

Strangeness production in Au+Au collisions at $\sqrt{s_{NN}} = 14.6, 19.6$ and 200 GeV with the STAR experiment

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- Motivation
- STAR detector and strange particles reconstruction
- Results
 - ✓ p_T spectra
 - ✓ Rapidity spectra
 - ✓ Nuclear modification factors
 - ✓ Ω/ϕ , $\bar{\Lambda}/K_S^0$ and ϕ/K^- ratios
- Summary

Supported in part by the



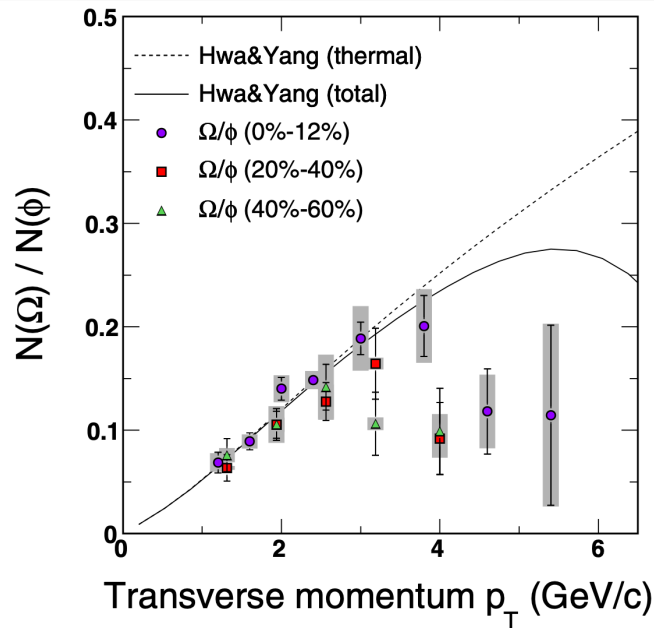
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Science

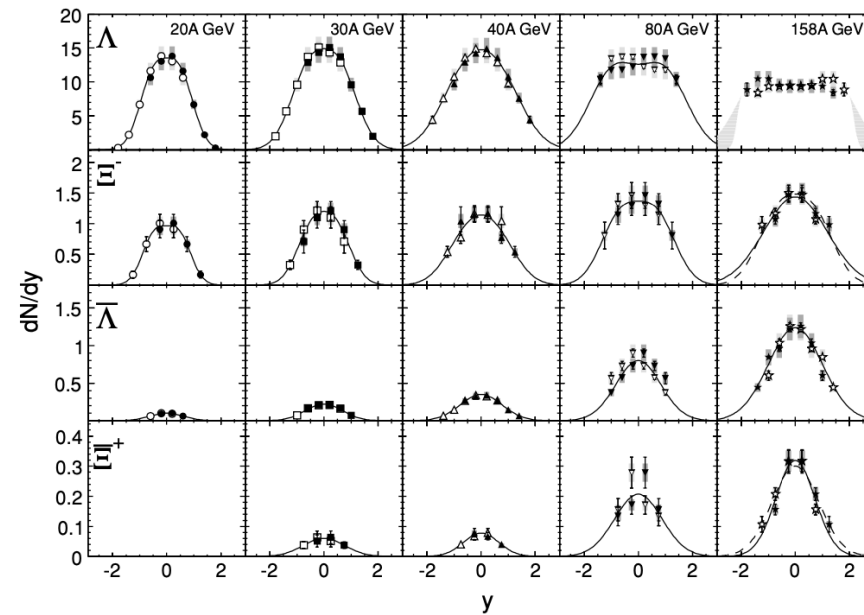
Motivation

- Strangeness production is suggested as a sensitive probe to the early dynamics of the medium created.
- 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.

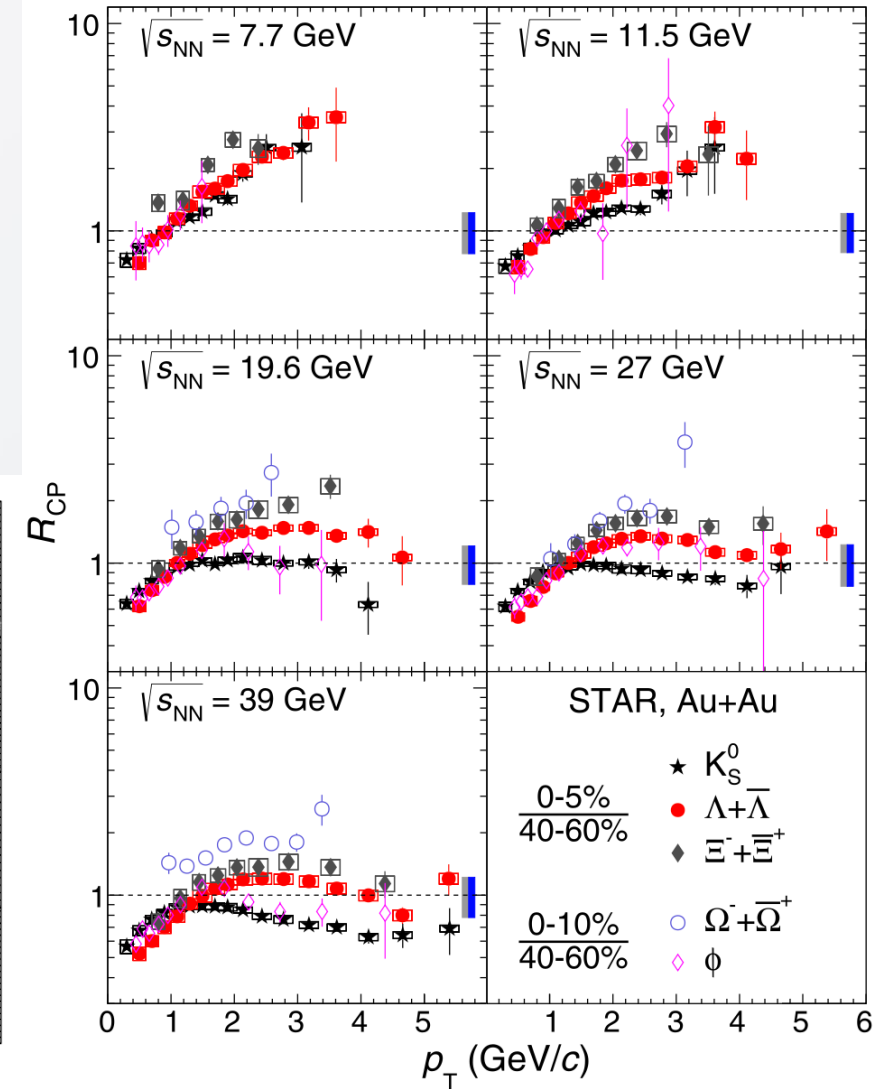
$$R_{CP} = \frac{[(dN/dp_T)/\langle N_{coll} \rangle]_{\text{central}}}{[(dN/dp_T)/\langle N_{coll} \rangle]_{\text{peripheral}}}$$



STAR, PRL 99, 112301 (2007)



NA49, PRC 78, 034918 (2008)



STAR, PRC 102, 034909 (2020)

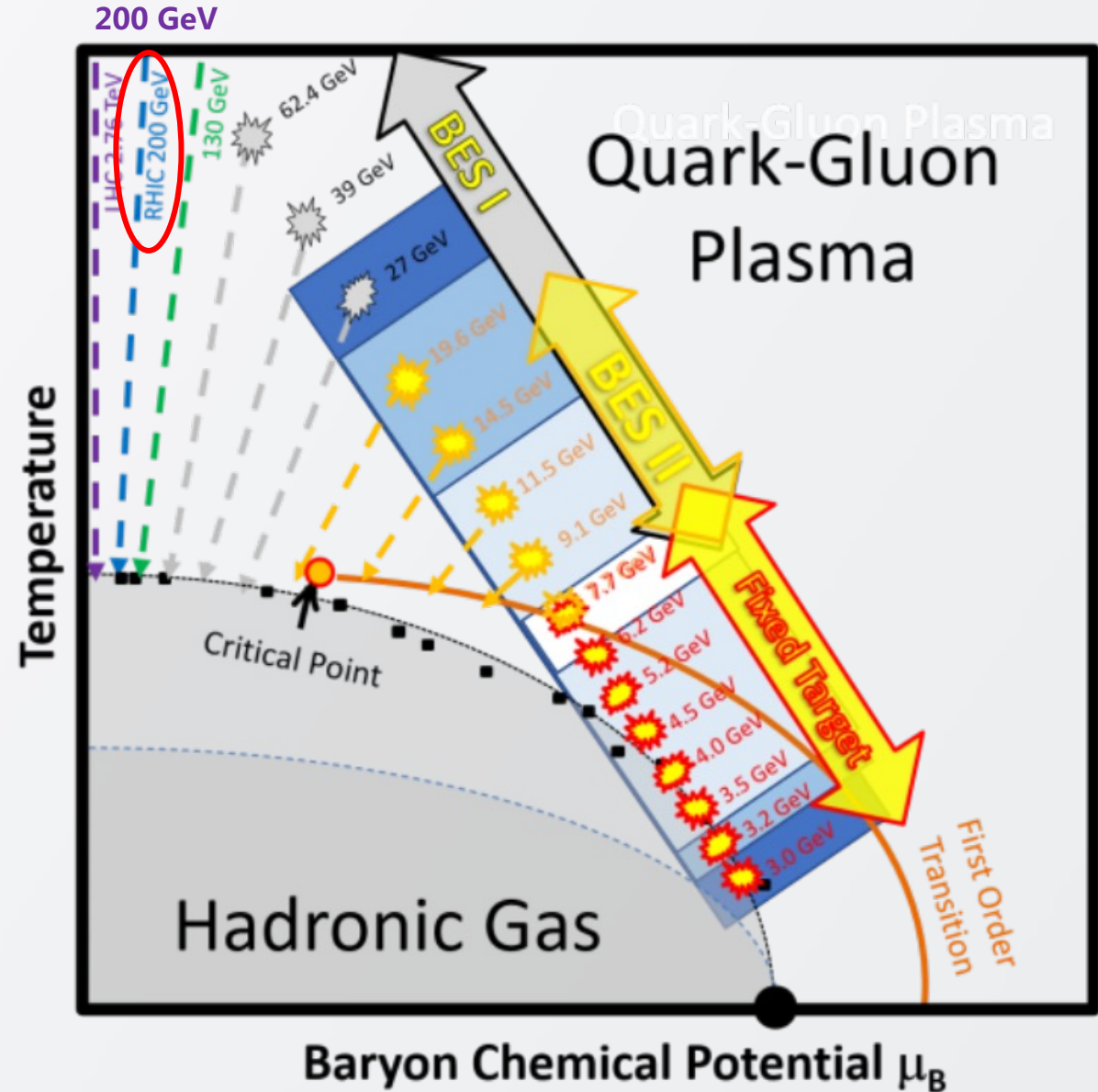
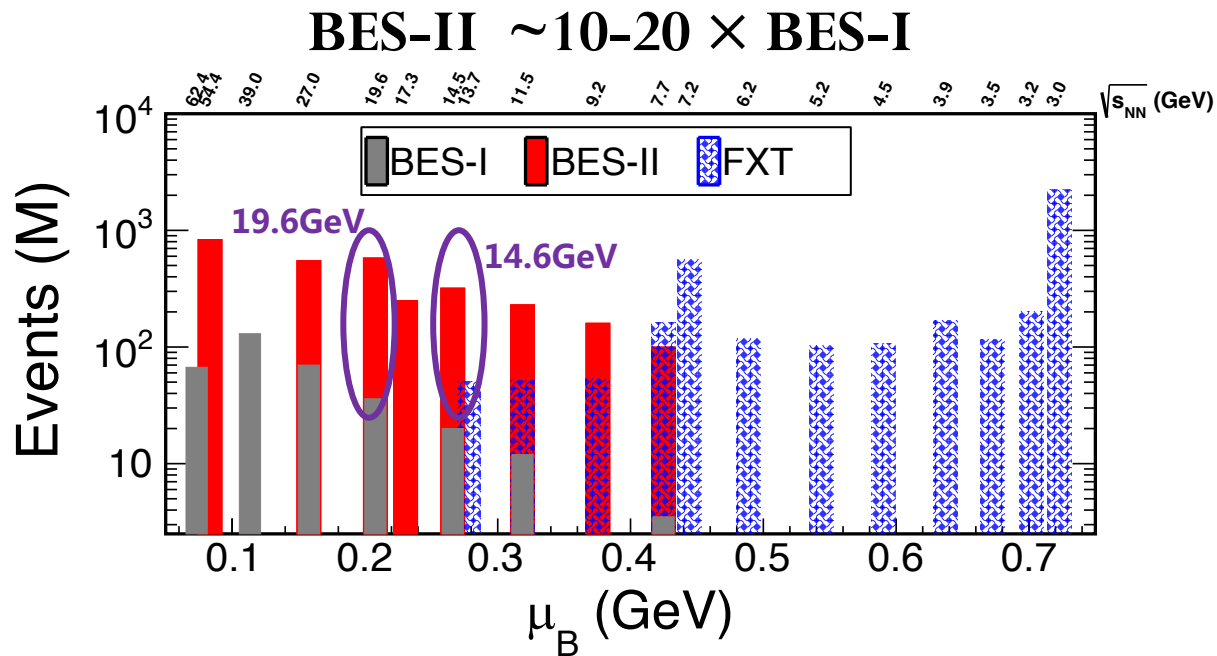
Motivation

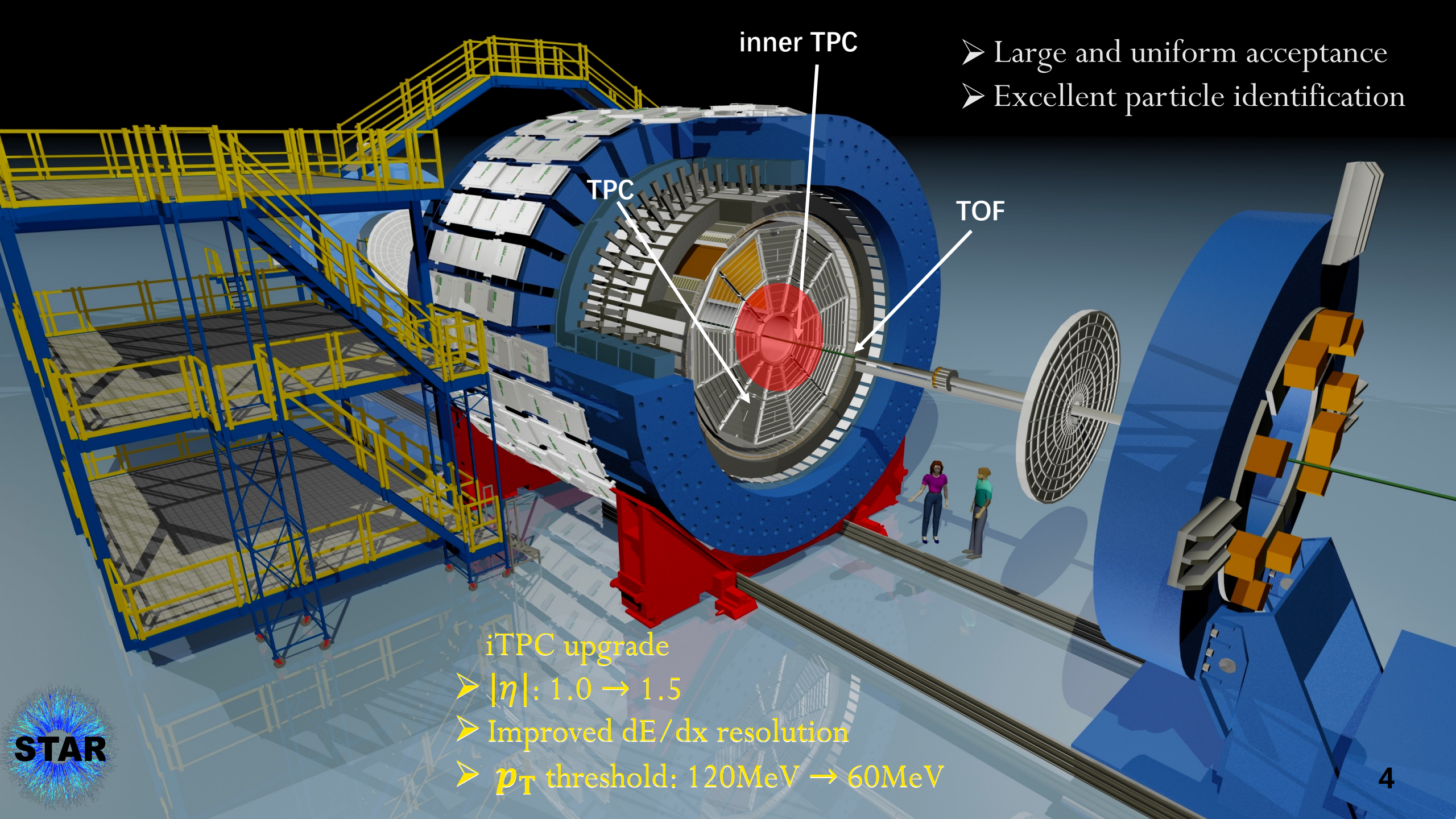
Heavy-ion collisions at top RHIC energy:

- Study QGP properties

Beam Energy Scan (BES) program:

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

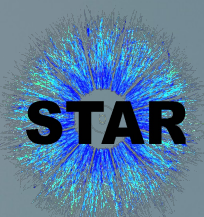




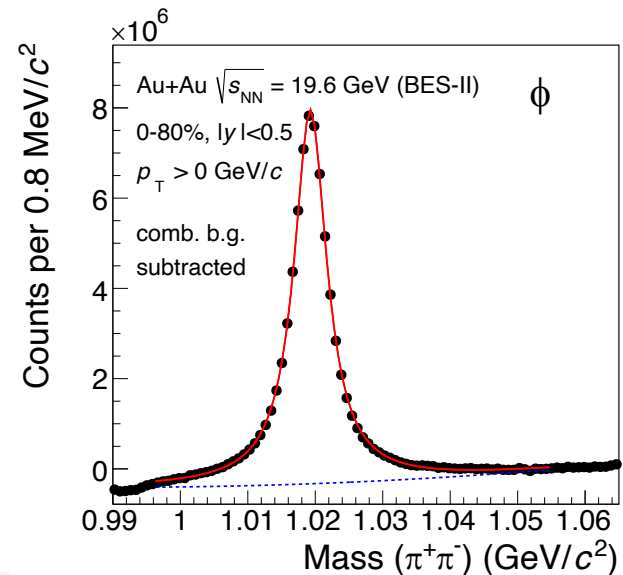
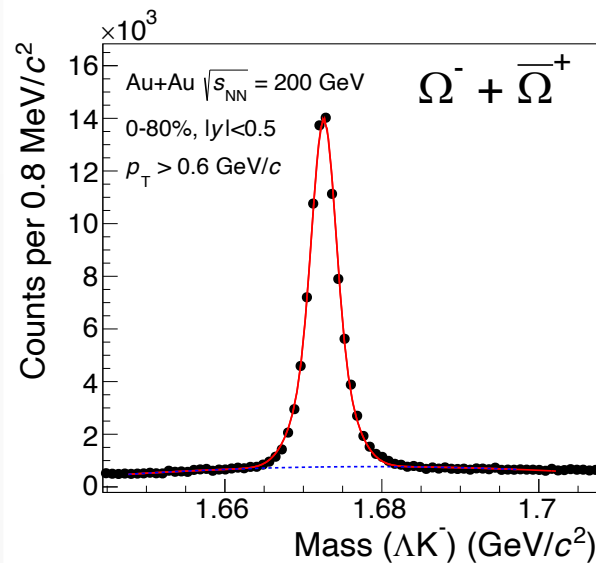
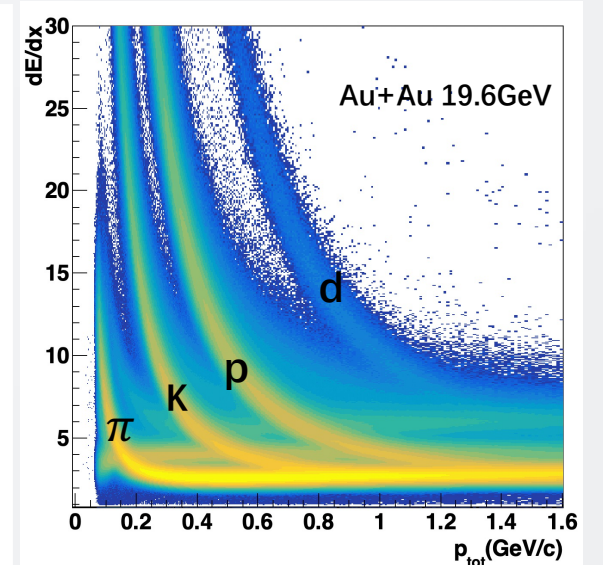
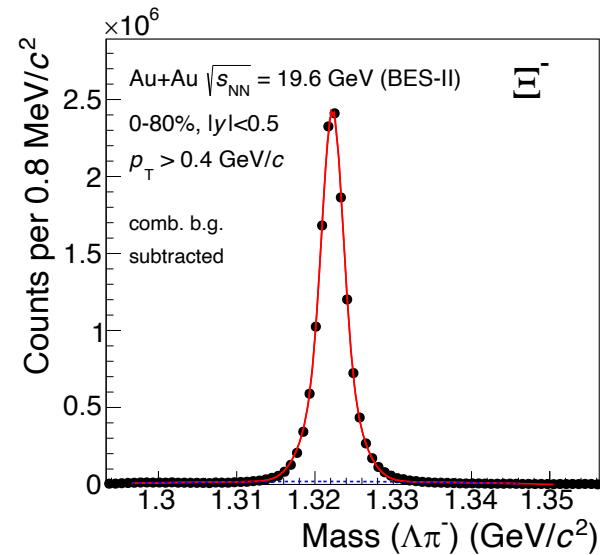
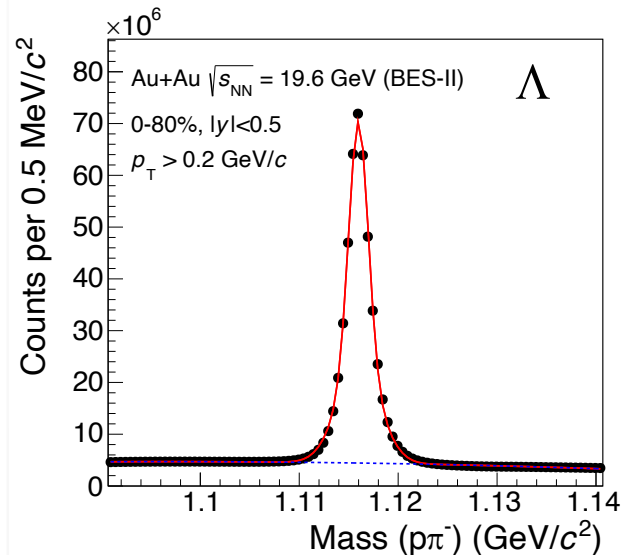
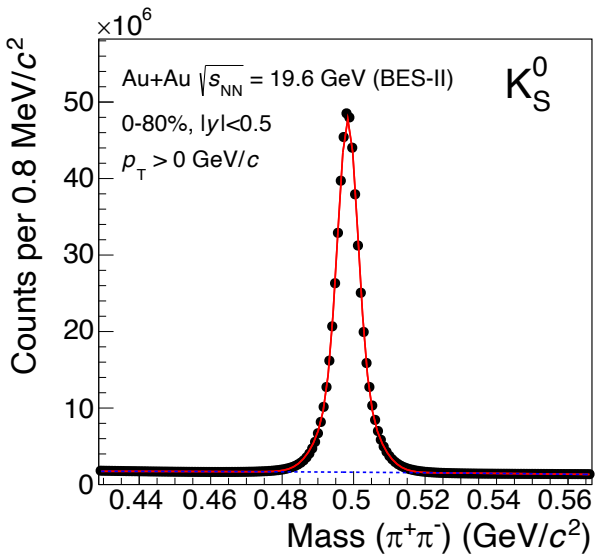
- Large and uniform acceptance
- Excellent particle identification

iTPC upgrade

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



Particle identification and reconstruction



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

$$K_S^0 \rightarrow \pi^+ + \pi^- (\mathcal{B} = 69.2\%)$$

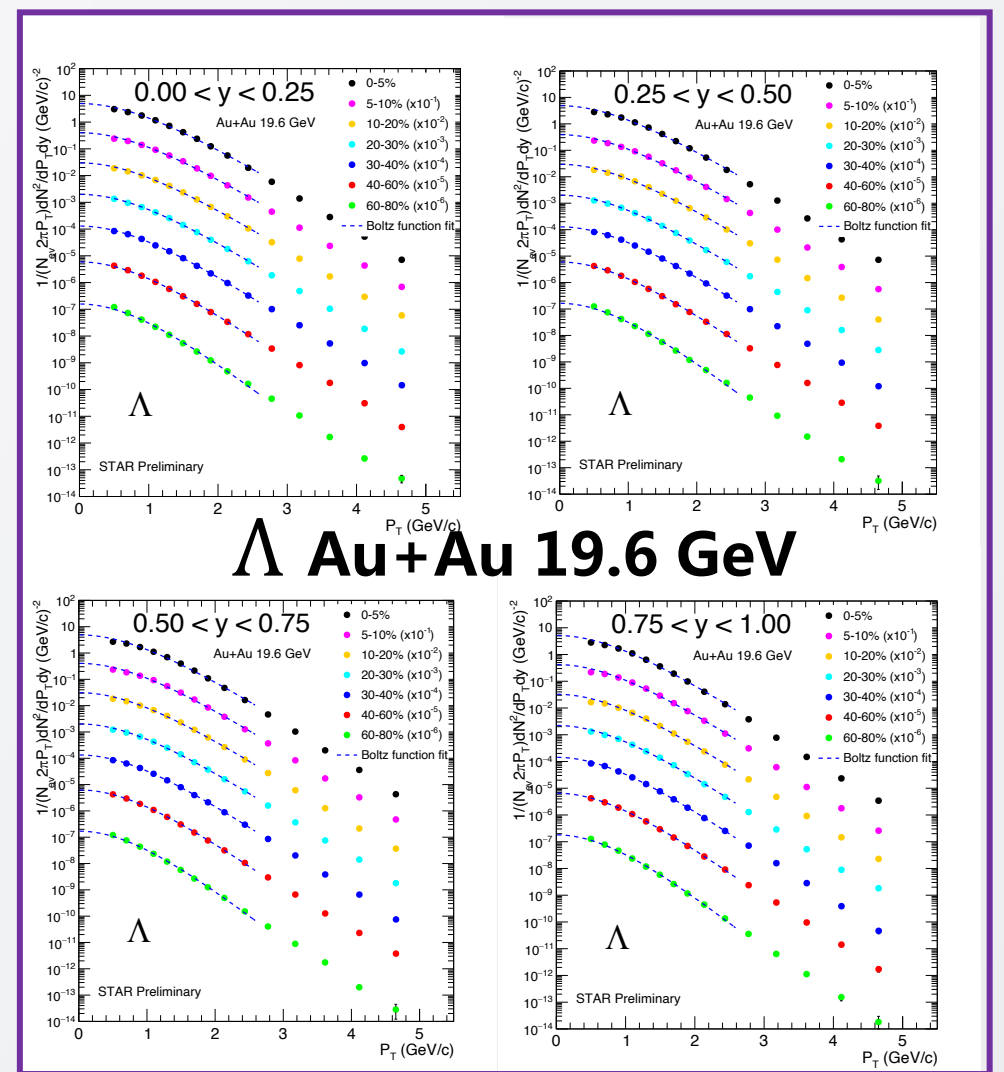
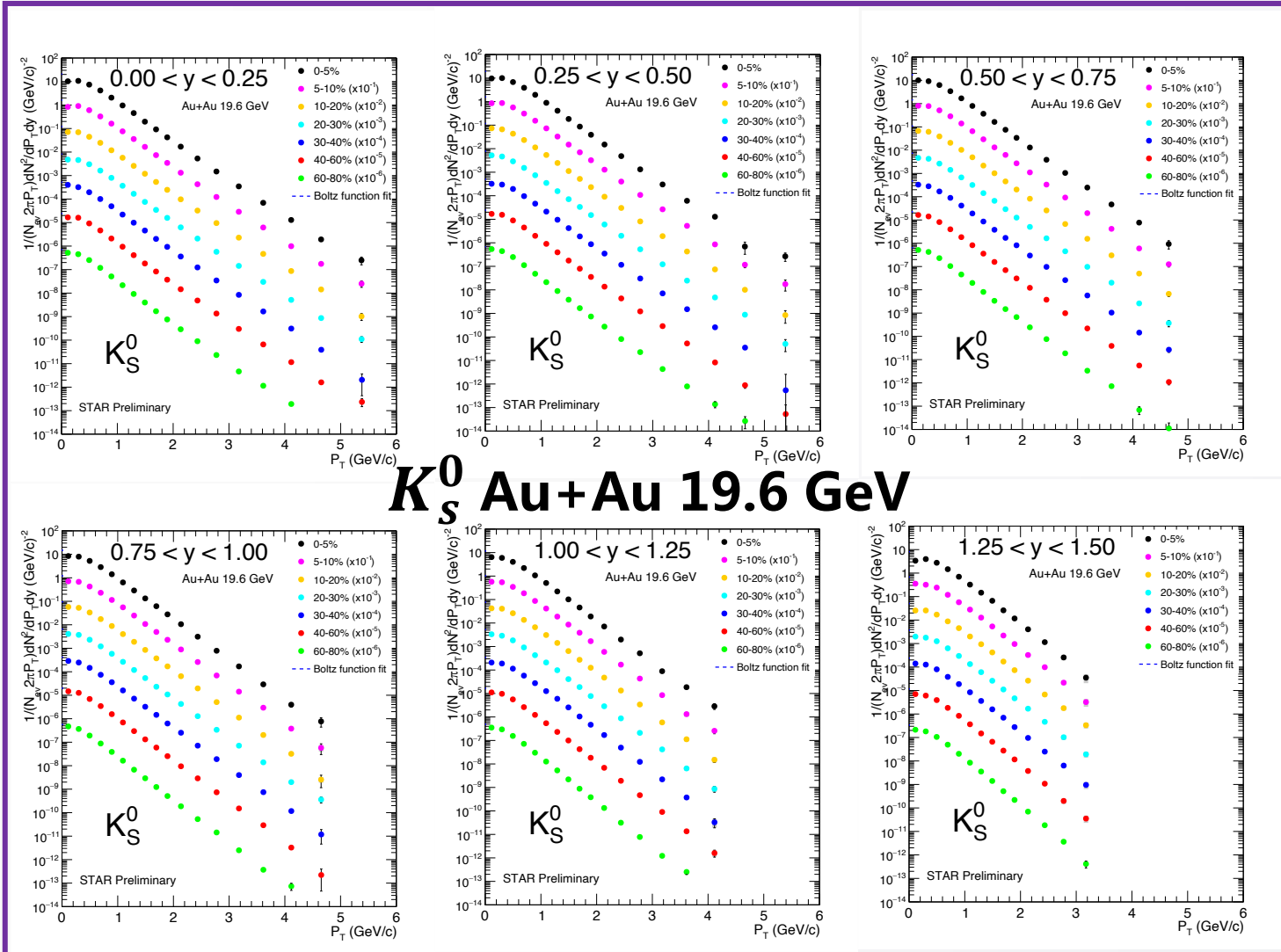
$$\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^- (\pi^+) (\mathcal{B} = 63.9\%)$$

$$\Xi^- (\bar{\Xi}^+) \rightarrow \Lambda(\bar{\Lambda}) + \pi^- (\pi^+) (\mathcal{B} = 99.9\%)$$

$$\Omega^- (\bar{\Omega}^+) \rightarrow \Lambda(\bar{\Lambda}) + K^- (K^+) (\mathcal{B} = 67.8\%)$$

$$\phi \rightarrow K^+ + K^- (\mathcal{B} = 49.1\%)$$

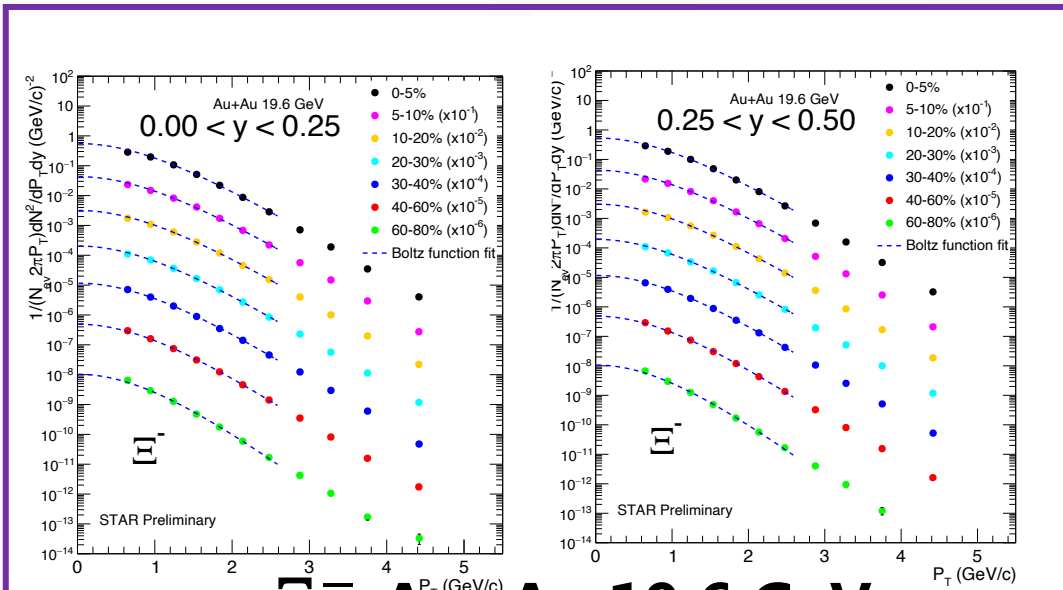
p_T spectra of K_S^0 and Λ at 19.6 GeV



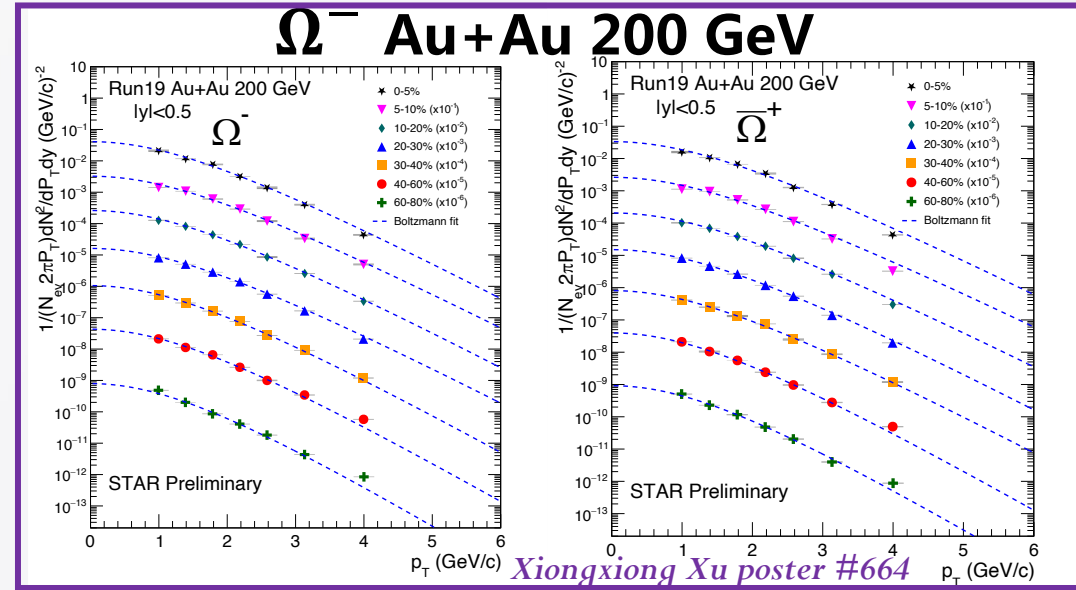
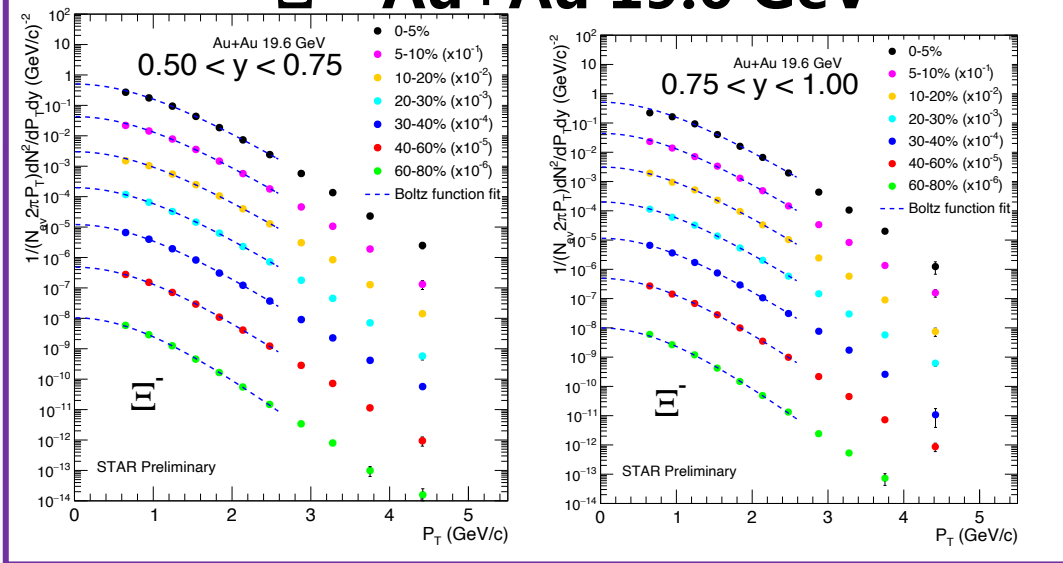
- K_S^0 : measured down to $p_T=0$, no need for extrapolation to obtain dN/dy
- Rapidity: $|y| < 1.5$

- Low p_T extrapolation: Boltzmann function
- Corrected for Ξ^- and Ξ^0 feed-down
- Rapidity: $|y| < 1$

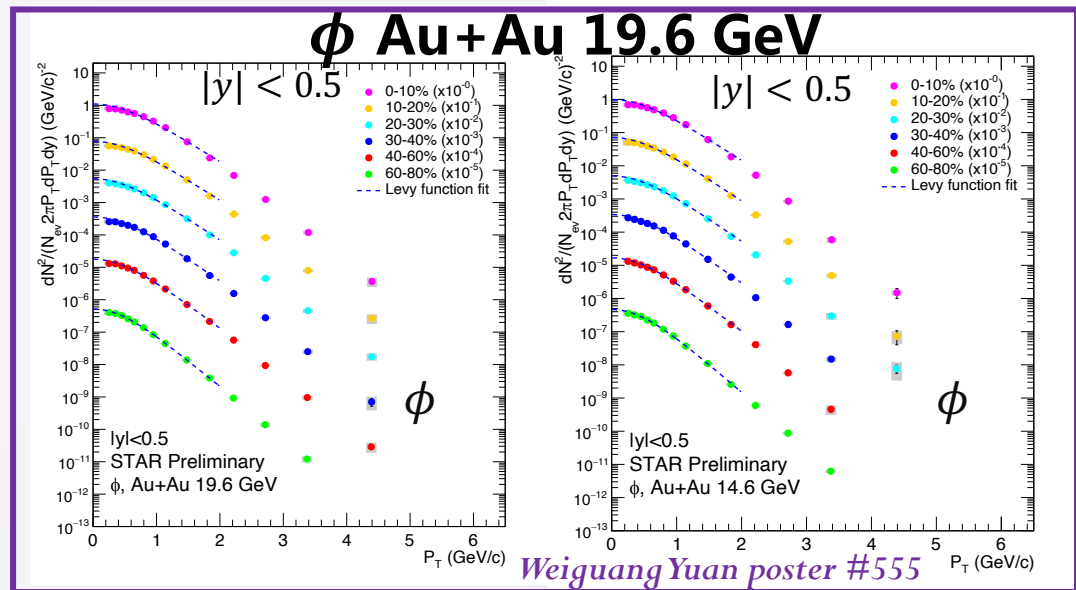
p_T spectra of Ξ^- , ϕ at 19.6 GeV and Ω^- ($\bar{\Omega}^+$) at 200 GeV



Ξ^- Au+Au 19.6 GeV



ϕ Au+Au 19.6 GeV

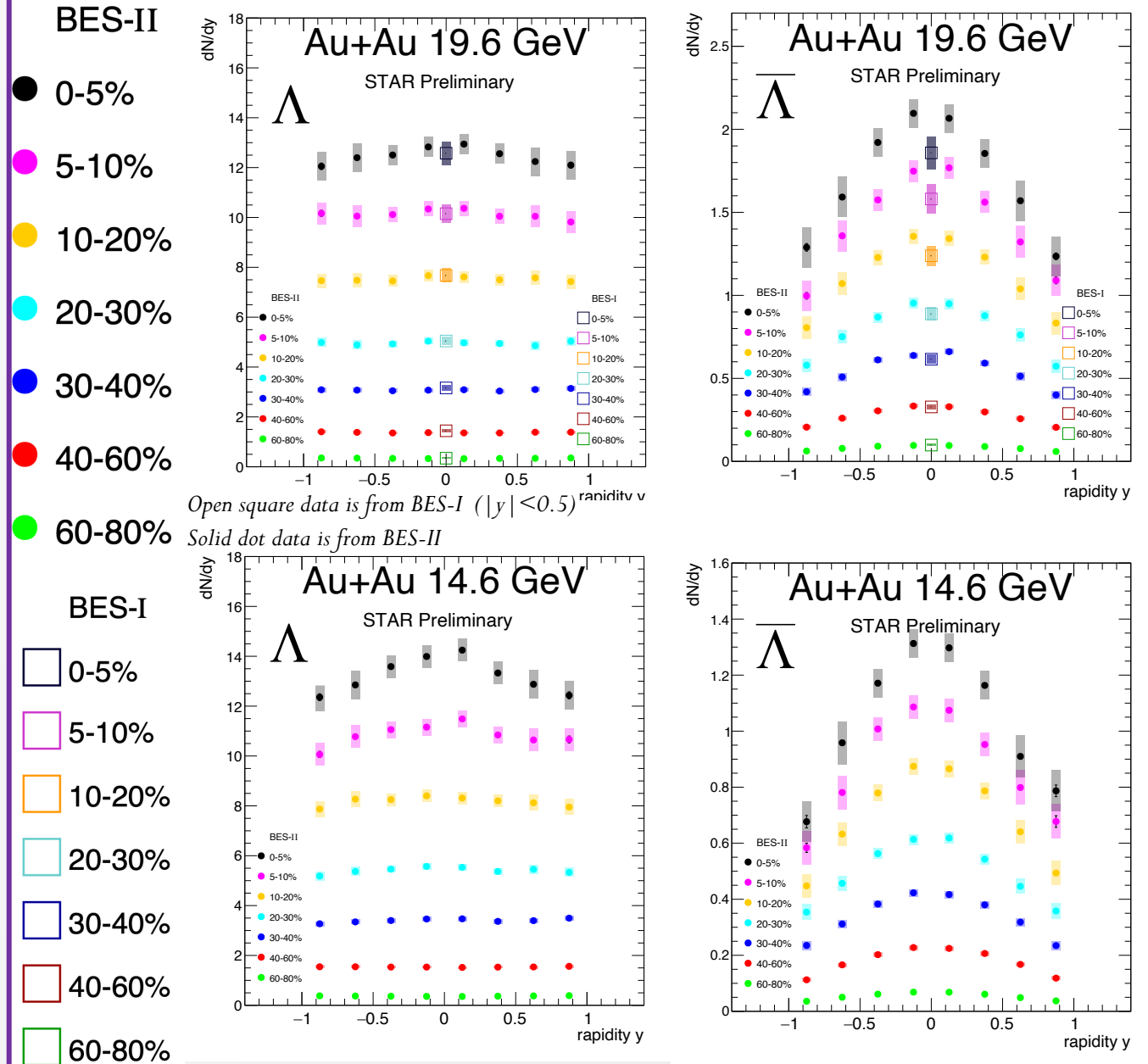


- Ξ^- Low p_T extrapolation: Boltzmann function
- Ω low p_T extrapolation: Boltzmann function
- ϕ low p_T extrapolation: Levy function
- Rapidity: $|y| < 1.0$
- Rapidity: $|y| < 0.5$
- Rapidity: $|y| < 0.5$

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.

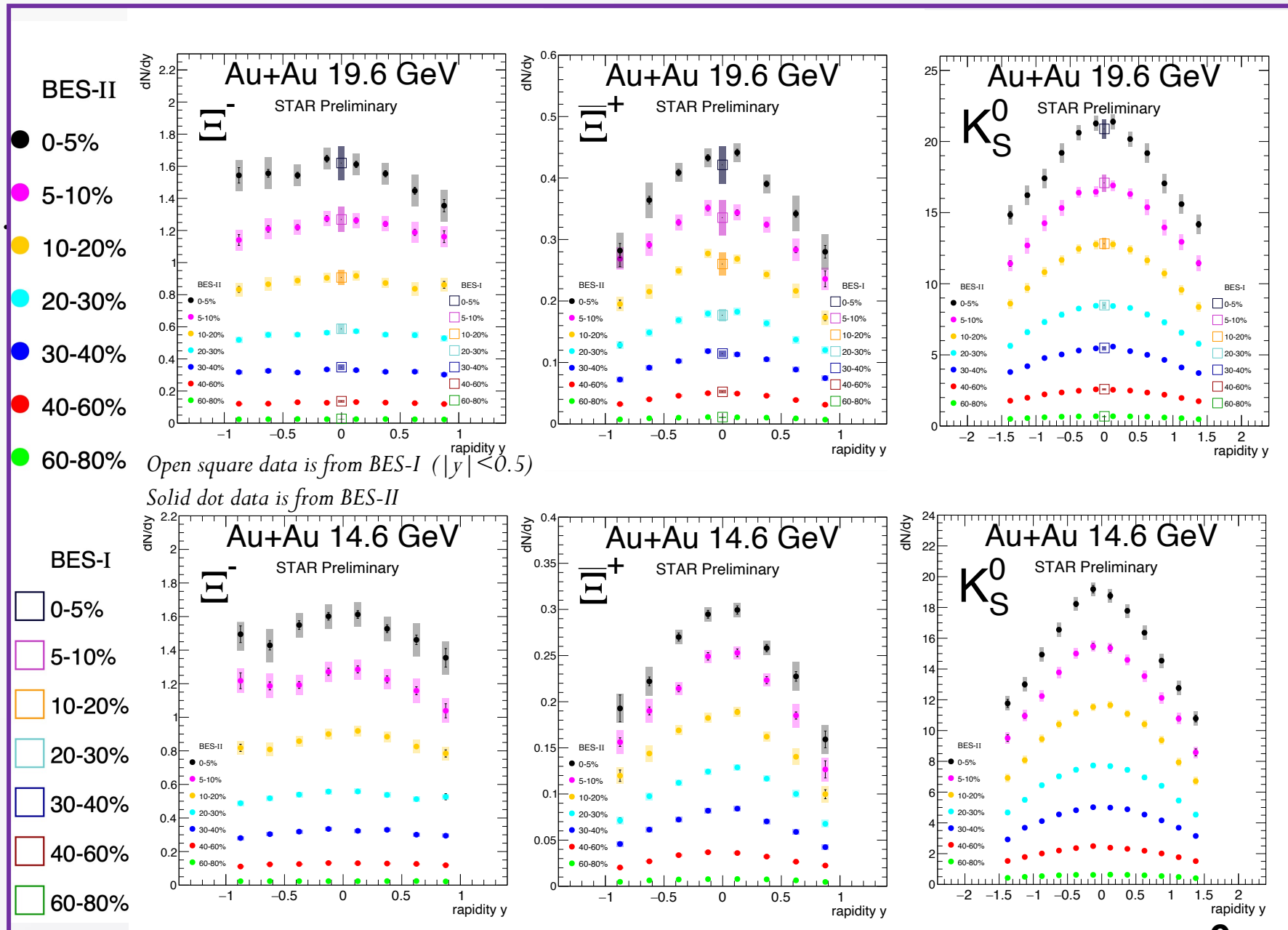
NA49, PRC 78, 034918 (2008)



Rapidity spectra of K_S^0 , Ξ^- and Ξ^+ at 19.6 and 14.6 GeV

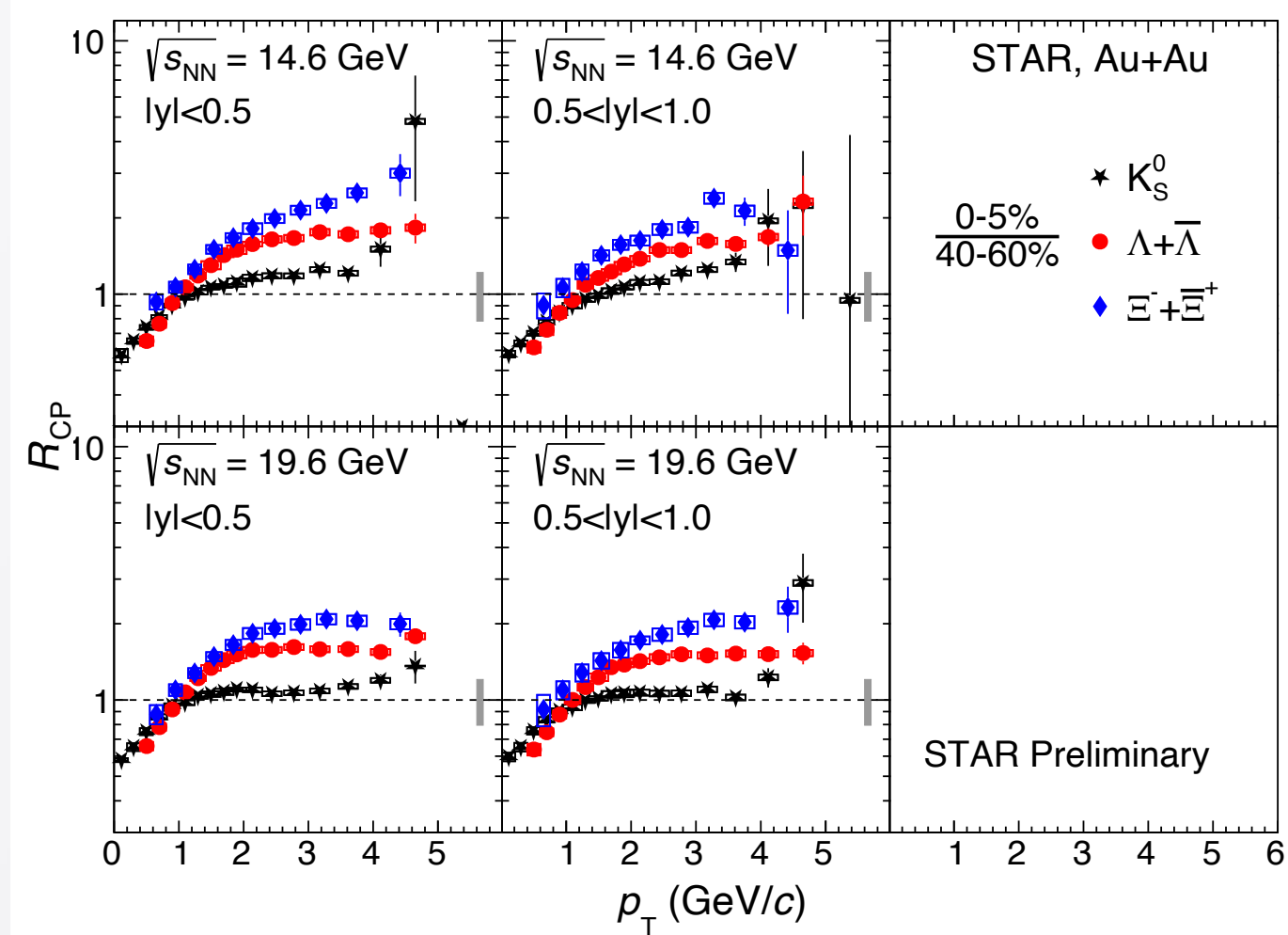
➤ Rapidity spectra of mesons (K_S^0) and anti-baryons (Ξ^+) are Gaussian-like distributions.

➤ Rapidity distribution of baryons (Ξ^-) are wider than the distributions of the anti-baryons (Ξ^+) in Au+Au collisions.



Nuclear modification factor at 19.6 and 14.6 GeV

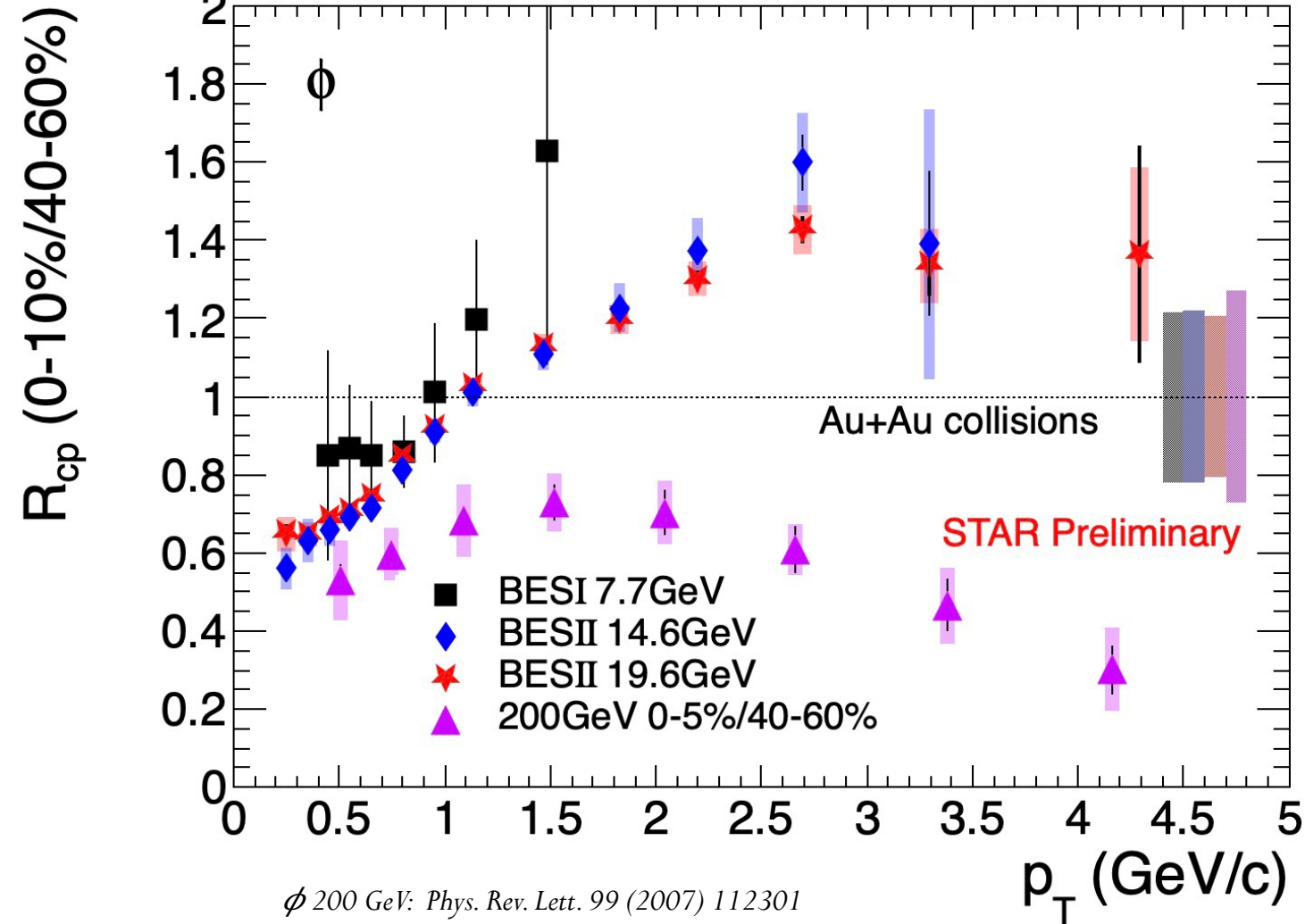
- R_{CP} will be unity if nucleus-nucleus collisions are just simple superpositions of nucleon-nucleon collisions.
- R_{CP} tends to be flat and larger than unity at $p_T > 2 \text{ GeV}/c$.
 - ✓ Radial flow
 - ✓ Quark coalescence
- The enhancement is stronger for Ξ^- compared to Λ and K_S^0
 - ✓ A strong enhancement for multi-strange particles is a proposed signature for QGP formation.



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

Energy dependence of R_{CP} for ϕ

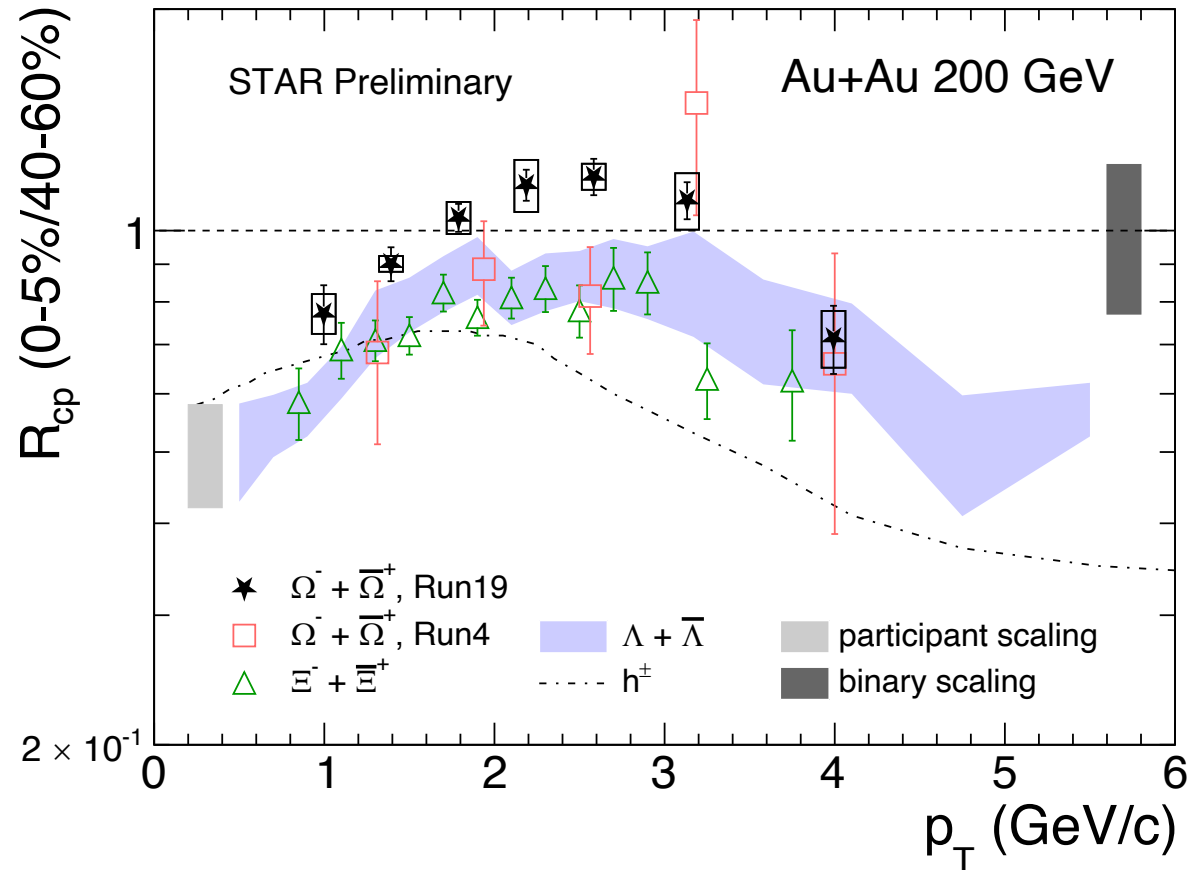
Weiguang Yuan poster #555



- $R_{CP} > 1$ for higher p_T at 19.6 GeV and lower energies
- $R_{CP} < 1$ for all p_T at 200 GeV
 - ✓ Strong energy loss in QGP at top RHIC energy

R_{CP} of strange hadrons at 200 GeV

Xiongxiong Xu poster #664



$\Omega + \bar{\Omega}$ Run4 & $\Xi + \bar{\Xi}$: STAR, Phys. Rev. Lett. 98 (2007) 062301

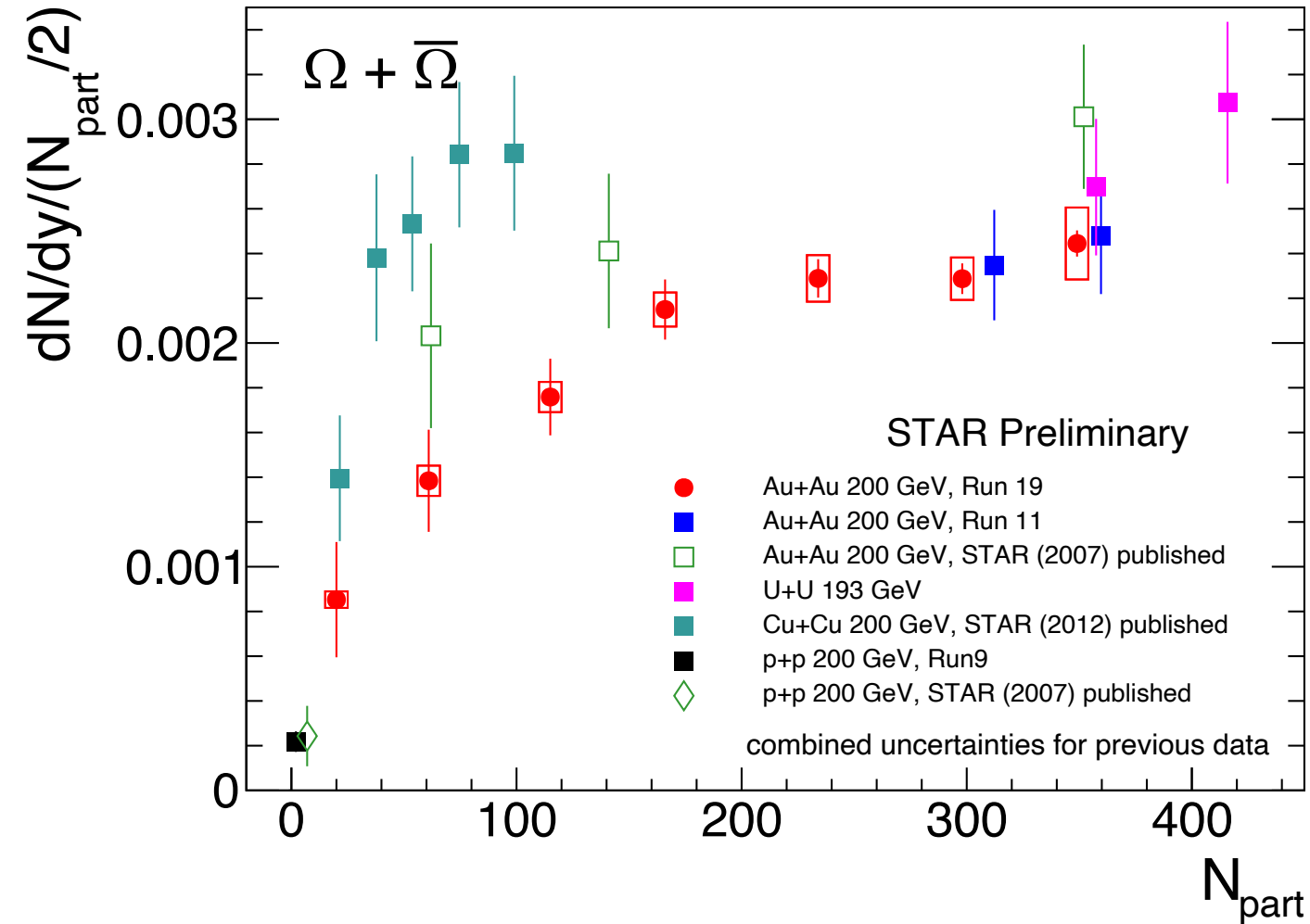
$\Lambda + \bar{\Lambda}$: STAR, Phys. Rev. Lett. 92 (2004) 052302

h^\pm (charged hadrons): STAR, Phys. Rev. Lett. 91 (2003) 172302

- R_{cp} of Ω follows the same trend in p_T as that of Λ and Ξ , as expected from recombination model.
- The higher R_{cp} of Ω implies the faster increase of Ω yields with the increasing centrality.

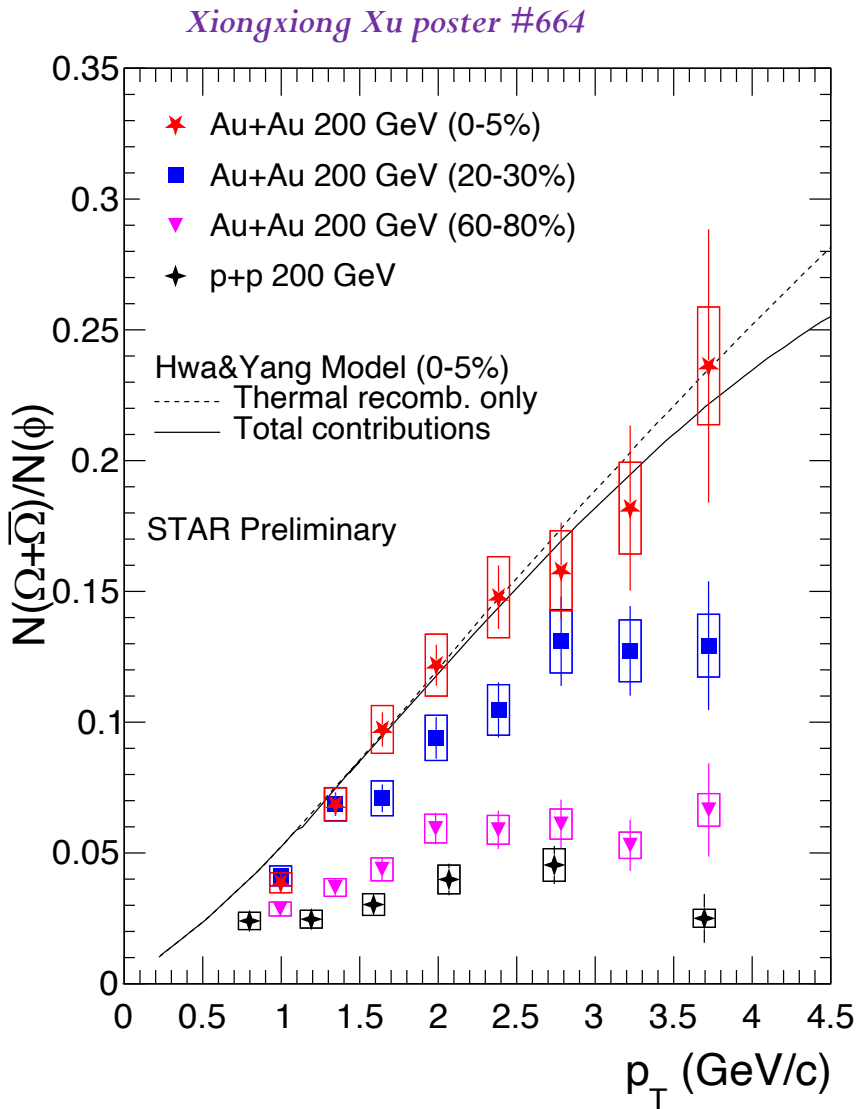
System size dependence of Ω yield at 200 GeV

Xiongxiang Xu poster #664



➤ In general, increasing Ω baryon enhancement compared to p+p collisions with increasing system size is observed.

Ω/ϕ ratio at 200 GeV



- In central collisions, good agreement between data and recombination model calculations.
 - ✓ Ω and ϕ are predominantly produced through the recombination of thermalized strange quarks in QGP.
- At intermediate p_T , ratio increases gradually with increasing system size. Significant Ω enhancement over ϕ is observed.
- Ω/ϕ ratio in p+p collisions is close to that in peripheral Au+Au collisions.
 - ✓ Hint of smooth transition from p+p collisions to Au+Au collisions.

d+Au collisions see Ishu's talk Sep 6, 2023, 4:30 PM Ballroom C

"Multiplicity Dependence of Strange Hadron Production in Small Systems using the STAR detector"

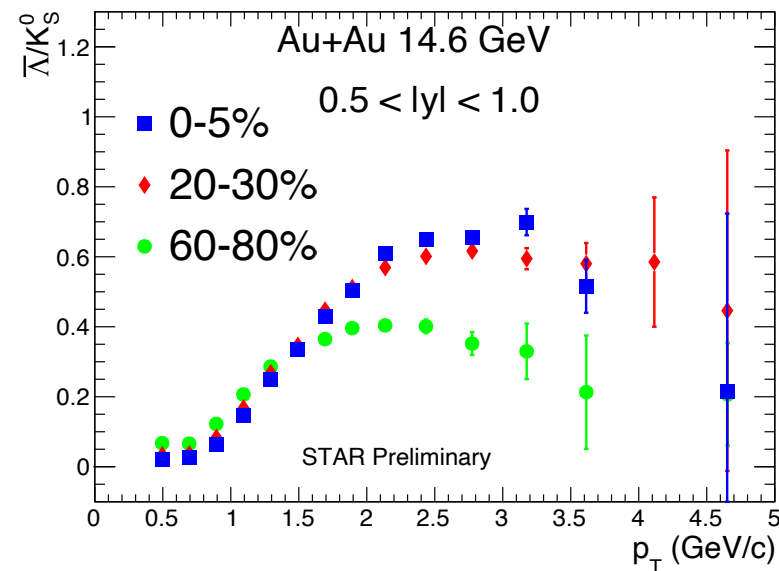
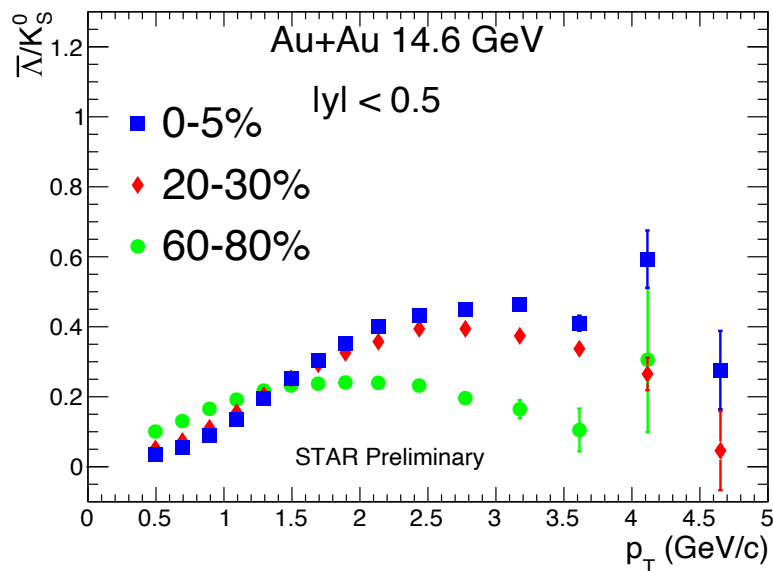
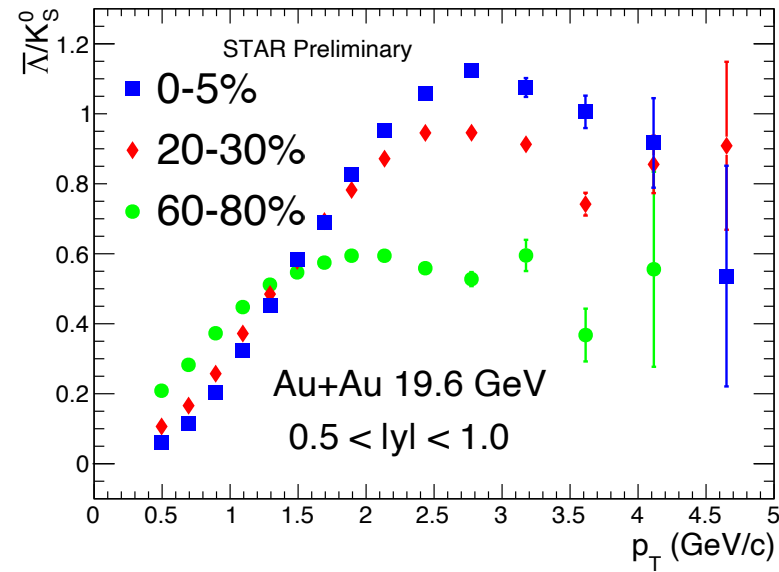
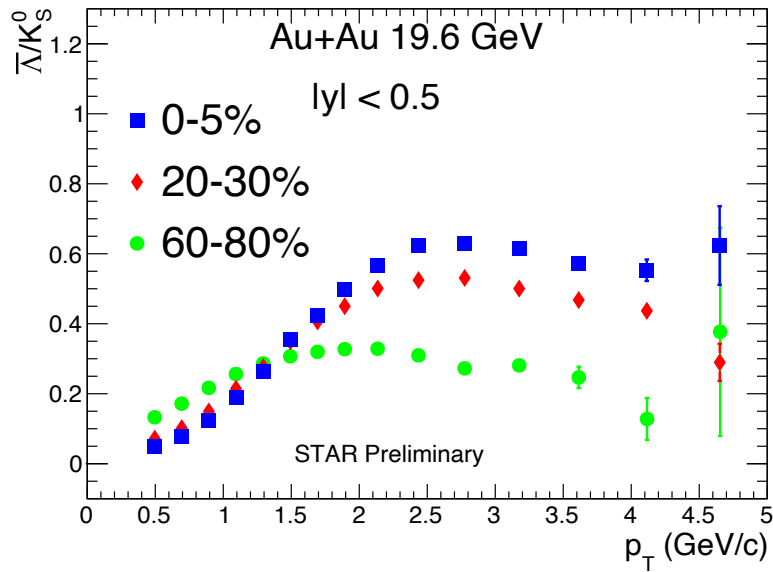
Ω p_T binning adapted to match ϕ data.

Au+Au 200 GeV ϕ : STAR, Phys. Rev. Lett. 99(2007) 112301

p+p 200GeV $\Omega + \bar{\Omega}$: X. Zhu, QM2014; p+p 200GeV ϕ : STAR, Phys. Rev. C 79(2009) 064903

Theory: Phys. Rev. C, 2007, 75: 054904. theoretical calculation only for central collisions

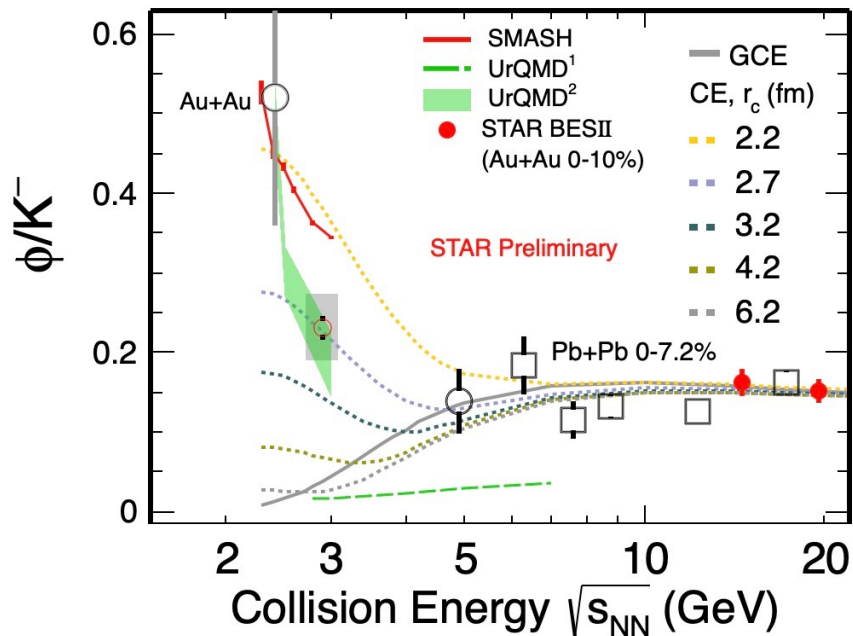
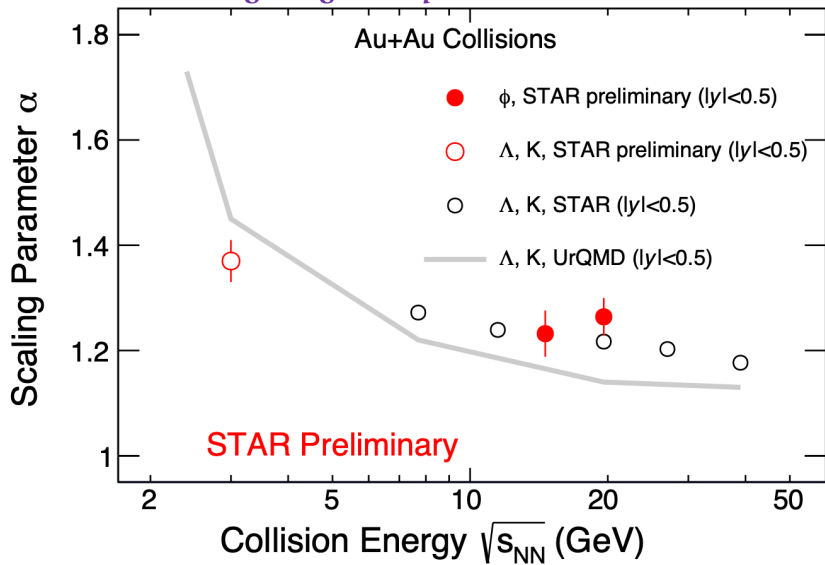
$\bar{\Lambda}/K_s^0$ ratio at 19.6 and 14.6 GeV



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

Energy and centrality dependence of strangeness production

Weiguang Yuan poster #555



➤ Fit function: $\frac{dN/dy}{N_{part}/2} = k \times N_{part}^{\alpha-1}$

➤ Common centrality dependence for ϕ , Λ , K production at 19.6 GeV.

➤ Above 7.7 GeV, data indicates a steeper increase on strangeness yields towards central collisions compared to UrQMD.

✓ Might point to production mechanisms beyond hadronic interactions in this energy range.

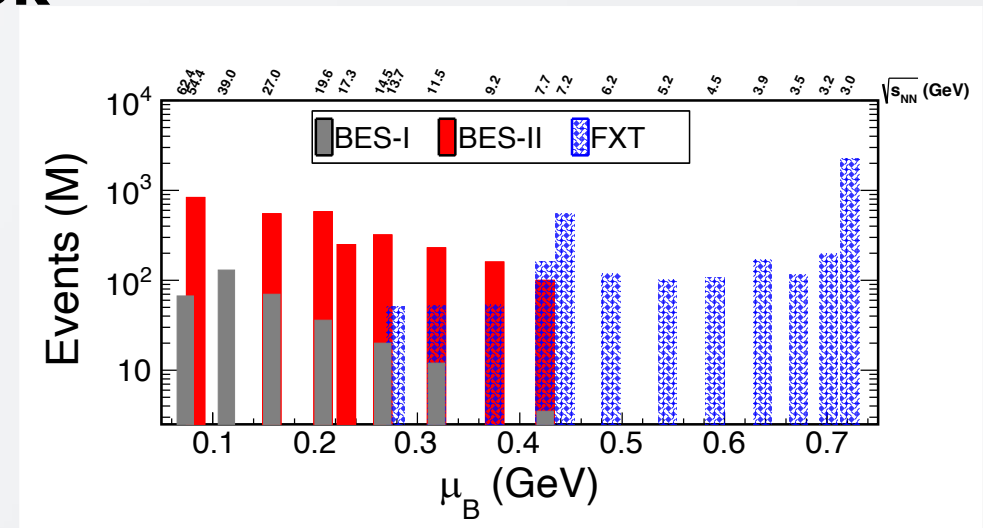
➤ In contrast to 3 GeV, ϕ/K^- reach grand canonical ensemble limit at 19.6 and 14.6 GeV.

Summary

- **Precise strangeness measurements** with extended p_T and rapidity at 14.6 19.6 and 200 GeV.
- Rapidity spectra of baryons (Λ , Ξ^-) are wider than those of the anti-baryons($\bar{\Lambda}$, $\bar{\Xi}^+$) at 14.6 and 19.6 GeV \rightarrow extra contributions from stopped baryons.
- Baryon enhancement is observed from 14.6 to 200GeV \rightarrow consistent with QGP formation.
- Ω measurements at 200 GeV indicates a smooth trend in strangeness enhancement from small to large systems.

Outlook

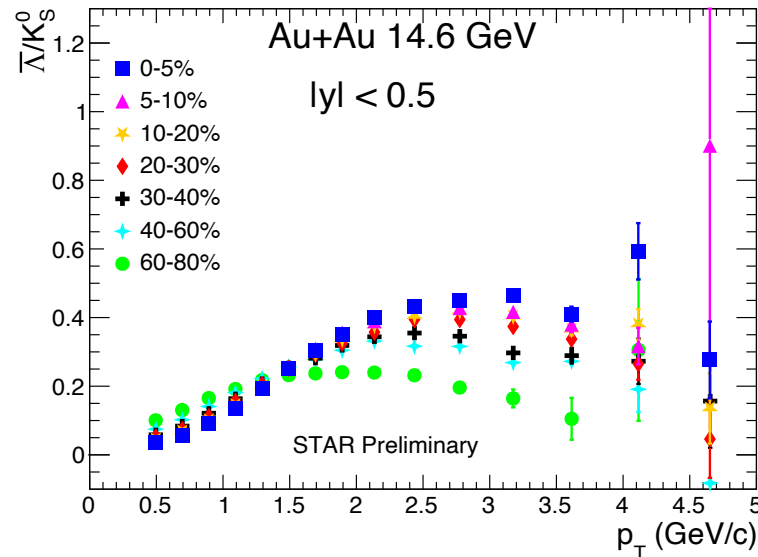
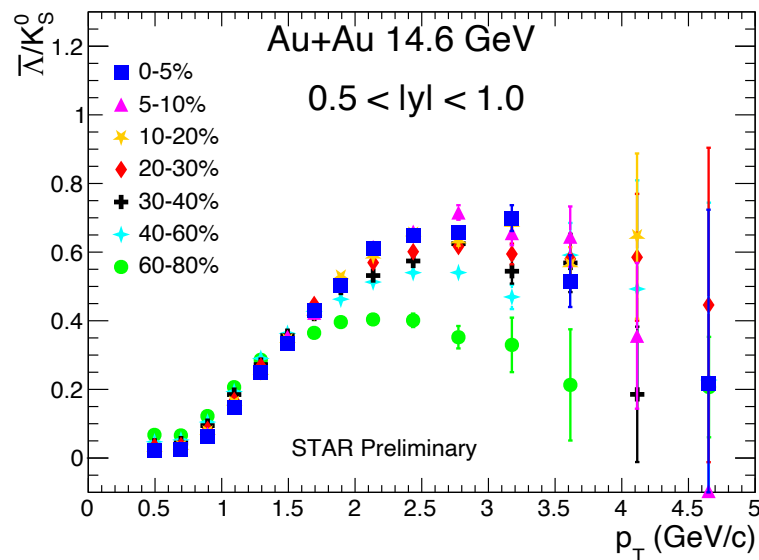
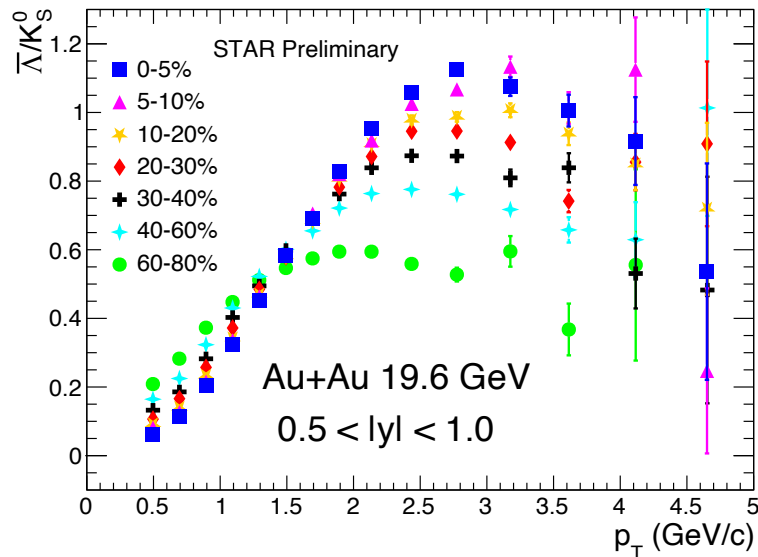
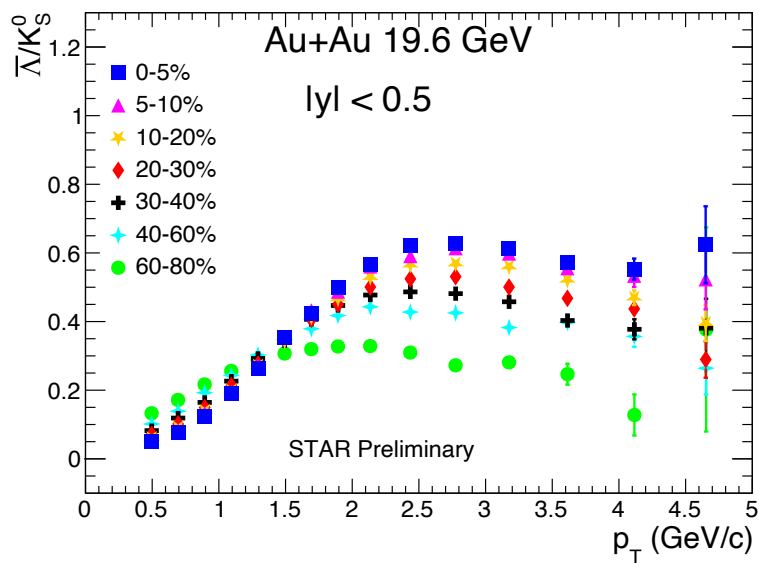
- Strangeness measurements from 3.2 to 14.6 GeV in BES-II will probe the onset of deconfinement.



Back up

Back up

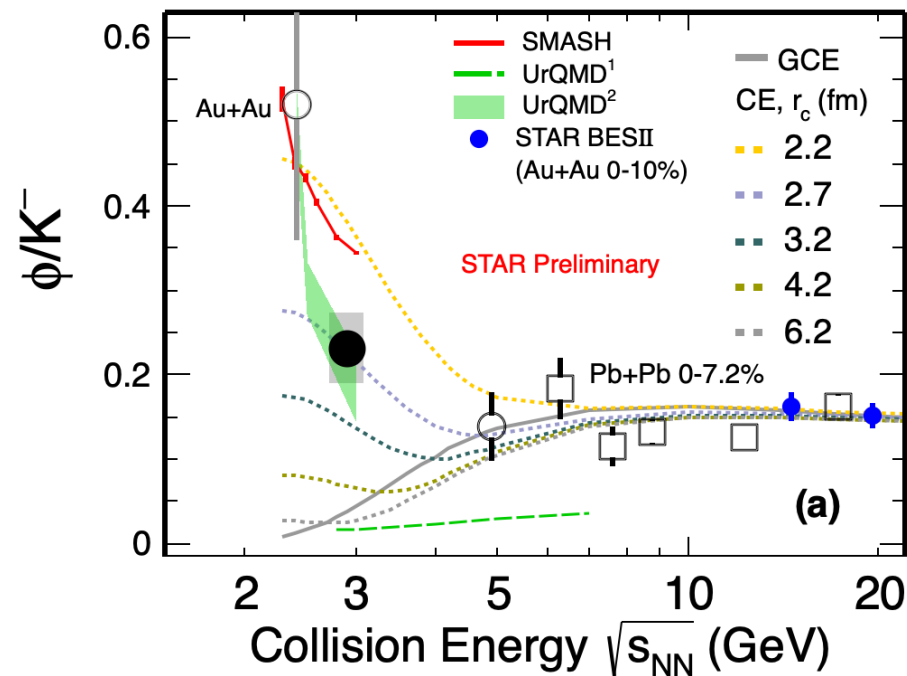
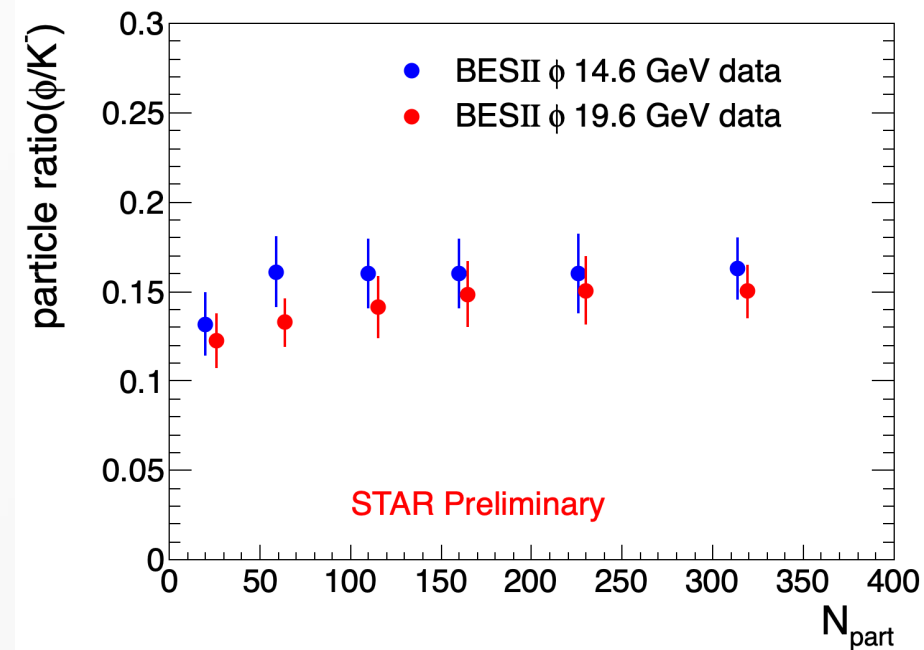
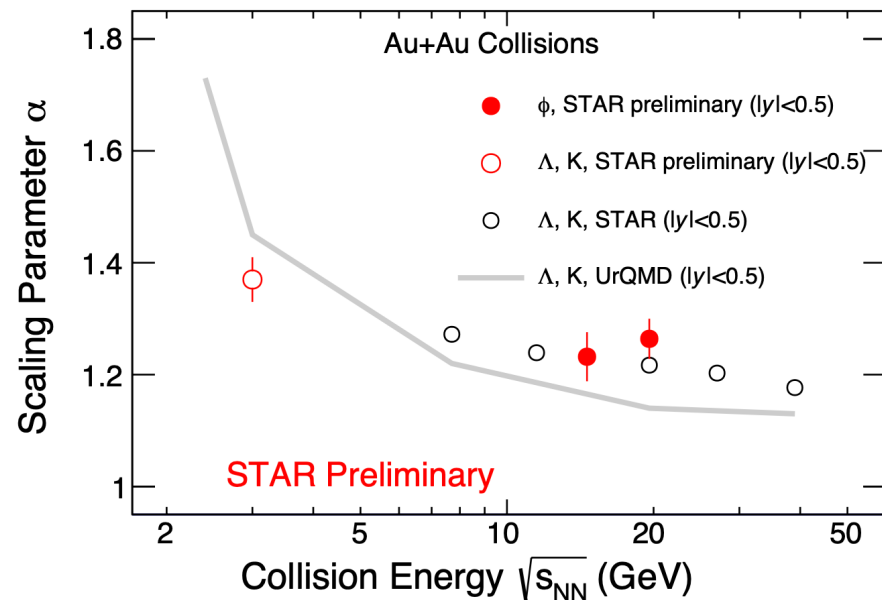
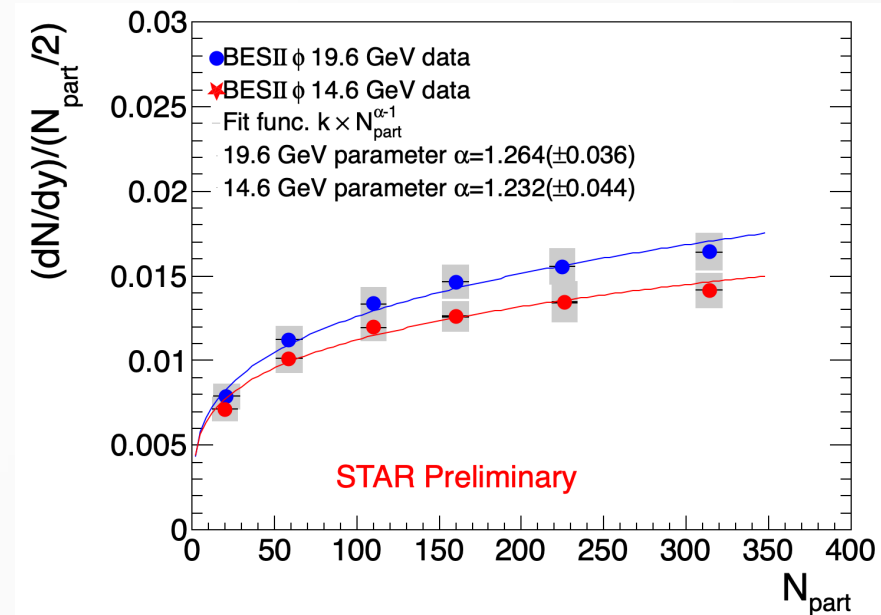
$\bar{\Lambda}/K_S^0$ Ratio at 19.6 and 14.6 GeV of all centralities



➤ Clear centrality and rapidity dependence of (anti-)baryon-to-meson ratio at intermediate p_T .

➤ Baryon enhancement is observed in all measured regions.

Energy and centrality dependence of strangeness production



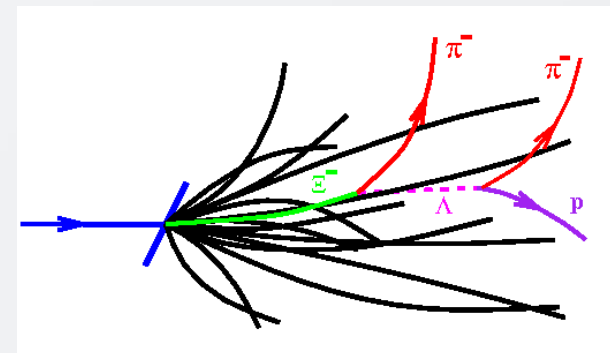
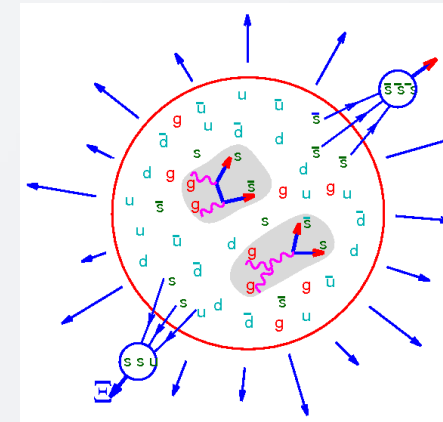
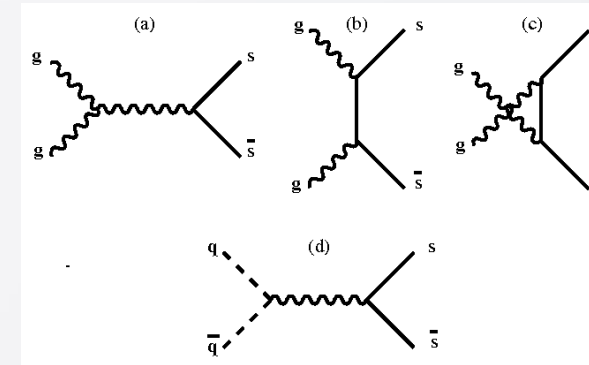
Why strangeness?

Rafelski & Müller, 1982

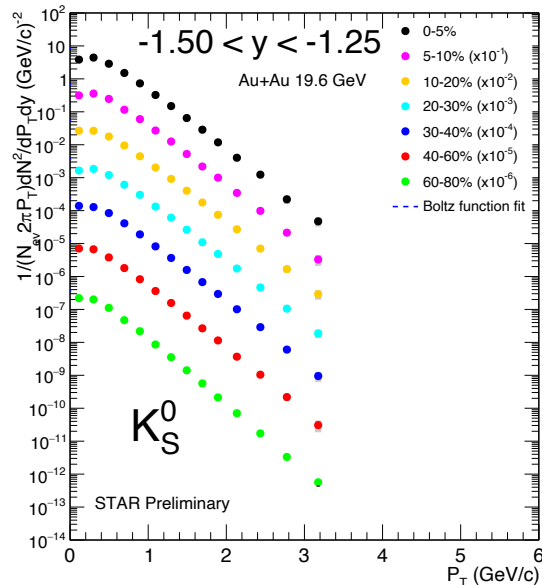
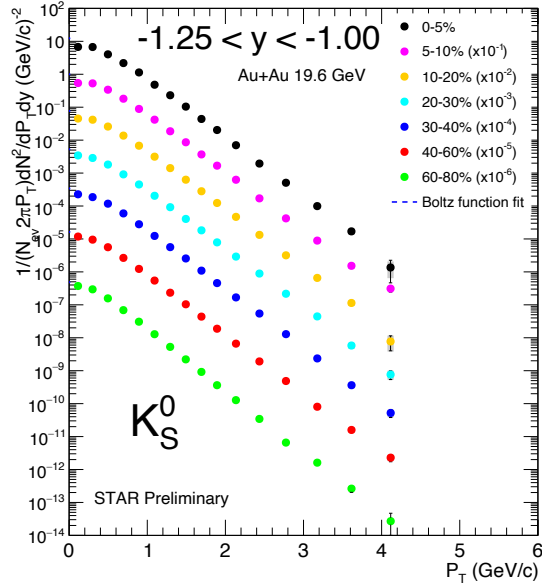
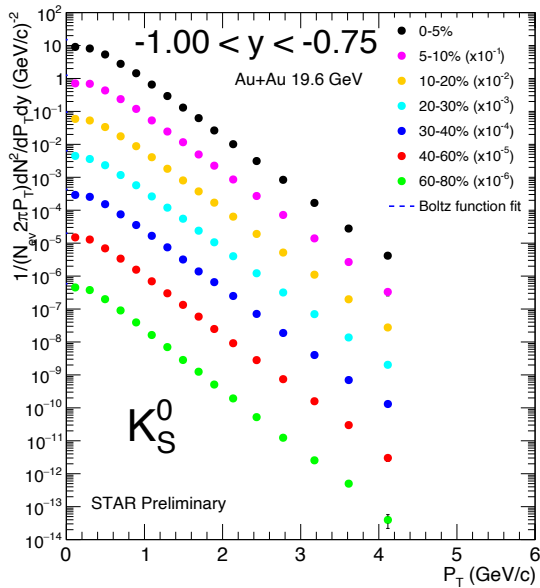
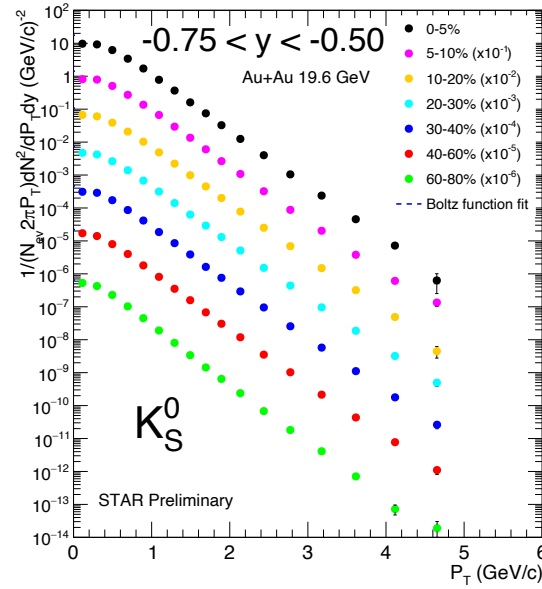
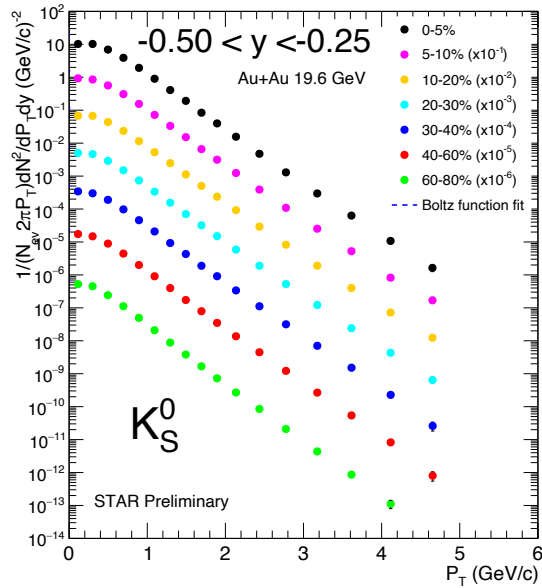
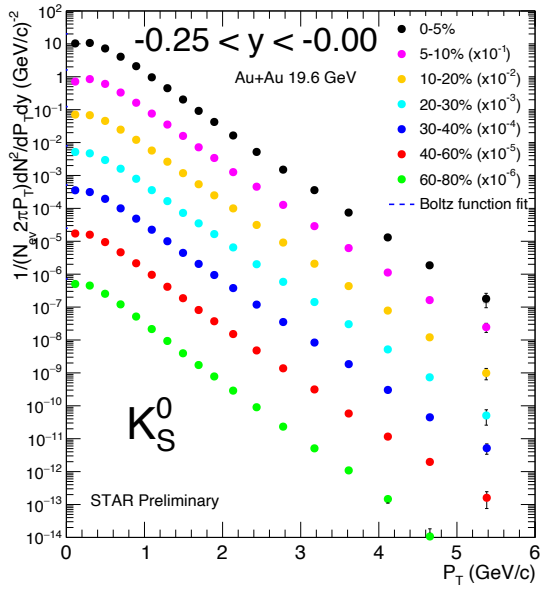
- Strange quarks
 - Not exist in colliding nuclei
 - Current mass $\sim 100 \text{ MeV} < T_c$
 - Easily pair-produced in de-confined QGP medium

→ **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 !

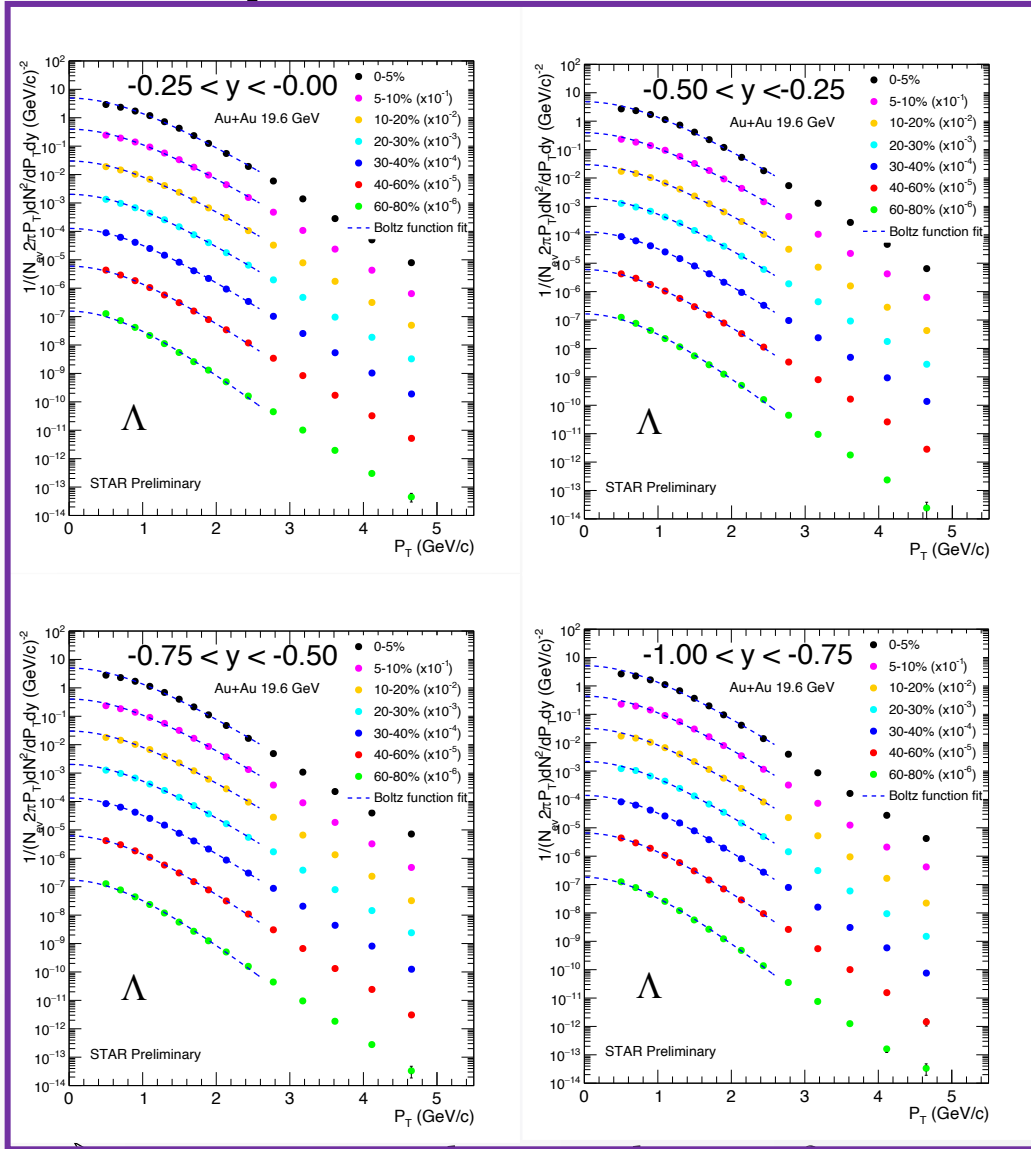


Back up p_T spectra of K_S^0 at 19.6 GeV at backward rapidity

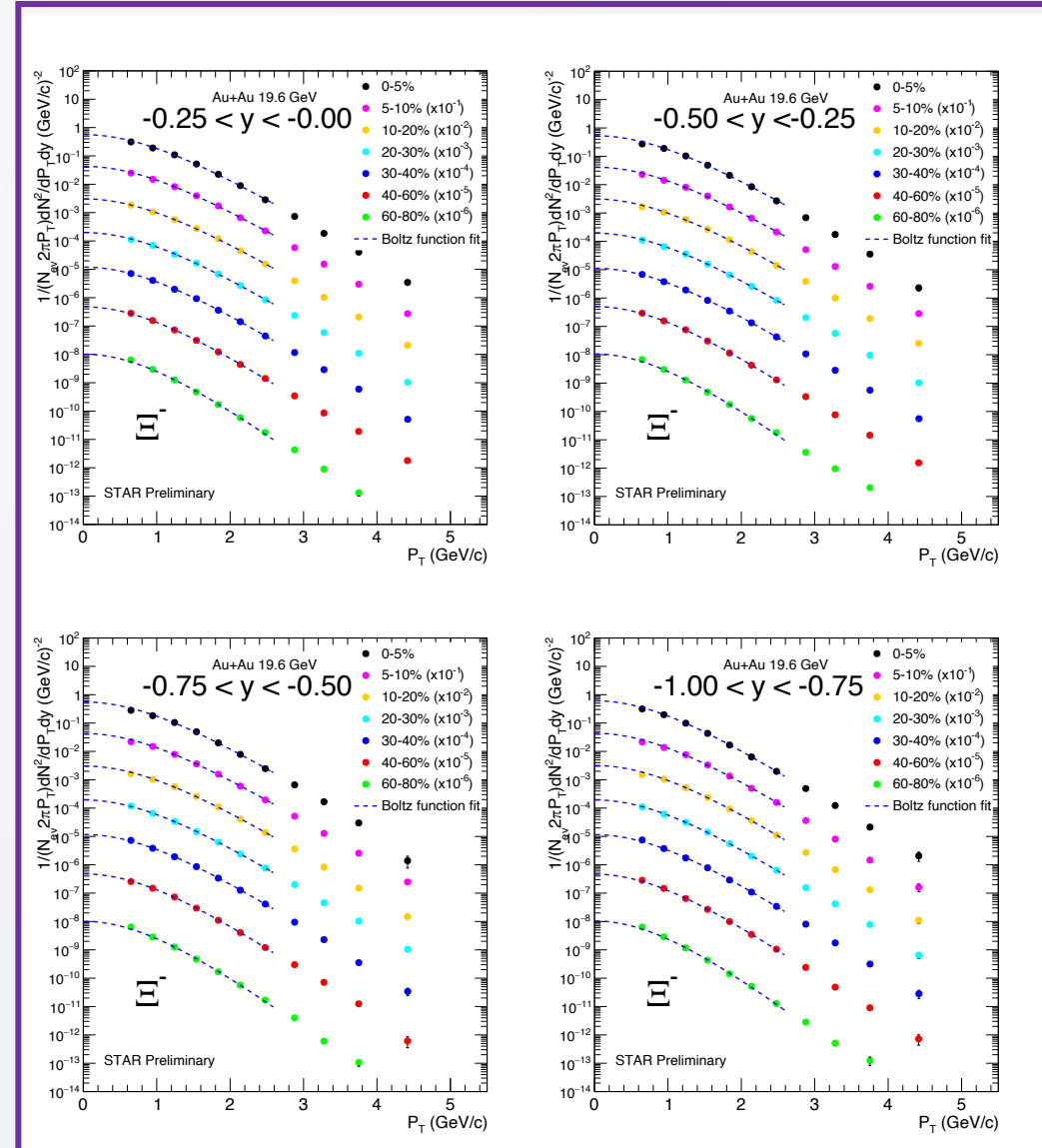


- K_S^0 : measured down to $p_T=0$, no need for extrapolation to obtain dN/dy
- Rapidity: $|y| < 1.5$

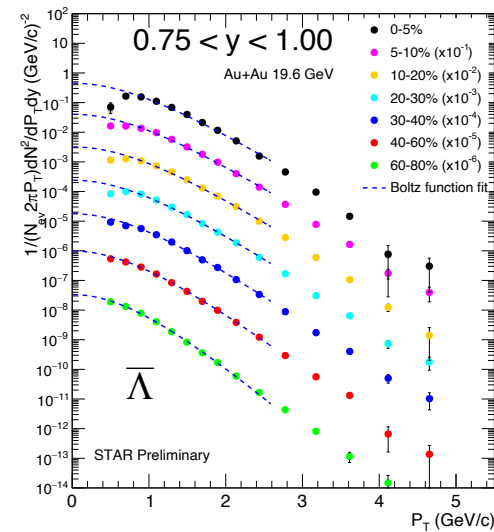
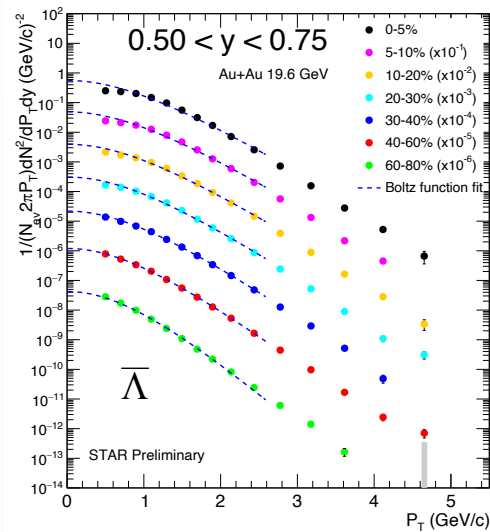
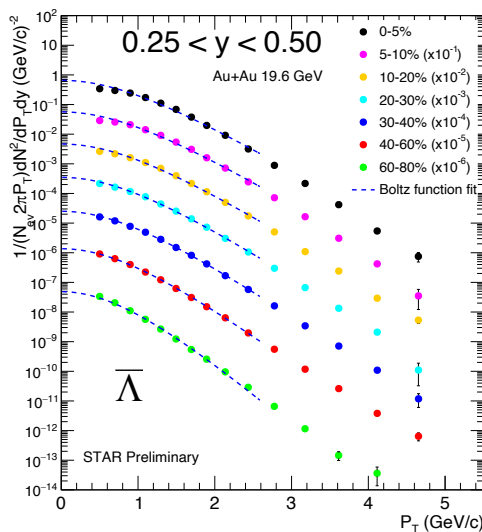
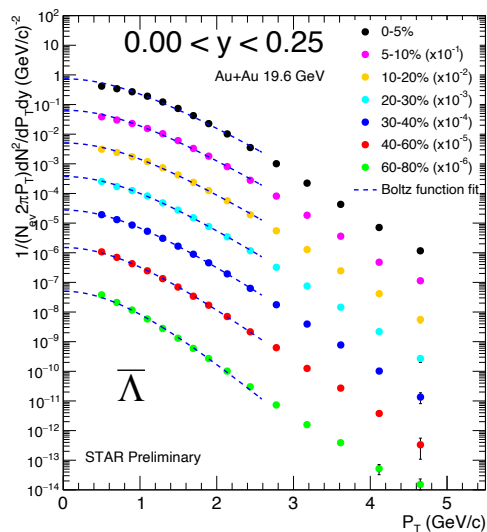
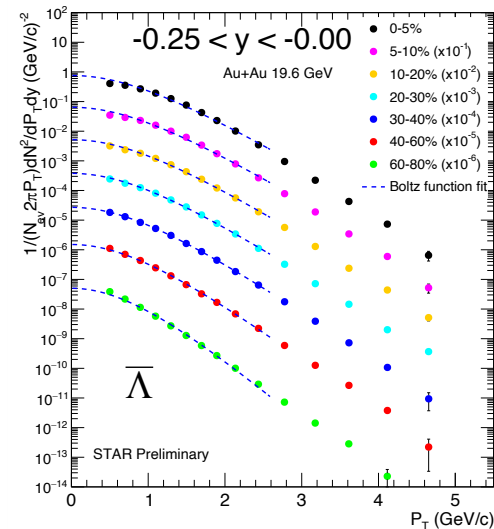
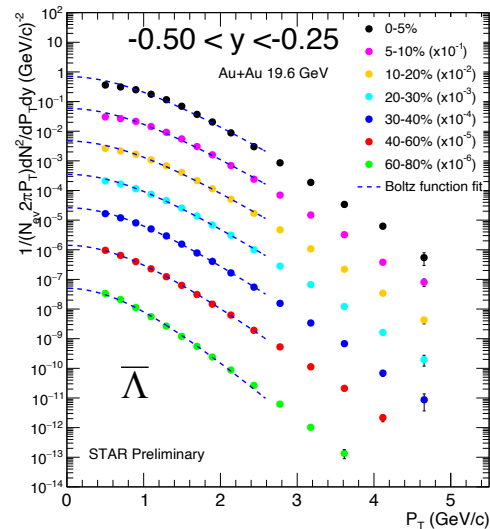
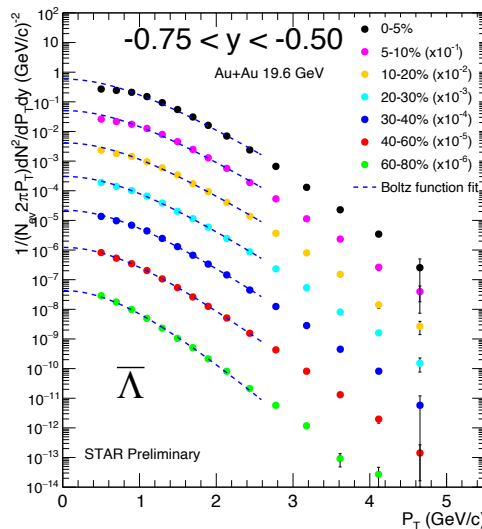
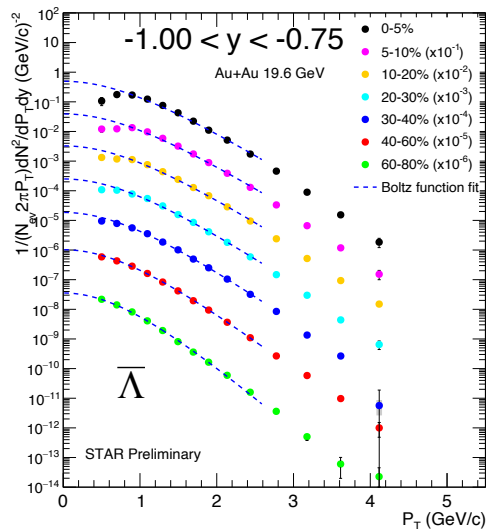
Back up p_T spectra of Λ and Ξ^- at 19.6 GeV at backward rapidity



- Low p_T extrapolation: Boltzmann function
- Ξ^- and Ξ^0 decay feed-down corrected
- Rapidity: $|y| < 1.0$



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

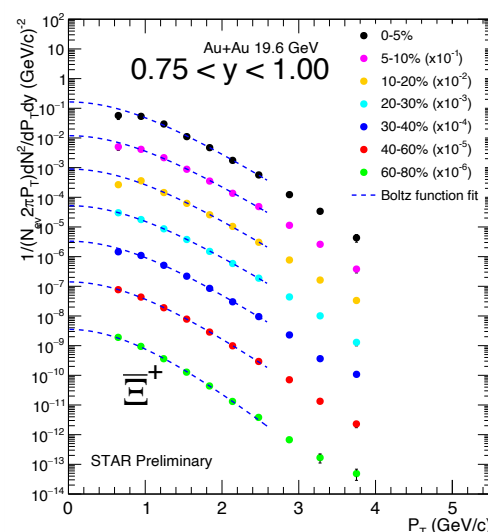
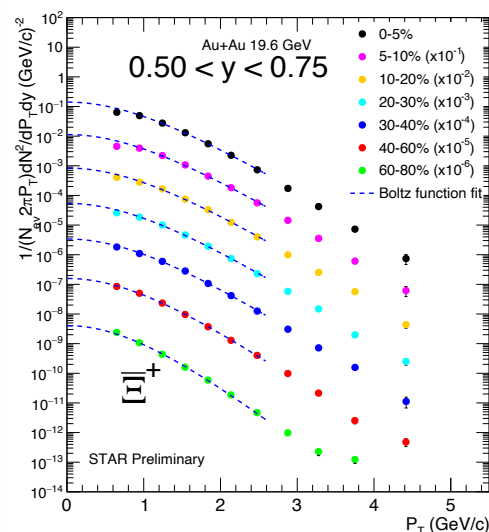
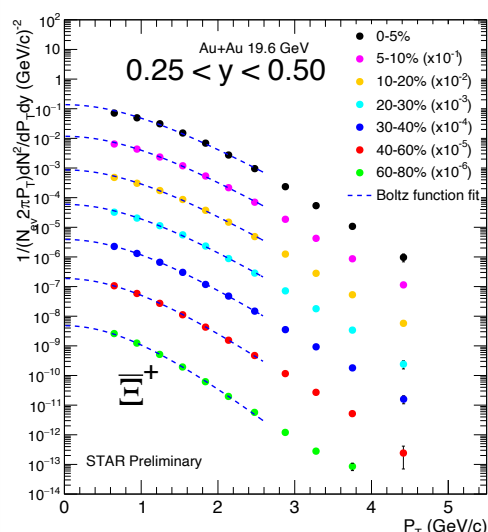
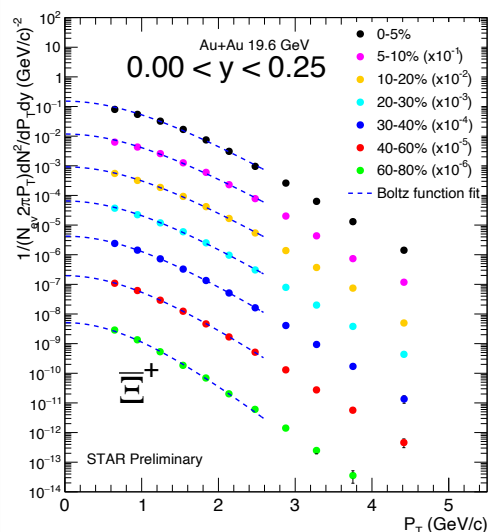
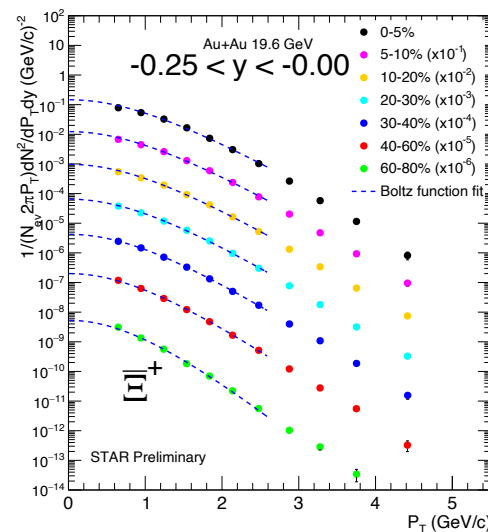
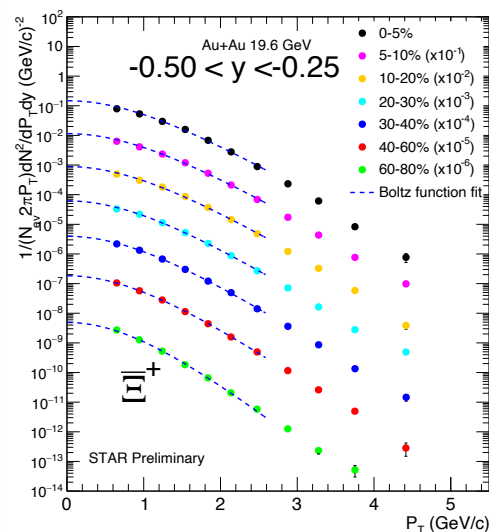
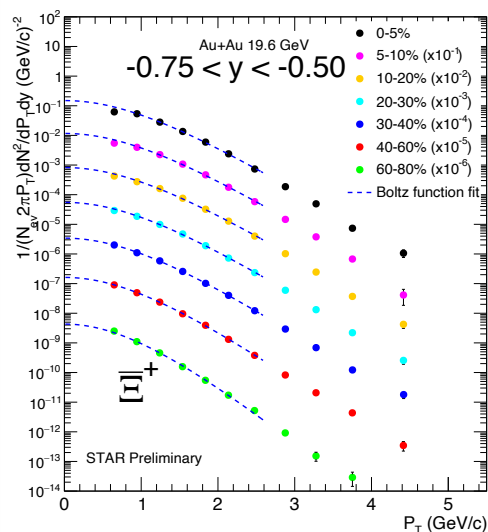
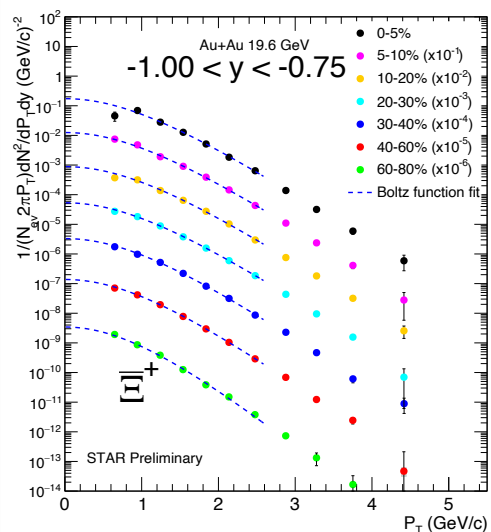


- Low p_T extrapolation: Boltzmann function
- Ξ^+ and Ξ^0 decay feed-down corrected

- Rapidity: $|y| < 1.0$

Back up

p_T spectra of Ξ^+ at 19.6 GeV

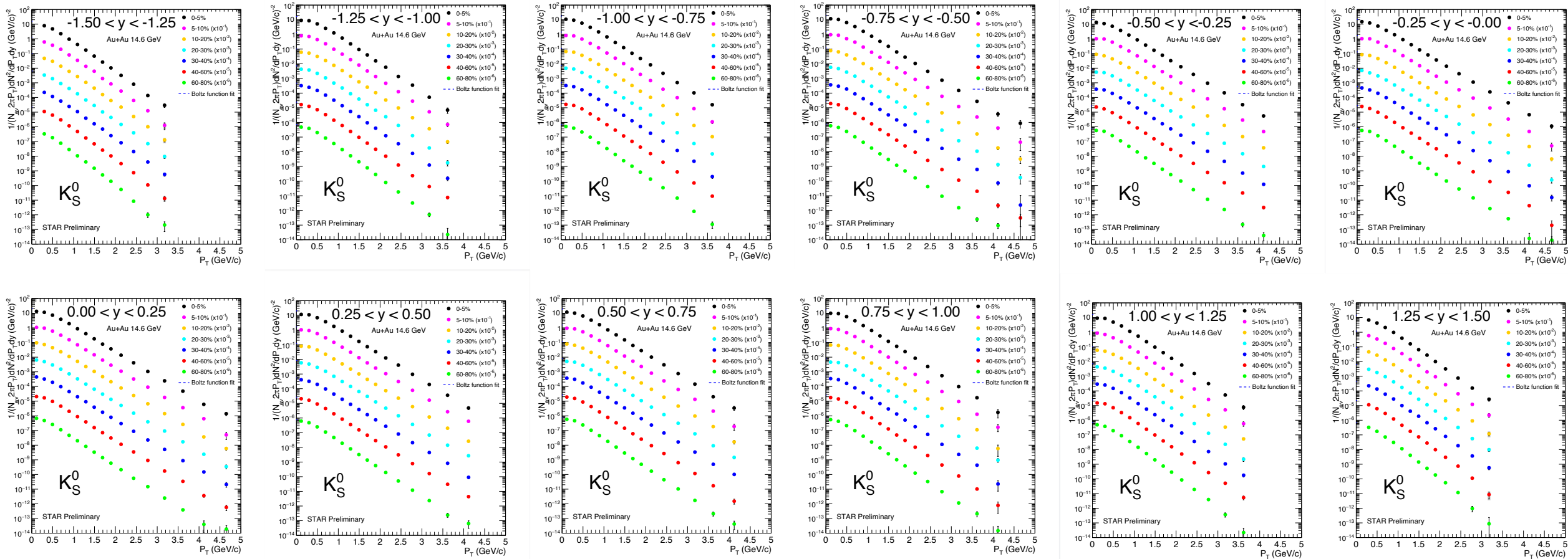


➤ Low p_T extrapolation: Boltzmann function

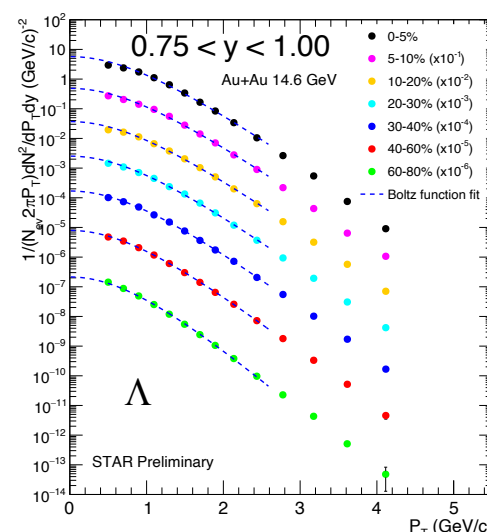
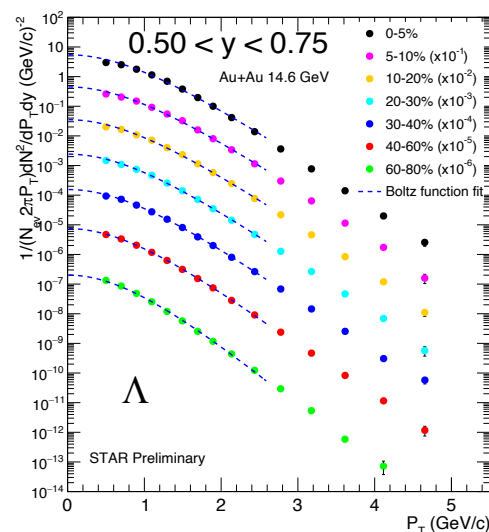
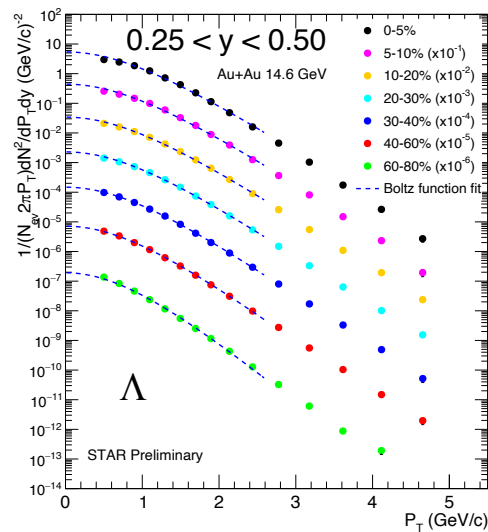
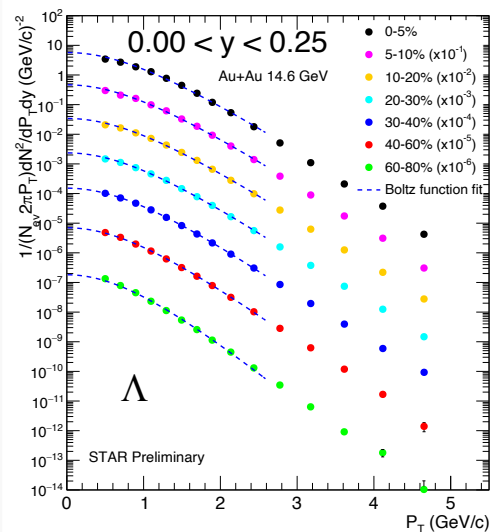
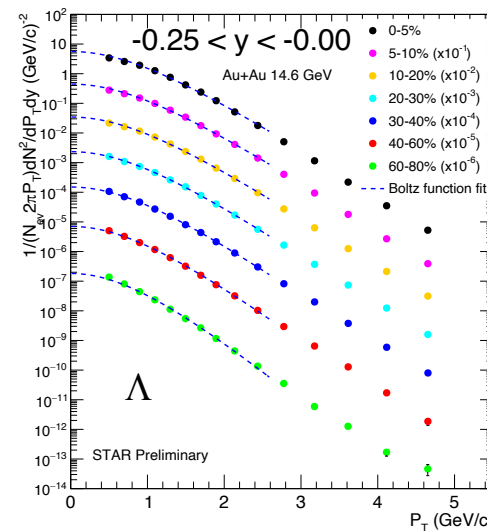
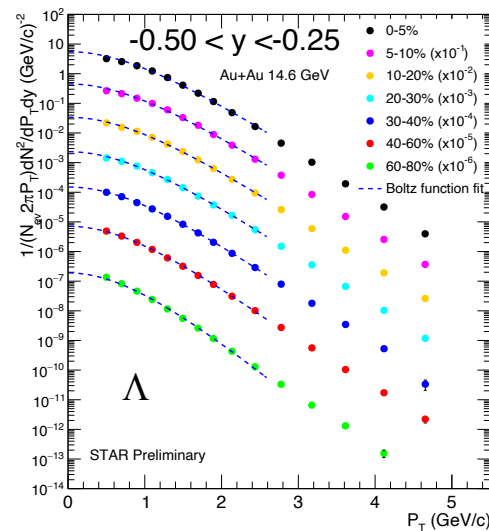
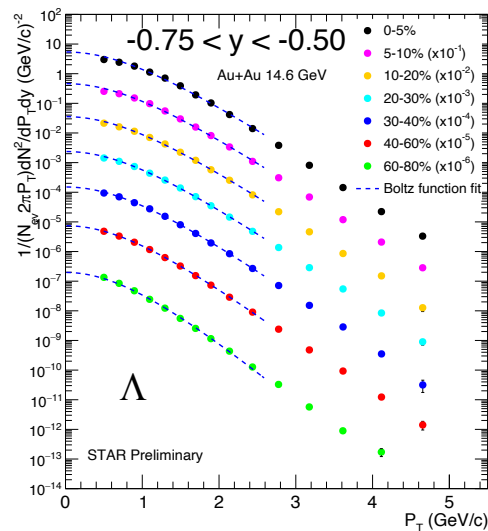
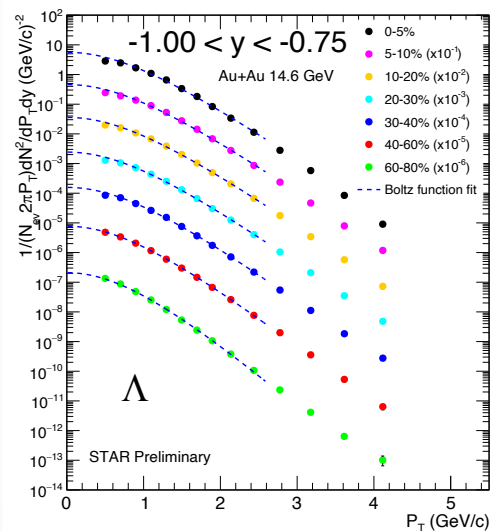
➤ Rapidity: $|y| < 1.0$

Back up

p_T spectra of K_S^0 at 14.6 GeV



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

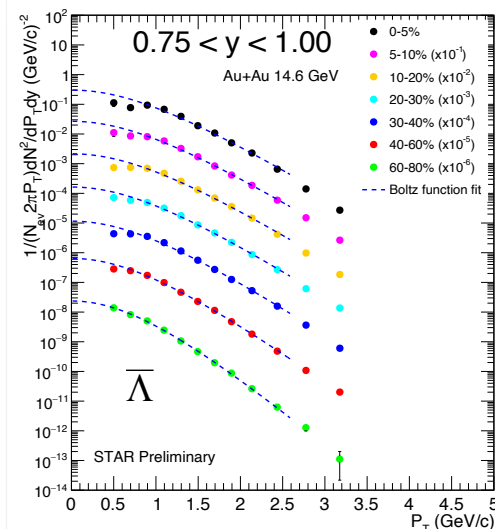
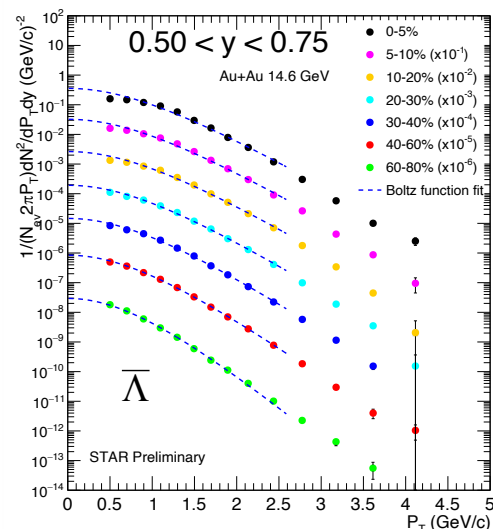
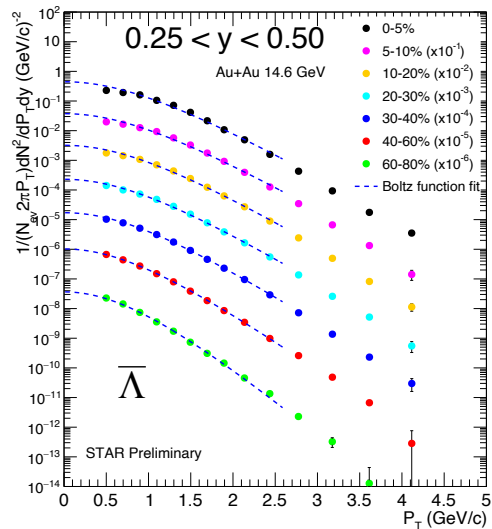
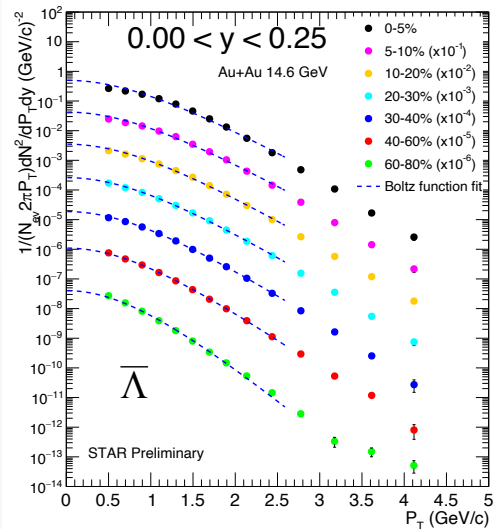
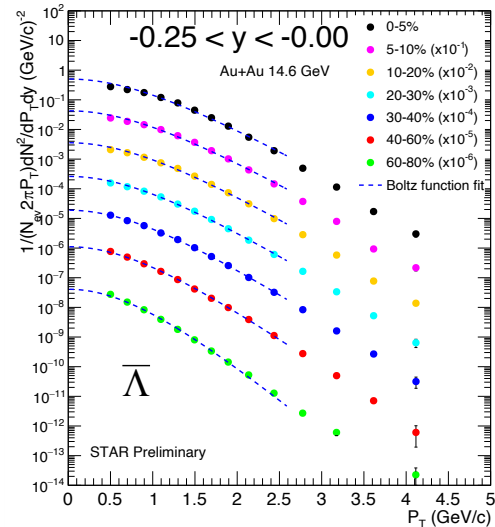
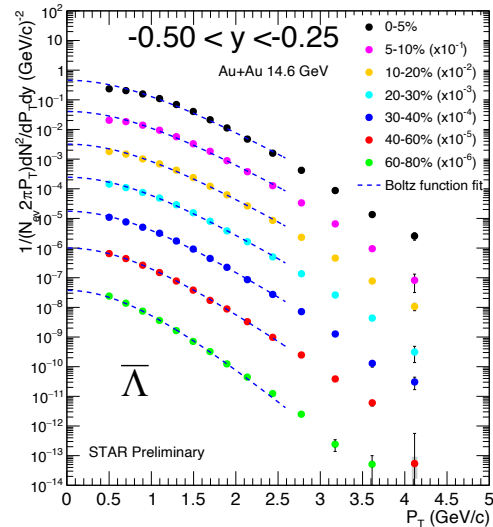
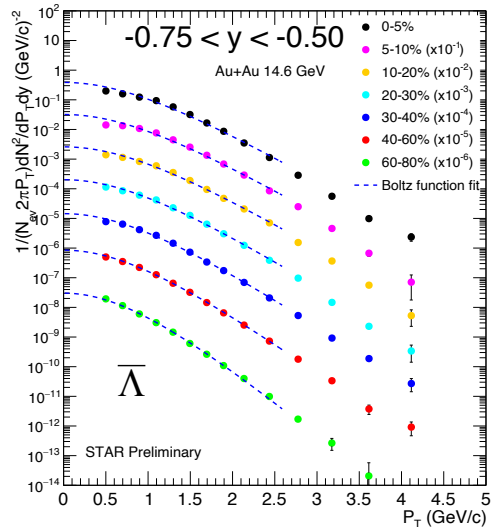
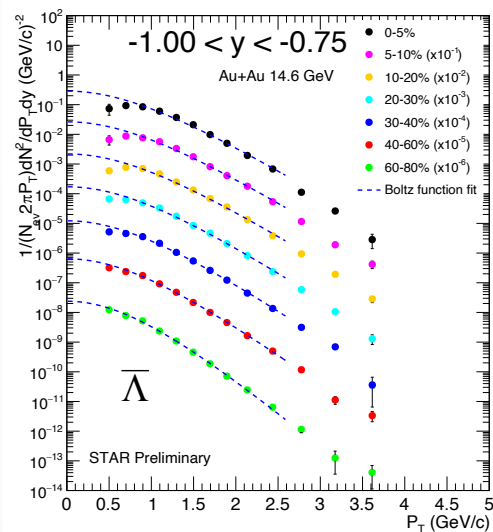


- Low p_T extrapolation: Boltzmann function
- Ξ^- and Ξ^0 decay feed-down corrected

- Rapidity: $|y| < 1.0$

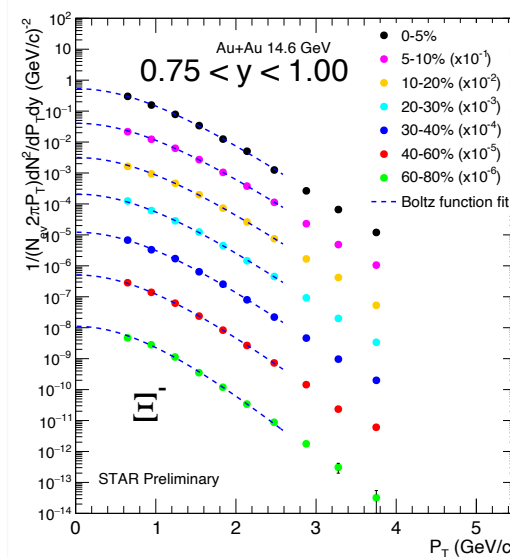
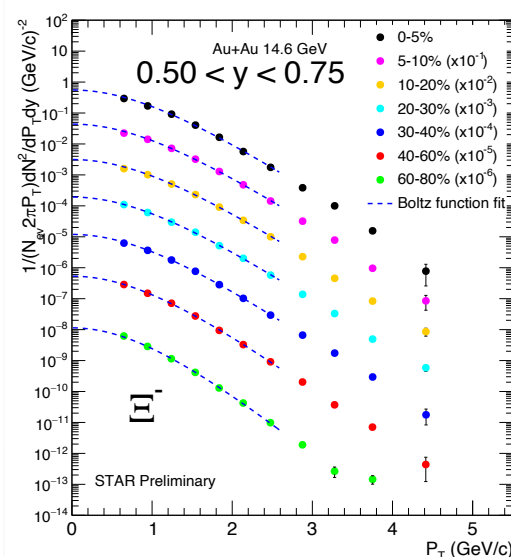
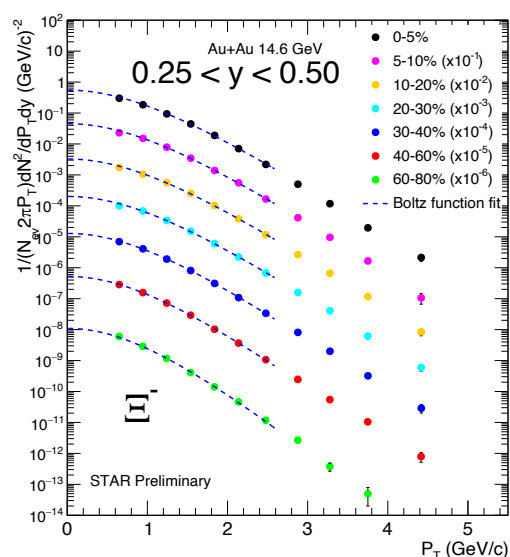
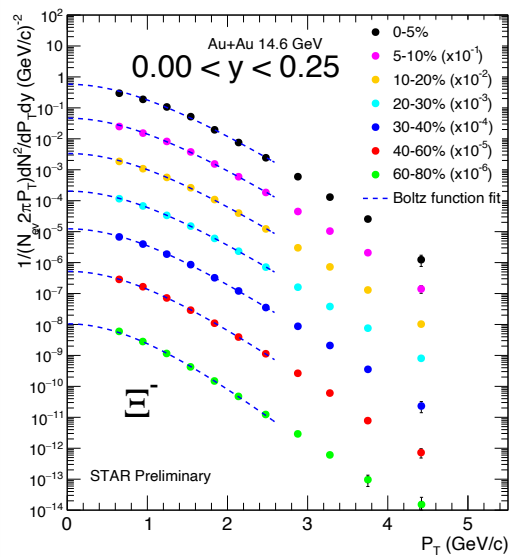
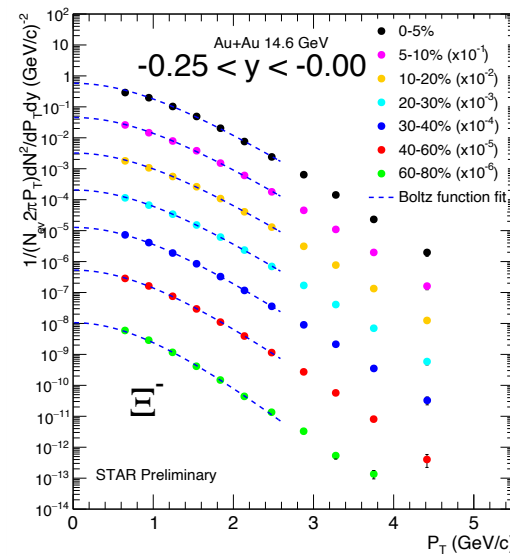
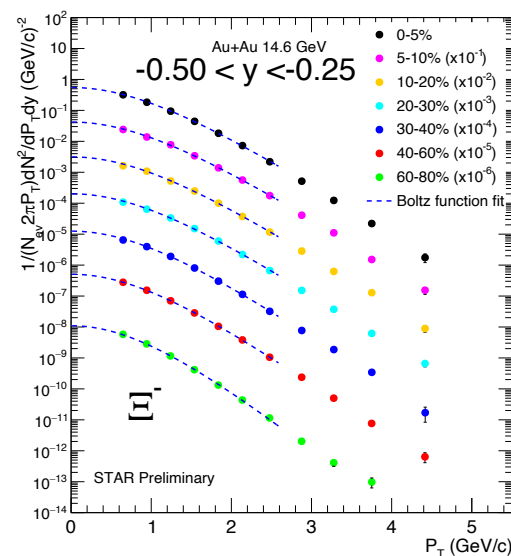
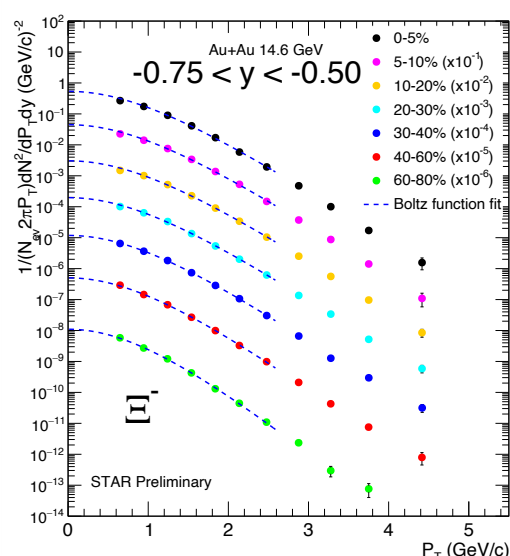
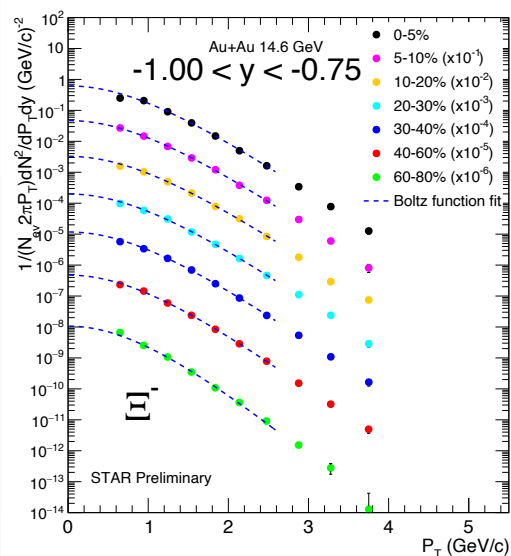
Back up

p_T spectra of $\bar{\Lambda}$ at 14.6 GeV



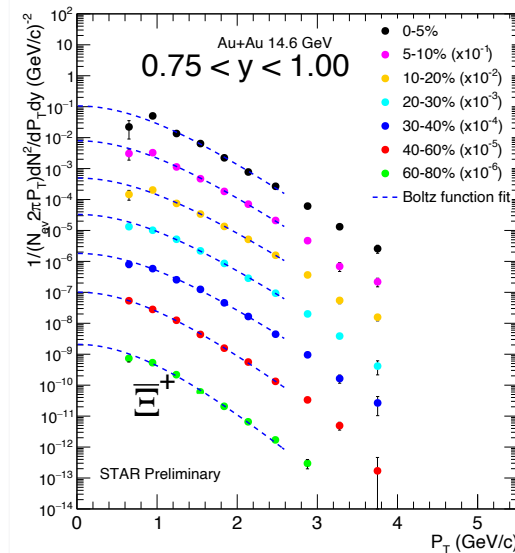
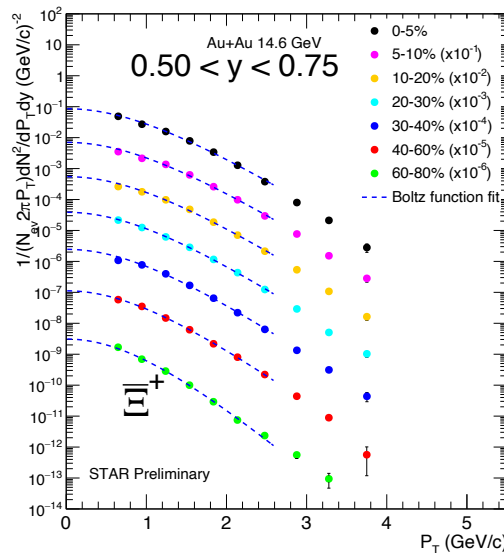
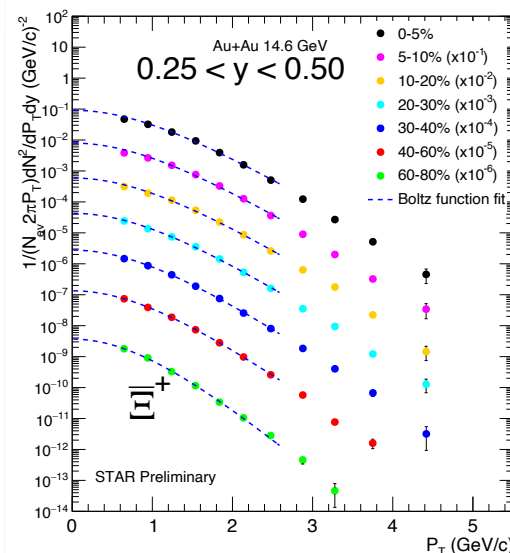
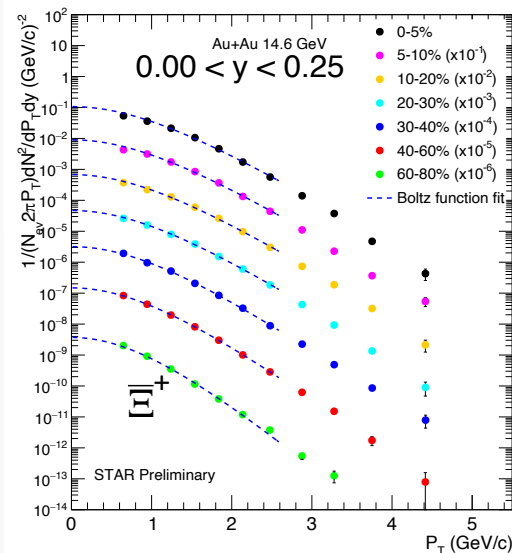
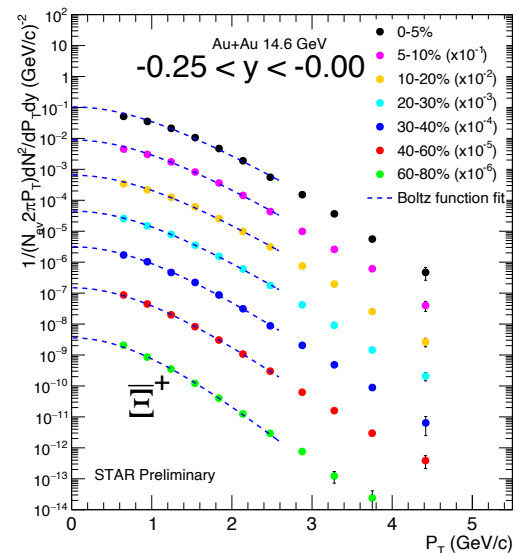
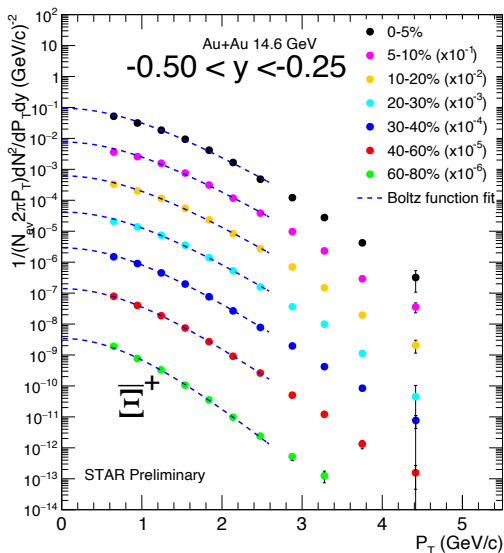
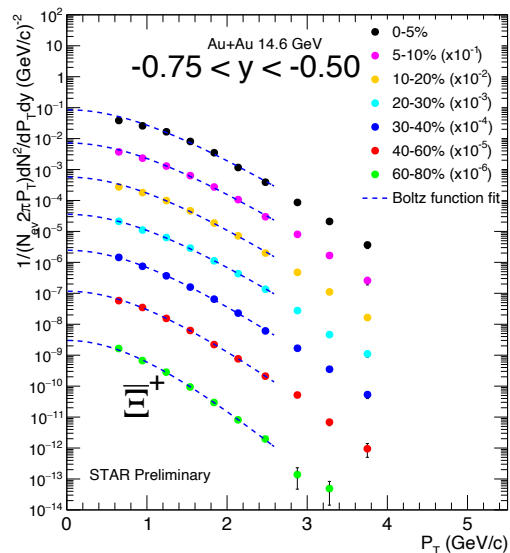
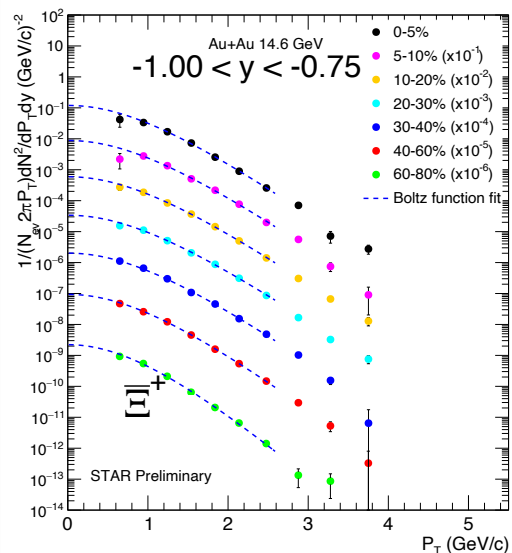
- Low p_T extrapolation: Boltzmann function
- Ξ^+ and Ξ^0 decay feed-down corrected

- Rapidity: $|y| < 1.0$



➤ Low p_T extrapolation: Boltzmann function

➤ Rapidity: $|y| < 1.0$



➤ Low p_T extrapolation: Boltzmann function

➤ Rapidity: $|y| < 1.0$