Recent STAR results on strangeness/hypernuclei production

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Why strangeness?

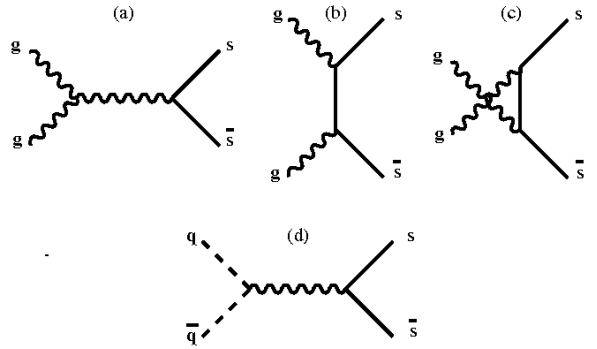
- Strange quarks
  - Not exist in colliding nuclei
  - Current mass ~100 MeV < T_c
  - Easily pair-produced in de-confined QGP medium

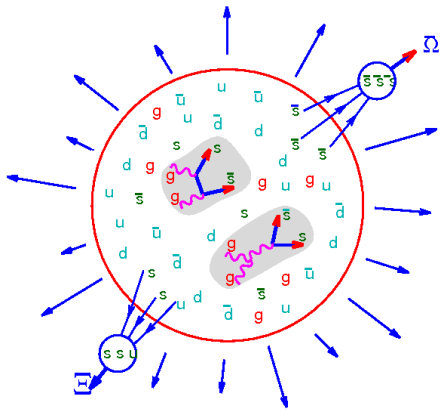
⟶ Strangeness enhancement !

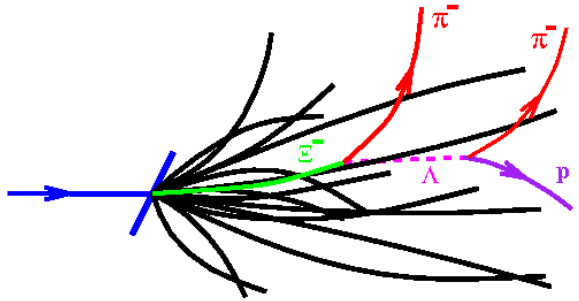
- Hadrons with (multiple) strange quarks
  - Small hadronic cross section
  - Sensitive to the early stage dynamics of the medium
  - Can be easily reconstructed and identified in experiment, up to high p_T !

⟶ Systematic study of medium properties!

Rafelski & Müller, 1982



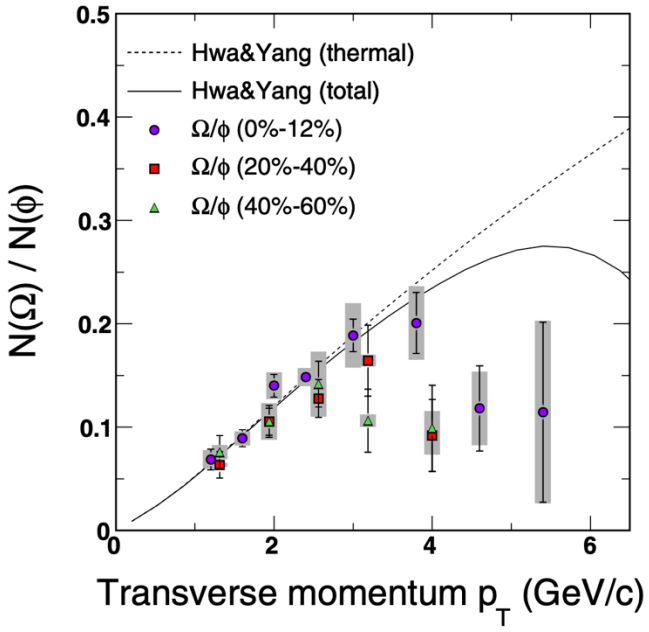




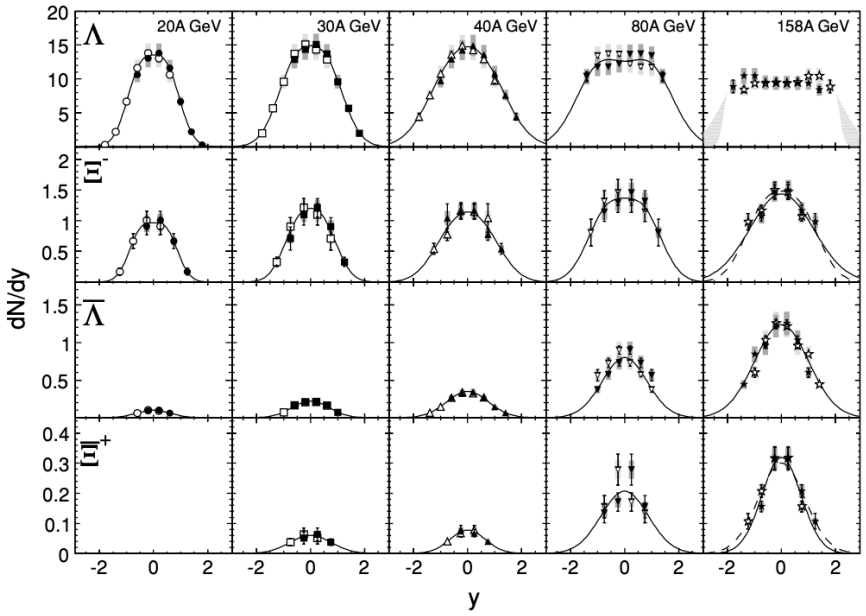
Motivation

- 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.

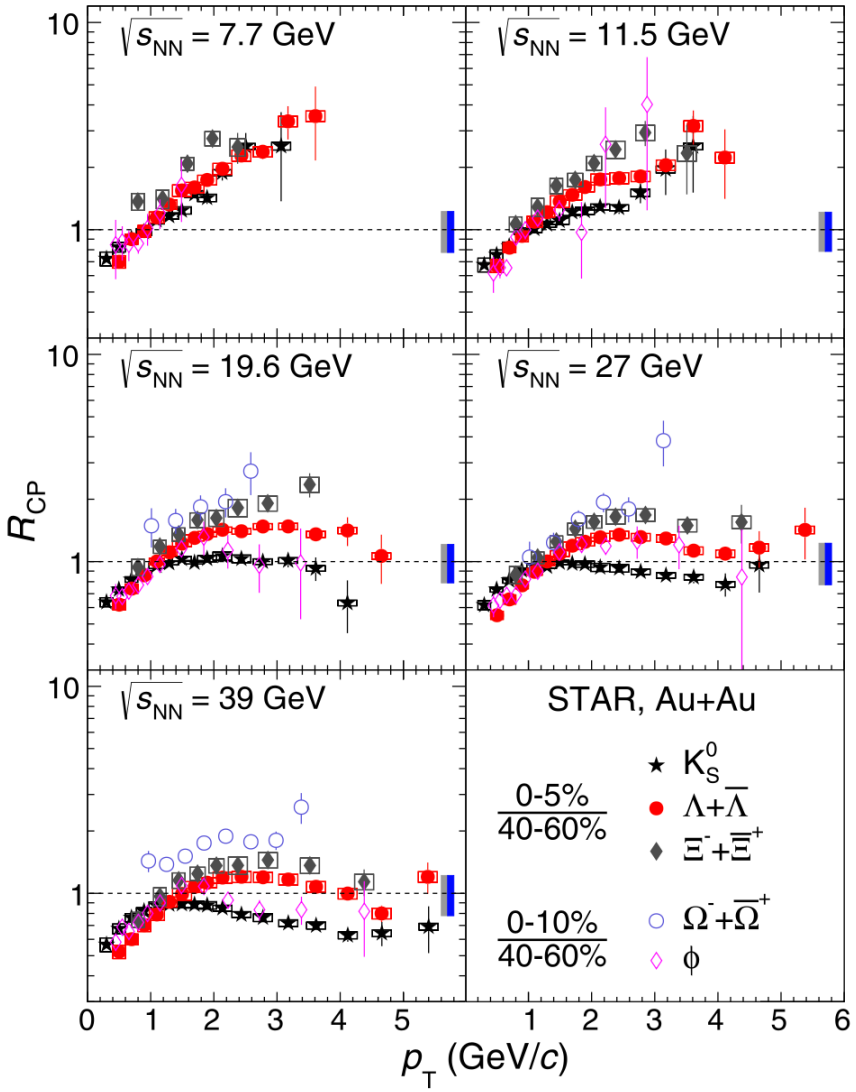
$$R_{CP} = \frac{[(dN/dp_T)/\langle N_{coll}\rangle]_{central}}{[(dN/dp_T)/\langle N_{coll}\rangle]_{peripheral}}$$



STAR, PRL 99, 112301 (2007)



NA49, PRC 78, 034918 (2008)

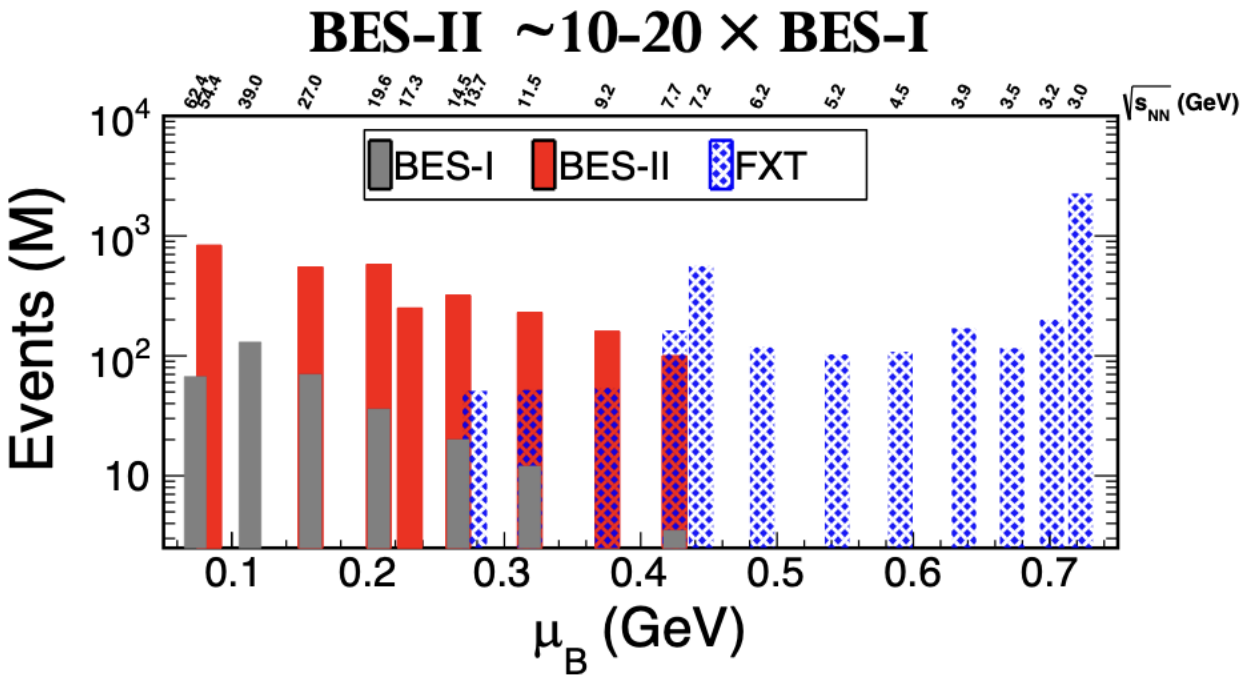


STAR, PRC 102, 034909 (2020)

Motivation

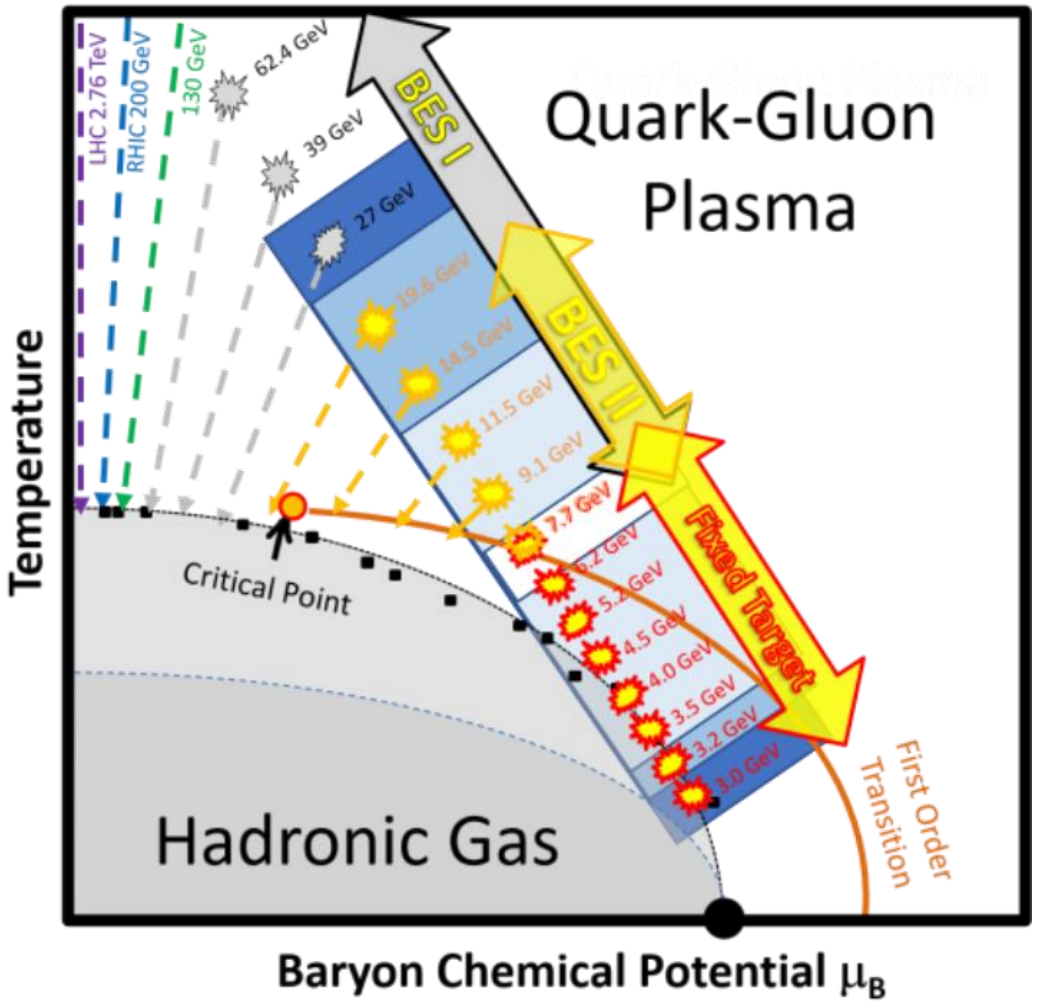
Beam Energy Scan (BES) program:

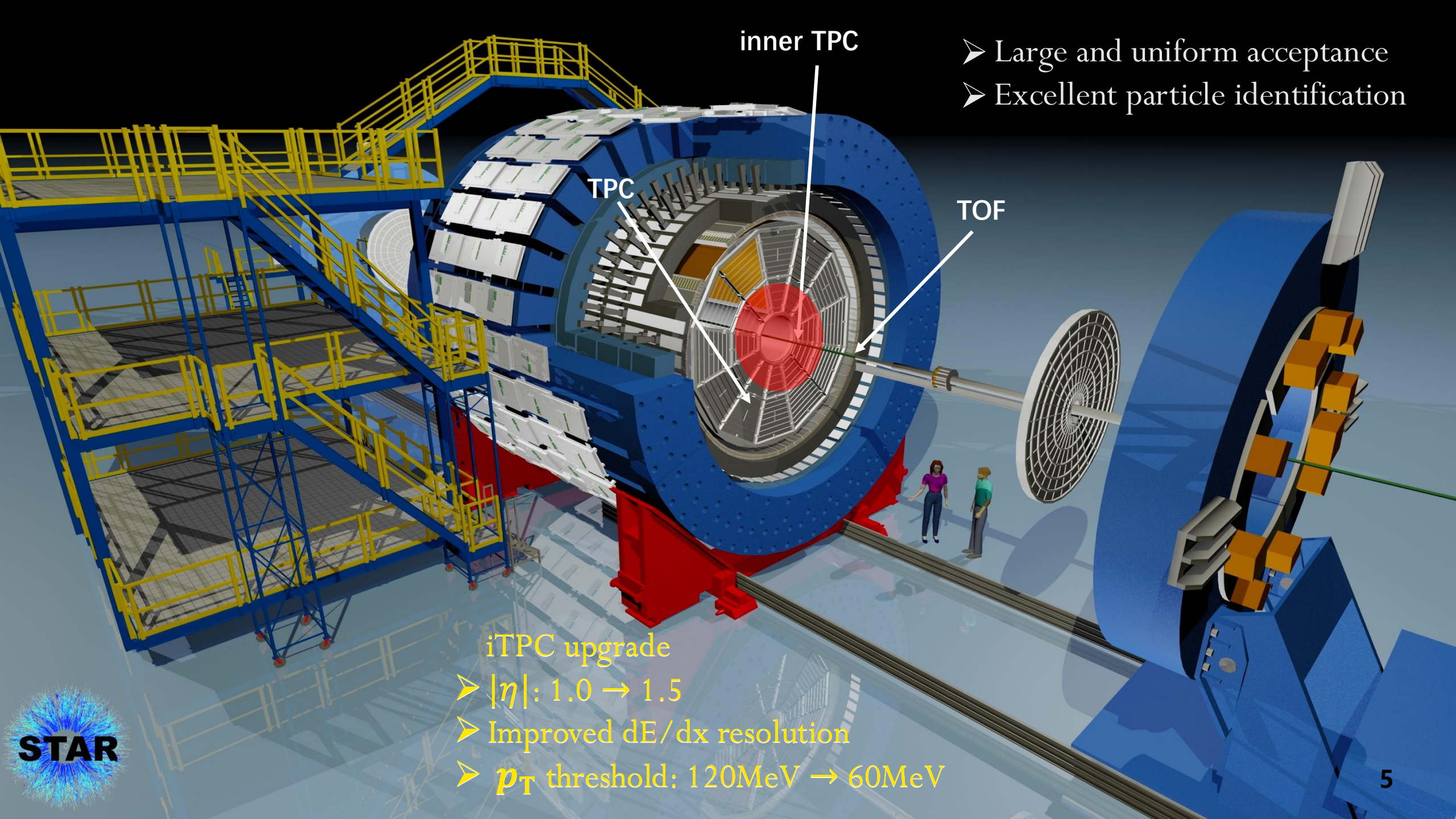
- Search for the onset of deconfinement
- Search for the first-order phase transition
- Search for the critical point



Yi Fang, Xiongxiong Xu, Weiguang Yuan, QM23/SQM24/CPS24

Hongcan Li, Xiujun Li, SQM24; Yingjie Zhou, iHIC24





- Large and uniform acceptance
- Excellent particle identification

iTPC upgrade

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

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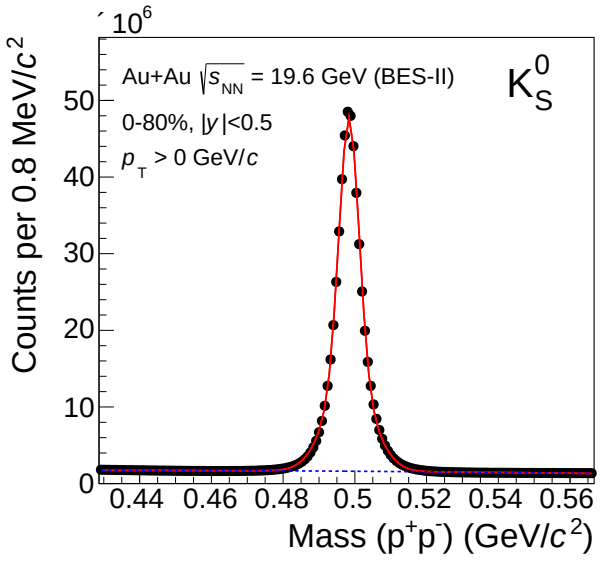
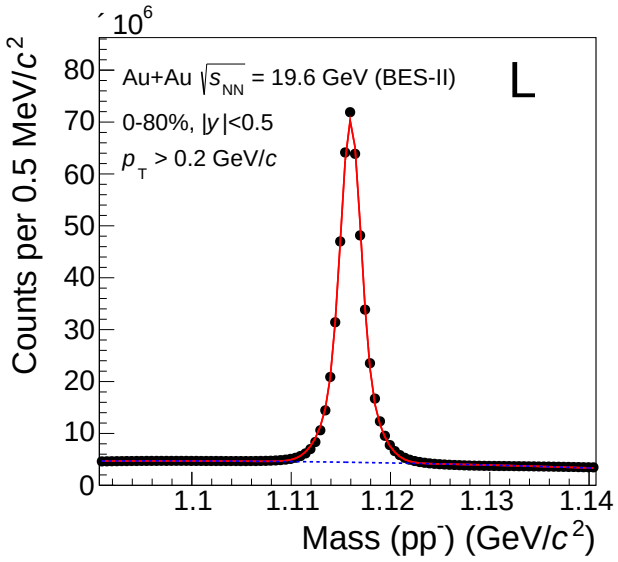
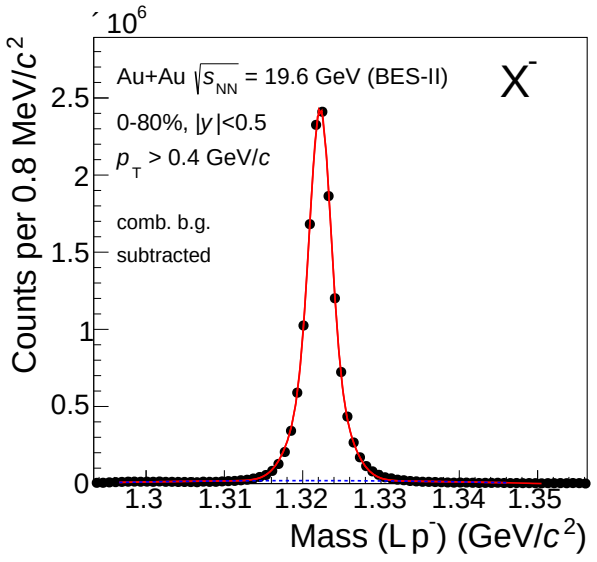
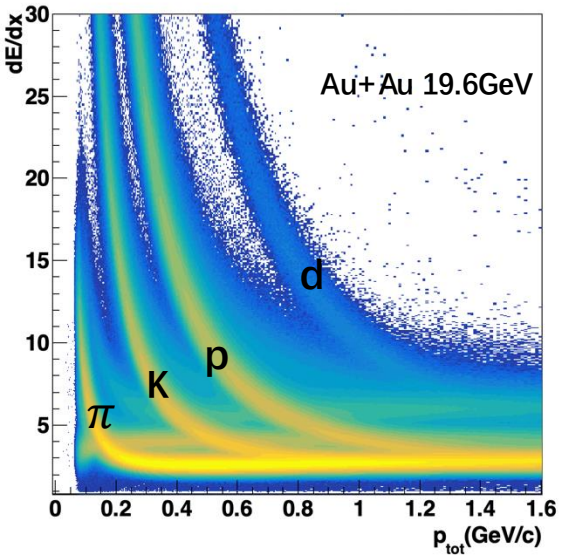
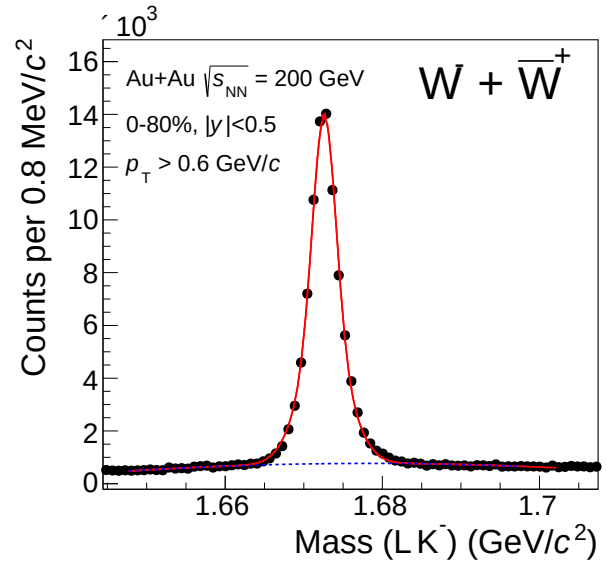
Particle identification and reconstruction

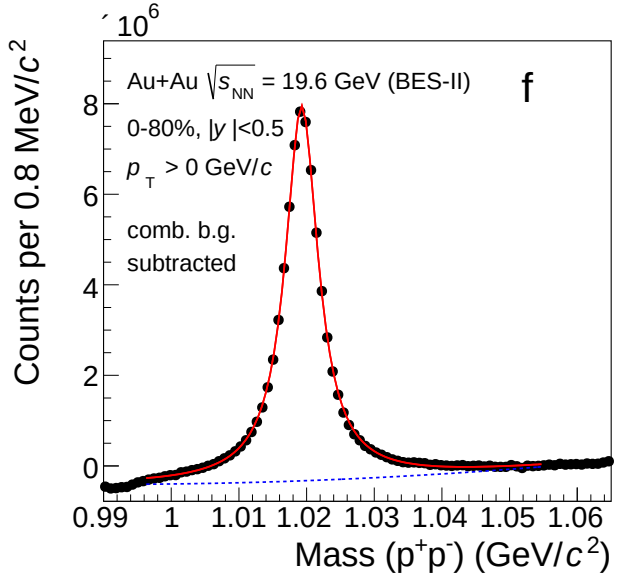








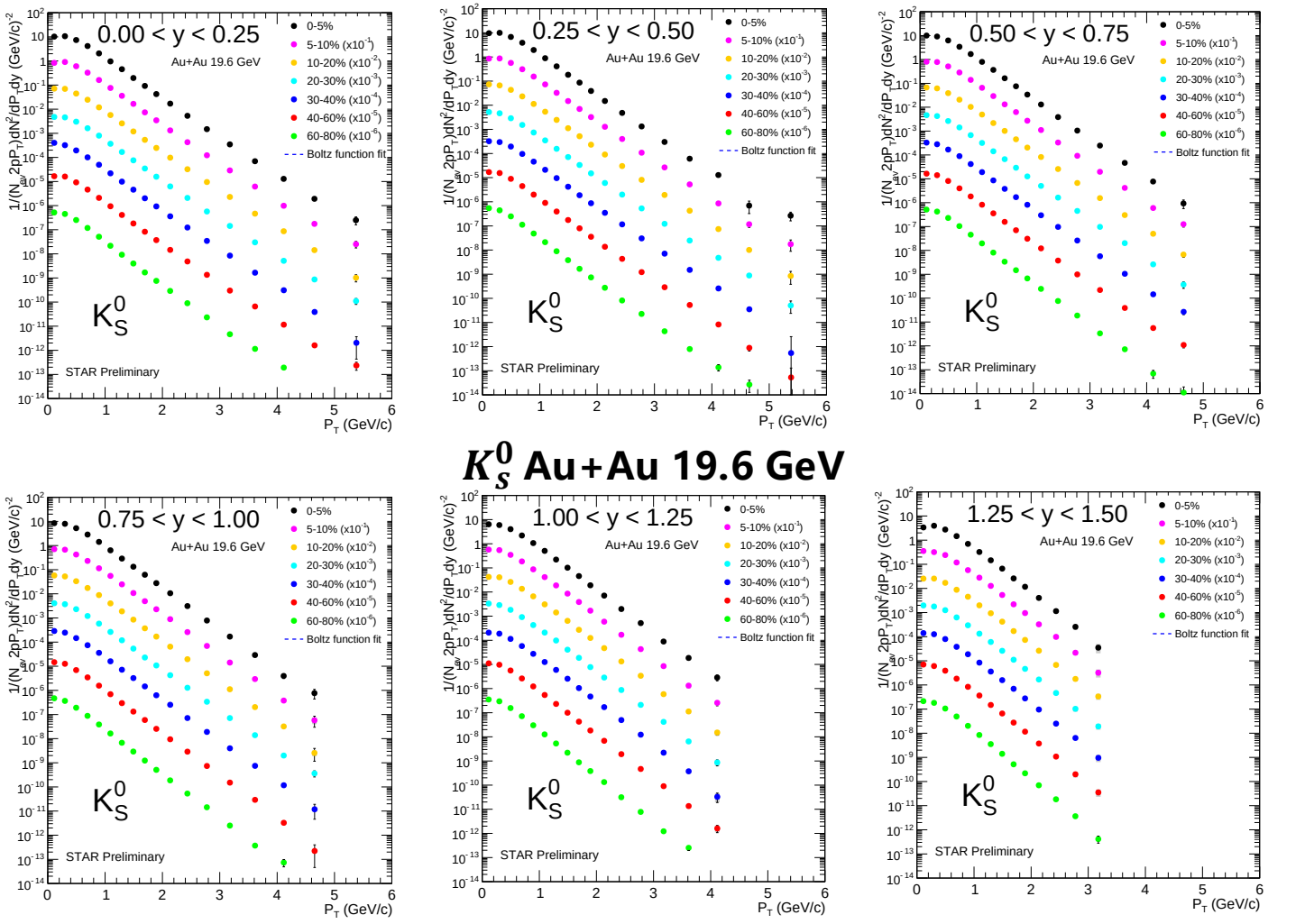




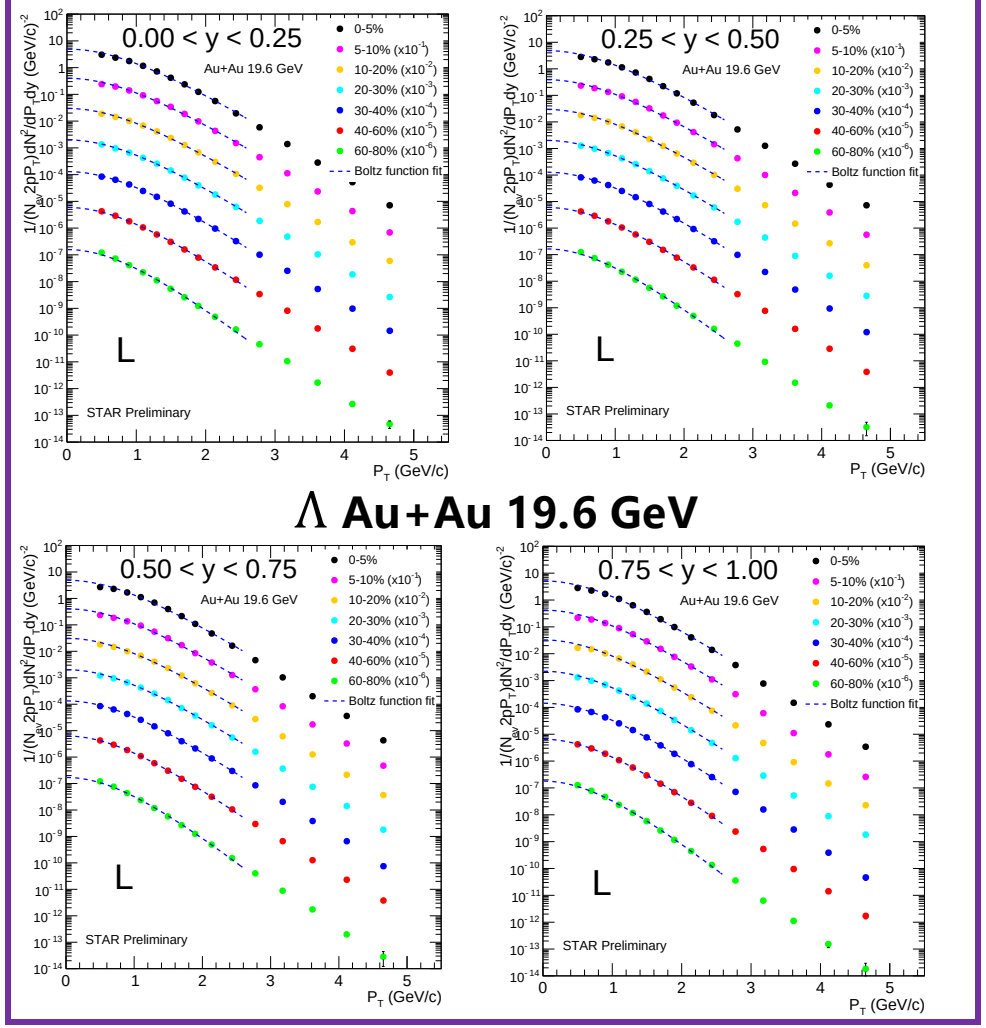
- Particle identification with dE/dx.
- π, K, p are used to reconstruct the secondary vertex of strange particles.
- TMVA optimization to improve Ω signal significance
- Large number of strange particles allow multi-differential measurements.

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

p_T spectra of K_s^0 and Λ at 19.6 GeV



K_s^0 Au+Au 19.6 GeV



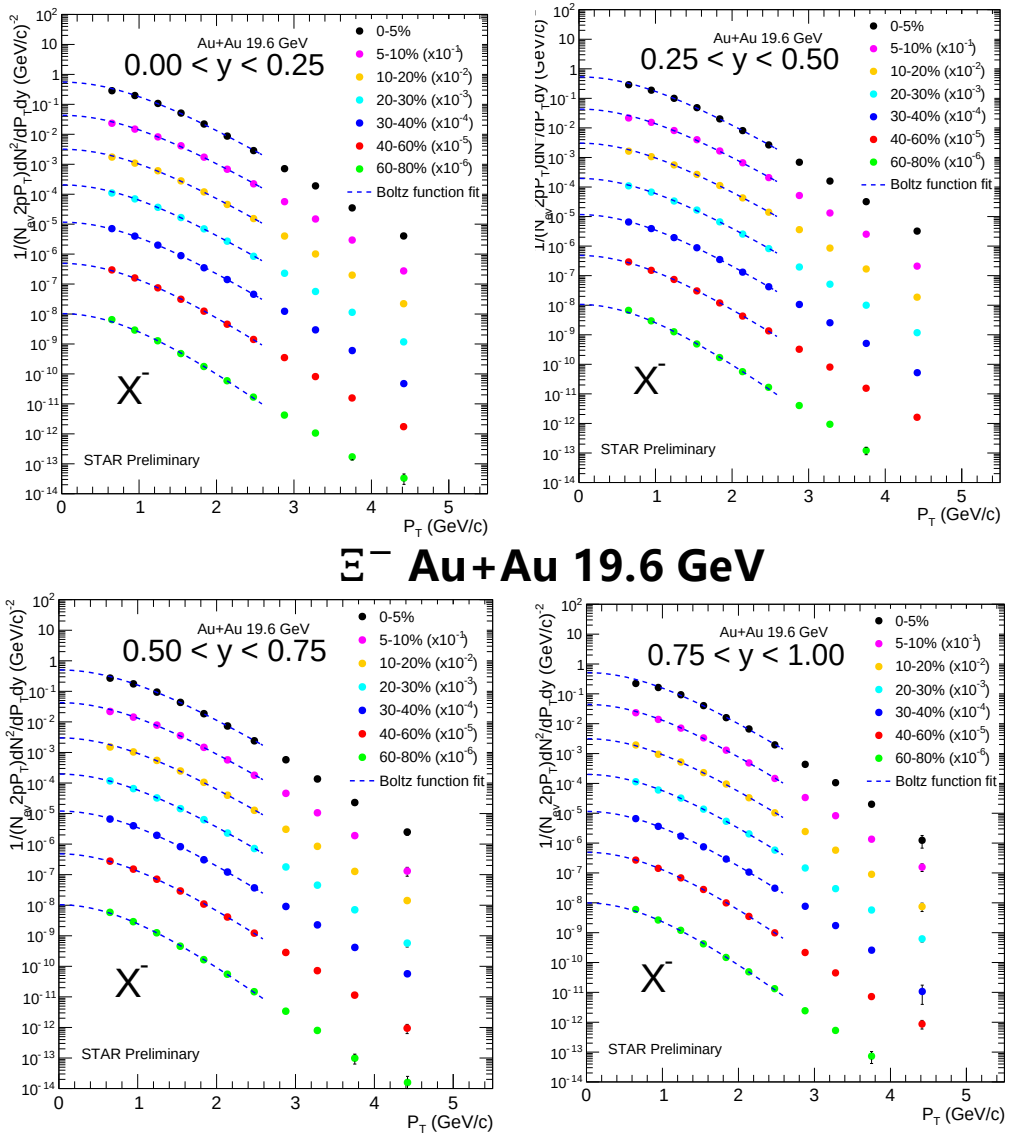
Λ Au+Au 19.6 GeV

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

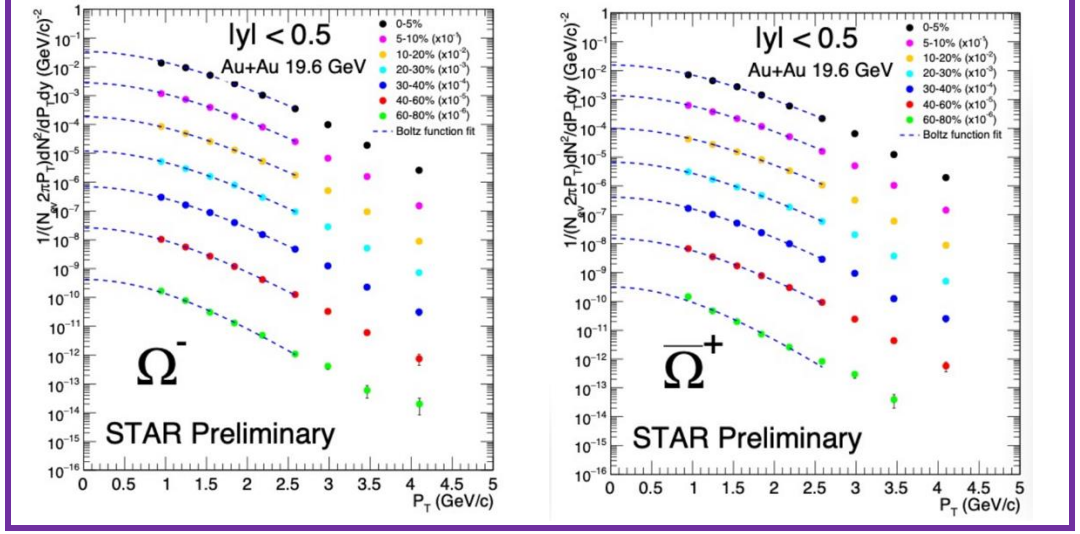
- Low p_T extrapolation: Boltzmann function
- Corrected for Ξ^- and Ξ^0 feed-down

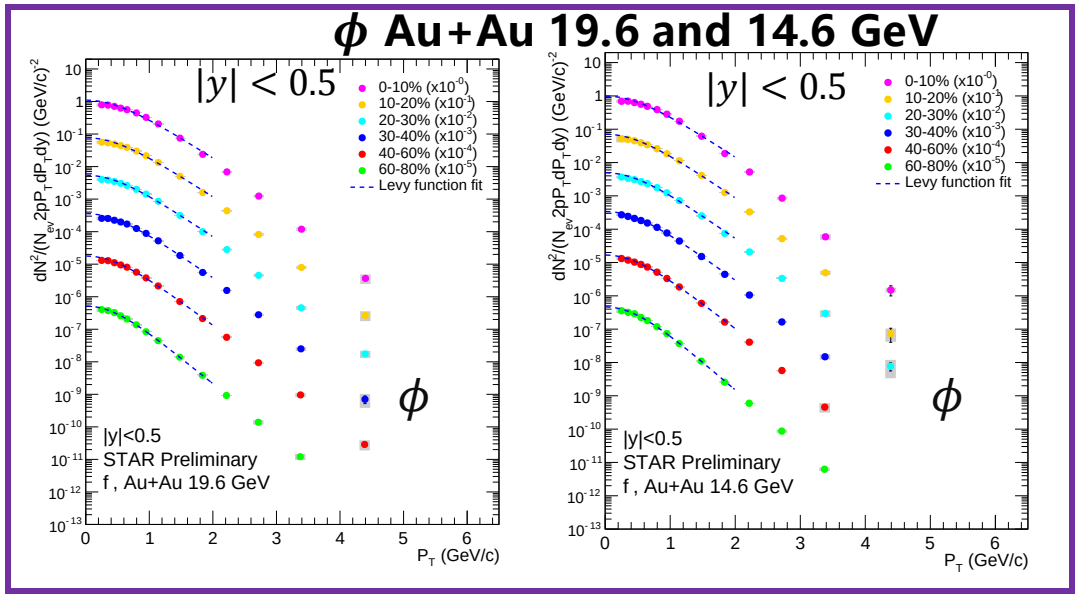
Rapidity: $|y| < 1$

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



Ξ^- Au+Au 19.6 GeV



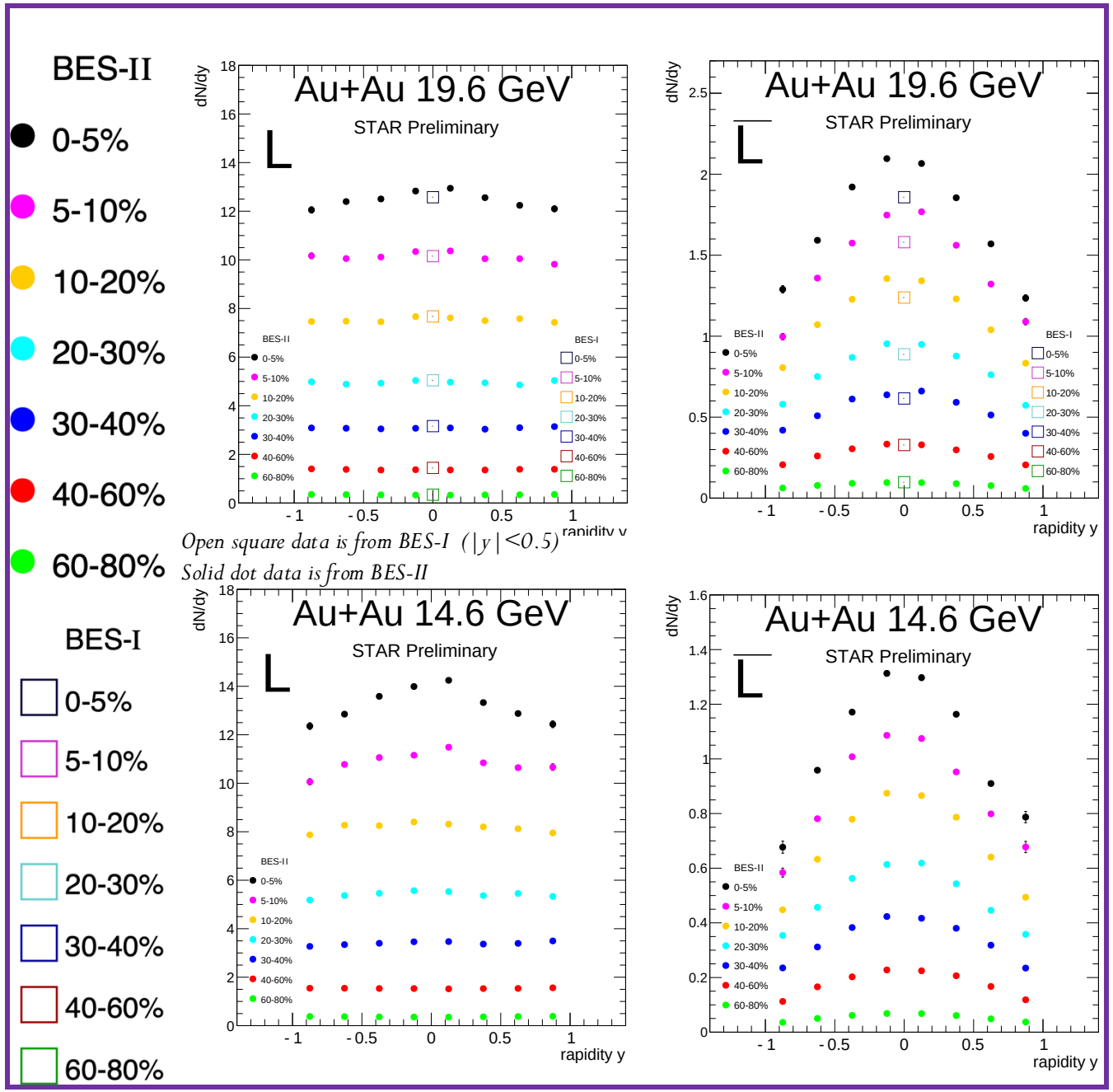


- Ξ^- Low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 1.0$
- Ω low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 0.5$
- ϕ low p_T extrapolation: Levy function
- Rapidity: $|y| < 0.5$

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

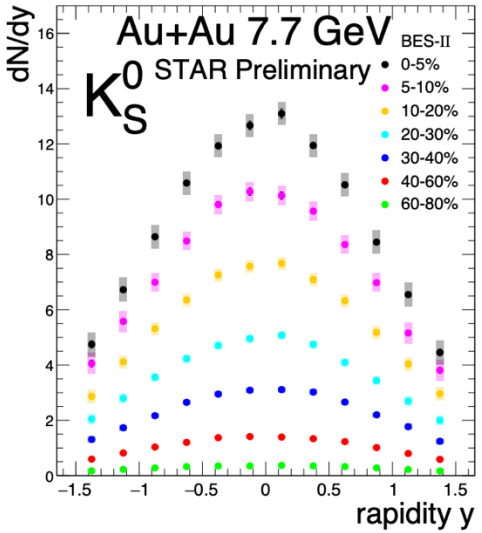
- Rapidity spectra of anti-baryons($\bar{\Lambda}$) are Gaussian-like distributions.
- Rapidity distribution of baryons(Λ) are wider than that of anti-baryons ($\bar{\Lambda}$).
  - ✓ Extra contributions from stopped baryons
- Similar trends observed by NA49.

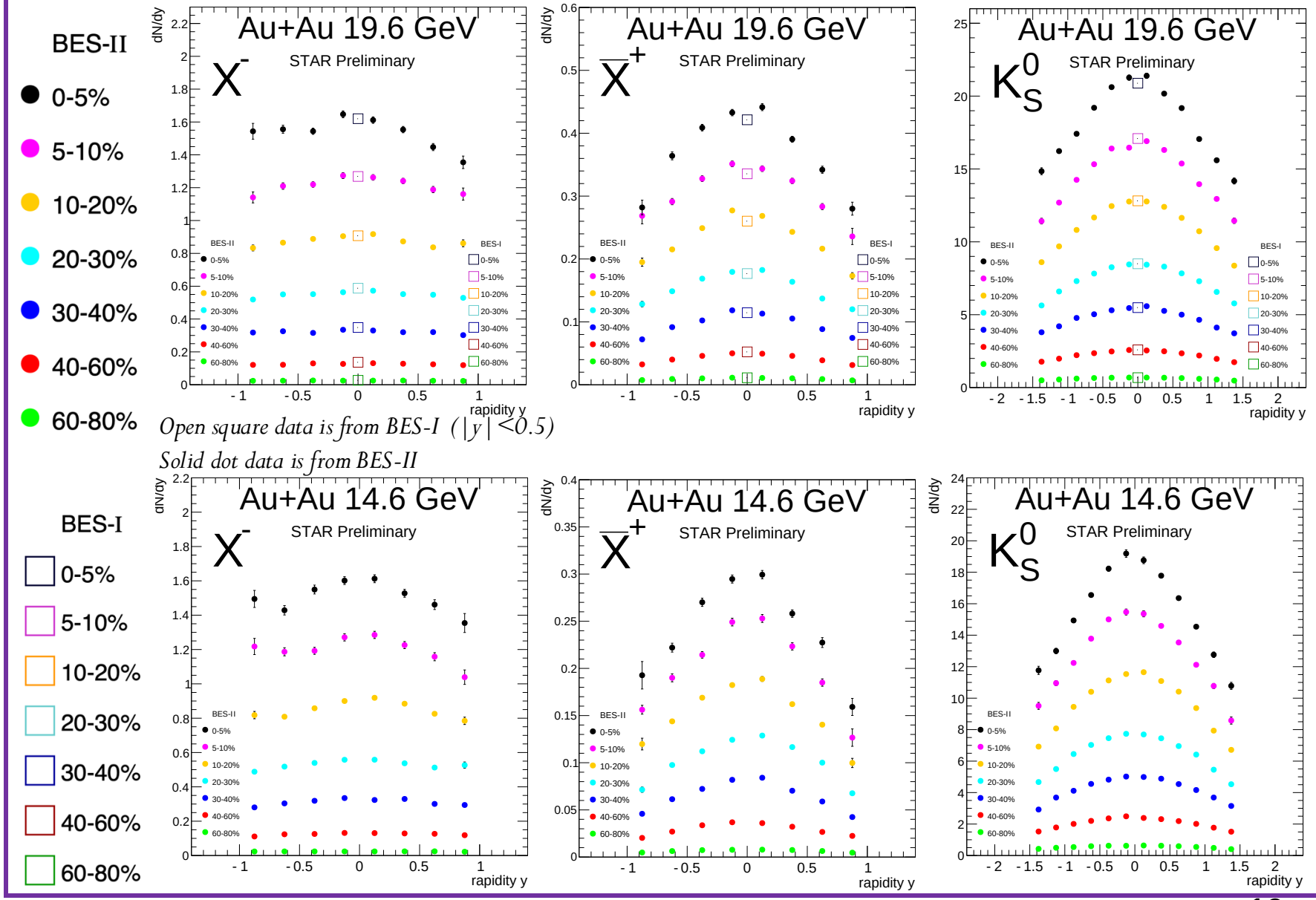
NA49, PRC 78, 034918 (2008)



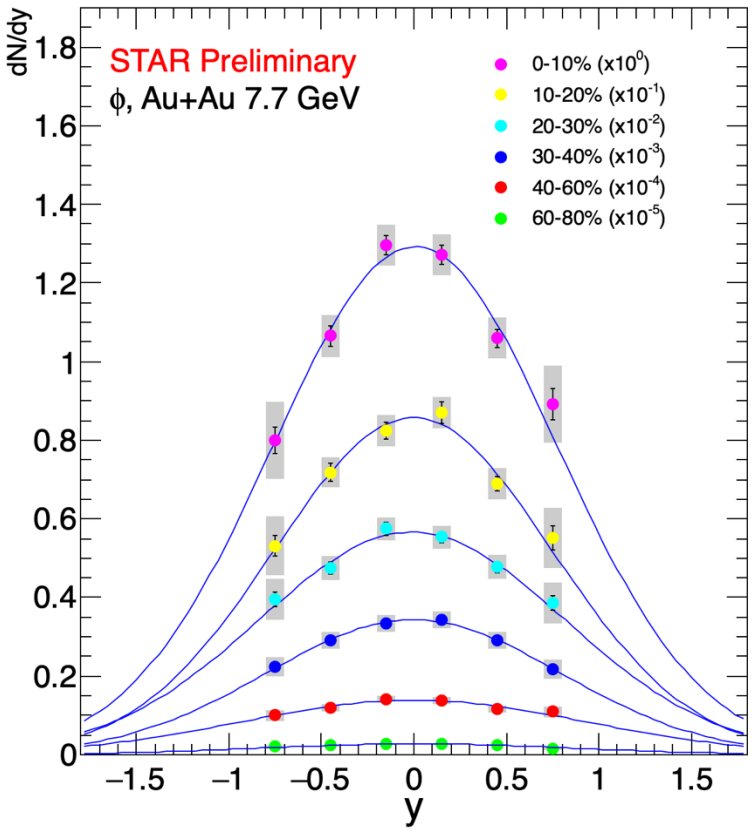
Rapidity spectra of K_s^0, Ξ^- and $\bar{\Xi}^+$ at 19.6 and 14.6 GeV

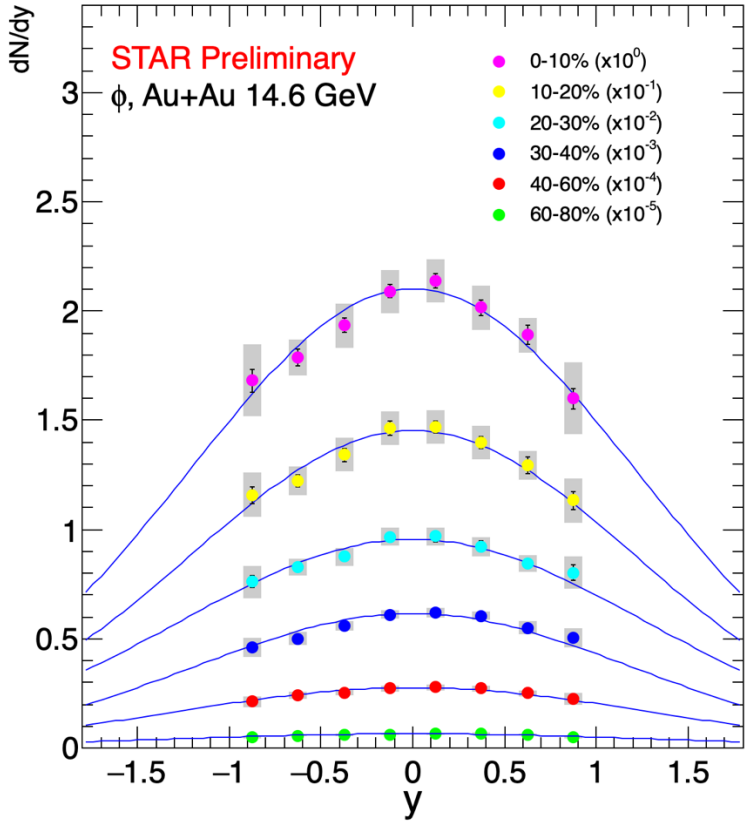
- Rapidity spectra of mesons (K_s^0) and anti-baryons($\bar{\Xi}^+$) are Gaussian-like distributions.
- Rapidity distribution of baryons(Ξ^-) are wider than the distributions of the anti-baryons($\bar{\Xi}^+$) in Au+Au collisions.

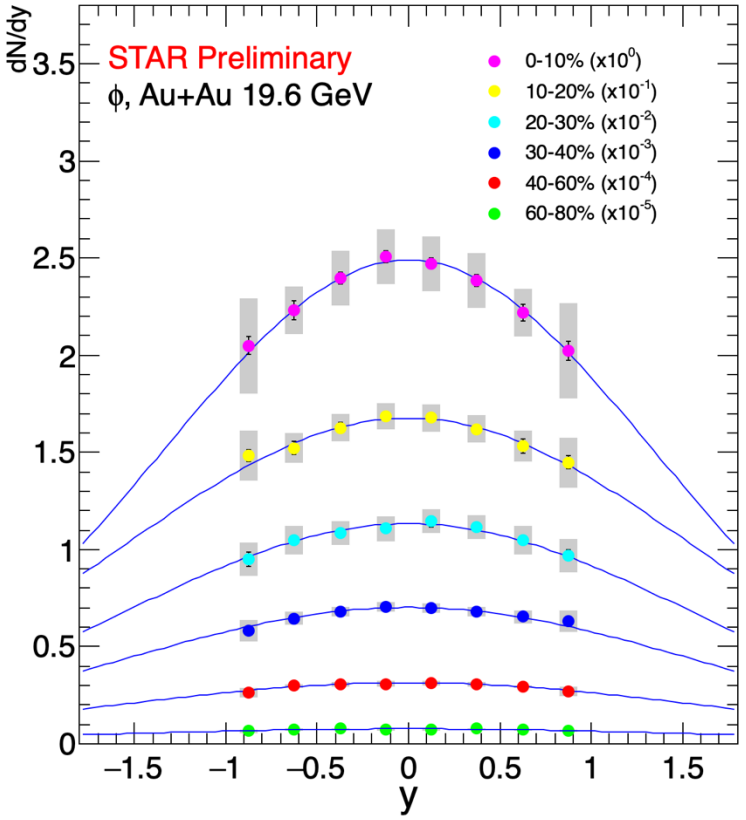




Rapidity spectra of ϕ



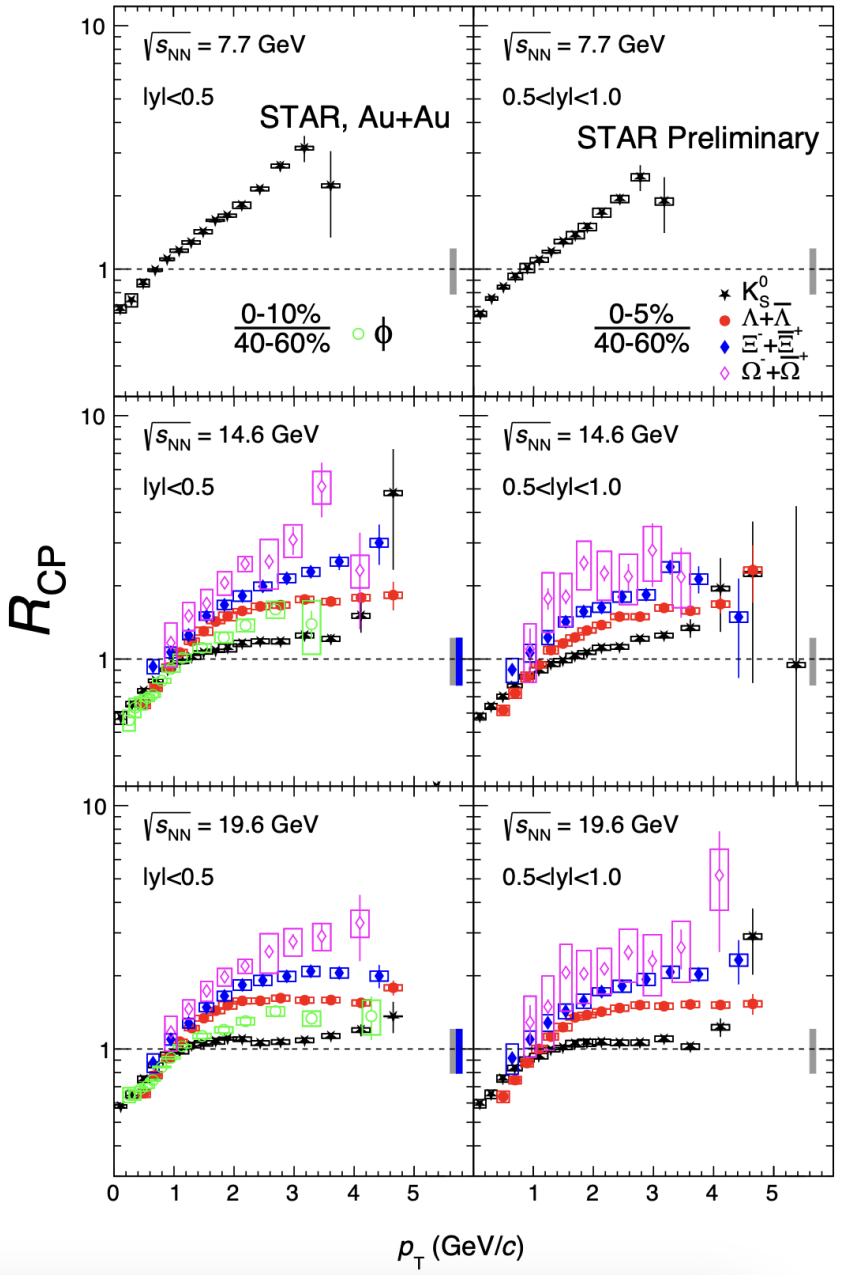




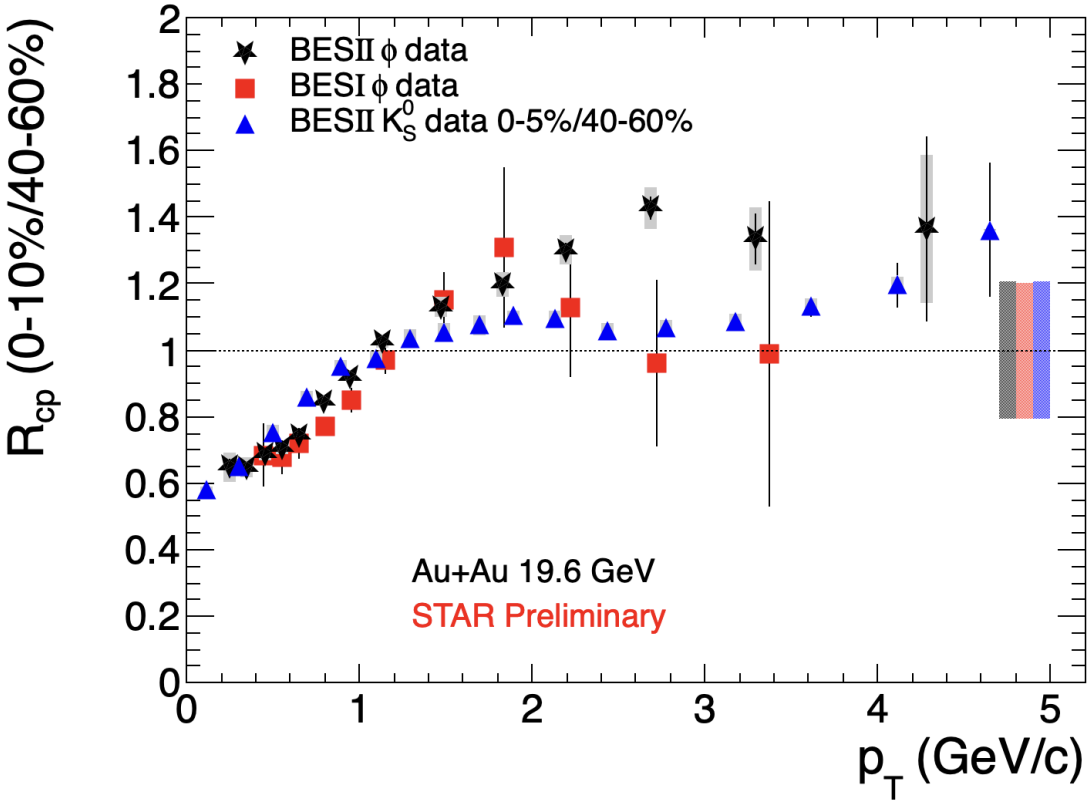
- Rapidity spectra of ϕ are Gaussian-like distributions
- Rapidity distribution become wider with increasing energy

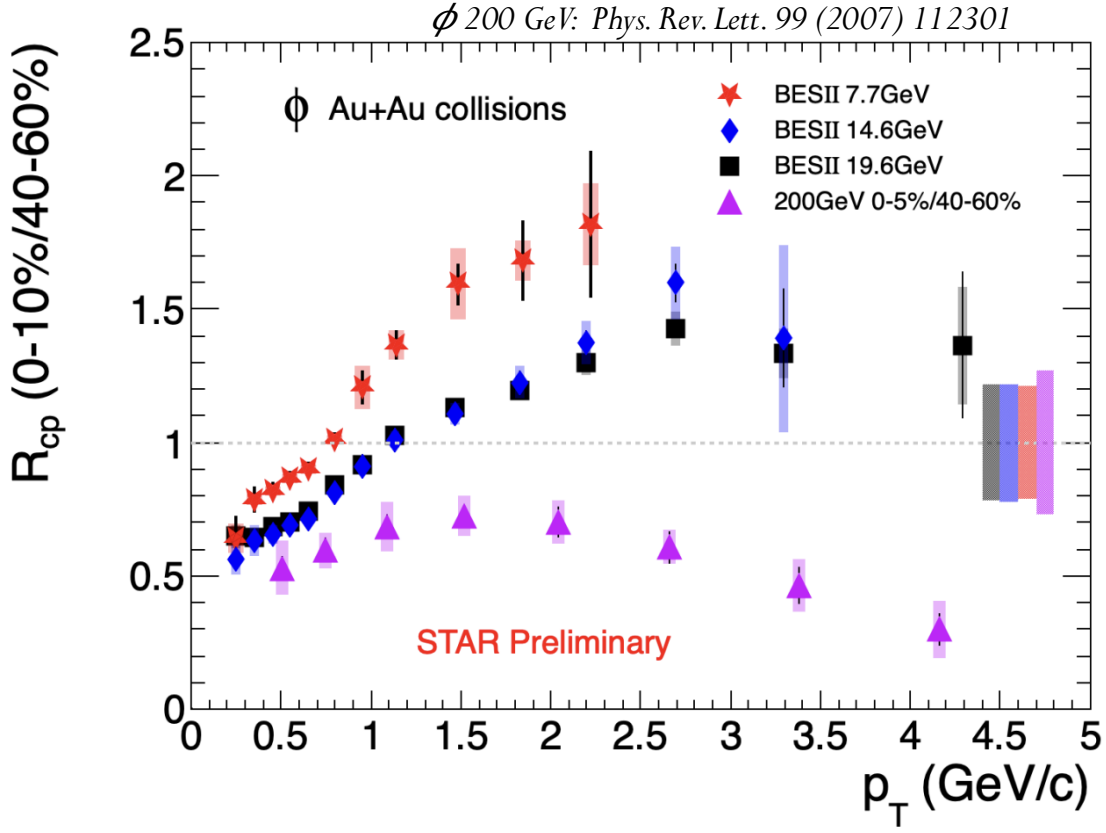
Nuclear modification factor at 19.6, 14.6 and 7.7 GeV

- 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.



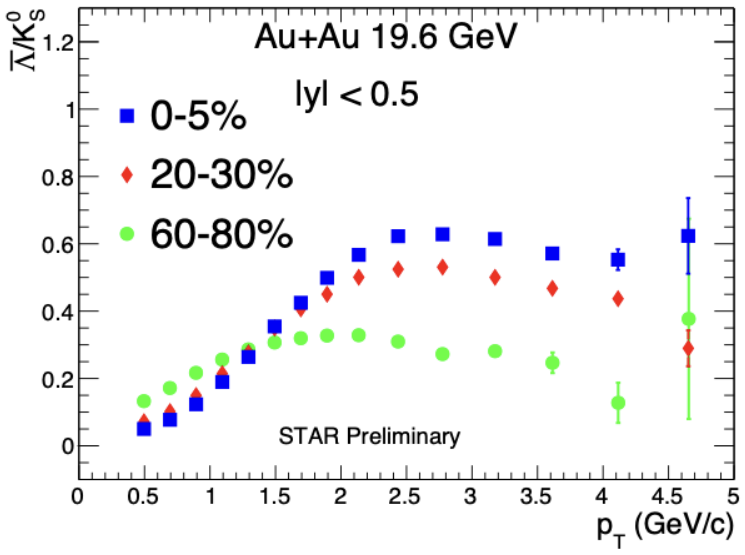
Nuclear modification factor for ϕ

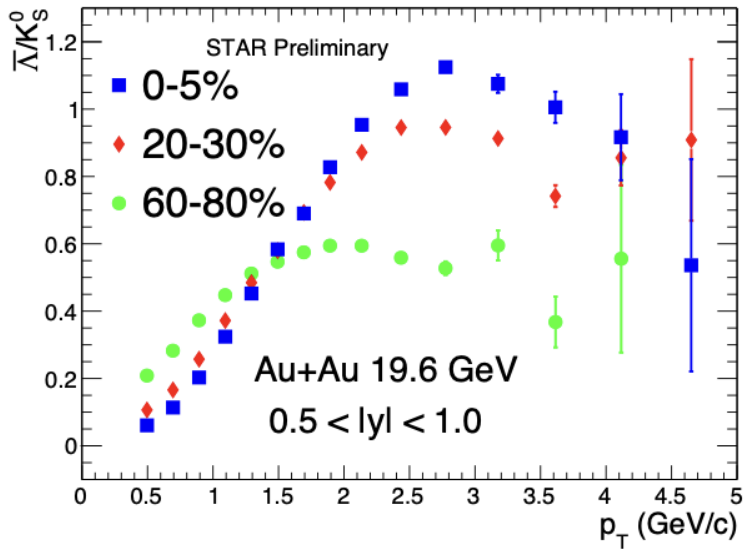


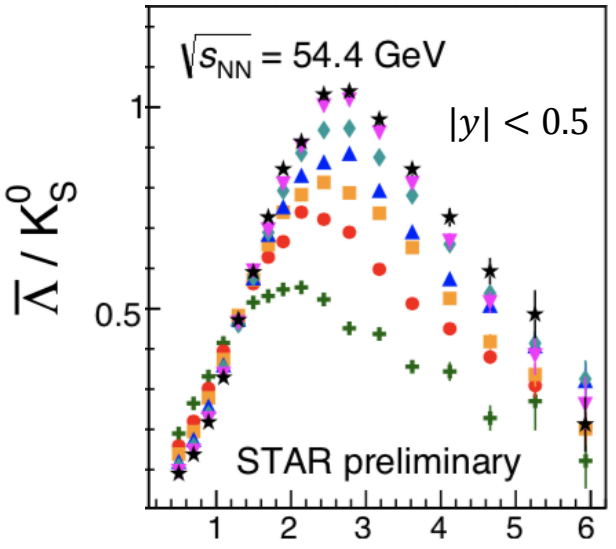


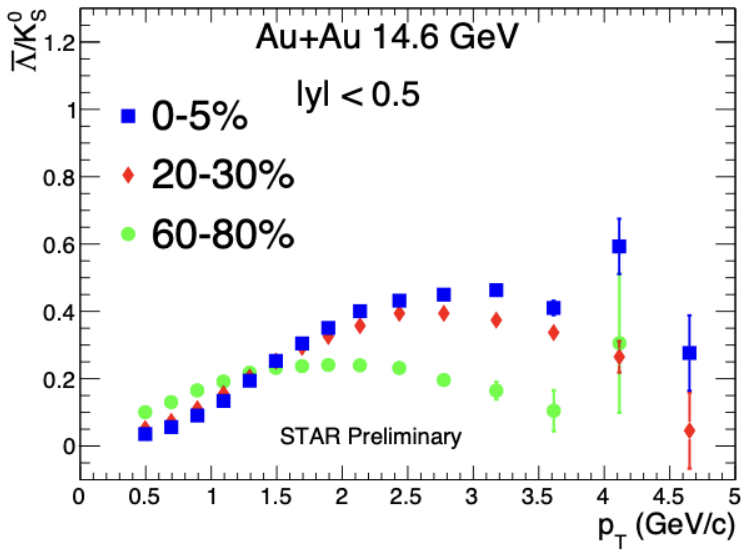
- BES-II result is consistent with BES-I with greatly improved precision
- $R_{CP}(\phi) > R_{CP}(K^0_S)$ at $2 < p_T < 4$ GeV/c
- $R_{CP} < 1$ for higher p_T at 200 GeV → Partonic energy loss in the QGP medium
- $R_{CP} > 1$ for higher p_T at 19.6 GeV and lower energies → Cronin-type interactions, radial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

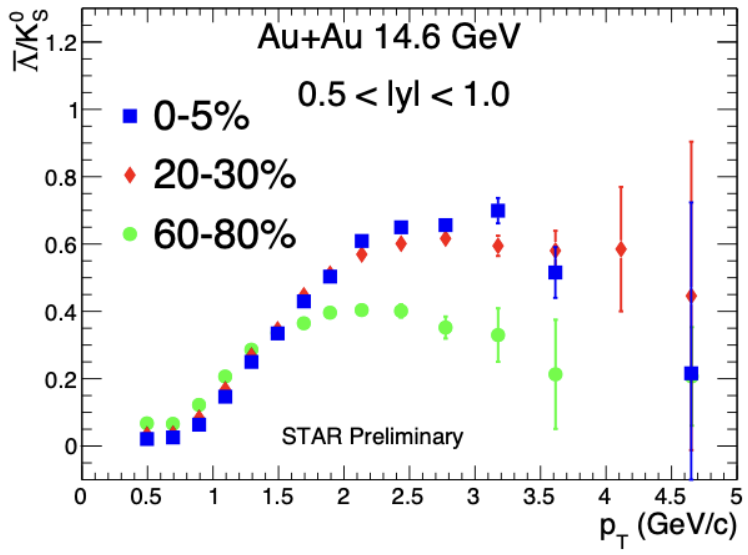
$\overline{\Lambda}/K_s^0$ ratio at 54.4, 19.6 and 14.6 GeV





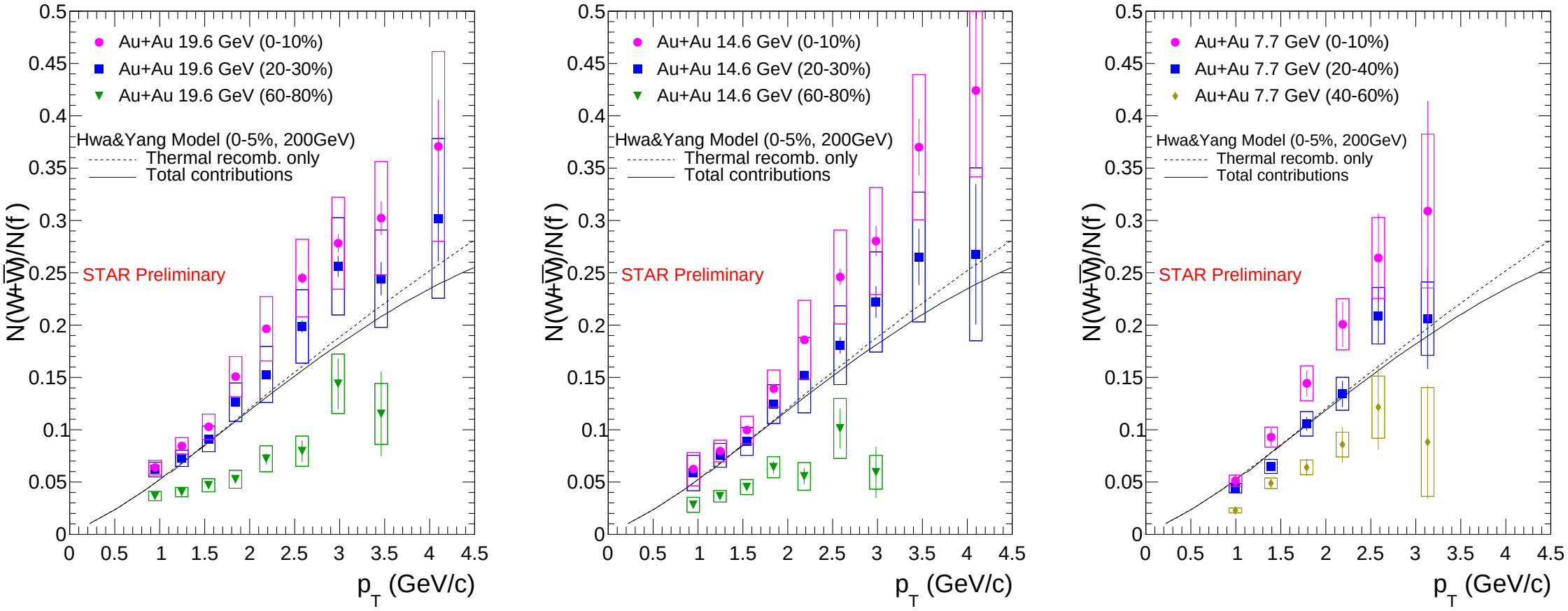






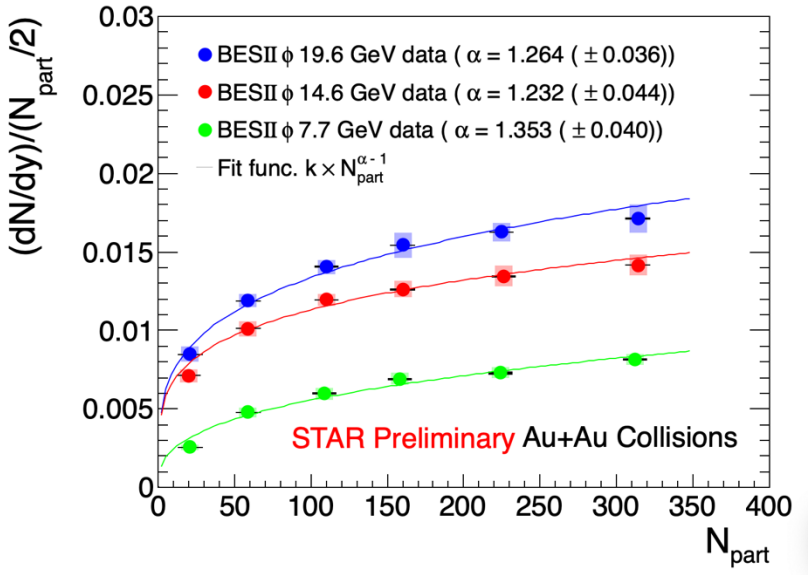
- Clear centrality and rapidity dependence of (anti-)baryon-to-meson ratio at intermediate p_T.
- Baryon enhancement is observed in all measured rapidity regions.

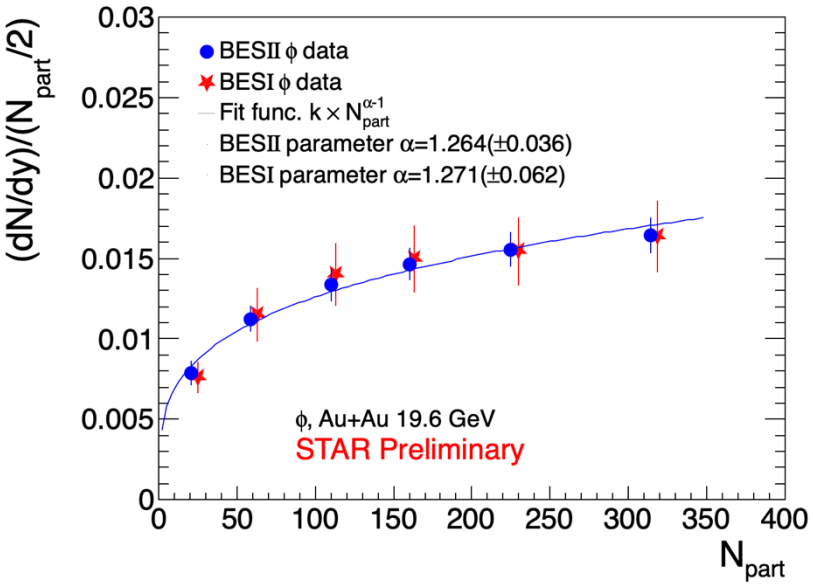
$\Omega(sss)/\phi(s\bar{s})$ ratio



- 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

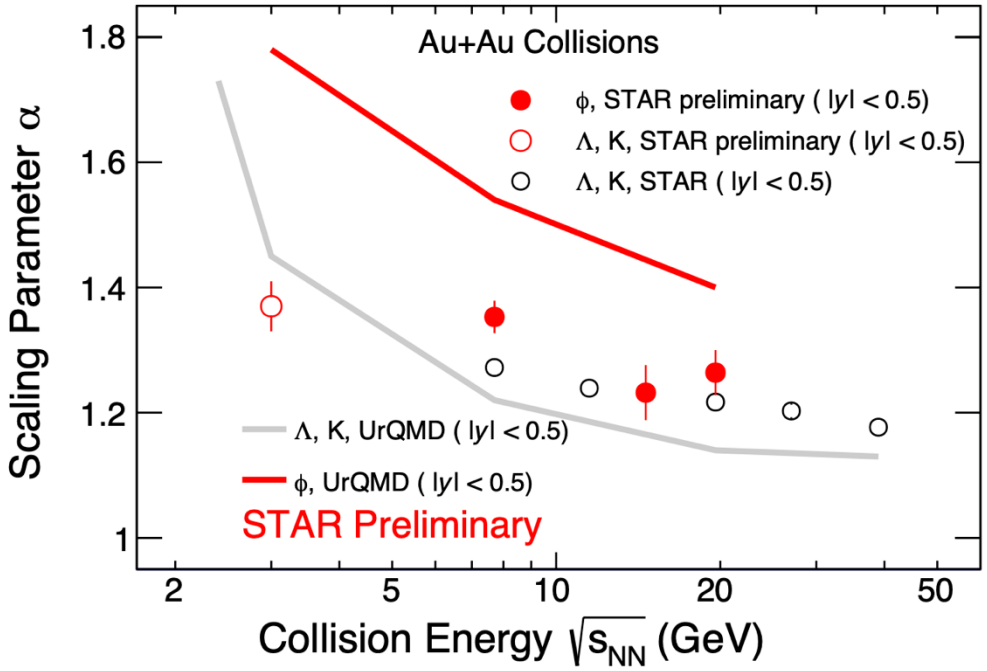
Centrality dependence of ϕ production





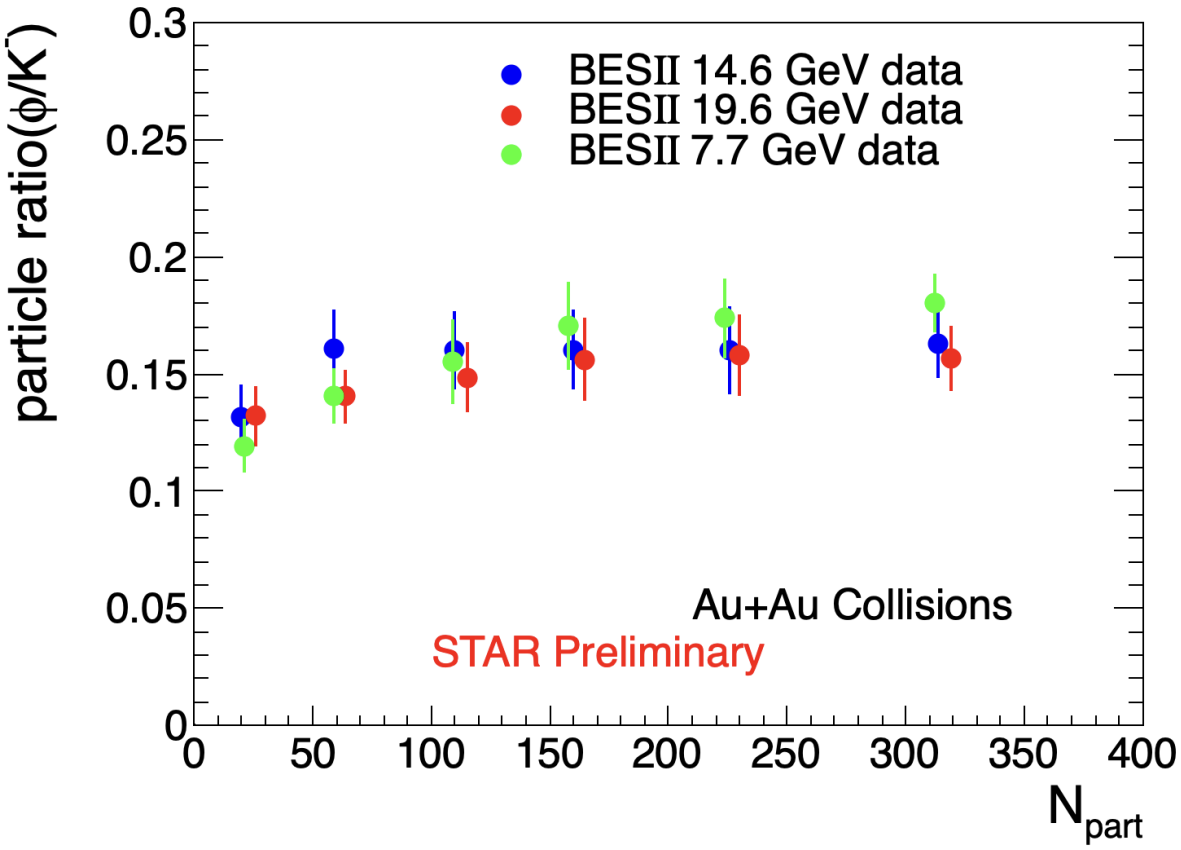
The bottom two plots show the total errors

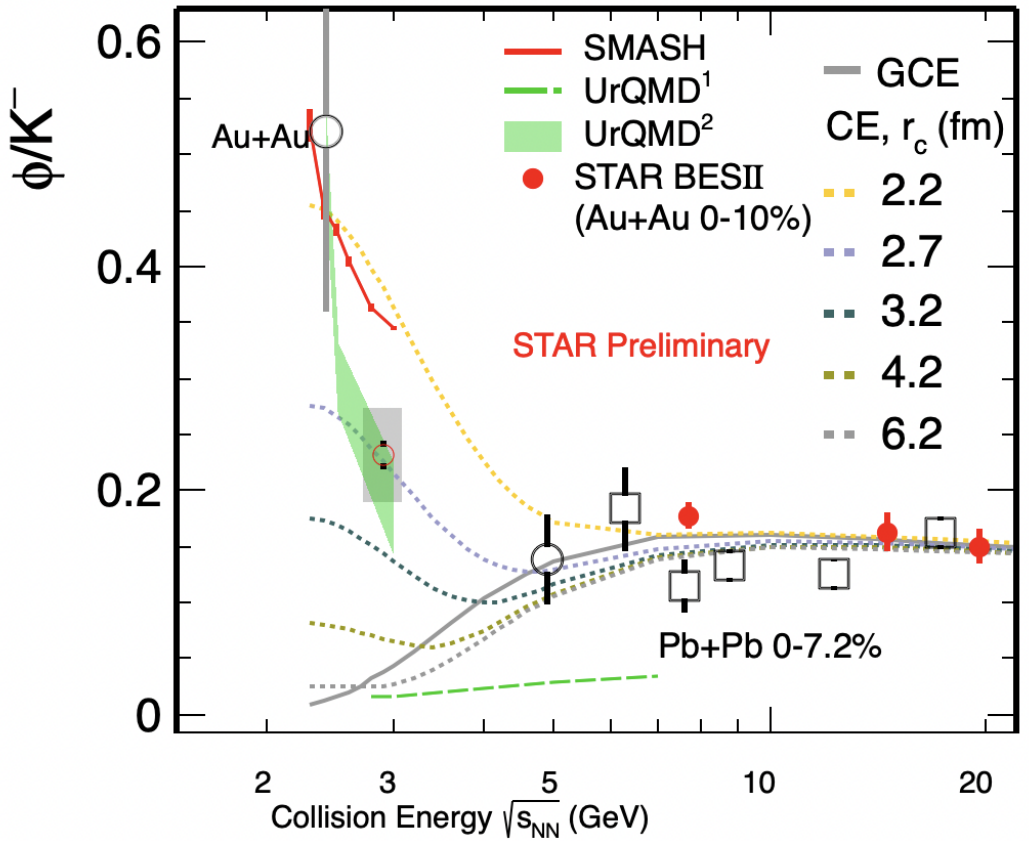
- Fit function: $\frac{dN/dy}{N_{part}/2} = k \times N_{part}^{\alpha-1}$
- Common centrality dependence for ϕ, Λ, K production at 19.6GeV.
- α parameter for ϕ is slightly larger than that for Λ, K and less than UrQMD predictions



STAR: arXiv: 2407.10110

Centrality and Energy dependence of ϕ/K^- ratio

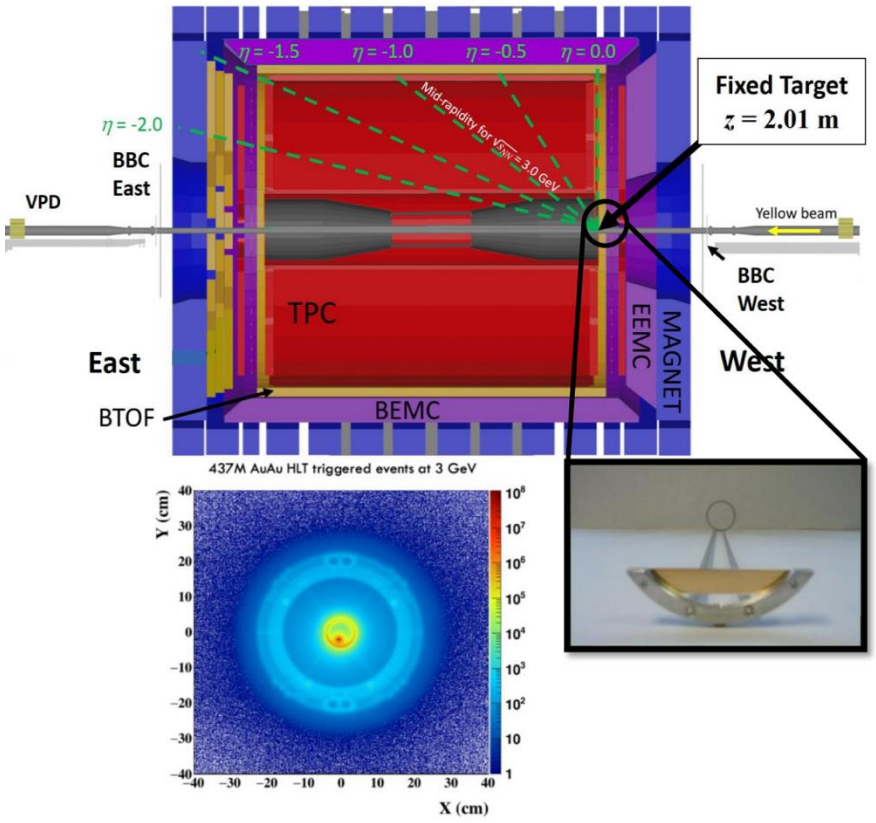


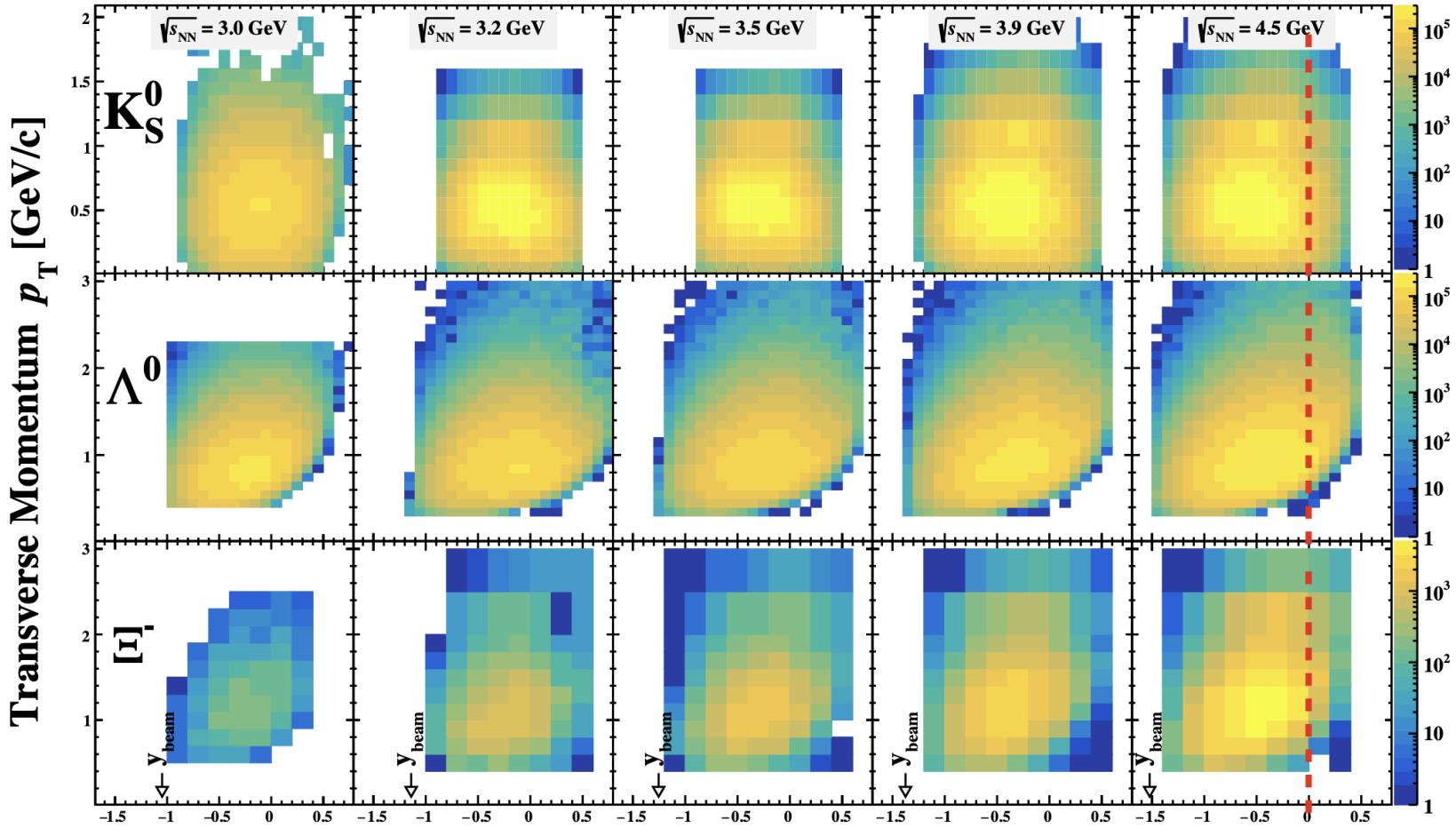


STAR: Phys. Rev. C 96 (2017) 044904
STAR: Phys. Rev. C 101 (2020) 024905
STAR: Phys. Lett. B 831 (2022) 137152

- 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

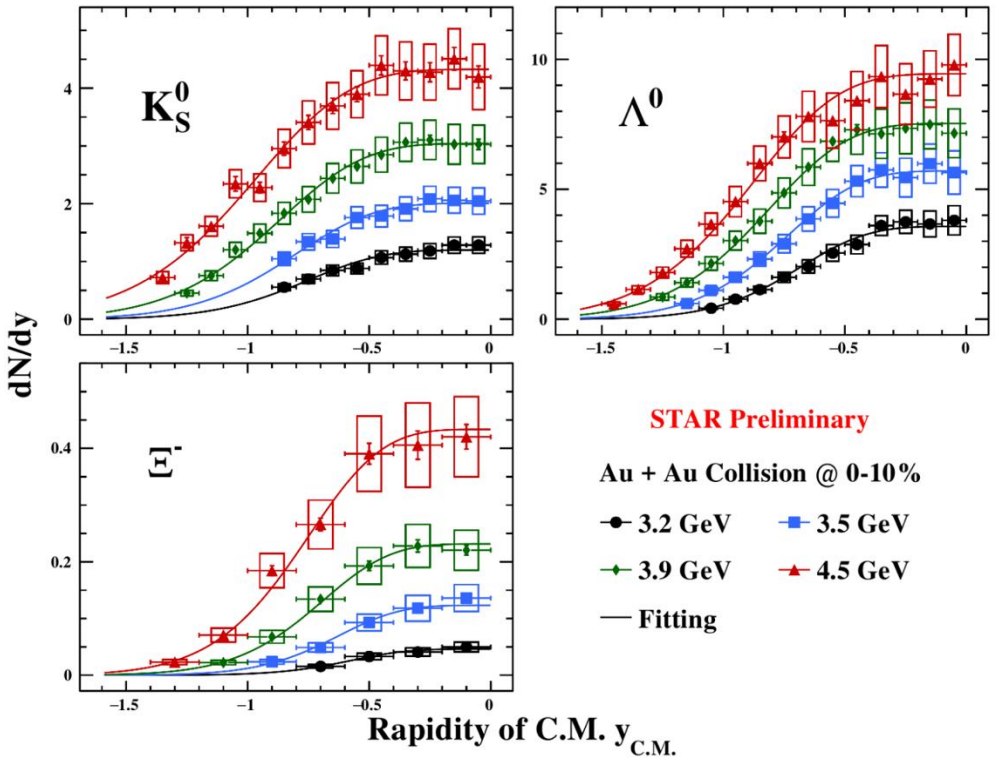




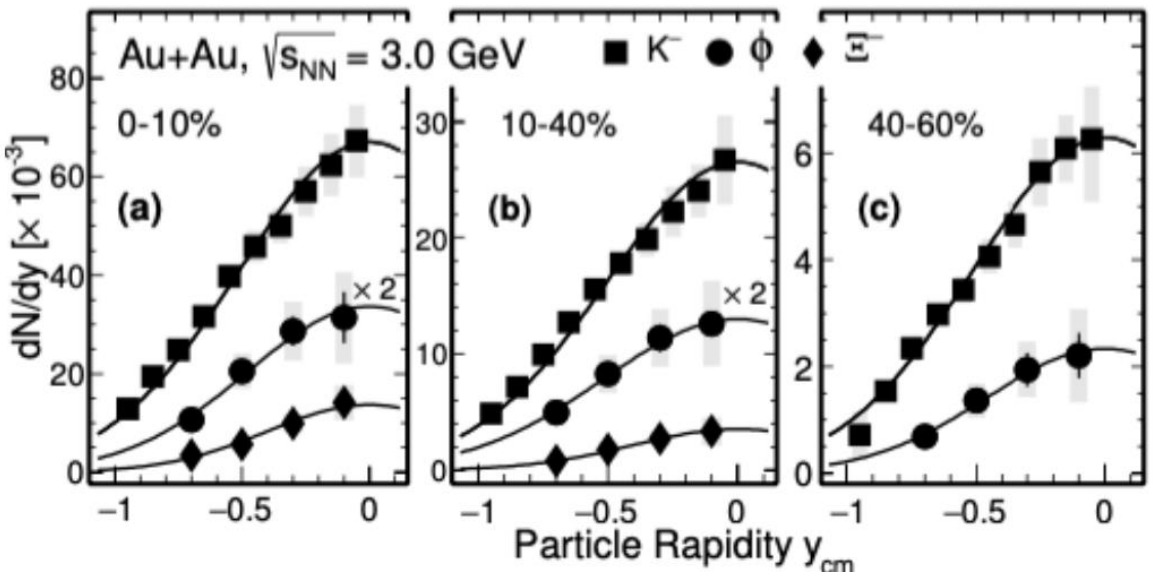
- Particle rapidity coverage from beam rapidity to mid-rapidity

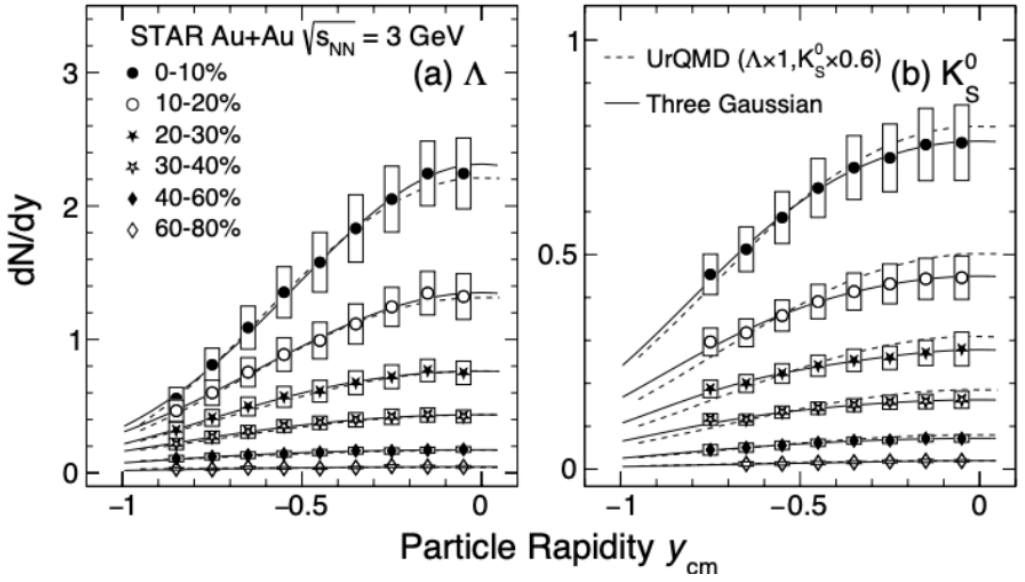
Strangeness measurements in fixed-target collisions

Hongcan Li, SQM24



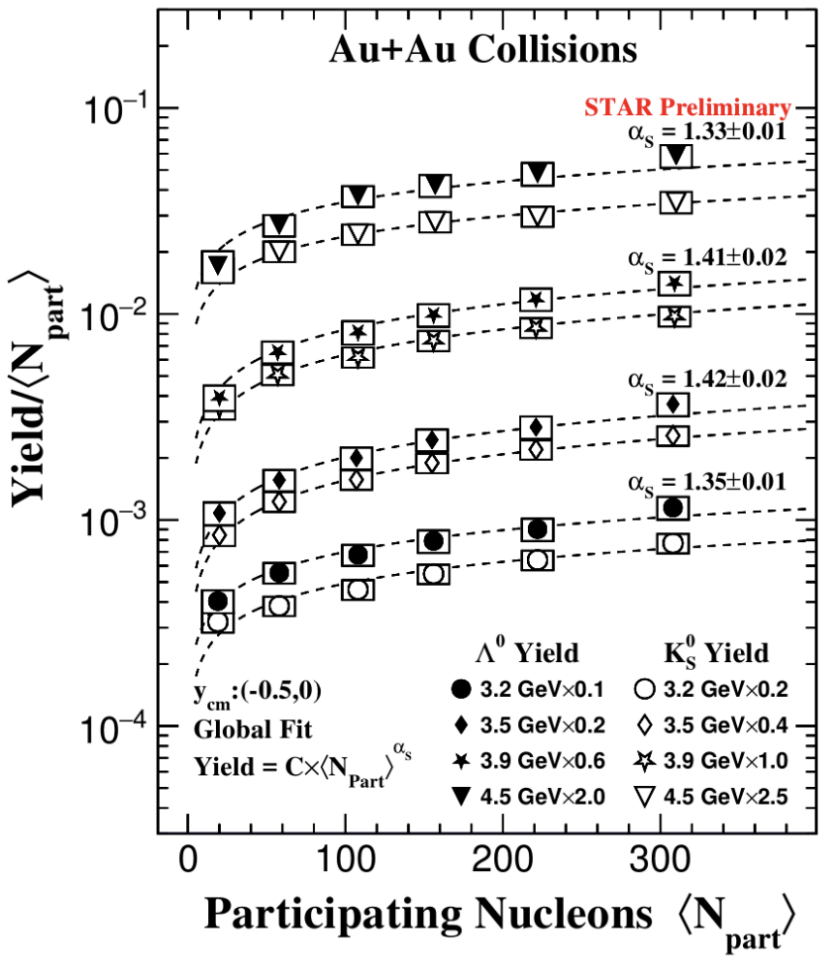
STAR: Phys. Lett. B 831 (2022) 137152; arXiv: 2407.10110

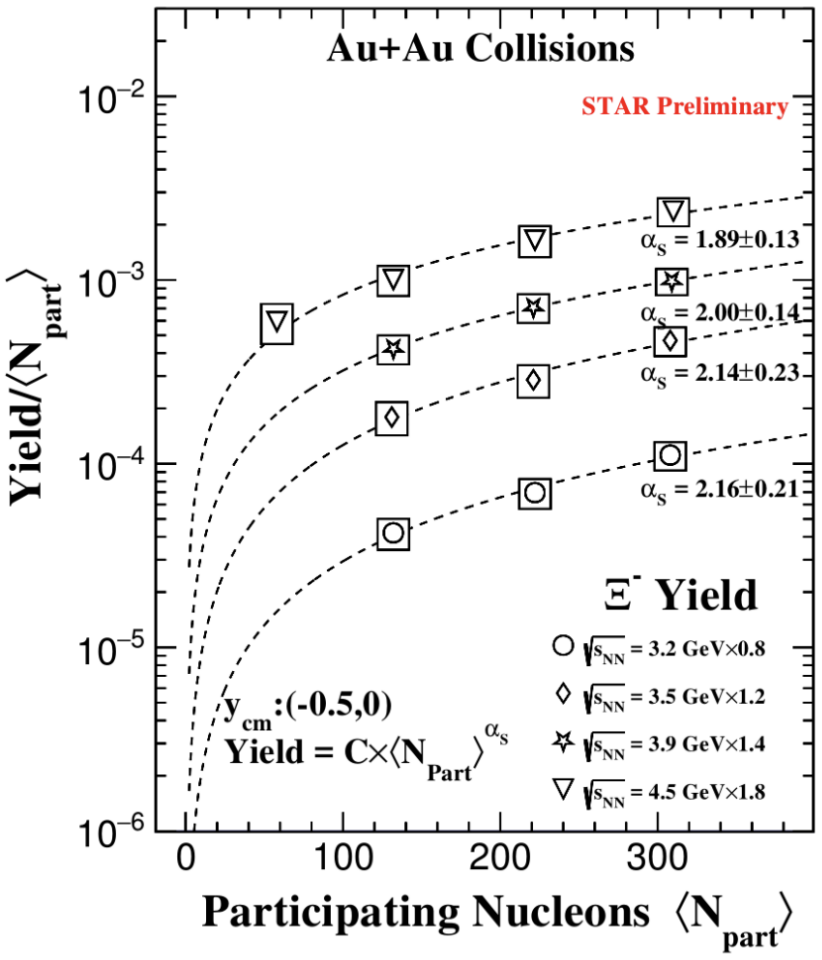




- Comprehensive measurement of strangeness production at different energies from 3 to 4.5 GeV

Centrality dependence of mid-rapidity yields



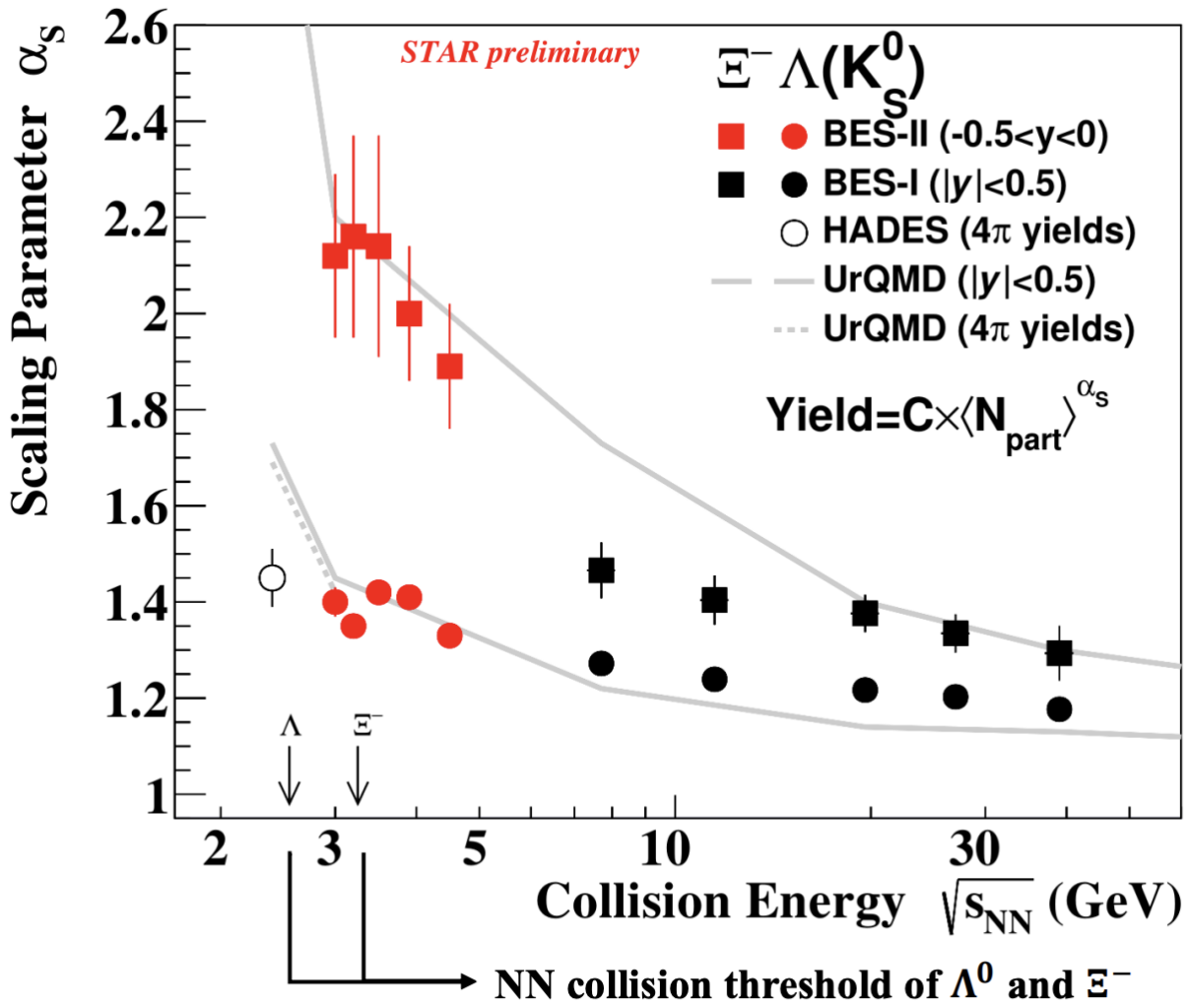


- **Scaling formula:**

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

- **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 → NΛK**
    - ☐ **NN → NΞKK**

Energy dependence of scaling parameter α_S



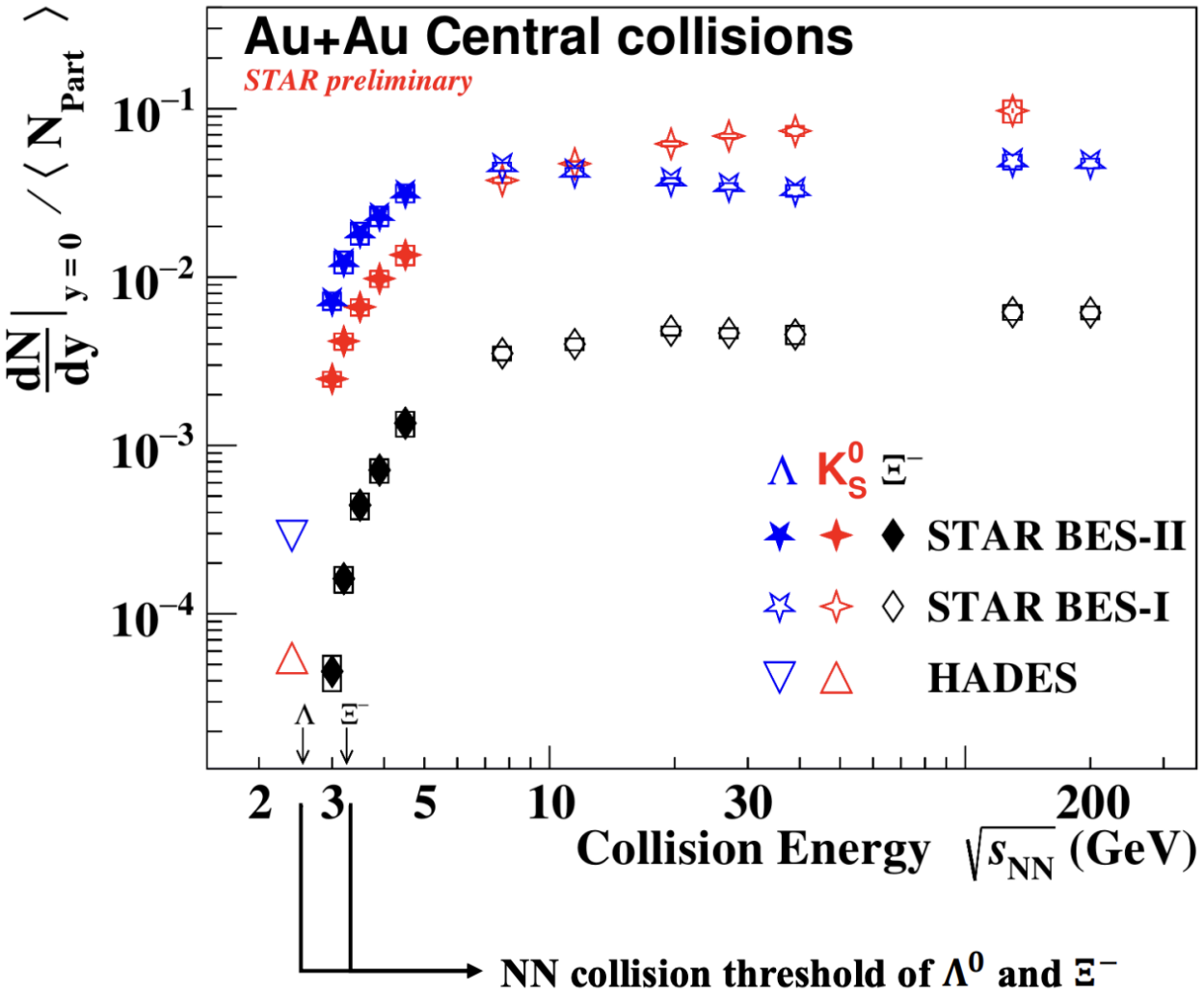
- **Rapid decrease of scaling parameter α_S for Ξ^- from 4.5 to 7.7 GeV, and saturate at high energy**
  - **The mechanism of strange hadron production may change**
  - **Strange hadron production predominantly from hadronic interactions at $\sqrt{s_{NN}} < 4.5$ GeV**

- **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)**

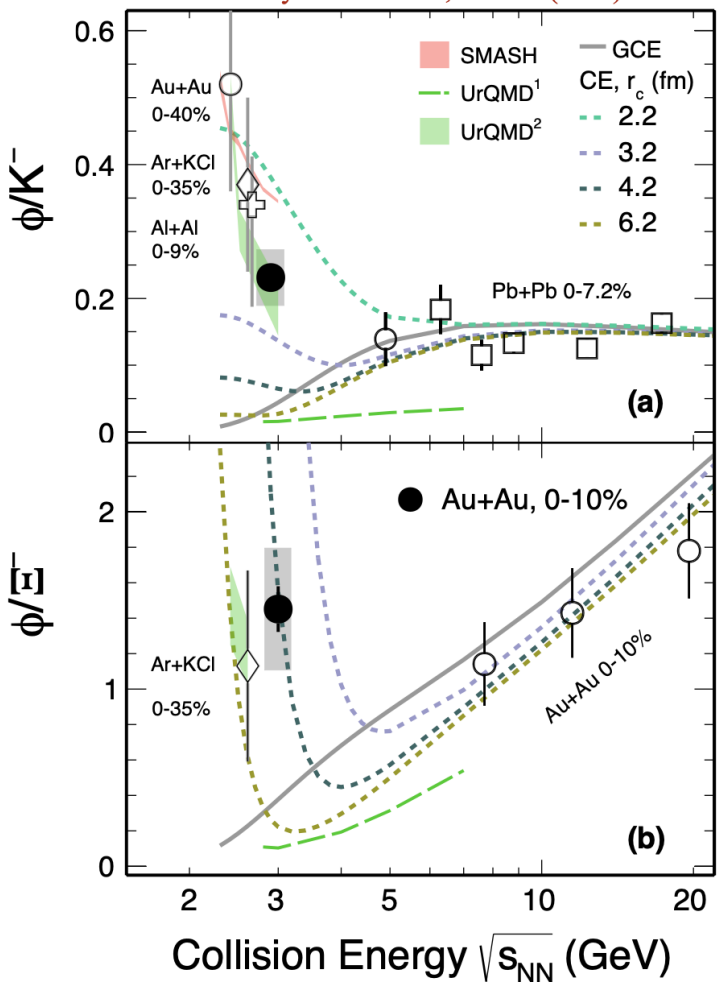
      $gg \rightarrow s\bar{s}$ or $q\bar{q} \rightarrow s\bar{s}$
    - **Hadronic interaction (associated production)**

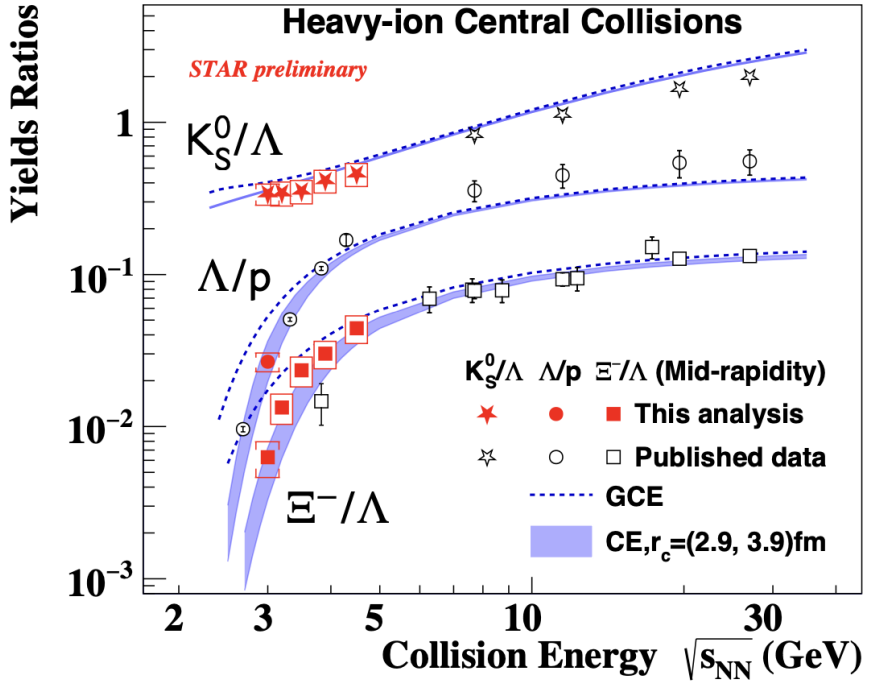
      $BB \rightarrow BYK$ or $BB \rightarrow B\Xi KK$

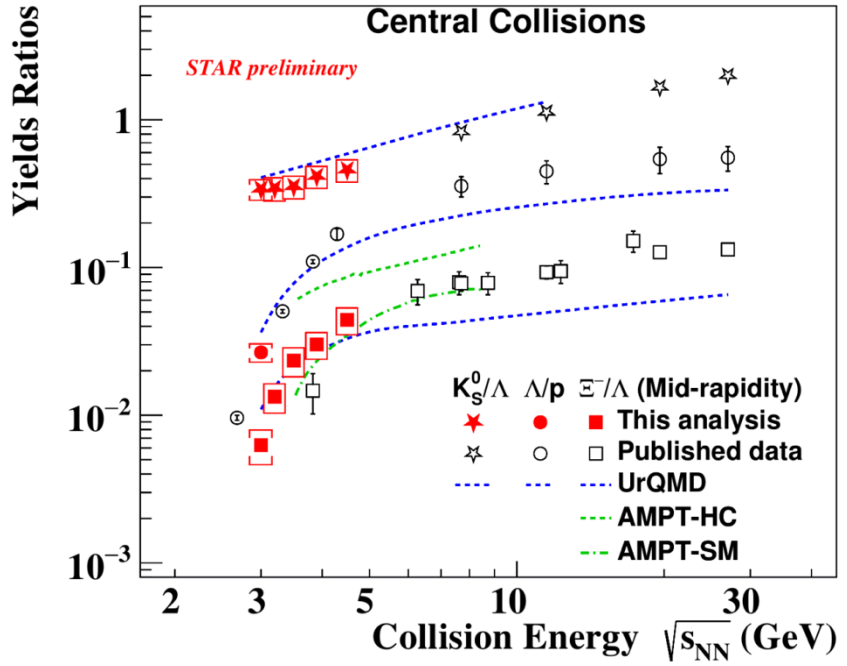
      B: N, p, Δ, etc. Y: Λ, Σ, etc. K: K^+, K^0
  - **Baryon-dominated to meson-dominated transitions**
    - **K^0_s and Λ^0 mid-rapidity yield cross at ~ 8 GeV**
  - **First measurement of Ξ^- near- / sub-threshold energies in Au+Au collision**

Energy dependence of mid-rapidity yield ratios

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







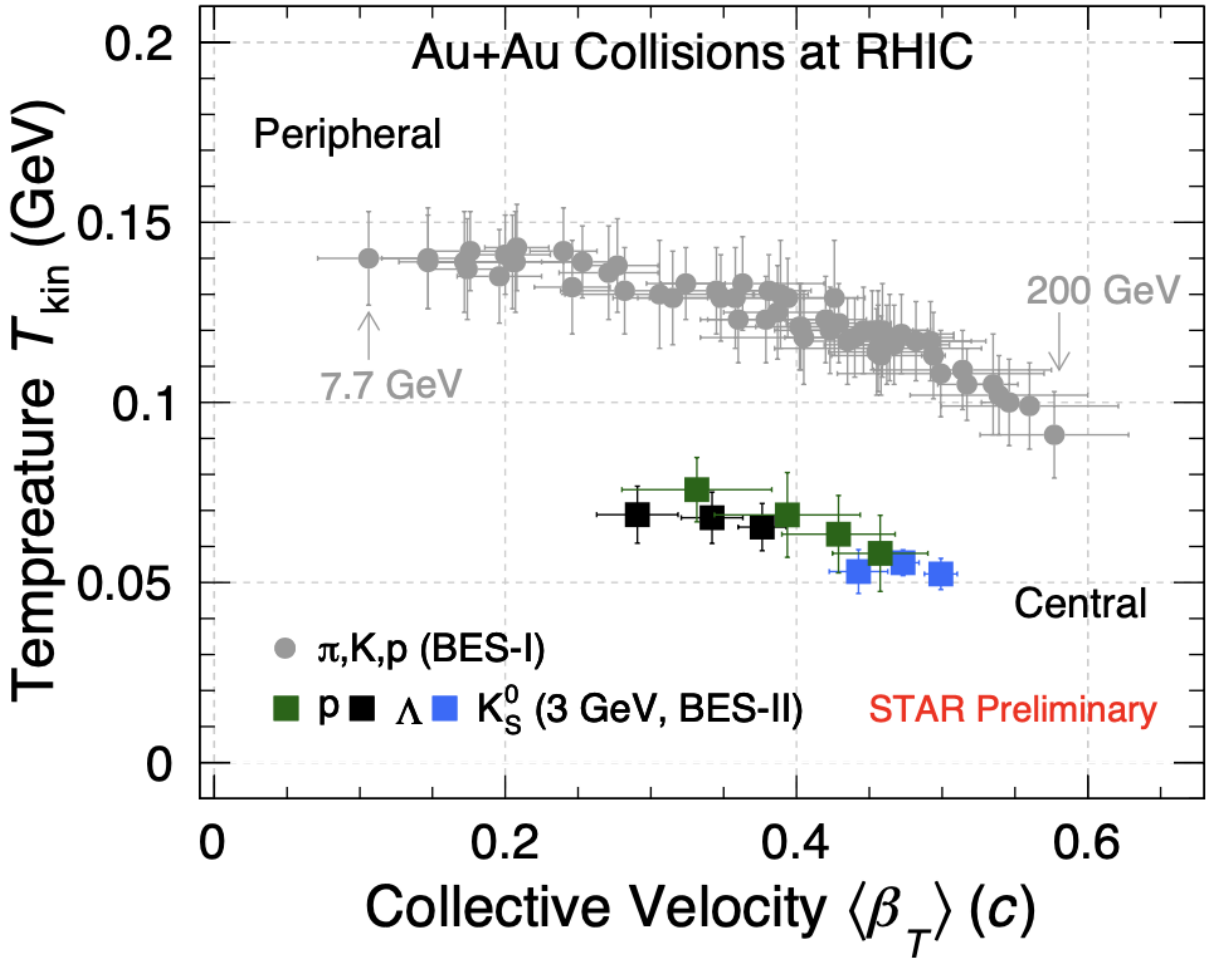
1) Canonical Ensemble (CE) with strangeness correlation length 2.9 – 3.9 fm, simultaneously describes K^0_S/Λ, Λ/p, and Ξ^-/Λ in the measured energy range, GCE fails at low energies

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

➡Change of medium properties at the high-density region

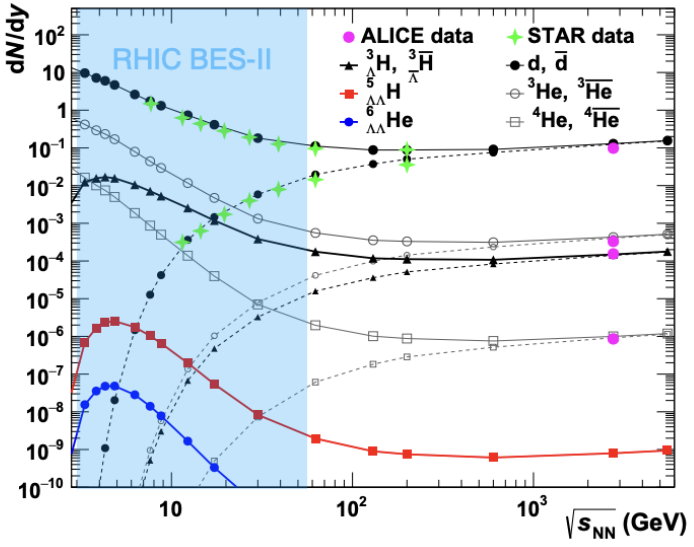
UrQMD: cascade mode, hard EOS

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

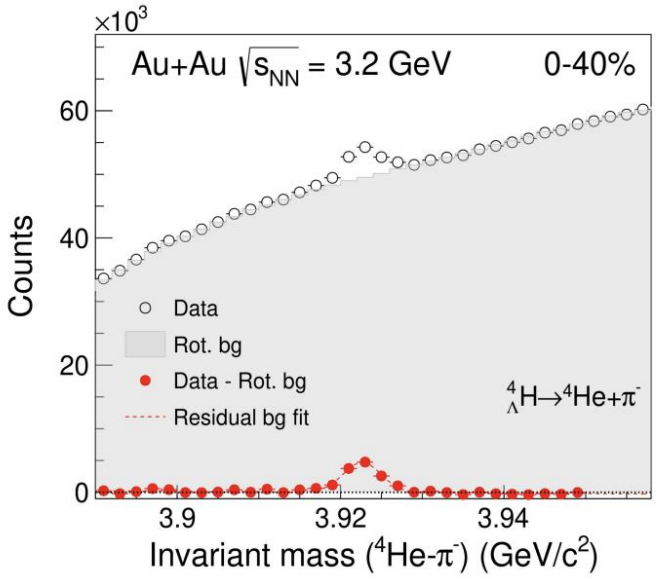
Hypernuclei measurements in BES-II

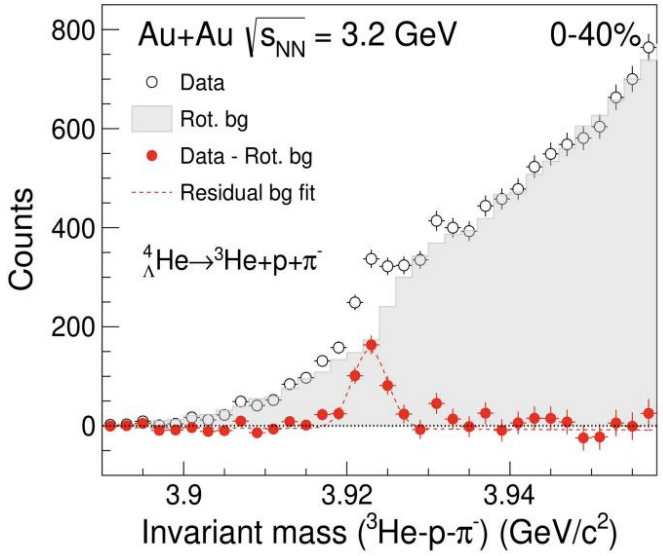


- Hypernuclei measurements are scarce in HI collision experiments
- At **low beam energies**, hypernuclei production is expected to be **enhanced** due to high baryon density

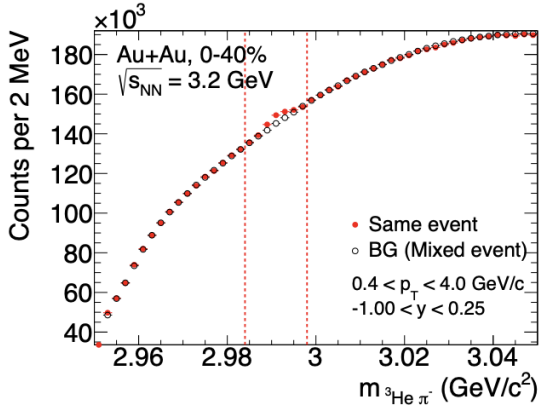
RHIC BES-II offers great opportunity for hypernuclei measurements.

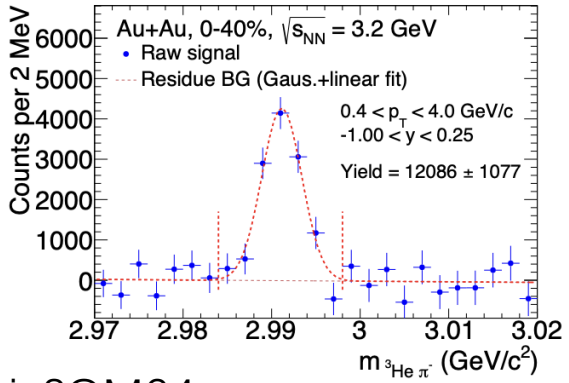
B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al. PLB (2011) 697:203–207





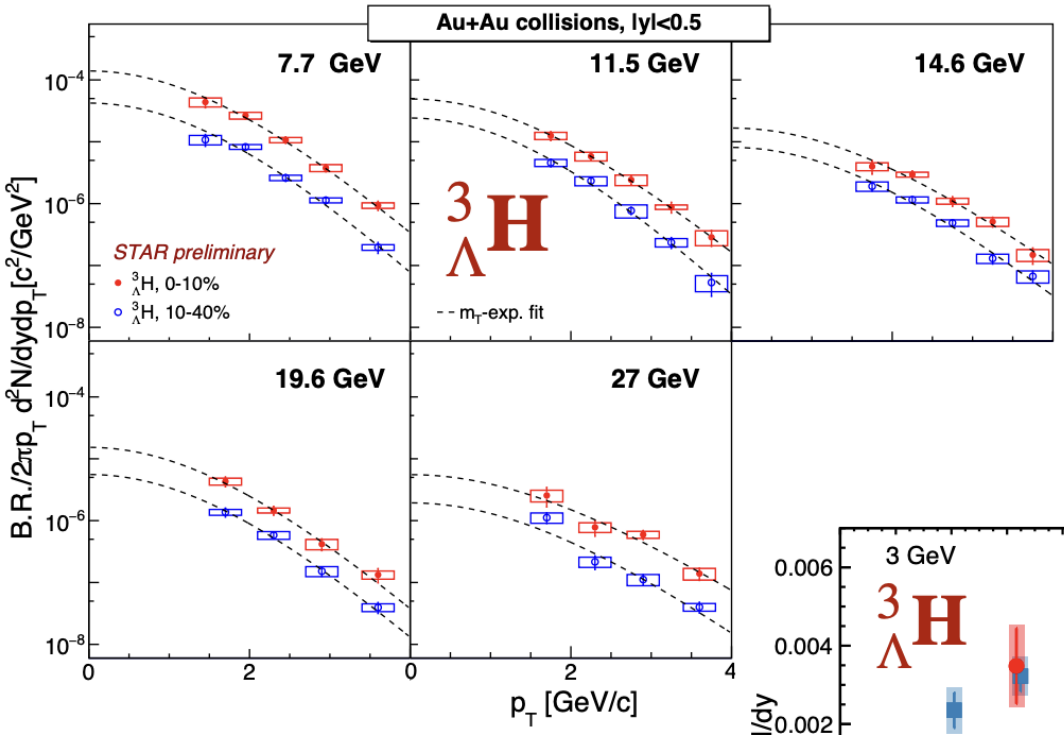
Chenlu Hu, SQM24





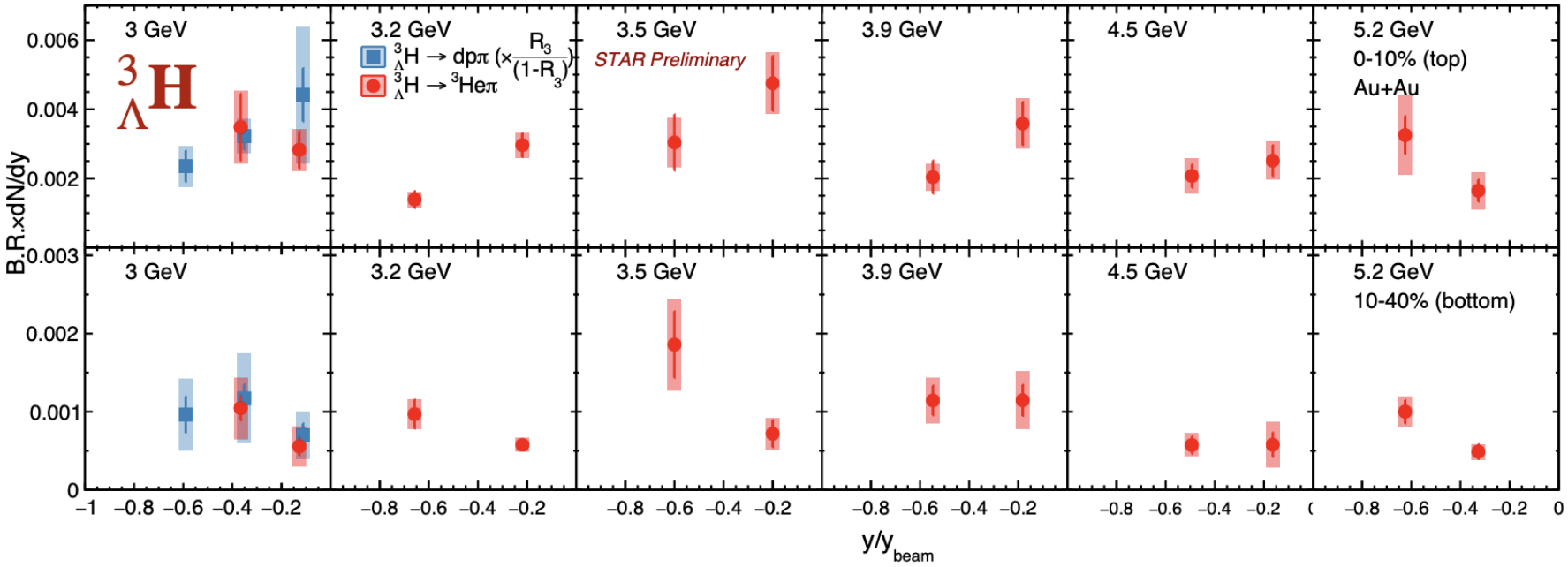
Xiujun Li, SQM24

Hypertriton production measurements in BES-II

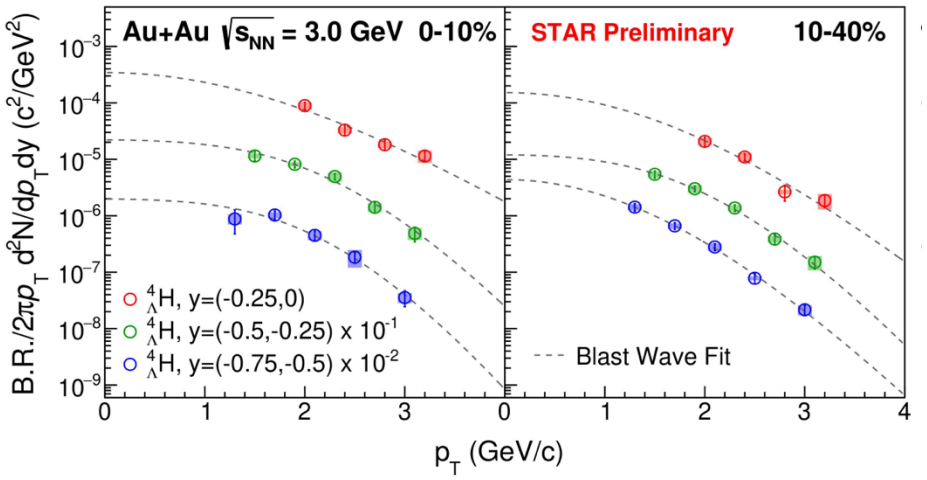


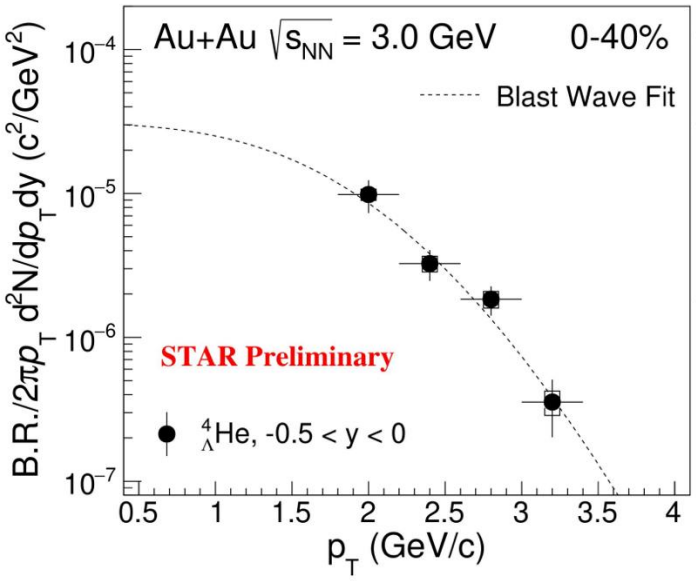
- Measurements cover 11 different energies

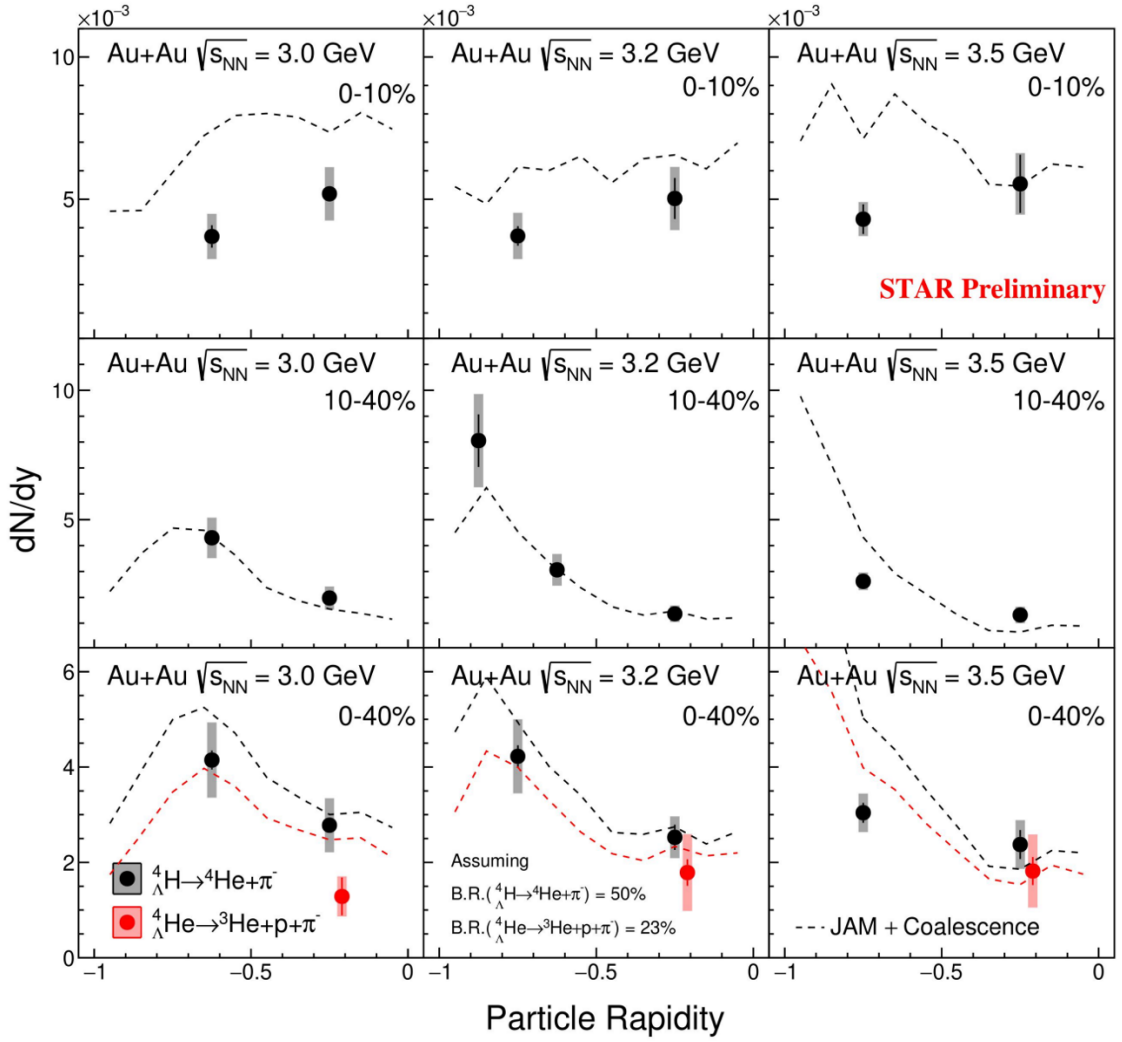
Collider: 7.7, 11.5, 14.6, 19.6, 27 GeV
Fixed Target: 3.0, 3.2, 3.5, 3.9, 4.5, 5.2 GeV



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

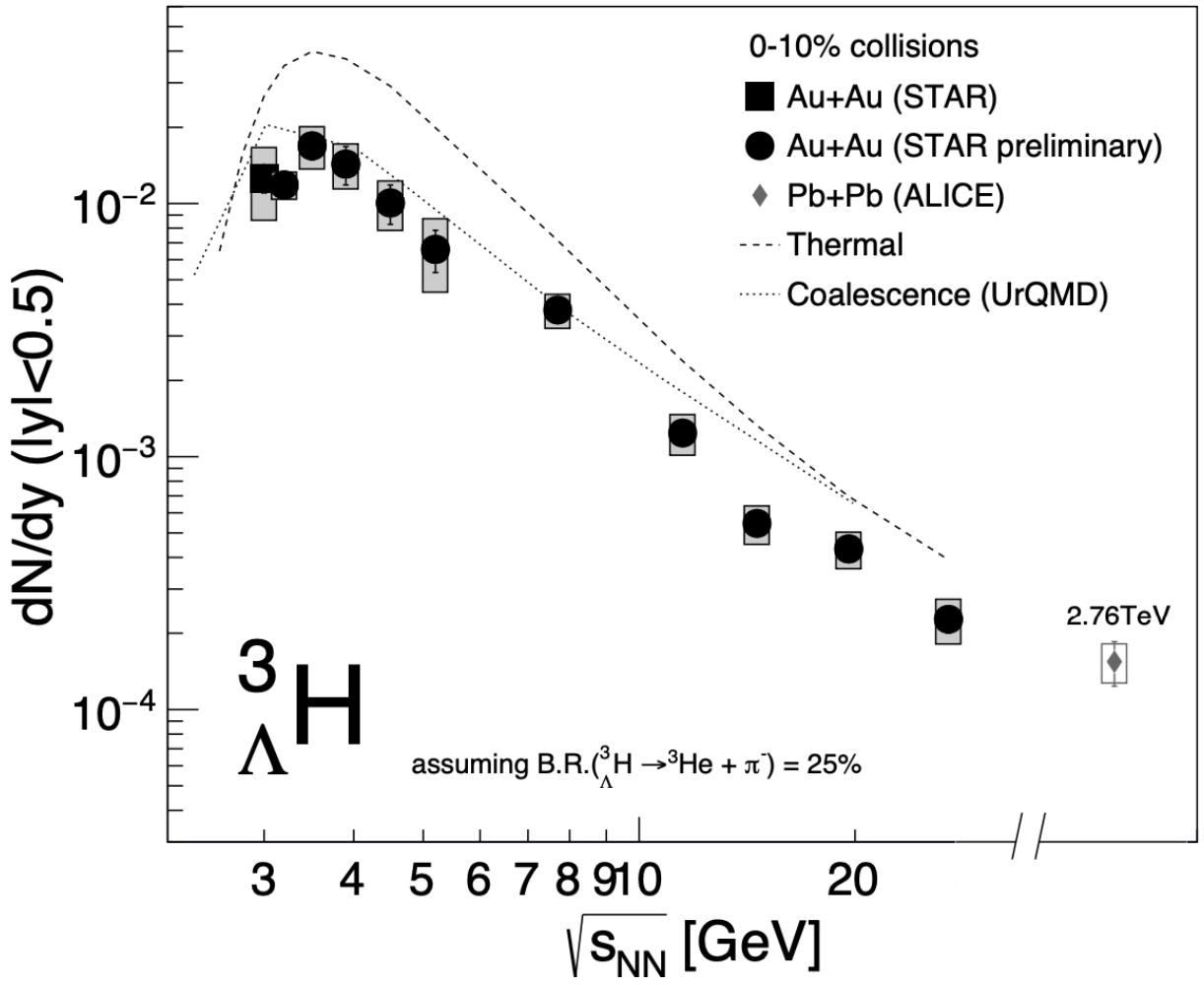






Different trend in ${}^{4}_{\Lambda}\mathrm{H}$ rapidity distribution in central and mid-central collisions, which reproduced by JAM+coalescence model

Energy dependence of hypertriton production

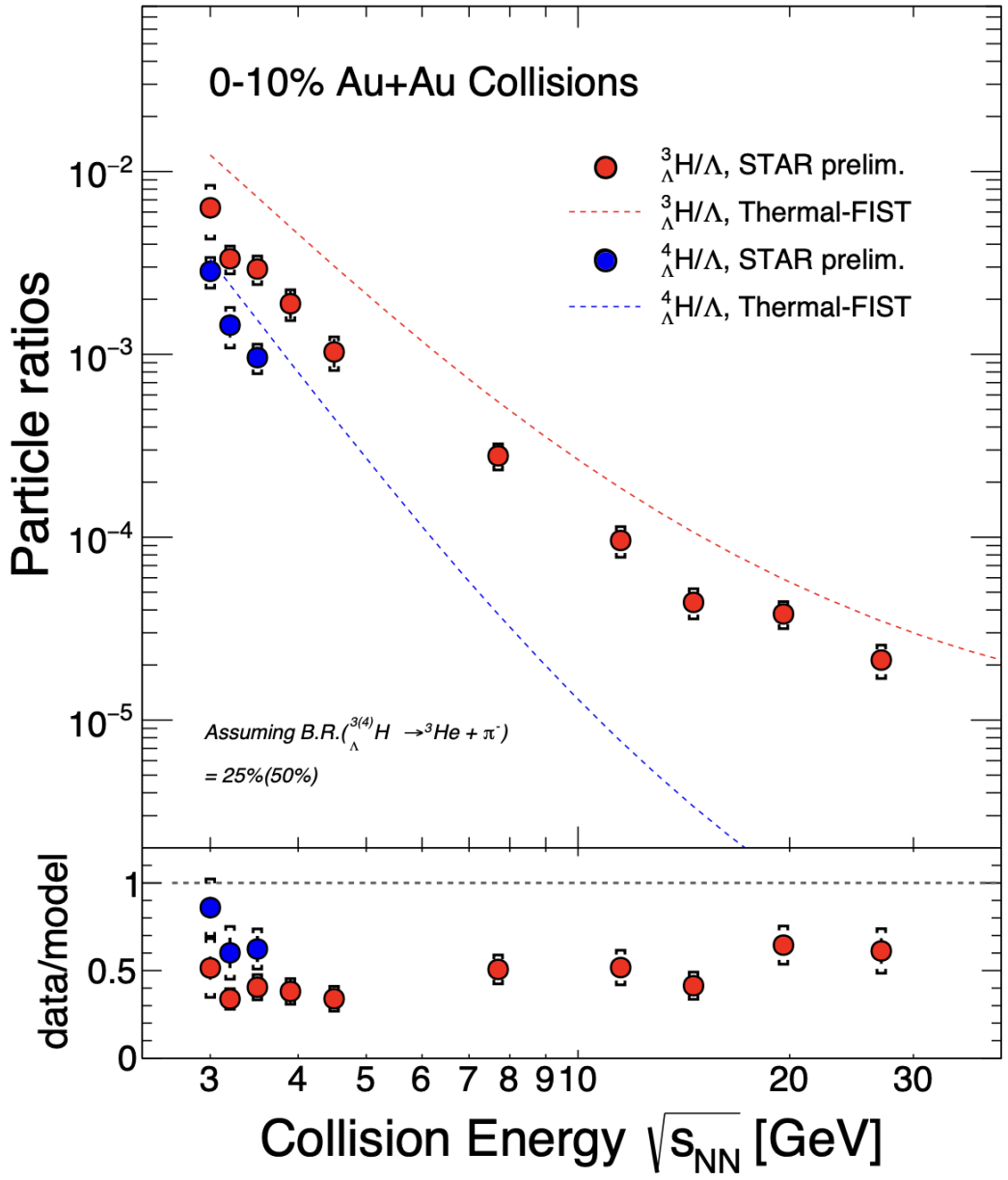


STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360
T. Reichert, et al, PRC 107 (2023) 014912

- 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 $^{3}_{\Lambda}\mathrm{H}/\Lambda$ and $^{4}_{\Lambda}\mathrm{H}/\Lambda$ 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.