Directed Flow of Vector Meson in the High Baryon Density Region at RHIC

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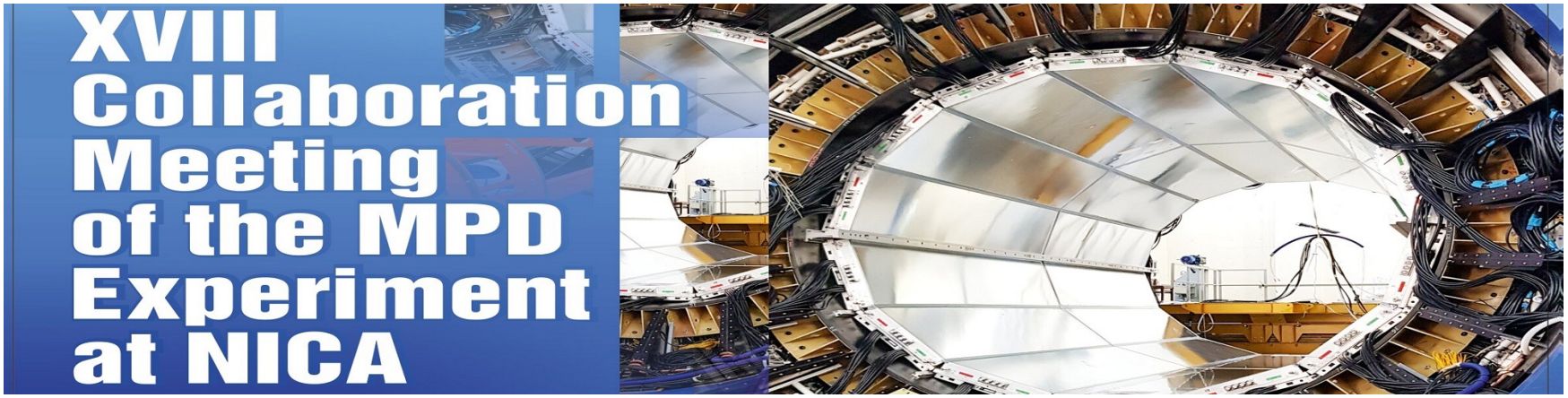
XVIII MPD Collaboration Meeting



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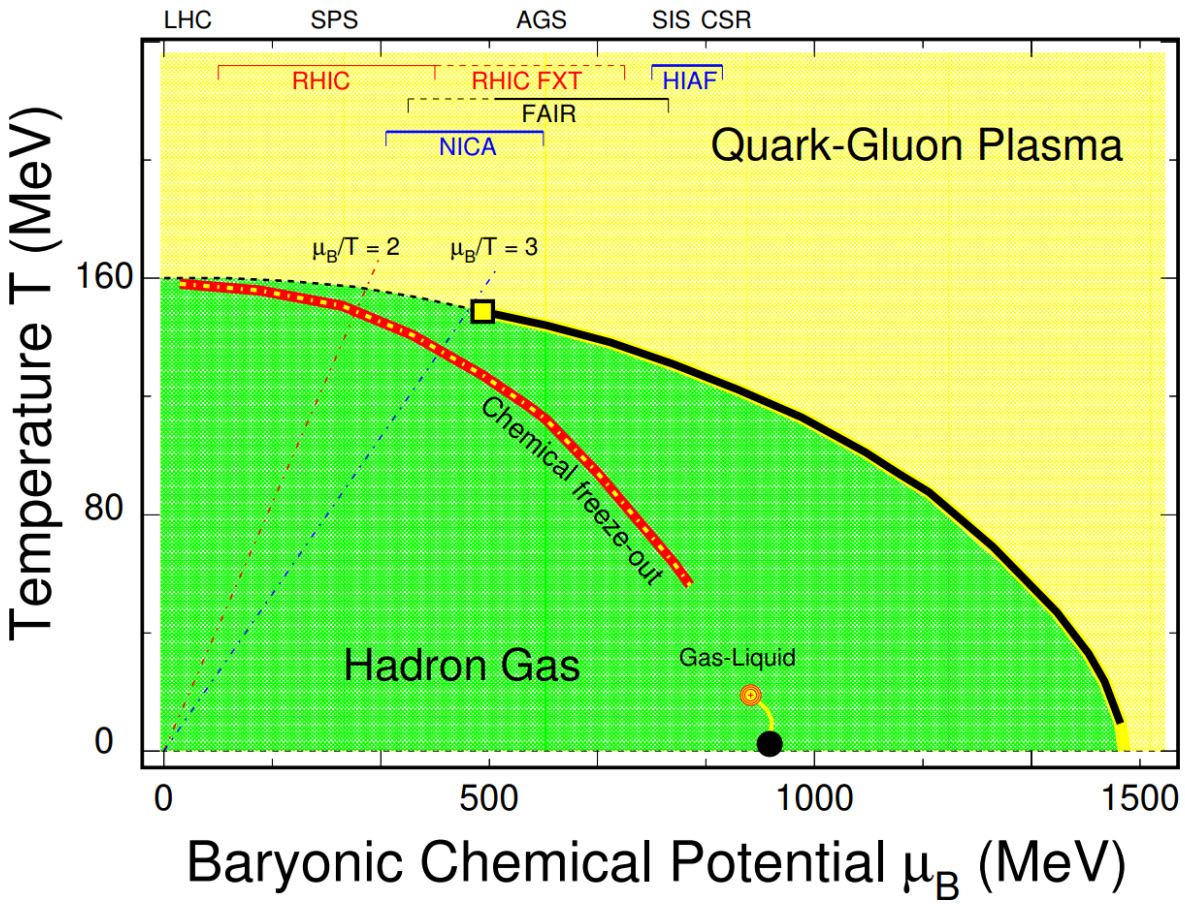
- Introduction
- Experimental Setup
- Results
- Summary

Introduction



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

RHIC STAR beam energy scan program

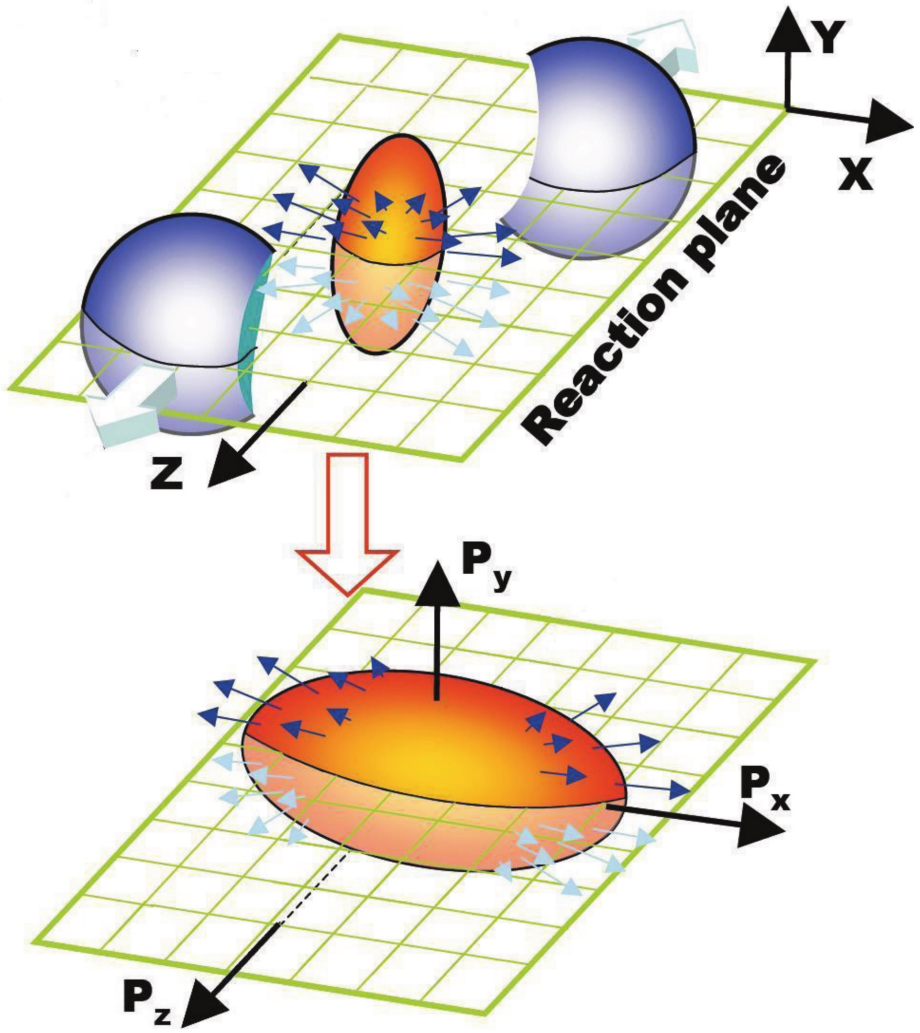
- Explore the QCD phase diagram
- Probe properties of dense QCD matter

- Collider Runs (7.7 - 62.4 GeV)
- Fixed-Target Program (3.0 - 13.7 GeV)

  → $\mu_B \approx 750–280$ MeV (highest μ_B at RHIC)

  → Access the highest baryon density region at RHIC

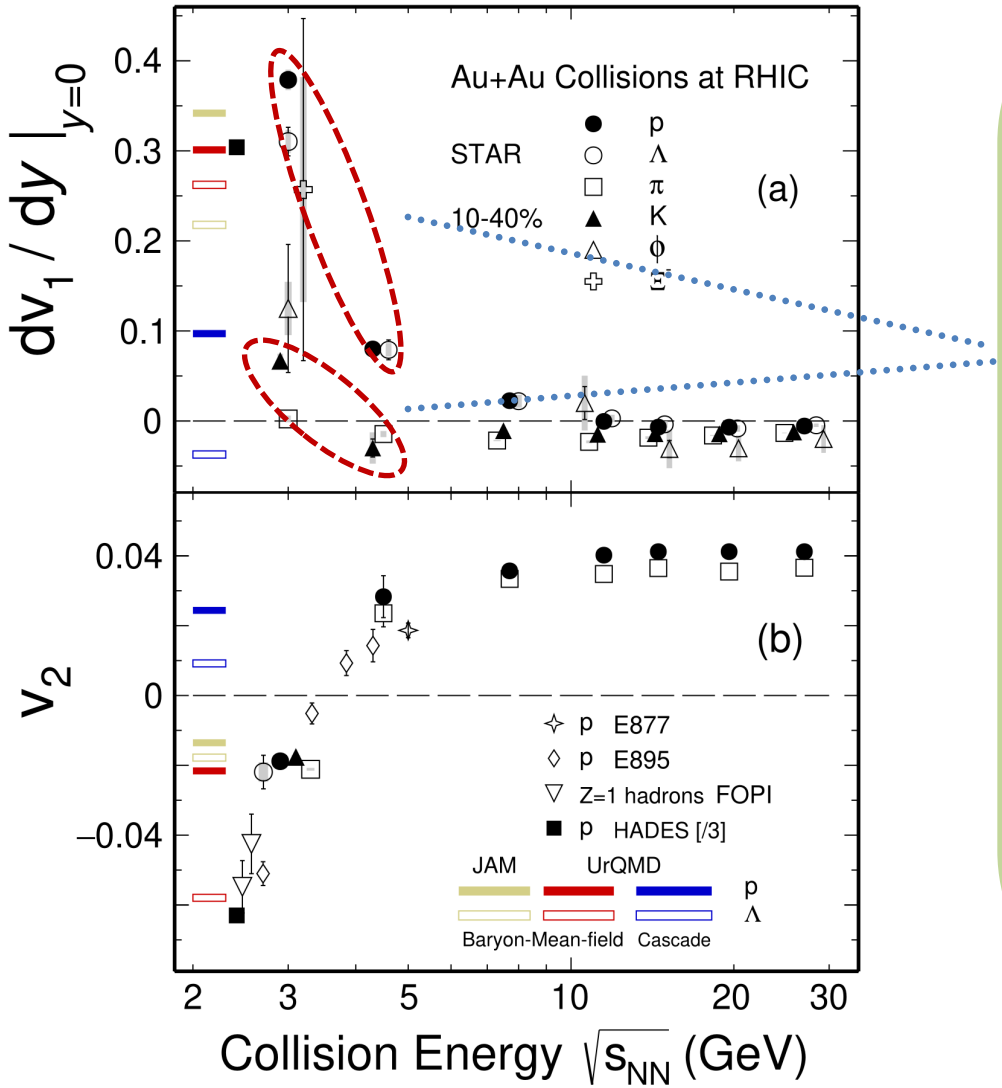
Anisotropic Flow



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

- 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



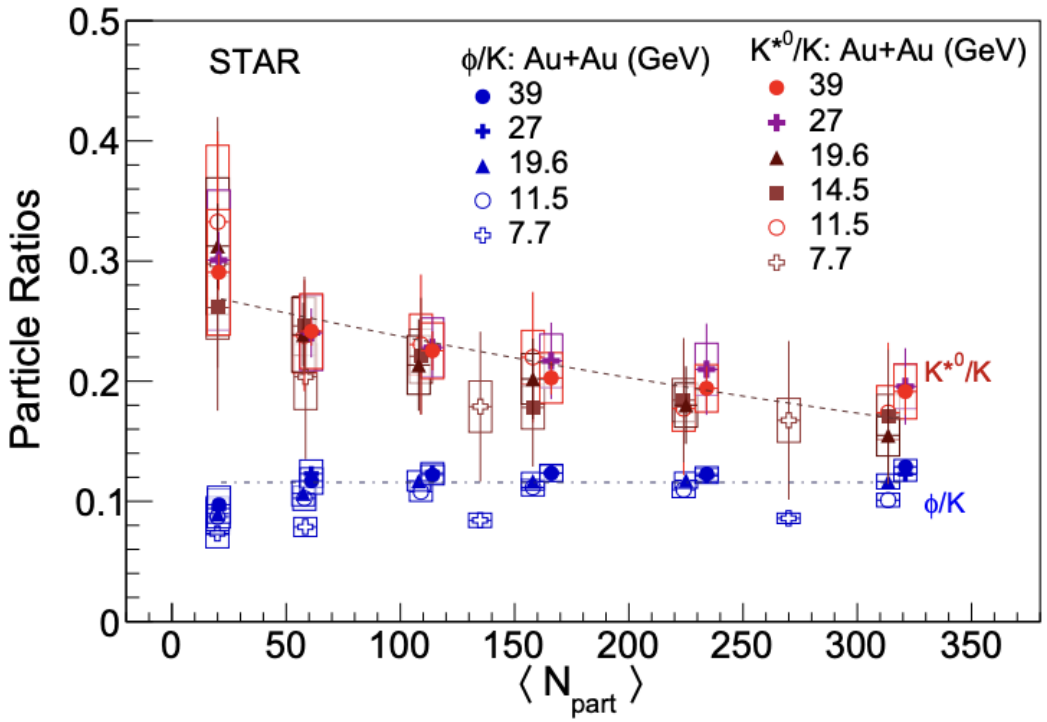
STAR, Phys.Lett.B 827 (2022) 137003

- 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 (~46 fm/c) .

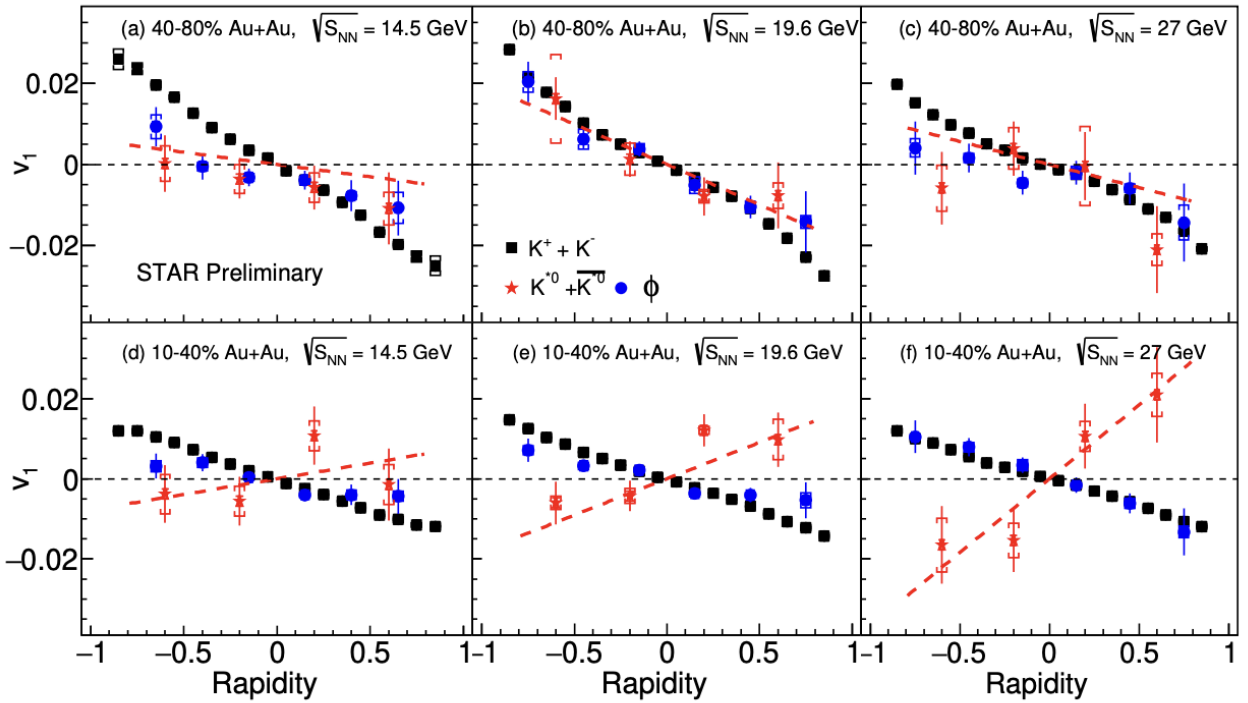
STAR, Phys. Rev. Lett. 118, 212301 (2017)
B. Mohanty, N. Xu, Journal of Physics G 36, 064022 (2009)

Resonances Probe Hadronic Medium

STAR, Phys. Rev. C 107 (2023) 34907

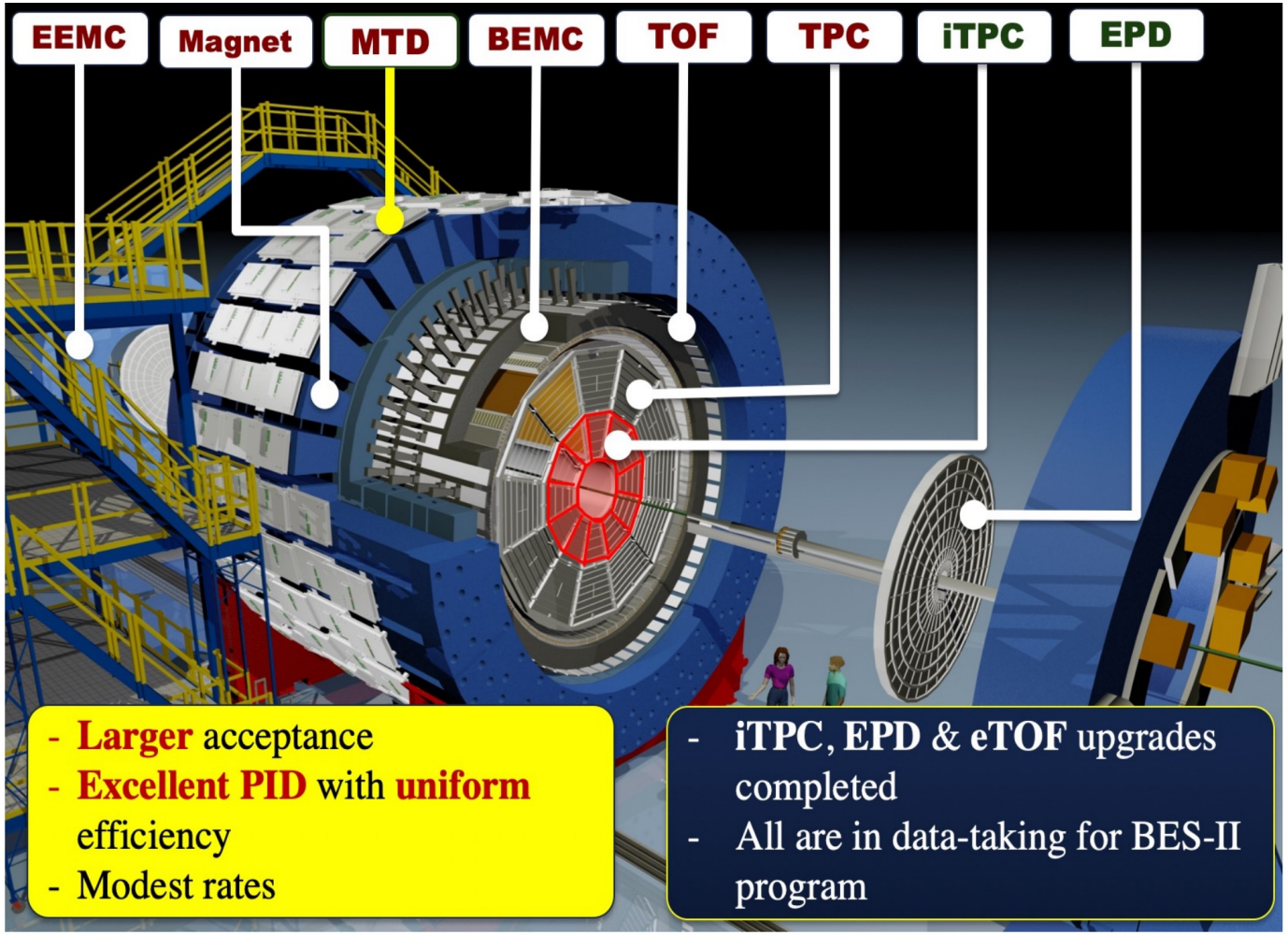


Md Nasim. QM2025



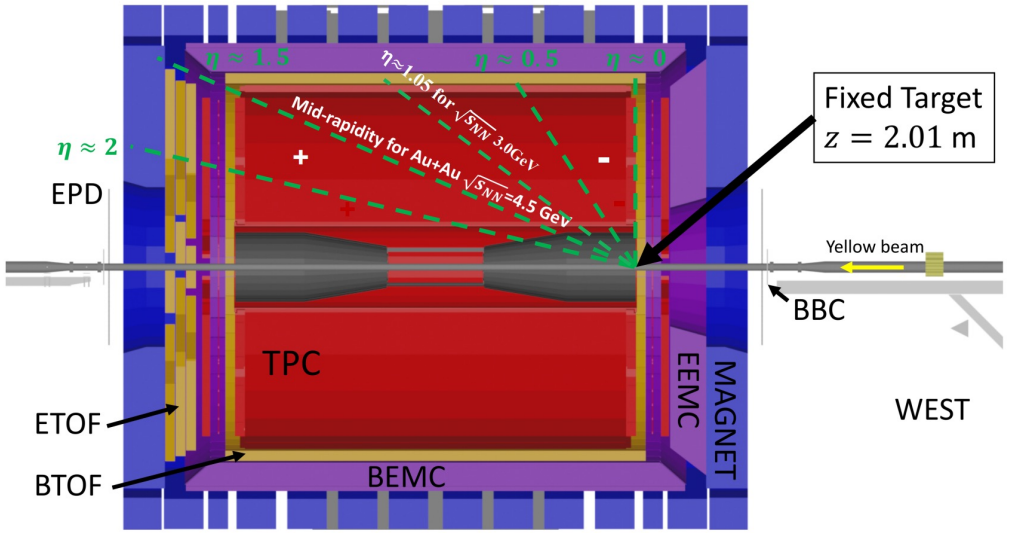
- Reconstructed K*⁰ yields are modified by hadronic re-scattering of decay daughters, leading to a loss of reconstructable signals.
- At BES-II energy K^{*0} shows a similar v_1 slope like ϕ and kaons in peripheral collisions, but exhibits a sign change in mid-central collisions, indicating the impact of hadronic interactions.
- K^{*0} along with ϕ provide sensitivity to different mechanisms to understand the origin of collectivity in high baryon density.

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 ($2.1 < |\eta| < 5.1$)



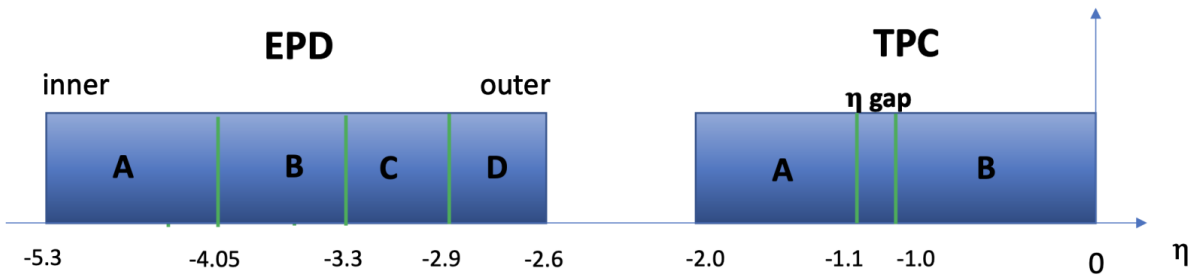
Event Plane Reconstruction

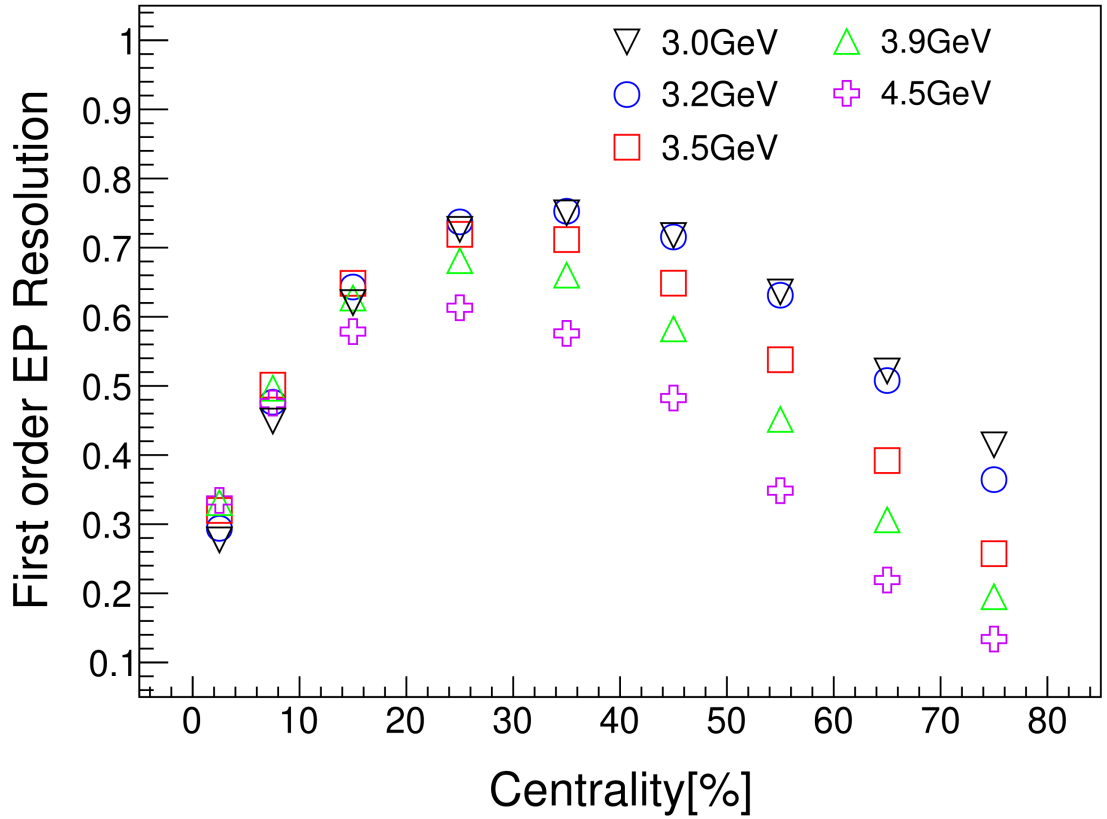
A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C58, 1671 (1998)

- The nth 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.

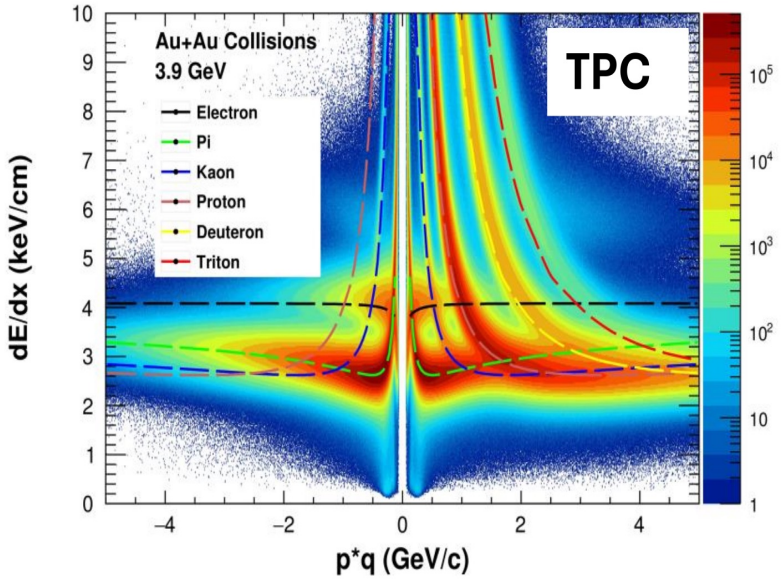
$$\vec{Q} = \begin{pmatrix} Q_y \\ Q_x \end{pmatrix} = \begin{pmatrix} \sum_i w_i \sin(n\phi_i) \\ \sum_i w_i \cos(n\phi_i) \end{pmatrix} \qquad \Psi_n = \tan^{-1}\left(\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)} \right) / n$$

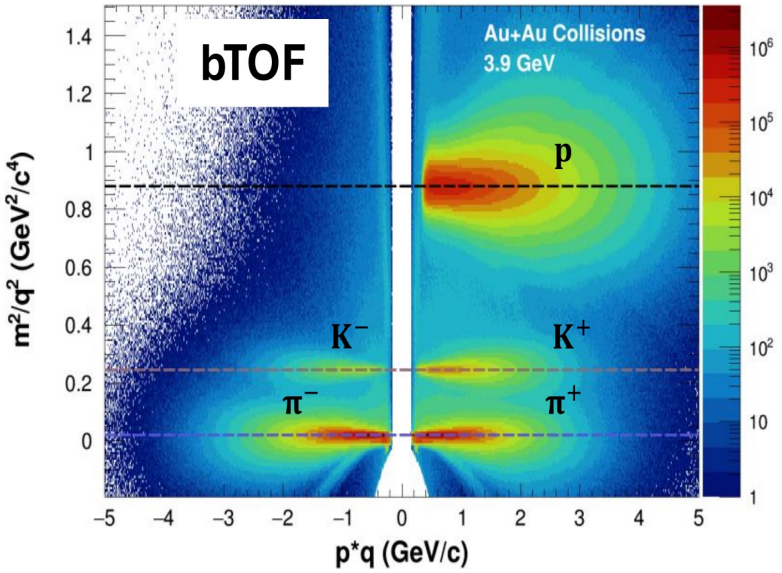
$$R_1 = \sqrt{\frac{\langle \cos(\Psi_1^a - \Psi_1^b) \rangle \langle \cos(\Psi_1^a - \Psi_1^c) \rangle}{\langle \cos(\Psi_1^b - \Psi_1^c) \rangle}} \qquad v_1 = \frac{v_1^{obs}}{R_1} = \frac{\langle cos(\phi - \Psi_1) \rangle}{\langle cos(\Psi_1 - \Psi_r) \rangle}$$

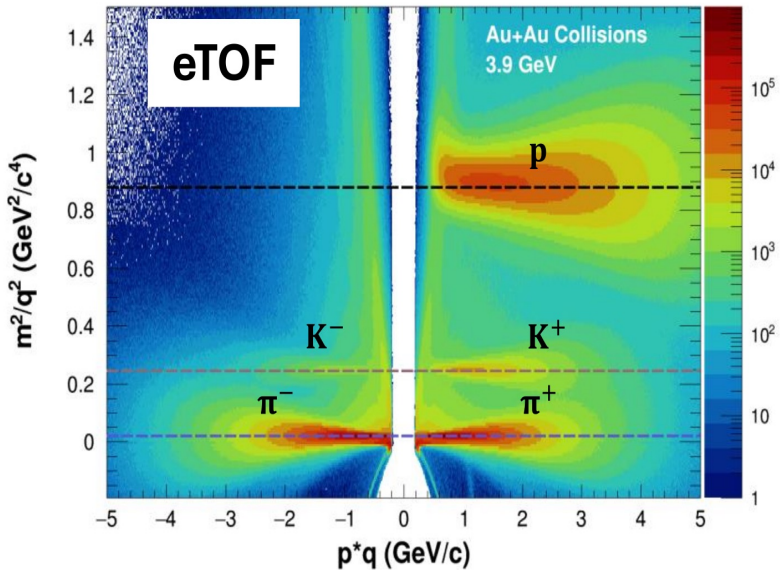




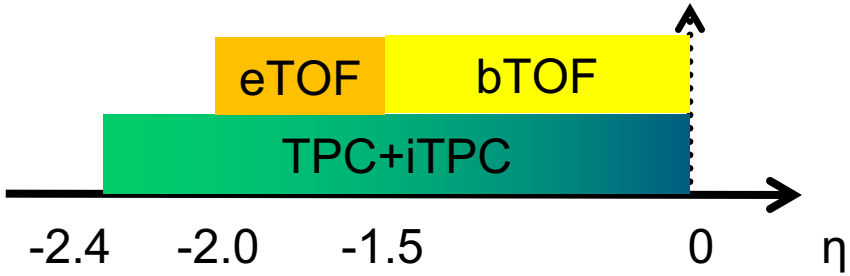
Particle Identification



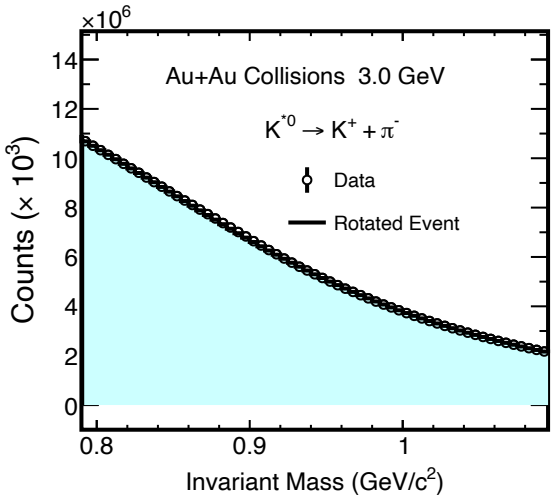


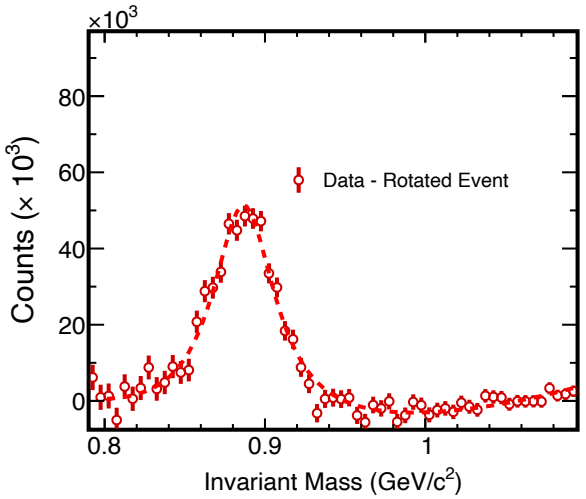


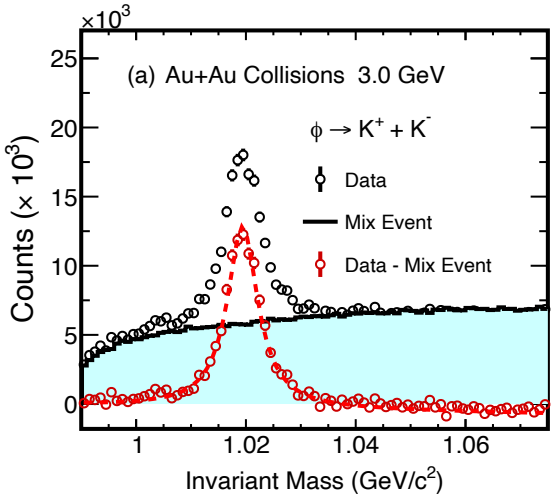
- Good particle identification capability based on TPC (dE/dx) and TOF (β) for charged pion, kaon and proton identification.
- Large acceptance for TPC+iTPC ($-2.4 < \eta < 0$) and bTOF+eTOF ($-2.0 < \eta < 0$)

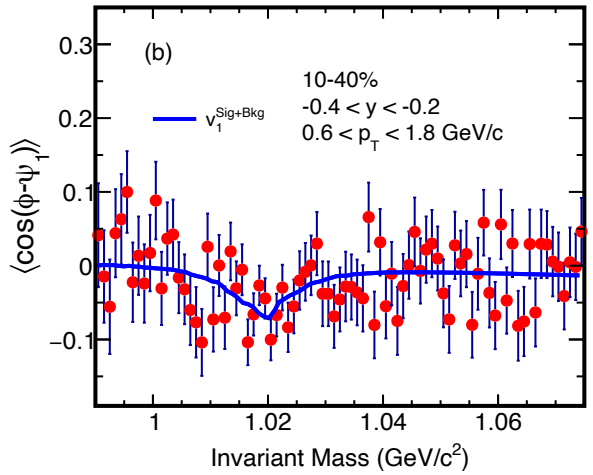


Resonances Reconstruction





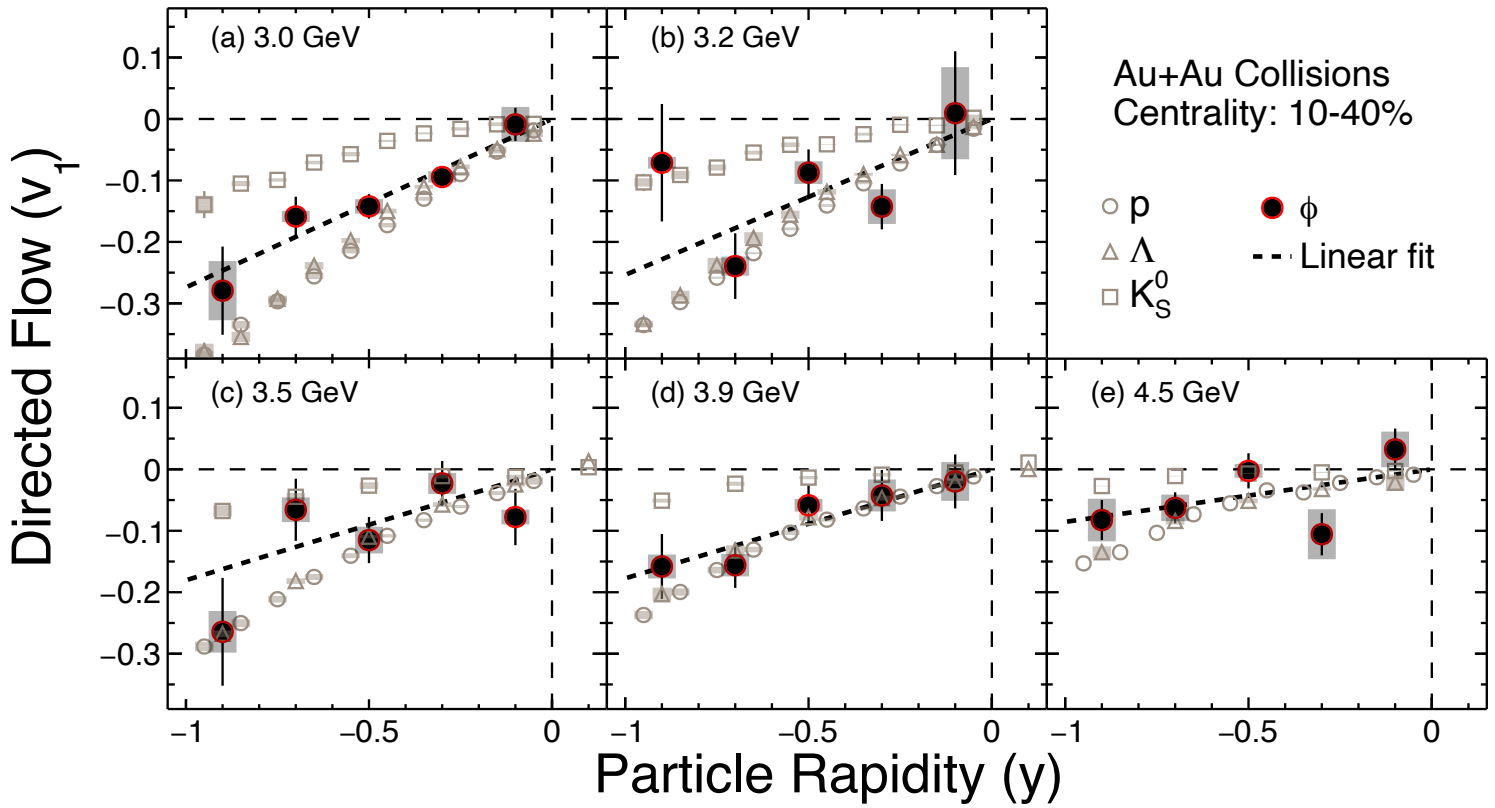




- Signal is reconstructed by paring K^+K^- ($K^+\ \pi^-$), background from mixed (rotated) events.
- Breit-Wigner function and polynomial function are used to describe the singal and residual background
- Invariant mass method is used to extract v_1.

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

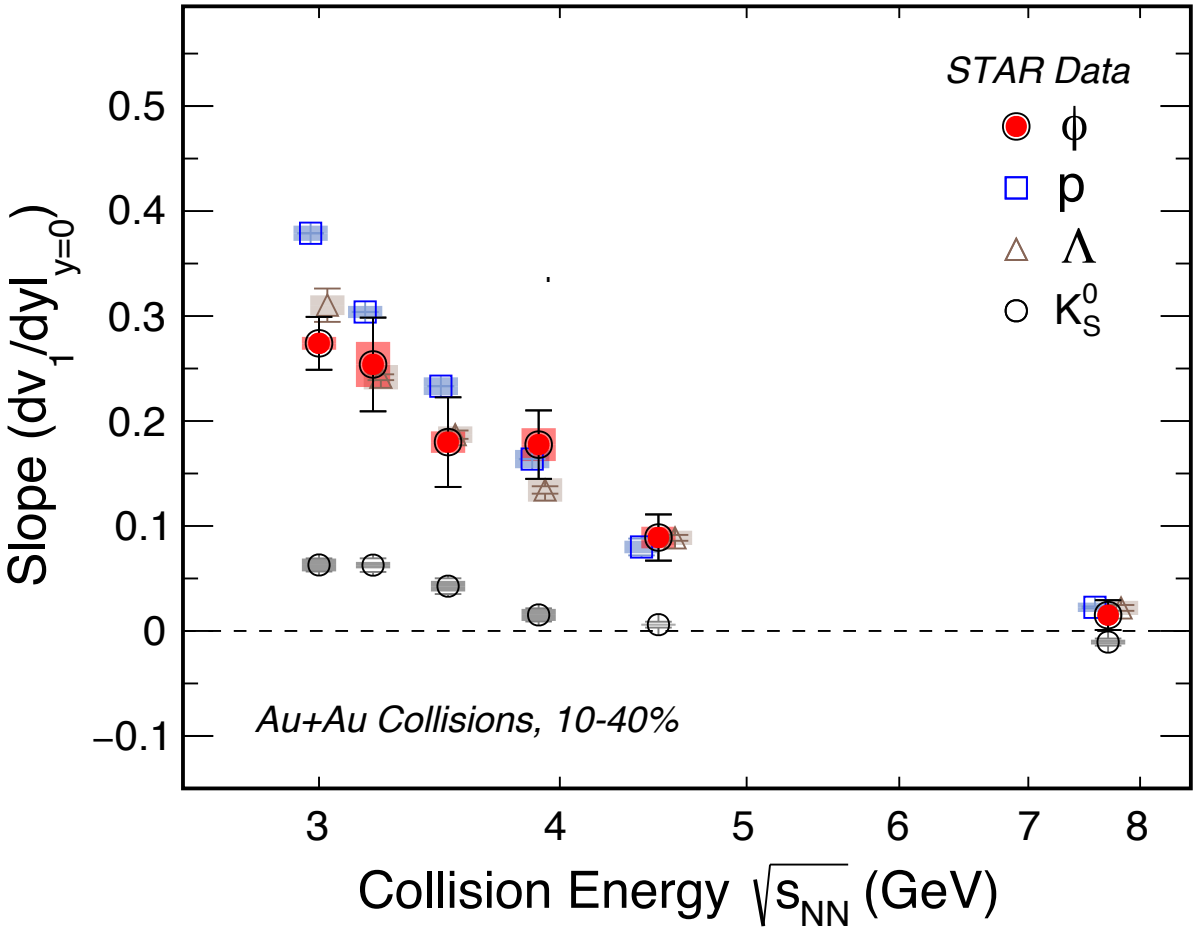
Rapidity Dependence of ϕ meson v_1



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)	

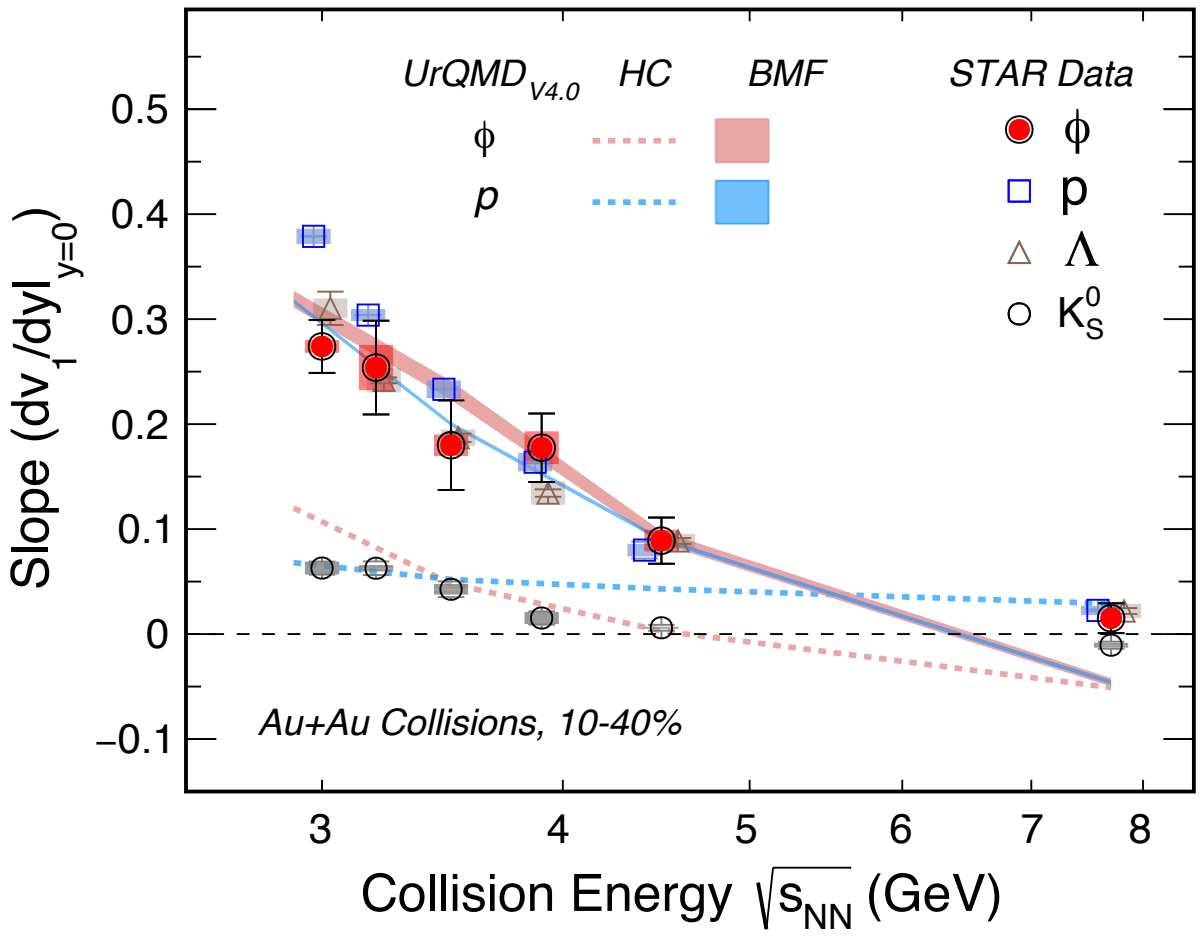
- The ϕ meson $v_1(y)$ is similar in magnitude and sign to those of protons and Λ baryons, but significantly larger than that of K_S^0.
- The magnitude of v_1 for all particle species decreases with increasing collision energy

Energy Dependence of ϕ meson 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
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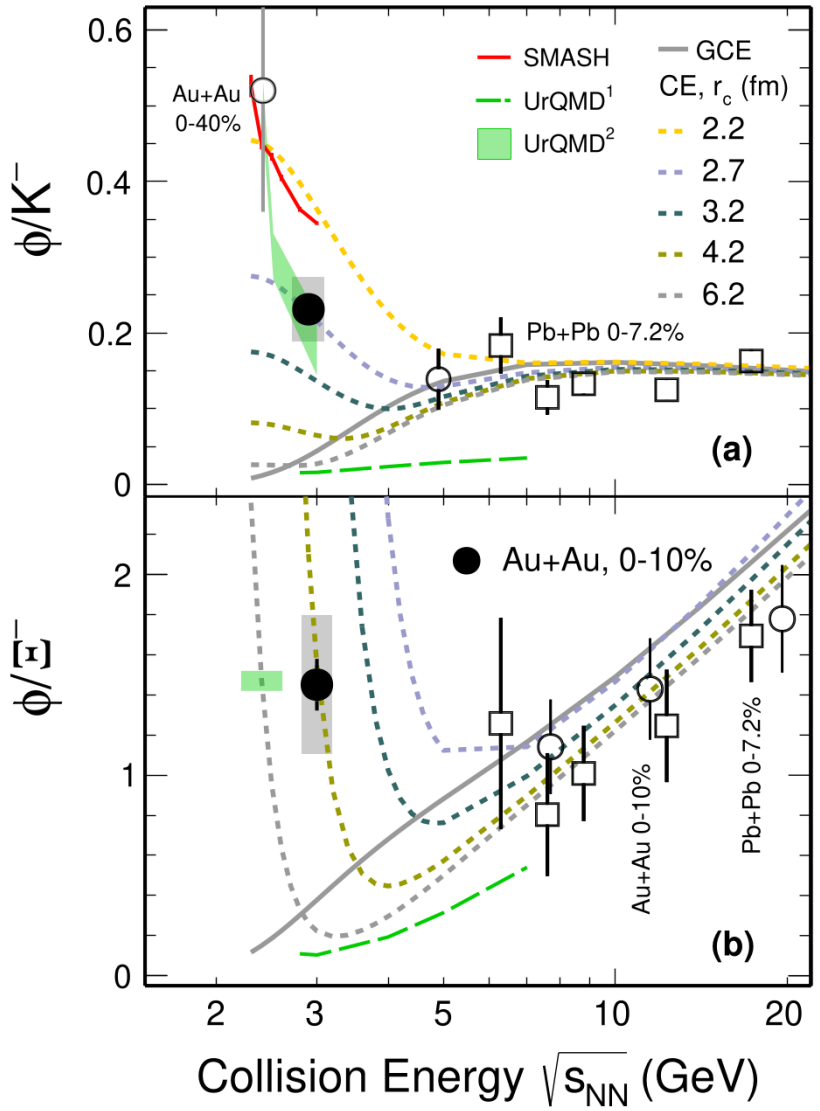
Role of Baryon Resonances



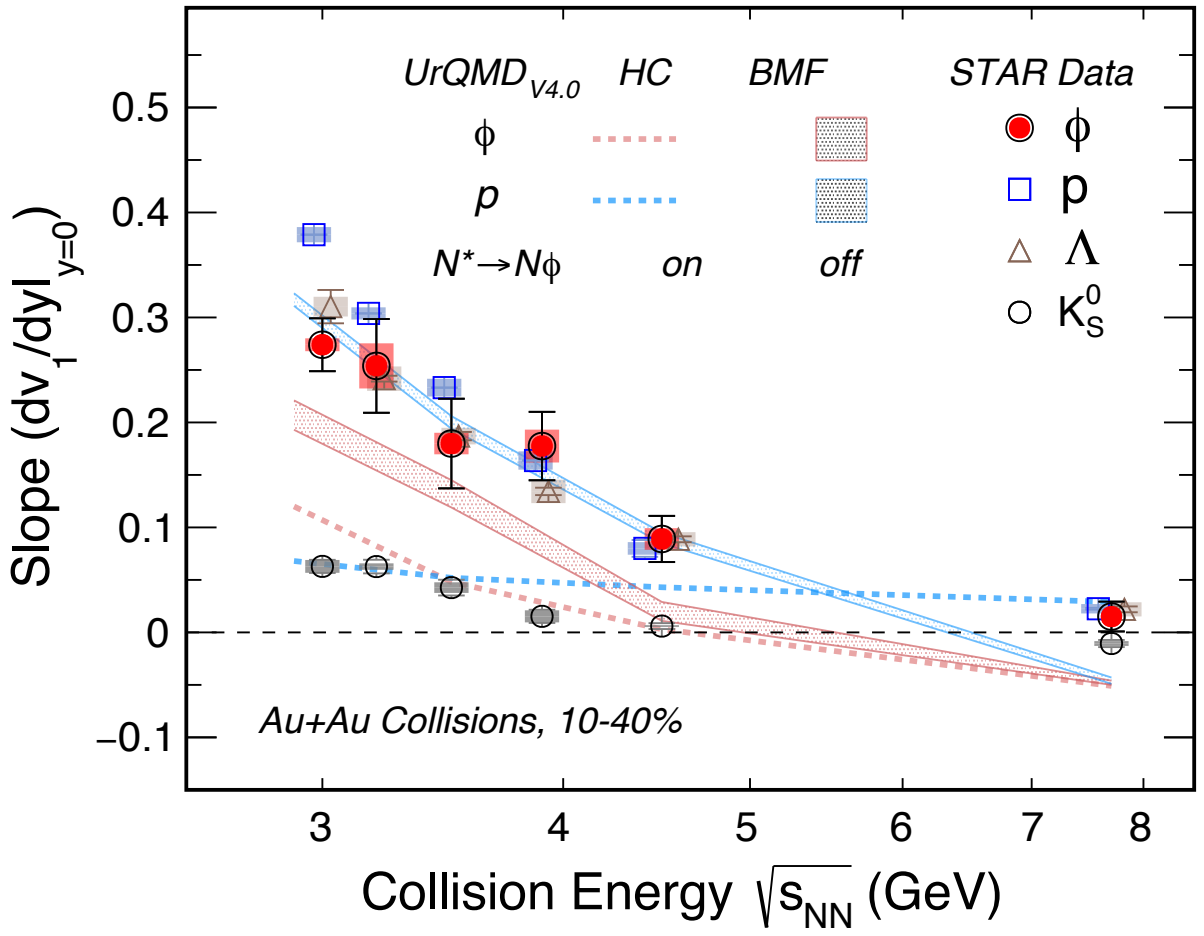
- Previous measurements of ϕ production indicate an enhanced yield ratio of ϕ/K^- and ϕ/Ξ^- in the high baryon density region.
- Transport calculations indicate that baryon resonance excitation can significantly contribute to ϕ production at low energies.

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

- 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.

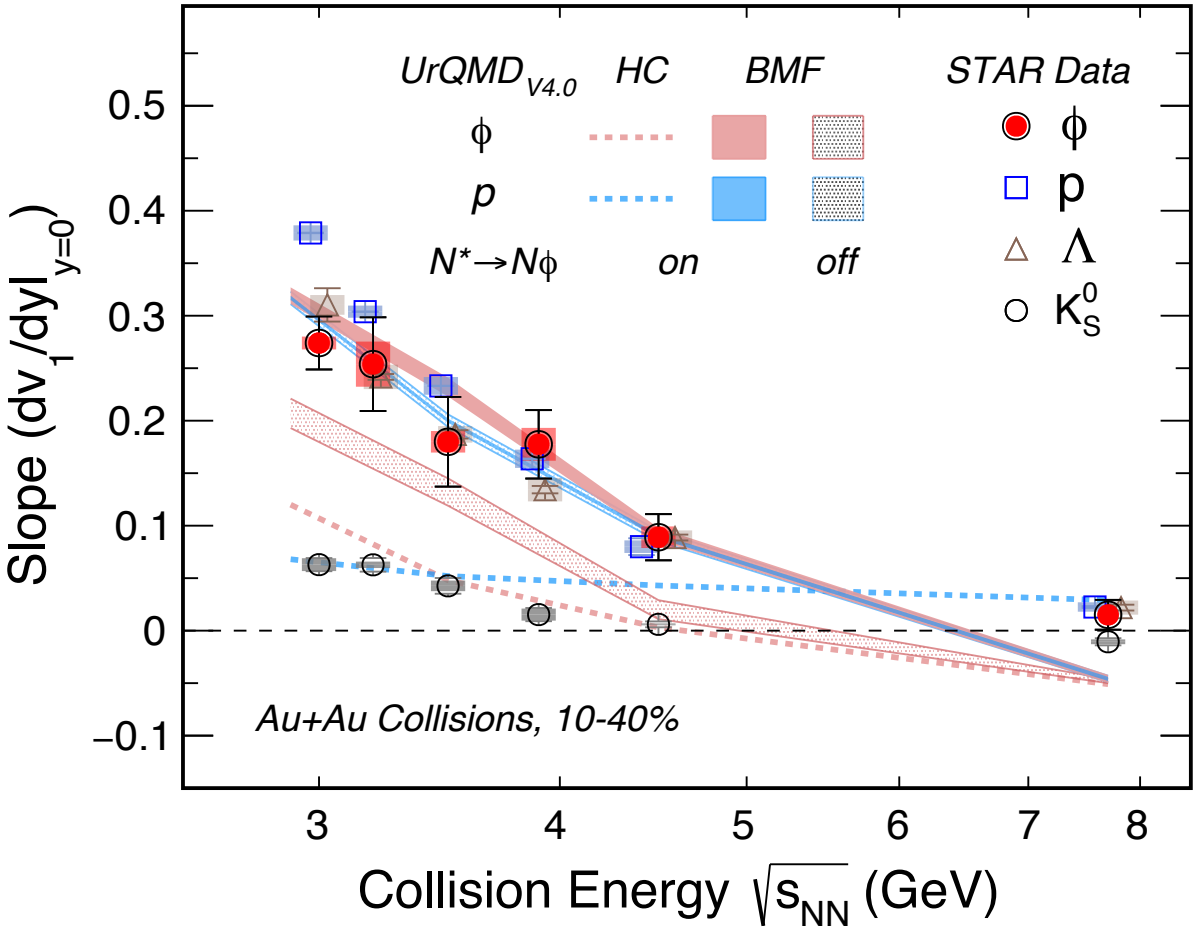
Phys. Lett. B 831 (2022) 137152
UrQMD[1]: With out high mass baryon resonances decay to ϕ
UrQMD[2]: With high mass baryon resonances decay to ϕ

Role of Baryon Resonances



- "w/o N*" 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.

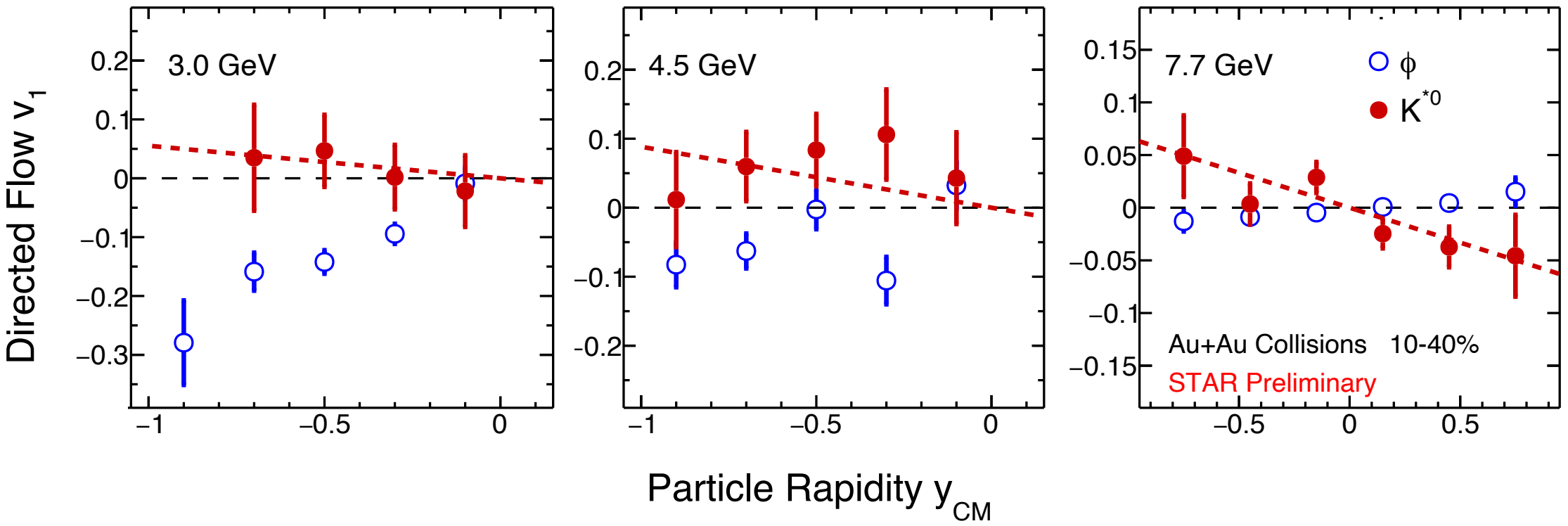
Role of Baryon Resonances



- 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]

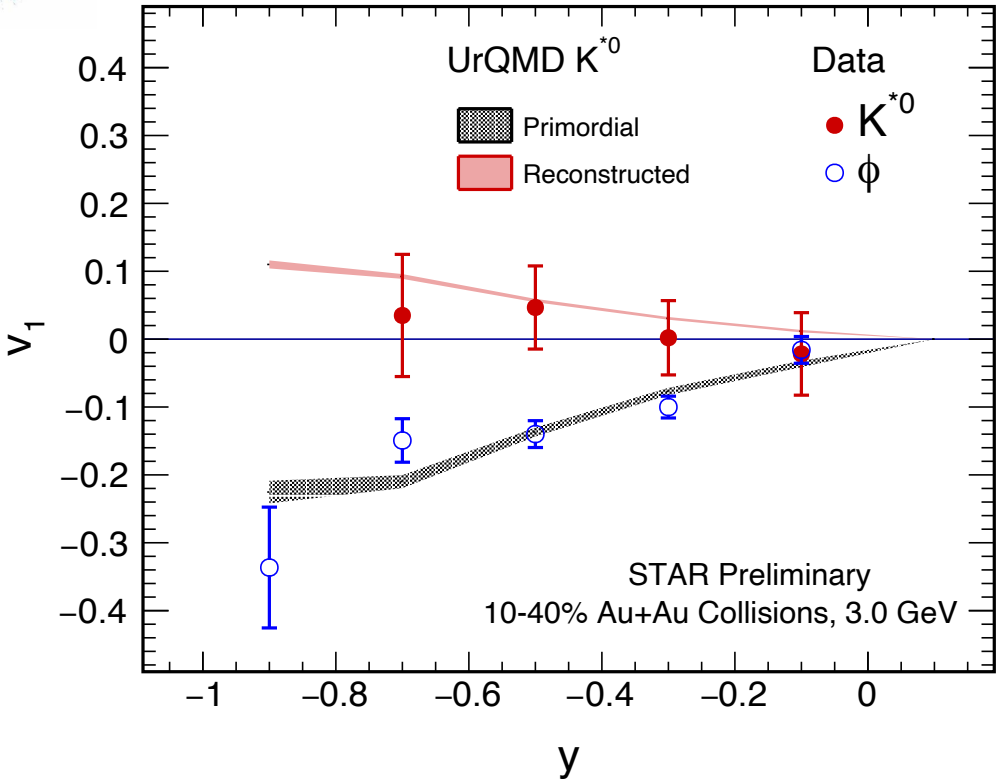
[1] J. Steinheimer, T. Reichert, and Marcus Bleicher, Phys.Lett.B 869 (2025) 139870

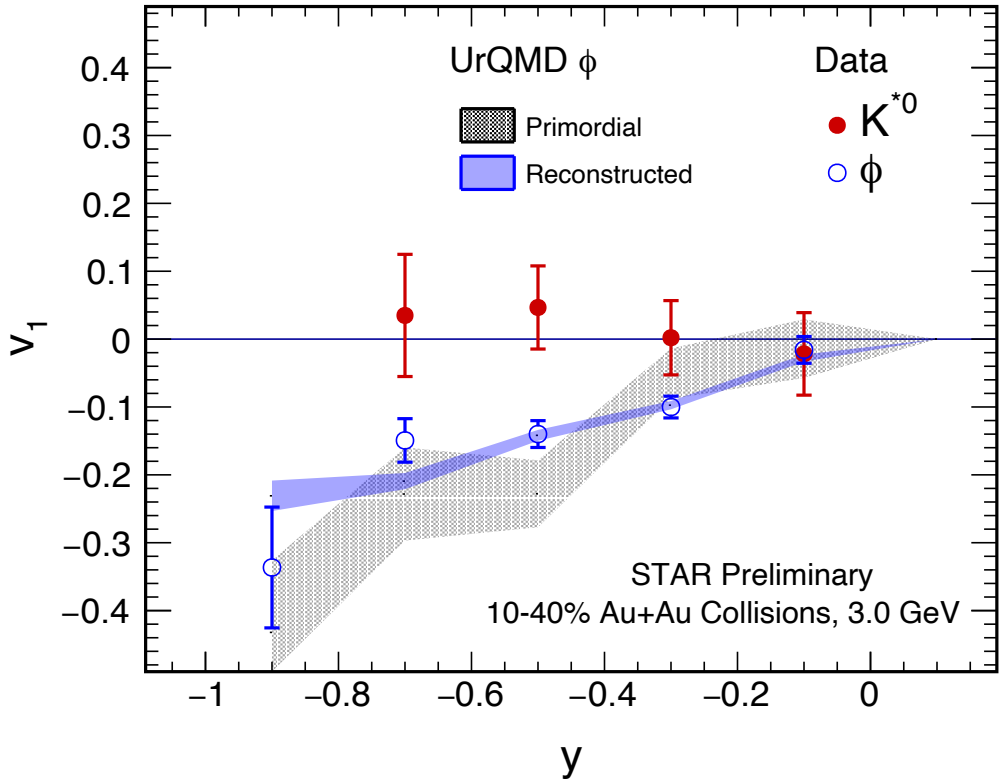
Rapidity Dependence of K^{*0} meson v_1



- The K^{*0} meson v_1 is consistent with a negative slope and tends to differ from that of the ϕ meson, within current uncertainties. in corresponding energies.
- The energy dependence is weak within uncertainties.

Model Comparison





Primordial: Resonance decay is switched off in the simulation.
Reconstructed: Resonance decay daughters survive without rescattering.

- Comparison with transport models suggests that the K^{*0} v_1 is sensitive to hadronic re-scattering of its decay daughters, with the data tending to favor the reconstructed scenario.
- ϕ remains largely unaffected due to its long lifetime and weak interaction, decaying mostly outside the hadronic medium

Summary

- Baryon-like directed flow of the ϕ meson
  - The ϕ meson v_1 slope is positive and comparable to that of protons and Λ baryons, while other mesons show significantly smaller flow.
  - Model comparisons high-mass baryon resonances play an important role in describing the observed ϕ meson flow.
  - Suggests sensitivity to early-stage baryonic dynamics and resonance production
- Complementary constraints from K^{*0}
  - The K^{*0} flow is sensitive to rescattering of its decay daughters, providing complementary insights into hadronic-stage dynamics.