Recent measurements of flow from RHIC Beam Energy Scan (BES) Program

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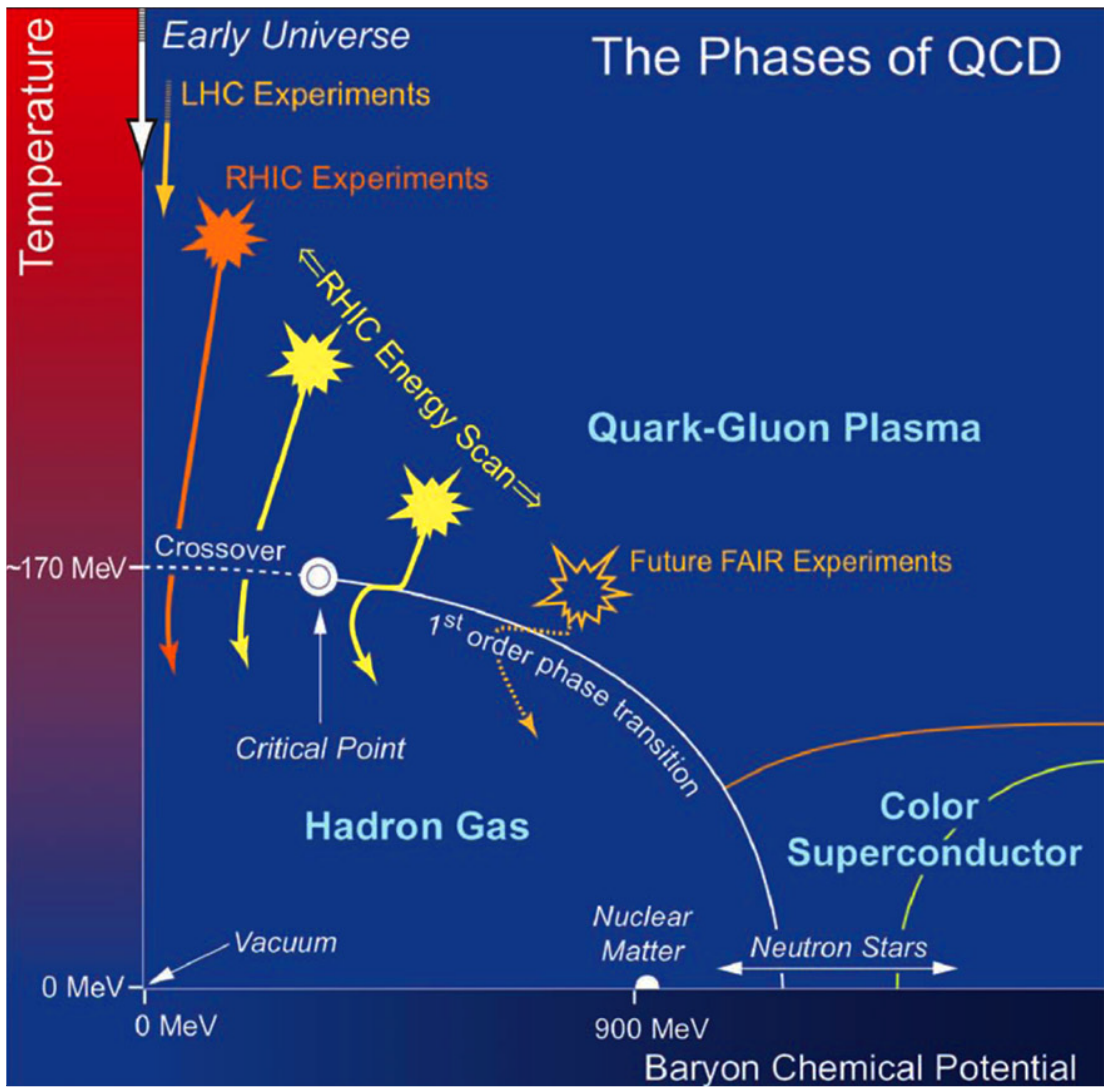
Outlook

- RHIC Beam Energy Scan (BES) Program
- STAR Experiment and flow results from BES-I
- A few selected results from BES-II
  - Directed (v_1) flow
  - Elliptic (v_2) flow
- Summary

RHIC BES program

Conjectured QCD Phase diagram



Partonic dominant → Hadronic dominant

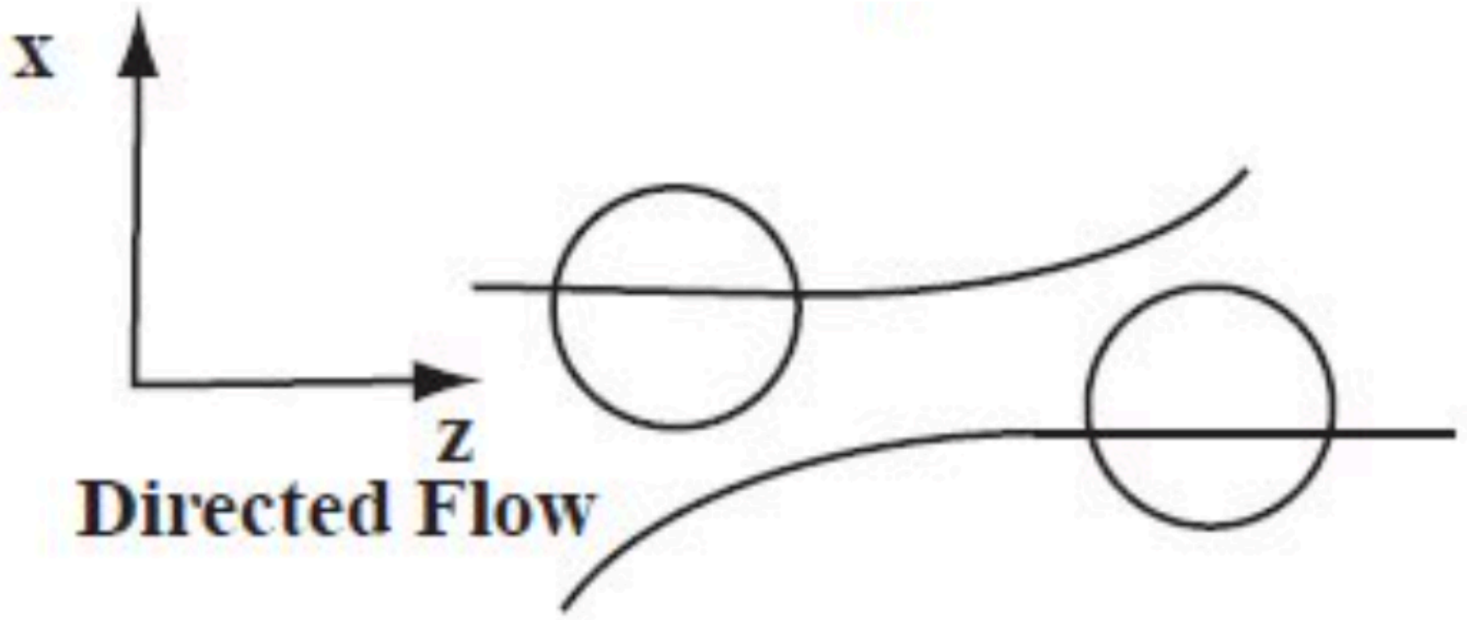
Baryonic

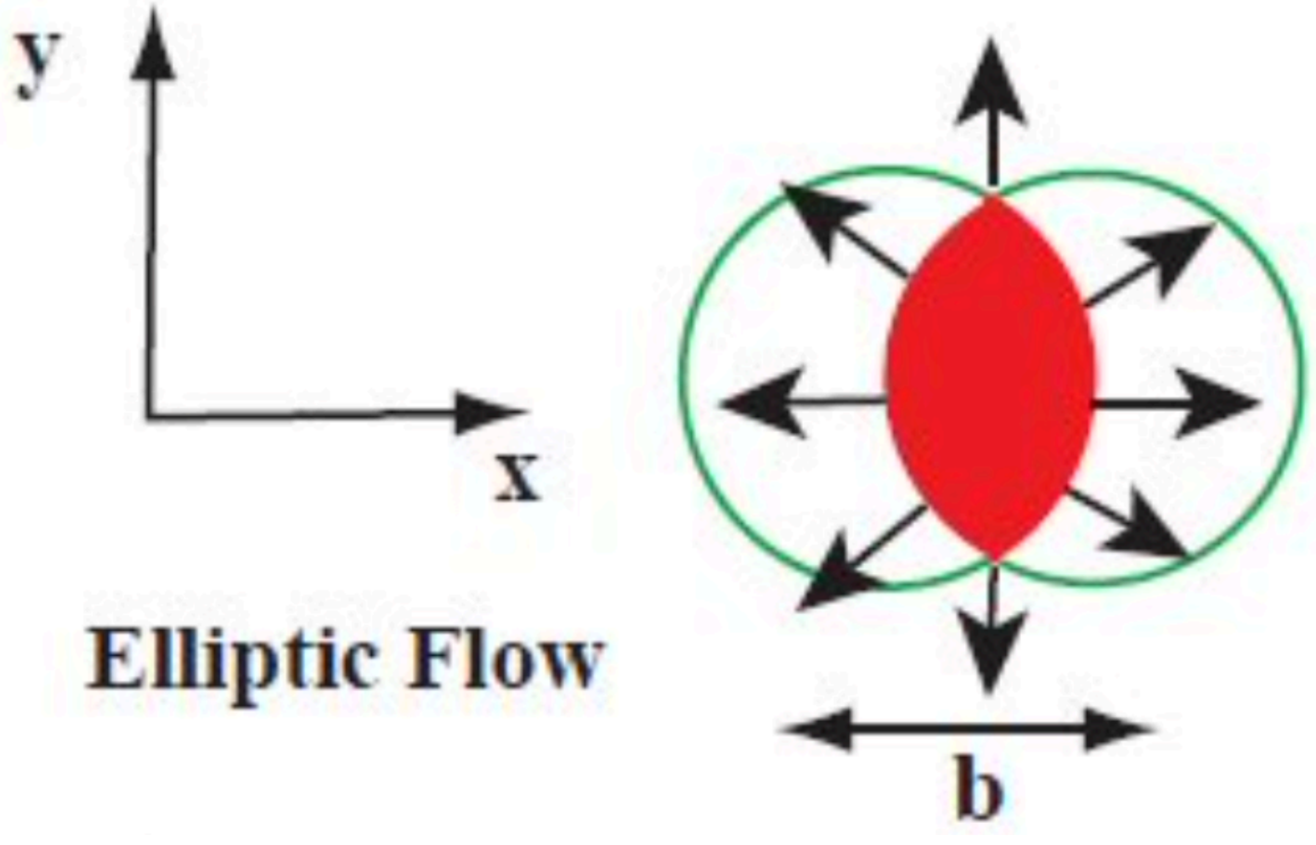
BES Program:

Explore QCD Phase diagram by varying beam energy, proxy for baryon chemical potential (μ_B)

- Map the turn off signature of Quark Gluon Plasma
- Search for signatures of Cross-over, Critical point, 1st order Phase Transition

Collective flow





A. Poskanzer el. al. arXiv: 0809.2949

- Collective flow can be measured from the Fourier expansion

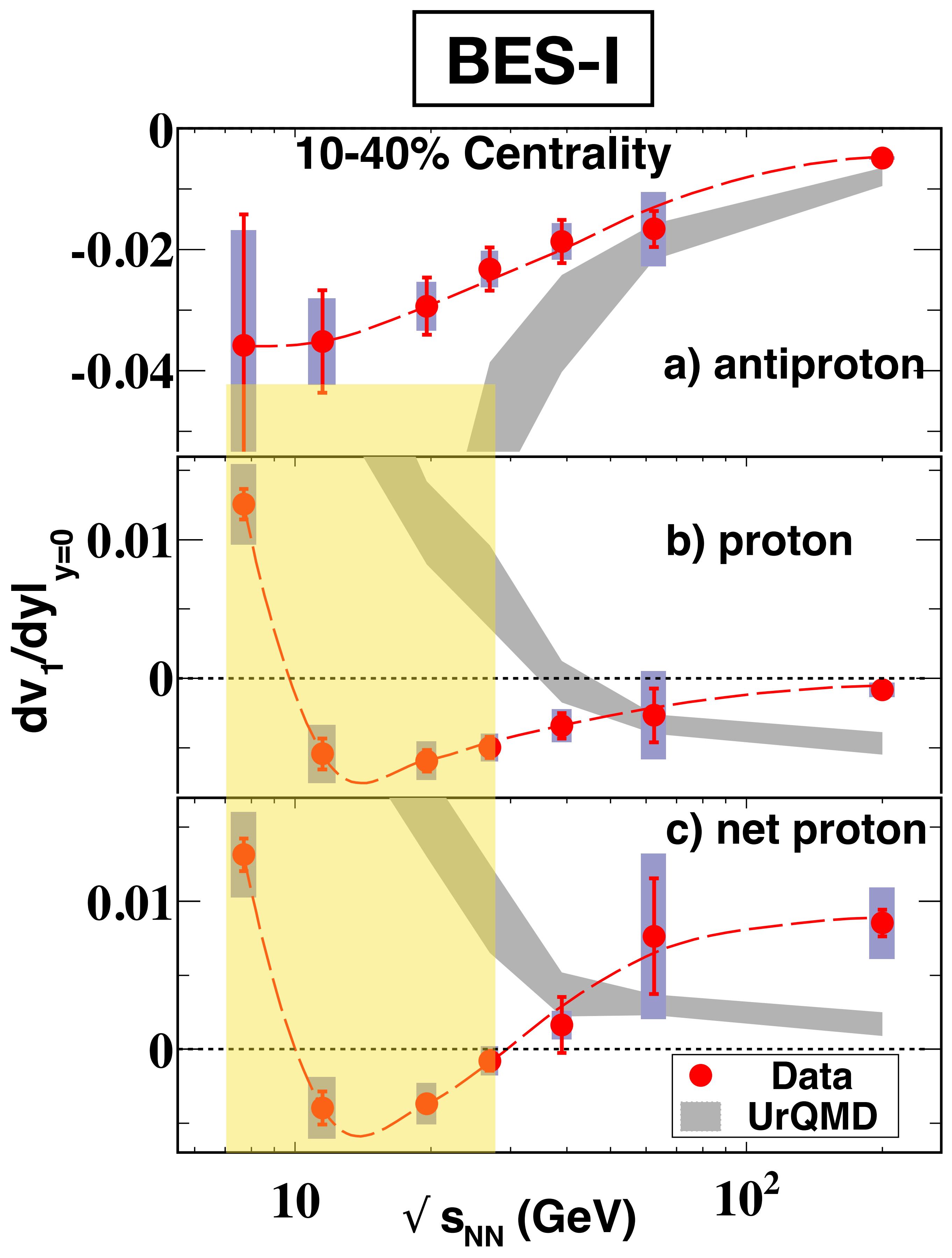
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum 2v_n \cos n(\phi - \Psi_n^{EP})\right)$$

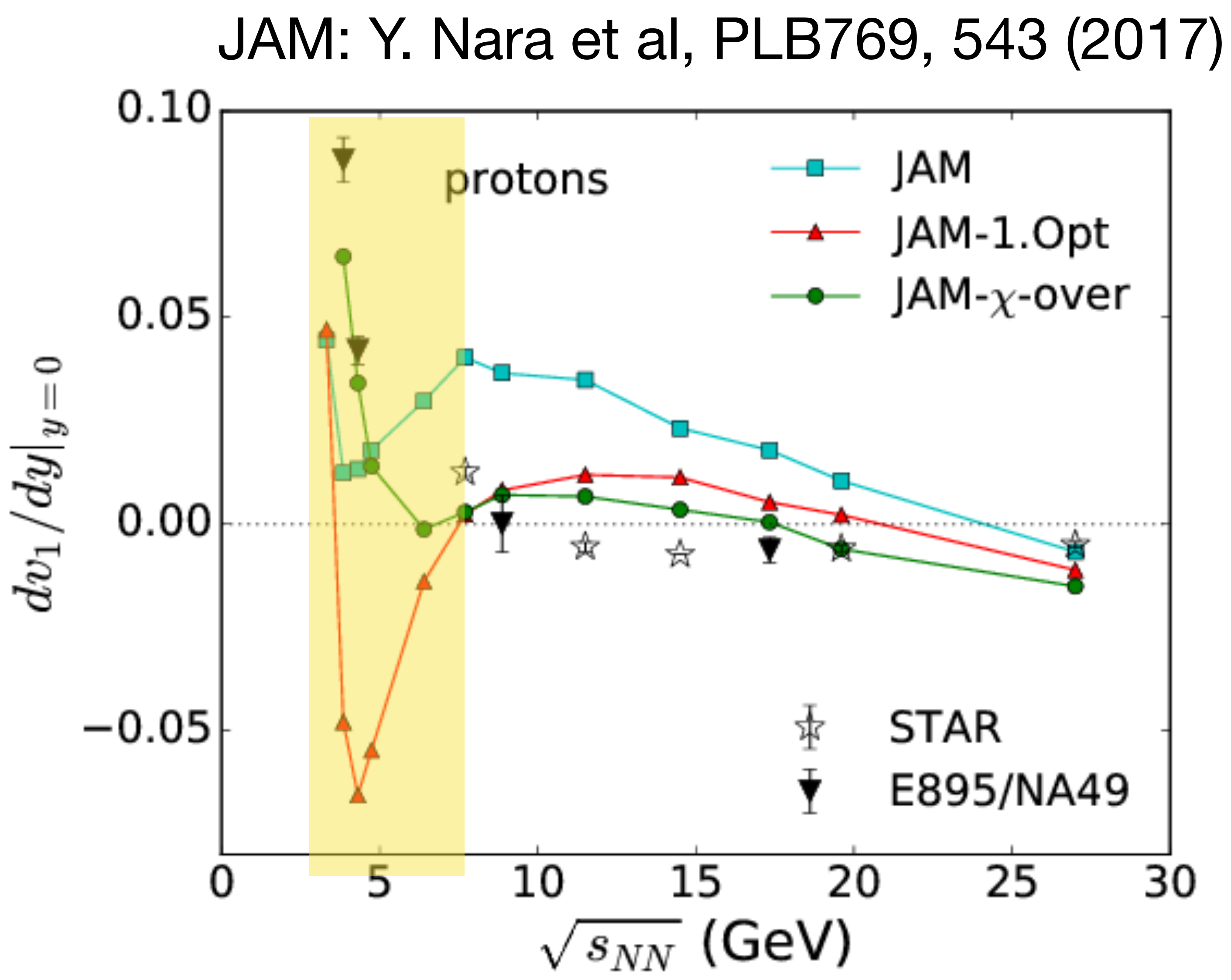
- v_1 : Directed flow
- v_2 : Elliptic flow
- v_3 : Triangular flow

$$v_n = \langle \cos n(\phi - \Psi_n^{EP})\rangle / \Psi_{Resolution}$$

- Flow coefficients are sensitive to the initial state and properties of the medium; Sensitive to EoS and degrees of freedom

Directed flow measurements from BES-I





- Model with 1st order phase transition predicted sign change at ~ 5 GeV

- proton and net-proton v_1 change sign around 10-20 GeV

Challenge to the present models to capture the magnitude and features in v_1

STAR: PRL 112, 162301 (2014)
PRL 120, 062301 (2018)

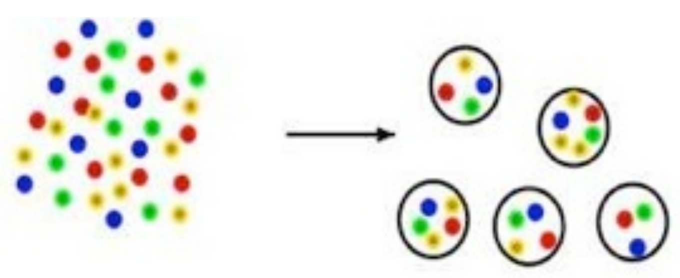
Quark coalescence hypothesis

Test the assumption that the de-confined quarks acquired v_n, then they form hadrons:

$$v_n^{\text{hadron}} = \sum v_n^{\text{constituent-quarks}}$$

The origin of scaling is interpreted as an evidence for dominance of quark degrees of freedom

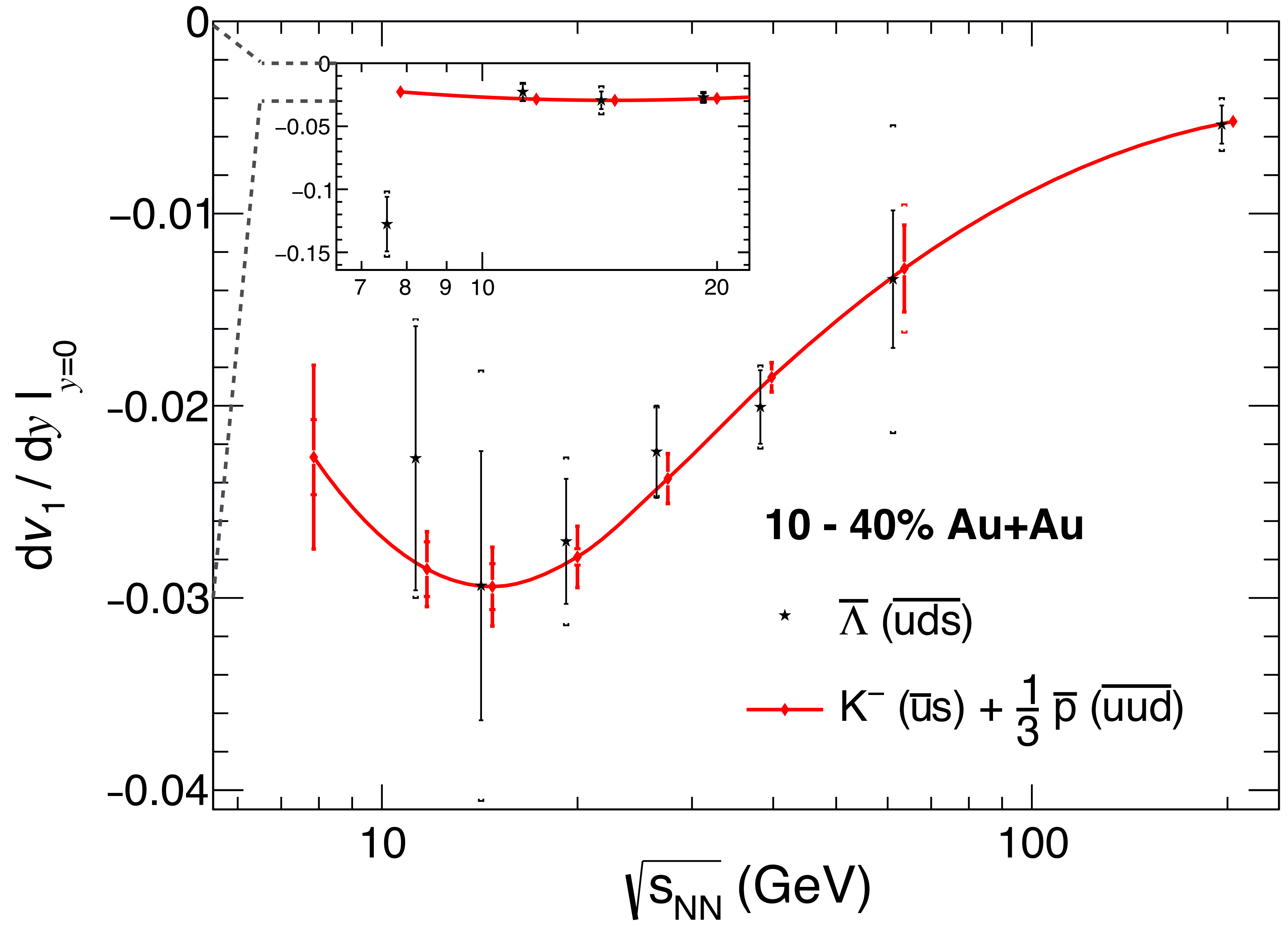
Particle	Quark content
anti-Λ	$\overline{\text{uds}}$
anti-p	$\overline{\text{uud}}$
K-	$\bar{\text{u}}$s



qq vs. qqq

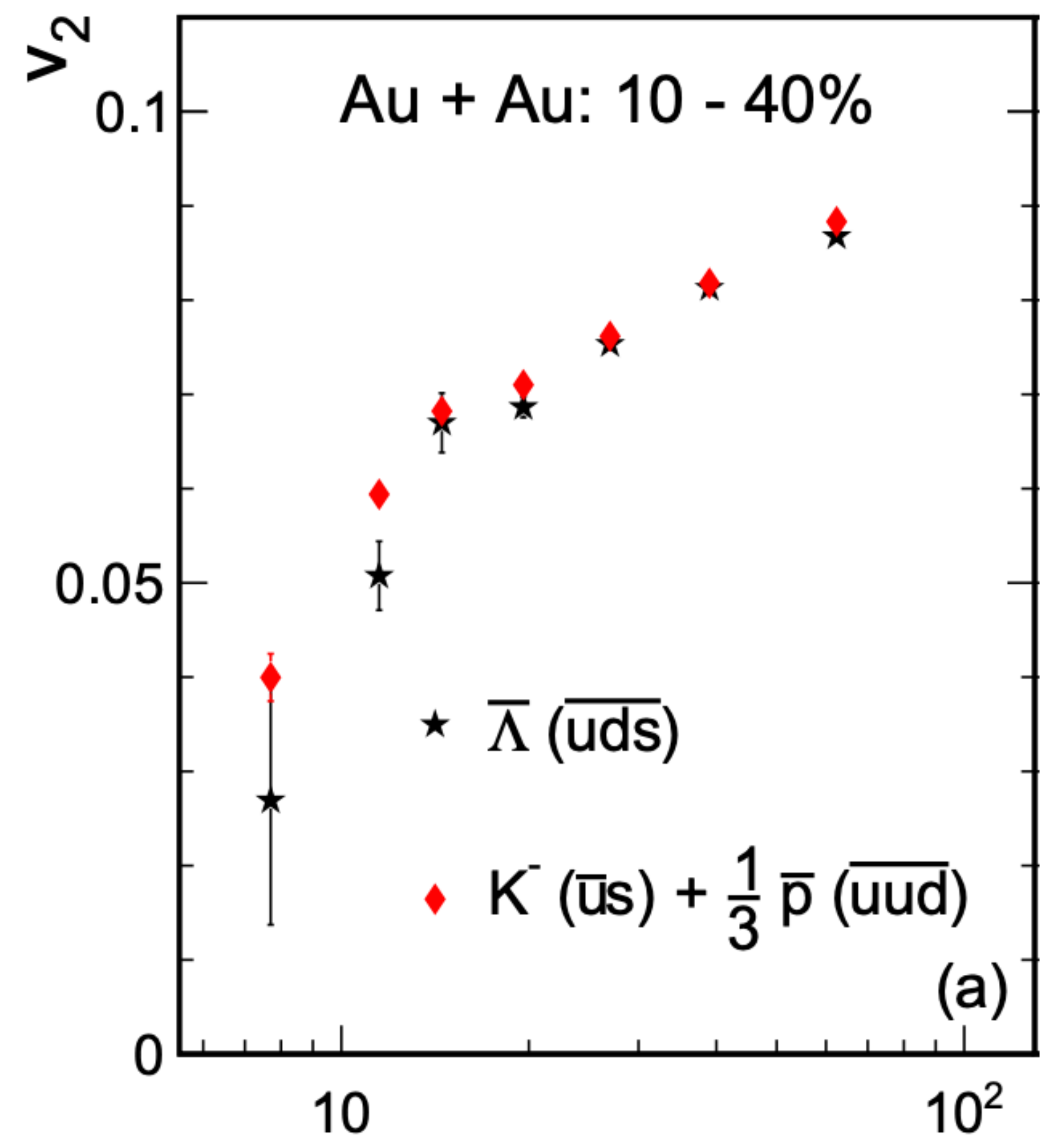
BES-I

Directed flow: $v_1 \sim \langle \cos(\phi - \Psi_R) \rangle$



STAR: PRL 112, 162301 (2014)
PRL 120, 062301 (2018)

Elliptic flow: $v_2 \sim \langle \cos 2(\phi - \Psi_R) \rangle$



Goudarzi et al:
PLB 811, 135974 (2020)

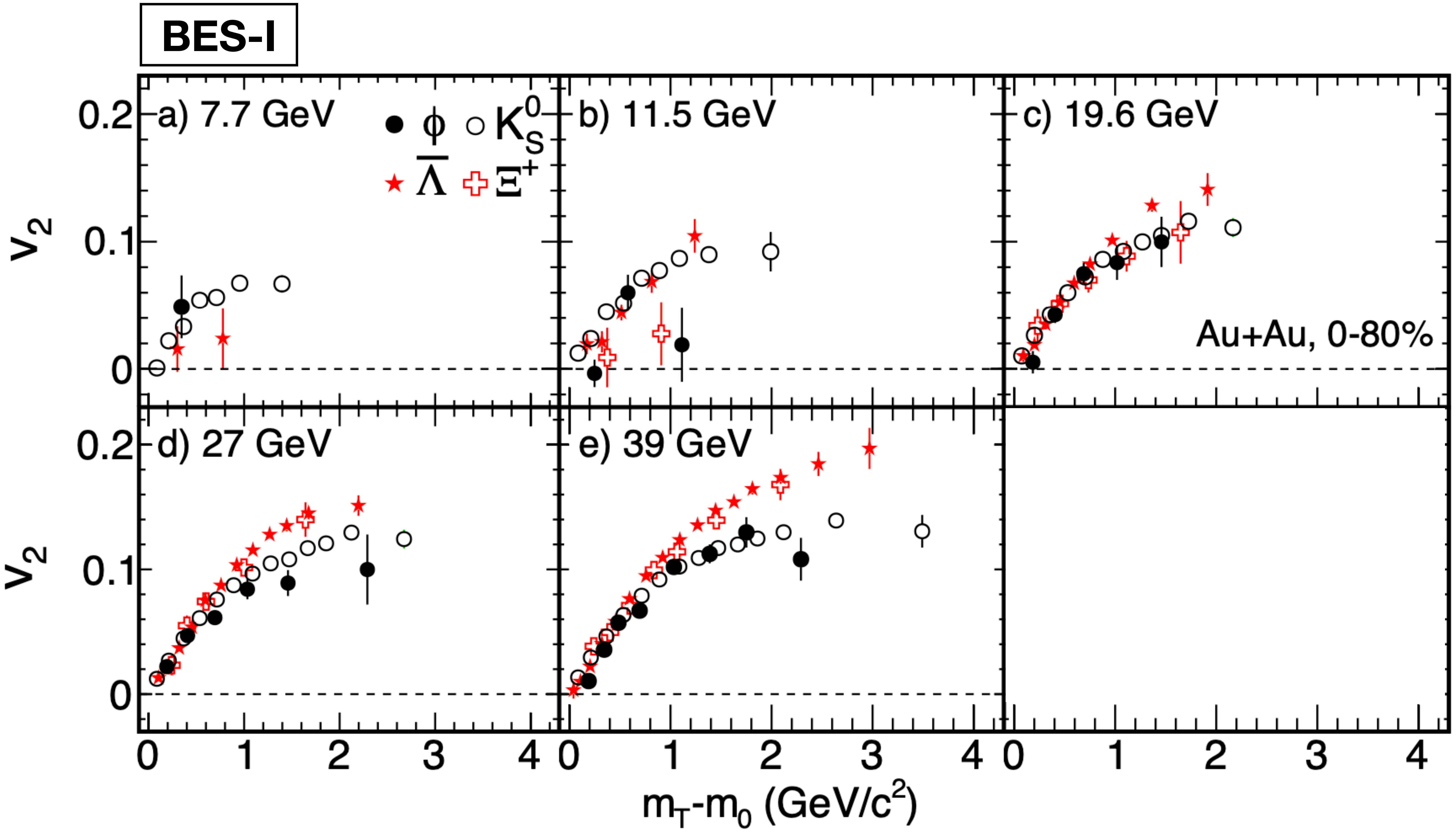
- Using anti-particles quark coalescence sum rule:
- Holds for $\sqrt{s_{NN}} \geq 11.5$ GeV
- Breaks at $\sqrt{s_{NN}} = 7.7$ GeV

- Quark coalescence hypothesis holds over a broad energy range

Where does coalescence hypothesis breaks ? → BES-II data can provide high precision test

Subhash Singha @ MPD 2025

Elliptic flow measurements from BES-I



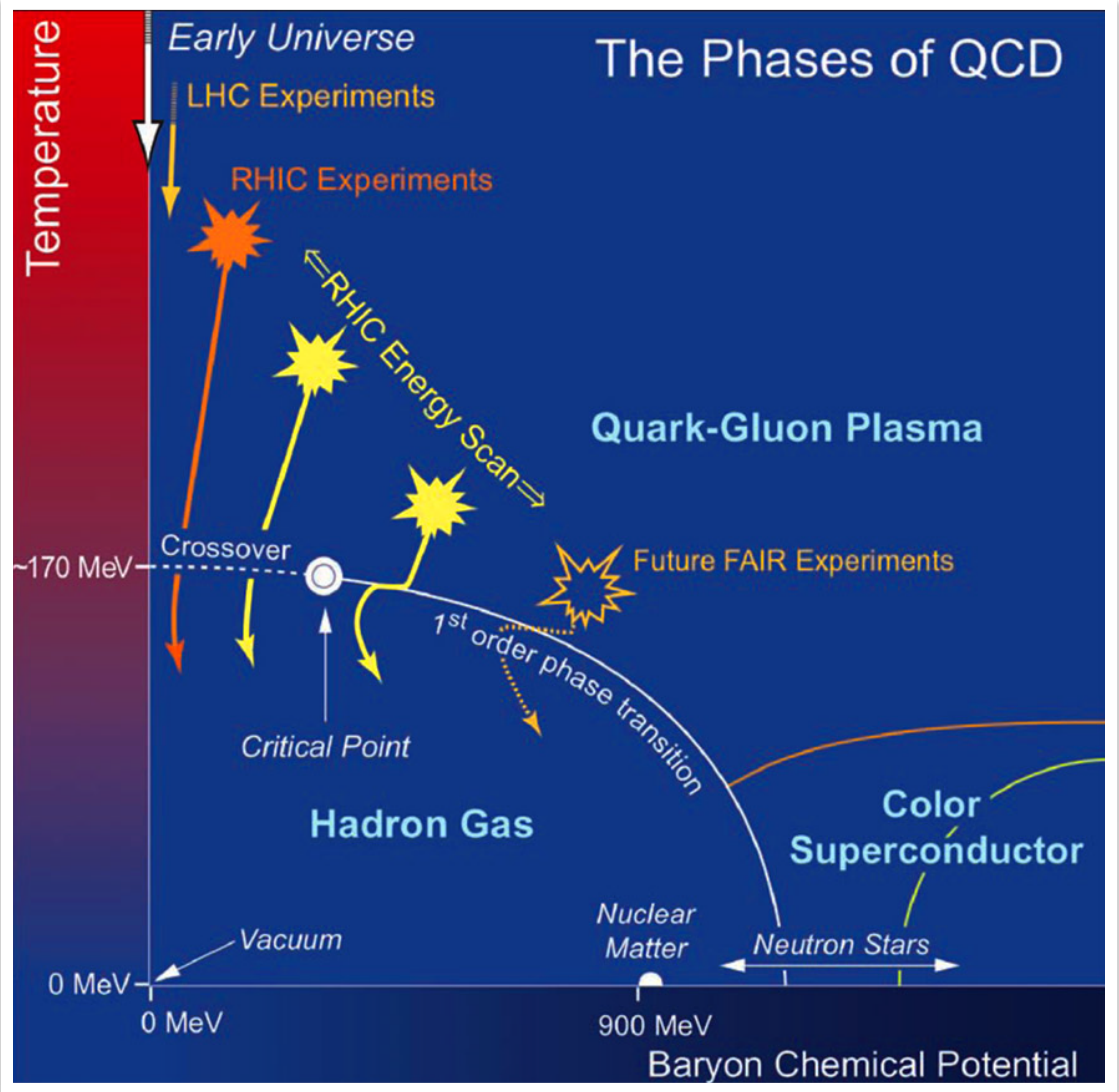
Can we probe on-set of partonic collectivity via precise v_2 measurements?

- Baryon-meson separation in v_2 for $\sqrt{s_{NN}} > 19.6$ GeV (expected from parton recombination)
- Not sufficient precision at lower energies, but hints for ϕ not following mesons!
- High precision measurement from BES-II can make it clear

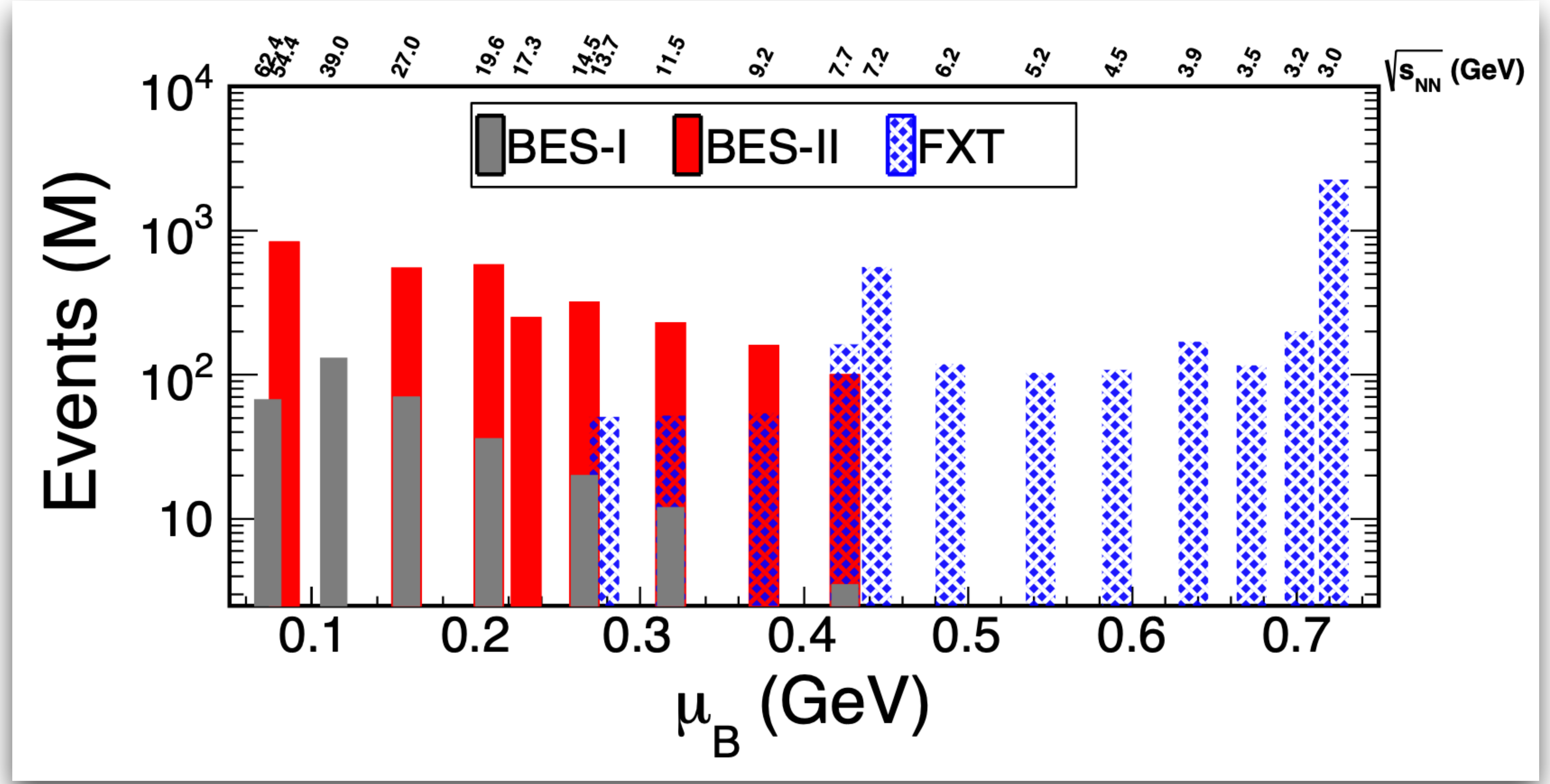
STAR: PRL 110, 142301 (2013)
STAR: PRC 88, 014902 (2013)

RHIC BES-II program

Conjectured QCD Phase diagram



BES Program:

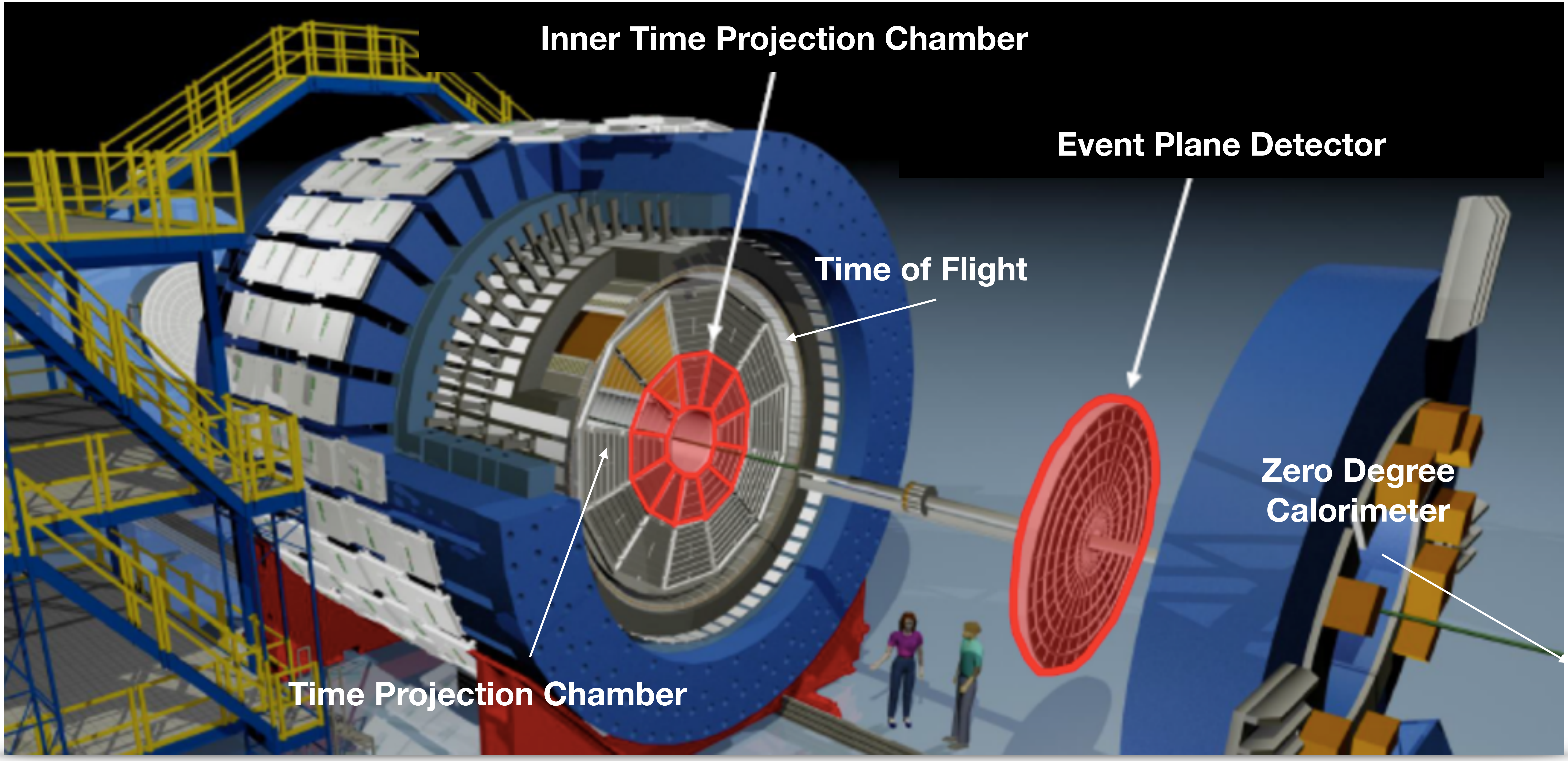


Collider: 7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27, 39, 54.4, 62.4, 200 (GeV)
Fixed Target: 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7, 9.2, 11.5, 13.7 (GeV)

High statistics data and detector upgrade in BES-II enhances the capability of various measurements with excellent precision

BES-II upgrades: **iTPC, EPD, eTOF**

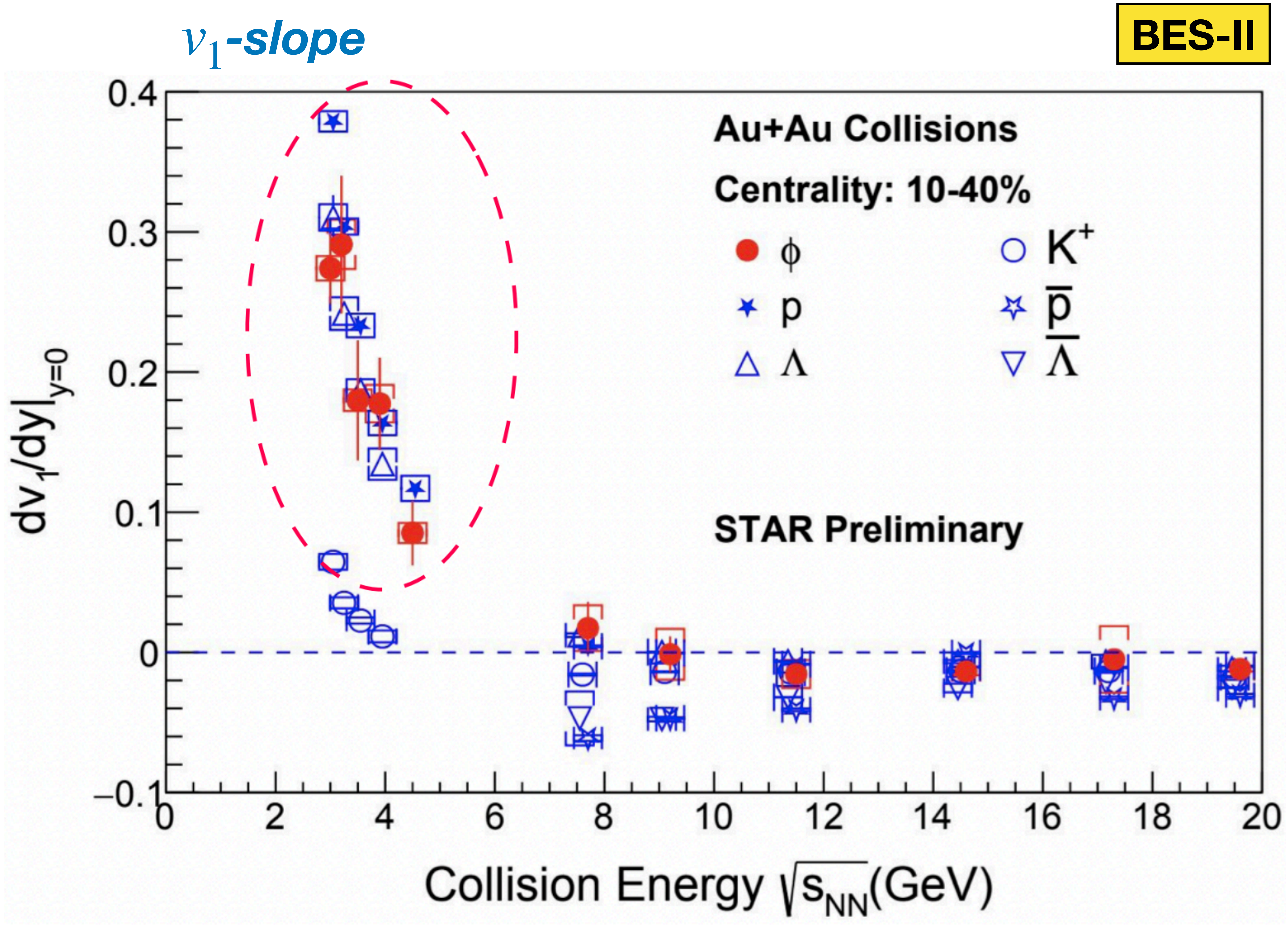
STAR Detector



- Uniform acceptance, full azimuthal coverage, excellent PID capability
- TPC (iTPC): tracking, centrality and event plane
- EPD, ZDC: event plane reconstruction
- TPC+TOF (eTOF): particle identification

Selected Results from BES-II

Directed flow from STAR BES-II



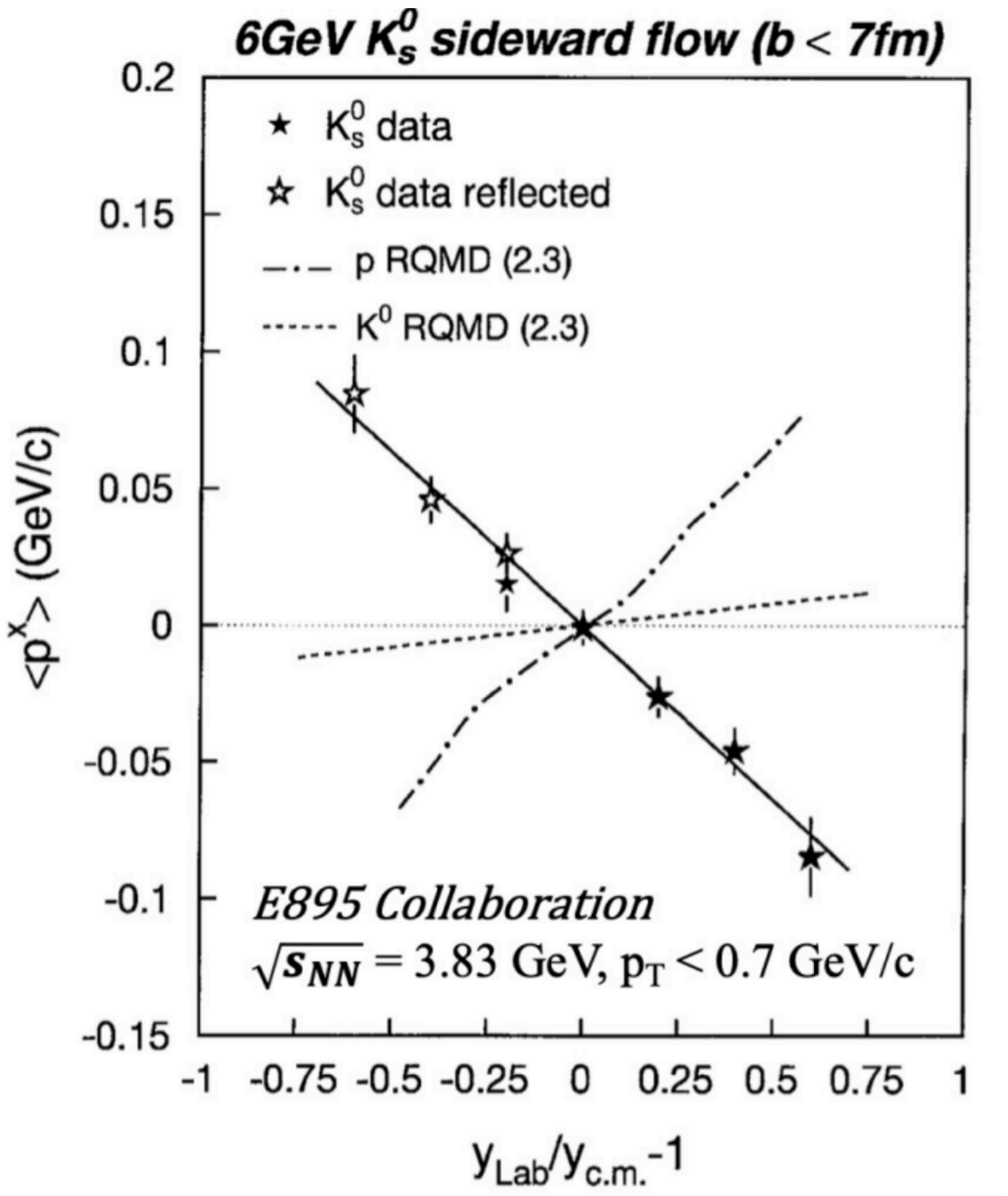
Directed flow: $v_1 \sim \langle \cos(\phi - \Psi_R) \rangle$

QM 2025 (STAR)

- Identified particle's v_1 extended to STAR Fixed target energies at $\sqrt{s_{NN}}$ = 3.0 - 4.5 GeV
- Kaons changes sign at $\sqrt{s_{NN}}$ = 4.5 - 7.7 GeV, while proton changes sign at $\sqrt{s_{NN}}$ = 11.5 - 14.5 GeV
- ϕ-meson v_1 follows baryons (p and Λ) high μ_B, unexpected trend !!

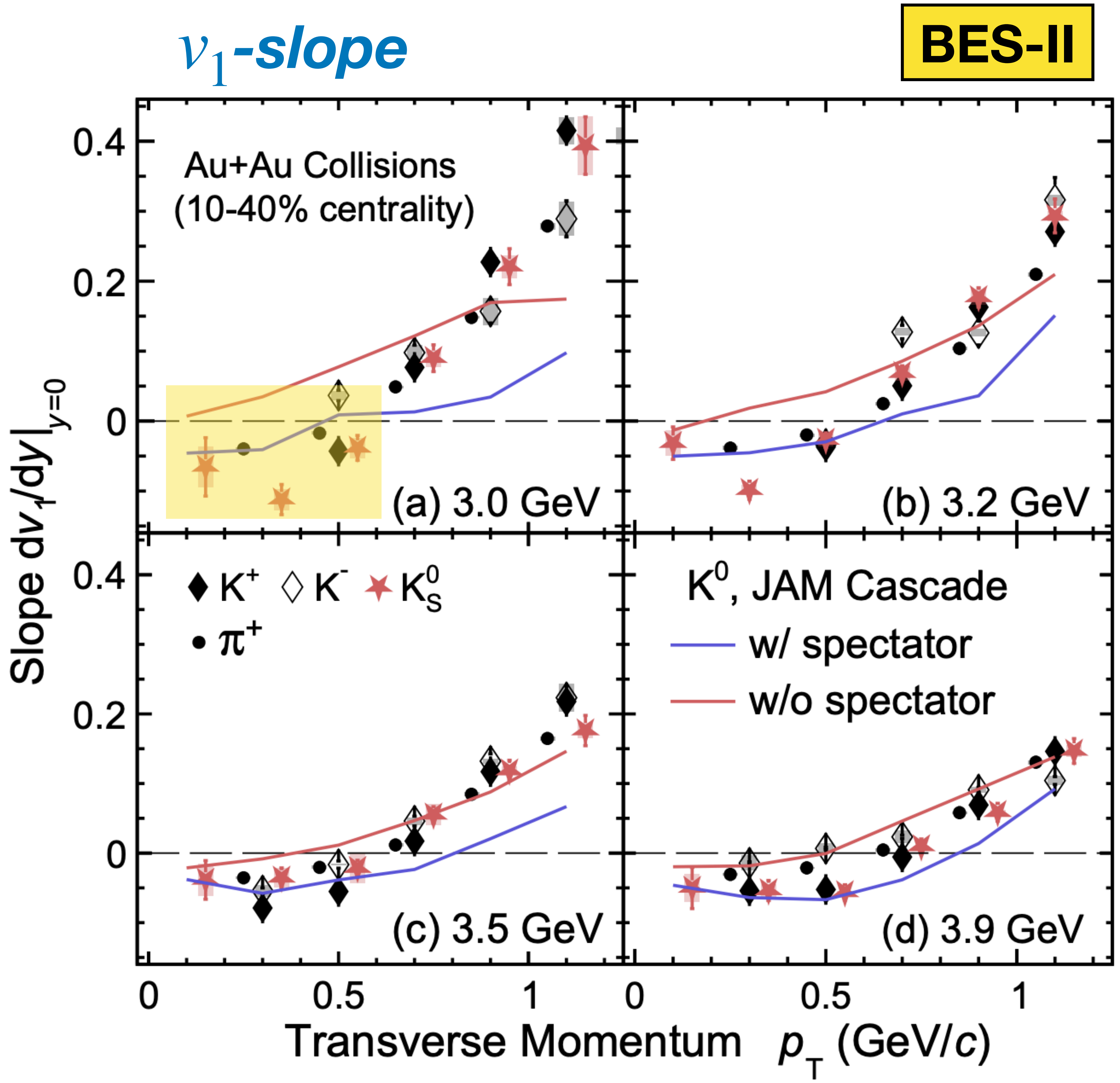
Need theoretical inputs to understand these features

Directed flow from STAR BES-II



Kaon anti-flow observed in Au+Au at $\sqrt{s_{NN}} = 3.83$ GeV

→ Observation explained by Kaon potential



Directed flow: $v_1 \sim \langle \cos(\phi - \Psi_R) \rangle$

arXiv: 2503.23665 (STAR)

- At low p_T: $\pi^+, K^\pm$ and K_S^0 v_1-slope is negative
- Anti-flow can be explained by JAM with nuclear shadowing, *Kaon potential is not necessary*

Number of constituent quark scaling (NCQ) at RHIC

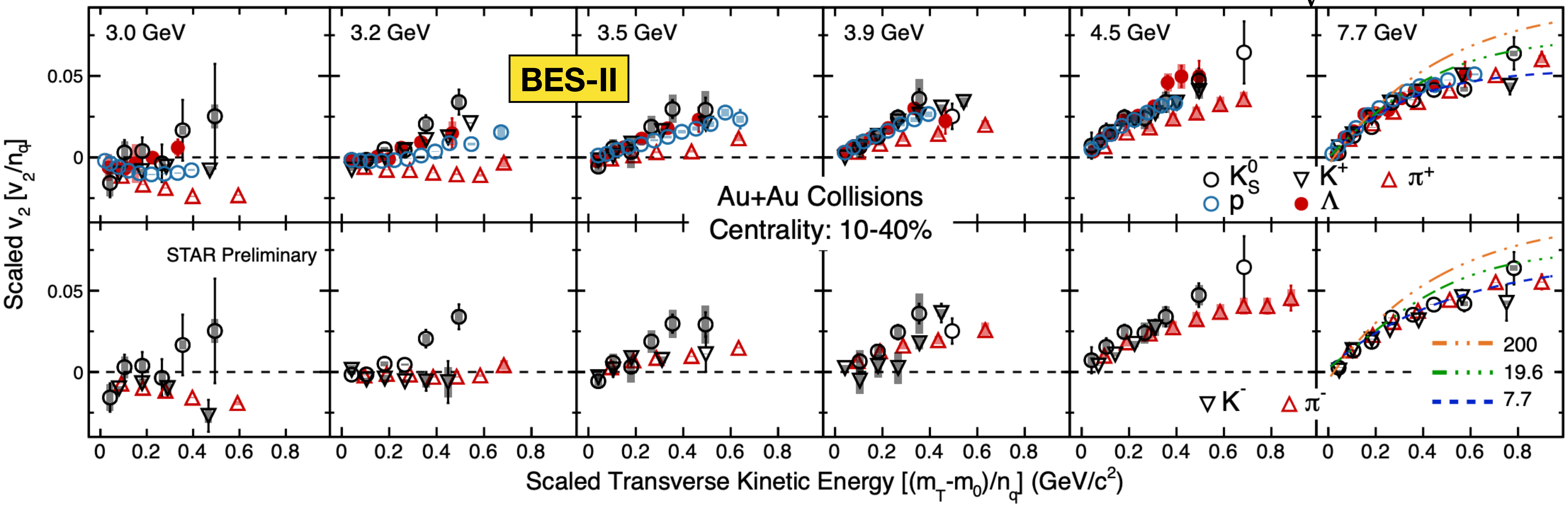
QM 2025, Morind 2025 (STAR)

Elliptic flow: $v_2 \sim \langle \cos 2(\phi - \Psi_R) \rangle$ $\quad v_2^h(p_T) = n v_2^q(\frac{p_T}{n})$

Fixed target: $\sqrt{s_{NN}}$ = 3.0 - 4.5 GeV

NCQ Scaled v_2

Collider: $\sqrt{s_{NN}}$ = 7.7 GeV

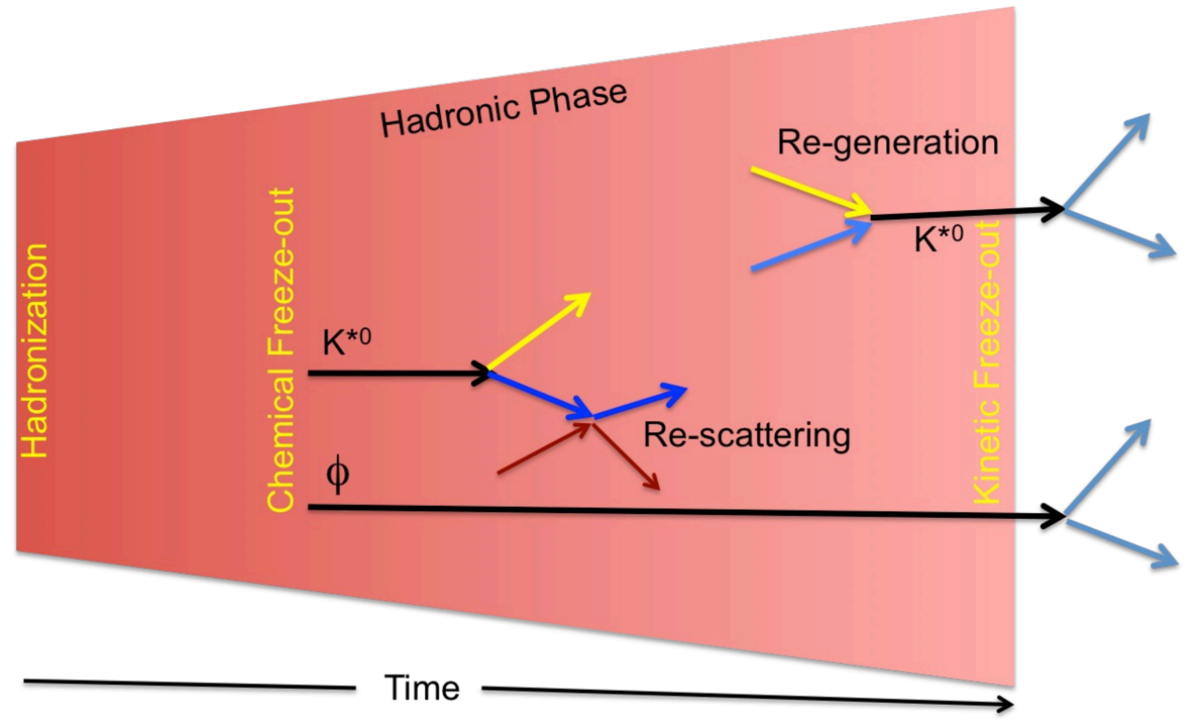


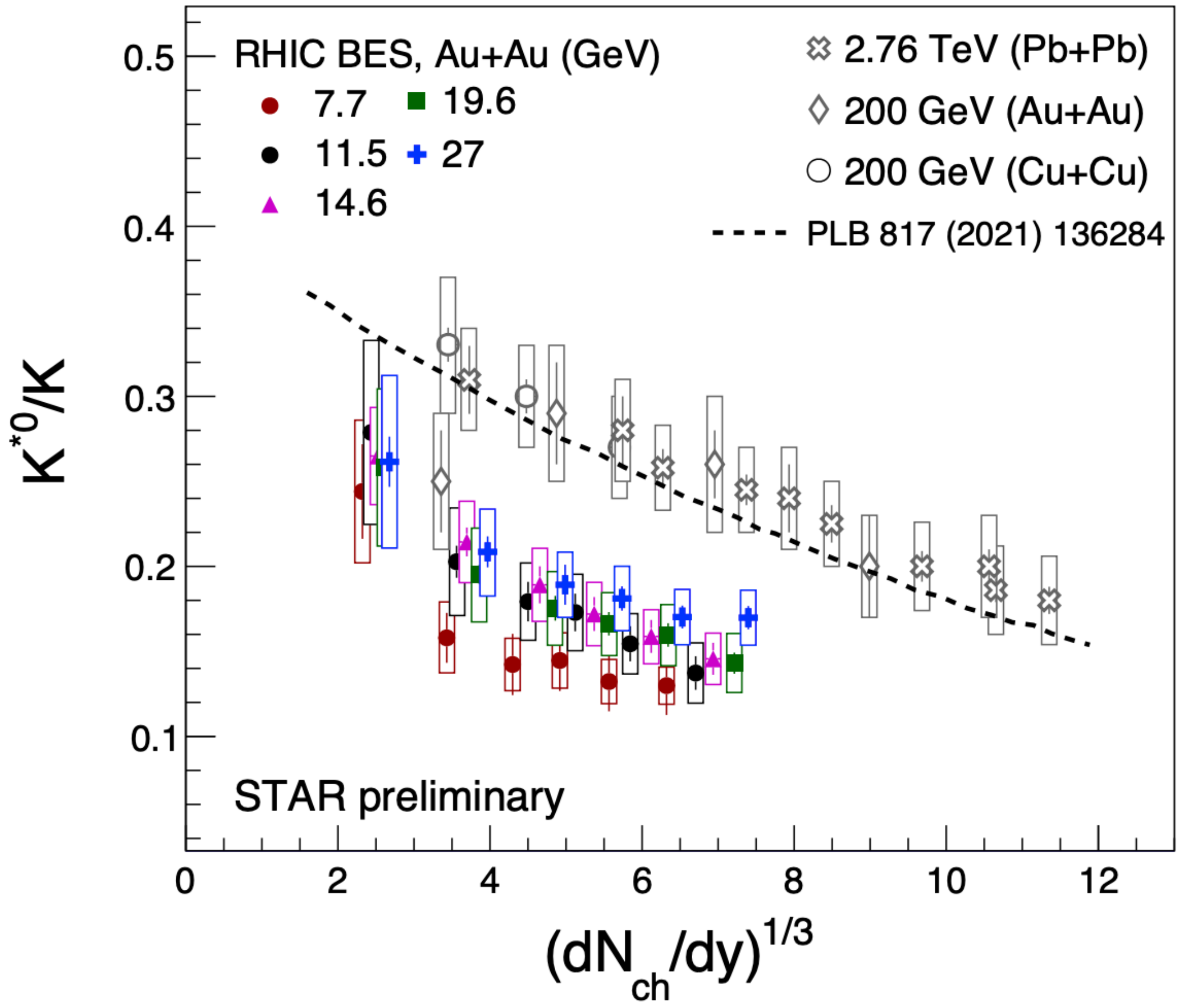
- $\sqrt{s_{NN}} < 4.5$ GeV → Gradual breaking of NCQ
- $\sqrt{s_{NN}} \geq 7.7$ GeV → NCQ scaling holds

Dominance of hadronic interactions ↔ *Dominance of partonic interactions*

These measurements can help constrain the on-set of partonic collectivity and role of nuclear shadowing

K* directed flow and hadronic re-scattering





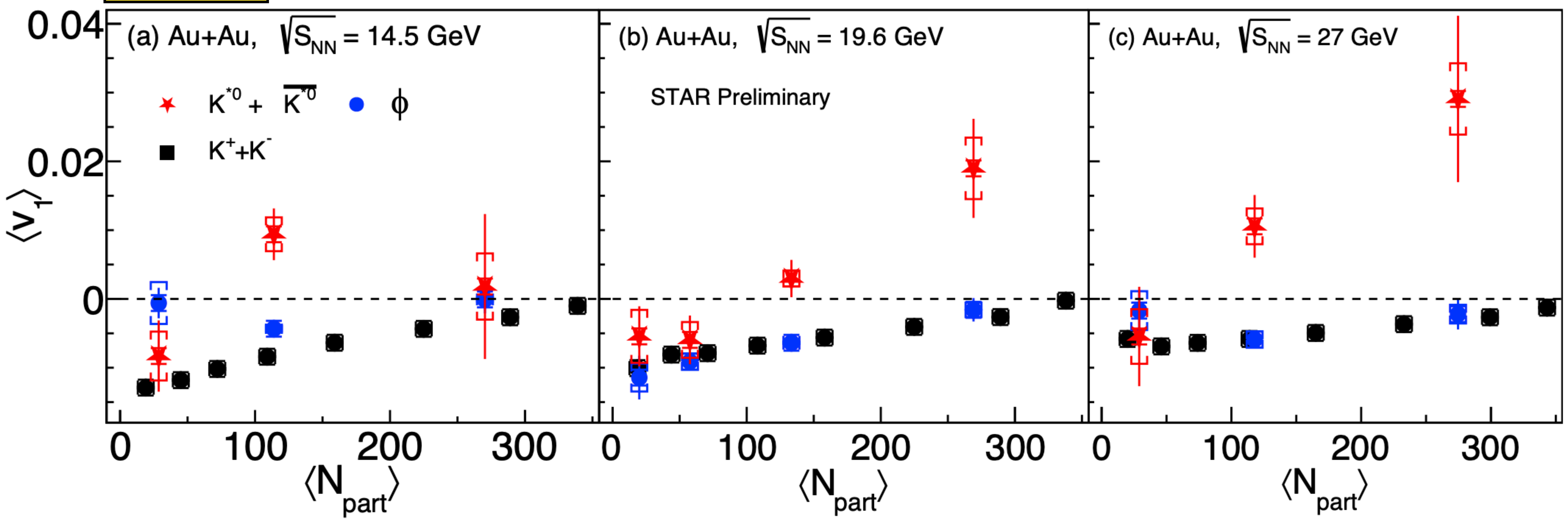
K* suffers from hadronic re-scattering

→ Probed via K*/K ratio

BES-II

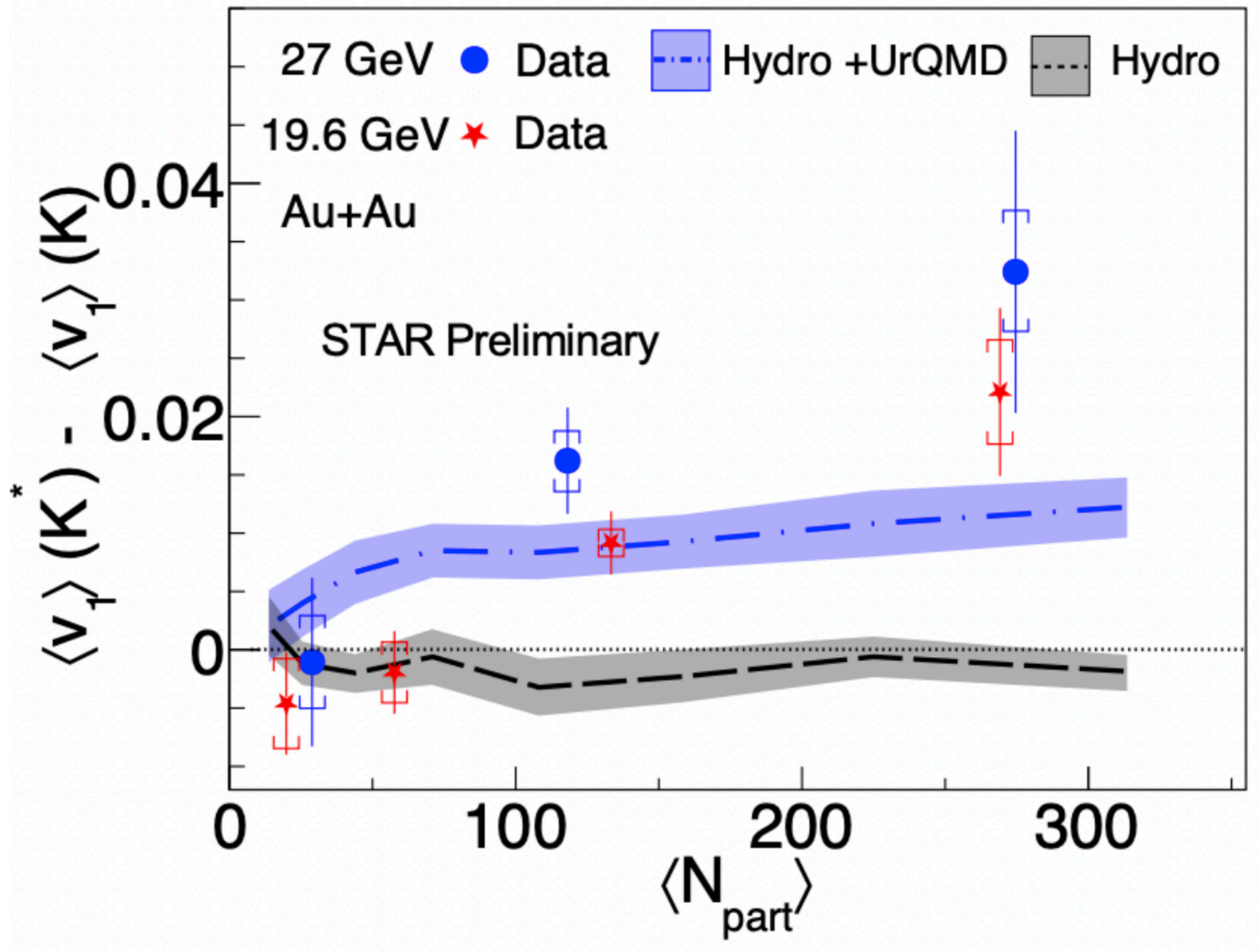
Mean-v_1

QM 2025 (STAR)



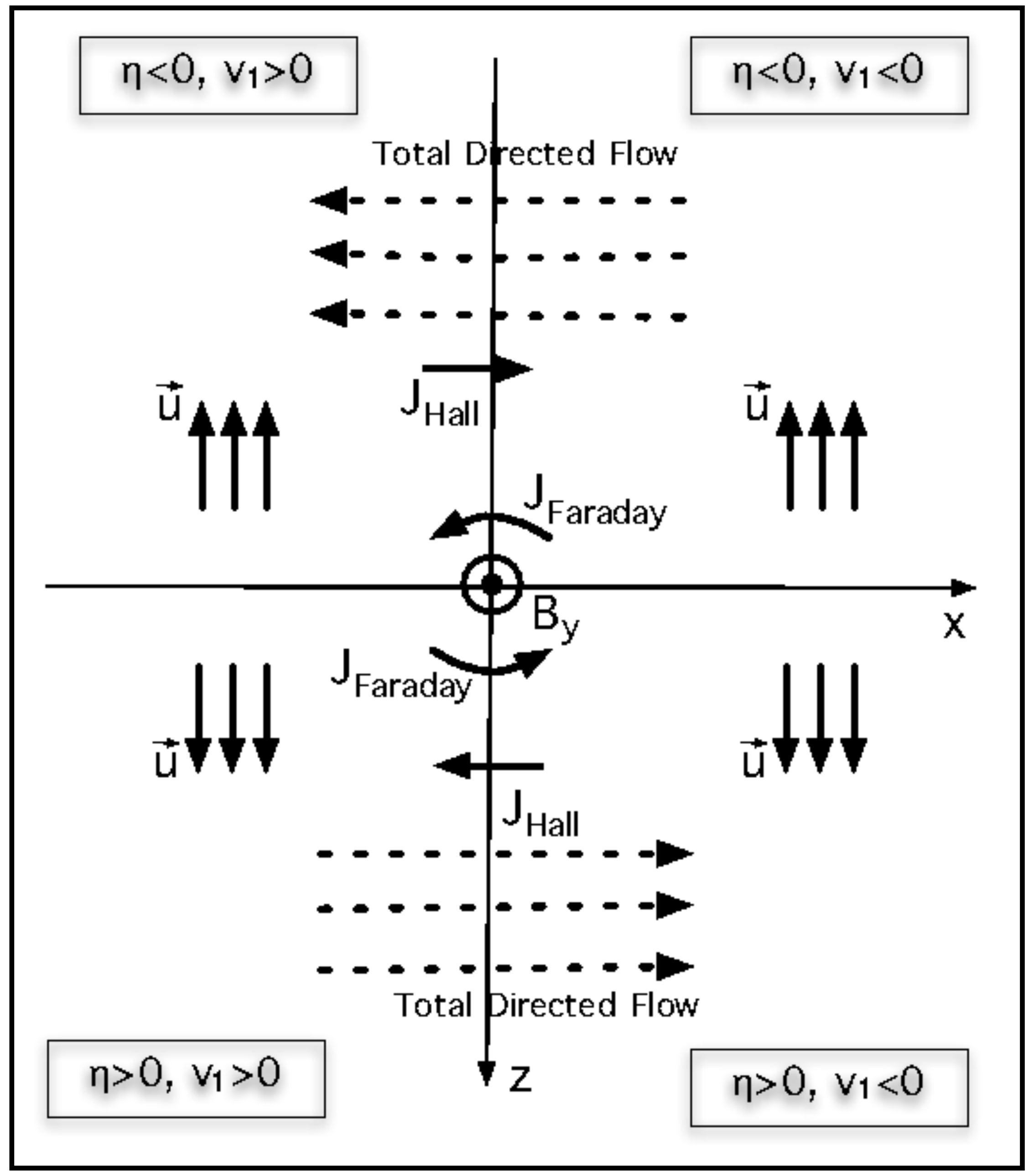
- K^{*0} v_1 changes sign from peripheral to central collisions unlike ϕ meson
- Pattern can be reproduced by Hydro model with hadronic re-scattering

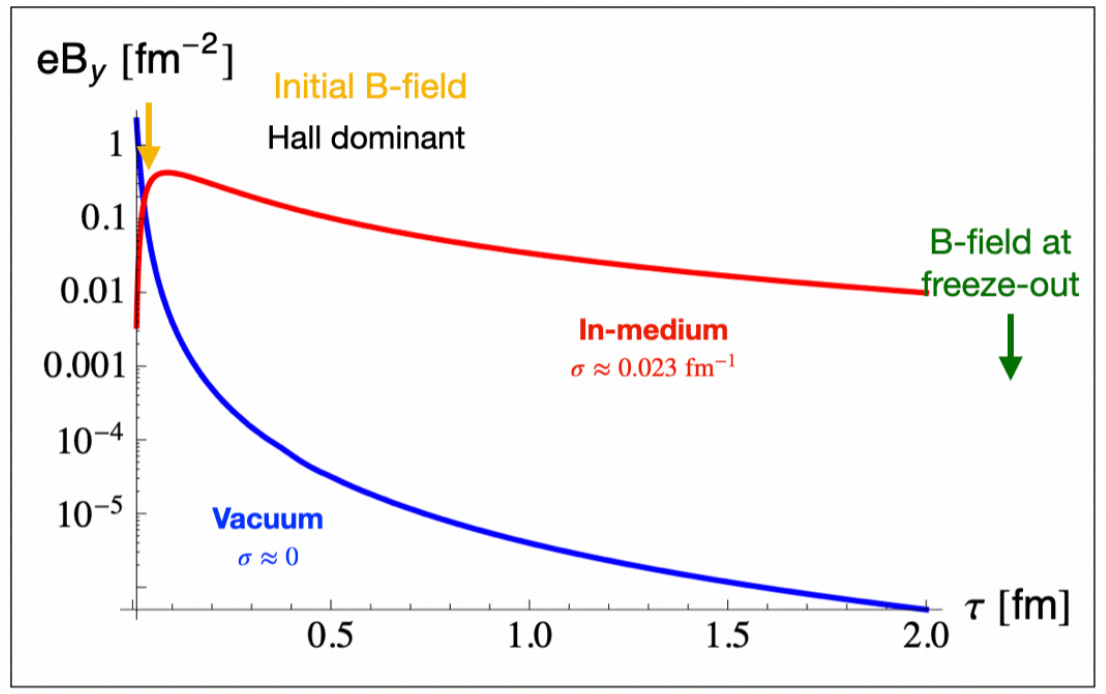
Parida et al, PRC 109, 044905 (2024)



Electromagnetic field in HIC

Gursoy et al, Phys Rev C 89, 054905 (2014)





Directed flow: $v_1 \sim \langle \cos(\phi - \Psi_R) \rangle$

- The moving spectators can produce enormously large **B** field (eB ~10^{18} G)
- There could be three competitive effects
- Hall effect: $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$
  Lorentz force exerts a sideways push on charged particles
  In opposite directions for opposite particles
  (along -ve X-direction in +ve rapidity and vice-versa)
- Faraday effect: $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
  Time dependent **B** field generates a large **E** field
  Induced Faraday current will oppose the drift due to **B** field
- Coulomb effect:
  Coulomb field of the charged spectators

- **Imprints of EM field effects**
- Hall: positive Δv_1
- Faraday: negative Δv_1
- Coulomb: negative Δv_1

Observable

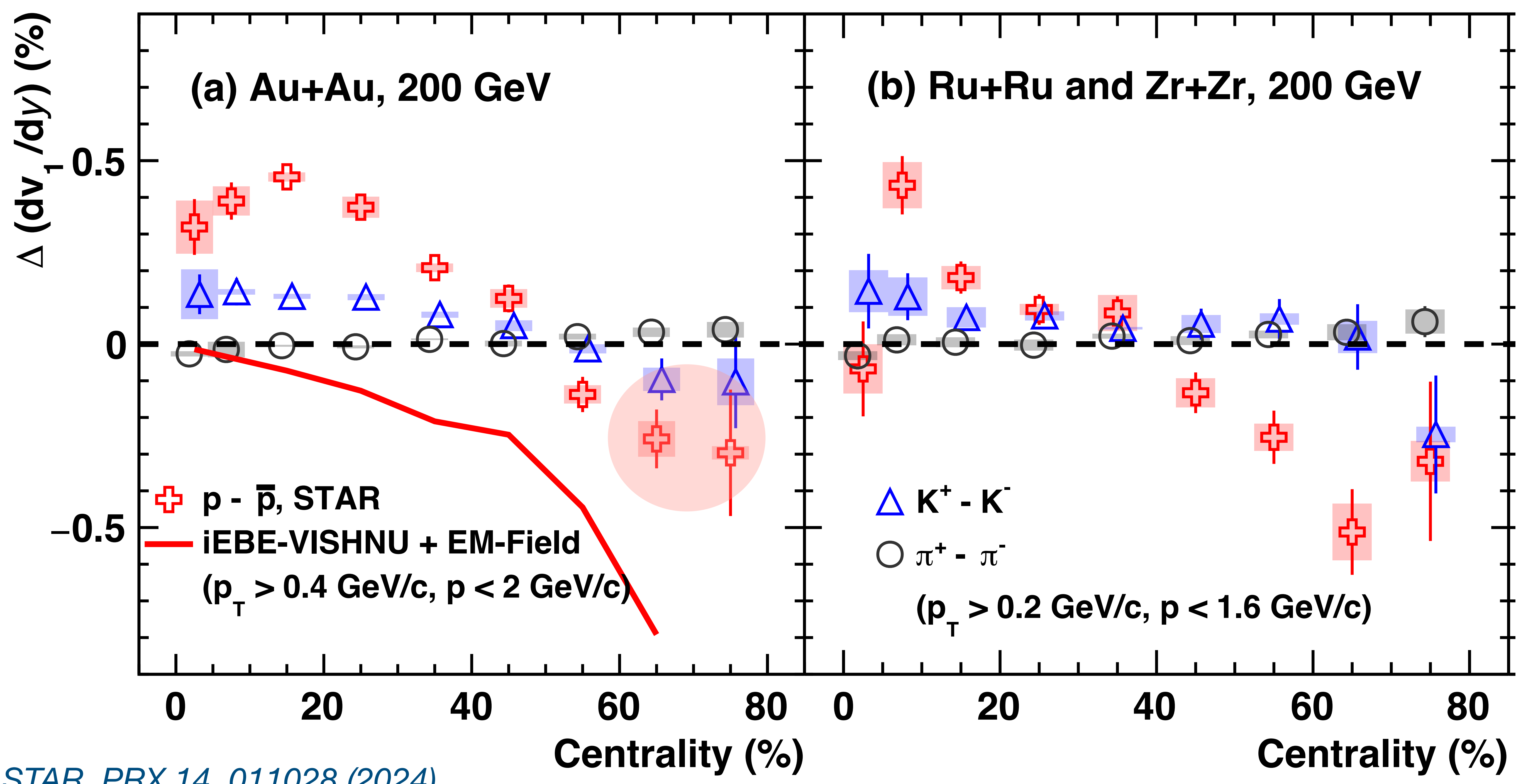
$$\Delta v_1 \sim v_1(h^+) - v_1(h^-)$$

- **Non-EM field effects**
- Transport: $\Delta v_1^{\dagger} \neq 0$
- ....

- Δv_1 sensitive to ***QGP conductivity (σ)***

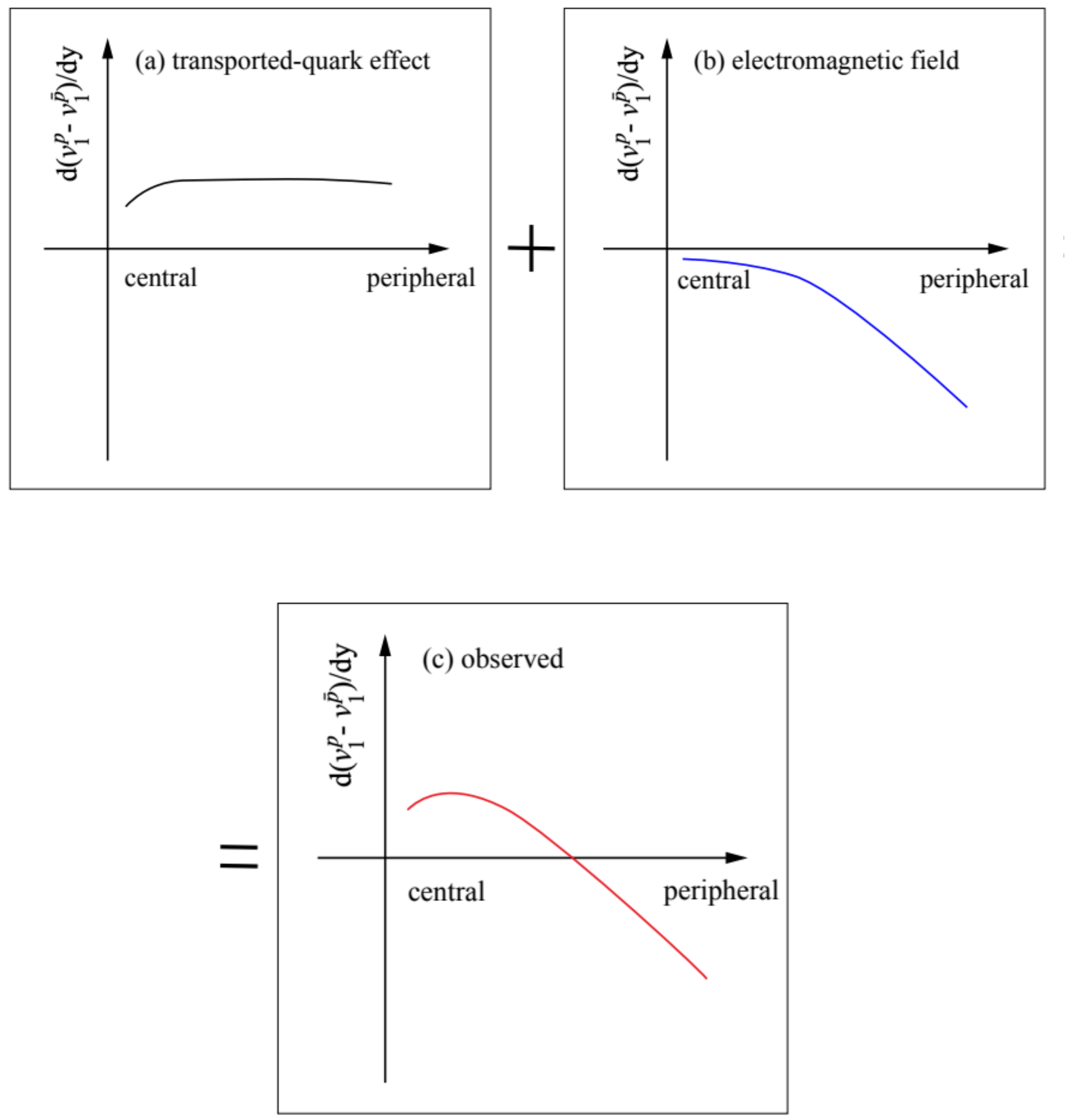
Charge dependent directed flow

Observation $\Delta v_1 : h^+ - h^-$



STAR, PRX 14, 011028 (2024)

Expectation



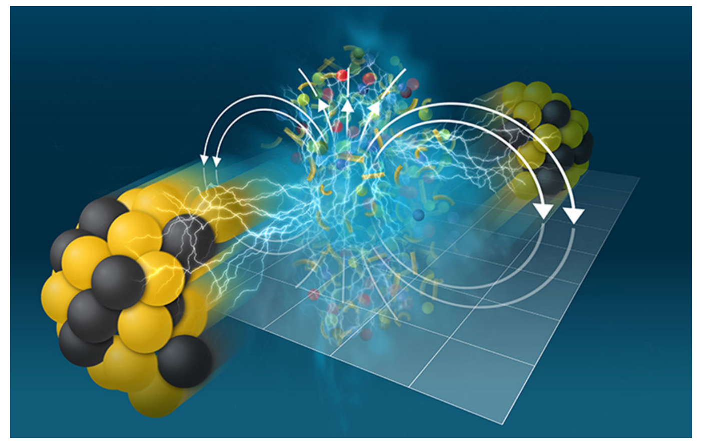
- For protons and kaons: sign change in Δv_1 in peripheral collisions

  (Negative Δv_1 consistent with Faraday+Coulomb dominates over Hall effect)

- For pions: Δv_1 ~ 0 (large uncertainty)

Strongest possible pulse of an electromagnetic field in a laboratory setting during heavy-ion collisions

Results featured in APS Phys



FOCUS

Colossal Magnetic Field Detected in Nuclear Matter

Collisions of heavy ions briefly produced a magnetic field 10^{18} times stronger than Earth's, and it left observable effects.

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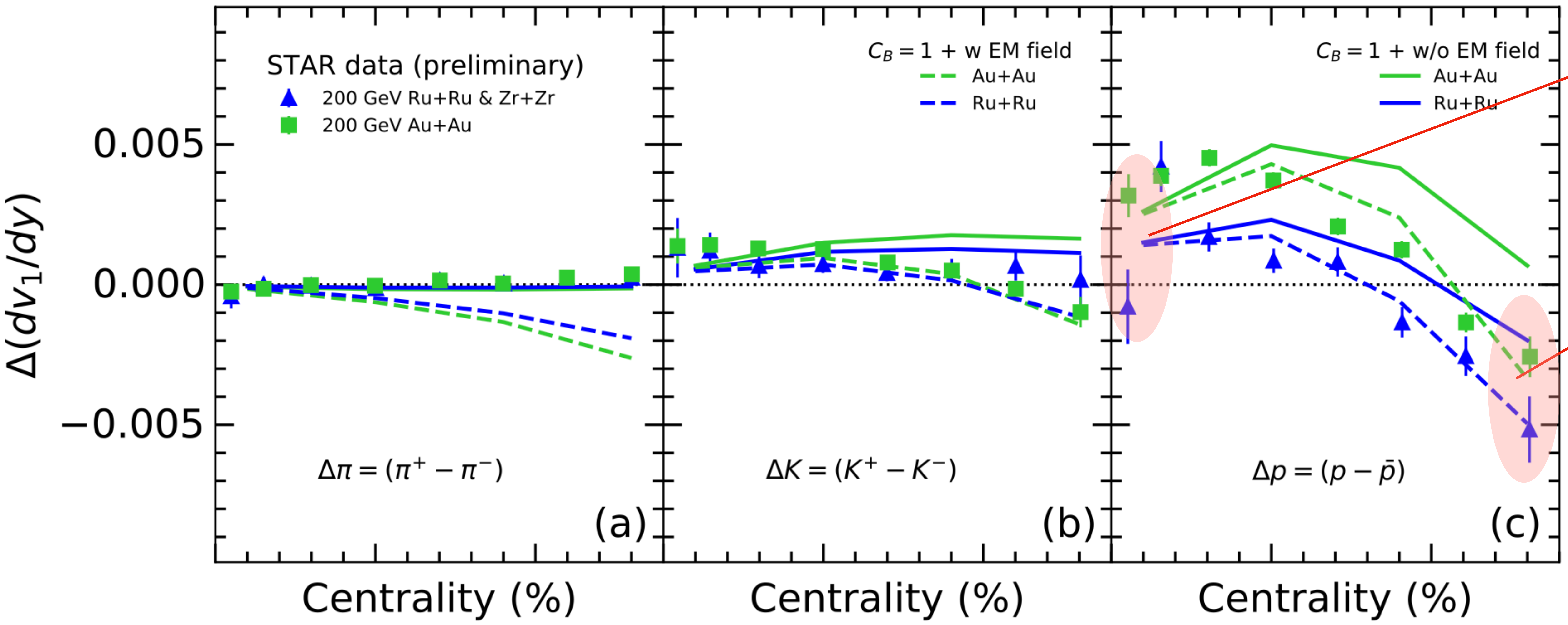
Charge dependent directed flow: with hydro + EM

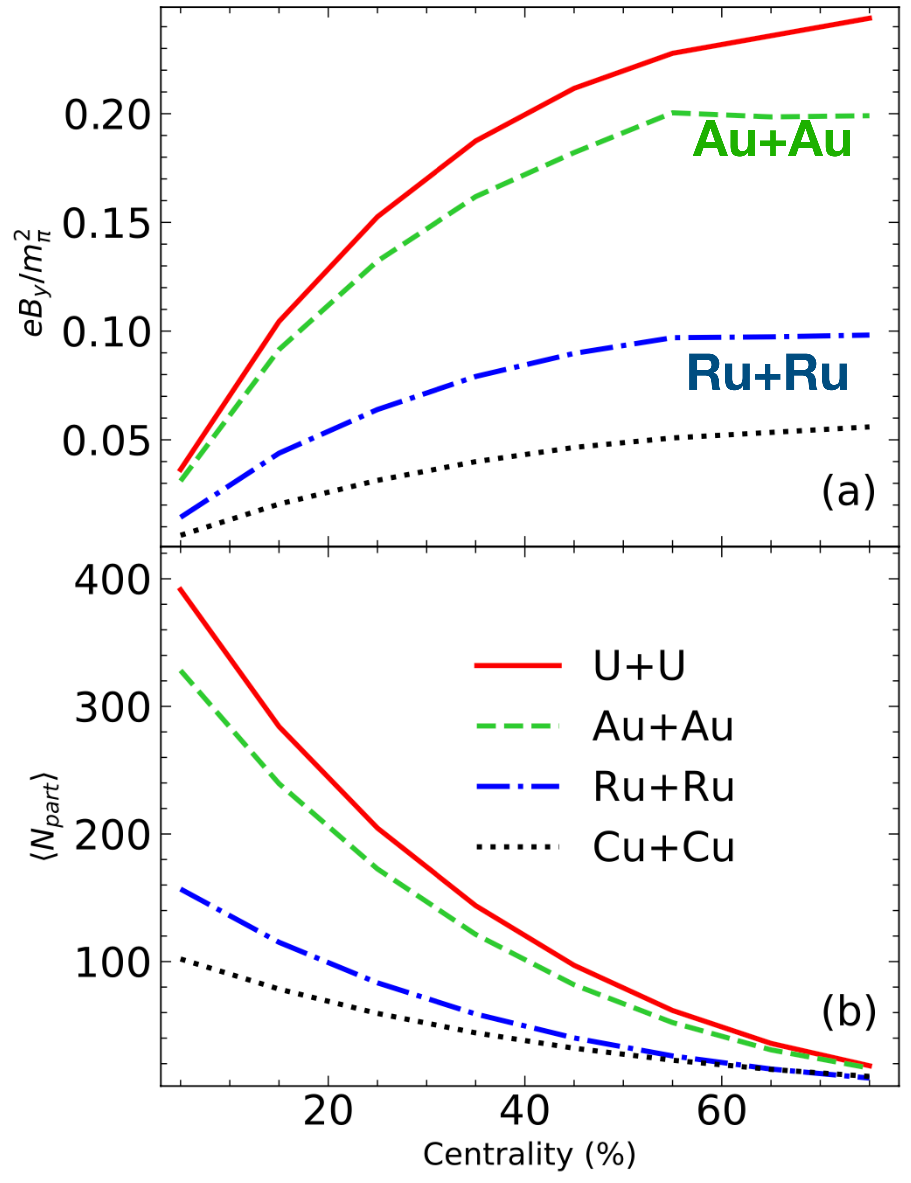
$\Delta v_1 : h^+ - h^-$



Splitting in most-central collisions → related to baryon transport

Proton splitting in mid-central and peripheral collisions → interplay between baryon transport and electro-magnetic field

Parida et al, 2305.08806, ATHIC 2025
Parida et al (2503.04660)



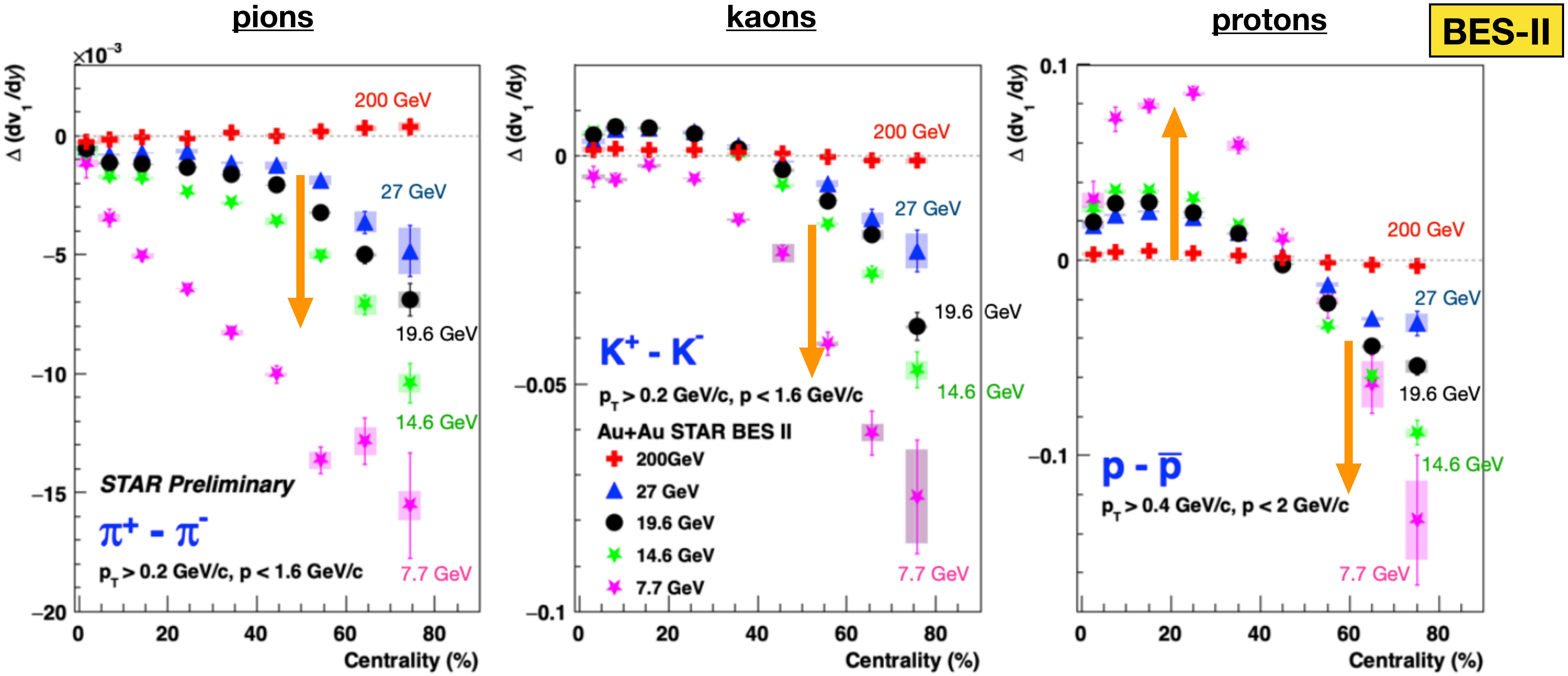
→EM-field
- Weaker in Central
- Stronger in Peripheral

→Baryon
- Stronger in Central
- Weaker in Peripheral

- <u>For proton's</u>
- **Baryon transport + EM field** *with* *QGP conductivity* $\sigma \sim 0.023$ fm^{-1} required to capture *system size dependence* across centrality
- Model fail to capture pions splitting, need more studies

Charge dependent directed flow: energy dependence

$\Delta v_1 : h^+ - h^-$



- <u>For proton's</u>
- In (mid-) central collisions: positive Δv_1 increases with decreasing beam energy (baryon transport)
- In peripheral, negative Δv_1 increases with decreasing beam energy (EM-field)

Baryon transport + EM-field → needed modeling at these energies

Summary

- <u>A few selected collective flow (v_1, v_2) measurements from RHIC BES-program</u>

- $\sqrt{s_{NN}}$ = 4.5- 7.7 GeV → sign change in Kaon v_1
- Sign change in ϕ v_1 and it follows baryons (p and Λ)
- Observation of anti-flow for $\pi^+, K^\pm$ and K_S^0 → explained by shadowing (Kaon potential is not necessary)

- For $\sqrt{s_{NN}} \geq$ 7.7 GeV →v_2 NCQ-scaling holds
- $\sqrt{s_{NN}} <$ 4.5 GeV → Gradual breaking of v_2 NCQ-scaling
- Dominance of *partonic* collectivity above 4.5 GeV

- Non-trivial Δv_1 pattern at RHIC, with sign change in peripheral collisions for protons
- Interplay of baryon transport and electromagnetic field with conducting QGP medium

From MPD CDR

$n_E \approx 1.5 - 2.0 n_0$. **Therefore, the major goal of the NICA/MPD Project is the study of in-medium properties of hadrons and the nuclear matter equation of state, including a search for possible signals of deconfinement and/or chiral symmetry restoration phase transitions and the QCD critical endpoint** in the region of the collider energy $\sqrt{s_{NN}} = 4 - 11$ GeV. Due to the high complexity of this

https://mpd.jinr.ru/wp-content/uploads/2023/11/MPD_CDR_en.pdf

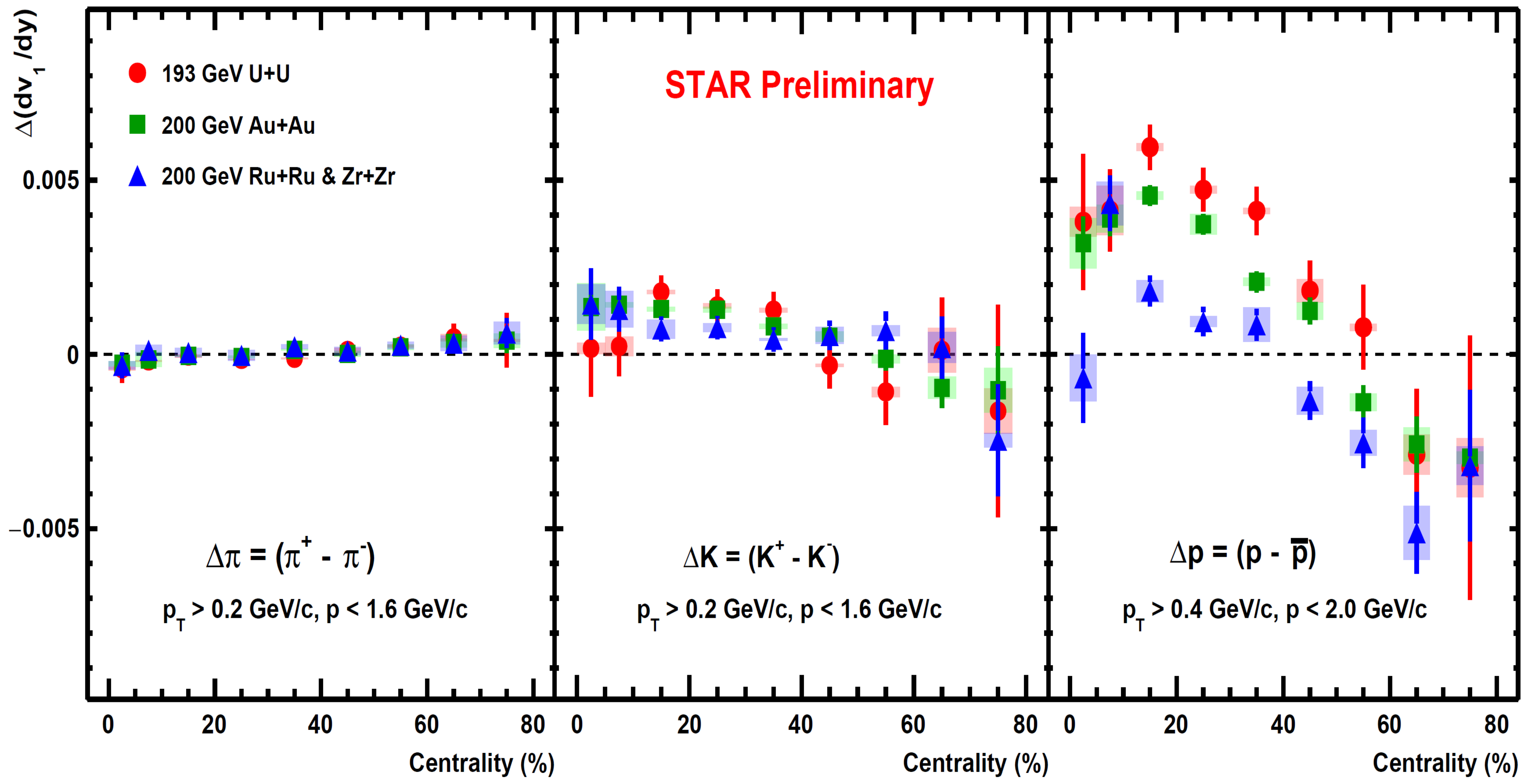
STAR-BES and MPD → complementary and essential to probe the QCD phase structure and medium properties in energy between 3 - 10 GeV

Thank you for your attention

Many thanks to STAR and theory colleagues for discussions

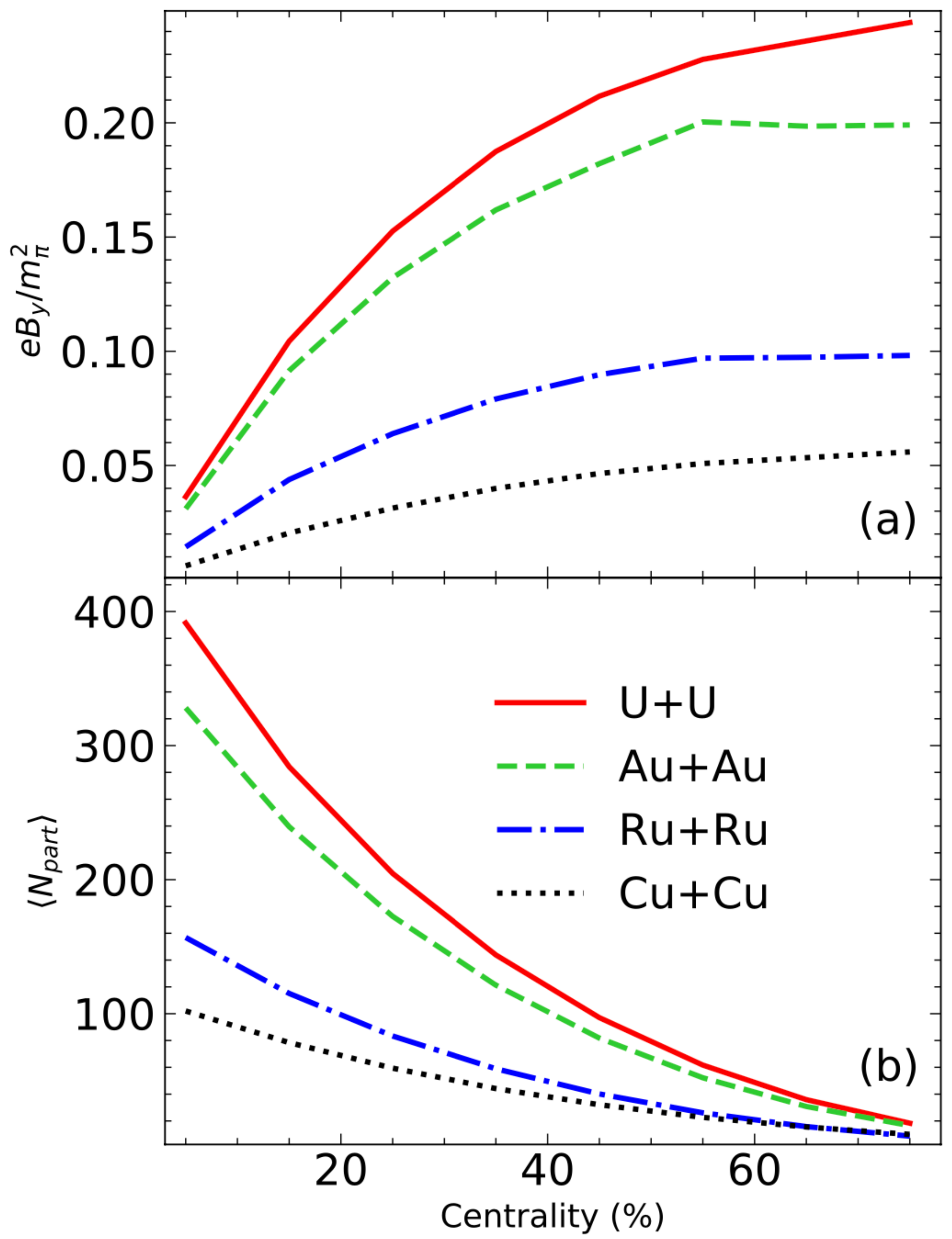
Charge dependent directed flow: system size dependence

Observation $\Delta v_1 : h^+ - h^-$



- pion's/kaon's Δv_1: no obvious system size dependence across centrality
- proton's Δv_1: system size dependence across centrality

Parida et al (2503.04660)



→EM-field

→Baryon

- Central: Baryon transport
- Peripheral: EM-field

in different systems several factors to be considered:
- strength and lifetime of EM-field
- QGP lifetime and conductivity
- transport
- …

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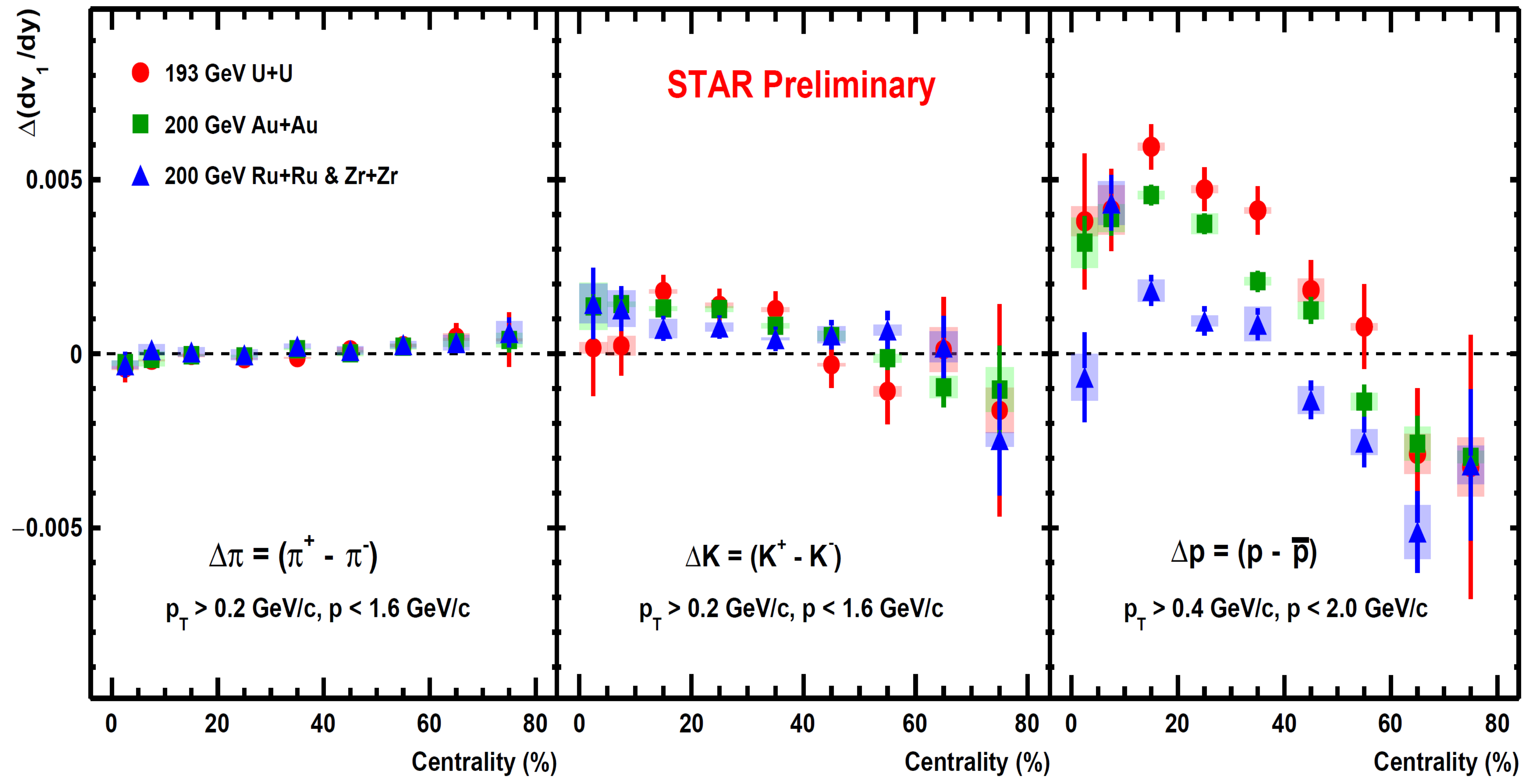
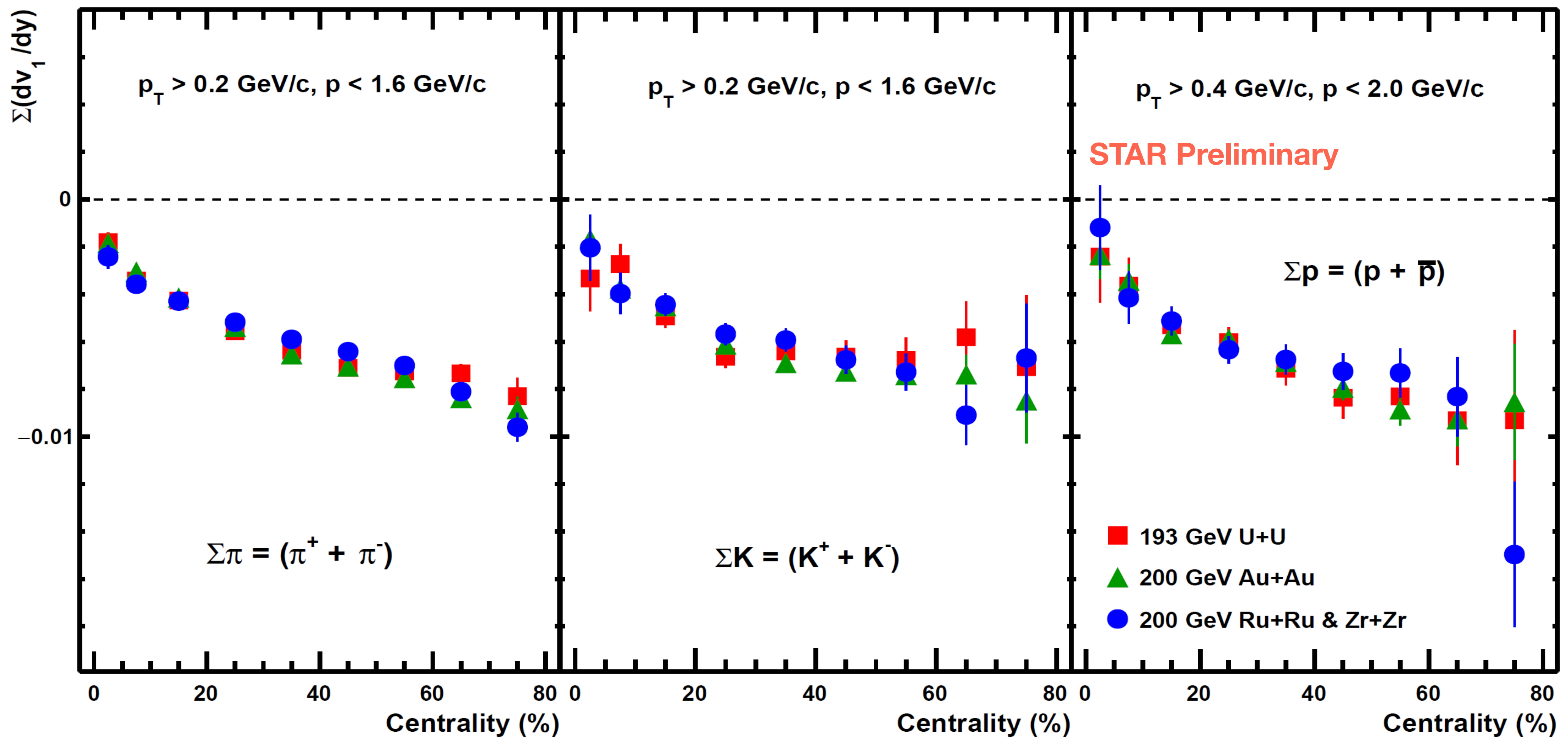
Charge dependent directed flow: system-size dependence



Net-baryon + EM

- **Difference** Δv_1: $h^+ - h^-$
- pions & kaons: U+U ~ Au+Au ~ Isobar
- protons: U+U < Au+Au < Isobar



SQM 2024 (STAR)

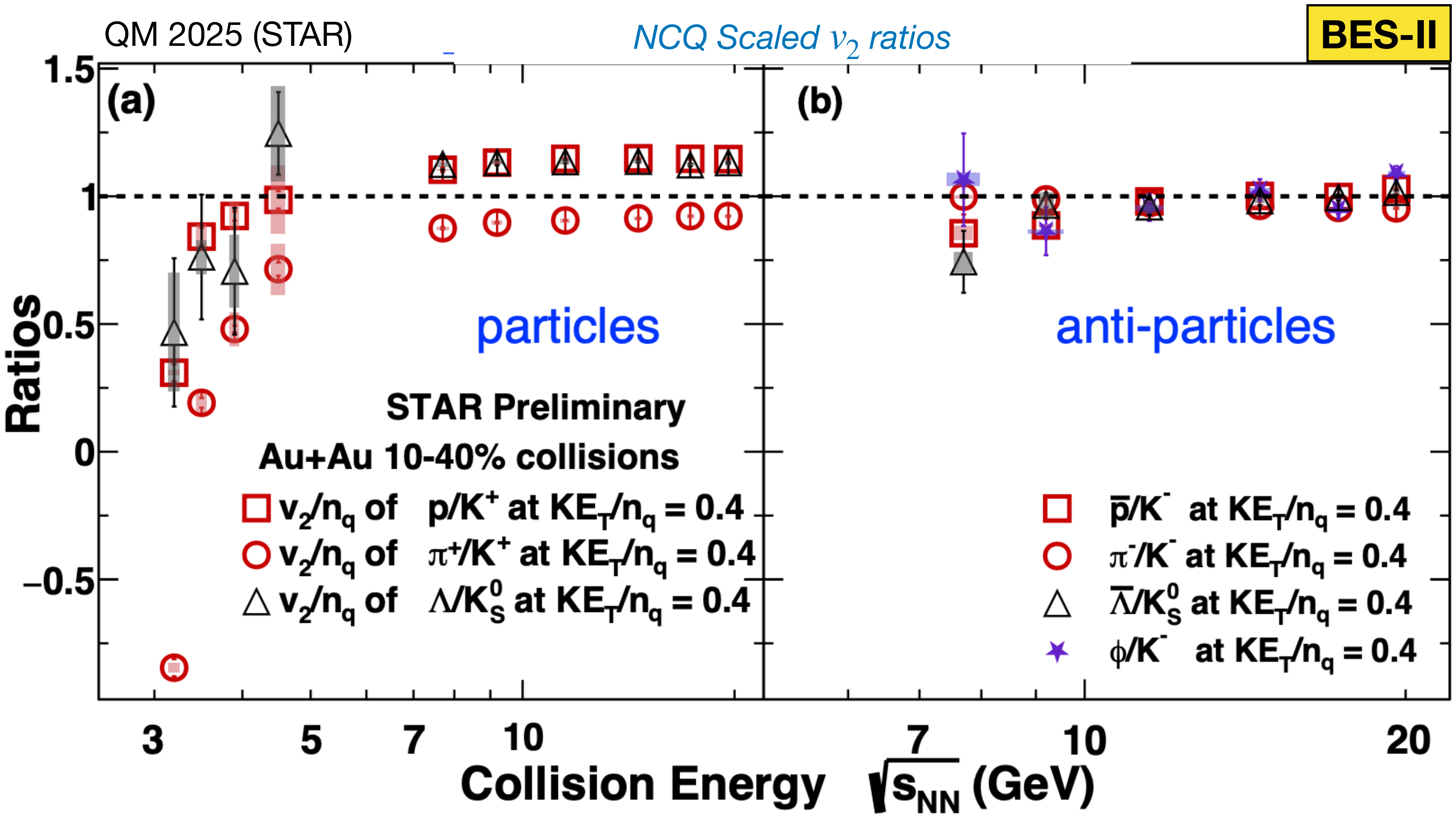
NO effect from Net-baryon + EM

- **Sum** Σv_1 : $h^+ + h^-$
- pions & kaons: U+U ~ Au+Au ~ Isobar
- protons: U+U ~ Au+Au ~ Isobar

Baryon transport + EM-field
→ can capture system size independence of $h^+ + h^-$

Parida et al, 2305.08806, ATHIC 2025
Parida et al (2503.04660)

Number of constituent quark scaling (NCQ) at RHIC



- $\sqrt{s_{NN}} < 4.5$ GeV → NCQ scaled ratios deviates