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

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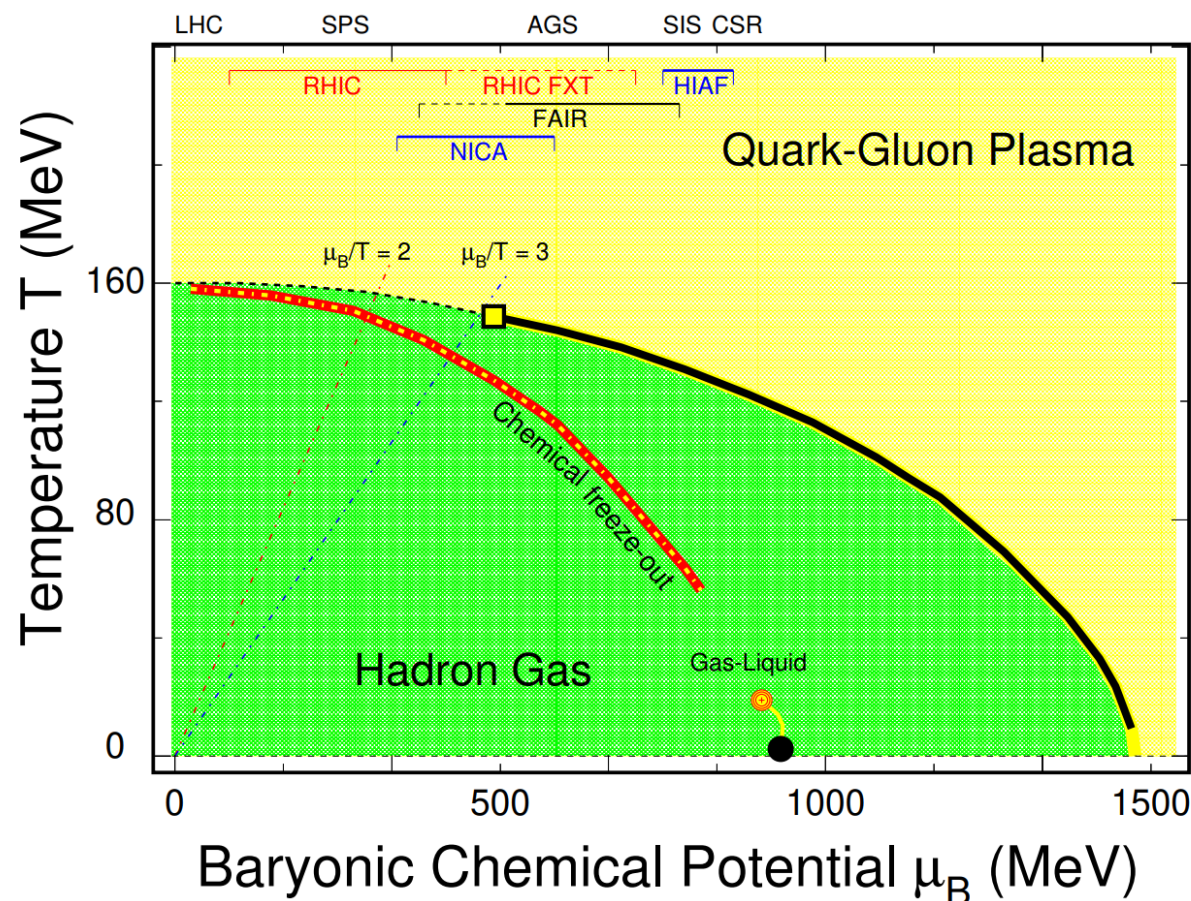


Outline

- Introduction
- Experimental Setup
- Analysis Method
- Results
- Summary



Introduction



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

RHIC STAR beam energy scan program

- Explore the QCD phase diagram
- Probe properties of dense QCD matter

➤ Collider Runs (7.7 - 62.4 GeV)

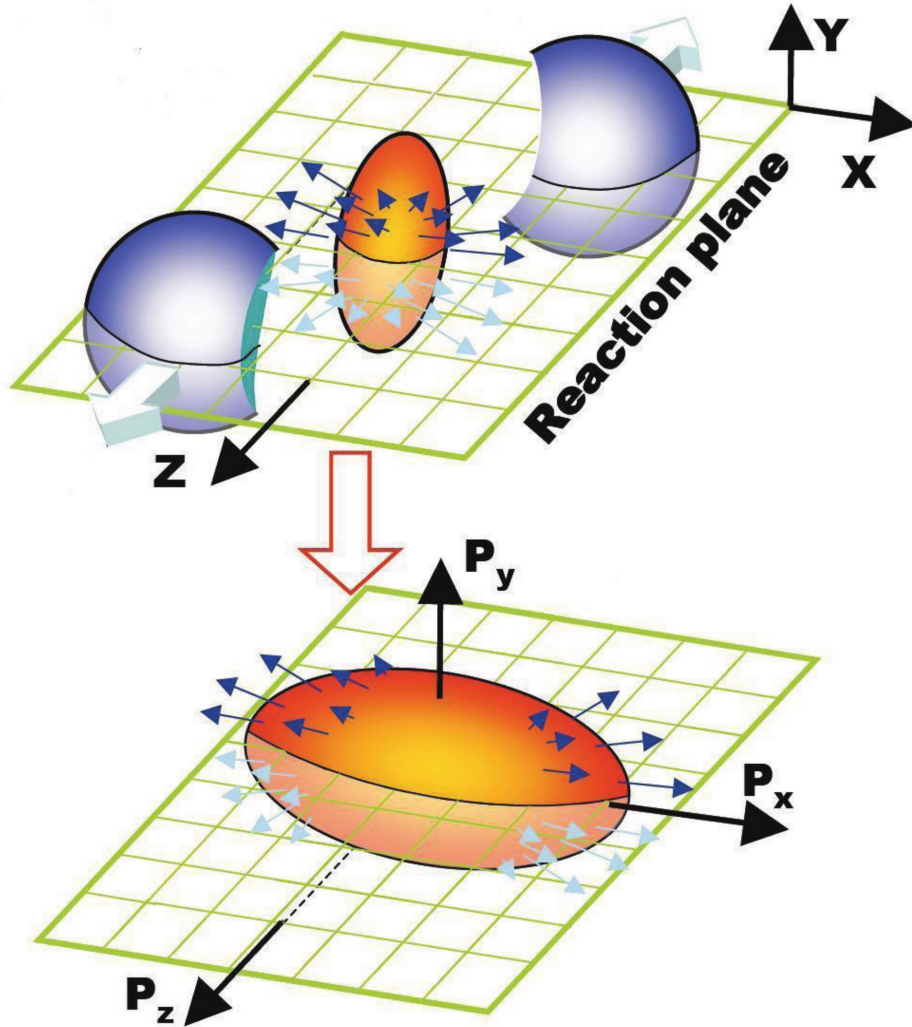
➤ **Fixed-Target Program** (3.0 - 13.7 GeV)

→ $\mu_B \approx 750\text{--}280\text{ MeV}$ (highest μ_B at RHIC)

→ Access the highest baryon density region at RHIC



Anisotropic Flow



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

$$v_1 = \cos (\phi - \psi_r) = \left\langle \frac{p_x}{p_T} \right\rangle$$

Directed flow

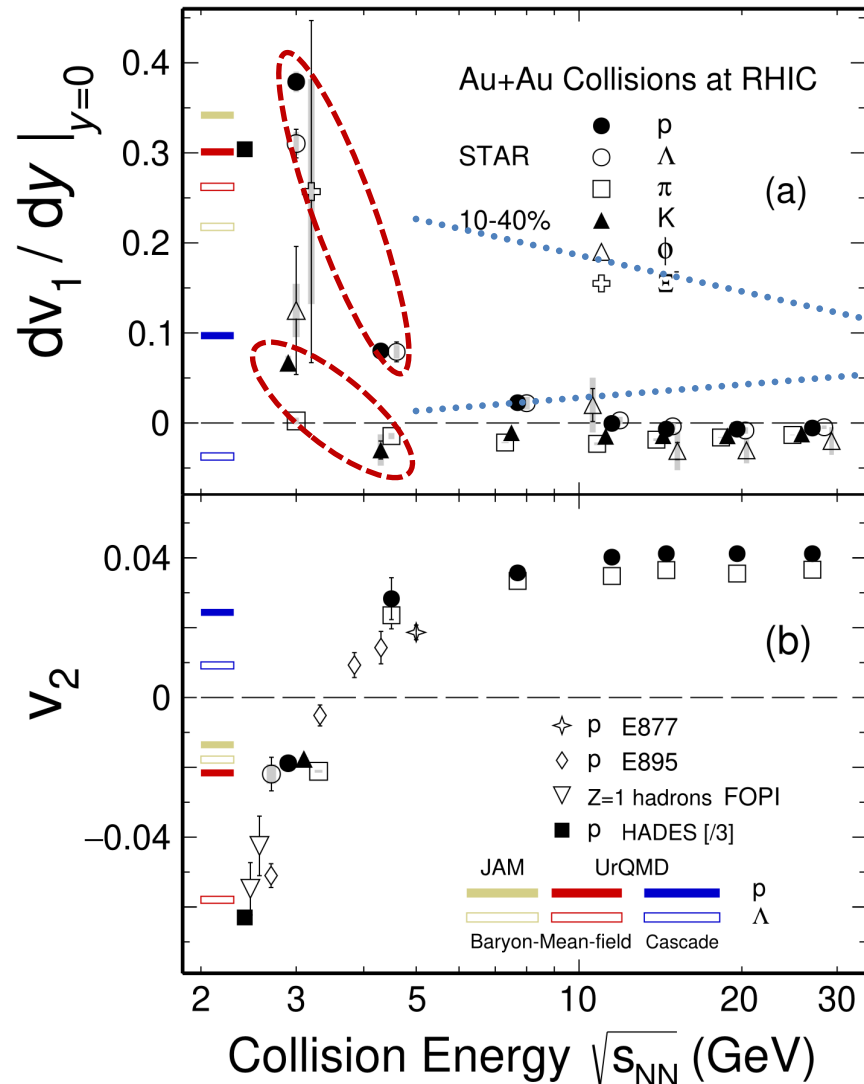
$$v_2 = \cos [2(\phi - \psi_r)] = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

Elliptic flow

- Directed flow originates from the sideward push of the compressed nuclear matter.
- As a sensitive probe of:
 - 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

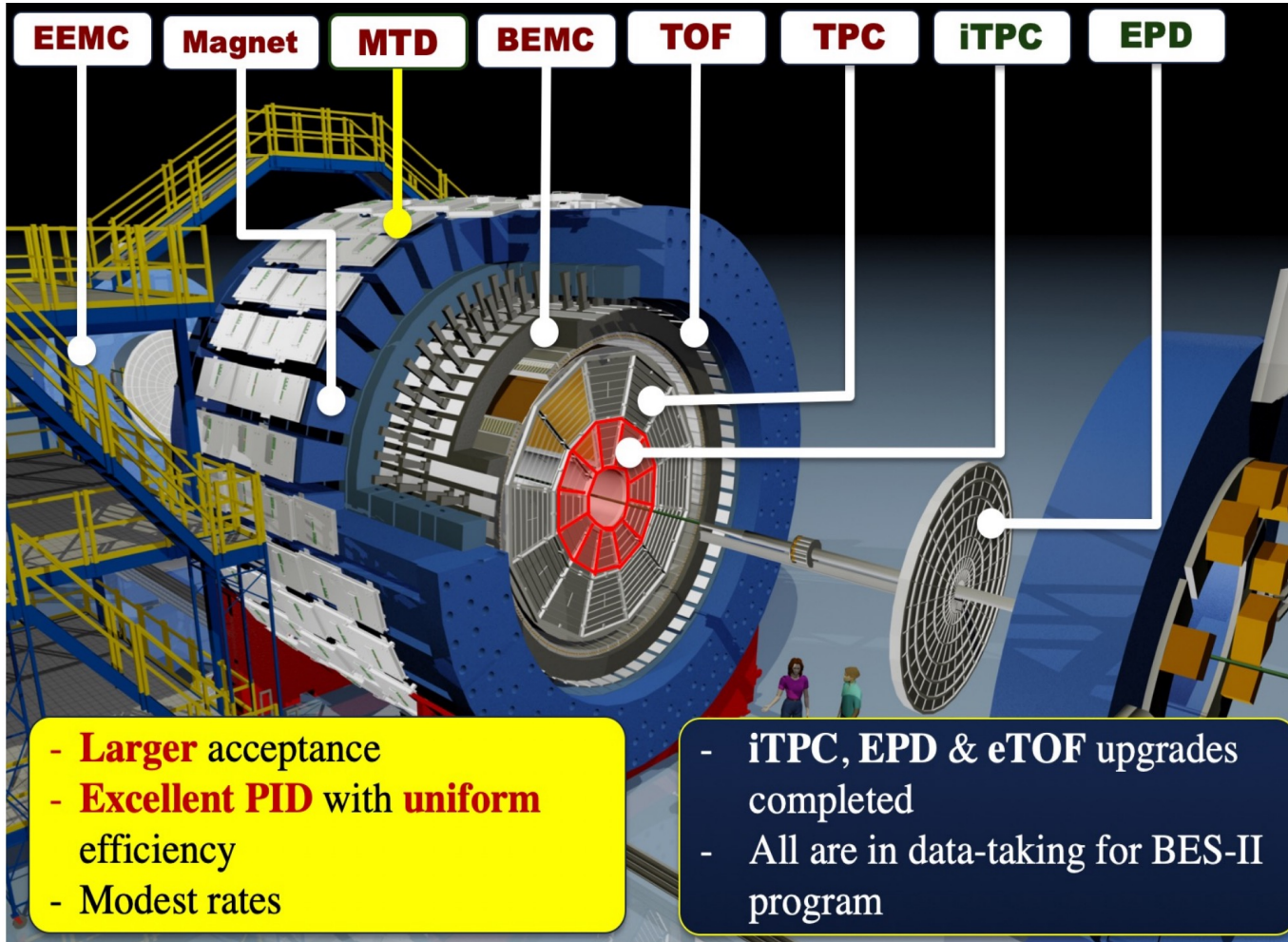
- BES-I (STAR) measured mid-rapidity v_1 for π , K , (anti-) protons, ϕ and (anti-) Λ over a wide energy range, show similar v_1 slope above 11.5 GeV.
- Increasing difference in the v_1 slope below 4.5 GeV for baryons (proton, Λ) and mesons (π , K)
 - Baryonic mean field?
 - Mass ordering?
 - Different hadronic cross sections?
- ϕ meson: a unique probe
 - Meson with close mass to baryons (proton, Λ)
 - Small hadronic cross section and long lifetime ($\sim 46\text{fm}/c$)

STAR, Phys. Rev. Lett. 118, 212301 (2017)

B. Mohanty, N. Xu, Journal of Physics G 36, 064022 (2009)

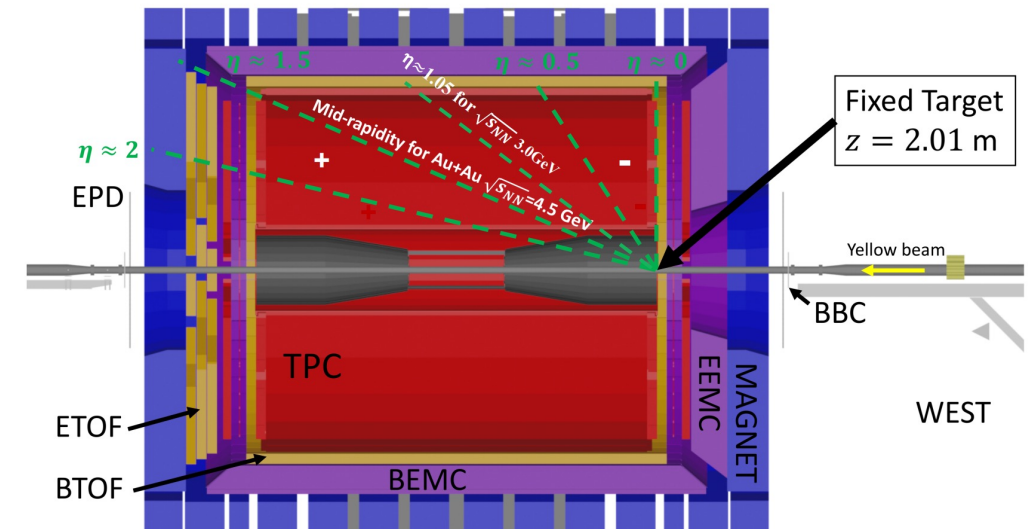


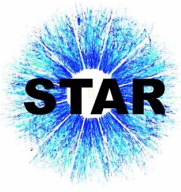
STAR Experimental Setup



➤ STAR Detector Upgrade:

- Inner-Time Projection Chamber: better track quality, larger acceptance
- Endcap Time Of Flight: particle identification
- Event Plane Detector: event plane determination ($2.1 < |\eta| < 5.1$)





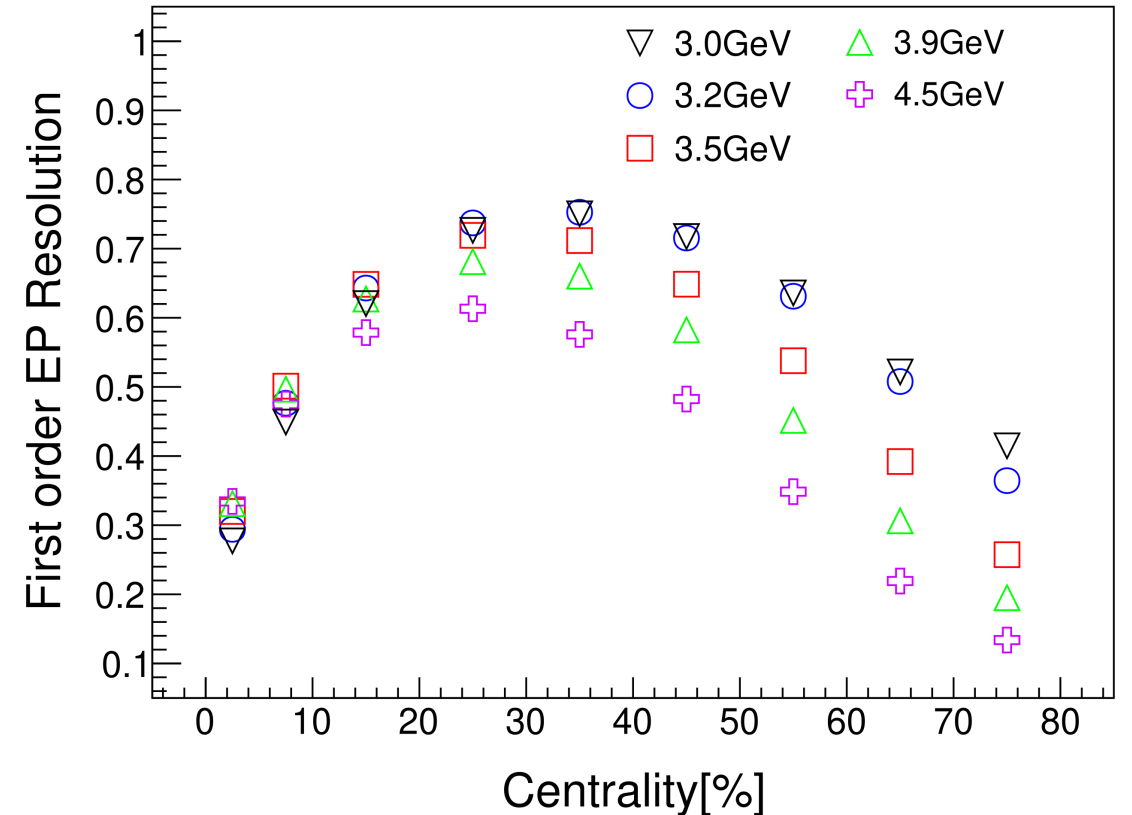
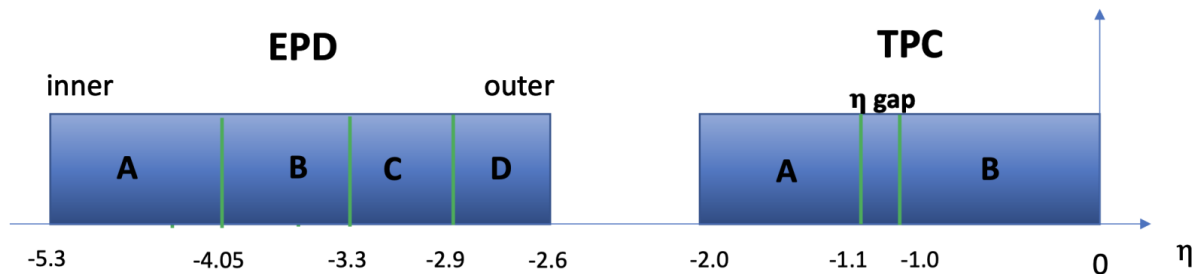
Event Plane Reconstruction

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.

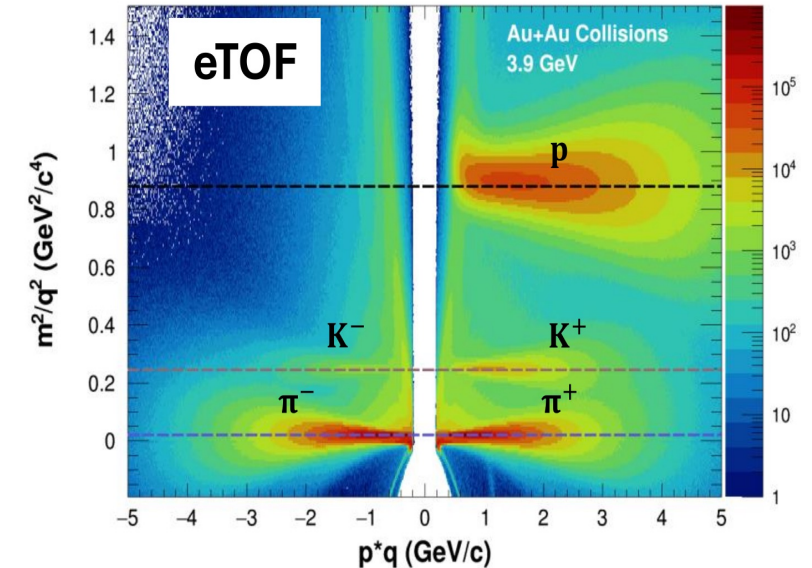
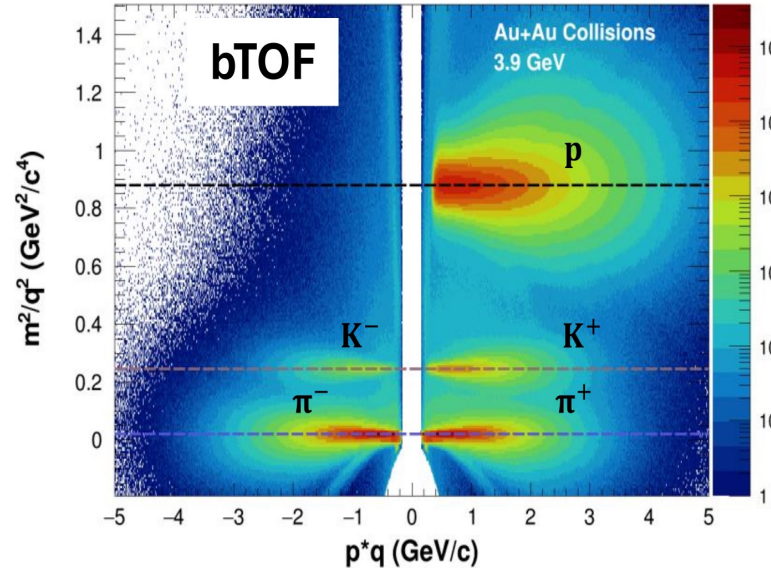
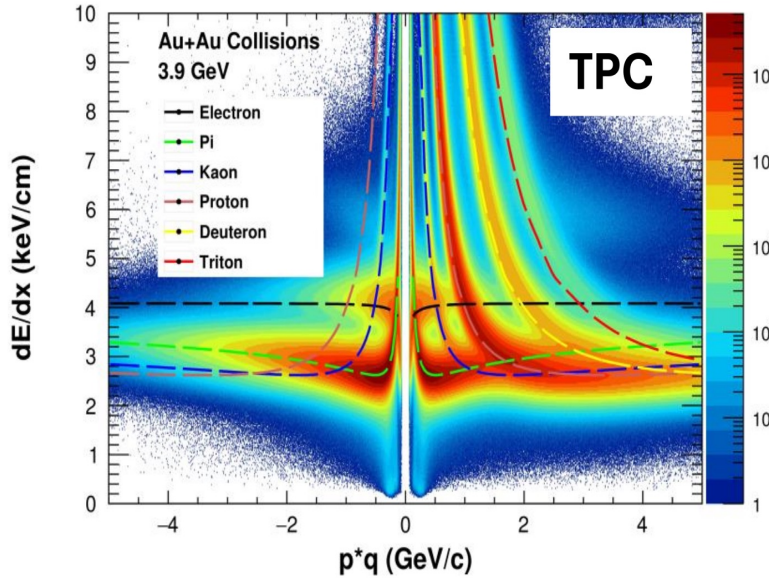
$$\vec{Q} = \begin{pmatrix} Q_y \\ Q_x \end{pmatrix} = \begin{pmatrix} \sum_i w_i \sin(n\phi_i) \\ \sum_i w_i \cos(n\phi_i) \end{pmatrix} \quad \Psi_n = \tan^{-1} \left(\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)} \right) / n$$

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

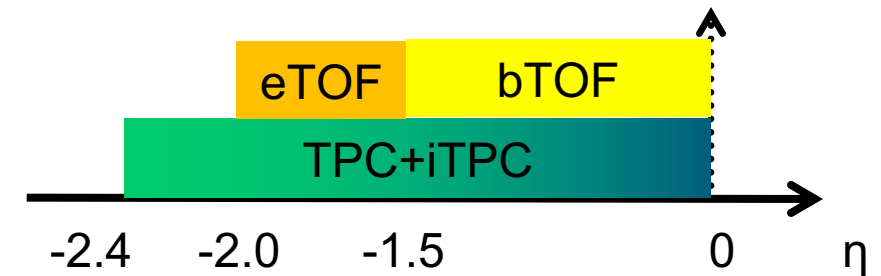




Particle Identification

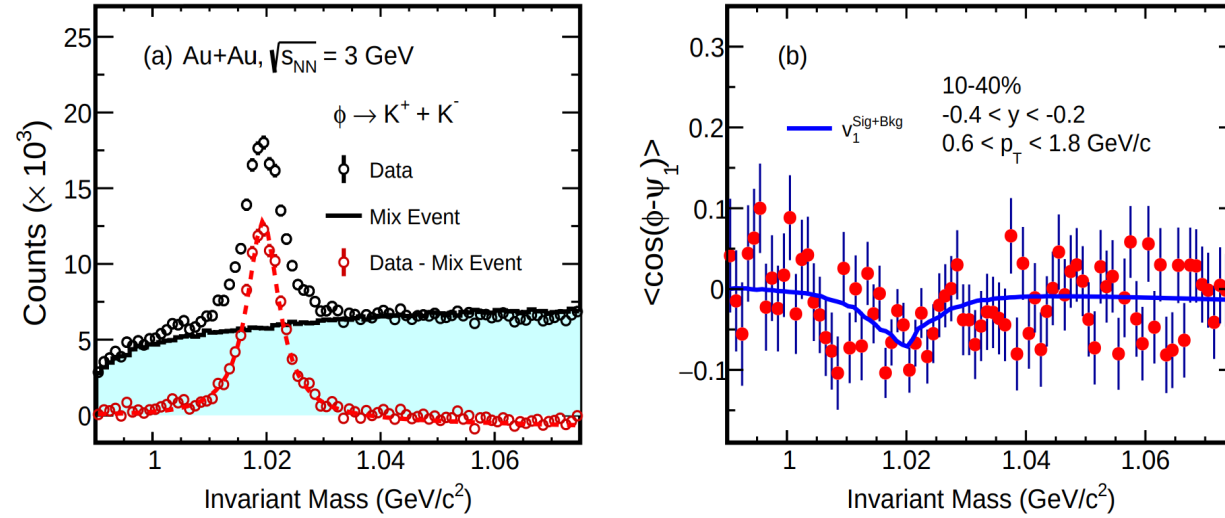


- Good particle identification capability based on TPC (dE/dx) and TOF (β) for charged pion, kaon and proton identification.
- Large acceptance for TPC+iTPC ($-2.4 < \eta < 0$) and bTOF+eTOF ($-2.0 < \eta < 0$)

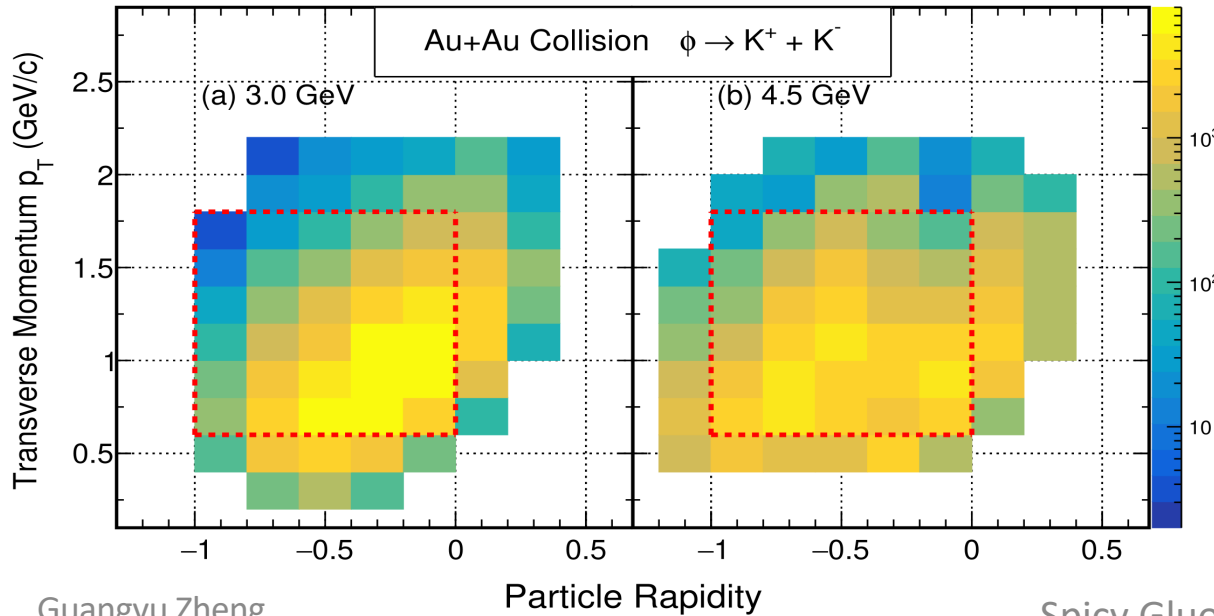




Signal Reconstruction



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



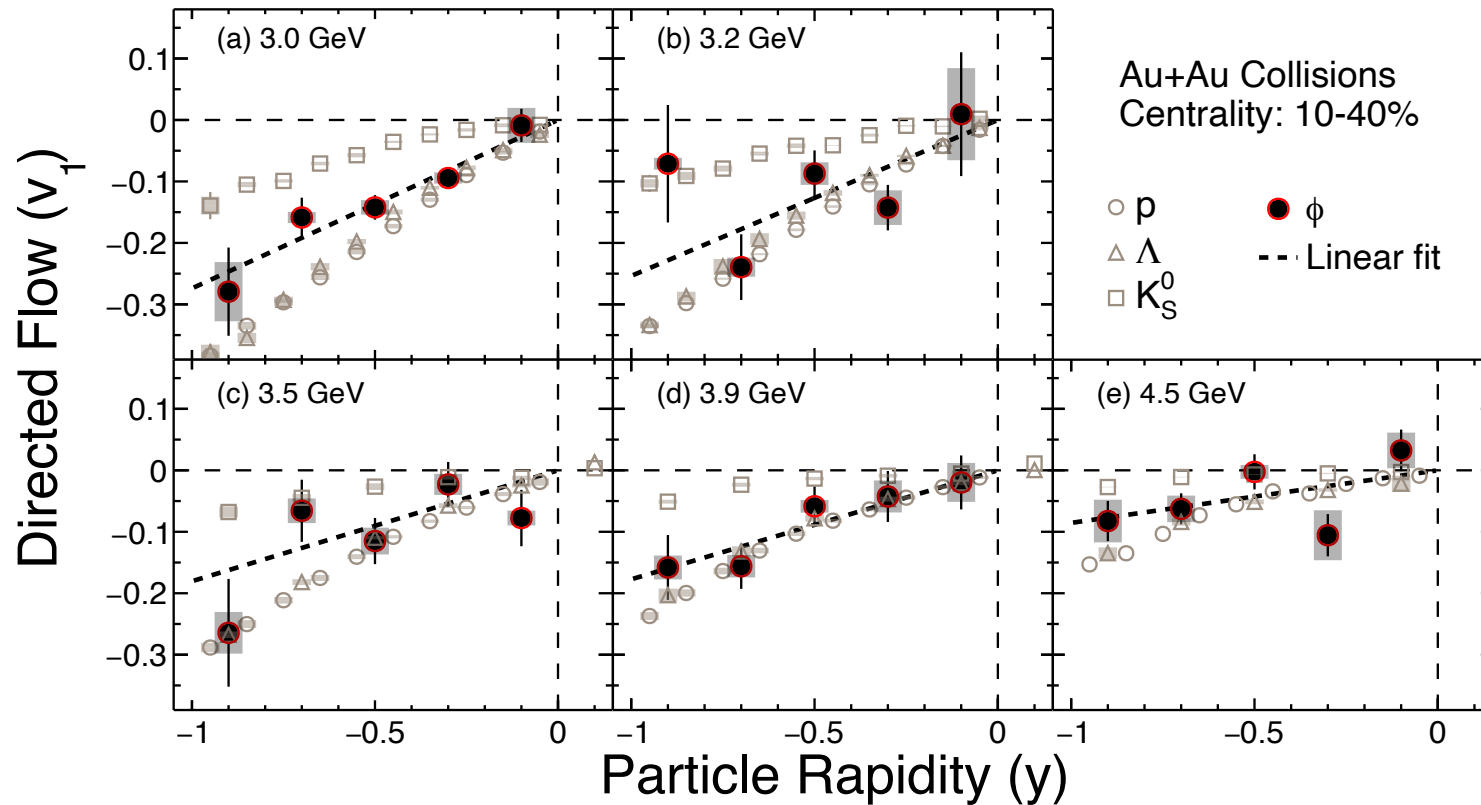
$$v_n^{\text{Sig+Bg}}(M_{\text{inv}}) = \left\langle \cos \left[n (\phi - \Psi_1) \right]_{M_{\text{inv}}} / R_n \right\rangle$$

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

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



Rapidity Dependence of v_1

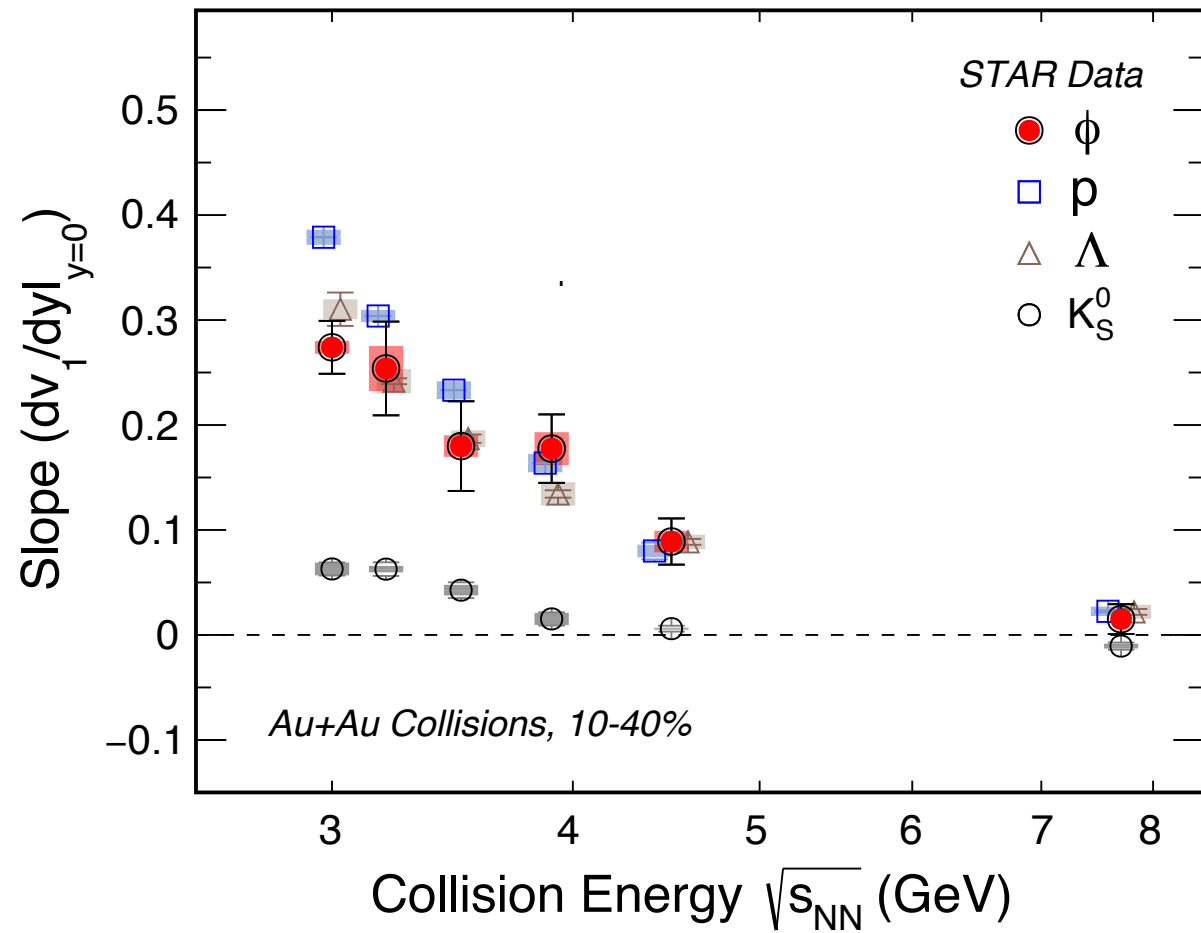


particle	p_T (GeV/c) range	Fitting function
ϕ	(0.6,1.8)	$F * y$
K_S^0	(0.4,1.6)	$F * y + C * y^3$
p	(0.4,2.0)	
Λ	(0.4,2.0)	

- 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



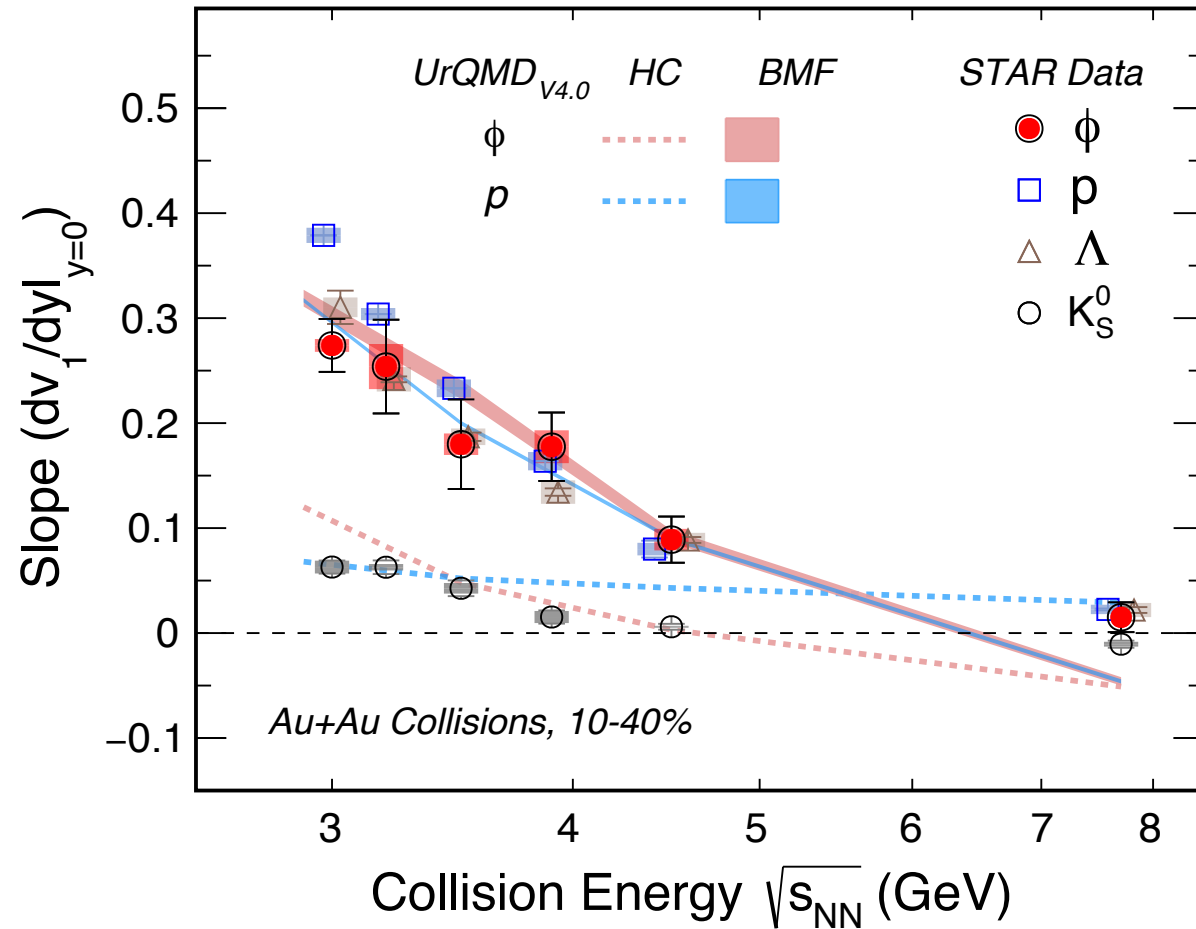
Energy Dependence of v_1 Slope



- Positive mid-rapidity v_1 slope observed for ϕ meson at 3.0, 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 K_S^0 show a much smaller v_1 .
- At 7.7 GeV and above, the v_1 slope of all particles, including the ϕ meson are similar.
- To understand this **baryon-like behavior**, we compare the results with transport models.



Model Comparison



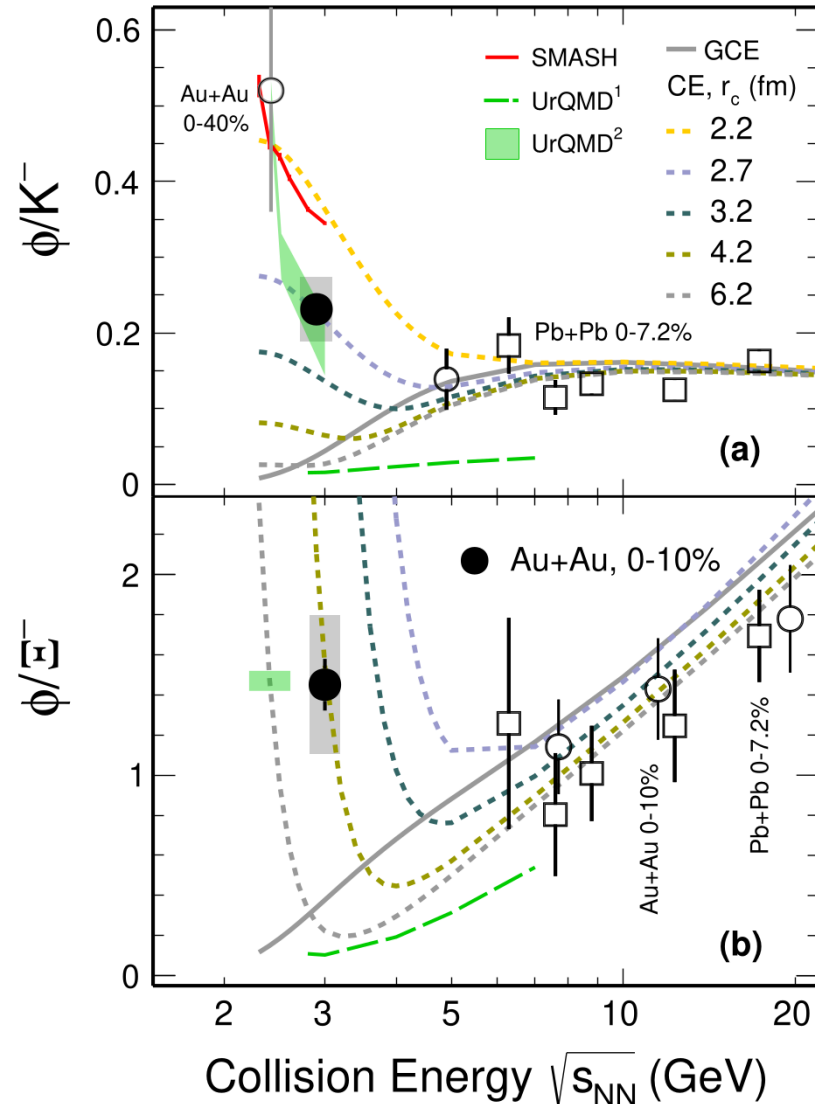
- UrQMD_{v4.0}[1,2] with baryonic mean-field reproduces the energy dependence of v_1 slope both for proton and ϕ meson at $3 < \sqrt{s_{NN}} < 4.5$ GeV.
- Baryonic mean-field is essential to describe proton and hyperon flow in the high baryon density region, while it is generally not suitable for meson.
- What drives the baryon-like behavior of ϕ ?

HC: hadronic cascade mode of the transport model.
BMF: baryonic mean-field potentials included in the transport model.

- [1] J. Steinheimer and M Bleicher J. Phys. G: Nucl. Part. Phys. 43 015104 (2016).
 [2] J. Steinheimer, T. Reichert, and Marcus Bleicher, Phys.Lett.B 869 (2025) 139870



Role of Baryon Resonances



- Previous measurements of ϕ production indicate an enhanced yield ratio of ϕ/K^- and ϕ/Ξ^- in the high baryon density region.
- Transport calculations indicate that baryon resonance excitation can significantly contribute to ϕ production at low energies.



- In this scenario, the ϕ meson is produced from baryon resonances that already carry collective motion, and therefore it can inherit the baryon-like directed flow.

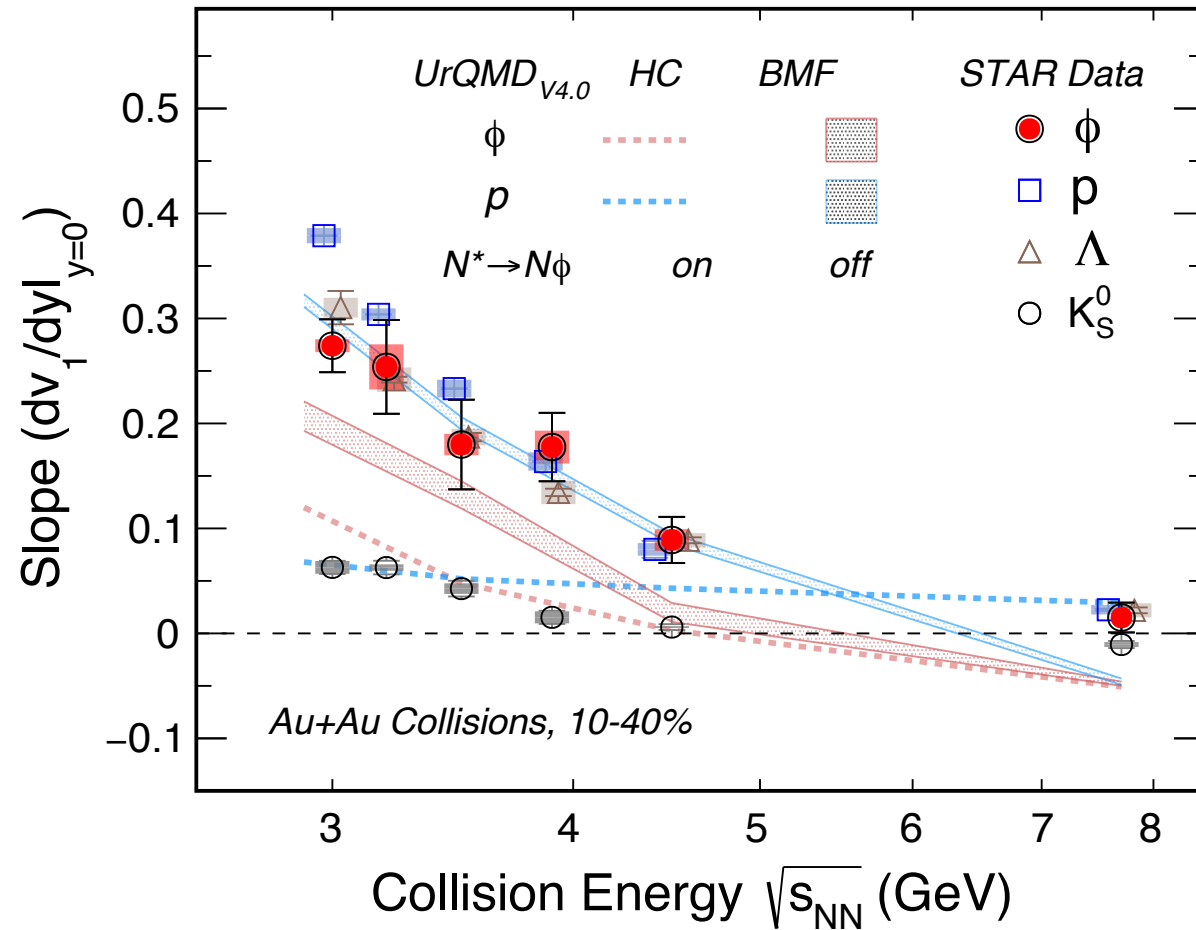
Phys. Lett. B 831 (2022) 137152

UrQMD¹: With out high mass baryon resonances decay to ϕ

UrQMD²: With high mass baryon resonances decay to ϕ



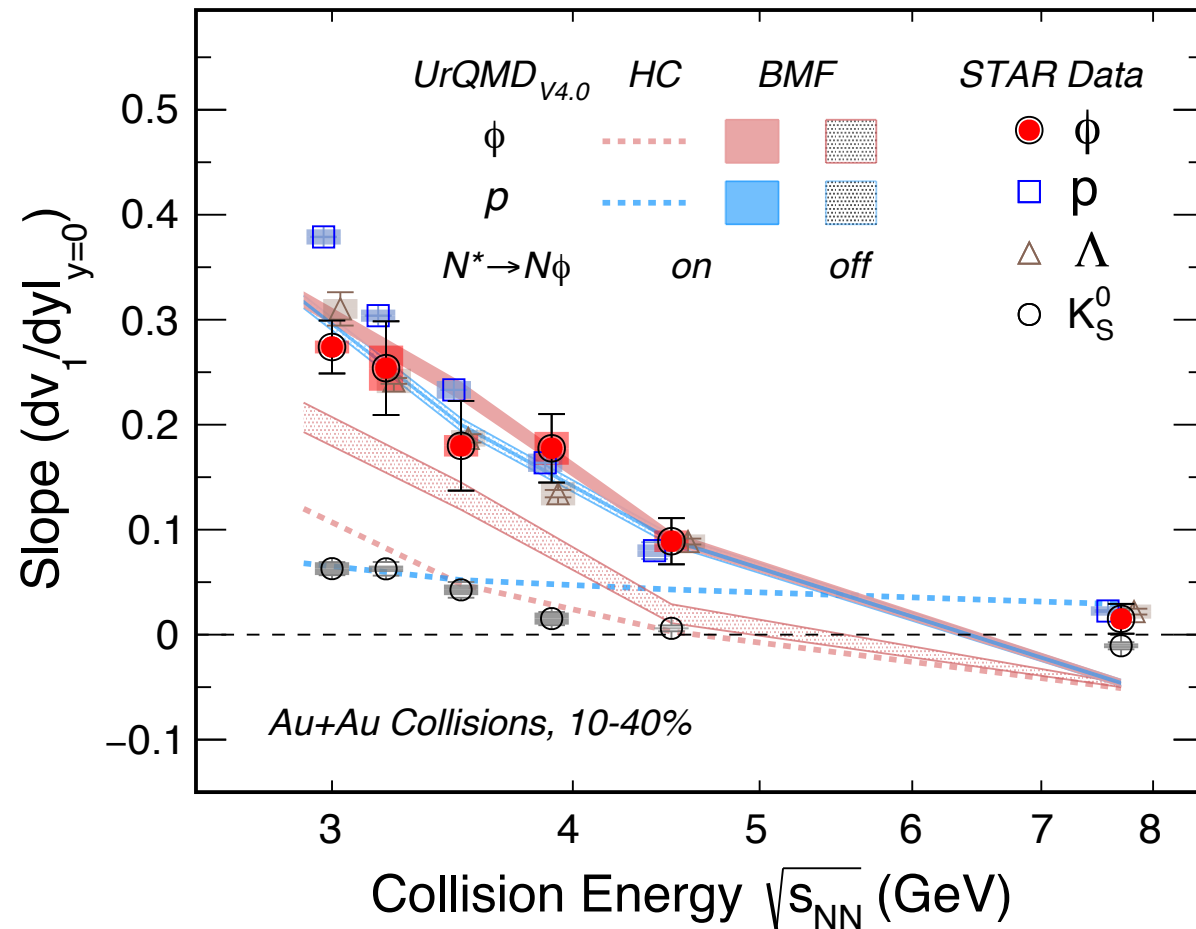
Role of Baryon Resonances



- “ $N^* \rightarrow N\phi$ off” means that the decay channels from high-mass baryon resonances (N^*) to ϕ are switched off.
- The proton v_1 slope shows little sensitivity to this setup and remains well described by the model.
- With baryonic mean-field but without N^* , UrQMD fails to reproduce the baryon-like directed flow of the ϕ meson.
- **Baryonic mean-field alone is not sufficient to explain the ϕ directed flow.**



Role of Baryon Resonances



- These results suggest that high-mass baryon resonances (N^*) **play a crucial role** in ϕ production and its baryon-like directed flow in the high baryon density region.
- Why can we observe such strong flow for ϕ , while other mesons do not show similar behavior?
 - High Contribution for ϕ from baryon resonances
 - Small ϕ -N interaction cross section[1]

[1] J. Steinheimer, T. Reichert, and Marcus Bleicher, Phys.Lett.B 869 (2025) 139870



Summary

- The directed flow of ϕ mesons has been measured in mid-central Au+Au collisions at $\sqrt{s_{NN}} = 3.0\text{--}4.5$ GeV in the high baryon density region at RHIC.
- The ϕ meson v_1 slope is positive and comparable to that of protons and Λ baryons, while other mesons show significantly smaller flow.
- Transport calculations suggest that ϕ mesons can be produced via high-mass baryon resonances (N^*), allowing them to inherit baryon-like collective flow.
- These measurements may provide new constraints on the ϕ -N interaction cross section in dense nuclear matter.

These results highlight the unique role of ϕ mesons as probes of baryon-resonance production and strange-hadron transport in the high-baryon-density region.