Strangeness Production at High Baryon Density

Outline

Introduction

Results and Discussion

1. Particle Yields and Yield Ratios
2. Centrality Dependence of Yields
3. Baryon to Meson Yield Ratio
4. Kinetic Freeze-out Properties

Summary and Outlook

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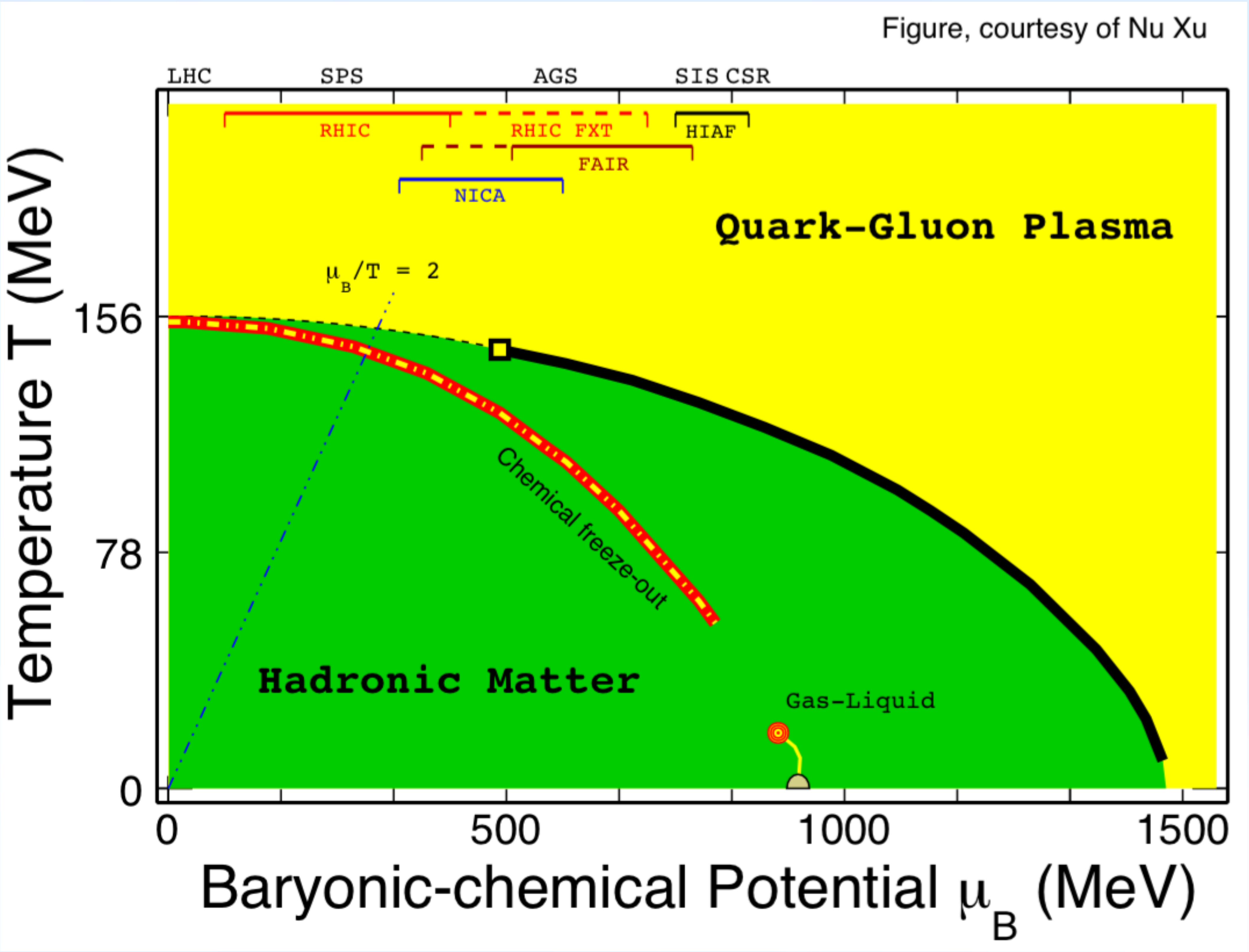
Apr. 14, 2025

PHD 2025, Darmstart, Germany

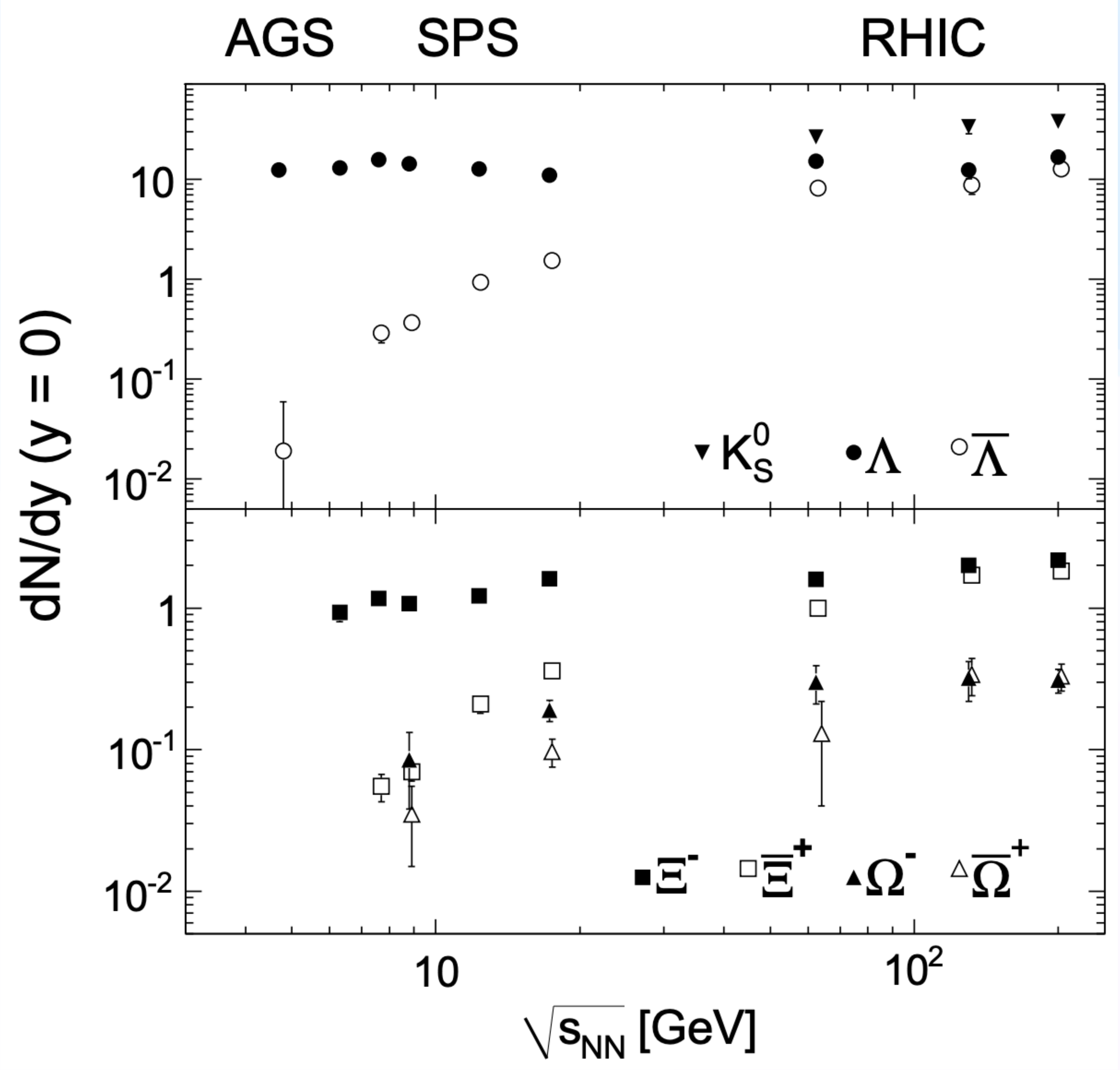
Strangeness as a Probe to Explore QCD Phase Diagram



- At small μB, LQCD predicts smooth crossover phase transition
- At large μB, QCD effective models predict 1st order phase transition

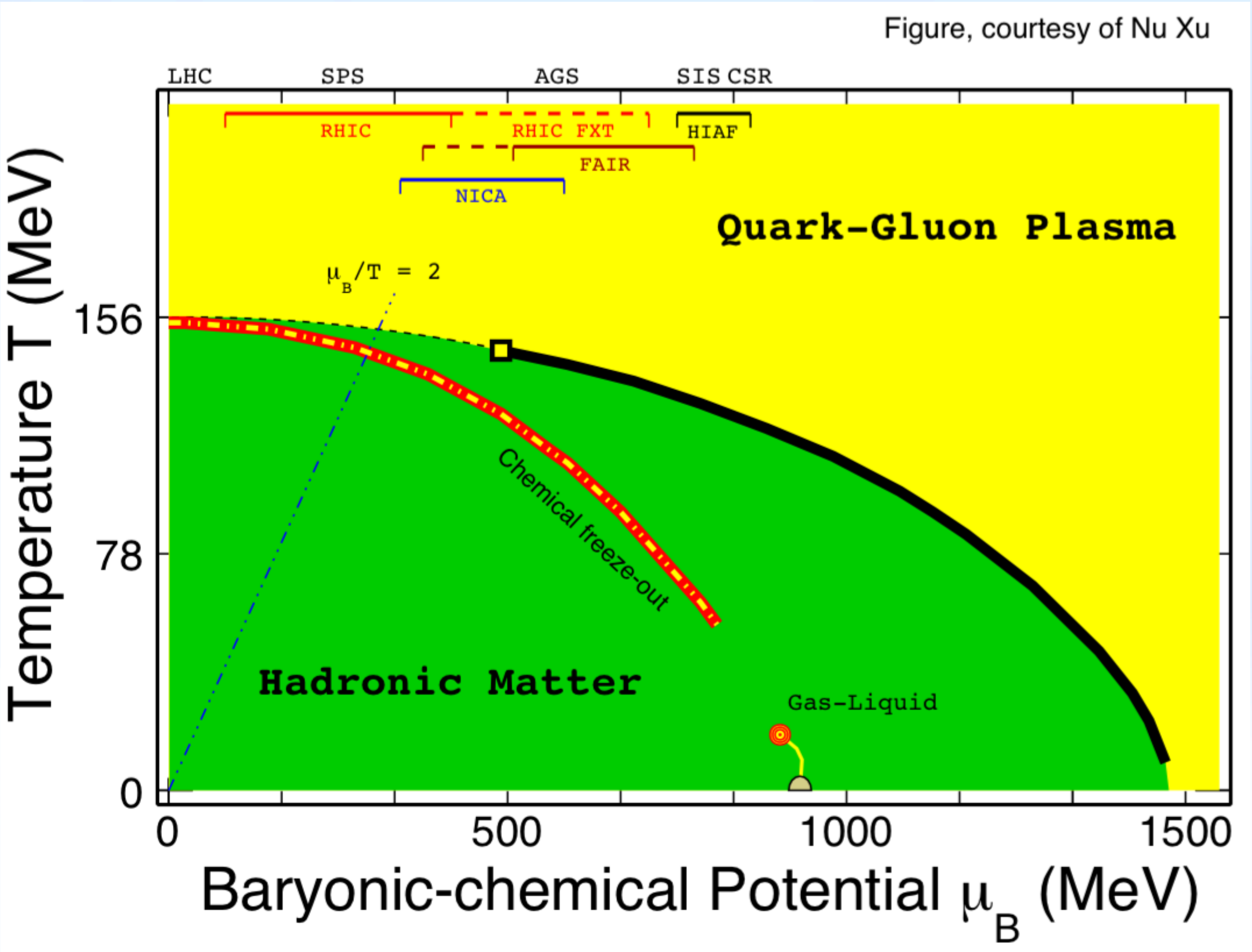
- Strange hadron have been measured in heavy-ion collisions over a broad range of baryon densities

hadronic interaction → pair production



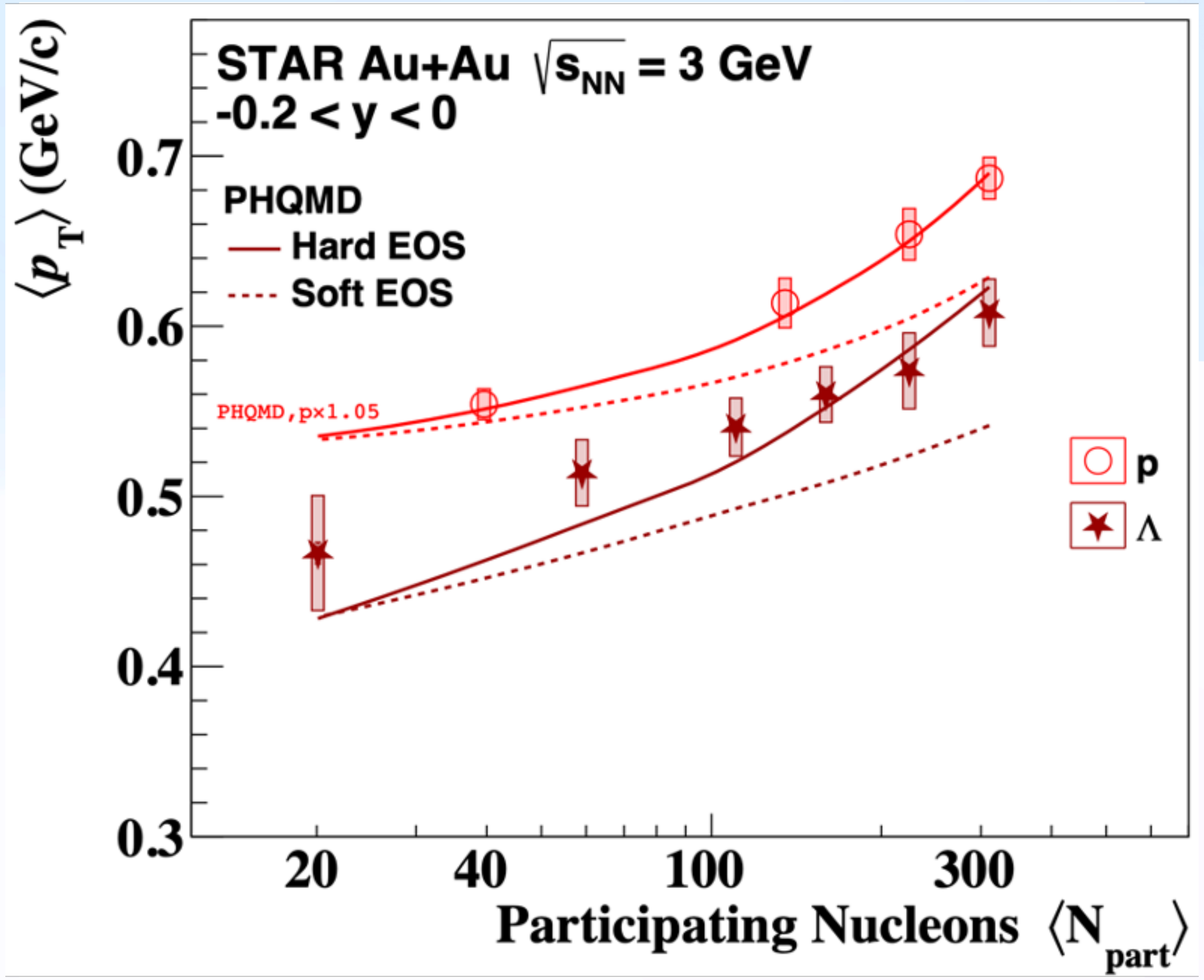
- Connections to the phase boundary, and onset of deconfinement?

Strangeness as a Probe to Study the Nuclear Matter



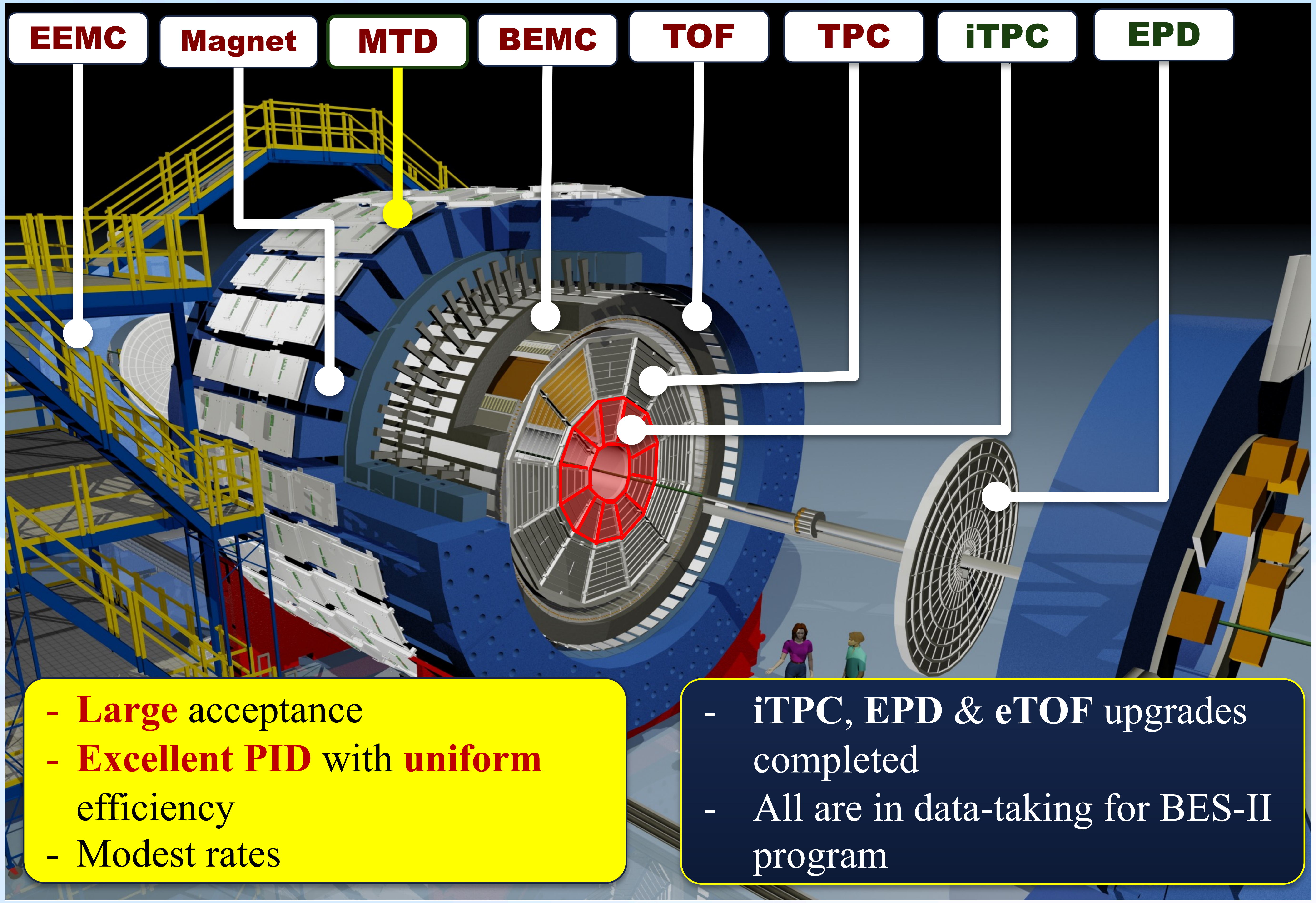
- At small μ_B, LQCD predicts smooth crossover phase transition
- At large μ_B, QCD effective models predict 1st order phase transition

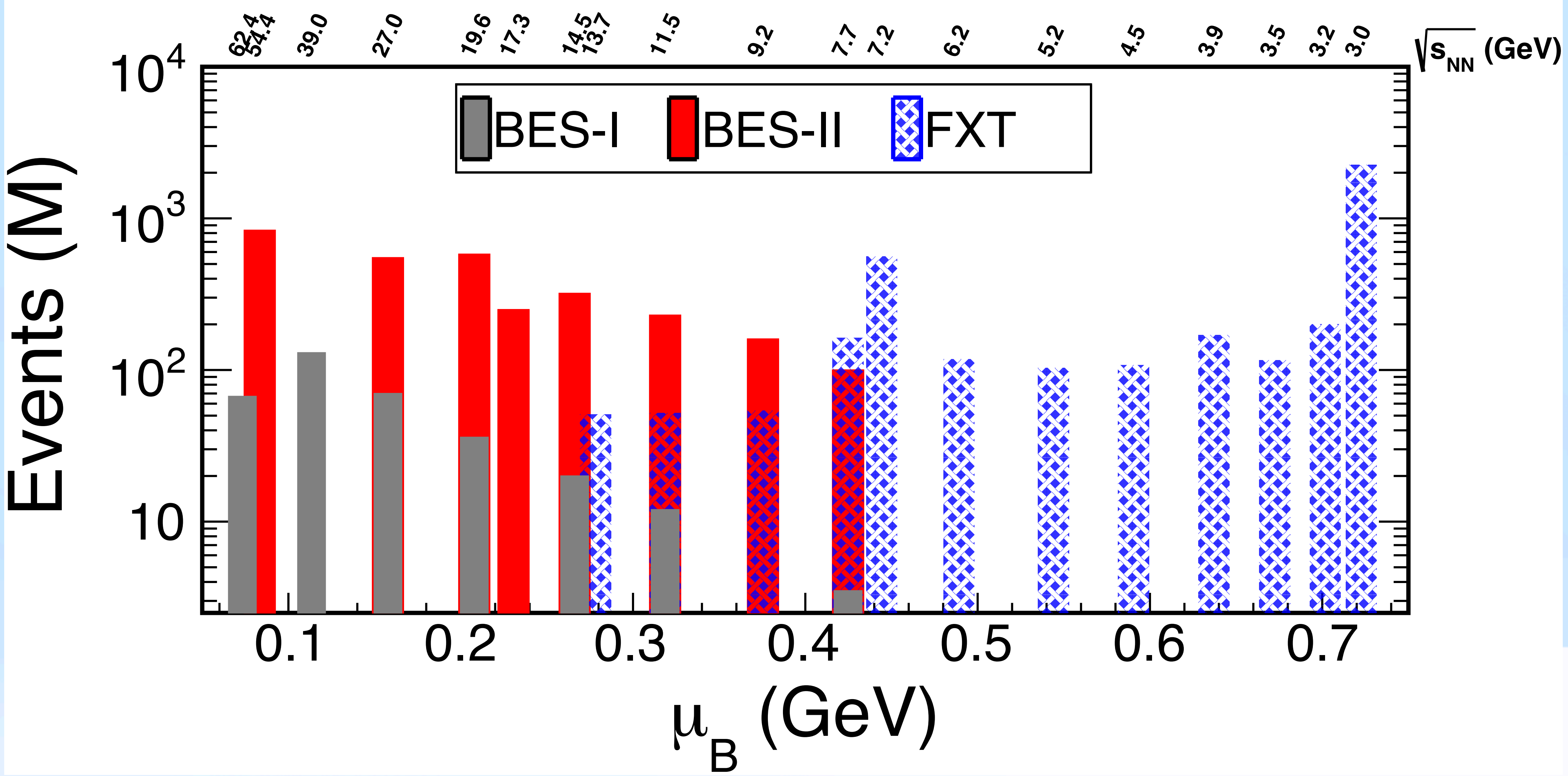
- Transport model predict a larger $\langle p_T \rangle$ at a stiffer EOS

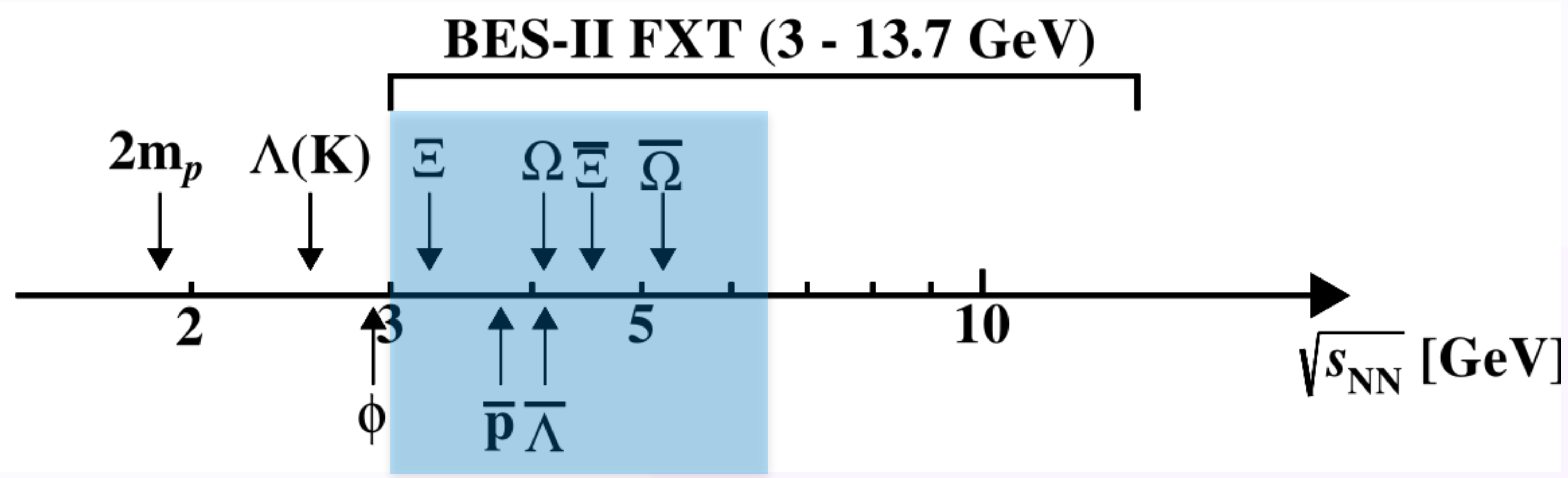


- Connections to the softness of dense nuclear matter?

STAR and Beam Energy Scan



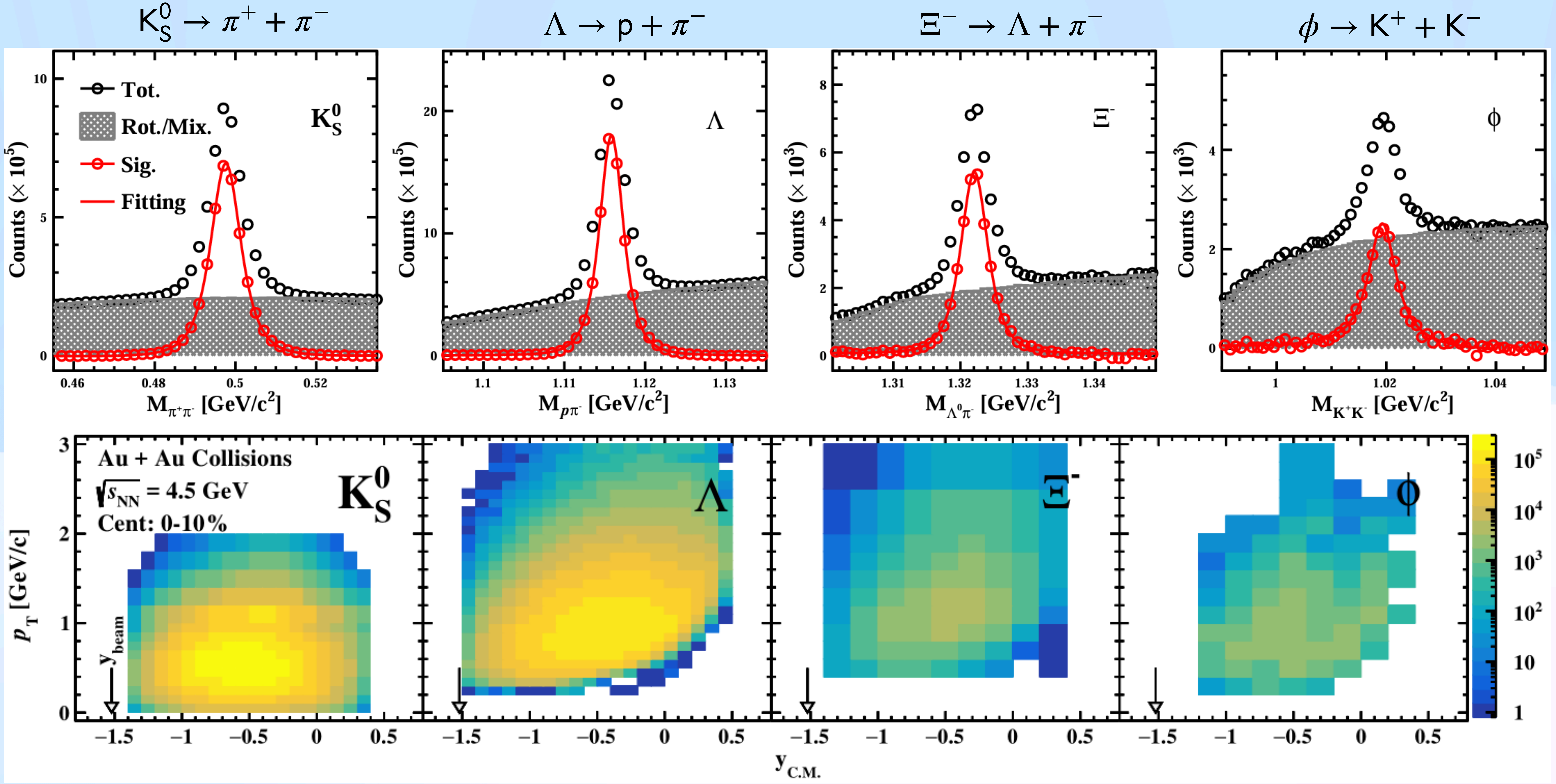




- RHIC BES-II offers great opportunity for near or sub-threshold strangeness measurements

New results from BES-II data at: 3.2, 3.5, 3.9, 4.5, 5.2, 6.2 GeV

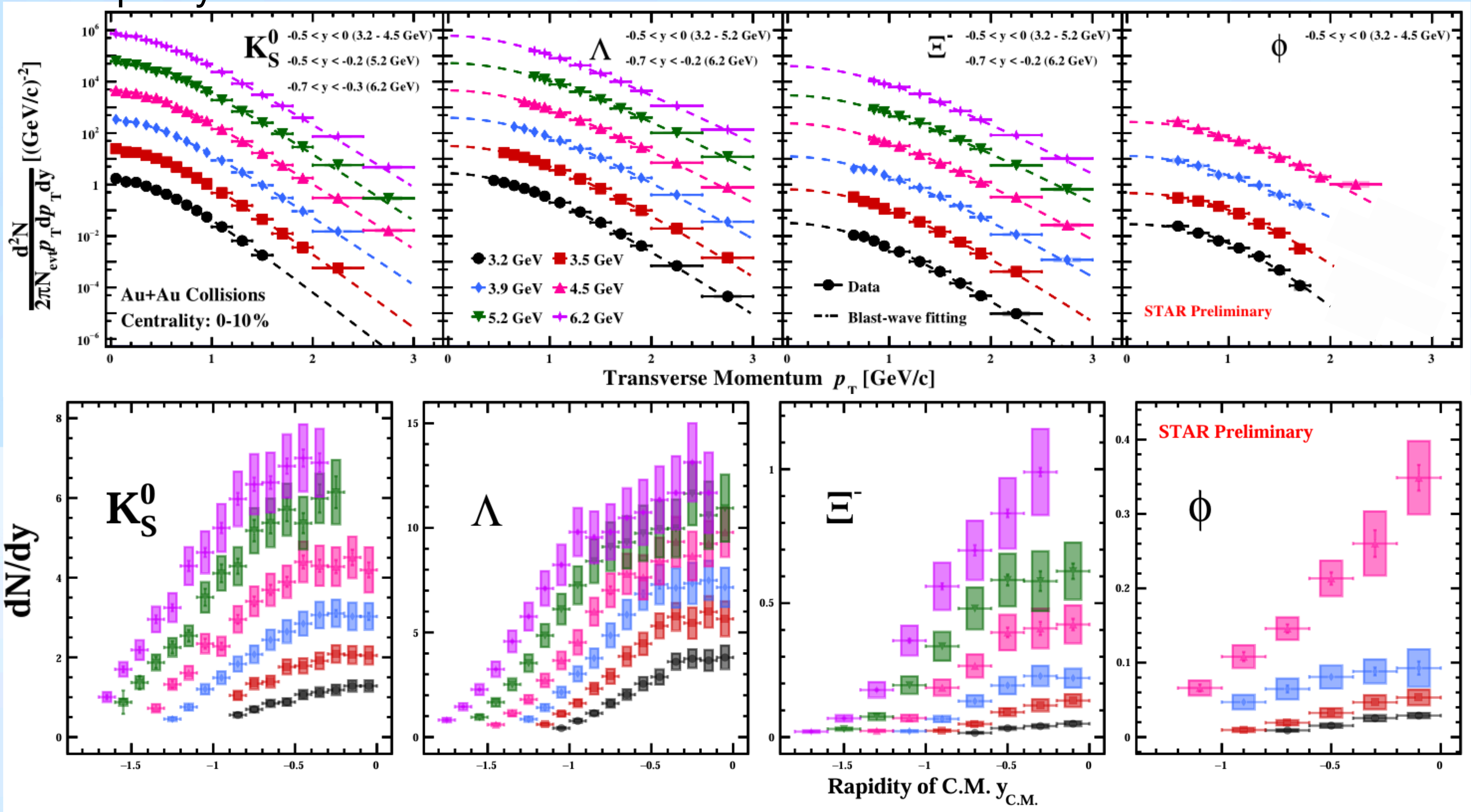
Strangeness Reconstruction



- Combinatorial background estimated via mixed-event or rotation technique
- Efficiency correction using a GEANT simulation

Strangeness p_T Spectra and Rapidity

Mid-rapidity



Au+Au 0-10%

6.2 GeV

5.2 GeV

4.5 GeV

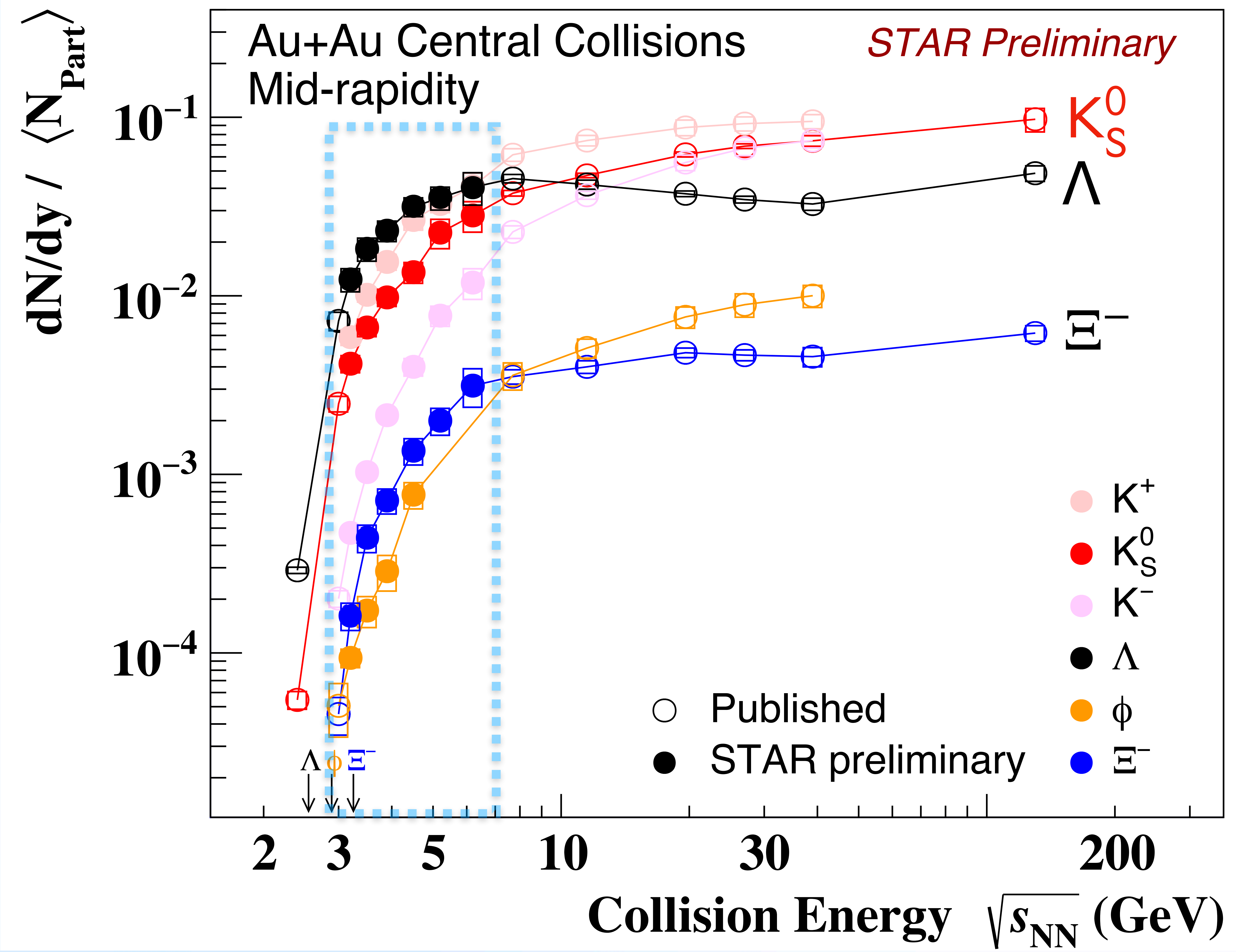
⋮

3.2 GeV

- p_T fitted by blast-wave function
- dN/dy = measured data + fit function

- Comprehensive strangeness measurements at different energies from 3.2 to 6.2 GeV

Excitation Function



STAR, PRC 96, 044904 (2017); PRC 102, 034909 (2020); PLB 831, 137152 (2022); JHEP 2024, 139 (2024)
HADES, PLB 793, 457 (2019)

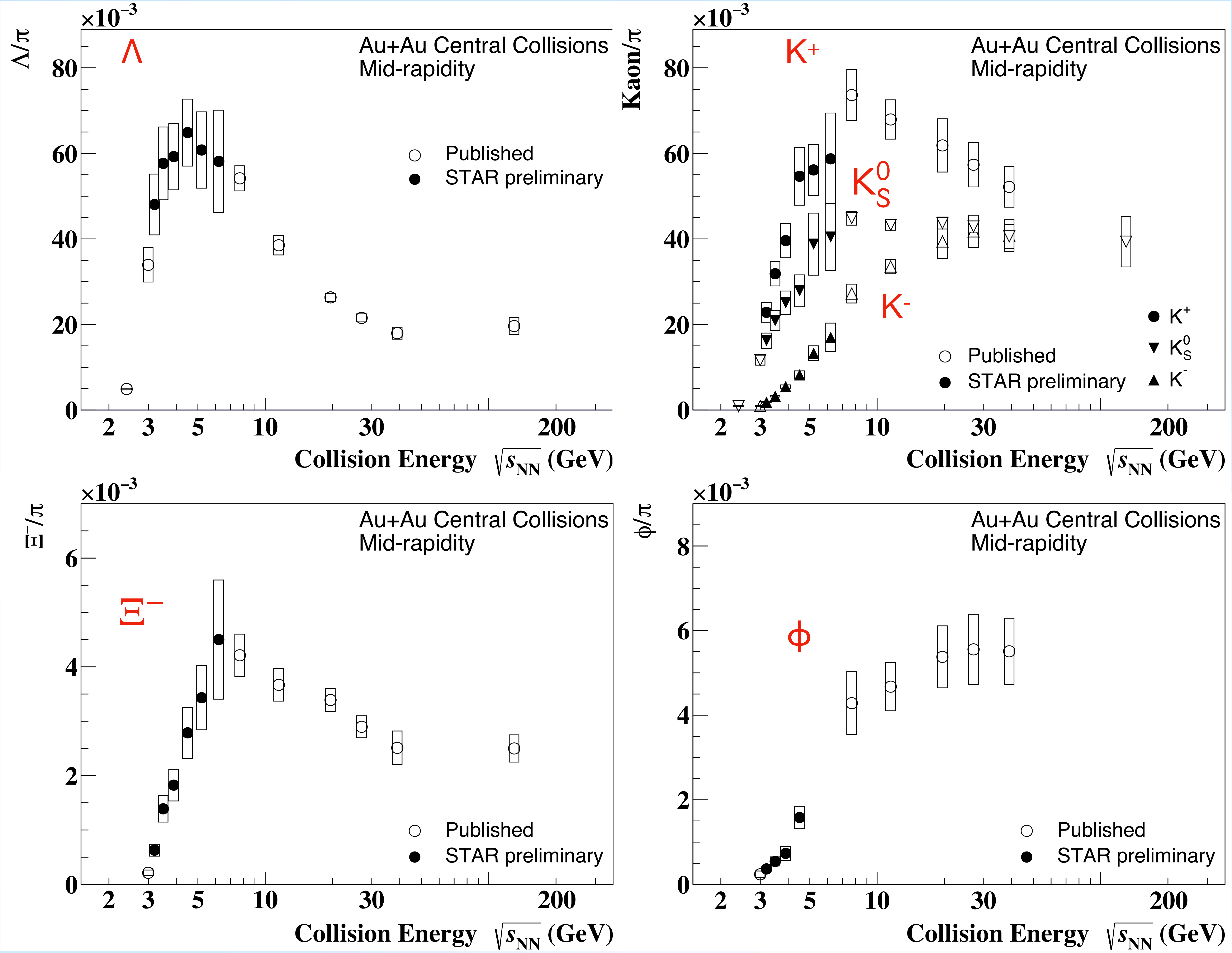
- Mid-rapidity yields increases rapidly at low energy and approximately saturate at high energy

  Λ yields exceed those of K^0_S below $\sqrt{s_{NN}}$ ~ 8 GeV

- First measurement of Ξ^- at sub-threshold energy in Au+Au collisions

Yield Ratios v.s. Collision Energy

Constructed from STAR Preliminary results: $K^{\pm}$, K^0_S, ϕ, Λ, and Ξ^-



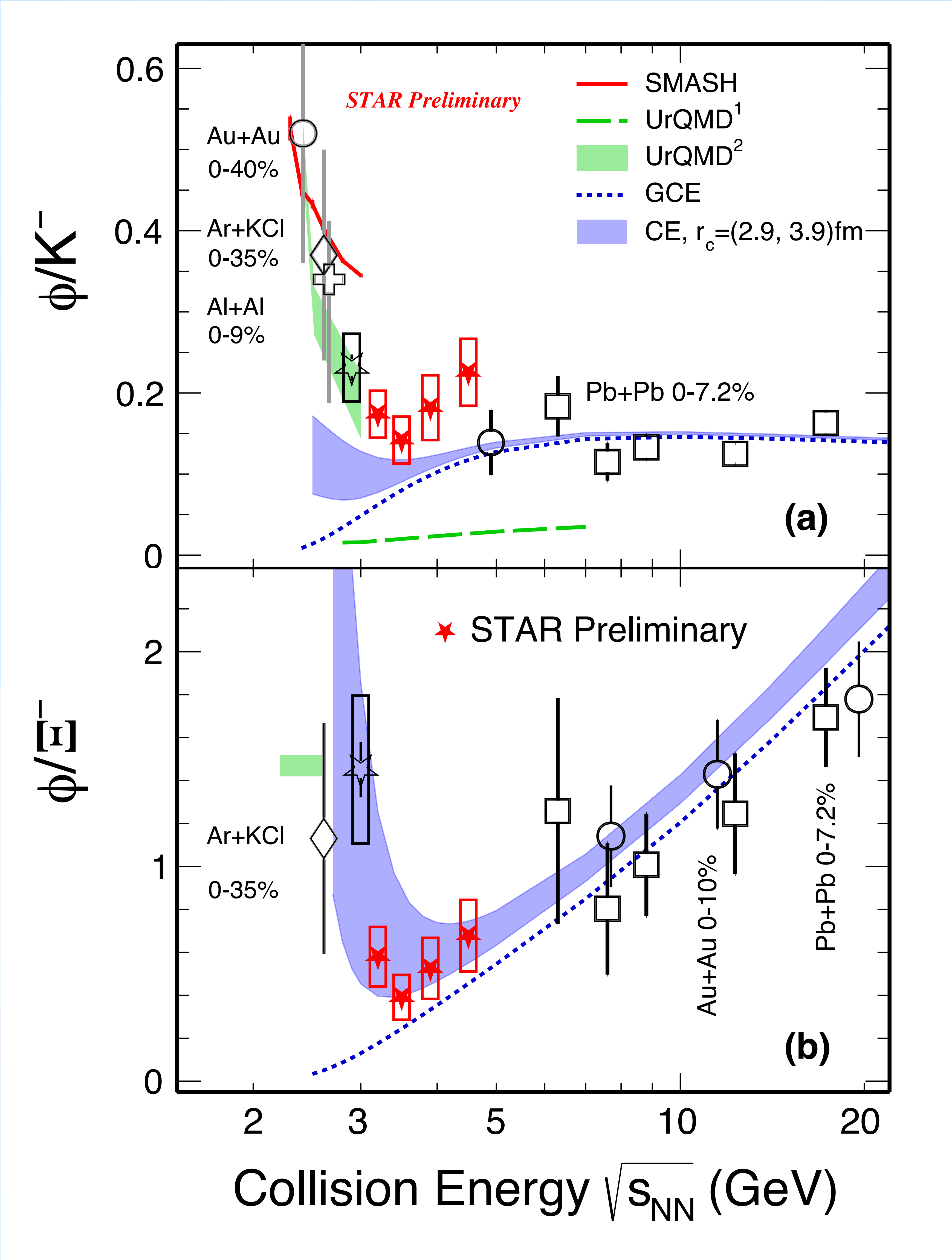
- K^+/π, Λ/π and Ξ^-/π exhibit a peak structure around $\sqrt{s_{NN}}$ = 7–10 GeV

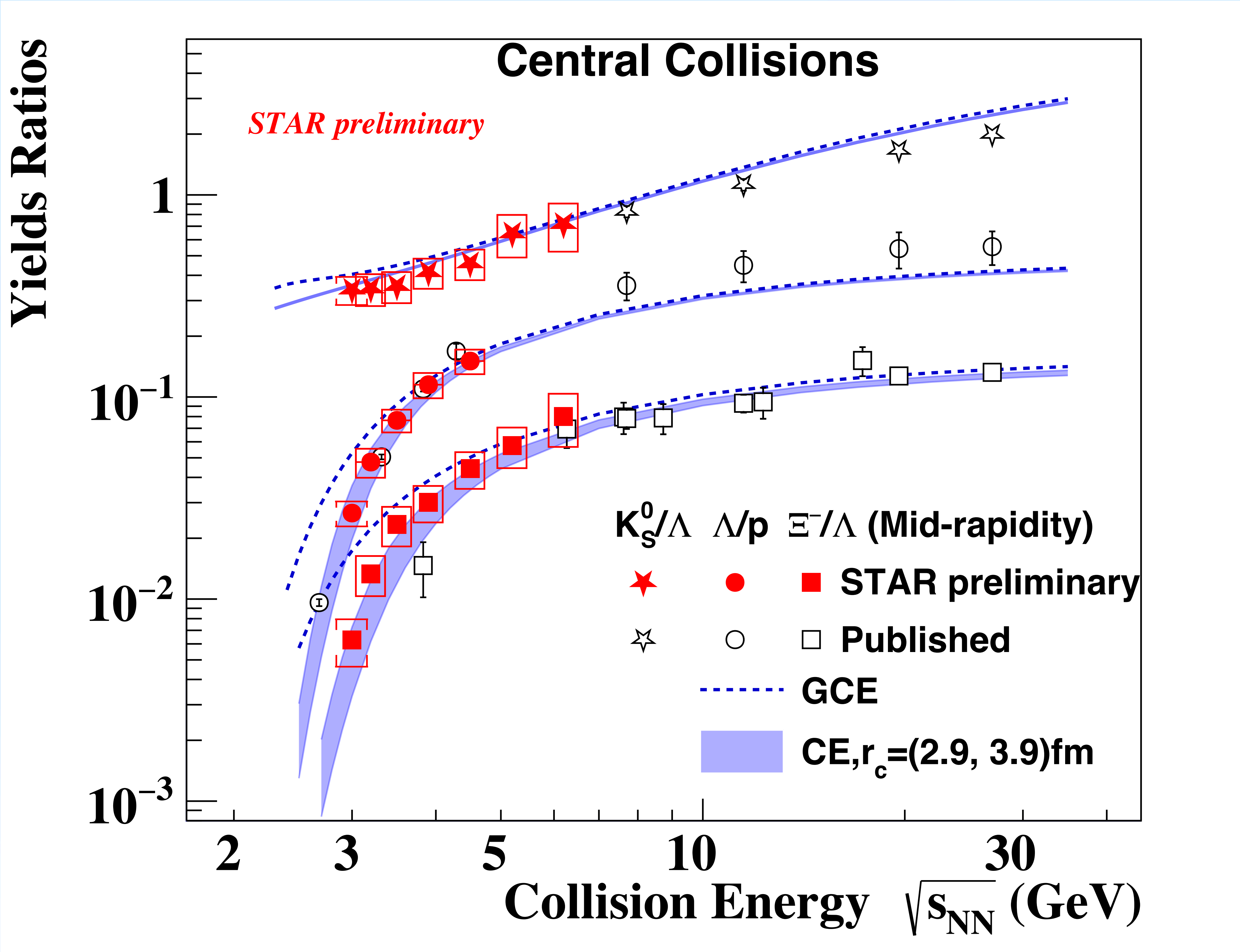
π extracted from published data fit

S. Chatterjee et al., Adv. High Energy Phys. 2015, 349013

STAR, PRC 96, 044904 (2017); PRC 102, 034909 (2020); PLB 831, 137152 (2022); JHEP 2024, 139 (2024)
HADES, PLB 793, 457 (2019)

Yield Ratios Comparison with Thermal Model



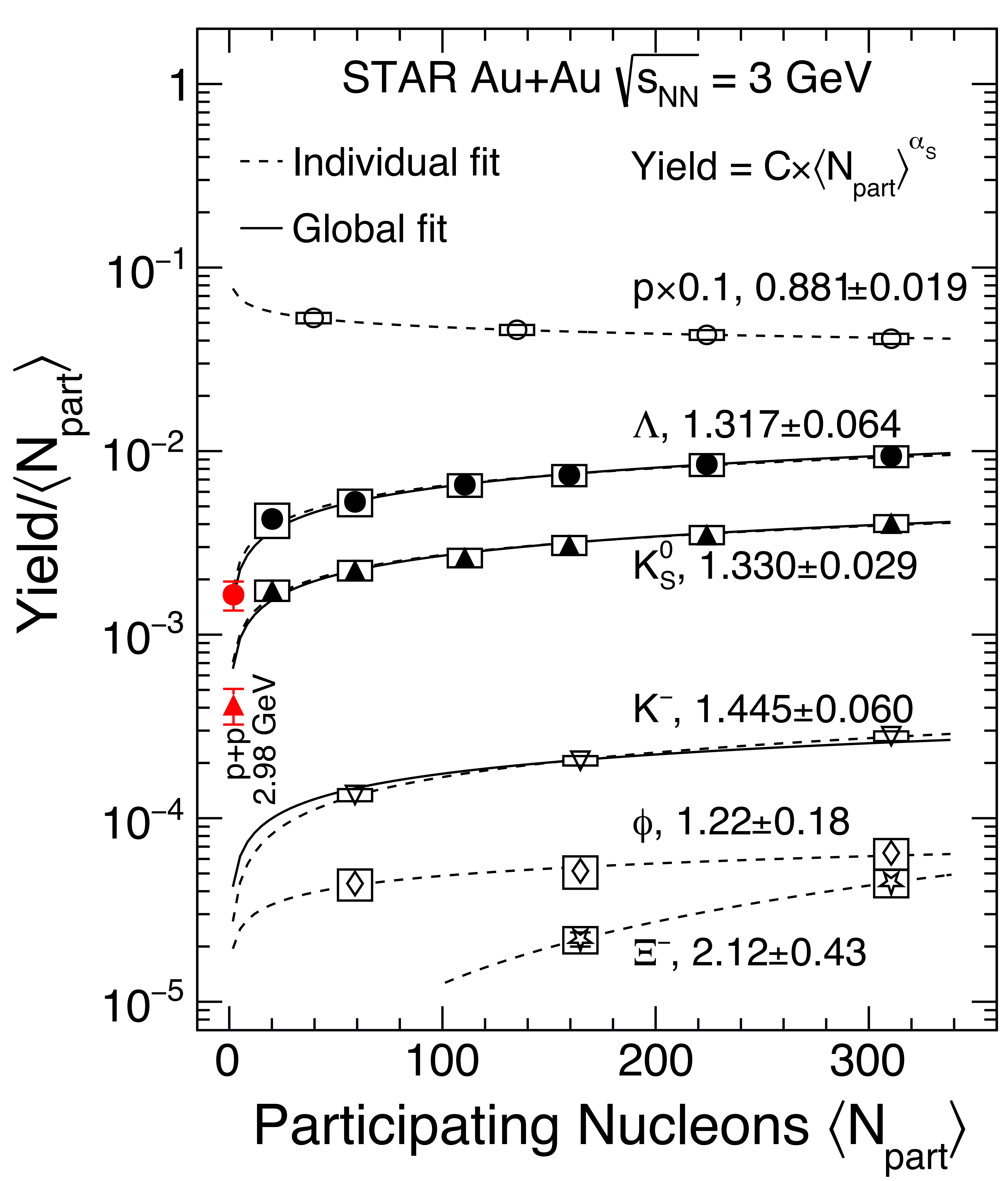


STAR: JHEP 2024, 139 (2024)
STAR, PRC 102, 034909 (2020)
HADES, PLB 793, 457 (2019)
Thermal: V. Vovchenko et al., PRC 93, 064906 (2016)
UrQMD: S.A. Bass, et.al. Prog. Part. Nucl. Phys. 41 (1998)

- Canonical Ensemble (CE) describe yield ratios with r_c ~ 3–4 fm, but GCE fails below $\sqrt{s_{NN}}$ ~ 5 GeV

Change of medium properties at the high-density region

Centrality Dependence of Yields at 3 GeV



STAR: JHEP 2024, 139 (2024)

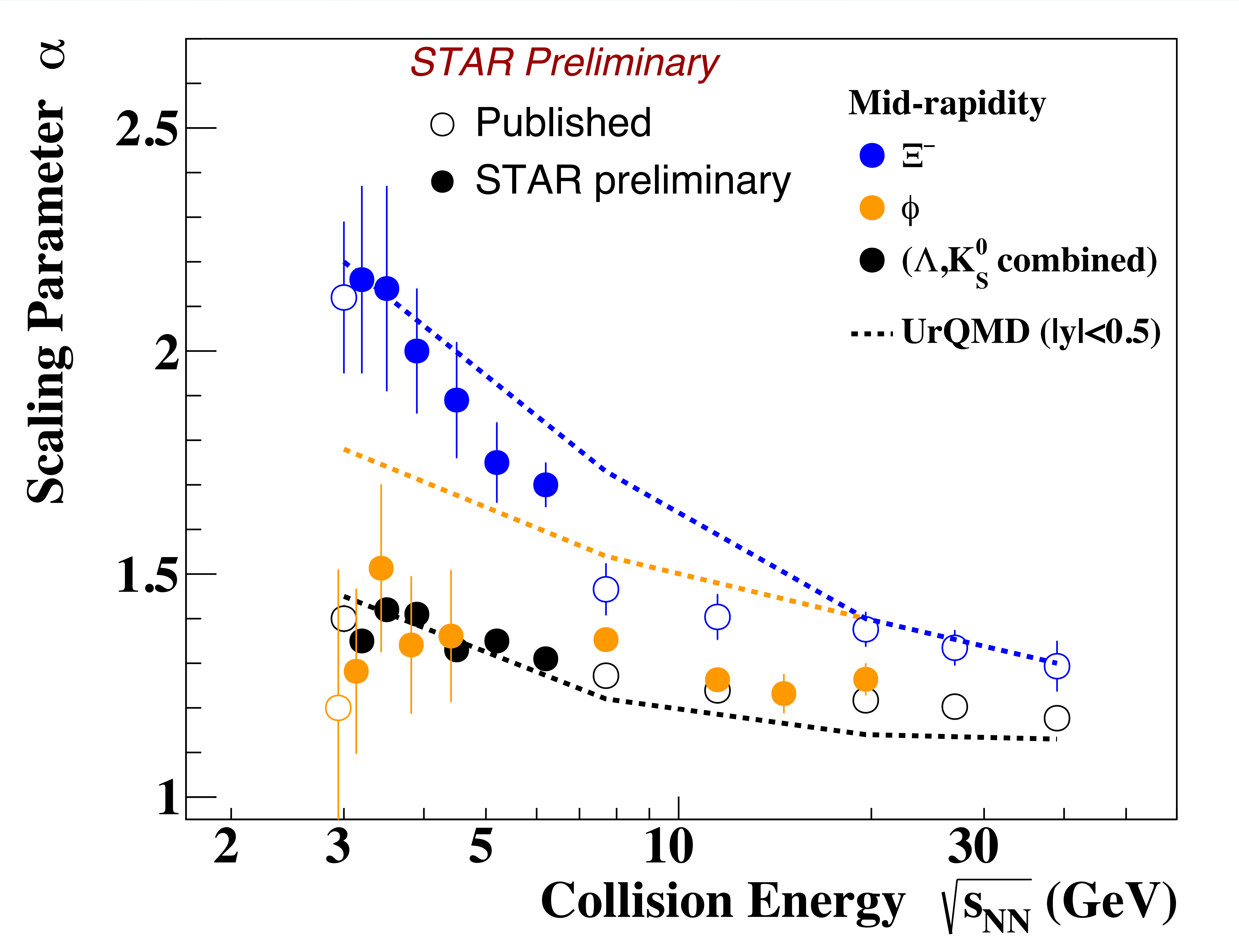
1. Single strange hadron yields (K^-, K^0_S, Λ) follow common ⟨N_{part}⟩ scaling, but Ξ^- seems to has significantly larger α (2σ deviation from S=1)
    - Likely due to Ξ^- mainly produced via multi-step hadronic interactions

      e.g. NN → NN*, NN* → NΞKK

2. p+p following the scaling trend

Hadronic interactions drive the observed trends

Centrality Dependence of Yields v.s. Collision Energy

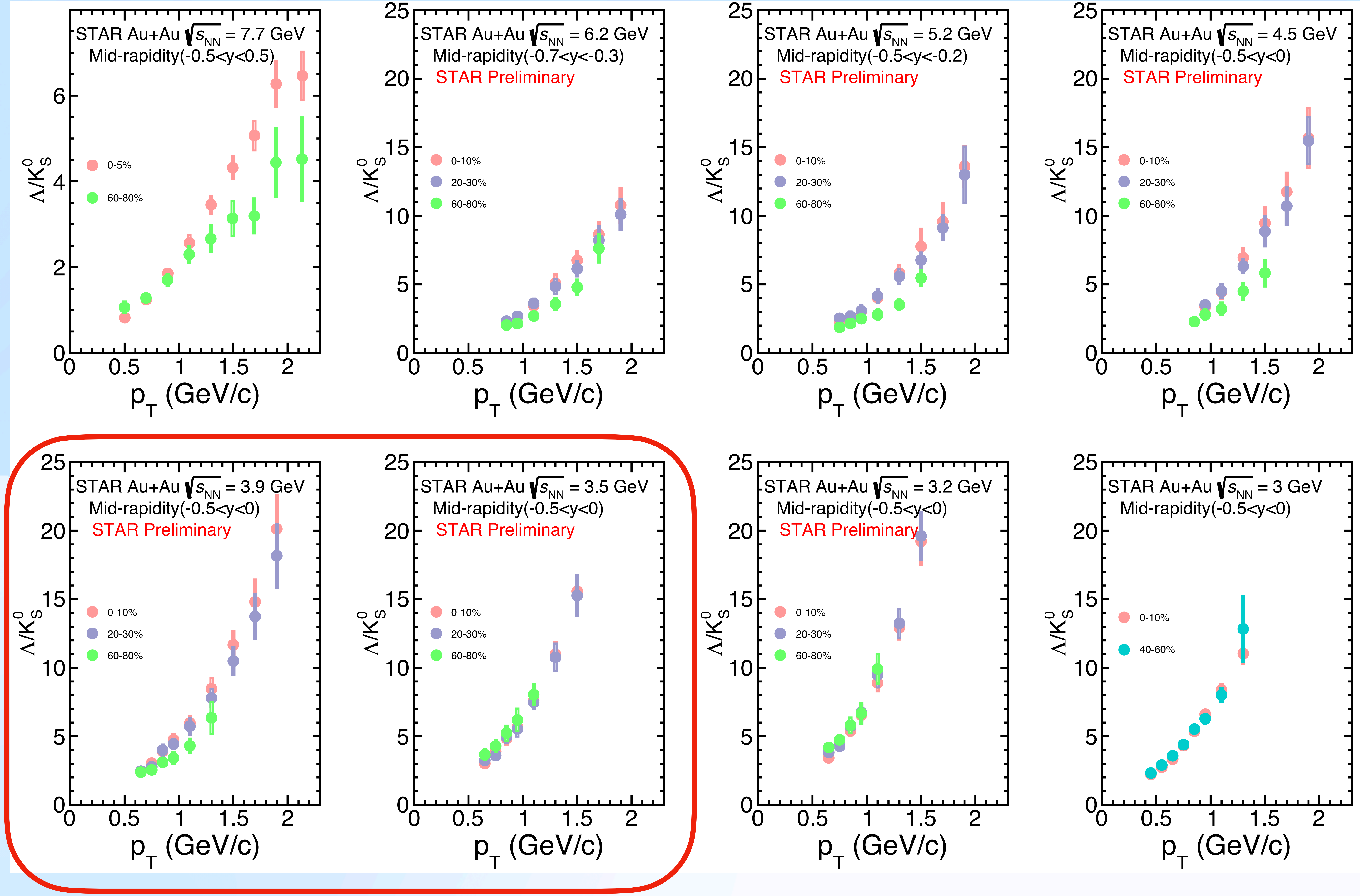


1. Rapid decrease of scaling parameter α for Ξ^- from 4.5 to 7.7 GeV, and saturate at high energy

2. UrQMD qualitatively reproduces the energy dependence
   - Overestimates α for ϕ meson

STAR: JHEP 2024, 139 (2024)
STAR, PRC 102, 034909 (2020)
HADES, PLB 793, 457 (2019)
UrQMD: S.A. Bass, et.al. Prog. Part. Nucl. Phys. 41 (1998)

Baryon to Meson Yield Ratio



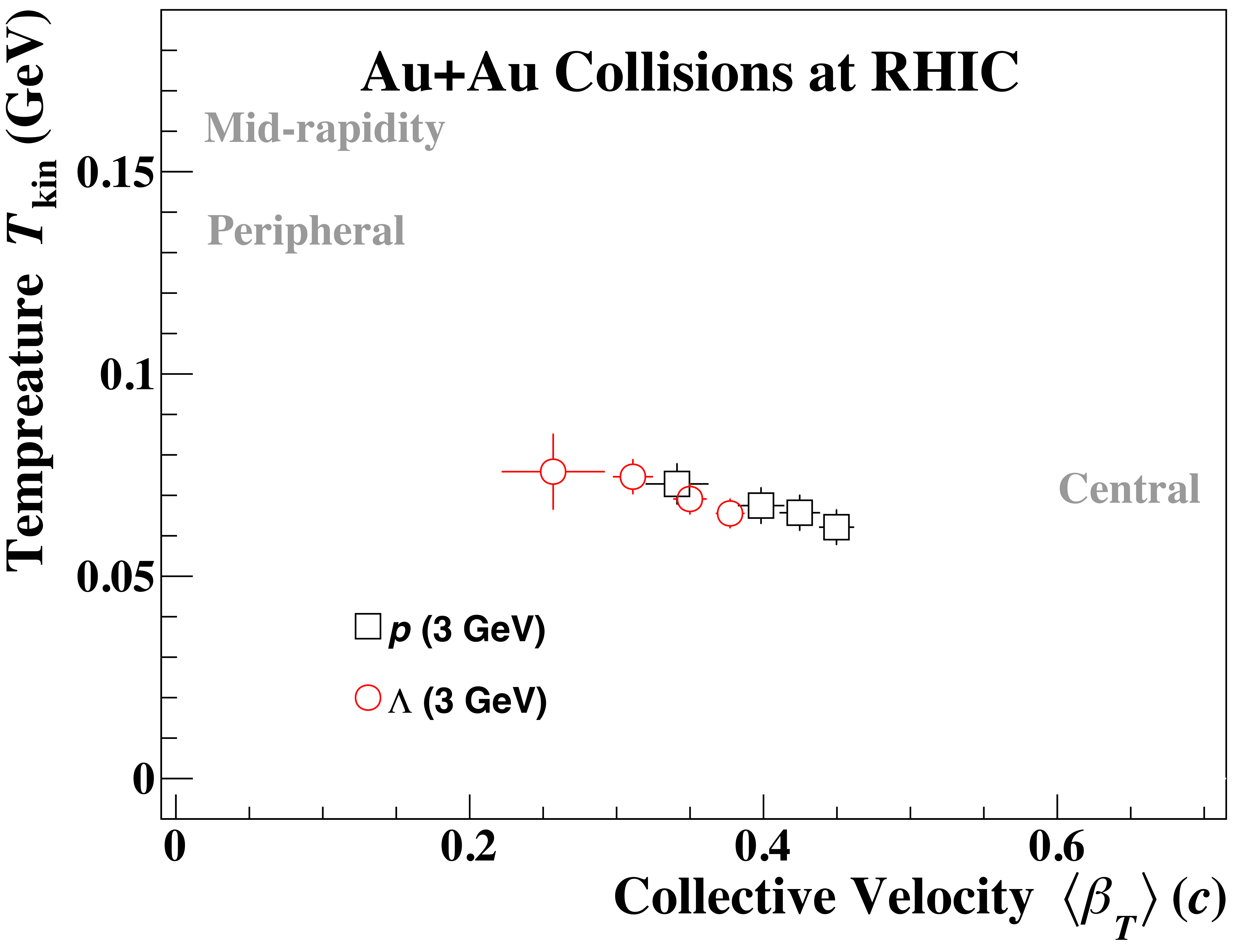
1. Quark recombination can lead to baryon to meson enhancement

2. Λ/K^0_S enhancement at $p_T > 1$ GeV/c is observed above $\sqrt{s_{NN}} = 3.9$ GeV, but not below

Theoretical inputs needed

STAR: JHEP 2024, 139 (2024)

Kinetic Freeze-out Properties



- $\langle\beta_T\rangle$ decreases while T_{kin} slightly increases from central to peripheral collisions at $\sqrt{s_{NN}}$ = 3 GeV

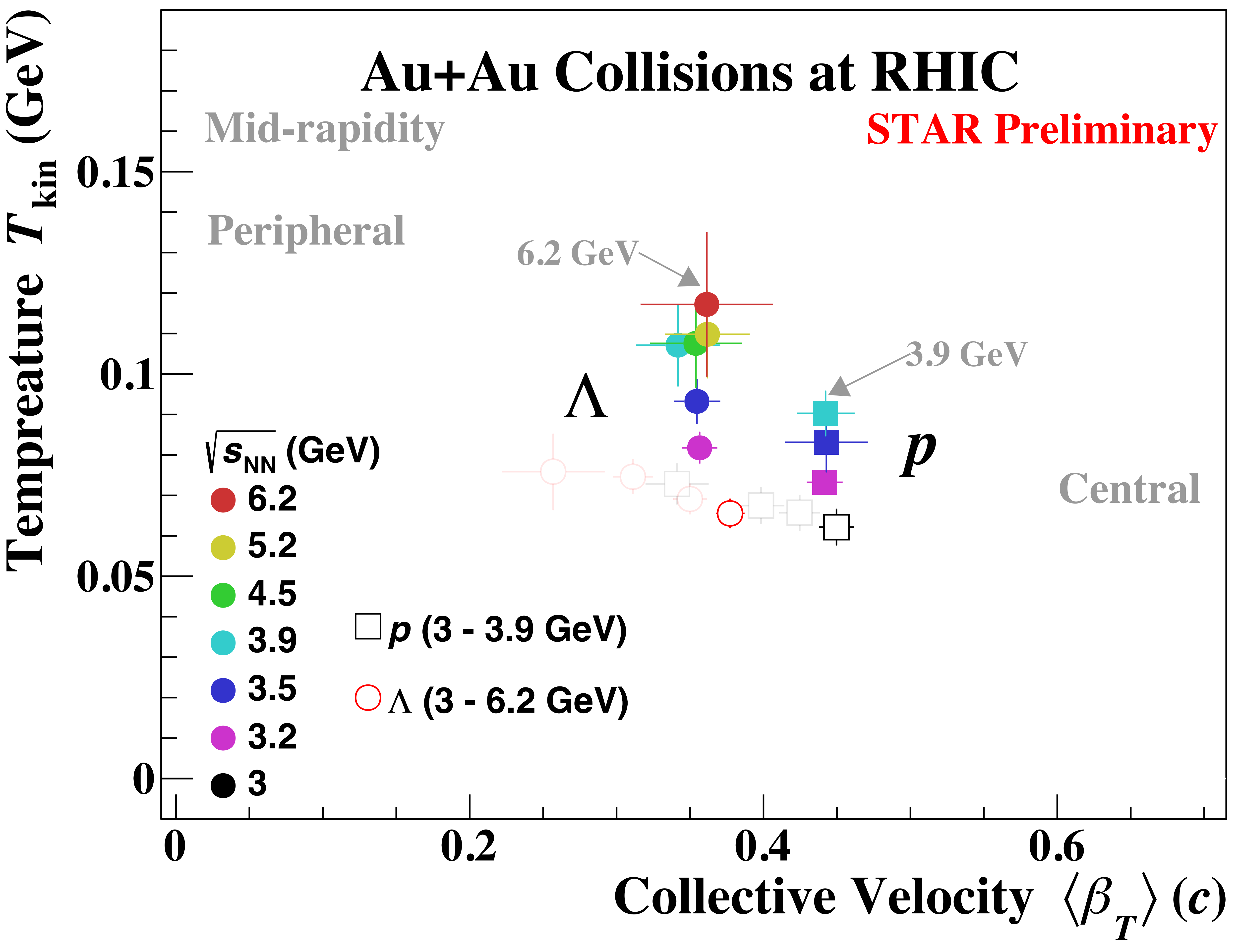
  Smaller fireball and weaker pressure in peripheral collisions

- Different freeze-out parameters (T_{kin}, $\langle\beta_T\rangle$) between proton and Λ

  Different production mechanism

STAR, PRC 110, 054911 (2024)
STAR: JHEP 2024, 139 (2024)

Kinetic Freeze-out Properties



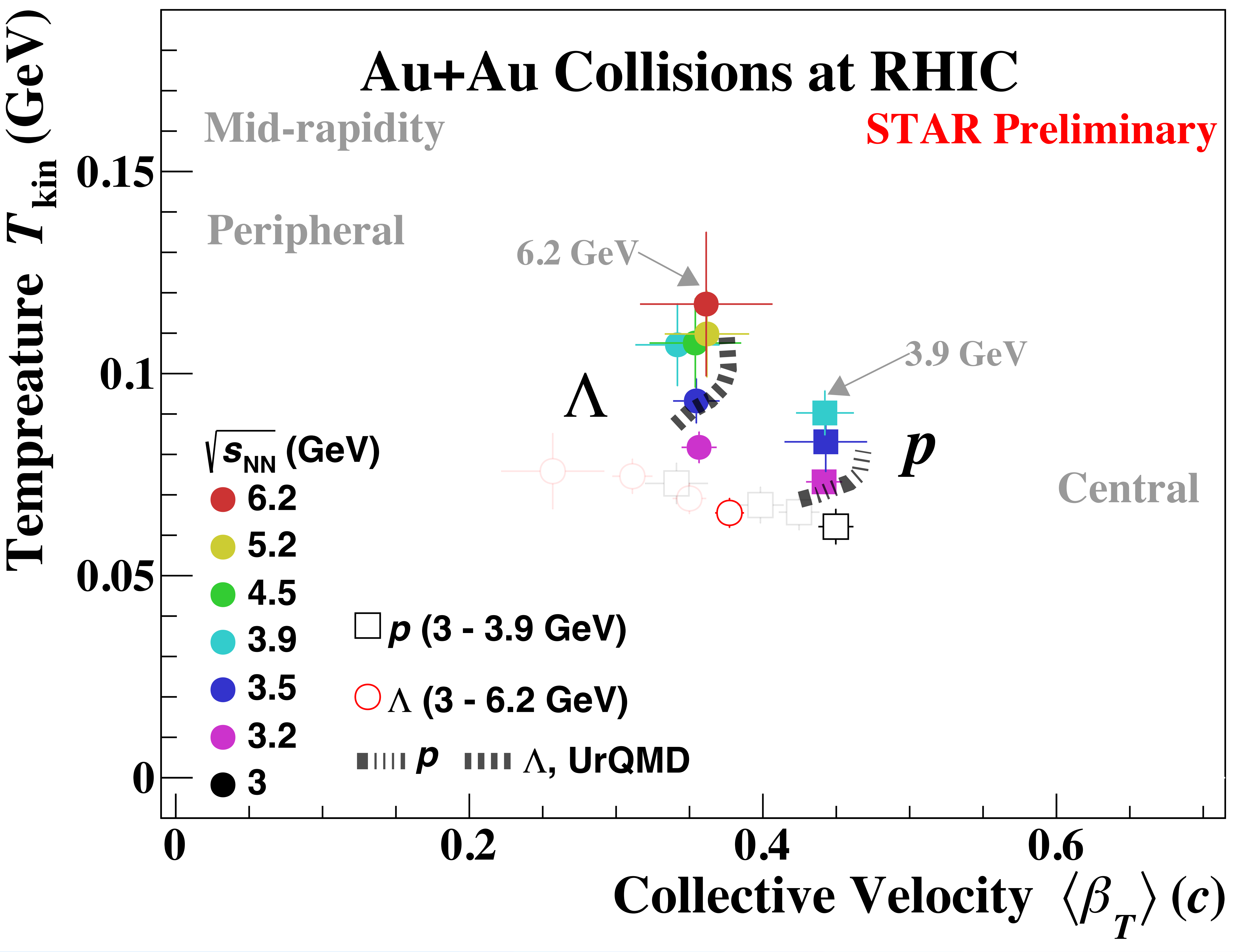
- Different freeze-out parameters between proton and Λ from $\sqrt{s_{NN}}$ = 3 – 3.9 GeV

  Different production mechanism

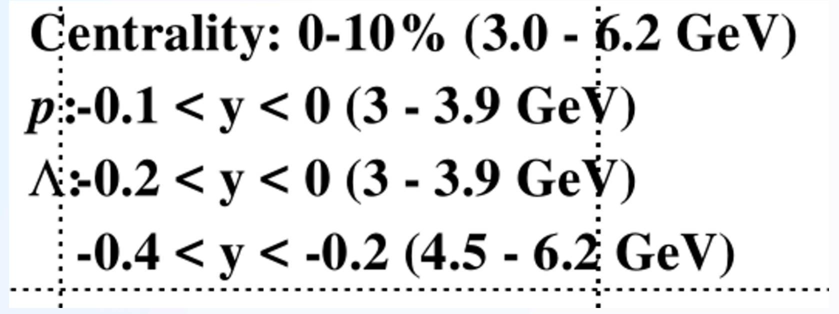
- T_{kin} increases while $\langle\beta_T\rangle$ remains almost constant from $\sqrt{s_{NN}}$ = 3 – 6.2 GeV for Λ

STAR, PRC 110, 054911 (2024)
STAR: JHEP 2024, 139 (2024)

Kinetic Freeze-out Properties



STAR, PRC 110, 054911 (2024)
STAR: JHEP 2024, 139 (2024)



- Different freeze-out parameters between proton and Λ from $\sqrt{s_{NN}}$ = 3 – 3.9 GeV

  Different production mechanism

- T_{kin} increases while $\langle\beta_T\rangle$ remains almost constant from $\sqrt{s_{NN}}$ = 3 – 6.2 GeV for Λ

- Hadronic transport model UrQMD qualitatively reproduces the trend at STAR FXT energies

Summary and Outlook

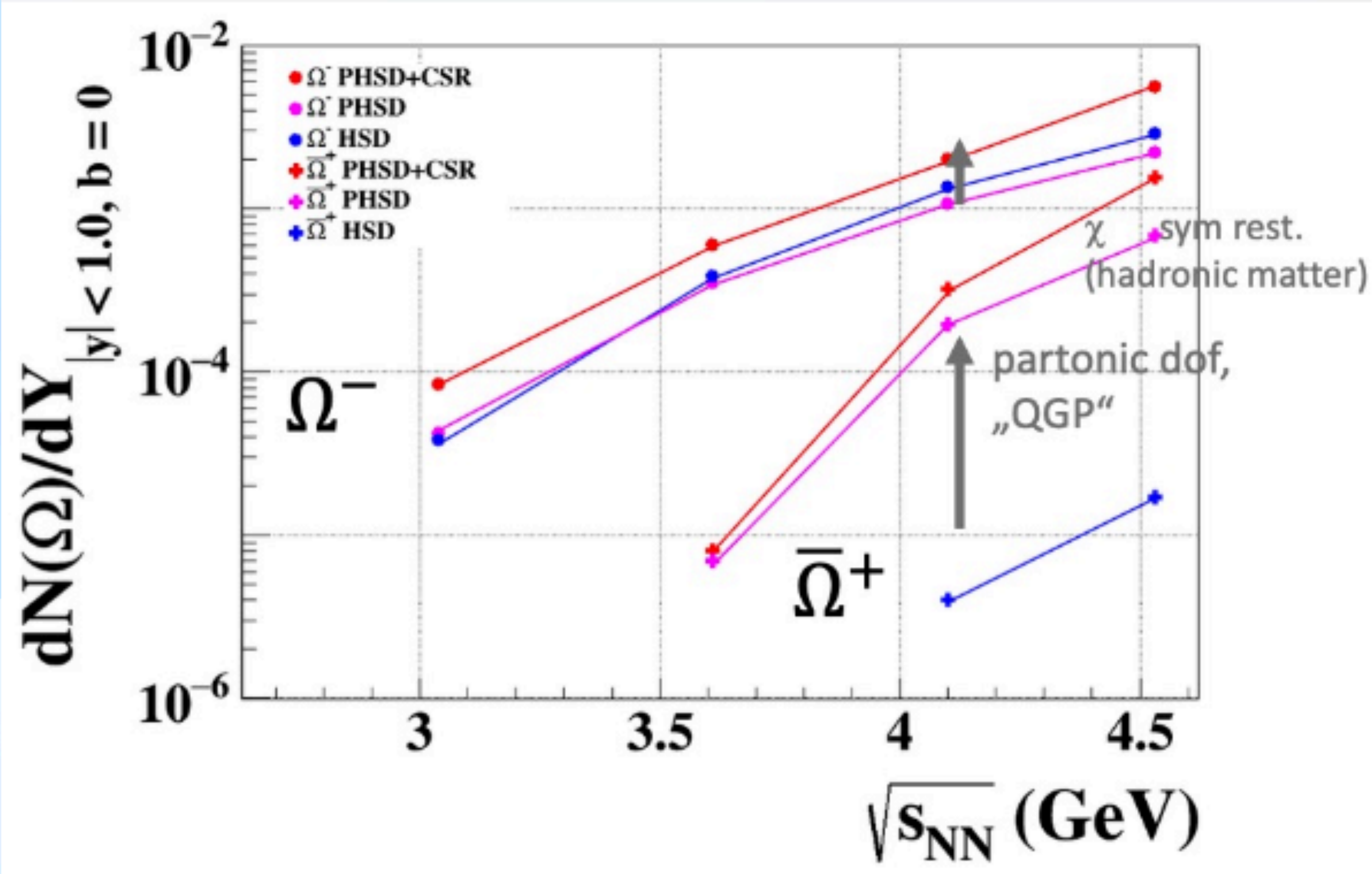
- Strange hadron yield measurements ($K^{\pm}$, K^0_S, ϕ, Λ, and Ξ^-) from STAR BES-II at $\sqrt{s_{NN}}$ = 3 – 6.2 GeV
  1. CE is mandatory to describe strange hadron yields below $\sqrt{s_{NN}}$ ~ 5 GeV → implying local strangeness conservation is important in high baryon density region
  2. Significantly larger centrality dependence (α) for Ξ^- compared to Λ, K^0_S and ϕ below $\sqrt{s_{NN}}$ ~ 7 GeV → likely due to production from multi-step hadronic interaction
  3. Different freeze-out parameters for proton and Λ from $\sqrt{s_{NN}}$ = 3 – 3.9 GeV → likely due to different production mechanisms

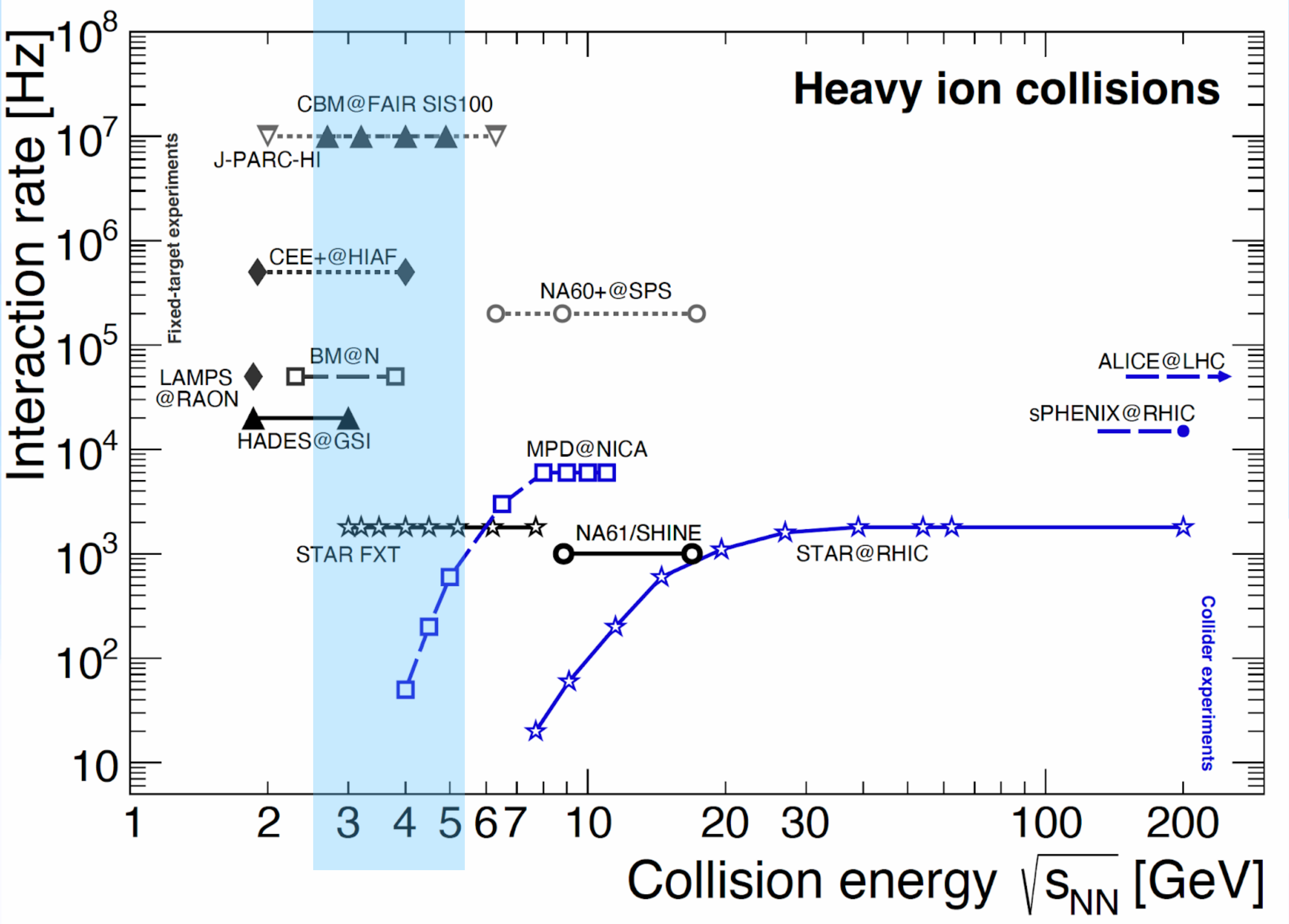
Outlook:

- Measurements of (anti-)strangeness production ($\overline{\Lambda}$, $\overline{\Xi}^+$, Ω^-, and $\overline{\Omega}^+$) at near/sub-threshold energy from STAR BES-II

Future Strangeness Studies with CBM

T. Galatyuk, Nucl.Phys.A 982 (2019) 163-169



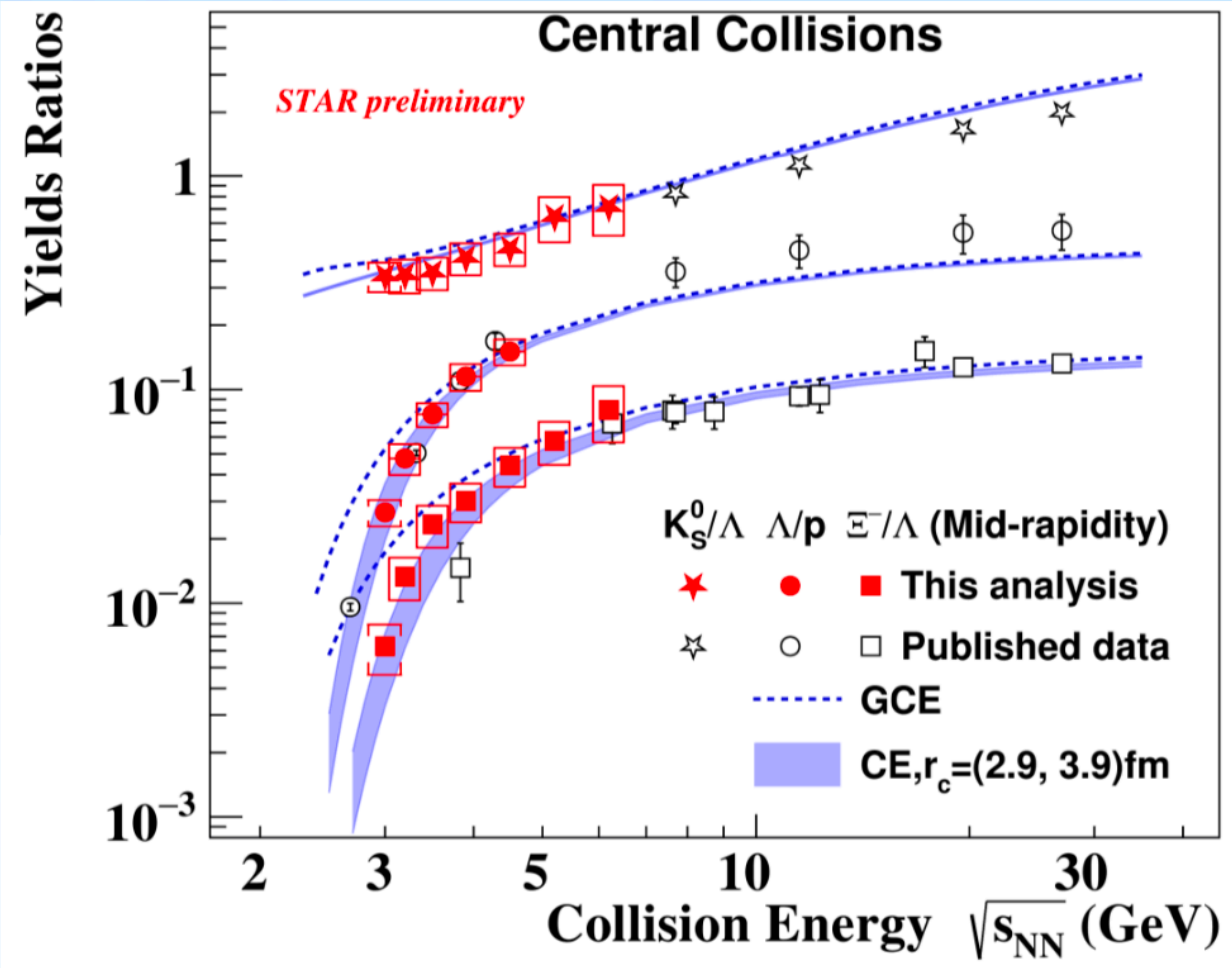


- Sub-NN-threshold particle production is sensitive to Equation-of-State (EOS)

- $\sqrt{s_{NN}}$ = 2.5-4.9 GeV Au+Au
- Interaction rates up to 10MHz
- Gives access to rare probes

Backup Slides Follow

Thermal Model



$$T_{chem} = 0.157 - 0.087\mu_B^2 - 0.092\mu_B^4\ ,\ \mu_B = \frac{1.477}{1+0.343\sqrt{s_{NN}}}$$

At 3 GeV, T_{ch} = 72.931 MeV, mu_B = 701.448 MeV

rc = 3.55 fm, R = 8.28 fm

constraining B/2Q = 1.24684
muS = muB/4.

V. Vovchenko et al., PRC 93, 064906 (2016)