Directed Flow of Identified Particles in Au+Au Collisions at $\sqrt{s_{NN}} = 19.6$ GeV

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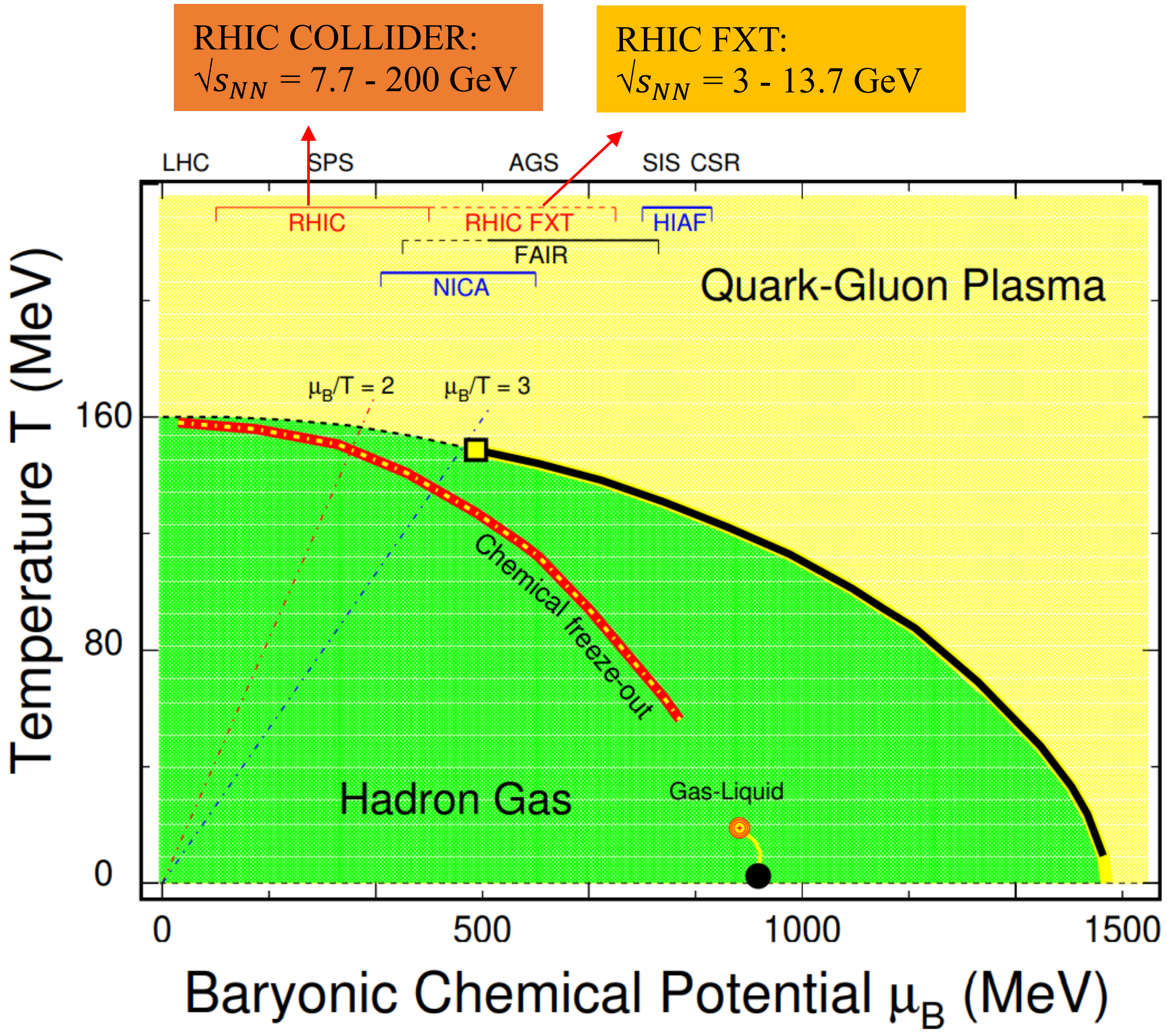
Outline

- ❑ Motivation
- ❑ STAR Detectors
- ❑ Results and Discussions
- ❑ Summary

Beam Energy Scan

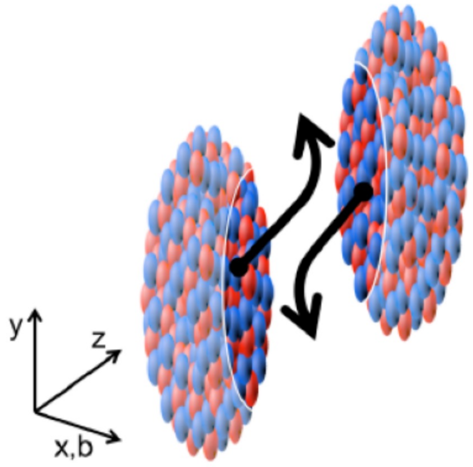


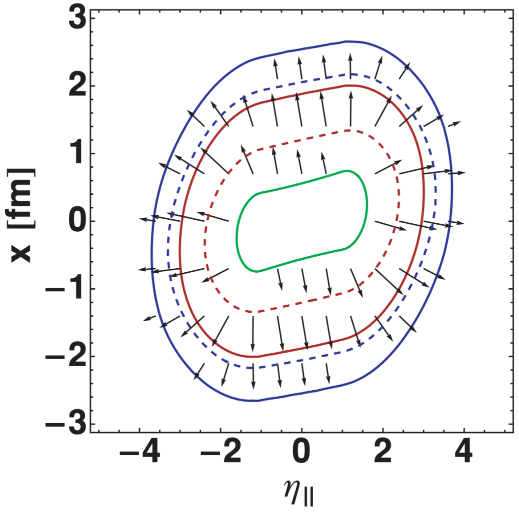
- RHIC Beam Energy Scan:
  - Colliding mode: $\sqrt{s_{NN}}$ = 7.7 – 200 GeV
  - Fixed-target(FXT) mode: $\sqrt{s_{NN}}$ = 3 – 13.7 GeV

- Baryon density region: μ_B = 20 – 750 MeV
  - Study the properties of QGP.
  - Search for the critical point and locate the first-order phase boundary.

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

Directed Flow



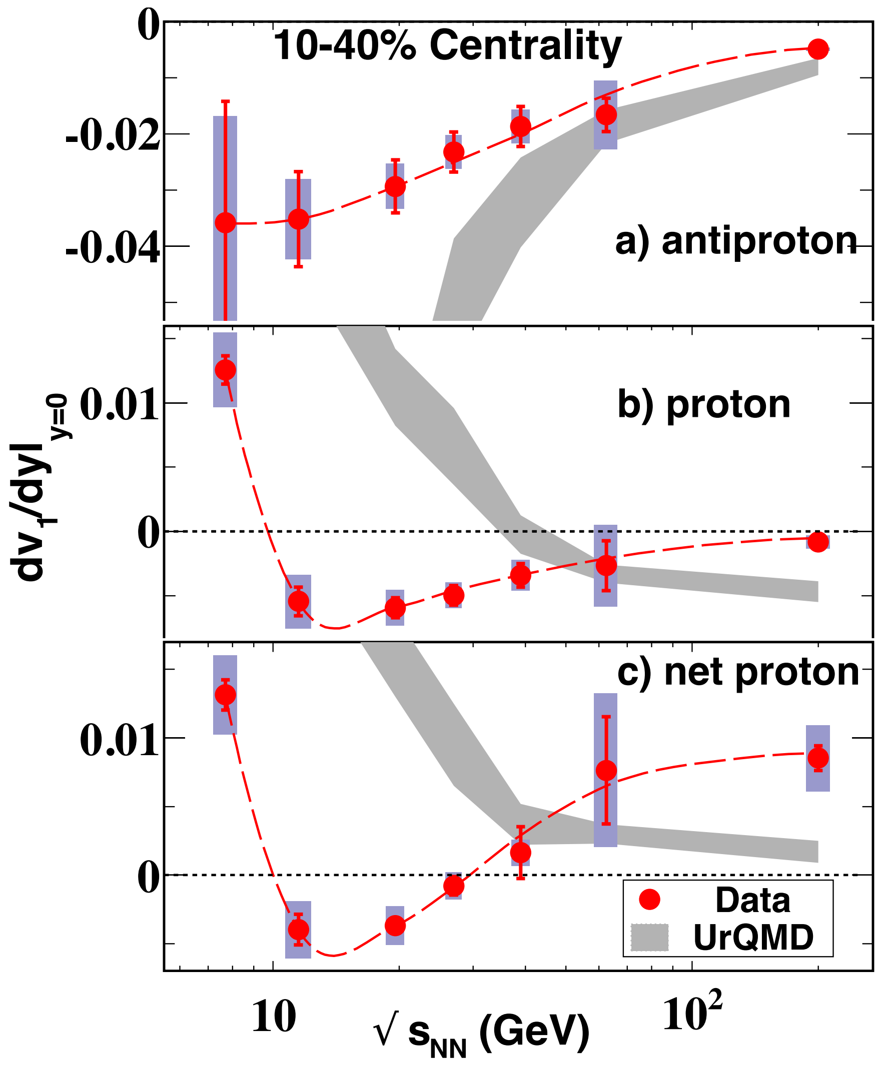


$$\frac{dN}{d(\phi-\Psi)} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi)) \qquad v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

- Directed flow(v_1) describes sideward collective behavior of emitted particles with respect to the reaction plane.
- Interplay between positive contribution during initial compression stage and negative contribution from titled source during expansion stage.
- Titled expansion overcomes " bounce-off " motion → Anti-flow.

H. Sorge, Phys. Rev. Lett. 78, 2309 (1997); P. Bozek et al, Phys. Rev. C.81.054902 (2010)

Motivation



- Hydrodynamic calculation with the 1st order phase transition motivates the study
- The proton and net-proton show non-monotonic slope (dv_1/dy) as function of collision energy.
  - EoS softest point?
  - The UrQMD model can not reproduce the trend.
- Centrality dependence of v_1 slope: BESII

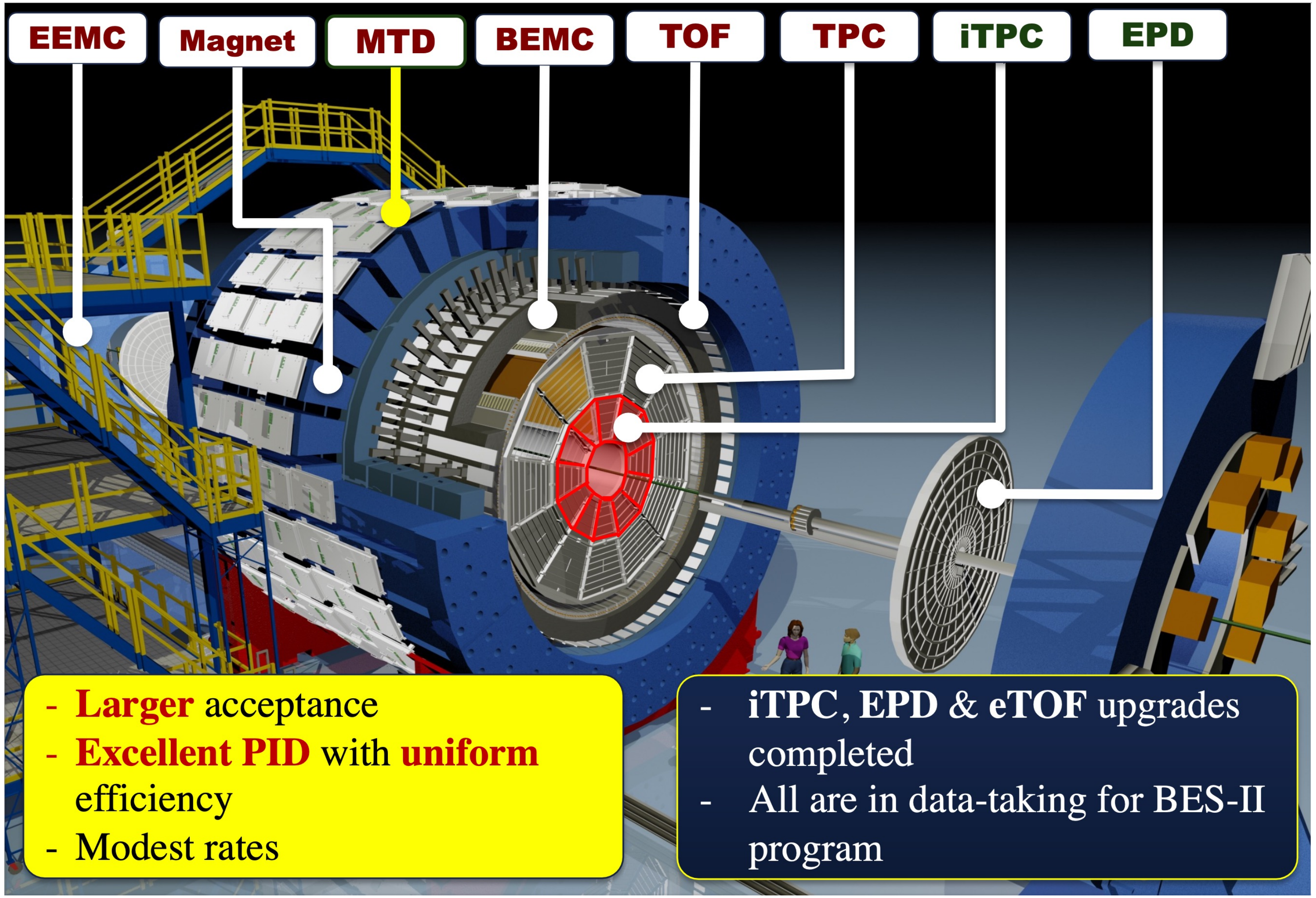
The slope of net-p is based on expressing the y dependence of v_1 for all protons as:

$$[v_1(y)]_p = r(y)[v_1(y)]_{\bar{p}} + [1 - r(y)][v_1(y)]_{\text{net-}p}$$

where r(y) is the ratio of $\bar{p}$ to p.
Note that v_1(p) and v_1(net-p) converge in the limit of negligible $\bar{p}$ production at lower energy.

L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 112, 162301 (2014); H. Stoecker, Nucl. Phys. A 750, 121(2005)

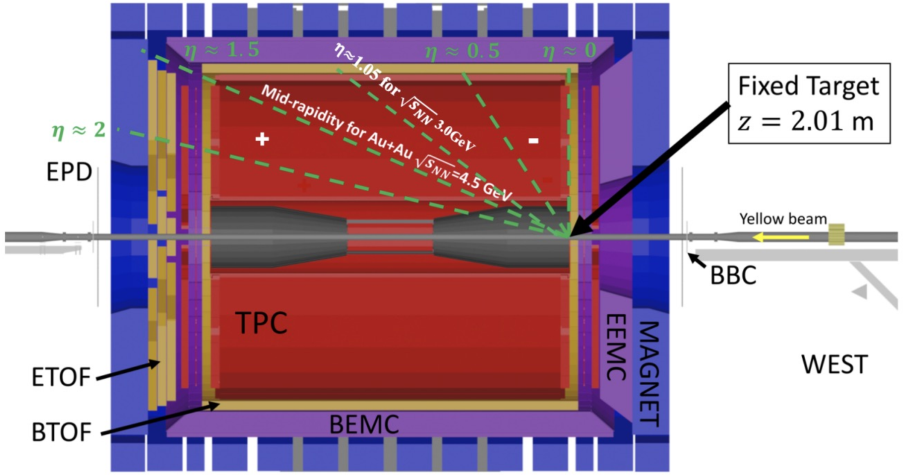
STAR Detectors



- **Larger** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program

FXT mode:



Solenoidal tracker detectors:

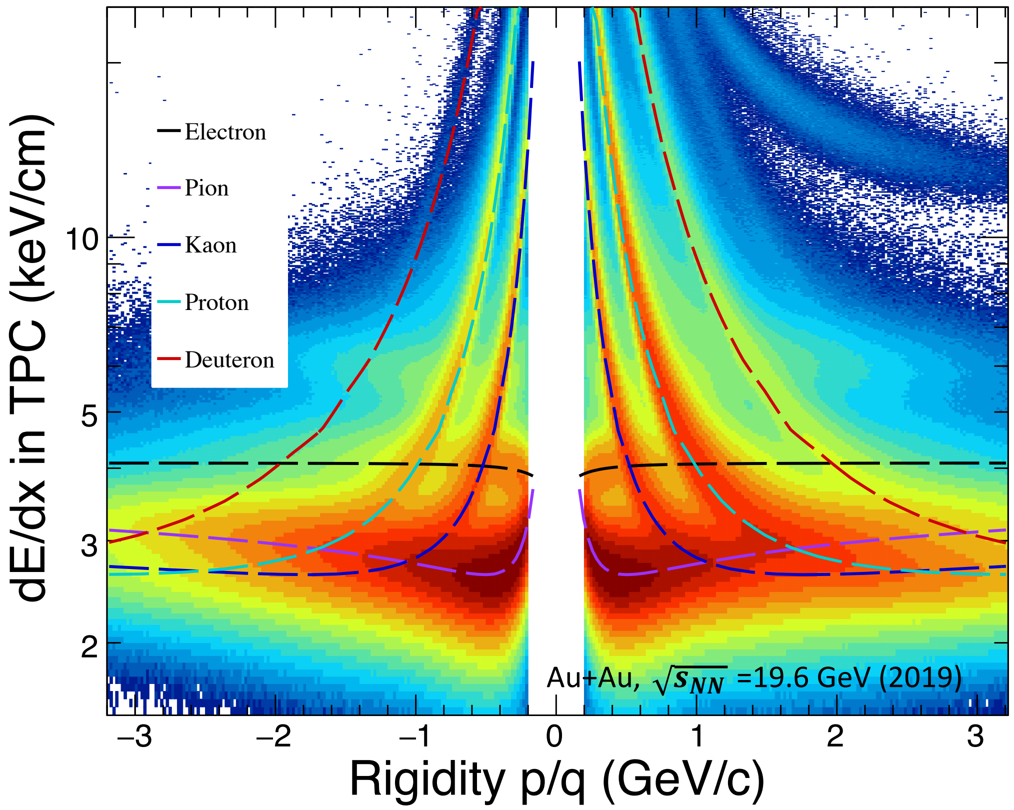
- ➢ Time Projection Chamber
  - Charged particle tracking
  - Particle identification
- ➢ Time Of Flight
  - Particle identification

Event plane determination:

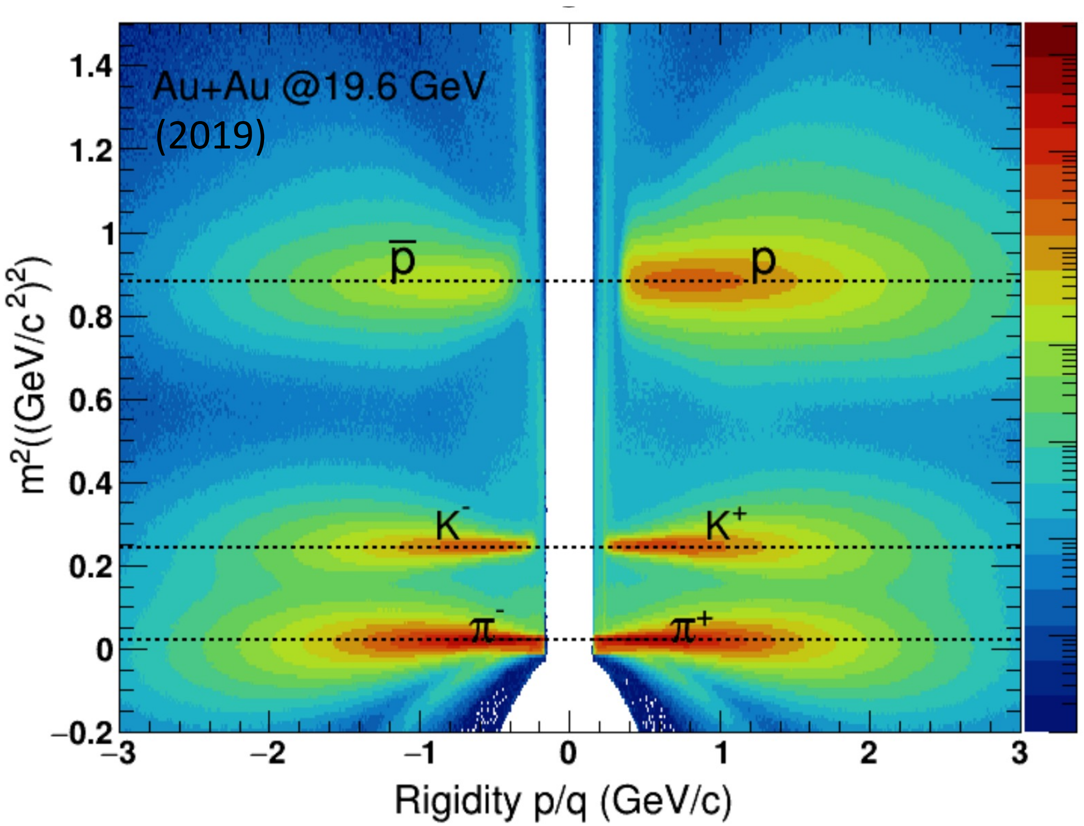
- ➢ Event Plane Detector
  - $2.1 < |\eta| < 5.1$

Particle Identification

TPC



TOF



➢ Good particle identification capability based on TPC and TOF.

Analysis Method

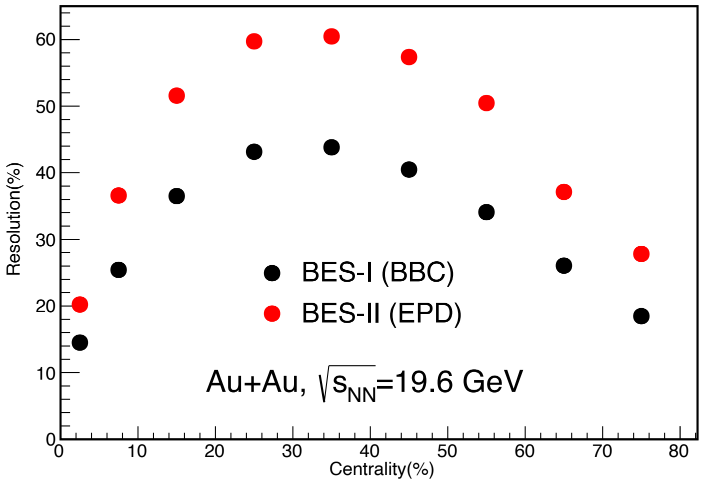
Event Plane Method: A. M. Poskanzer, S. A. Voloshin. Phys. Rev. C 58 1672 (1998)

The 1st harmonic event plane:

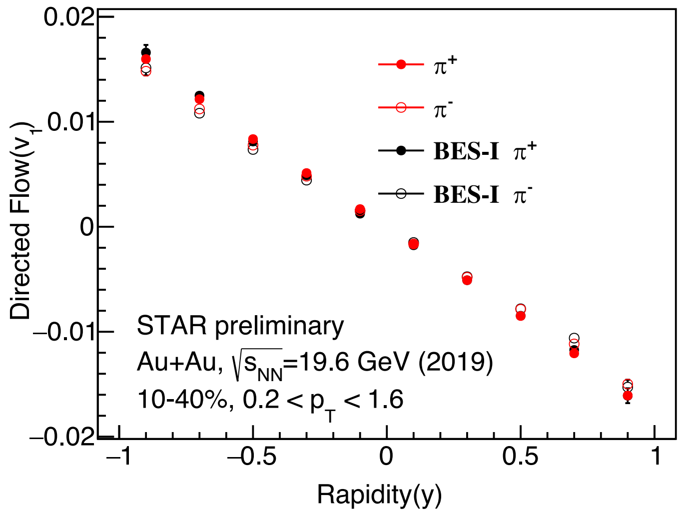
$$\vec{Q} = \begin{pmatrix} Q_y \\ Q_x \end{pmatrix} = \begin{pmatrix} \sum_i w_i \sin(n\phi_i) \\ \sum_i w_i \cos(n\phi_i) \end{pmatrix} \qquad \Psi_1 = \tan^{-1} \frac{\sum_i w_i \sin(\phi_i)}{\sum_i w_i \cos(\phi_i)}$$

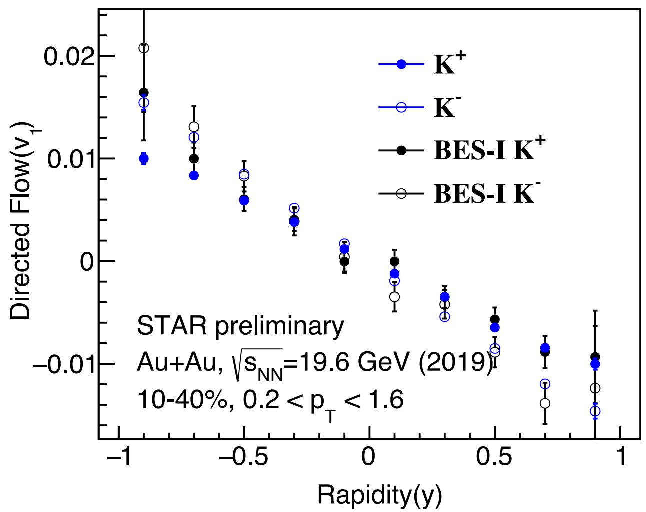
Resolution: $R_1 = \langle \cos(\Psi_{1,EP} - \Psi_{RP}) \rangle$

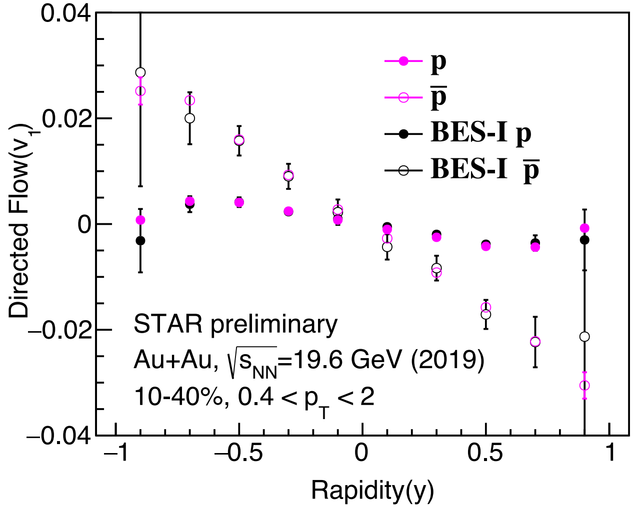
1st order EP resolution



Rapidity dependence of identified particle v_1 :



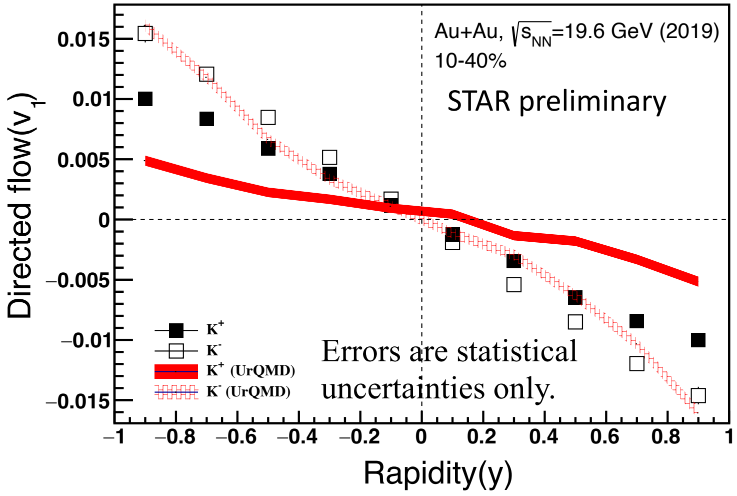


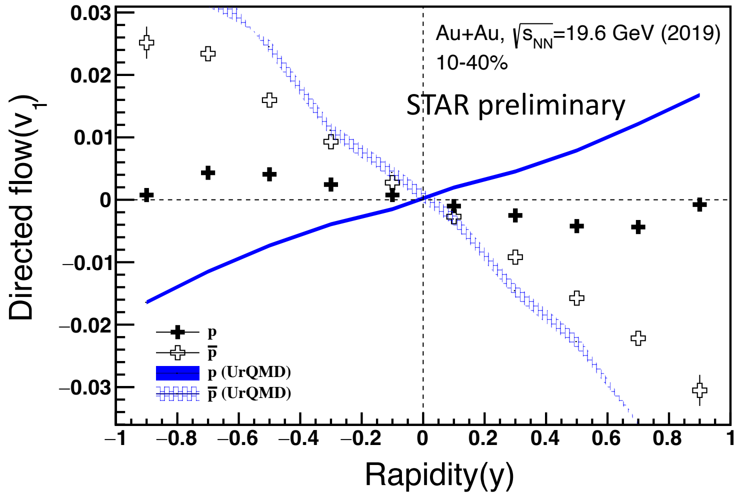


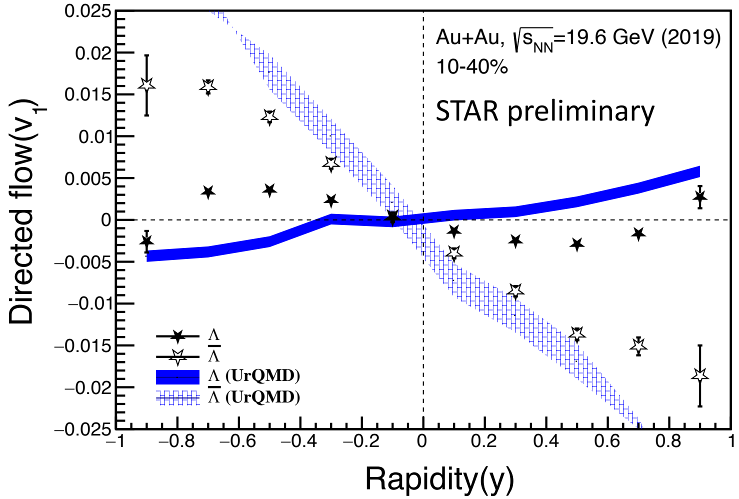
Errors are statistical uncertainties only.

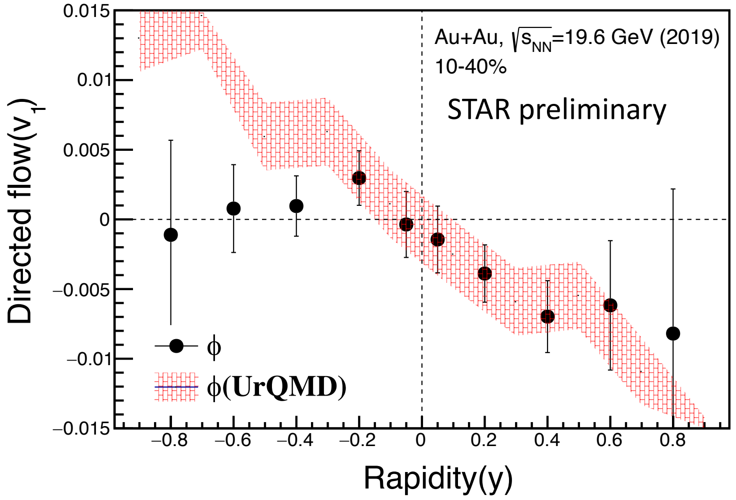
- Resolution improved about 50% comparing to BES-I
- The statistical uncertainties reduced by a factor 8 comparing to BES-I results.

Rapidity Dependence of v_1





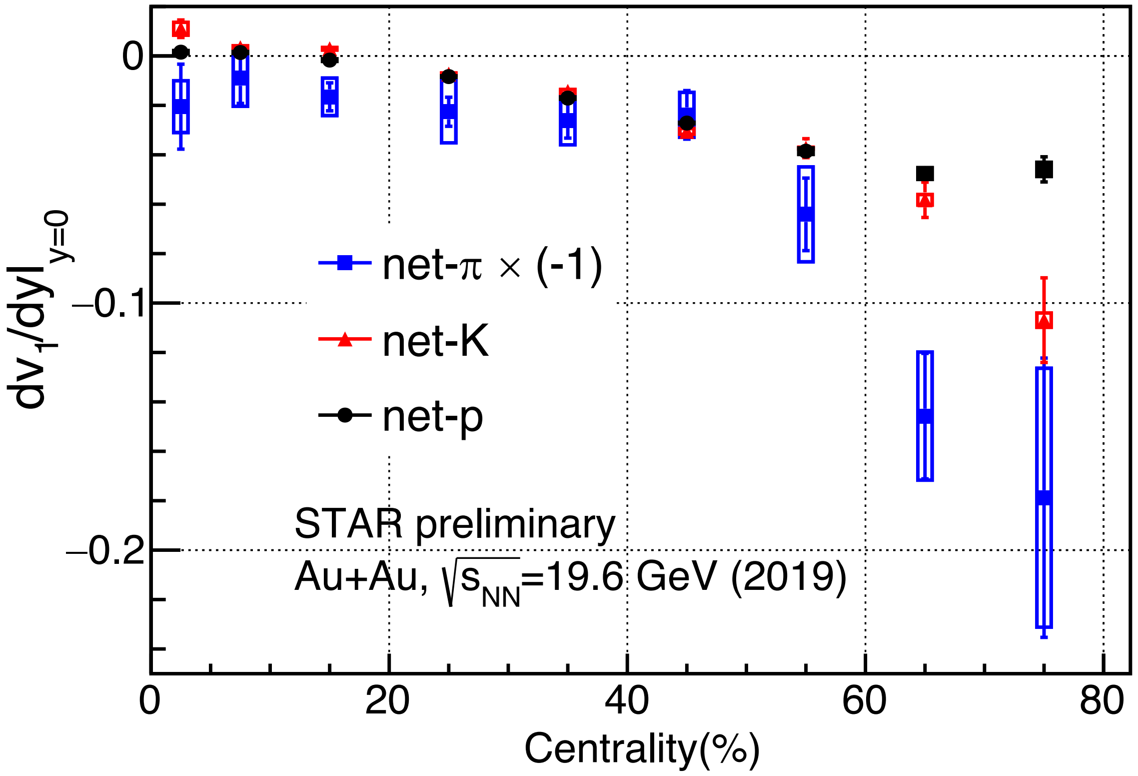




In mid-central collisions:

- ➢ Negative slopes for kaons, consistent with UrQMD calculation, but UrQMD underestimates the magnitude of K^+ v_1
- ➢ ϕ meson shows hint of positive slope at mid-rapidity in data
- ➢ Both proton and lambda show negative v1 slopes, while UrQMD shows opposite trend
  → Initial "bounce-off" motion may be too strong in UrQMD

dv_1/dy vs. Centrality



The slope of net-p is based on expressing the y dependence of v_1 for all protons as:

$$[v_1(y)]_p = r(y)[v_1(y)]_{\bar{p}} + [1 - r(y)][v_1(y)]_{\text{net-}p}$$

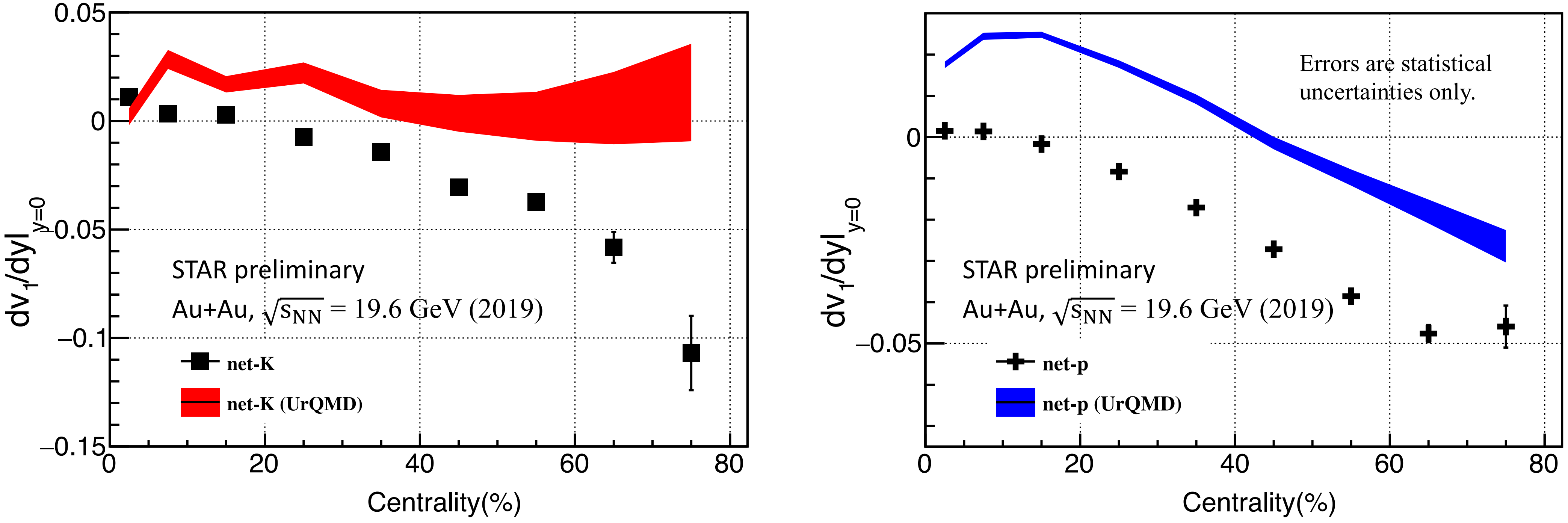
where r(y) is the ratio of $\bar{p}$ to p.
Note that v_1(p) and v_1(net-p) converge in the limit of negligible $\bar{p}$ production at lower energy.

- v_1 slope of net-particle is larger in magnitude for more peripheral collisions.
  → More transported quarks in the peripheral collisions.

- v_1 slopes of net-proton and net-kaon are similar in central and mid-central collisions.

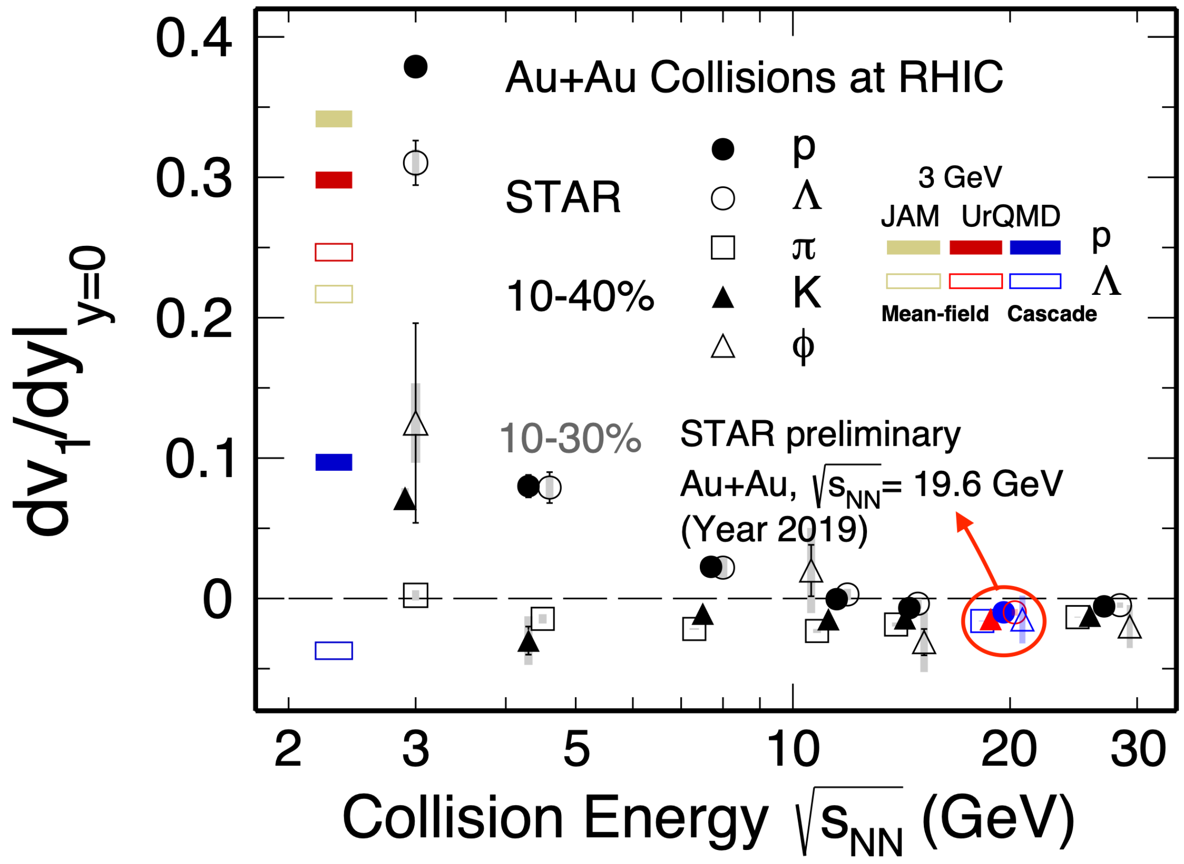
Net-pion dv_1/dy is positive at all centralities. To facilitate plotting in the figure opposite, net-pion dv_1/dy is shown with reversed sign.

dv_1/dy: Comparison to UrQMD



- ➢ Net-kaon dv_1/dy: weaker centrality dependence in UrQMD
- ➢ Net-proton dv_1/dy: sign change at 10-20% centrality in data, while 40-50% in UrQMD
  → Initial “bounce-off” motion may be too strong in UrQMD

dv_1/dy vs. Collision Energy



- ➢ All particles show negative slope at 19.6 GeV, but positive slope at 3 GeV
- ➢ The calculations of JAM and UrQMD with baryonic mean-field quantitatively reproduce data in 3 GeV
  → The dominant degrees of freedom at 3 GeV are hadrons, unlike at 19.6 GeV
- ➢ Further study with other BES-II energies could offer more information on the change of equation of state and possible phase transition

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

Summary

- Higher statistics from BES-II improved v_1 measurements
  → The statistical uncertainties reduced by a factor 8

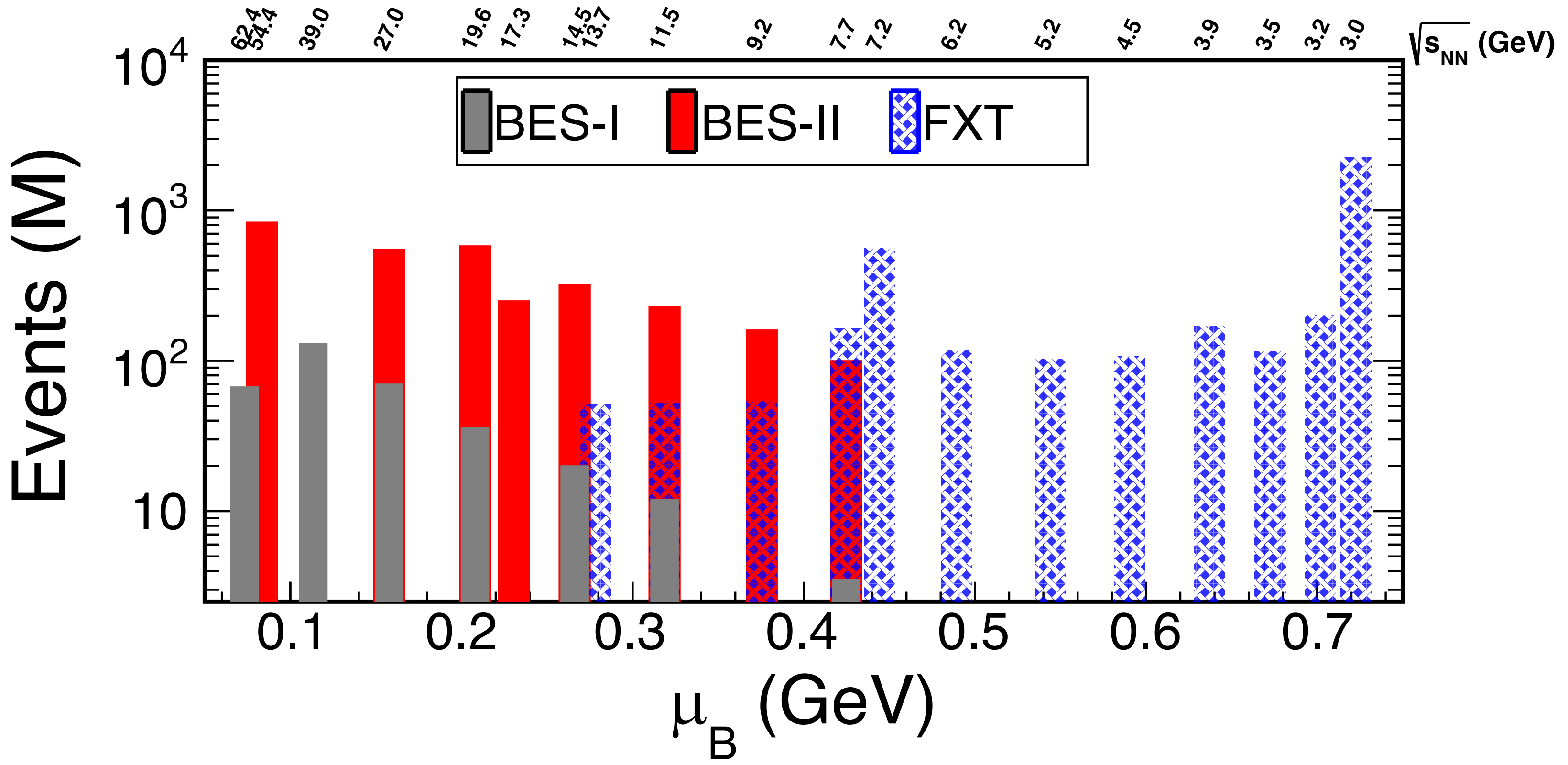
- $v_1(y)$: 19.6 GeV data shows negative v_1 slopes of proton and Λ, while opposite trend in UrQMD
  → Initial "bounce-off" motion may be too strong in UrQMD

- Centrality dependence of net-particle dv_1/dy at 19.6 GeV: Sigh change of v_1 slope in more central collisions than UrQMD
  →Offers more constrains on the models

- All particles show negative slope at 19.6 GeV, but positive slope at 3 GeV
  →Hadron degrees of freedom dominate at 3 GeV

Outlook

STAR BES-II (2019-2021):
$\sqrt{s_{NN}}$ = 3 - 19.6 GeV

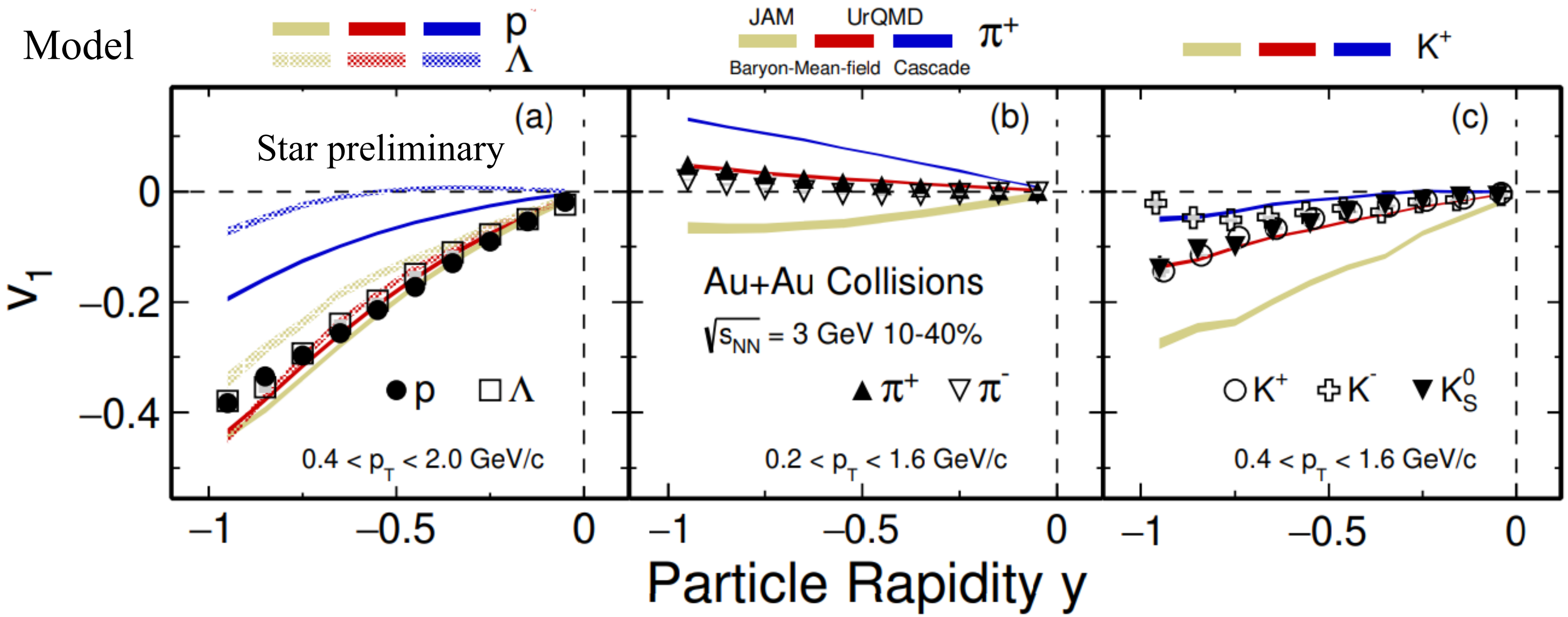


- Enhanced statistics, upgraded detectors from BES-II
- Explore the QCD phase diagram with BES-II 3-19.6 GeV dataset

Thank you for your attention!

Backup

3 GeV: Rapidity Dependence of Directed Flow



- The mid-rapidity slope($dv_1 /dy|_{y=0}$), are the largest for protons and Λ, and are close to zero for pions.
  → The strength of v_1 is proportional to the hadron mass.

- The repulsive interactions among baryons are enhanced via an additional mean-field option, resulting in good agreement with experimental data.

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