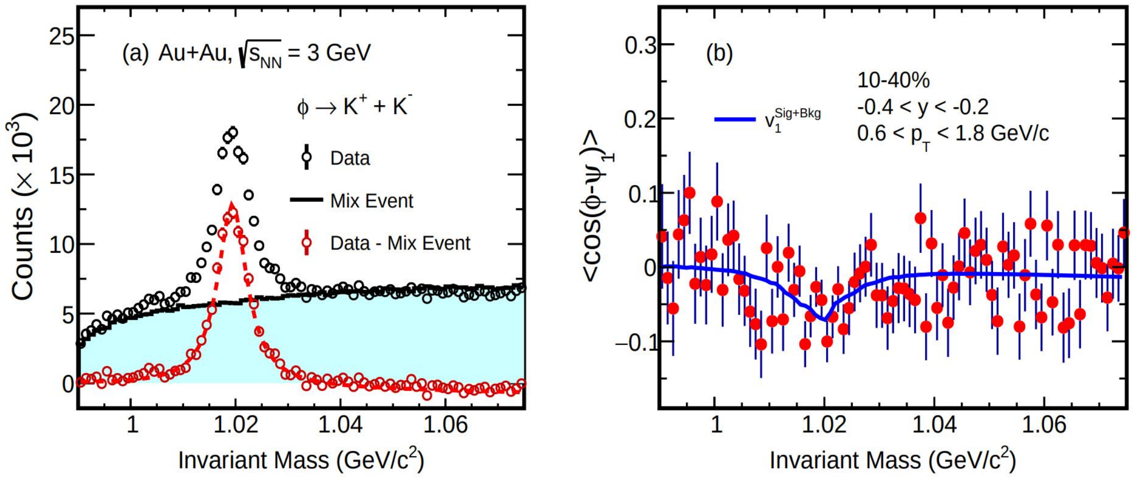


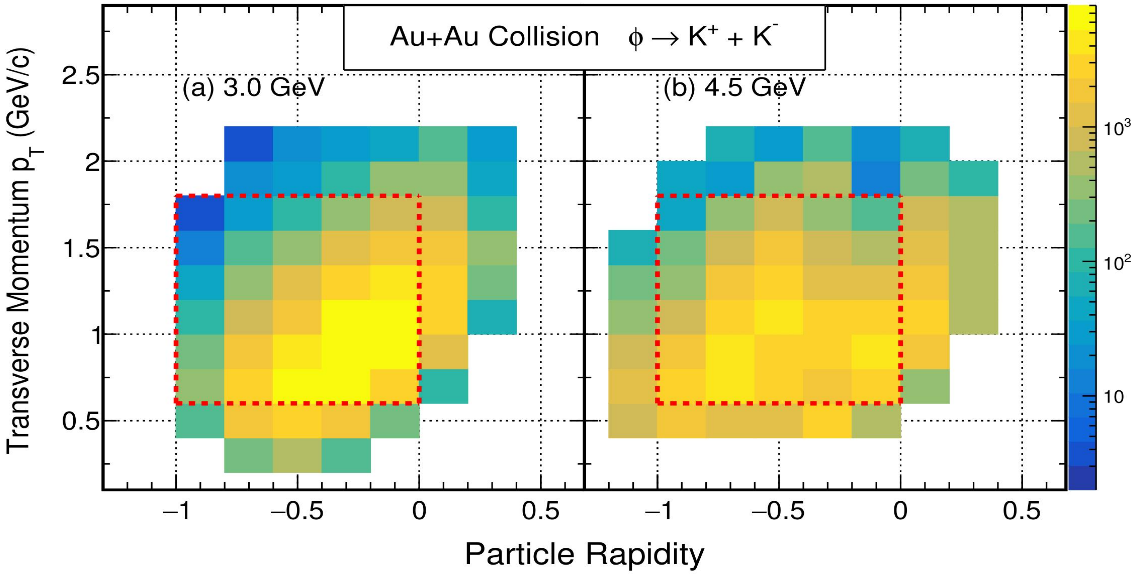


- Good particle identification capability based on TPC (dE/dx) and TOF (β) for charged pion, kaon and proton identification.
- Large acceptance for TPC+iTPC ($-2.4 < \eta < 0$) and bTOF+eTOF ($-2.0 < \eta < 0$)



Signal Reconstruction





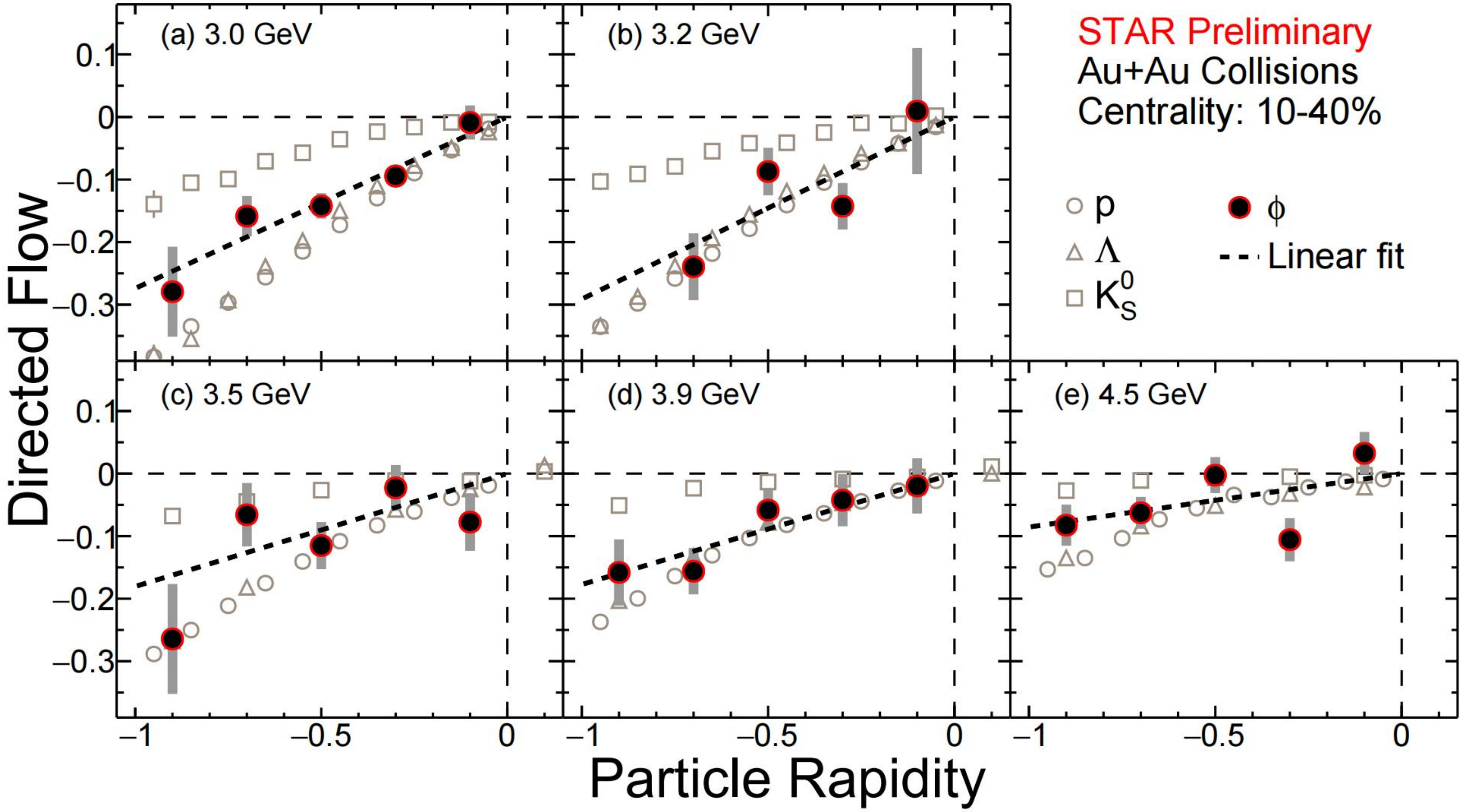
- Signal is reconstructed by paring K^+K^-, Background from mixed events.
- v_n value is the sum of signal and background contributions.
- Background term was parameterized with the polynominal.

$$v_n^{\mathrm{Sig+Bg}}(M_{\mathrm{inv}}) = \left\langle \cos\left[n\left(\phi - \Psi_1\right)\right]_{M_{inv}} / R_n \right\rangle$$

$$v_n^{\mathrm{Sig+Bg}}(M_{\mathrm{inv}}) = v_n^{\mathrm{Sig}} \frac{\mathrm{Sig}}{\mathrm{Sig+Bg}}(M_{\mathrm{inv}}) + v_n^{\mathrm{Bg}}(M_{\mathrm{inv}}) \frac{\mathrm{Bg}}{\mathrm{Sig+Bg}}(M_{\mathrm{inv}})$$

$$v_n^{\mathrm{Bg}}(M_{\mathrm{inv}}) = p_0 + p_1 M_{\mathrm{inv}}$$

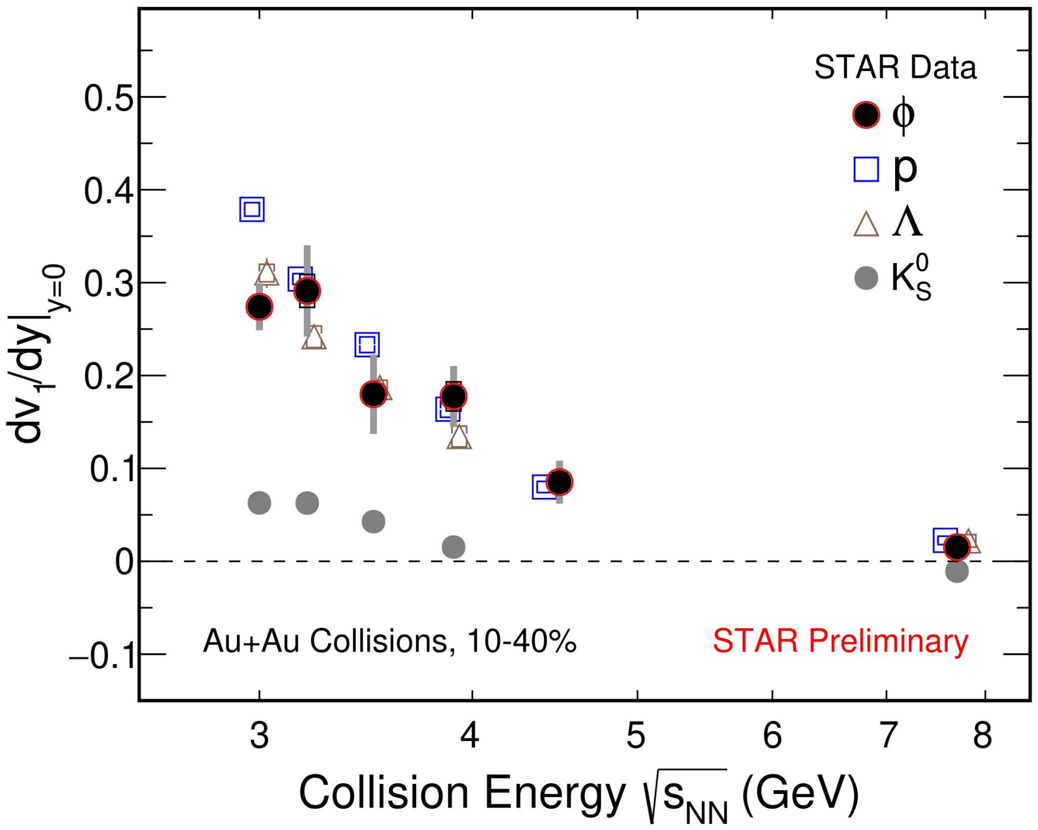
Rapidity Dependence of v_1



particle	p_T (GeV/c) range	Fitting function
ϕ	(0.6,1.8)	$F * y$
K_S^0	(0.4,1.6)	$F * y + C * y^3$
p	(0.4,2.0)	
Λ	(0.4,2.0)	

- The ϕ meson $v_1(y)$ is similar in magnitude and sign to those of protons and Λ baryons, but significantly larger than that of K_S^0.
- The magnitude of v_1 for all particle species decreases with increasing collision energy

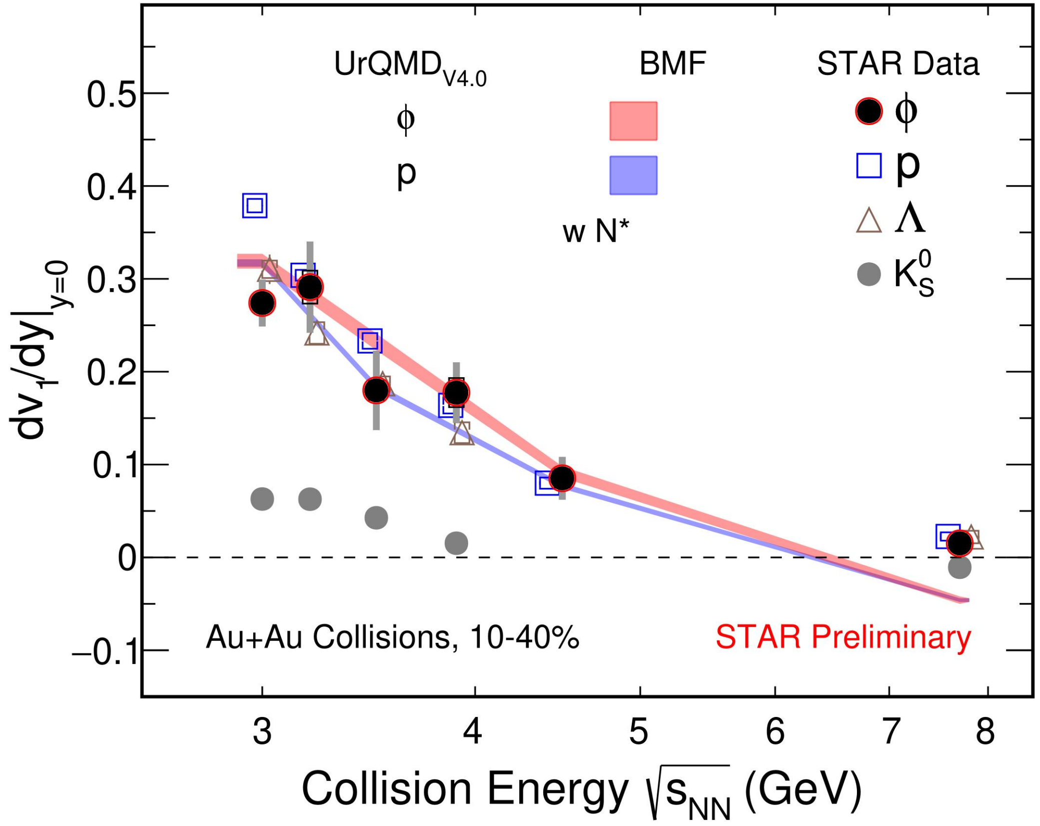
Energy Dependence of v_1 Slope



- Positive mid-rapidity v_1 slope observed for ϕ meson at 3,3.2,3.5,3.9 and 4.5 GeV.
- In the high baryon density region(3-4.5 GeV), ϕ meson v_1 is comparable in magnitude to that of protons and Λ baryons while Kaons show a much smaller v_1.
- At 7.7GeV and above, the v_1 slope of all particles, including the ϕ meson are similar .

Energy Dependence of v_1 Slope

[1] J. Steinheimer and M Bleicher J. Phys. G: Nucl. Part. Phys. 43 015104 (2016).
[2] J. Steinheimer, T. Reichert, and Marcus Bleicher, arXiv: 2507.19289.



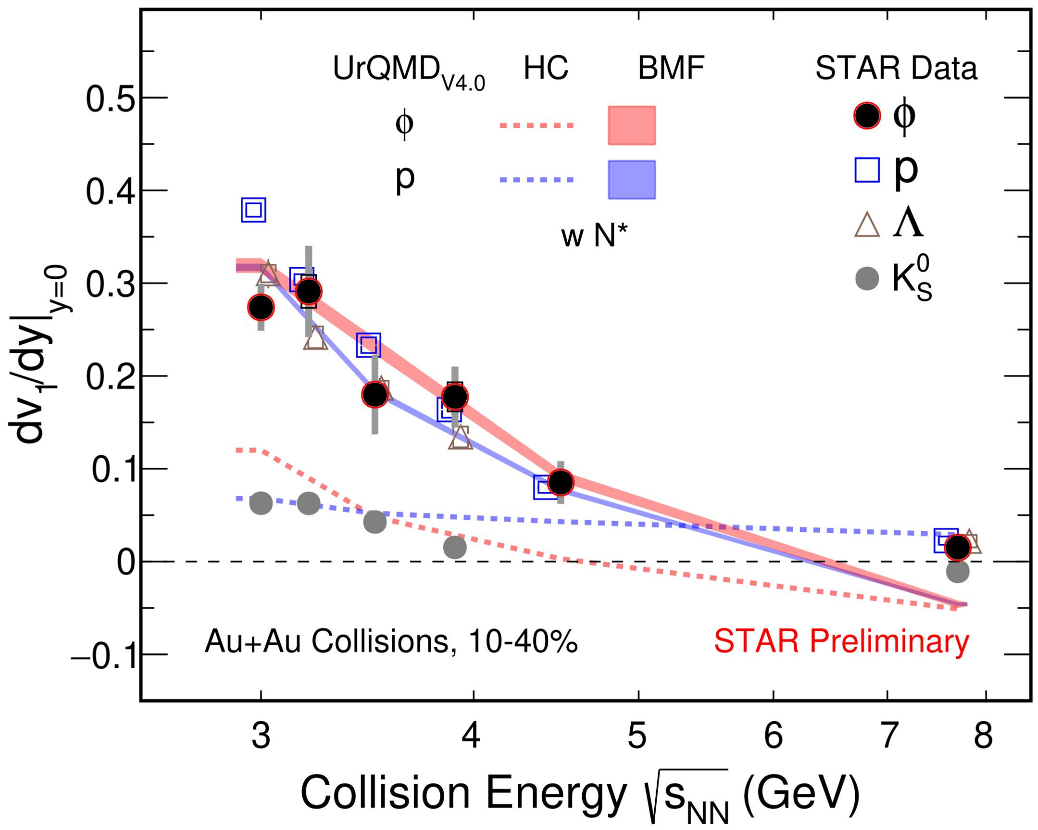
- UrQMD$_{v4.0}$[1,2] is the latest version with high-mass baryon resonances decaying to ϕ meson and Chiral Baryonic Mean-Field potentials.

$$N + N \rightarrow N^* + N \rightarrow N + \phi + N.$$

- high-mass baryon resonances plus the baryon mean-field reproduced the energy dependence of v_1 for proton (baryon) and ϕ (meson) quite well in the measured energy range $3 < \sqrt{s_{NN}} < 4.5$ GeV.

Energy Dependence of v_1 Slope

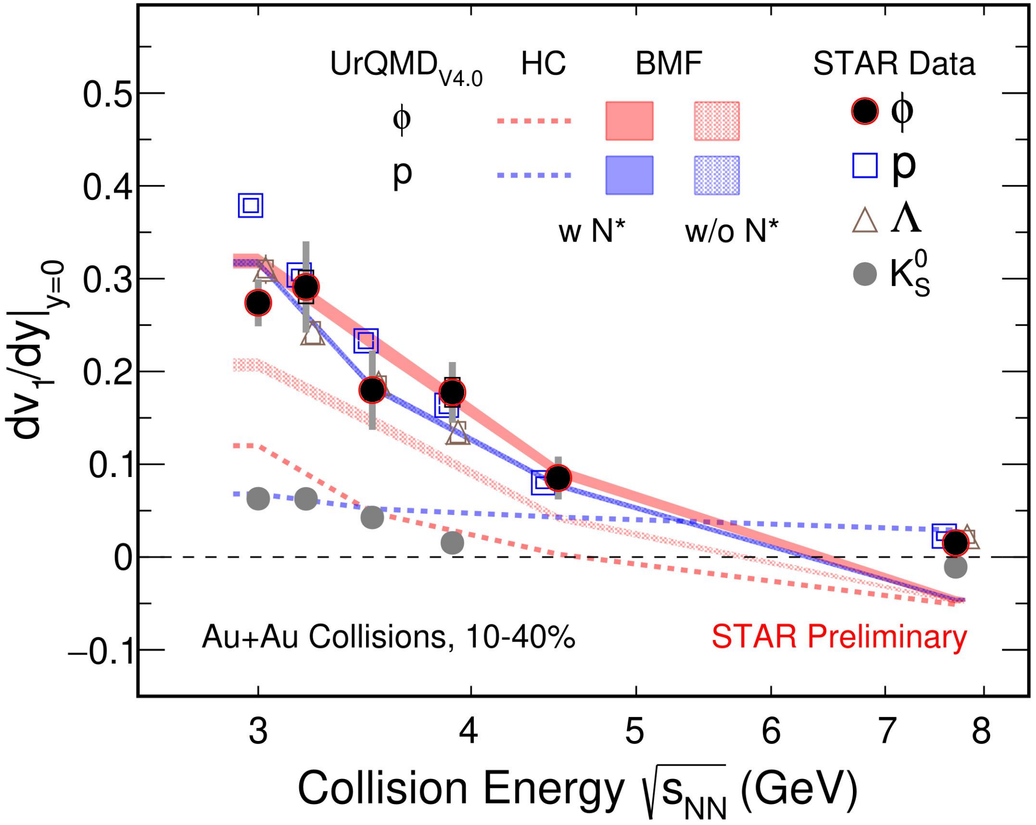
[1] STAR, Phys.Lett.B 827 (2022) 137003
[2] J. Steinheimer, et al. Phys. Lett. B 867, 139605 (2025)



- Baryonic mean-field is essential to describe proton and hyperon flow as well as strange hadron production yields in high baryon density region[1,2], while it is generally not suitable for meson.
- Without the baryonic mean-field, the model results underestimate the strength of the measured ϕ and proton v_1 by at least a factor of three.

Energy Dependence of v_1 Slope

[1]STAR, Phys. Lett. B831, 137152 (2022).



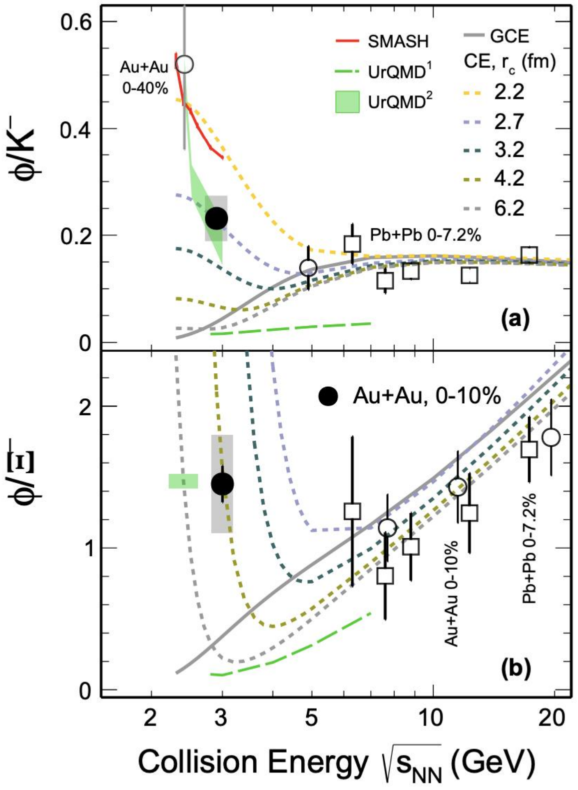
- With the baryonic mean-field but without the high-mass resonances implemented, the UrQMD$_{v4.0}$ model results for proton are the same but fail to reproduce the observed ϕ meson v_1.
- ϕ meson inherits the flow properties from the baryons (N*).
- High-mass resonances are also necessary for reproducing the enhancements of ratios for $N(\phi)/N(K^-)$ and $N(\phi)/N(\Xi)$ [1].
- The high-mass baryonic resonance is important for both strong ϕ meson v_1 and enhancement of its yields.

Summary

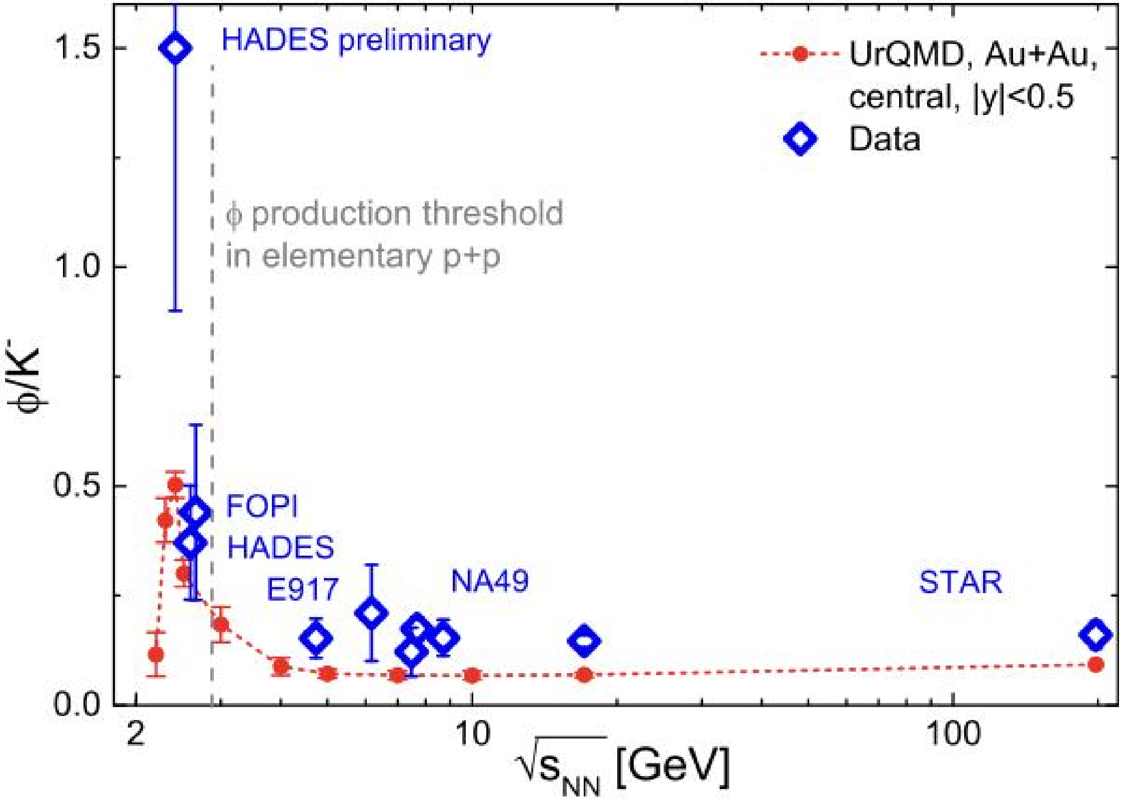
- ϕ Meson directed flow in 10-40% mid-central collisions at $\sqrt{s_{NN}}$ = 3.0, 3.2, 3.5, 3.9, 4.5 GeV.
  - Comparable in strength to that of protons and Λ baryons but significantly larger than that of other mesons.
- Transport model calculation with $\mathrm{UrQMD}_{v4.0}$.
  - Strong sensitivity of ϕ meson v_1 to baryonic mean-field potentials and production mechanism of high-mass baryonic resonance
- The high-mass baryonic resonance is important for both strong ϕ meson v_1 and enhancement of its yields.

Back up

STAR, Phys. Lett. B831, 137152 (2022).



J. Steinheimer and M. Bleicher, J. Phys. G: Nucl. Part. Phys. 43, 015104 (2015).



- High-mass resonances are also necessary for reproducing the enhancements of ratios for $N(\phi)/N(K^-)$ and $N(\phi)/N(\Xi)$.