Strangeness production at high baryon density in STAR BES-II FXT experiment

Yaping Wang (王亚平)

Central China Normal University (华中师大)

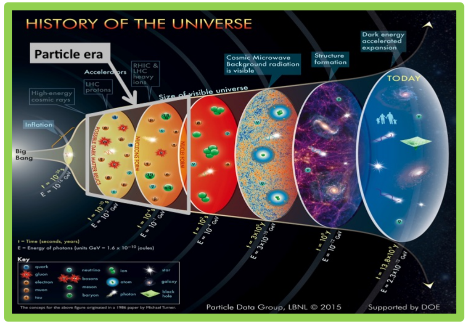
Collaborators: Wenyun Bo, Junyi Han, Hongcan Li, Li'Ang Zhang, et al. (CCNU)
Guannan Xie (UCAS), Yingjie Zhou (GSI)
Yue-Hang Leung (Heiderburg Univ.)

Outline

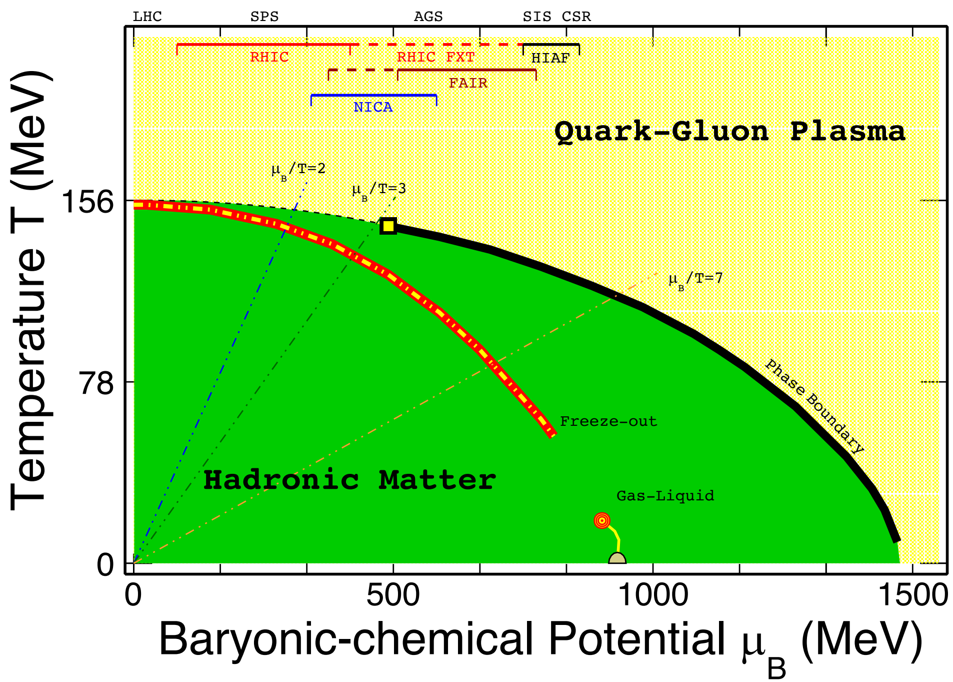
- Introduction
- STAR BES-II FXT experiment
- Strangeness production at high baryon density
- Summary and outlook

Explore QCD Phase Diagram

LHC | RHIC BES | FAIR, NICA, …

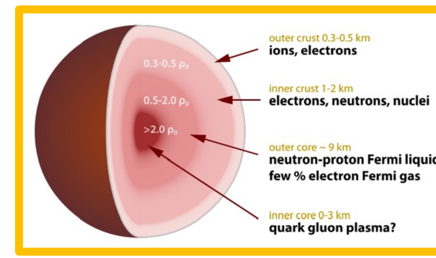


High temperature:
Early Universe evolution



Ref.: N. Xu @sQM2022

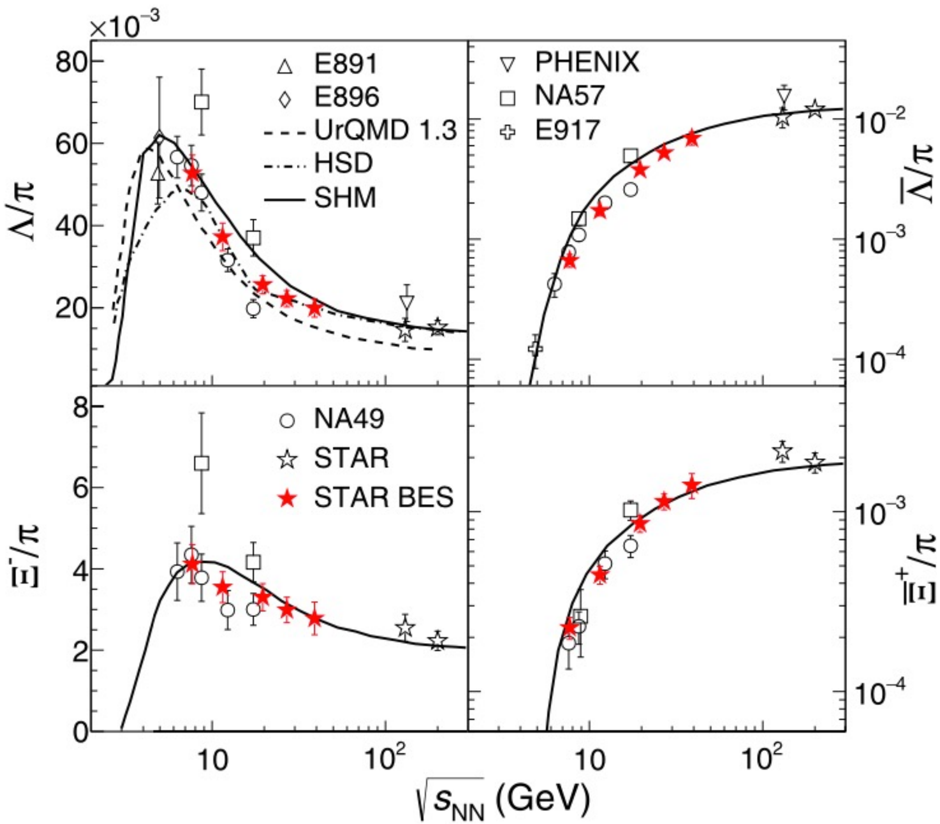
High baryon density:
Inner structure of
compact stars



- **At $\mu_B = 0$, smooth crossover (LGT + data)**
- **At large μ_B, 1st order phase transition → QCD critical point**

Strangeness Probe to Study the Nuclear Matter

STAR BES-I: Phys. Rev. C 102 (2020) 34909
[1] J. Randrup, et al. Phys. Rev. C74, 047901 (2006)



- Rich structure in strangeness excitation functions
  - ➢ Production mechanisms is different at low and high energies (high and low baryon density)
    - ☐ Partonic interaction (pair production)

      $gg \rightarrow s\bar{s}$ or $q\bar{q} \rightarrow s\bar{s}$
    - ☐ Hadronic interaction (associated production)

      $BB \rightarrow BYK$ or $BB \rightarrow B\Xi KK$

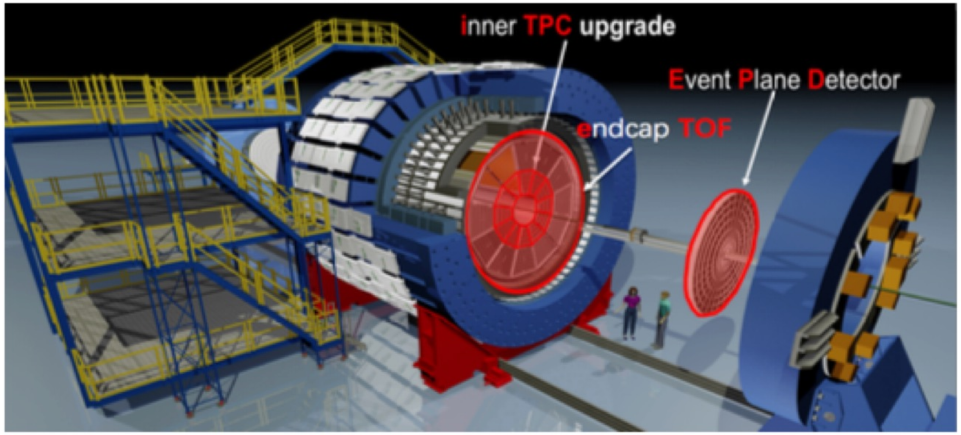
      B: N, p, Δ, etc. Y: Λ, Σ, etc. K: K^+, K^0
  - ➢ Baryon-dominated to meson-dominated transitions
    - ☐ Λ/π peaks at $\sqrt{s_{NN}}$ ~8 GeV

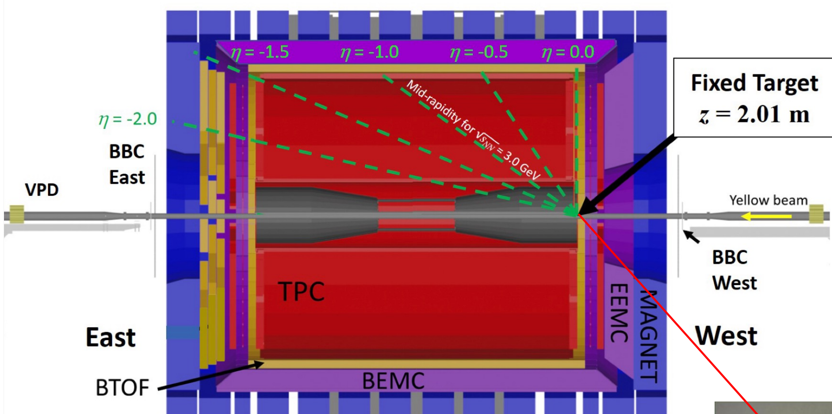
    → Model: Baryon density maximal at $\sqrt{s_{NN}}$ ~ 8 GeV

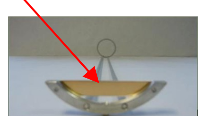
- **Scarce data at low energy, more data is needed!**

  → Connections to the softness of dense nuclear matter, phase boundary, and onset of deconfinement

STAR BES-II FXT Experiment

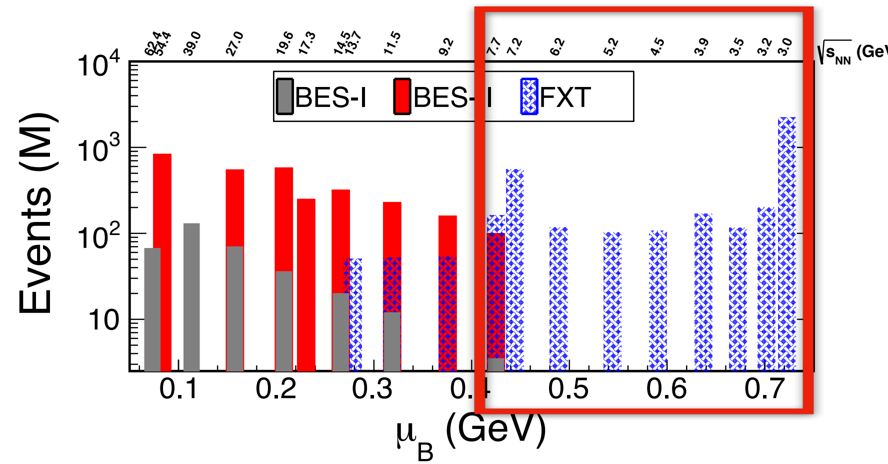






STAR BES-II ($\sqrt{s_{NN}} = 3 \sim 54.4$ GeV)

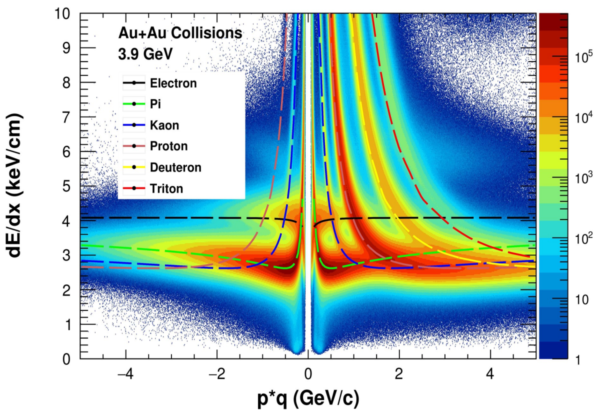
- 10x statistics compared to BES-I
- Detector upgrades: iTPC, eTOF, EPD
- FXT extends energy down to 3 GeV



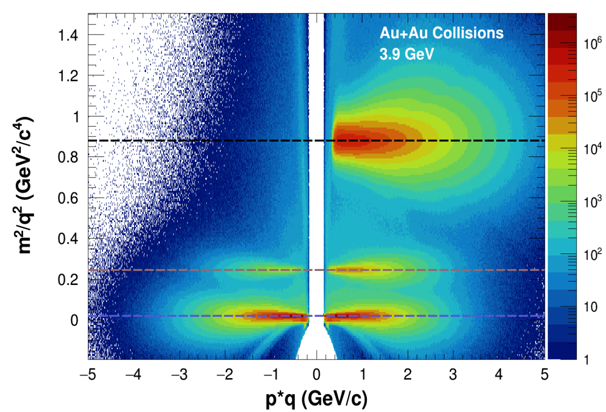
✓ New results from BES-II data at 3.0, 3.2, 3.5, 3.9, 4.5 GeV (5.2 to 7.7 GeV ongoing)

Particle Identification

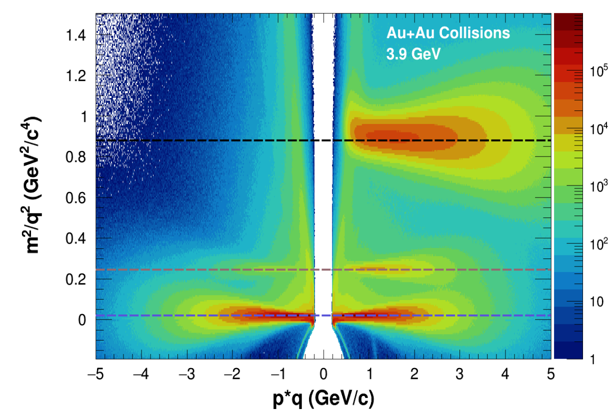
TPC



bTOF

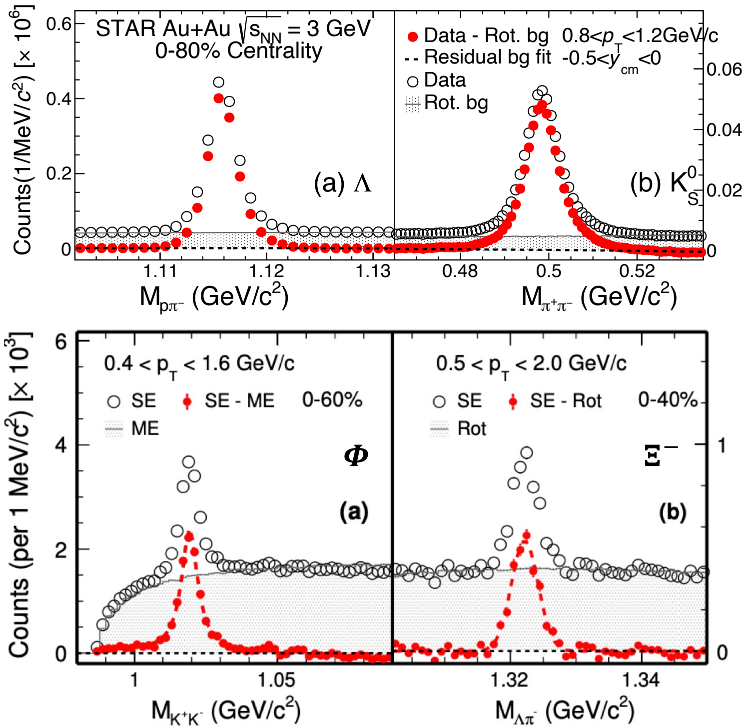


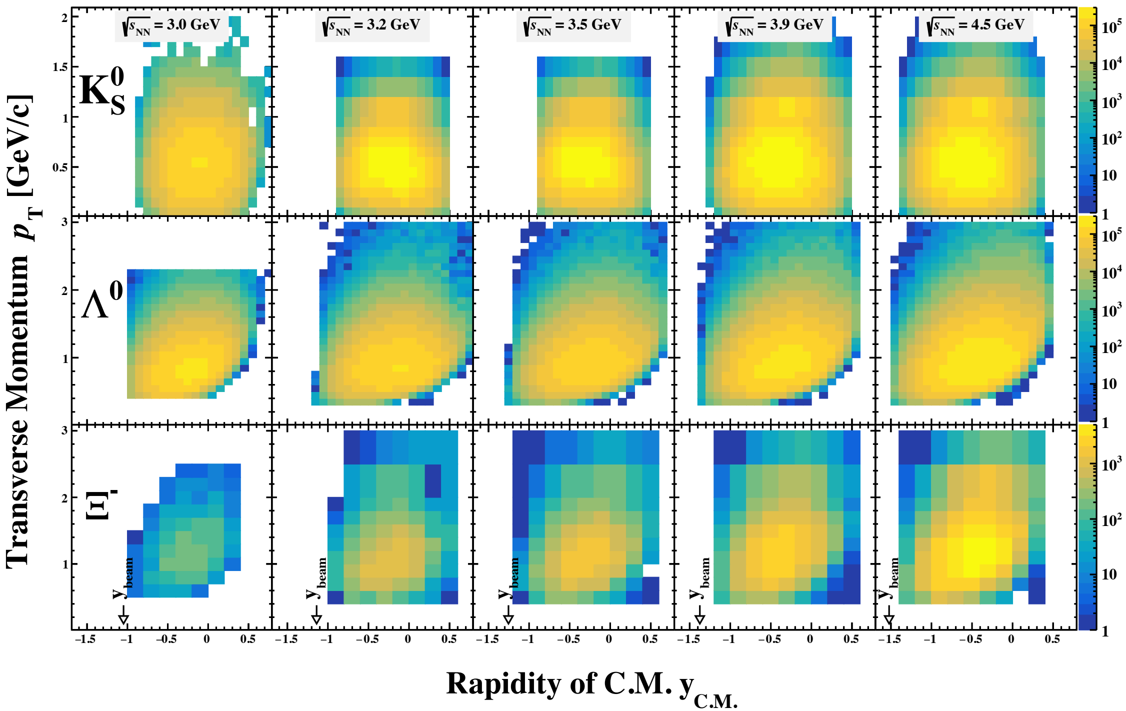
eTOF



- Strange hadrons ($\mathbf{K_S^0}$, ϕ, $\mathbf{\Lambda^0}$, $\mathbf{\Xi^-}$, …) are reconstructed via invariant mass method by identified decay daughters
- TPC (dE/dx) and TOF (β) for charged pion and proton identification
  - TOF m^2 formula: $\boldsymbol{m^2 = p^2\left(\frac{1}{\beta^2} - 1\right)}$

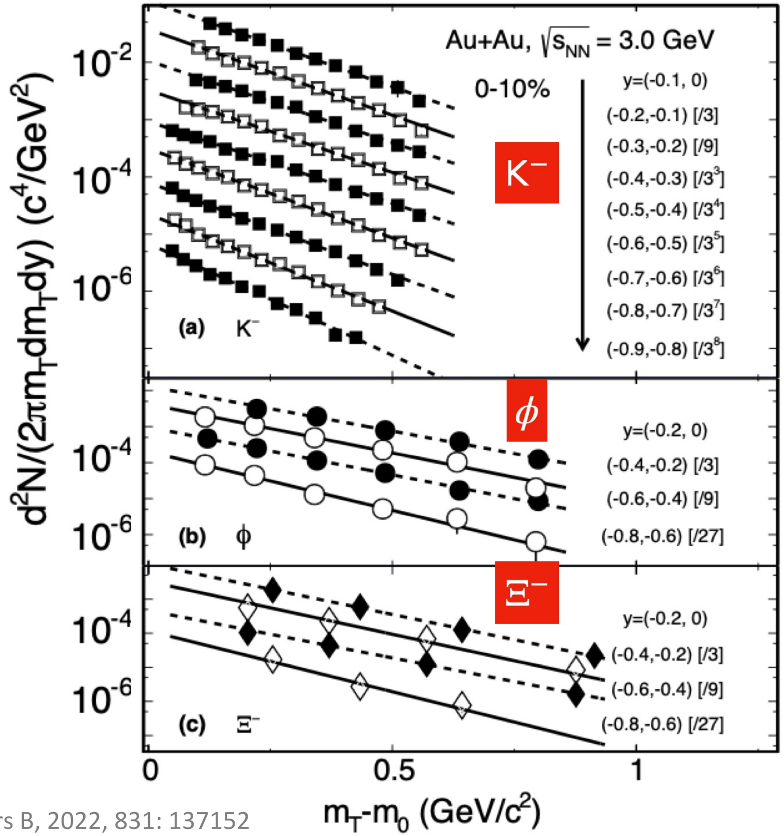
Strange Hadron Reconstruction & Acceptance



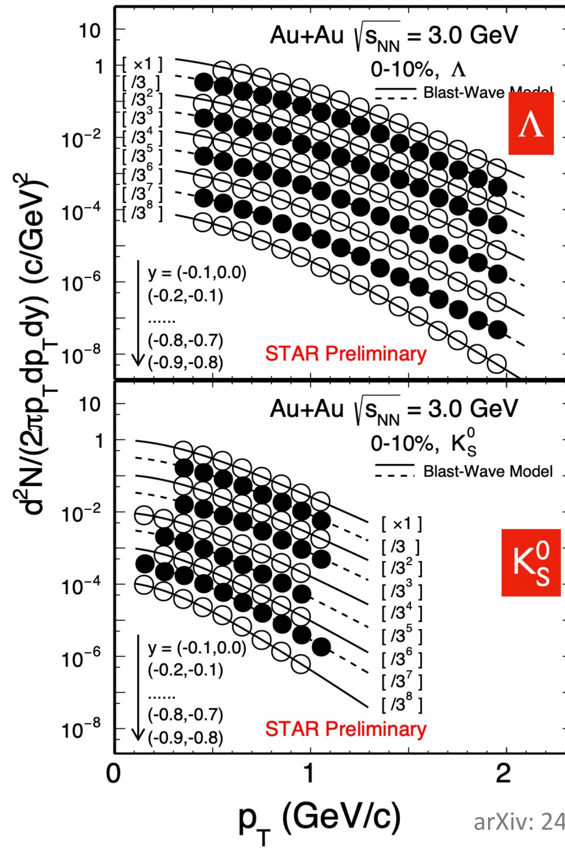


- KFParticle package is used for the reconstruction to improve the signal significance
- Combinatorial backgrounds are reconstructed by rotation (mixing-event) method
- Particle rapidity coverage from beam rapidity to mid-rapidity

Strange Hadron p_T Spectra



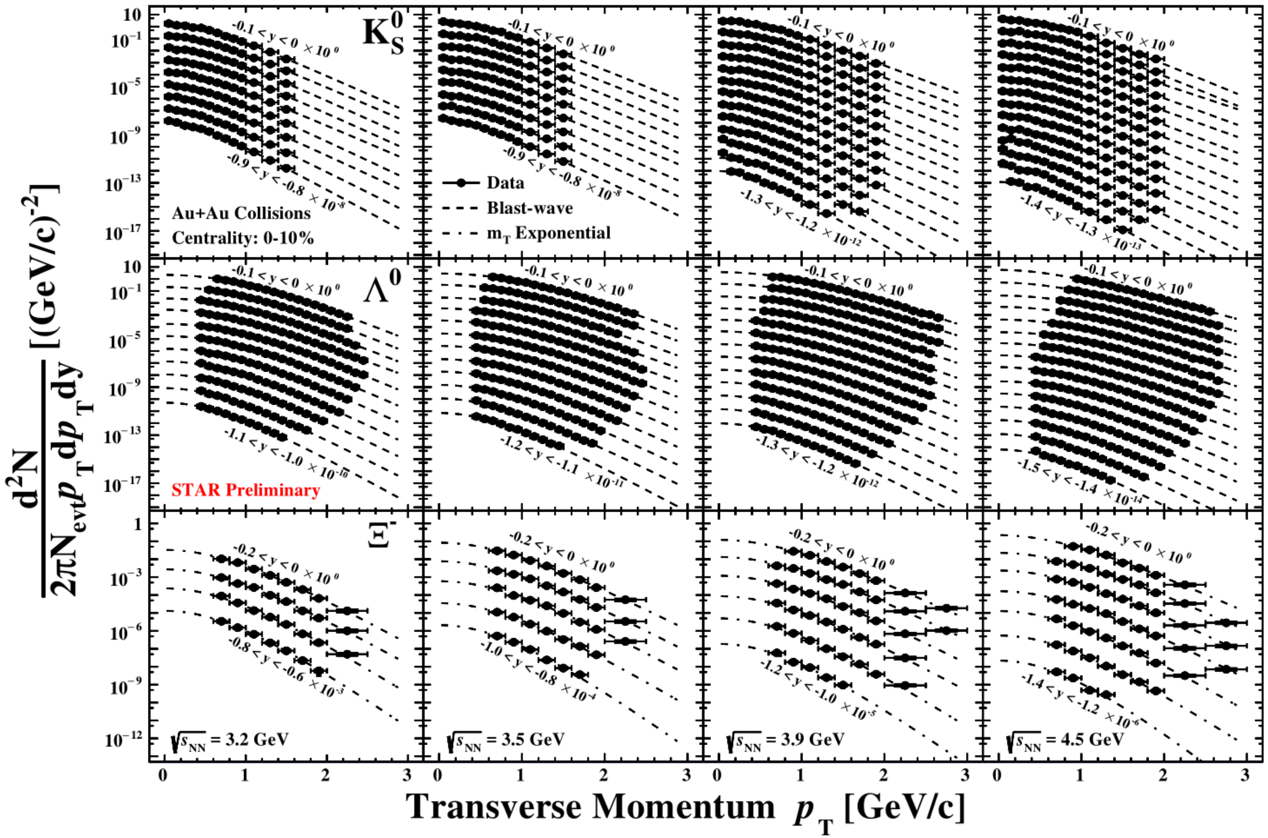
Physics Letters B, 2022, 831: 137152



arXiv: 2407.10110v1 (accepted by JHEP)

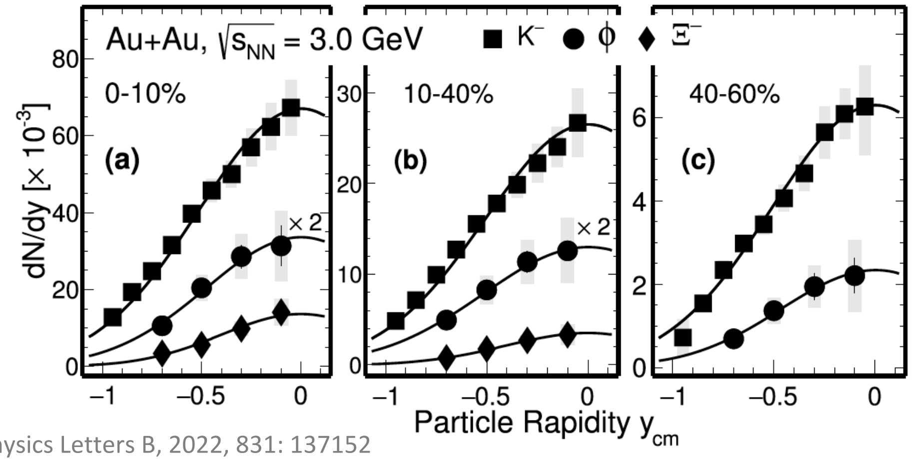
- Comprehensive strangeness (K⁻, K_S^0, $\boldsymbol{\Phi}$, Λ^0 and Ξ^-) measurements at different energies from 3 to 4.5 GeV

Strange Hadron p_T Spectra

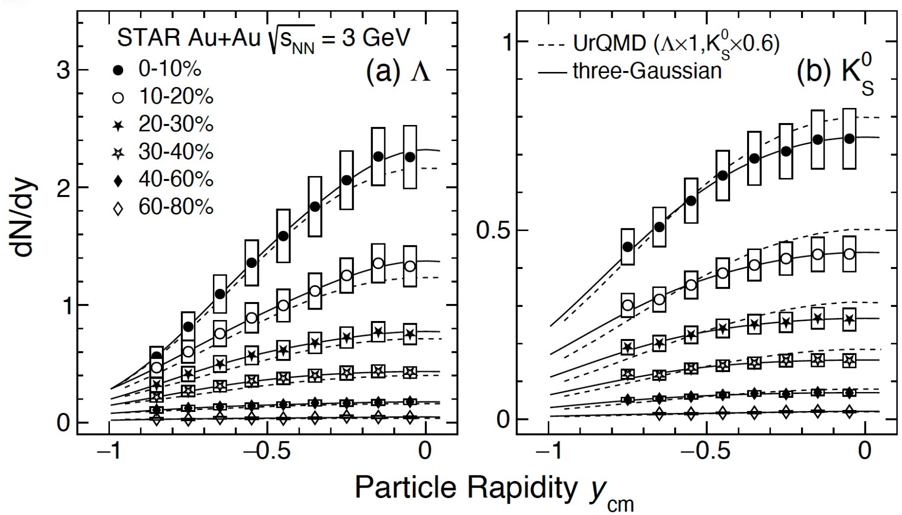


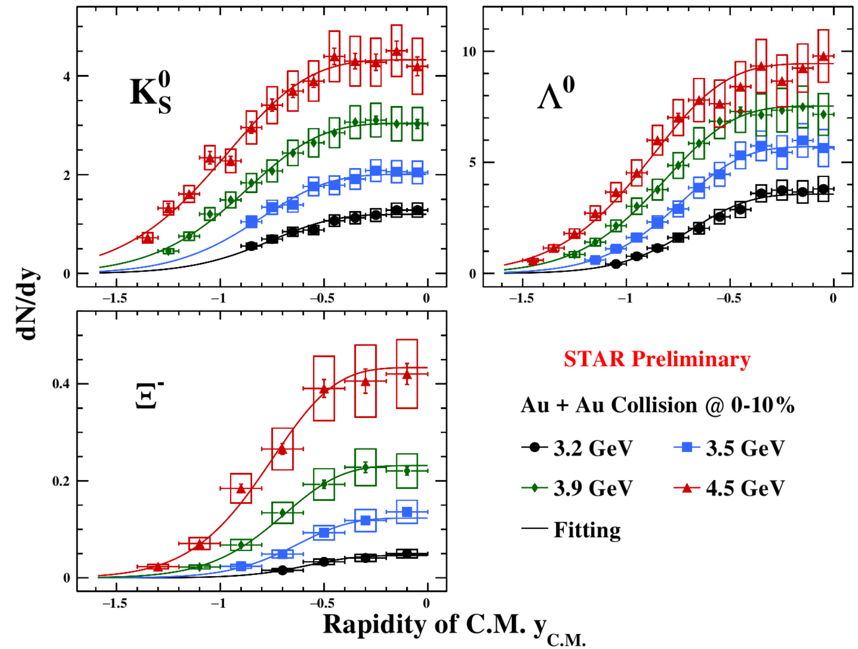
- Comprehensive strangeness (K$^-$, K_S^0, $\boldsymbol{\Phi}$, Λ^0 and Ξ^-) measurements at different energies from 3 to 4.5 GeV

Strange Hadron Rapidity Density Distribution



Physics Letters B, 2022, 831: 137152

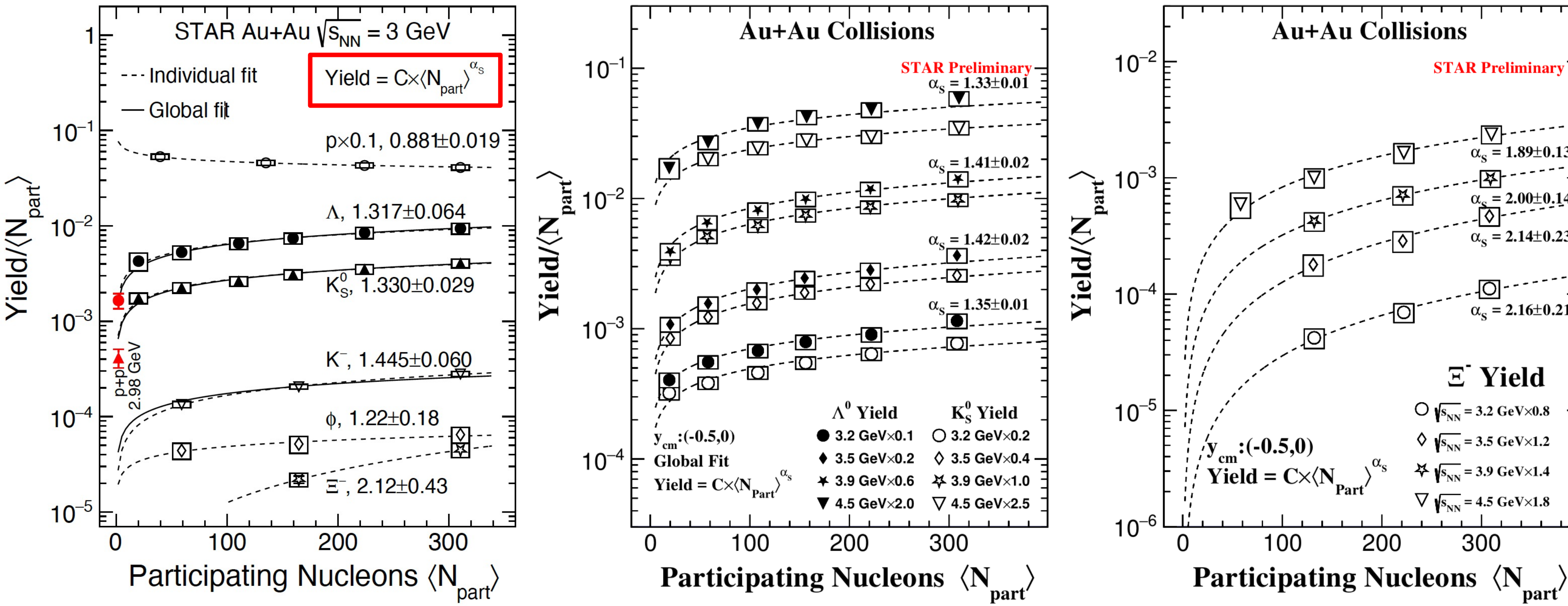




- Rapidity distributions are fit to Gaussian distribution to extrapolate to the unmeasured rapidity region
- UrQMD reproduces the yields of *Λ*, but overestimates K_s^0, K^-, Ξ^- and underestimates ϕ mesons

Strange Hadron Yields vs N_{part}

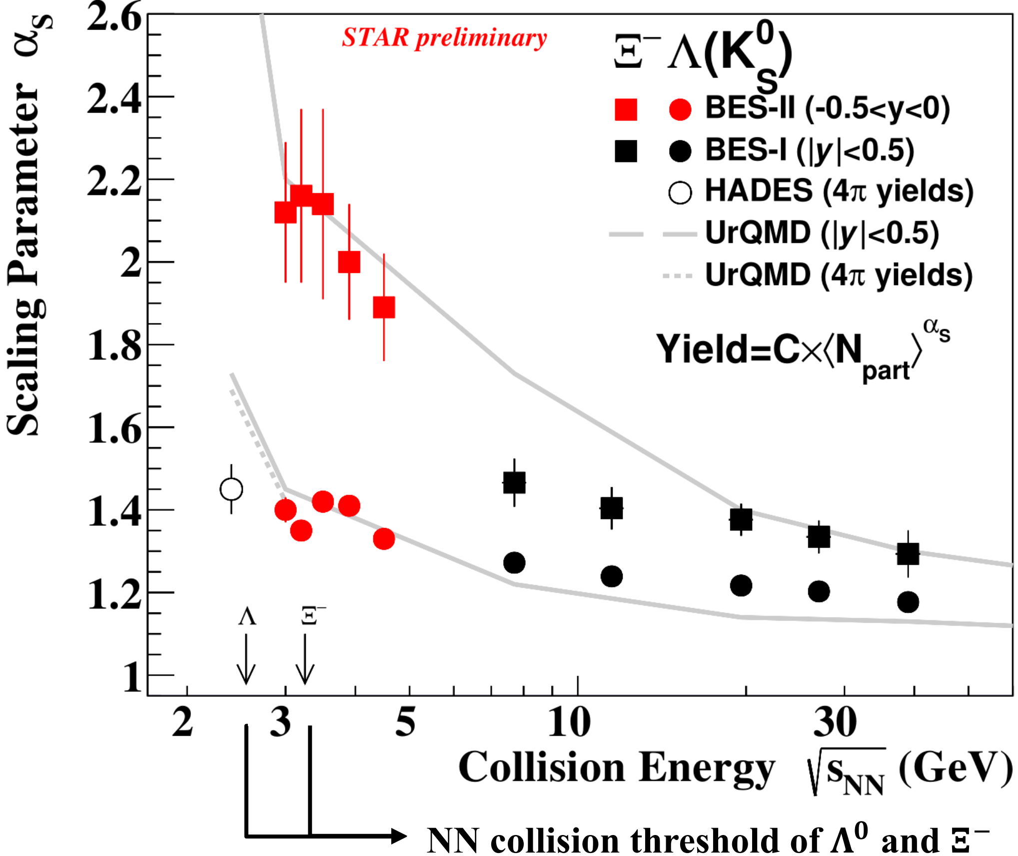
H.C. Li@sQM2024, Y.J. Zhou@CPOD2024



- Universal $\langle N_{part} \rangle$ dependence of strangeness production, rise stronger than linear with $\langle N_{part} \rangle$
- Scaling with absolute amount of strangeness, not with individual hadron states
  - ✓ Single strange hadrons K_S^0 and Λ^0 follow the common scaling trend
  - ✓ Double strange hadron Ξ^- deviate from the trend

Energy Dependence of Scaling Parameter α_S

H.C. Li@sQM2024, Y.J. Zhou@CPOD2024



STAR BES-I: Phys. Rev. C 102 (2020) 34909

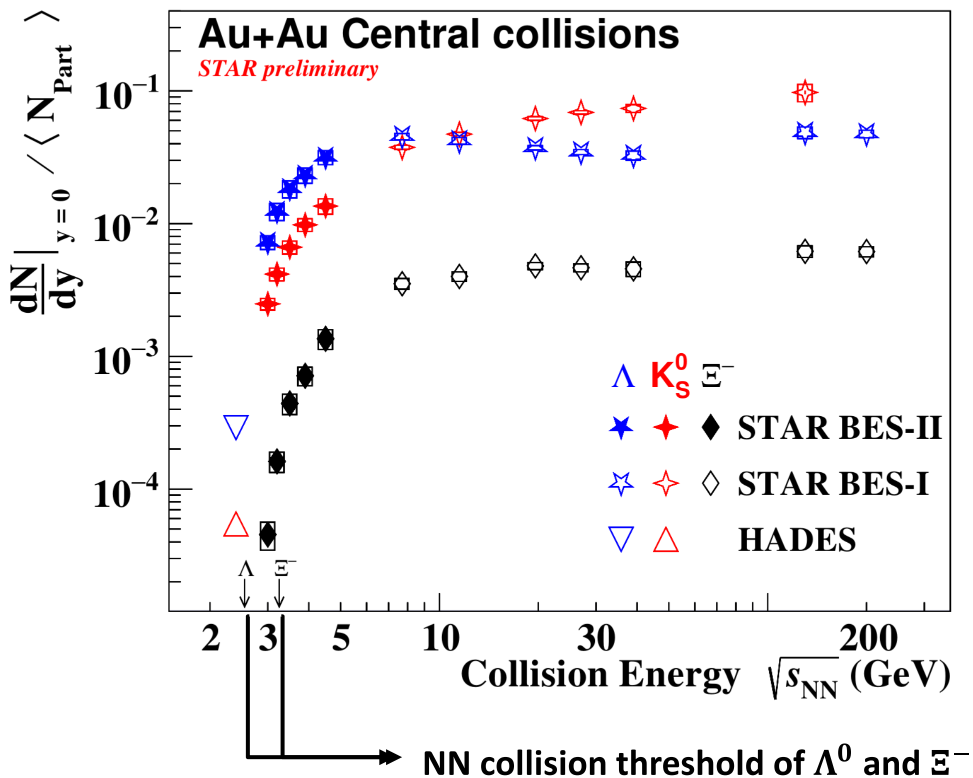
HADES: Phys.Lett.B 793 (2019) 457-463

- Rapid decrease of scaling parameter α_S for Ξ^- from 4.5 to 7.7 GeV, and saturate at high energy
  - ➢ Strange hadron production predominantly from hadronic interactions at $\sqrt{s_{NN}} < 4.5$ GeV
  - ➢ The mechanism of strange hadron production may change
- UrQMD qualitatively reproduces the energy dependence, but cannot quantitatively describe all energies
  - ➢ likely due to missing medium effects

UrQMD: cascade mode, hard EOS

S.A. Bass, et.al. Prog. Part. Nucl. Phys. 41 (1998)

Strangeness Excitation Function



Rich structure in these excitation functions

✓ Connections to the softness of dense nuclear matter, phase boundary, and onset of deconfinement

➢ Baryon-dominated to meson-dominated transitions
  - ☐ K_S^0 and Λ^0 mid-rapidity yield cross at ~ 8 GeV

➢ First measurement of Ξ^- at near-threshold energies in Au+Au collisions

STAR BES-I: Phys. Rev. C 102 (2020) 34909

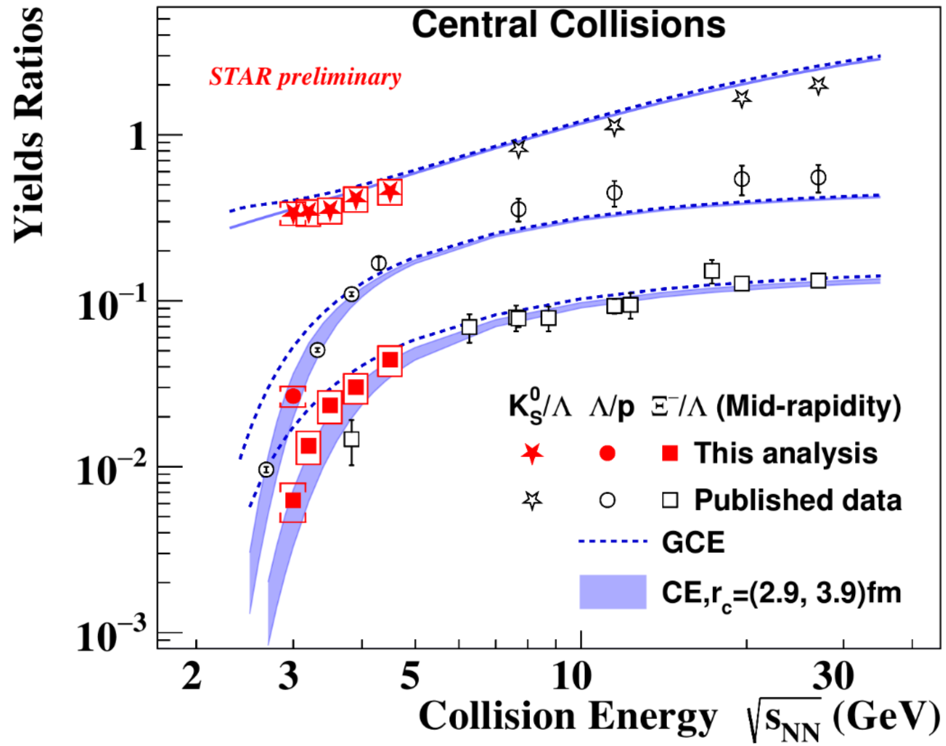
STAR: Phys. Rev. C 102, 034909 (2020)

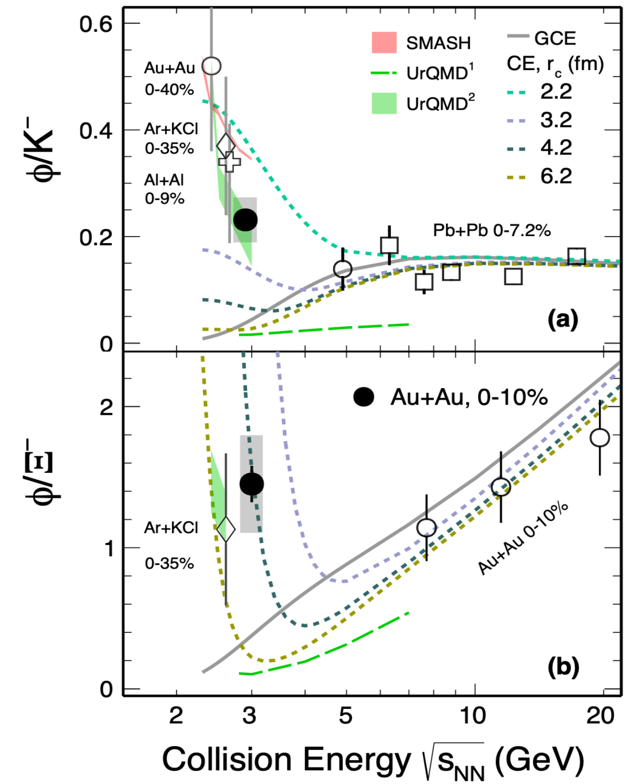
HADES: Phys. Lett. B 793 (2019) 457-463

H.C. Li@sQM2024, Y.J. Zhou@CPOD2024

Mid-rapidity Yield Ratio

STAR BES-I: Phys. Rev. C 102, 034909 (2020)
THERMUS: Comput. Phys. Commun. 180 (2009)
Thermal parameters (T and μ_b): V. Vovchenko et. al., Phys. Rev. C 93, 064906 (2016)





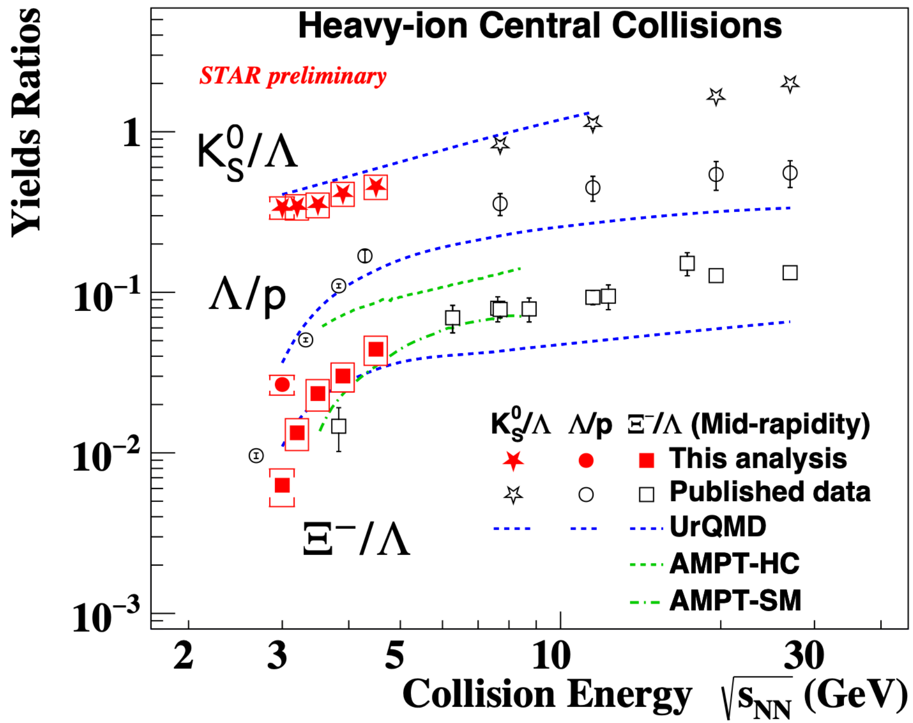
UrQMD: cascade mode, hard EOS

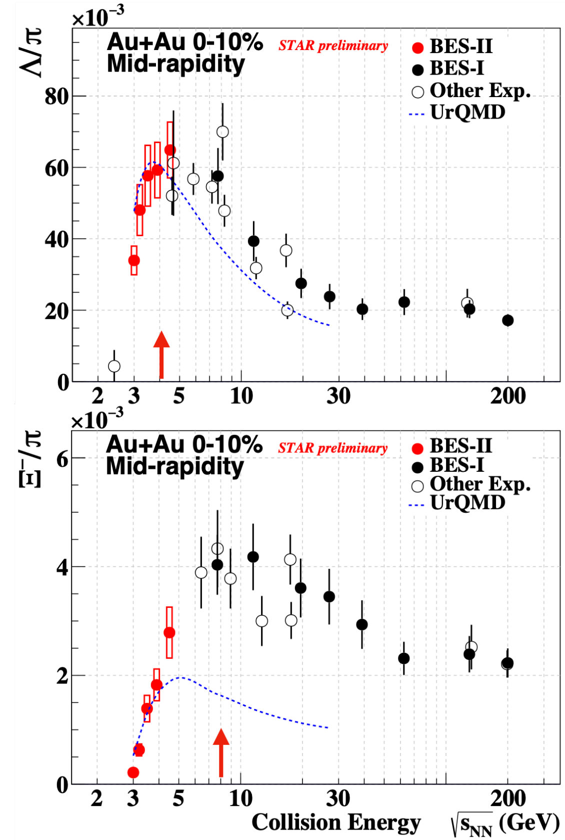
- **Comparison with thermal model**
  - ➢ Canonical Ensemble (CE) with strangeness correlation length r_c = 2.9 – 3.9 fm simultaneously describes $\mathbf{K_s^0/\Lambda}$, $\mathbf{\Lambda/p}$ and $\mathbf{\Xi^-/\Lambda}$ in the whole energies, but GCE fails at low energies

  → Change of medium properties at the high baryon density region

Physics Letters B, 2022, 831: 137152

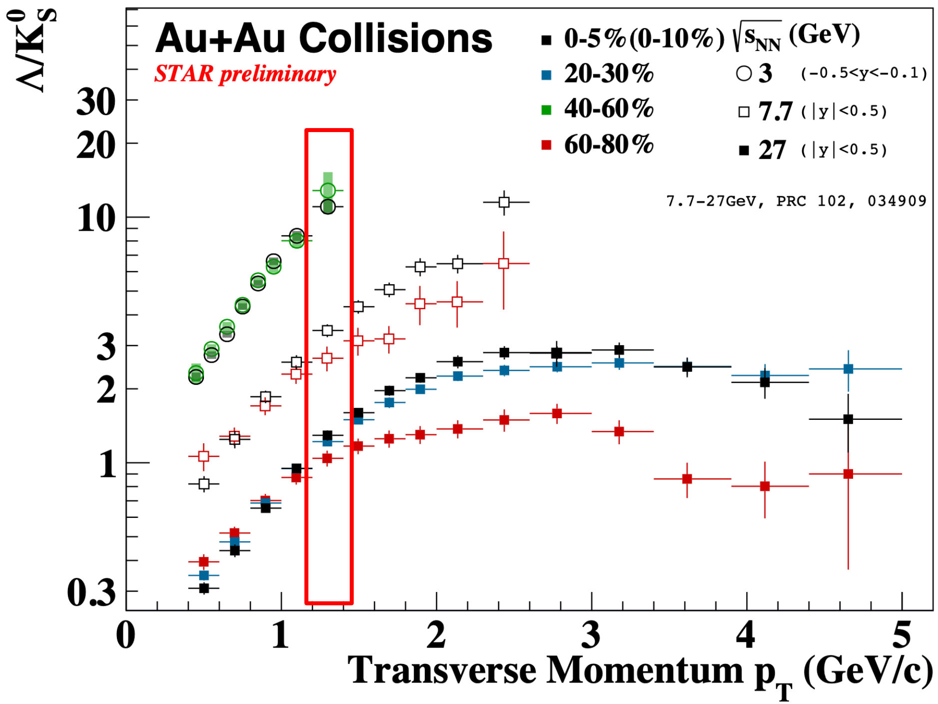
Mid-rapidity Yield Ratio

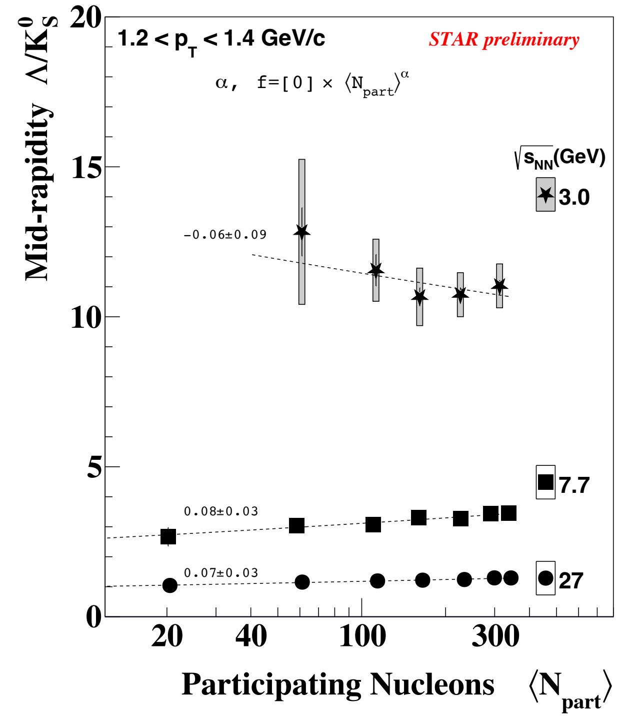




- **Comparison with transport model**
  - UrQMD and AMPT models cannot describe all data
  - Strange baryons, especially for the Ξ^-, are sensitive probes to the medium properties
  - Λ/π and Ξ^-/π seems to show a different maximum position

Baryon to Meson Yield Ratio

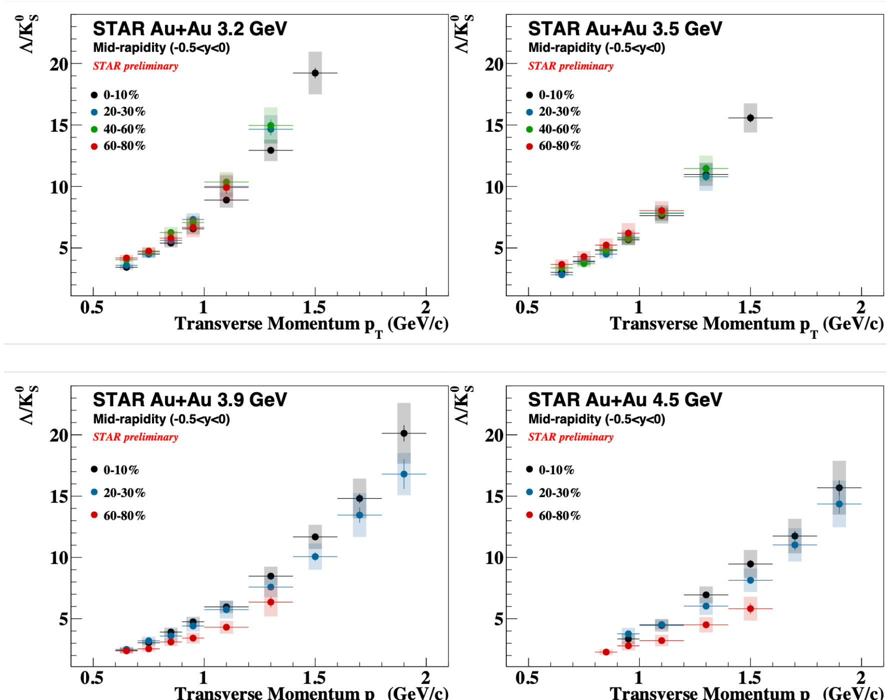


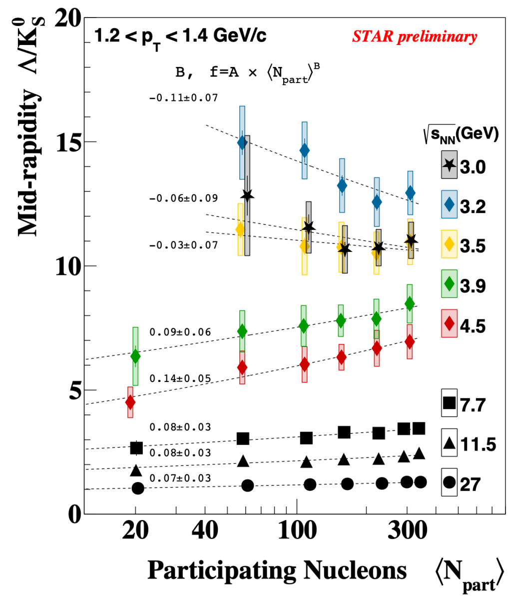


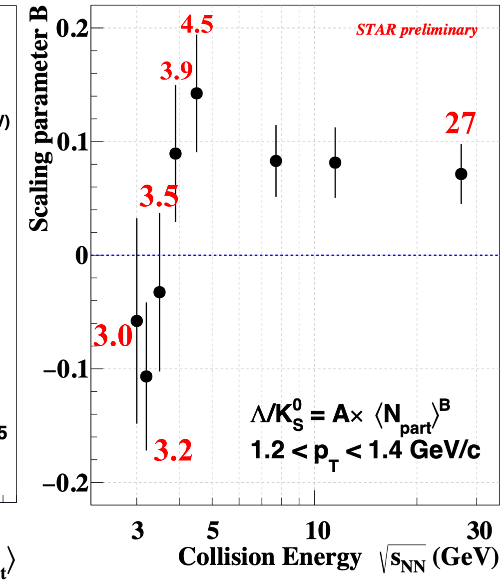
H.C. Li@sQM2024, Y.J. Zhou@CPOD2024 STAR BES-I: Phys. Rev. C 102, 034909 (2020)

- At high energies ($\sqrt{s_{NN}}$ > 7.7 GeV), Λ/K^0_S is enhanced in central collisions
- Λ/K^0_S enhancement is not observed at 3 GeV in the measured p_T range

Baryon to Meson Yield Ratio







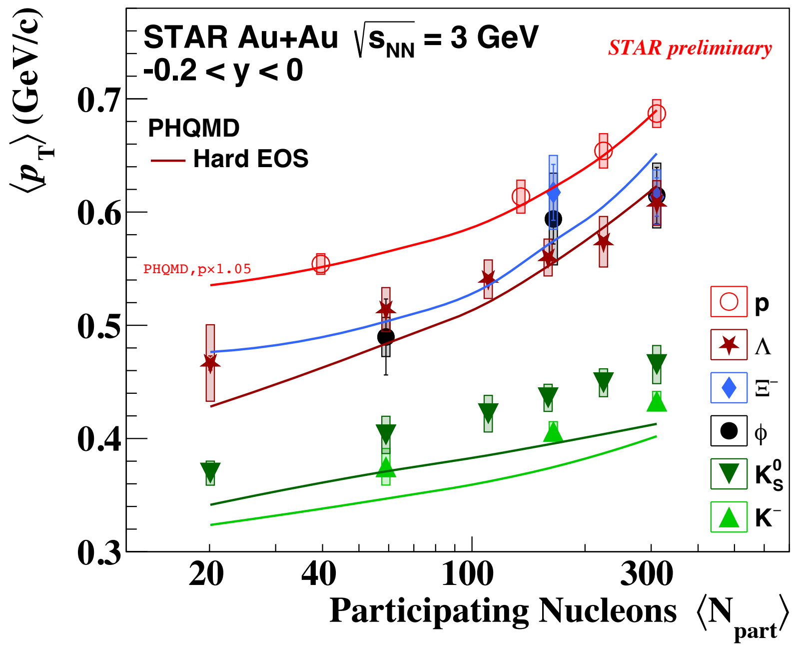
STAR BES-I: Phys. Rev. C 102, 034909 (2020)

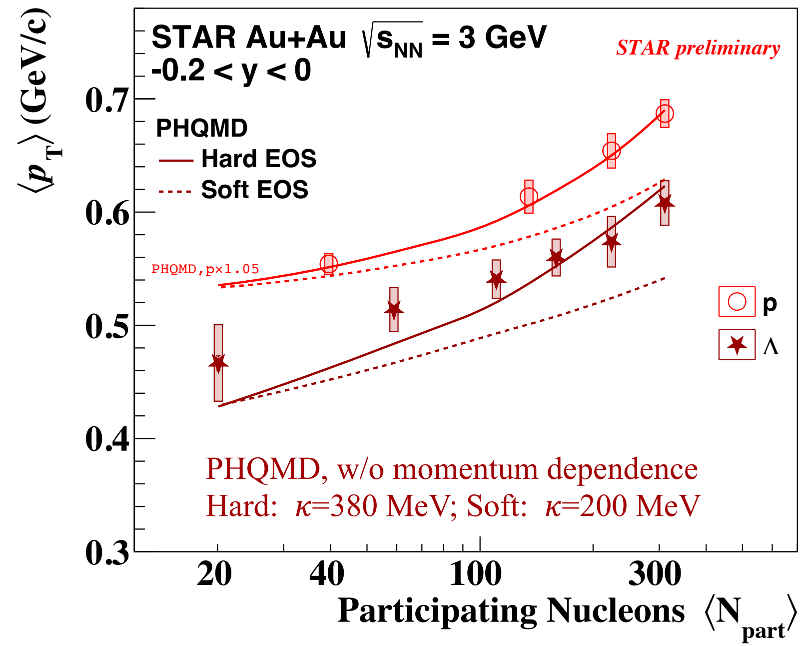
H.C. Li@sQM2024, Y.J. Zhou@CPOD2024

- Λ/K^0_S is enhanced in $1.2 < p_T < 1.4$ GeV/c in central collisions at above $\sqrt{s_{NN}}$ = 3.9 GeV

→ Possible change of medium properties

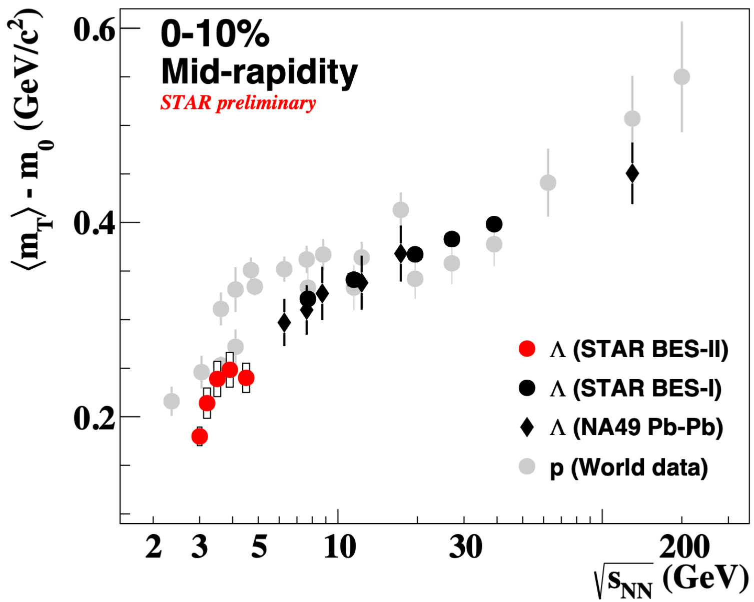
Average Transverse Momentum

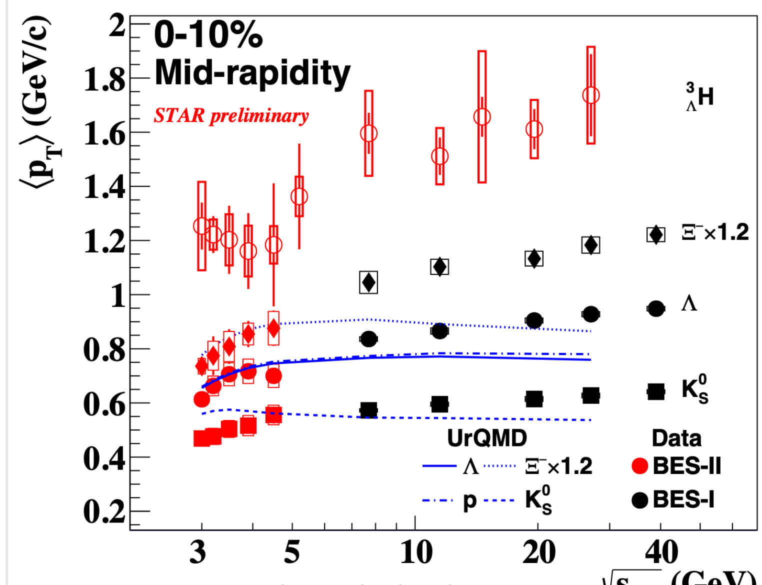




- **$\langle p_T \rangle$ vs. $\langle N_{part} \rangle$ consistent with radial flow caused by hadronic interactions**
  - ✓ Gradual increase in $\langle p_T \rangle$ as $\langle N_{part} \rangle$ increase
  - ✓ Data show $\langle p_T \rangle^{K^-} \approx \langle p_T \rangle^{K^0_S} < \langle p_T \rangle^{\emptyset} \approx \langle p_T \rangle^{\Lambda} \approx \langle p_T \rangle^{\Xi^-}$ following mass hierarchy
  - ✓ Data show $\langle p_T \rangle^{\Lambda} < \langle p_T \rangle^{p}$,possibly due to smaller Y-N interaction than N-N interaction
- **Transport model with baryon mean field offer consistent $\langle p_T \rangle$ for p, Λ, and Ξ^-**

Average Transverse Momentum



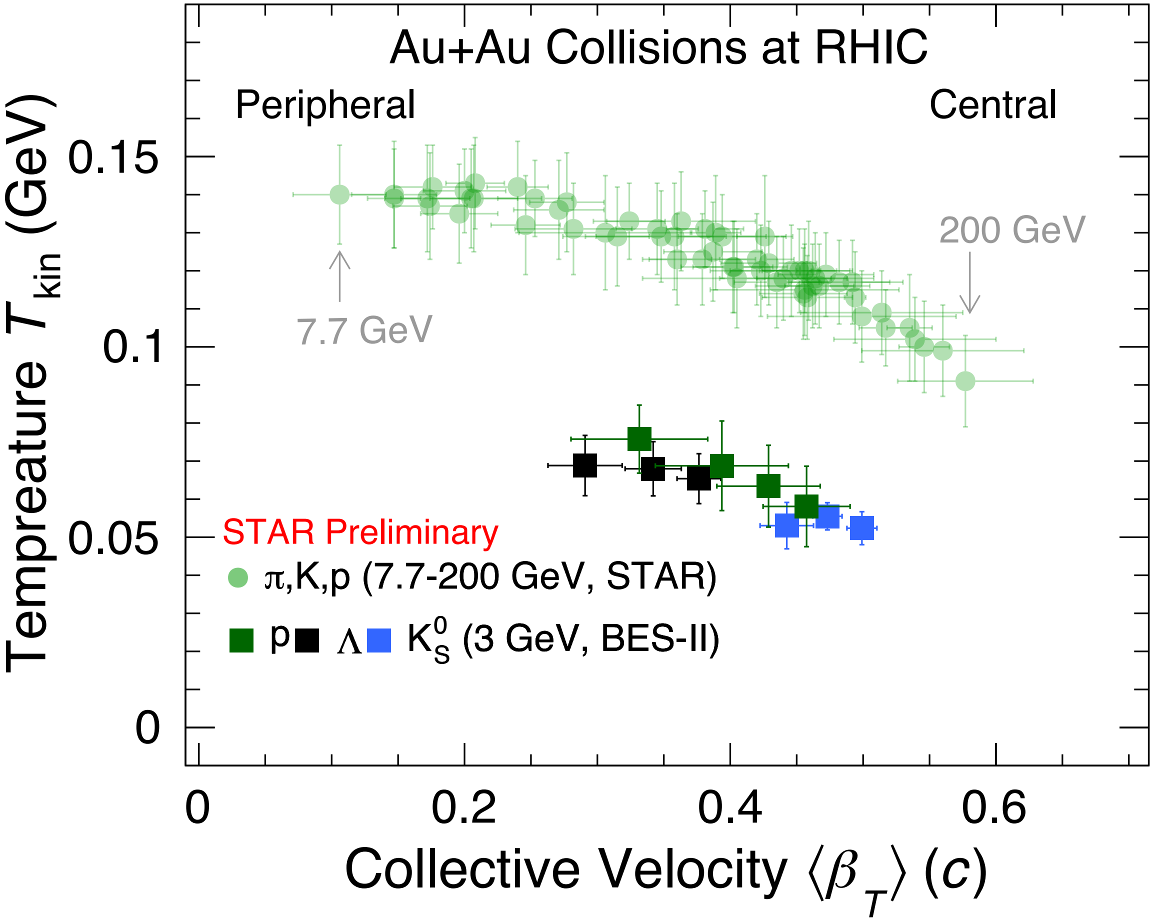


UrQMD: cascade mode, hard EOS

- Below 11.5 GeV, ***Λ*** tends to be smaller than proton, while they are compatible at 11.5 GeV or higher
- Transport model (UrQMD) offers consistent $\langle p_T \rangle$ for ***Λ***, and Ξ^- below 5 GeV, but fails at 7.7 GeV and higher energies

→ Transition from a **hadronic interaction dominated matter** to **matter dominated by quark degrees of freedom** somewhere between 4.5 and 7.7 GeV?

Kinematic Freeze-out Properties



- **Freeze-out parameters ($T_{kin.}$, ⟨β_T⟩) of p, Λ and K^0_S at 3 GeV do not follow the same trend as π, K, p at 7.7 – 200 GeV**
- **Λ and K^0_S: Similar value for freeze-out velocity but much lower temperatures at 3 GeV**

→ Change in medium properties (EOS) or expansion dynamics

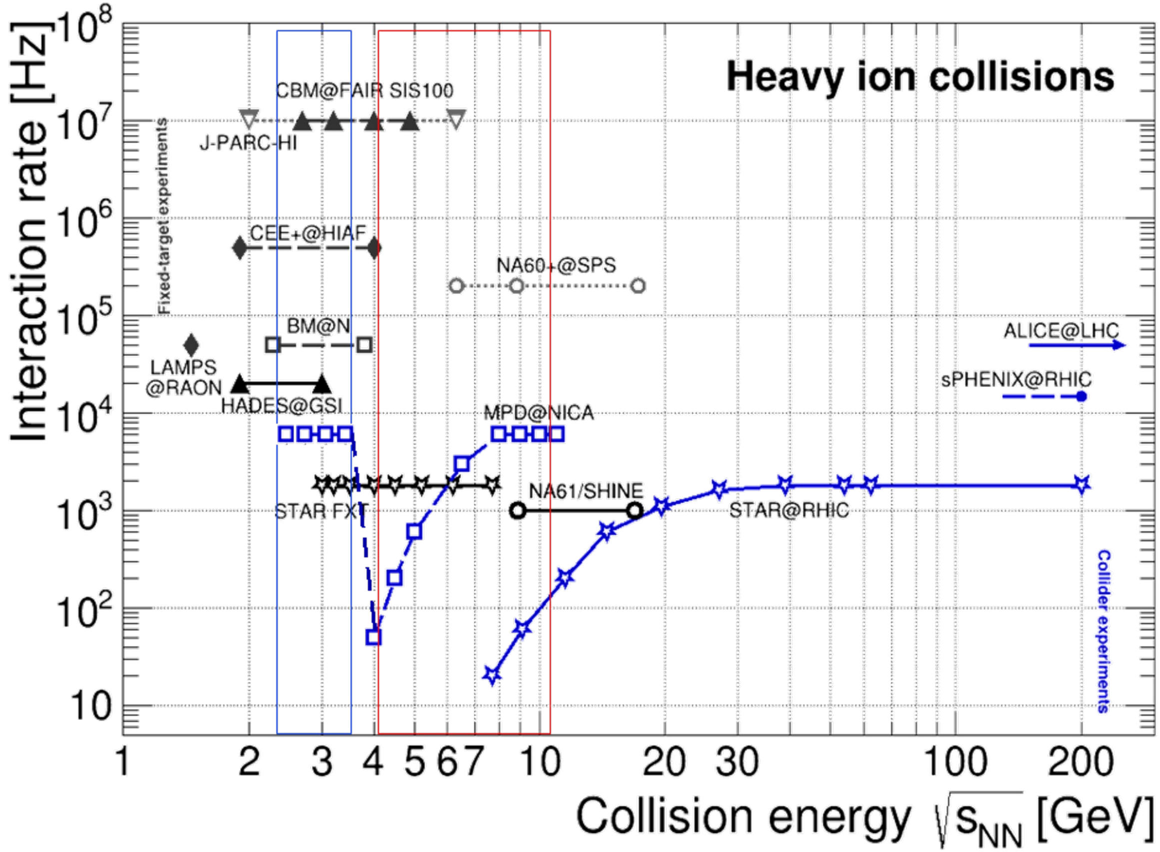
Y.J. Zhou@sQM2022

Summary and outlook

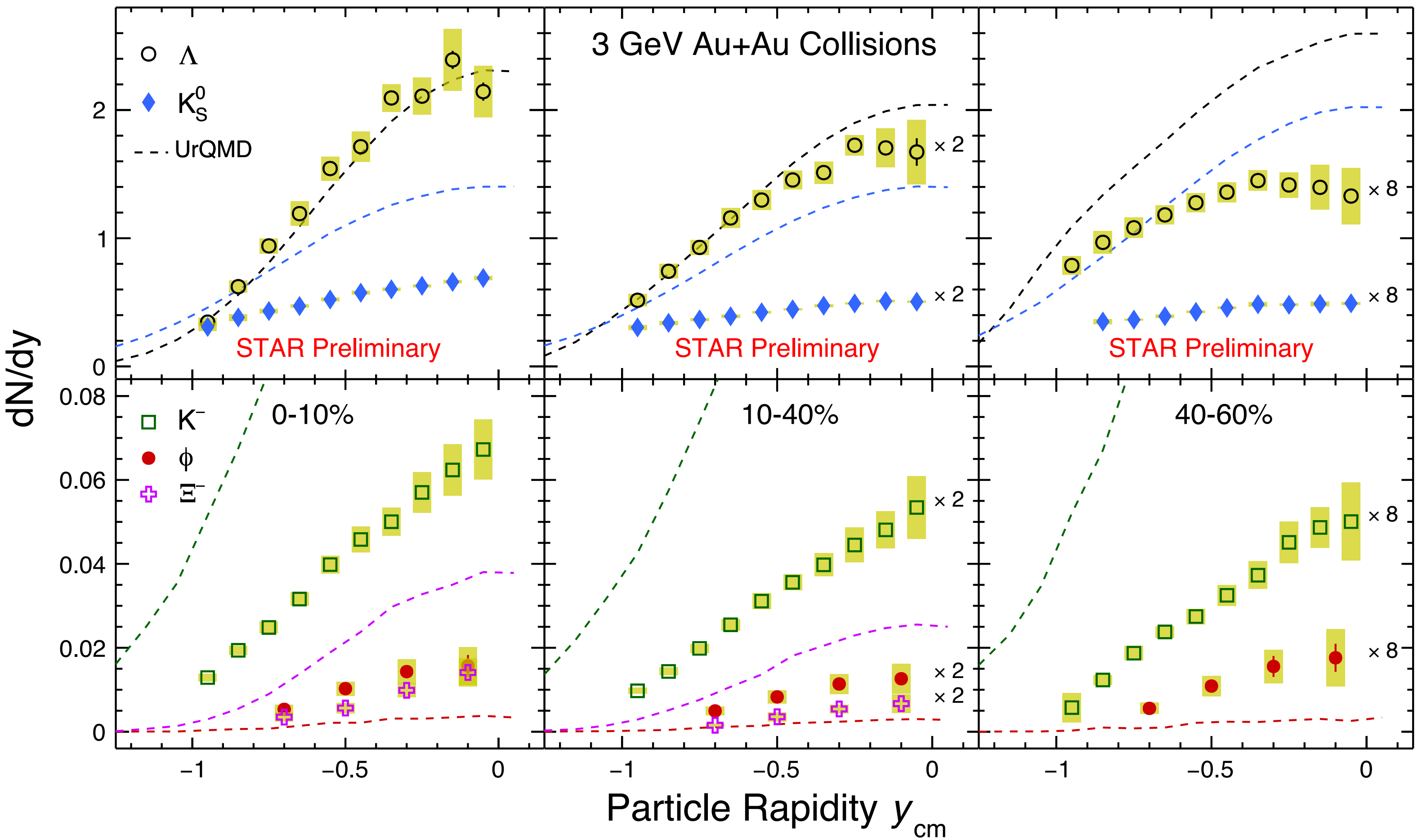
- Precision measurements of strange hadrons production in Au+Au collision at $\sqrt{s_{\mathrm{NN}}}$ = 3.0 – 4.5 GeV
  1) Steeper centrality dependence of Ξ^{-} mid-rapidity yields (α_S) at $\sqrt{s_{\mathrm{NN}}}$ = 3.0 – 4.5 GeV than that at higher energies
  2) Canonical suppression of strangeness is observed below $\sqrt{s_{\mathrm{NN}}}$ = 3.5 GeV
  3) Baryon-to-meson ratio ($\Lambda/\mathrm{K}^0_{\mathrm{S}}$) enhancement not observed at $\sqrt{s_{\mathrm{NN}}}$ = 3.0 – 3.5 GeV, but observed at above 3.9 GeV energies
  4) Freeze-out parameters ($T_{\mathrm{kin.}}$, $\langle\beta_{\mathrm{T}}\rangle$) of p, Λ and K^0_S at 3 GeV do not follow the same trend as π, K, p at 7.7 – 200 GeV

- More precise and systematic measurements of strange hadron ($K^{\pm}$, ϕ, Ω^{-} etc.) production from BES-II ($\sqrt{s_{\mathrm{NN}}}$ = 5.2, 6.2, 7.2, 7.7 GeV)

Summary and outlook



Thanks for your attention!



3 GeV Au+Au Collisions
Λ
K^0_S
UrQMD
STAR Preliminary
STAR Preliminary
STAR Preliminary
× 2
× 2
× 8
× 8
K^-
ϕ
Ξ^-
0-10%
10-40%
40-60%
× 2
× 2
× 2
× 8
× 8
dN/dy
Particle Rapidity y_{cm}