Hadron Production in Au+Au Collisions from STAR Fixed-Target Experiment

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for the STAR Collaboration

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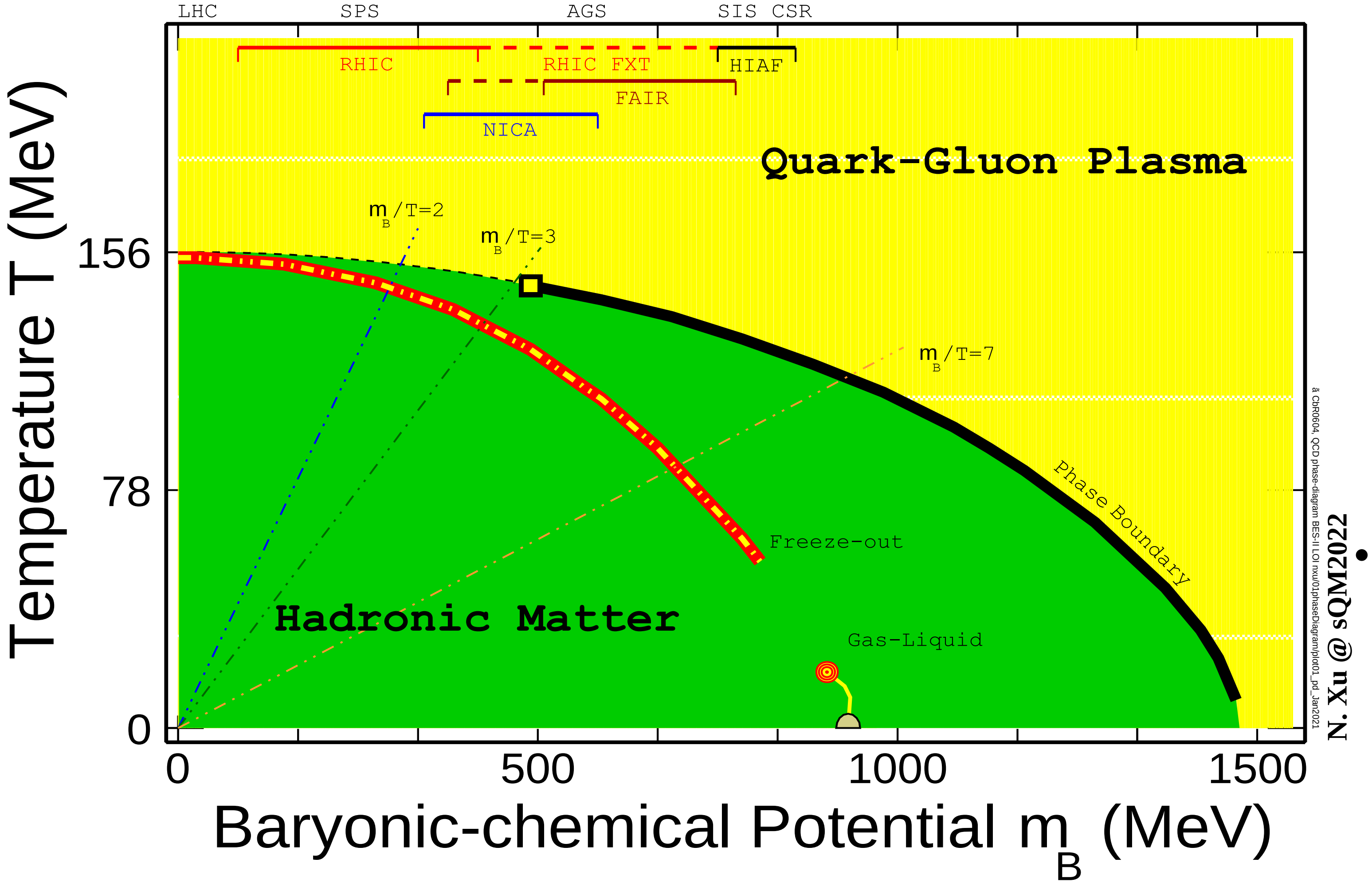
STAR Collaboration

Outline

- **Motivation**
- **Experimental Setup**
- **Measurement of Strange Hadron Production**
  - **Yield and yield ratio**
  - **Baryon to meson ratio**
  - **Kinetic freeze-out**
- **Summary and Outlook**

Exploring the QCD Phase Diagram

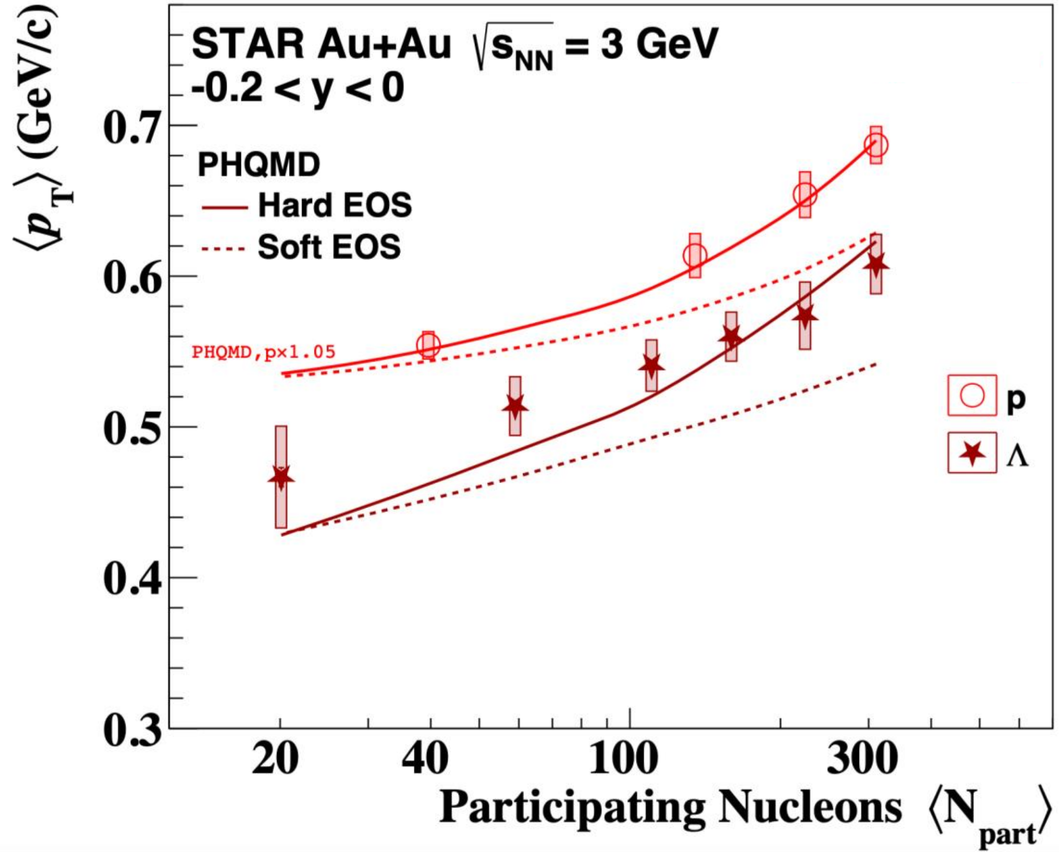


- **Study the nature of QGP and QCD phase boundary using high energy heavy-ion collisions**
  - ➢ **At small μ_B, LQCD predicts smooth crossover phase transition**
  - ➢ **At large μ_B, QCD effective models predict 1st order phase transition**
  - ➢ **QCD critical point ?**

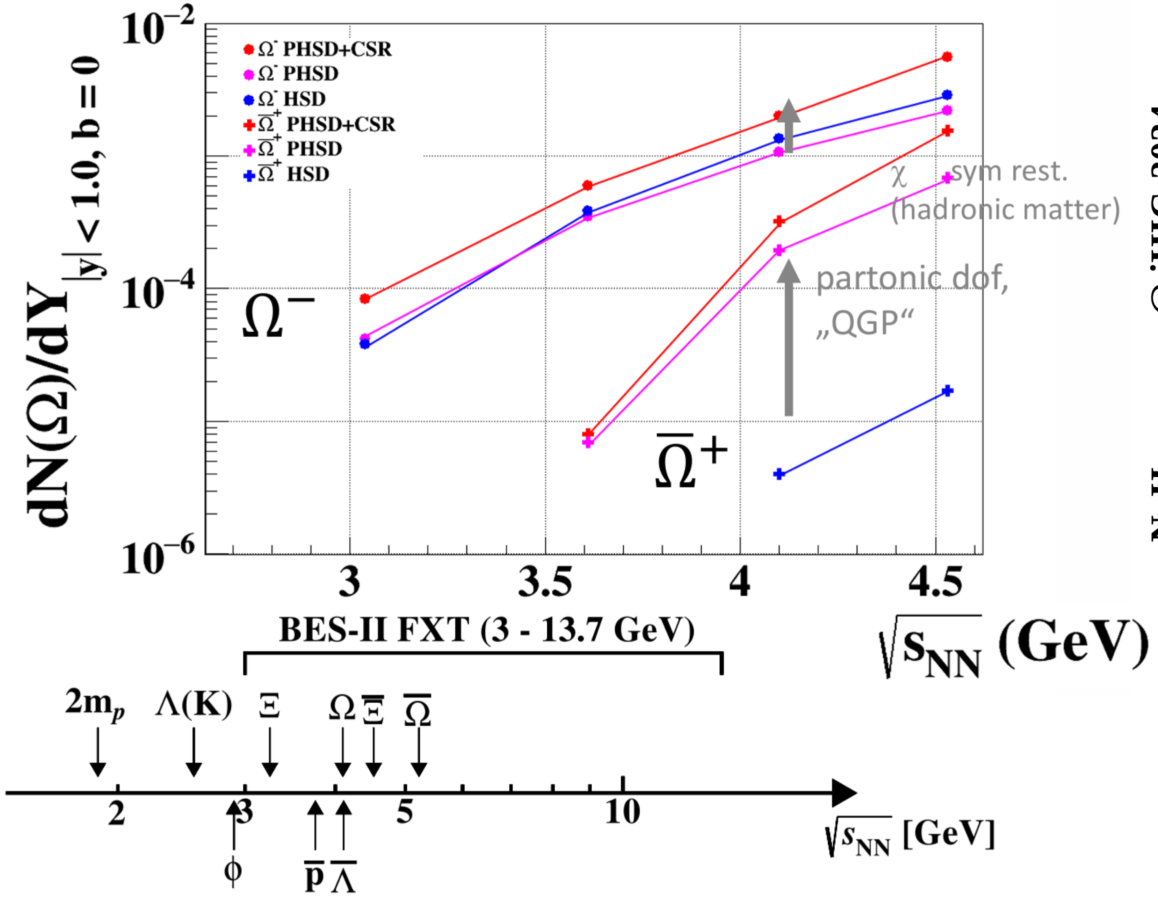
- **Experimental exploration of QCD phase diagram in high μ_B region**

Strange Hadron Production at Near/sub–threshold Energies

STAR Collaboration. Phys. Rev. C 110, 054911 (2024); JHEP 2024, 139 (2024)
PHQMD: J. Aichelin, et.al. Phys. Rev. C 101, 044905 (2020)



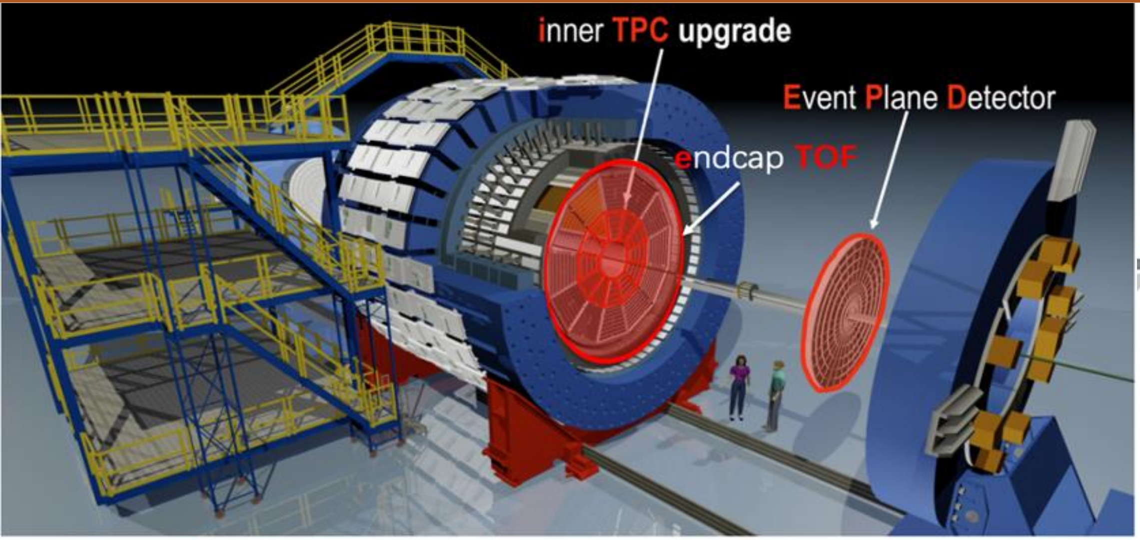
Y. Zhou @ CPOD-2024

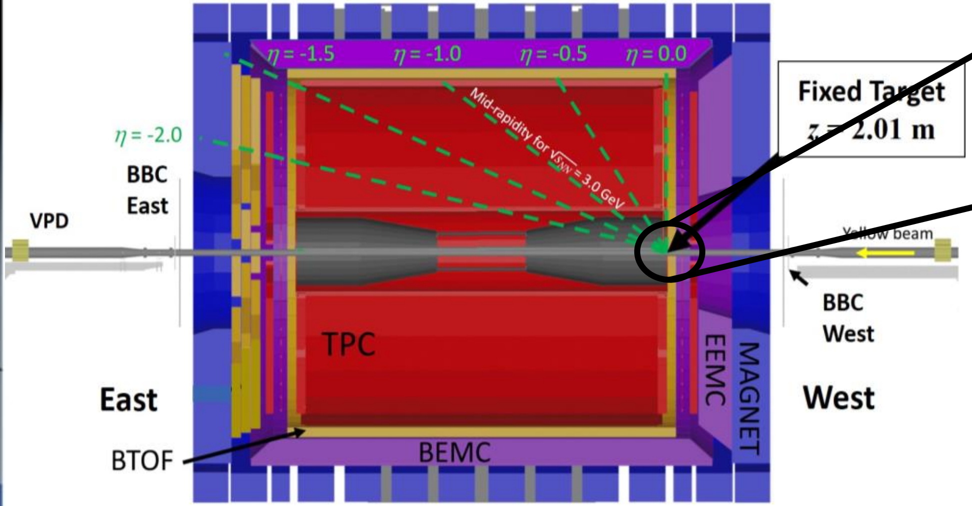


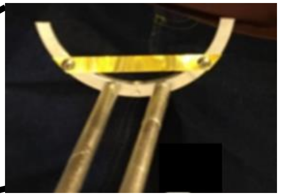
N. Herrmann @ iHIC-2024

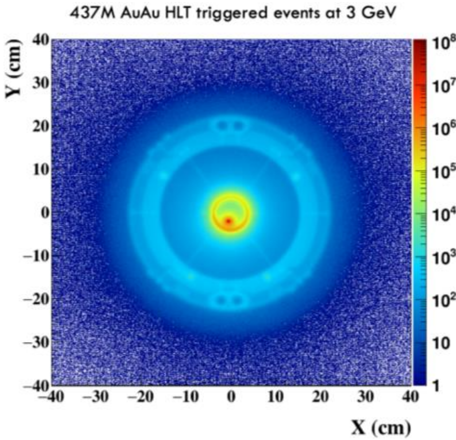
- Strange hadron production at high baryon density is a good probe to study medium properties
- The STAR BES-II FXT experiment provides unique opportunity to study strange hadron production at near or sub-threshold energies

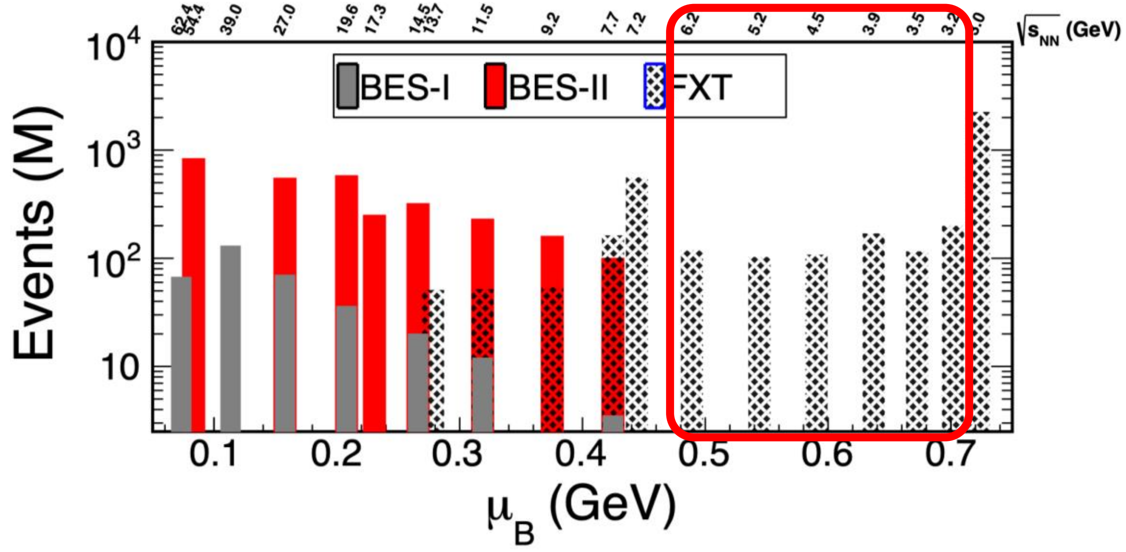
STAR Detector and Fixed Target Setup





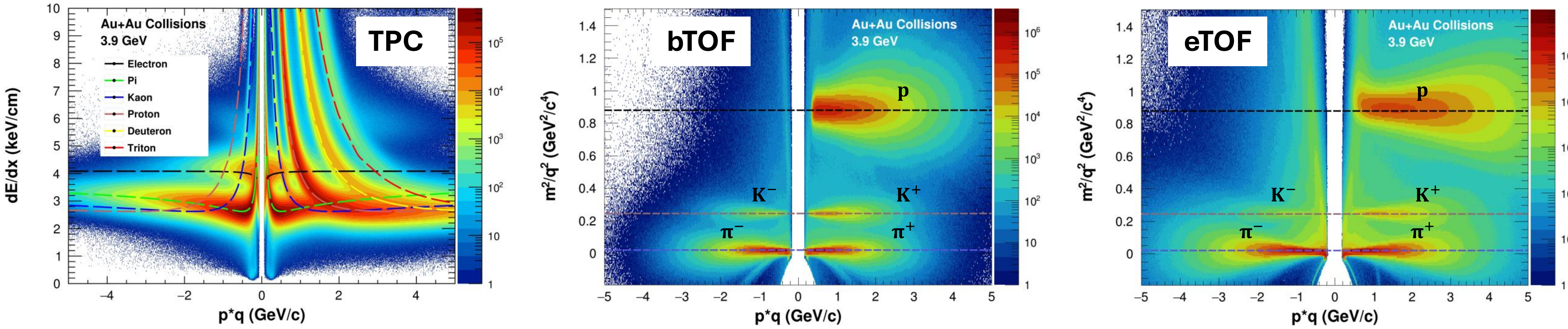






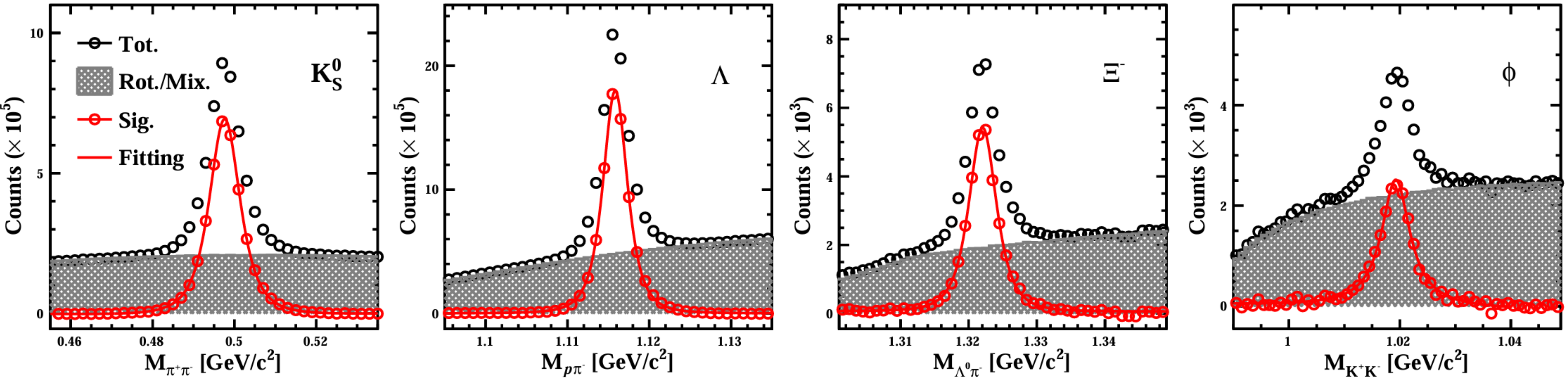
- **Detector upgrades**
  - ➢ **Time Projection Chamber (TPC & inner TPC: -2.4 < η < 0)**
  - ➢ **Time-of-Flight**
    Barrel TOF: -1.45 < η < 0 & end-cap TOF: -2.15 < η < -1.55
- **Fixed target mode (Au + Au collisions at $\sqrt{s_{NN}}$ = 3.0 – 13.7 GeV)**
  - ➢ **10× statistics compared to BES-I**
  - ➢ **This talk: $\sqrt{s_{NN}}$ = 3.2 – 6.2 GeV**

Particle Identification



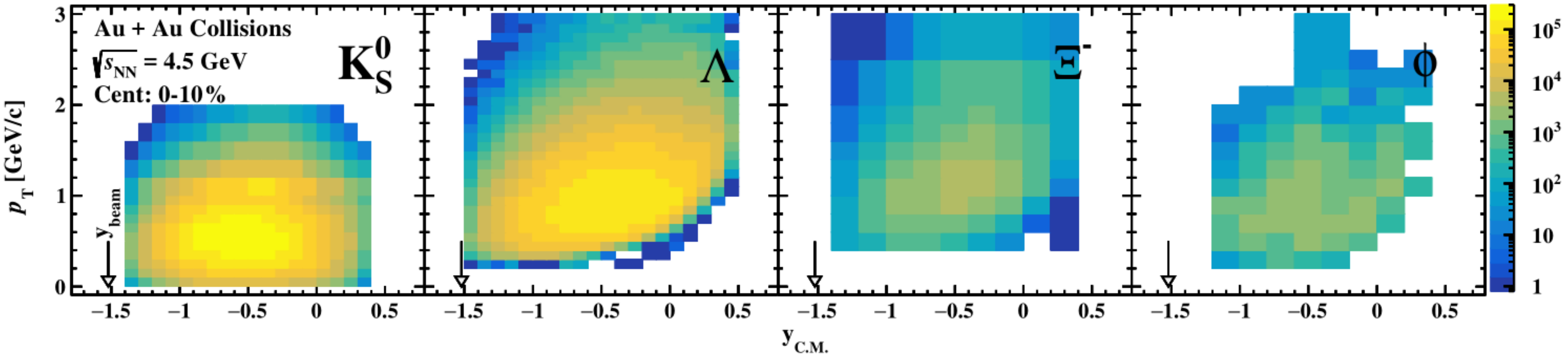
- **TPC (dE/dx) and TOF (β) for charged pion, kaon and proton identification**
  - **TOF** $m^2 = p^2\left(\frac{1}{\beta^2} - 1\right)$
- **Invariant mass method is used to reconstruct decay strange hadrons (K_S^0, ϕ, Λ and Ξ^-) from their decay daughters**
  - $m_{inv.} = \sqrt{\left(E_{dau,1} + E_{dau,2}\right)^2 - \left(\vec{p}_{dau,1} + \vec{p}_{dau,2}\right)^2}$

Signal Extraction



Decay Channel:
$K_S^0 \to \pi^+ + \pi^-$
$\phi \to K^+ + K^-$
$\Lambda \to p + \pi^-$
$\Xi^- \to \Lambda + \pi^-$

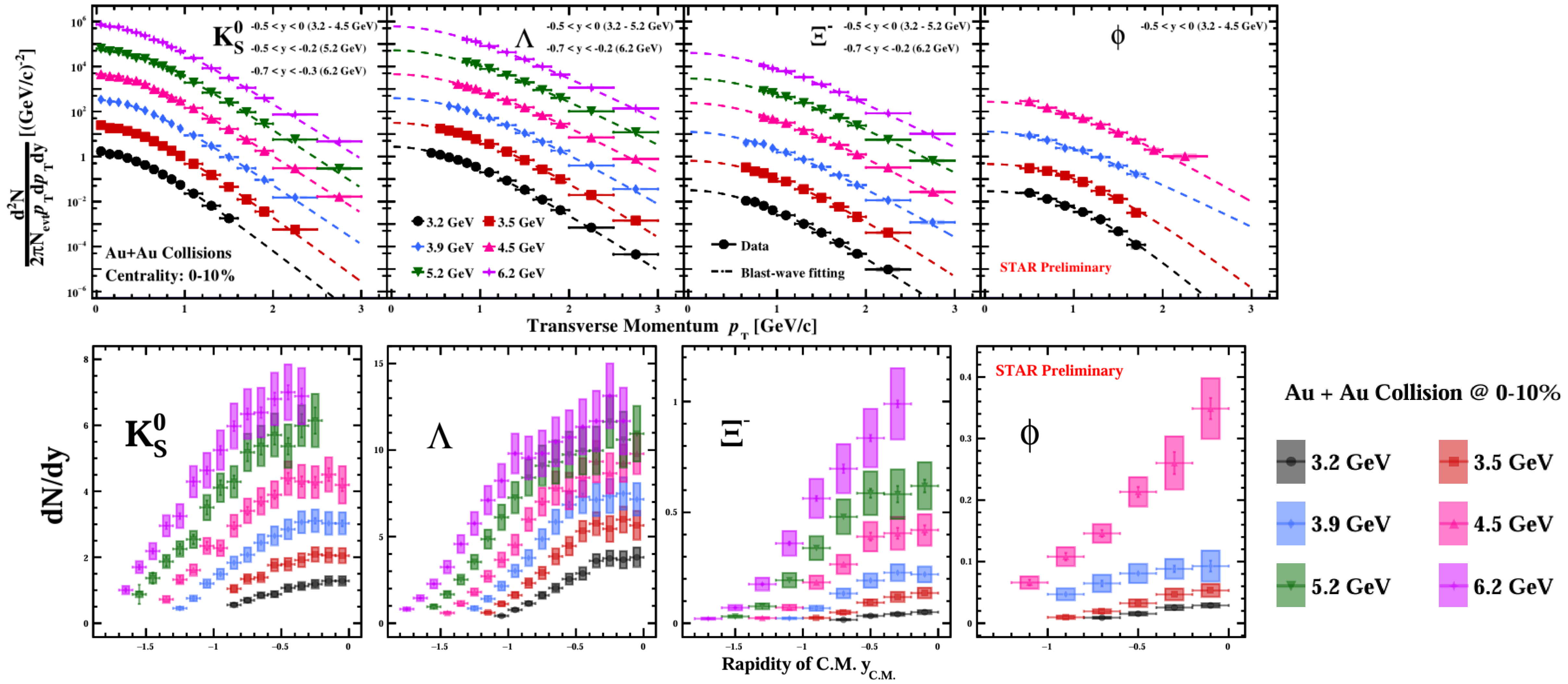
Fitting function:
Sig: Student-t for K_S^0, Λ, Ξ^-
Breit-Wigner for ϕ
Bkg: Polynomial



$\sqrt{s_{NN}}$	y_{beam}
3.2	1.14
3.5	1.25
3.9	1.38
4.5	1.52
5.2	1.68
6.2	1.87

- **Combinatorial background is reconstructed by mixed-event or track rotation method**
- **Good coverage from beam-rapidity to mid-rapidity for K_S^0, Λ, Ξ^- and ϕ**

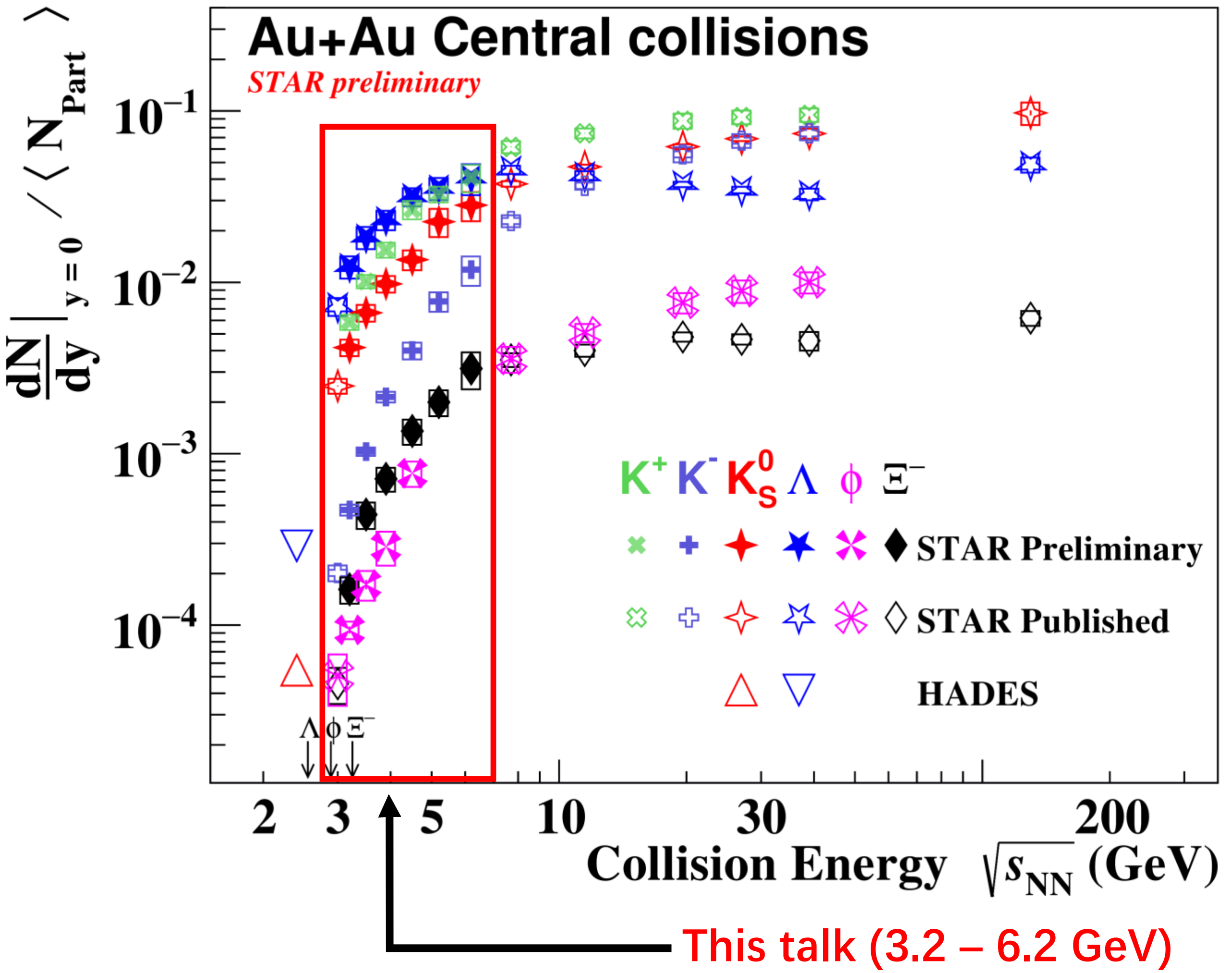
p_T Spectra and Rapidity Density Distributions



- Comprehensive measurements for strange hadron production at STAR FXT energies

Energy Dependence of Mid–Rapidity Yields

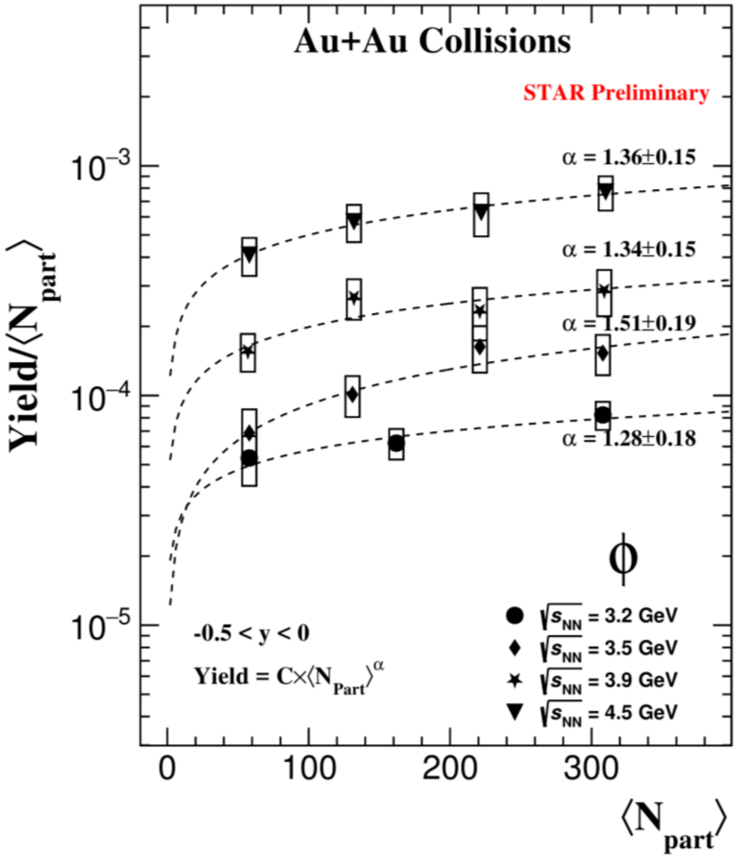
STAR Collaboration. Phys. Rev. C 96 (2017) 044904, 2017; Phys. Rev. C 102, 034909 (2020); Phys. Lett. B 831, 137152 (2022); JHEP 2024, 139 (2024)
HADES Collaboration. Phys. Lett. B 793, 457 (2019)

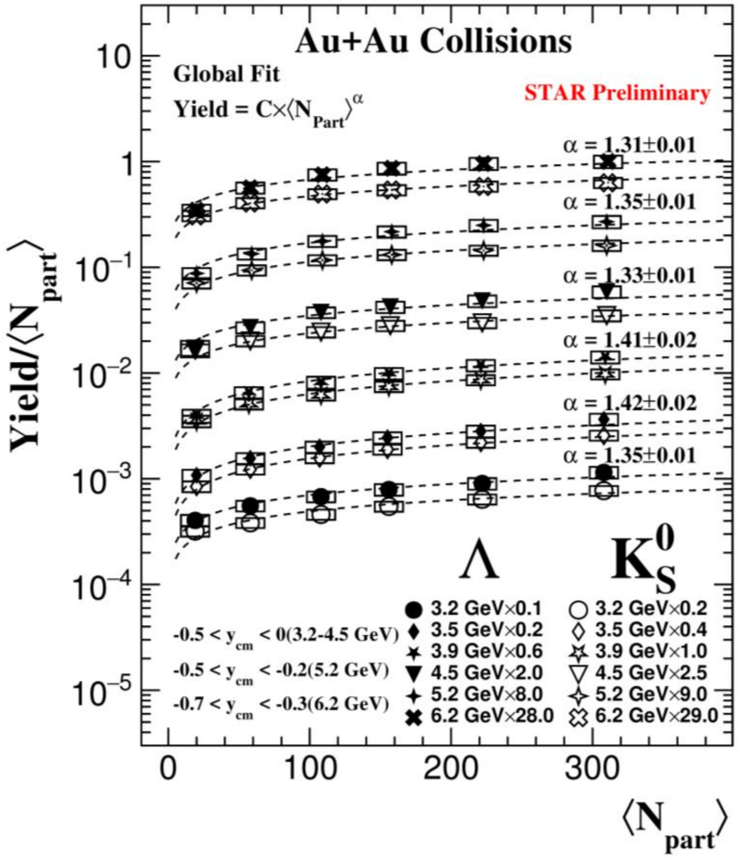


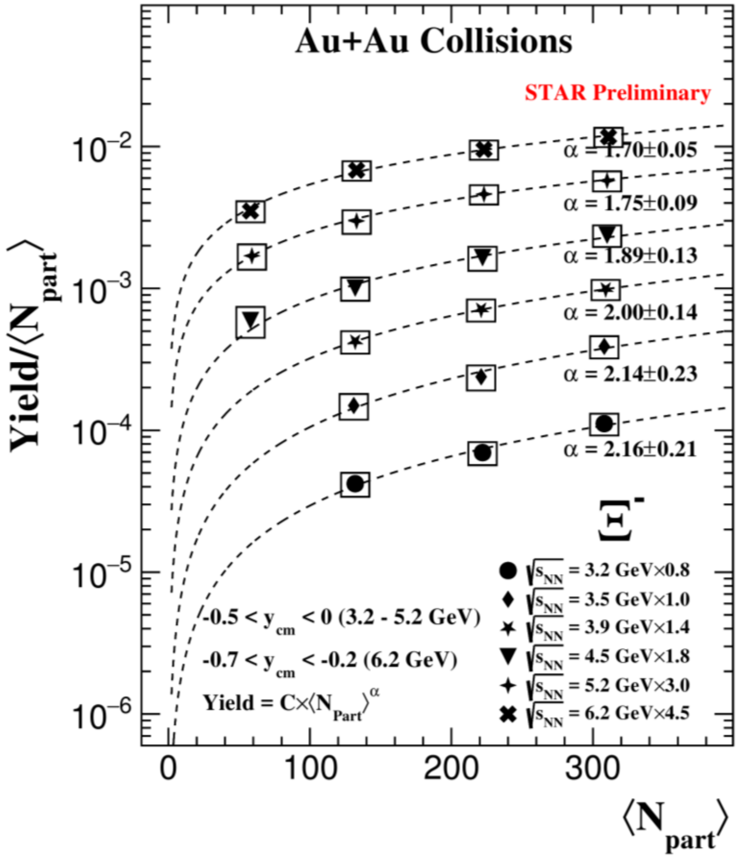
- **Mid-rapidity yields increases rapidly at low energy and approximately saturate at high energy**
  - ➢ **Partonic interaction (pair production)**
    $gg \rightarrow s\bar{s}$ or $q\bar{q} \rightarrow s\bar{s}$
  - ➢ **Hadronic interaction (associated production)**
    $BB \rightarrow BYK$ or $BB \rightarrow B\Xi KK$
    B: N, p, Δ, etc. Y: Λ, Σ, etc. K: K^+, K^0
- **First measurement of Ξ^- at sub-threshold energies in Au+Au collisions**
- **Λ yields exceed those of K^0_S below $\sqrt{s_{NN}} \sim 8$ GeV**
  - ➢ **Due to higher baryon density at low collision energies**

Mathias Labonte, Poster ID 809
Ziyue Xiang, Poster ID 832

Centrality Dependence of Mid–Rapidity Yields

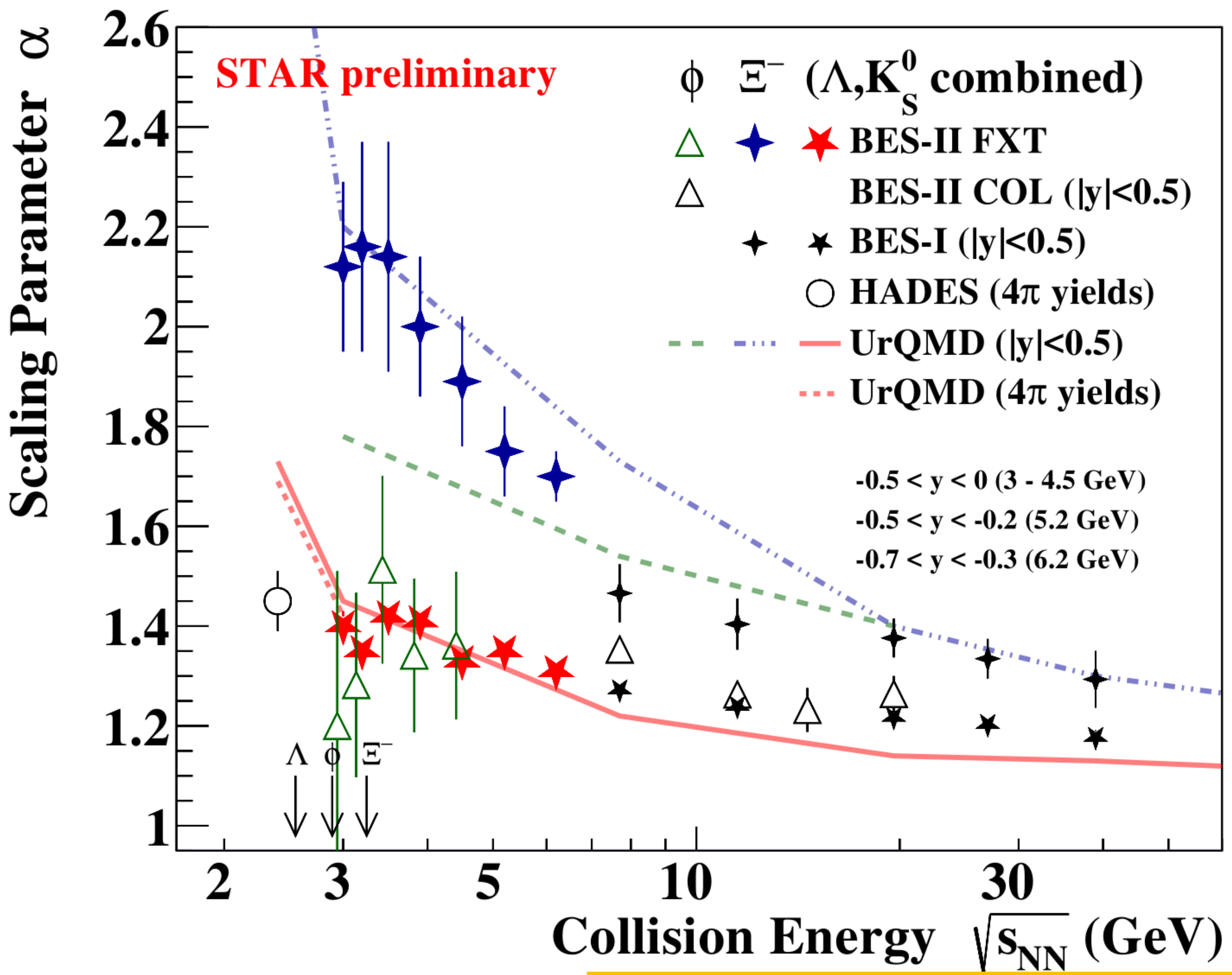






- Centrality dependence can be described by power law scaling: Yield $= c \times \langle \mathrm{N_{part}} \rangle^{\alpha}$
- Strange hadron yields increase faster than $\langle \mathrm{N_{part}} \rangle$ from peripheral to central collisions

Energy dependence of Scaling Parameter α



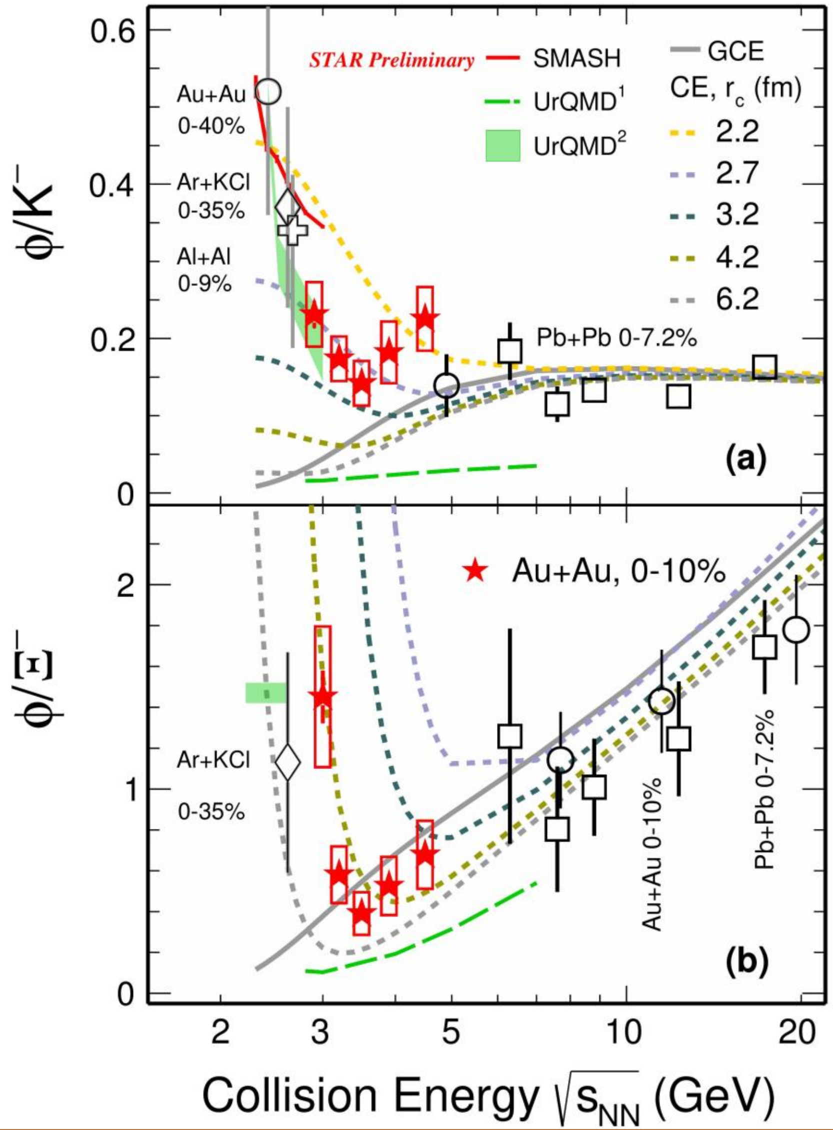
STAR Collaboration. Phys. Rev. C 102, 034909 (2020)
HADES Collaboration. Phys. Lett. B 793, 457 (2019)

Weiguang Yuan, Talk Wed. 9:40

- Centrality dependence of near-threshold production may be sensitive to EoS
- Scaling parameter α decreases with energy
  - ➢ $\Lambda(K_S^0)$ and ϕ have similar α
  - ➢ Ξ^- has significantly larger α compared to Λ, K_S^0 and ϕ below $\sqrt{s_{NN}} \sim 7$ GeV
    - ◻ Likely due to Ξ^- mainly produced via multi-step hadronic interactions
      e.g.: $NN \rightarrow NN^*$ & $N^*N \rightarrow N\Xi KK$
      $NN \rightarrow N\Lambda K$ & $\Lambda\Lambda \rightarrow N\Xi$
- Transport model simulations UrQMD
  - ➢ Qualitatively reproduces the energy dependence
  - ➢ Overestimates α for ϕ meson

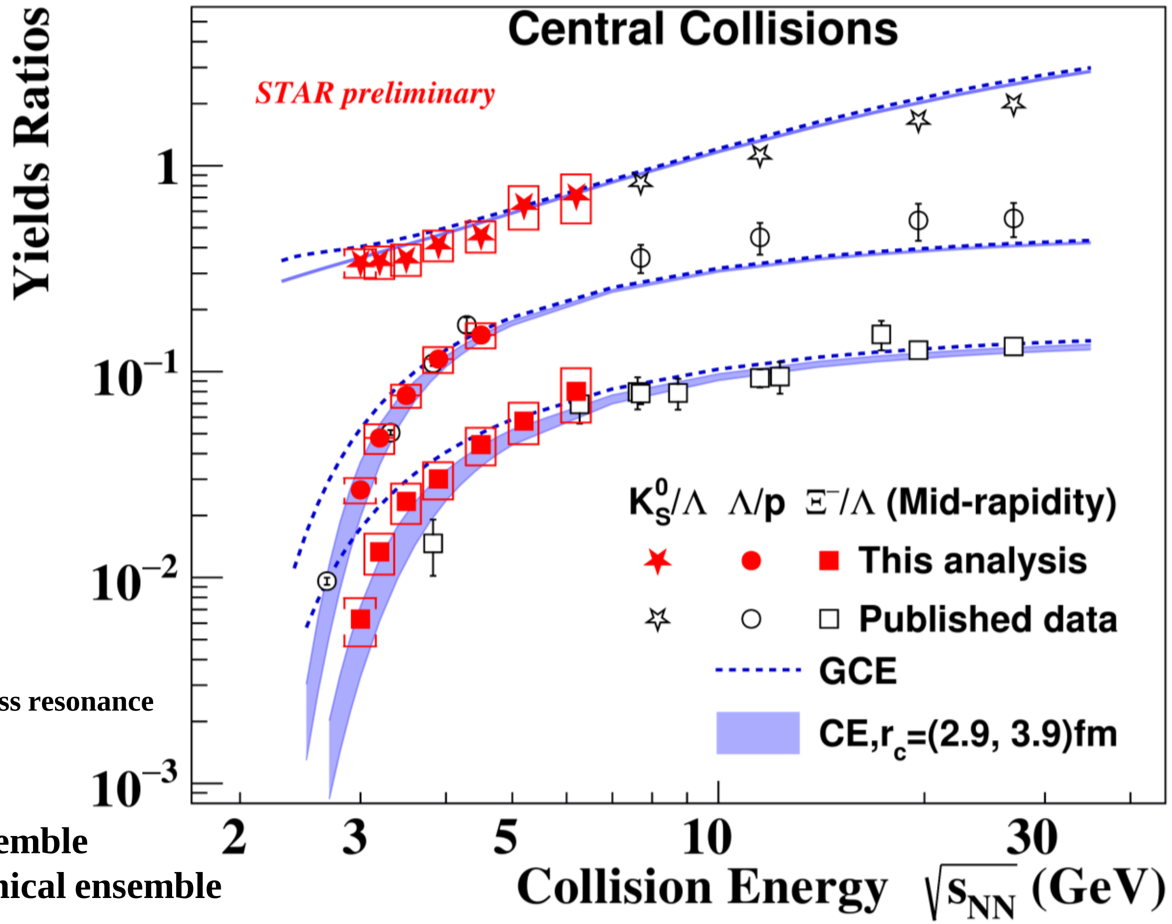
UrQMD: S.A. Bass, et.al. Prog. Part. Nucl. Phys. 41 (1998)

Energy Dependence of Yield Ratios



STAR Collaboration. Phys. Lett. B 831, 137152 (2022)
UrQMD[1]: Prog. Part. Nucl. Phys. 41 (1998) 225-370
UrQMD[2]: J. Phys. G: Nucl. Part. Phys. 43 015104

UrQMD[1]: Default
UrQMD[2]: with high mass resonance

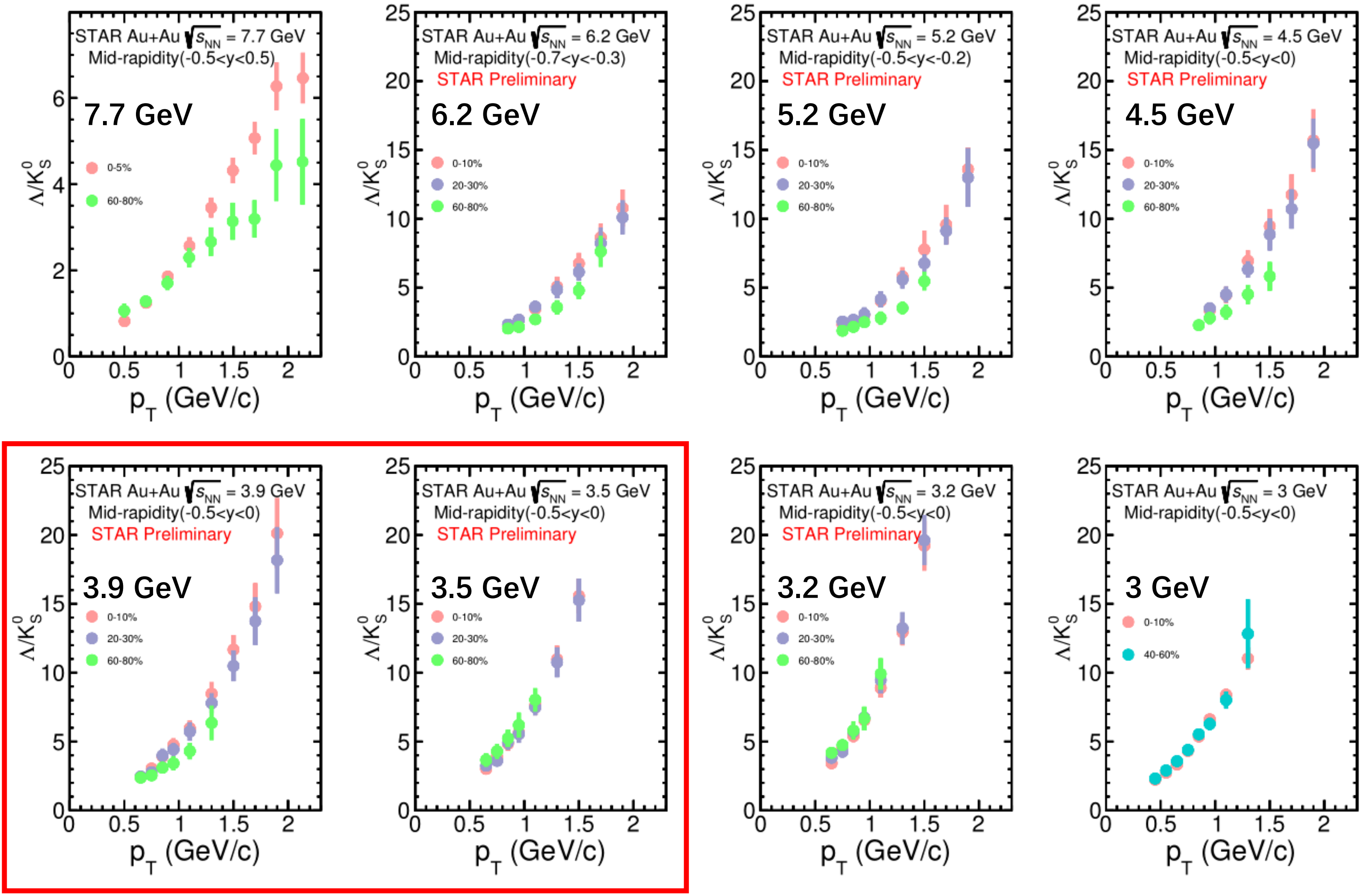


CE: canonical ensemble
GCE: grand canonical ensemble

STAR Collaboration. Phys. Rev. C 102, 034909 (2020); Phys. Rev. C 110, 054911 (2024); JHEP 2024, 139 (2024)
V. Vovchenko, et.al. Phys. Rev. C 93, 064906 (2016)
S. Wheaton, et.al. Comput.Phys.Commun. 180 (2009)

- CE describe yield ratios with $r_c \sim 3-4$ fm, but GCE fails below $\sqrt{s_{NN}} \sim 5$ GeV
- Local strangeness conservation is important in high baryon density region
- Medium properties may change in high baryon density region

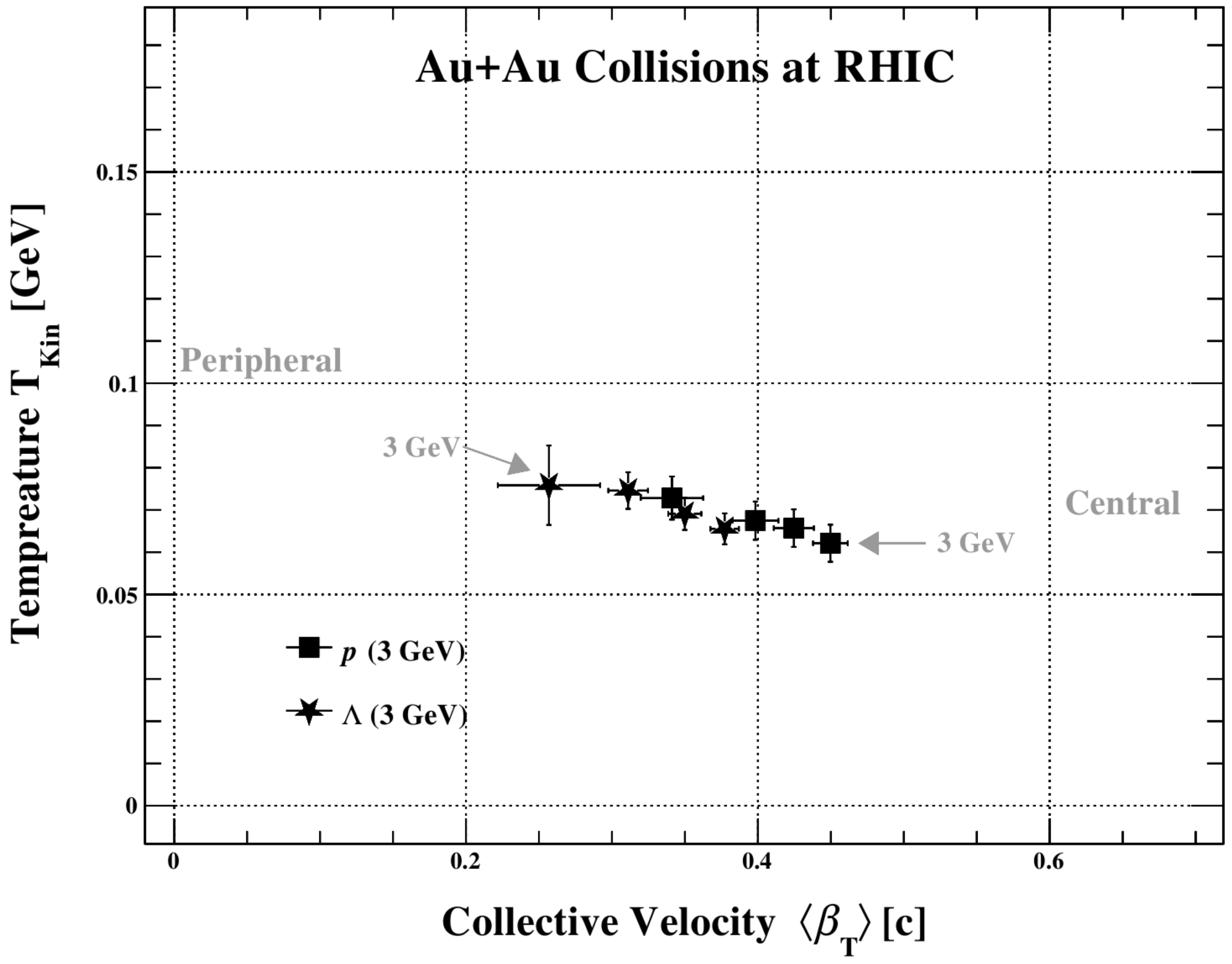
Baryon to Meson Ratios



- **Quark recombination can lead to baryon to meson enhancement**
- **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**

Kinetic Freeze–out

STAR Collaboration. Phys. Rev. C 110, 054911 (2024); JHEP 2024, 139 (2024)



- **Blast-wave model**

$$\frac{d^2N}{2\pi p_T dp_T dy} \propto \int_0^R r dr\, m_T I_0\left(\frac{p_T sinh\rho(r)}{T_{Kin}}\right) K_1\left(\frac{m_T cosh\rho(r)}{T_{Kin}}\right)$$

$$\rho(r) = \frac{1}{2} ln\frac{1+\beta_T(r)}{1-\beta_T(r)}, \qquad \beta_T(r) = \beta_{T,Max}\left(\frac{r}{R}\right)^n$$

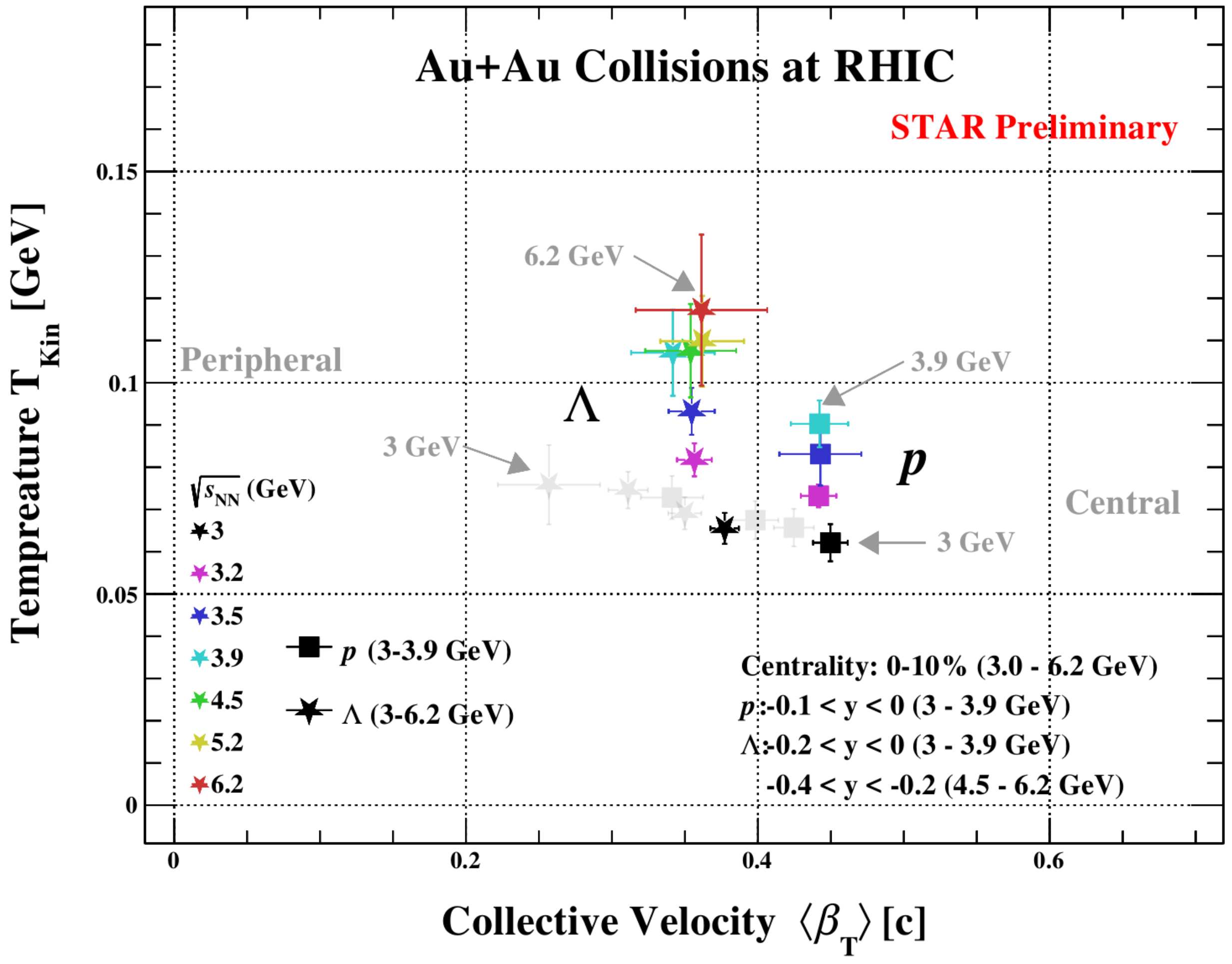
  - ➢ **Kinetic freeze-out temperature: T_{Kin}**
  - ➢ **Collective velocity: $\langle\beta_T\rangle = \frac{2}{n+2}\beta_{T,Max}$**

- **Apply Blast-wave fits to proton and Λ spectra separately**

- **$\langle\beta_T\rangle$ 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**

Kinetic Freeze–out

STAR Collaboration. Phys. Rev. C 110, 054911 (2024); JHEP 2024, 139 (2024)

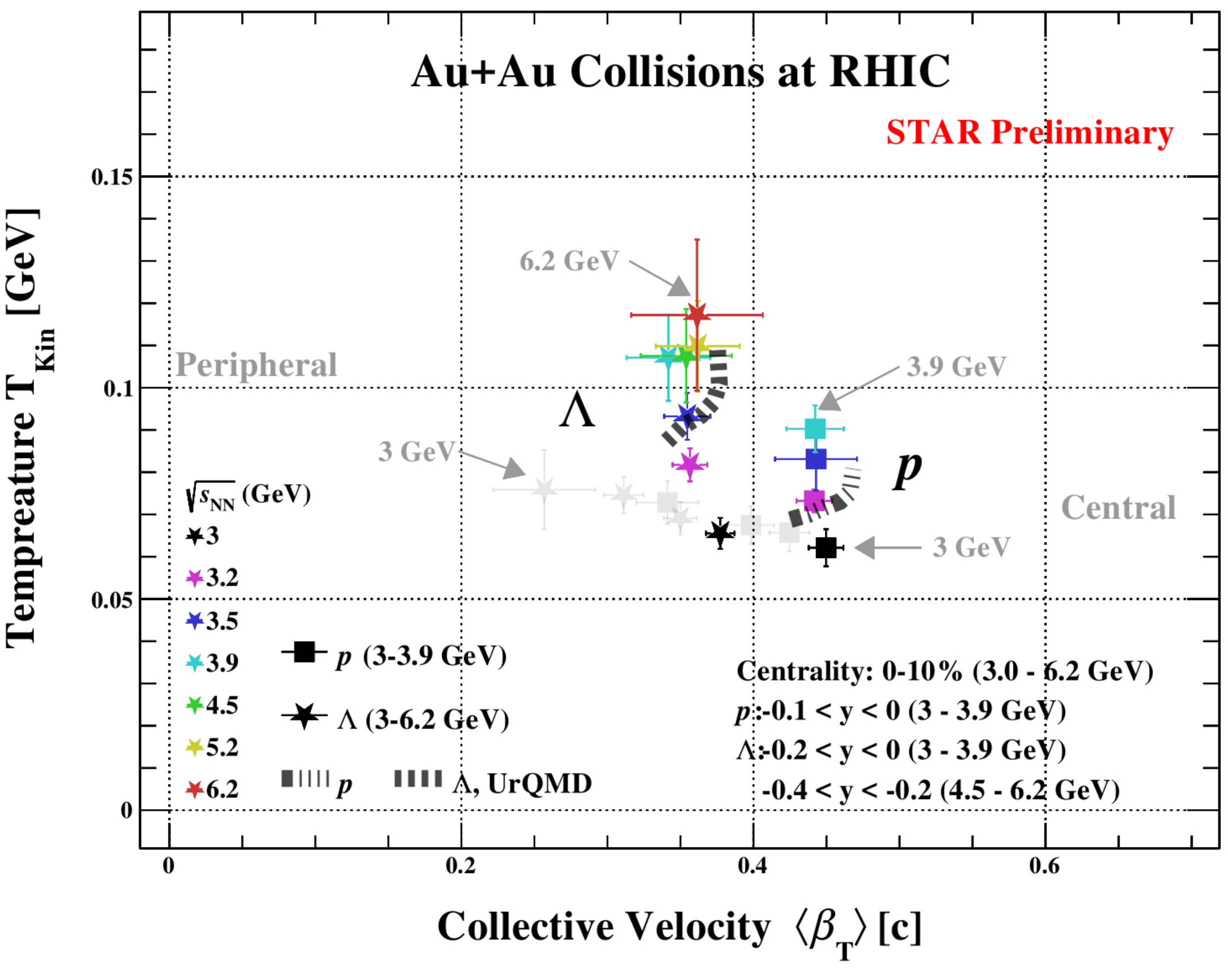


- **Clear energy dependence**
  - ➢ T_{Kin} **increases while** $\langle\beta_T\rangle$ **remains almost constant from** $\sqrt{s_{NN}}$ **= 3 – 6.2 GeV for Λ**

- **Different freeze-out parameters between proton and Λ from** $\sqrt{s_{NN}}$ **= 3 – 3.9 GeV**
  - ➢ **May be due to different production mechanisms**

Kinetic Freeze–out

STAR Collaboration. Phys. Rev. C 110, 054911 (2024); JHEP 2024, 139 (2024)



- **Clear energy dependence**
  - ➢ T_{Kin} increases while $\langle\beta_T\rangle$ remains almost constant from $\sqrt{s_{NN}}$ = 3 – 6.2 GeV for Λ
- **Different freeze-out parameters between proton and Λ from $\sqrt{s_{NN}}$ = 3 – 3.9 GeV**
  - ➢ May be due to different production mechanisms
- **Hadronic transport model UrQMD qualitatively reproduces the trend at STAR FXT energies**

Liubing Chen, Poster ID 711

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

Summary and Outlook

- **Summary**
  - ➢ **Strange hadron measurements (K^+, K^-, K_S^0, ϕ, Λ and Ξ^-) in Au+Au collisions from $\sqrt{s_{NN}}$ = 3.2 – 6.2 GeV**
    - ☐ **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**
    - ☐ **Significantly larger α for Ξ^- compared to Λ, K_S^0 and ϕ below $\sqrt{s_{NN}}$ ~ 7 GeV → likely due to production from multi-step hadronic interaction**
    - ☐ **Λ/K_S^0 is enhanced above at p_T > 1 GeV/c in central collisions above $\sqrt{s_{NN}}$ = 3.9 GeV**
    - ☐ **Different freeze-out parameters for proton and Λ from $\sqrt{s_{NN}}$ = 3 – 3.9 GeV → likely due to different production mechanisms**

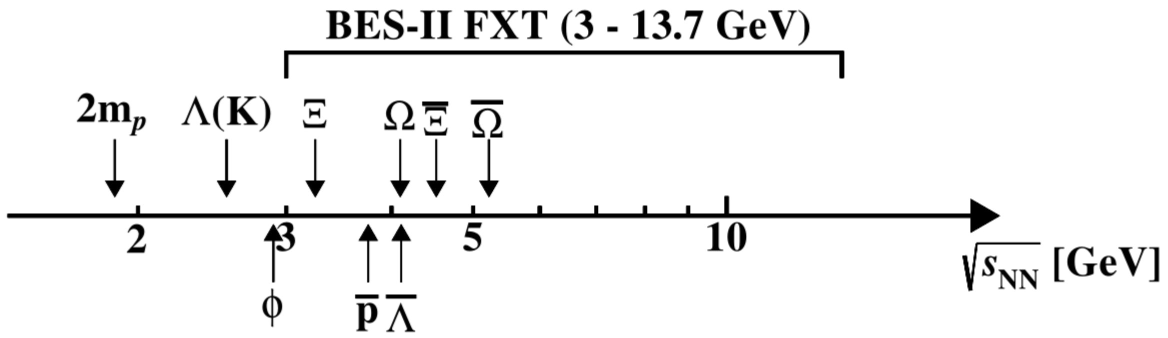
- **Outlook**
  - ➢ **Measurements of $\bar{\Lambda}$, $\bar{\Xi}^+$, Ω^- and $\bar{\Omega}^+$ production at near/sub-threshold energy from BES-II**

Thanks for your attention!

Back up

NN Collision Threshold Energies

NN Collision Threshold Energy	
$NN \rightarrow N\Lambda K \sim 2.548$ GeV	$NN \rightarrow NNK\bar{K} \sim 2.864$ GeV
$NN \rightarrow NN\phi \sim 2.896$ GeV	$NN \rightarrow N\Xi KK \sim 3.247$ GeV
$NN \rightarrow NNN\bar{N} \sim 3.753$ GeV	$NN \rightarrow N\Omega KKK \sim 4.096$ GeV
$NN \rightarrow NN\Lambda\bar{\Lambda} \sim 4.107$ GeV	$NN \rightarrow NN\Xi\bar{\Xi} \sim 4.520$ GeV
$NN \rightarrow NN\Omega\bar{\Omega} \sim 5.221$ GeV	



Baryon to Meson Ratio