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Strange Hadron Production at High Baryon Density

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for the STAR Collaboration

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Strangeness in Quark Matter

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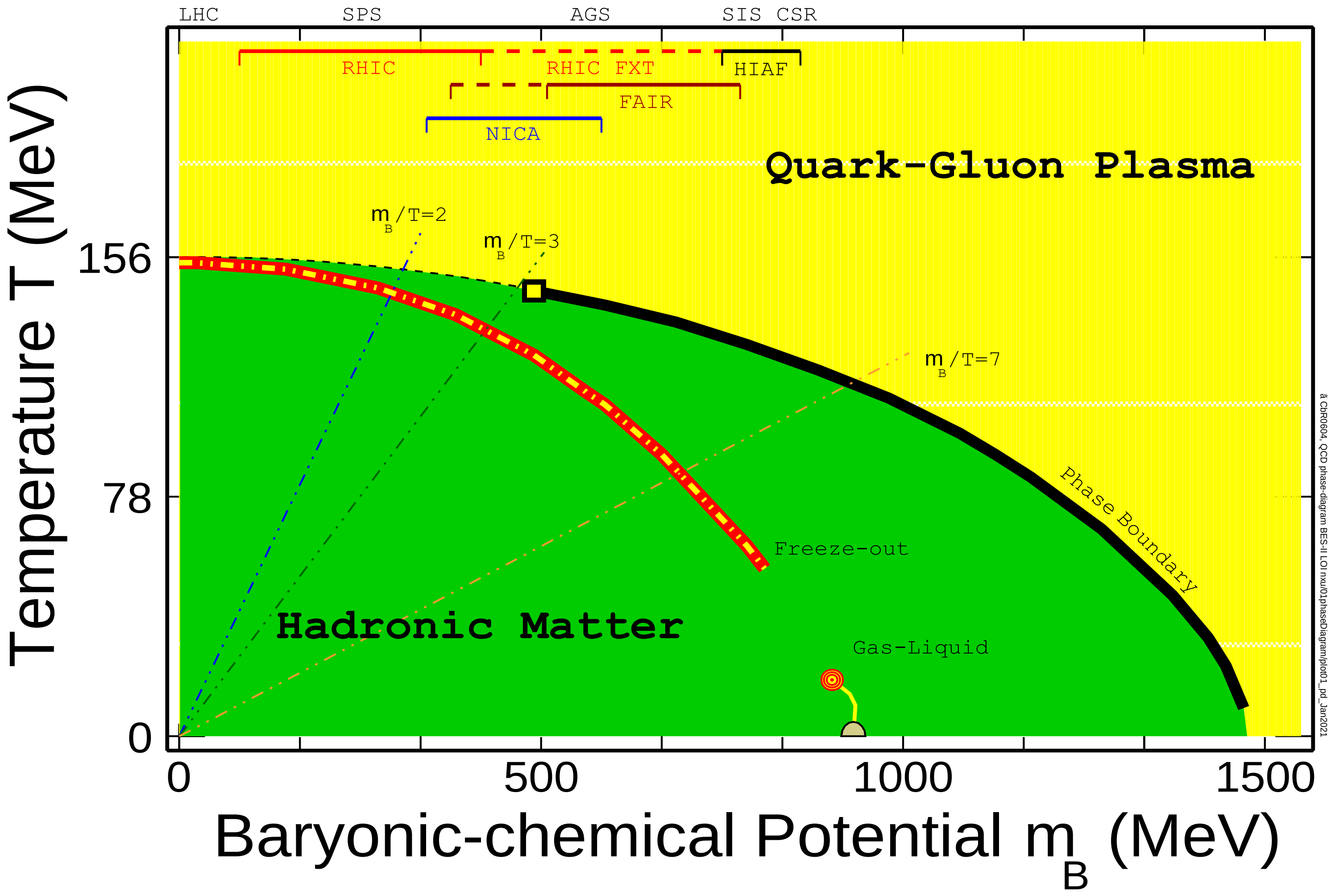
STAR

Outline

- **Motivation**
- **Experimental Setup**
- **Measurement of Strange Hadron Yield**
- **Physical Results and Discussion**
- **Summary and Outlook**

Explore QCD Phase Diagram



- **Study the natures of QGP and QCD phase structure by high energy heavy-ion collisions**
  - ➢ **LHC**
  - ➢ **RHIC**
  - ➢ **……**

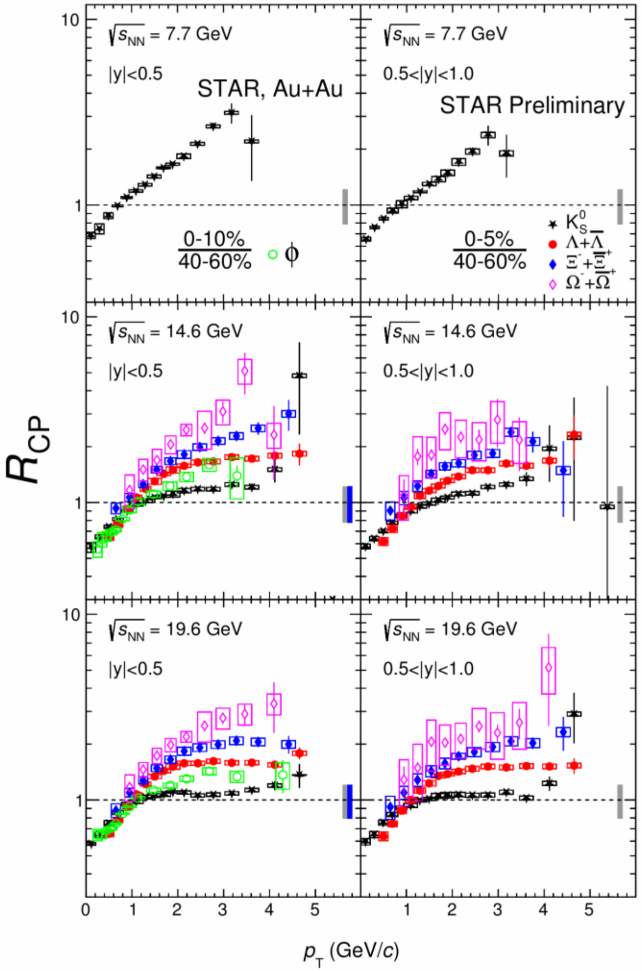
- **Phase transition between Quark-Gluon Plasma (QGP) and hadronic matter has not been experimentally determined**
  - ➢ **At small μ_B, smooth crossover**
  - ➢ **At large μ_B, 1st order phase transition → QCD critical point**

Reference: N. Xu @ sQM2022

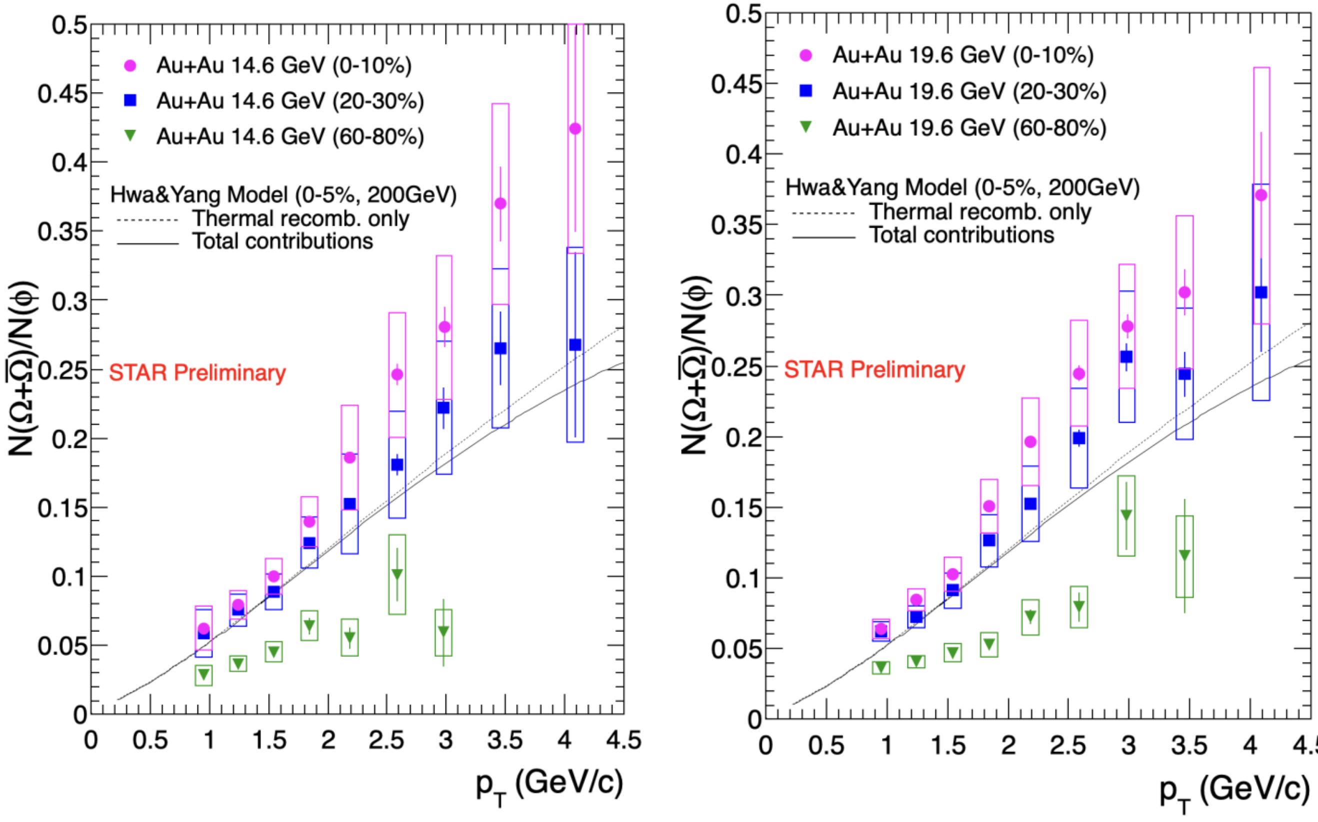
Strangeness as a Probe to Study the Nuclear Matter

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

Yi Fang, Poster ID 102



Weiguang Yuan, Poster ID 192

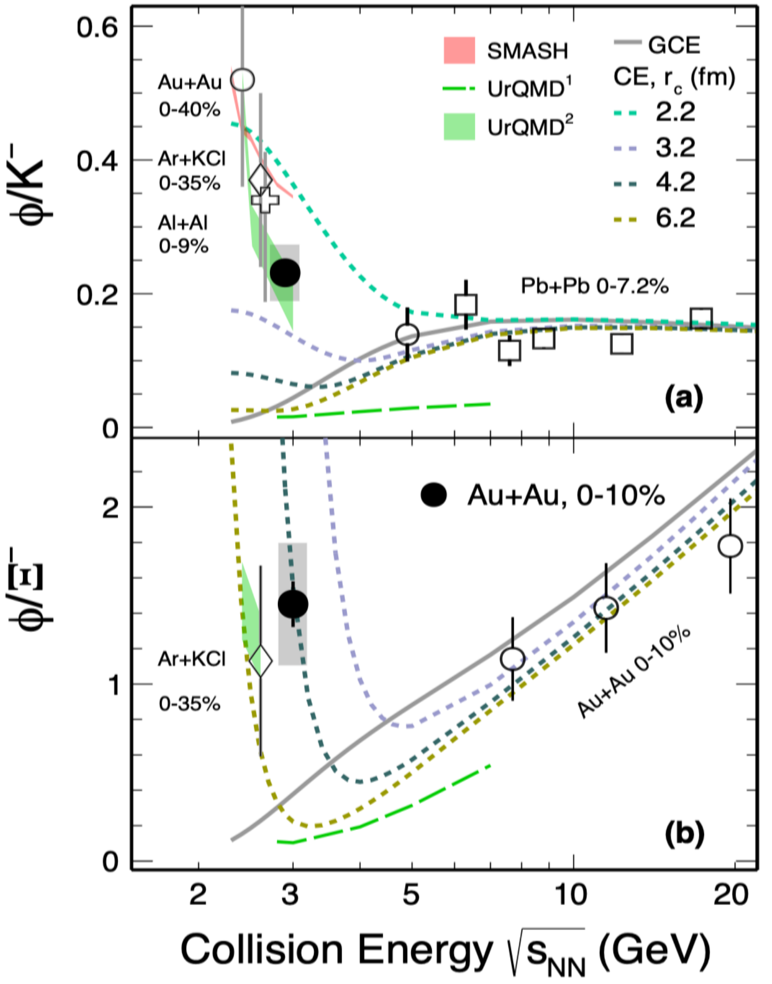


➢ **Strangeness enhancement has been observed at $\sqrt{s_{NN}}$ = 14.6 GeV and higher energies, consistent with QGP formation**

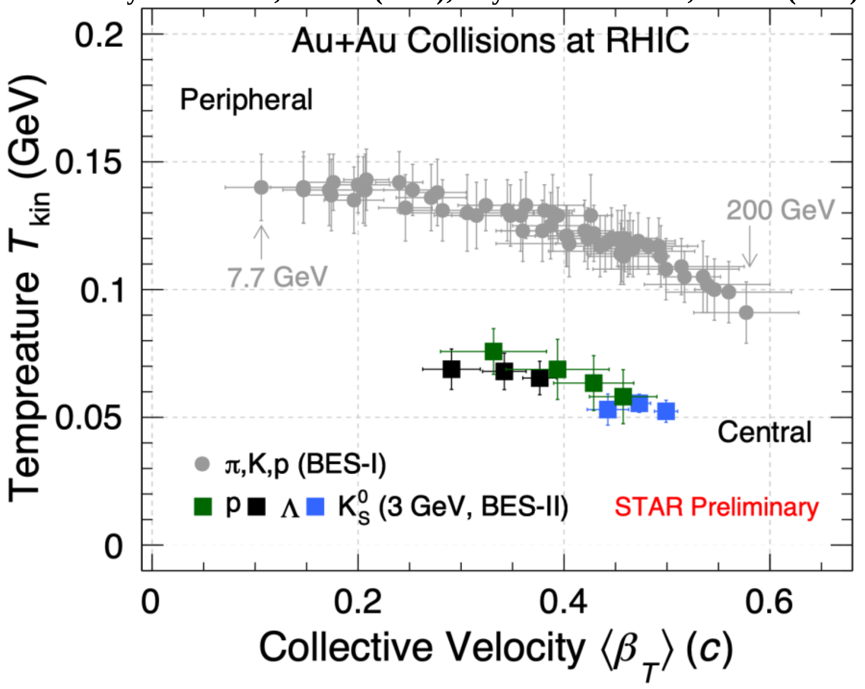
Strangeness as a Probe to Study the Nuclear Matter

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

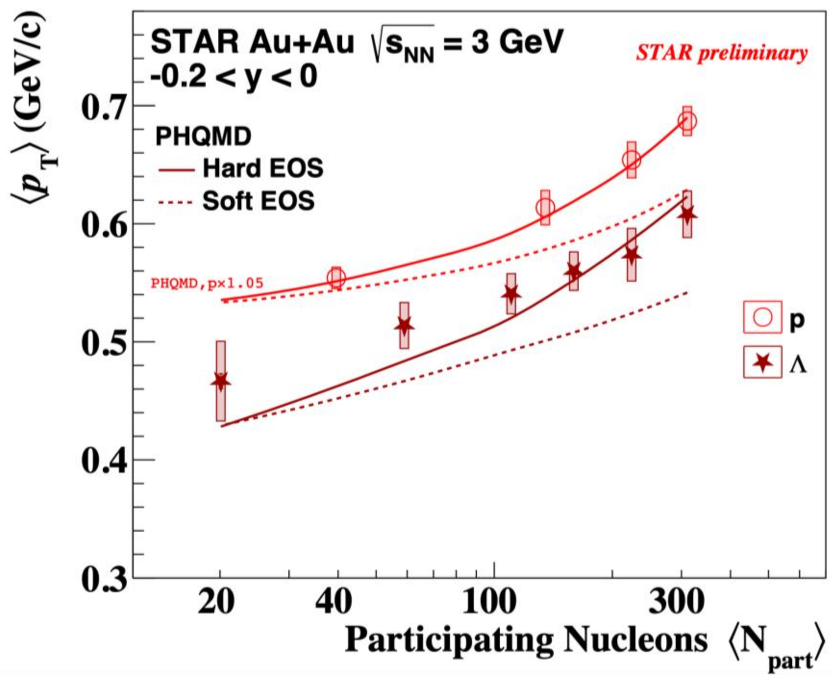
STAR Collaboration. Physics Letters B, 2022, 831: 137152



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



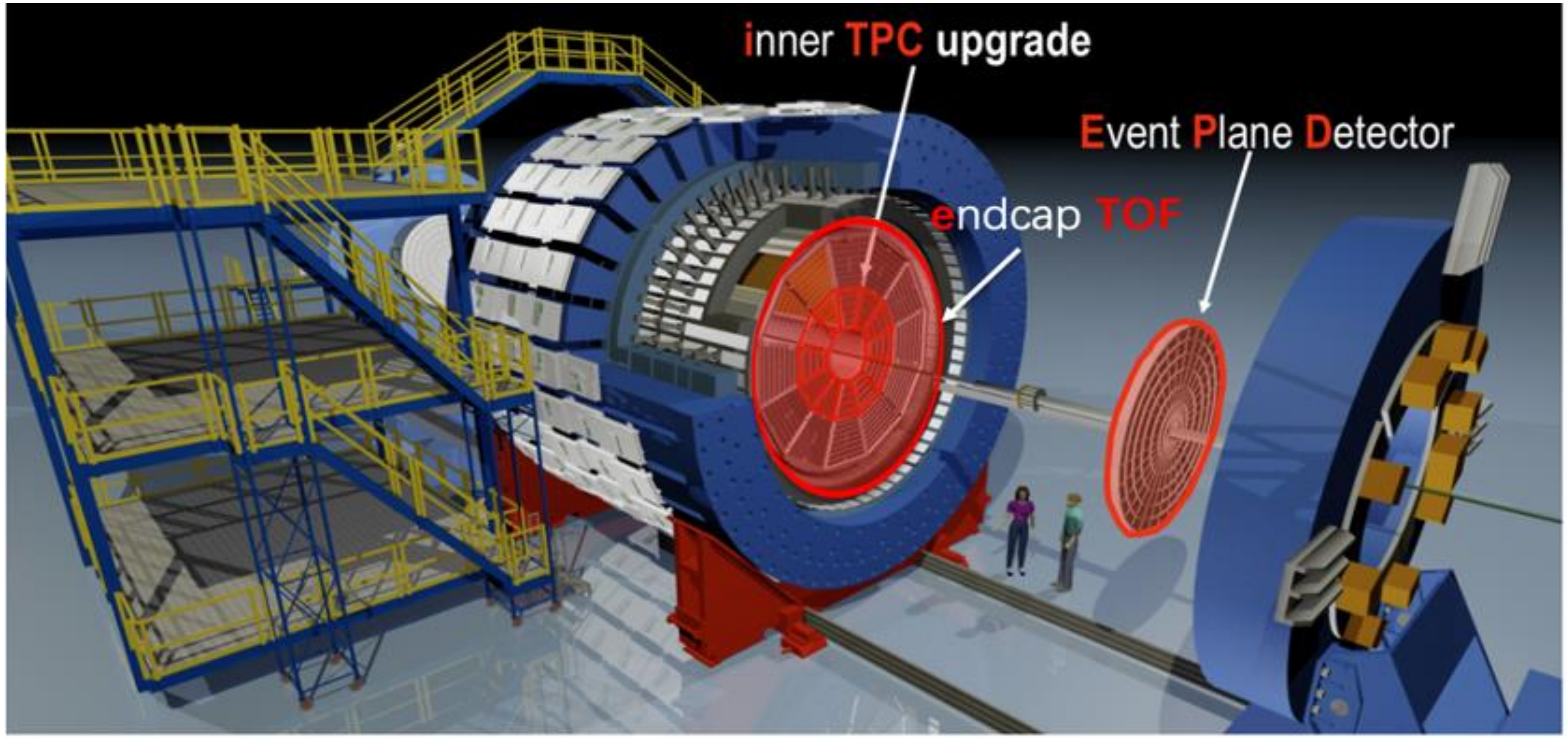
J. Aichelin, et.al. Phys. Rev. C 101, 044905 (2020)



➢ **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 Λ^0 and K^0_S at $\sqrt{s_{NN}} = 3$ GeV is substantially lower than π, K, p at higher energy collisions
- ☐ PHQMD reproduces $\langle p_T \rangle$ shape with the hard EOS

STAR Detector and Fixed Target Setup



Time Projection Chamber (TPC)

- **Charged particle tracking**
- **Momentum reconstruction**
- **Particle Identification**
- **Pseudorapidity coverage for FXT mode:**
  TPC with iTPC upgrade $-2.4 < \eta < 0$

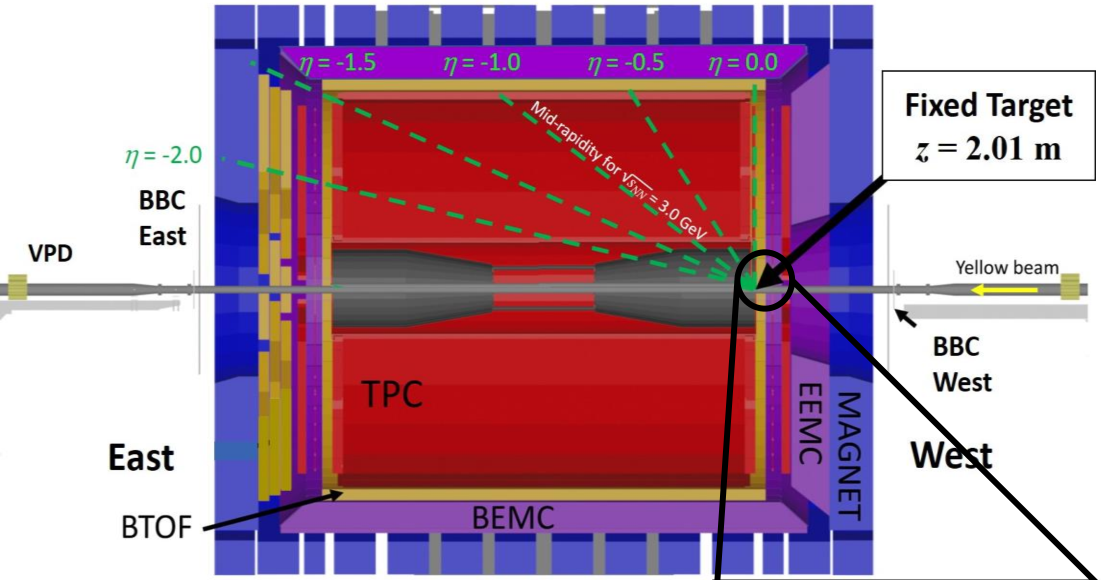
Time-of-Flight (TOF)

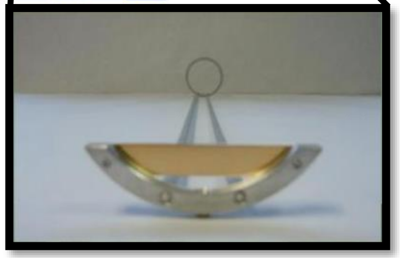
- **Particle Identification**
- **Pseudorapidity coverage for FXT mode:**
  barrel TOF (bTOF): $-1.45 < \eta < 0$
  end-cap TOF(eTOF): $-2.15 < \eta < -1.55$

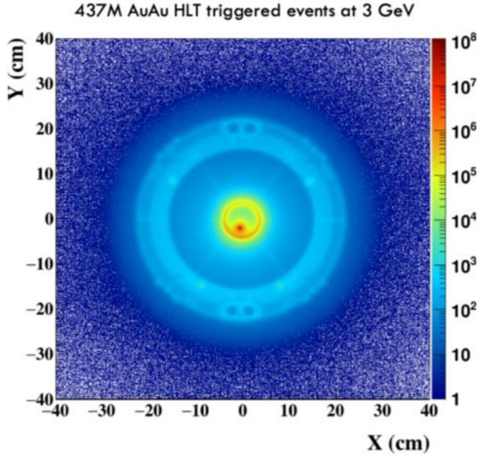
- **Large** acceptance
- **Excellent PID** with **uniform** efficiency

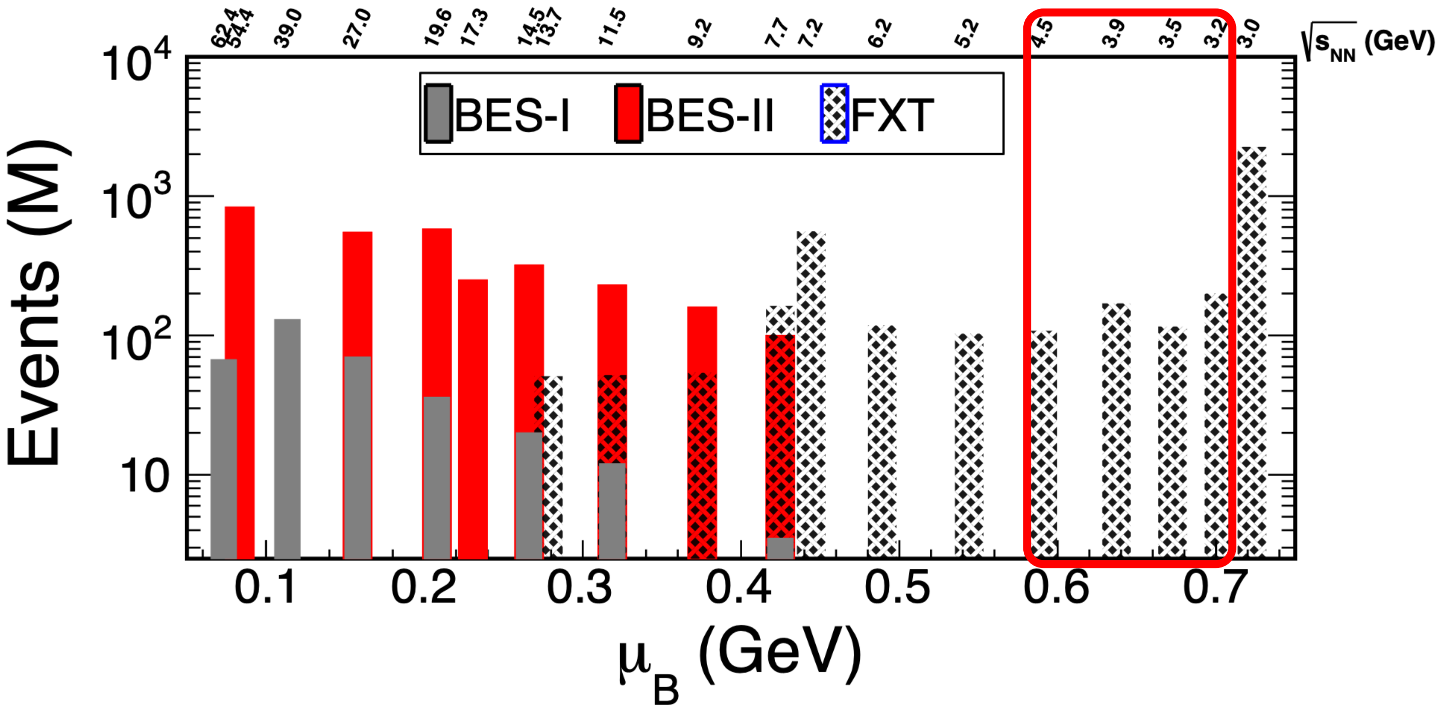
- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program

STAR Detector and Fixed Target Setup



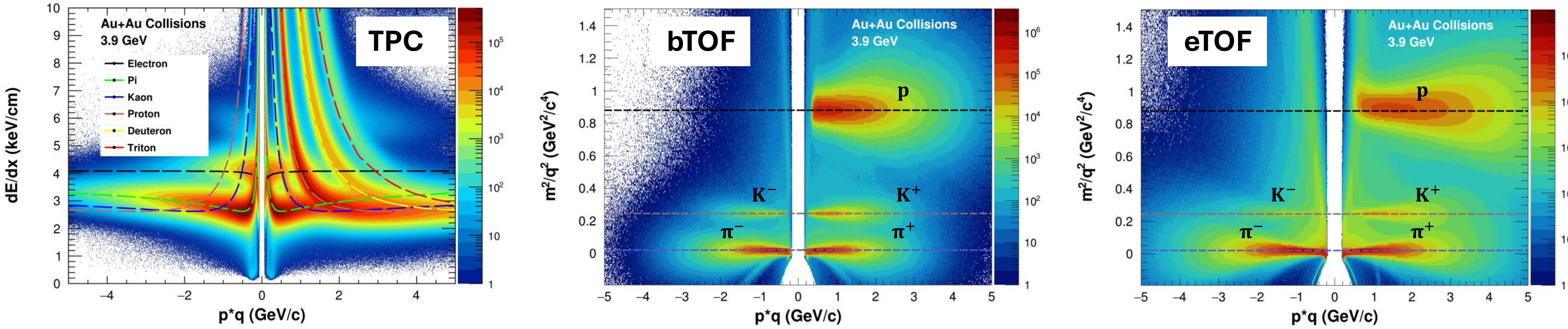






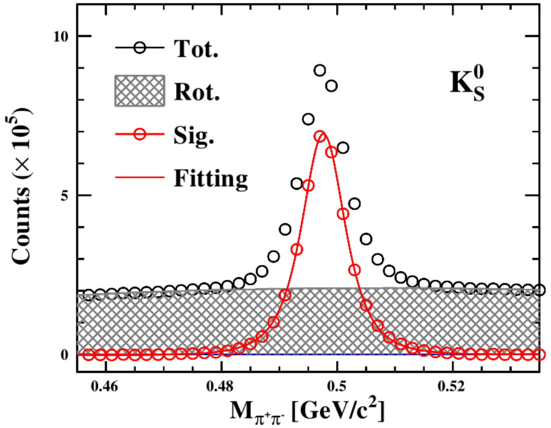
- **Fixed target mode (Au + Au collisions at $\sqrt{s_{NN}}$ = 3.0 – 13.7 GeV)**
  - **Extends energy reach down to 3 GeV**
  - **10× statistics compared to BES-I**
  - **This analysis: $\sqrt{s_{NN}}$ = 3.2 – 4.5 GeV**

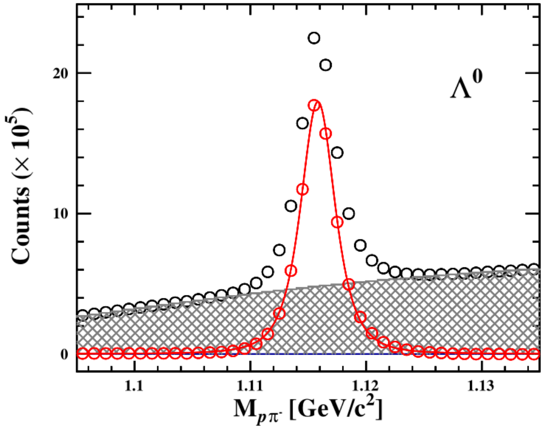
Particle Identification

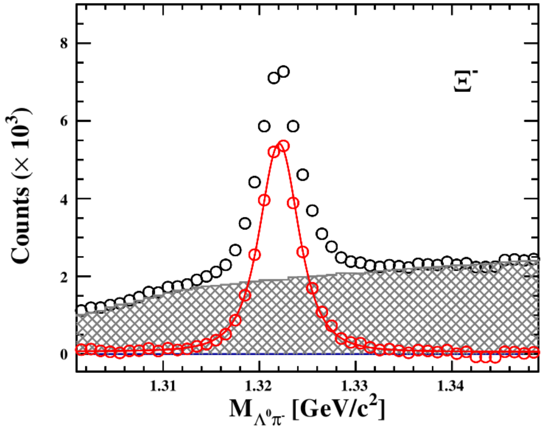


- **TPC (dE/dx) and TOF (β) for charged pion and proton identification**
  - **TOF m^2 formula: $m^2 = p^2\left(\frac{1}{\beta^2} - 1\right)$**
- **K_S^0, Λ^0 and Ξ^- hadrons are reconstructed by invariant mass method by identifying decay daughters**

Strange Hadron Reconstruction







Decay Channel:

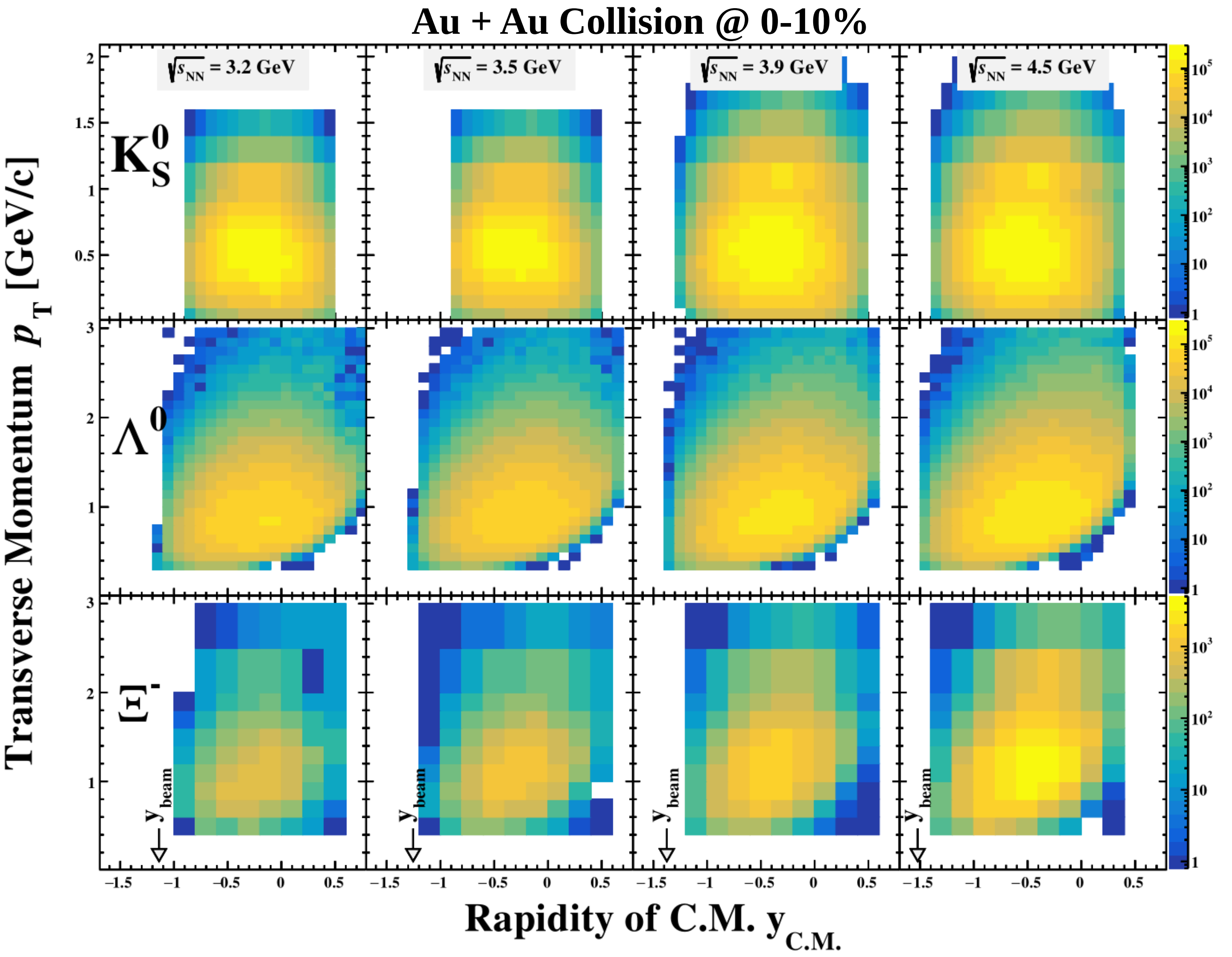
$K_S^0 \rightarrow \pi^+ + \pi^-$

$\Lambda^0 \rightarrow p + \pi^-$

$\Xi^- \rightarrow \Lambda^0 + \pi^-$

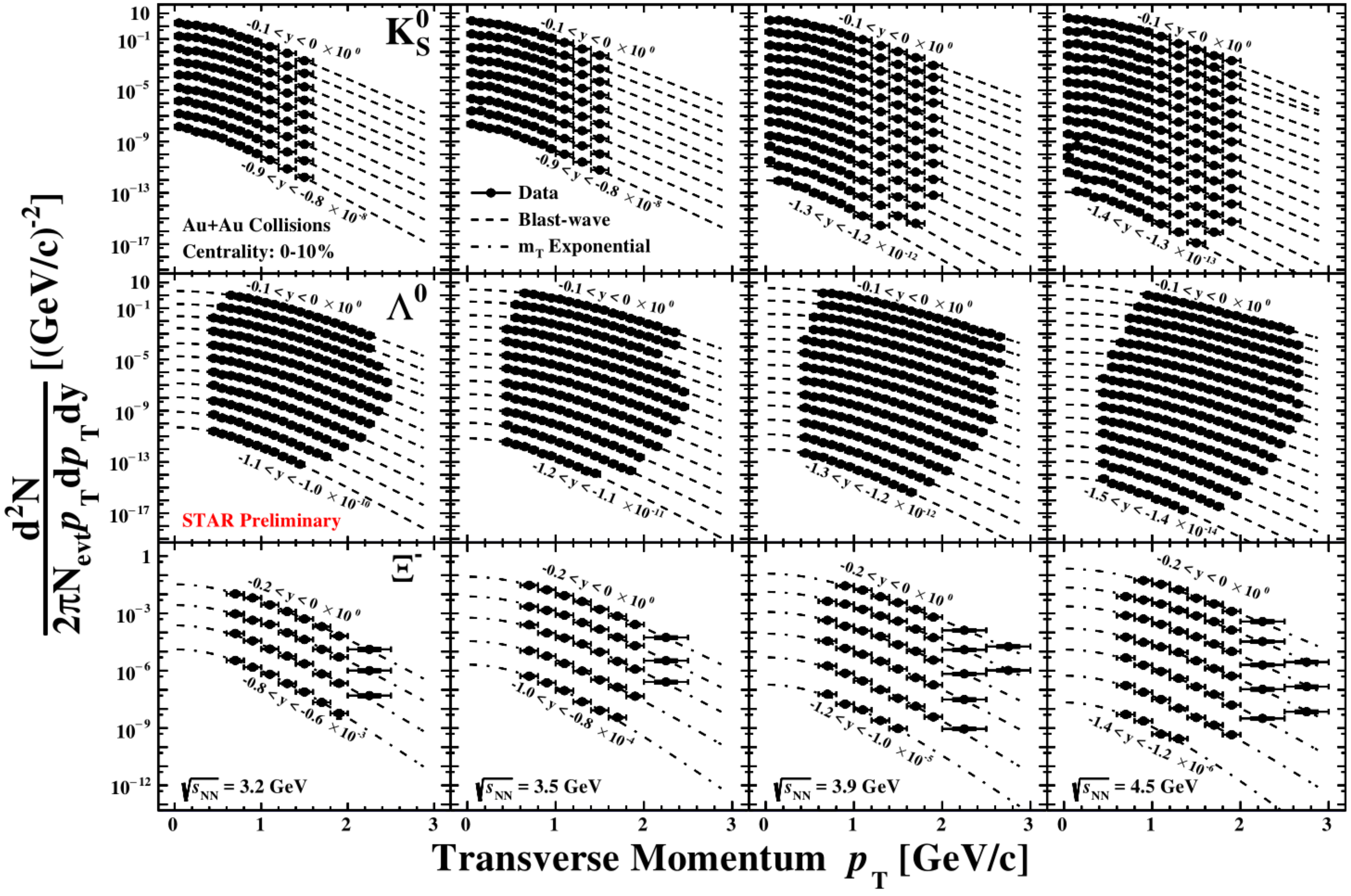
Fitting Function:

Student-t + $2^{nd}_{K_S^0,\Lambda^0}$ / $1^{st}_{\Xi^-}$ Polynomial



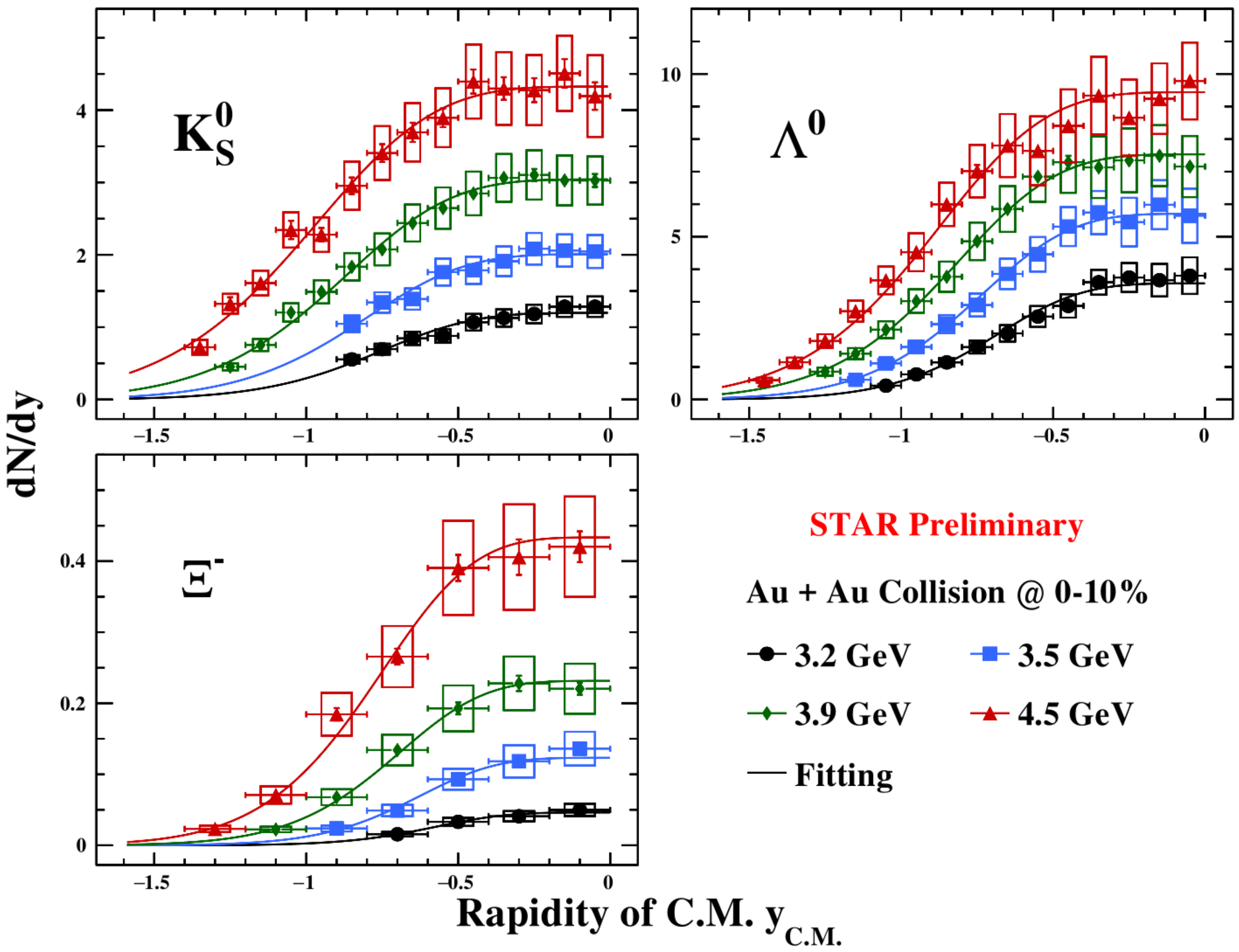
- **KFParticle package is used for the strange hadron reconstruction to improve the signal significance**
- **Combinatorial backgrounds are reconstructed by the rotation method**
- **Good coverage from beam-rapidity to mid-rapidity for K_s^0, Λ^0 and Ξ^-**

Strange Hadron p_T Spectra



- Raw p_T spectrum corrected by acceptance ⊗ reconstruction efficiency estimated via embedding data
- Feed-down effect corrections for Λ^0
- Function fit for p_T spectra exptrapolation
  - Blast-wave fit for K_S^0 and Λ^0
  - m_T exponential fit for Ξ^-
- Diffierent function fit (Blast-wave, m_T exponential and $p_T{}^{3/2}$ exponential) as a systematic error source in dN/dy calculation

Strange Hadron Rapidity density distribution

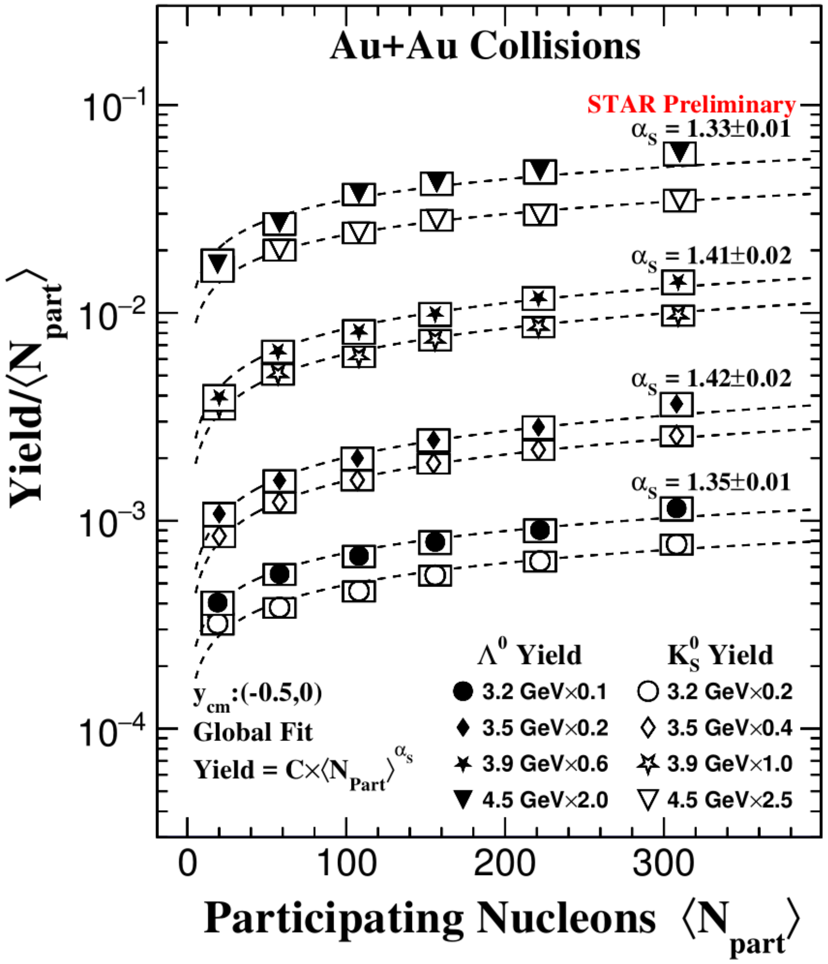


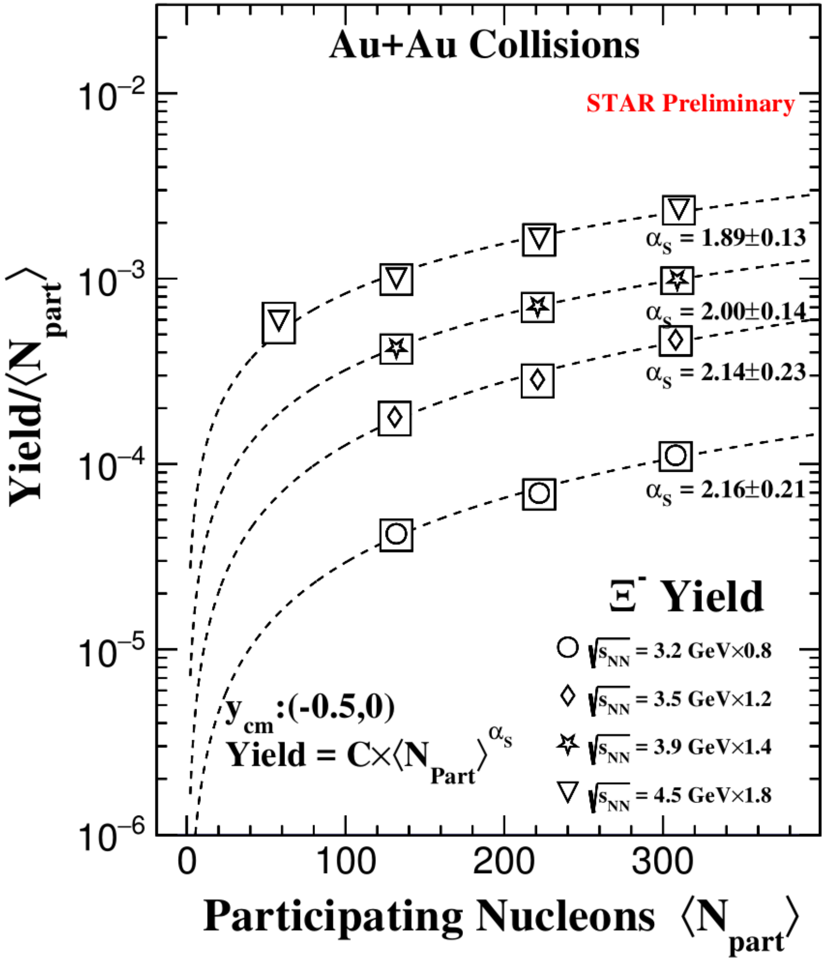
- **Comprehensive strangeness measurements for K_S^0, Λ^0 and Ξ^- from 3.2 to 4.5 GeV**
  - ➢ **dN/dy is calculated by integral of p_T spectra**
  - ➢ **Fitting function for dN/dy**

$$\frac{dN}{dy} \sim \frac{1}{Cosh\left(\frac{y^2}{2\sigma^2}\right)} = \frac{2}{e^{\frac{y^2}{2\sigma^2}} + e^{-\frac{y^2}{2\sigma^2}}}$$

- ☐ **Flat at mid rapidity**
- ☐ **Gaussian-like at backward rapidity**

Centrality Dependence of Mid–rapidity Yield



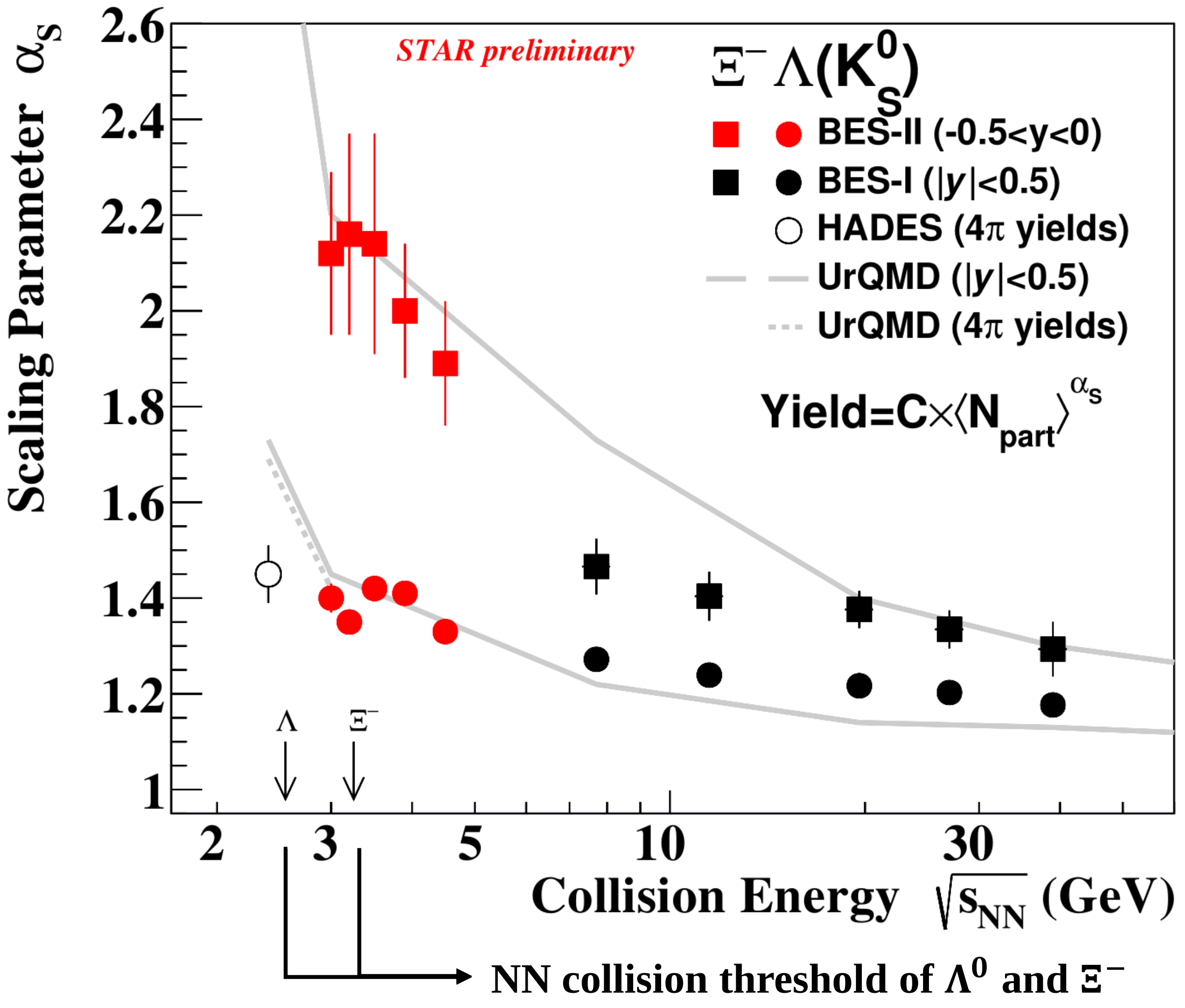


- **Scaling formula:**

$$\text{Yield} = c \times \langle N_{part} \rangle^{\alpha_S}$$

- **Single strange hadrons K^0_S and Λ^0 follow common scaling trend, but double strange hadron Ξ^- deviate from the common scaling trend**
  - ➢ **Associated production mode**
    - □ $NN \to N\Lambda K$
    - □ $NN \to N\Xi KK$

Energy dependence of Scaling Parameter α_S



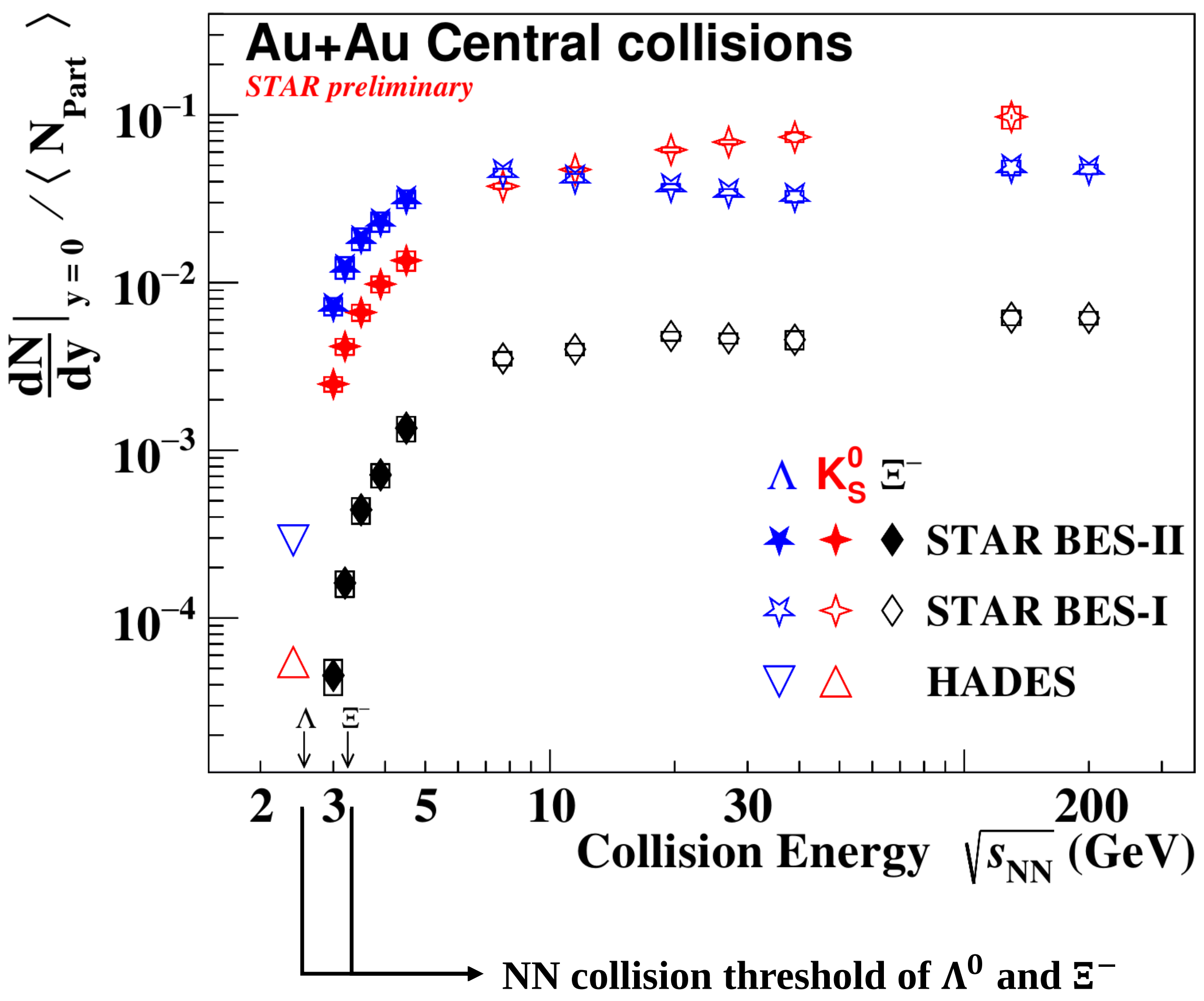
- Rapid decrease of scaling parameter α_S for Ξ^- from 4.5 to 7.7 GeV, and saturate at high energy
  - ➢ The mechanism of strange hadron production may change
  - ➢ Strange hadron production predominantly from hadronic interactions at $\sqrt{s_{NN}}$ < 4.5 GeV

- 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)

Strangeness Excitation Function



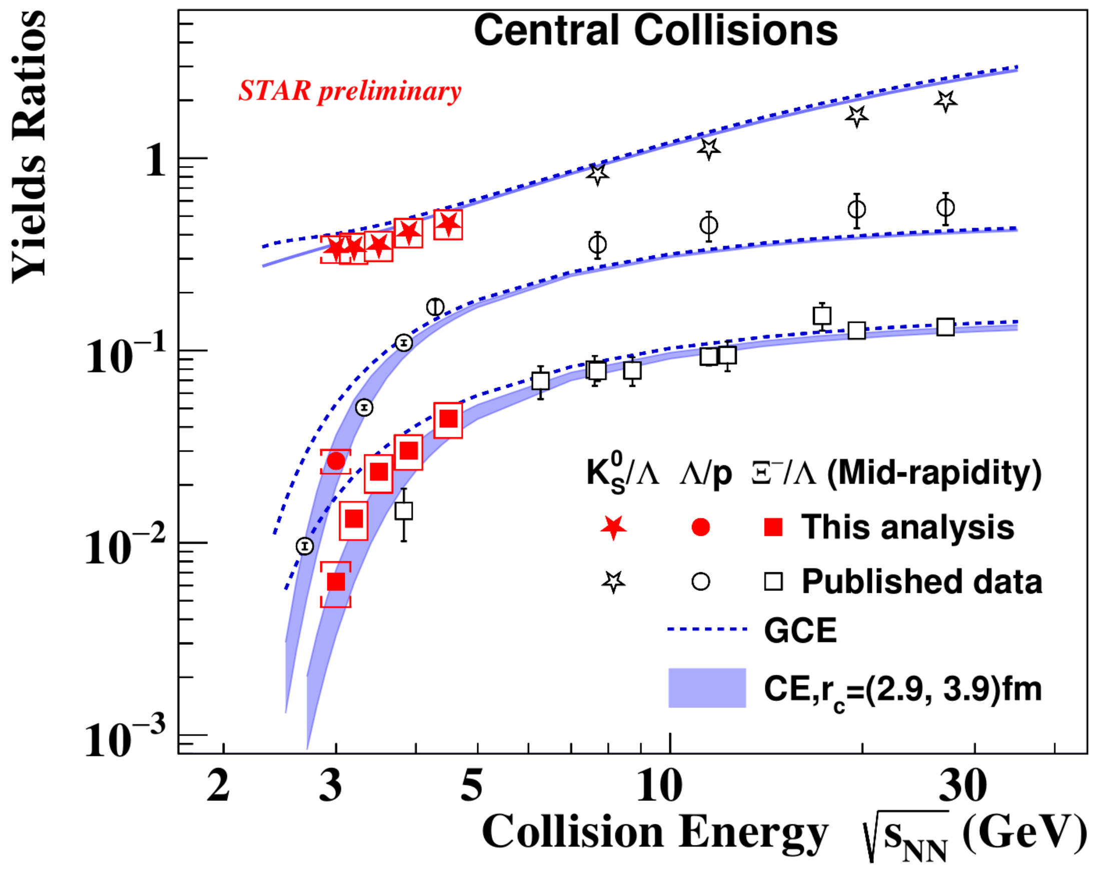
- **Rich structure in strangeness excitation functions**
  - **Production mechanisms is different at low and high energies (high and low baryon density)**
    - ☐ **Partonic interaction (pair production)**

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

      BB → BYK or BB → BΞKK

      B: N, p, Δ, etc.   Y: Λ, Σ, etc.   K: K^+, K^0
  - **Baryon-dominated to meson-dominated transitions**
    - ☐ K^0_s **and** Λ^0 **mid-rapidity yield cross at ~ 8 GeV**
  - **First measurement of** Ξ^- **near- / sub-threshold energies in Au+Au collision**

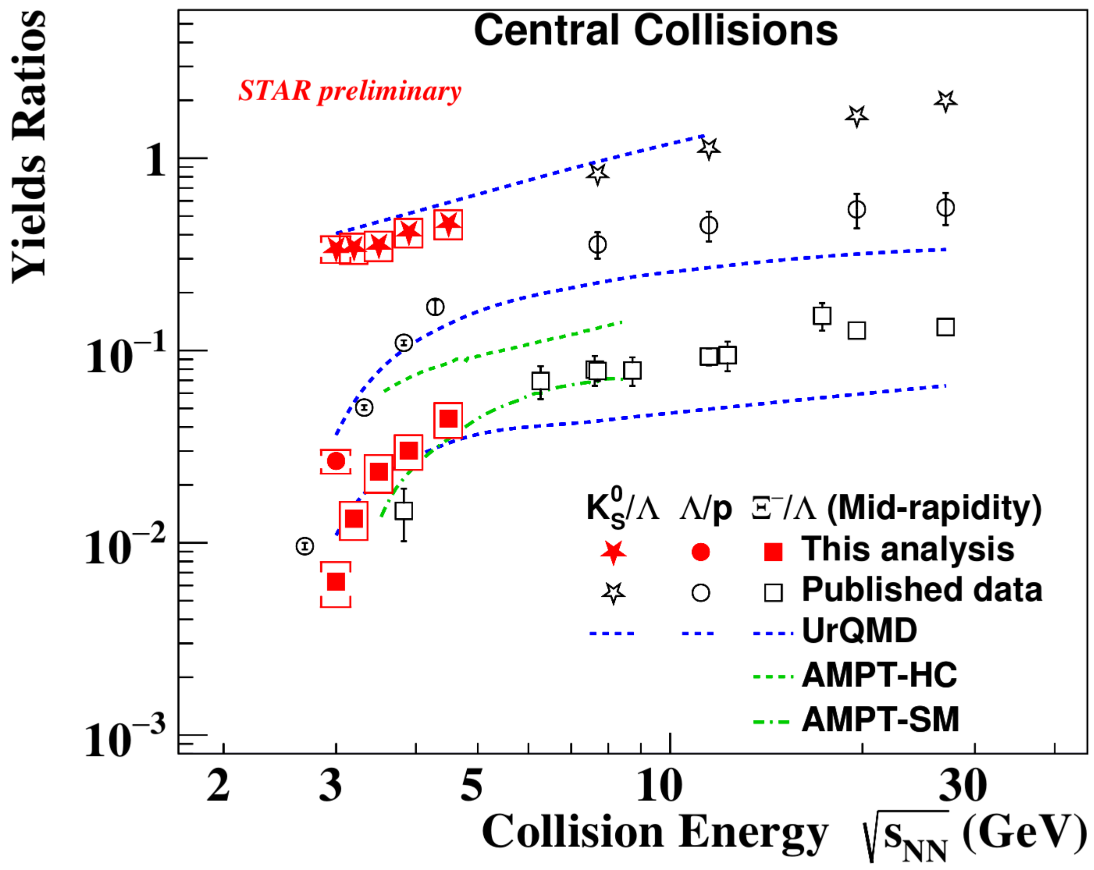
Energy Dependence of Mid-rapidity Yield Ratio



- **Comparison with thermal model**
  - **Grand Canonical Ensemble (GCE) fails at low energies**
  - **Canonical Ensemble (CE) wtih strangeness correlation length r_c = 2.9 – 3.9 fm simultaneously describes K^0_s/Λ, Λ/p and Ξ^-/Λ in the whole energies**
  - **Change of medium properties at the high baryon density region**

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

Energy Dependence of Mid-rapidity Yield Ratio



- Comparison with thermal model
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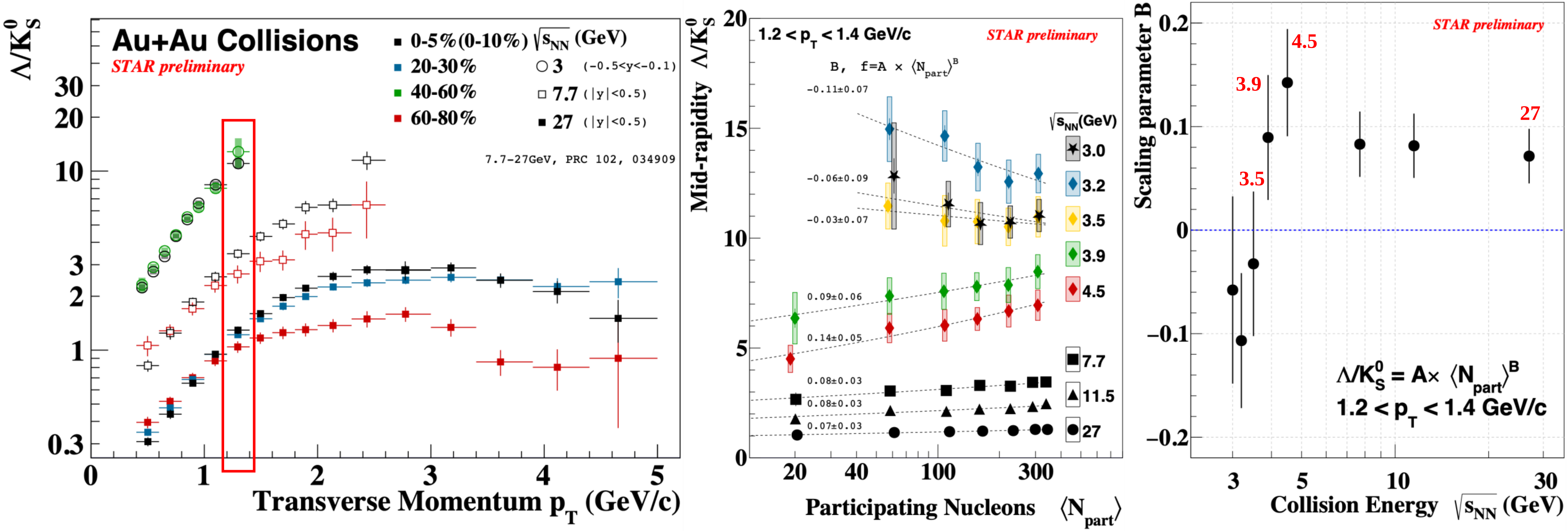
  - Canonical Ensemble (CE) wtih strangeness correlation length r_c = 2.9 – 3.9 fm simultaneously describes K^0_s/Λ, Λ/p and Ξ^-/Λ in the whole energies
  - Change of medium properties at the high baryon density region

- **Comparison with transport model**
  - **UrQMD and AMPT models cannot describe all data**
  - **Strange baryons, especially for the double strangeness Ξ^-, are sensitive probes to the medium properties**

STAR Collaboration. Phys. Rev. C 102, 034909 (2020)
S.A. Bass, et.al. Prog. Part. Nucl. Phys. 41 (1998)
G.C. Yong. Phys. Lett .B 843, 138051 (2023)

Baryon to Meson Yield Ratio



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

Summary and Outlook

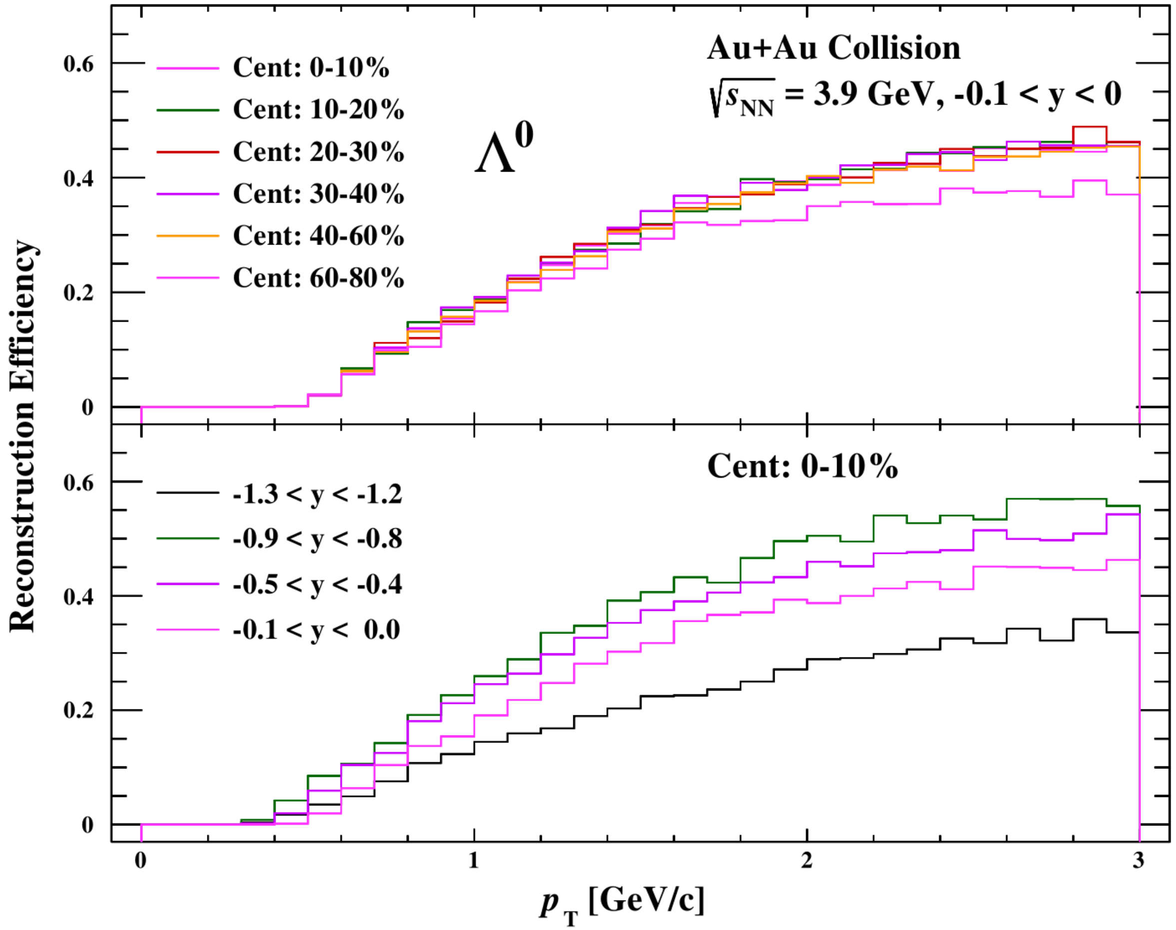
- **Summary**
  - **Precision measurements of strange hadrons (K^0_S, Λ^0, Ξ^-) production in Au+Au collision at $\sqrt{s_{NN}}$ = 3.2 – 4.5 GeV**
  - **Steeper centrality dependence of Ξ^- mid-rapidity yields (α_S) at $\sqrt{s_{NN}}$ = 3.0 – 4.5 GeV than that at higher energies**
  - **Canonical suppression of strangeness is observed below $\sqrt{s_{NN}}$ = 3.5 GeV**
  - **Hadron dominated medium created at $\sqrt{s_{NN}}$ = 3 GeV**
  - **Enhancement of Λ/K^0_S is observed above $\sqrt{s_{NN}}$ = 3.9 GeV**
- **Outlook**
  - **More precise and systematic measurements of strange hadron production from BES-II (K, ϕ, Ω^- etc.)**
  - **Further understanding of nuclear matter at high baryon density by data and model**

Thanks for your attention!

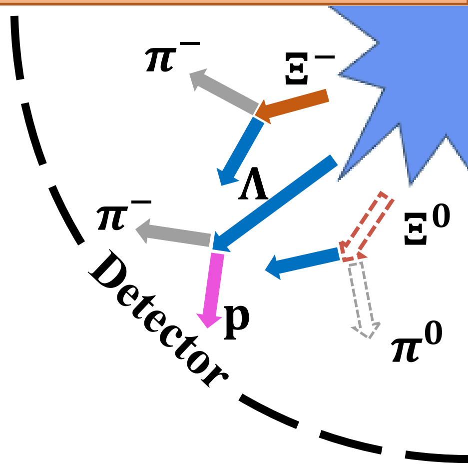
Back up

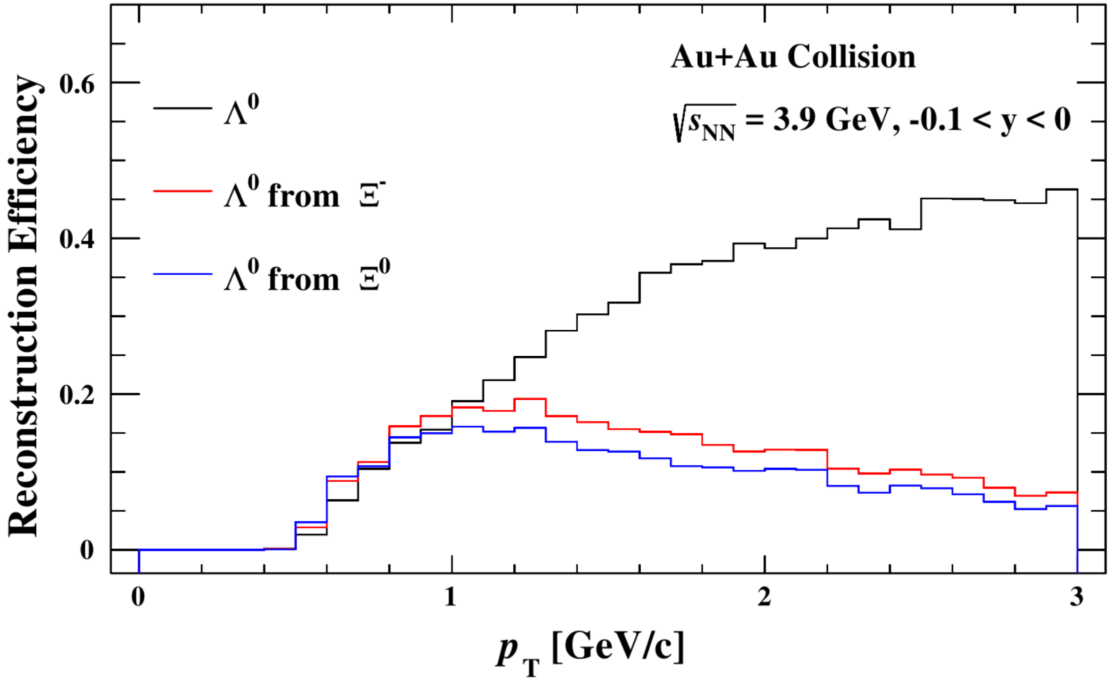
Efficiency Correction

- **Acceptance ⊗ Reconstruction Efficiency**
  - ➢ Using the embedding data to calculate decay particle reconstruction efficiency



- **Feed down Effect**
  - ➢ Week decay source
    - ☐ $\Xi^- \rightarrow \Lambda^0 + \pi^-$
    - ☐ $\Xi^0 \rightarrow \Lambda^0 + \pi^0$
    - ☐ $\Omega^- \rightarrow \Lambda^0 + K^-$ (negligible)





Baryon to Meson Yield Ratio