Recent STAR results on strangeness/hypernuclei production

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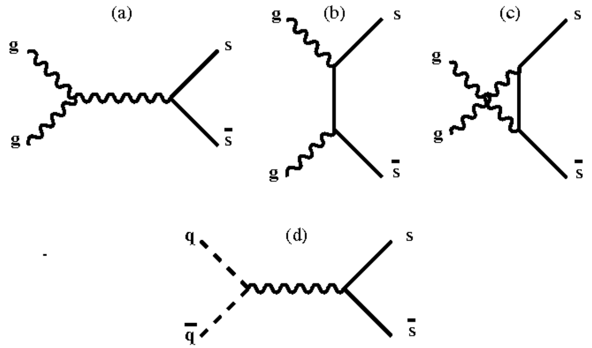
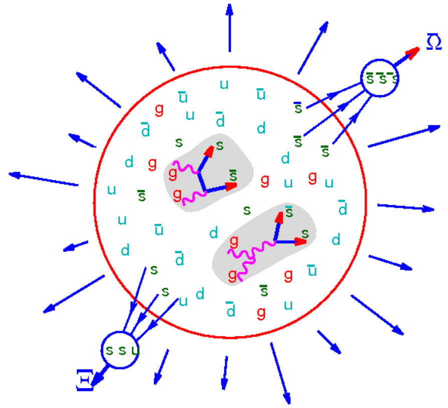
10/16/2024

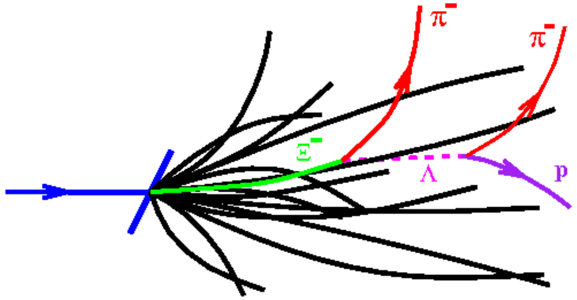
XIV MPD Collaboration Meeting
Dubna, 2024.10.14-16

Why strangeness?

Rafelski & Müller, 1982







- Strange quarks
  - Not exist in colliding nuclei
  - Current mass ~100 MeV < T_c
  - Easily pair-produced in de-confined QGP medium

⟶ Strangeness enhancement !

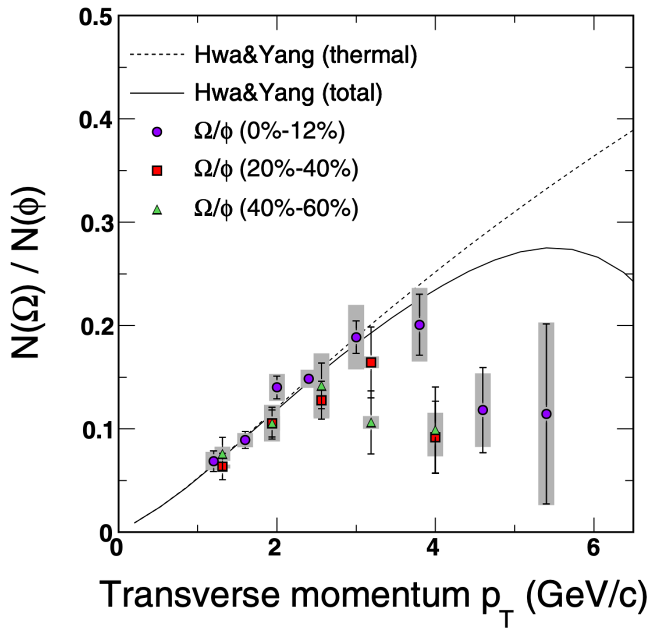
- Hadrons with (multiple) strange quarks
  - Small hadronic cross section
  - Sensitive to the early stage dynamics of the medium
  - Can be easily reconstructed and identified in experiment, up to high p_T !

⟶ Systematic study of medium properties!

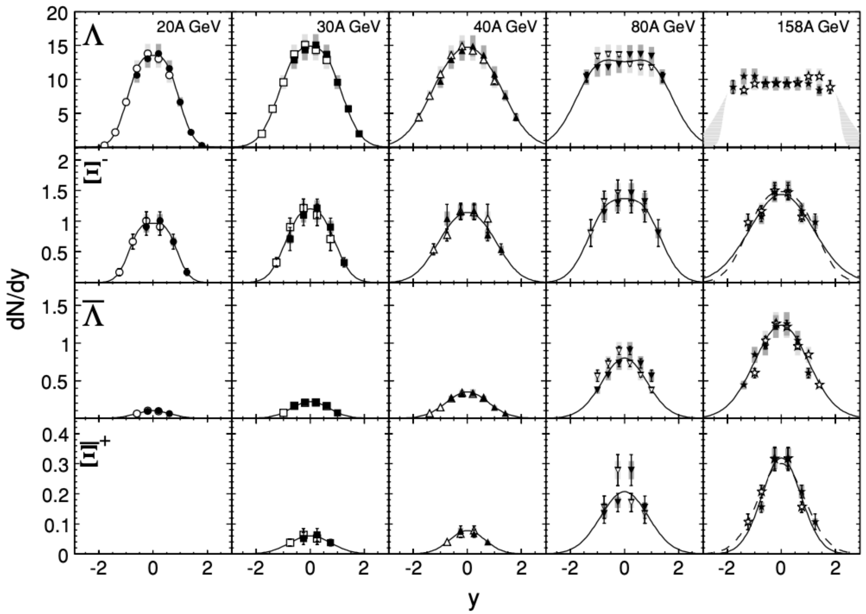
Motivation

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

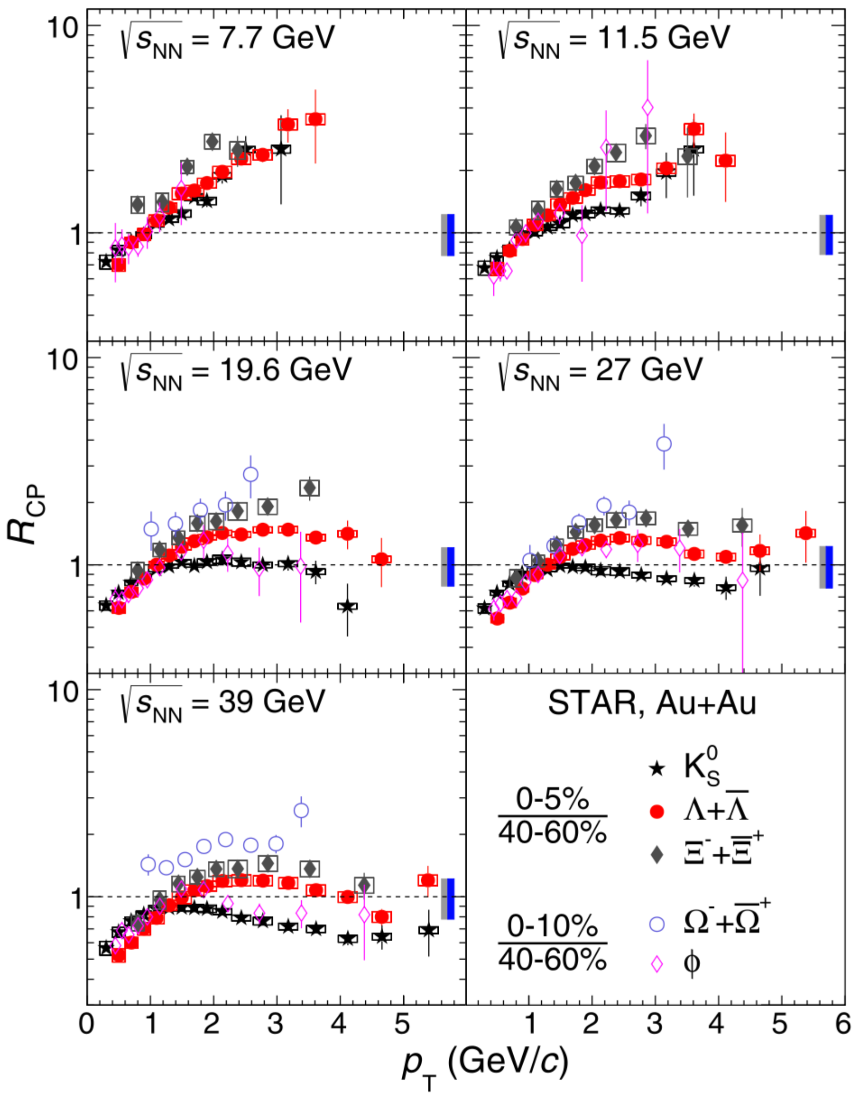
- Nuclear modification factor of strange hadrons to evaluate the partonic energy loss in deconfined medium.
- Strange baryon-to-meson ratio can be utilized to understand hadronization mechanism.
- Rapidity density of (anti-)strange baryons may give insight on the baryon stopping mechanism.



STAR, PRL 99, 112301 (2007)



NA49, PRC 78, 034918 (2008)



STAR, PRC 102, 034909 (2020)

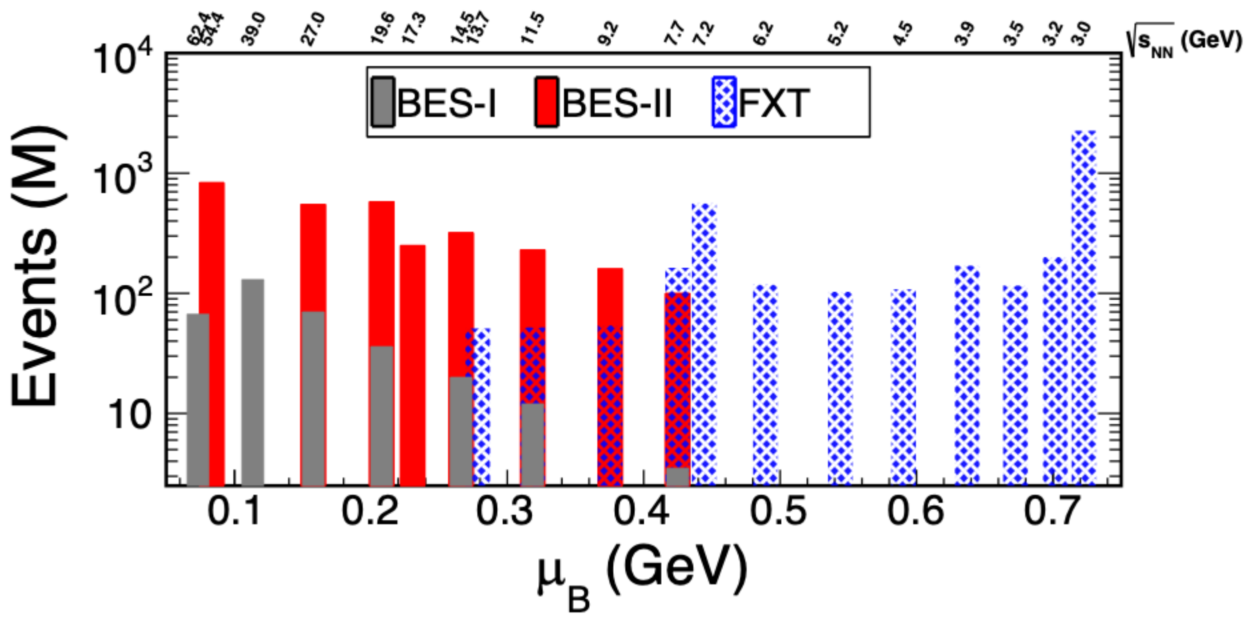
Motivation

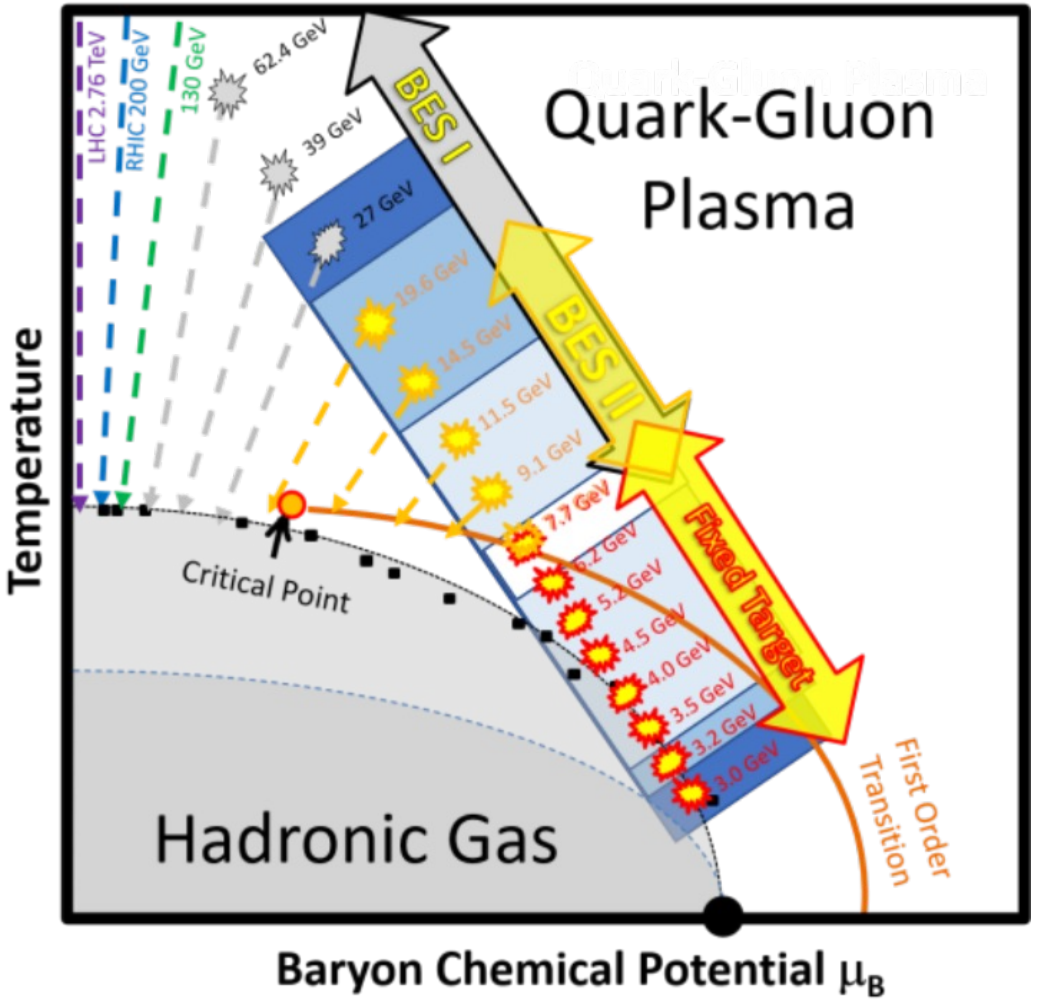
Yi Fang, Xiongxiong Xu, Weiguang Yuan, QM23/SQM24/CPS24
Hongcan Li, Xiujun Li, SQM24; Yingjie Zhou, iHIC24

Beam Energy Scan (BES) program:

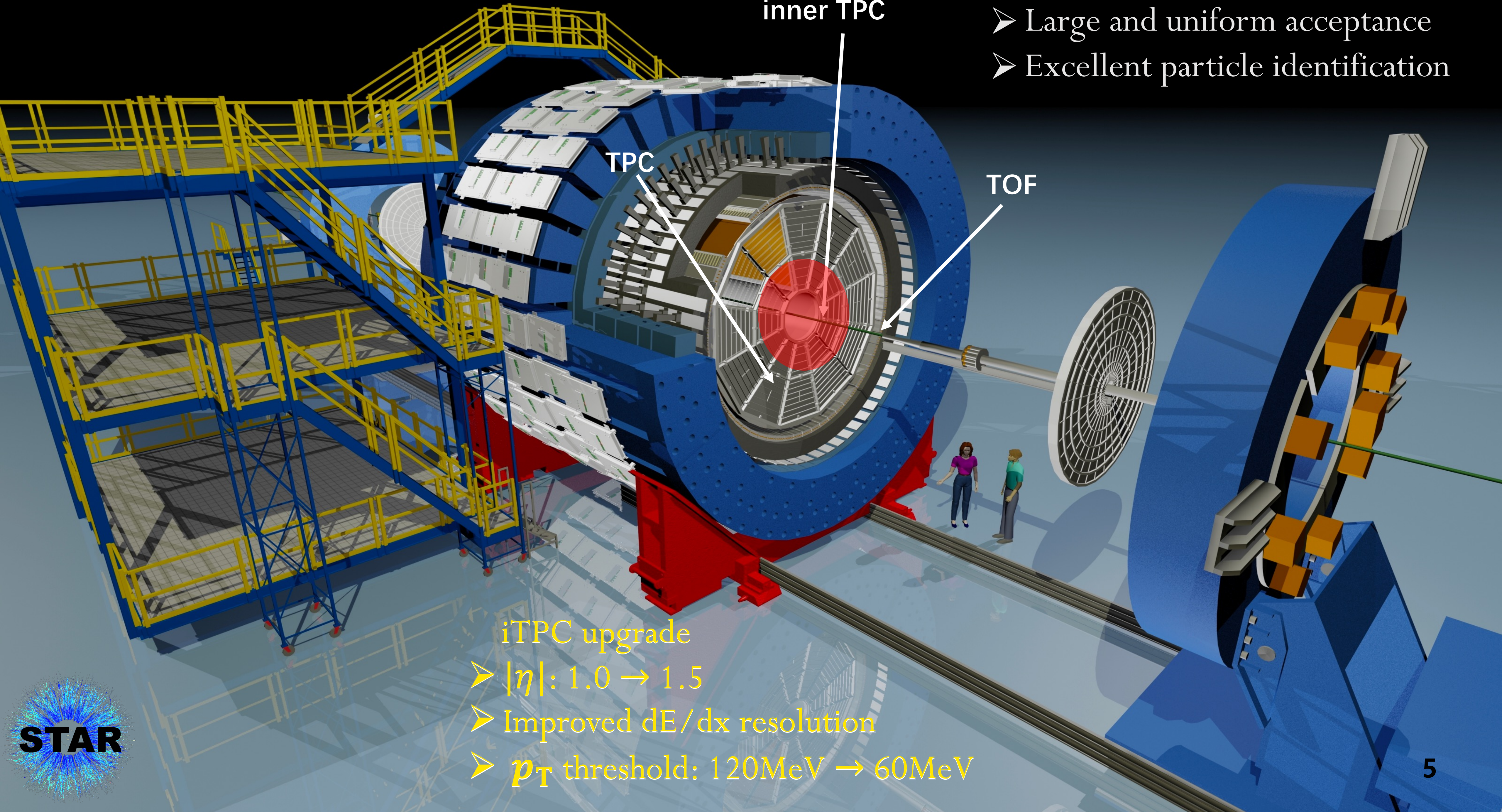
- ➢ Search for the onset of deconfinement
- ➢ Search for the first-order phase transition
- ➢ Search for the critical point

BES-II ~10–20 × BES-I





- Large and uniform acceptance
- Excellent particle identification

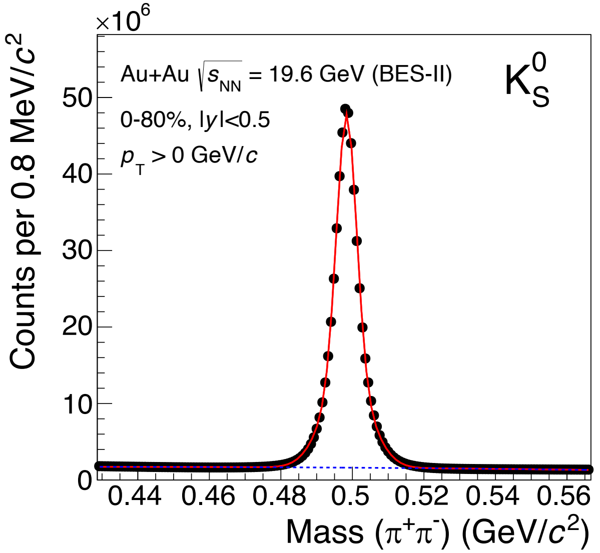


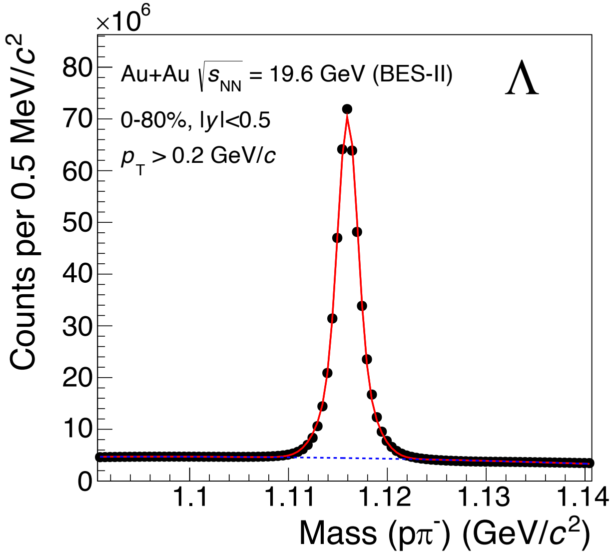
iTPC upgrade

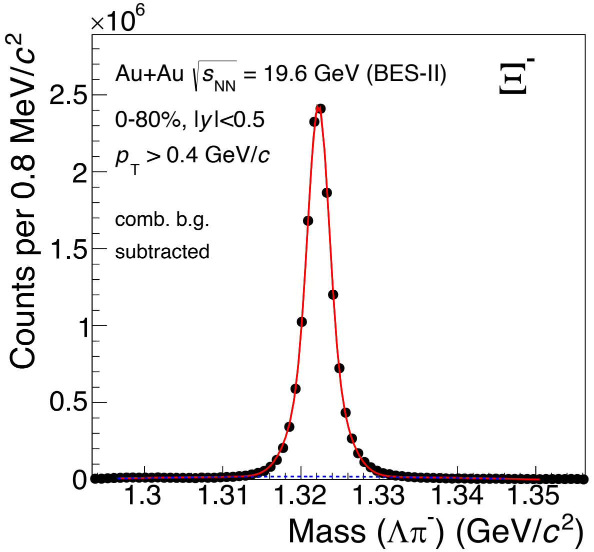
- $|\eta|$: 1.0 → 1.5
- Improved dE/dx resolution
- p_T threshold: 120MeV → 60MeV

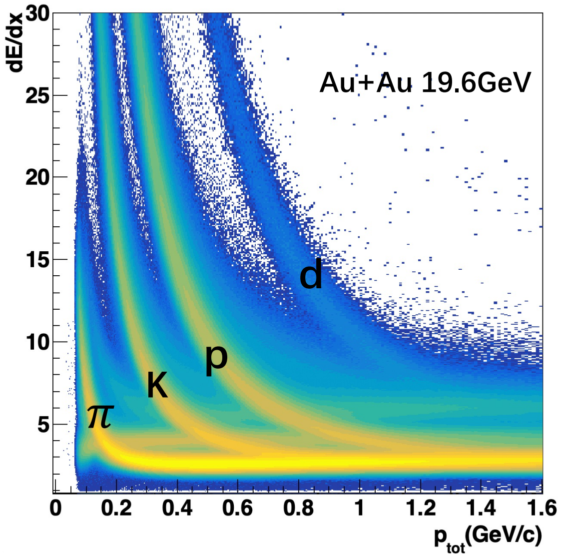
STAR

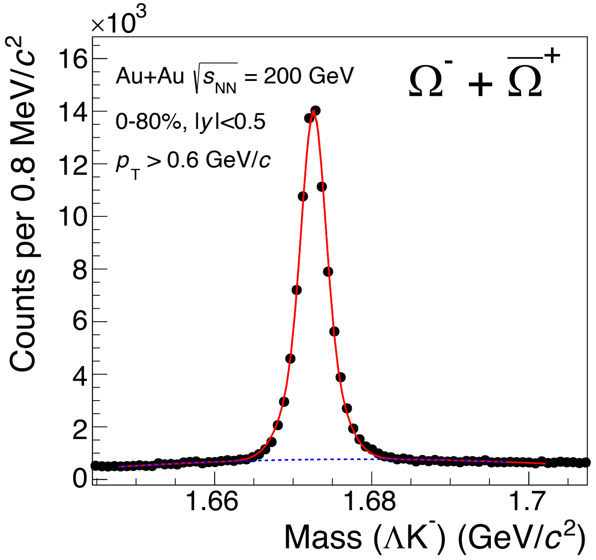
Particle identification and reconstruction

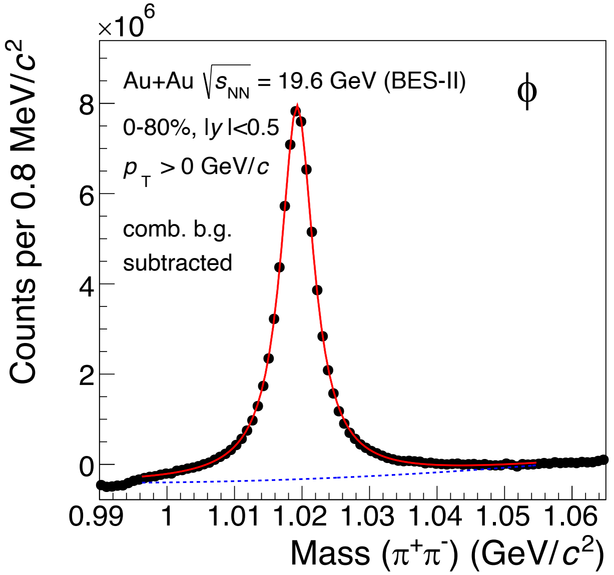








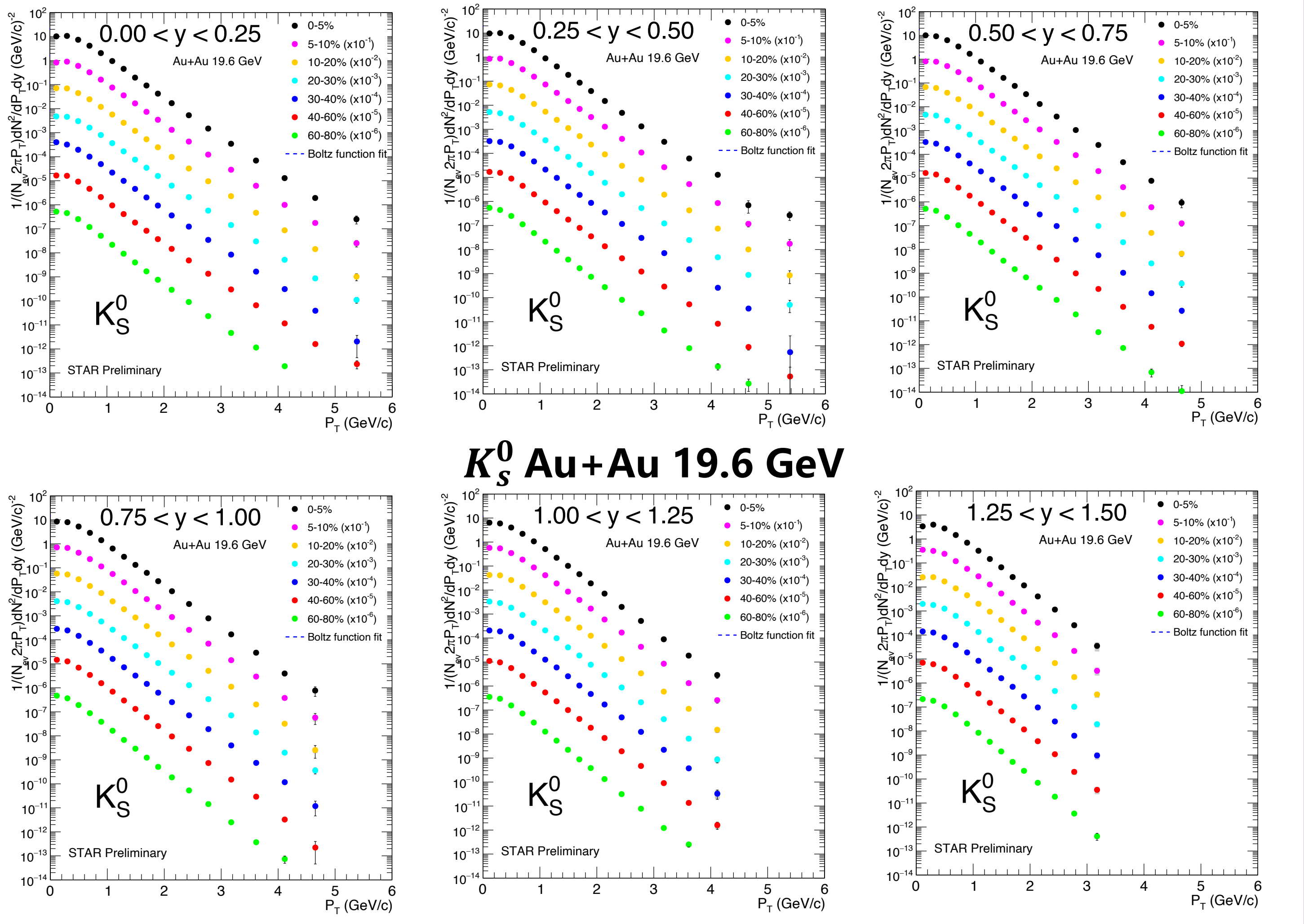




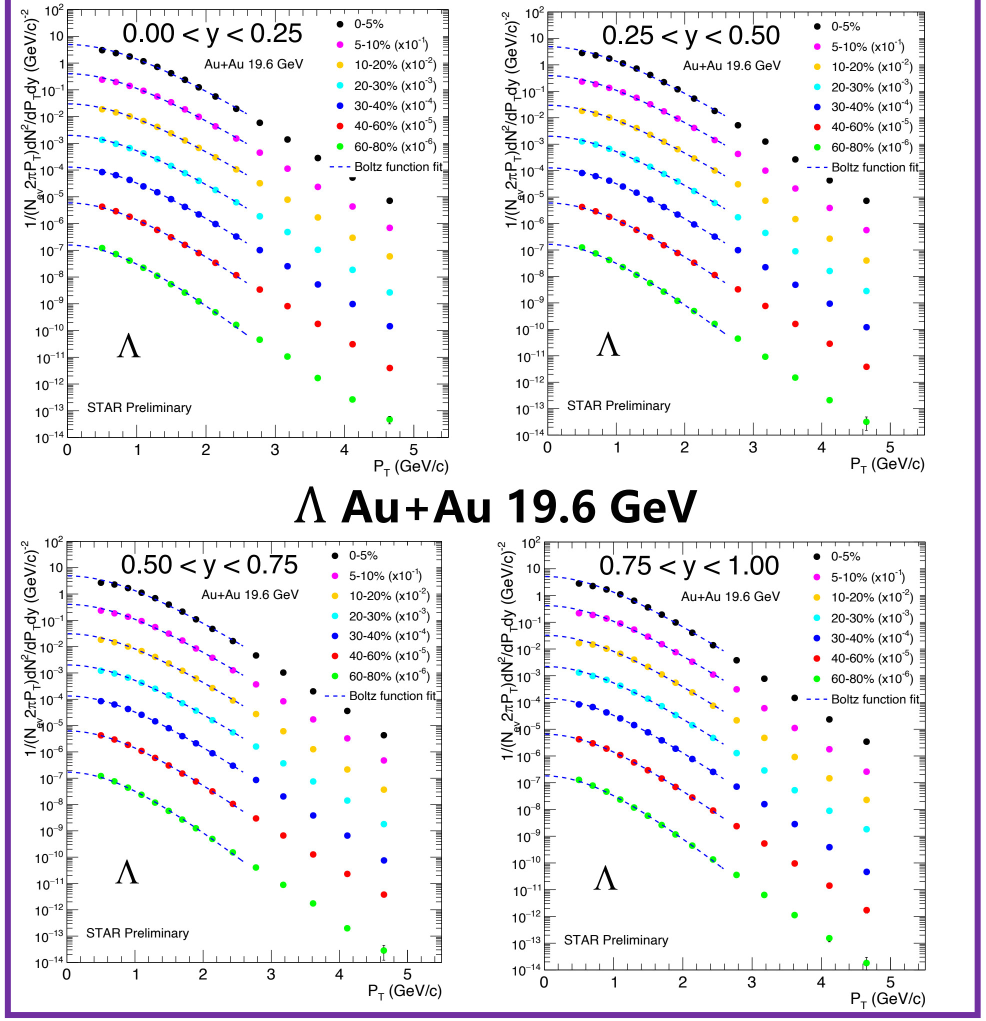
- Particle identification with dE/dx.
- π, K, p are used to reconstruct the secondary vertex of strange particles.
- TMVA optimization to improve Ω signal significance
- Large number of strange particles allow multi-differential measurements.

$$\mathrm{K_S^0} \to \pi^+ + \pi^- (\mathcal{B} = 69.2\%)$$
$$\Lambda(\bar{\Lambda}) \to p(\bar{p}) + \pi^-(\pi^+)(\mathcal{B} = 63.9\%)$$
$$\Xi^-\left(\bar{\Xi}^+\right) \to \Lambda(\bar{\Lambda}) + \pi^-(\pi^+)(\mathcal{B} = 99.9\%)$$
$$\Omega^-\left(\bar{\Omega}^+\right) \to \Lambda(\bar{\Lambda}) + K^-(K^+)(\mathcal{B} = 67.8\%)$$
$$\phi \to \mathrm{K}^+ + \mathrm{K}^- (\mathcal{B} = 49.1\%)$$

p_T spectra of K_s^0 and Λ at 19.6 GeV



K_s^0 Au+Au 19.6 GeV



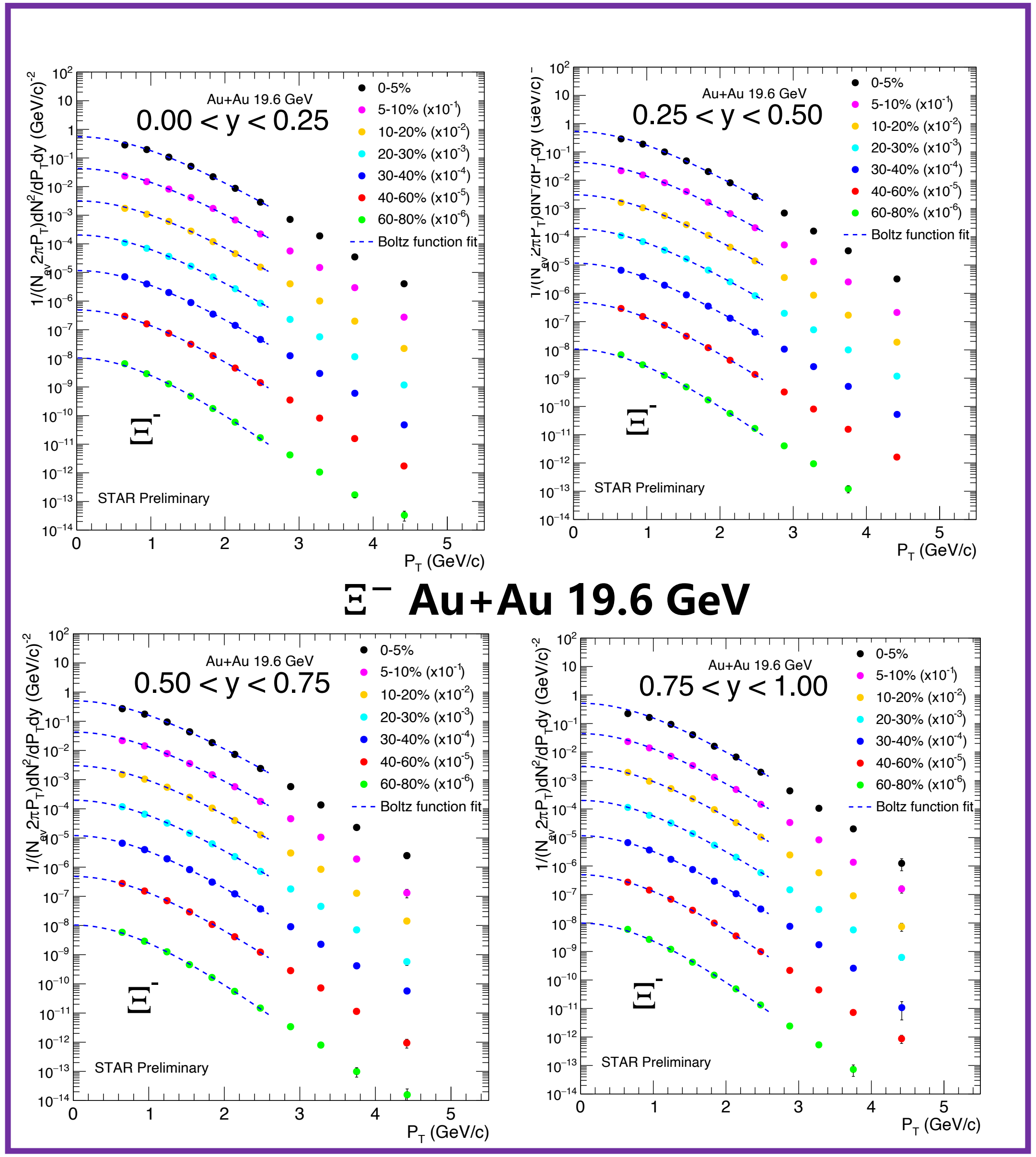
Λ Au+Au 19.6 GeV

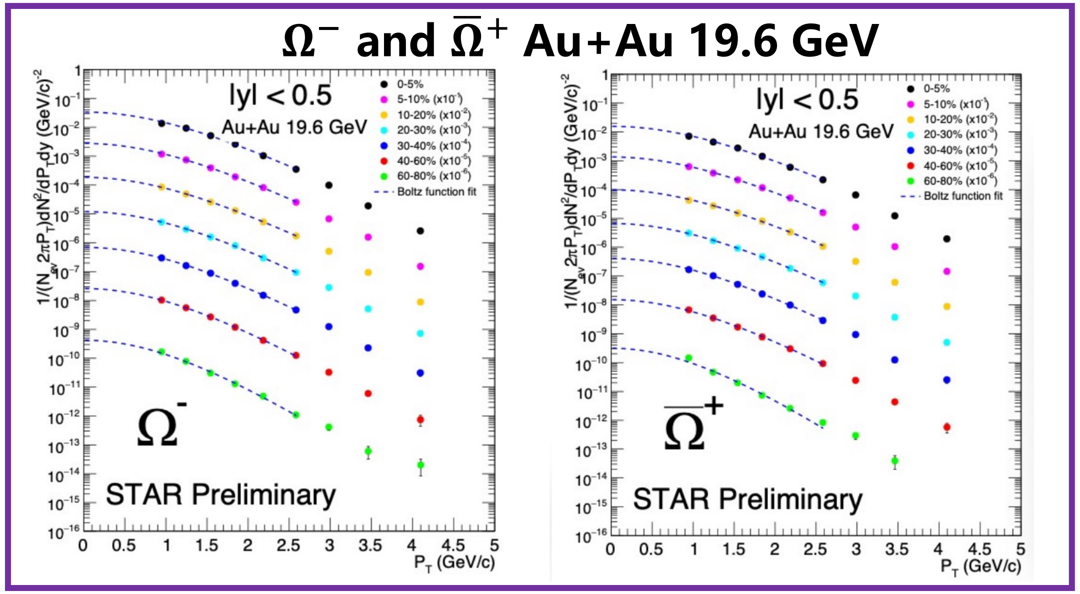
- ➢ K_s^0: measured down to p_T=0, no need for extrapolation to obtain dN/dy
- ➢ Rapidity: $|y| < 1.5$

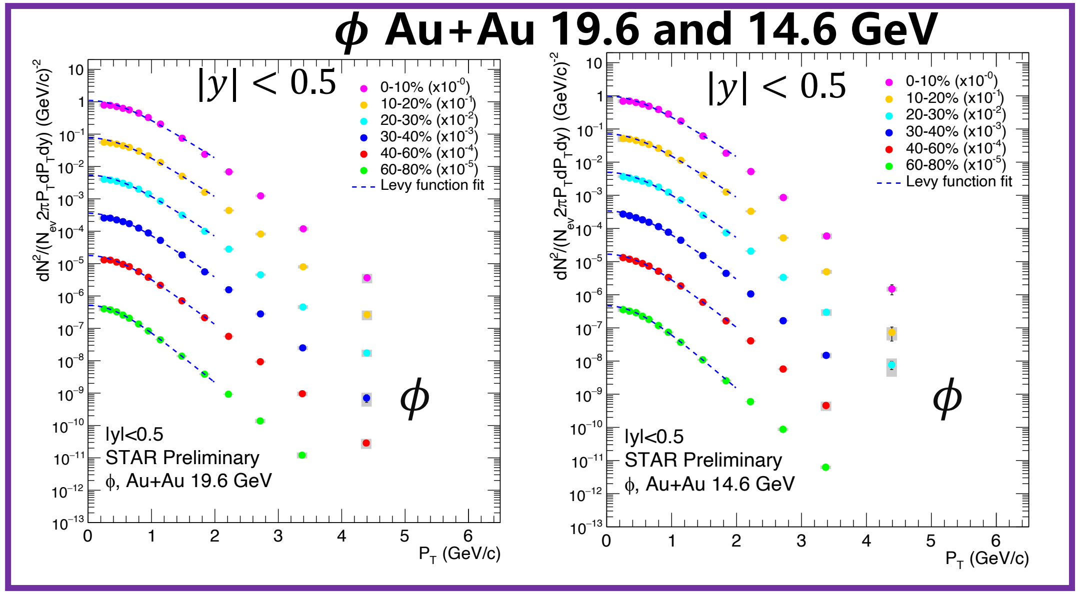
- ➢ Low p_T extrapolation: Boltzmann function
- ➢ Corrected for Ξ^- and Ξ^0 feed-down

Rapidity: $|y| < 1$

p_T spectra of Ξ^-, ϕ and $\Omega^-(\bar{\Omega}^+)$ at 19.6 GeV







- Ξ^- Low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 1.0$

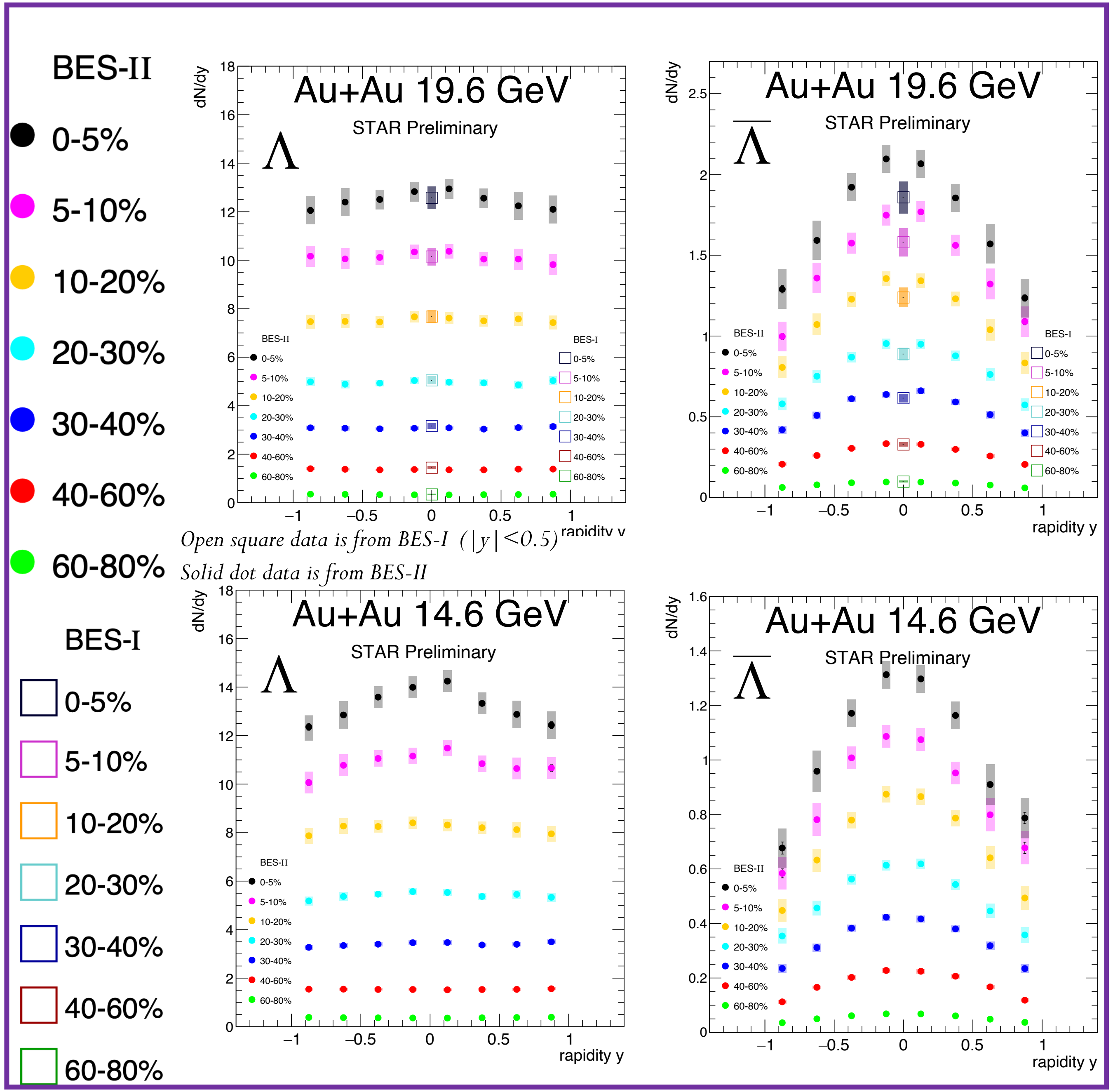
- Ω low p_T extrapolation: Boltzmann function
- Rapidity: $|y|<0.5$

- ϕ low p_T extrapolation: Levy function
- Rapidity: $|y|<0.5$

Rapidity spectra of $\Lambda(\bar{\Lambda})$ at 19.6 and 14.6 GeV

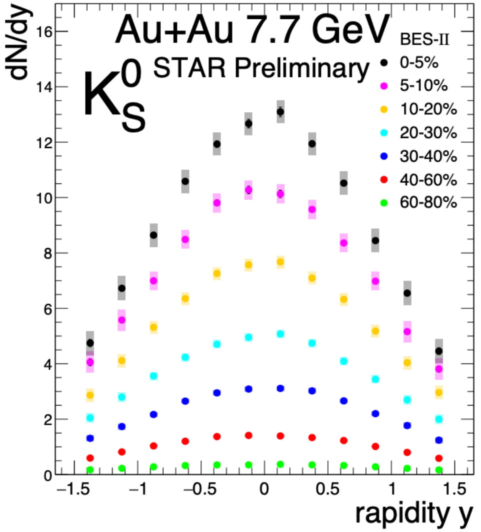
- ➢ Rapidity spectra of anti-baryons($\bar{\Lambda}$) are Gaussian-like distributions.
- ➢ Rapidity distribution of baryons(Λ) are wider than that of anti-baryons ($\bar{\Lambda}$).
  - ✓ Extra contributions from stopped baryons
- ➢ Similar trends observed by NA49.

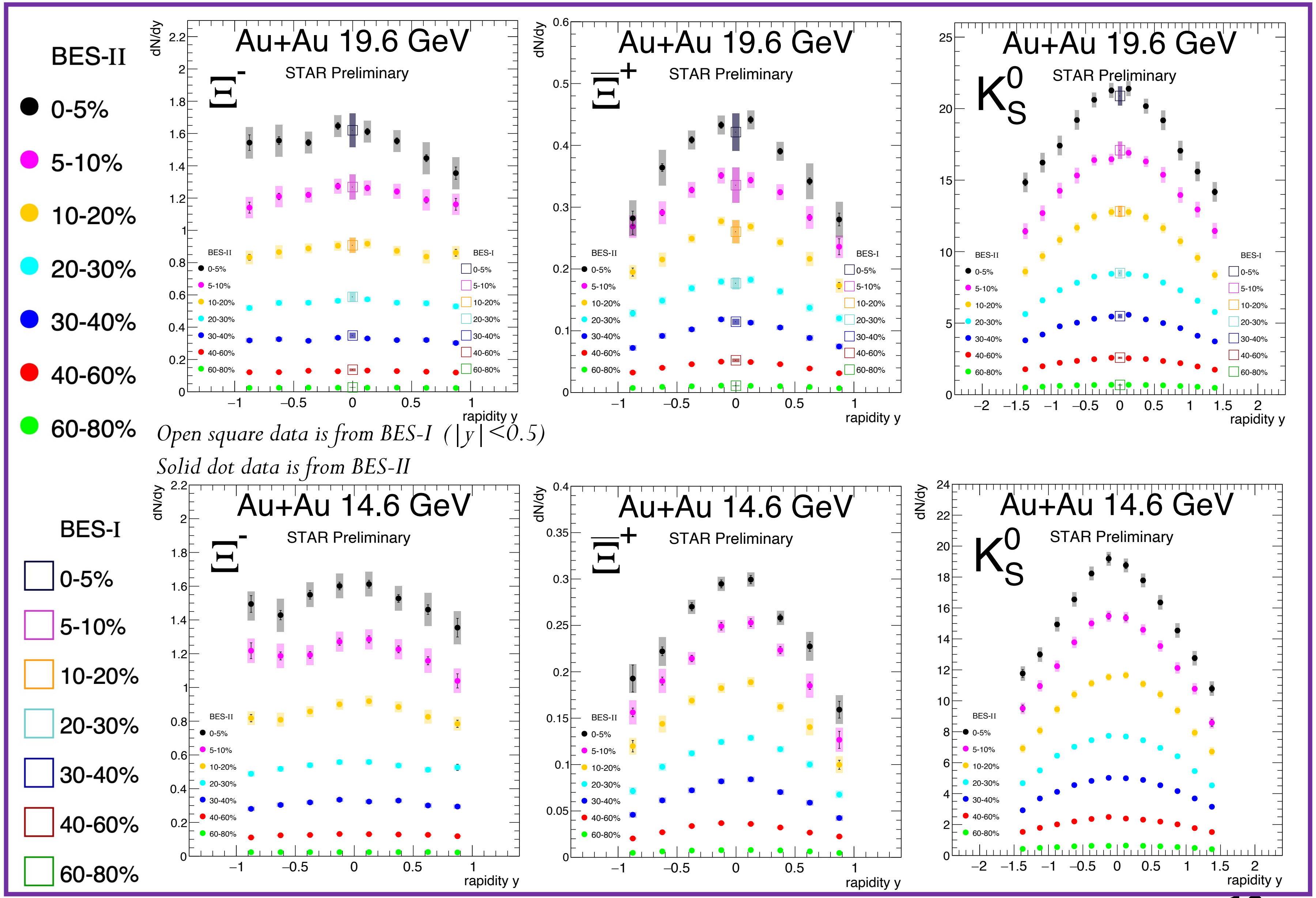
NA49, PRC 78, 034918 (2008)



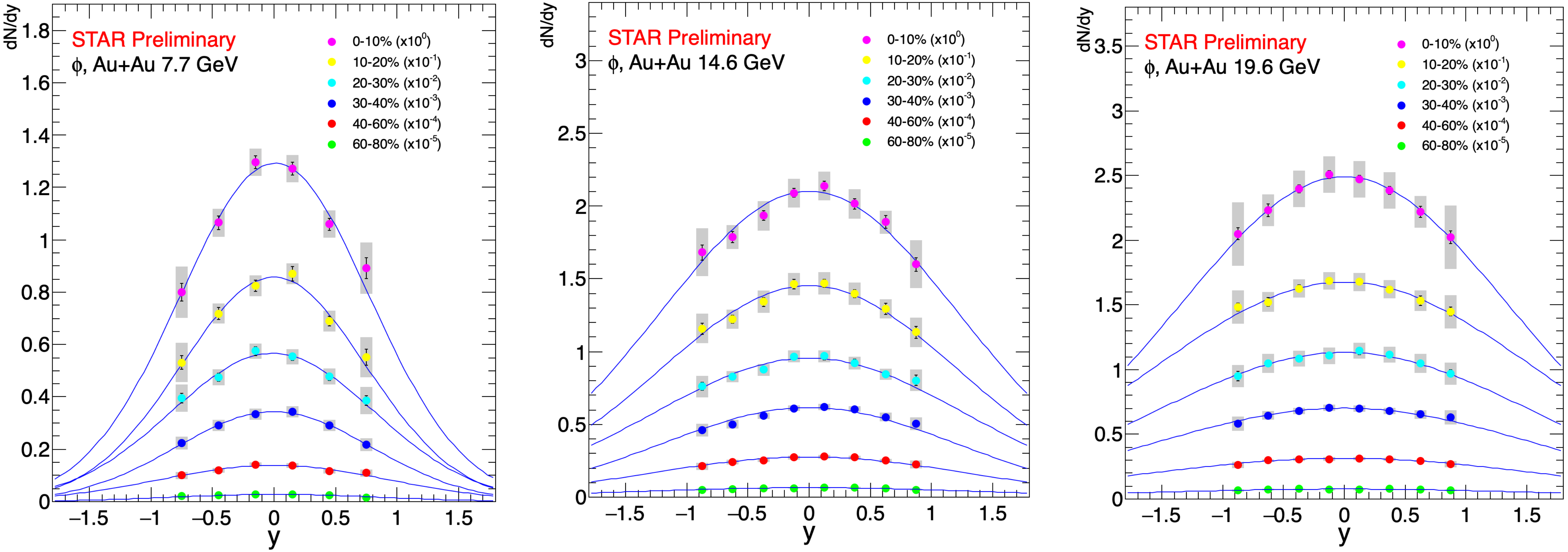
Rapidity spectra of K_s^0, Ξ^- and $\bar{\Xi}^+$ at 19.6 and 14.6 GeV

- Rapidity spectra of mesons (K_s^0) and anti-baryons($\bar{\Xi}^+$) are Gaussian-like distributions.
- Rapidity distribution of baryons(Ξ^-) are wider than the distributions of the anti-baryons($\bar{\Xi}^+$) in Au+Au collisions.





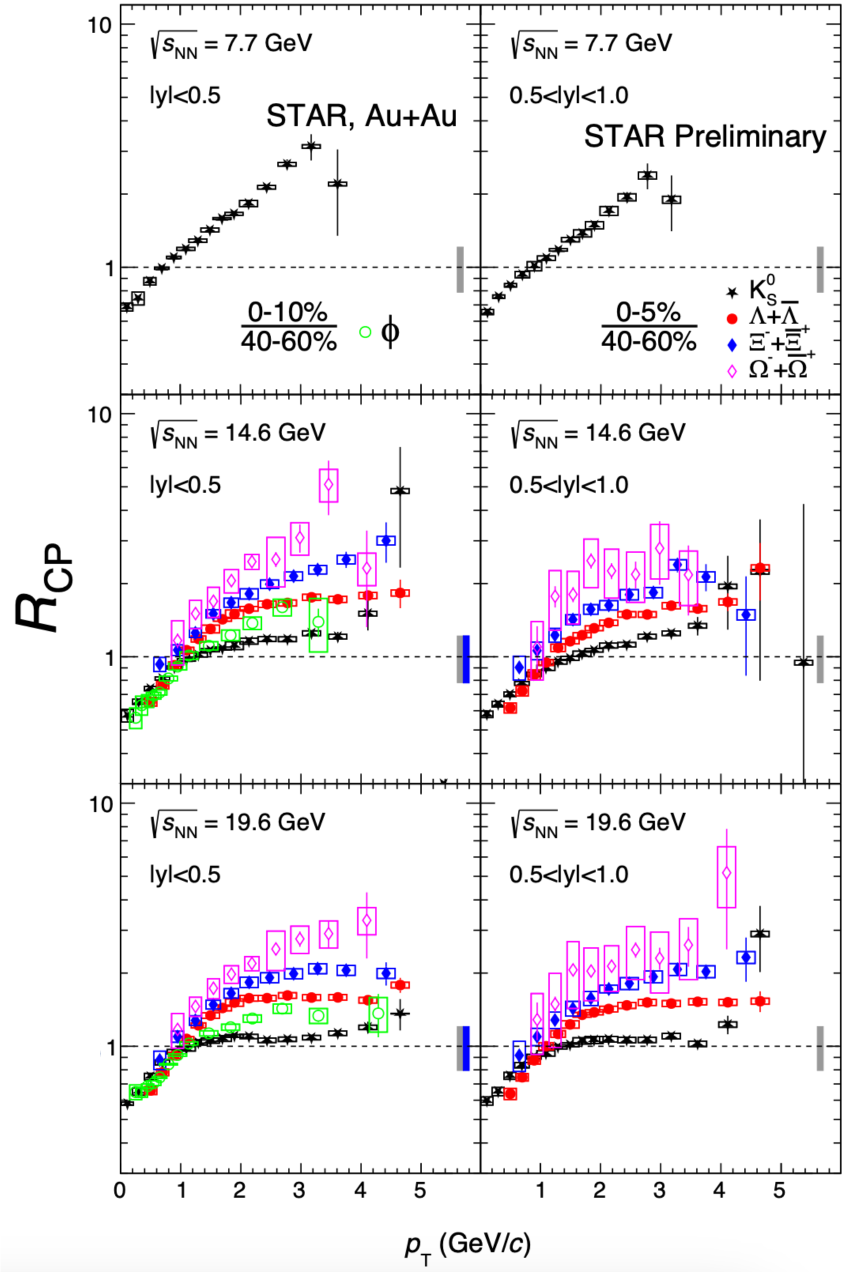
Rapidity spectra of ϕ



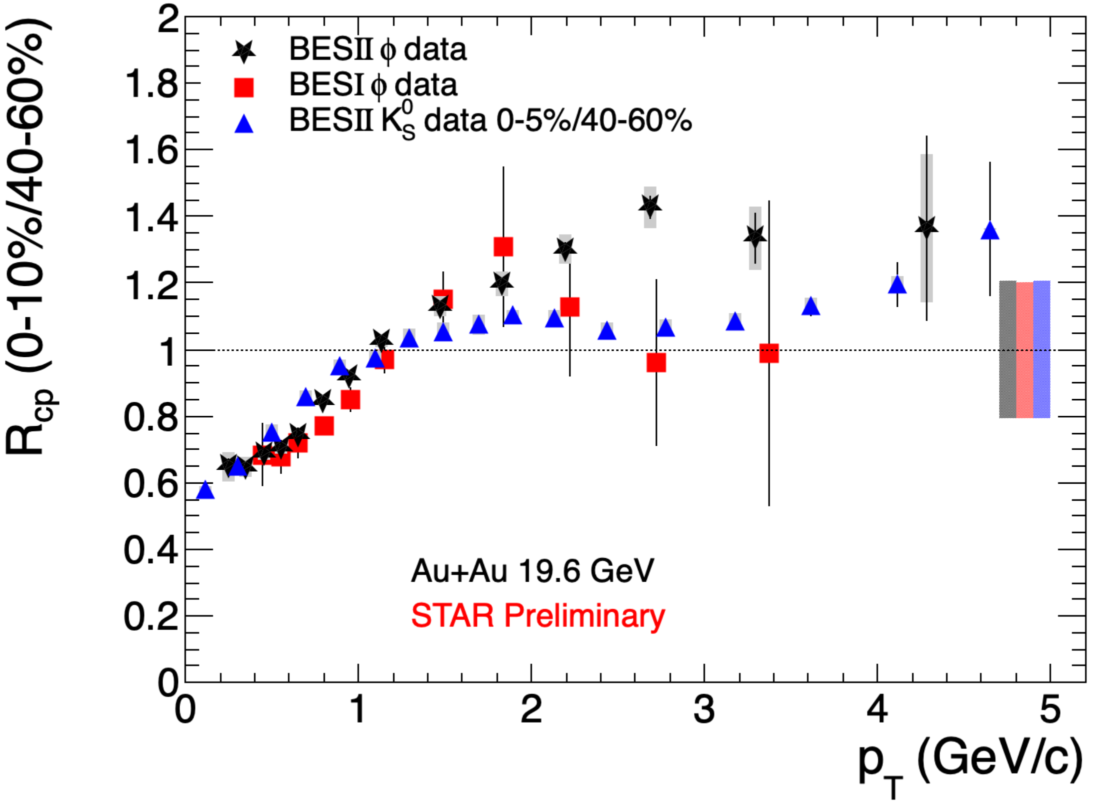
- Rapidity spectra of ϕ are Gaussian-like distributions
- Rapidity distribution become wider with increasing energy

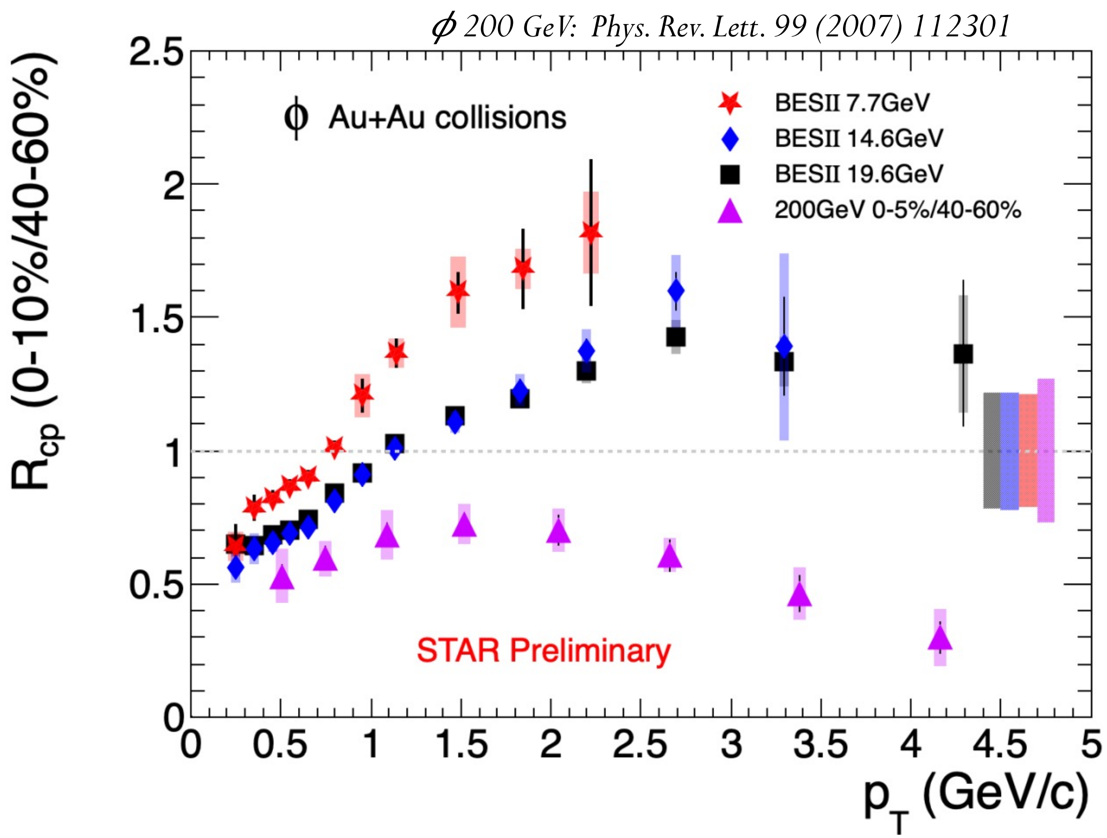
Nuclear modification factor at 19.6, 14.6 and 7.7 GeV

- ➢ R_{CP} of K_s^0 increases with decreasing collision energies at p_T>2GeV/c:
  - ✓ Partonic energy loss less important
  - ✓ Cold nuclear matter effect more important
- ➢ R_{CP} tends to be flat and larger than unity at p_T>2GeV/c.
  - ✓ Radial flow
  - ✓ Quark coalescence
- ➢ The enhancement is stronger for Ω compare to Ξ, Λ and K_s^0
  - ✓ A stronger enhancement for multi-strange particles is a proposed signature for QGP formation.



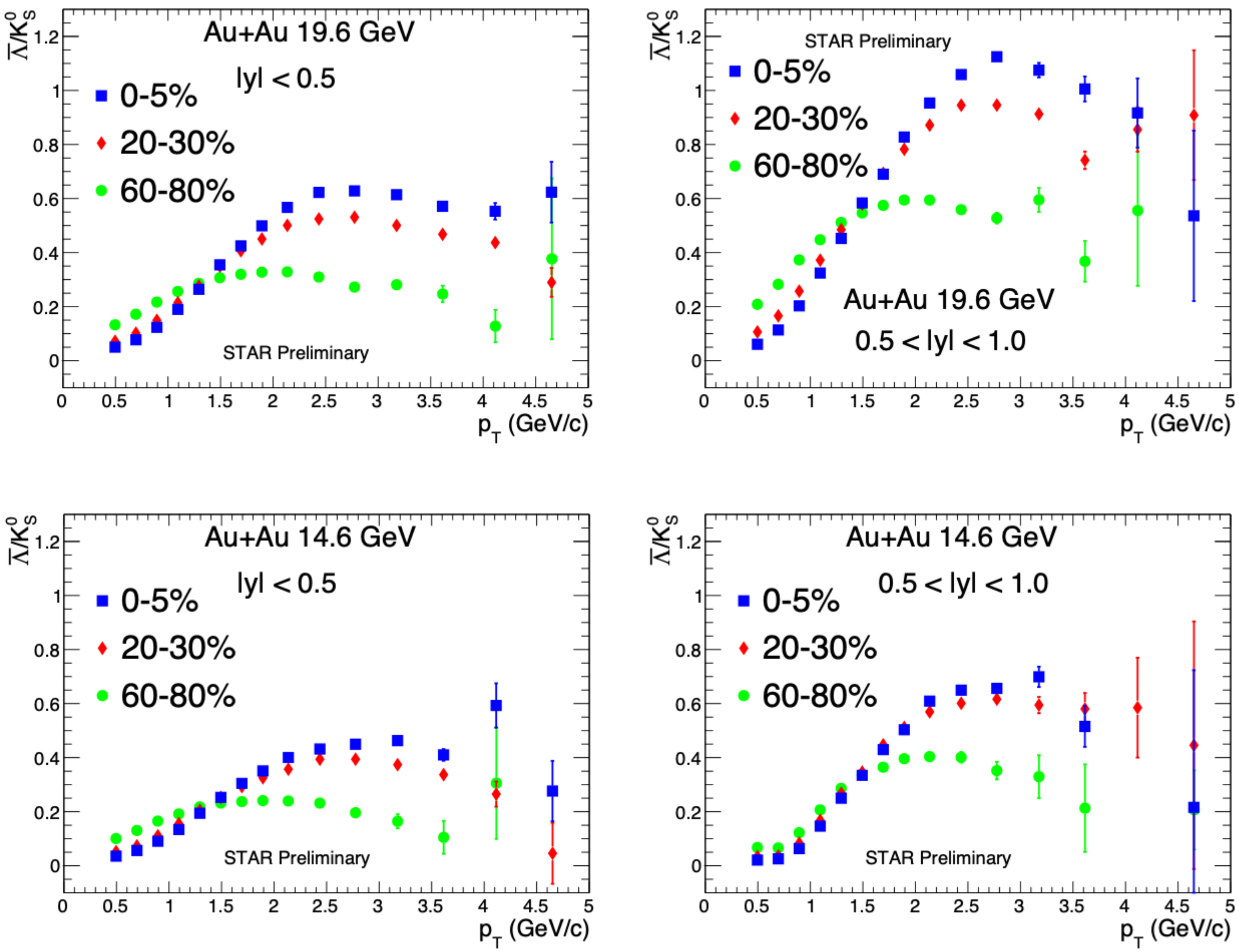
Nuclear modification factor for ϕ

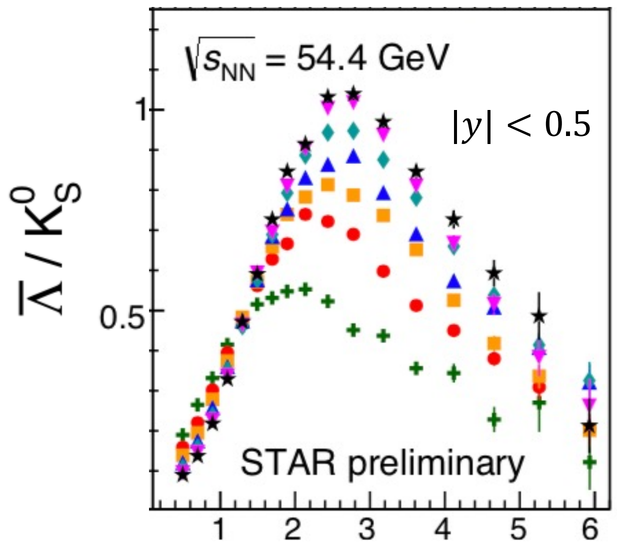




- BES-II result is consistent with BES-I with greatly improved precision
- $R_{CP}(\phi) > R_{CP}(K_S^0)$ at $2 < p_T < 4$ GeV/c
- $R_{CP} < 1$ for higher p_T at 200 GeV → Partonic energy loss in the QGP medium
- $R_{CP} > 1$ for higher p_T at 19.6 GeV and lower energies → Cronin-type interactions, radial flow and/or coalescence hadronization

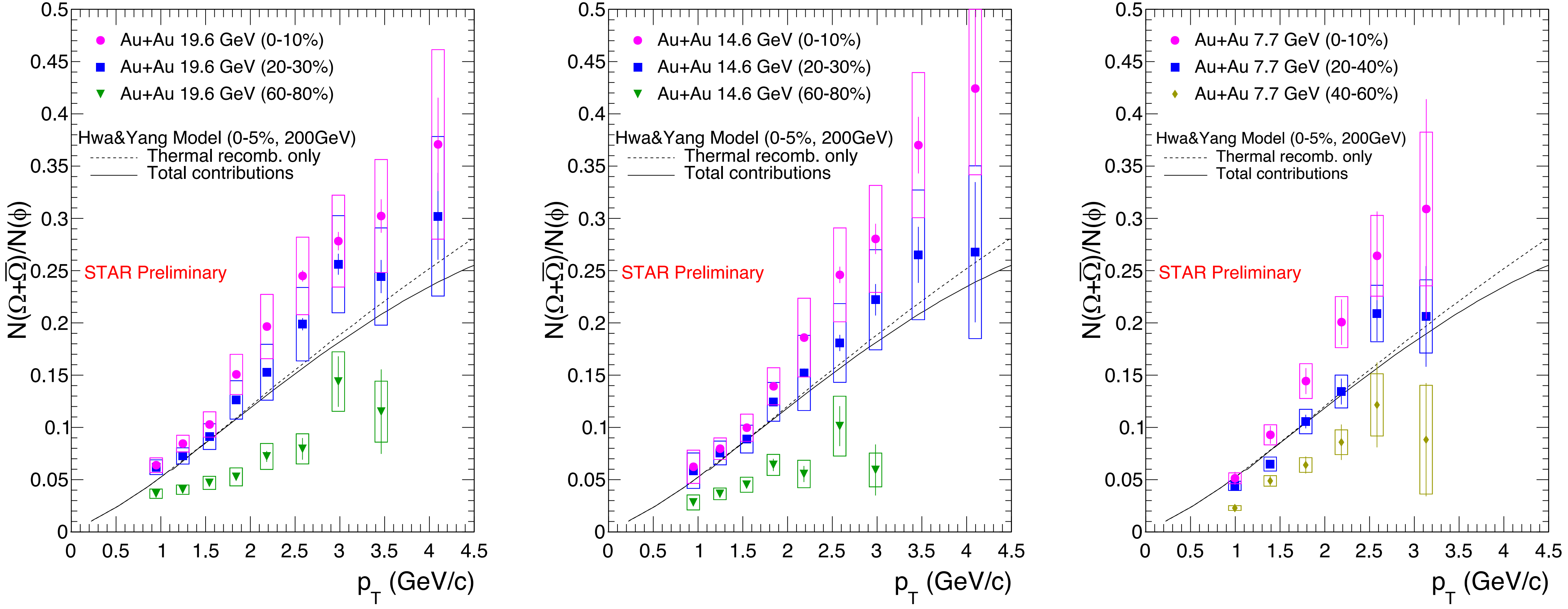
$\bar{\Lambda}/K_s^0$ ratio at 54.4, 19.6 and 14.6 GeV





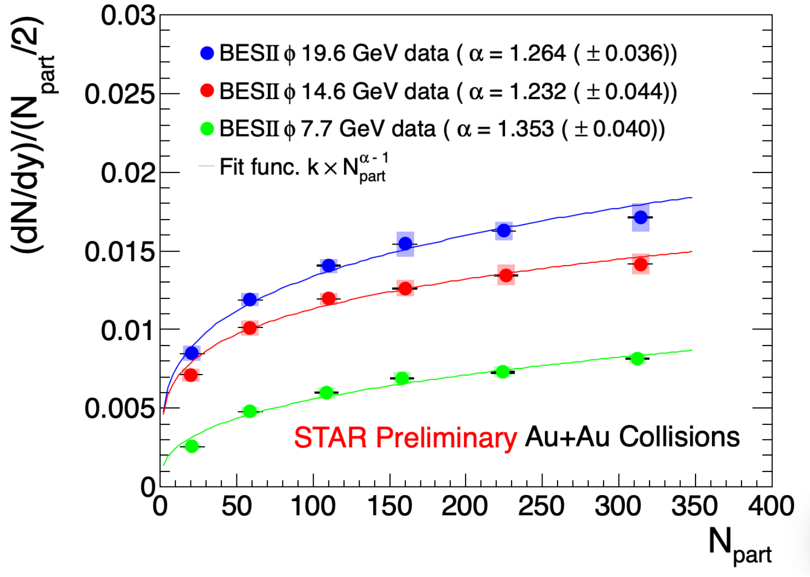
- Clear centrality and rapidity dependence of (anti-)baryon-to-meson ratio at intermediate p_T.
- Baryon enhancement is observed in all measured rapidity regions.

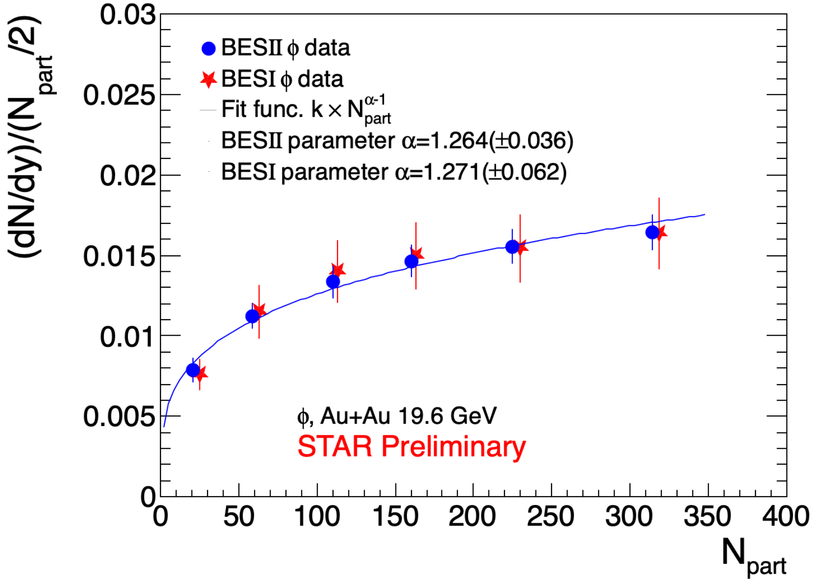
$\Omega(sss)/\phi(s\bar{s})$ ratio



- Similar to the observation at $\sqrt{s_{NN}}$ = 200 GeV, the Ω/ϕ ratio increases from peripheral to central collisions at intermediated p_{T}, which is compatible with the existence of QGP at $\sqrt{s_{NN}} \geq 7.7$ GeV

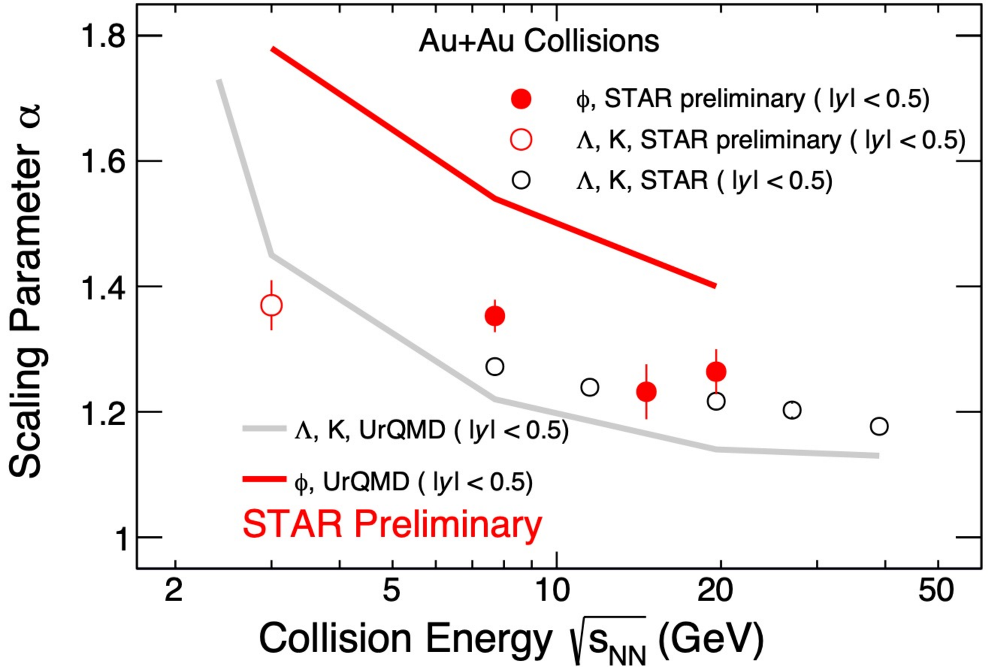
Centrality dependence of ϕ production





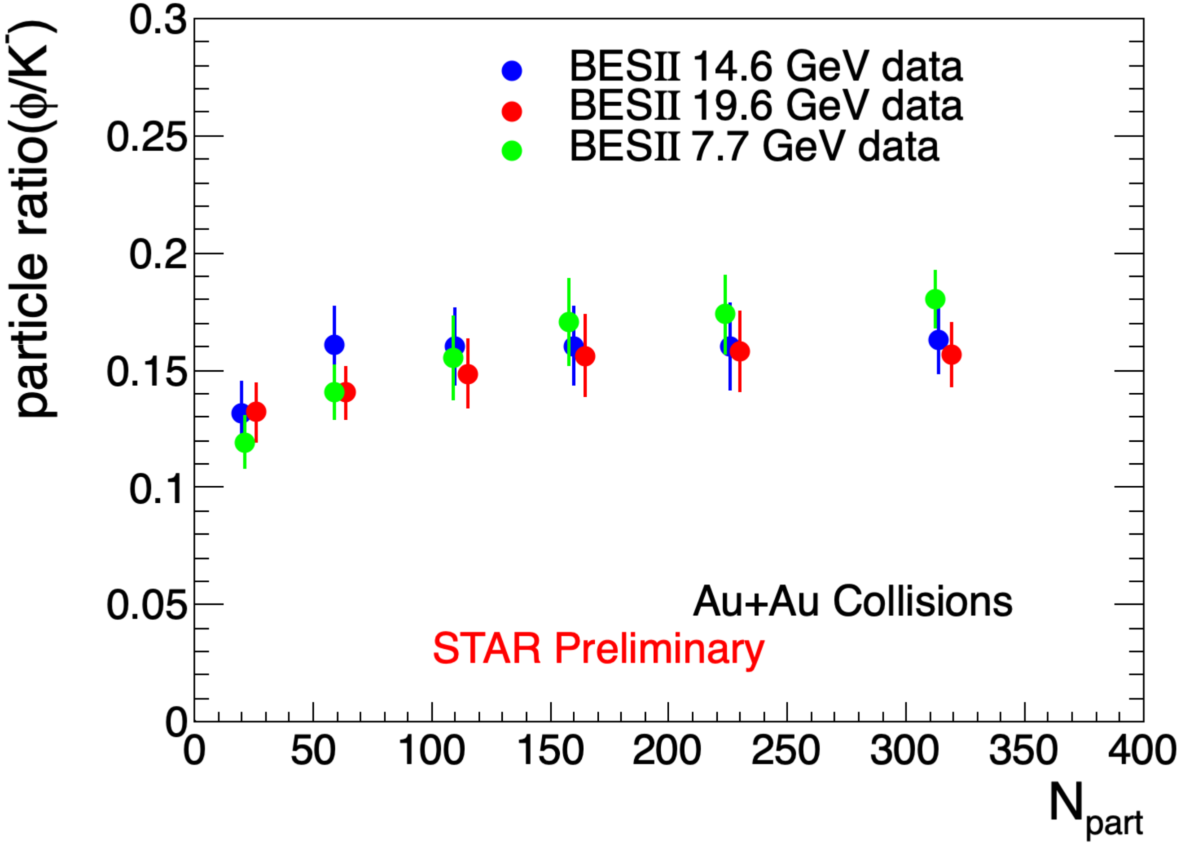
The bottom two plots show the total errors

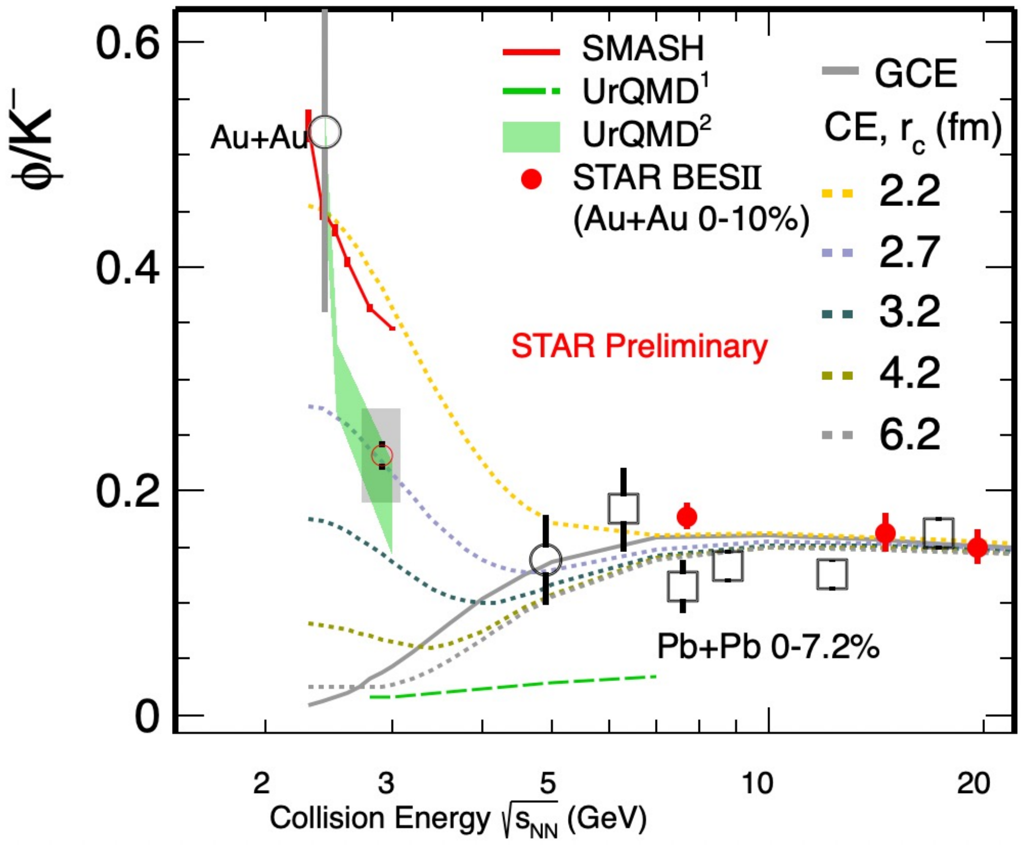
- Fit function: $\frac{\mathrm{dN/dy}}{N_{\mathrm{part}}/2} = k \times N_{\mathrm{part}}^{\alpha-1}$
- Common centrality dependence for ϕ, Λ, K production at 19.6GeV.
- α parameter for ϕ is slightly larger than that for Λ, K and less than UrQMD predictions



STAR: arXiv: 2407.10110

Centrality and Energy dependence of ϕ/K^- ratio

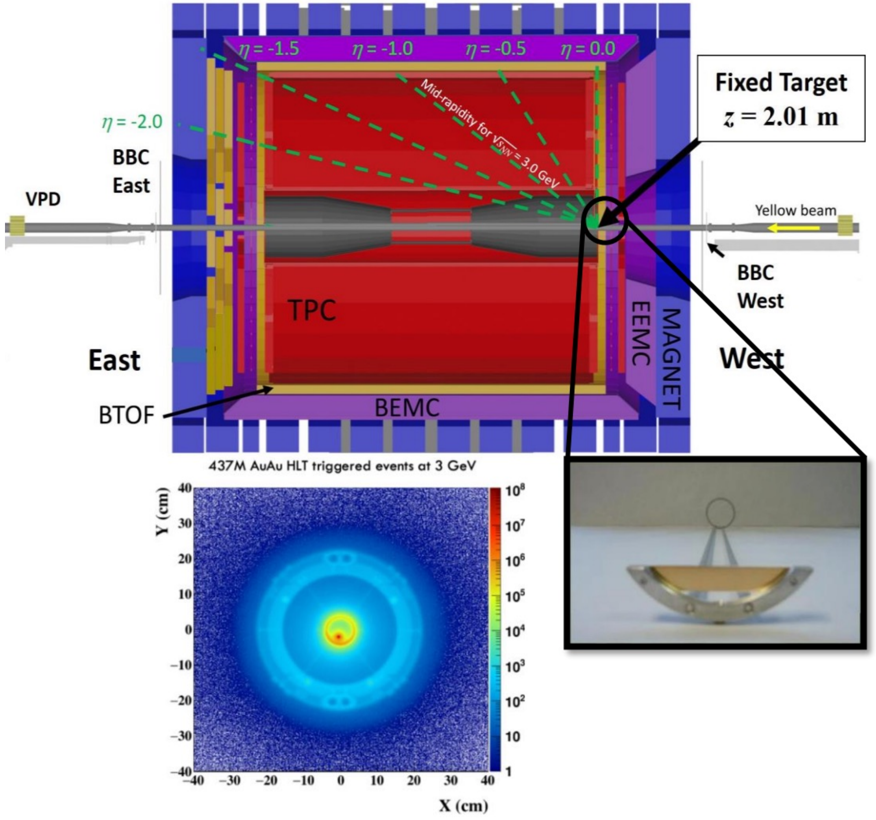


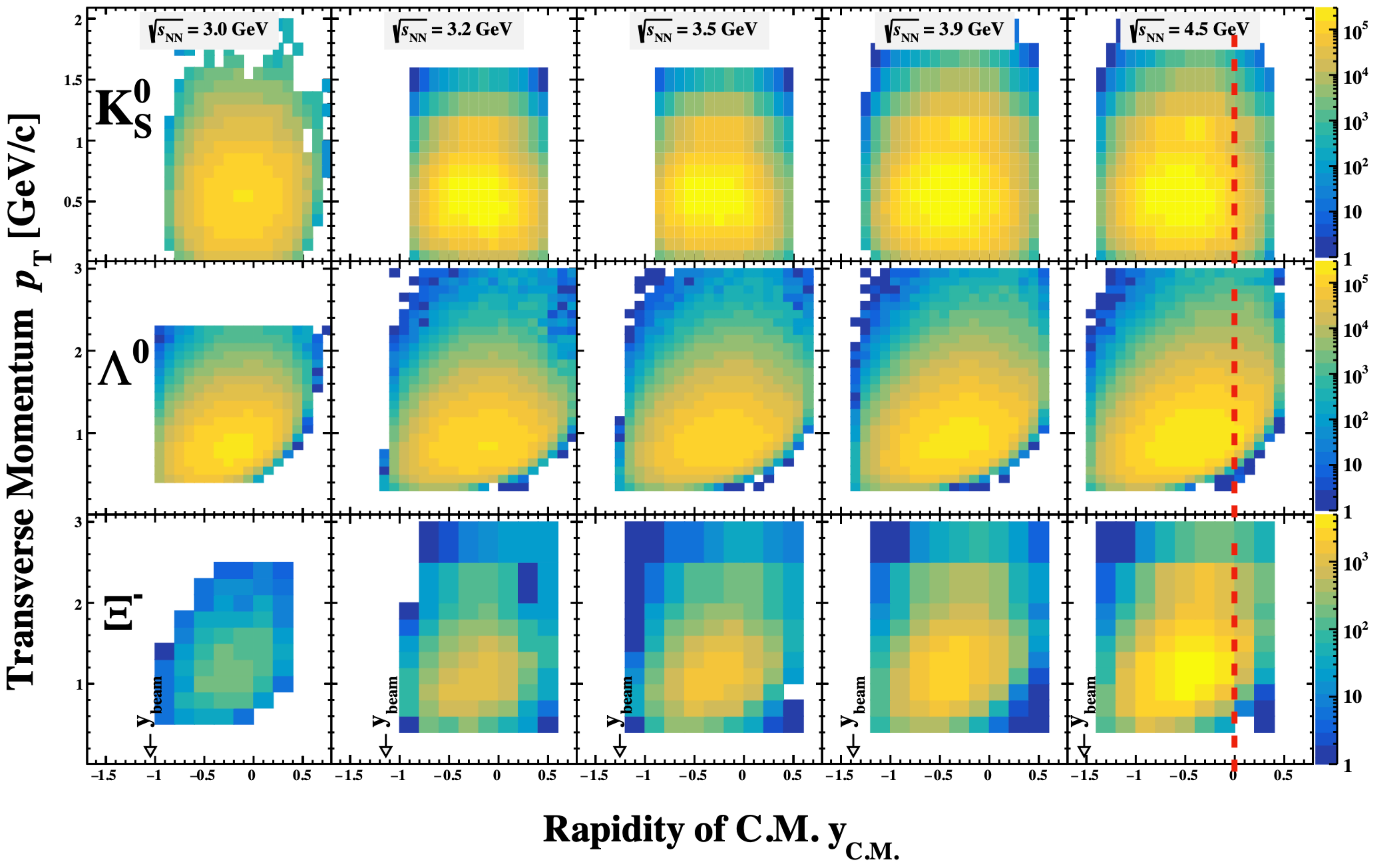


STAR: Phys. Rev. C 96 (2017) 044904
STAR: Phys. Rev. C 101 (2020) 02905
STAR: Phys. Lett. B 831 (2022) 137152

- The ϕ/K^- ratio exhibits no clear dependency on centrality or energy across the range of $\sqrt{s_{NN}}$ = 7.7 to 19.6 GeV
- The ϕ/K^- ratio reaches the GCE limit at $\sqrt{s_{NN}}$ = 7.7, 14.6 and 19.6 GeV

Strangeness measurements in fixed-target collisions

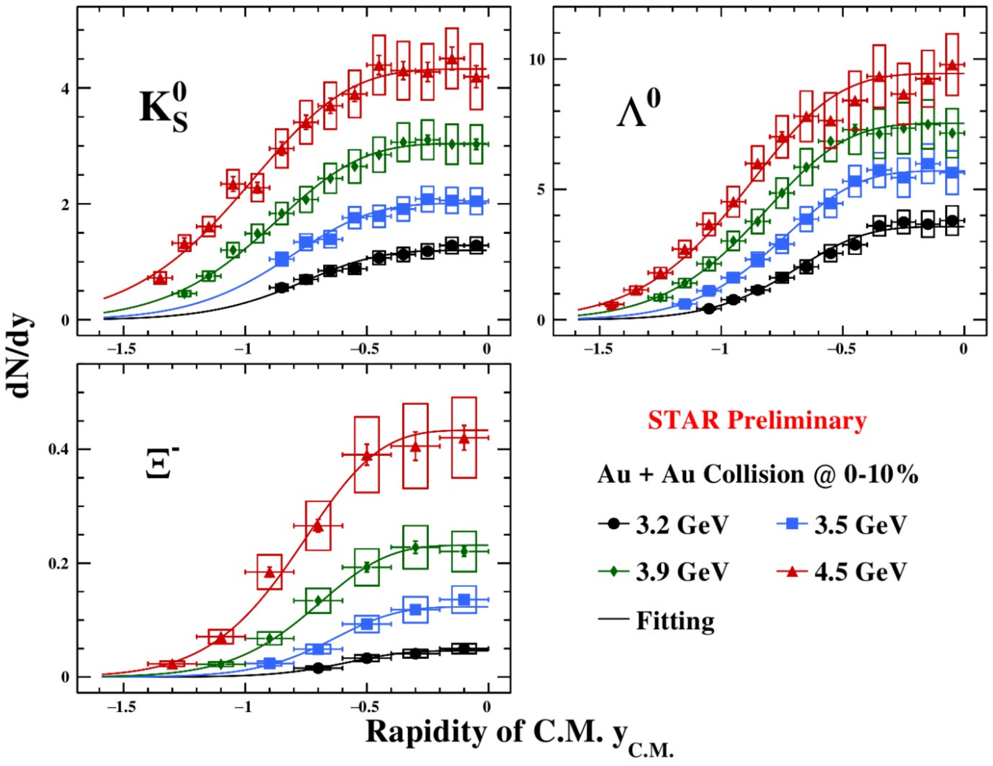




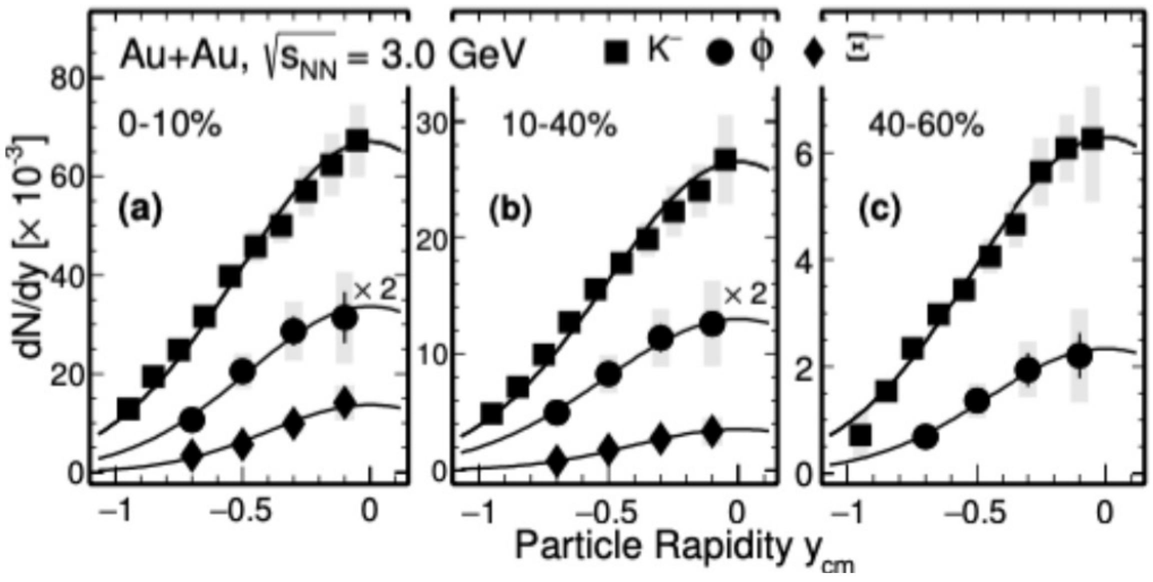
- **Particle rapidity coverage from beam rapidity to mid-rapidity**

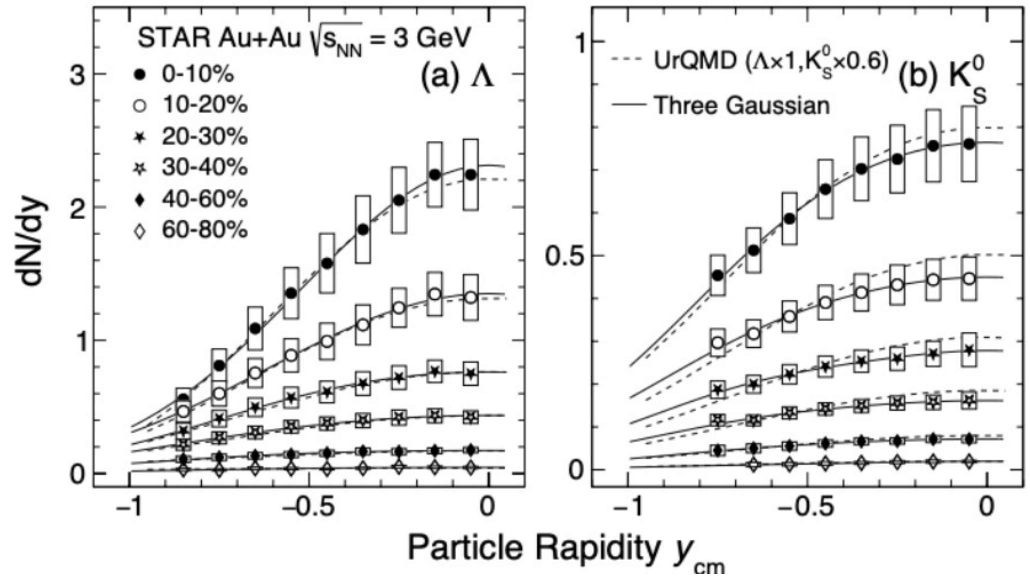
Strangeness measurements in fixed-target collisions

Hongcan Li, SQM24



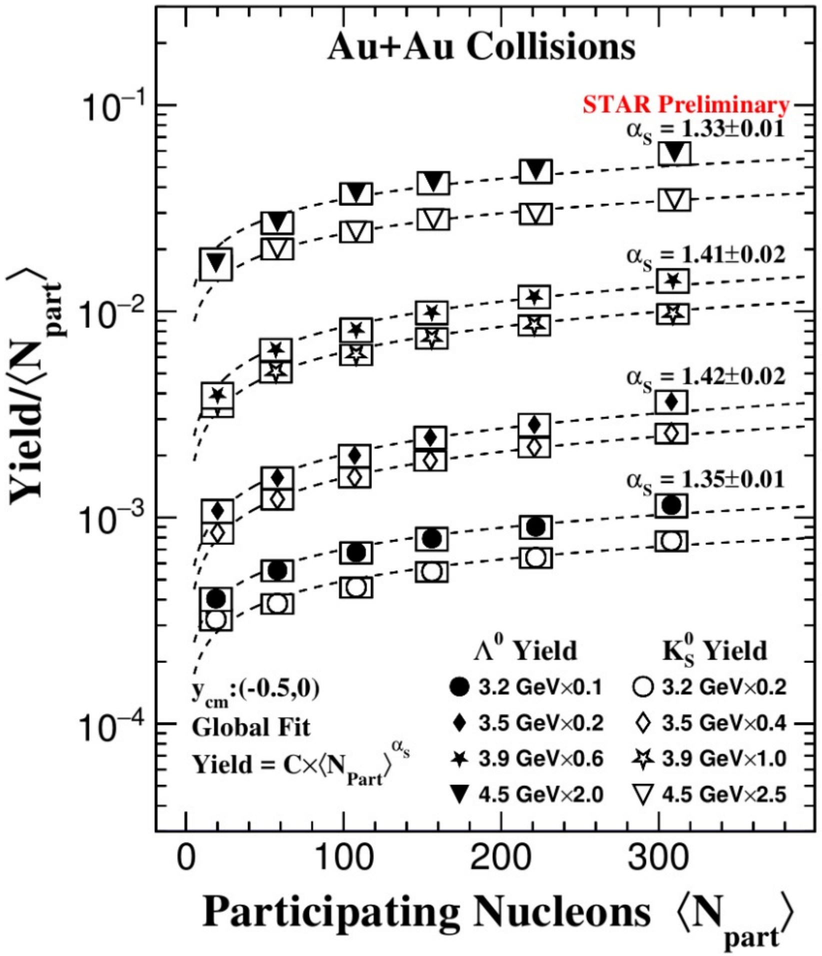
STAR: Phys. Lett. B 831 (2022) 137152; arXiv: 2407.10110

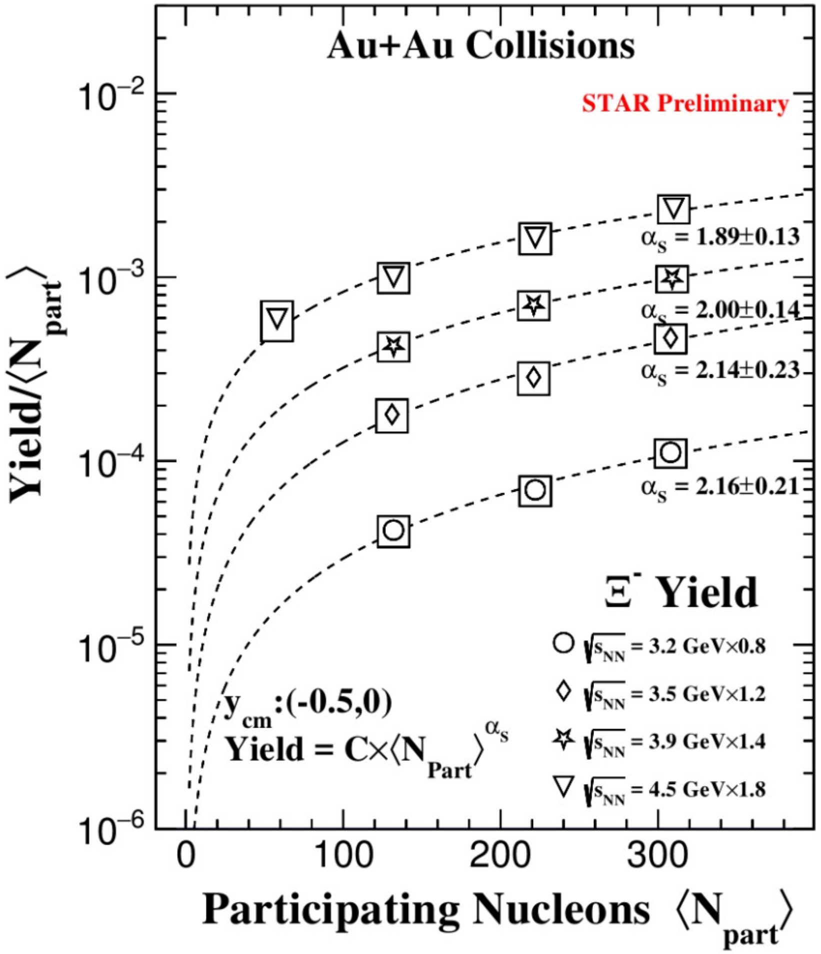




- Comprehensive measurement of strangeness production at different energies from 3 to 4.5 GeV

Centrality dependence of mid-rapidity yields



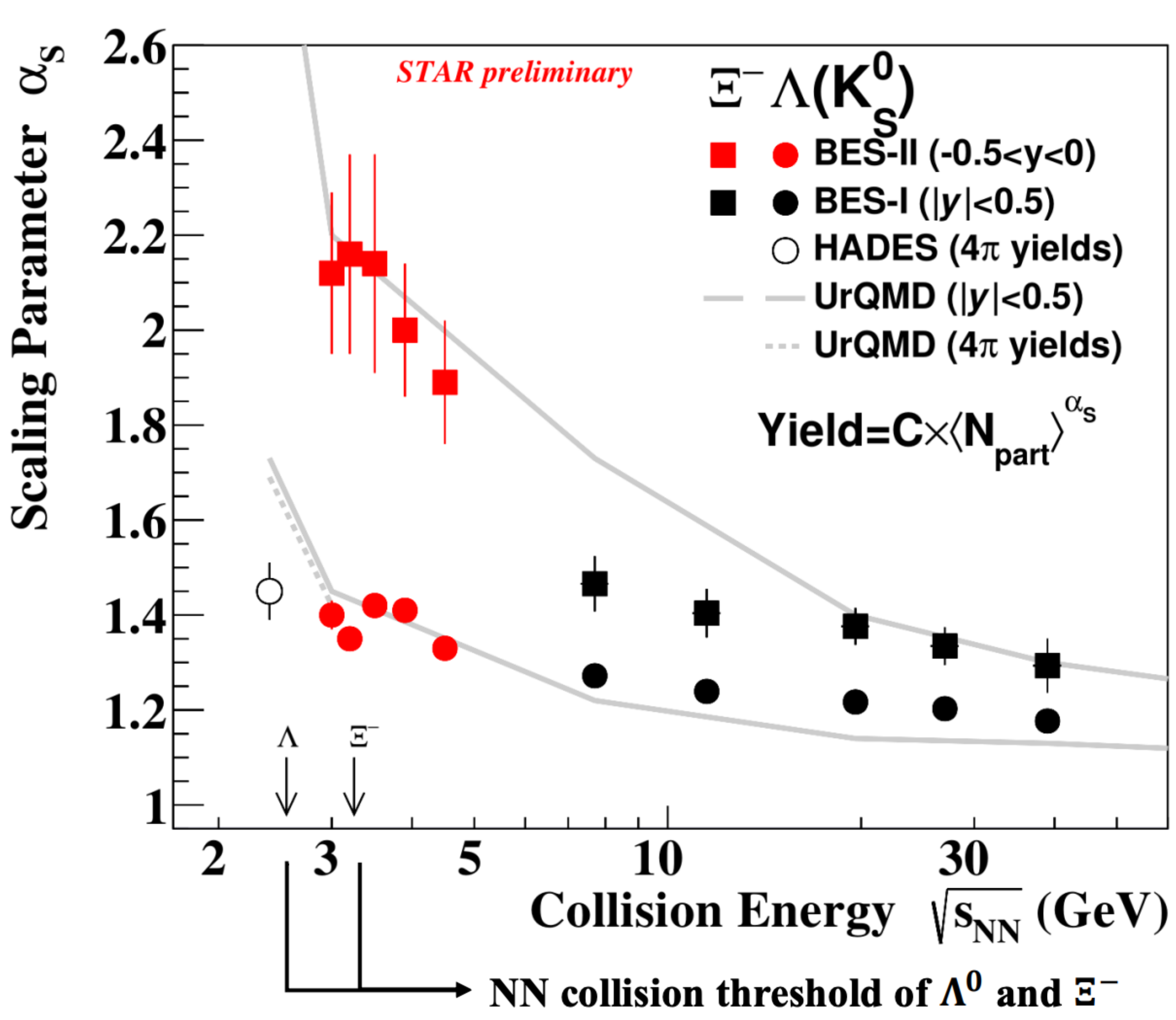


- **Scaling formula:**

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

- **Single strange hadrons K_S^0 and Λ^0 follow common scaling trend, but double strange hadron Ξ^- deviate from the common scaling trend**
  - ➢ **Associated production mode**
    - ☐ **NN → NΛK**
    - ☐ **NN → NΞKK**

Energy dependence of scaling parameter α_S



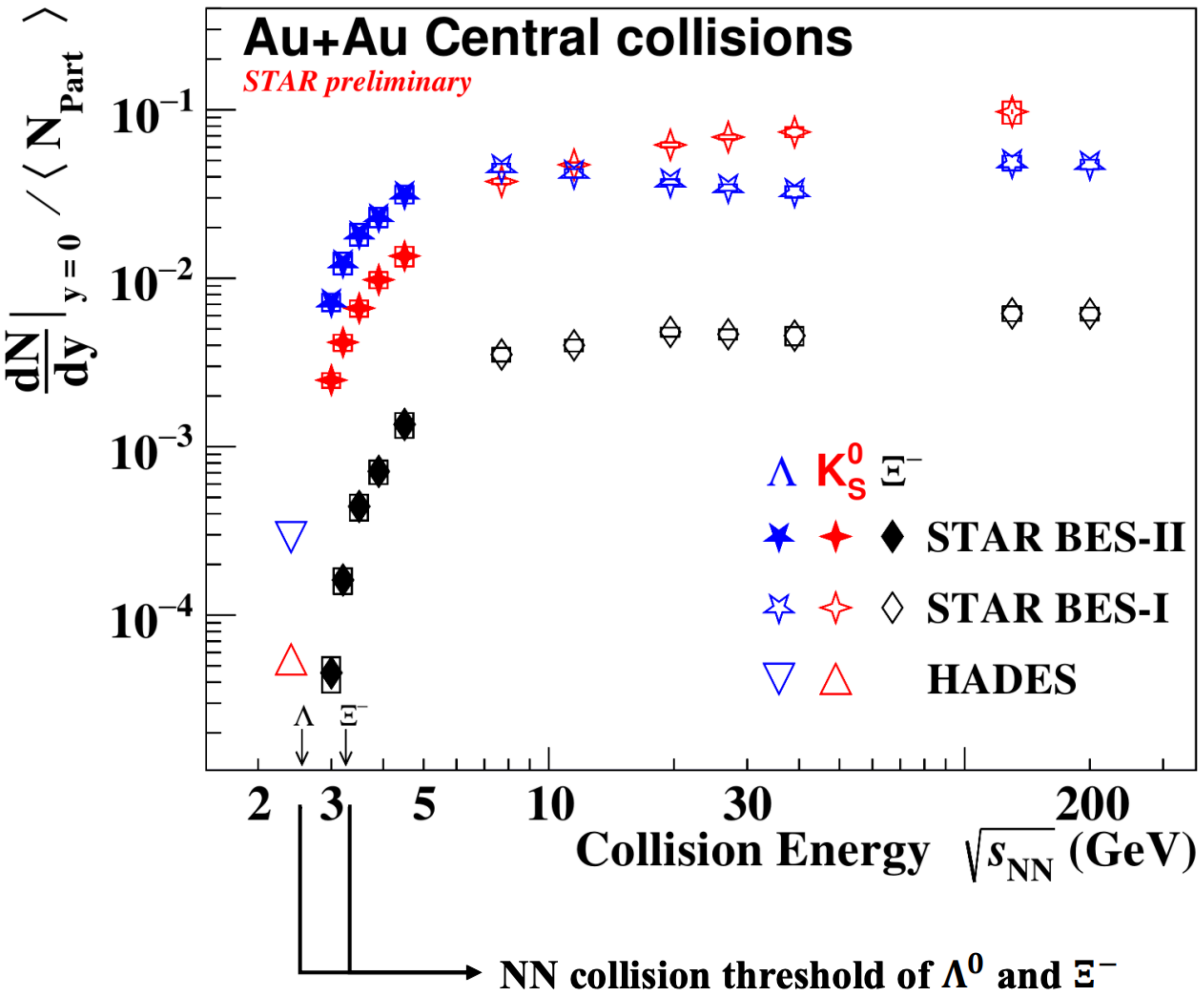
- **Rapid decrease of scaling parameter α_S for Ξ^- from 4.5 to 7.7 GeV, and saturate at high energy**
  - **The mechanism of strange hadron production may change**
  - **Strange hadron production predominantly from hadronic interactions at $\sqrt{s_{NN}} < 4.5$ GeV**

- **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)

Energy dependence of mid-rapidity yields



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

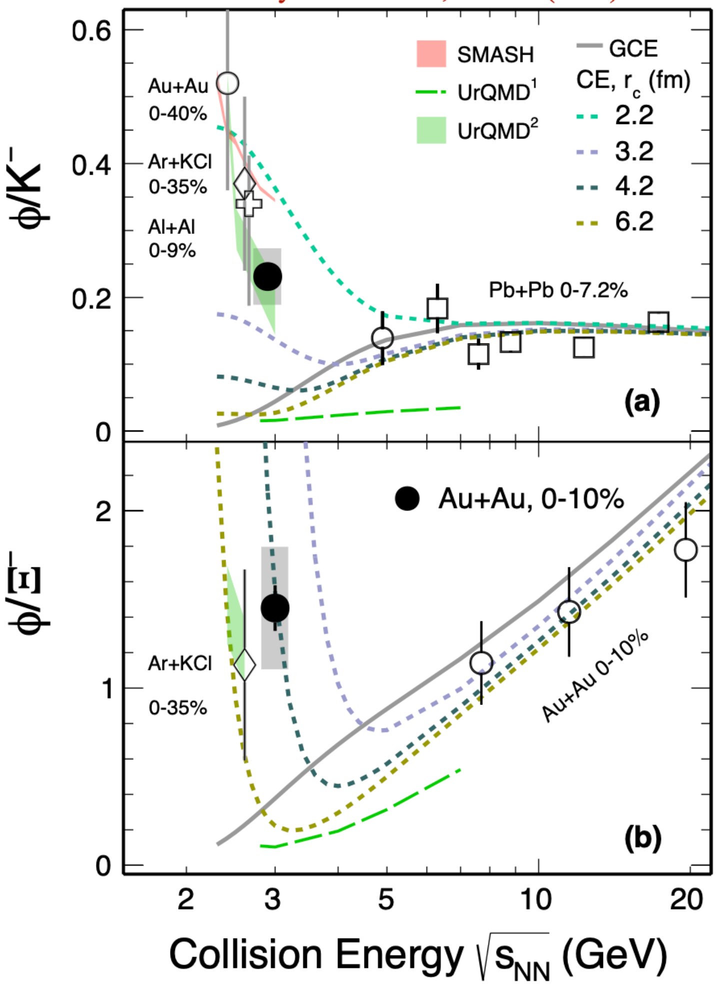
      $gg \to s\bar{s}$ or $q\bar{q} \to s\bar{s}$
    - ☐ **Hadronic interaction (associated production)**

      BB → BYK or BB → BΞKK

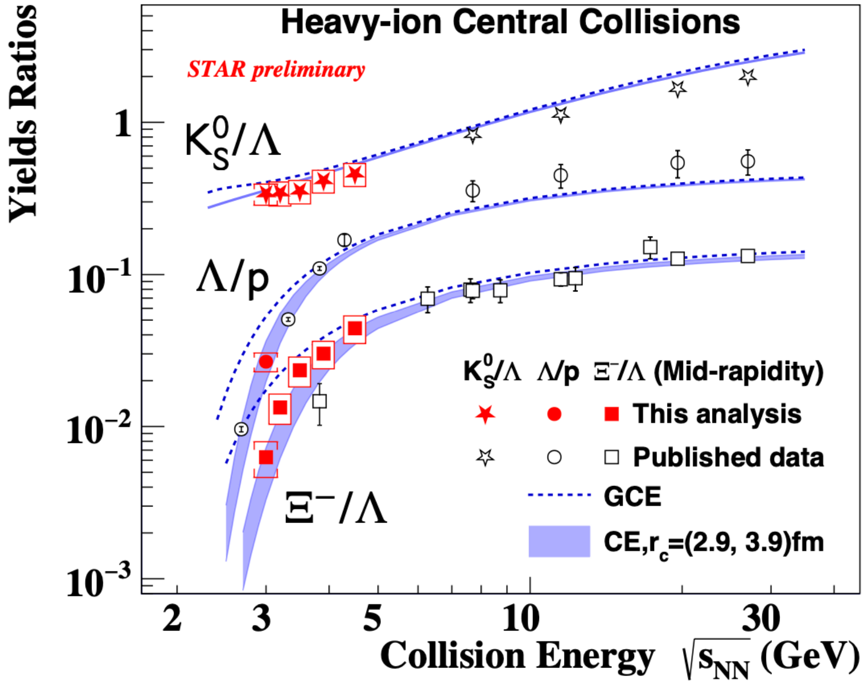
      B: N, p, Δ, etc.   Y: Λ, Σ, etc.   K: K^+, K^0
  - ➢ **Baryon-dominated to meson-dominated transitions**
    - ☐ K_s^0 and Λ^0 mid-rapidity yield cross at ~ 8 GeV
  - ➢ **First measurement of Ξ^- near- / sub-threshold energies in Au+Au collision**

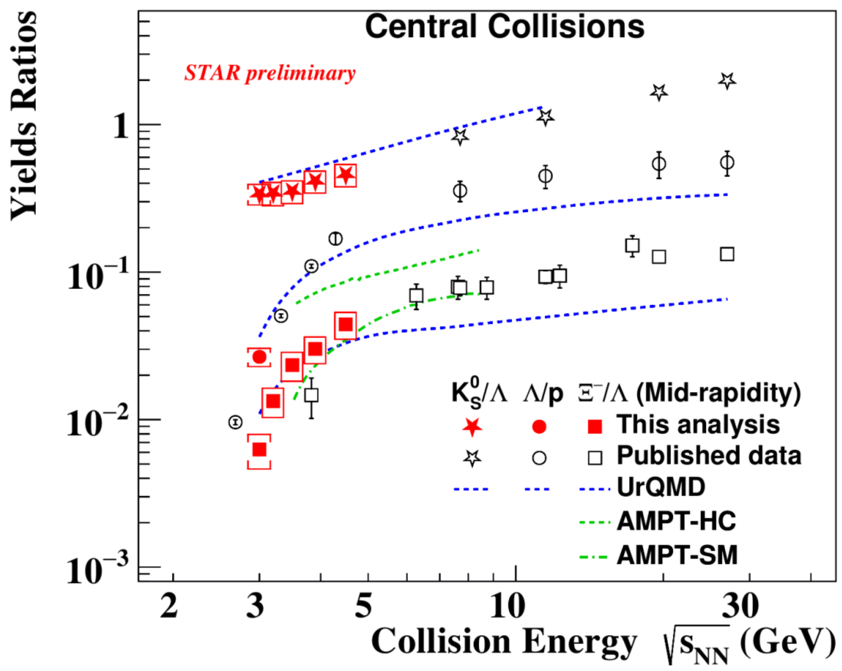
Energy dependence of mid-rapidity yield ratios

STAR: Phys. Lett. B 831, 137152 (2022)



UrQMD: cascade mode, hard EOS



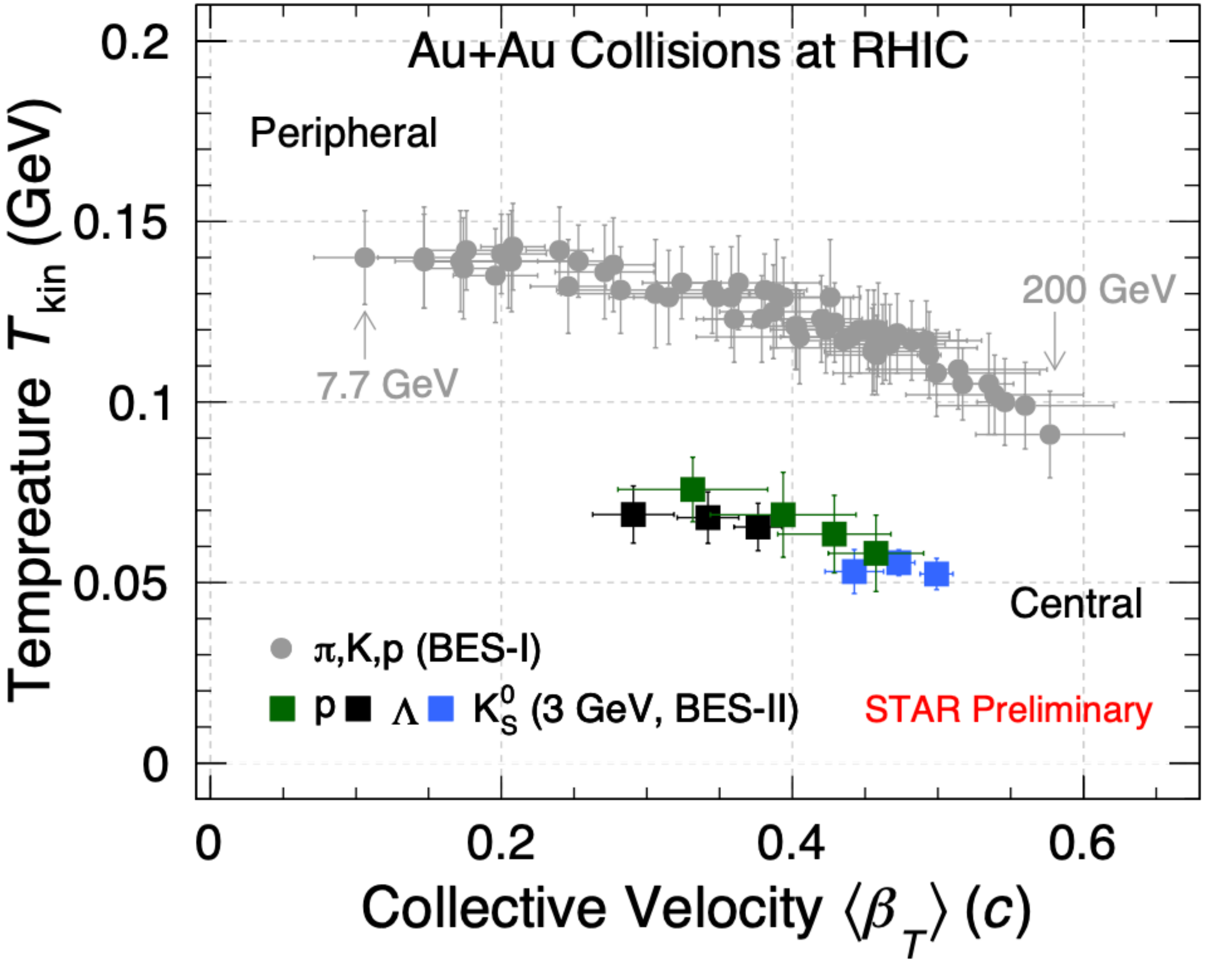


1) Canonical Ensemble (CE) with strangeness correlation length 2.9 – 3.9 fm, simultaneously describes K_S^0/Λ, Λ/p, and Ξ^-/Λ in the measured energy range, GCE fails at low energies

- **Similar observations for ϕ/K^- and ϕ/Ξ^-**

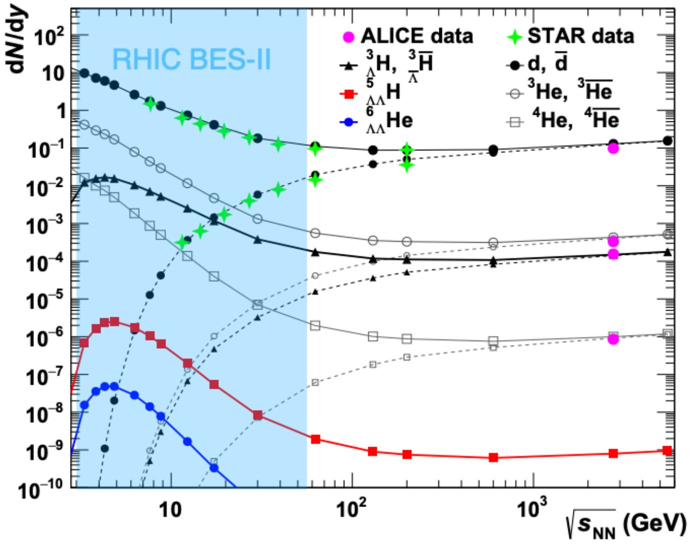
➡Change of medium properties at the high-density region

Kinetic freeze-out properties at 3 GeV



- T_{kin} of Λ and $K^0{}_S$ at 3 GeV is lower than π, K, p at higher energy collisions
- Similar observations for protons and deuterons, implying different EOS at freeze-out

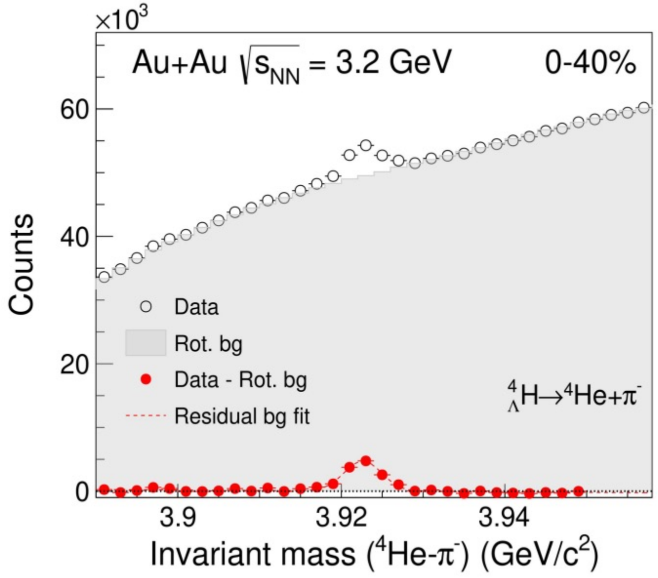
Hypernuclei measurements in BES-II

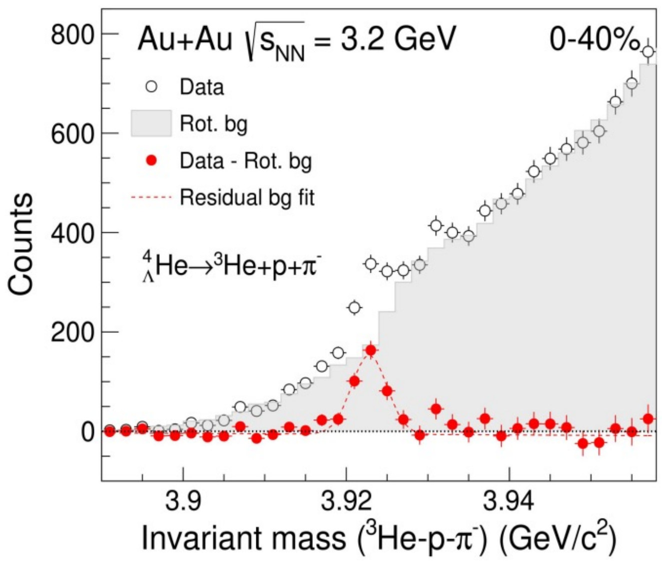


- Hypernuclei measurements are scarce in HI collision experiments
- At **low beam energies**, hypernuclei production is expected to be **enhanced** due to high baryon density

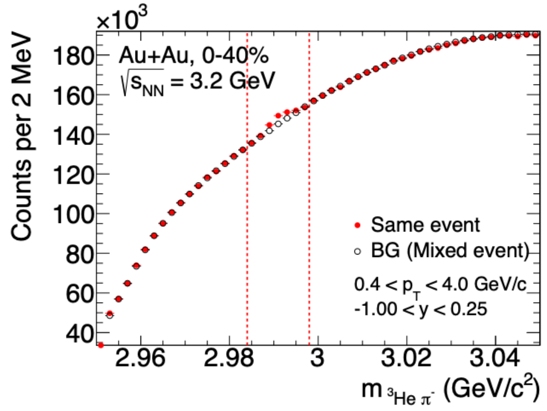
RHIC BES-II offers great opportunity for hypernuclei measurements.

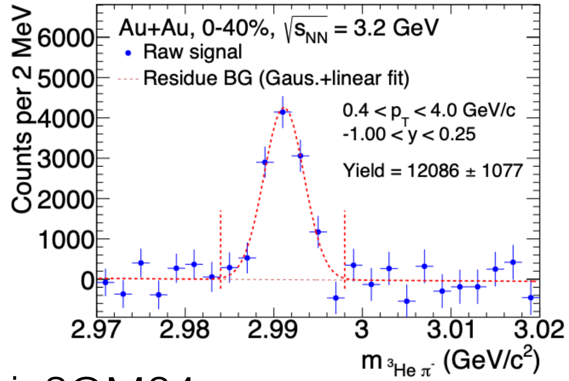
B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al. PLB (2011) 697:203–207





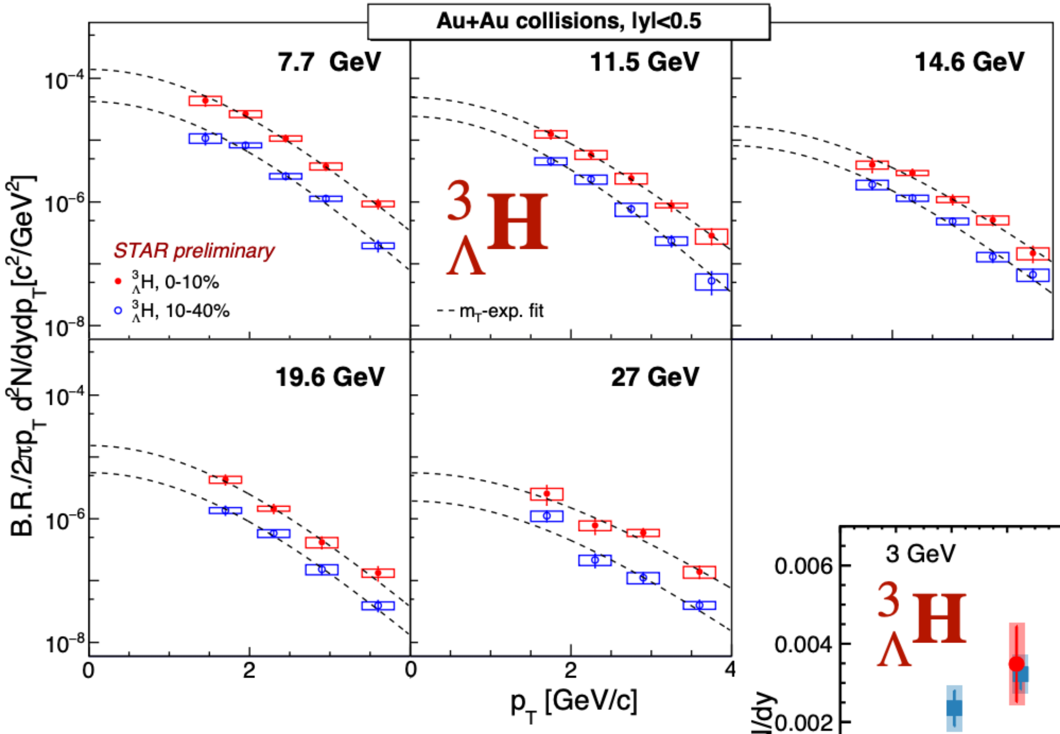
Chenlu Hu, SQM24





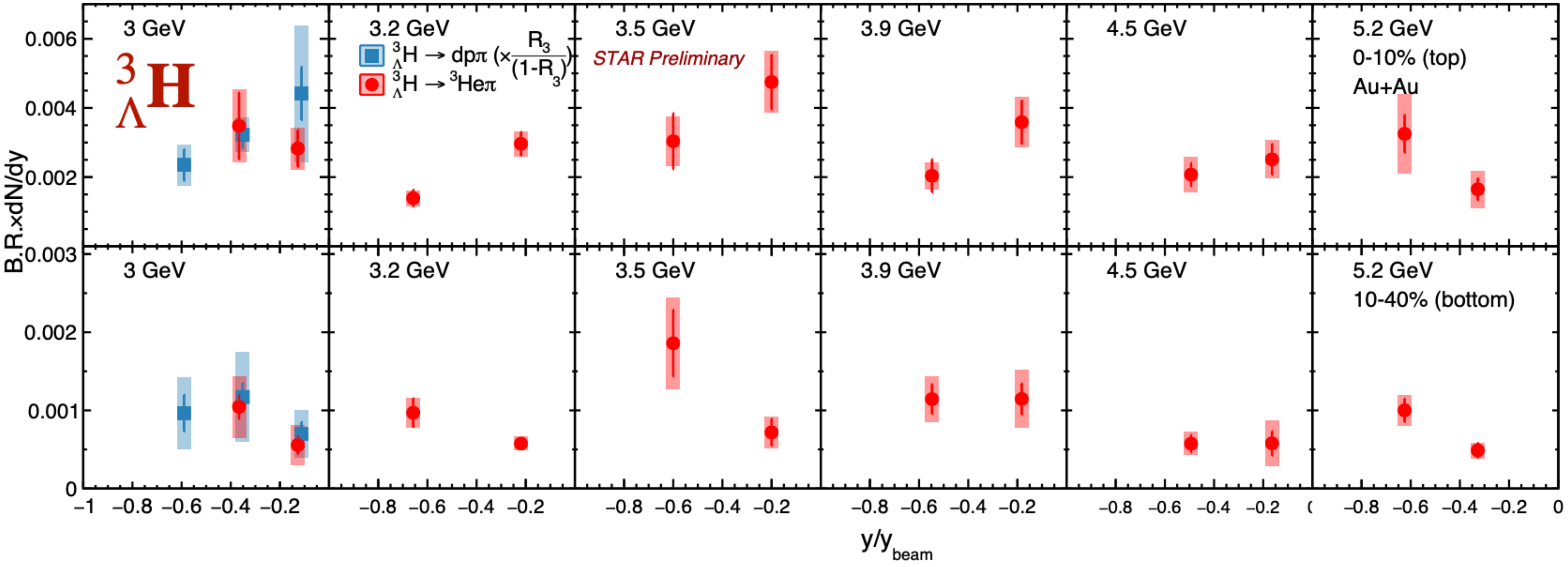
Xiujun Li, SQM24

Hypertriton production measurements in BES-II

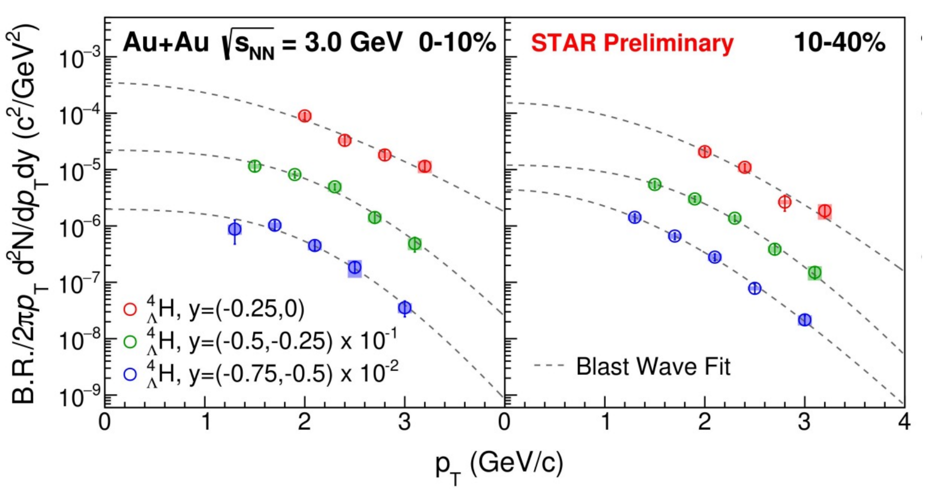


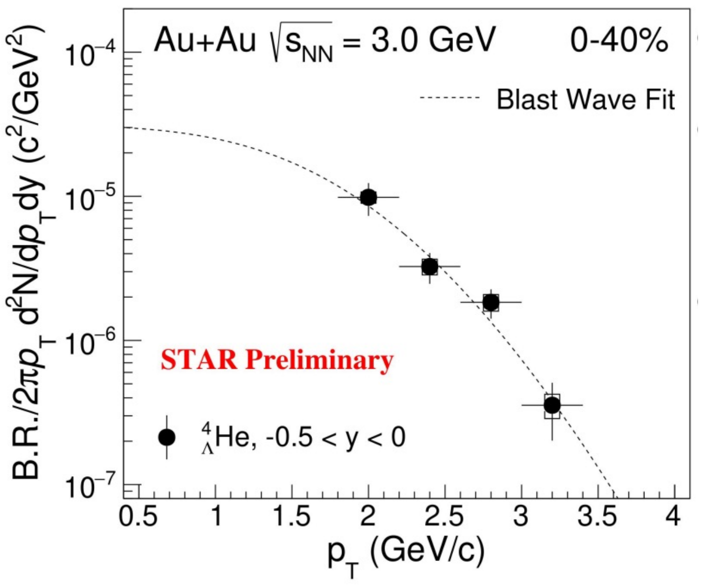
- Measurements cover 11 different energies

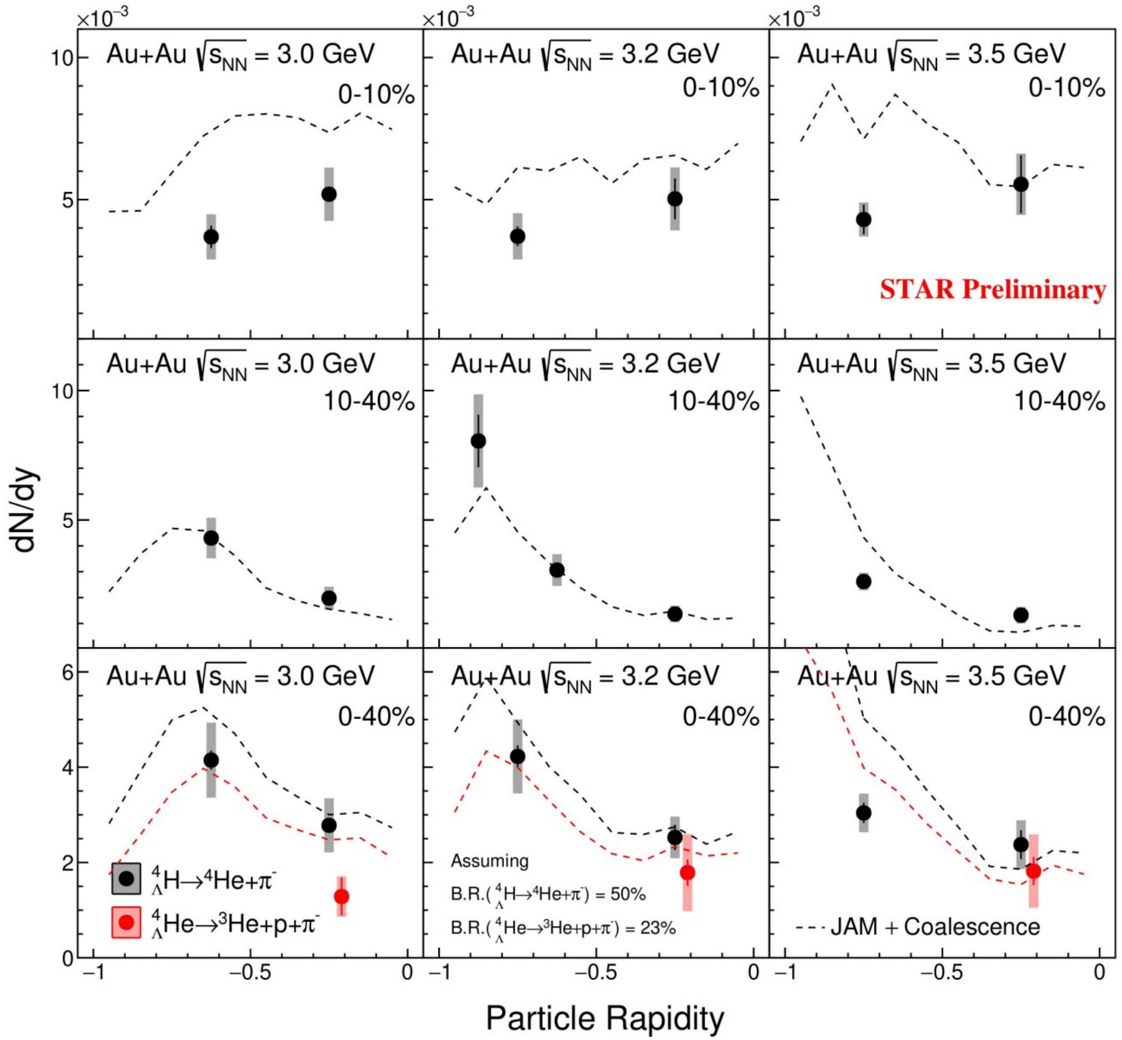
Collider: 7.7, 11.5, 14.6, 19.6, 27 GeV
Fixed Target: 3.0, 3.2, 3.5, 3.9, 4.5, 5.2 GeV



$^4_\Lambda$H and $^4_\Lambda$He production measurements in BES-II

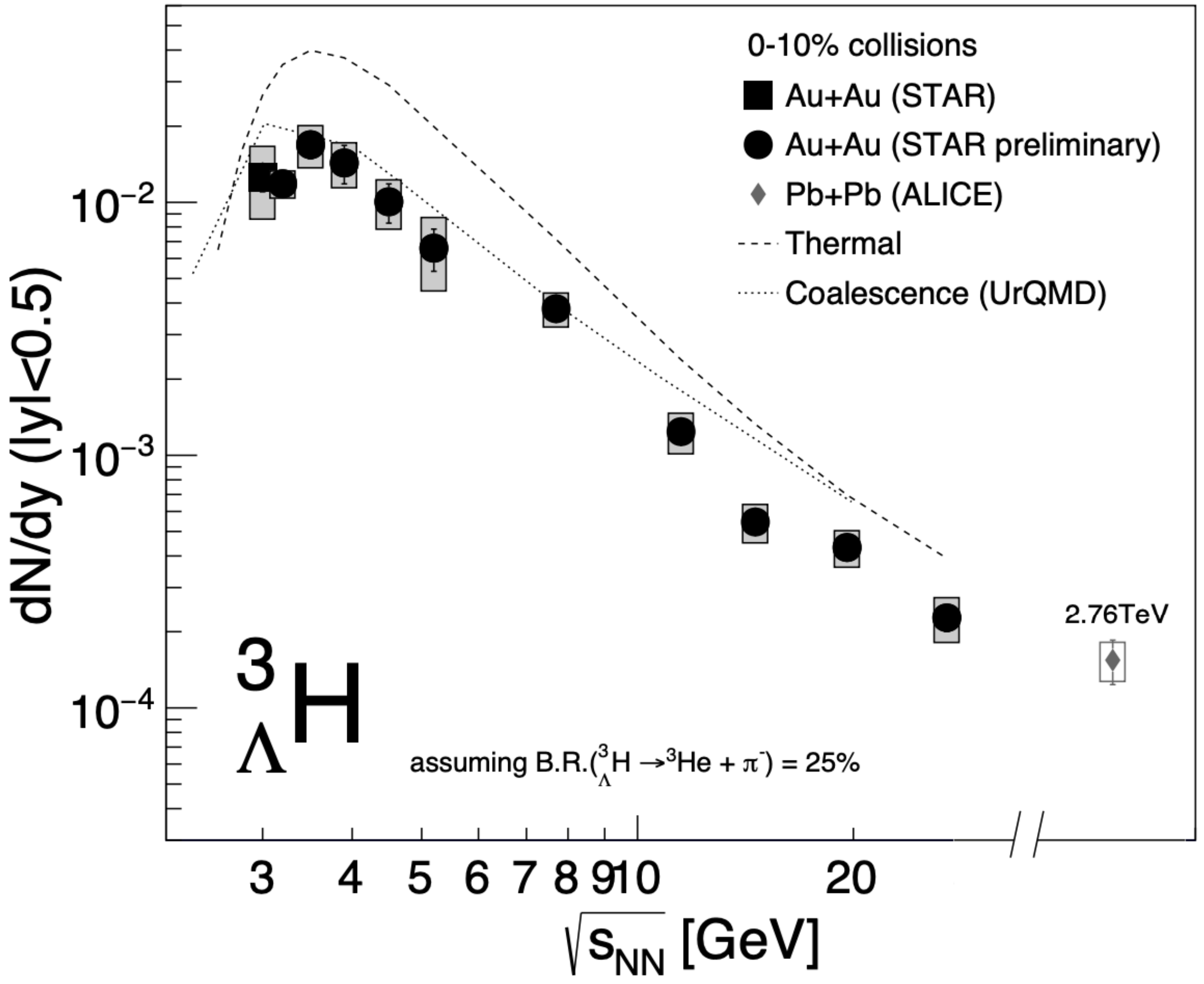






Different trend in $^4_\Lambda$H rapidity distribution in central and mid-central collisions, which reproduced by JAM+coalescence model

Energy dependence of hypertriton production

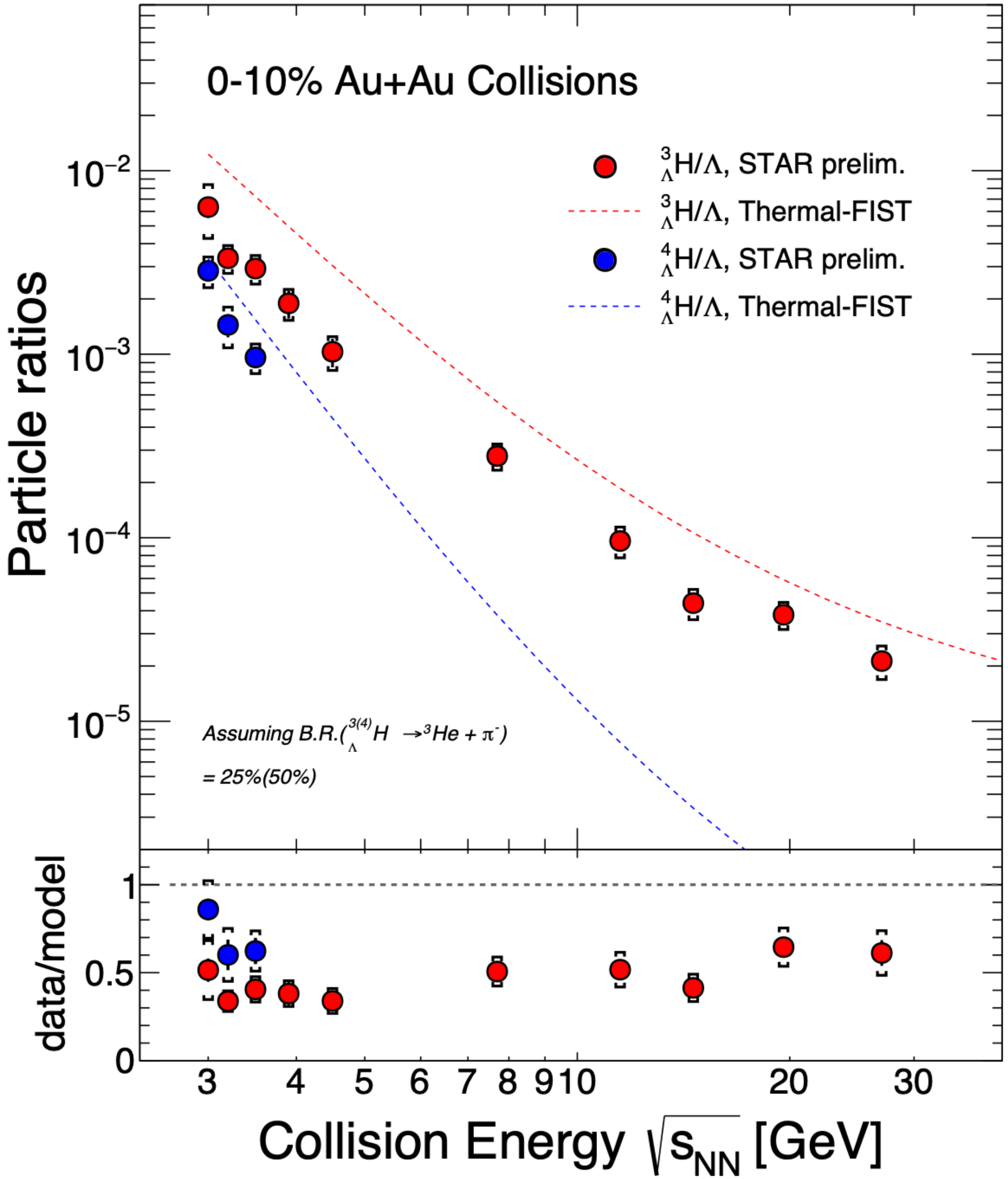


STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360
T. Reichert, et al, PRC 107 (2023) 014912

- Yields increase strongly from $\sqrt{s_{NN}}$ = 27 GeV to ~4 GeV
- Peak at 3-4 GeV
- Hadronic transport + coalescence models qualitatively describe the data
- Thermal model overestimates the data

First energy dependence of $^{3}_{\Lambda}H$ production yields in the high-baryon-density region

Energy dependence of hypernuclei to Λ yield ratios



Thermal model over-predicts $^{3}_{\Lambda}H/\Lambda$ and $^{4}_{\Lambda}H/\Lambda$ ratios.

Summary

- Comprehensive strangeness measurements in STAR beam energy scan phase II.
- Baryon enhancement is observed from 7.7 to 200GeV → consistent with QGP formation.
- Strangeness and hypernuclei production dominated by hadronic interactions at 3 GeV.
- Looking forward to the search for the onset of deconfinement in BES-II and NICA/MPD.