Highlights from RHIC Beam Energy Scan Program

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Outline

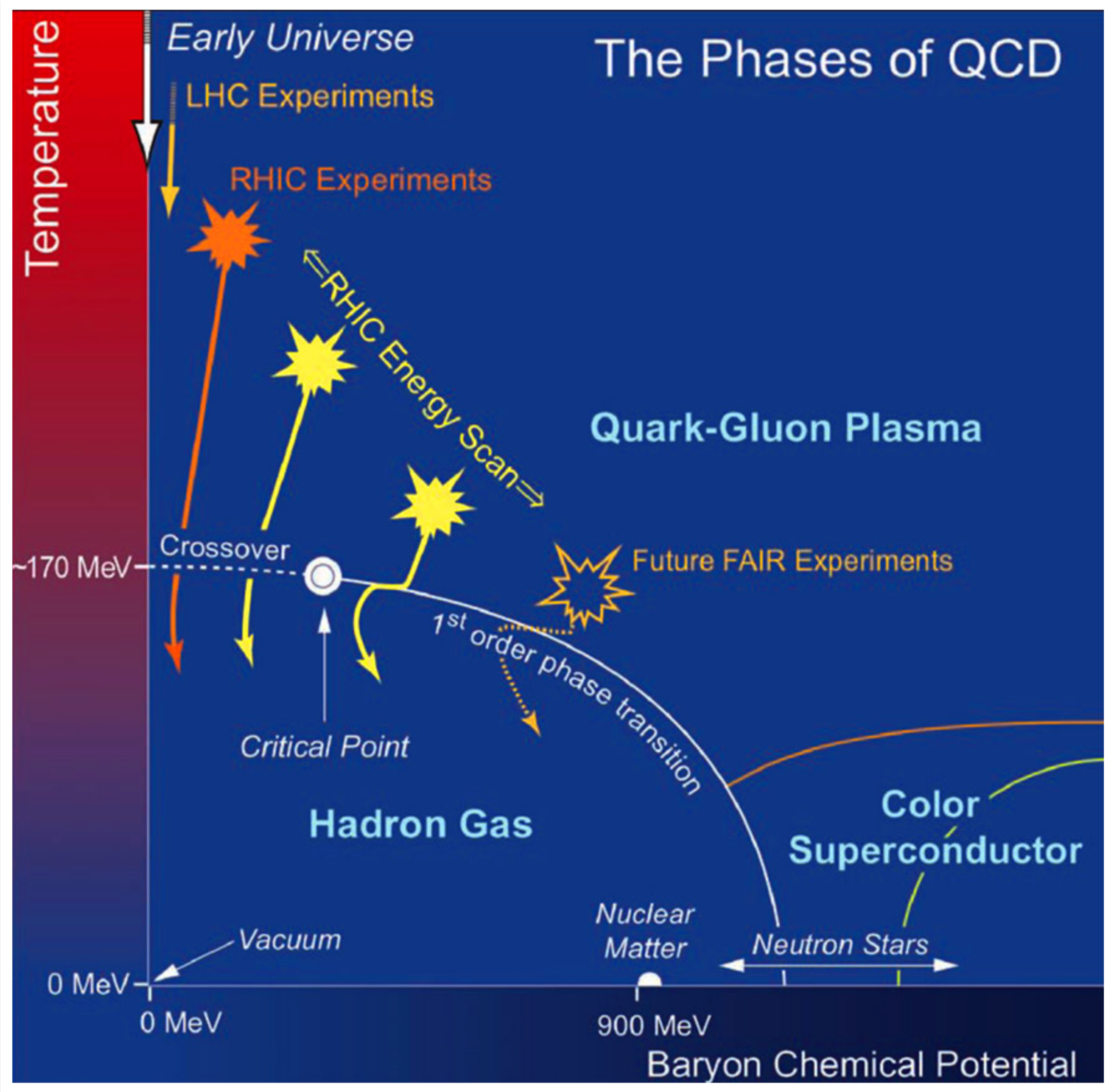
- RHIC Beam Energy Scan (BES) program
- Selected highlights RHIC BES program in STAR

1. **Particle yields**
2. **Collective flow**
3. **Critical point search**
4. **Spin dynamics**

- Summary

RHIC BES program

Conjectured QCD Phase diagram



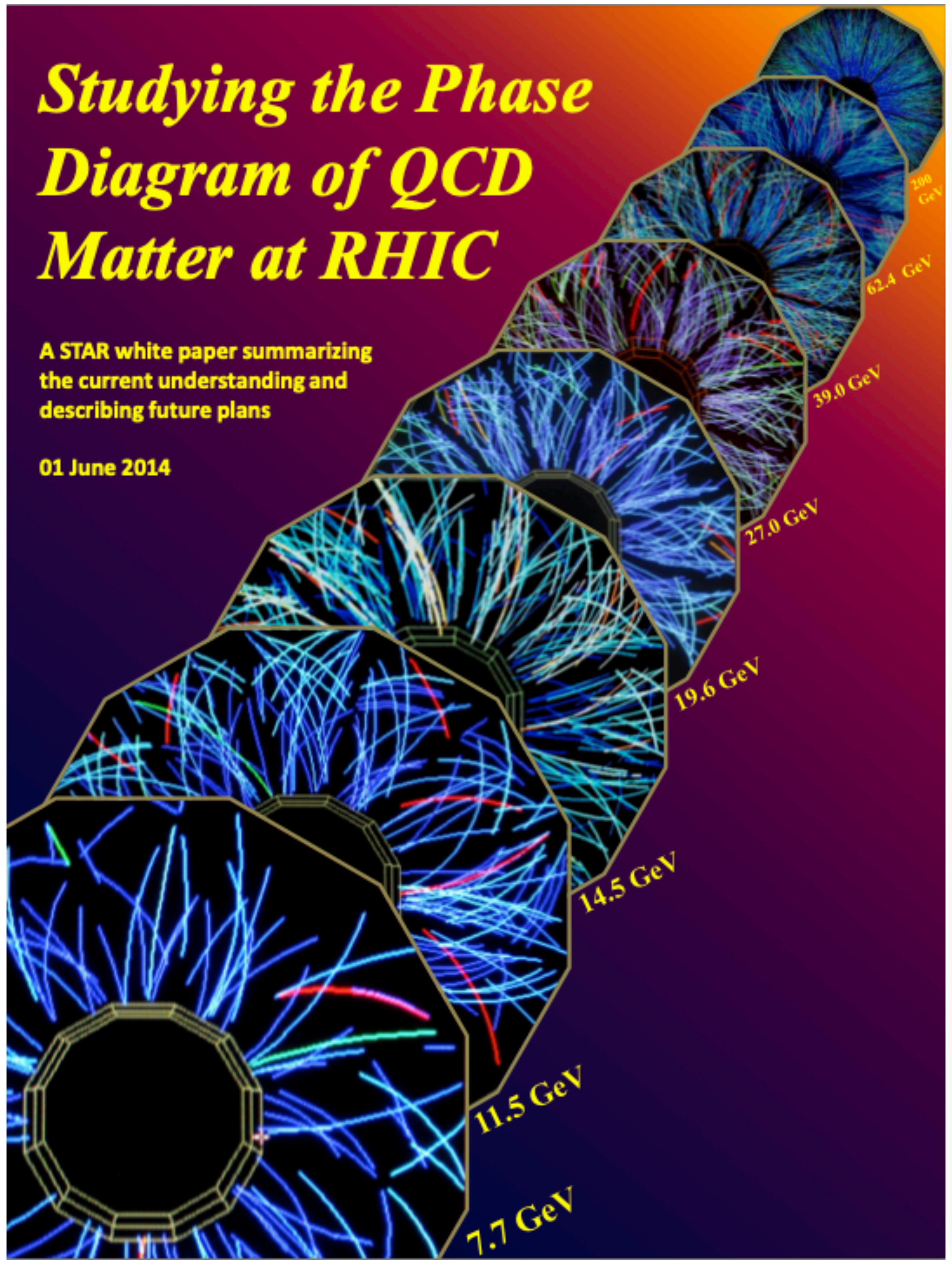
Partonic dominant → Hadronic dominant

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

RHIC Beam Energy Scan



Contents

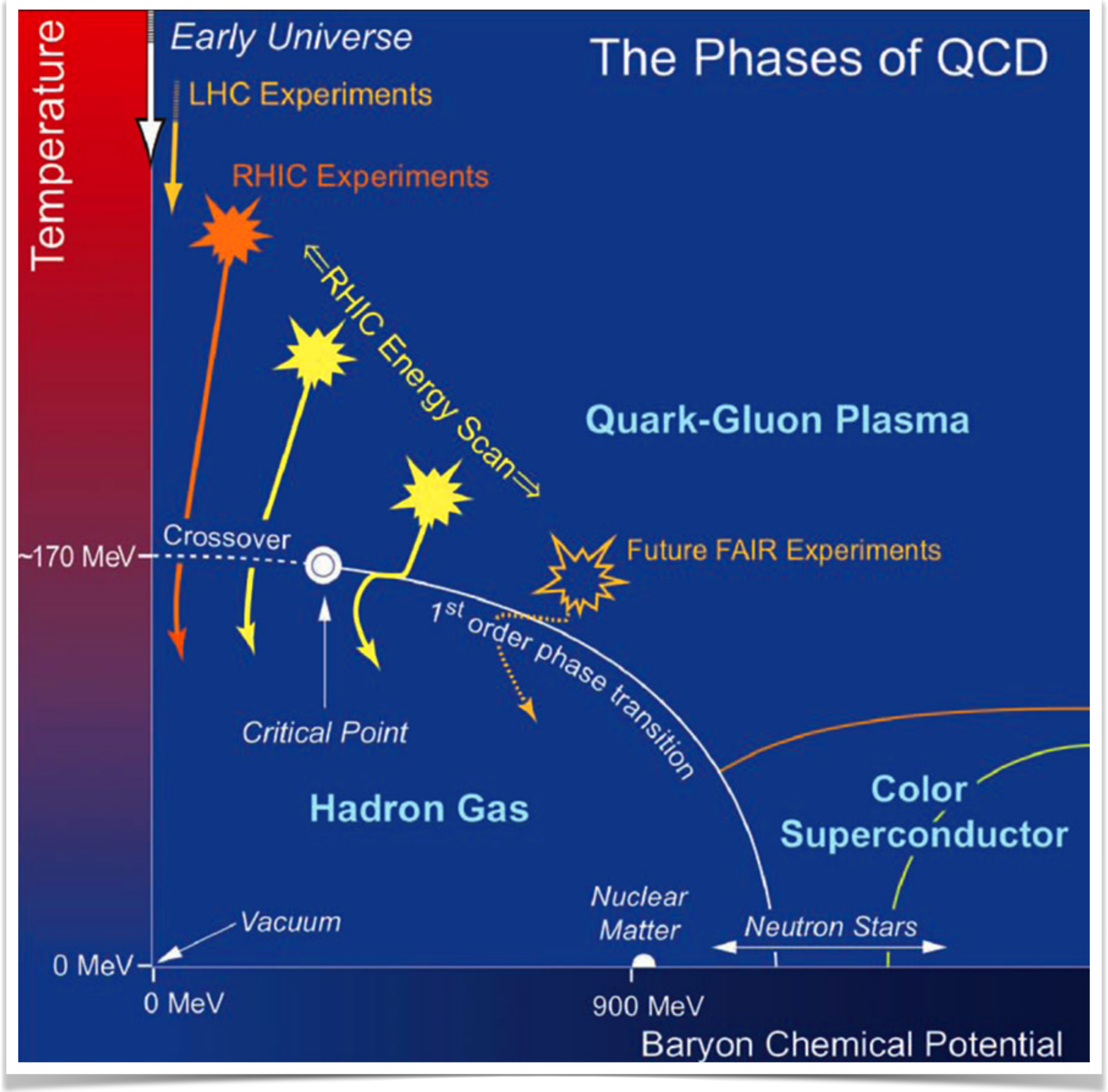
Executive Summary

The STAR Collaboration proposes a second phase of the Beam Energy Scan program at RHIC (BES Phase-II) to answer compelling questions about the phase structure of QCD matter that cannot be addressed using existing measurements. We propose dedicated low-energy running in 2018 and 2019 to take full advantage of accelerator and detector upgrades and focus on precision measurements in a targeted region identified in BES Phase-I.

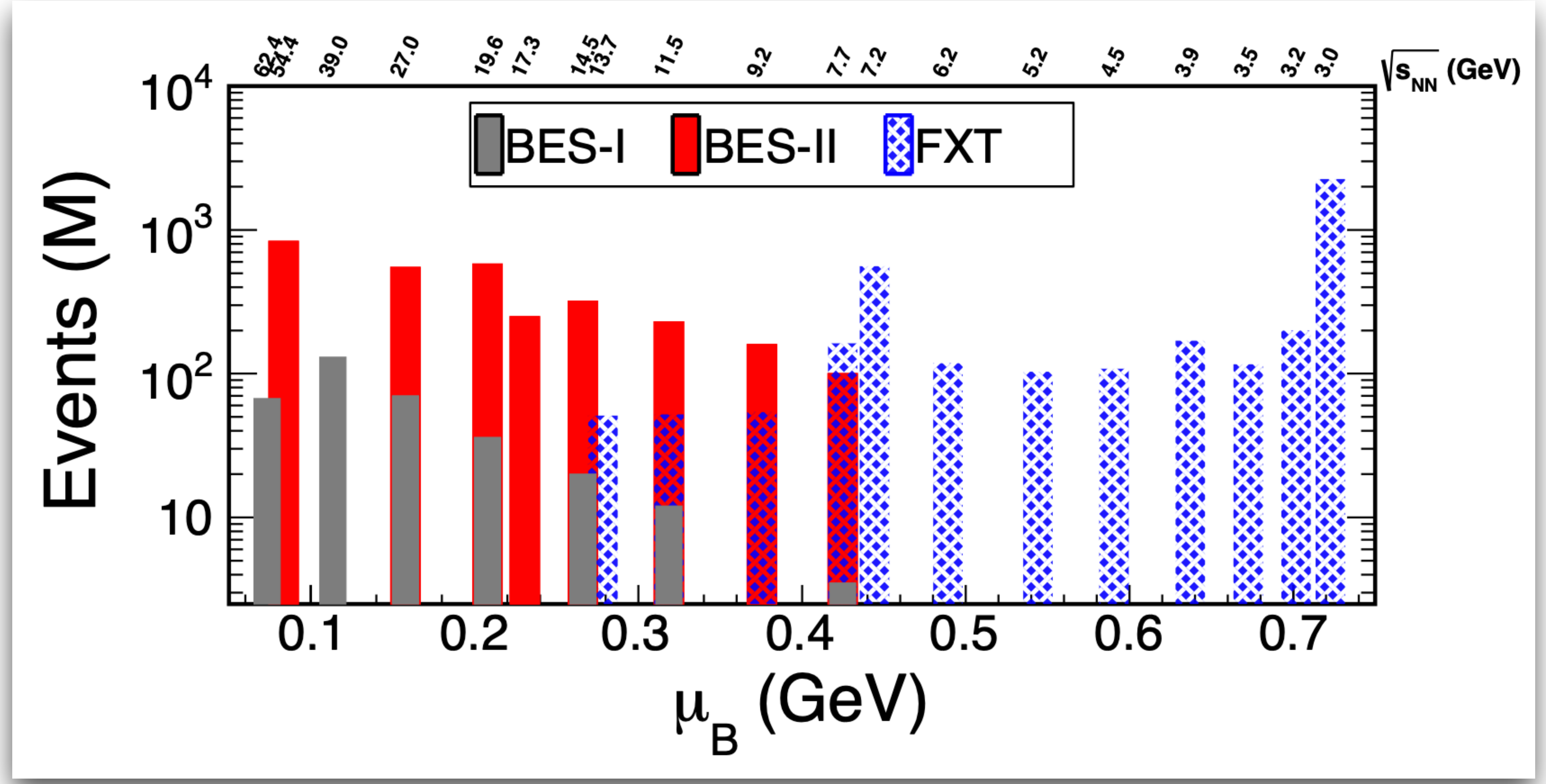
- The first phase of the Beam Energy Scan program (BES-I) plus the top energy at RHIC has allowed access to a region of the QCD phase diagram covering a range of baryon chemical potential (μ_B) from 20 to 420 MeV corresponding to Au+Au collision energies from $\sqrt{s_{NN}}$ = 200 to 7.7 GeV, respectively. Results from BES-I have further confirmed the evidence for the quark-gluon plasma (QGP) discovery at the top RHIC energy $\sqrt{s_{NN}}$ = 200 GeV. The results of the search for the critical point and the first-order phase boundary have narrowed the region of interest to collision energies below $\sqrt{s_{NN}}$ = 20 GeV. Current lattice QCD calculations suggest that key features of the phase diagram like the critical point and the first-order phase transition lie within the μ_B reach of the RHIC BES Phase-II program.
- The BES-I program has provided new information with measurements made at varying baryon density (e.g. azimuthal anisotropy of produced particles and dilepton invariant mass distributions). The lowest beam energies in the BES-I are expected to correspond to the highest compression of baryonic matter. Further, several measurements in BES-I coherently indicate that the role of partonic (hadronic) interactions increases (decreases) with beam energy.
- The proposed upgrades to the collider will increase the luminosity for future low energy runs by a factor of four to fifteen, depending on beam energy. The upgrades to the STAR detector system will significantly improve the quality of the measurements. The BES Phase-II program, with these upgrades, will allow for high-statistics measurements, with an extended kinematic range in rapidity and transverse momentum, using sensitive observables, to reveal the structure of the QCD phase diagram.

RHIC BES program

Conjectured QCD Phase diagram



BES Program:

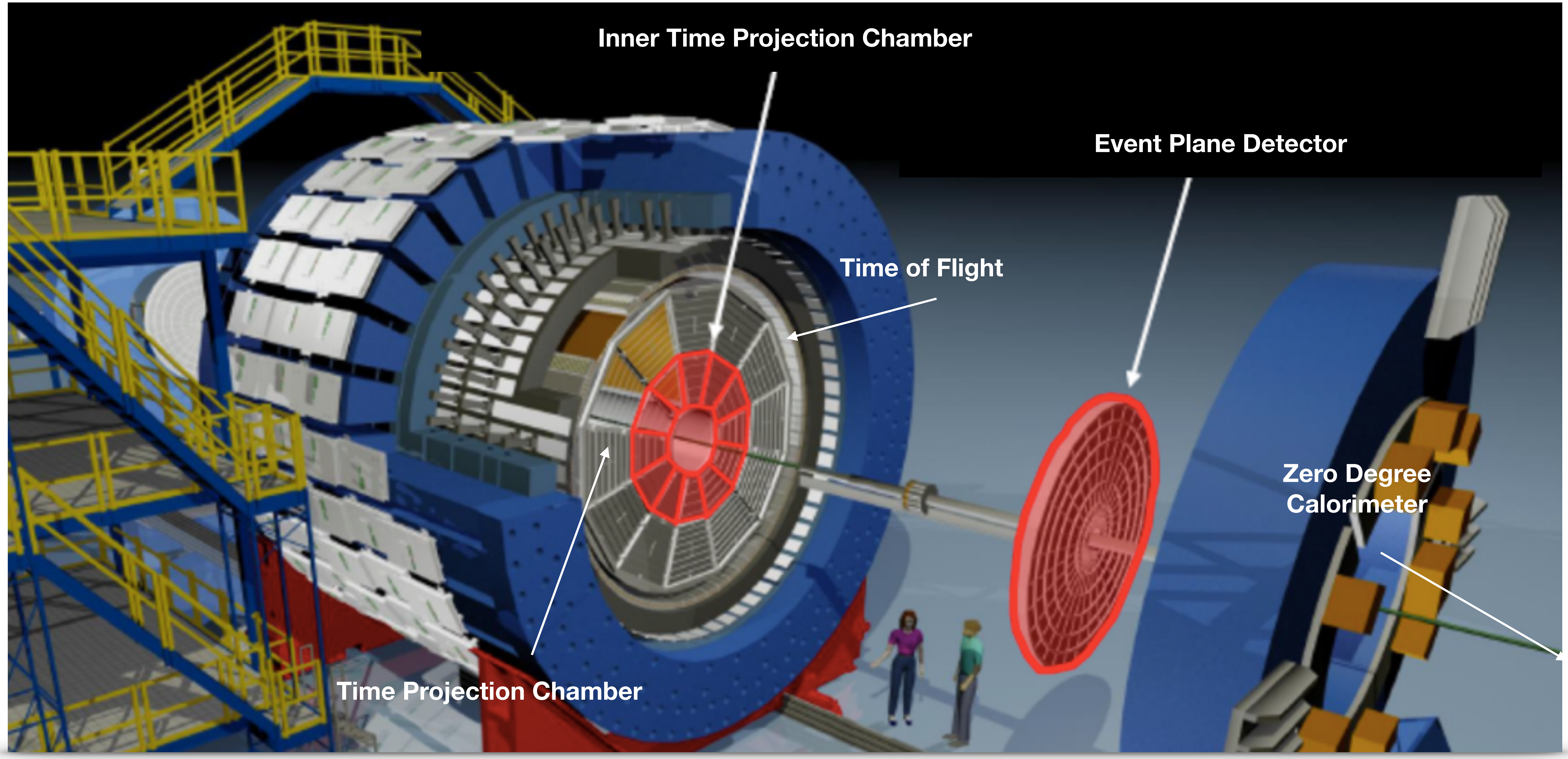


Collider: 7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27, 39, 54.4, 62.4, 200 (GeV)
Fixed Target: 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7, 9.2, 11.5, 13.7 (GeV)

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, BBC**: event plane
- **TPC+TOF**: particle identification

Particle yields

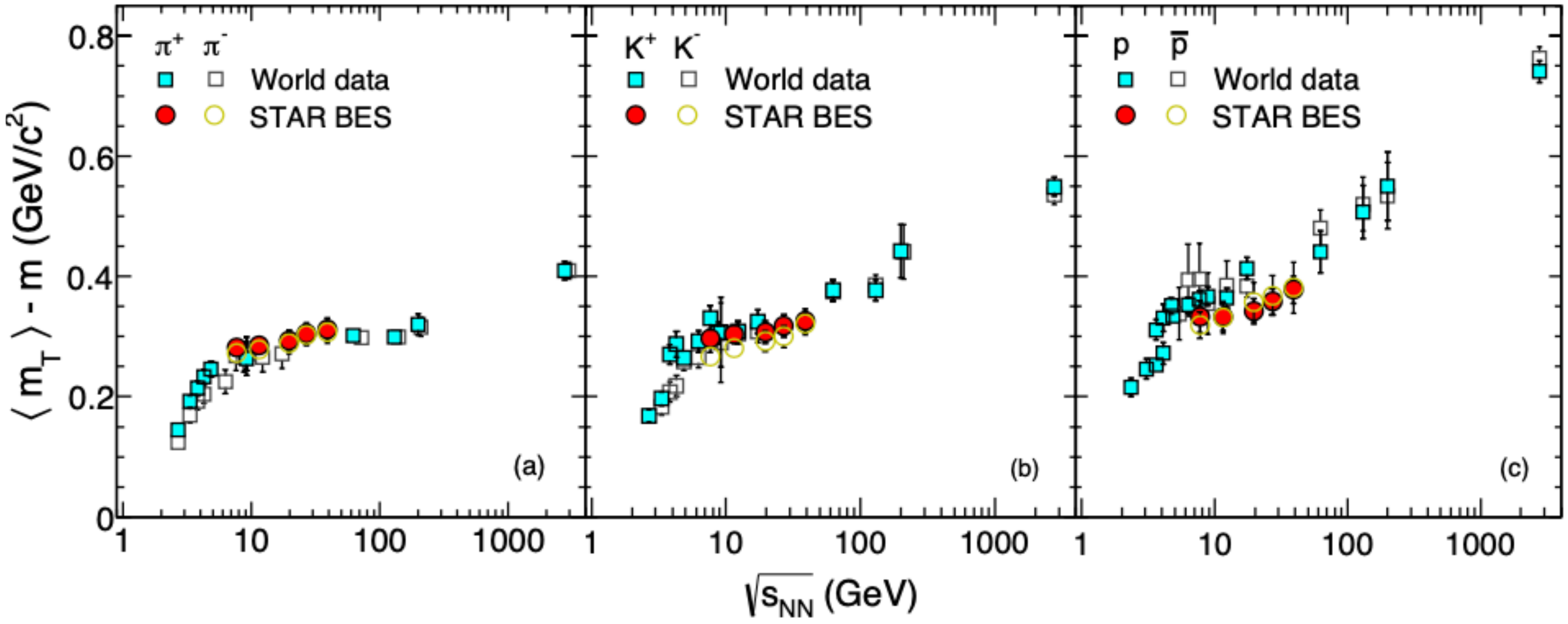
Yields and ratios at mid-rapidity

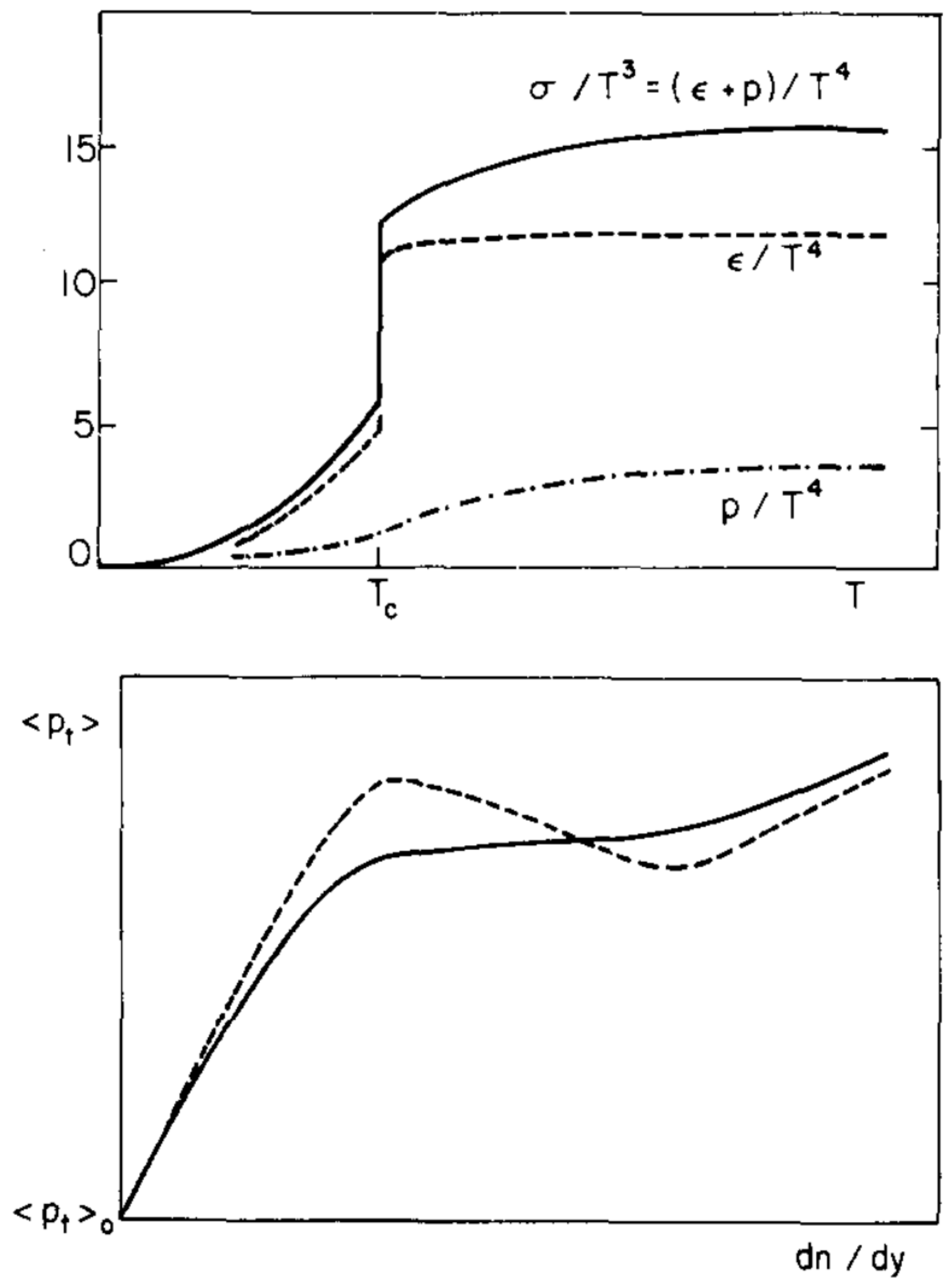
- $\pi^{\pm}$ linear increase with kink at ~ 19.6 GeV
- $K^{\pm}$: Interplay of associated production and pair production
- Increasing baryon stopping at low energy

- Peak in K^{+}/π^{+} ratio ~ 8 GeV at predicted maximum baryon density region

STAR: PRC 96, 044904 (2017); PRC 101, 024905 (2020);
PRC 102, 034909 (2020);

Mean-transverse mass





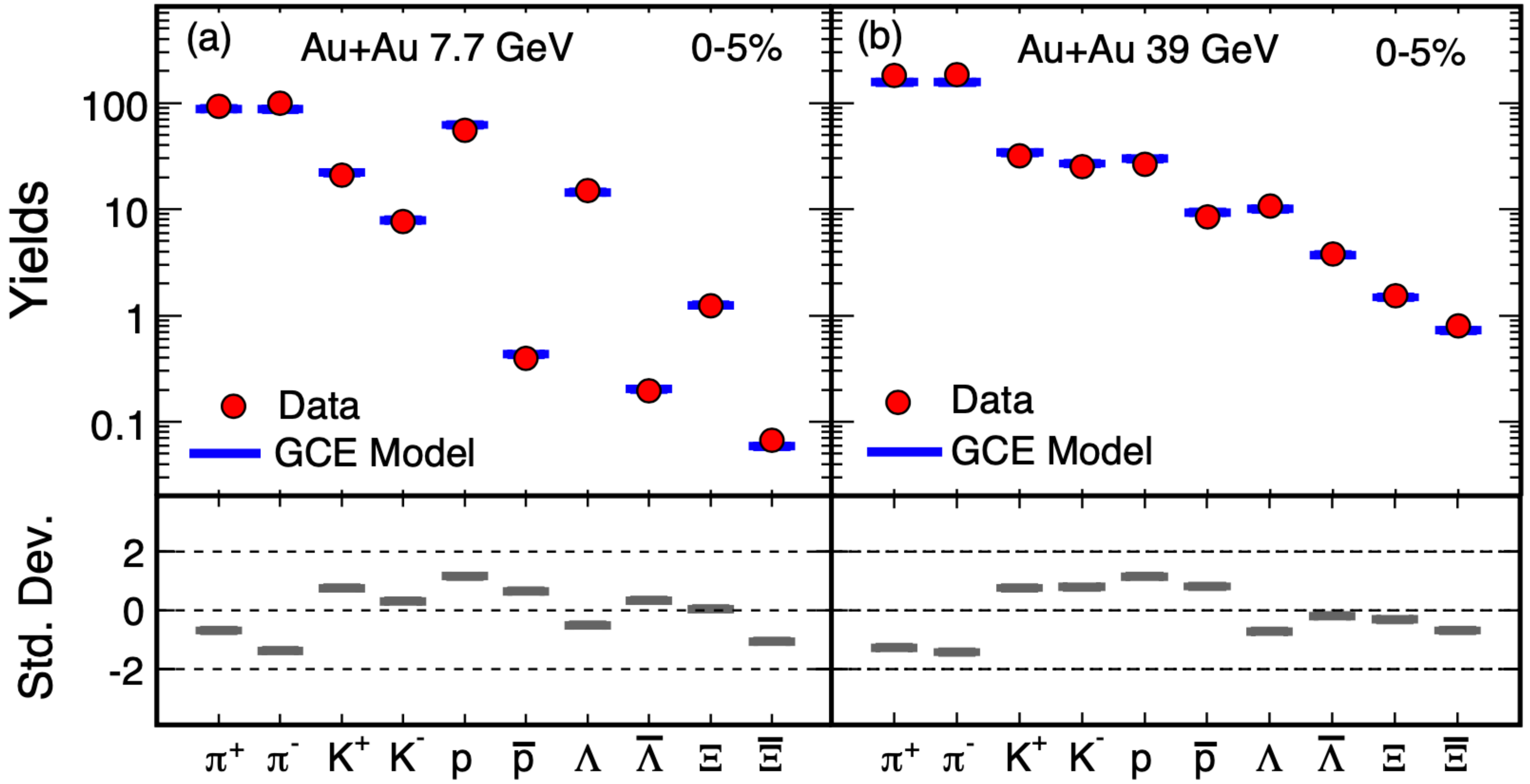
L. Van Hove, Phys. Lett. B 118, 138 (1982)

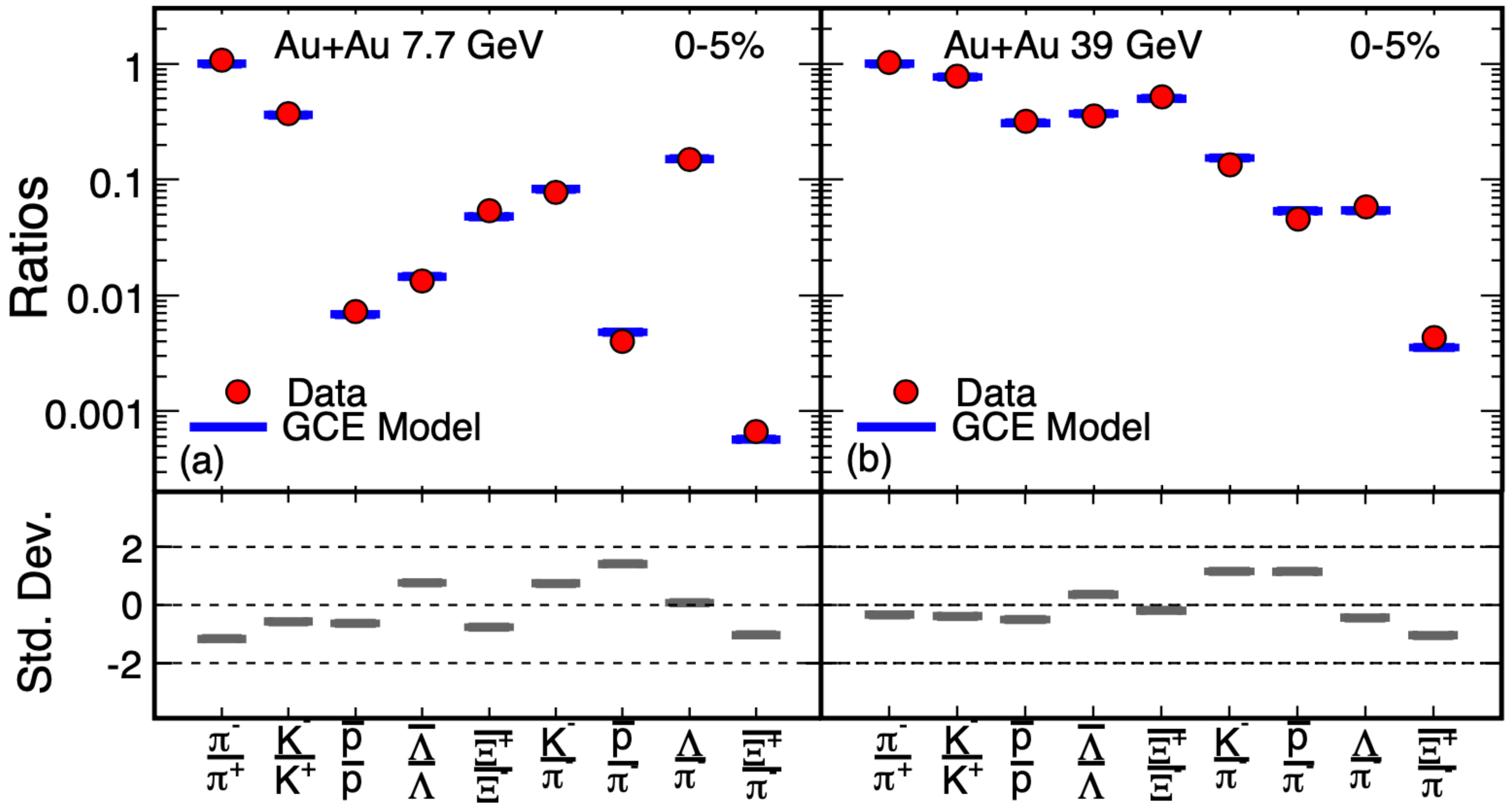
- Constant $(\langle m_T \rangle - m)$ around BES region (expected from 1st order Phase Transition) ?

  Van Hobe type signature

STAR: PRC 96, 044904 (2017); PRC 101, 024905 (2020);
PRC 102, 034909 (2020);

Freeze-out temperature



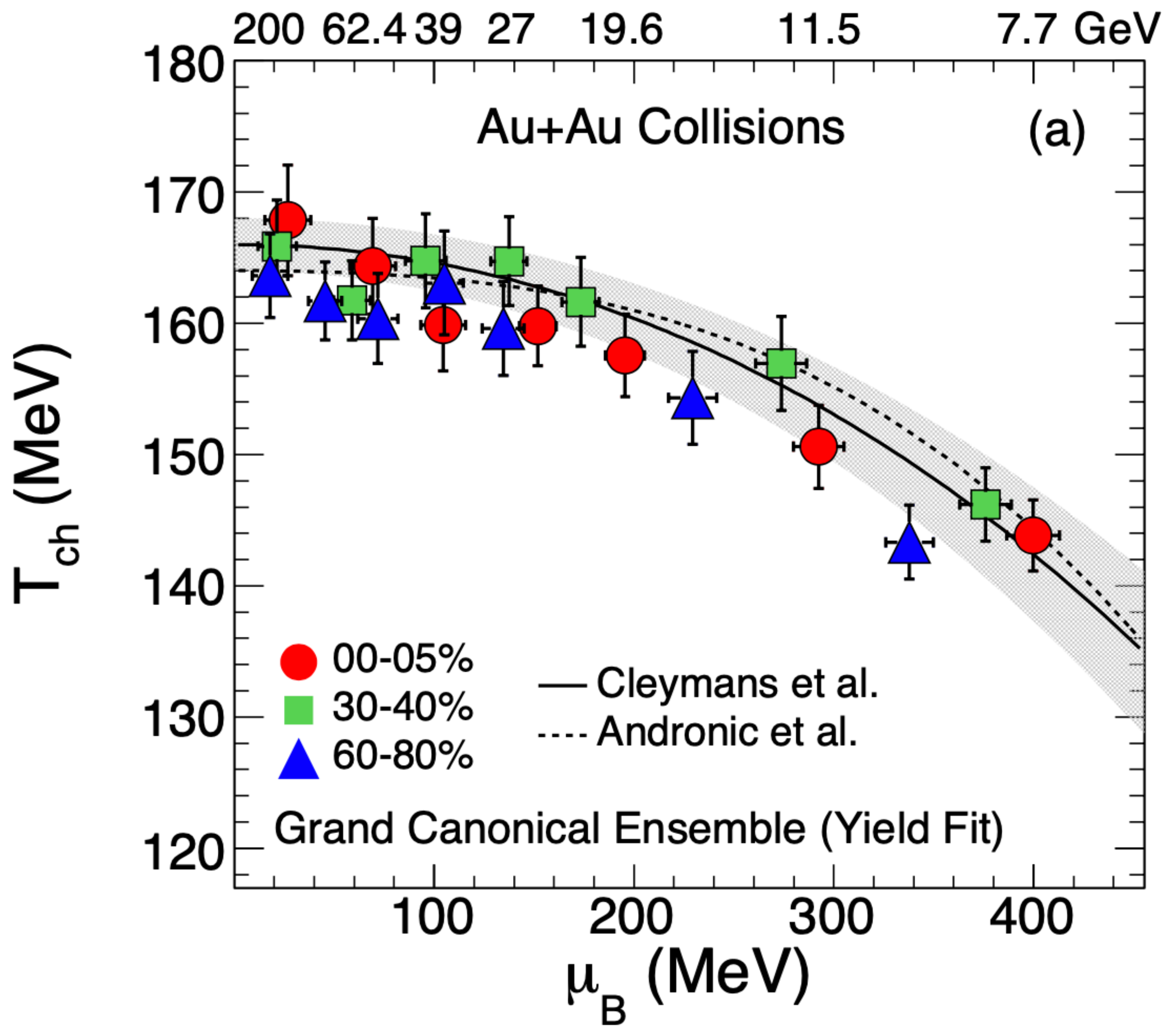


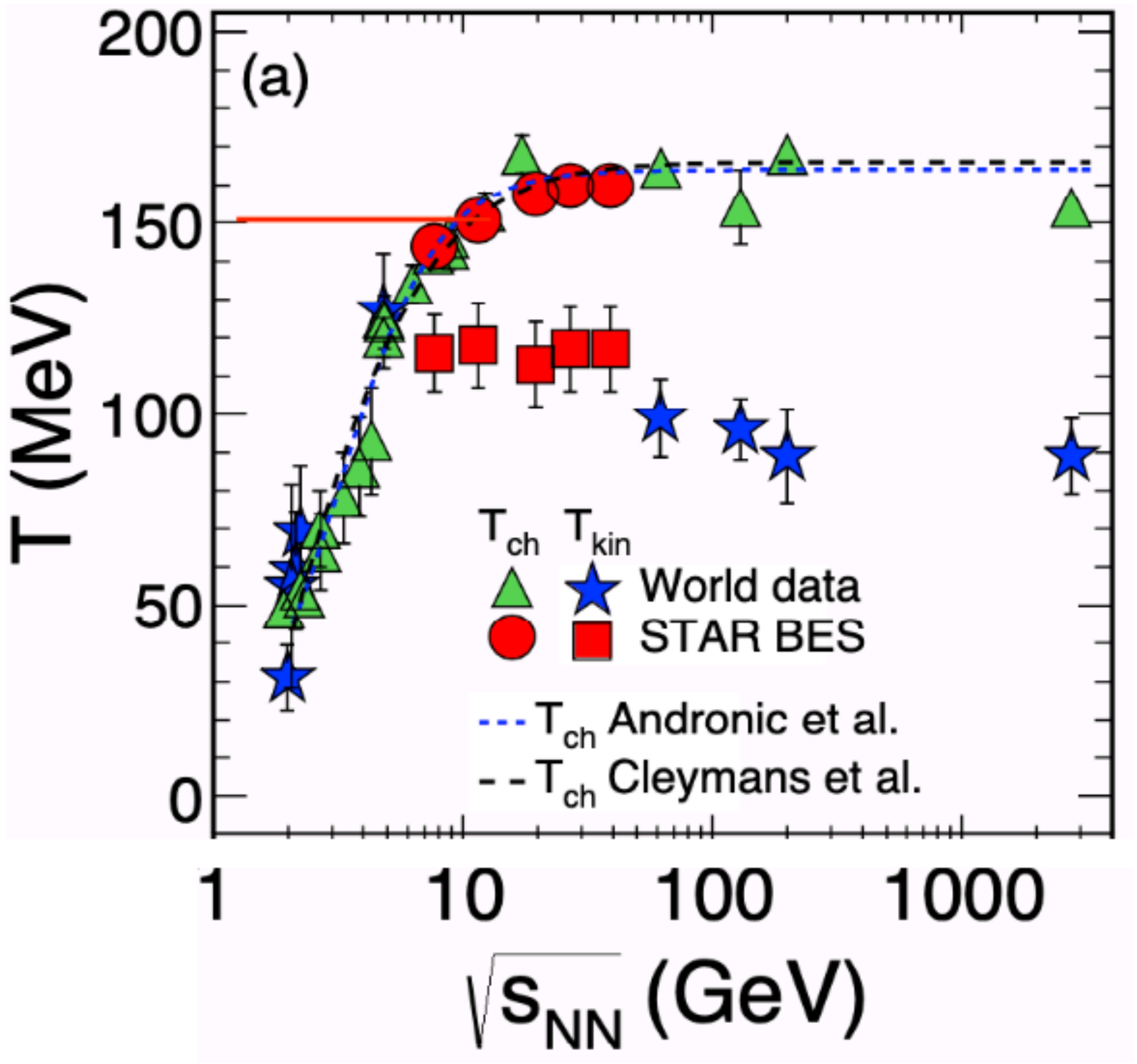
- Freeze-out temperatures and baryon chemical potential extracted from hadron yields via *THERMUS* model

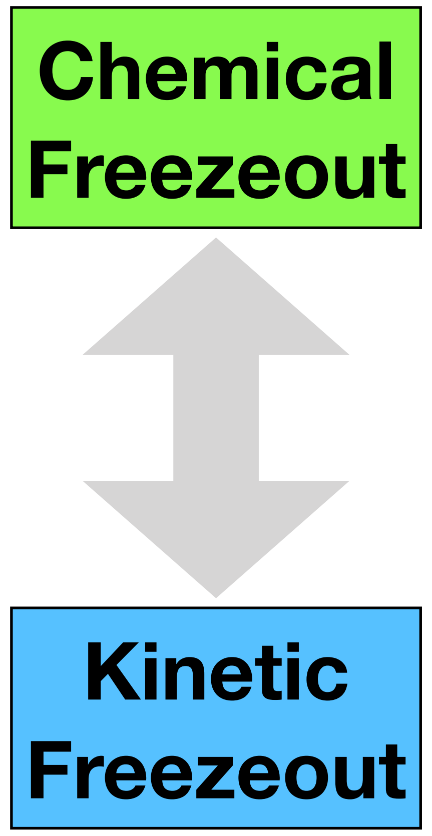
THERMUS: S. Wheaton et al, CPC 180, 84 (2009).

*** p are not corrected for weak-decay*

Chemical and kinetic freeze-out





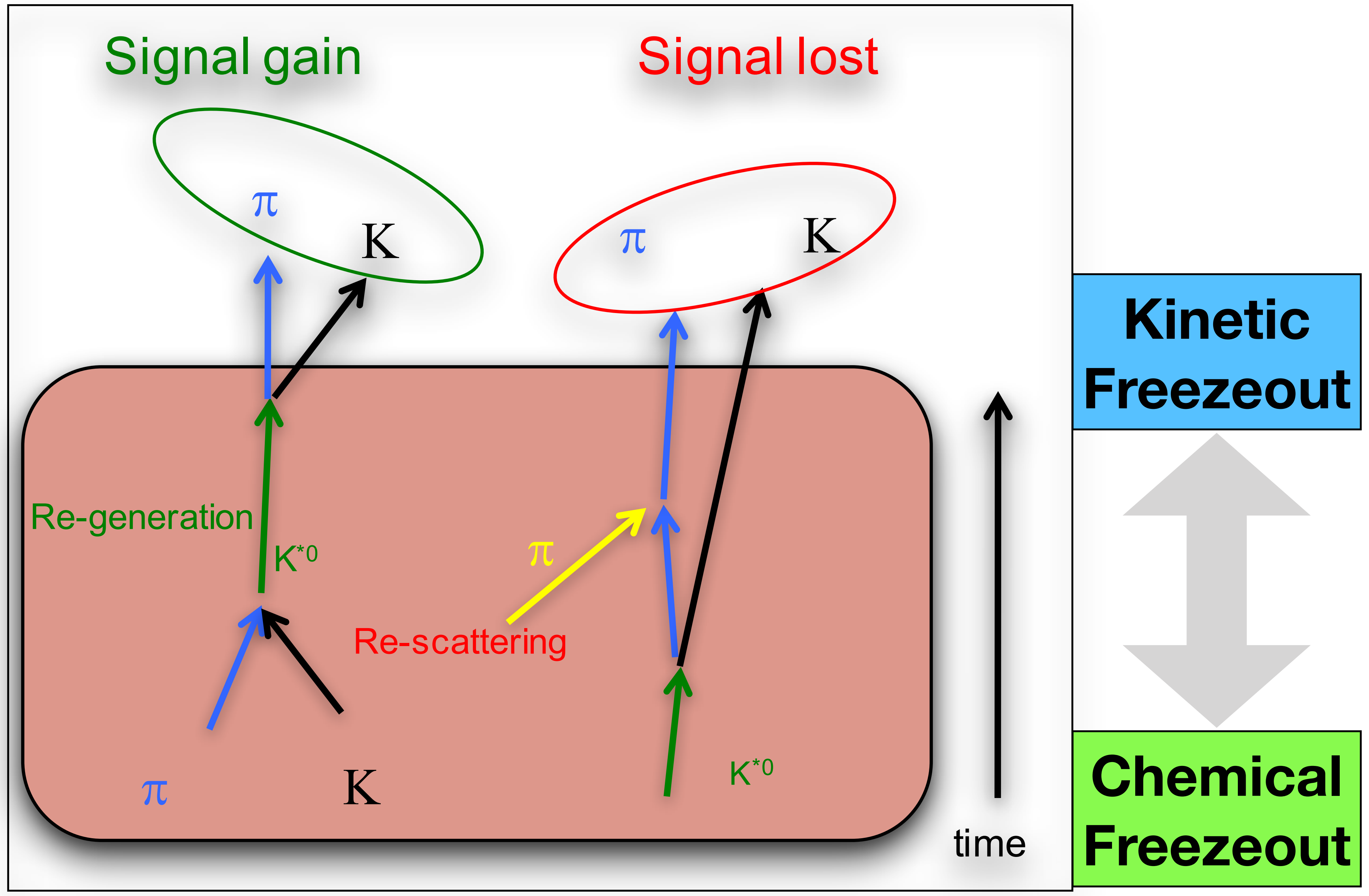


- Large baryon density with decreasing energy

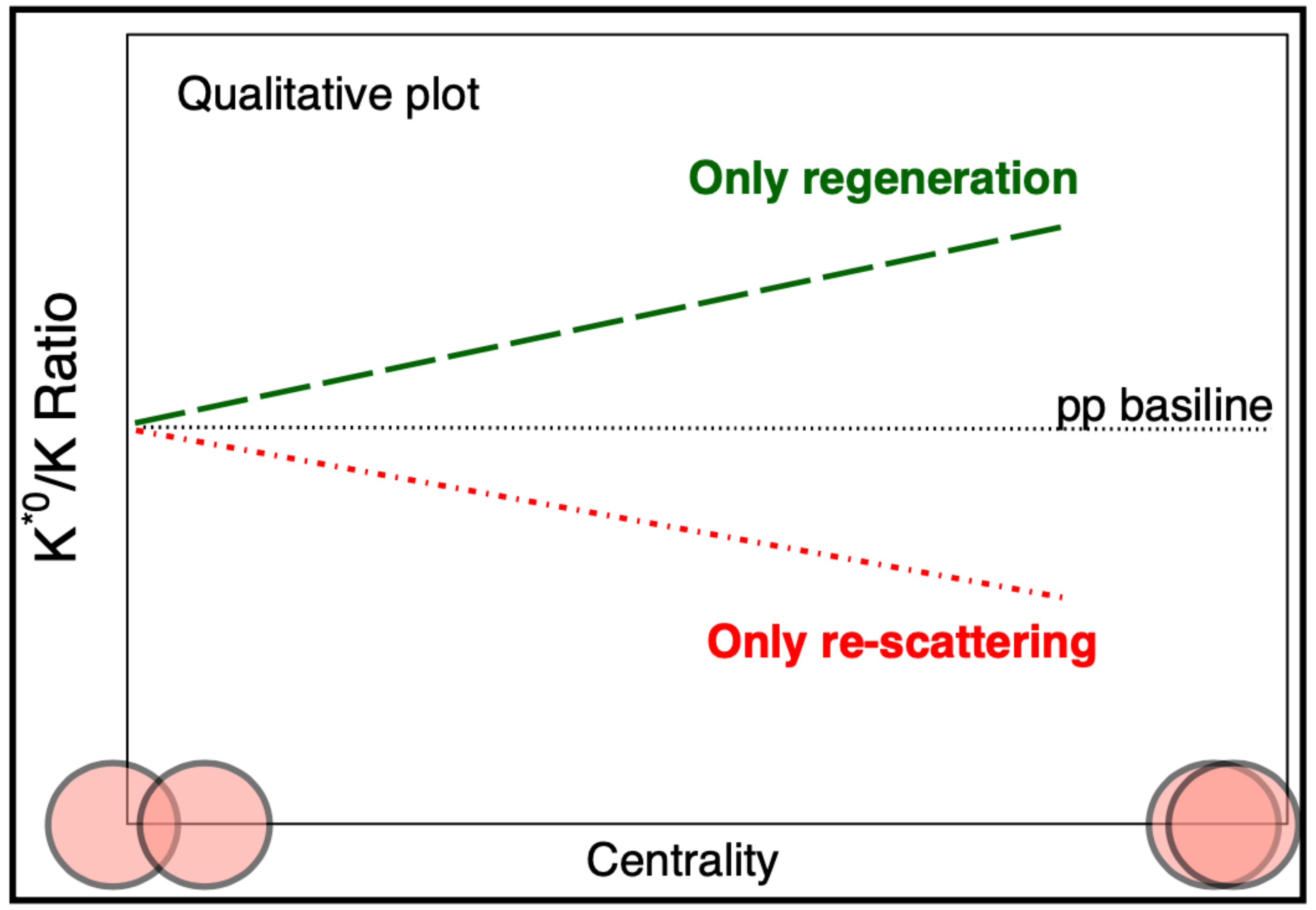
STAR: PRC 96, 044904 (2017); PRC 101, 024905 (2020);
PRC 102, 034909 (2020);

Resonance to non-resonance ratios

Re-scattering and regeneration:

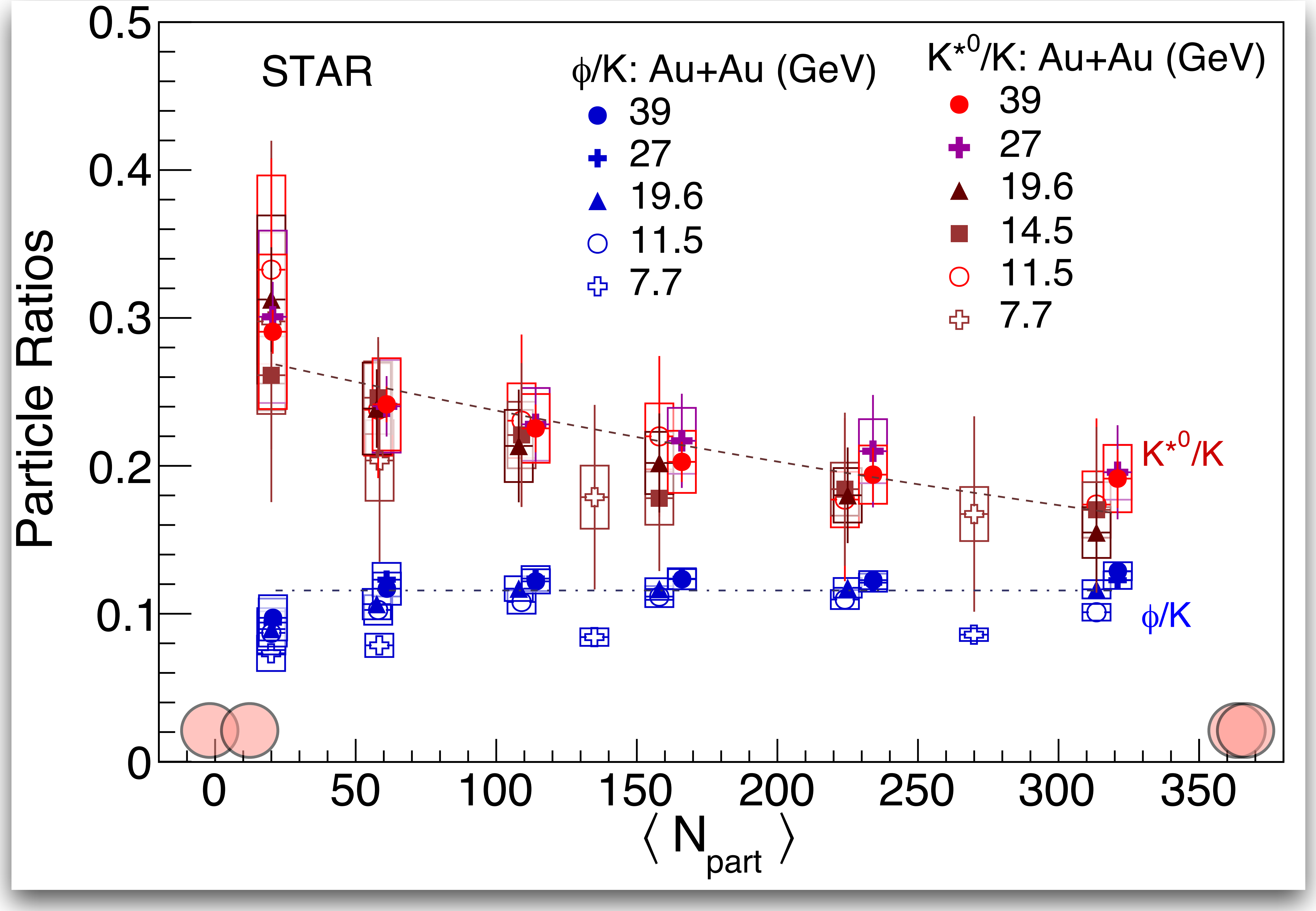


Naive Expectation:



• K*/K and ϕ/K

STAR: PRC 107, 34907 (2023)



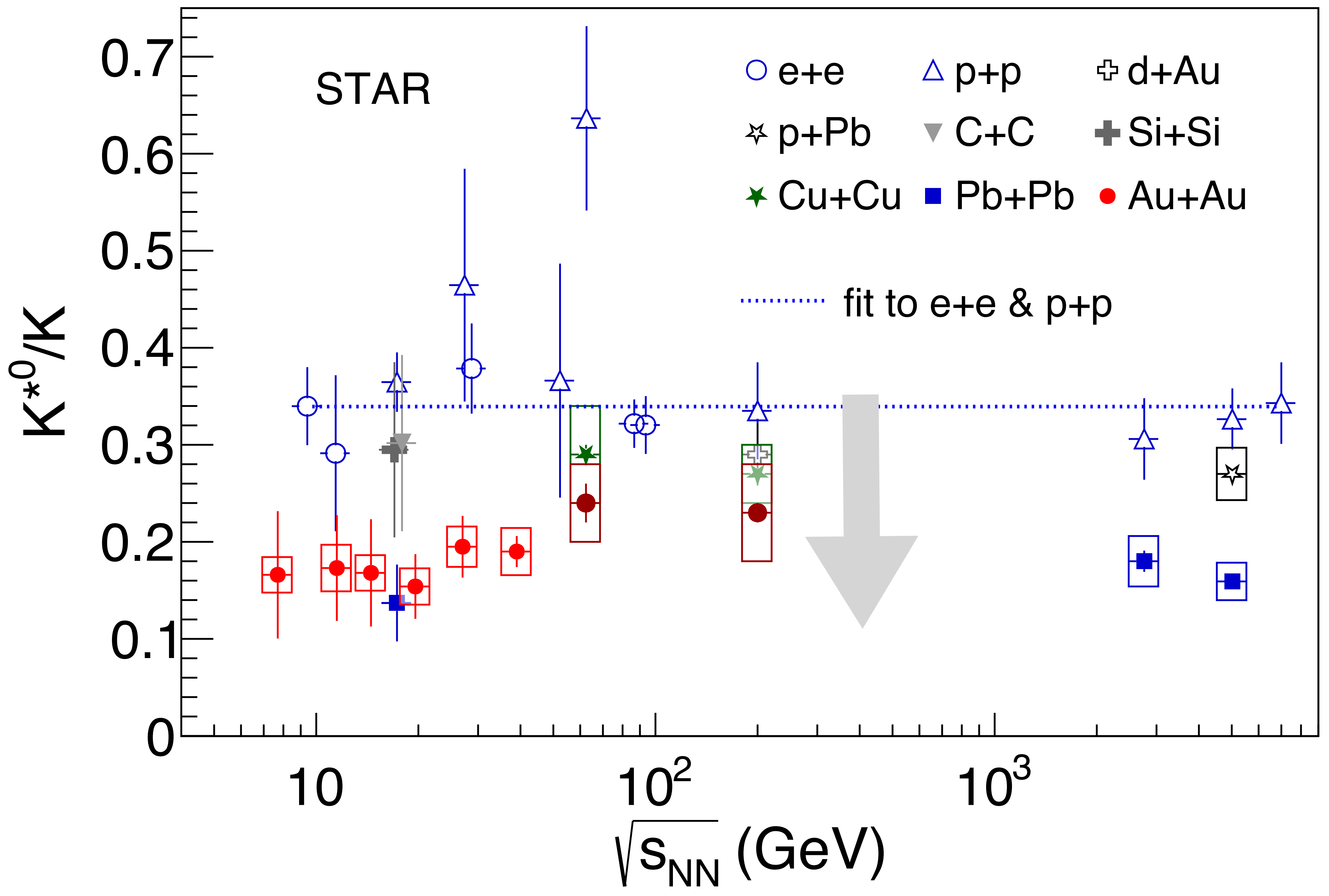
- $(K^*/K)_{central} < (K^*/K)_{peripheral}$
- (ϕ/K) ~ centrality independent

→ Dominance of re-scattering at RHIC

Hadronic phase lifetime

STAR: PRC 107, 34907 (2023)

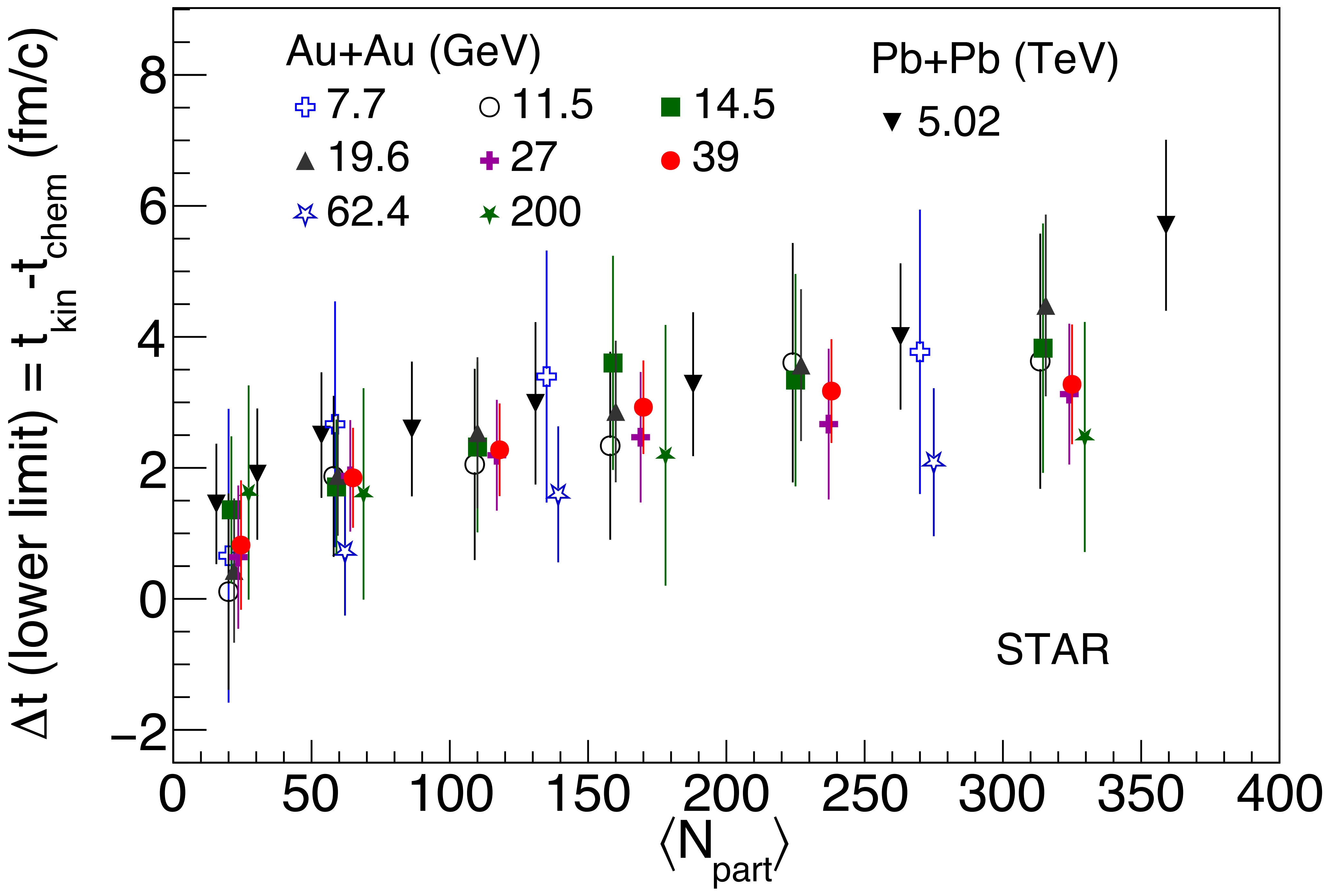
- K^*/K vs $\sqrt{s_{NN}}$



- $(K^*/K)_{A+A} < (K^*/K)_{p+p}$

Dominance of re-scattering

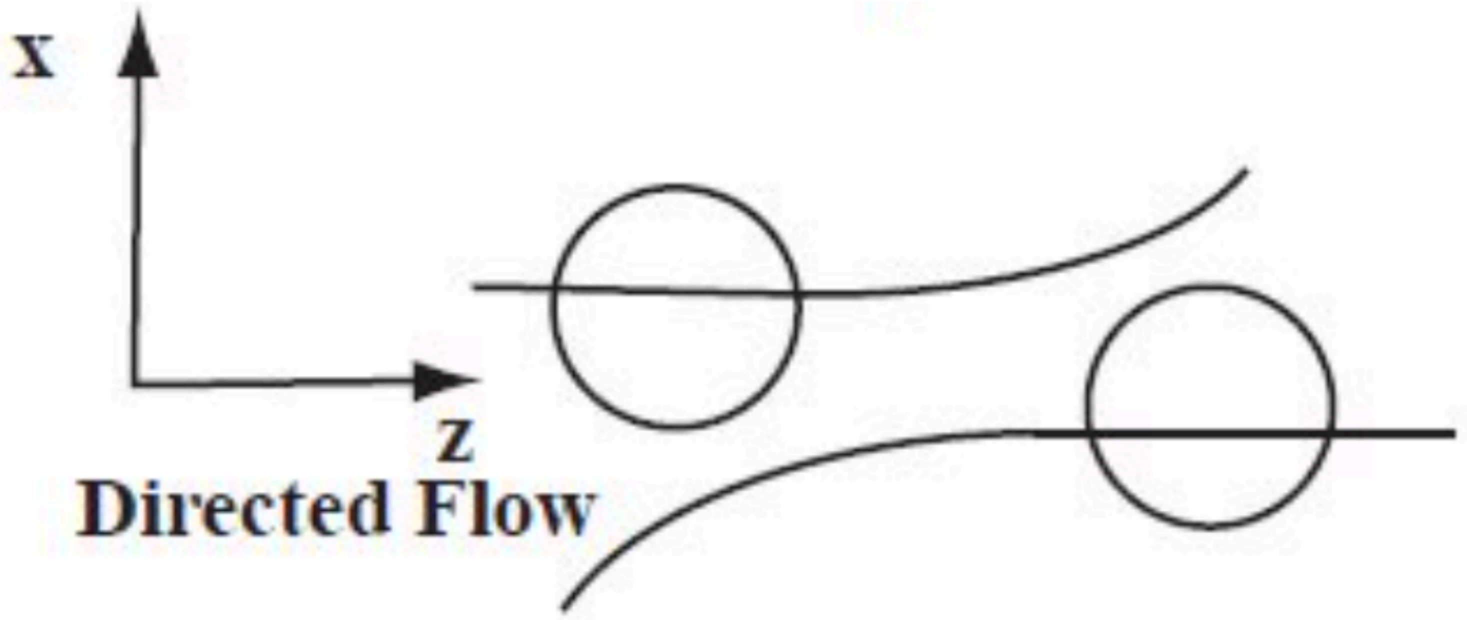
- Based on assumption: $\left(\frac{K^{*0}}{K}\right)_{KFO} = \left(\frac{K^{*0}}{K}\right)_{CFO} \times e^{-\Delta t/\tau_{K^{*0}}}$

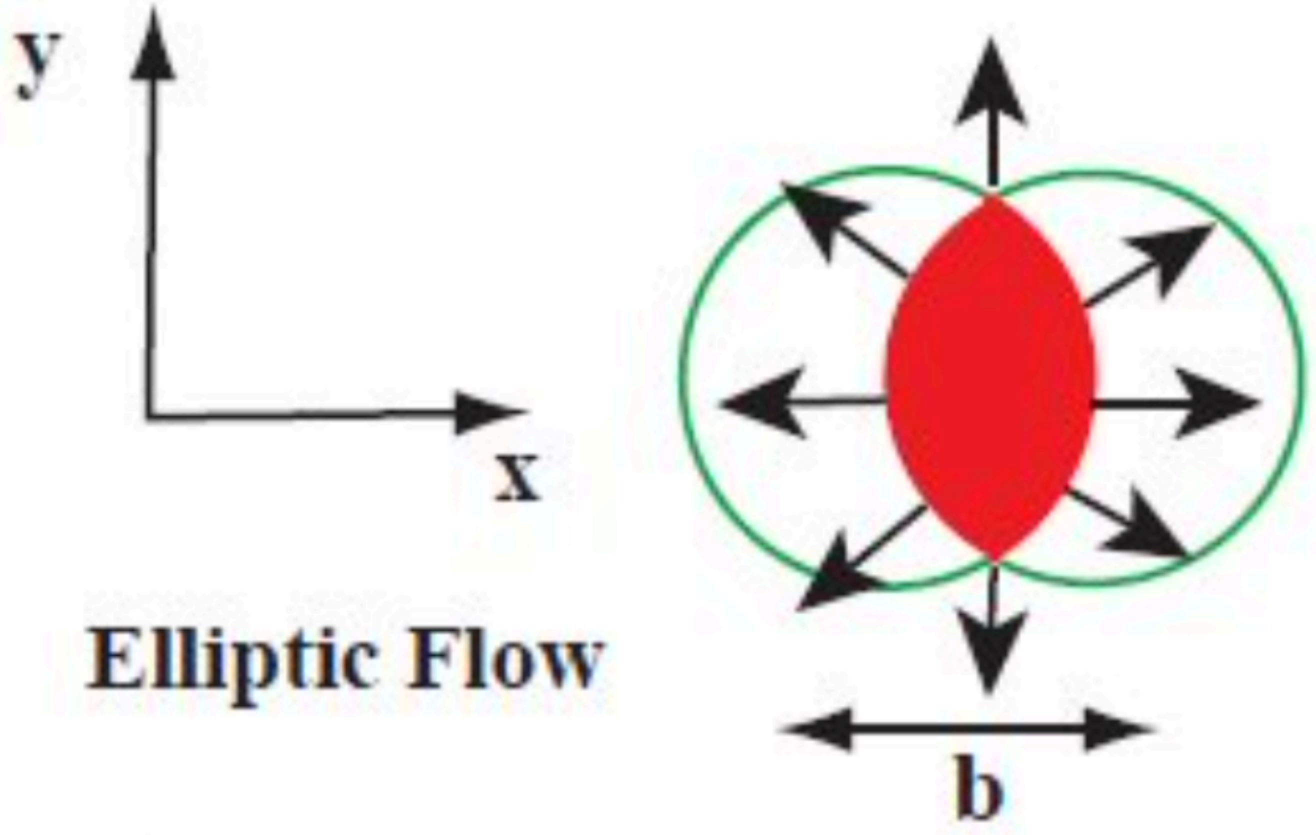


- Lower limit on hadronic phase lifetime

Collective flow

Collective flow





A. Poskanzer el. al. arXiv: 0809.2949

- Collective flow can be measured from the Fourier expansion

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

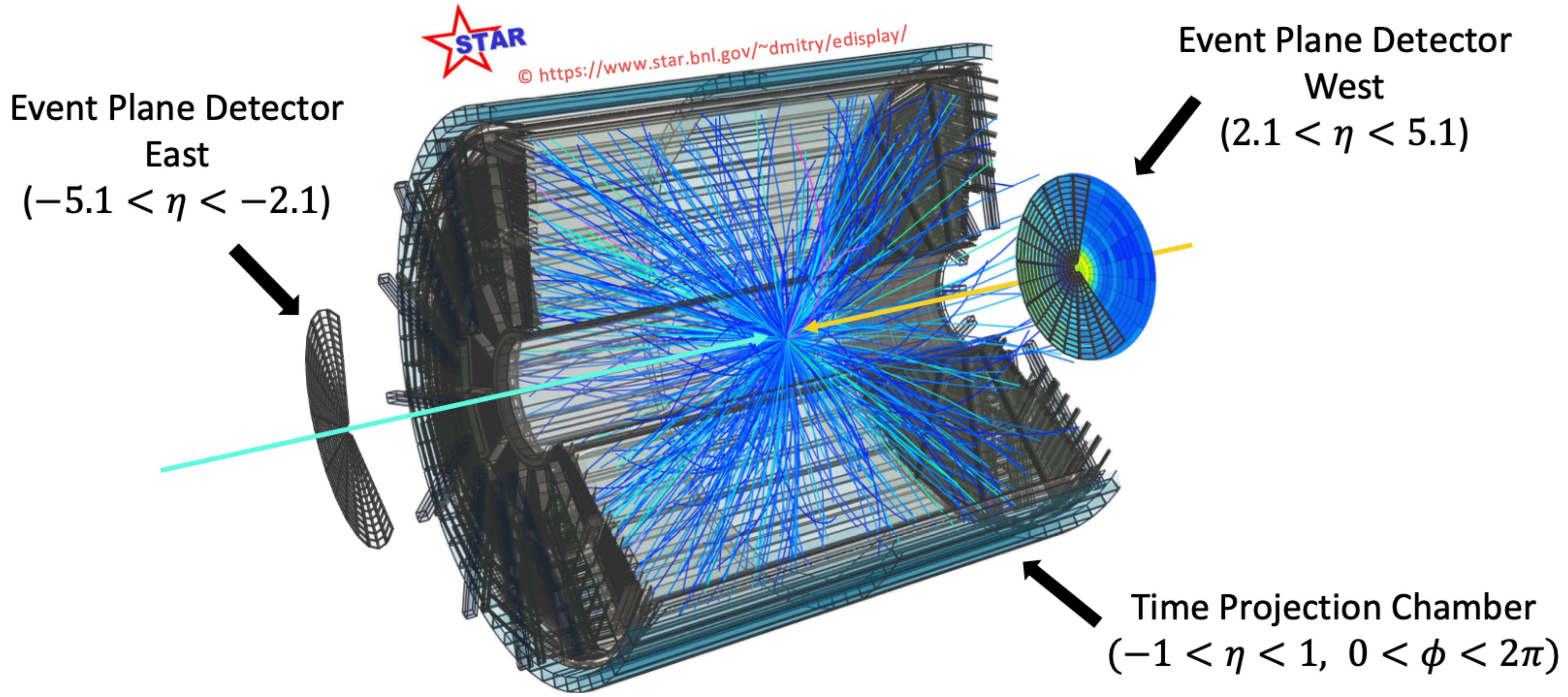
- v_1 : Directed flow
- v_2 : Elliptic flow
- v_3 : Triangular flow

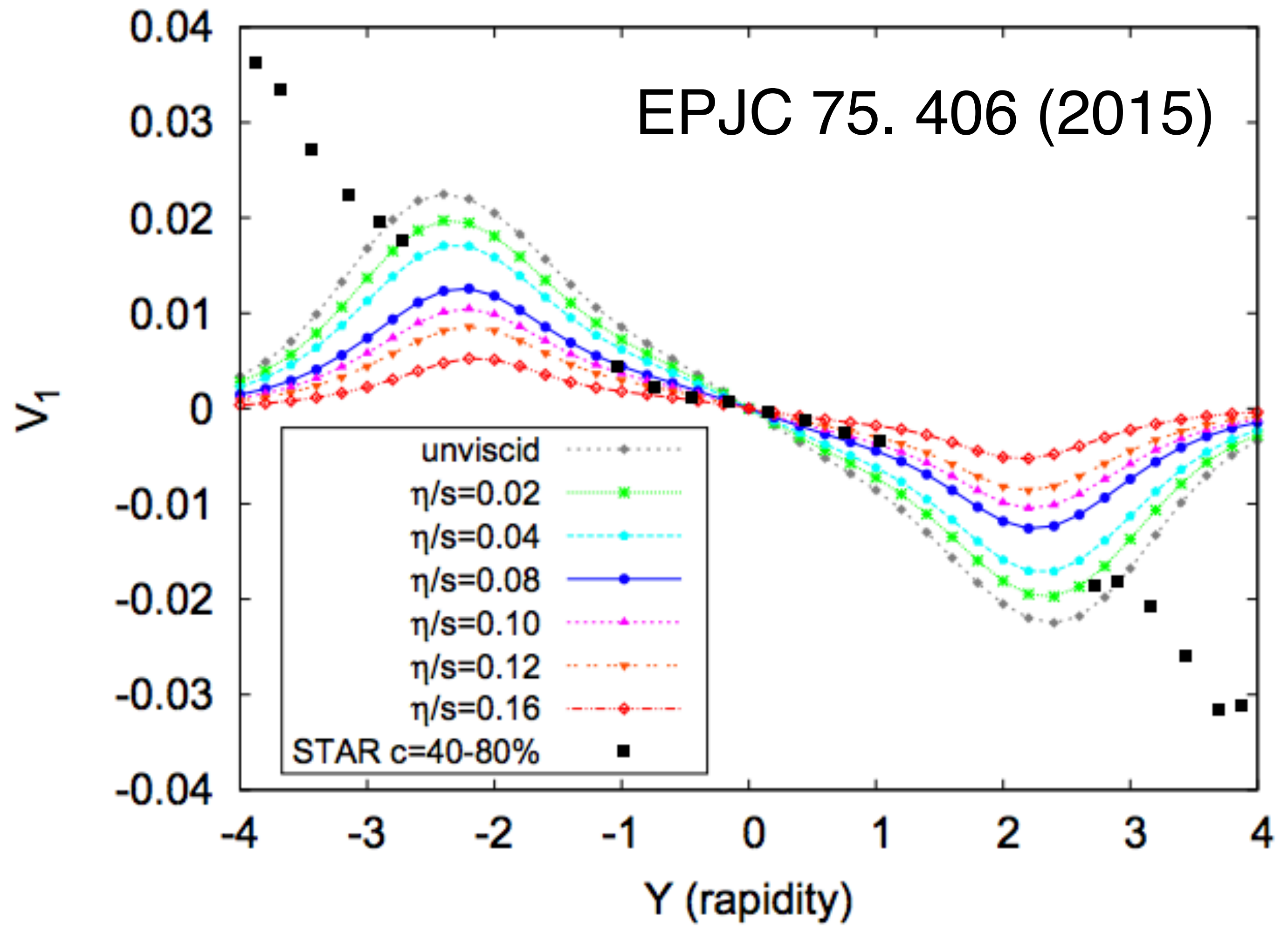
$$v_n = \langle \cos n(\phi - \Psi_n^{EP}) \rangle / \Psi_{Resolution}$$

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

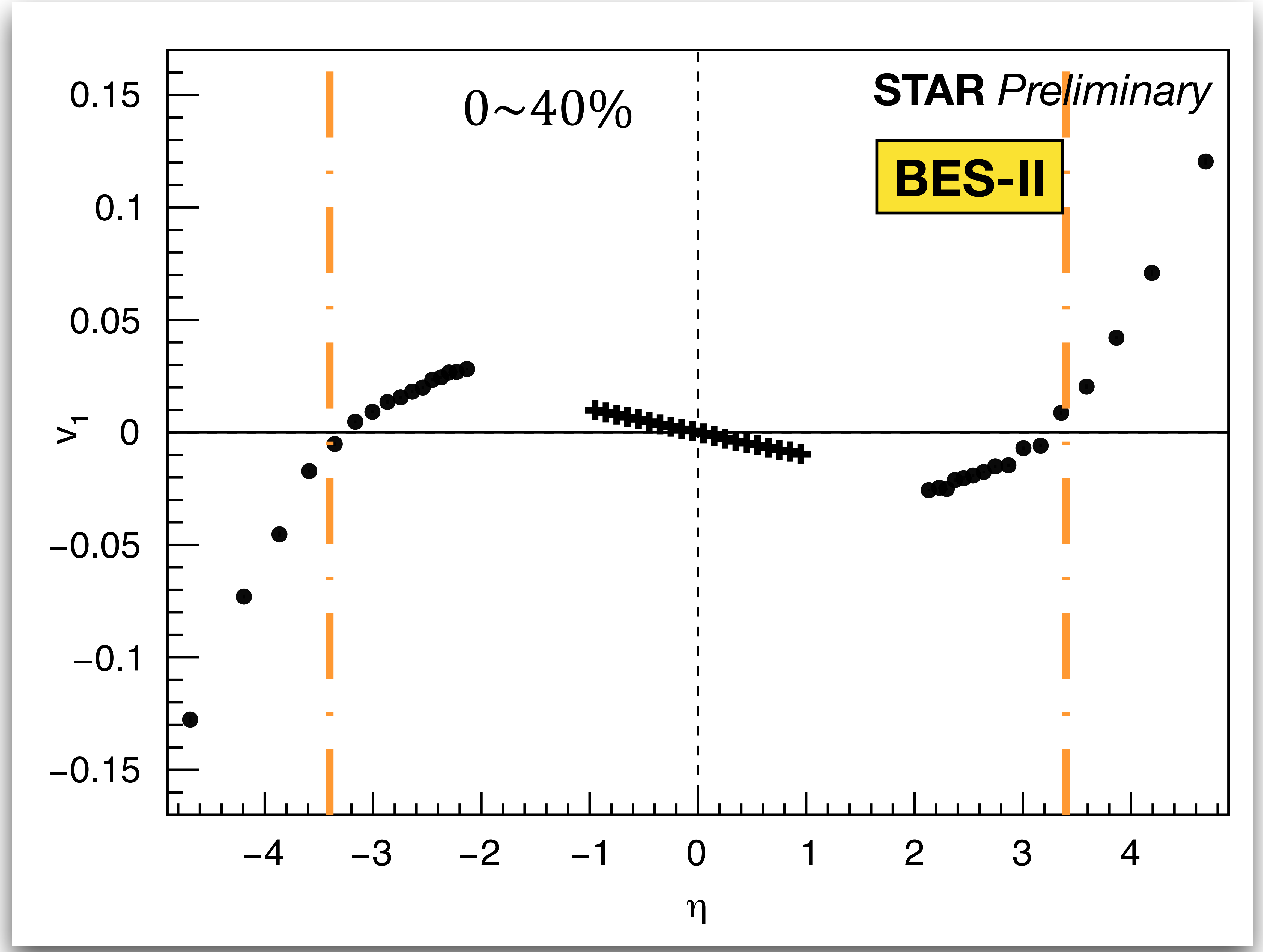
Directed flow of charged hadrons

See Talk
Xiaoyu Liu (STAR)



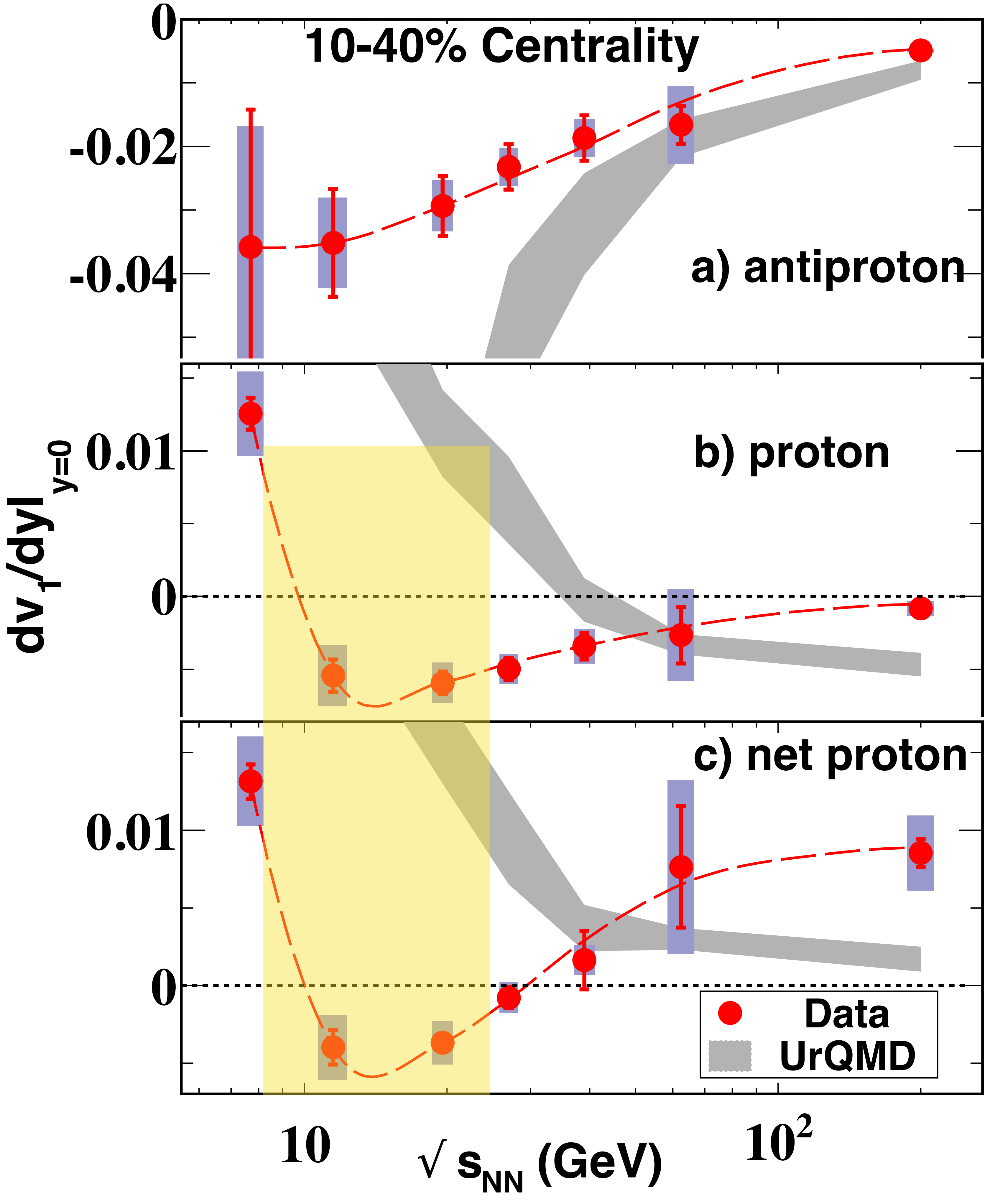


- v_1 (η) sensitive to the shear viscosity to entropy (η/s) ratio

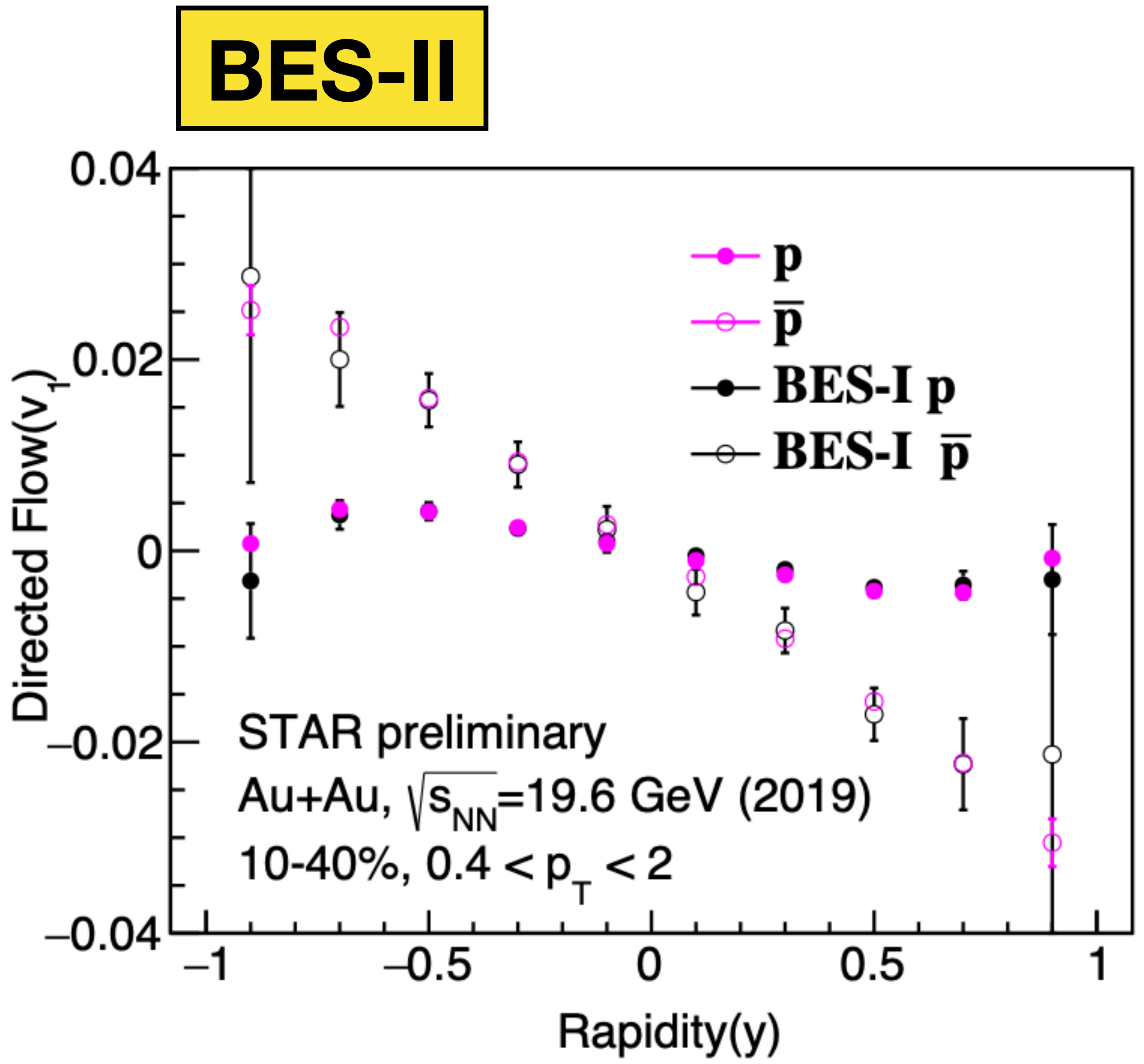


- With EPD, v_1 is measured within ~ 10 units in η

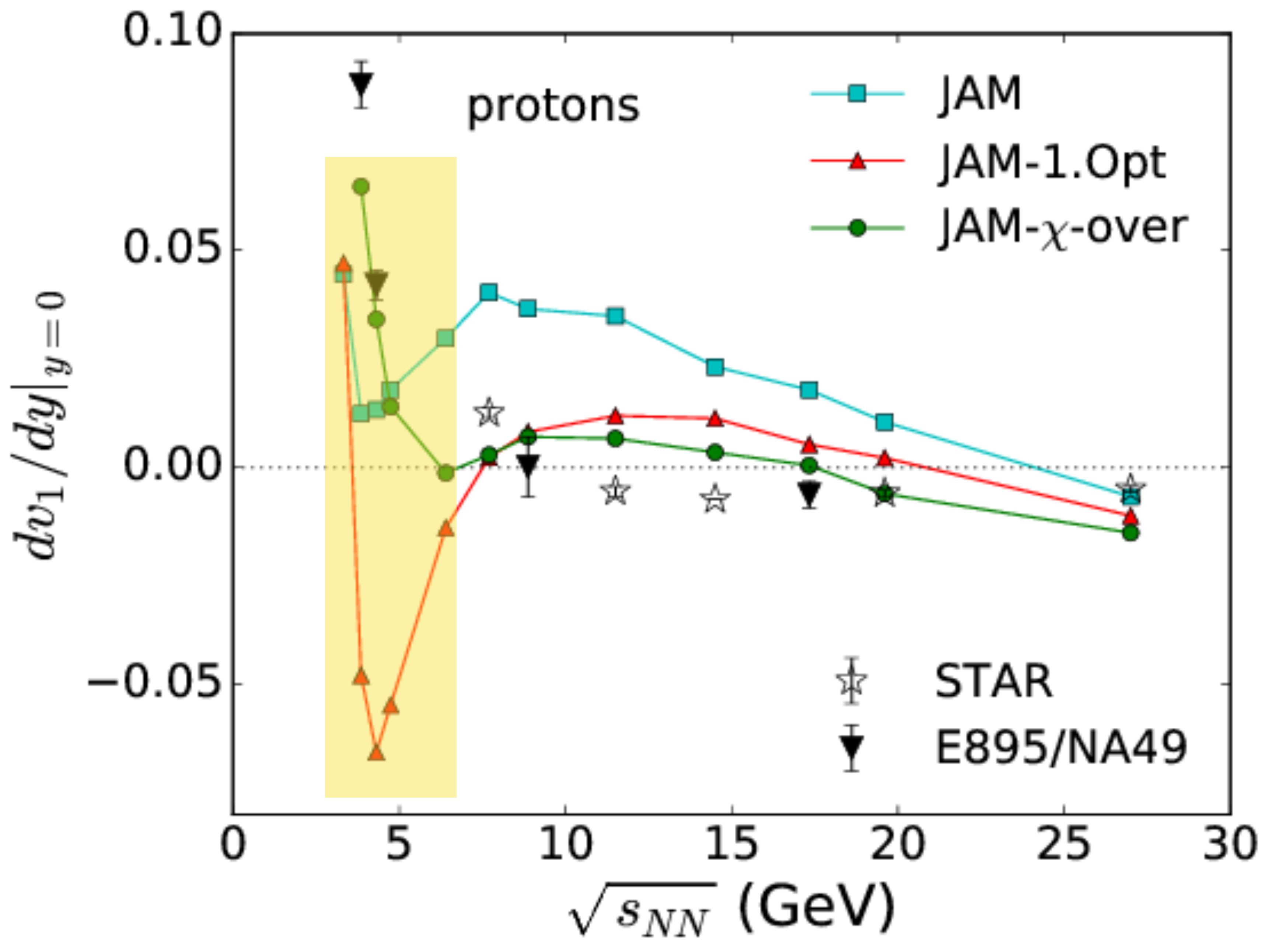
Directed flow of (net) protons



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



JAM: Y. Nara et al, PLB769, 543 (2017)



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

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

Test of quark coalescence sum rule using v_1

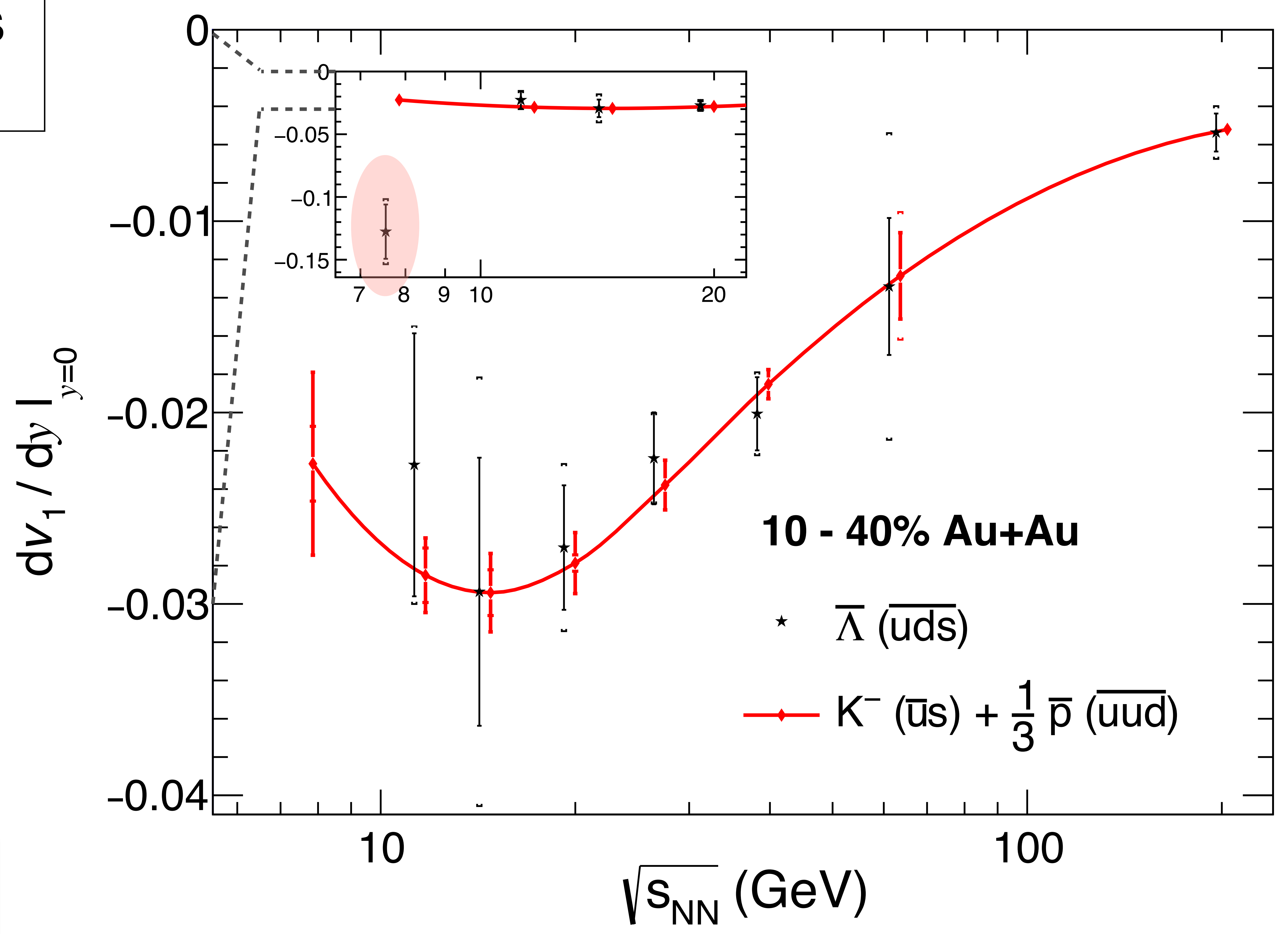
Test the assumption that the de-confined quarks acquired v_n, then they form hadrons:

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

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

Particle	Quark content
anti-Λ	uds
anti-p	uud
K-	us

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

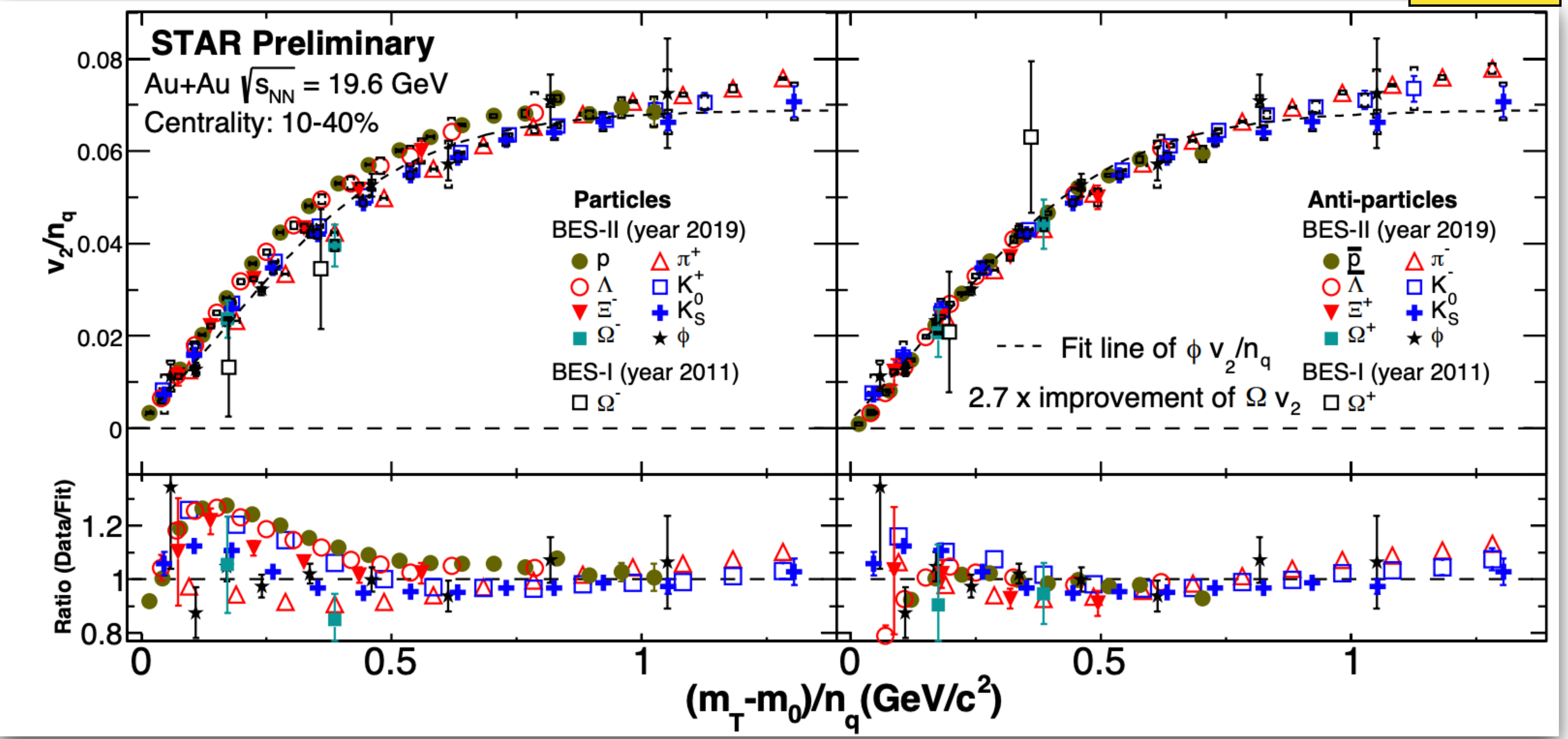


Indication of *partonic* collectivity

Subhash Singha @ ATHIC 2023

Number of Constituent Quark (NCQ) scaling of v_2

BES-II



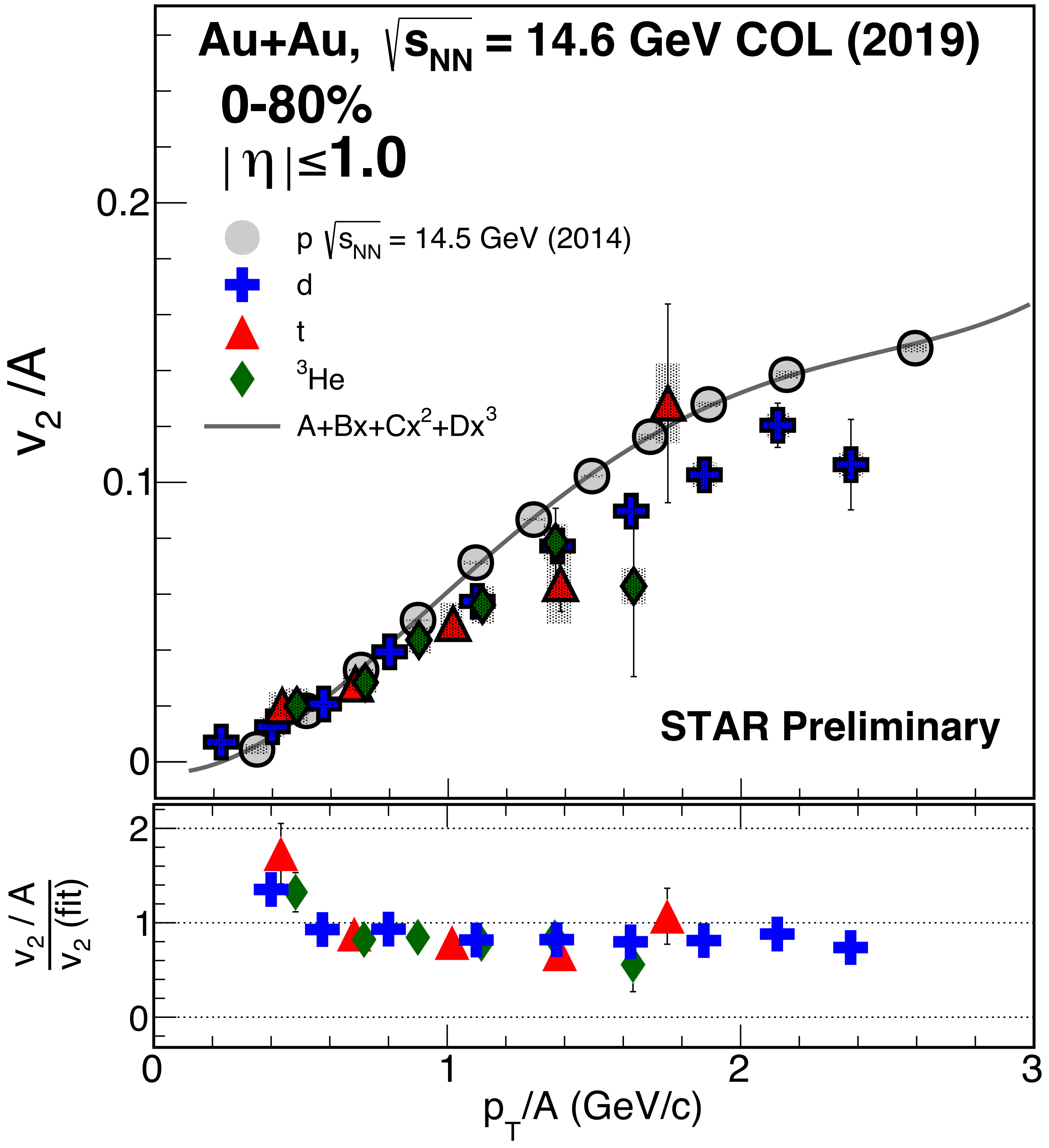
$$v_2^h(p_T) = nv_2^q(\frac{p_T}{n})$$

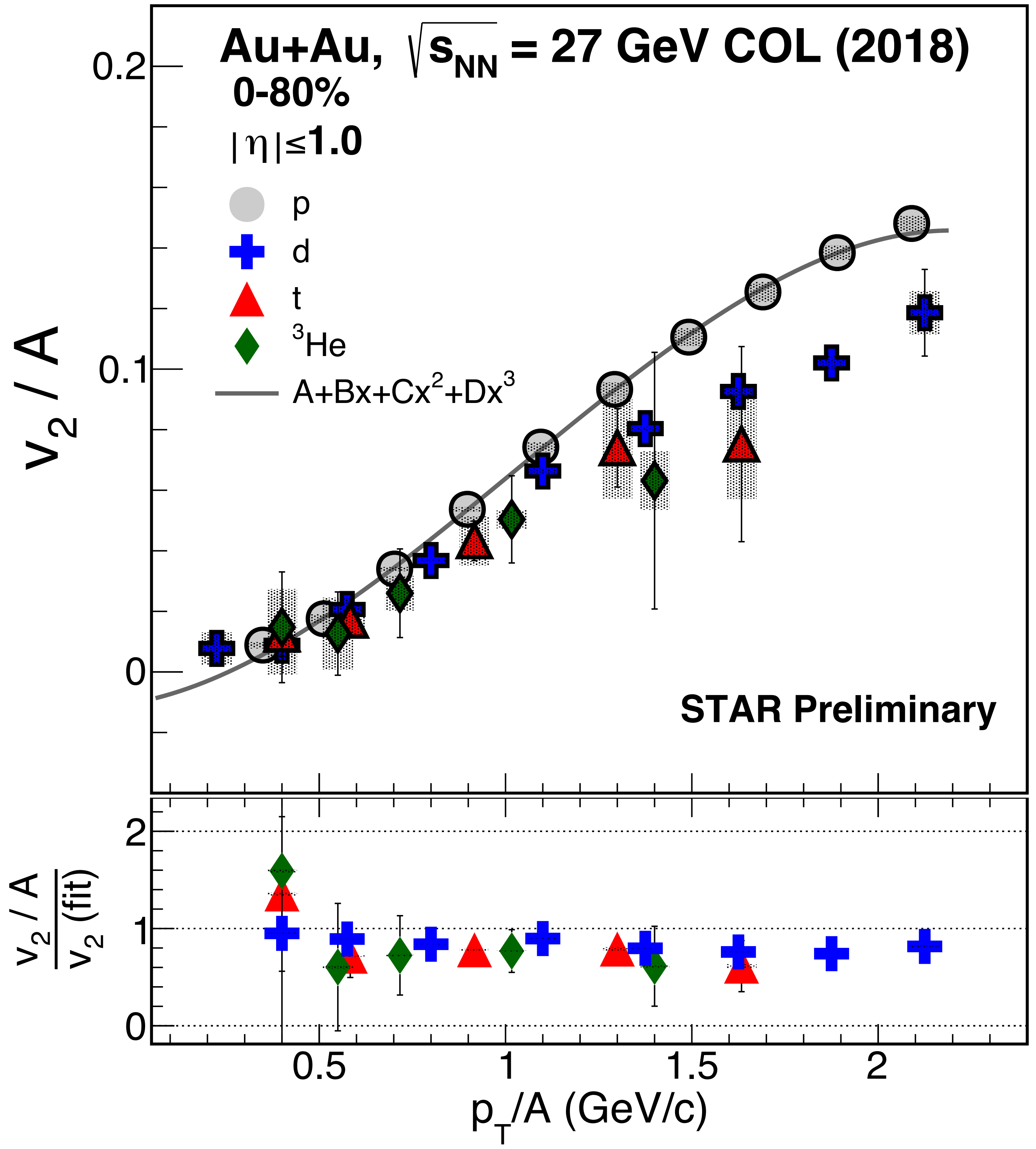
- **NCQ scaling** of v_2 holds ~ 20% for particles; ~ 15% for anti-particles
- ϕ mesons follow an approximate NCQ scaling

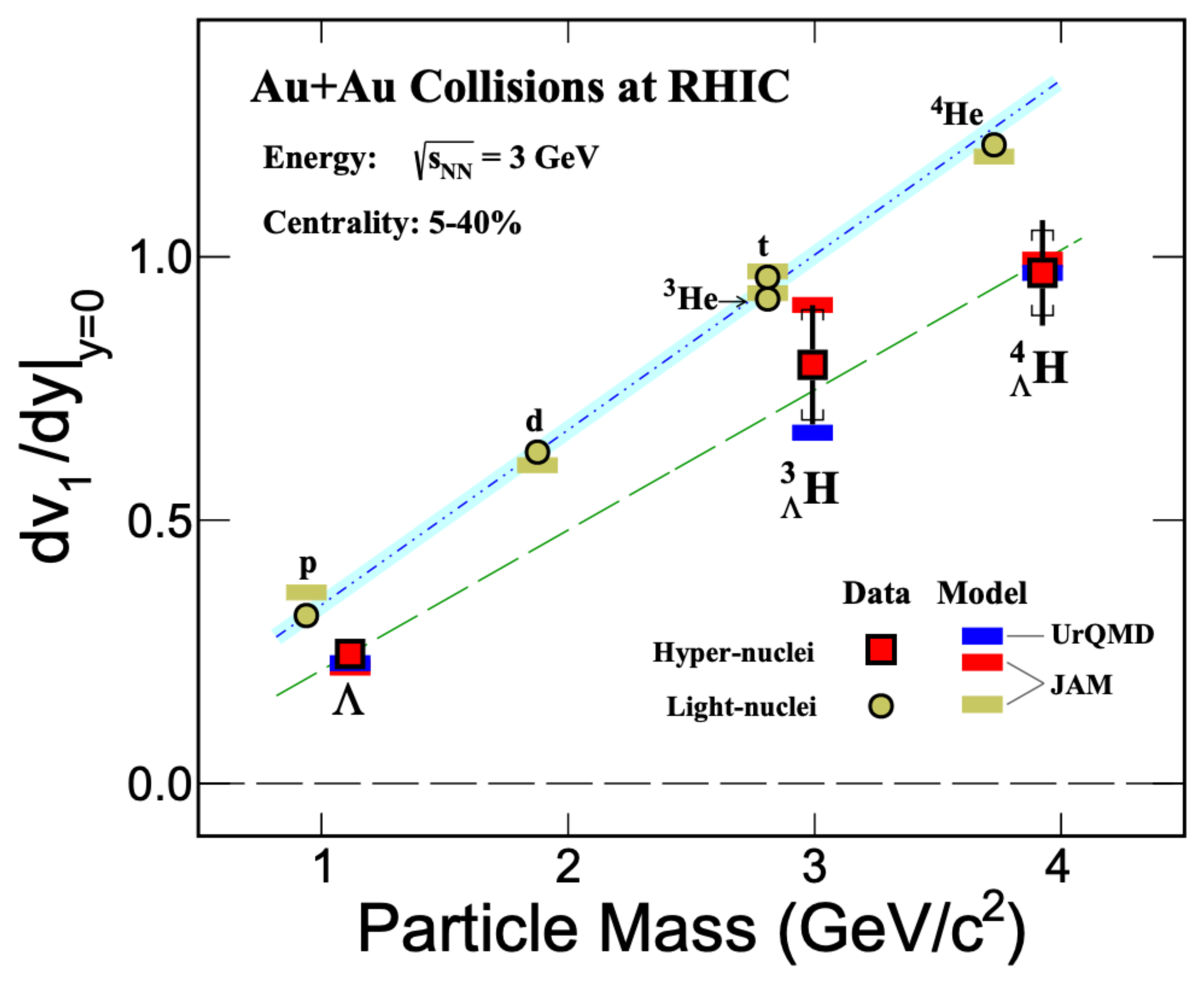
Indication of *partonic* collectivity

Flow of light and hyper-nuclei

BES-II





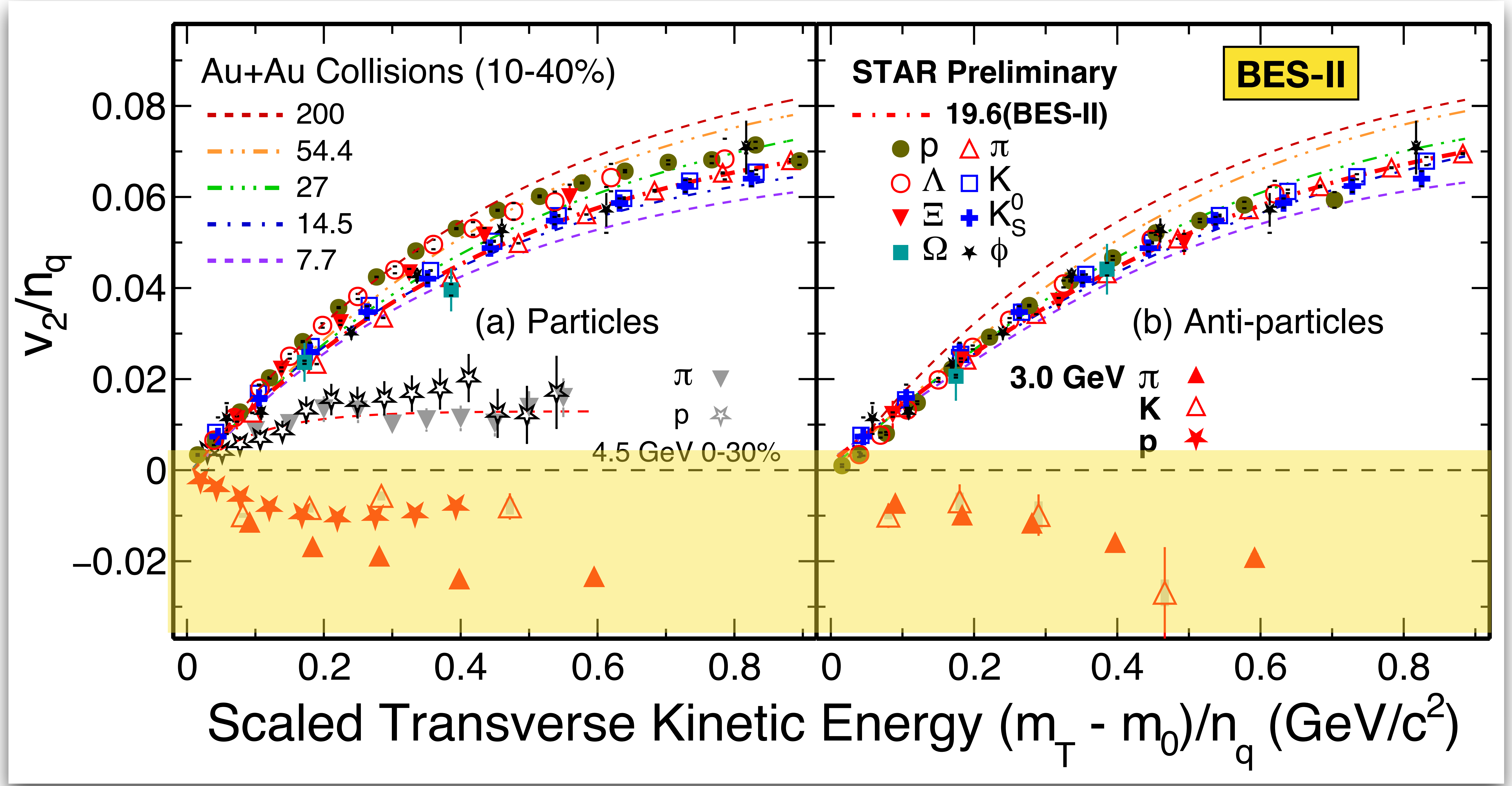


STAR: 2211.16981, Accepted in PRL

- Light nuclei v_2 obey mass number scaling at ~ 30% level
- Hyper-nuclei $^3_\Lambda H$ and $^4_\Lambda H$ v_1 follow mass number scaling

Role of *coalescence mechanism* in light (hyper) nuclei formation

Breaking of NCQ scaling of v_2

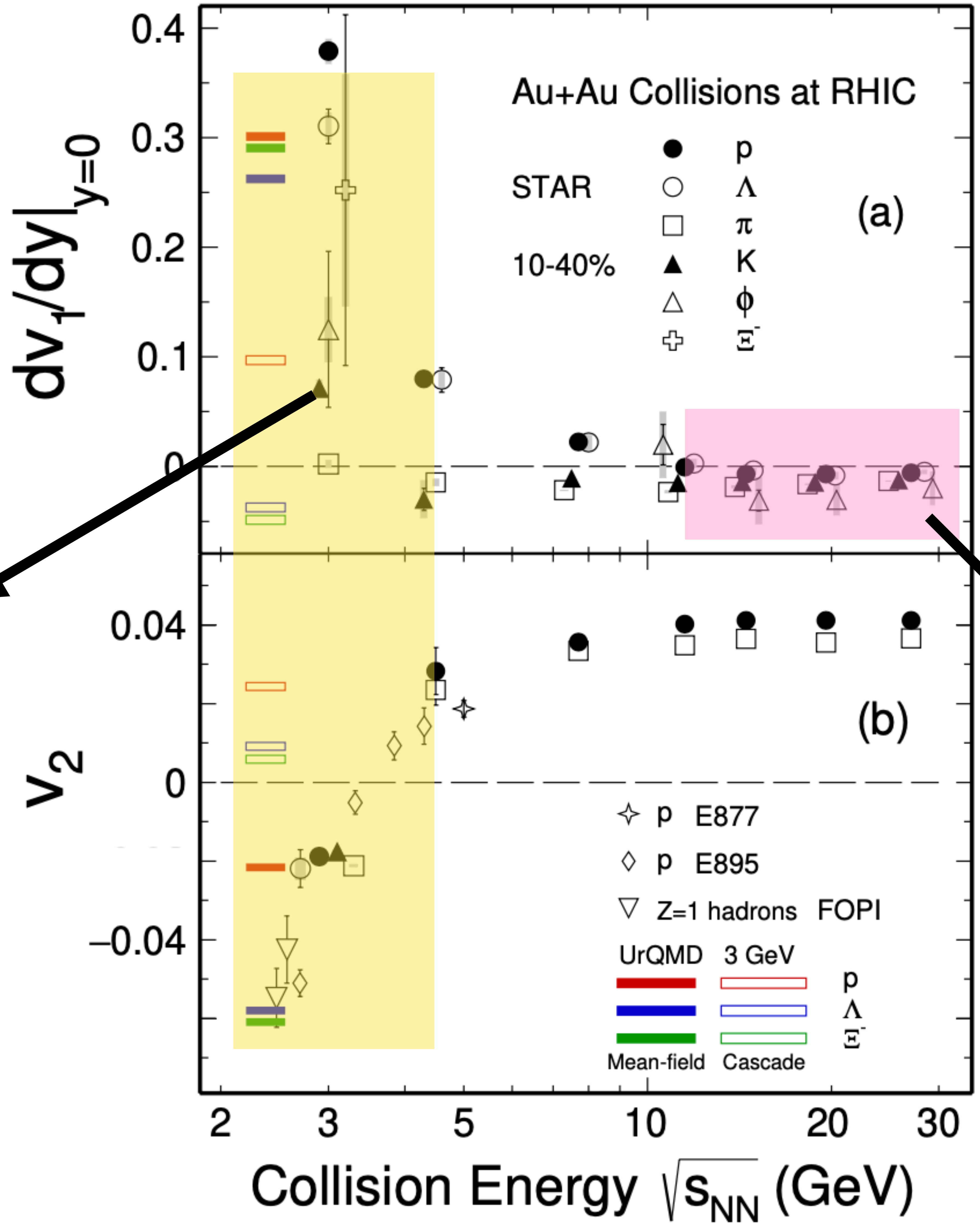


- NCQ scaling for v_2 breaks at 3 GeV

Indication of *disappearance* of partonic collectivity

STAR: PLB 827, 137003, (2021)

Energy dependence of $v_{1,2}$



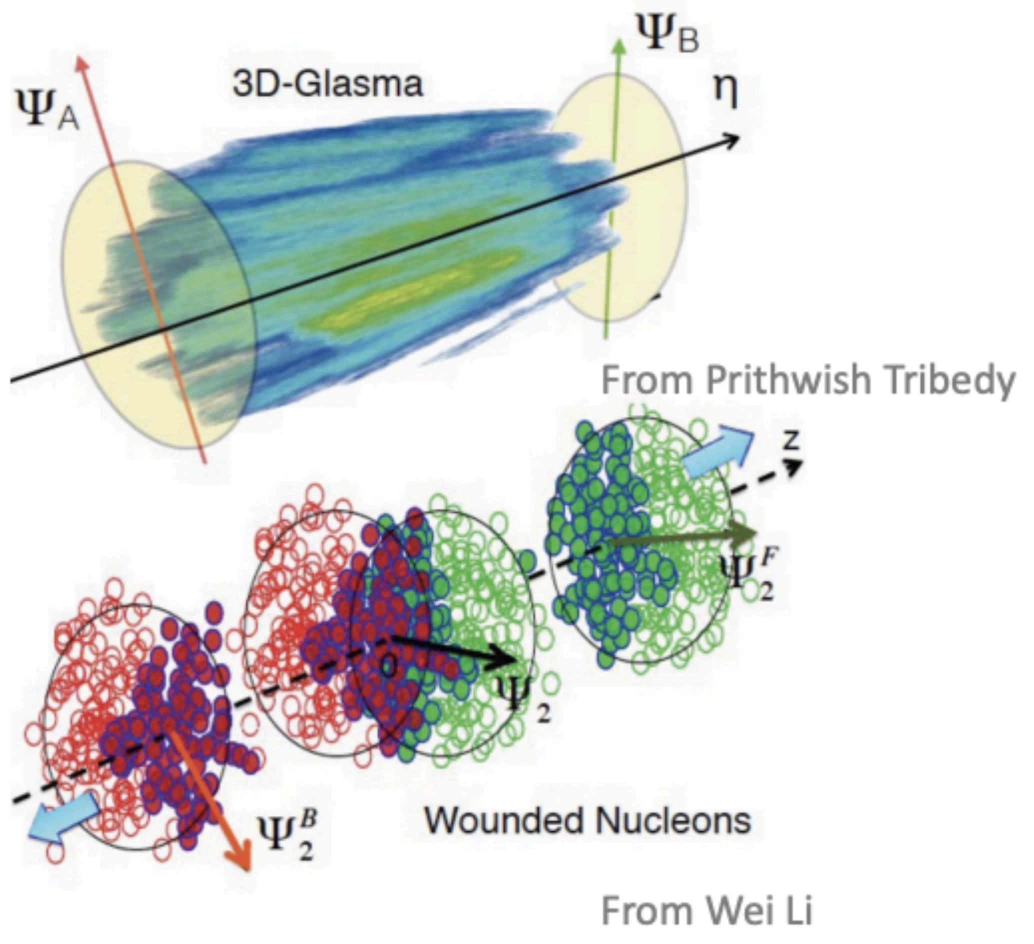
Hadronic dominant matter

Partonic dominant matter

STAR: PLB 827, 137003, (2021)

- At $\sqrt{s_{NN}} \sim 3$ GeV:
- v_1 is positive and is v_2 negative
- Transport model including baryonic field can reproduce both v_1 and v_2
- Hadronic matter is dominant at 3 GeV

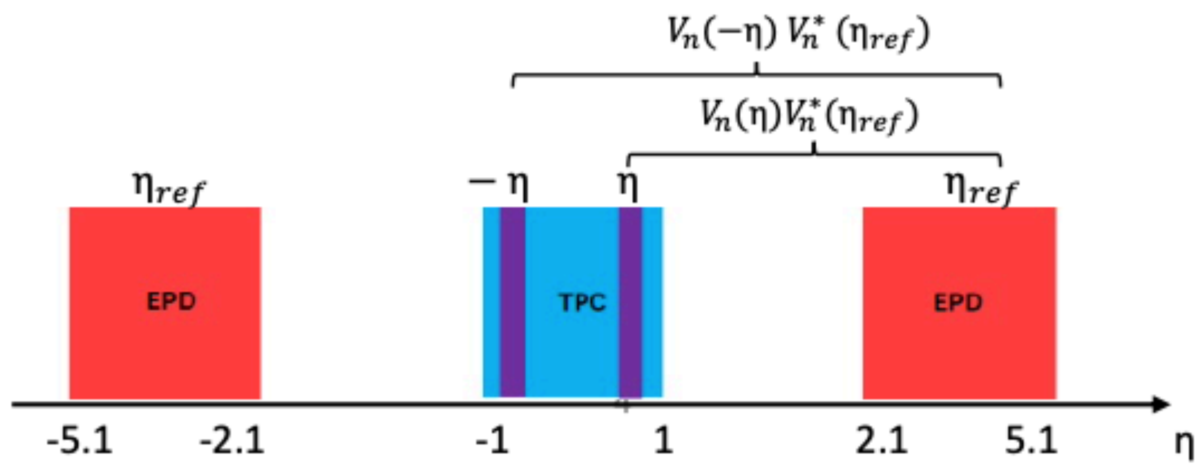
Longitudinal flow de-correlation



$$r_n(-\eta,\eta) = \frac{V_{n\Delta}(-\eta,\eta_{ref})}{V_{n\Delta}(\eta,\eta_{ref})}$$

$$= \frac{\langle v_n(-\eta) v_n(\eta_{ref}) \cos\{n[\Psi_n(-\eta) - \Psi_n(\eta_{ref})]\}\rangle}{\langle v_n(\eta) v_n(\eta_{ref}) \cos\{n[\Psi_n(\eta) - \Psi_n(\eta_{ref})]\}\rangle}$$

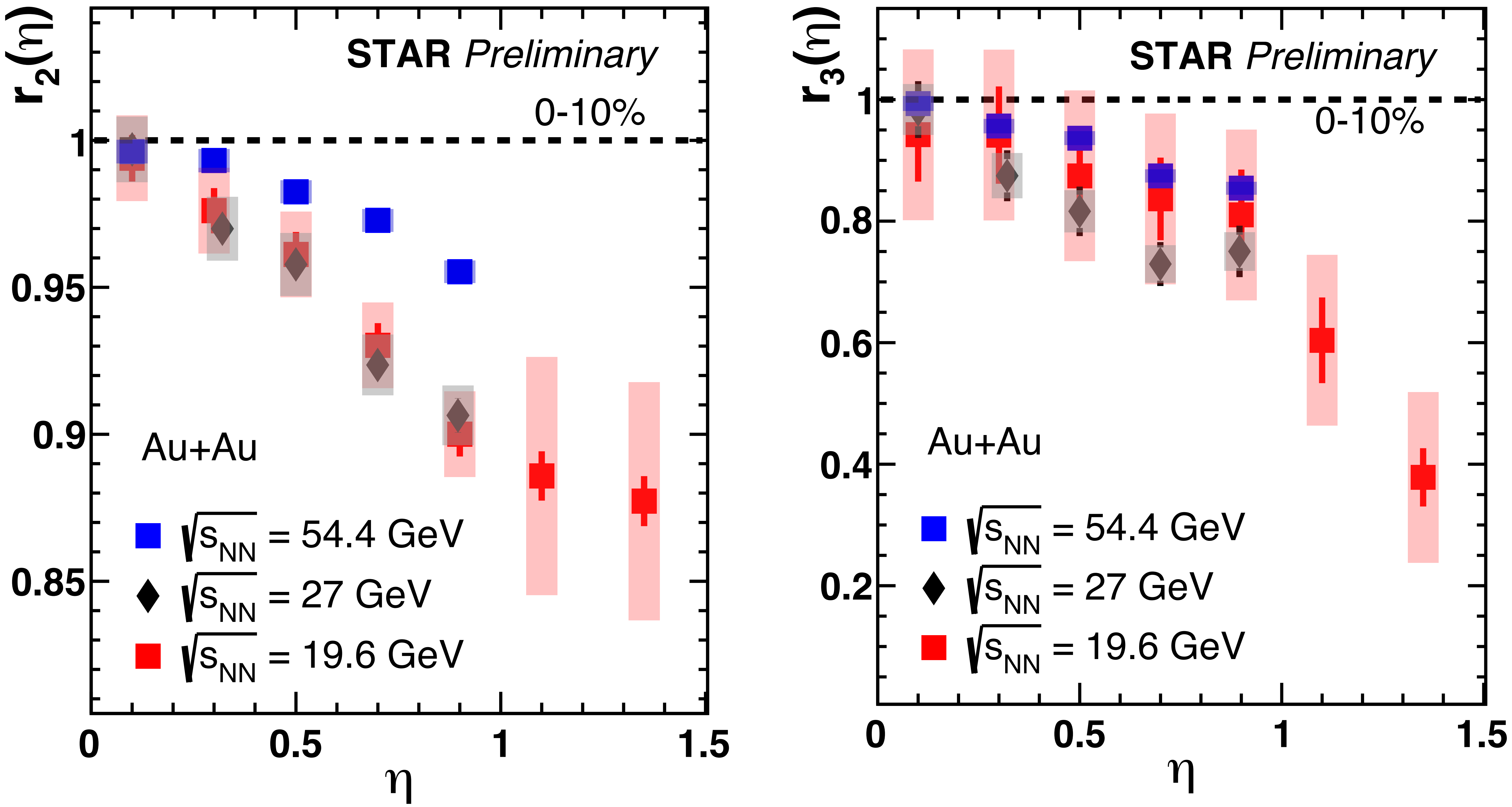
✓ The $r_n(-\eta,\eta)$ measures decorrelation between $-\eta$ and η



✓ The large η gap can avoid short-range correlation

$r_n(-\eta,\eta)$:
Measures relative fluctuation between $v_n(-\eta)$ and $v_n(\eta)$

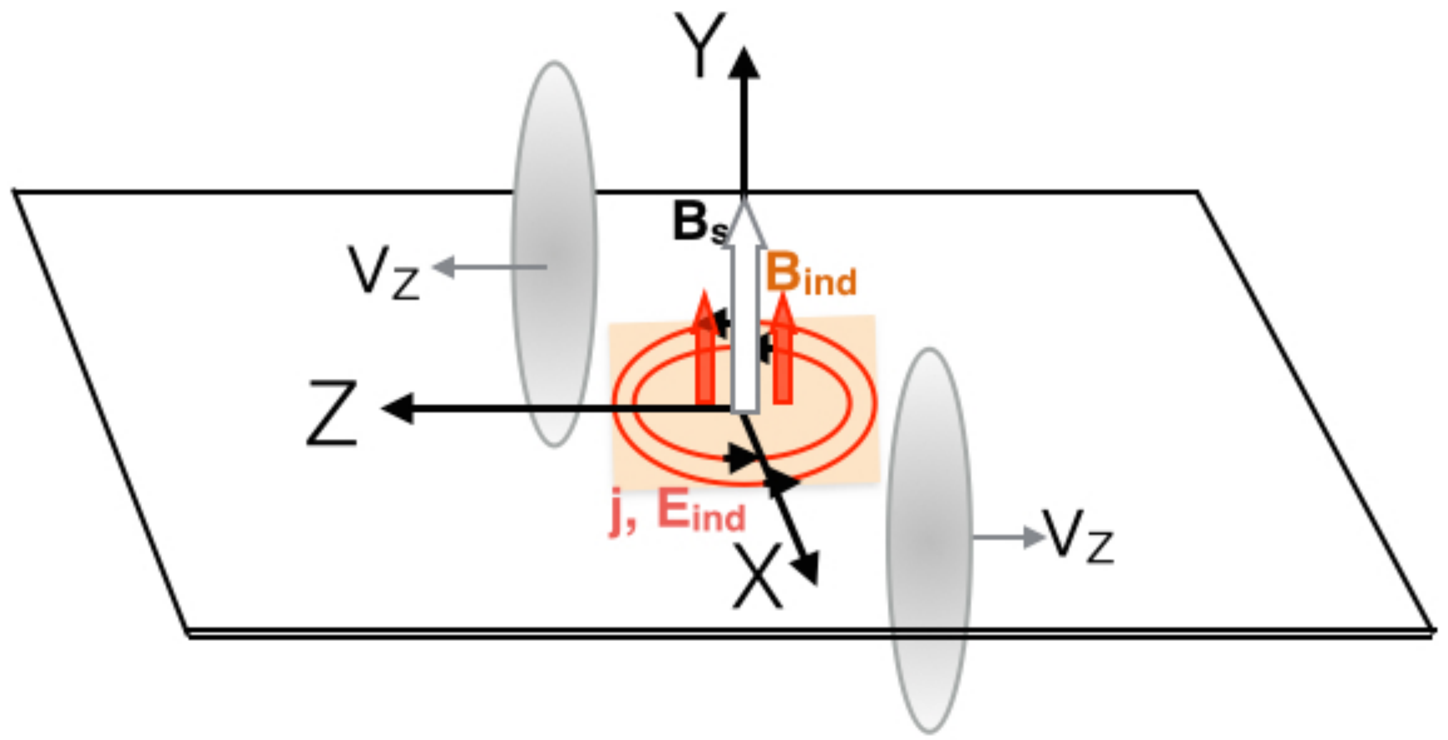
BES-II

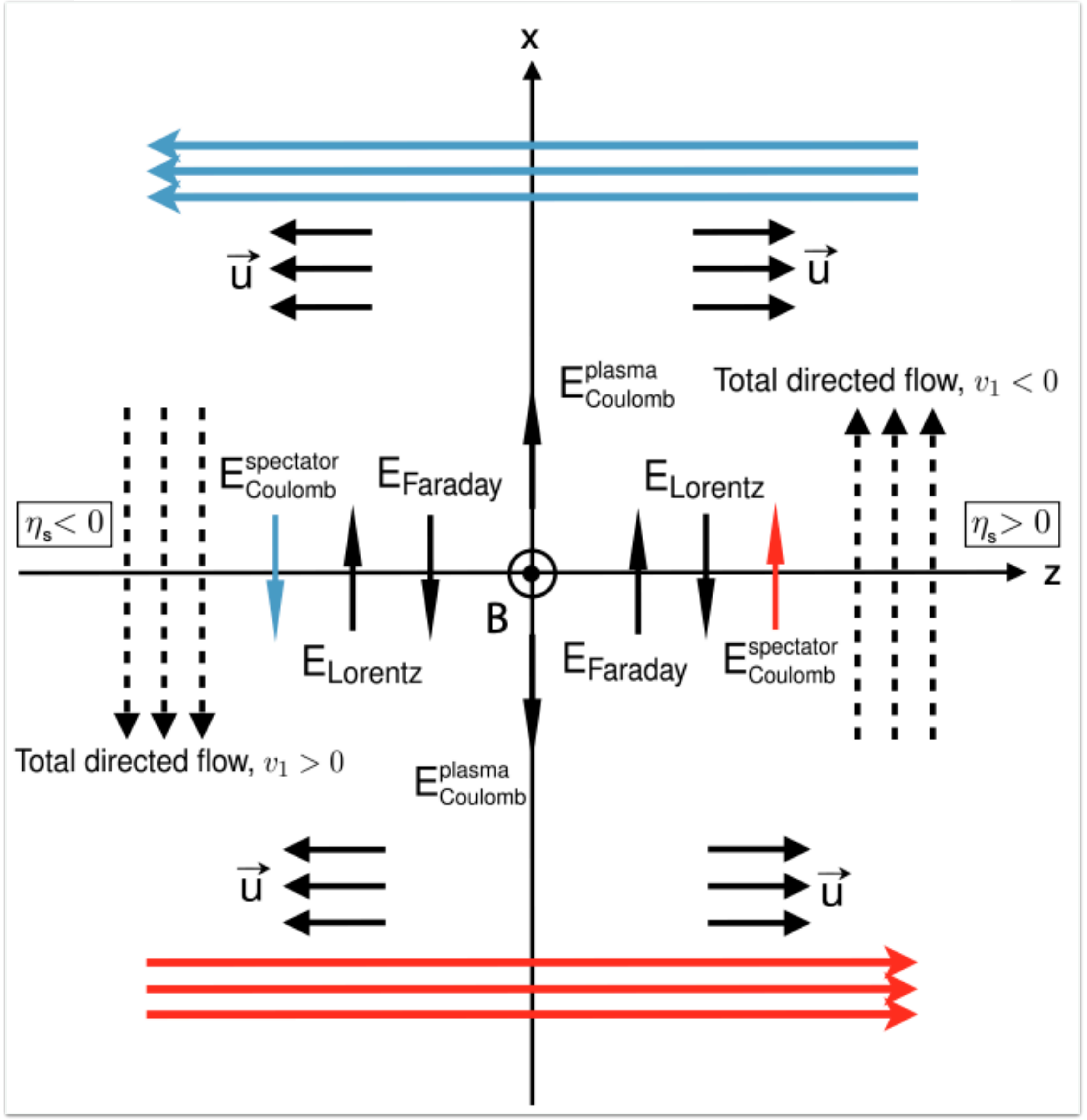


- Larger flow de-correlation at lower beam energies
- System is not longitudinally *boost invariant*

See Talk:
Gaoguo Yan

Directed flow from initial strong electromagnetic field



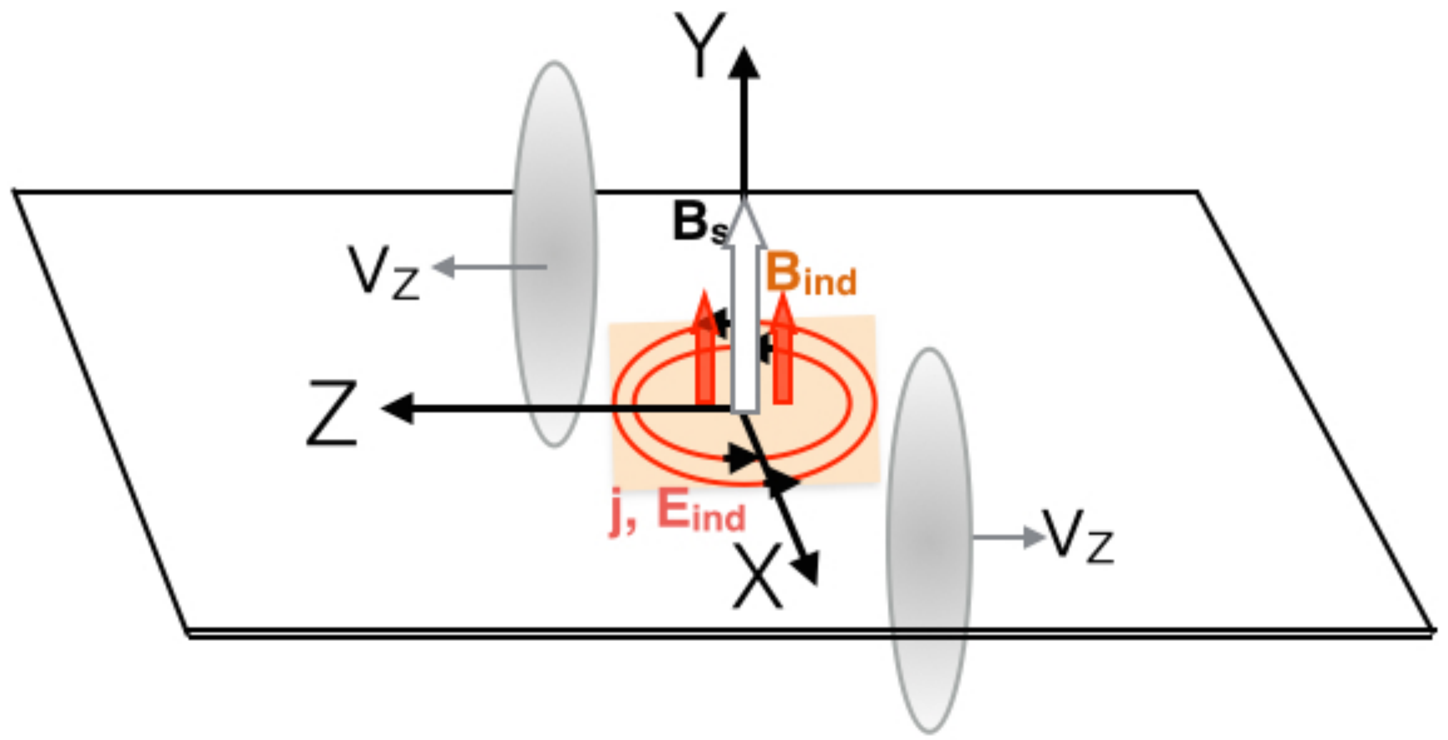


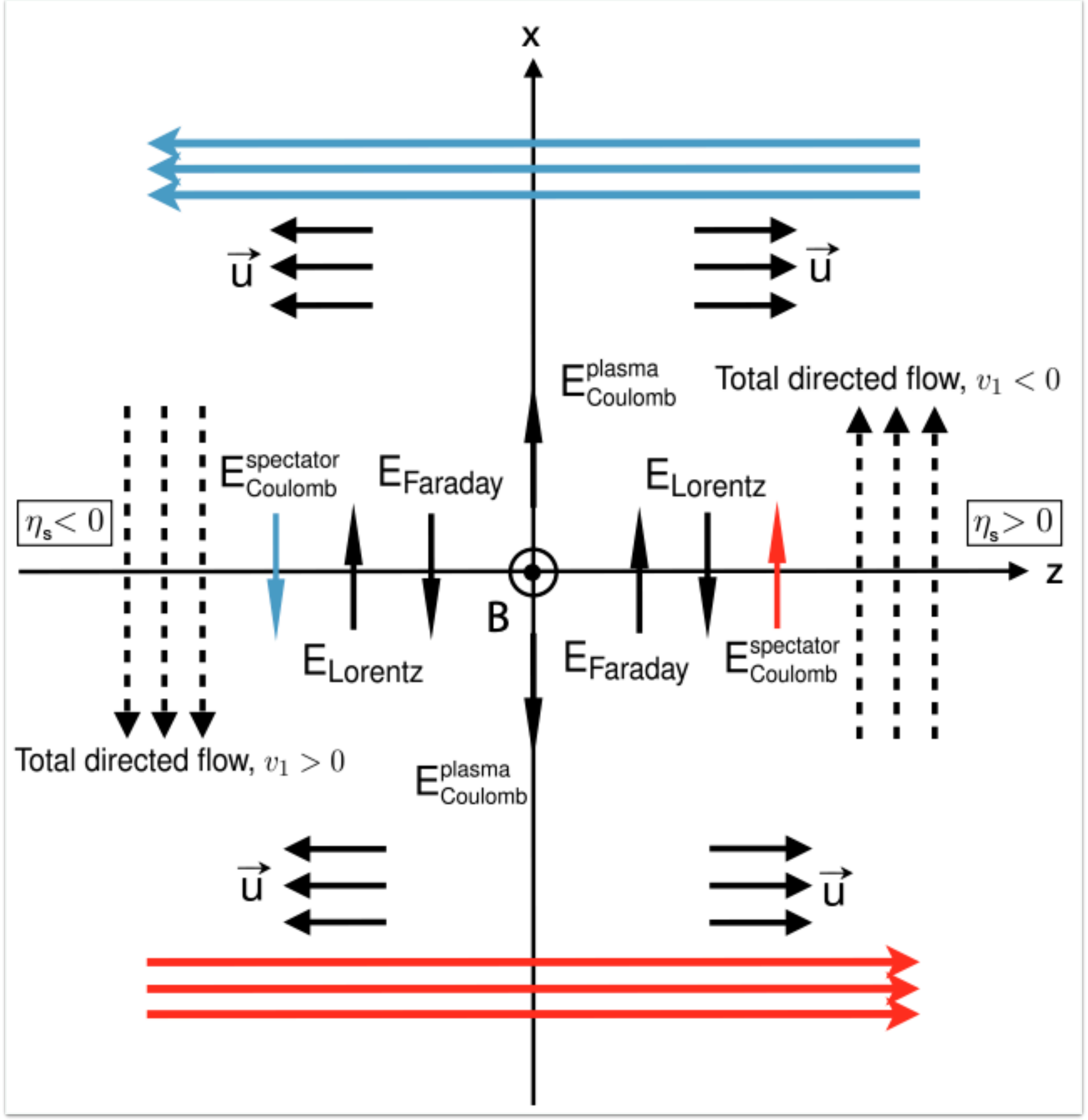
- The moving spectators can produce an enormously large **B** field (eB ~10^{18} G)
- It can *induce following competitive effects* in rapidity-odd v_1

- **Hall effect:**
  Lorentz force exerts a sideways push on charged particles
  In opposite directions at opposite rapidity
- **Faraday effect:**
  Rapid decay of **B** field induces Faraday current to generate large **E** field
  Induced Faraday current will oppose the drift due to **B** field
- **Coulomb effect:**
  Coulomb field of the charged spectators

U. Gursoy el. al.PRC 98, 055201 (2018); PRC 89, 054905 (2014)

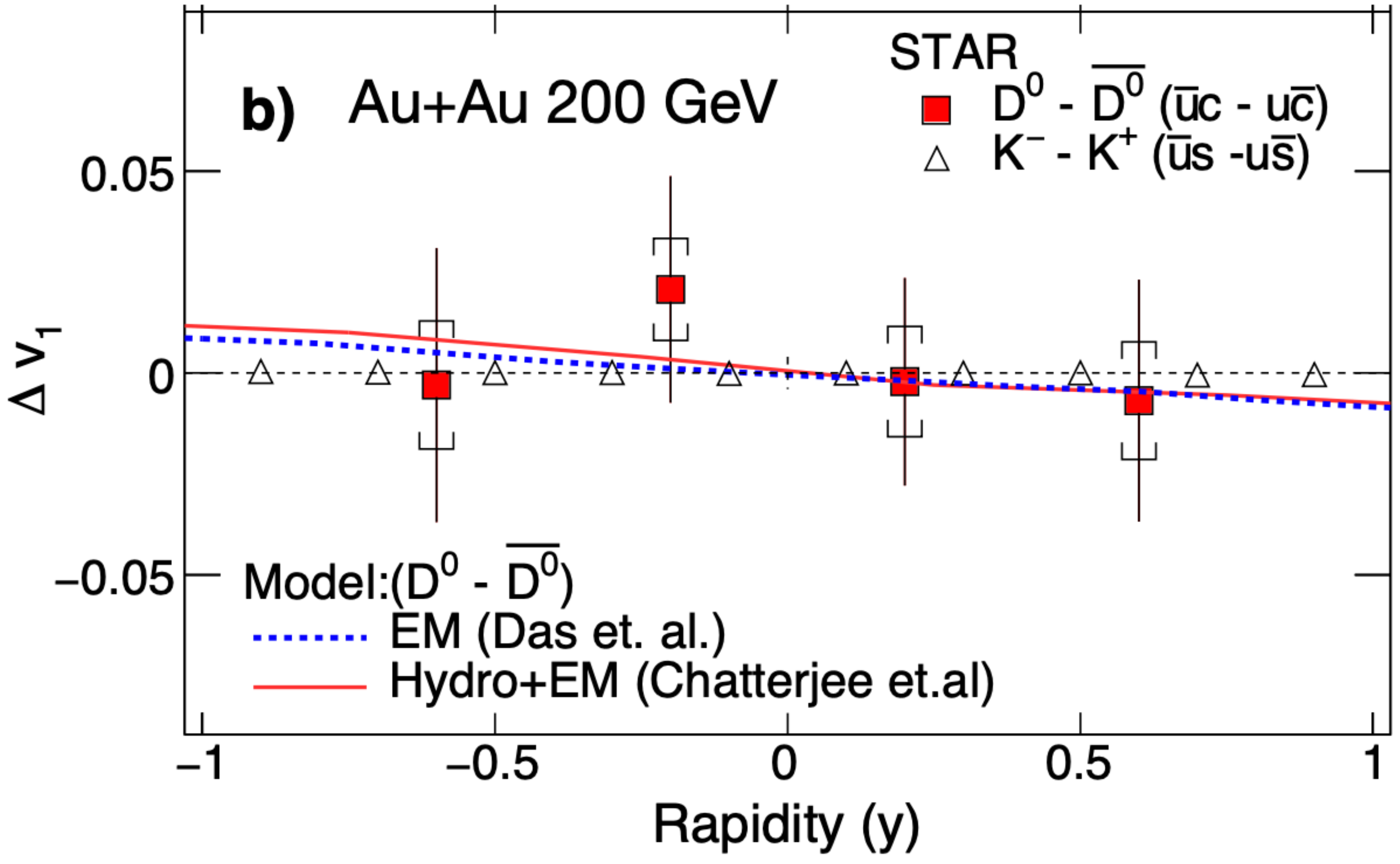
Directed flow from initial strong electromagnetic field

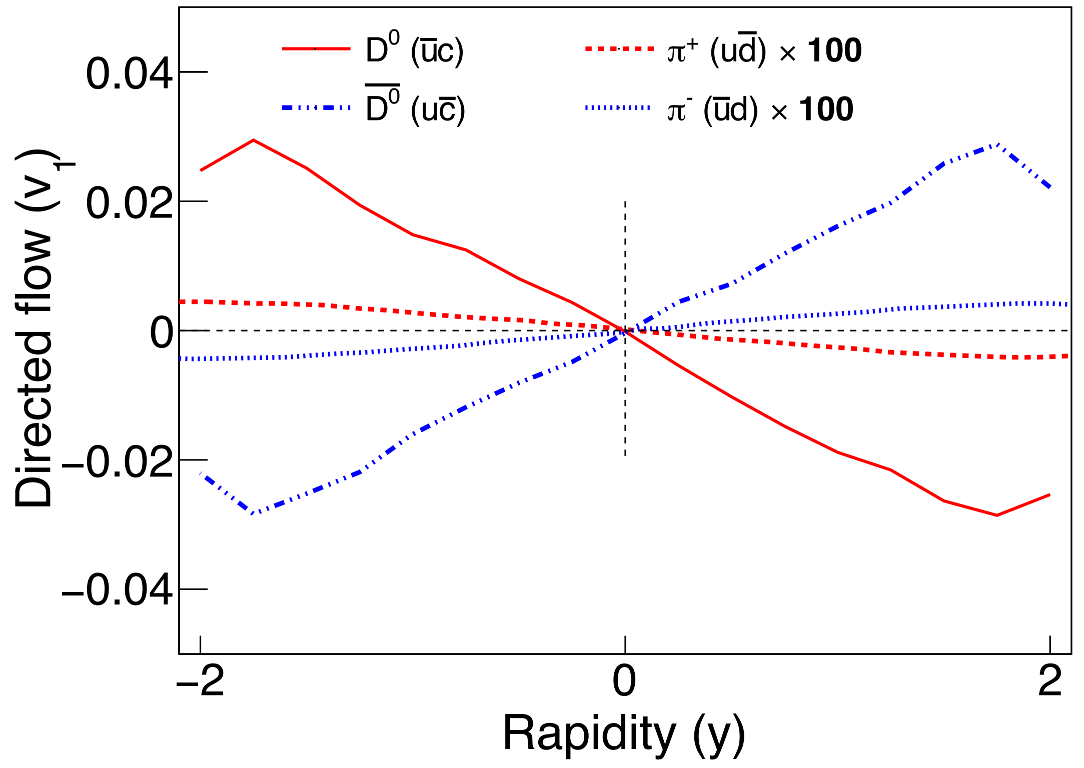




U. Gursoy el. al.PRC 98, 055201 (2018); PRC 89, 054905 (2014)

STAR: PRL 123 , 162301 (2019)



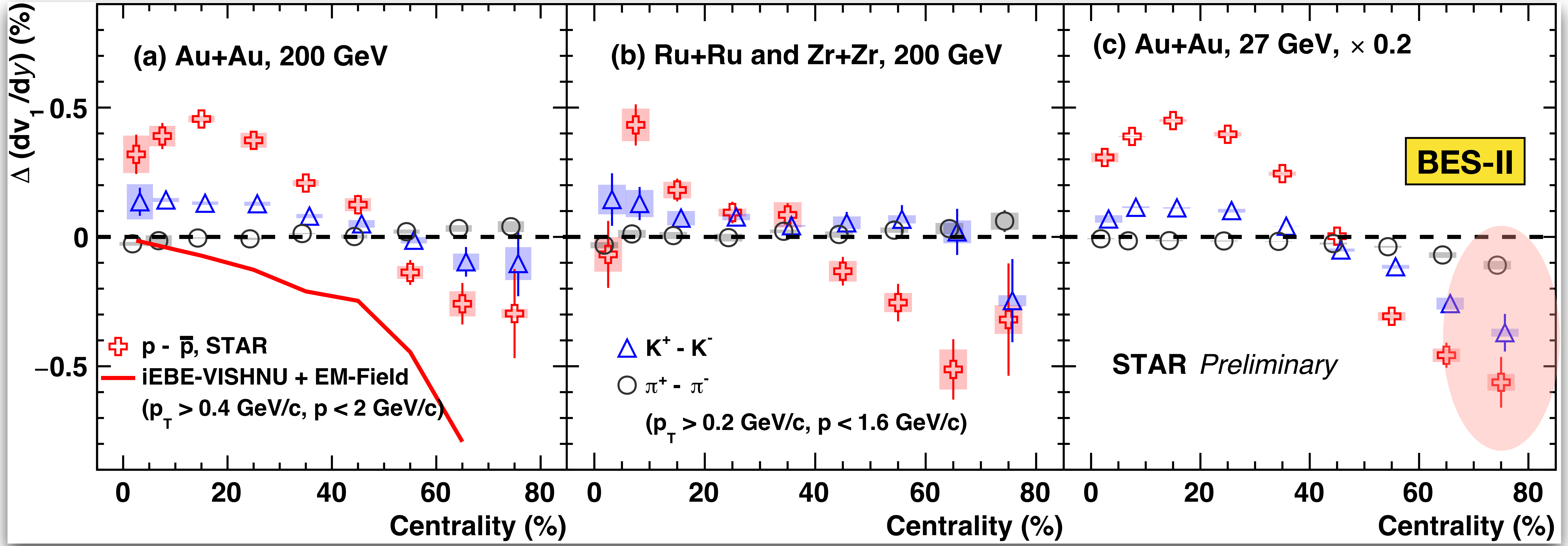


S. Das et al, PLB 768, 260 (2017)
S. Chatterjee et al, PLB 798, 134955 (2019)

- First attempt to measure Δv_1 using charm hadrons
- Results are inconclusive

Charge dependent directed flow

STAR: 2304.03430



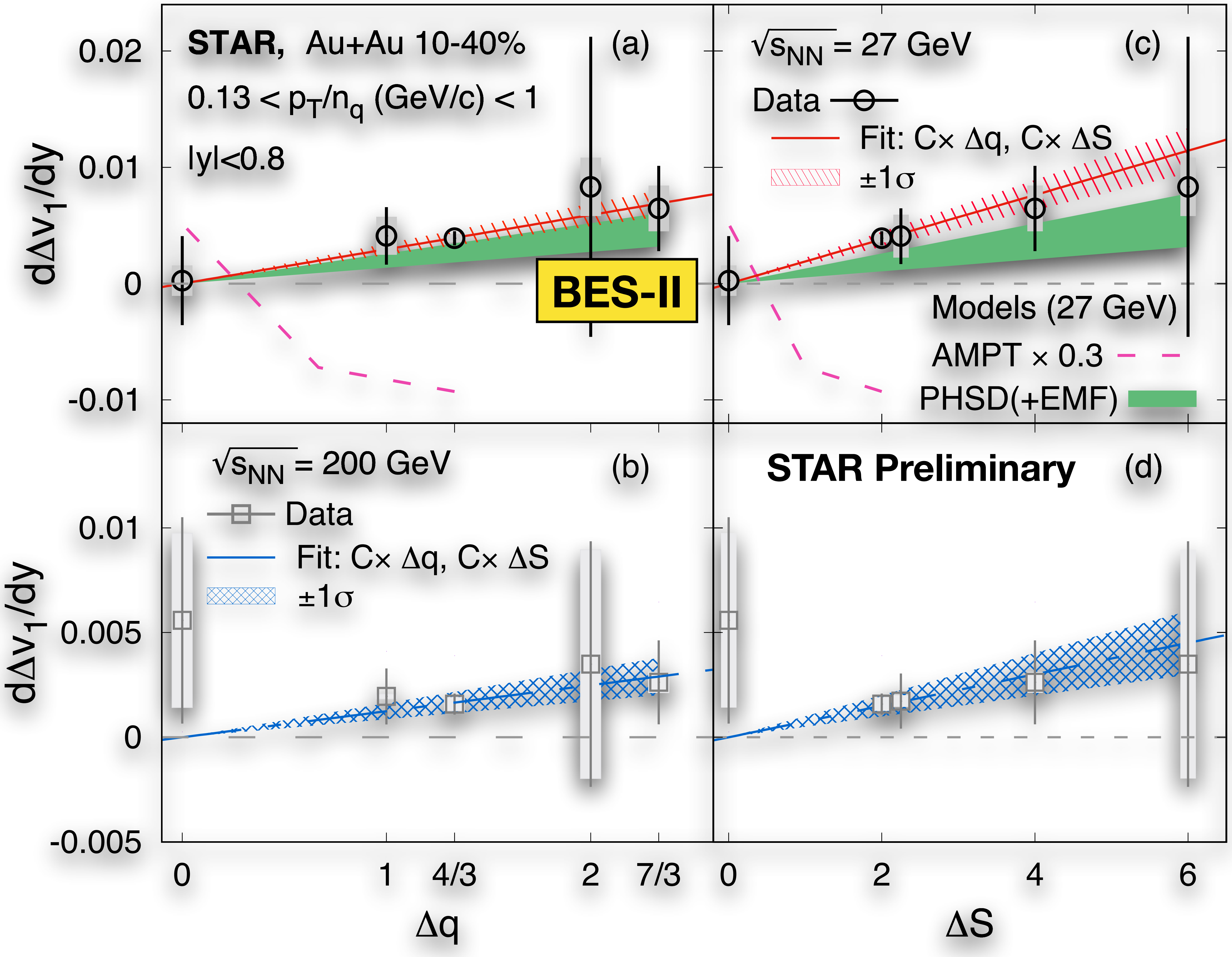
Among p and $\bar{p}$

- in (mid) central collisions: **positive v_1-slope difference** (Transported quark effect)
- in peripheral collisions: **negative v_1-slope difference (> 5σ)**, which increases with decrease in beam energy (Could be due to the dominance of Faraday+Coulomb effect)

Indication of *EM* field driven effects in HIC

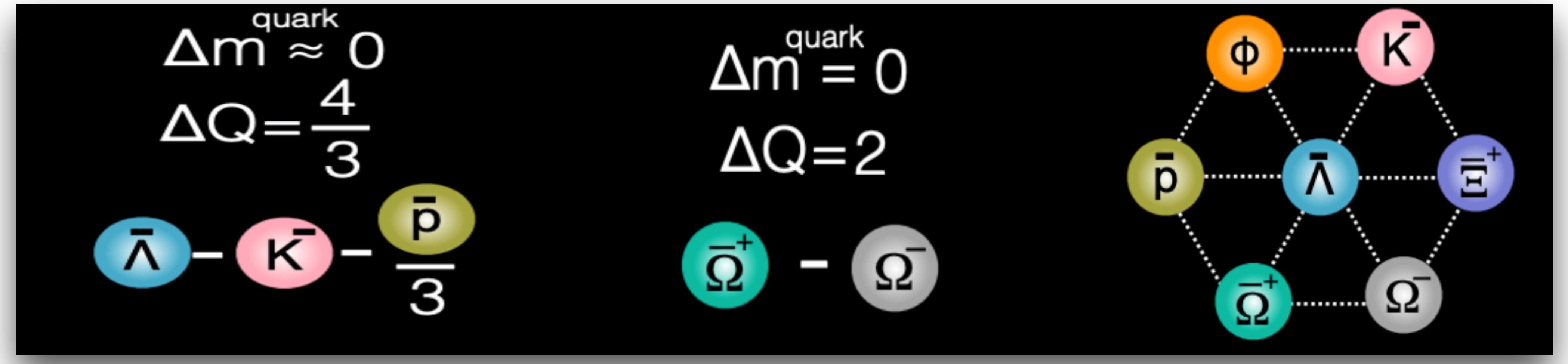
Charge dependent directed flow

STAR: 2304.02831



Indication of *EM* field driven effects in HIC

v_1 splitting measured using combination of *transported-quark-free* hadrons



- **v_1-slope difference** observed as function of charge difference (Δq) and strangeness difference (ΔS)
- **Larger v_1-slope difference** at 27 GeV than 200 GeV

Higher moments

Search for Critical point (region)

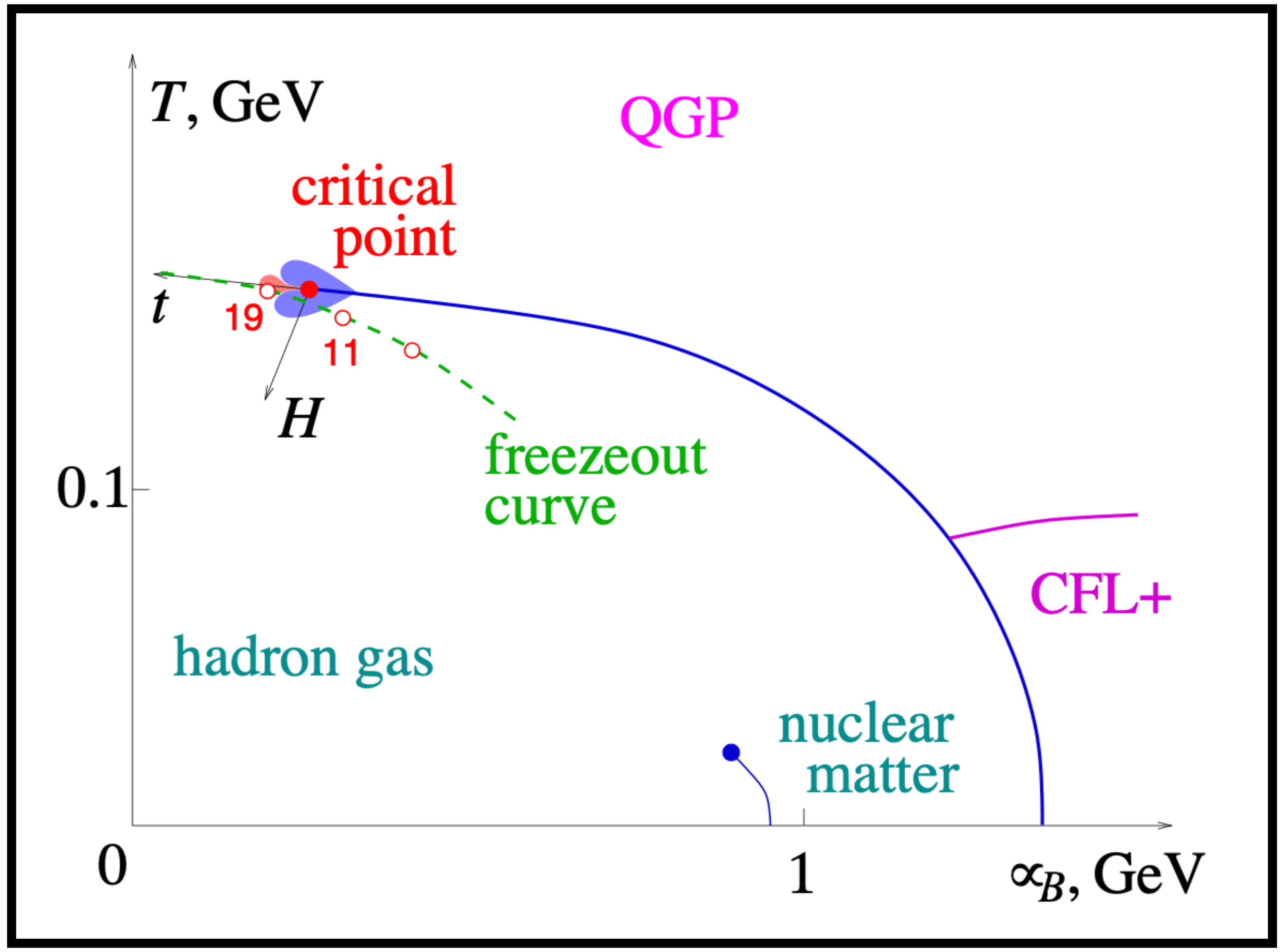
M. A. Stephanov,
PRL 107, 052301 (2011)

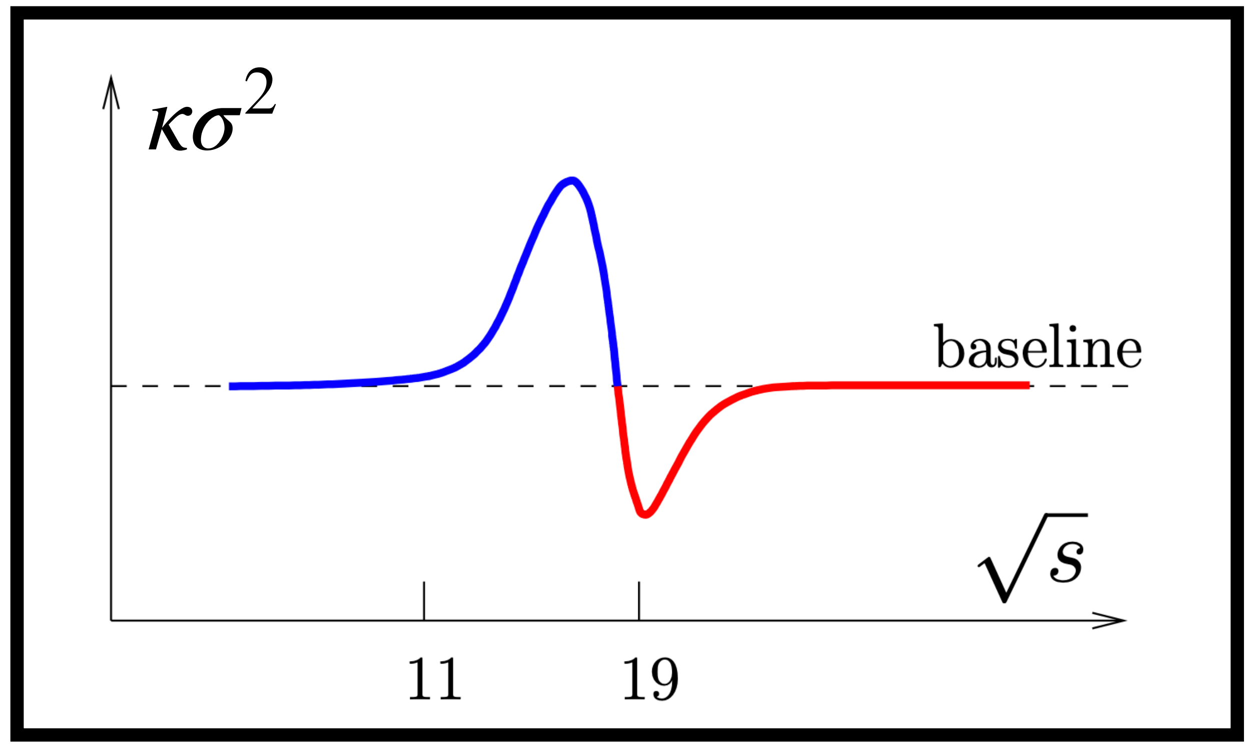
- **B, Q, S** are conserved quantities
- Near critical point correlation lengths diverges
- Higher moments/cumulants (**M**, σ, **S**, κ) :

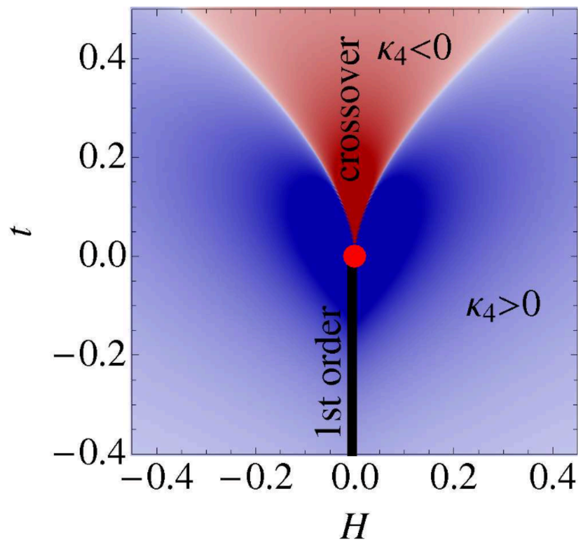
  Sensitive to correlation lengths (ζ), phase structure
- **S**, σ: Sensitive to non-gaussian fluctuations

$$
\begin{aligned}
\text{mean}: \mathrm{M} = \langle N \rangle &= C_1, \\
\text{variance}: \sigma^2 = \langle (\delta N)^2 \rangle &= C_2, \\
\text{skewness}: \mathrm{S} = \langle (\delta N)^3 \rangle / \sigma^3 &= C_3 / C_2^{3/2}, \\
\text{kurtosis}: \kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 &= C_4 / C_2^2 .
\end{aligned}
$$

- **Experimental signature:**
- Non-monotonic pattern in net-proton $\kappa\sigma^2$

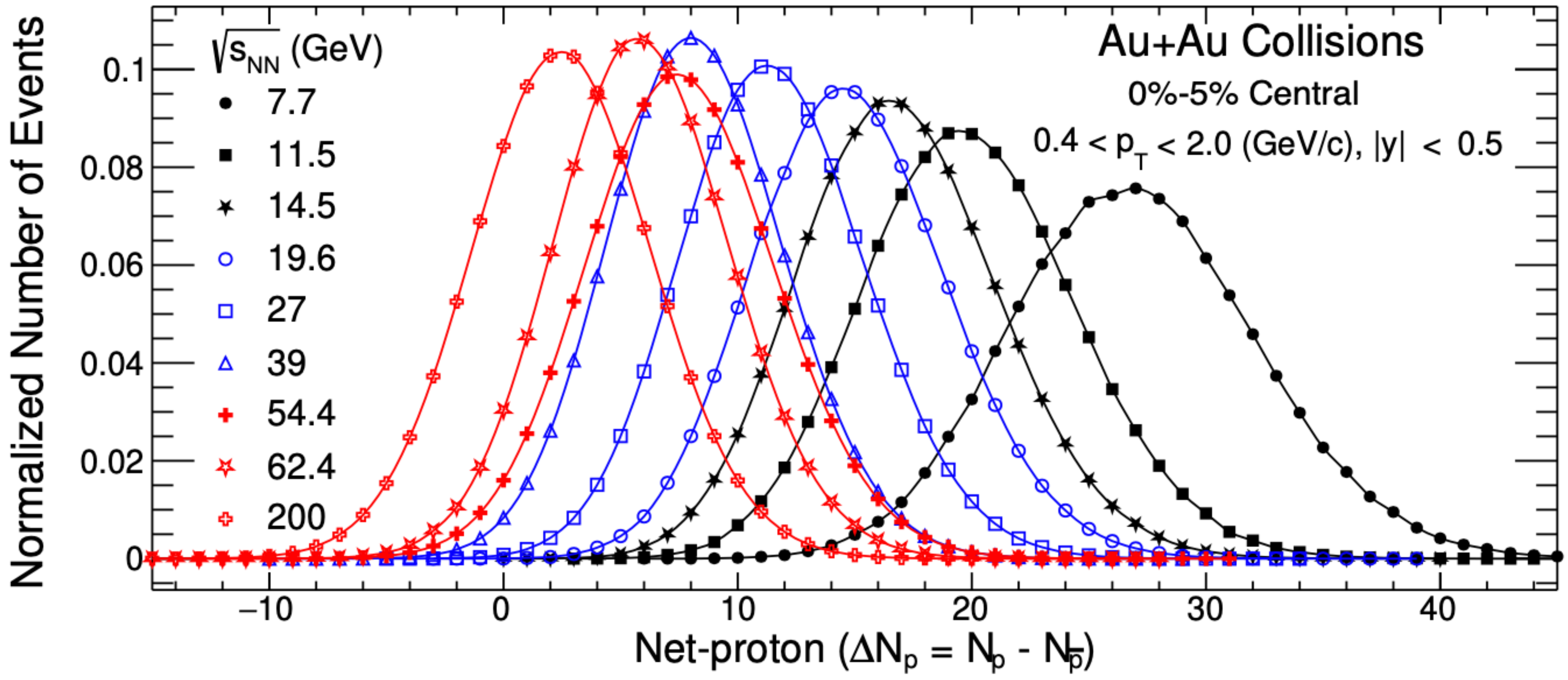






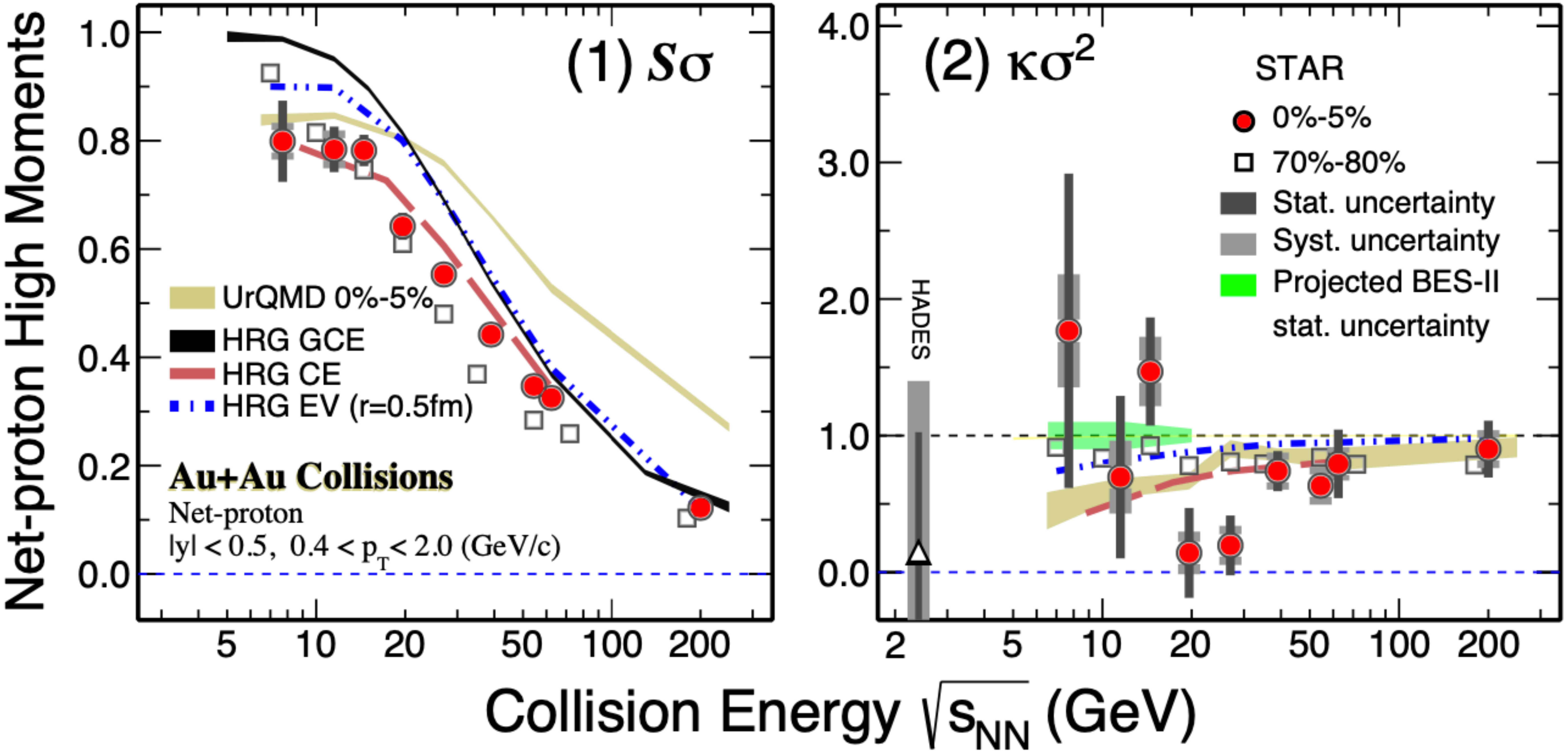
Net-proton distribution

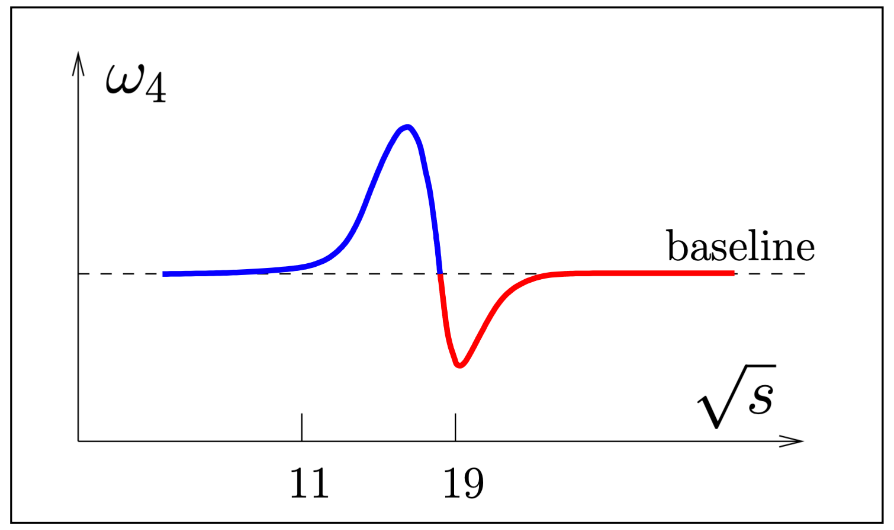
STAR: PRL 127, 262301 (2021)



- Event by event raw net-proton distribution

Net-proton higher moments



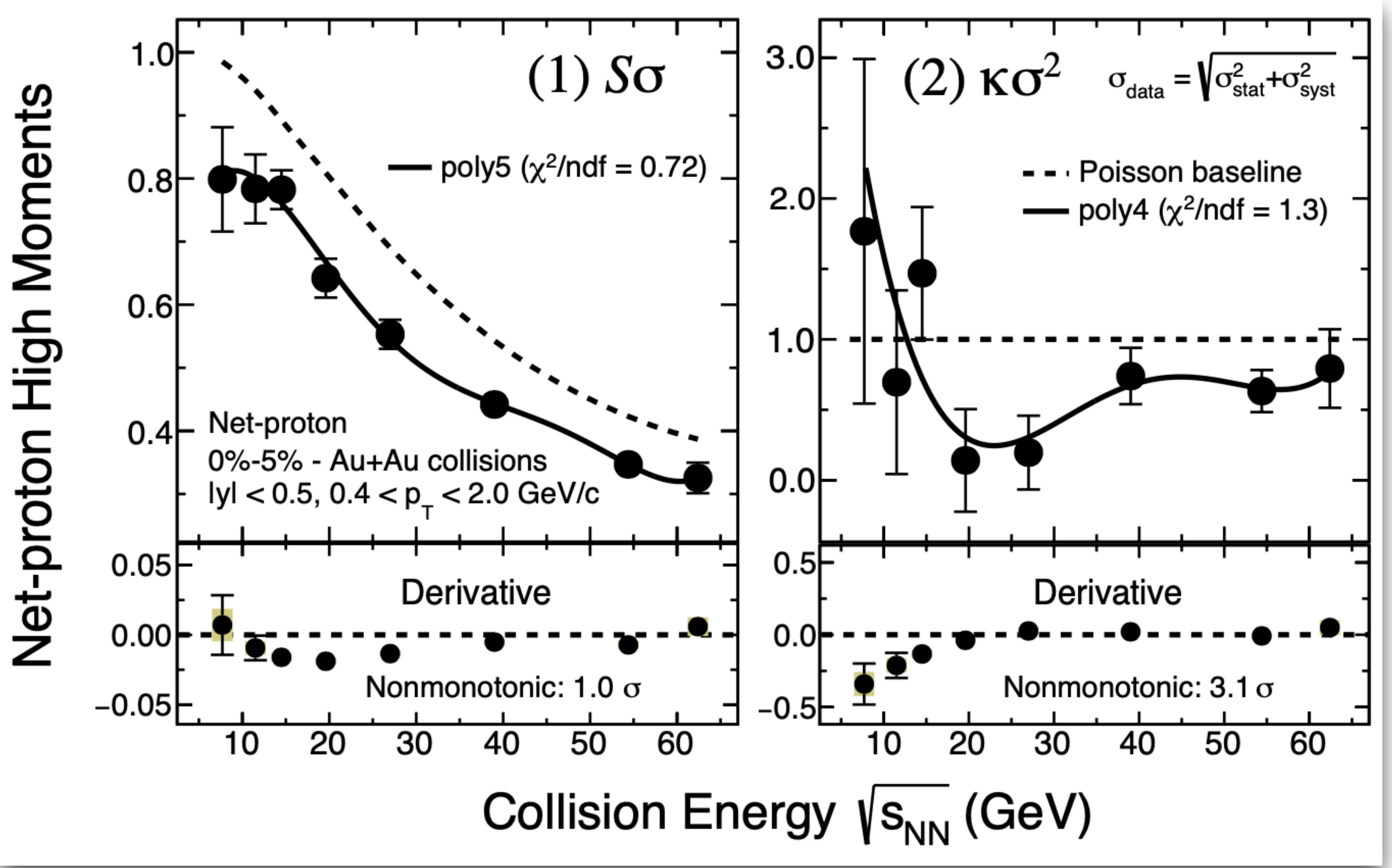


STAR: PRL 127, 262301 (2021)

STAR: PRL 126, 092301 (2021)

- Net-proton $S\sigma$ monotonic
- Net-proton $\kappa\sigma^2$ non-monotonic pattern

Net-proton higher moments

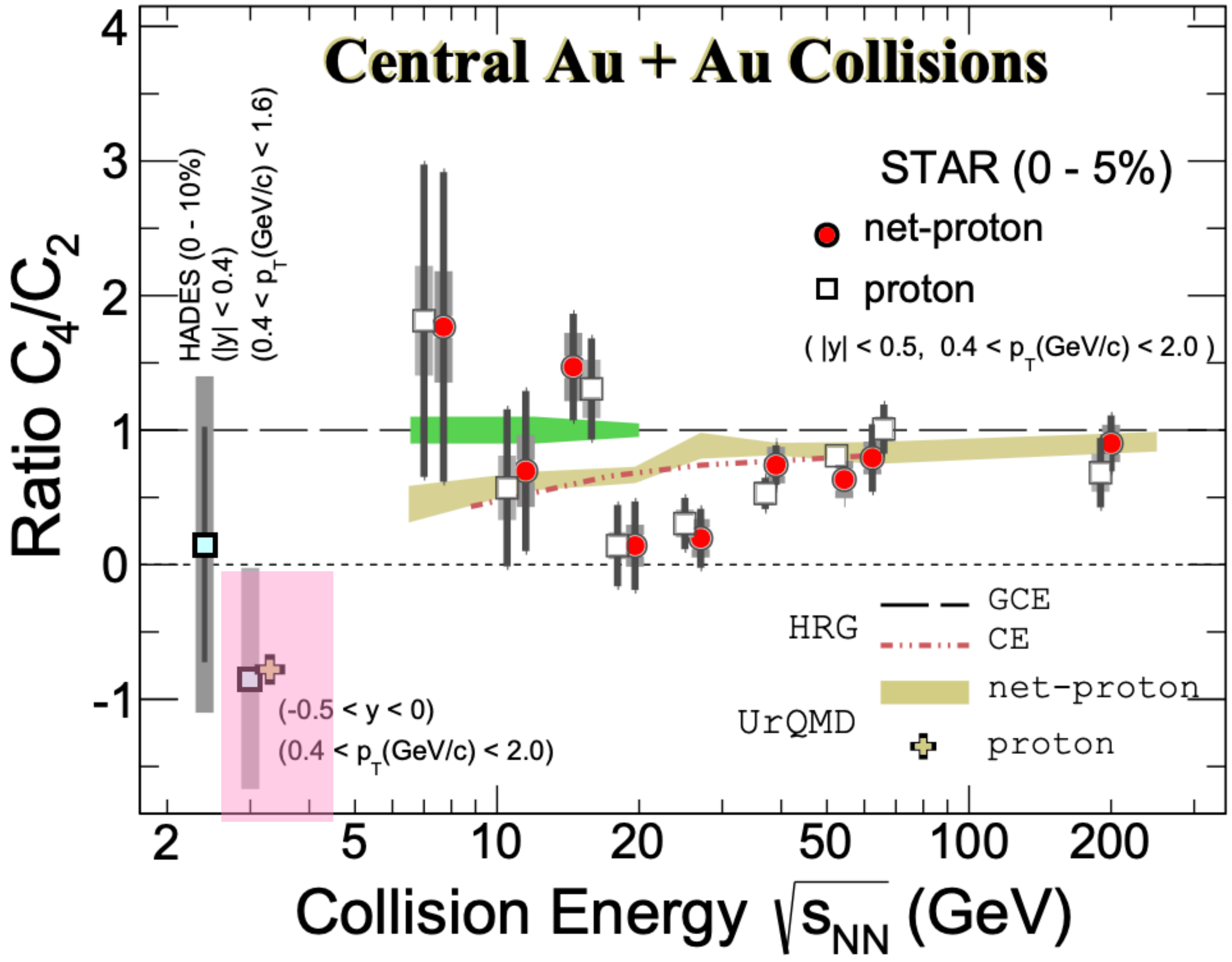


STAR: PRL 127, 262301 (2021)

STAR: PRL 126, 092301 (2021)

- Statistical test performed on deviation from Poisson (monotonic or non-monotonic)
- $S\sigma$ ~ 1.0σ & $\kappa\sigma^2$ ~ 3.1σ deviation ⟶ Could be an indication of critical region

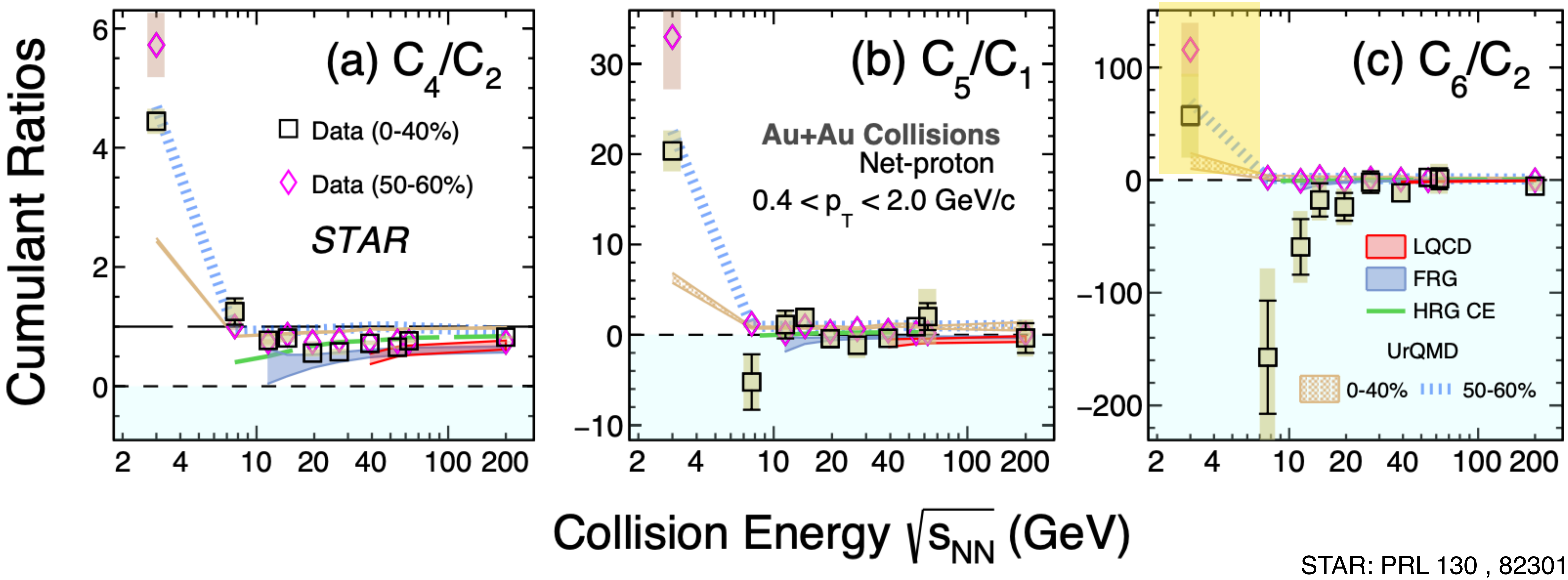
Net-proton higher moments



STAR: PRL128, 202303 (2022)

- At $\sqrt{s_{NN}} \leq 3$ GeV below: Net-proton $\kappa\sigma^2$ negative
- Consistent with UrQMD ⟶ Medium dominated by hadronic interactions

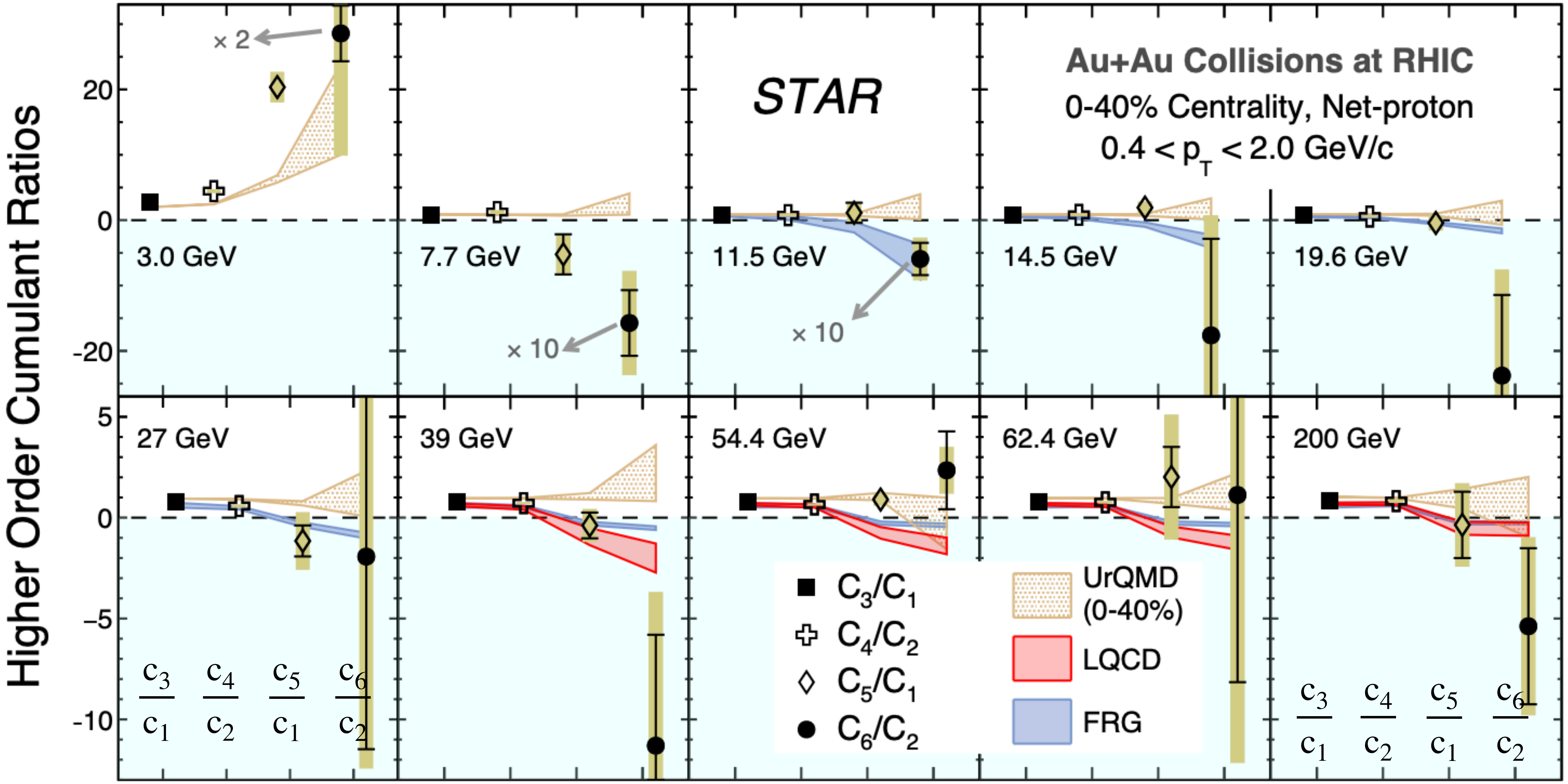
Net-proton higher moments



STAR: PRL 130 , 82301 (2023)

- C_6/C_2 : Negative for $\sqrt{s_{NN}} \sim$ 7.7 - 200 GeV
- C_6/C_2 : Positive at $\sqrt{s_{NN}} = 3$ GeV

Net-proton higher moments

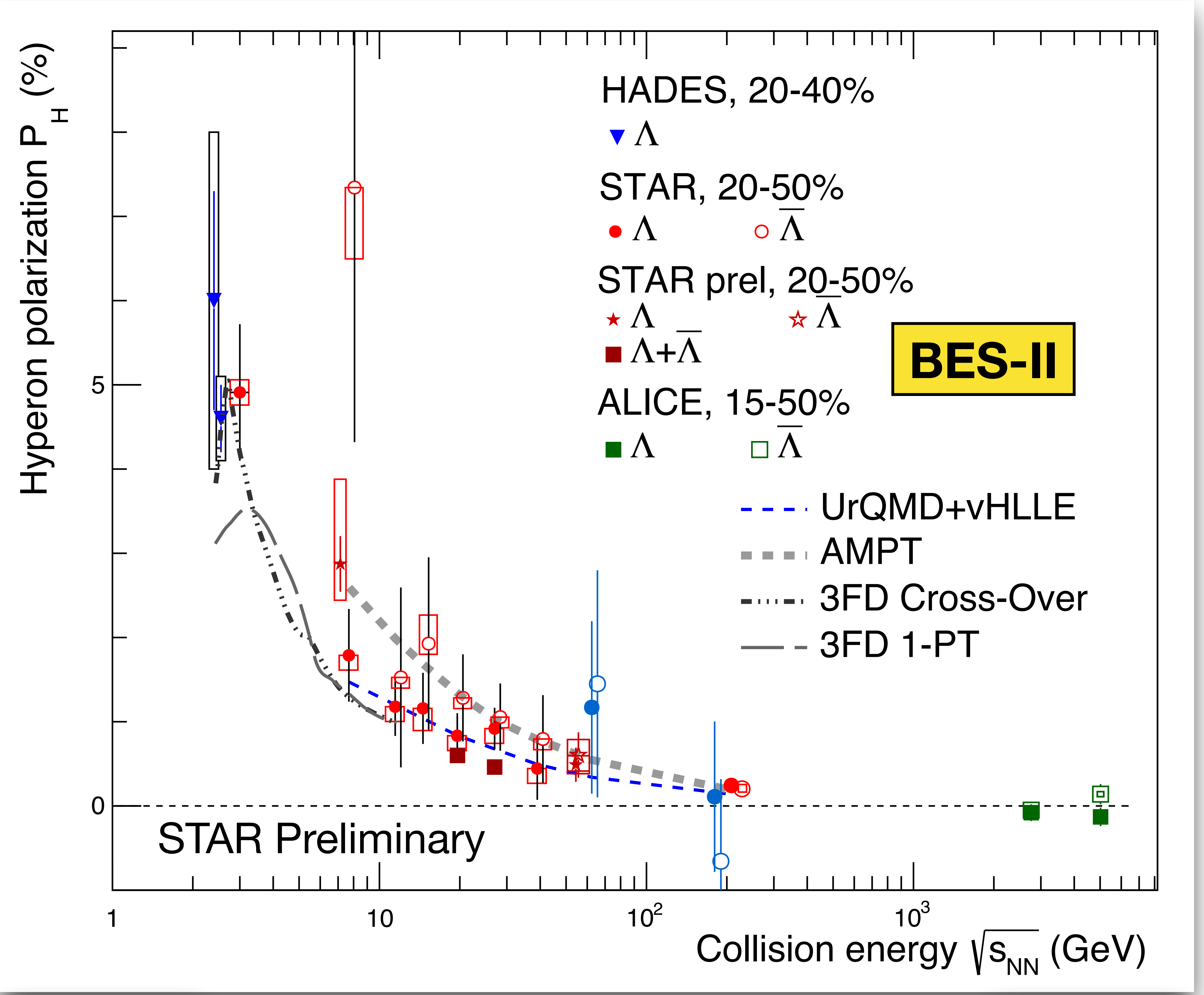


STAR: PRL 130 , 82301 (2023)

- Ordering in cumulant ratios: $C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$
- Opposite ordering at 3 GeV

Spin dynamics

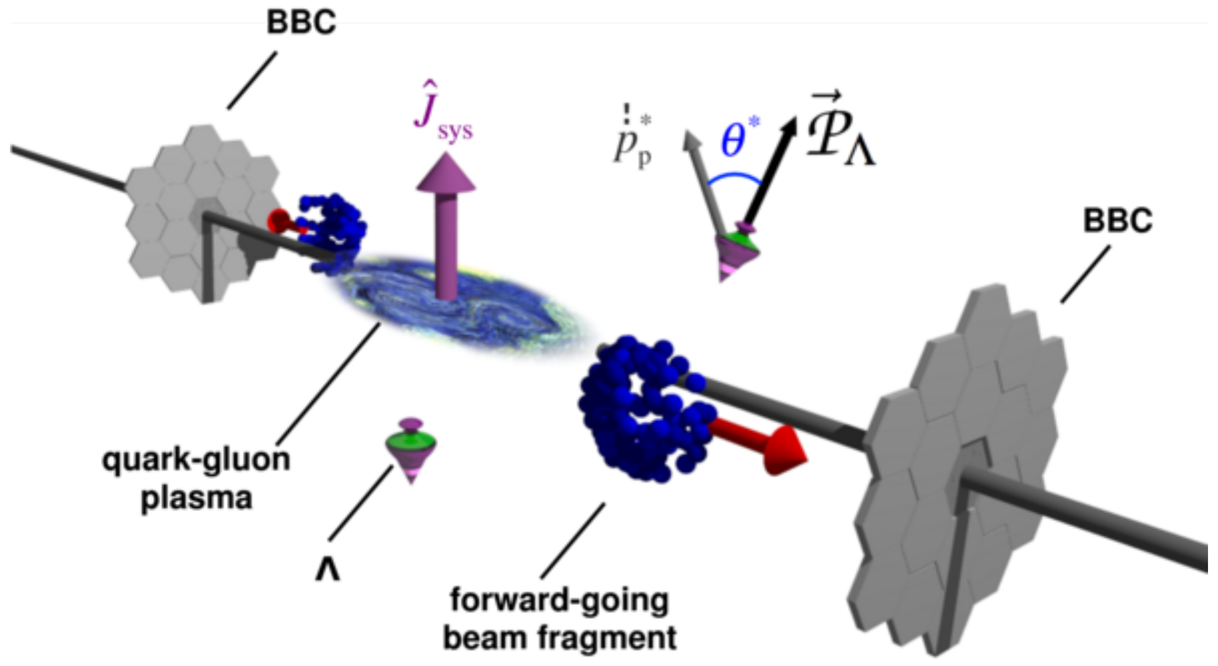
Global spin polarization of Λ



Hadronic dominant

Partonic dominant

Expected, $P_\Lambda \sim 0$ at $\sqrt{s_{NN}} \sim 2m_N$

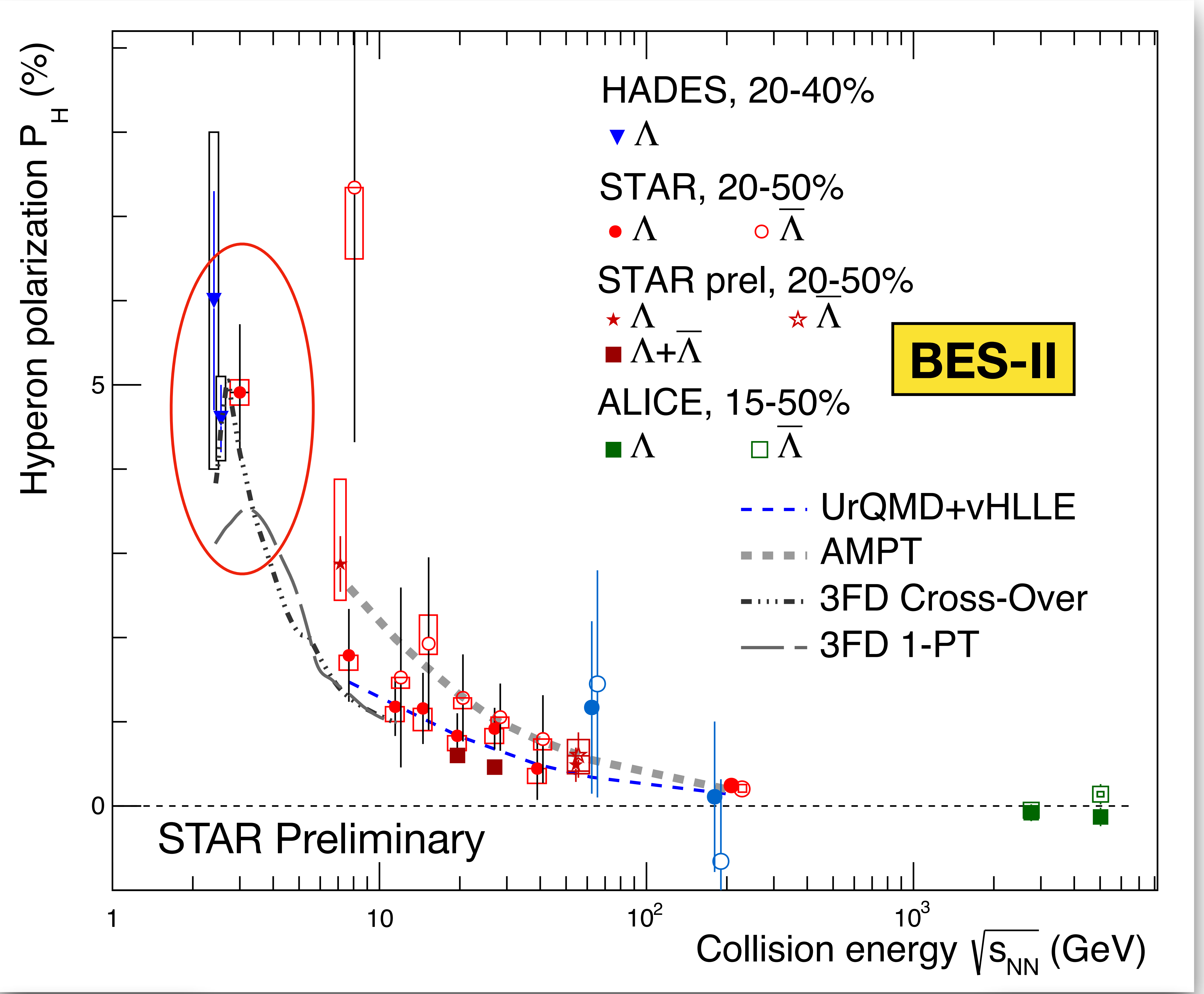


$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

- Global Λ polarization increases monotonically with decreasing beam energy

STAR: PRC 76, 024915 (2007); Nature 548, 62 (2017); PRC 101, 044611 (2020); PRC 104, 061901 (2021)
ALICE: PRC 101, 044611 (2020); HADES: PLB 137506 (2022)

Global spin polarization of Λ



Hadronic dominant

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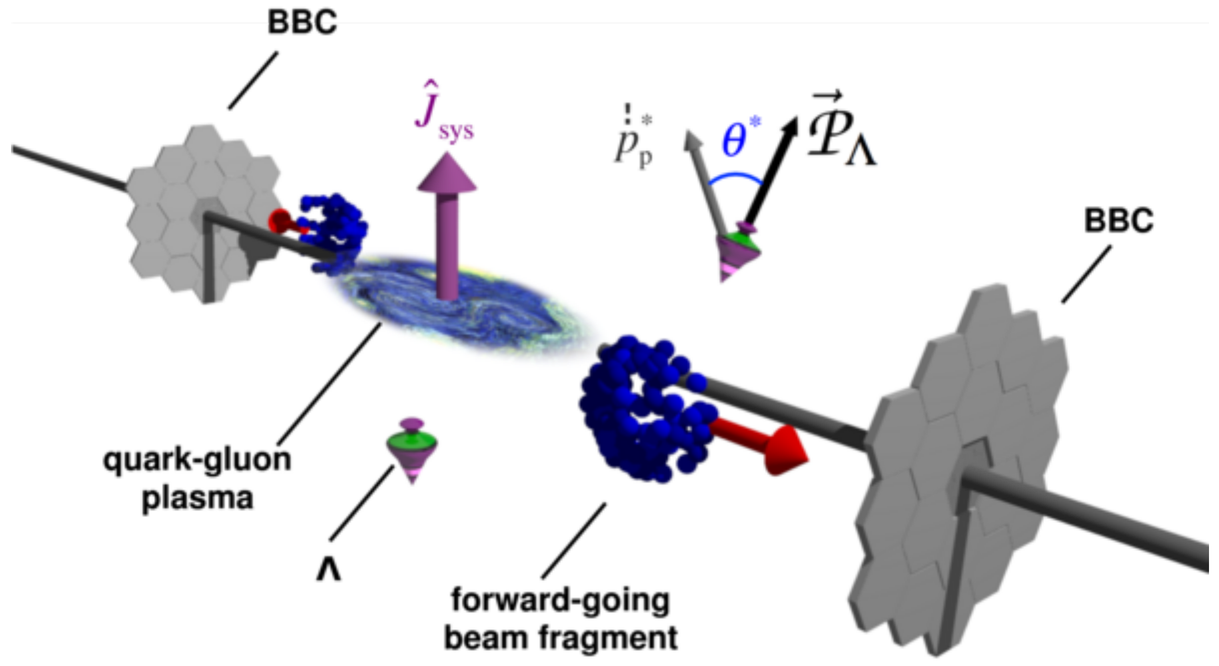

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- Global Λ polarization increases monotonically with decreasing beam energy

Does the hadronic dominant matter retain more vorticity (?)

Where do we observe highest polarization?

STAR: PRC 76, 024915 (2007); Nature 548, 62 (2017); PRC 101, 044611 (2020); PRC 104, 061901 (2021)
ALICE: PRC 101, 044611 (2020); HADES: PLB 137506 (2022)

Baryonic Spin Hall effect (SHE)

Condensed matter

$$s \propto \pm p \times E$$

Heavy Ion Collisions

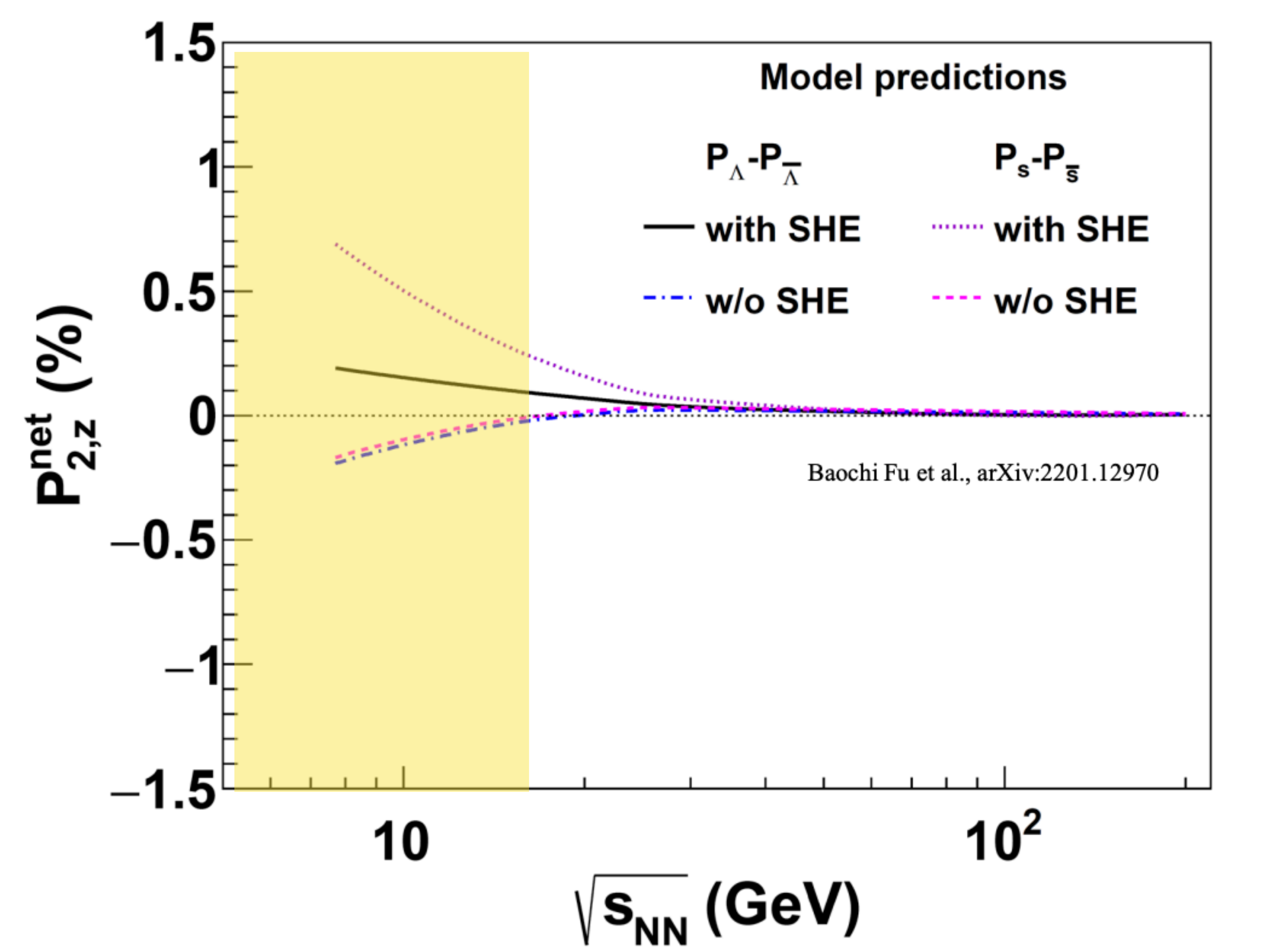
$$s \propto \pm p \times \nabla \mu_B$$

Predicted Spin Hall type effect driven by gradient of baryonic density ($\nabla \mu_B$)

Can be accessed by splitting in local polarization of Λ and $\overline{\Lambda}$: $P_z^{\Lambda} - P_z^{\overline{\Lambda}}$

Fu et., al., arXiv: 2201.12970

Polarization ~ vorticity $\oplus$ ∇T $\oplus$ Shear $\oplus$ $\nabla \mu_B$



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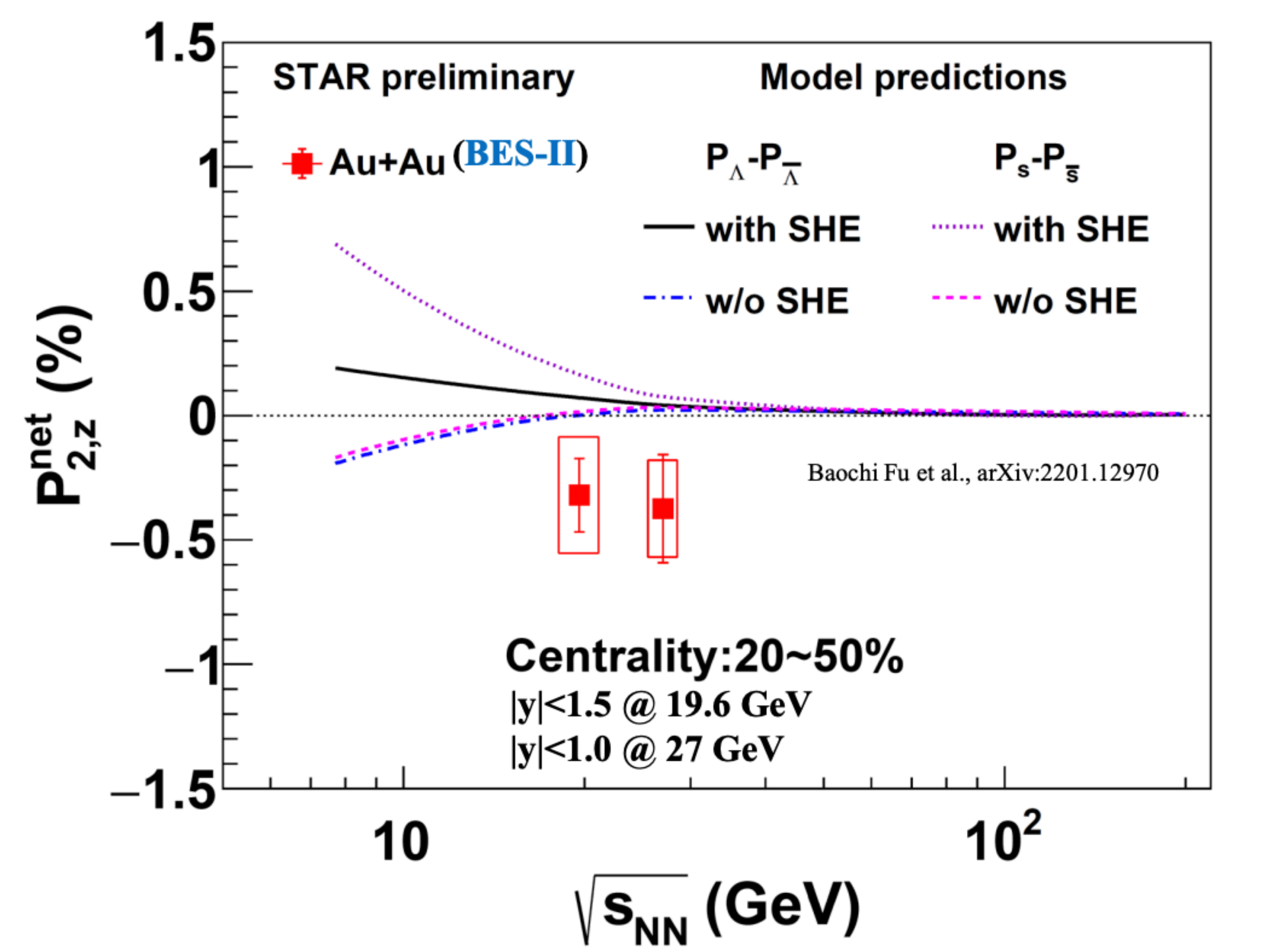
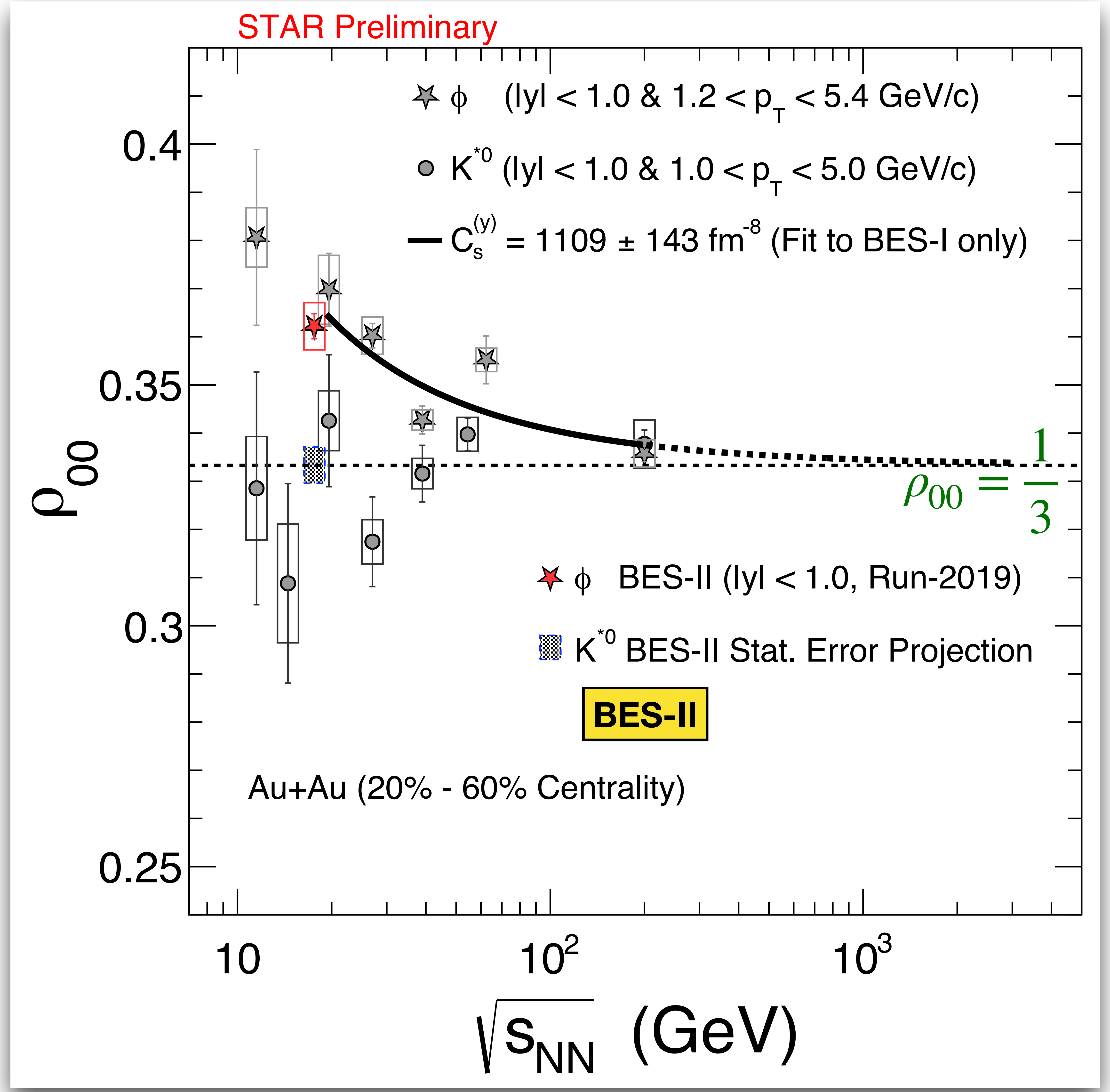


$P_z^{\Lambda} - P_z^{\overline{\Lambda}}$ ~< 0 : No indication of baryonic SHE yet

See Talk:
Qiang Hu

Global spin alignment (ρ_{00}) of φ and K^{*0}



STAR: **Nature**, 614, 244-248, (2023)
https://www.nature.com/articles/s41586-022-05557-5

$$\frac{dN}{d\cos\theta^*} = N_0\left((1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right)$$

- Surprisingly, ϕ ρ_{00} >> 1/3 but K^{*0} ρ_{00} ~ 1/3
- Can not be explained by *conventional* polarization mechanisms
- ϕ meson results can be accommodated by a model invoking a strong force field of vector meson

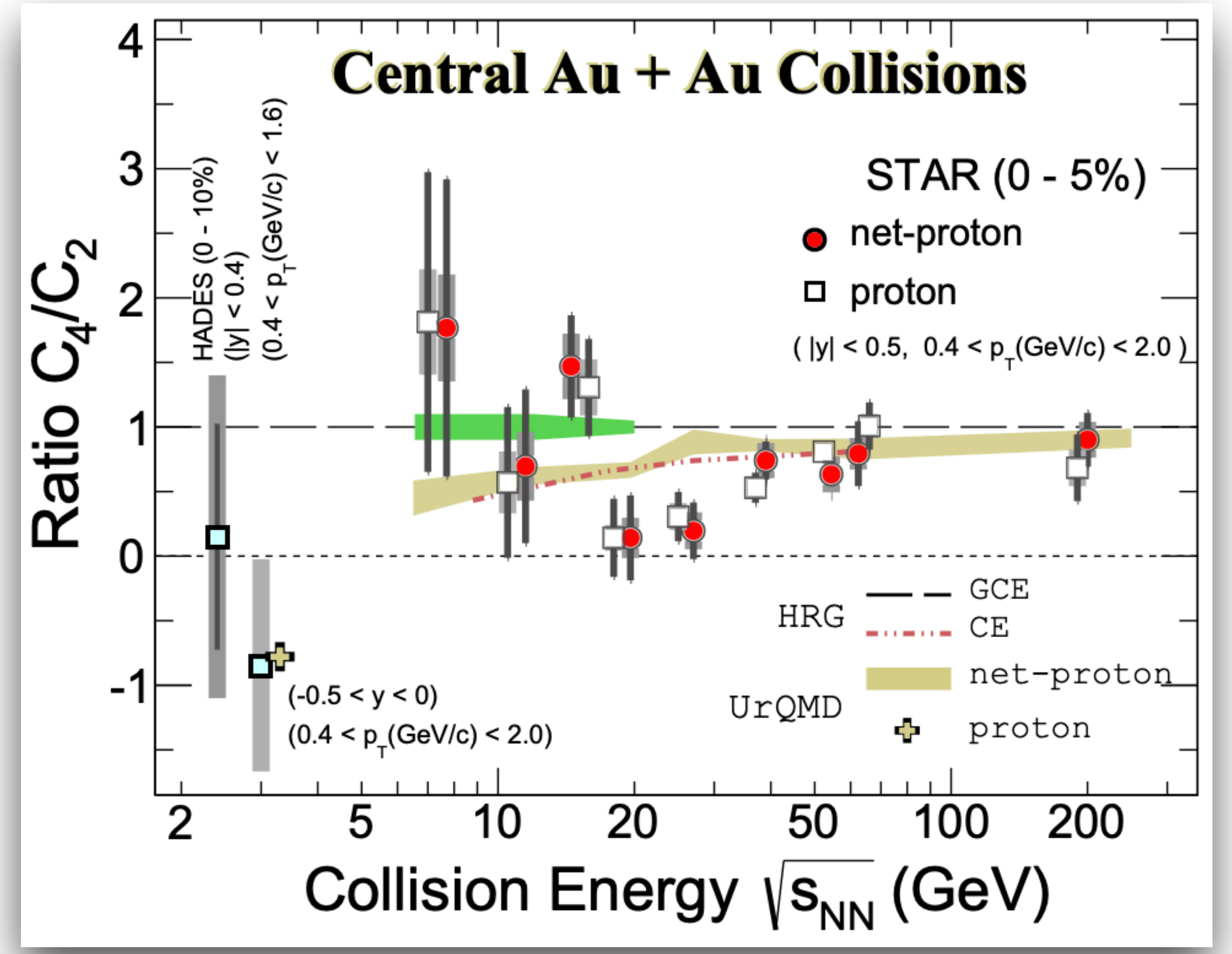
$$\rho_{00}(\phi) \approx \frac{1}{3} + \overbrace{c_\Lambda + c_\epsilon + c_E}^{\sim 10^{-4} - 10^{-5}} + c_\phi$$

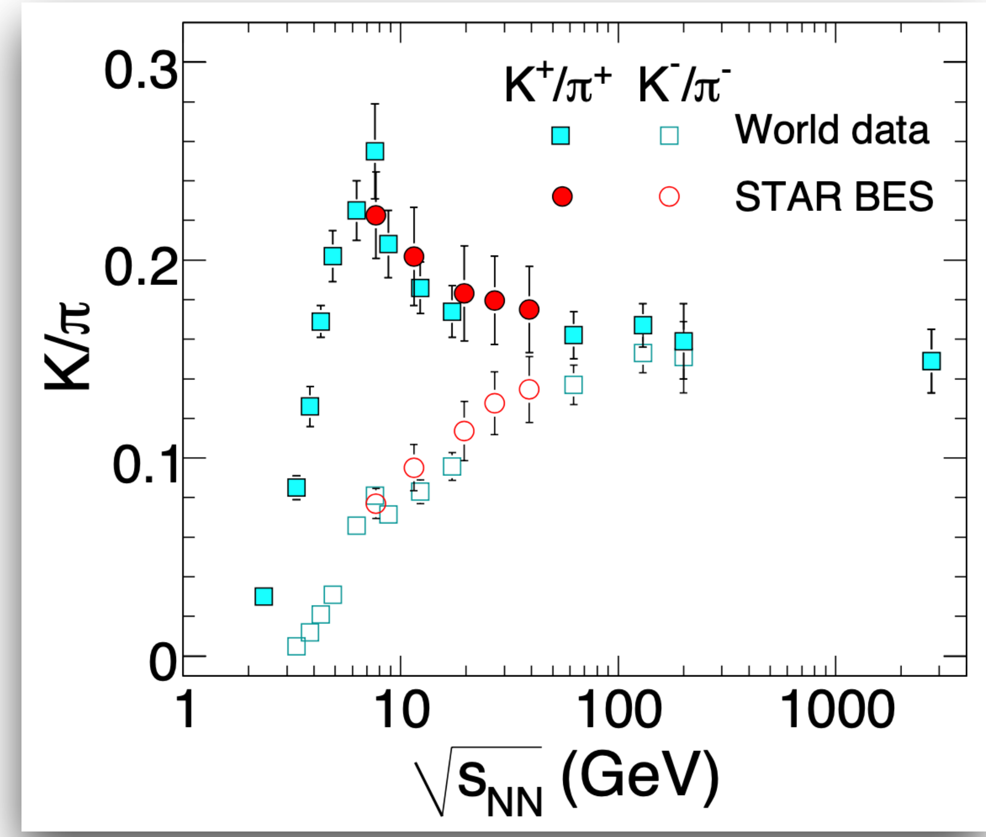
Sheng el. al., PRD 101, 096005 (2020)
Sheng el. al., PRD 102, 056013 (2020)

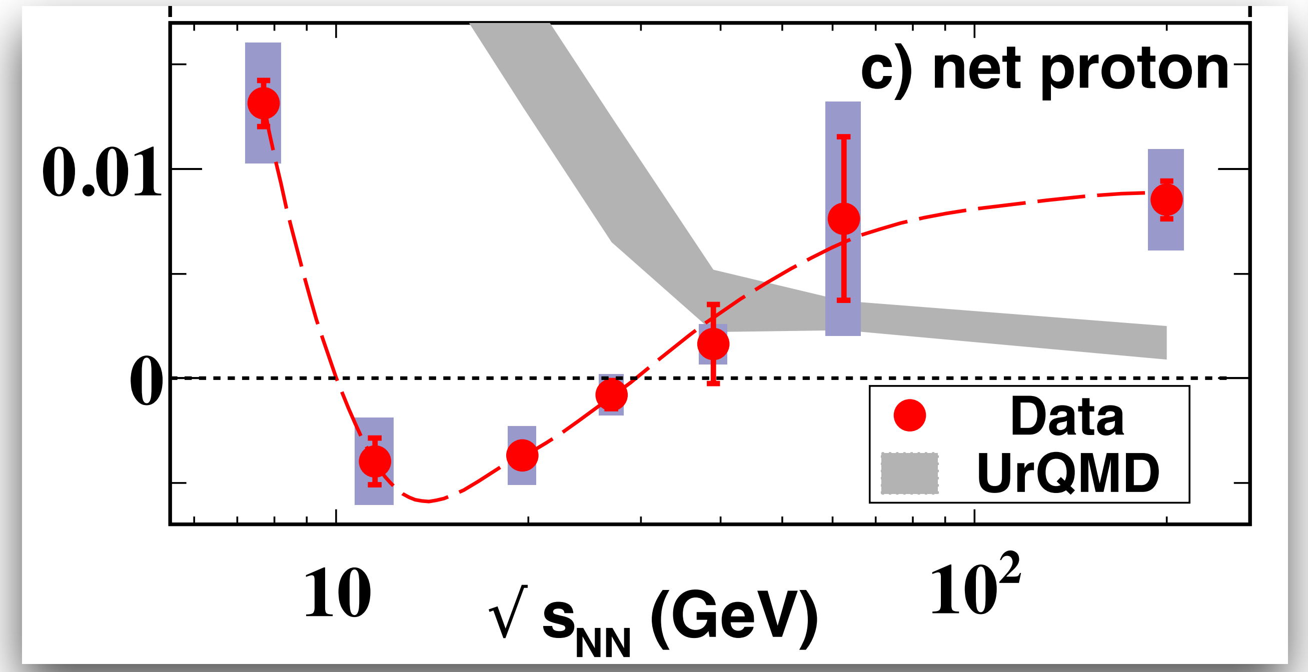
Summary

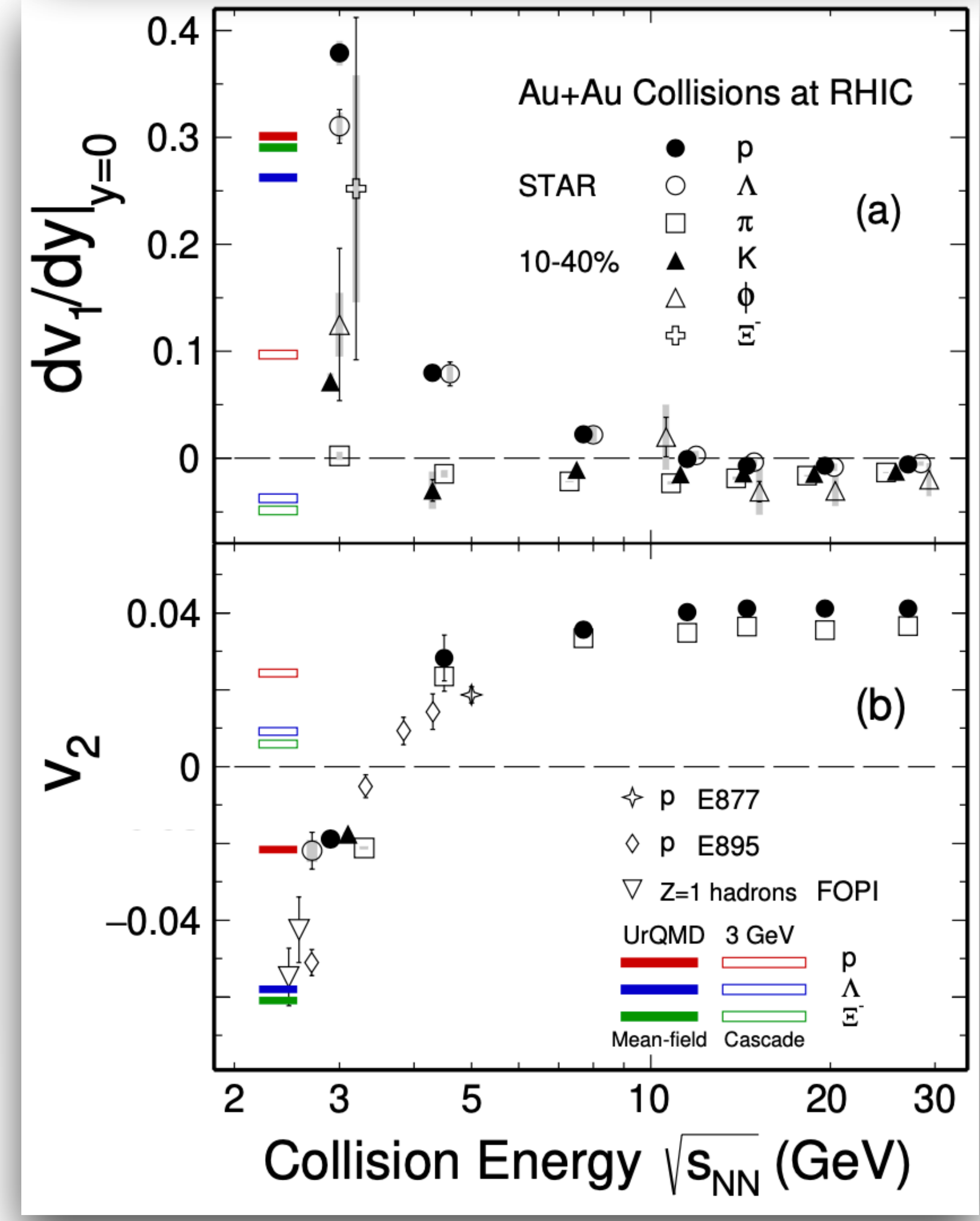
<u>At RHIC BES energies:</u>

- *Non-monotonic pattern* in observables
- Net proton higher moments
- (net) proton directed flow v_1
- K/π ratio









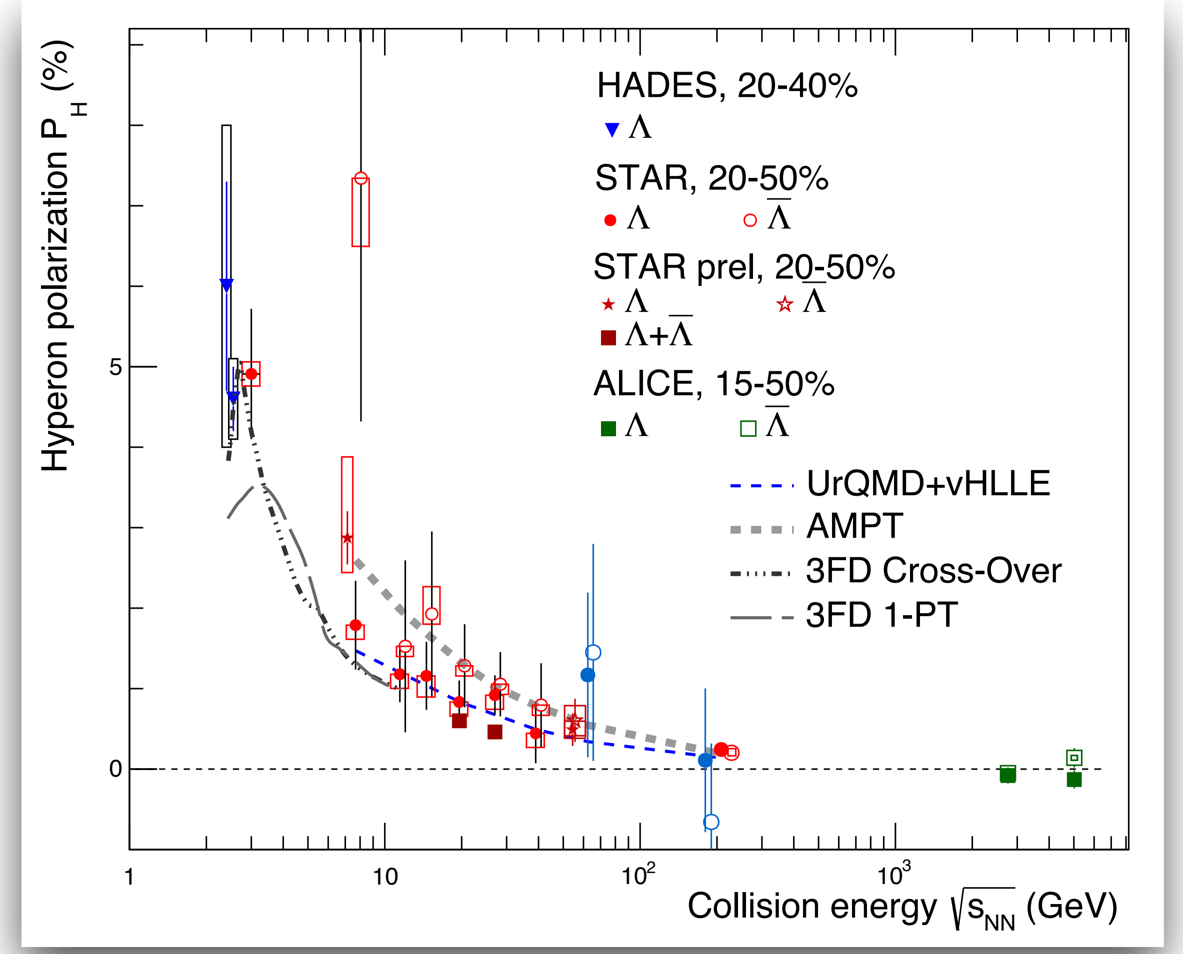
Indication of critical behavior
and *turn off* of QGP signatures

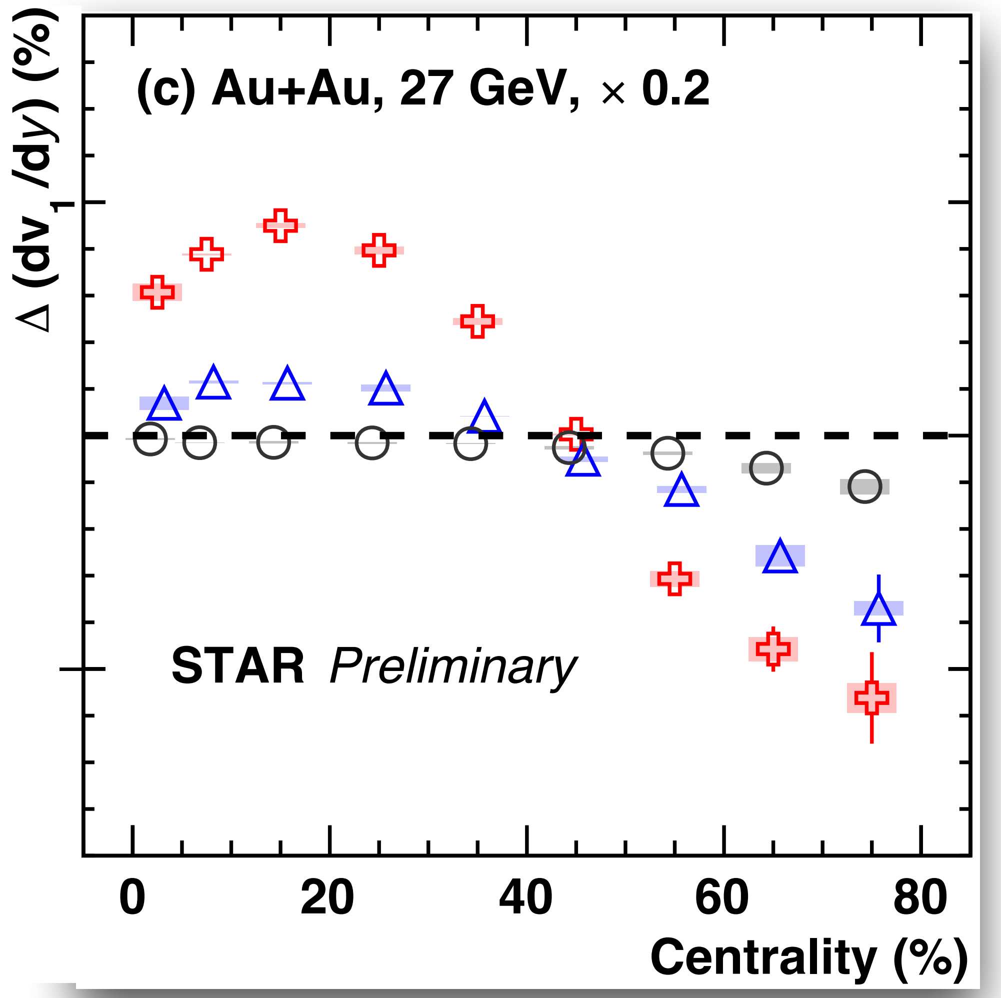
Structure of QCD matter starkly different at 3 GeV than at 200 GeV

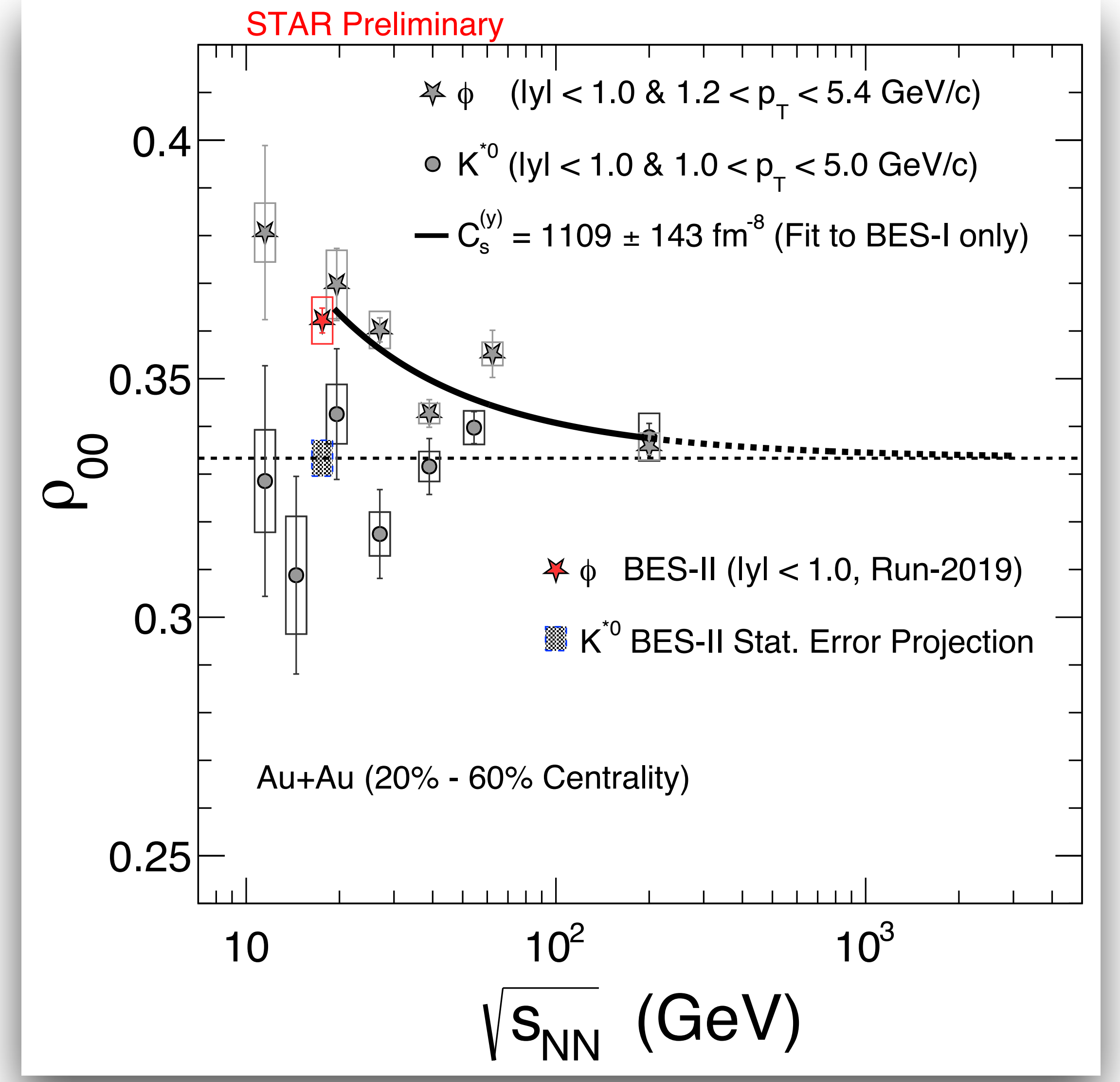
Summary

<u>At RHIC. BES energies:</u>

- *Monotonic pattern* in observables
- Global spin polarization
- Vector meson spin alignment
- Precision charge splitting in v_1 (Δv_1)







Intense initial strong fields at work:

Enormous vorticity & magnetic field
Vector meson strong force-field

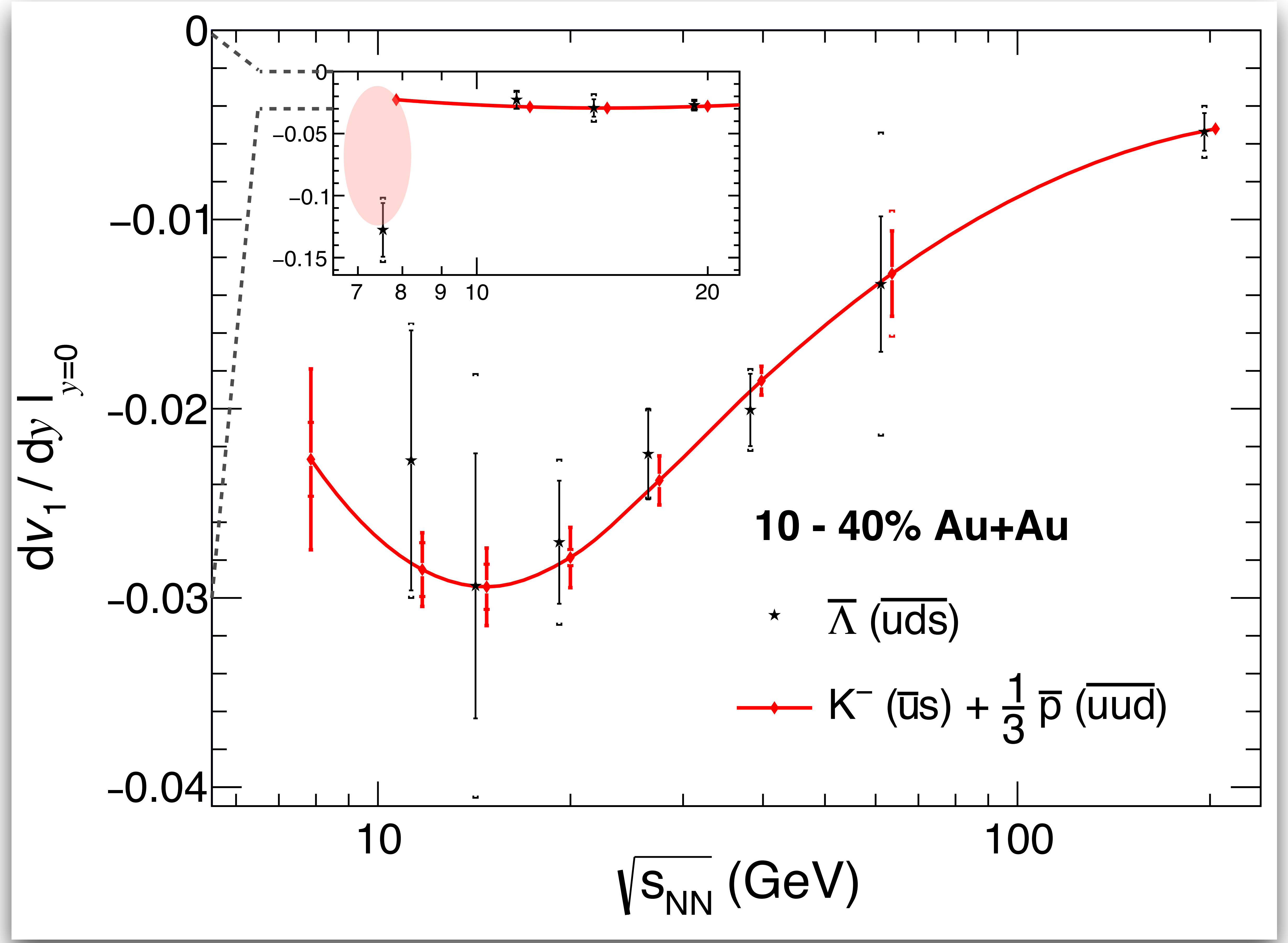
Subhash Singha @ ATHIC 2023

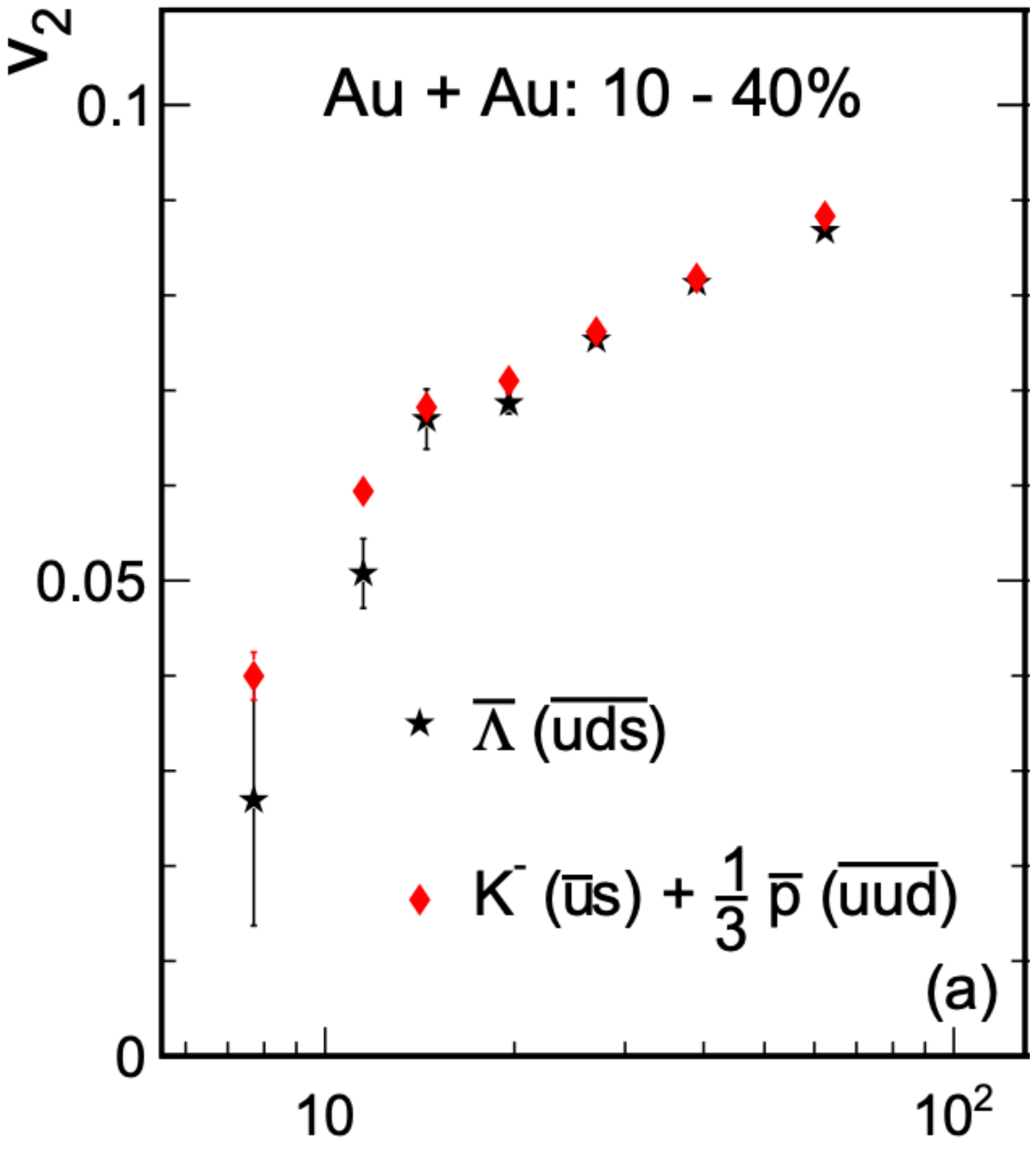
Stay tuned for exciting high-precision measurements from RHIC BES-II

Thank you for your attention

Many thanks to STAR colleagues for discussions

Quark coalescence sum rule using $v_{1,2}$





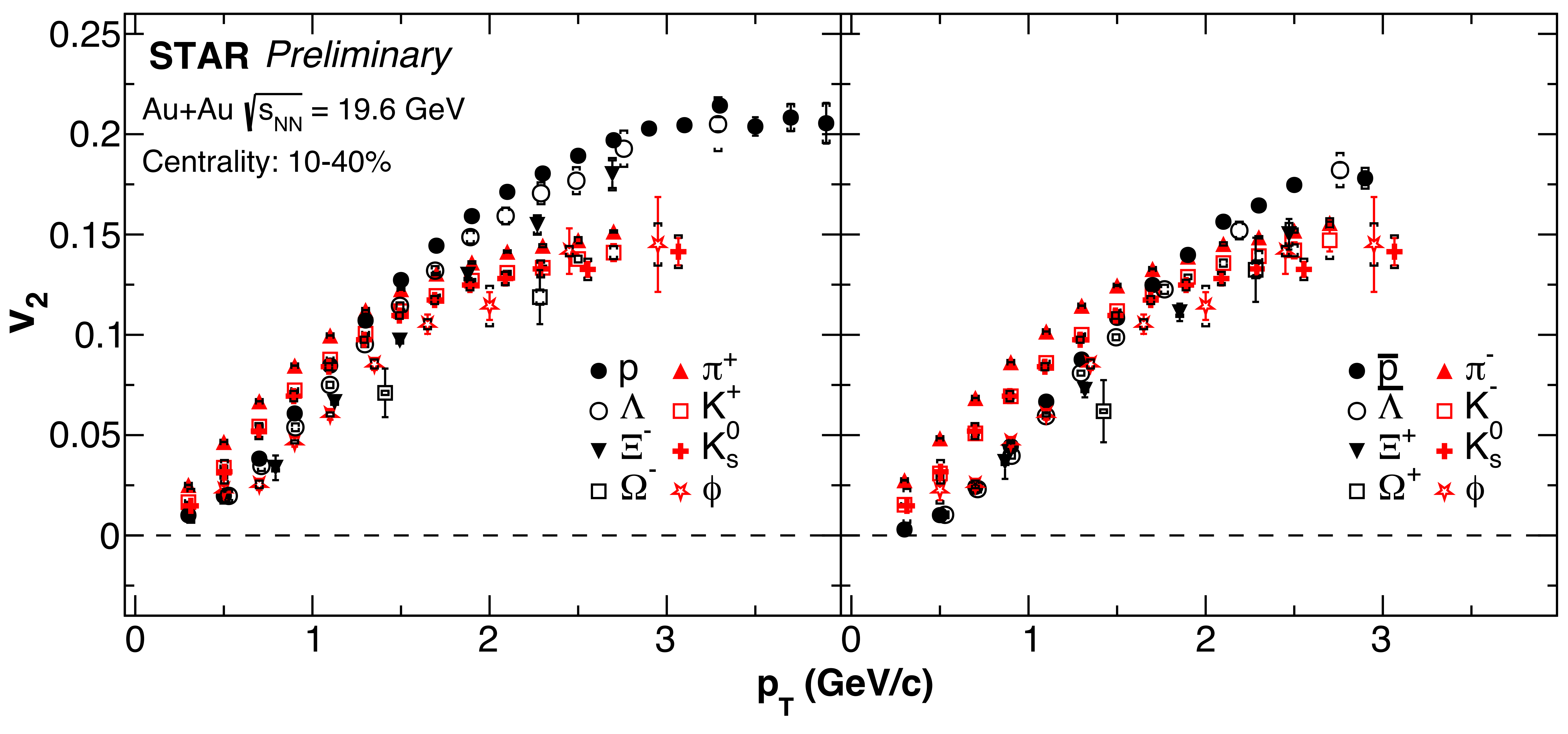
A. Goudarzi, et al,PLB 811, 135974 (2020)

Particle	Quark content
anti-Λ	uds
anti-p	uud
K-	us

Testing *quark coalescence* hypothesis

Elliptic flow (v_2) of identified particles

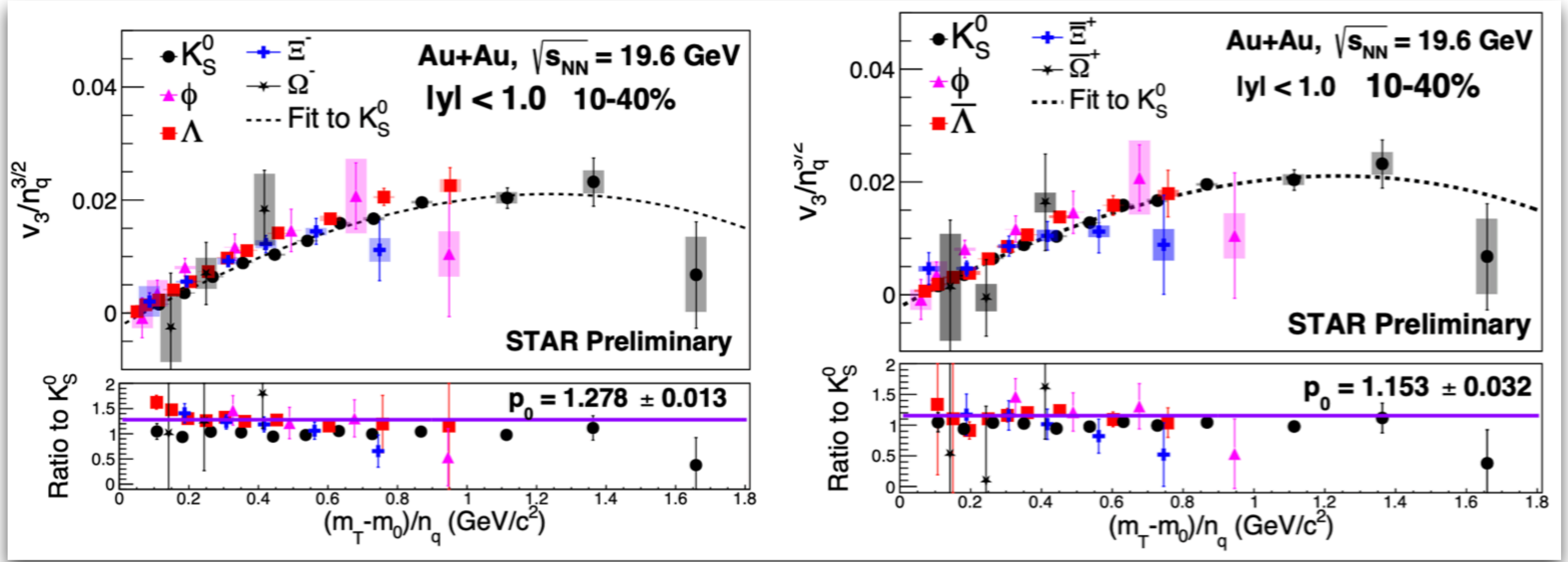
BES-II



- At low p_T: **mass ordering** in v_2
- At intermediate p_T: v_2 shows **baryons vs. mesons** ordering

NCQ scaling of v_3

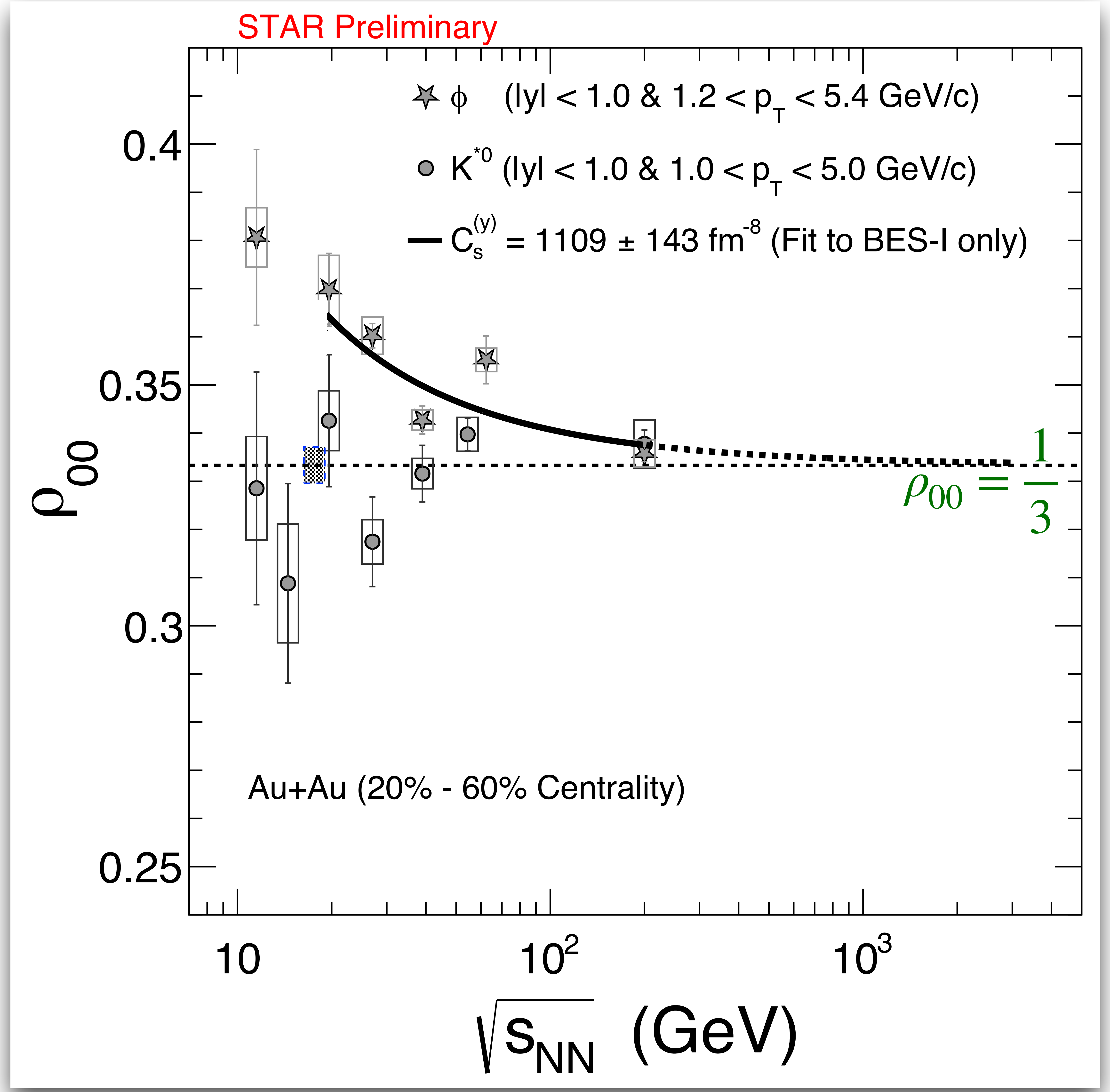
BES-II



• **NCQ scaling** for v_3 holds ~ 30% for particles; ~ 15% for anti-particles

Indication of *partonic* collectivity

Global spin alignment (ρ_{00}) of ϕ and K^{*0}



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Sheng el. al., Phys Rev D 101, 096005 (2020)
Sheng el. al., Phys Rev D 102, 056013 (2020)

Baryon stopping and transport