

# **Recent experiment results of strangeness production in heavy-ion collisions at high baryon density**

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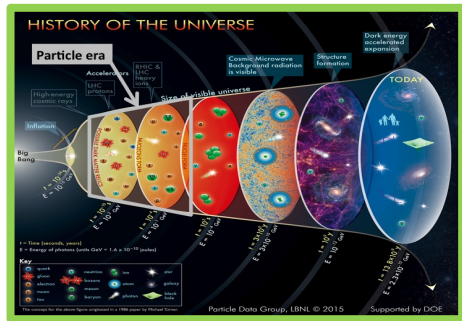
**Collaborators:** Hongcan Li, Junyi Han, Li'Ang Zhang, Wenyun Bo (CCNU), Yingjie Zhou (GSI), Yue-Hang Leung (Heidelberg Univ.), Guannan Xie (UCAS)

# Outline

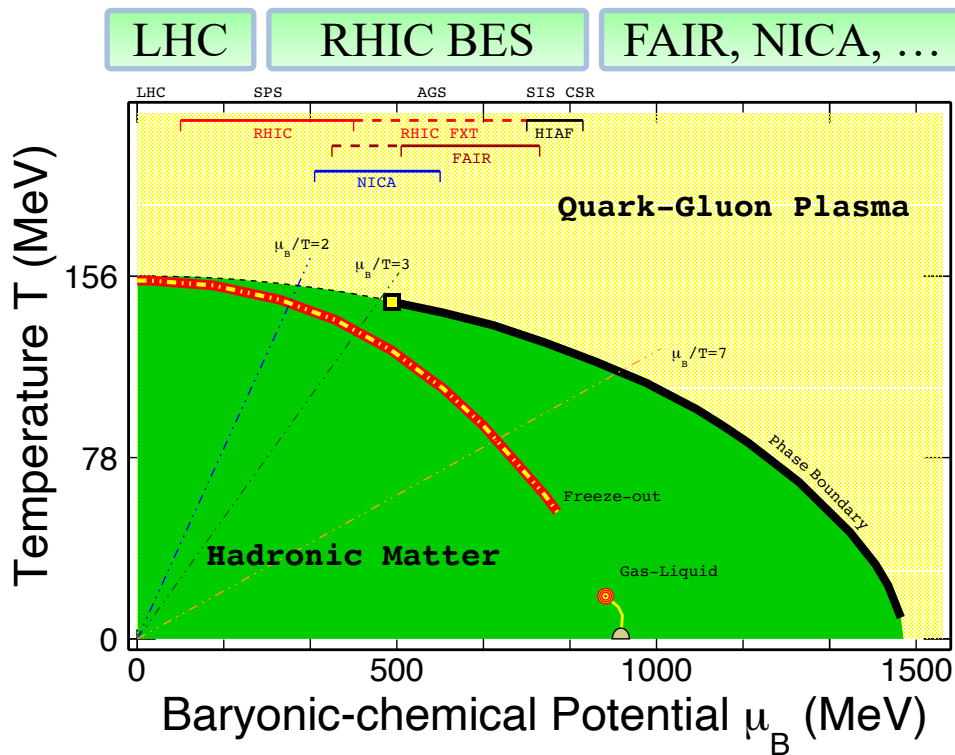
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- Introduction
- Strangeness enhancement in heavy-ion collisions
- Strangeness production at high baryon density
- Summary and outlook

# High-Energy Nuclear Collisions & QCD Phase Diagram

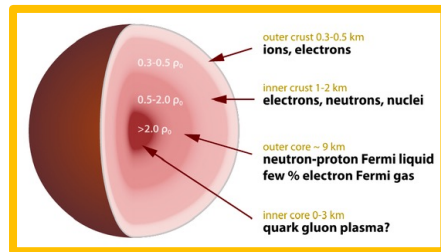


High temperature:  
Early Universe evolution



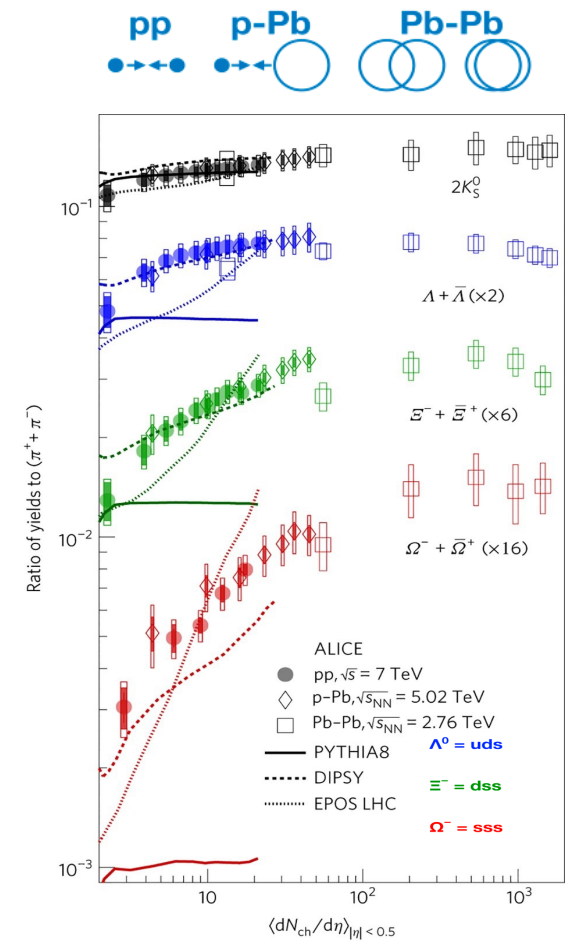
Ref.: N. Xu @sQM2022

High baryon density:  
Inner structure of  
compact stars



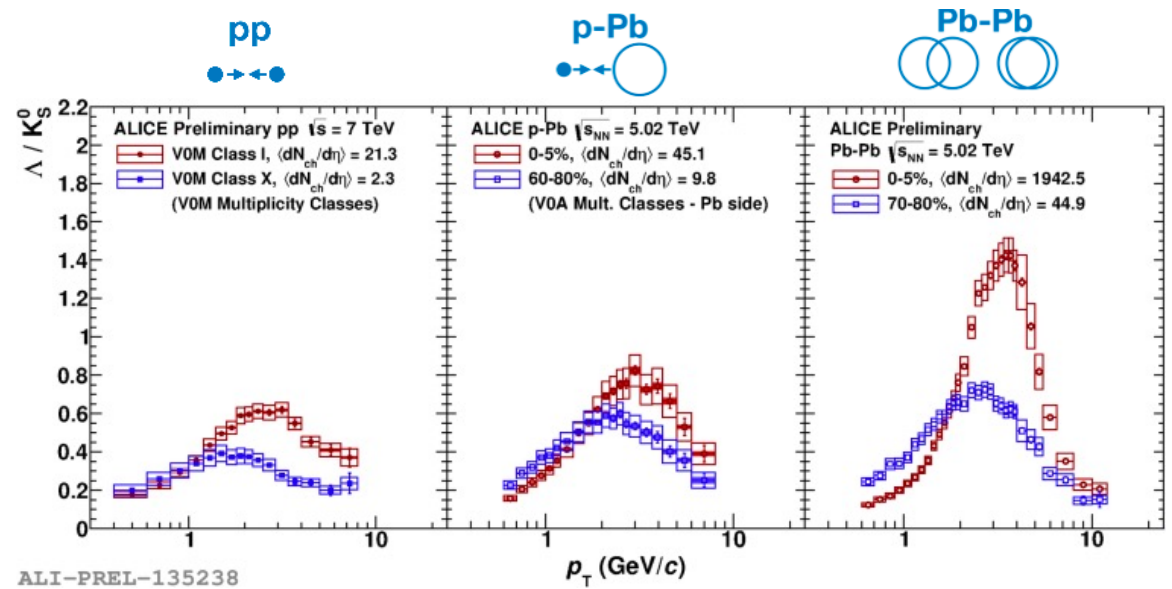
- At  $\mu_B = 0$ , smooth crossover (LGT + data)
- At large  $\mu_B$ , 1<sup>st</sup> order phase transition → QCD critical point

# Strangeness enhancement



Nature Phys. 13, 535-539 (2017)

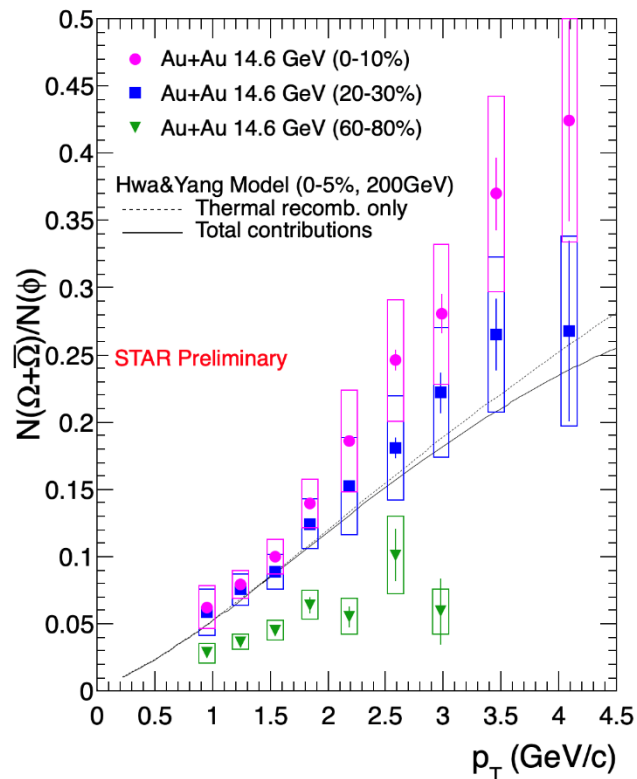
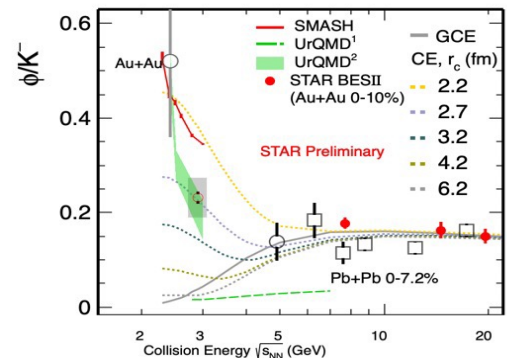
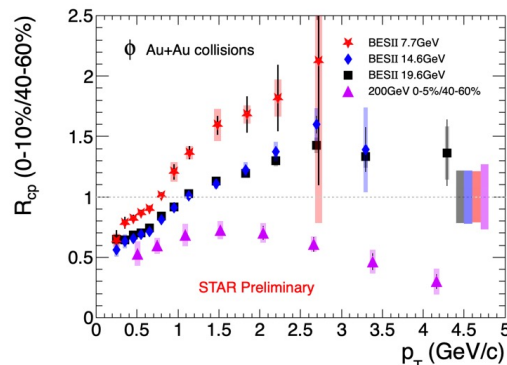
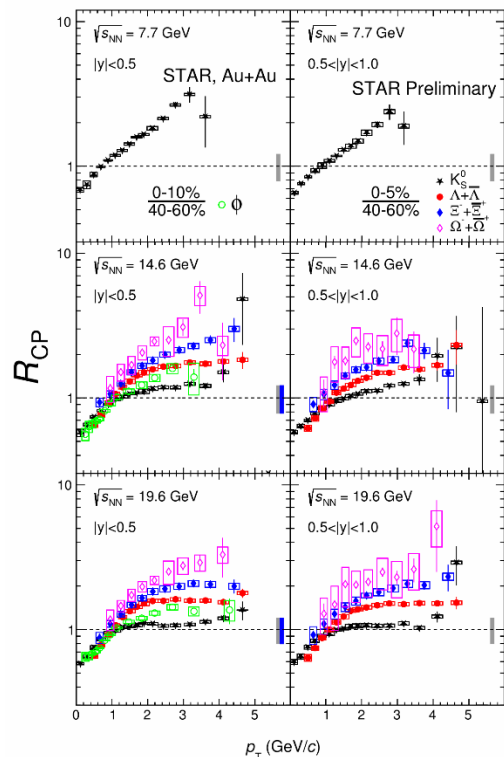
- At SPS, RHIC and LHC energies, the enhancement of strange hadrons in high multiplicity (low centrality) events was observed as a QGP signature
- Recent findings show universal strangeness enhancement with the event charged particle multiplicity, independently from collision system



ALI-PREL-135238



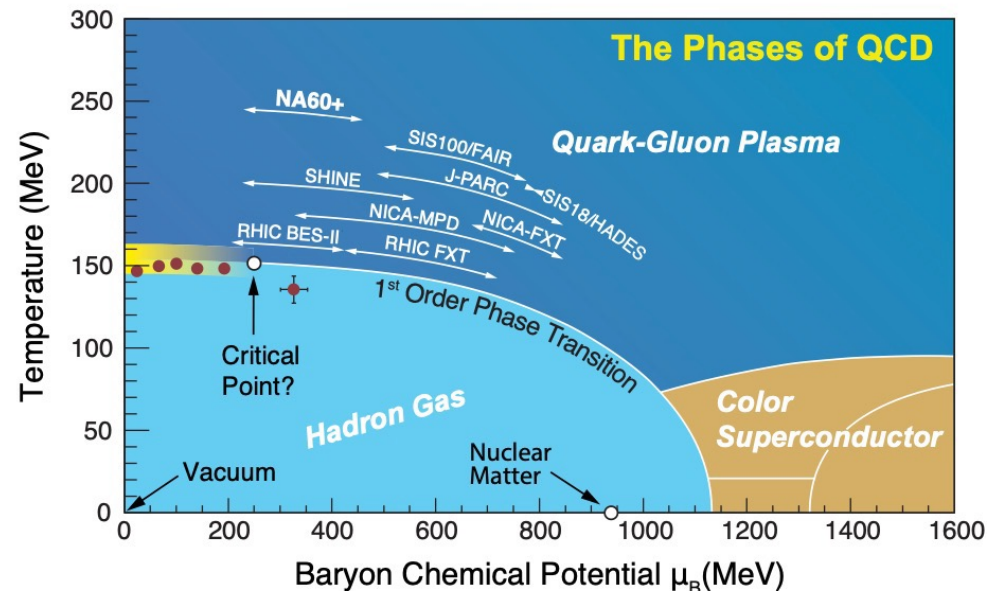
# Strangeness enhancement



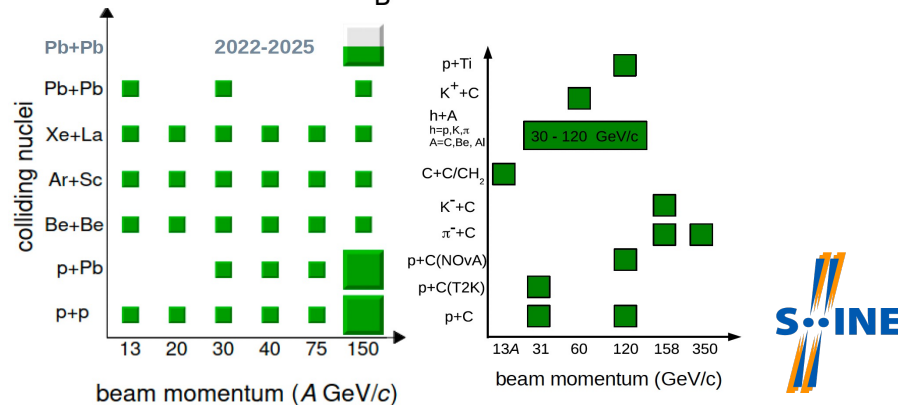
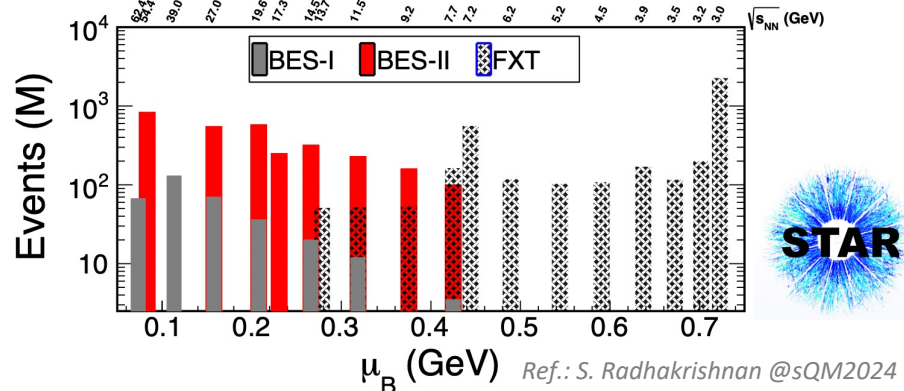
Ref.: W.G. Yuan, Y. Fang@sQM2024

- Strangeness enhancement has been observed in Au+Au collisions at above  $\sqrt{s_{NN}} = 14.6$  GeV with STAR BES-II data, consistent with QGP formation

# Heavy-ion collisions at high baryon density region



HADES Ref.: M. Lorenz@sQM2024



2012: Au+Au @  $\sqrt{s_{NN}} = 2.42$  GeV,  $7 \times 10^9$  evts.  
 2019: Ag+Ag @  $\sqrt{s_{NN}} = 2.55$  GeV,  $14 \times 10^9$  evts.  
 2024: Au+Au @  $\sqrt{s_{NN}} = 2.24$  GeV,  $2 \times 10^9$  evts.  
 C+C  $3 \times 10^9$  evts.

BES with 0.6, 0.4 and 0.2 A GeV beam planned for 2025

- Results of strangeness production from STAR BES-II FXT, HADES, SHINE are selected, ...

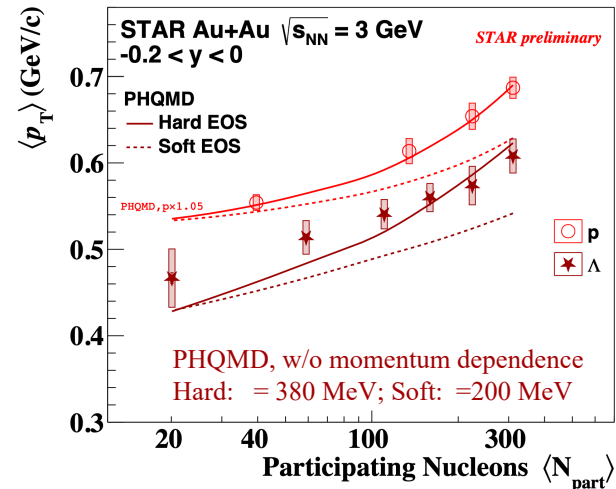
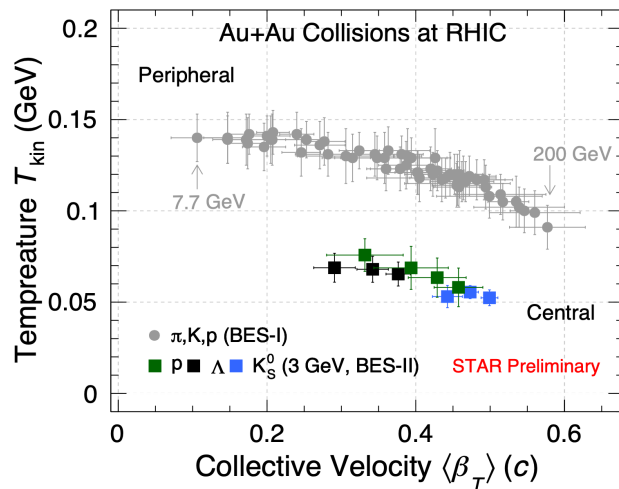
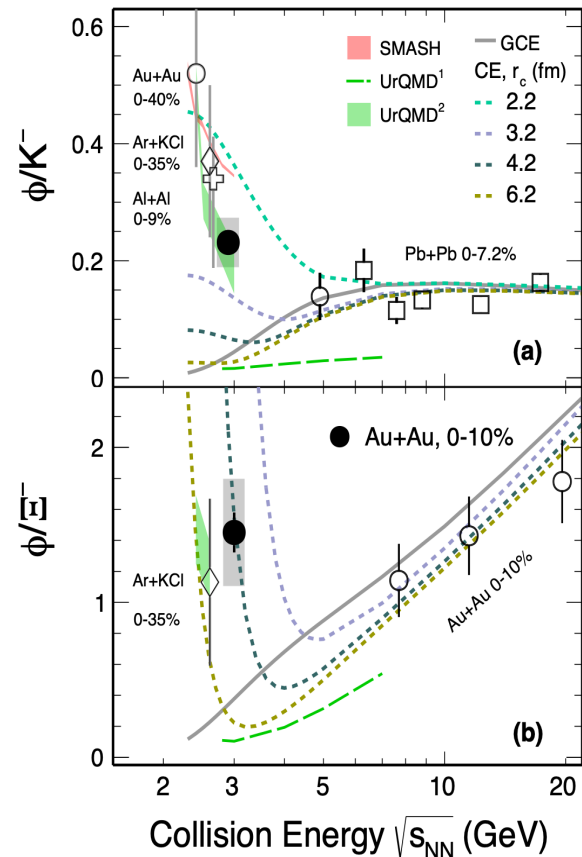
# Strangeness production at high baryon density region

- Strange hadrons production is sensitive to nuclear equation of state (EOS)

Physics Letters B, 2022, 831: 137152

Phys. Rev. C 102, 034909 (2020); Phys. Rev. C 96, 044904 (2017);  
Phys. Rev. Lett. 108, 072301 (2012)

Phys. Rev. C 101, 044905 (2020)



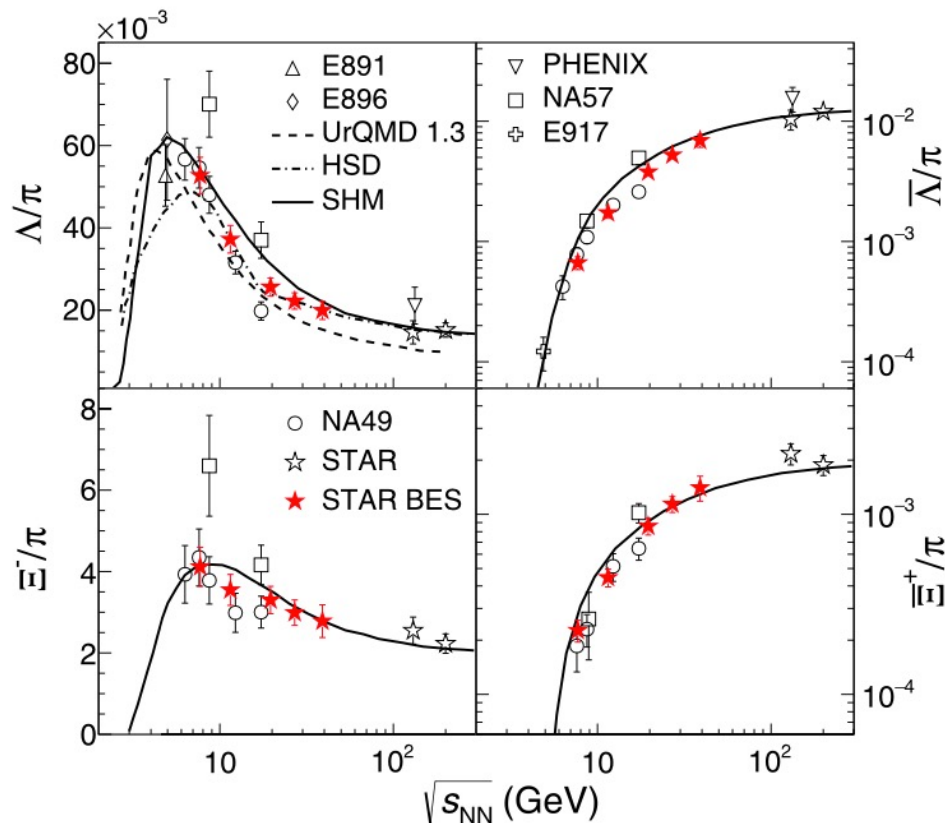
- Change of medium properties at the high baryon density region: **hadronic interaction dominated**

- ☐ CE with canonical suppression of strangeness is needed at  $\sqrt{s_{NN}} = 3$  GeV
- ☐  $T_{kin}$  of  $\Lambda^0$  and  $K_S^0$  at  $\sqrt{s_{NN}} = 3$  GeV is substantially lower than  $\pi, K, p$  at higher energy collisions
- ☐ PHQMD w/ baryon mean field reproduces  $\langle p_T \rangle$  shape with the hard EOS

# Strangeness excitation function

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

[1] J. Randrup, et al. Phys. Rev. C 74, 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)

$$gg \rightarrow s\bar{s} \text{ or } q\bar{q} \rightarrow s\bar{s}$$

- ▣ Hadronic interaction (associated production)

$$BB \rightarrow BYK \text{ or } BB \rightarrow BEKK$$

$$B: N, p, \Delta, \text{ etc. } Y: \Lambda, \Sigma, \text{ etc. } K: K^+, K^0$$

- Baryon-dominated to meson-dominated transitions

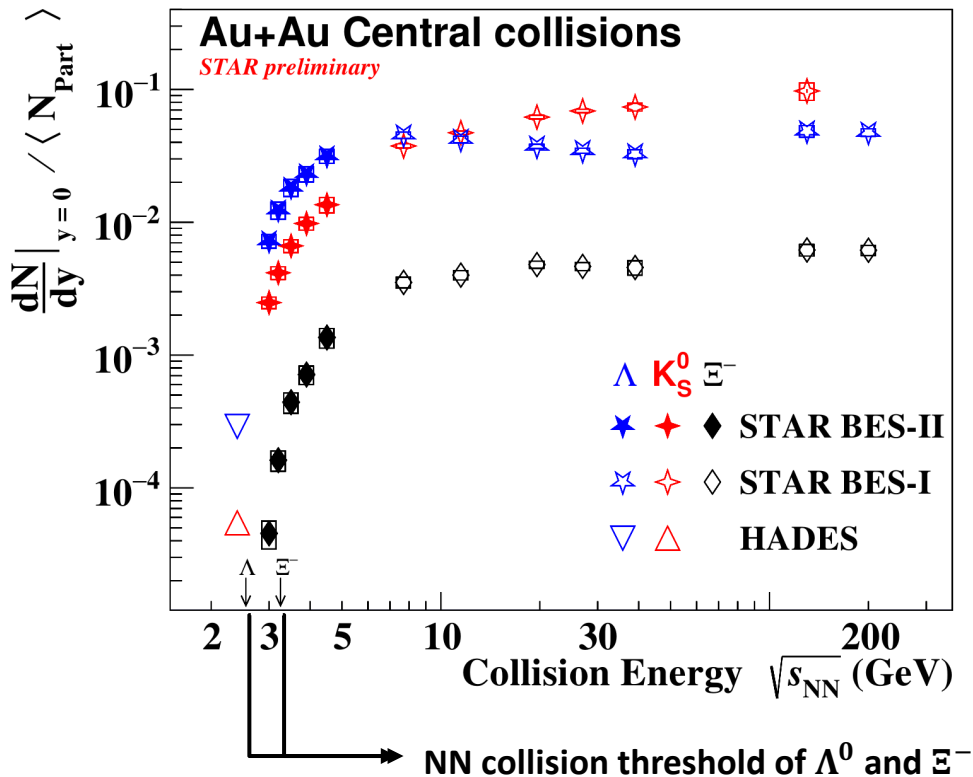
- ▣  $\Lambda/\pi$  peaks at  $\sqrt{s_{NN}} \sim 8 \text{ GeV}$

→ Model: Baryon density maximal at  $\sqrt{s_{NN}} \sim 8 \text{ GeV}$ [1]

# Strangeness excitation function

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

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



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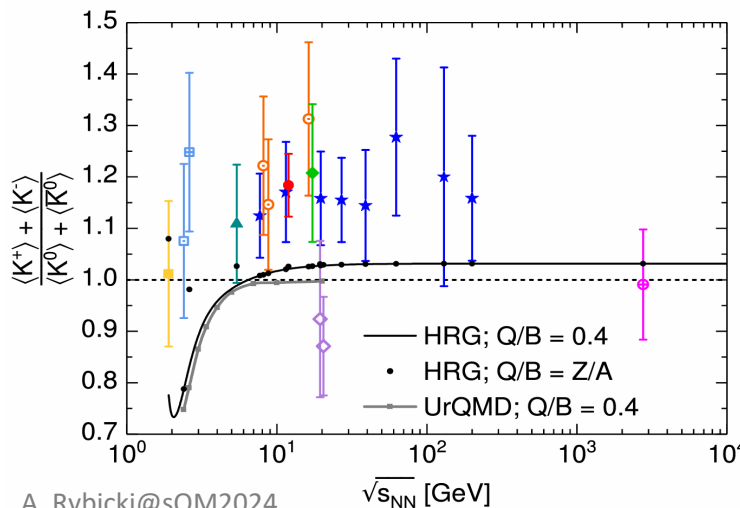
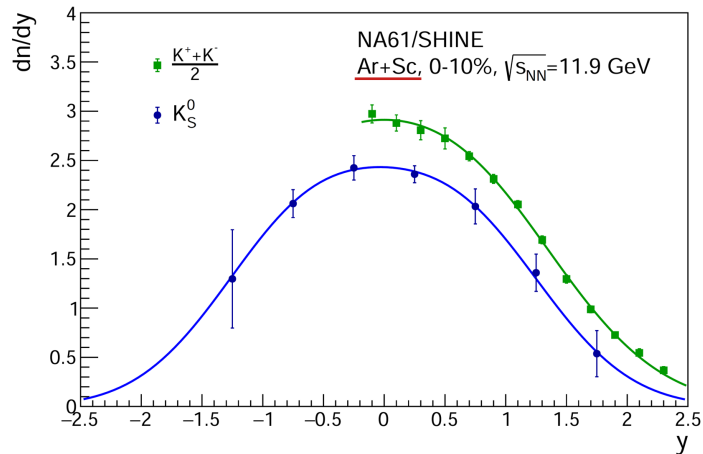
- Model: Baryon density maximal at  $\sqrt{s_{\text{NN}}} \sim 8 \text{ GeV}$

- ▣  $K_S^0$  and  $\Lambda^0$  mid-rapidity yield cross at  $\sim 8 \text{ GeV}$

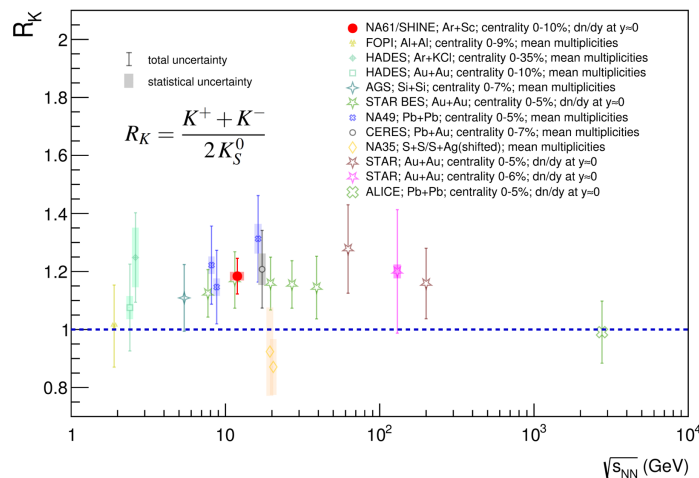
- First measurement of  $\Xi^-$  near- / sub-threshold energies in Au+Au collision

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

# Charged over neutral kaon



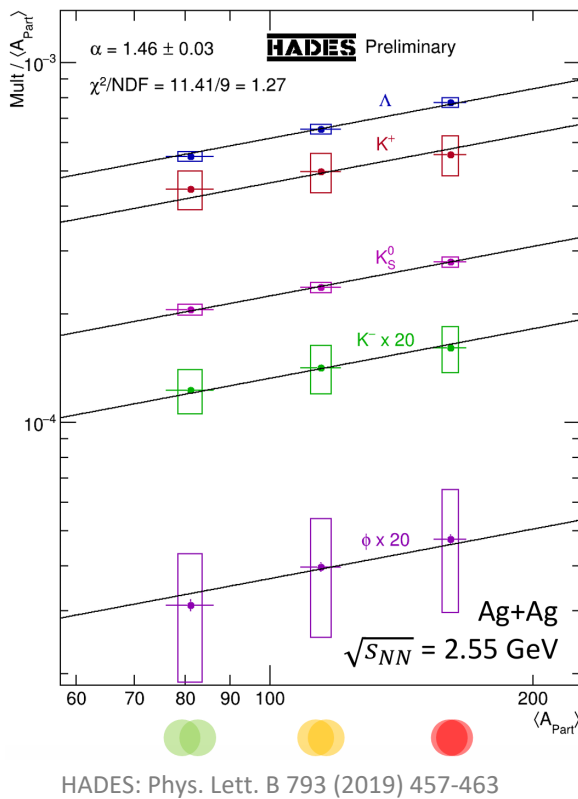
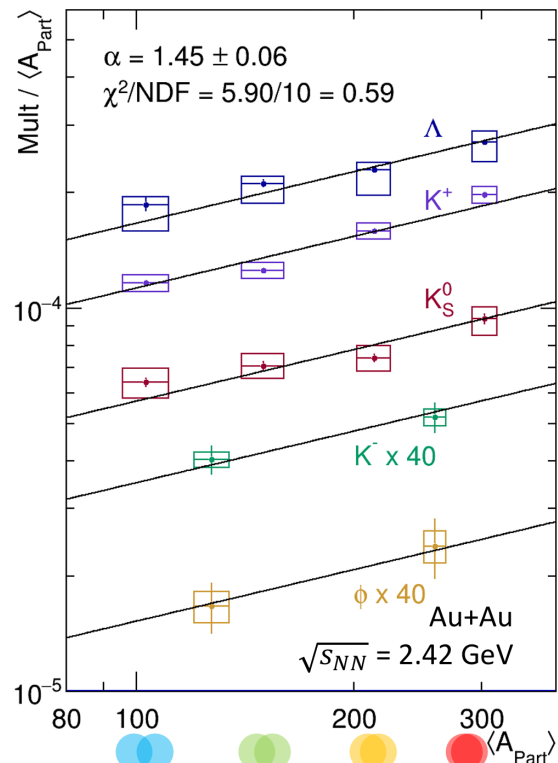
Ar:  $Q=18$ ,  $B=40$ ,  $Q/B=0.45$   
Sc:  $Q=21$ ,  $B=45$ ,  $Q/B=0.47$



A. Rybicki@SQM2024

- Unexpected excess of charged over neutral kaon production in A+A collisions
  - SHINE Ar + Sc @ 11.9 GeV:  $R_K = 1.184$ , More than HRG model
  - Similar effect visible in other experiments
- Indication of violation of isospin symmetry between **u** and **d** quarks?

# Strange hadron yields vs $N_{\text{part}}$



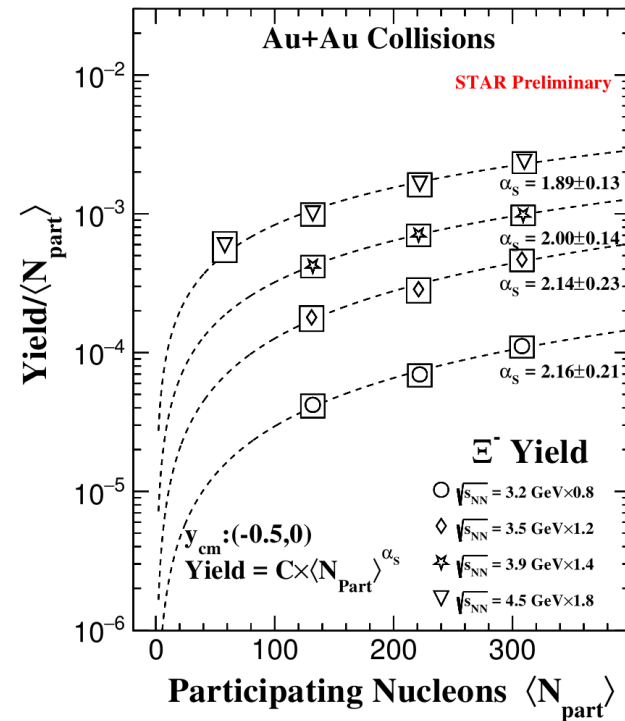
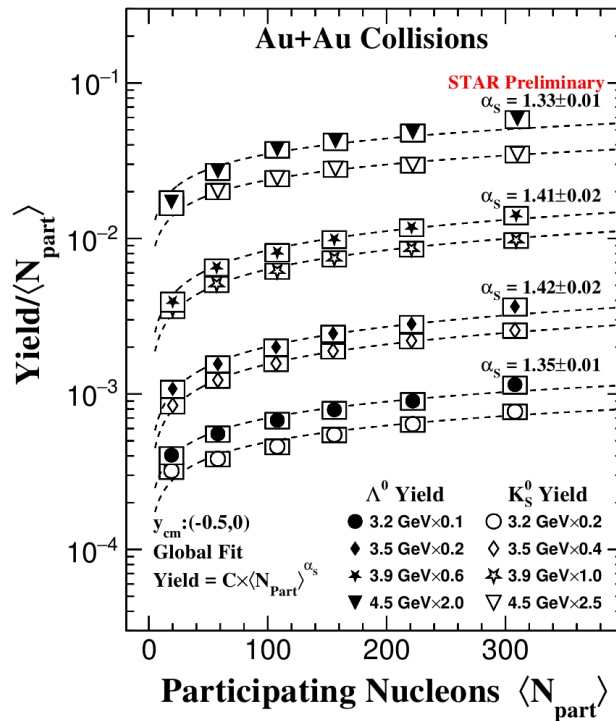
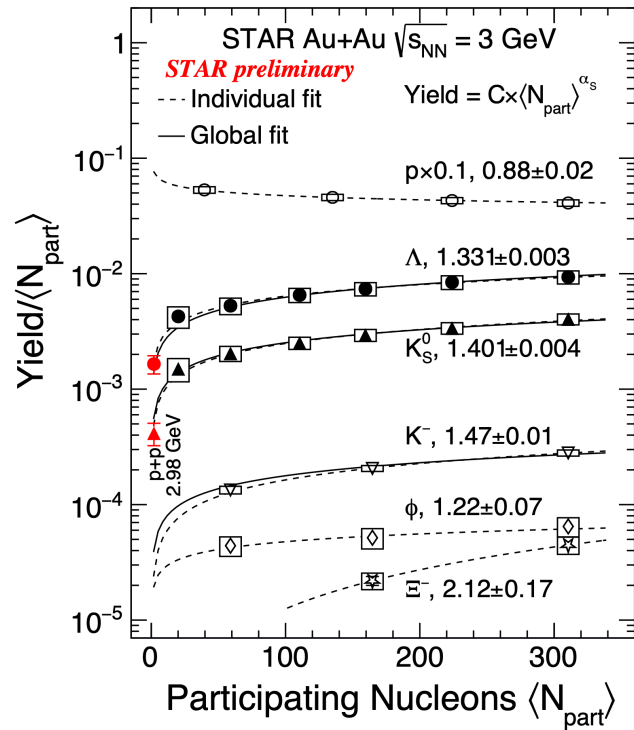
Strange production threshold:

- $NN \rightarrow N\Lambda K \sim 2.55$  GeV
- $NN \rightarrow NN\phi \sim 2.89$  GeV
- $NN \rightarrow N\Omega KKK \sim 4.10$  GeV
- $NN \rightarrow N\Xi\Xi \sim 4.52$  GeV
- $NN \rightarrow NNK\bar{K} \sim 2.86$  GeV
- $NN \rightarrow N\Xi KK \sim 3.25$  GeV
- $NN \rightarrow N\Lambda\Lambda \sim 4.10$  GeV
- $NN \rightarrow NN\Omega\bar{\Omega} \sim 5.22$  GeV

- Universal  $\langle A_{\text{part}} \rangle$  dependence of strangeness production, rise stronger than linear with  $\langle A_{\text{part}} \rangle$
- Hierarchy in production threshold not reflected
- Scaling with absolute amount of strangeness, not with individual hadron states



# Strange hadron yields vs $N_{\text{part}}$



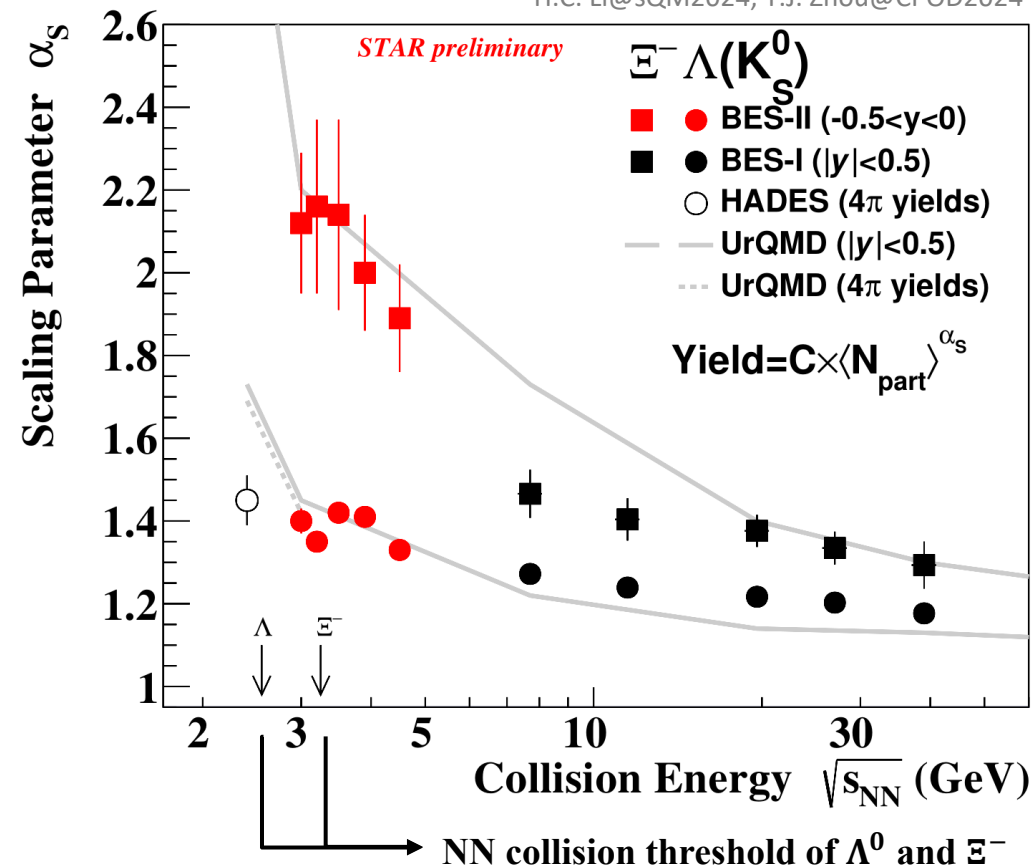
H.C. Li@sQM2024, Y.J. Zhou@CPD2024

- New measurement of  $K^-, K_S^0, \Lambda$  and  $\Xi^-$  at STAR-FXT energies
- Single strange hadrons  $K_S^0$  and  $\Lambda^0$  follow common scaling trend
- Double strange hadron  $\Xi^-$  deviate from the common scaling trend



# Strange hadron yields vs $N_{\text{part}}$

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



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

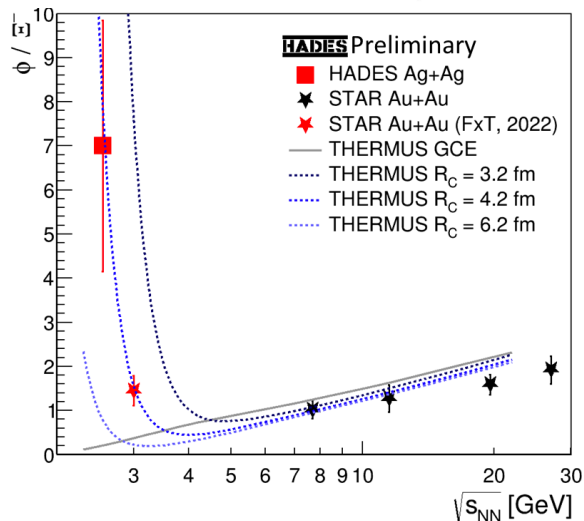
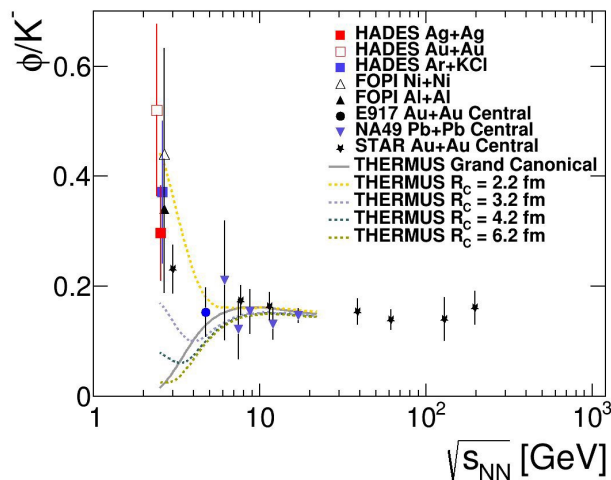
UrQMD: cascade mode, hard EOS

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

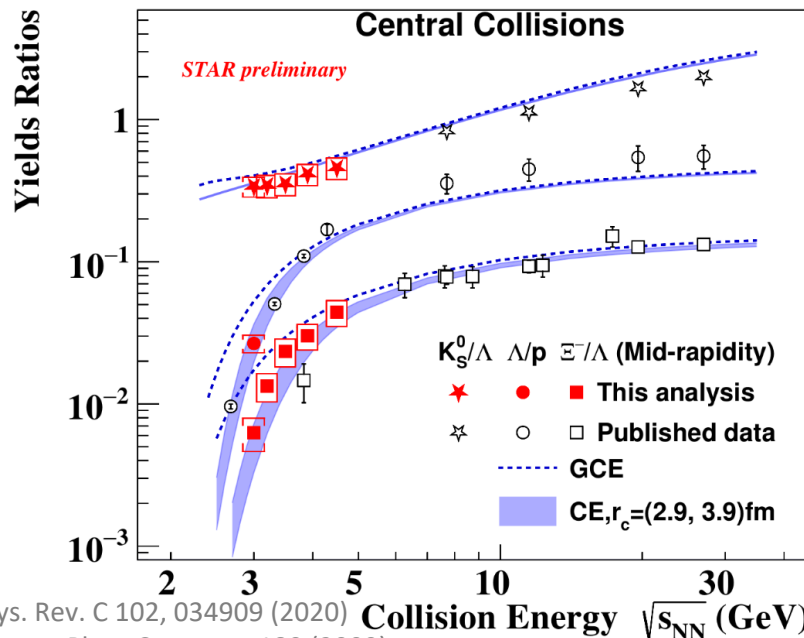
STAR BES-I: Phys. Rev. C 102 (2020) 34909

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

# Strange hadron yields ratio



Phys. Lett. B778 (2018) 403-407  
M. Lorenz@sQM2024

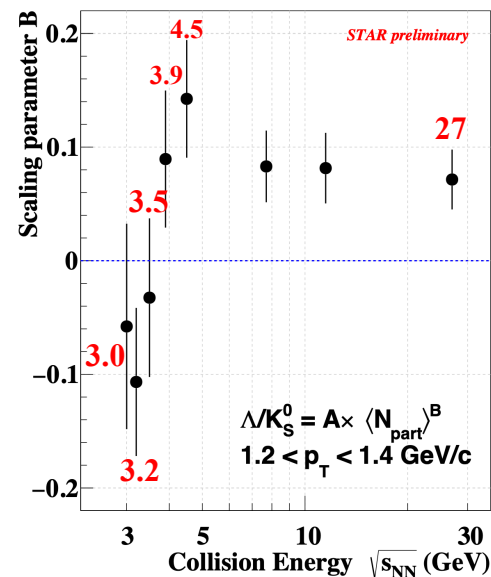
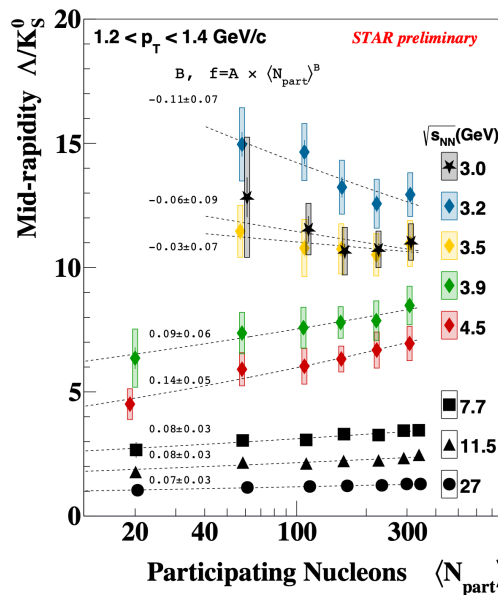
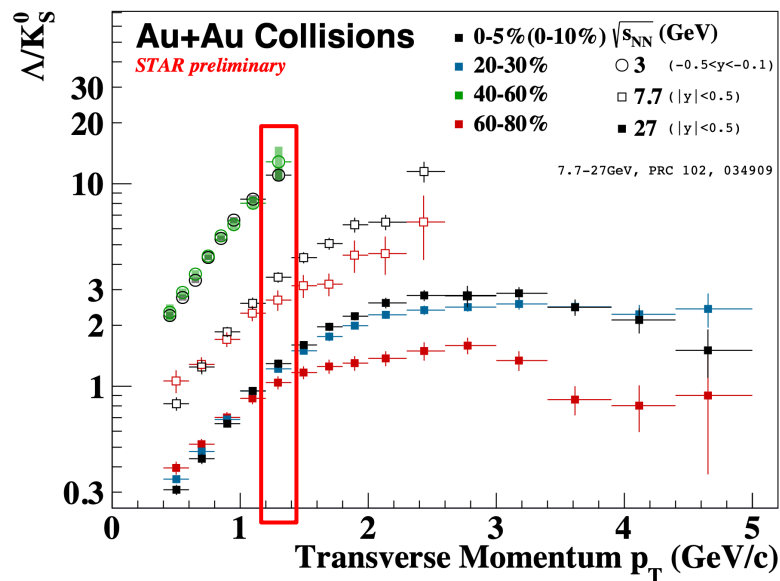


H.C. Li@sQM2024, Y.J. Zhou@CPD2024

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

- $\phi/K^-$  and  $\phi/\Xi^-$  ratios can not be described simultaneously with same value for  $r_c$  in HADES, similar observation at STAR 3 GeV
- Canonical suppression of strangeness production at high  $\mu_B$
- Canonical Ensemble simultaneously describes STAR data with strangeness correlation radii of  $r_c \sim 2.9-3.9$  fm

# Baryon to meson yield ratio



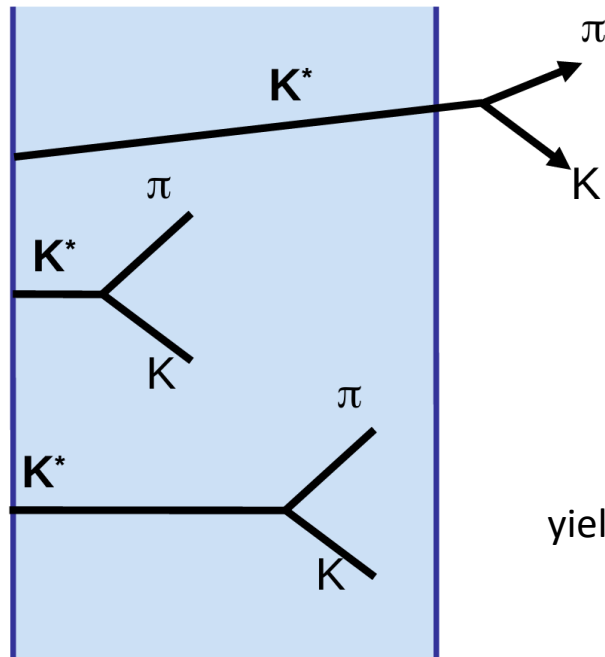
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STAR BES-I: Phys. Rev. C 102, 034909 (2020)

- At high energies ( $\sqrt{s_{NN}} > 7.7$  GeV),  $\Lambda/K_S^0$  is enhanced in central collisions
- $\Lambda/K_S^0$  enhancement is not observed at 3 GeV in the measured  $p_T$  range
- $\Lambda/K_S^0$  is enhanced in  $1.2 < p_T < 1.4$  GeV/c in central collisions at above  $\sqrt{s_{NN}} = 3.9$  GeV

# Resonance production and hadronic phase time

$K^*(892)^0$



Chemical  
freeze-out

Kinetic  
freeze-out

time

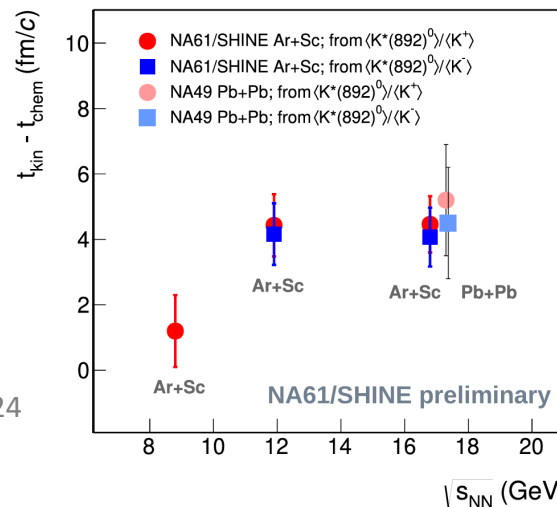
- $K^*$  lifetime ( $\sim 4$  fm/c) is comparable with the time between two freeze-outs
- Some  $K^*$  resonances may decay inside the fireball
- Suppression of observed  $K^*$  yield
- Assuming no regeneration processes, the time  $\Delta t$  between freeze-outs can be determined

$$\frac{K^*}{K}(\text{Kin}) = \frac{K^*}{K}(\text{Chem}) \cdot e^{-\frac{\Delta t}{\tau}}$$

←  $K^*$  lifetime

yield ratio in AA

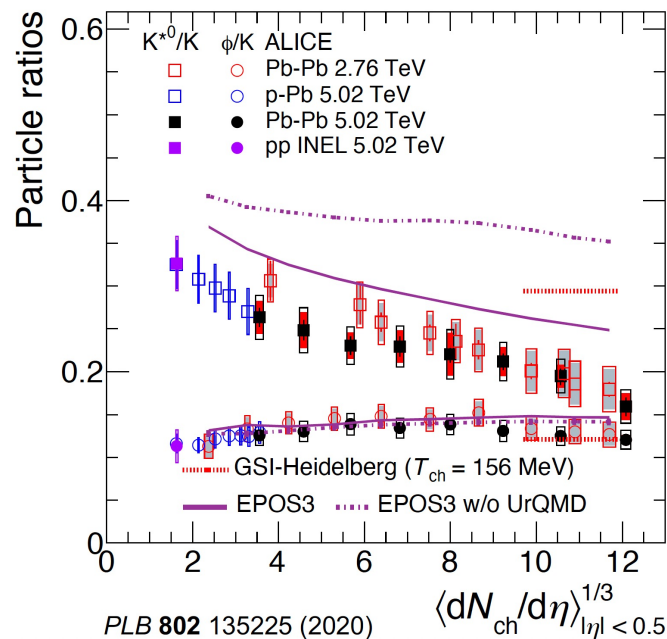
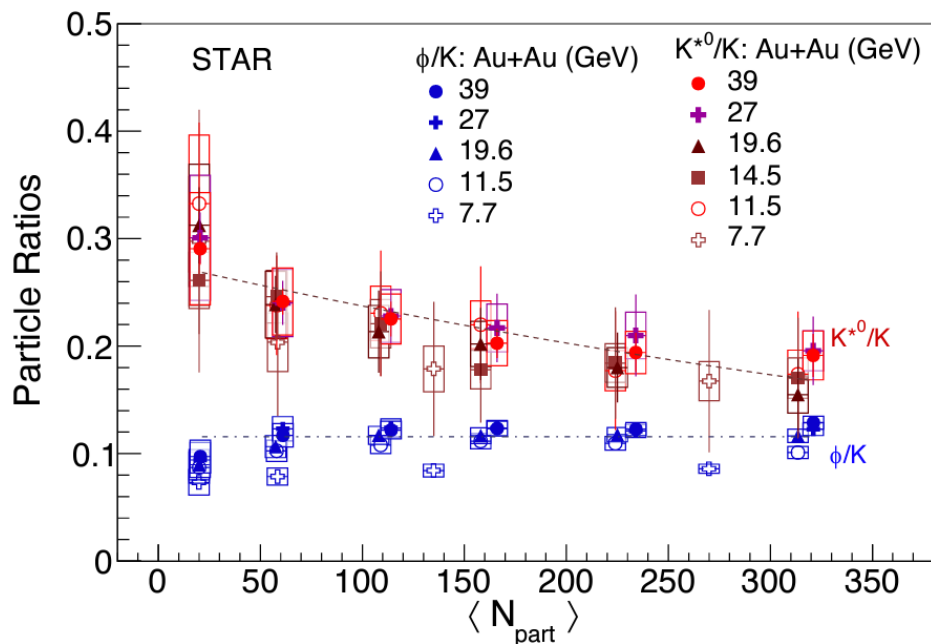
yield ratio in pp



A. Rybicki@SQM2024

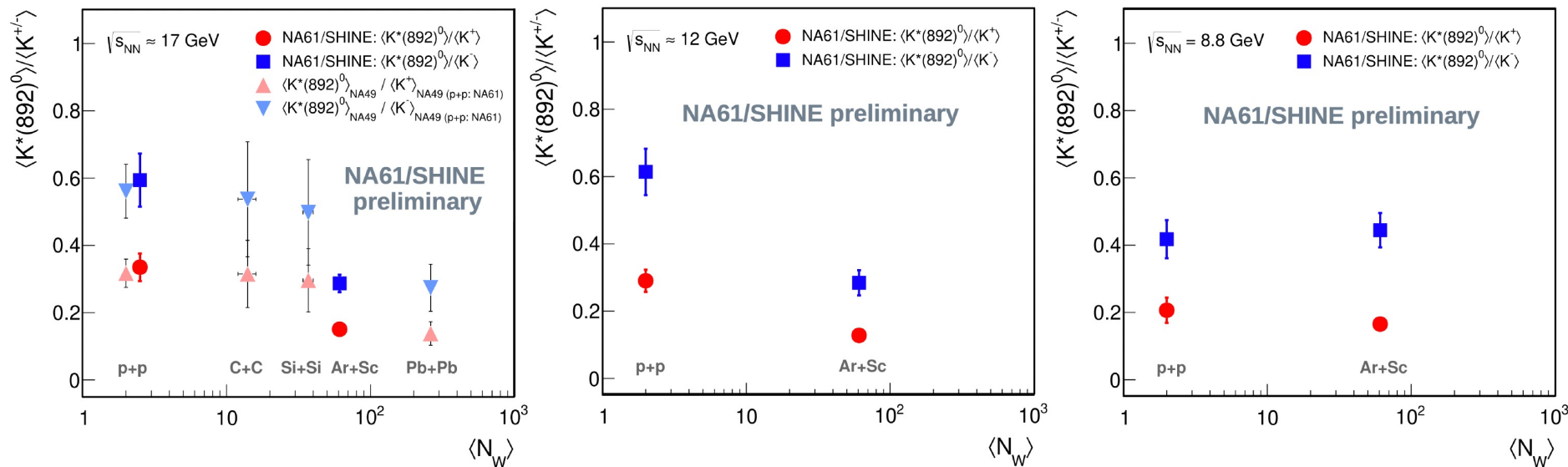
# Resonance production and hadronic phase time

- **Suppression of  $K^{*0}/K$  in central A+A collisions** → Suggests that **re-scattering is dominant** over regeneration
- $\phi/K$  not suppressed, consistent w/ statistical models → Re-scattering effects not significant



# Resonance production and hadronic phase time

- NA61/SHINE observes suppression w.r.t. p+p of  $K^*0/K$  ratios in Ar+Sc collisions at  $\sqrt{s_{NN}} = 17$  and 12 GeV
- But that suppression turns off for  $\sqrt{s_{NN}} = 8.8$  GeV
  - Shorter lifetime for hadronic phase  $\rightarrow$  less influence of re-scattering



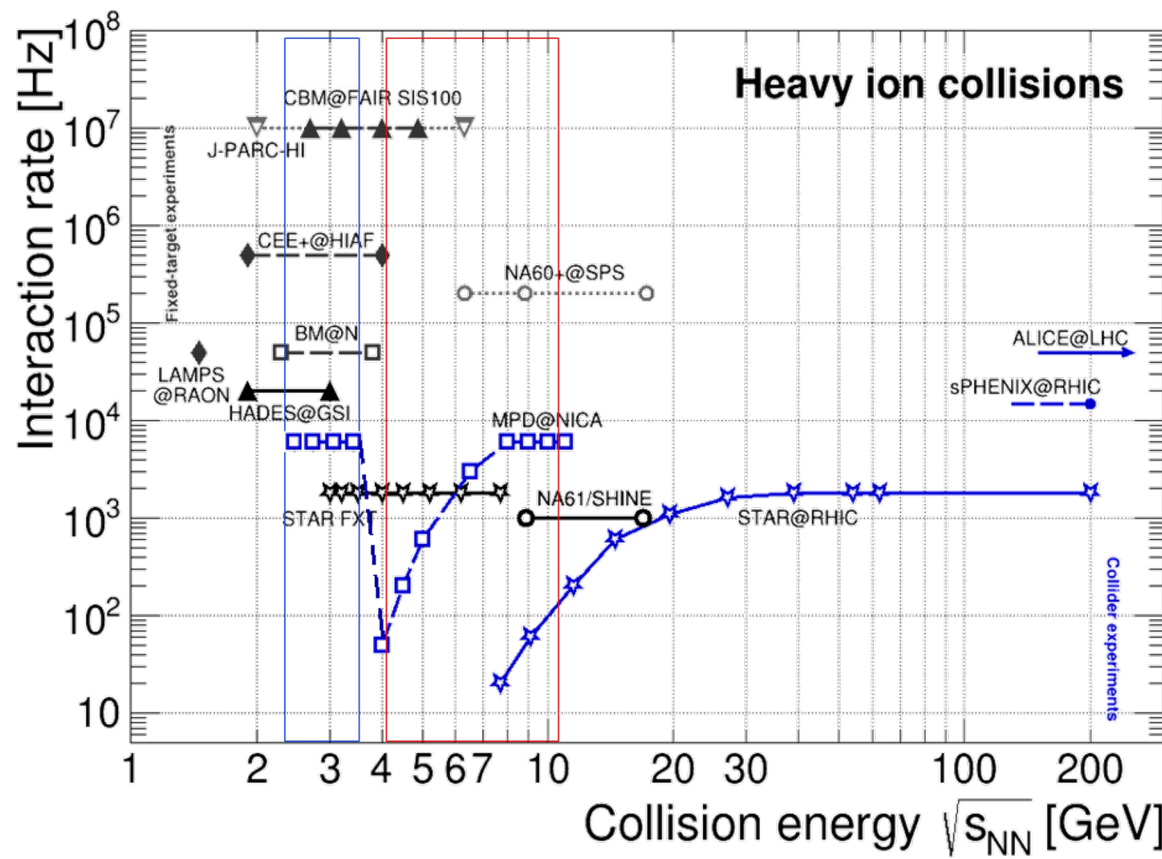
B. Kozlowski@sQM2024

# Summary and outlook

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- Big interest to study the QCD phase diagram and nuclear matter properties in A+A collisions at high baryon density
- Strangeness production is a sensitive probe for the nuclear matter study, the results from high baryon density region indicates the change of medium properties
- STAR FXT experiments at BES-II, HADES, NA61/SHINE has collected big data for studies of the phase diagram and matter EOS, and complementary to each other
- Future is bright: More heavy ion collision data at high baryon density region will be taken by NA61/SHINE, CSR/CEE, NICA/MPD, FAIR/CBM ....

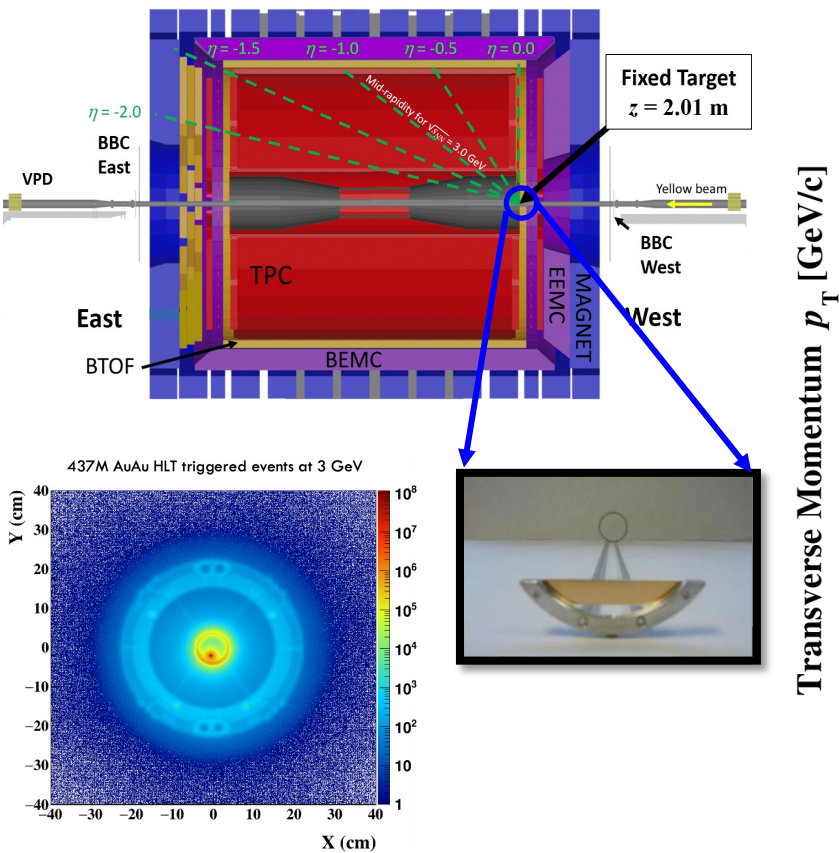
# Summary and outlook



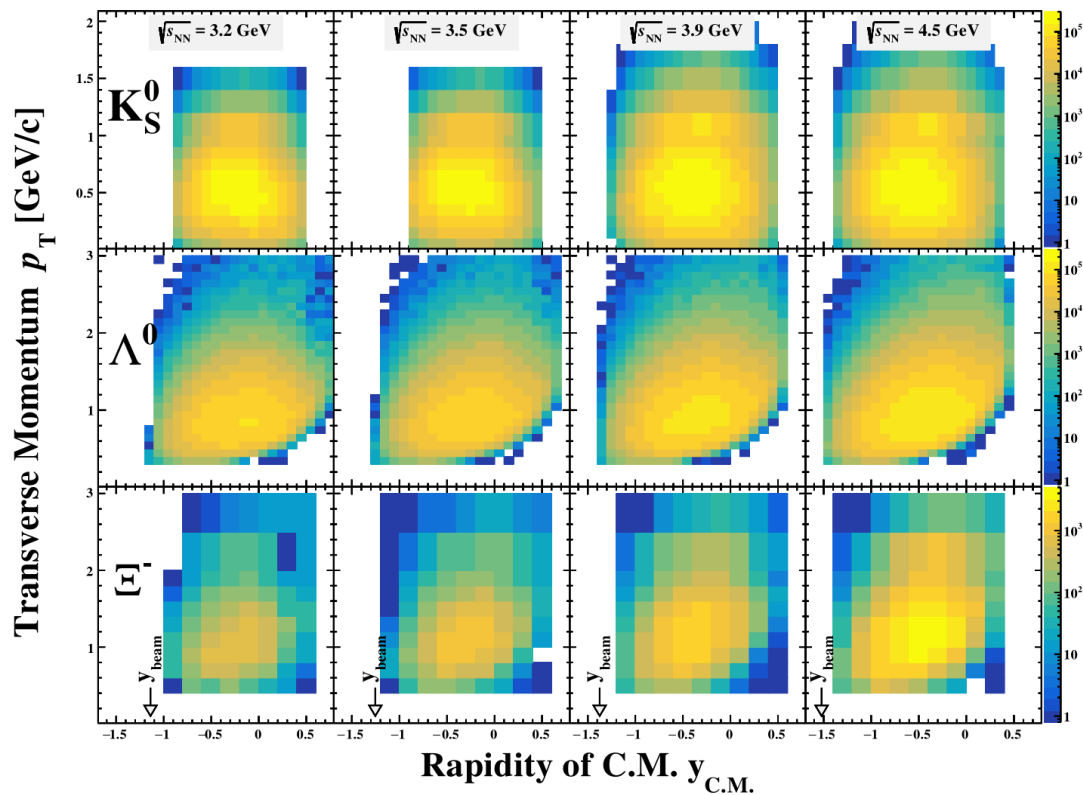
Thanks for your attention!



# Heavy-ion collisions at high baryon density region



## Au + Au Collision @ 0-10%



- Good coverage from beam-rapidity to mid-rapidity for  $K_S^0$ ,  $\Lambda^0$  and  $E^-$

# $K^*$ production and hadronic phase time

