Probing the QCD phase structure with elliptic flow in Au + Au collisions at $\sqrt{s_{NN}} = 7.7 - 19.6$ GeV at RHIC

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STAR collaboration

Outline

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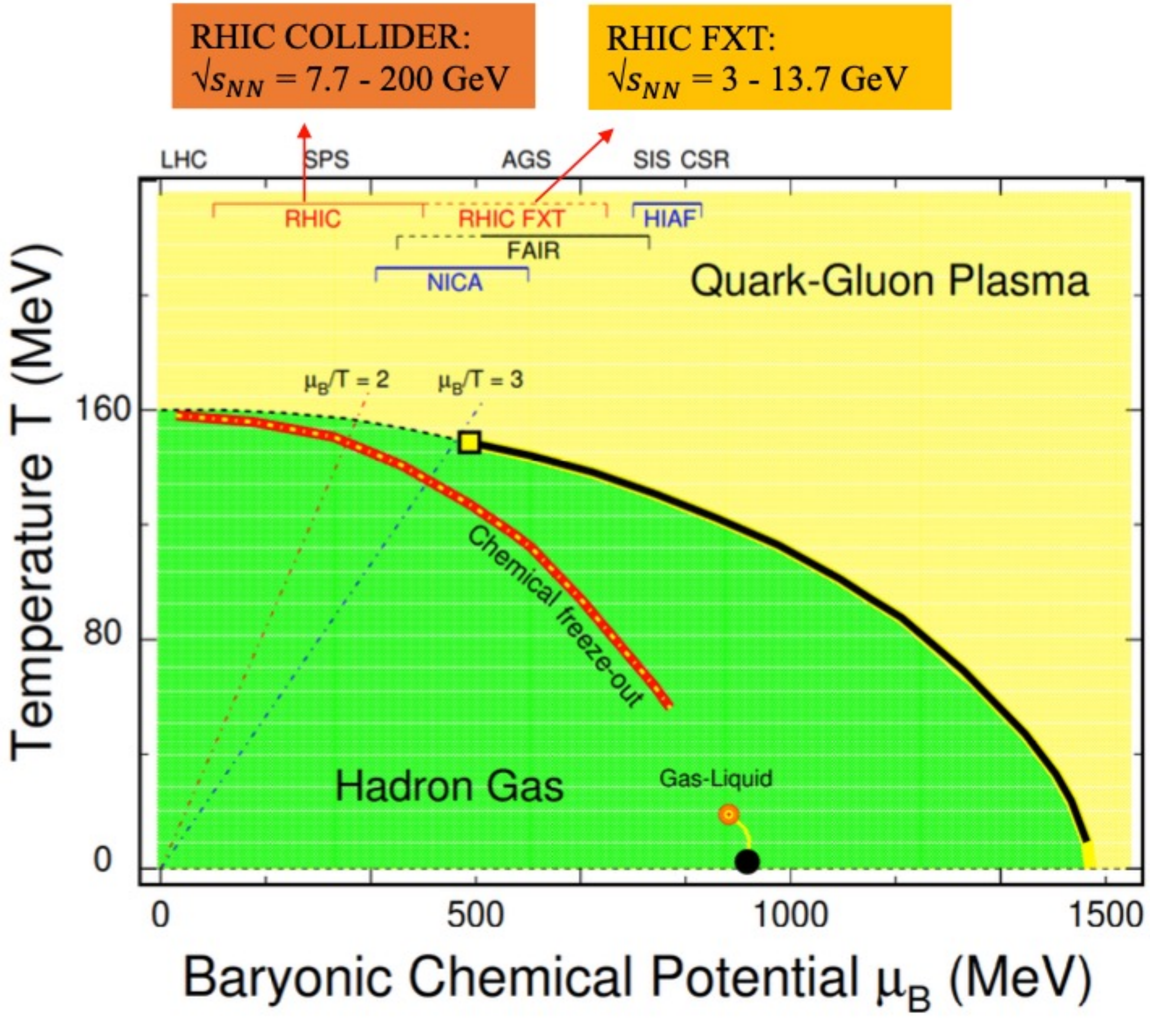
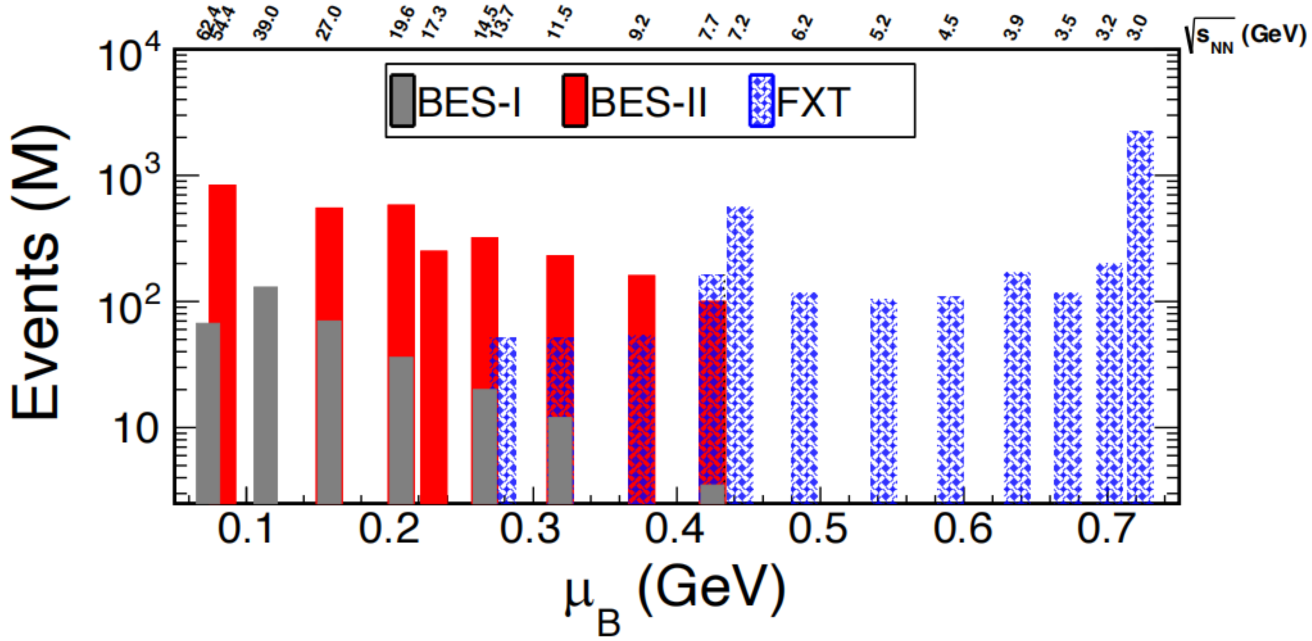
- STAR experiment
- Analysis details
- Results and discussion
- Summary

Introduction



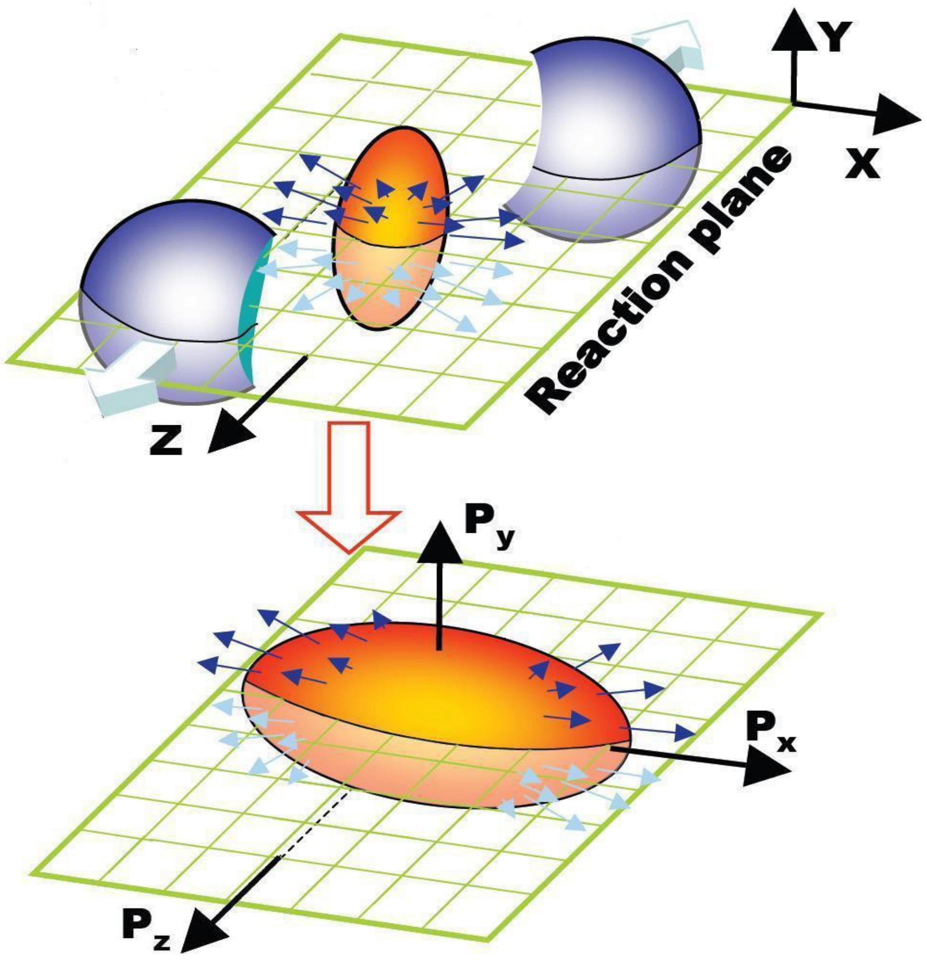
Beam Energy Scan (BES) program at RHIC:

- Study the properties of QGP
- Search for the QCD critical point
- Explore the first-order phase boundary



X. Luo, S. Shi, Nu Xu et al. Particle 3, 278 (2020)

Motivation



◆ Azimuthal distribution of particles:

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

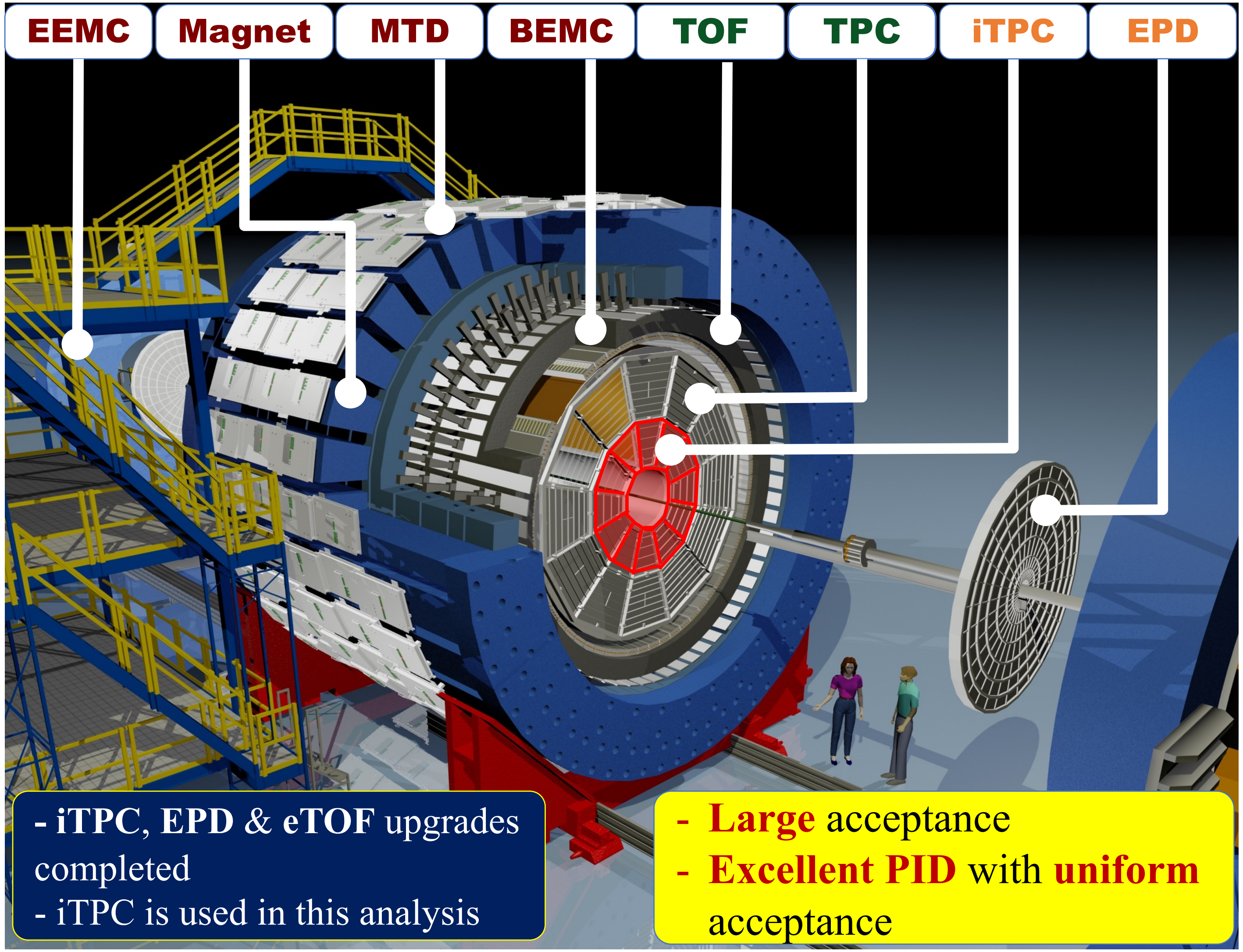
- Elliptic flow:

$$v_2 = \langle \cos 2(\phi - \Psi_2) \rangle$$

➢ Why are we interested in v_2?
- ✓ sensitive to the equation of state
- ✓ sensitive to the degrees of freedom of the produced medium.

A. M. Poskanzer, S. A. Voloshin, PHYSICAL REVIEW C 58, 1671(1998)

STAR Experiment



Time Projection Chamber (TPC):
- Particles identification with dE/dx
- Tracking for charged particles
- Momenta measurement $p \in (0.1, 30)$ GeV/c

Time of Flight (TOF):
- Particles identification with m^2
- Pile-up rejection

inner TPC upgrade:
- Improves dE/dx
- Extends $|\eta|$ coverage from 1.0 to 1.5

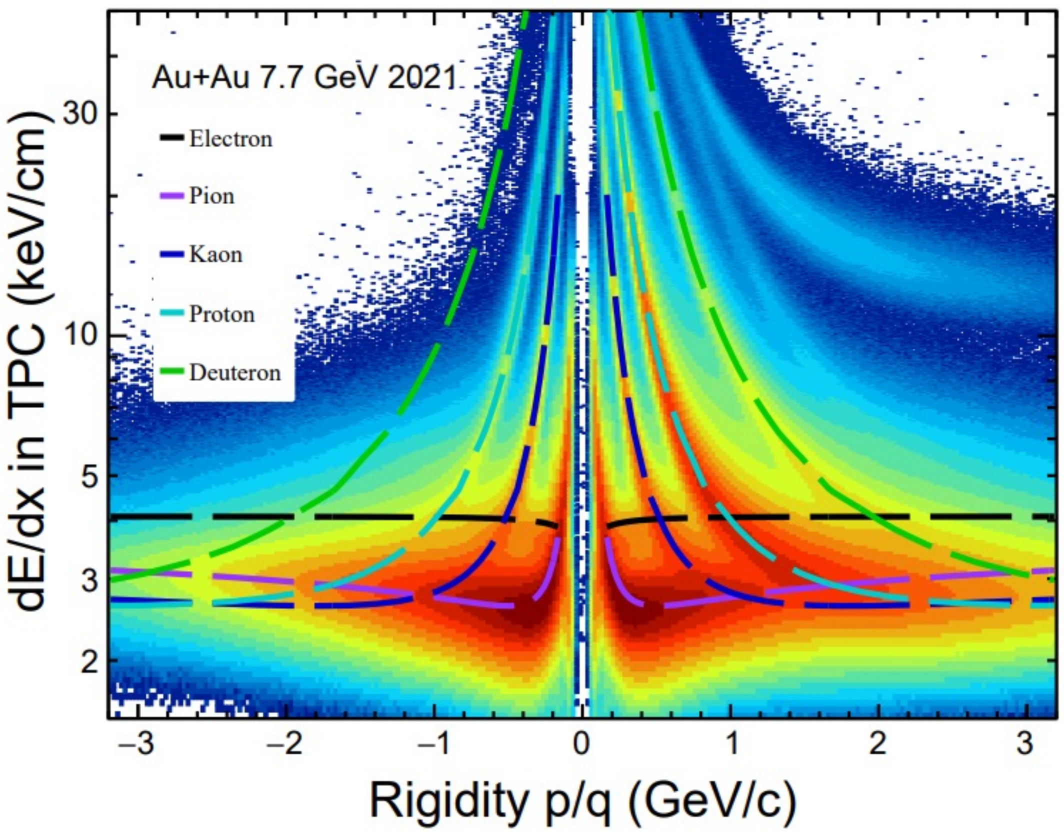
⇓

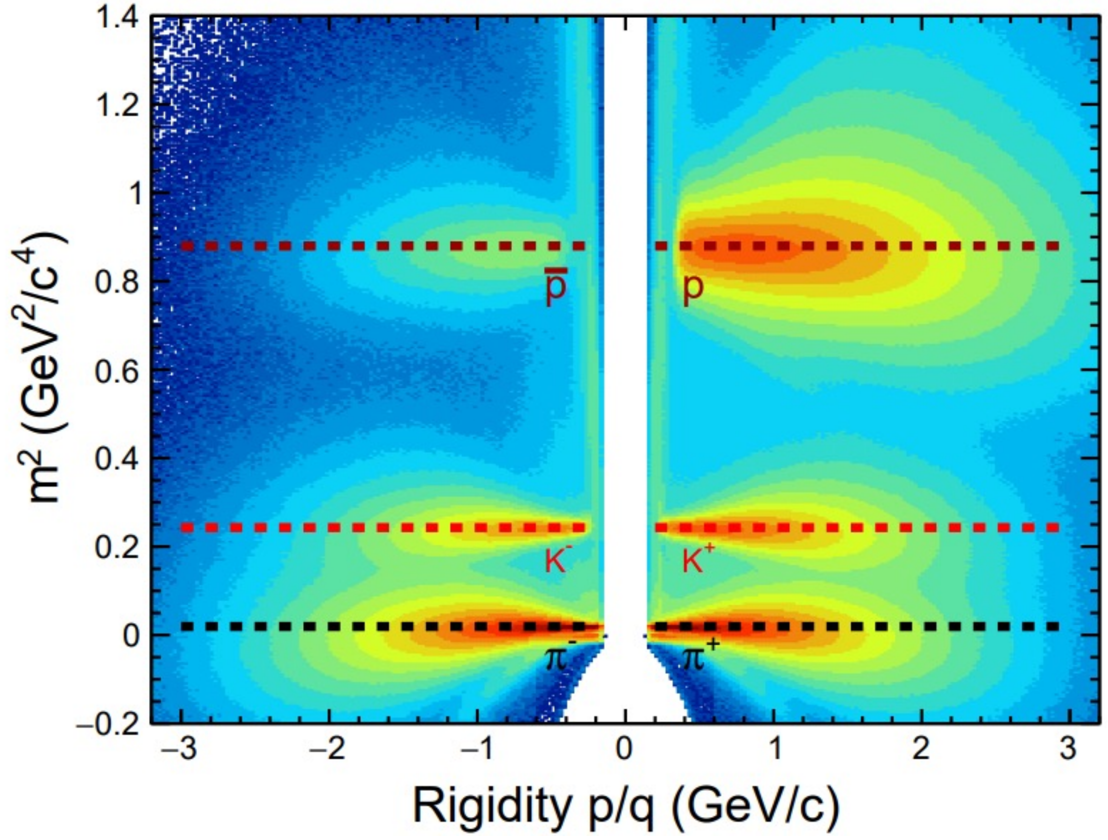
✓ Better particle identification
✓ Larger pseudo-rapidity acceptance
✓ Greater event plane resolution

Particle Identification with TPC and TOF

TPC: $-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2}]$

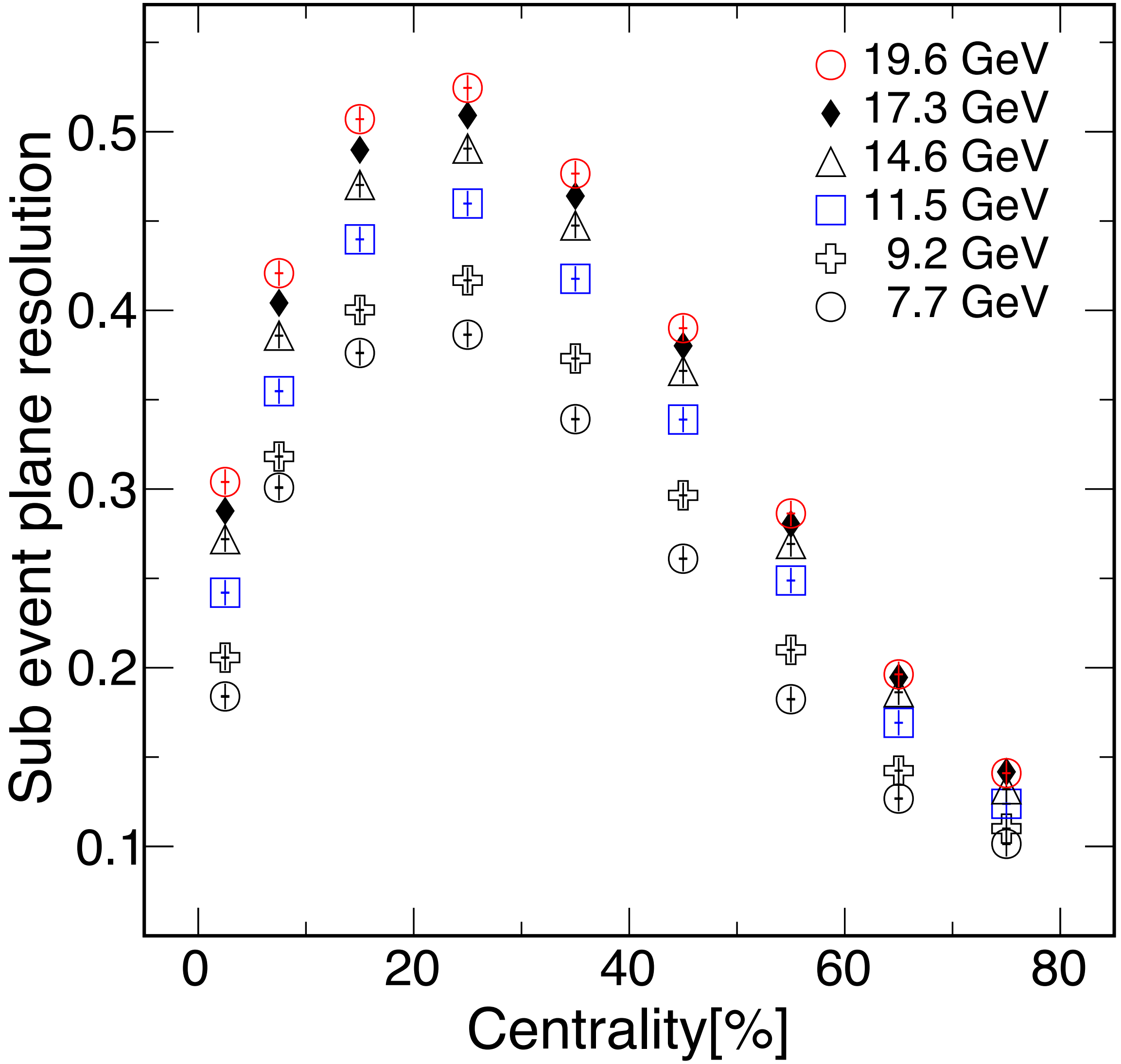
TOF: $m^2 = p^2 (\frac{c^2 T^2}{L^2} - 1)$



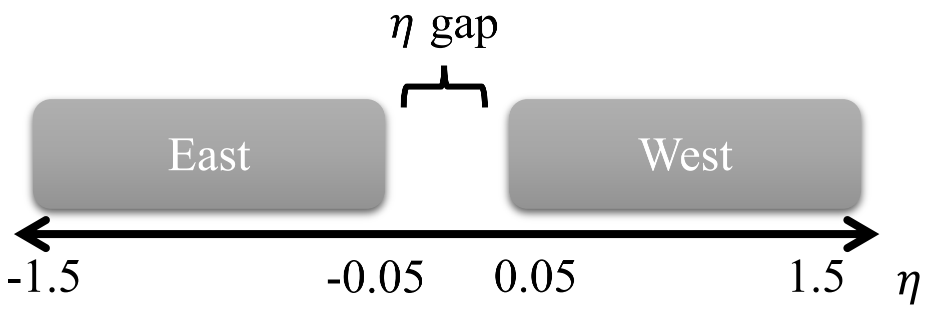


- Good particle identification capability based on TPC and TOF

Event Plane Resolution



- The 2nd order event plane (Ψ_2) is determined by the TPC



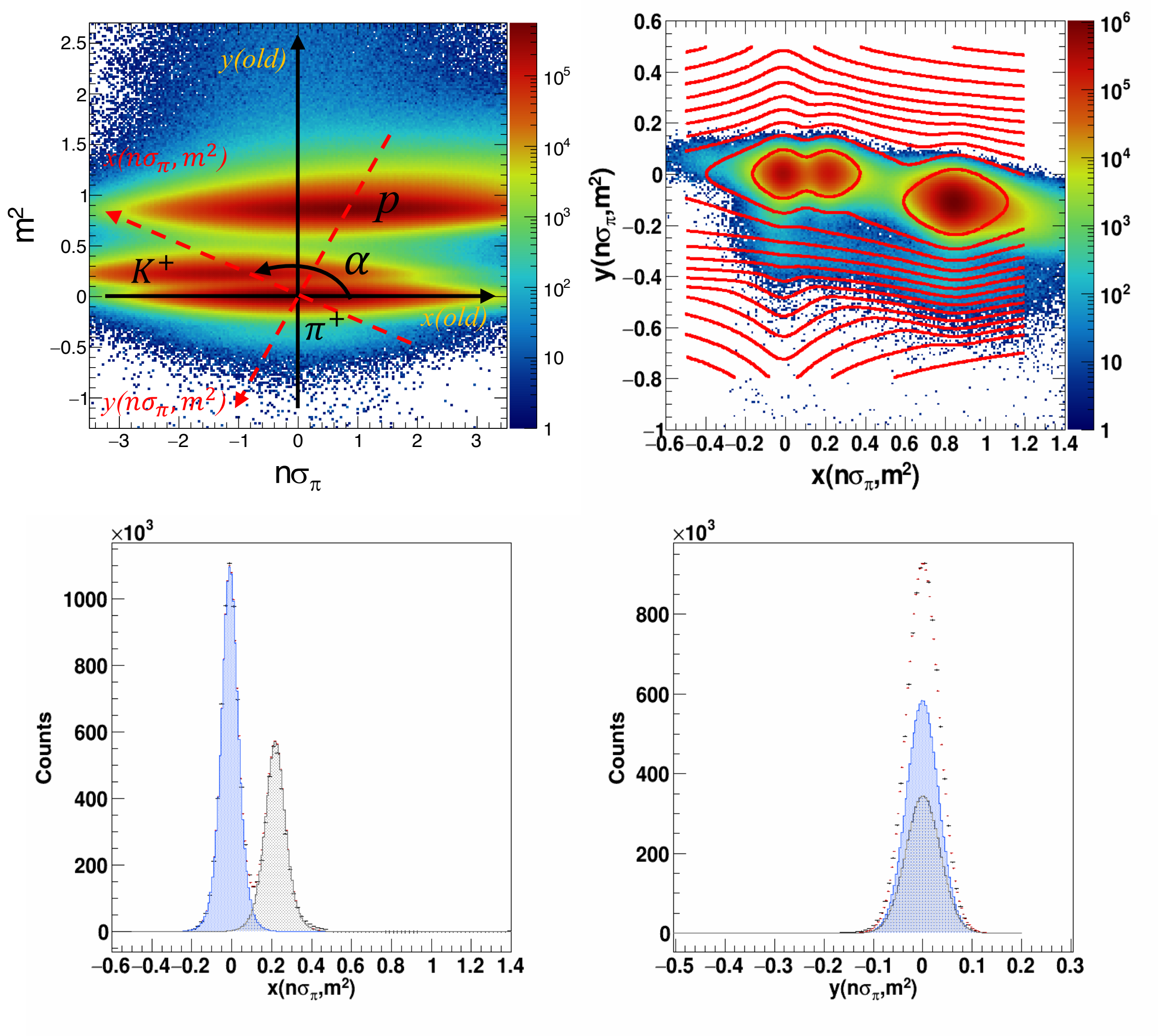
- Finite multiplicity limits the estimation of the Ψ_2

$$R_2^{sub} = \sqrt{\langle \cos[2(\Psi_2^{East} - \Psi_2^{West})] \rangle}$$

$$R_n \propto v_n \sqrt{M}$$

A. M. Poskanzer, S. A. Voloshin, PHYSICAL REVIEW C 58, 1671(1998)

Particles identification for $\pi^{\pm}$, $K^{\pm}$ and $p(\bar{p})$



- (Anti-)Protons are identified by TOF m^2, with an additional dE/dx cut of $|n\sigma_p| < 3$
- Pion and kaons are extracted by 2-D PID method:

$$\begin{pmatrix} x(n\sigma_\pi, m^2) \\ y(n\sigma_\pi, m^2) \end{pmatrix} = \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix}$$

$$\alpha = -tanh\left\{\frac{\mu_K(m^2) - \mu_\pi(m^2)}{[\mu_K(n\sigma_\pi) - \mu_\pi(n\sigma_\pi)]/f_{scale}}\right\}$$

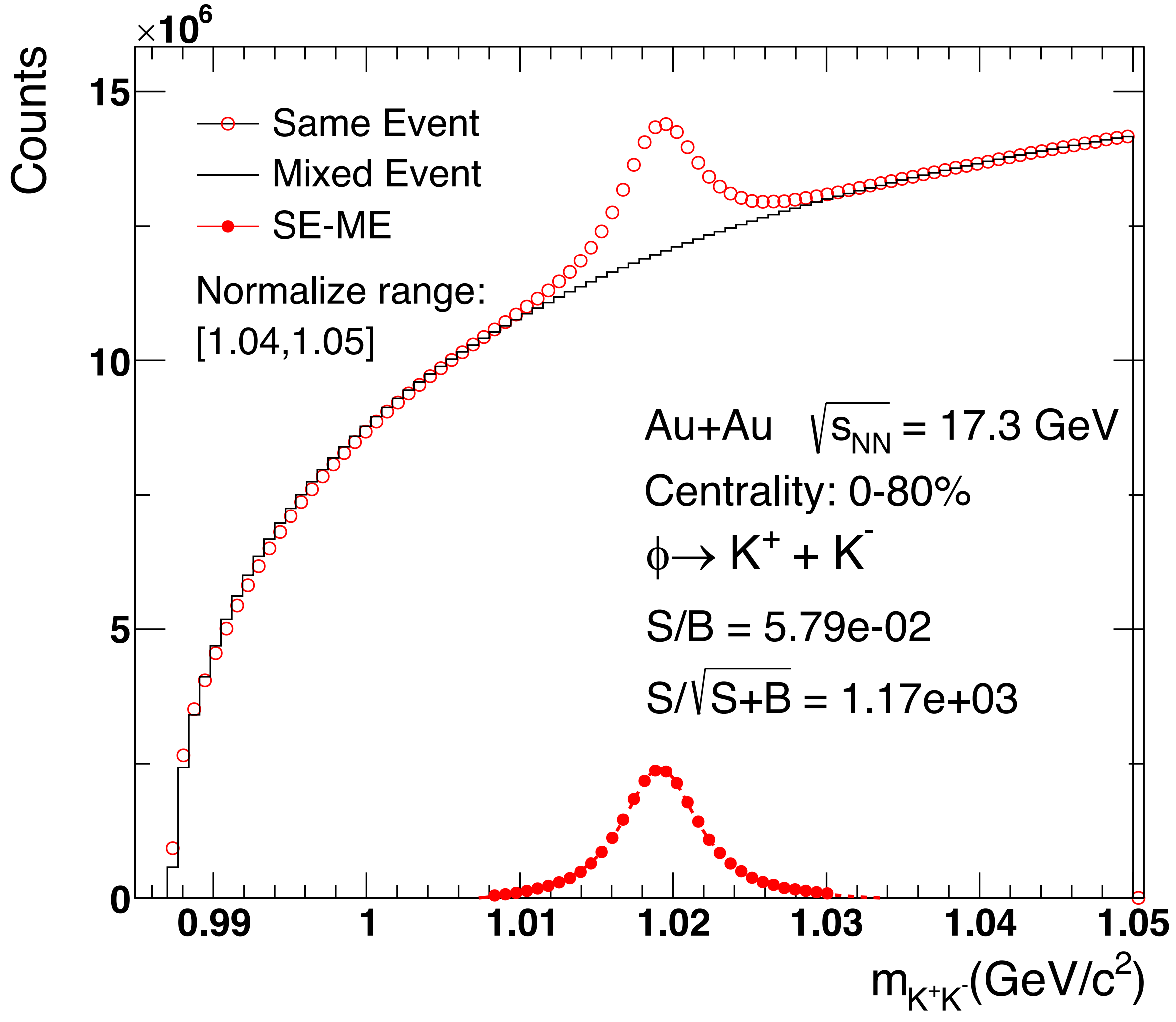
$$f_{scale} = \omega_\pi(n\sigma_\pi)/\omega_\pi(m^2)$$

$$x' = [n\sigma_\pi - \mu_\pi(n\sigma_\pi)]/f_{scale}$$

$$y' = m^2 - \mu_\pi(m^2)$$

STAR Collaboration, PHYSICAL REVIEW C 88, 014902 (2013)

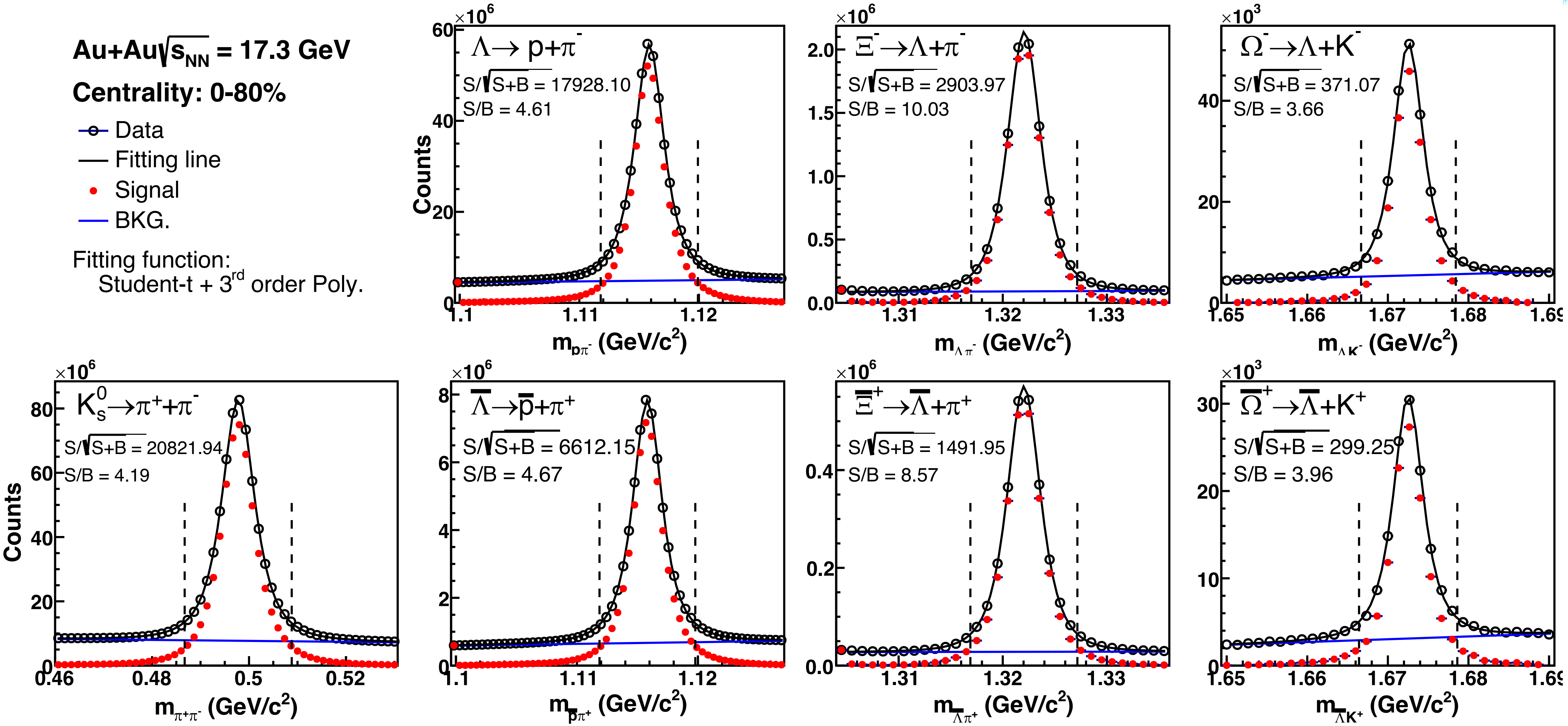
ϕ Meson Reconstruction



- ϕ mesons are reconstructed via the decay channel: $\phi \to K^+K^- (48.9 \pm 0.5)\%$
- Subtracting the combinatorial background, estimated by mixed event method

$$M_{inv}^2 = (p_A + p_B)^2 = (E_A + E_B)^2 - |\mathbf{p}_A + \mathbf{p}_B|^2$$

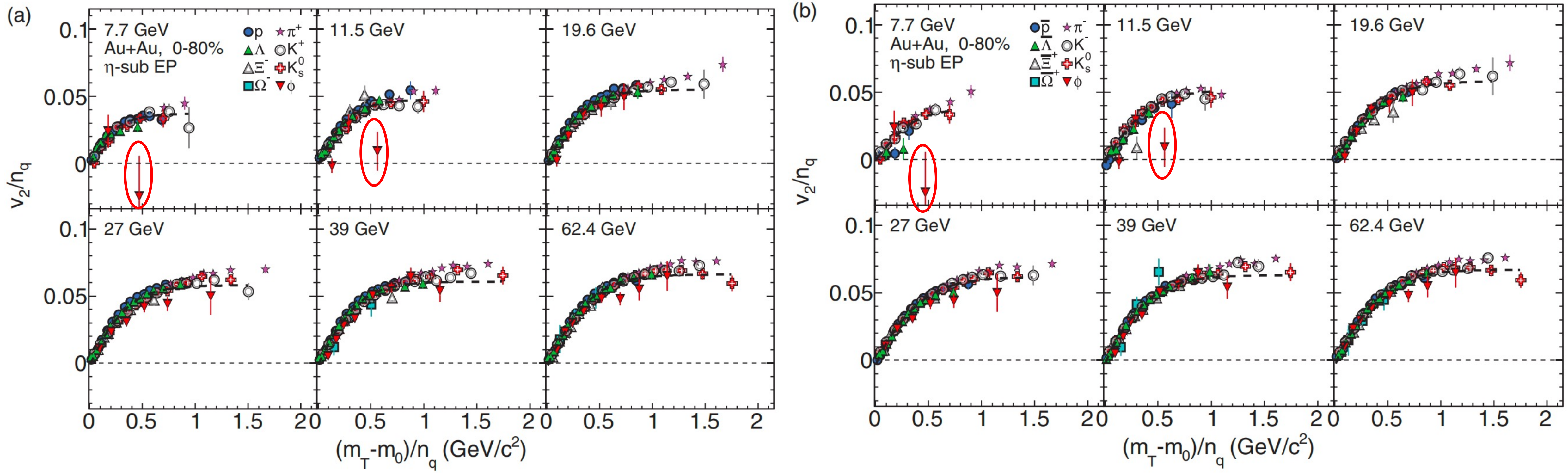
Reconstruction of Hadrons with Weak Decays



➢ The weak decayed hadrons are reconstructed by Kalman filter method

T. Kailath, in Lectures on Wiener and Kalman Filtering (Springer, 1981) pp. 1–143.
STAR Collaboration, Nuclear Science and Techniques 34, 158 (2023).

NCQ scaled v_2: BES-I



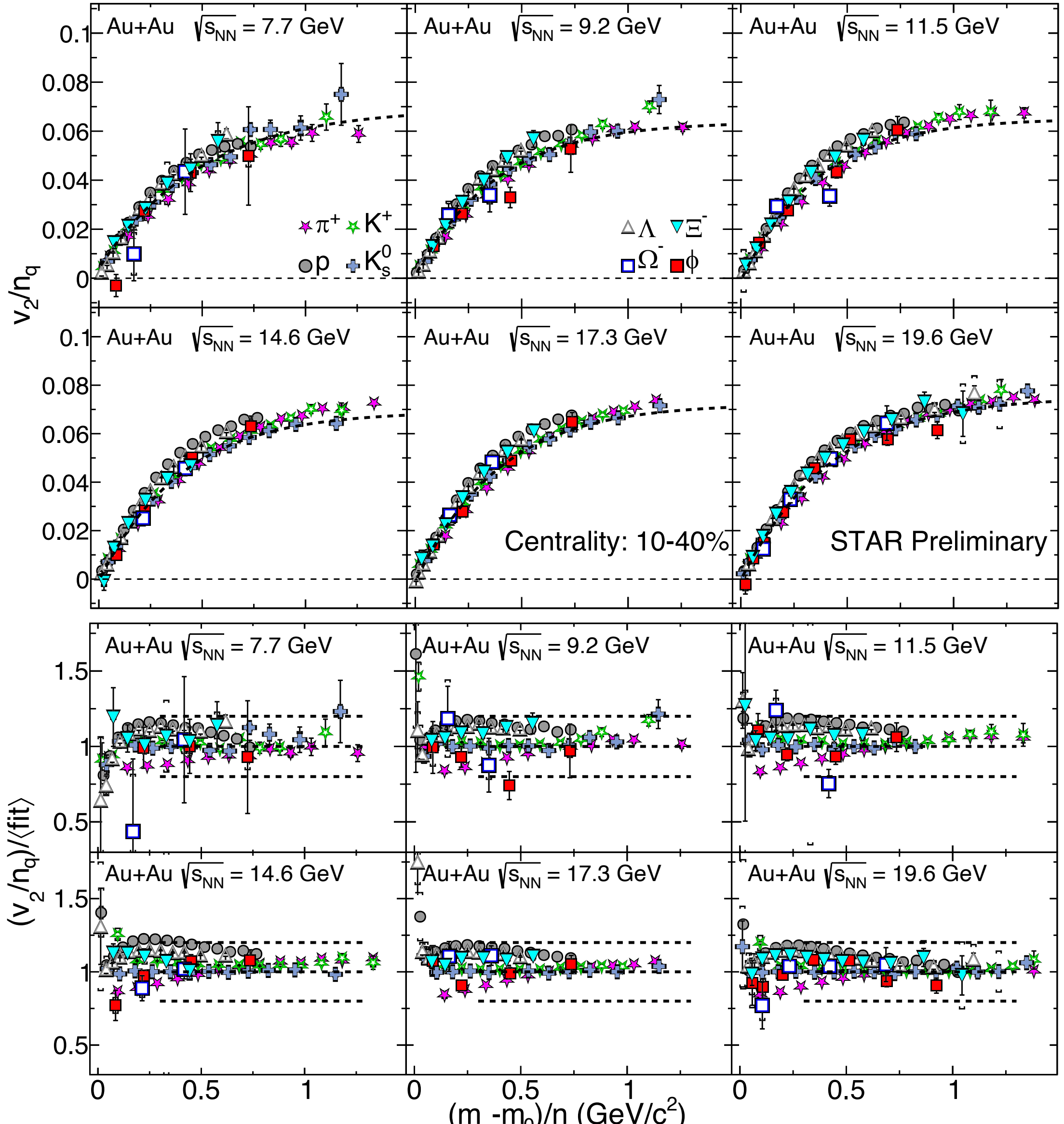
- At $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV, the v_2 of ϕ meson at the highest measured $m_T - m_0$ is observed to be lower than that of other particles and anti-particles, with statistical significances of 1.8σ and 2.3σ, respectively.

High-precision data needed **➞ BES-II**

- These observations may suggest that hadronic interactions dominate over partonic effects in the systems formed at collision energies ≲ 11.5 GeV.

STAR Collaboration, PHYSICAL REVIEW C 88, 014902 (2013)
STAR Collaboration, PHYSICAL REVIEW LETTERS110, 142301 (2013)

NCQ scaled v_2 from BES-II: particles



Fitting function:

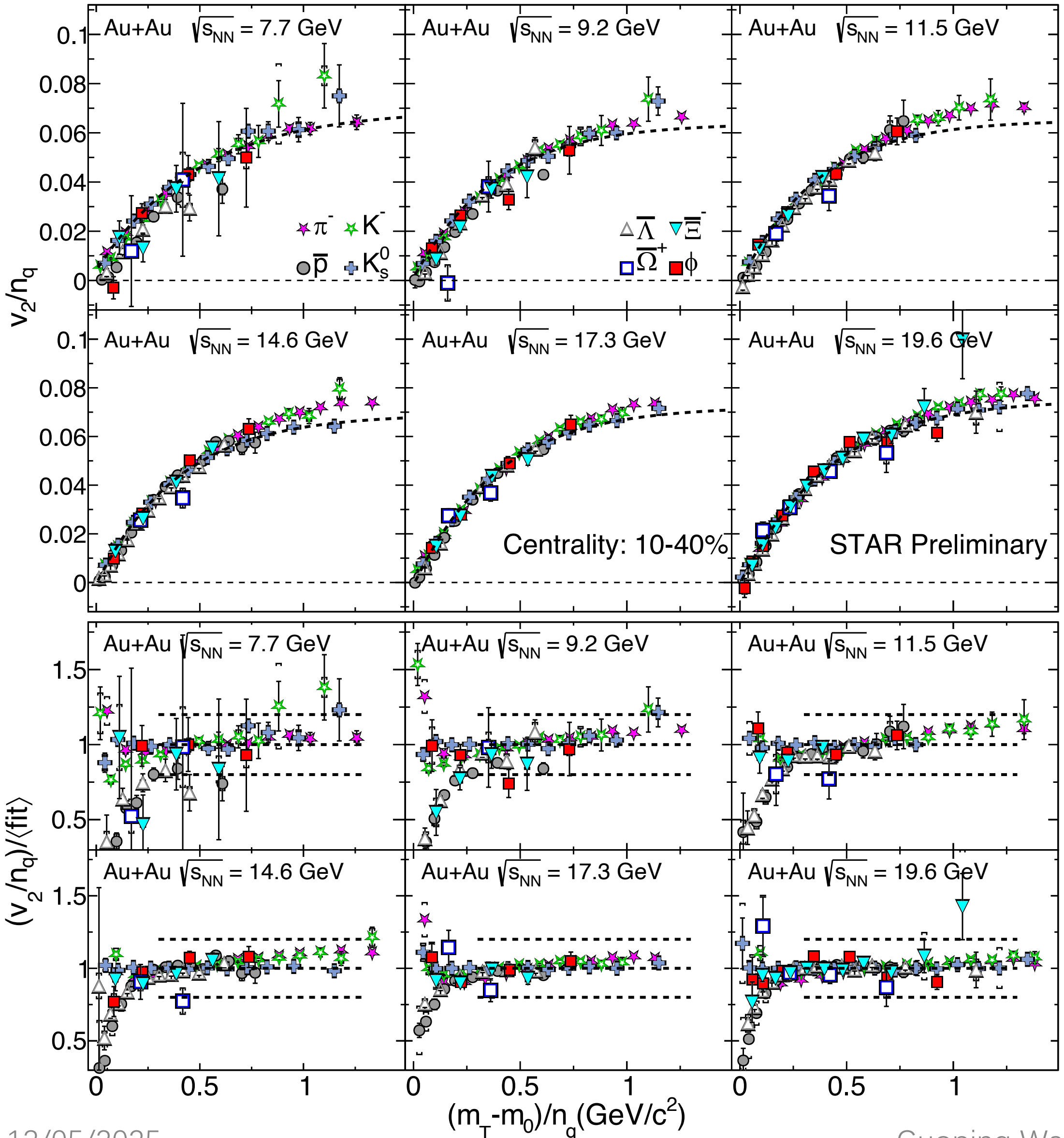
$$f_{v_2}(n) = \frac{a*n}{1+\exp(-(\frac{p_T}{n}-b)/c)} - d*n$$

a, b, c, and d are free fitting parameters, and n is the number of constituent quarks.

- The performance of NCQ scaling is similar across these six energies.
- The ϕ meson and multi-strange hadrons v_2/n_q show no qualitative deviation from other particles.

X. Dong et al. Physics Letters B 597 (2004) 328–332

NCQ scaled v_2 from BES-II : anti-particles



Fitting function:

$$f_{v_2}(n) = \frac{a*n}{1+\exp(-(\frac{p_T}{n}-b)/c)} - d*n$$

a, b, c, and d are free fitting parameters, and n is the number of constituent quarks.

- The performance of NCQ scaling is similar across these six energies.
- The ϕ meson and multi-strange hadrons v_2/n_q show no qualitative deviation from other anti-particles.

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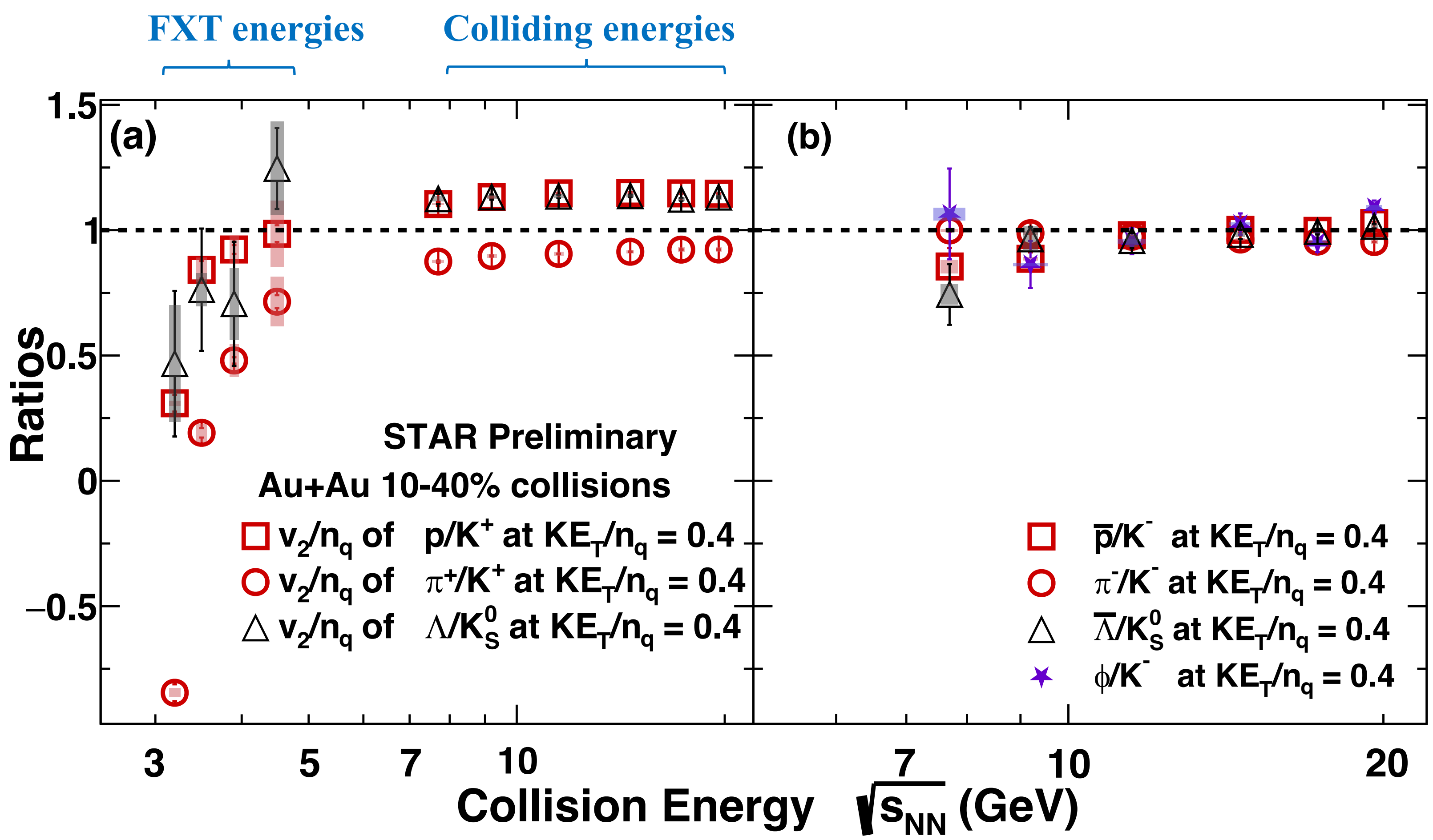
Energy dependence of NCQ scaled v_2 Ratios



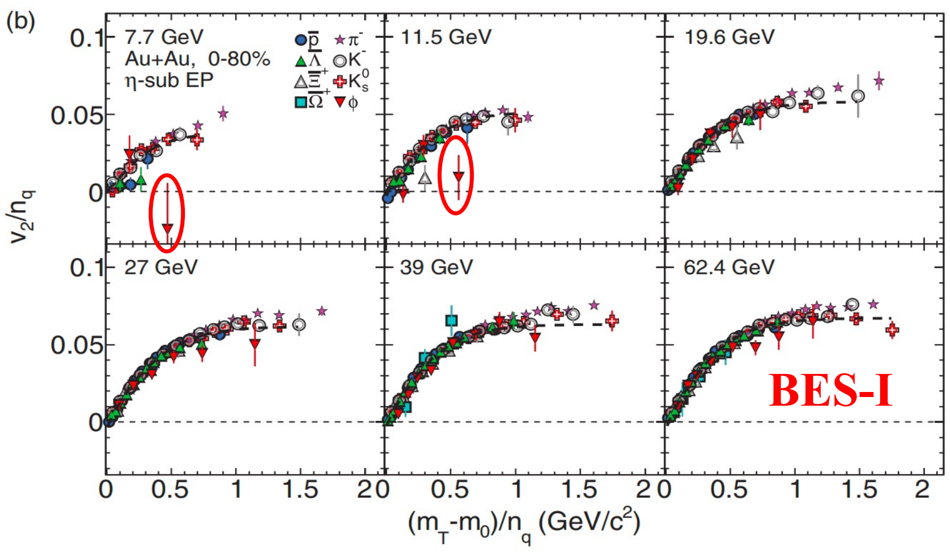
- The NCQ scaled v_2 ratios are close to 1 at $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV and are less dependent on the collision energy.
- Partonic collectivity in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV .

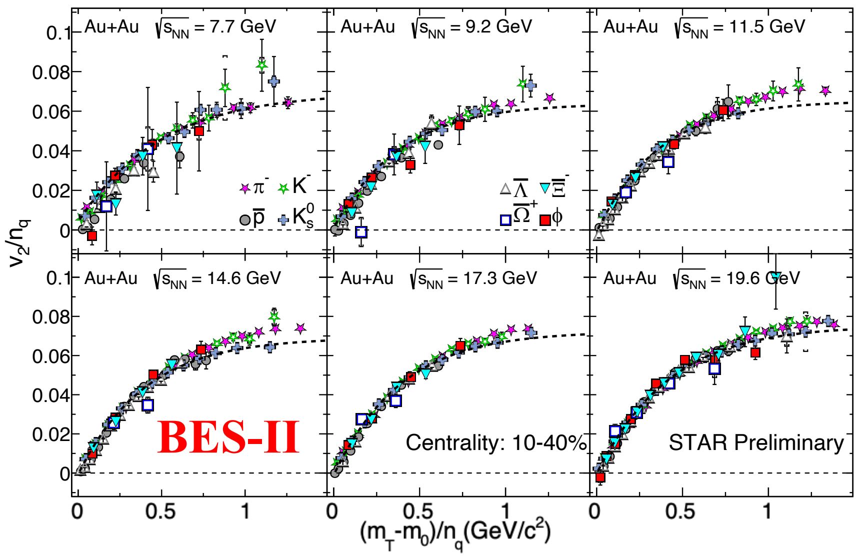
STAR Collaboration. arXiv: 2504.02531

Summary

- The ϕ meson and multi-strange hadrons v_2/n_q show no qualitative deviation from other particles and anti-particles：

Answered the question posed by BES-I





- Partonic collectivity in Au + Au collisions at $\sqrt{s_{NN}} = 7.7 – 19.6$ GeV.

Thank you for your attention!