Recent STAR Results on Strangeness Production in Heavy-ion Collisions

Outline

Introduction

Results and Discussion

- Energy Dependence of Strange Hadron Yields
  1. Freeze-out Properties
  2. R_{cp}, Baryon to Meson Yield Ratio
  3. Centrality Dependence
- System Size Dependence of Strange Hadron Yields

Summary and Outlook

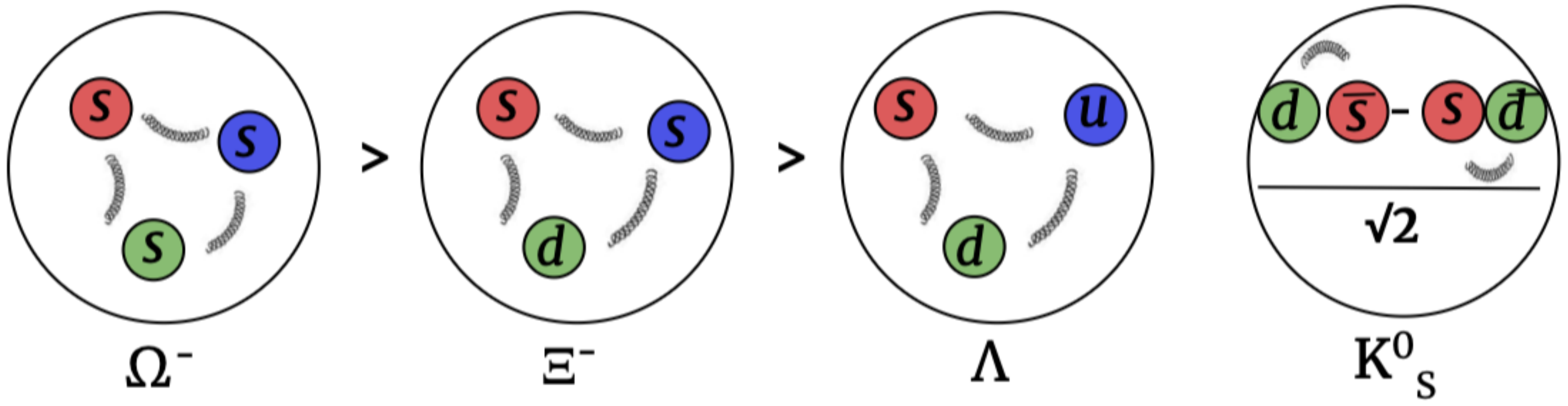
Yingjie Zhou

GSI, FAIR

PHD 2025, Wuhan, China

Oct. 16, 2025

Strangeness as a Probe to Explore QCD Phase Diagram



- Strangeness enhancement was one of the first observables predicted as a signature of the QGP

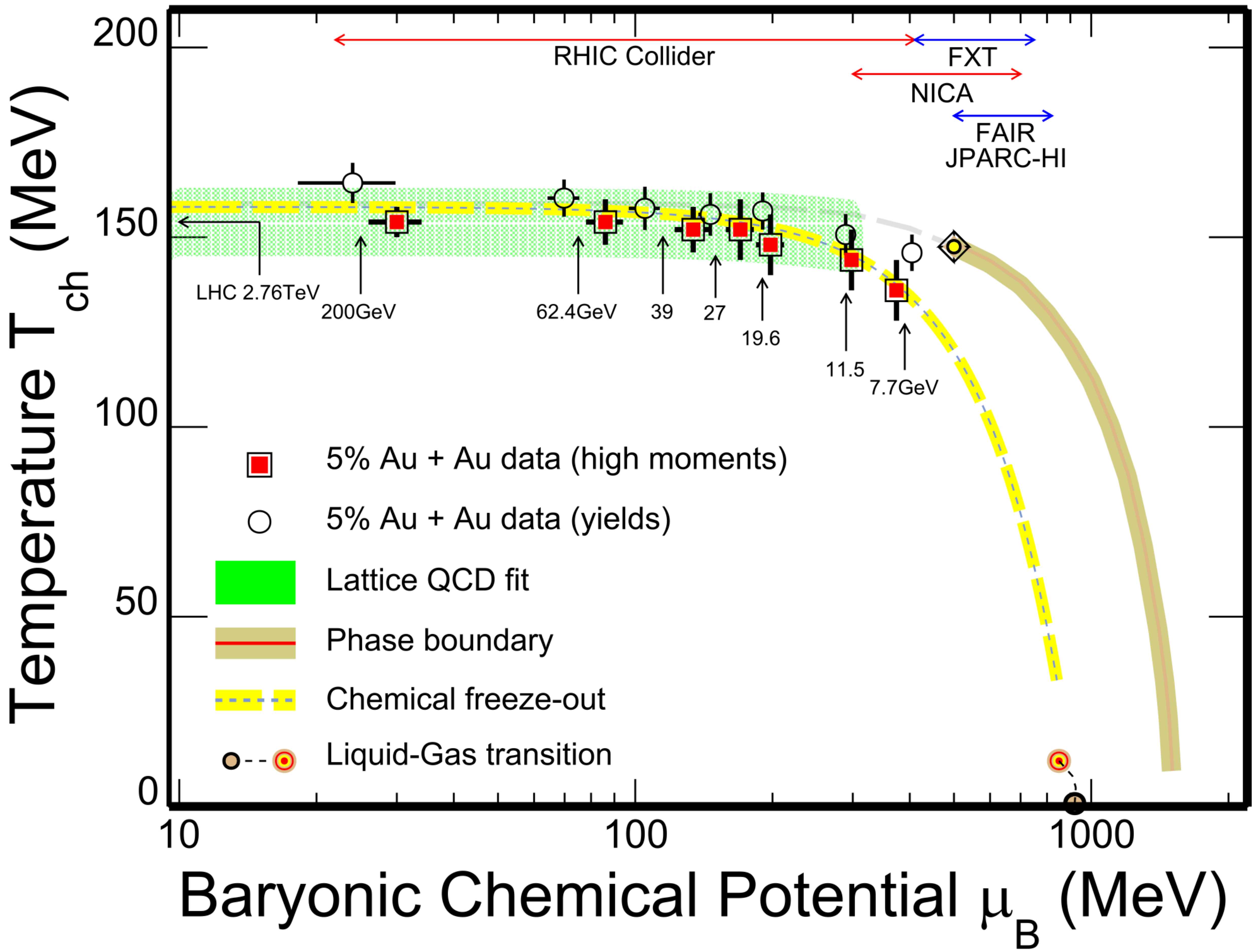
1. pair production: $gg \to s\bar{s}$, $q\bar{q} \to s\bar{s}$
2. hadronic interaction: $BB \to BYK$, $BB \to BBK\bar{K}$

B: N, p, Δ etc. Y: Λ, Ξ, etc. K: K^0, K^+

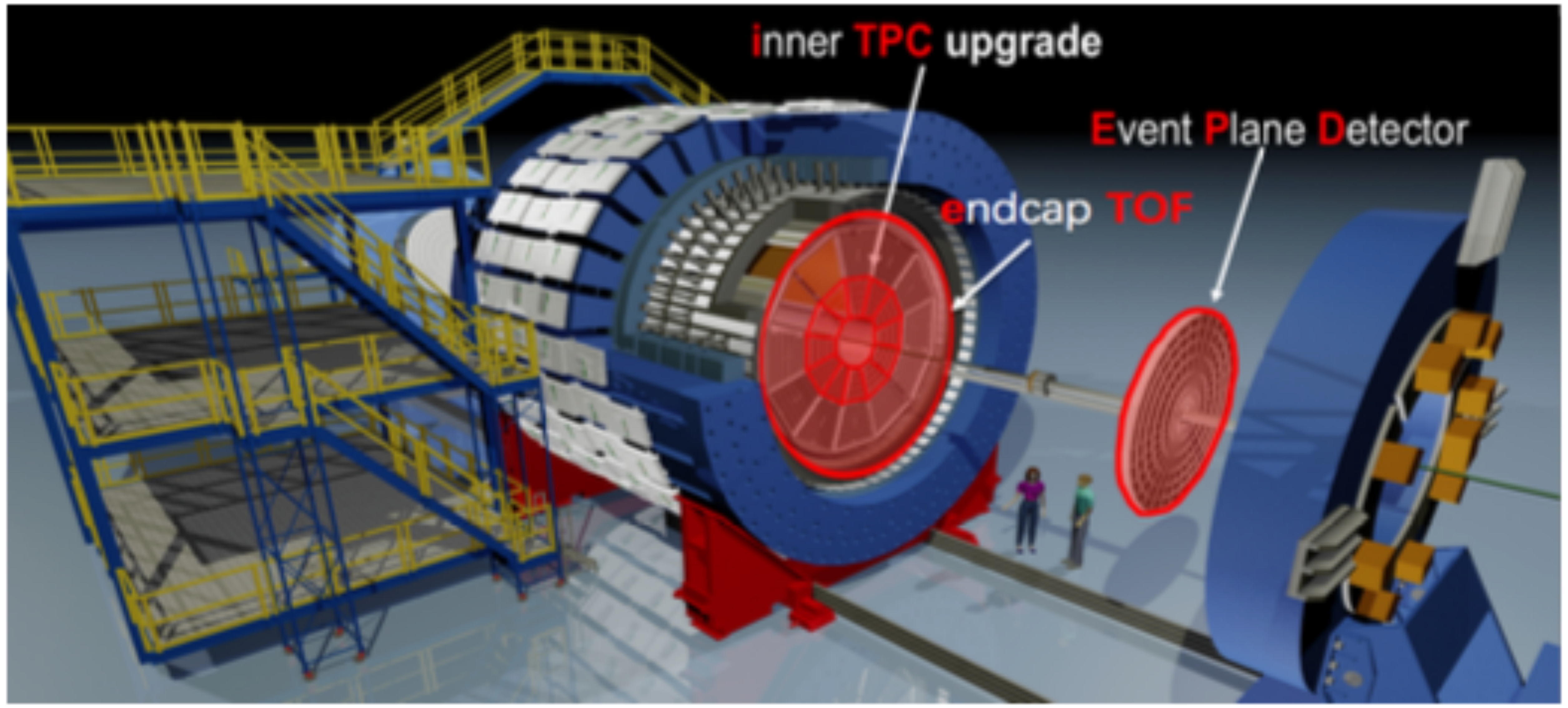
Sensitive probe to:

- Study QGP properties
- Search for the onset of deconfinement
- Constrain the equation-of-state

see P. Senger, 9:40 16/10 (Thu.)

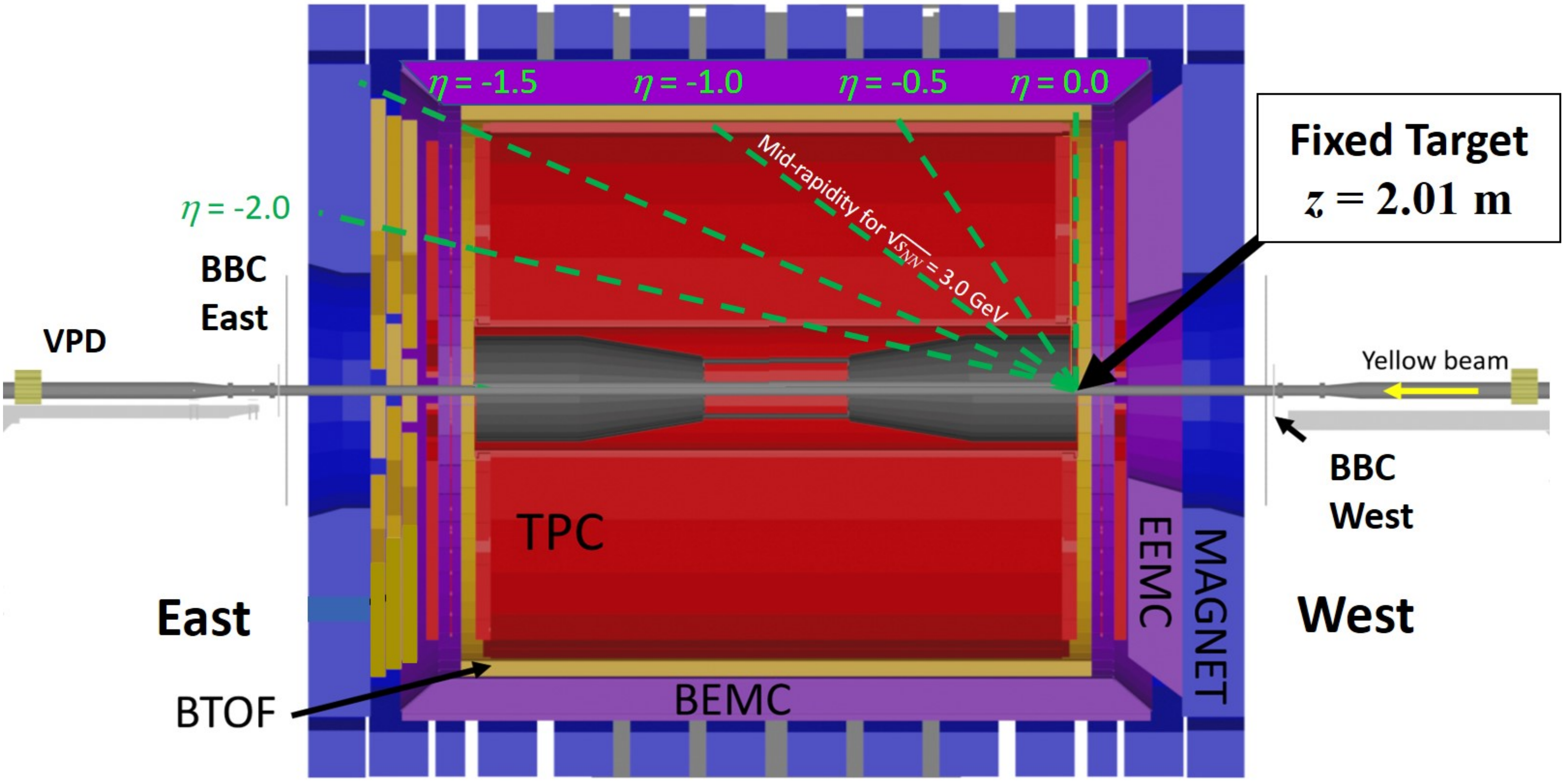


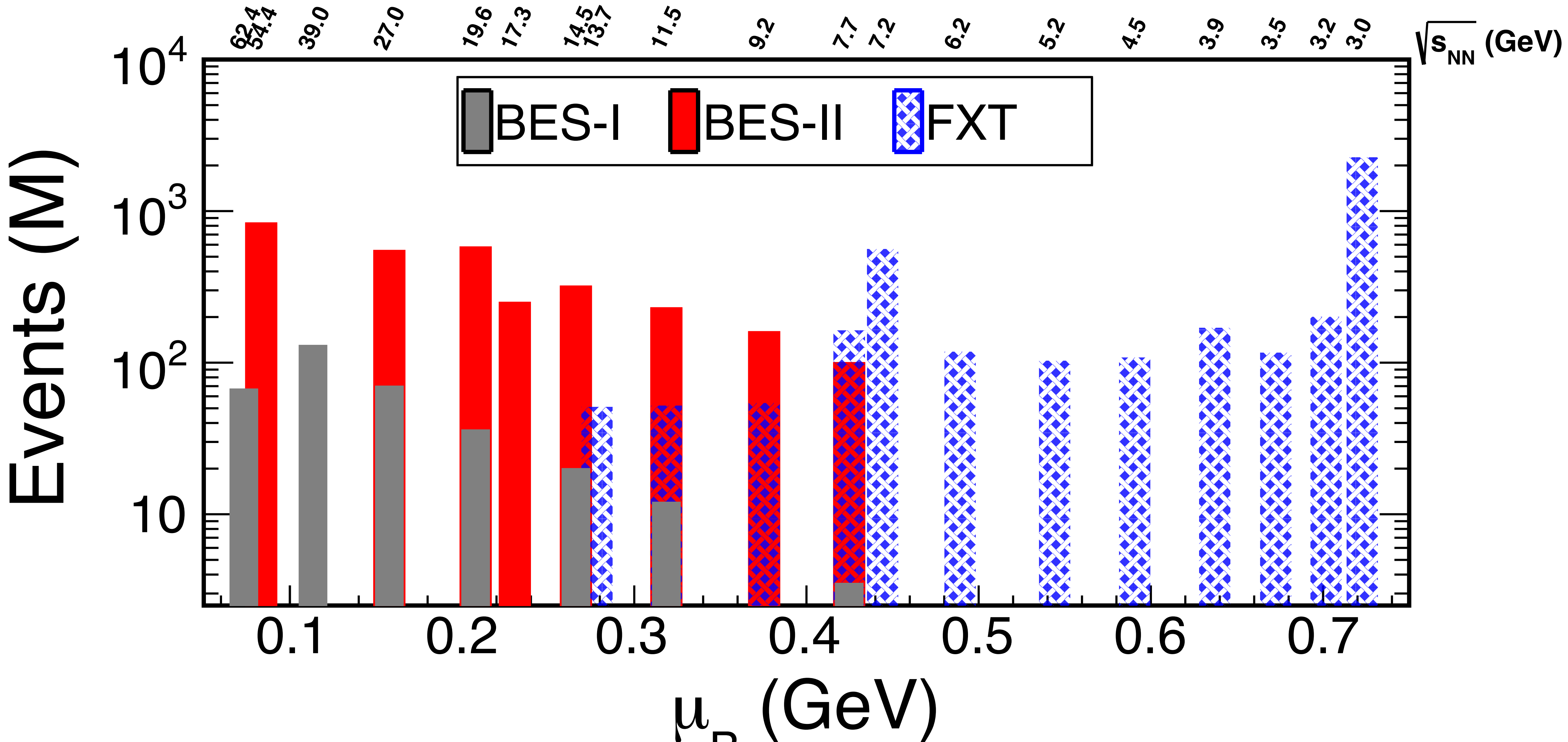
STAR Detector and Beam Energy Scan (BES)



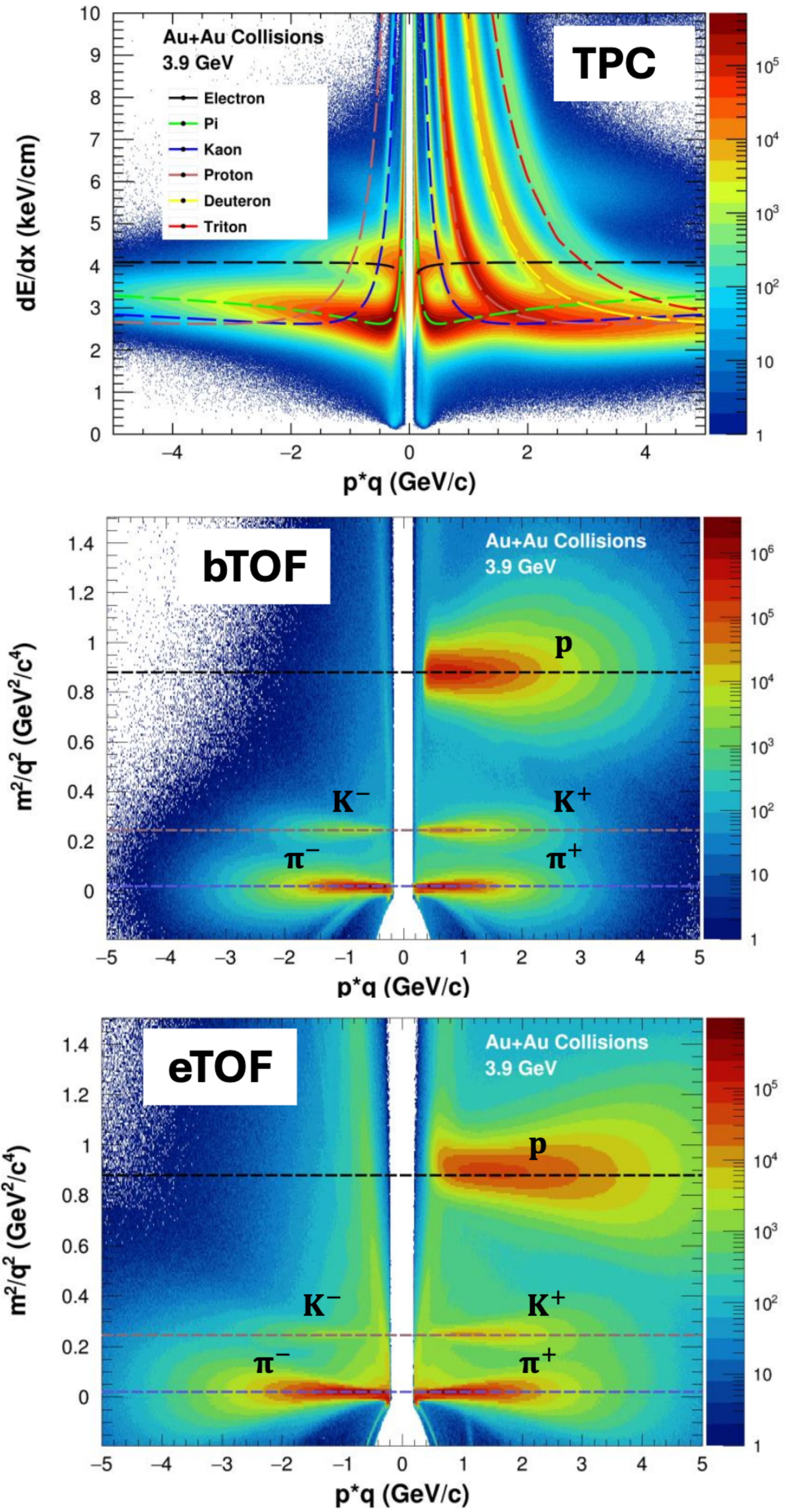
- BES-II $\sqrt{s_{NN}}$ = 3-54 GeV (2018-2021)
  - **10× higher statistics than BES-I**
  - **Detector upgrades: iTPC, eTOF**
  - **Fixed-target mode extends reach to 3 GeV → access to high-μ_B region**

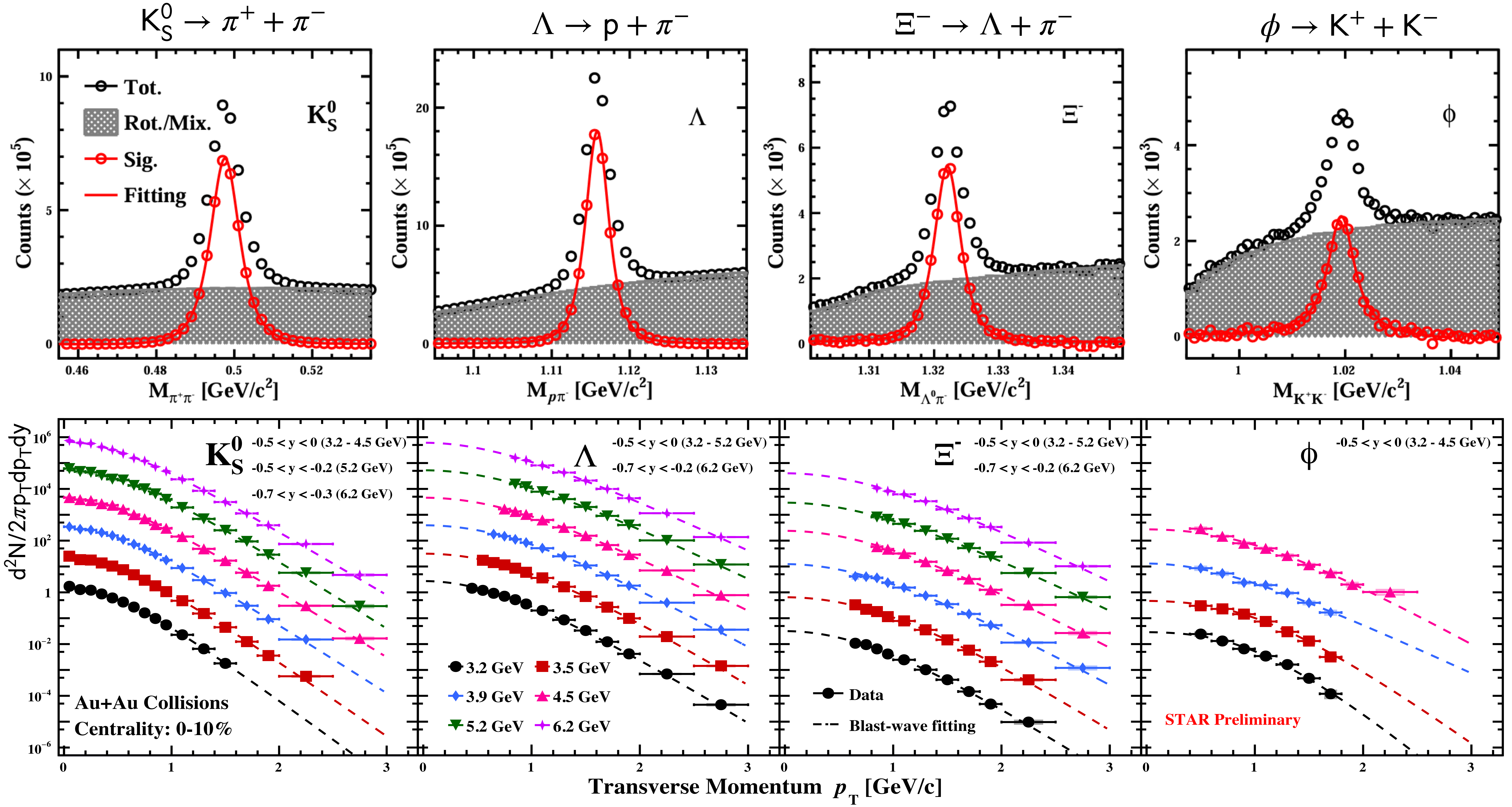
BES-I: 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4
BES-II: 7.7, **9.2**, 11.5,14.5, **17.3**, 19.6, 27, **54.4**
FXT: **3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2**, 7.7, 9.2, 11.5, **13.7**





Strange Hadron Reconstruction

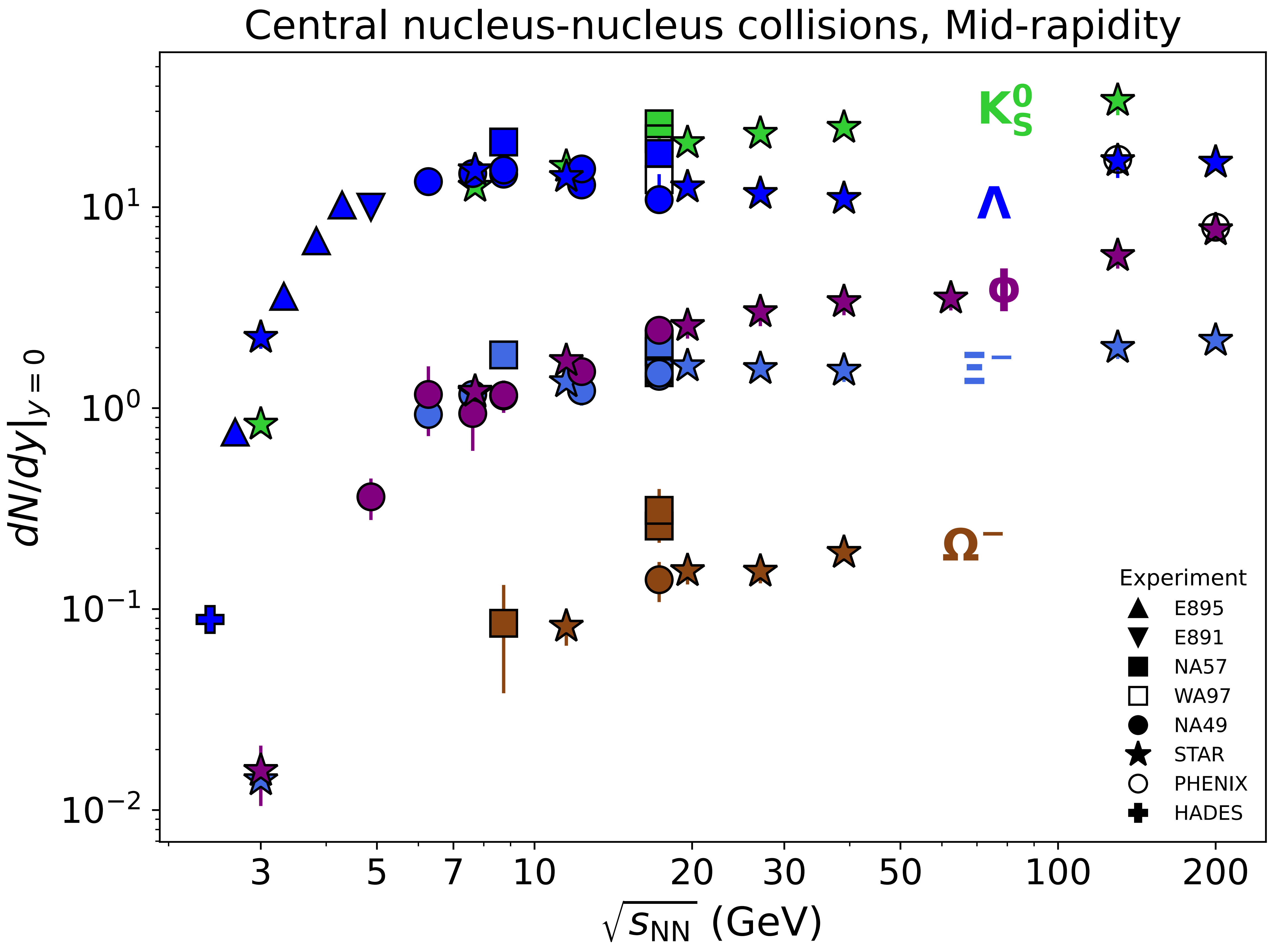


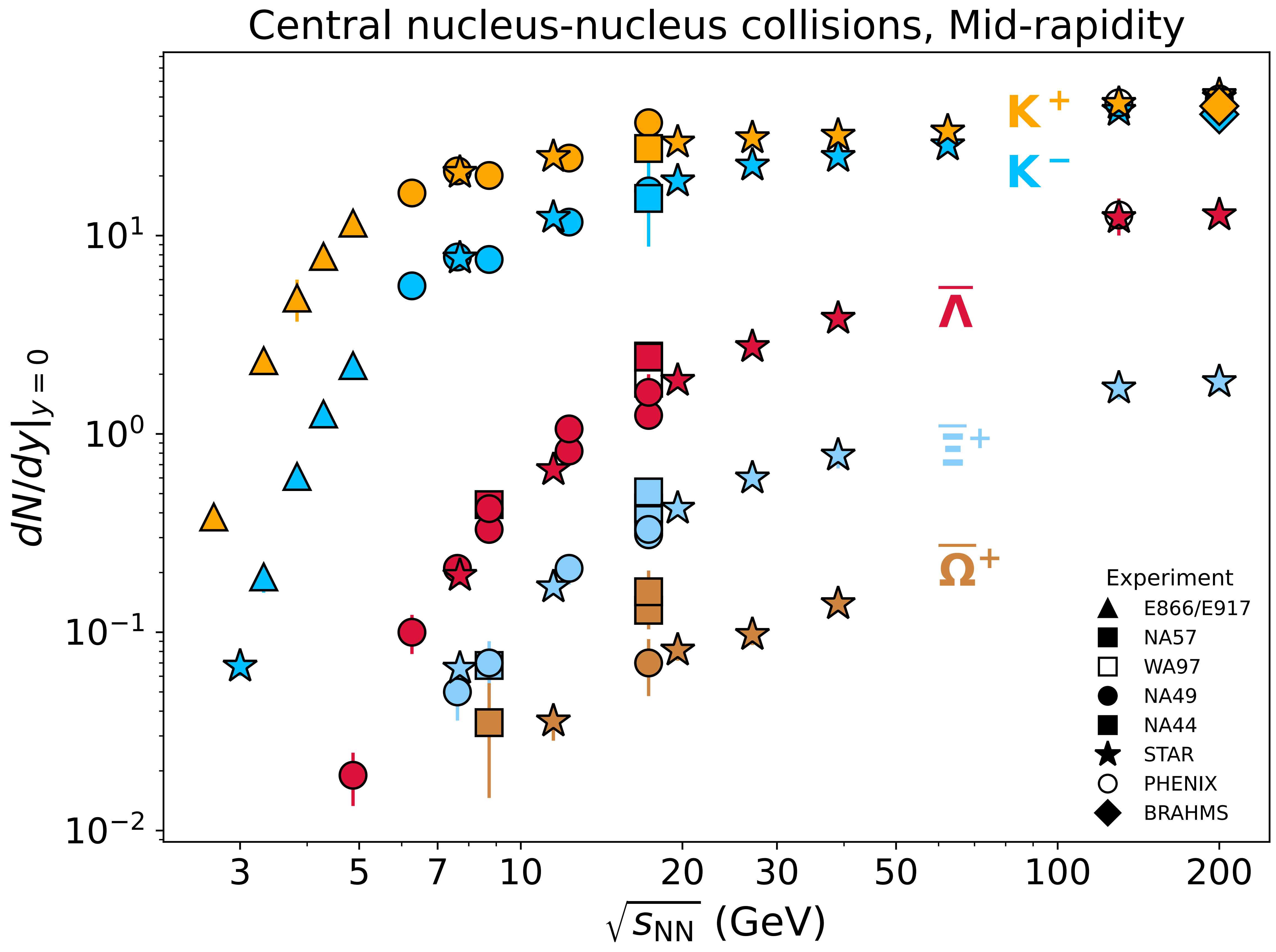


- TPC and TOF/eTOF used for particle identification
- Strange hadron reconstructed via hadronic decay channels
- KFParticle package utilising information from error matrices applied to maximise significance

Mid-rapidity Excitation Functions (Published Data)

Central nucleus-nucleus collisions

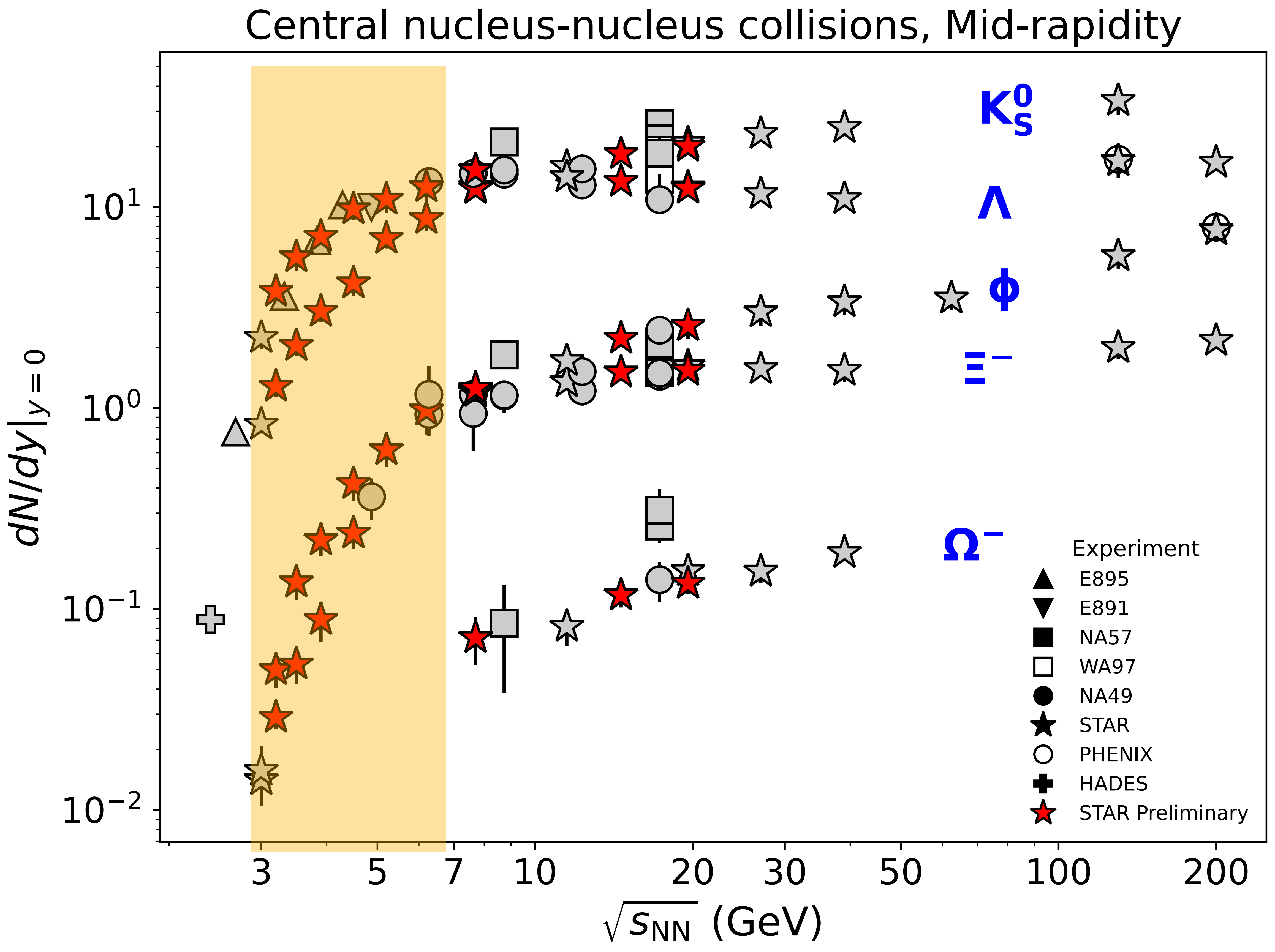


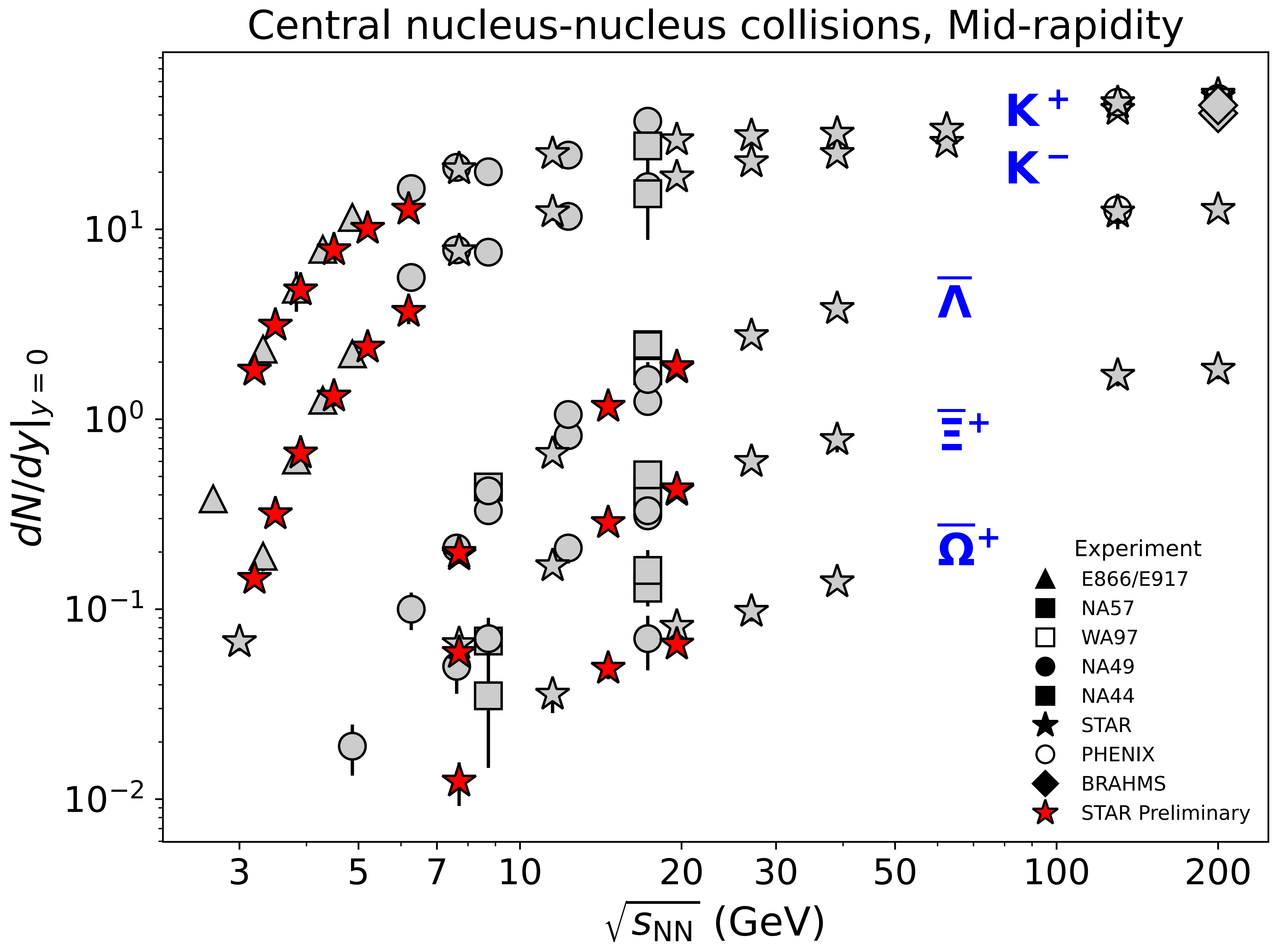


- $N_\Lambda > N_{K^0_S}$ and $N_{K^+} > N_{K^-}$ below $\sqrt{s_{NN}}$ ~ 8 (20) GeV

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

Mid-rapidity Excitation Functions (STAR BES-II Preliminary)





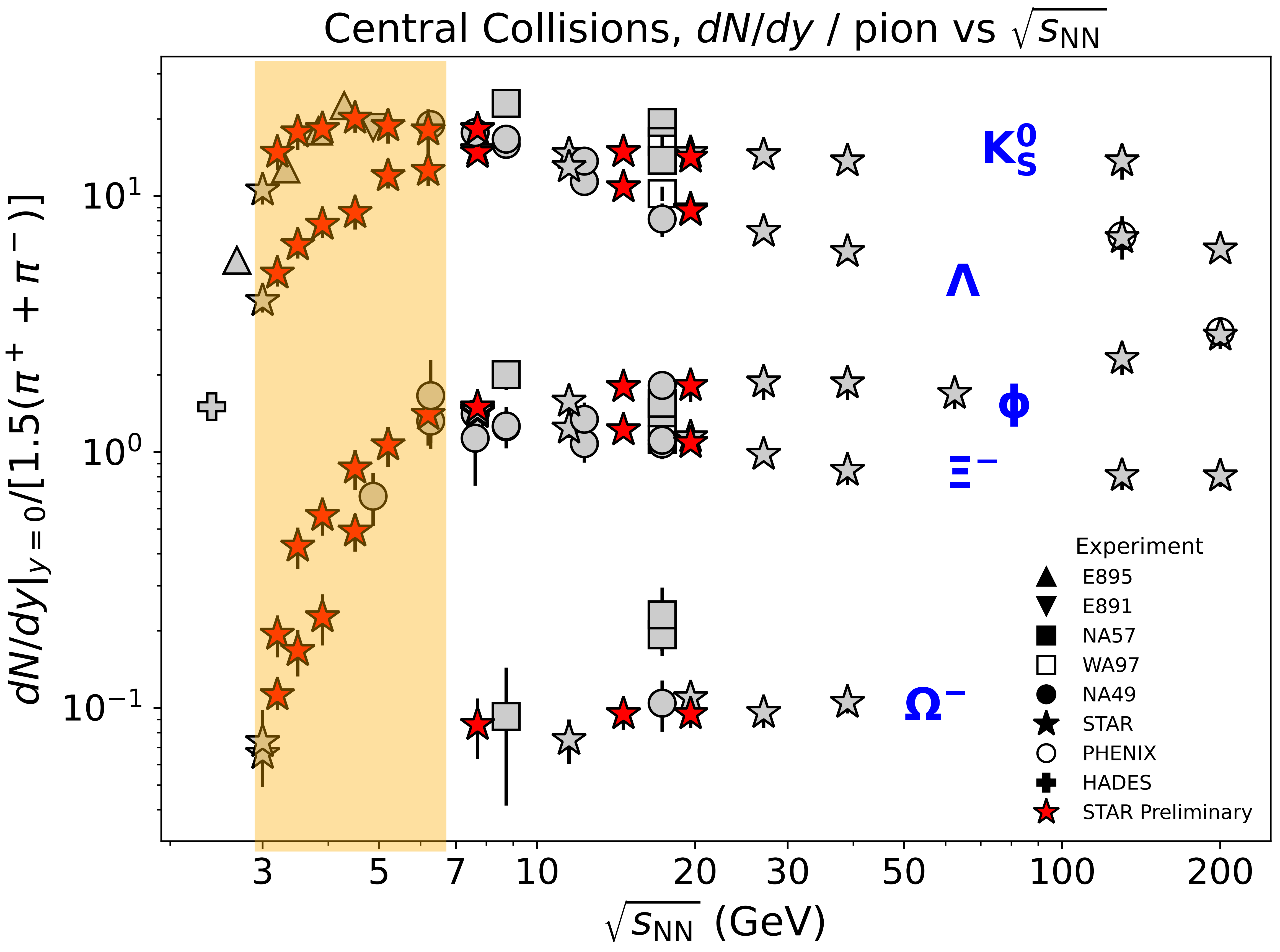
- New STAR Preliminary result consistent with previous results with higher precision
- **FXT energy region fills the gap between HADES, AGS and STAR (collider mode)**

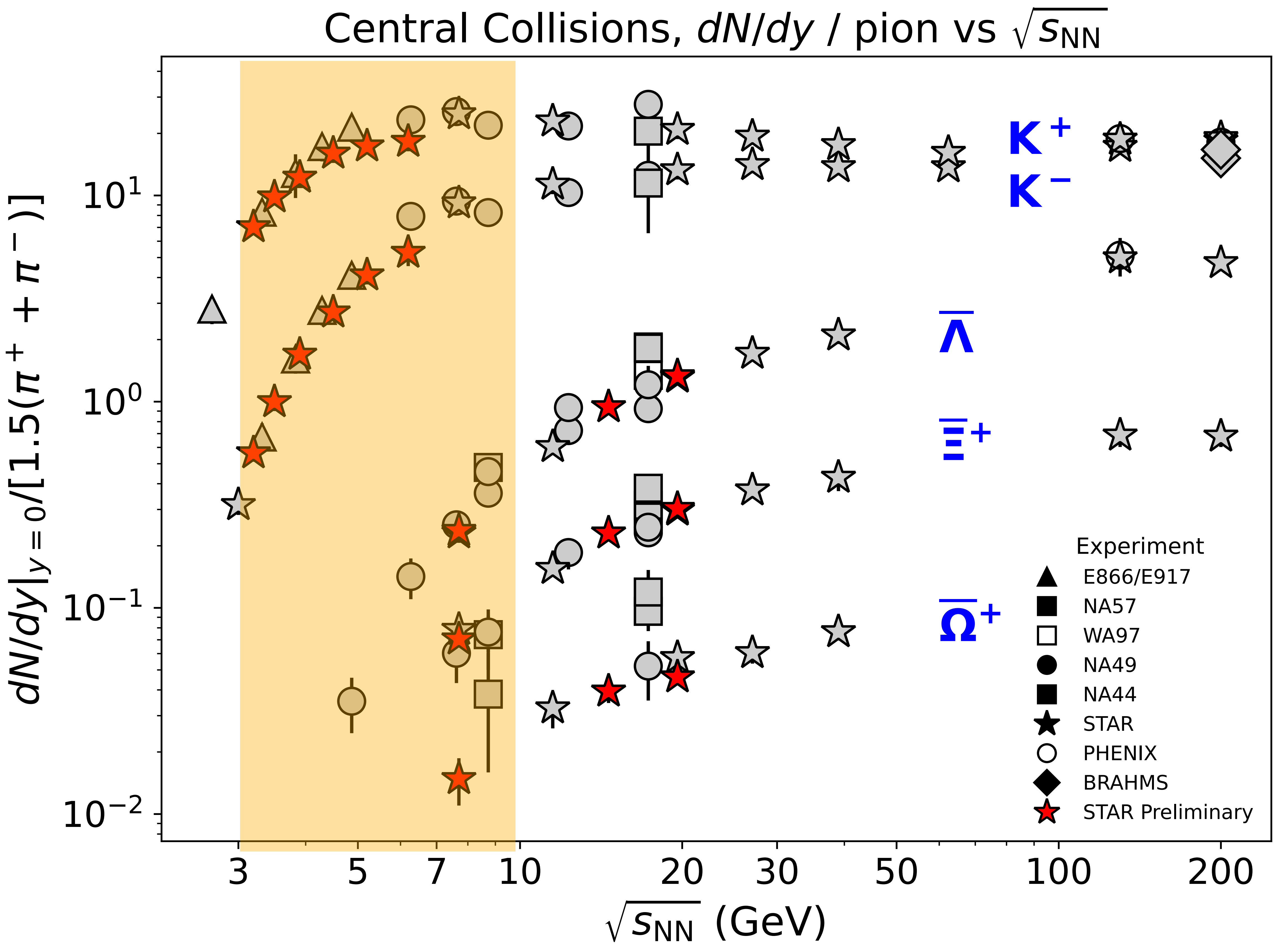
STAR, PRC 96, 044904 (2017); PRC 102, 034909 (2020); PLB 831, 137152 (2022); JHEP 2024, 139 (2024)
HADES, PLB 793, 457 (2019)

Mid-rapidity Strange Hadron to Pion Ratio

π yields estimated through interpolation of published data

STAR BES-II Preliminary



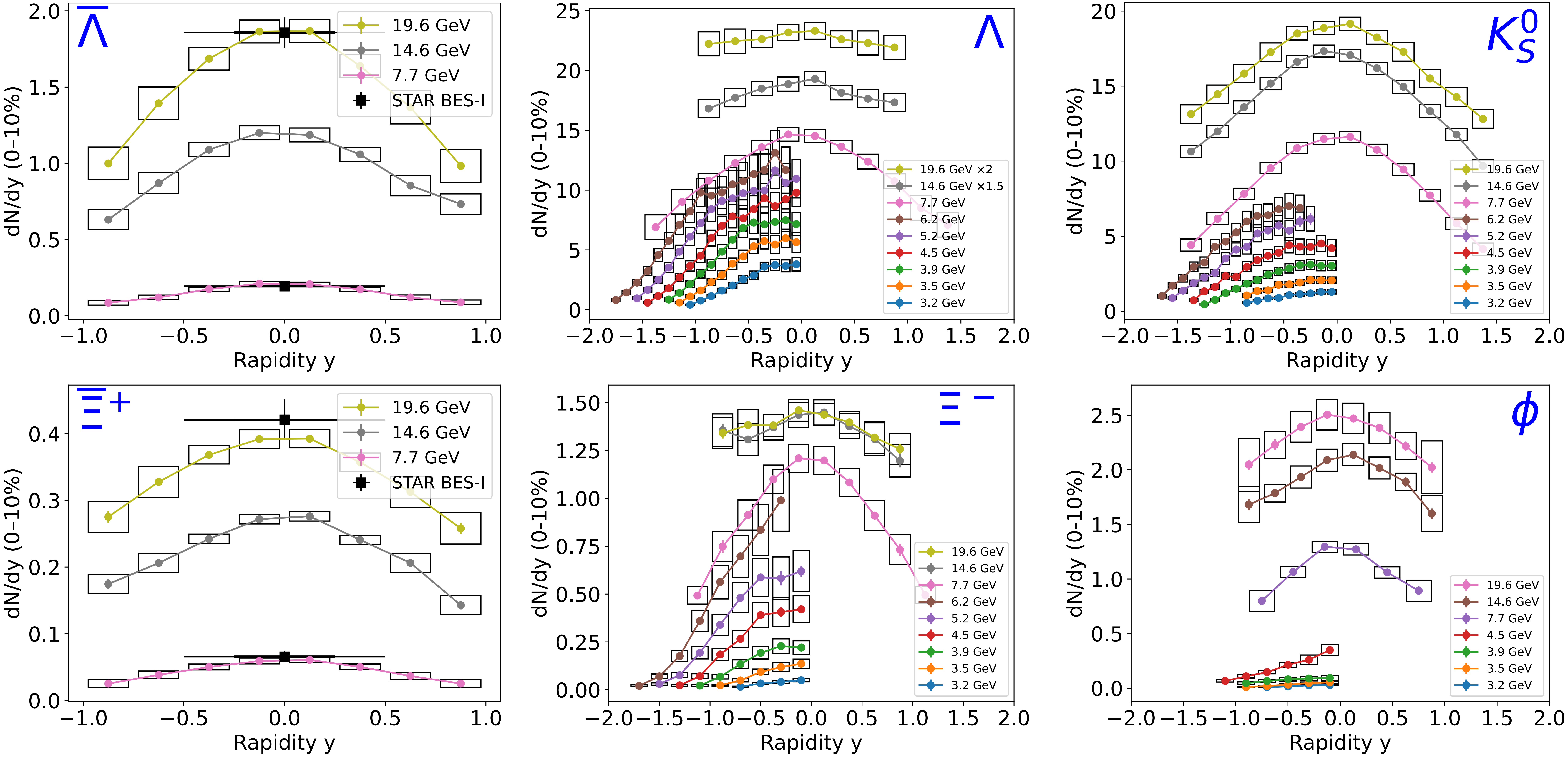


- K^+/π, Λ/π and Ξ^-/π exhibit a peak structure around $\sqrt{s_{NN}}$ = 4–10 GeV
- **Maximum net-baryon density around ~ 7 GeV at freezeout**

STAR, PRC 96, 044904 (2017); PRC 102, 034909 (2020); PLB 831, 137152 (2022); JHEP 2024, 139 (2024); HADES, PLB 793, 457 (2019)
S. Chatterjee et al., Adv. High Energy Phys. 2015, 349013

Rapidity Distributions

STAR BES-II Preliminary   Au+Au 0-10%

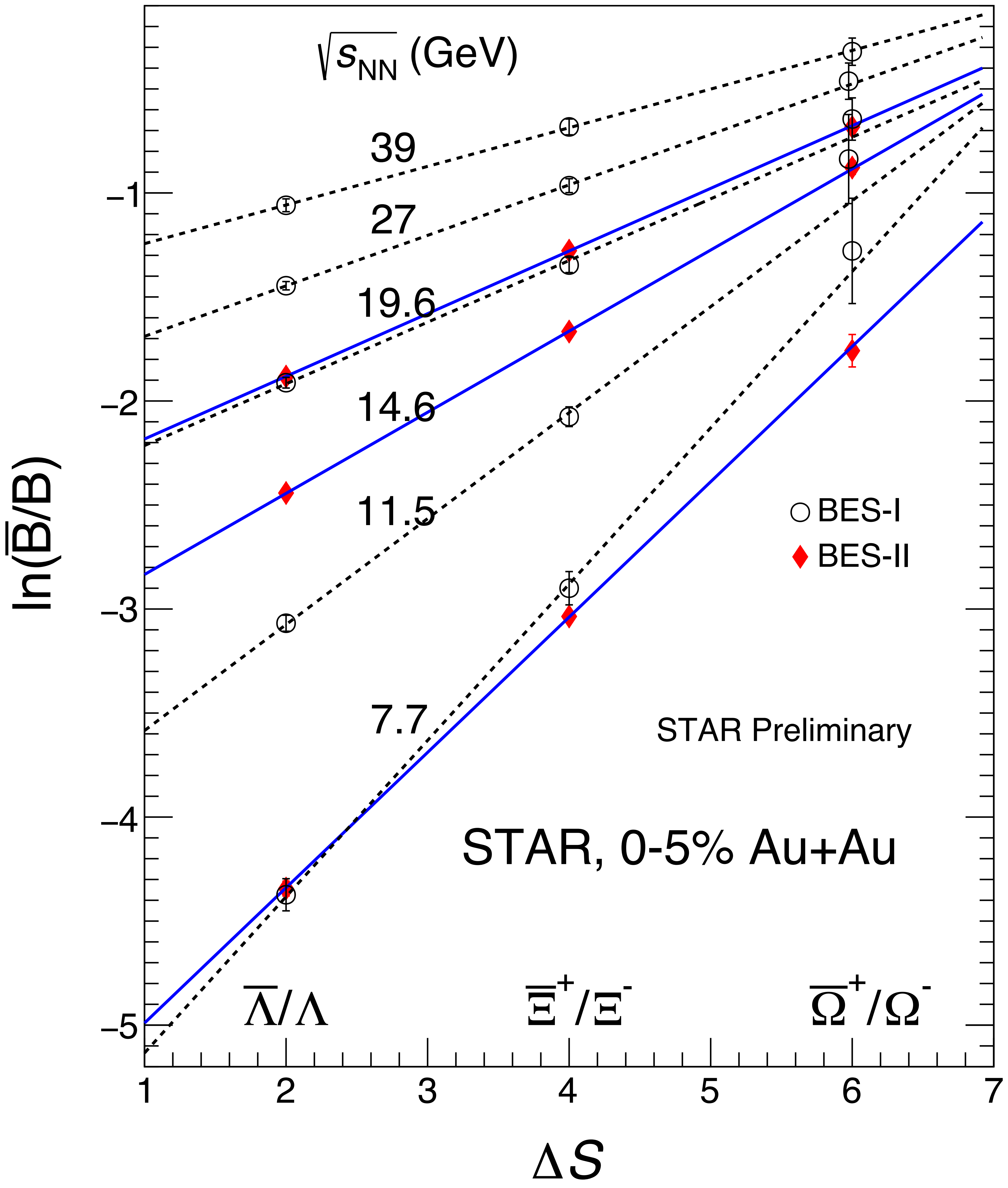


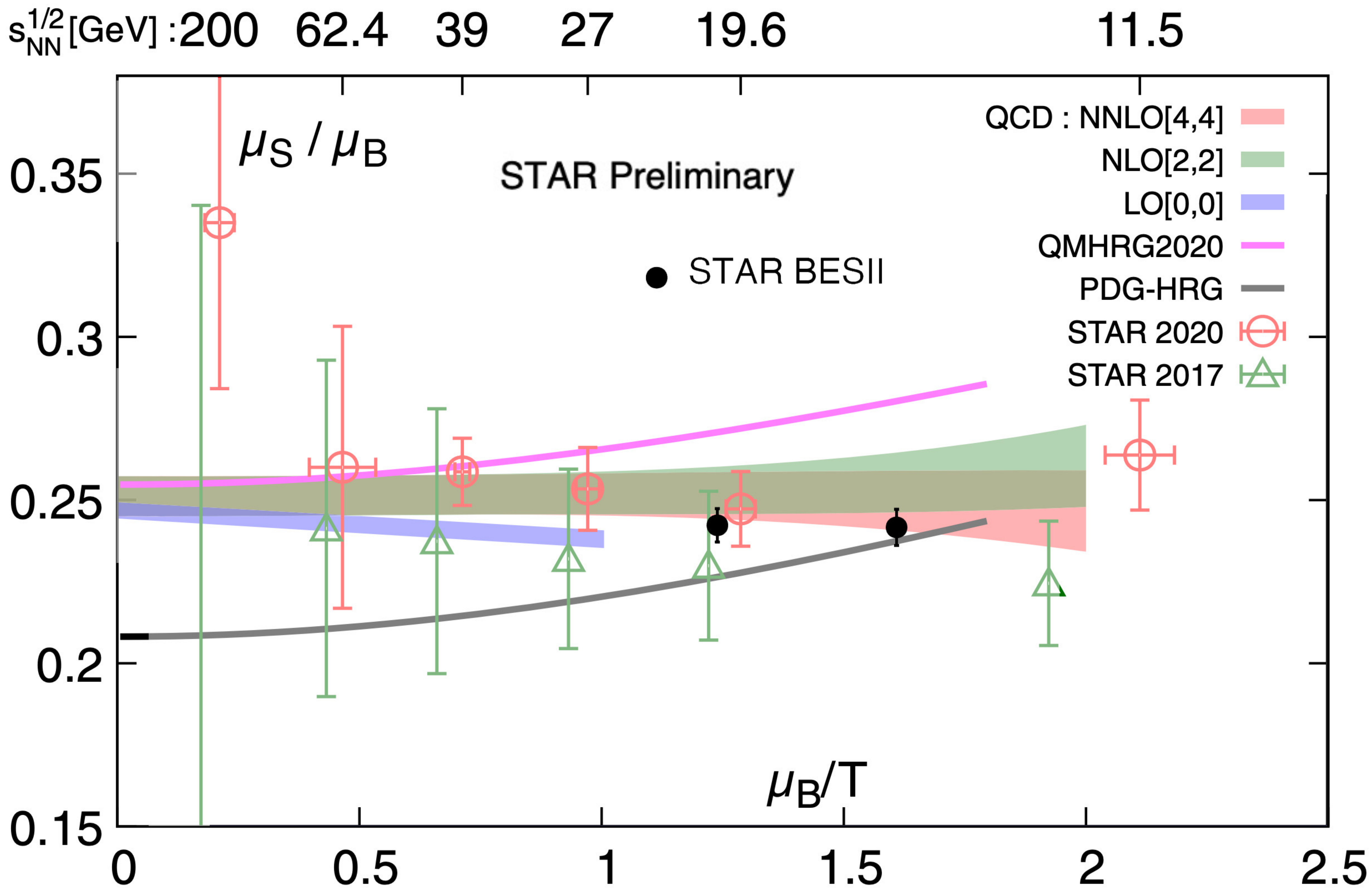
- Baryon yields give insight on baryon transport mechanism

STAR: Phys. Rev. C 102, 034909 (2020)

Chemical Freeze-out parameters

Thermal (GCE): $ln(\overline{B}/B) = -2\mu_B/T_{ch} + \mu_S/T_{ch}\Delta S$





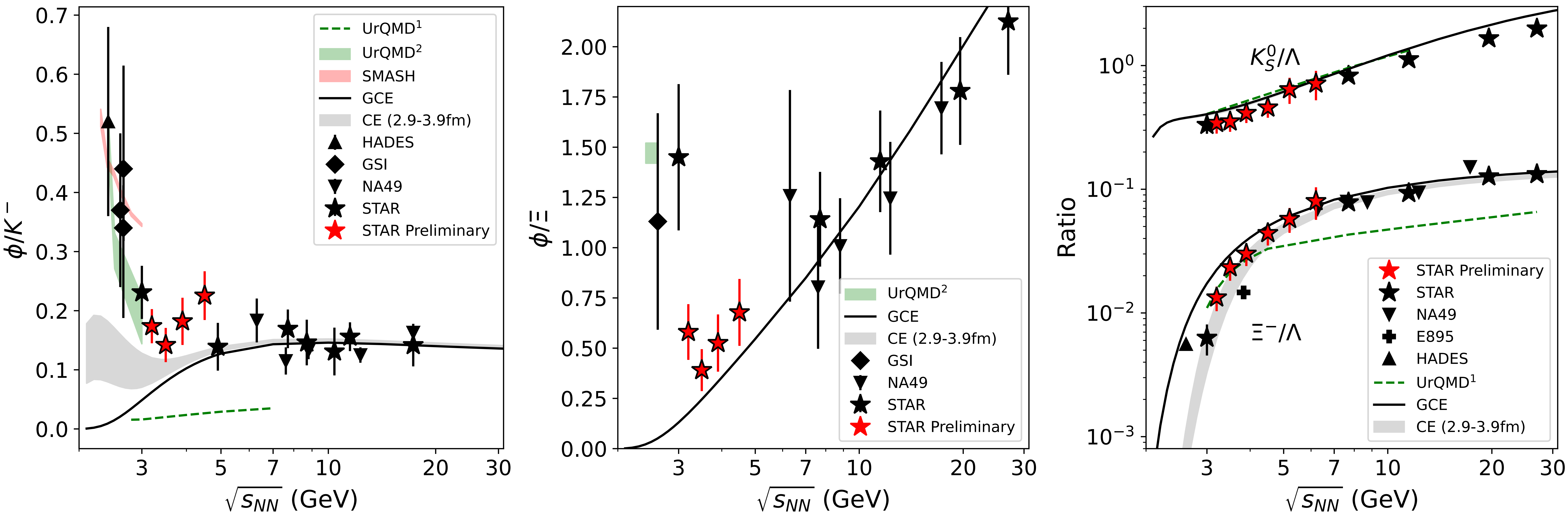
- Precise extraction of μ_B/T_{ch} and μ_S/T_{ch} from BES-II data
- Results from thermal model fits are in good agreement with lattice QCD calculation results

STAR: Phys. Rev. C 102, 034909 (2020)

Chemical Freeze-out Properties

Phys. Rev. C 102, 034909 (2020)
Thermal: V. Vovchenko, et al. Phys. Rev. C 93, 064906 (2016), UrQMD: S. A. Bass, et al. Prog. Part. Nucl. Phys. 41 (1998)

Chemical Freeze-out Properties



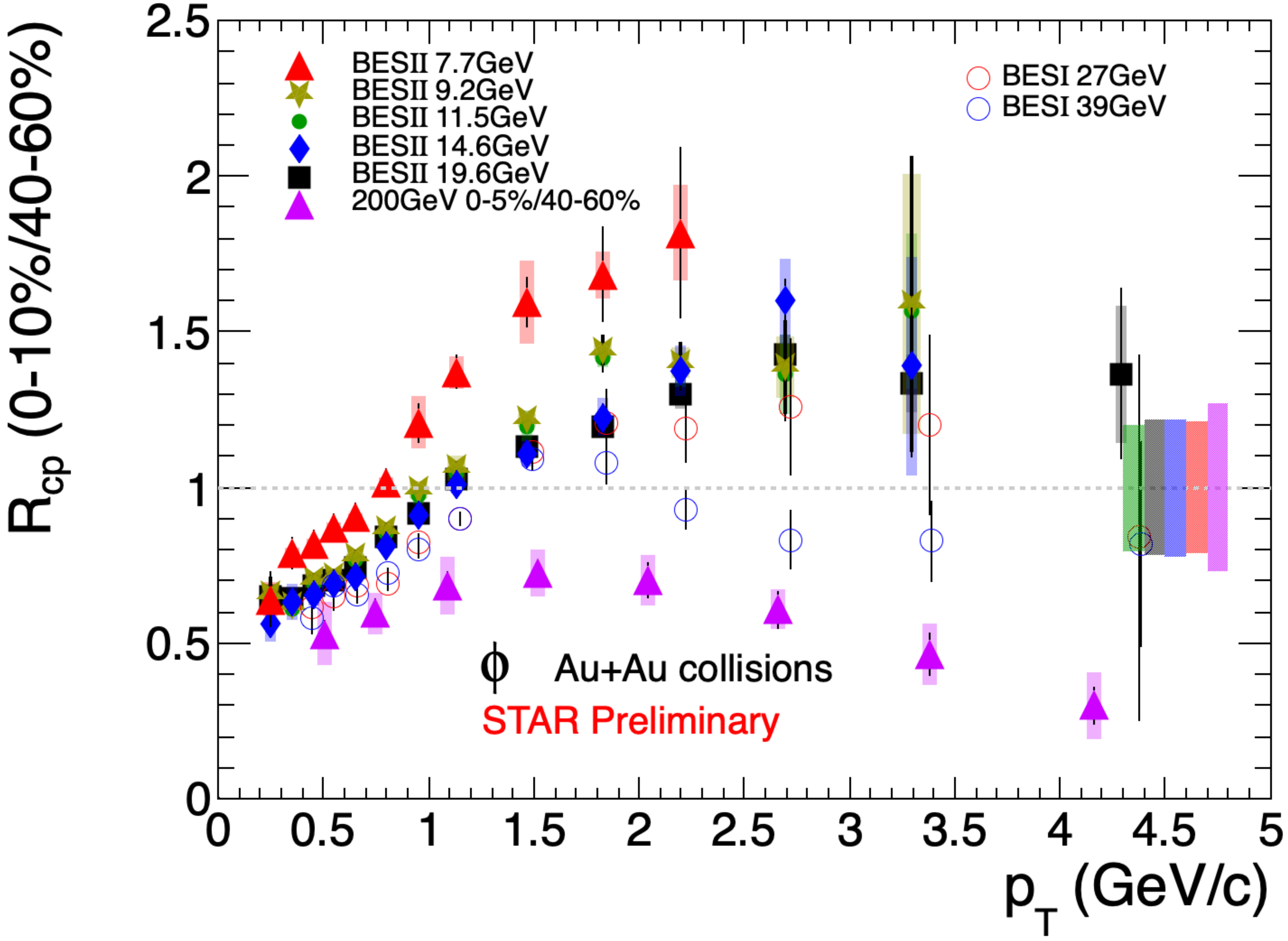
- Grand Canonical Ensemble (GCE) fails below $\sqrt{s_{NN}}$ ~ 5 GeV, CE (r_c~3–4 fm) is mandatory to describe data

Change of medium properties at the high-density region?

STAR: Phys. Lett. B 831, 137152 (2022), Phys. Rev. C 102, 034909 (2020)
Thermal: V. Vovchenko, et al. Phys. Rev. C 93, 064906 (2016), UrQMD: S. A. Bass, et al. Prog. Part. Nucl. Phys. 41 (1998)

Energy Dependence of ϕ R_{cp}

STAR BES-II Preliminary

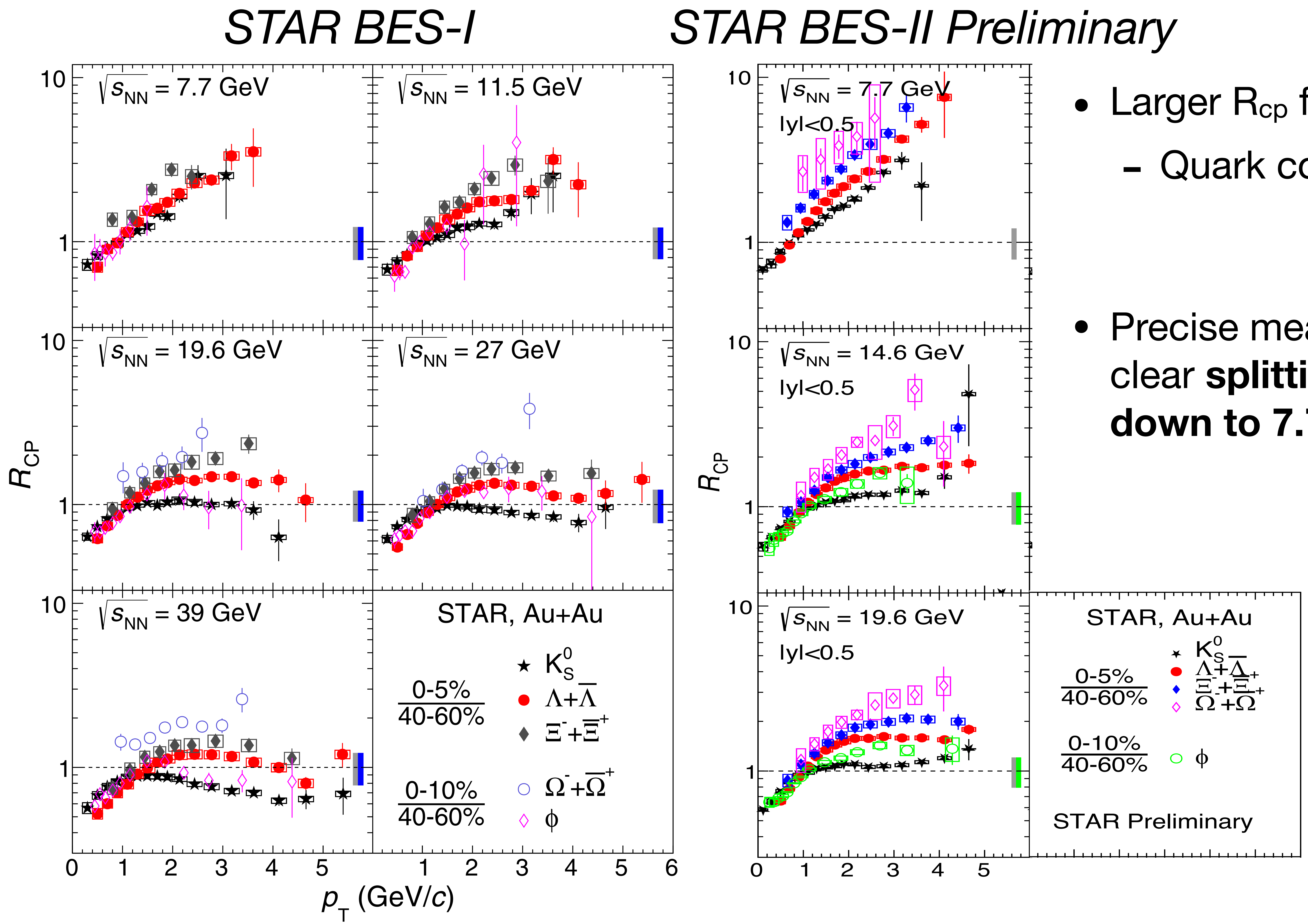


$$R_{CP} = \frac{[(dN/dp_T)/\langle N_{\text{coll}}\rangle]_{\text{central}}}{[(dN/dp_T)/\langle N_{\text{coll}}\rangle]_{\text{peripheral}}}$$

- ϕ meson, with small hadronic scattering cross-sections, serves as a clean probe of the partonic stage
- 200 GeV: Nuclear modification factor $R_{cp} < 1$
  - Reflect strong **partonic energy loss** in QGP
- 9.2 – 27GeV: $R_{cp} > 1$ but saturate at p_T~2 GeV/c
  - Interplay between **Cronin effect, Radial flow, Quark coalescence** and Energy loss
- 7.7 GeV: R_{cp} significantly larger than that at 9.2 GeV and above

STAR: Phys. Rev. C 102, 034909 (2020)

Energy Dependence of R_{cp}

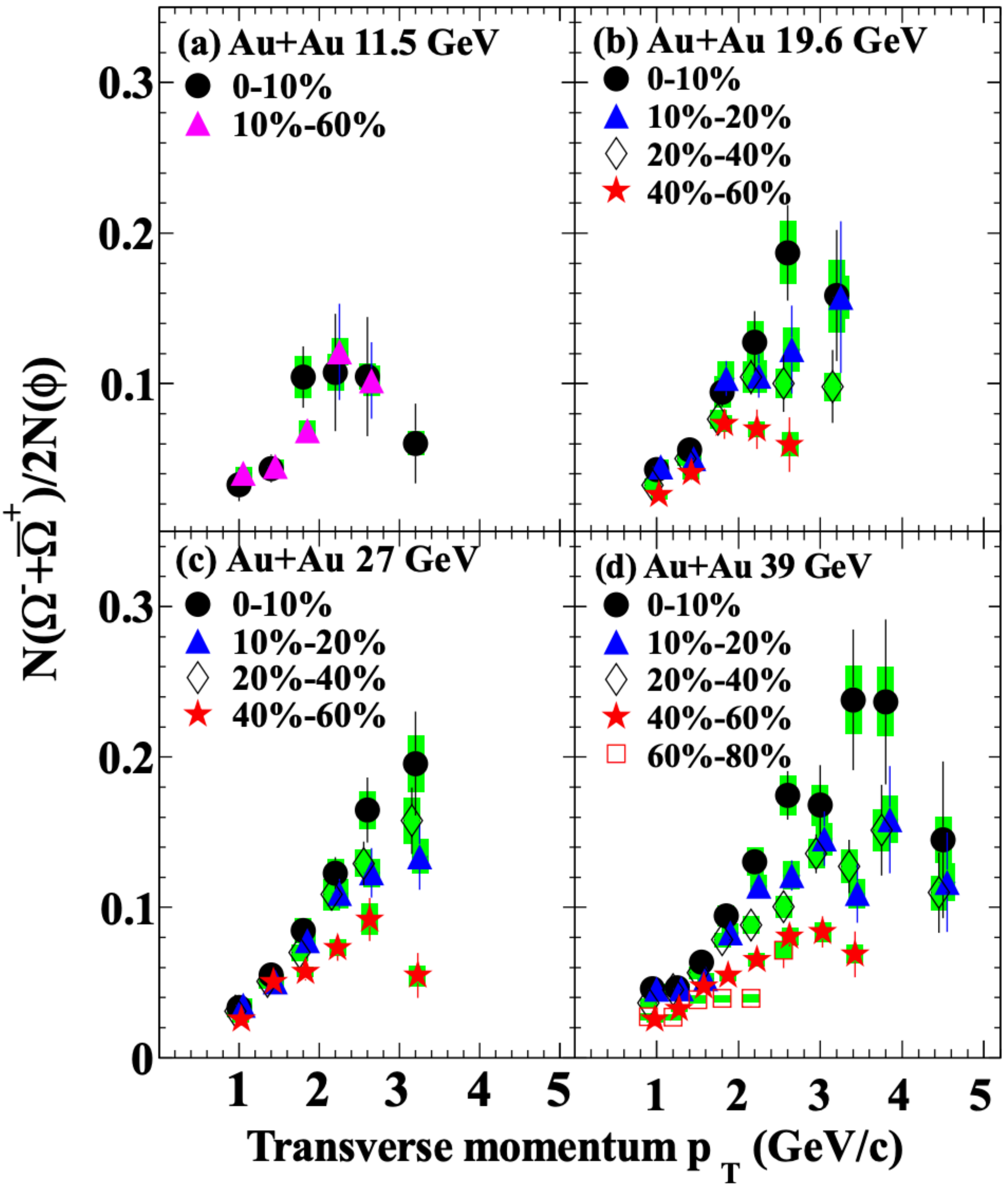


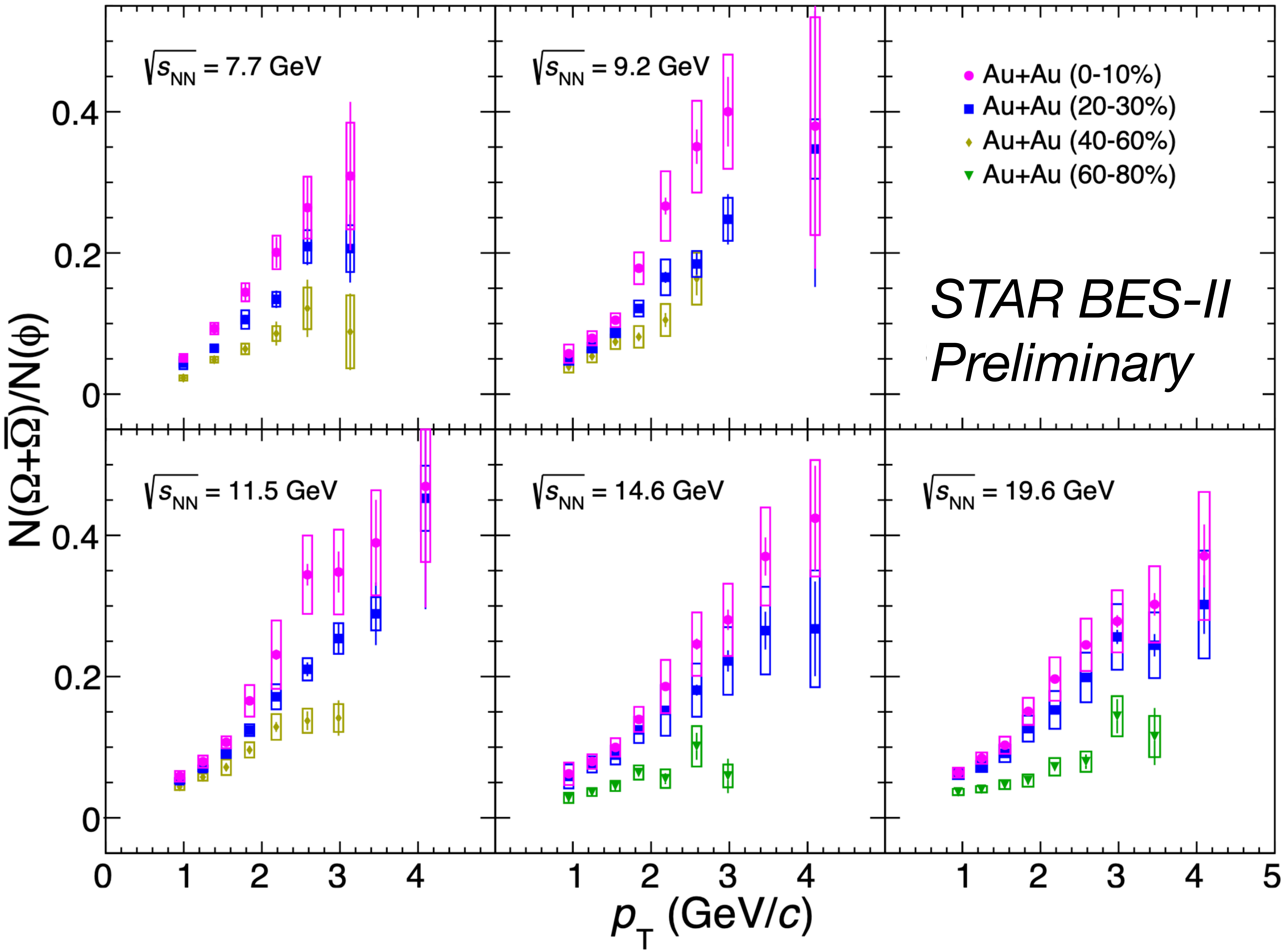
- Larger R_{cp} for Ω, Ξ than Λ, K^0_S and ϕ
  - Quark coalescence
- Precise measurements at BES-II show clear **splitting** among different species **down to 7.7 GeV**

STAR: Phys. Rev. C 102, 034909 (2020)

Energy Dependence of Baryon-to-Meson Ratio

STAR BES-I



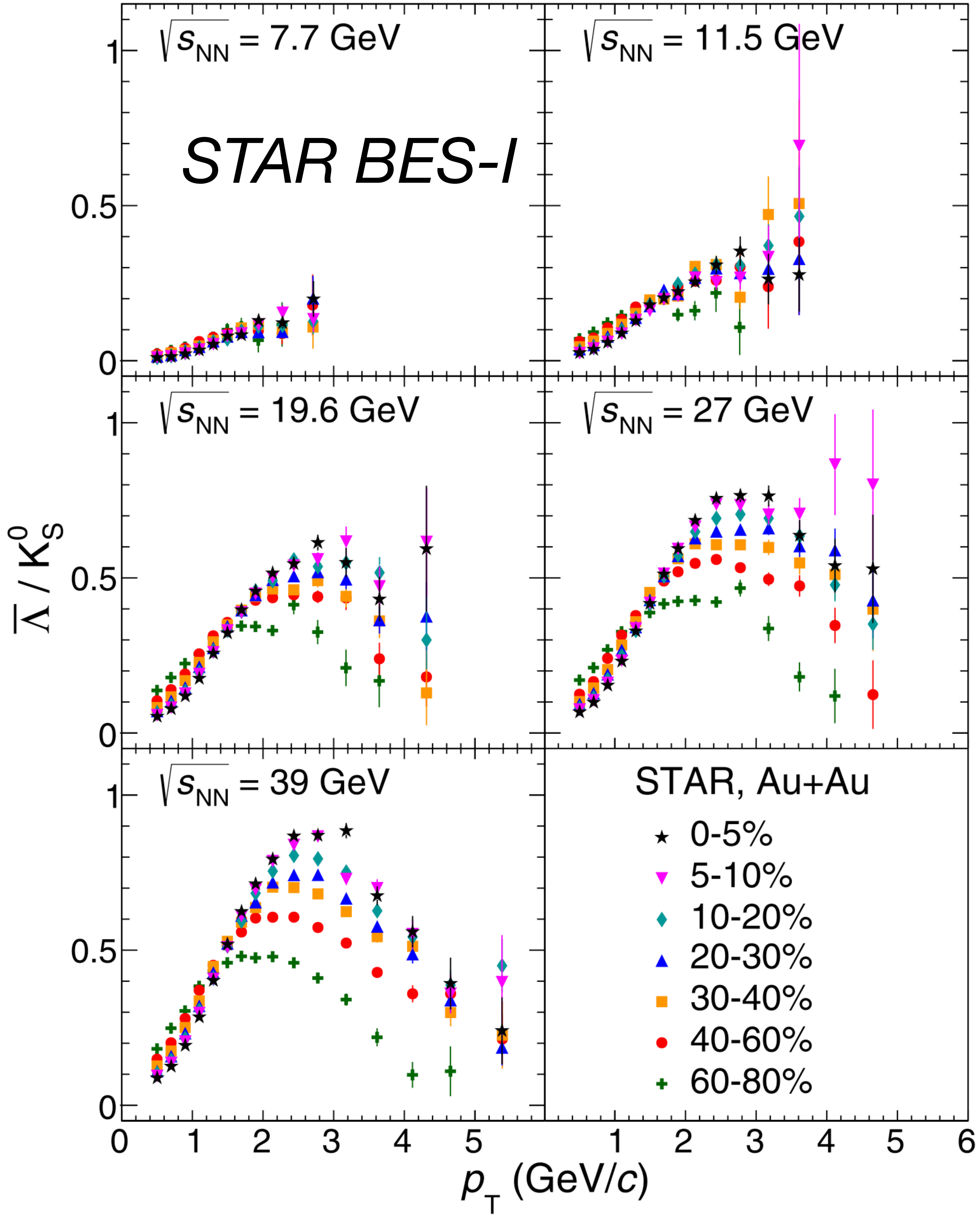


- Intermediate p_T region: Ω/ϕ enhancement in central collisions
  - Reflects **quark recombination**

- **Ω/ϕ enhancement persists down to 7.7 GeV**

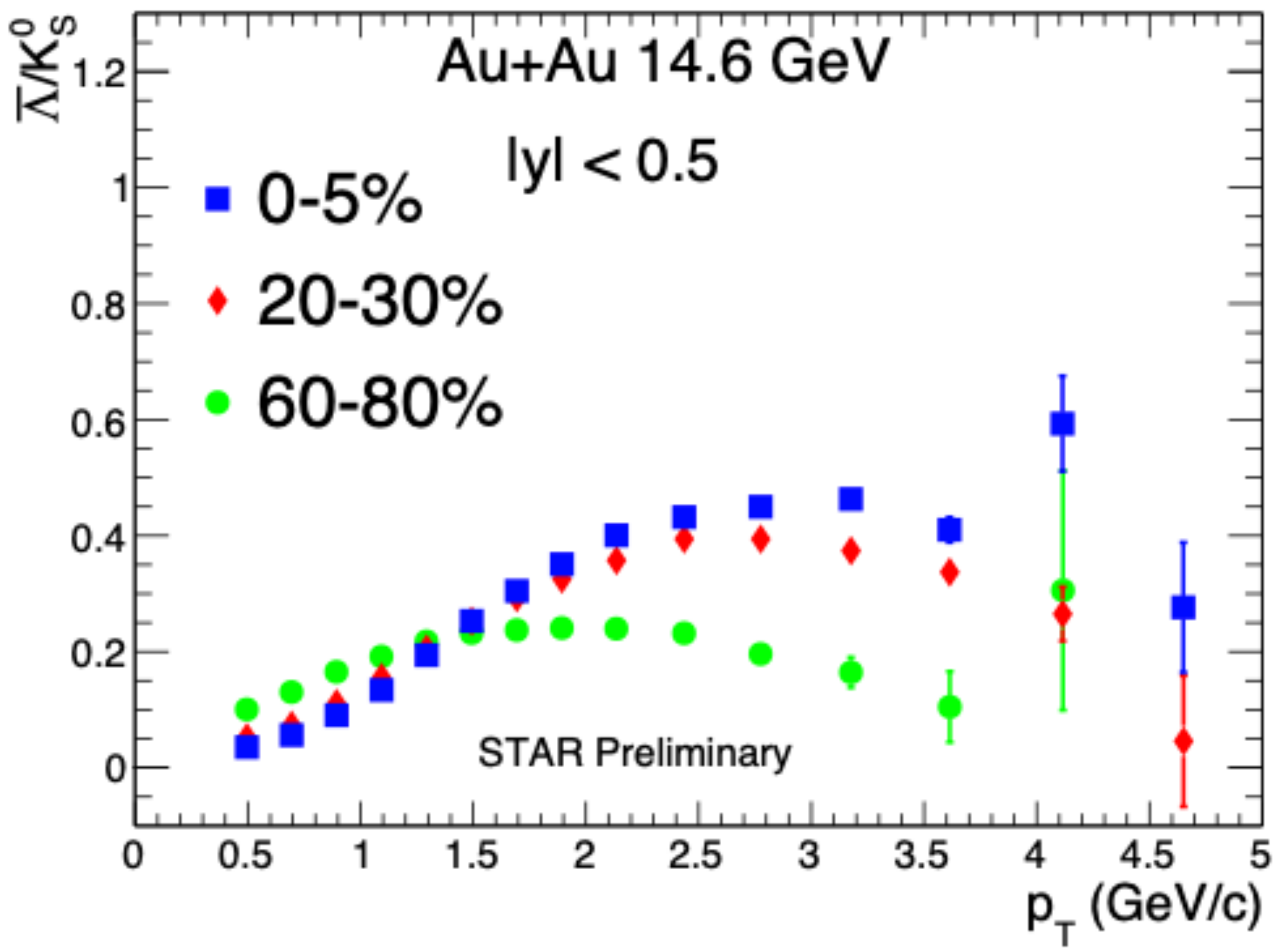
STAR, PRC 93, 021903 (2016)

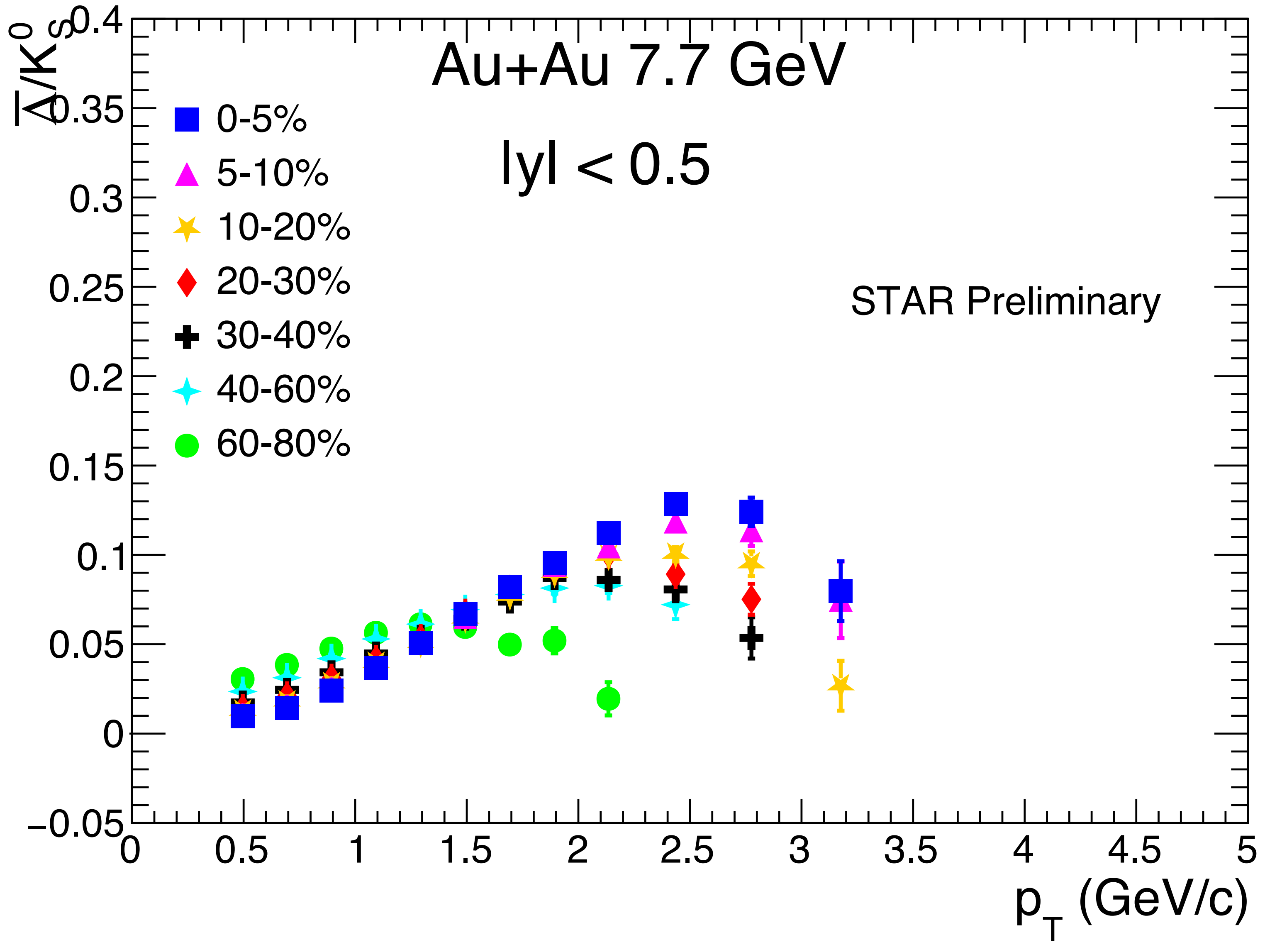
Energy Dependence of Baryon-to-Meson Ratio



STAR: Phys. Rev. C 102, 034909 (2020)

STAR BES-II Preliminary

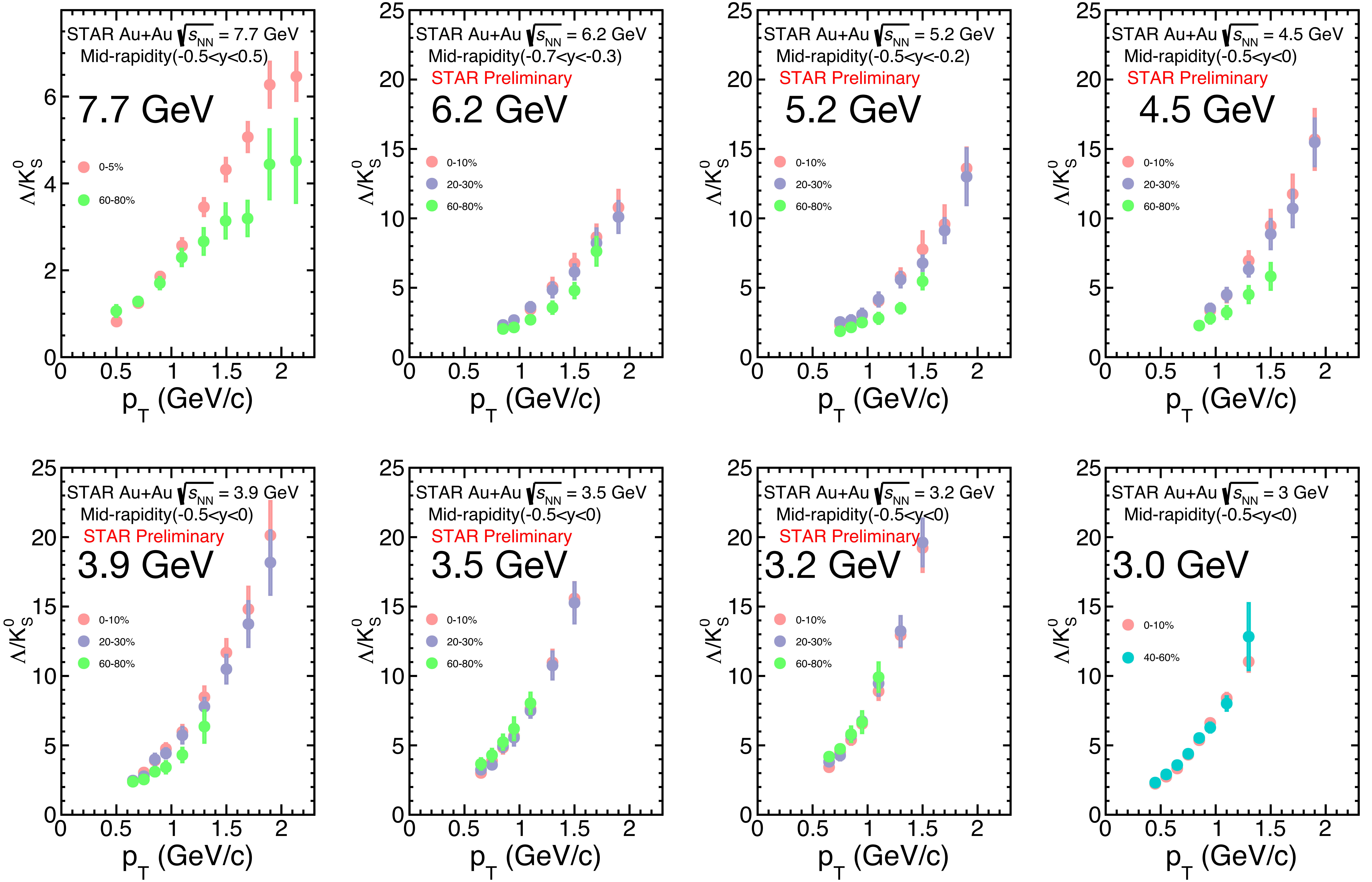




- Anti-Λ is a newly produced baryon in the baryon-rich medium created at lower Beam Energy Scan energies
- Precise measurements at BES-II show **baryon enhancement persists down to 7.7 GeV**

Energy Dependence of Baryon-to-Meson Ratio

STAR BES-II FXT Preliminary

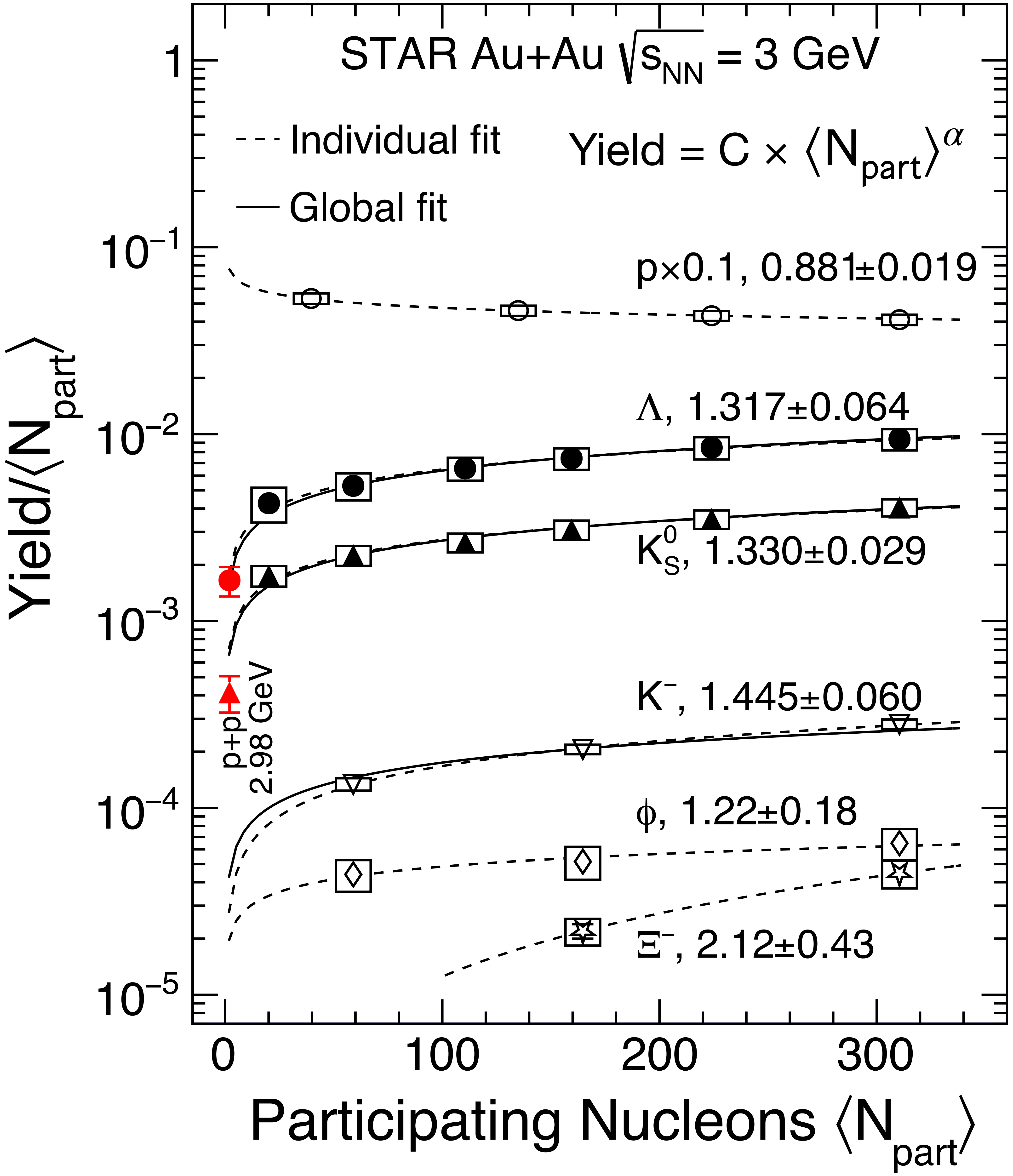


- To explore **below 7.7 GeV**, we extend to FXT energies
- Anti-Λ at mid-rapidity is statistics-limited **below 7.7 GeV** → use Λ/K^0_S as proxy

- **Baryon enhancement** at $p_T > 1$ GeV/c **persists down to 3.9 GeV**, but not below

- Possible **change of medium properties between 7.7 and 3 GeV → theory input needed**

Centrality Dependence of Yields at 3 GeV



STAR: JHEP 2024, 139 (2024)

Hadronic interaction dominated medium at 3 GeV

- Parameterize the centrality dependence of yields

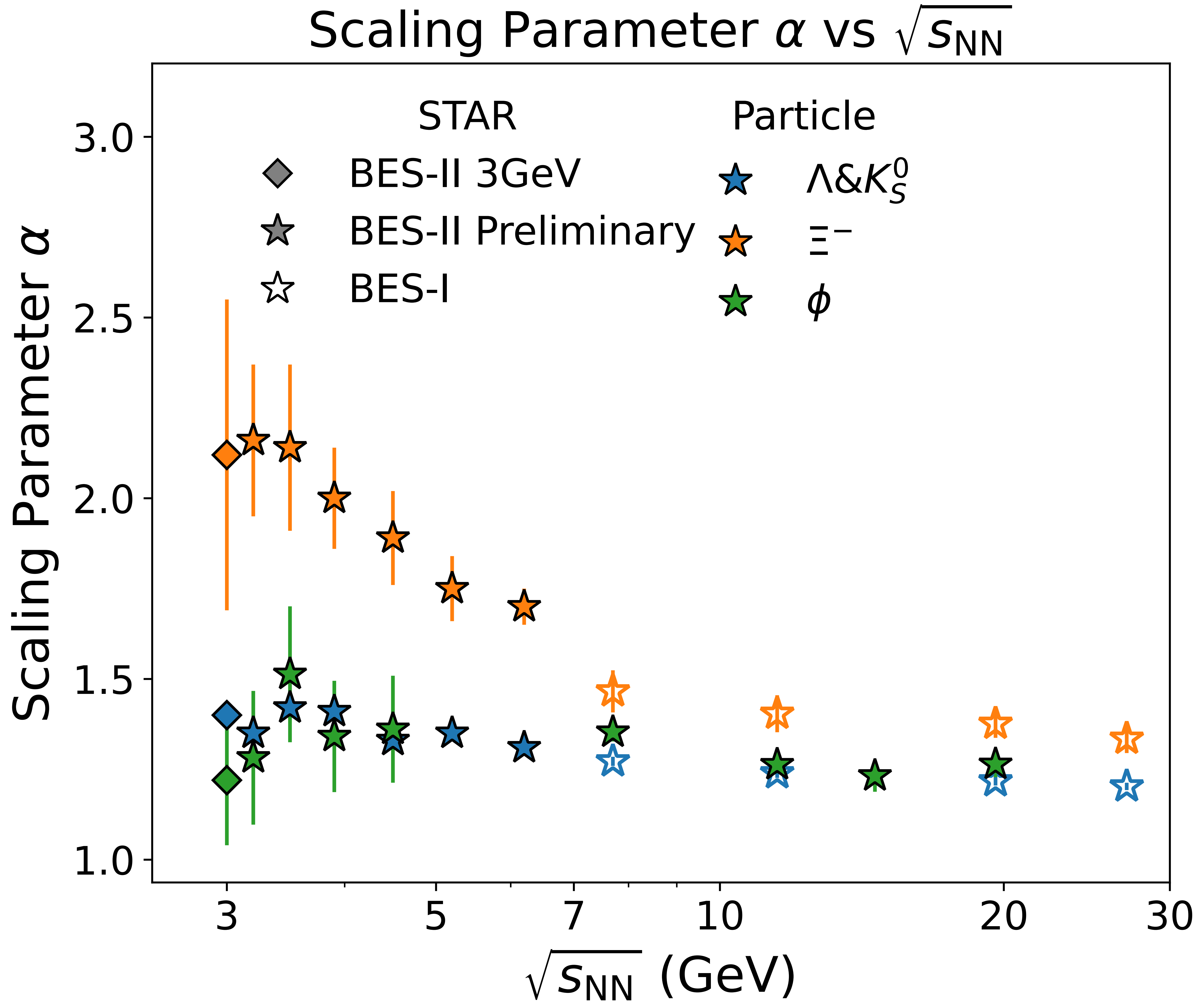
$$\text{Yield} = C \times \langle N_{part} \rangle^{\alpha}$$

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

Production channel	$E_{\text{Beam,thr}}$ [GeV]
$NN \to NK^+\Lambda$	2.55
$NN \to NK^0\Lambda$	2.56
$NN \to NNK^+K^-$	2.86
$NN \to NN\phi$	2.89
$NN \to N\Xi^-K^{+/0}K^{+/0}$	3.25

- p+p following the scaling trend

Collision Energy Dependence of α

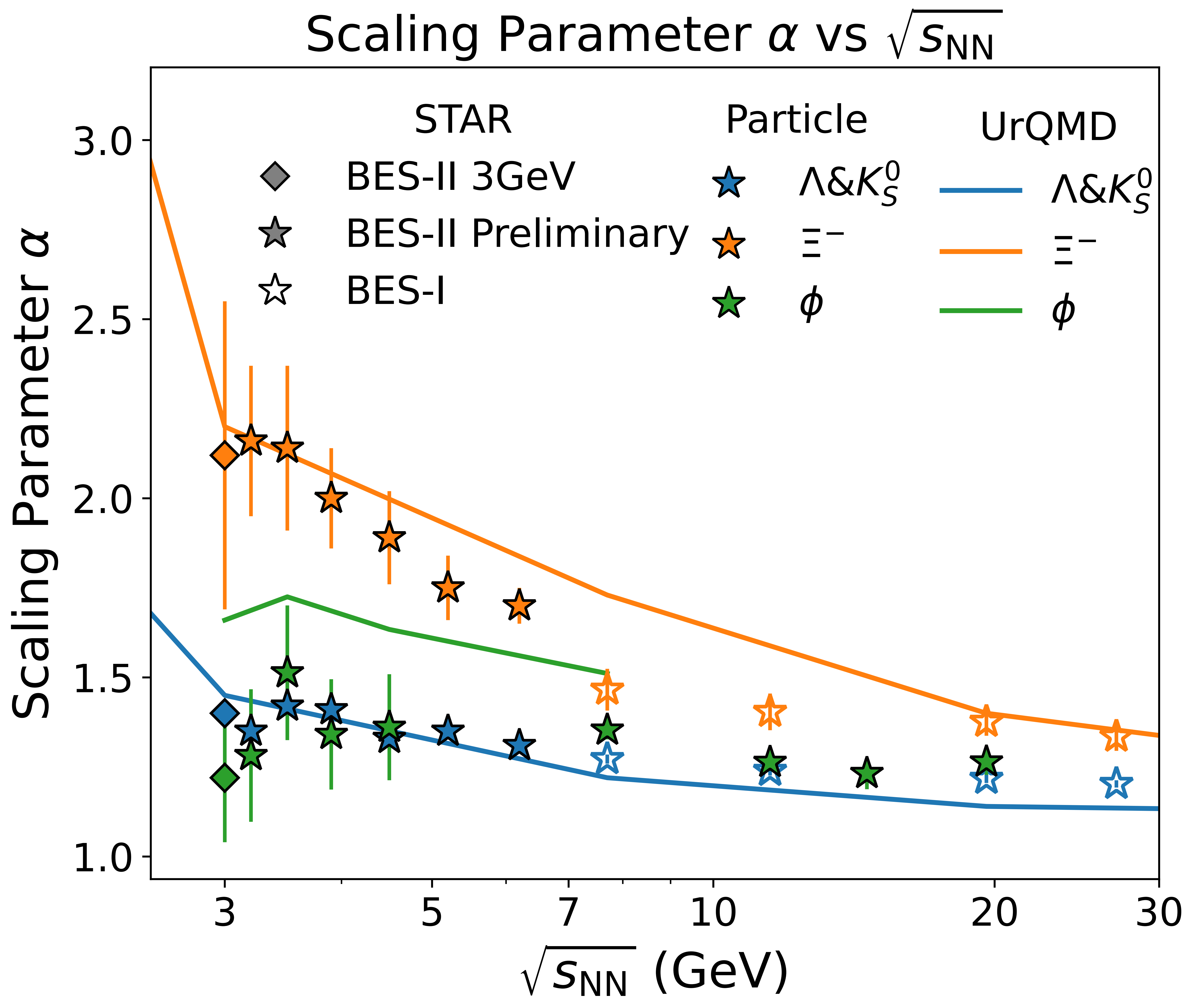


- Rapid decrease of scaling parameter α for Ξ^- from 3 to 7.7 GeV, and saturate at high energies
  - Production of Ξ^- and Λ likely driven by hadronic interactions below 7.7 GeV

STAR: JHEP 2024, 139 (2024)

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

Collision Energy Dependence of α

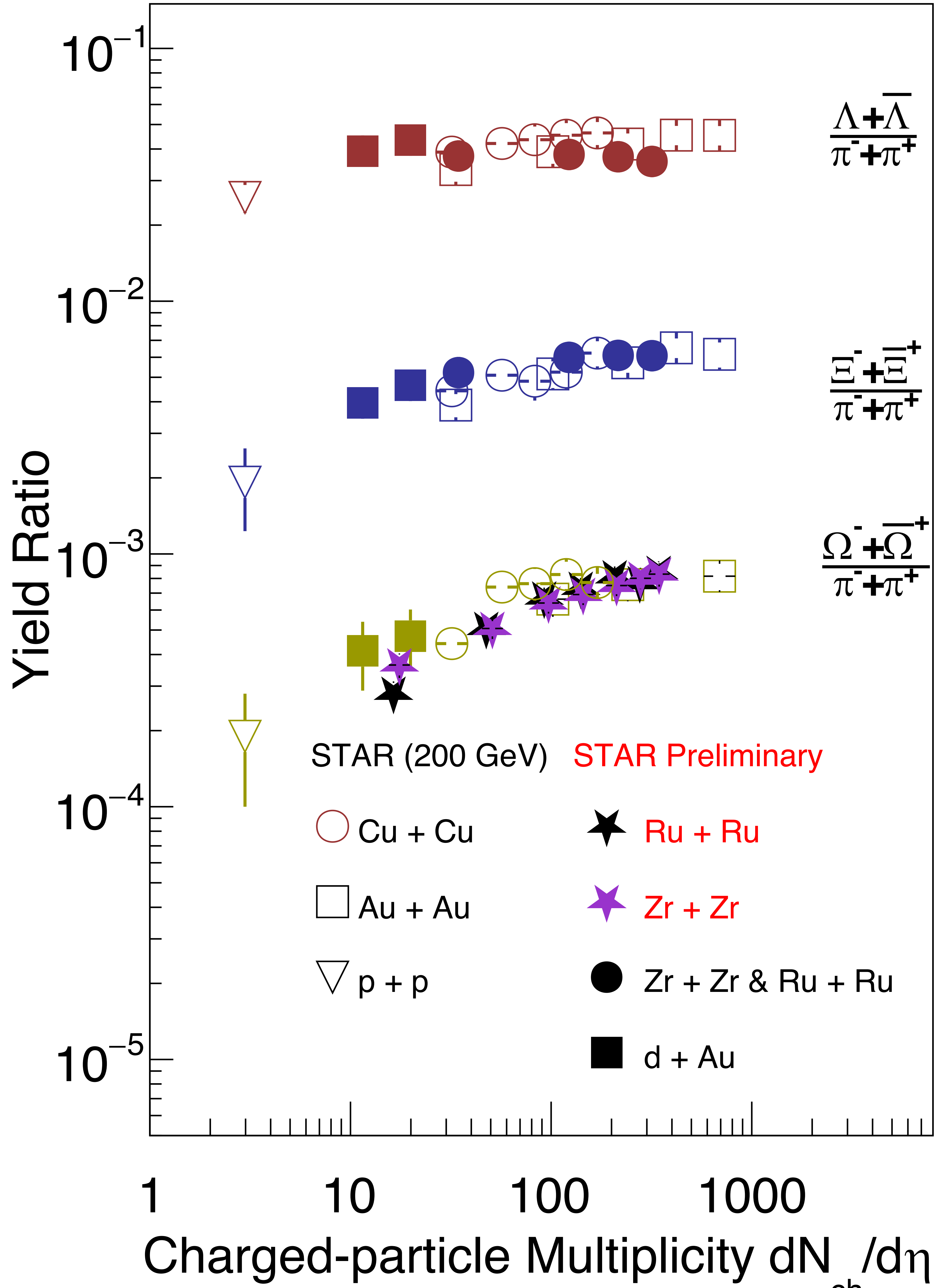


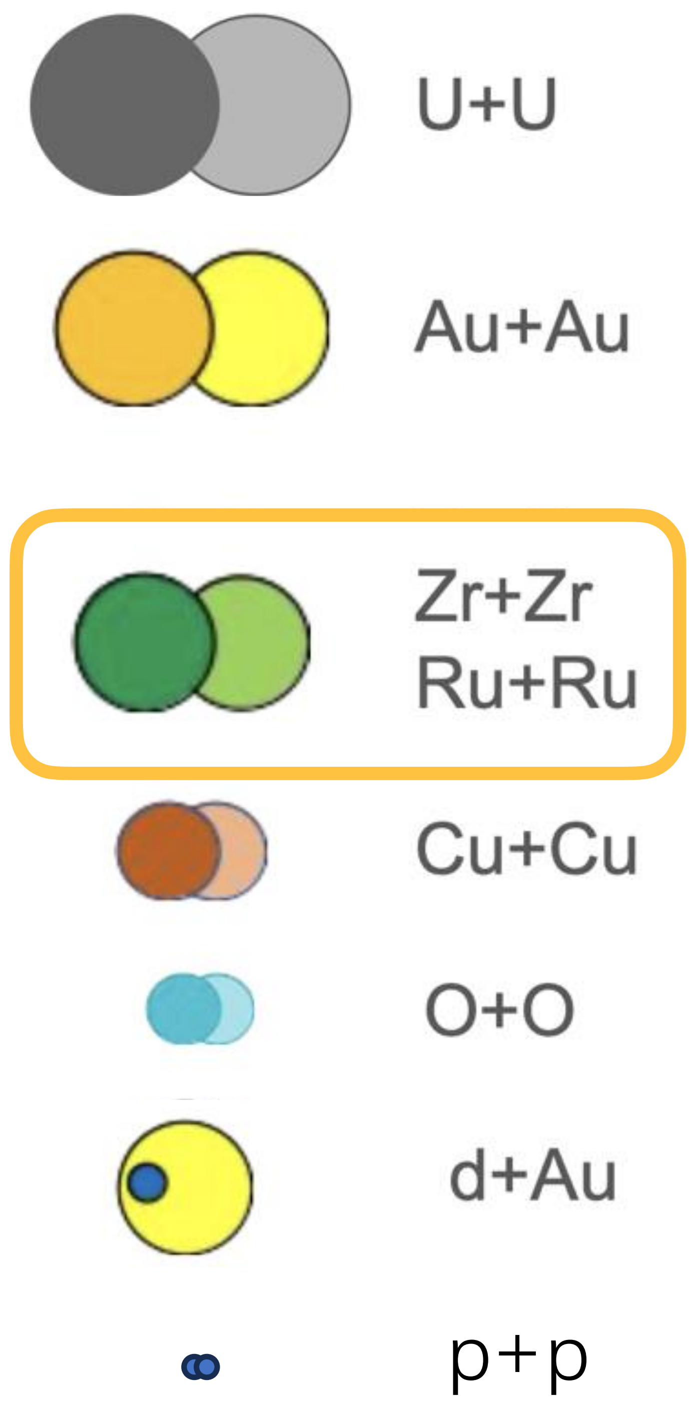
- Rapid decrease of scaling parameter α for Ξ^- from 3 to 7.7 GeV, and saturate at high energies
  - Production of Ξ^- and Λ likely driven by hadronic interactions below 7.7 GeV
- UrQMD qualitatively reproduces the energy dependence
  - Overestimates α for ϕ meson

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

STAR: JHEP 2024, 139 (2024)

System Size Dependence of Strange Hadron Production

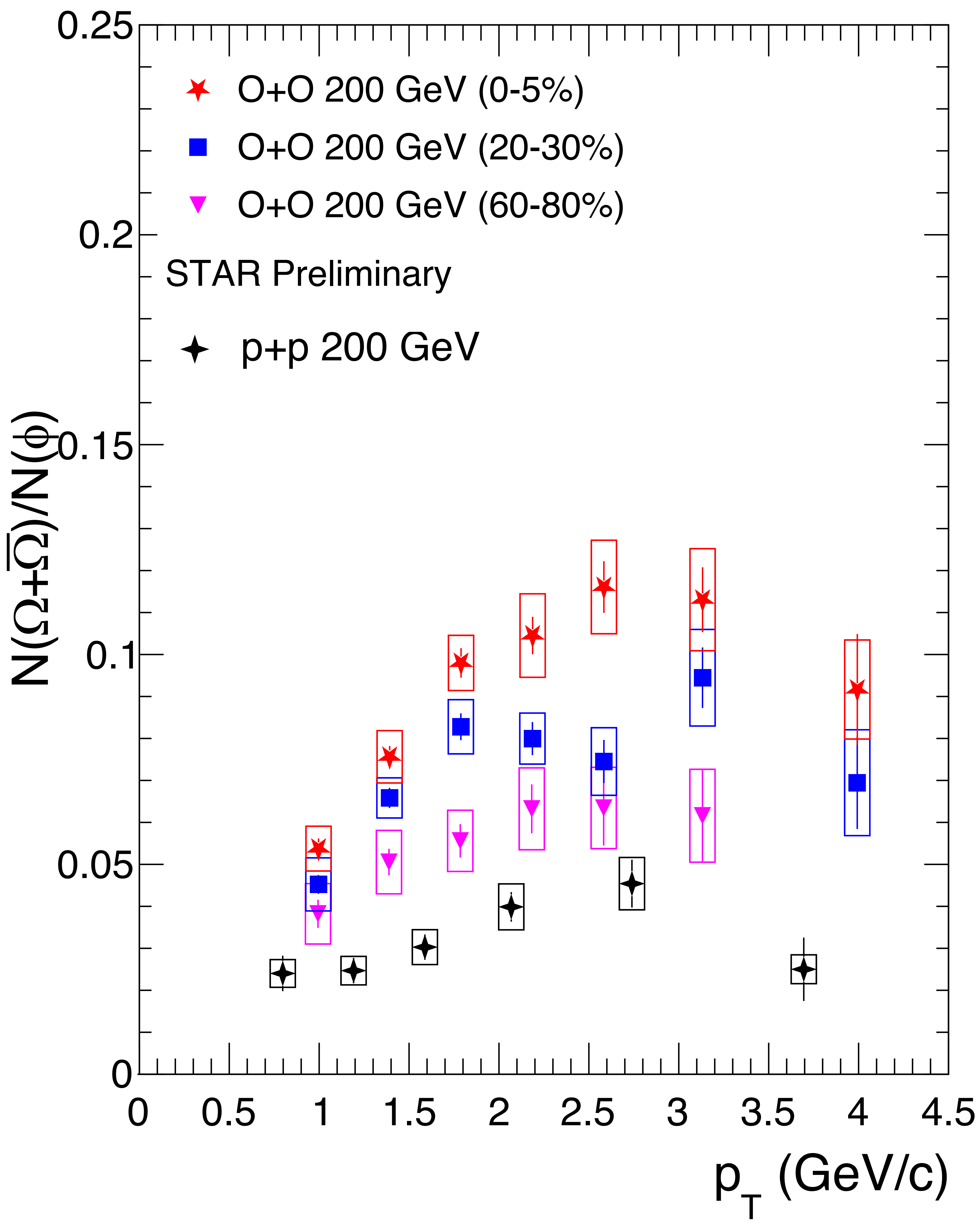


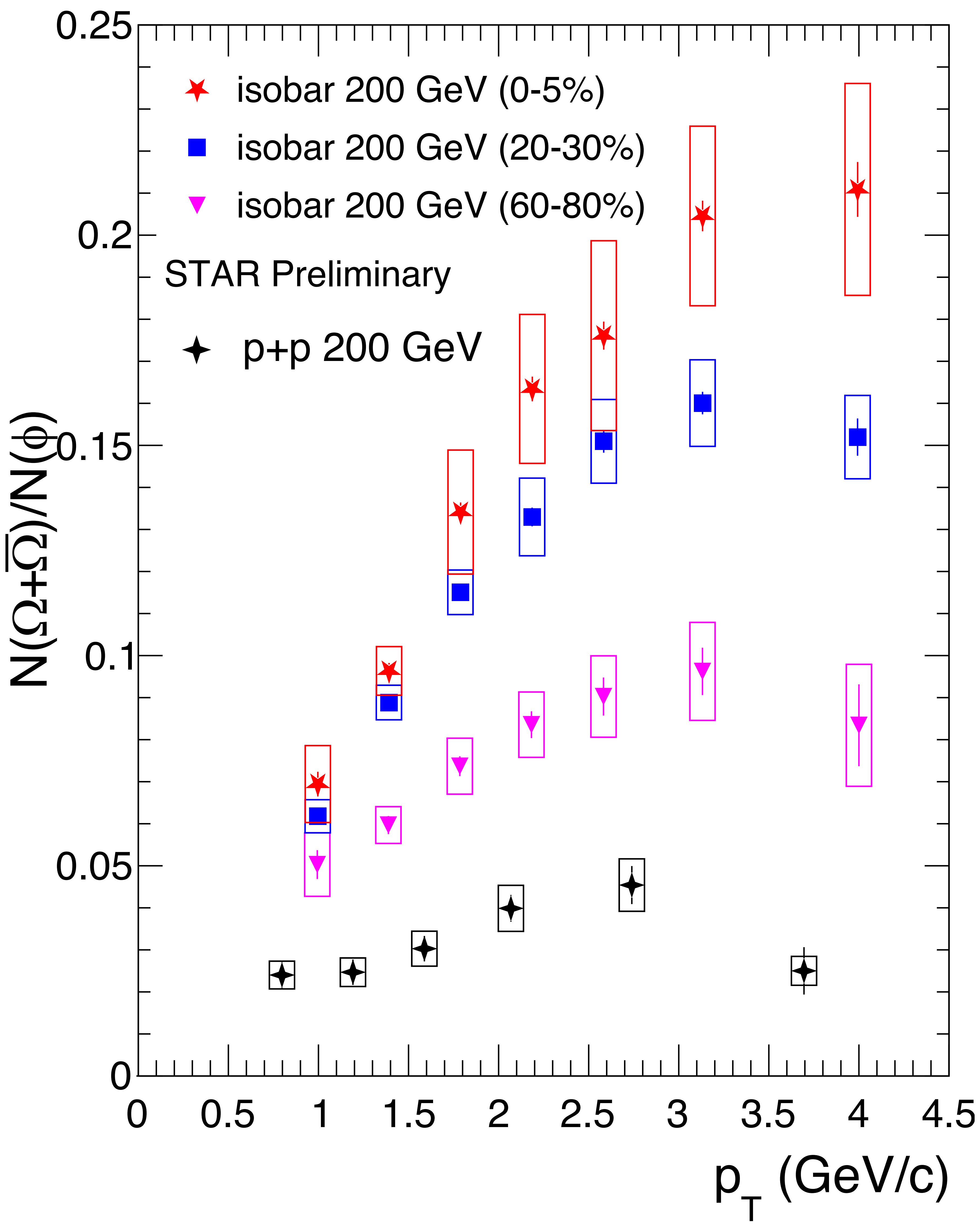


- Smooth transition of ratios of the strange particles from p+p to A+A collisions
- Yield ratios of strange particles to pions with more strangeness content decrease faster from high to low multiplicity

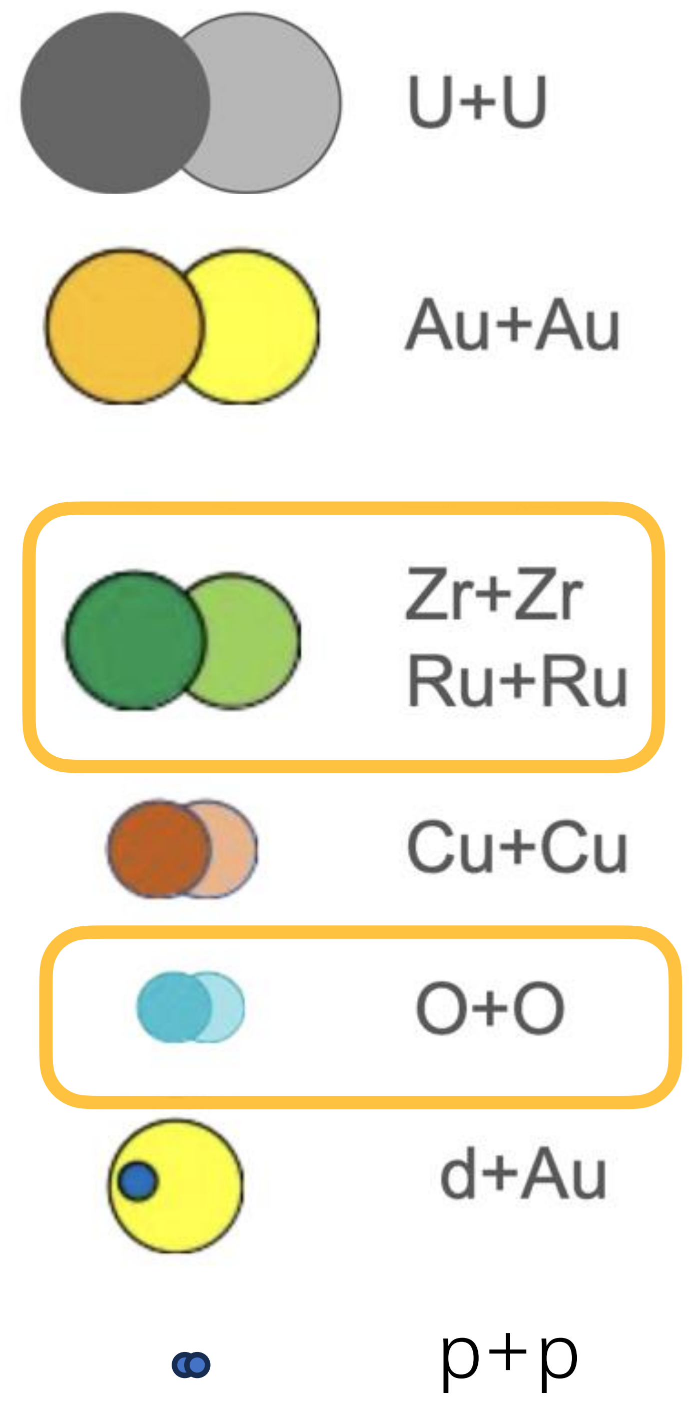
D. Li sQM 24
I. Aggarwal sQM 24
STAR : Phys. Rev. C 75, 064901 (2007), Phys. Rev. Lett. 108, 072301 (2012), Phys. Rev. C 79, 034909 (2009), Phys. Rev. C 83, 034910 (2011)

Centrality Dependence of Ω/ϕ Ratio in Different Systems

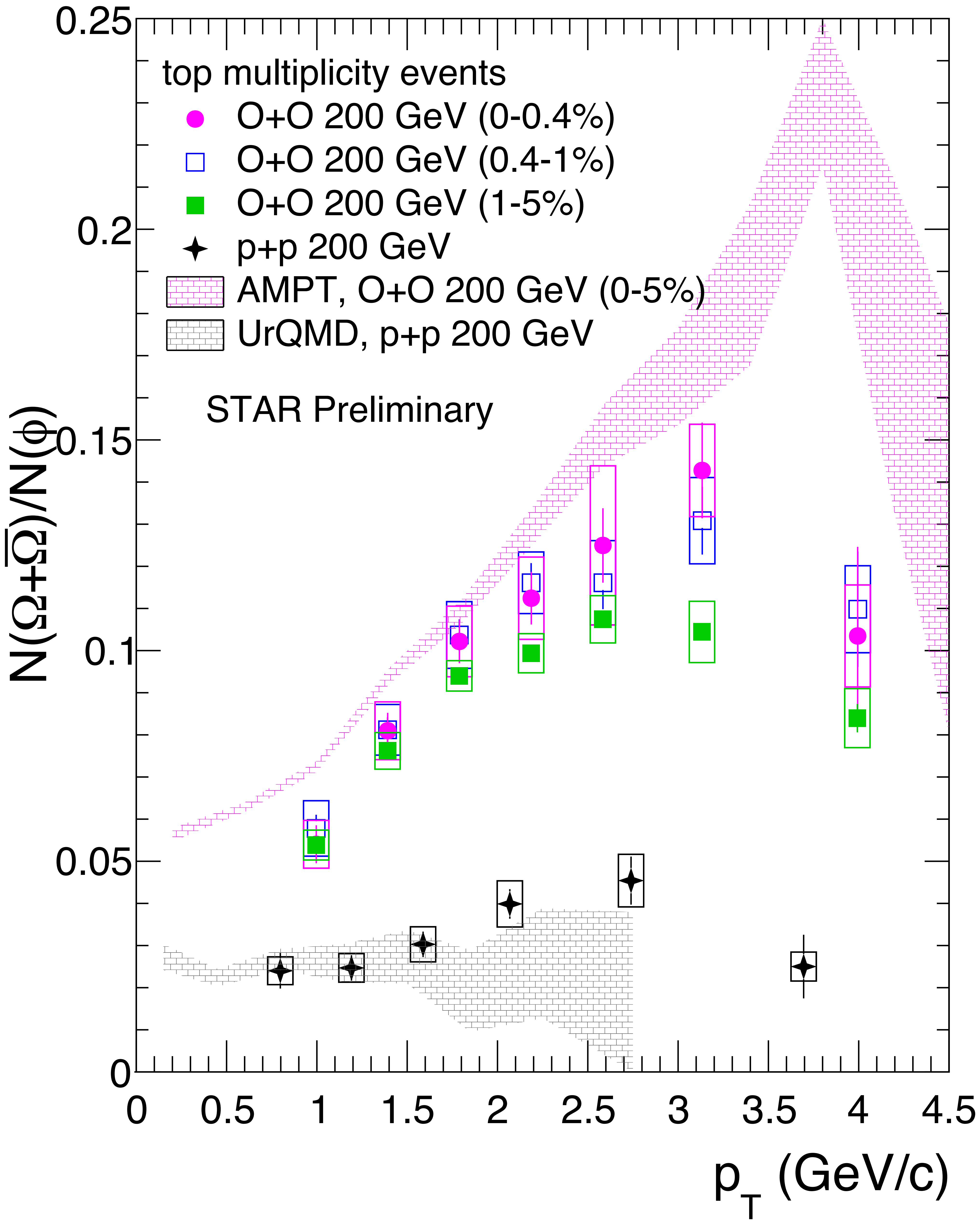




- Ω/ϕ enhancement observed in isobar and O+O collisions



Centrality Dependence of Ω/ϕ Ratio in Different Systems



- Ω/ϕ enhancement even within the most central (0-5%) O+O collisions

- p_T dependence can be described by AMPT model (String Melting), which favours recombination hadronization mechanism in central O+O collisions

AMPT: GC Yong, Phys.Lett.B 843, 138051 (2023)
UrQMD: S.A. Bass, et.al. Prog. Part. Nucl. Phys. 41 (1998)

Take Home Message

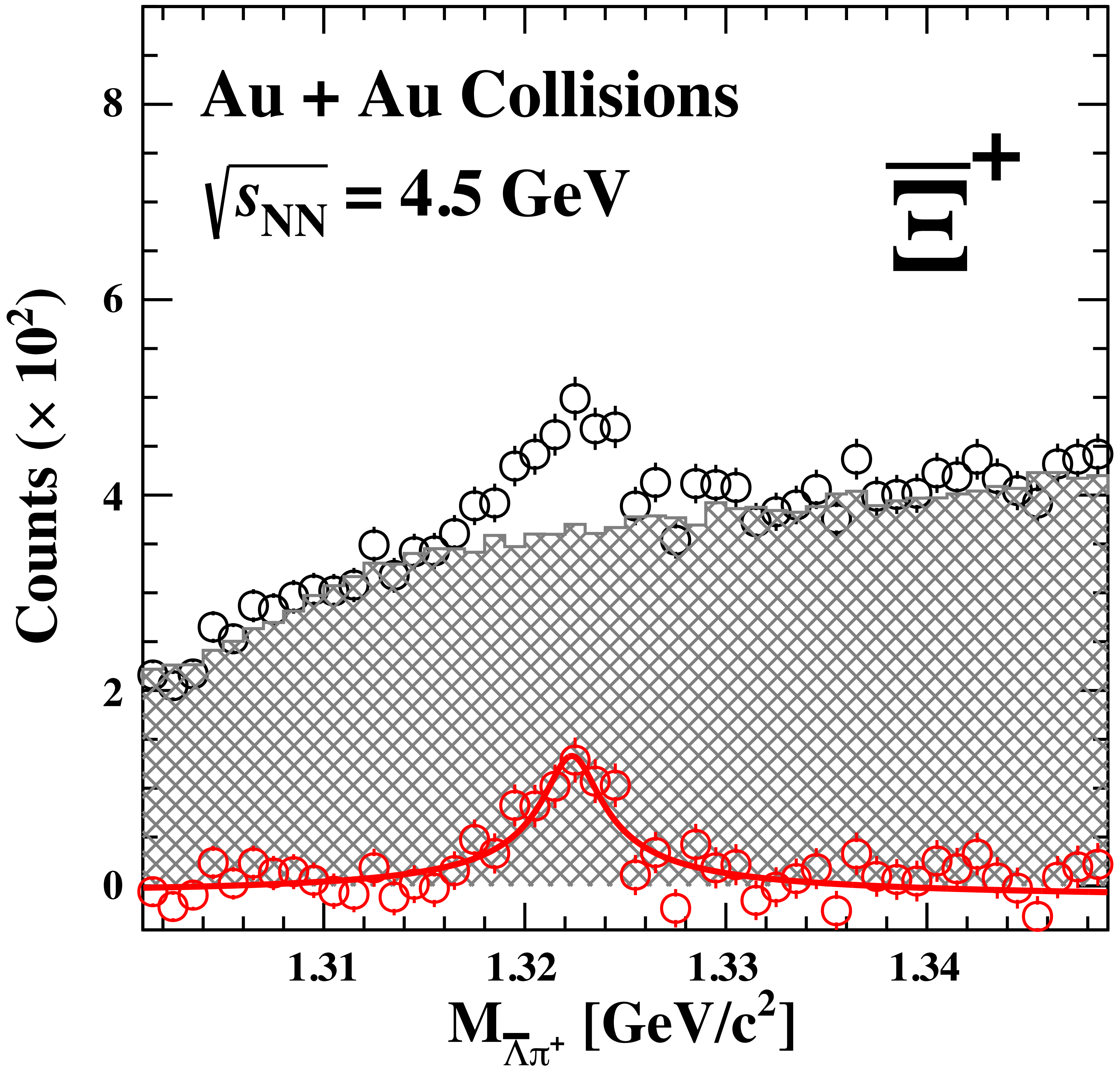
- **Energy dependence of strange hadron yields (STAR BES-II)**

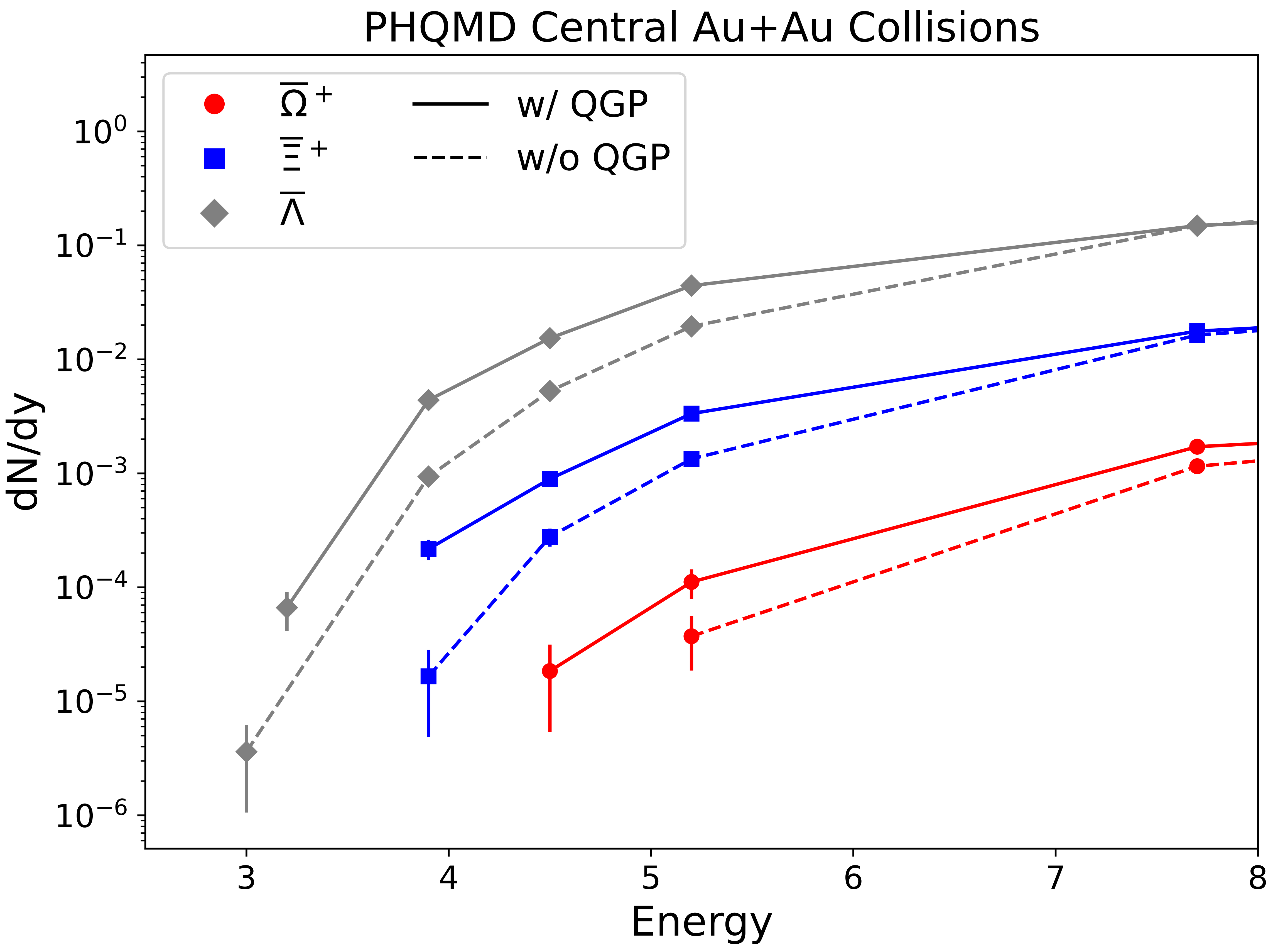
1. **Precise** measurements show that **baryon enhancement persists down to 7.7 GeV**
2. **At low energy** (below ~5 GeV), **CE is dominant and GCE does not work anymore imply the change of the medium**
3. **Steeper centrality dependence** of Ξ^- yields is observed **below 7.7 GeV** indicates the **formation of a baryon-rich medium where hadronic interactions dominate**

- **System size dependence (200 GeV)**

1. The **strange-hadron-to-pion ratios** approximately **follow** $dN_{ch}/d\eta$ **dependence** from **pp→ Zr+Zr/Ru+Ru → Au+Au**
2. Ω/ϕ **baryon enhancement** is observed in both central **isobar** and **O+O** collisions, favoring a **recombination-dominated hadronization** picture even in small systems

Outlook





PHQMD: J. Aichelin et al., Phys. Rev. C 101 (2020) 044905

- **Next steps:** Extend measurements of **anti-strangeness production** ($\overline{\Lambda}$, $\overline{\Xi}^+$,and $\overline{\Omega}^+$) **below 7.7 GeV** using FXT data
- Comparison with transport model calculations (e.g. PHQMD with and without a QGP phase), will further constrain the transition from **hadronic → partonic** dynamics and EOS at low energies

Many Thanks to

RHIC operation team, STAR Collaboration and Theory Colleagues

Wenyun Bo, Yi Fang, Junyi Han, Yue-Hang Leung, Hongcan Li, Yaping Wang, Xiongxiong Xu, Weiguang Yuan, Guannan Xie, Li'Ang Zhang, Guangyu Zheng, Xianglei Zhu

Thank you for your attention!