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, $\overline{\Lambda}/K_S^0$ and ϕ/K^- ratios
- Summary

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Motivation

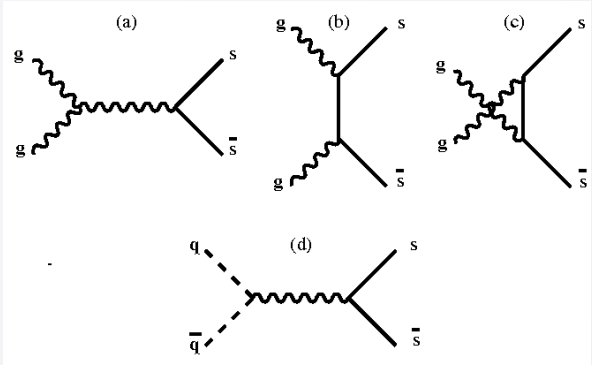
Why strangeness?

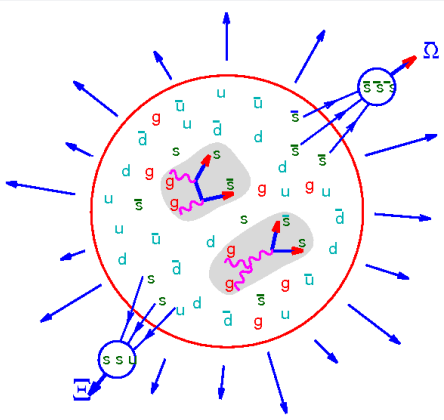
- Strange quarks
  - Not exist in colliding nuclei
  - Current mass ~100 MeV < T_c
  - Easily pair-produced in de-confined QGP medium

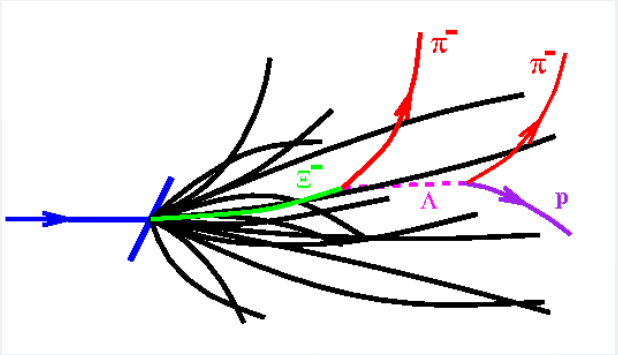
→ **Strangeness enhancement !**

- 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 !

Rafelski & Müller, 1982



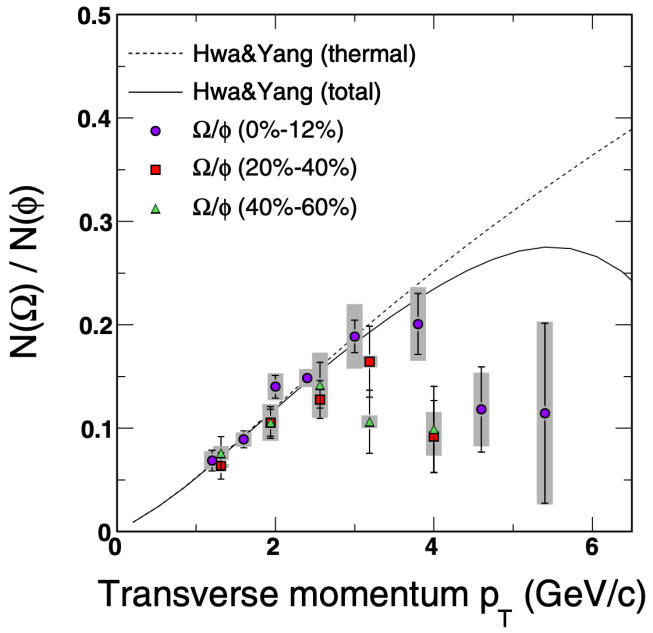


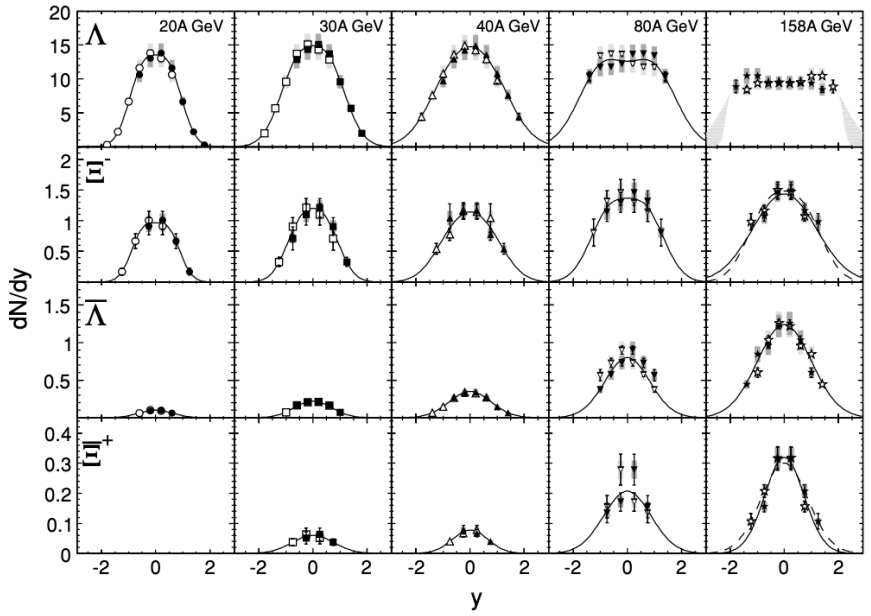


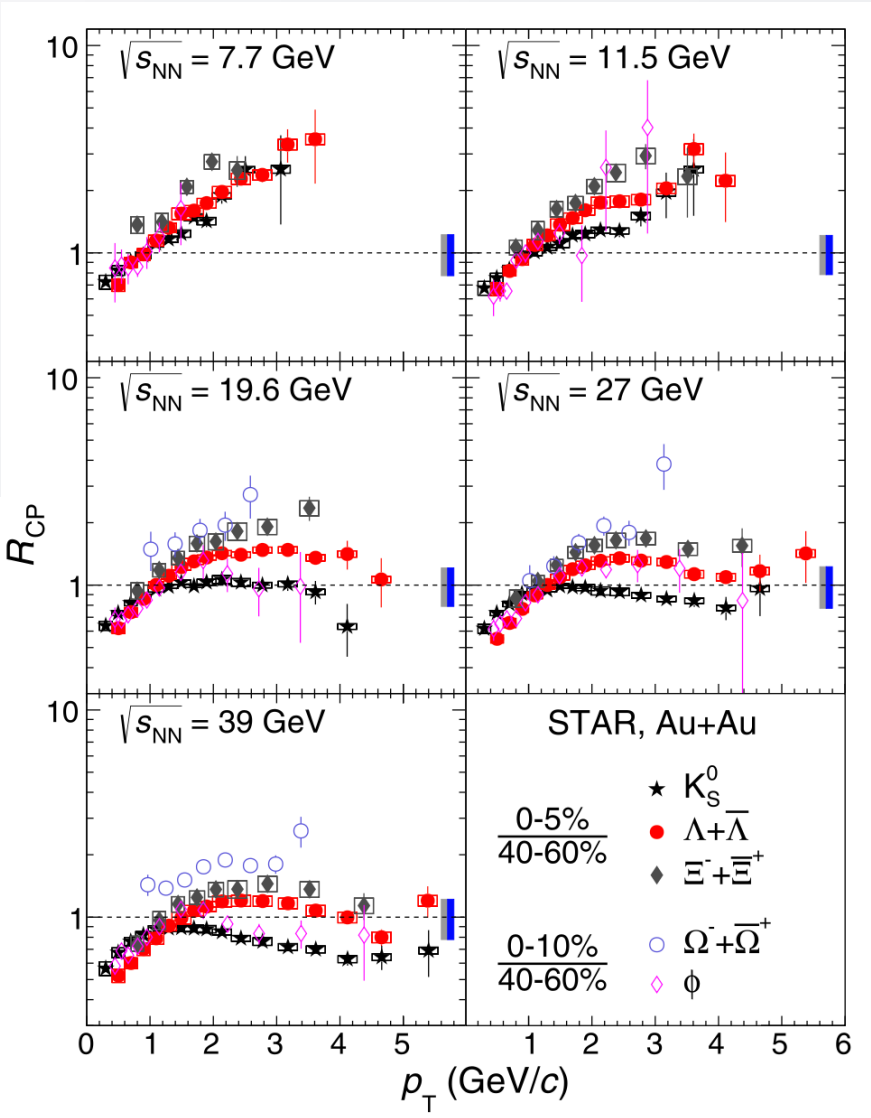
Motivation

- 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.

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







STAR, PRL 99, 112301 (2007)

NA49, PRC 78, 034918 (2008)

STAR, PRC 102, 034909 (2020)

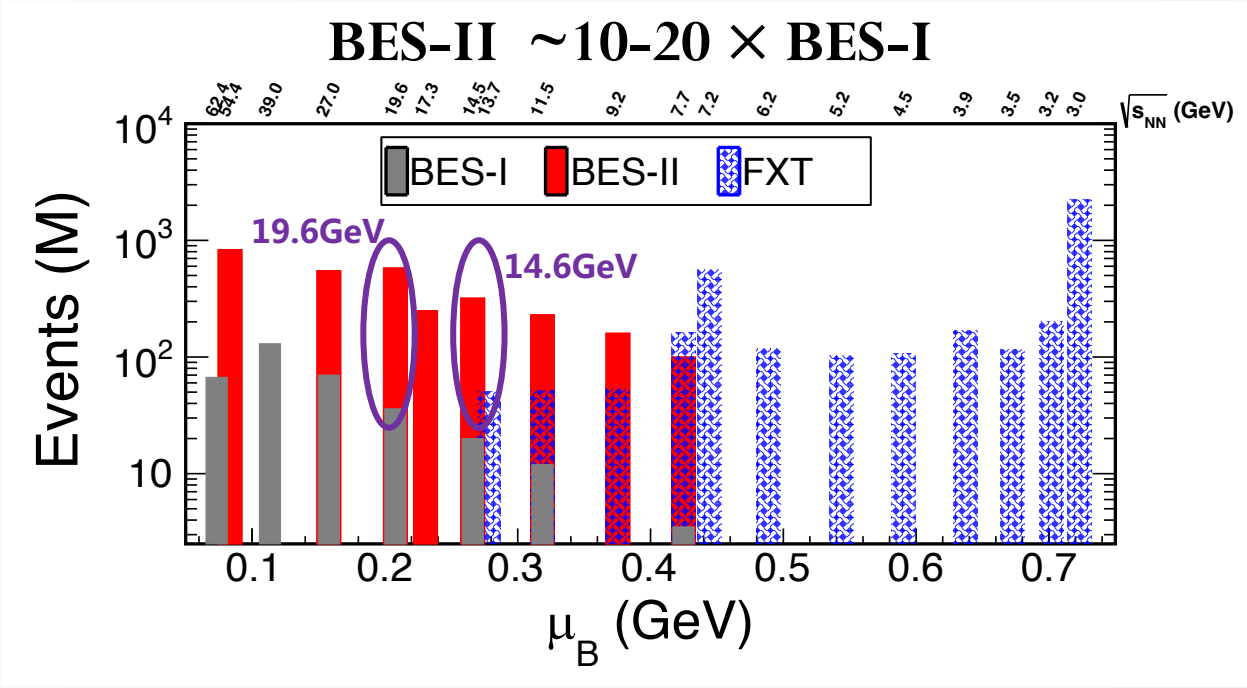
Motivation

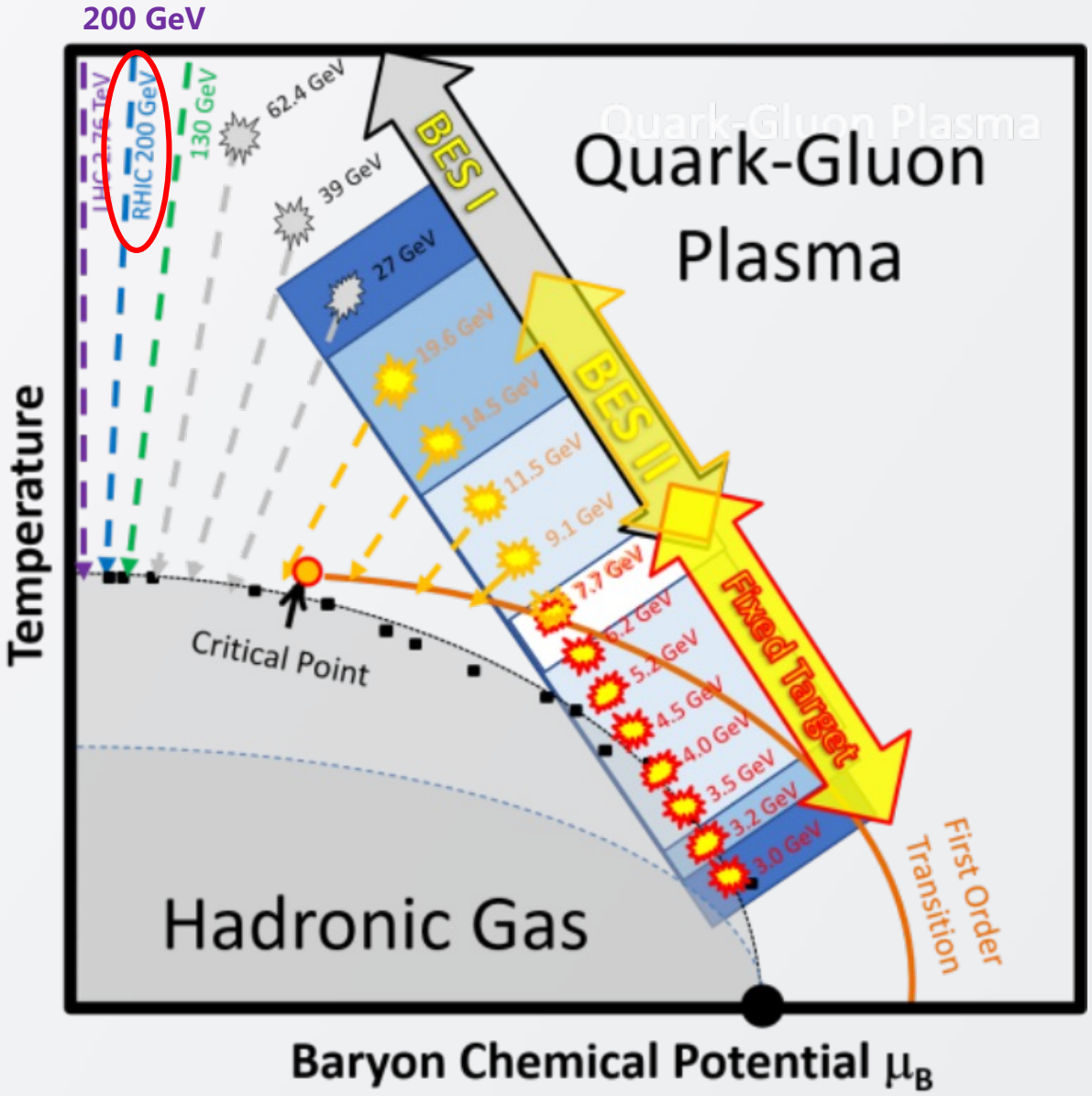
Heavy-ion collisions at top RHIC energy:

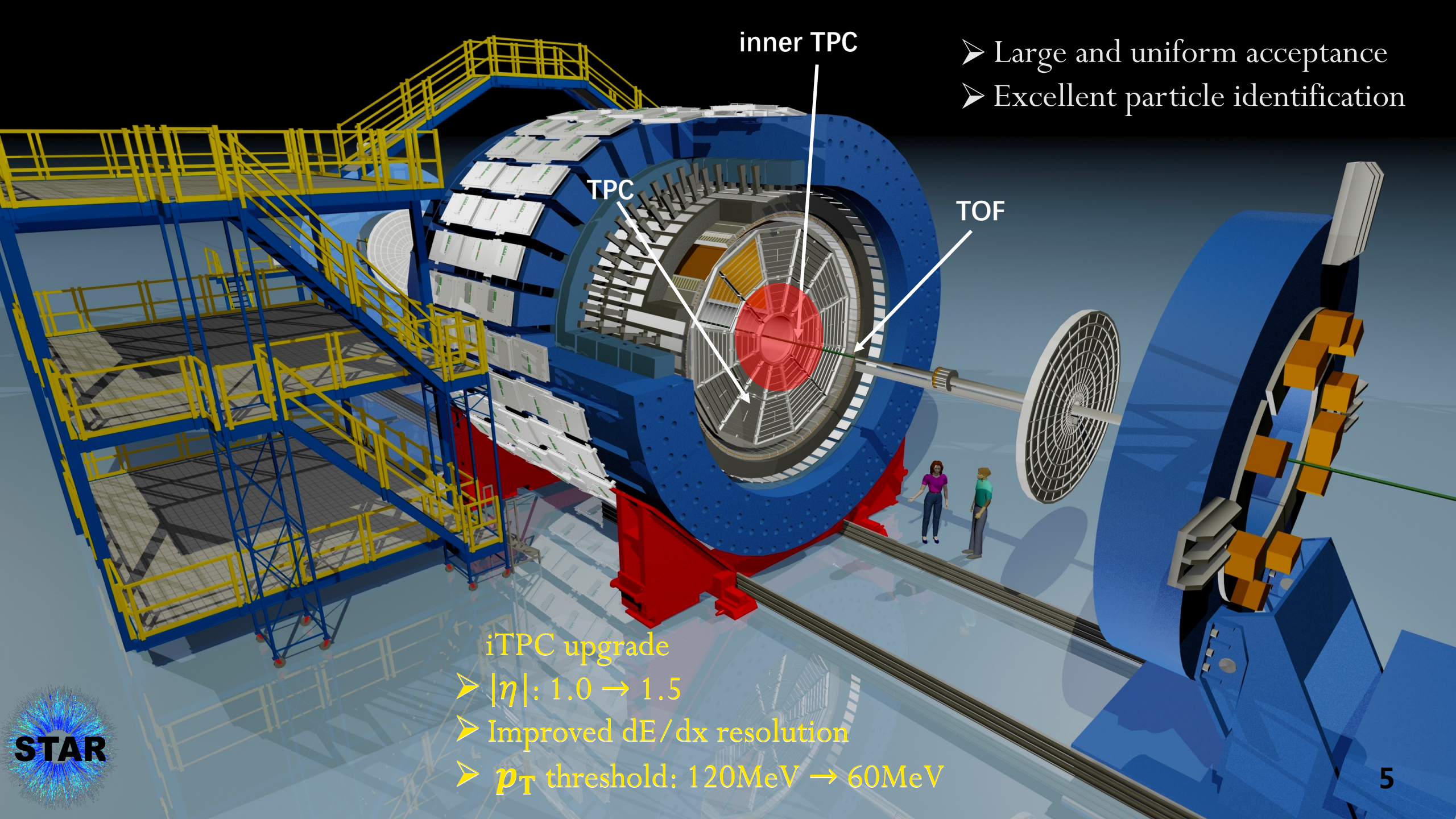
- Study QGP properties

Beam Energy Scan (BES) program:

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







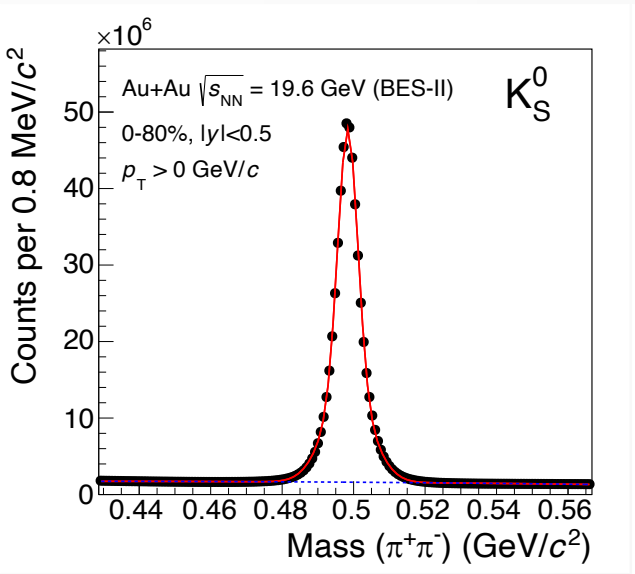
- Large and uniform acceptance
- Excellent particle identification

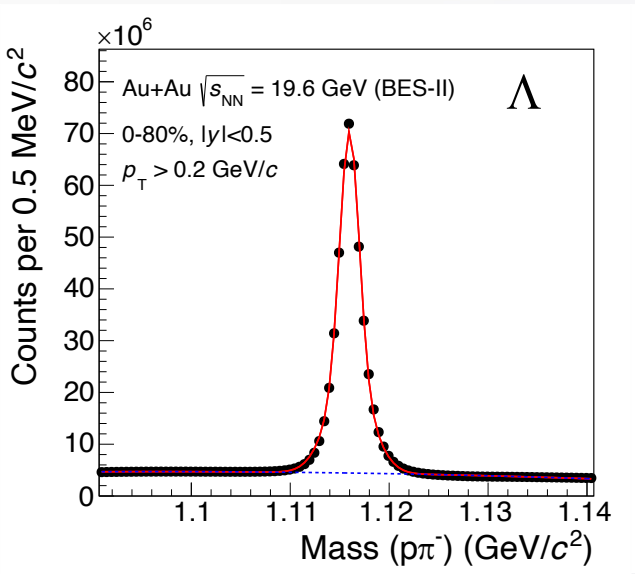
iTPC upgrade

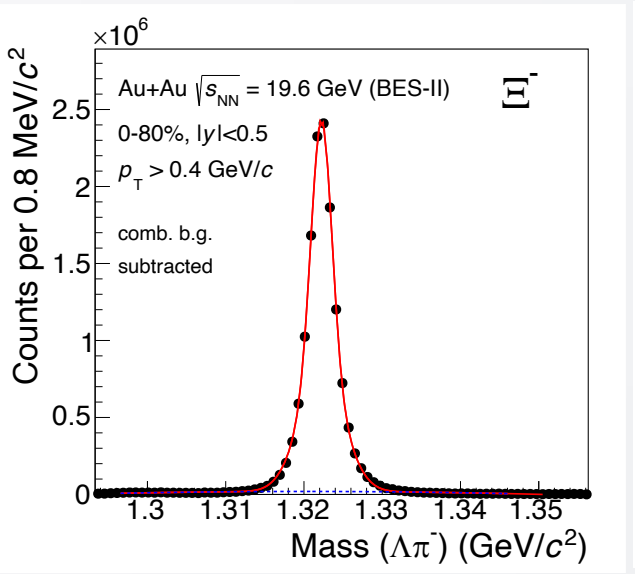
- $|\eta|$: 1.0 → 1.5
- Improved dE/dx resolution
- p_T threshold: 120MeV → 60MeV

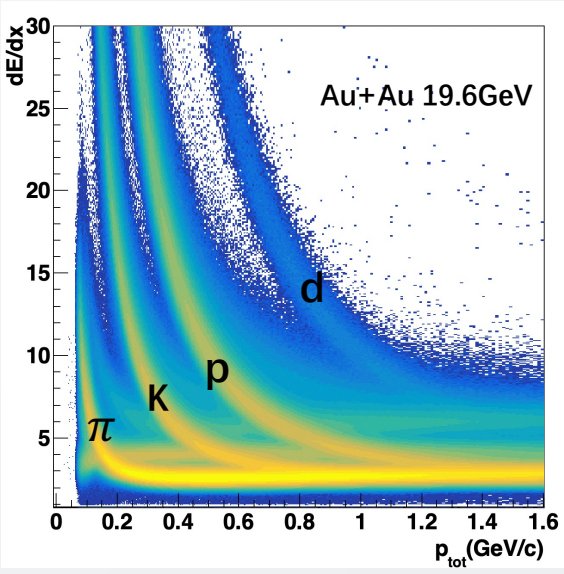
STAR

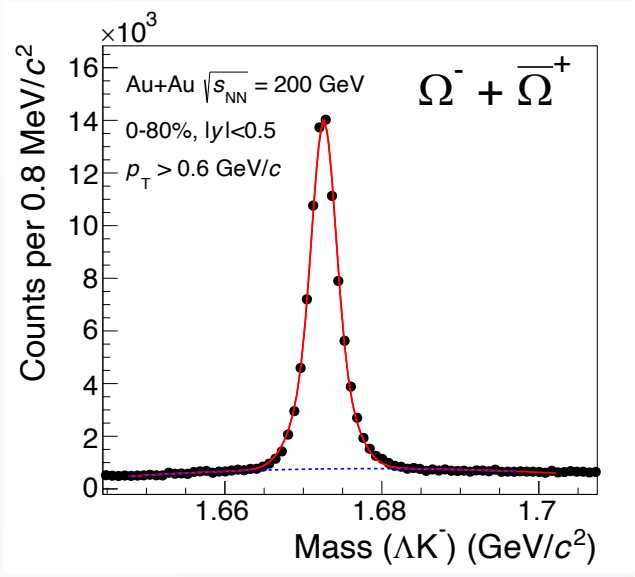
Particle identification and reconstruction

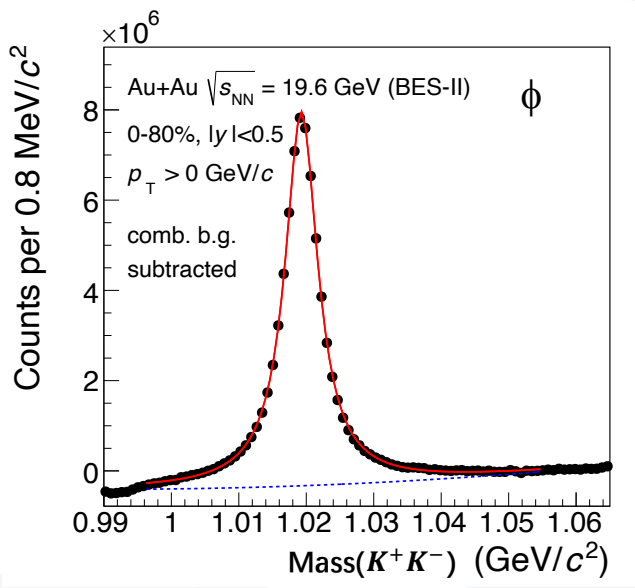








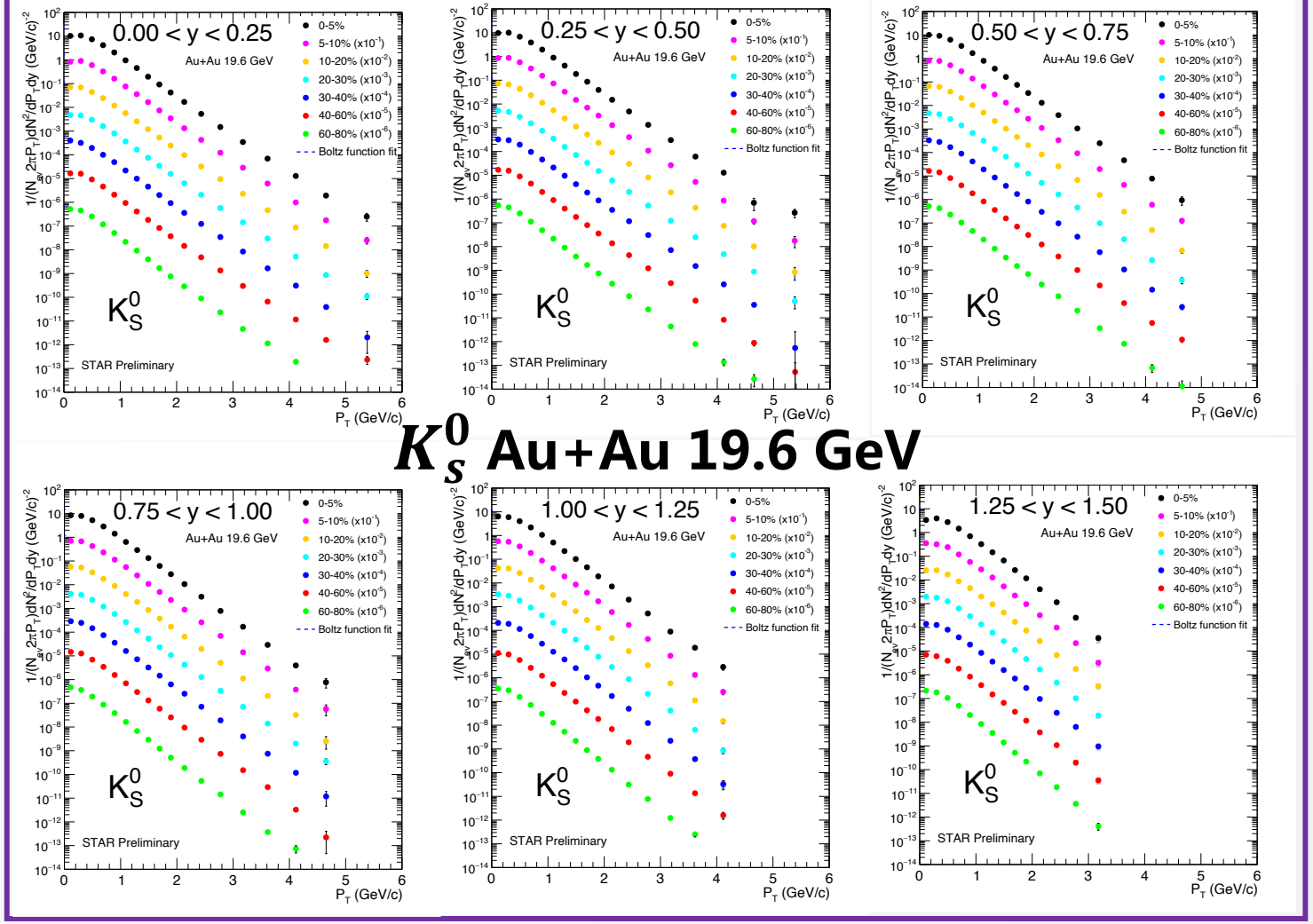




- Particle identification with dE/dx.
- π, K, p are used to reconstruct the secondary vertex of strange particles.
- Large number of strange particles allow multi-differential measurements.

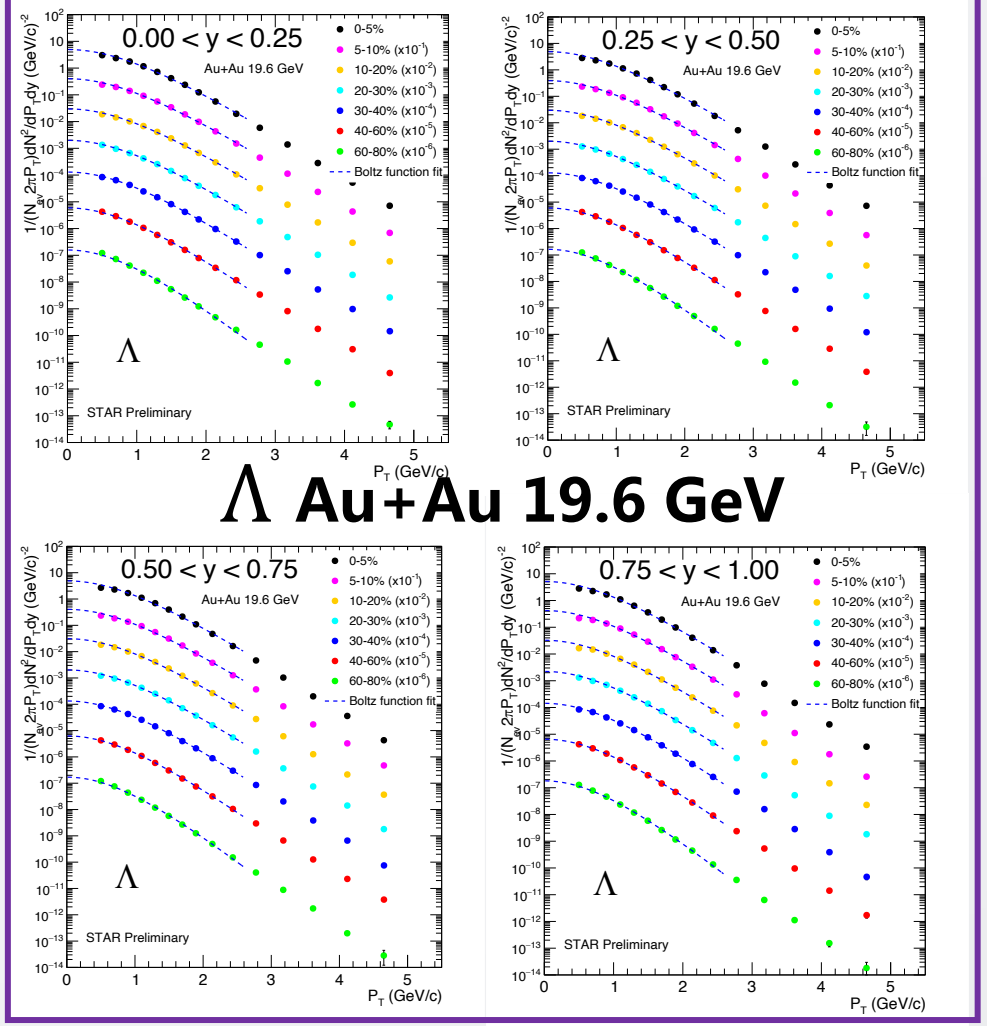
$$\mathrm{K}^0_\mathrm{S} \to \pi^+ + \pi^- (\mathcal{B} = 69.2\%)$$
$$\Lambda(\bar{\Lambda}) \to p(\bar{p}) + \pi^- (\pi^+) (\mathcal{B} = 63.9\%)$$
$$\Xi^- \left(\bar{\Xi}^+\right) \to \Lambda(\bar{\Lambda}) + \pi^- (\pi^+) (\mathcal{B} = 99.9\%)$$
$$\Omega^- \left(\bar{\Omega}^+\right) \to \Lambda(\bar{\Lambda})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

p_T spectra of K_s^0 and Λ at 19.6 GeV



K_s^0 Au+Au 19.6 GeV

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



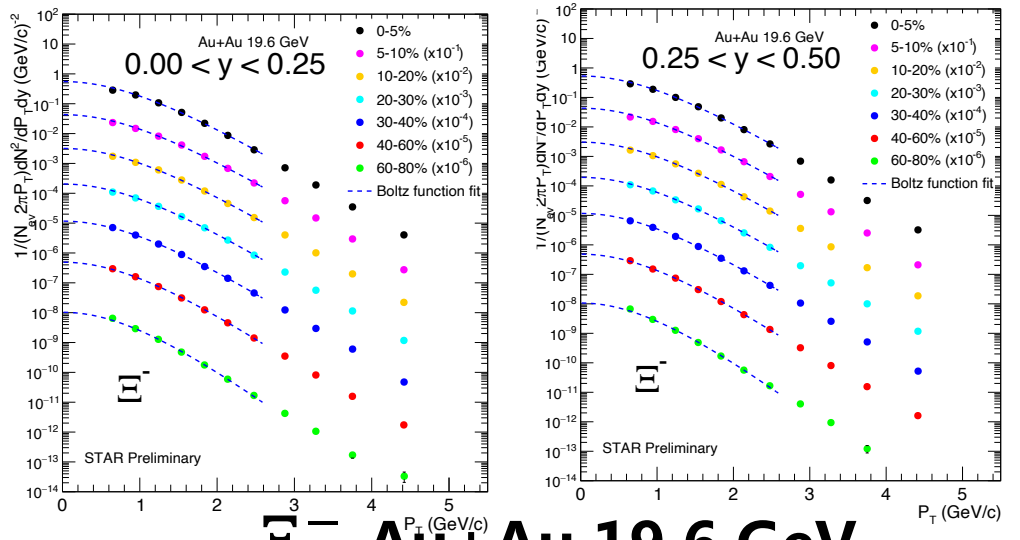
Λ Au+Au 19.6 GeV

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

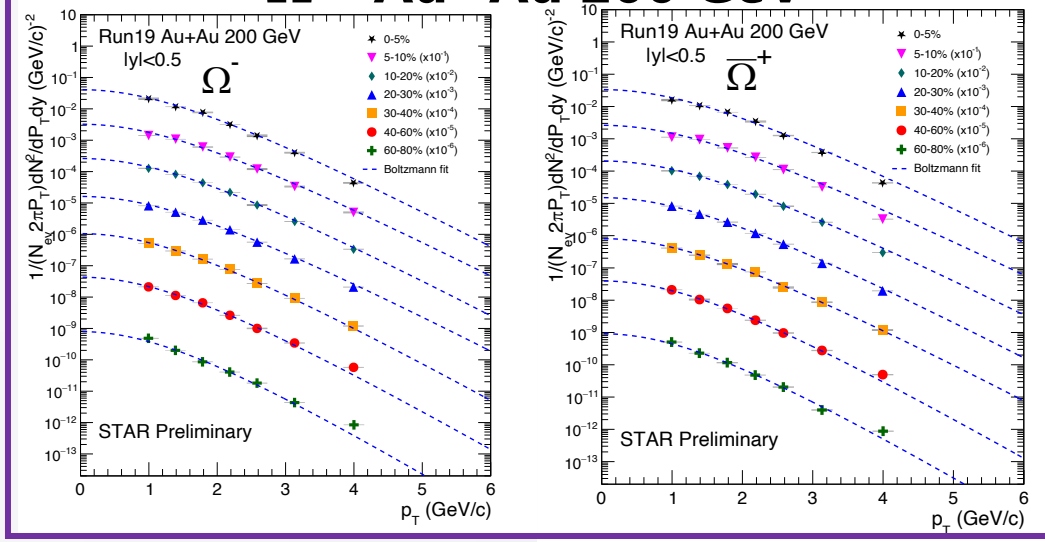
Rapidity: |y| < 1

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

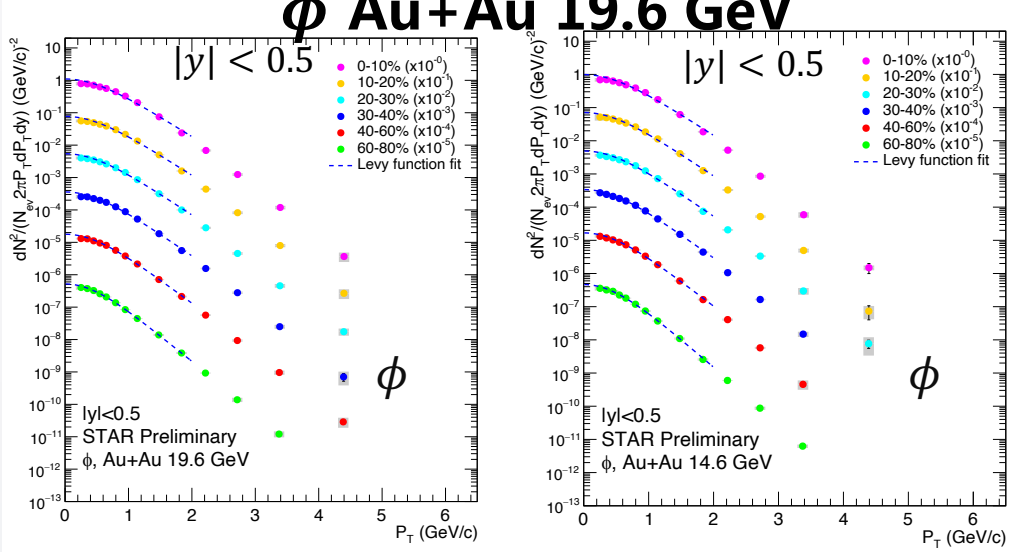
Ξ^- Au+Au 19.6 GeV



Ω^- Au+Au 200 GeV



ϕ Au+Au 19.6 GeV

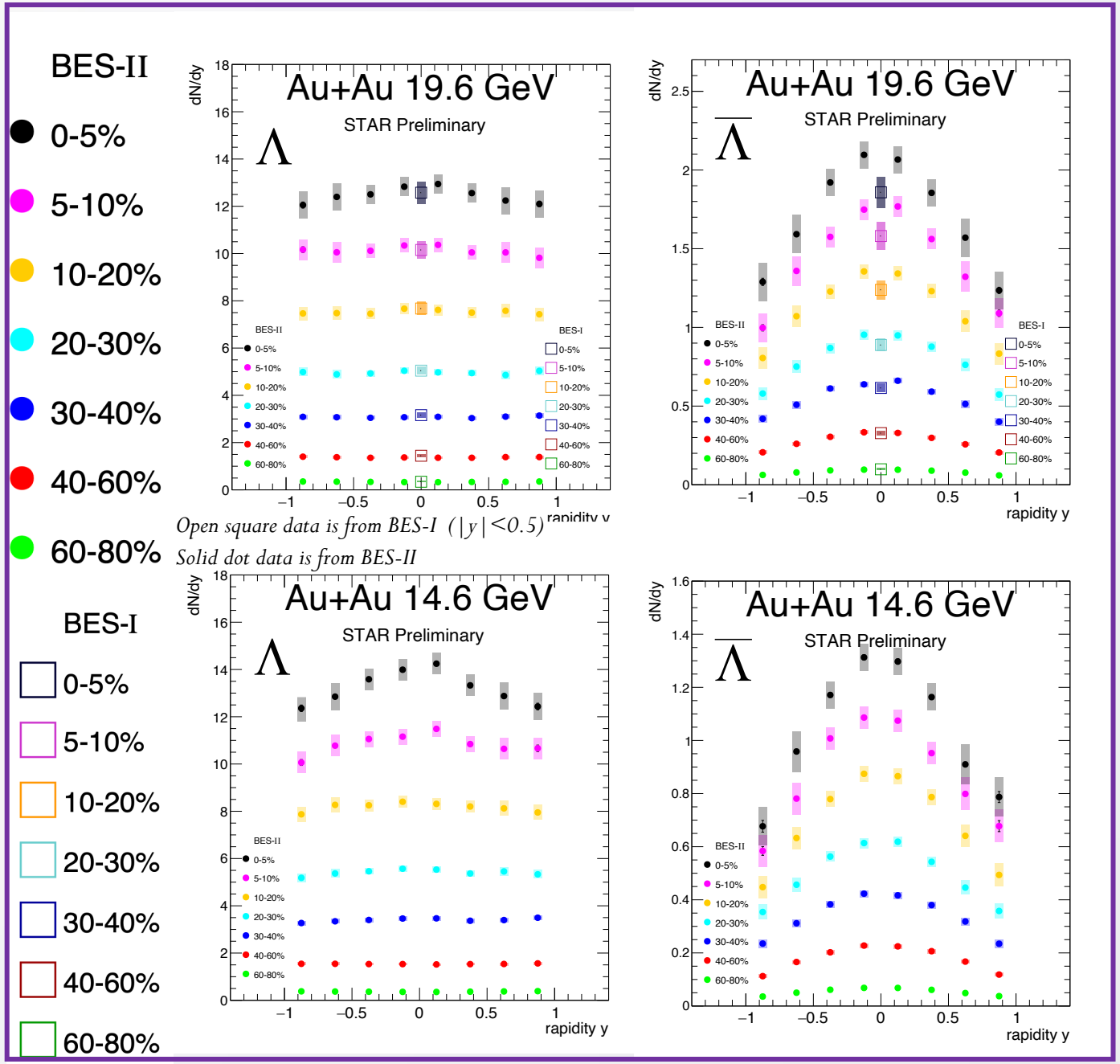


- Ξ^- Low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 1.0$
- Ω low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 0.5$
- ϕ low p_T extrapolation: Levy function
- Rapidity: $|y| < 0.5$

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

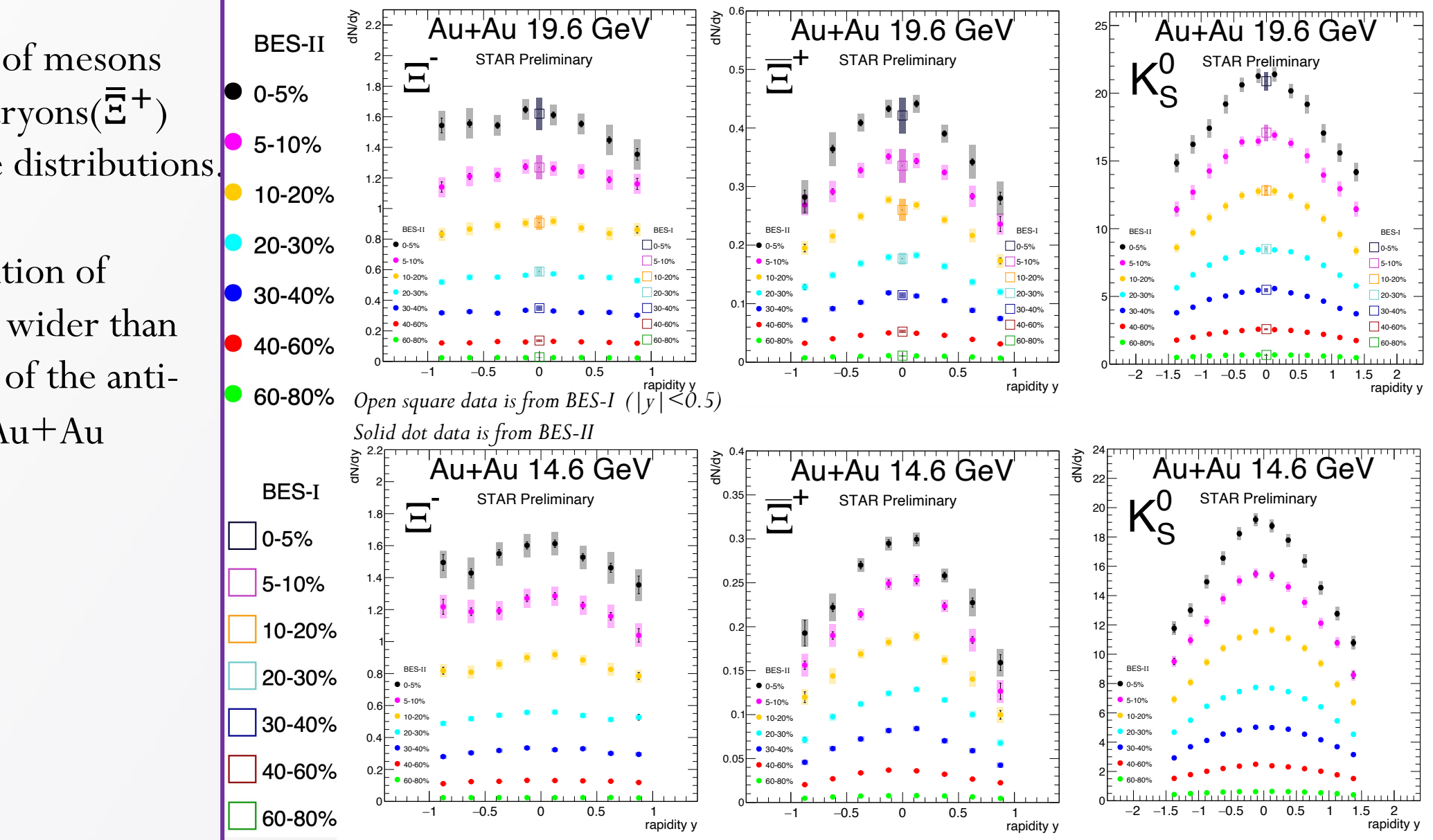
- Rapidity spectra of anti-baryons($\bar{\Lambda}$) are Gaussian-like distributions.
- Rapidity distribution of baryons(Λ) are wider than that of anti-baryons ($\bar{\Lambda}$).
  - ✓ Extra contributions from stopped baryons
- Similar trends observed by NA49.

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.

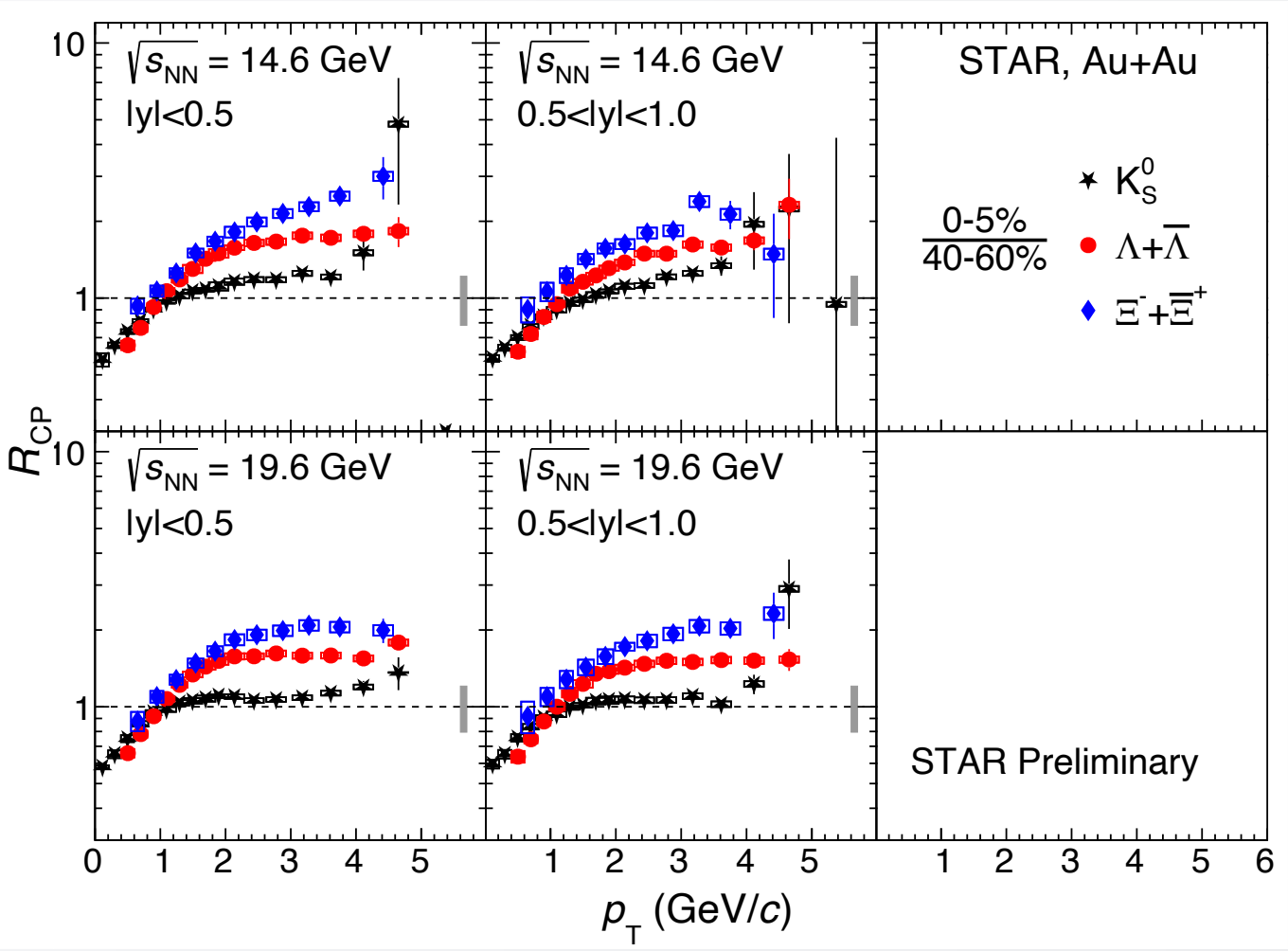


Open square data is from BES-I ($|y|<0.5$)

Solid dot data is from BES-II

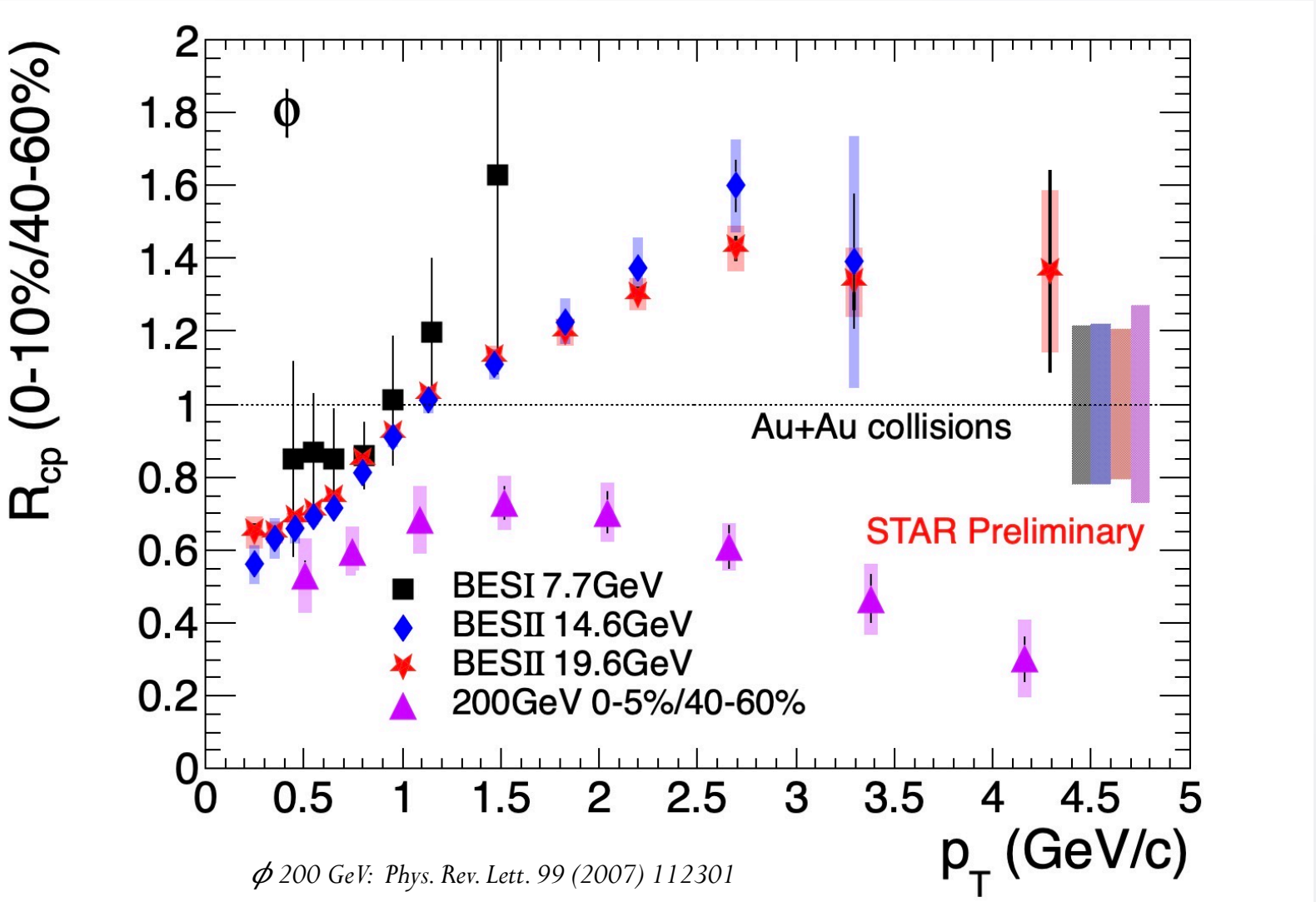
Nuclear modification factor at 19.6 and 14.6 GeV

- 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>2GeV/c.
  - ✓ Radial flow
  - ✓ Quark coalescence
- The enhancement is stronger for Ξ^- compare to Λ and K_s^0
  - ✓ A strong enhancement for multi-strange particles is a proposed signature for QGP formation.
- R_{CP} shows minor rapidity dependence.



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

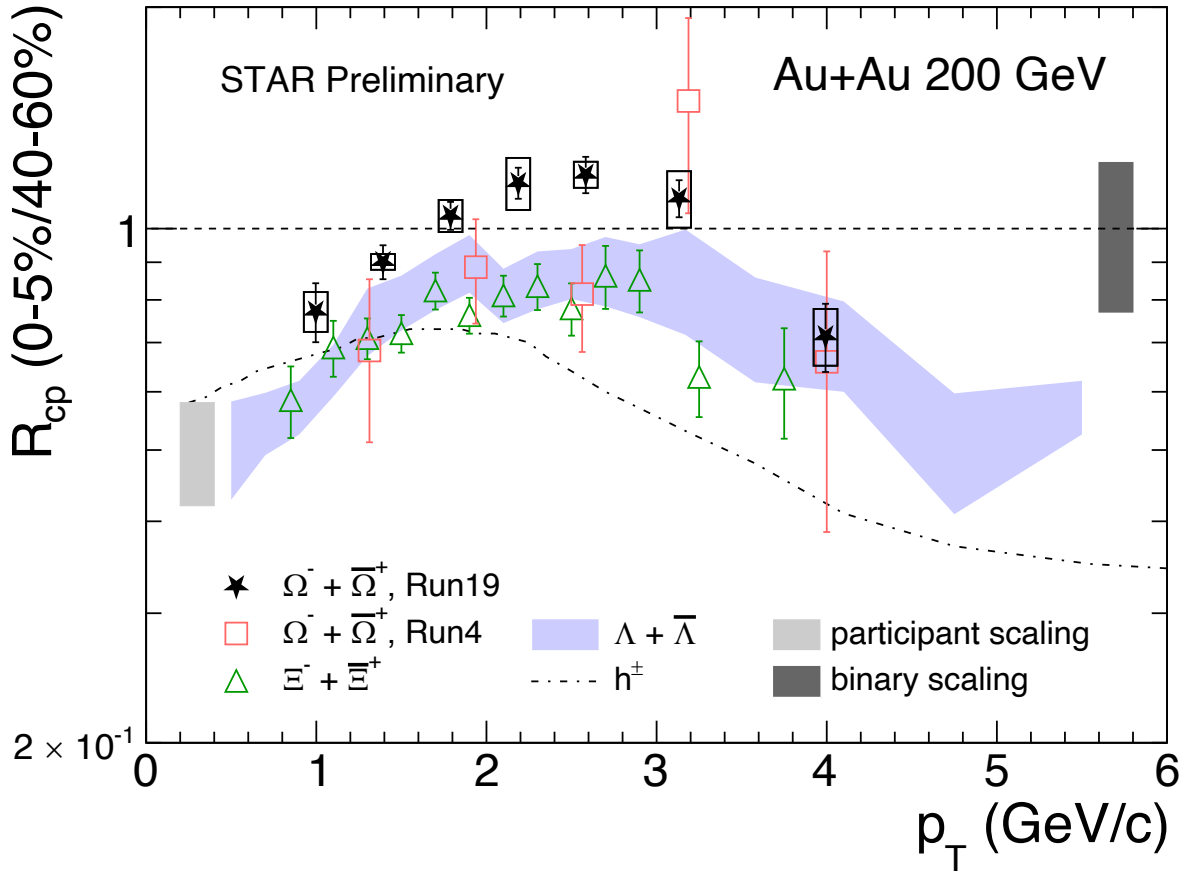
Energy dependence of R_{CP} for ϕ



ϕ 200 GeV: Phys. Rev. Lett. 99 (2007) 112301

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

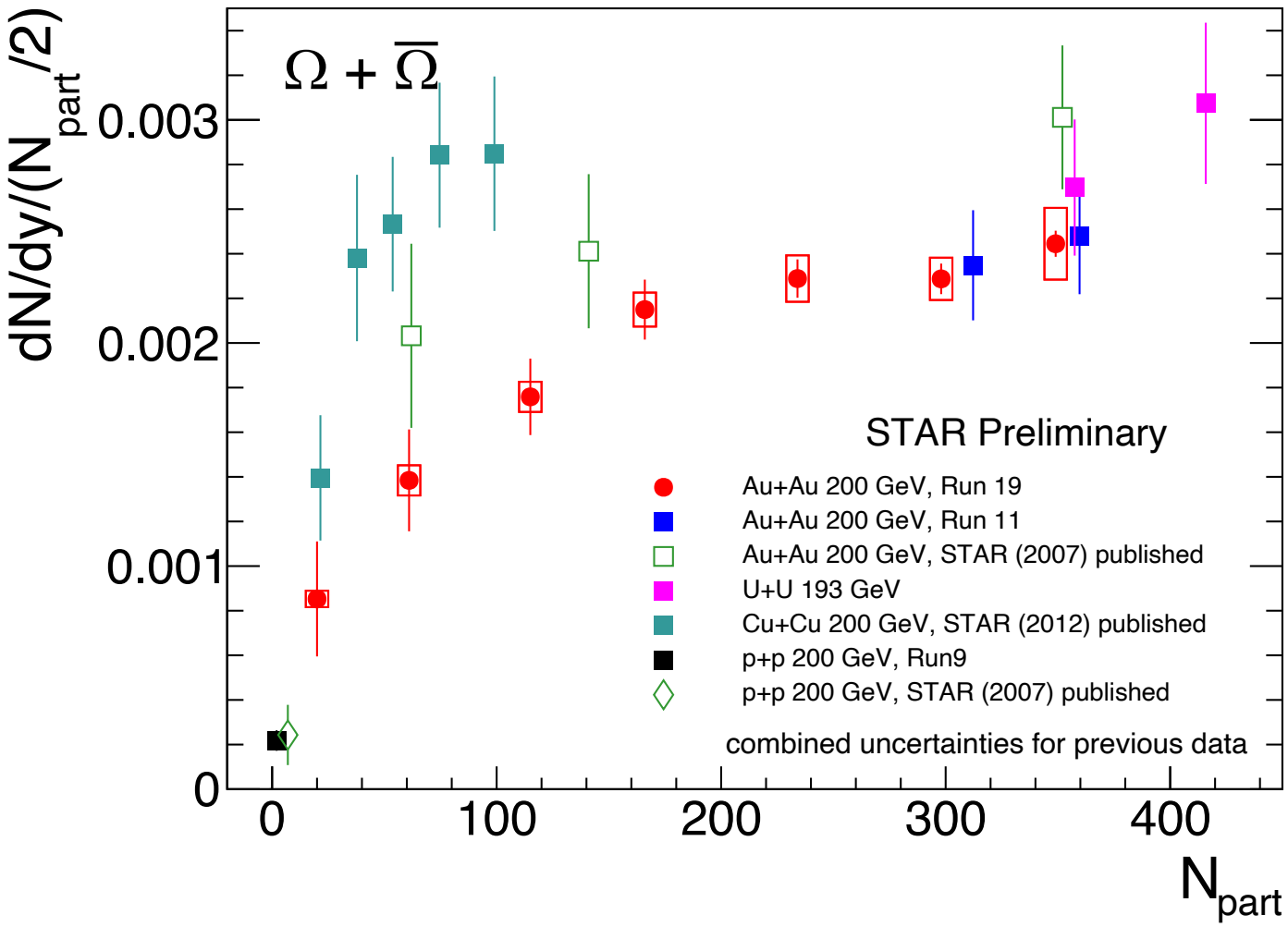
R_{CP} of strange hadrons at 200 GeV



- 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.

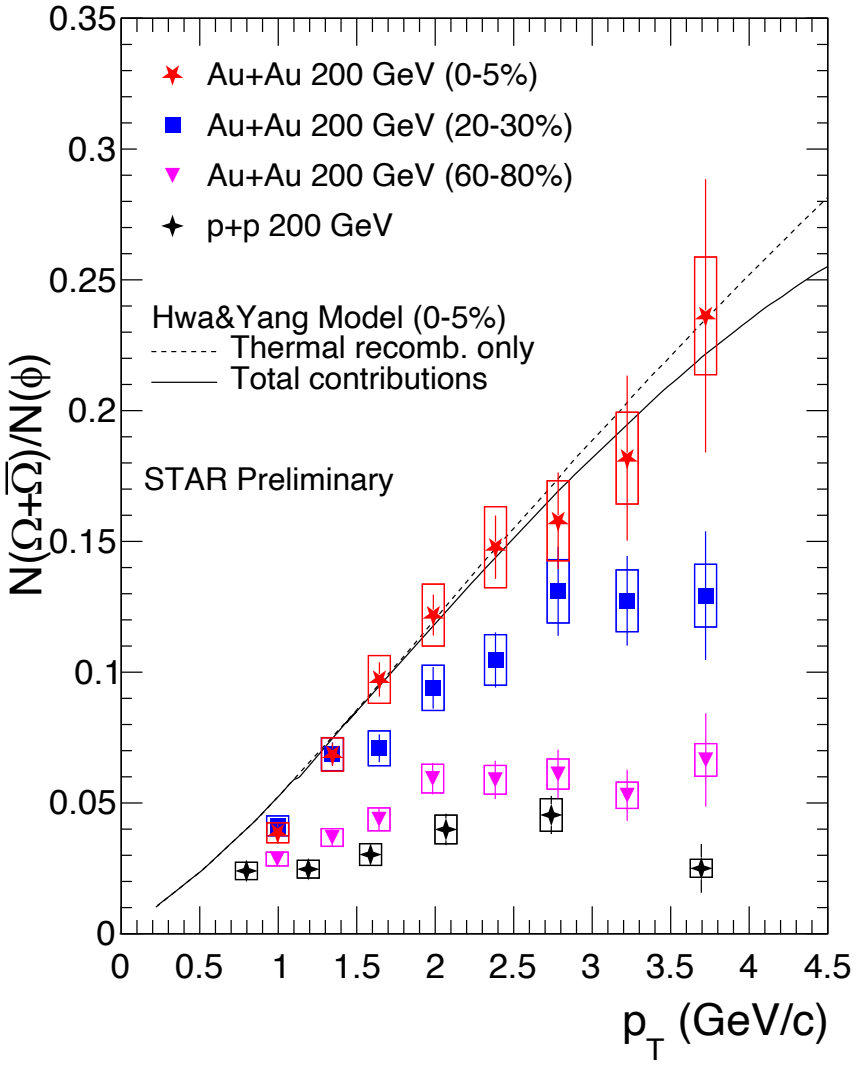
$\Omega + \bar{\Omega}$ Run4 & $\Xi + \bar{\Xi}$: STAR, Phys. Rev. Lett. 98 (2007) 062301
$\Lambda + \bar{\Lambda}$: STAR, Phys. Rev. Lett. 92 (2004) 052302
$h^\pm$(charged hadrons): STAR, Phys. Rev. Lett. 91 (2003) 172302

System size dependence of Ω yield at 200 GeV



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

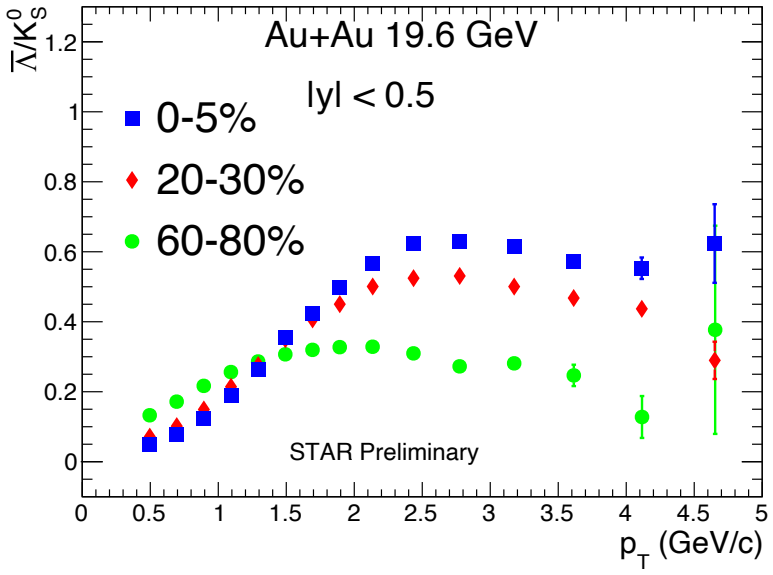
Ω/ϕ ratio at 200 GeV

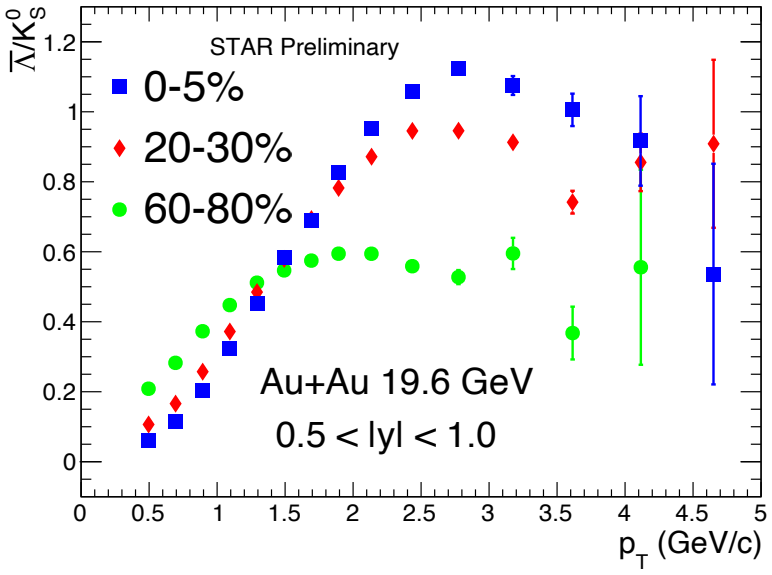


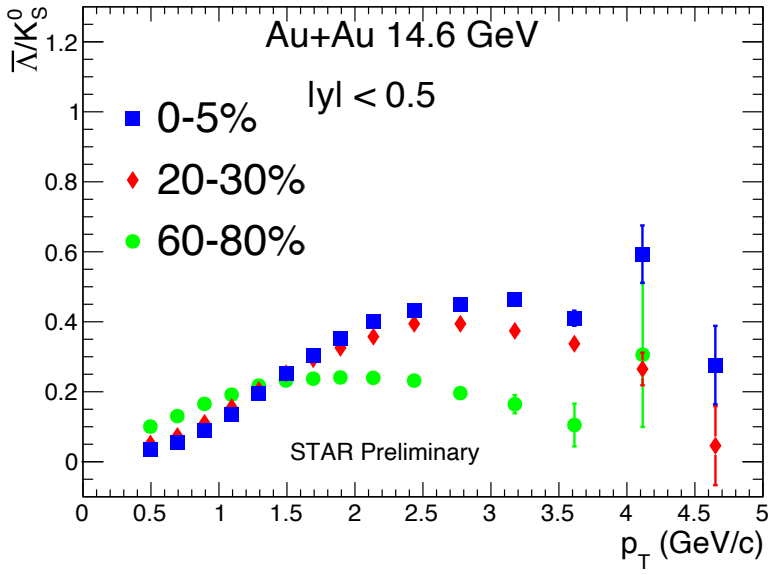
- In central collisions, good agreement between data and recombination model calculations.
  - ✓ Ω and ϕ are predominantly produced through the recombination of thermalized strange quarks in QGP.
- At intermediate p_T, ratio increases gradually with increasing system size. Significant Ω enhancement over 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.

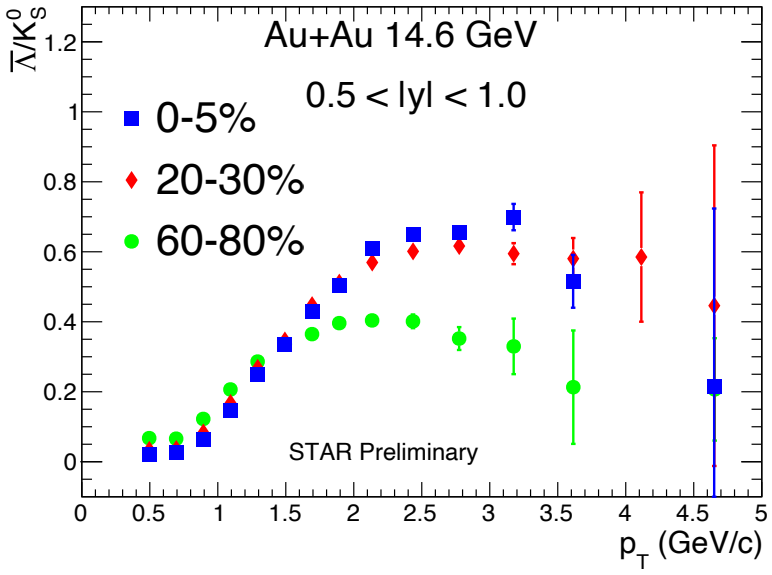
Ω p_T binning adapted to match ϕ data.
Au+Au 200 GeV ϕ: STAR, Phys. Rev. Lett. 99(2007) 112301
p+p 200GeV $\Omega + \bar{\Omega}$: X. Zhu, QM2014; p+p 200GeV ϕ: STAR, Phys. Rev. C 79(2009) 064903
Theory: Phys. Rev. C, 2007, 75: 054904. theoretical calculation only for central collisions

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



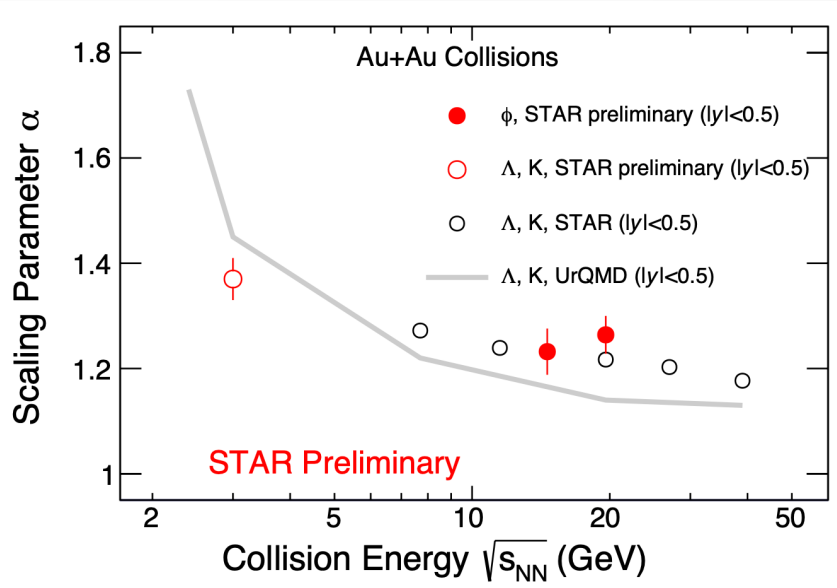


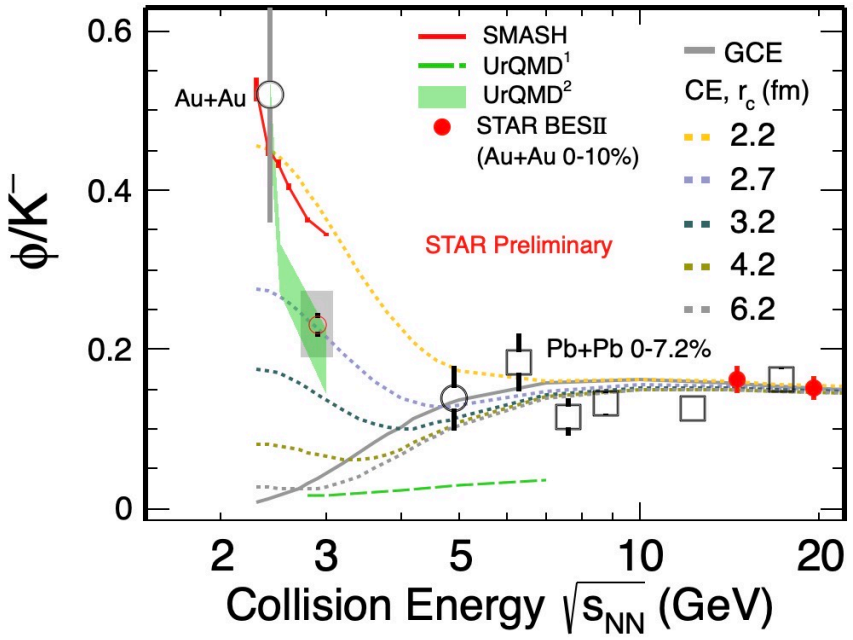




- Clear centrality and rapidity dependence of (anti-)baryon-to-meson ratio at intermediate p_T.
- Reach to maximum value~ p_T=2.5.
- Baryon enhancement is observed in all measured rapidity regions.

Energy and centrality dependence of strangeness production





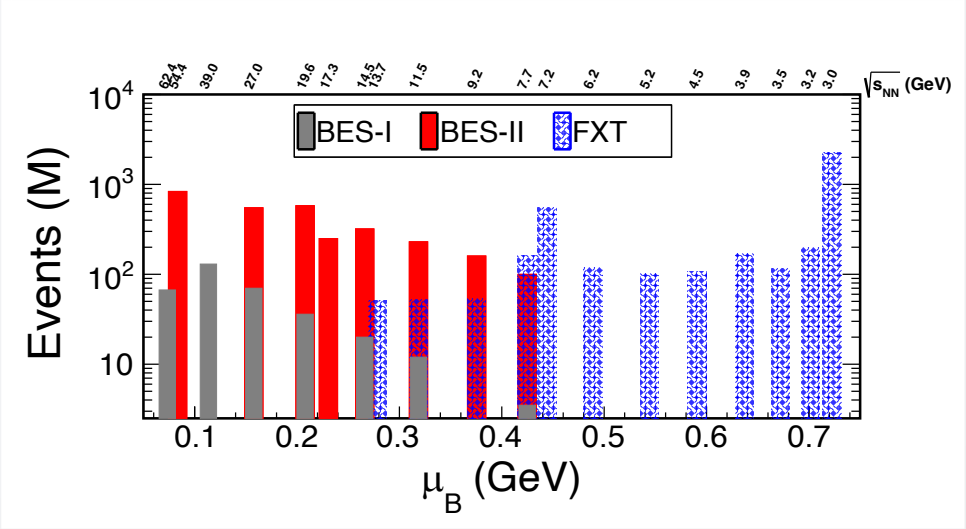
- Fit function: $\frac{dN/dy}{N_{part}/2} = k \times N_{part}^{\alpha-1}$
- Common centrality dependence for ϕ, Λ, K production at 19.6GeV.
- Above 7.7 GeV, data indicates a steeper increase on strangeness yields towards central collisions compared to UrQMD.
  - ✓ Might point to production mechanisms beyond hadronic interactions in this energy range.
- In contrast to 3GeV, 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 → extra contributions from stopped baryons.
- Baryon enhancement is observed from 14.6 to 200GeV → consistent with QGP formation.
- Ω measurements at 200 GeV indicates a smooth trend in strangeness enhancement from small to large systems.

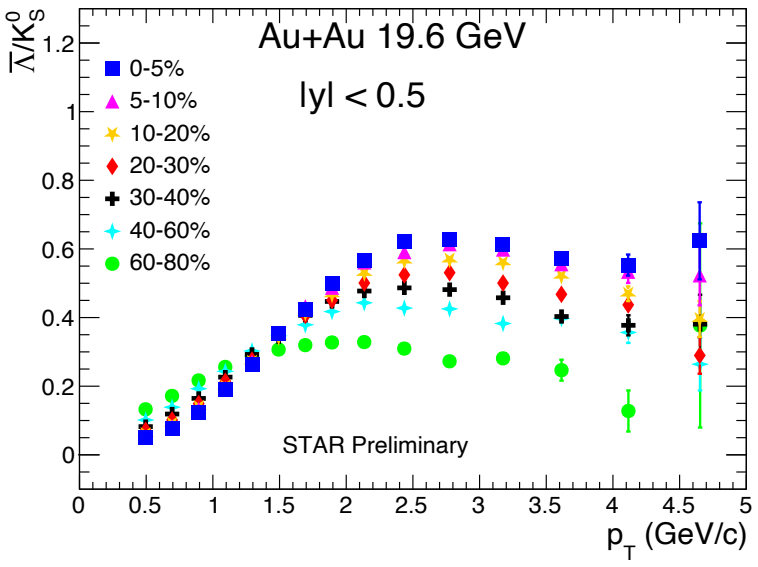
Outlook

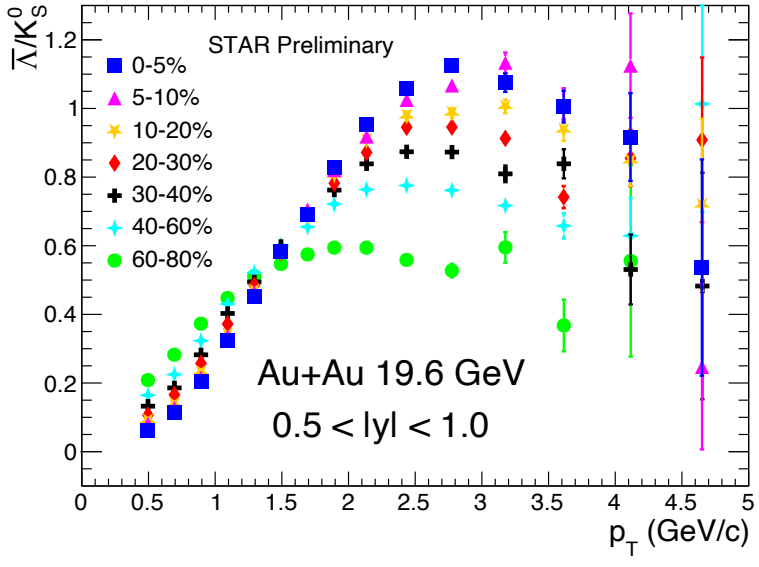
- Strangeness measurements from 3.2 to 14.6 GeV in BES-II will probe the onset of deconfinement.

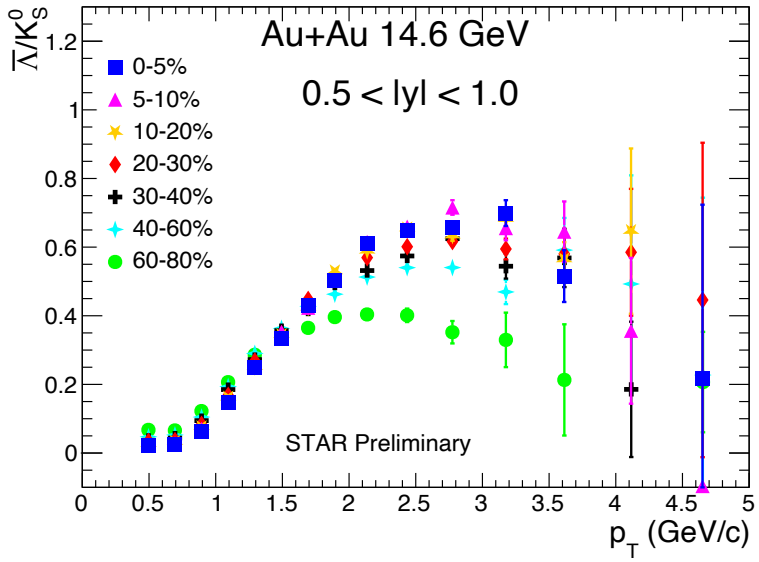


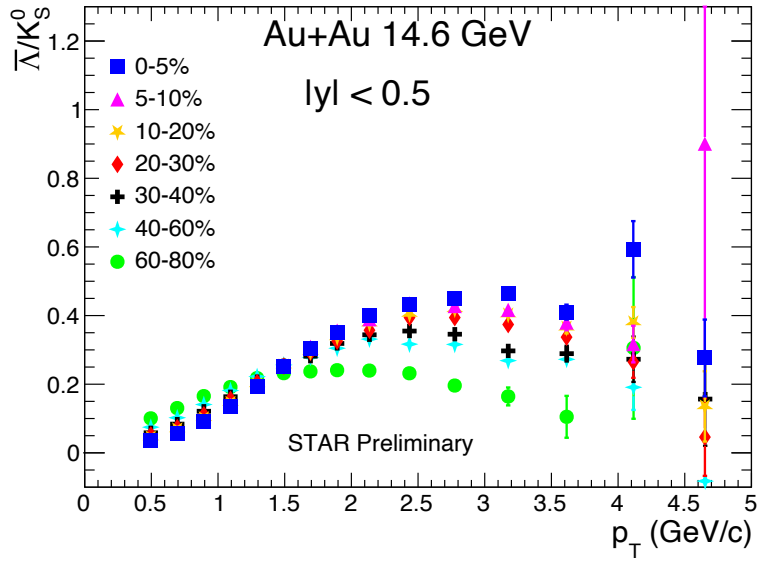
Back up

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



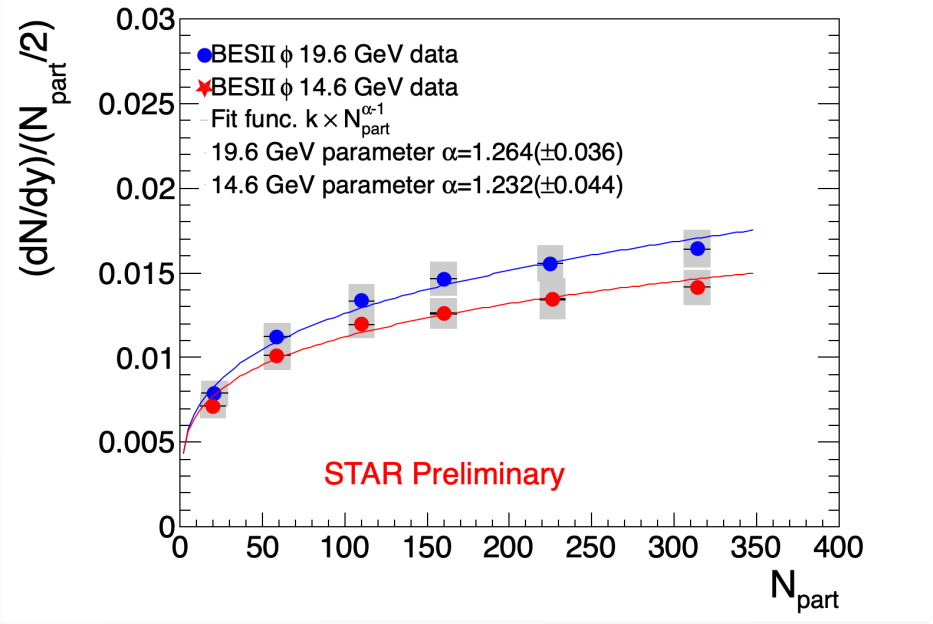


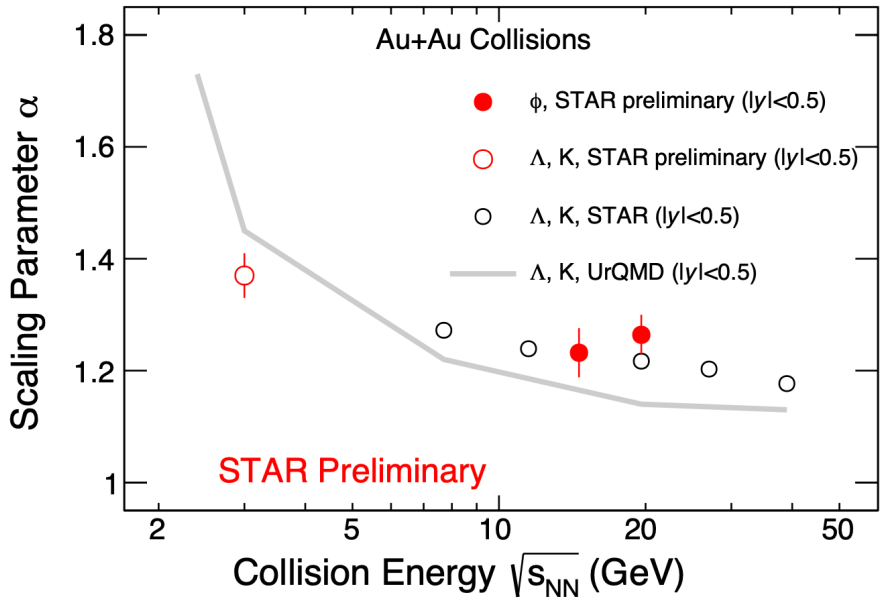


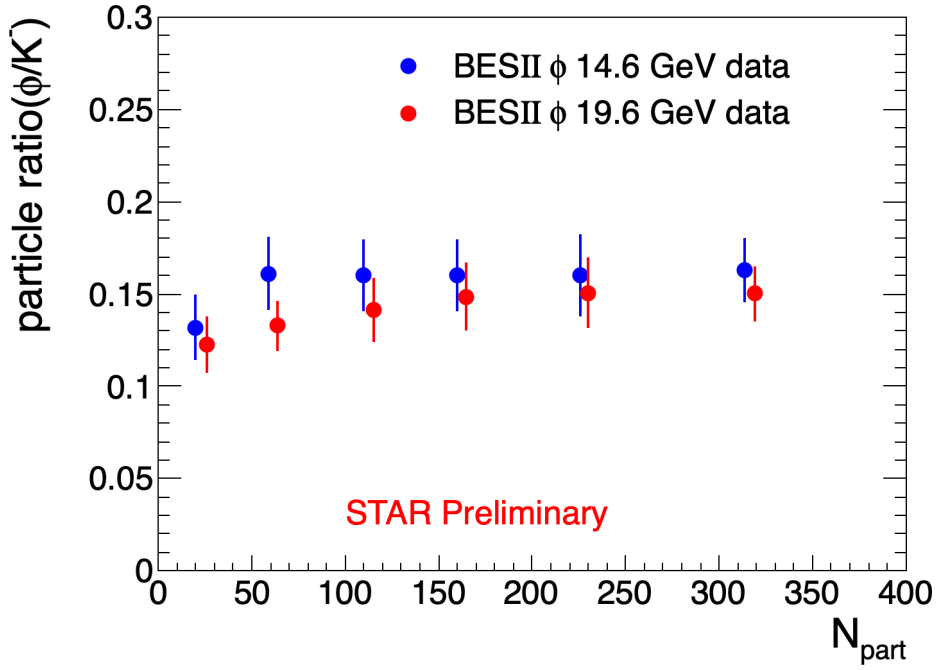


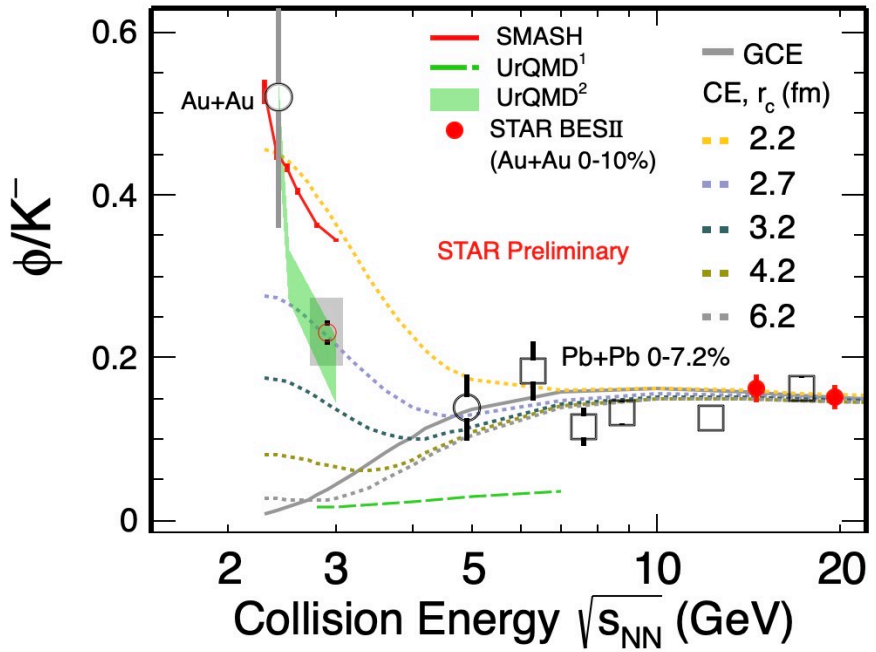
- Clear centrality and rapidity dependence of (anti-)baryon-to-meson ratio at intermediate p_T.
- Baryon enhancement is observed in all measured regions.

Energy and centrality dependence of strangeness production

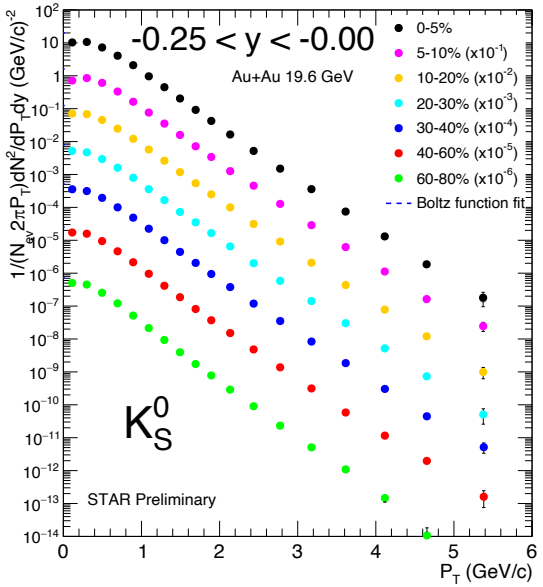


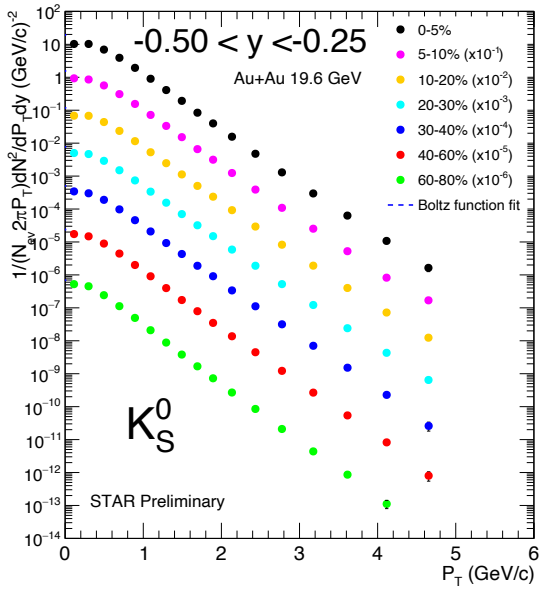


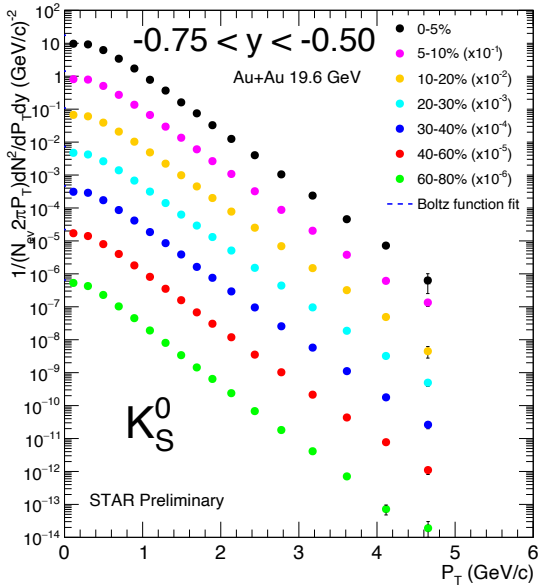


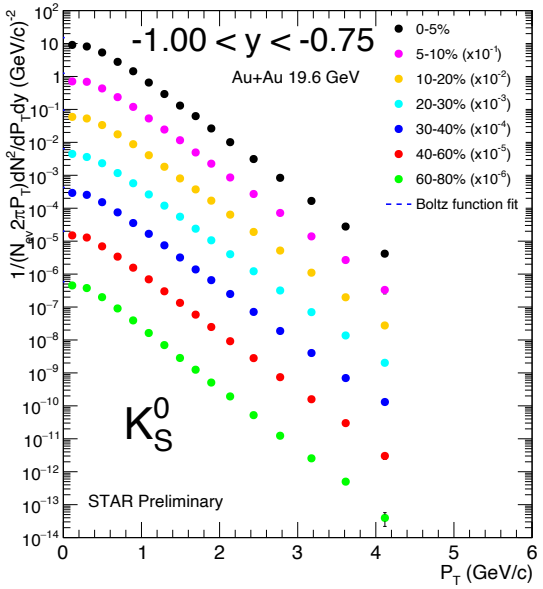


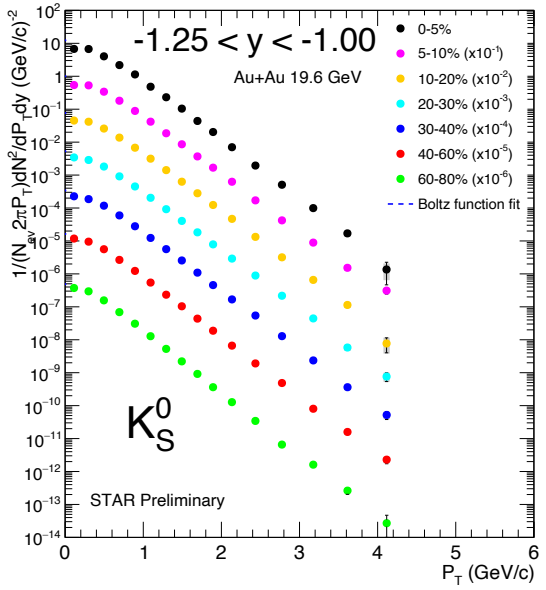
p_T spectra of K_s^0 at 19.6 GeV at backward rapidity

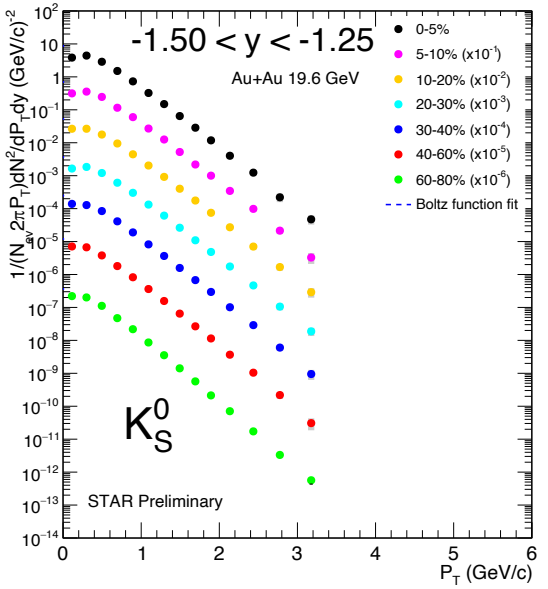






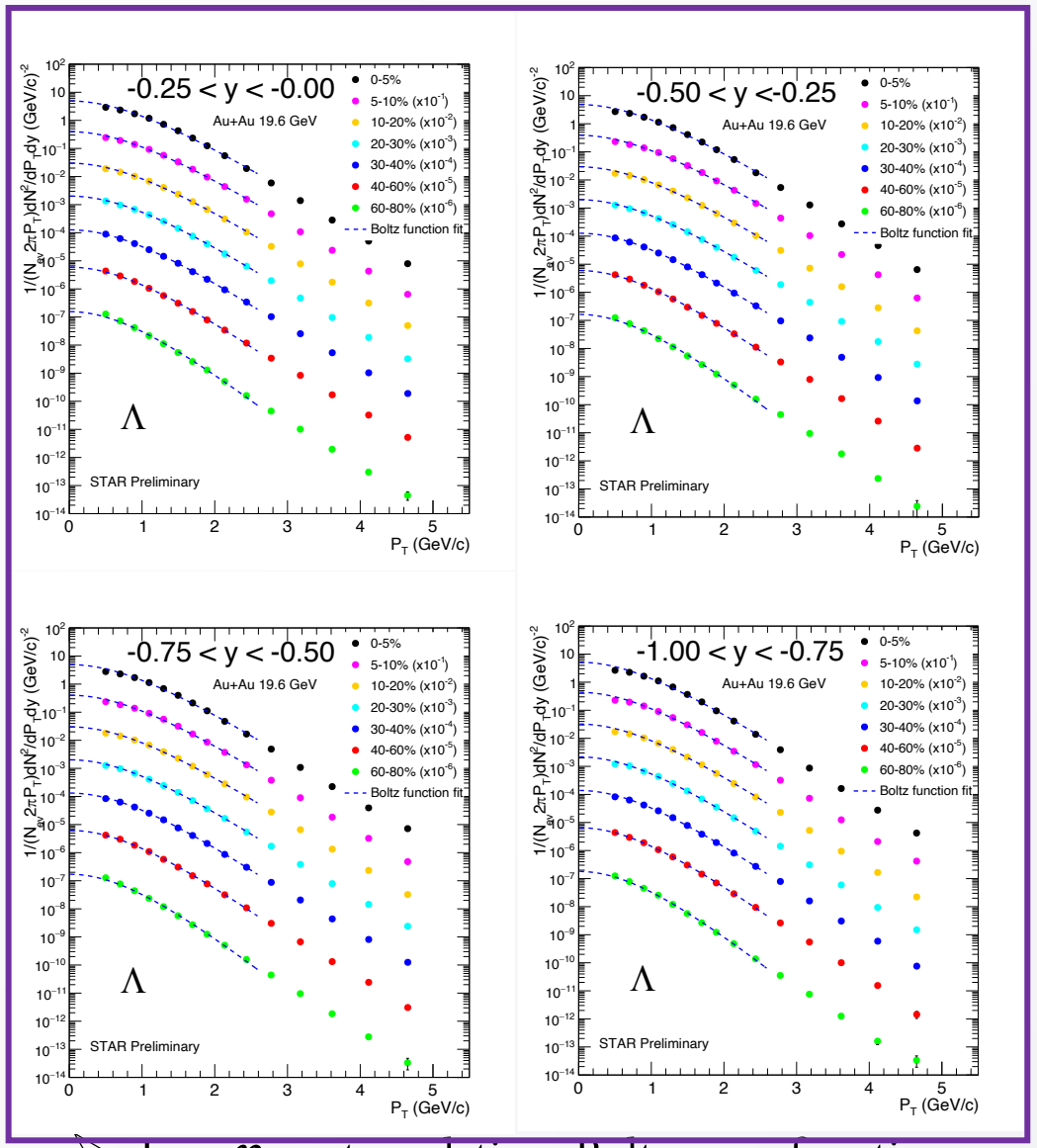




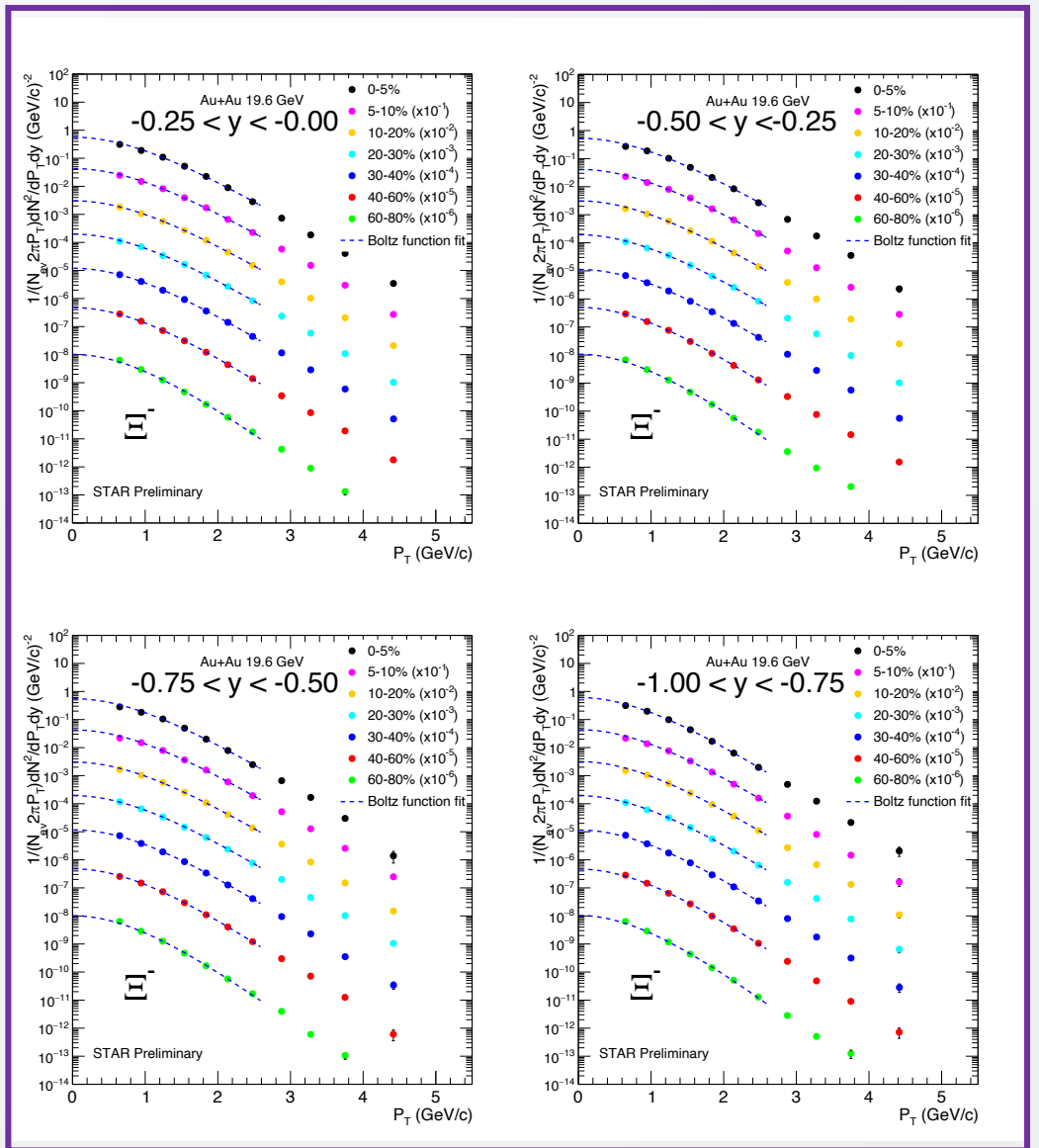


- K_s^0: measured down to p_T=0, no need for extrapolation to obtain dN/dy
- Rapidity: $|y| < 1.5$

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

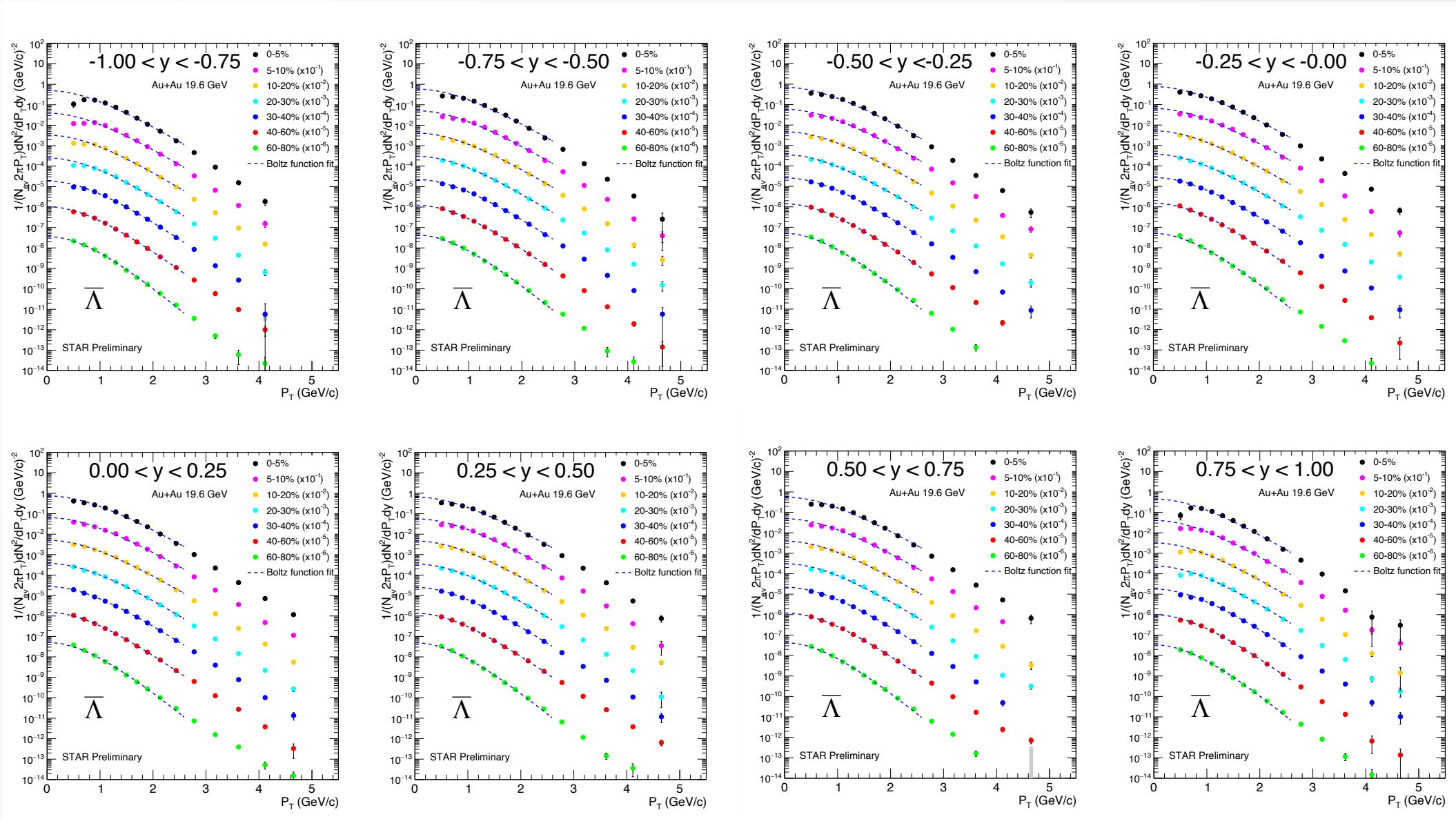


- Low p_T extrapolation: Boltzmann function
- Ξ^- and Ξ^0 decay feed-down corrected
- Rapidity: $|y| < 1.0$



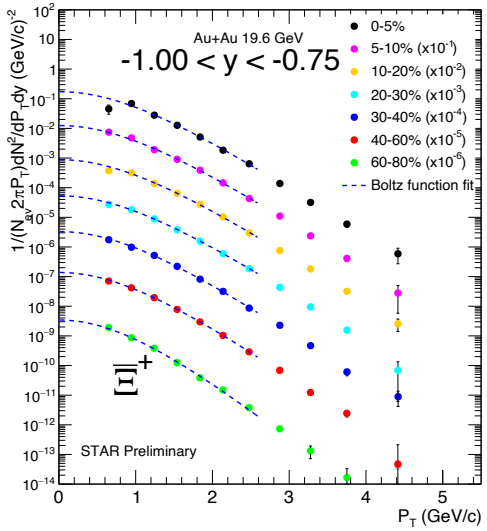
- Low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 1.0$

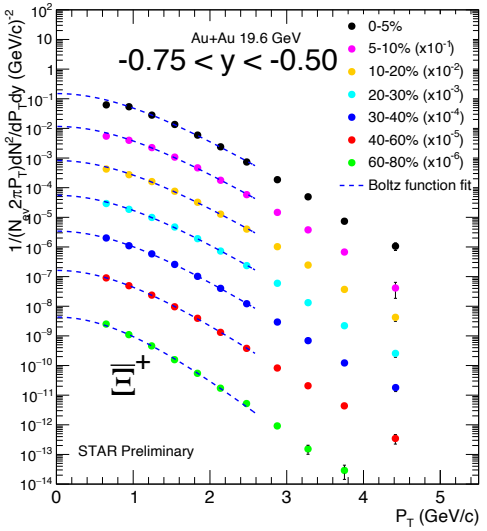
p_T spectra of $\bar{\Lambda}$ at 19.6GeV

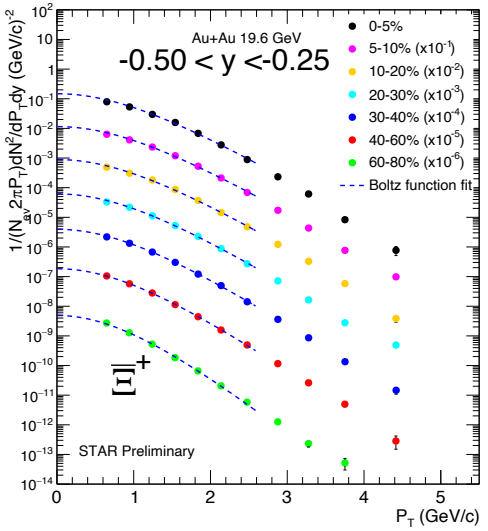


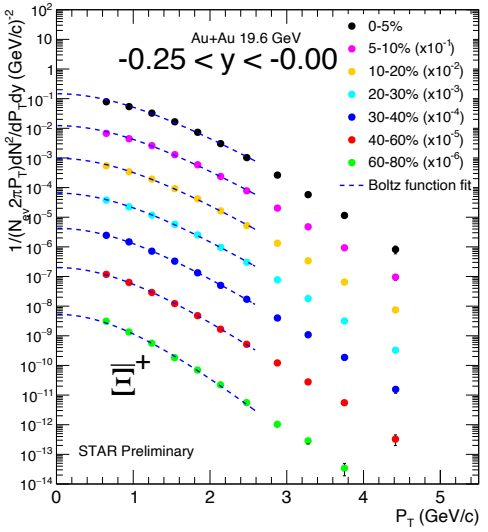
- Low p_T extrapolation: Boltzmann function
- Ξ^+ and $\bar{\Xi}^0$ decay feed-down corrected
- Rapidity: $|y| < 1.0$

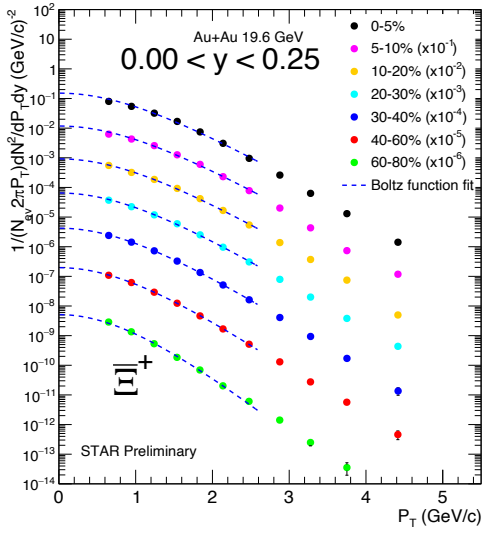
p_T spectra of $\bar{\Xi}^+$ at 19.6GeV

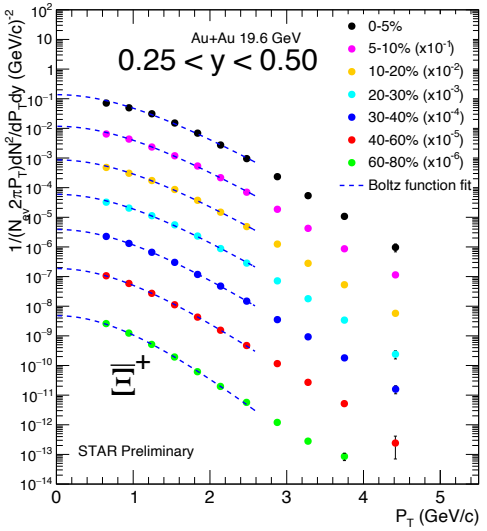


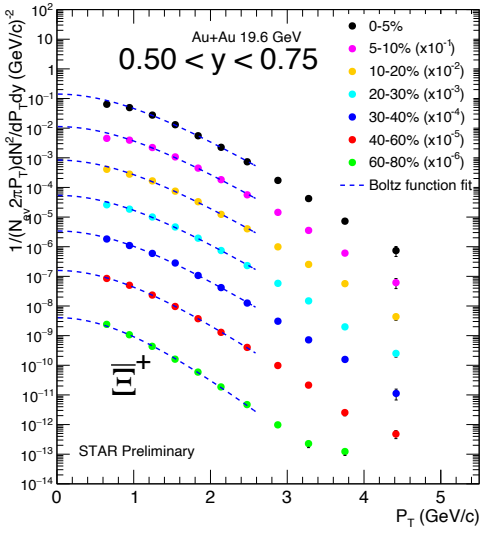


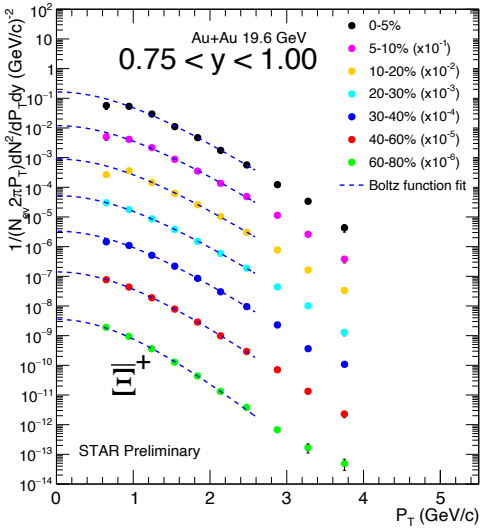






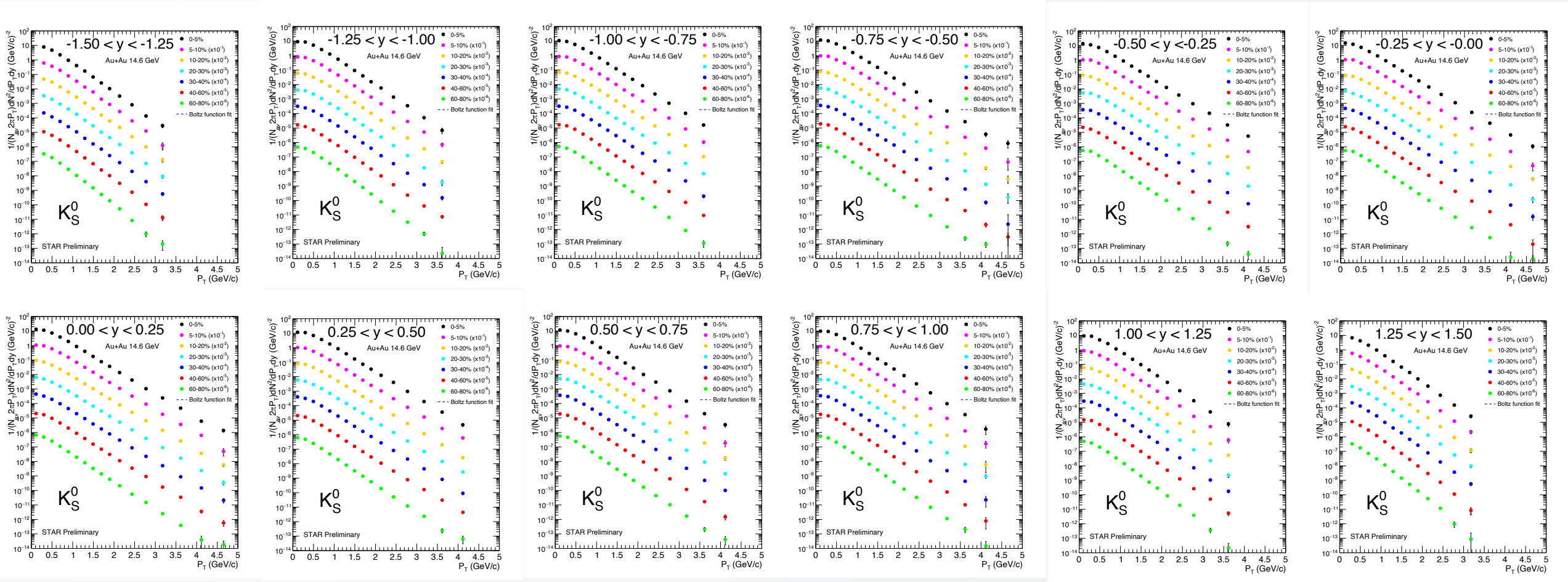






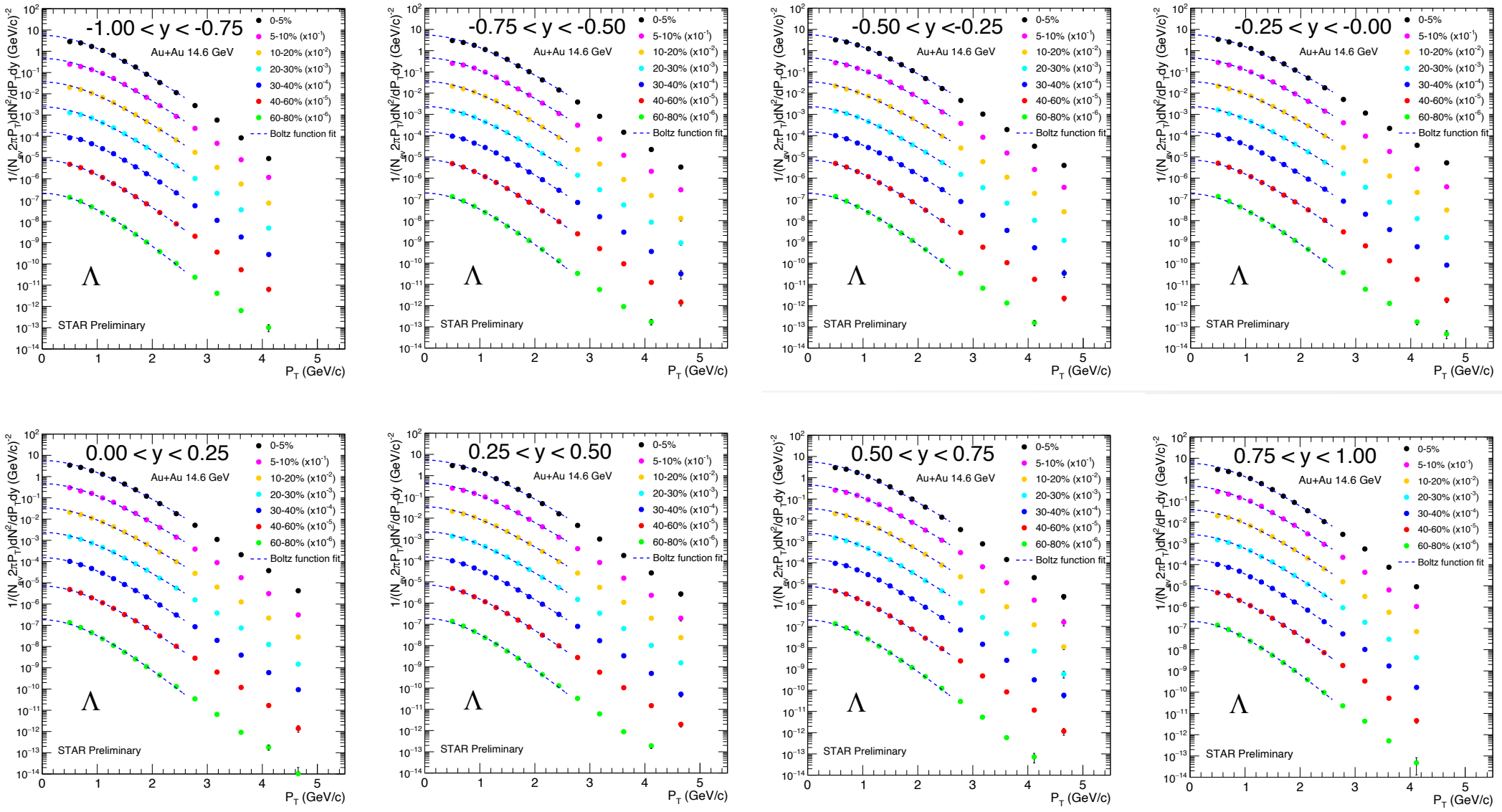
- Low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 1.0$

p_T spectra of K_s^0 at 14.6GeV



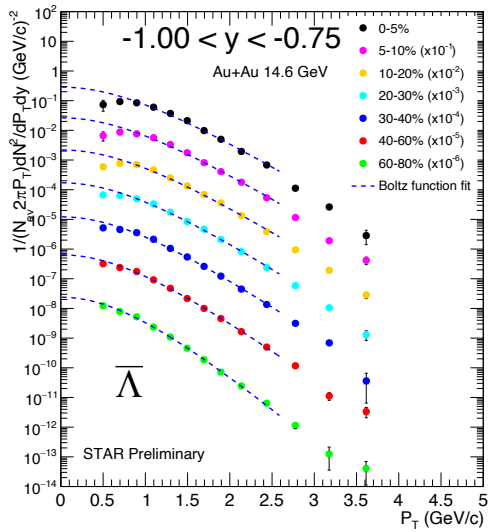
- K_s^0: measured down to p_T=0, no need for extrapolation to obtain dN/dy
- Rapidity: |y| < 1.5

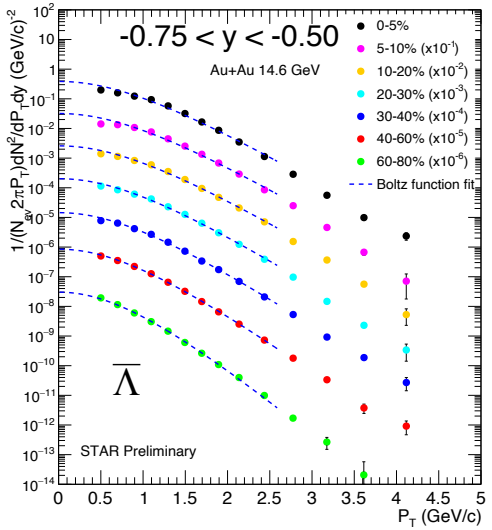
p_T spectra of Λ at 14.6GeV

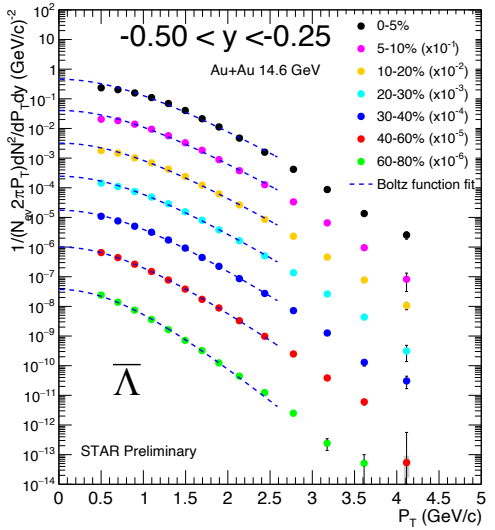


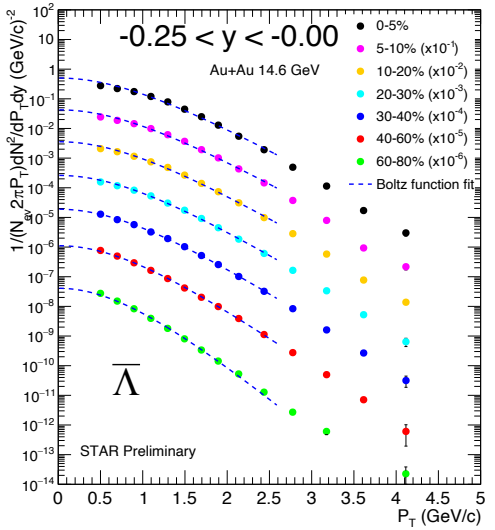
- Low p_T extrapolation: Boltzmann function
- Ξ^- and Ξ^0 decay feed-down corrected
- Rapidity: $|y| < 1.0$

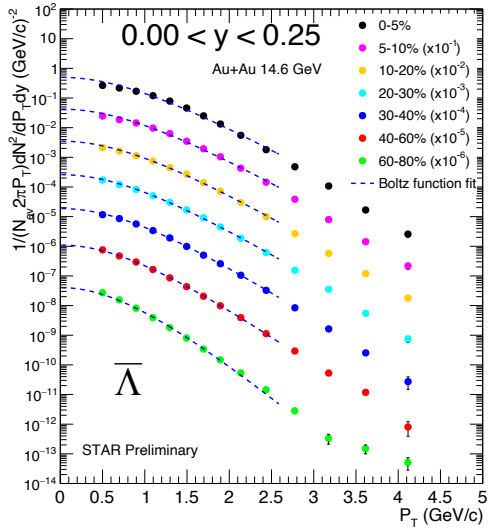
p_T spectra of $\bar{\Lambda}$ at 14.6GeV

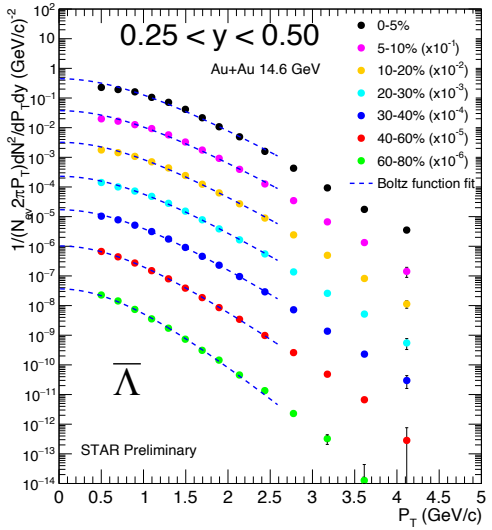


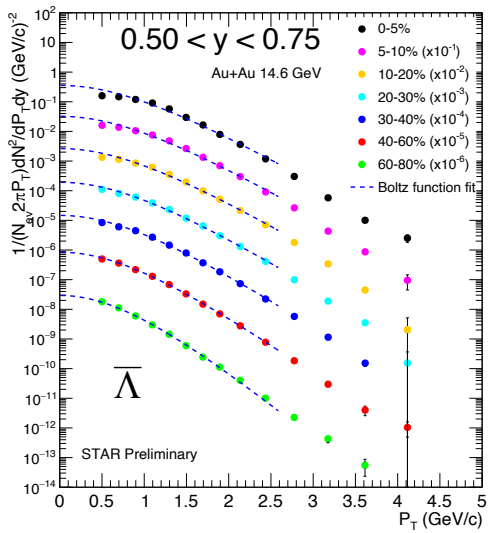


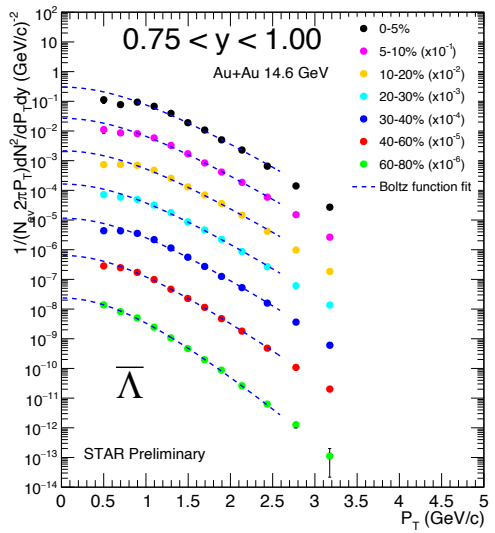






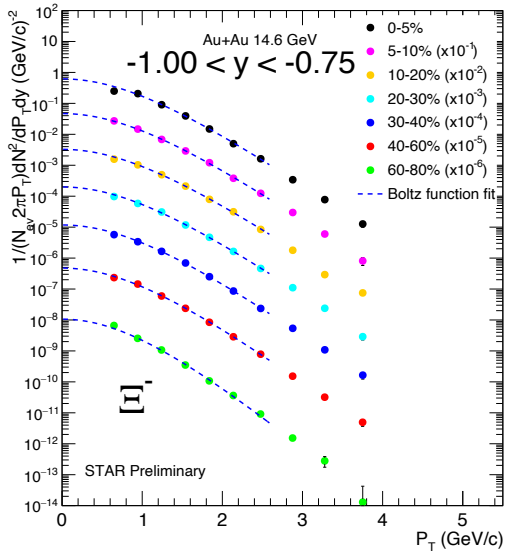


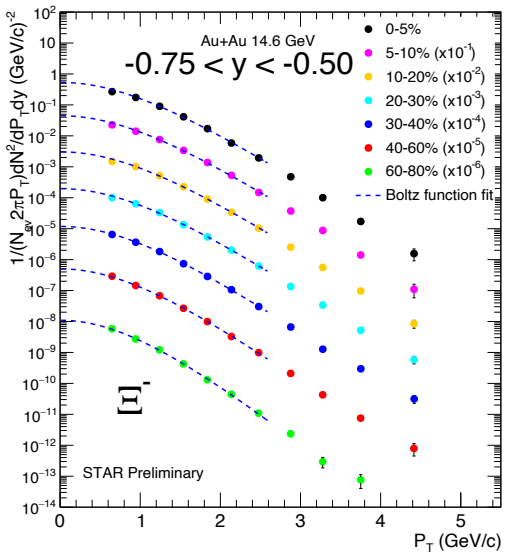


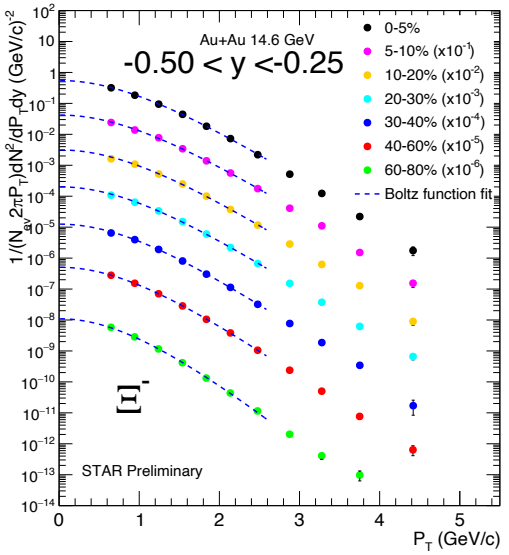


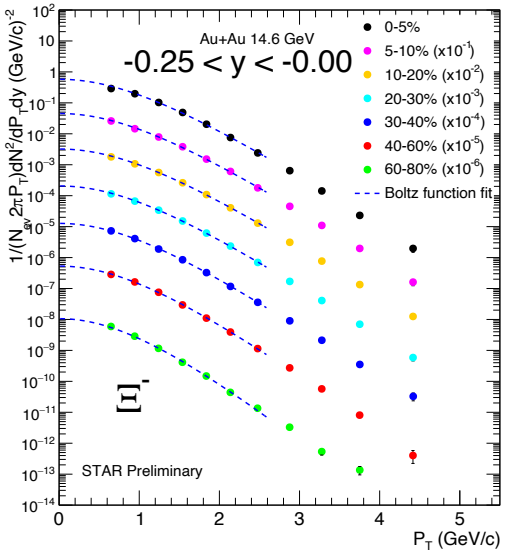
- Low p_T extrapolation: Boltzmann function
- Ξ^+ and $\bar{\Xi}^0$ decay feed-down corrected
- Rapidity: $|y| < 1.0$

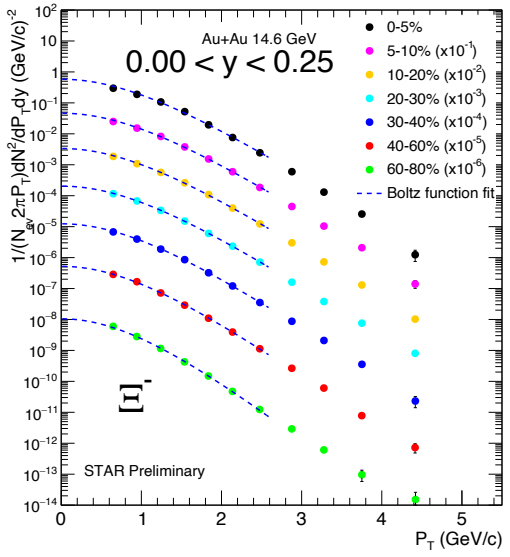
p_T spectra of Ξ^- at 14.6GeV

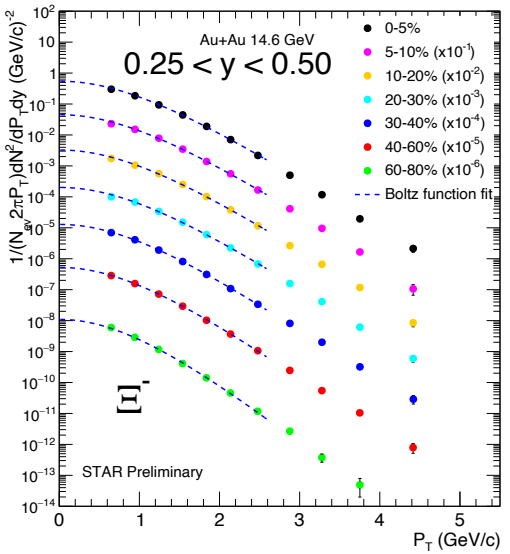


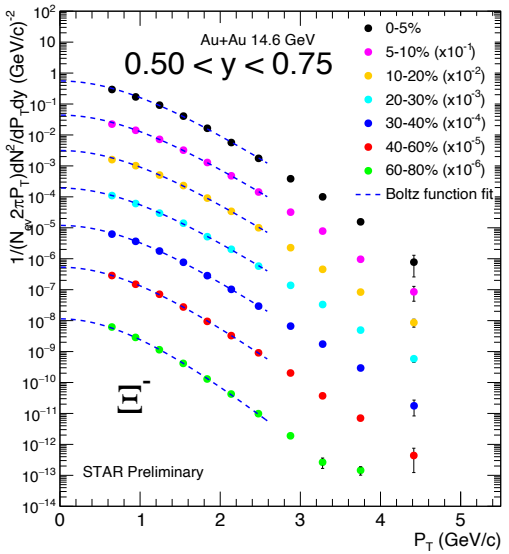


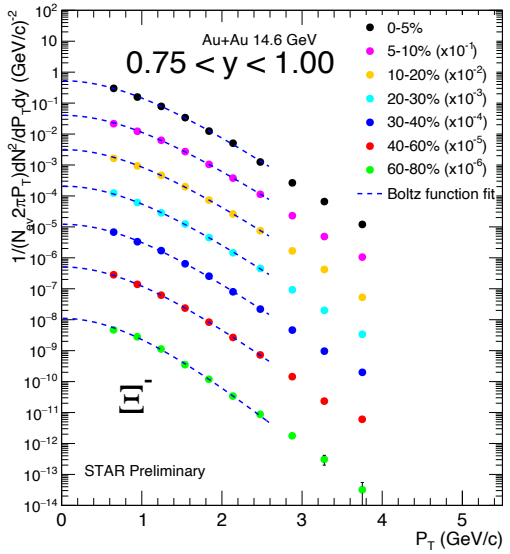






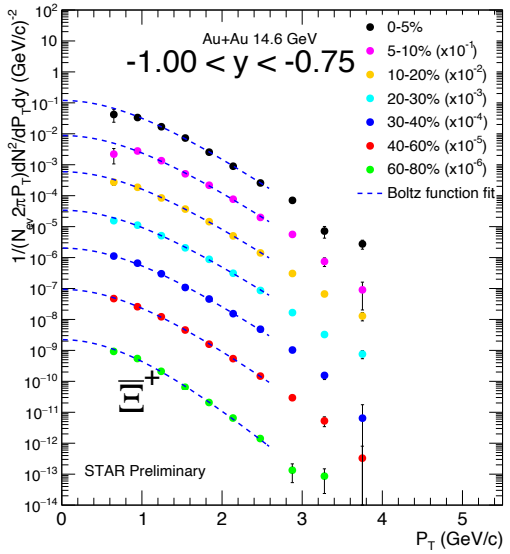


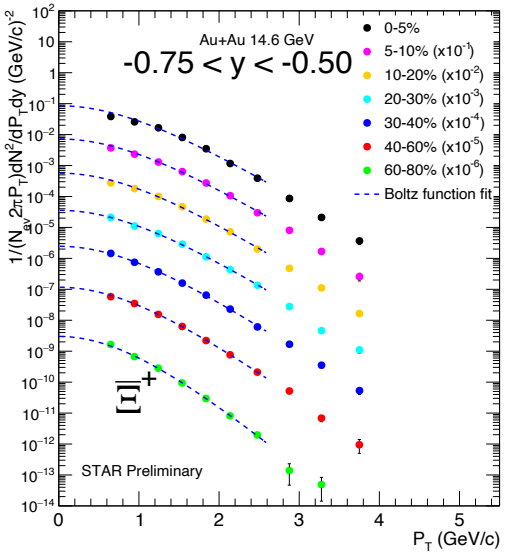


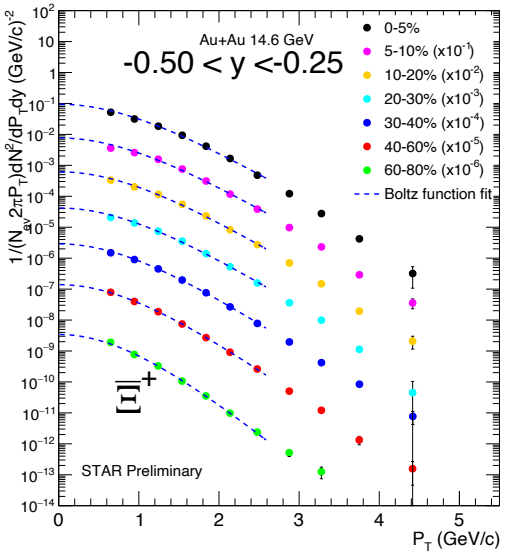


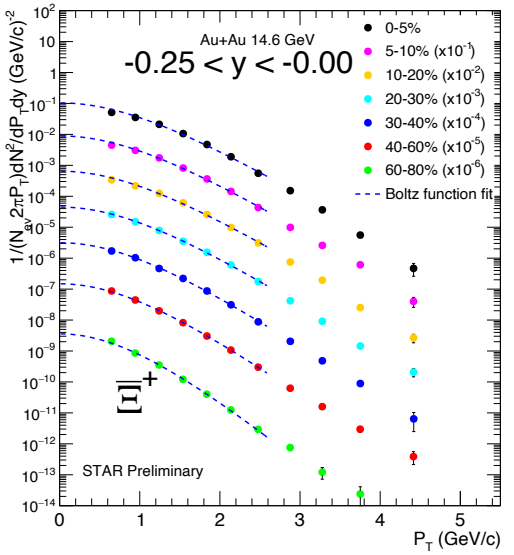
- Low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 1.0$

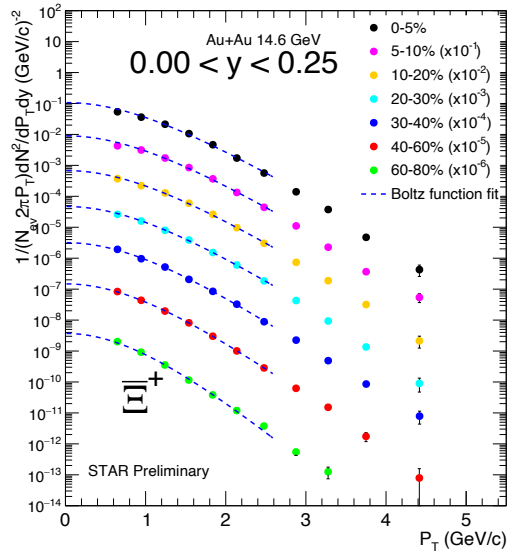
p_T spectra of $\bar{\Xi}^+$ at 14.6GeV

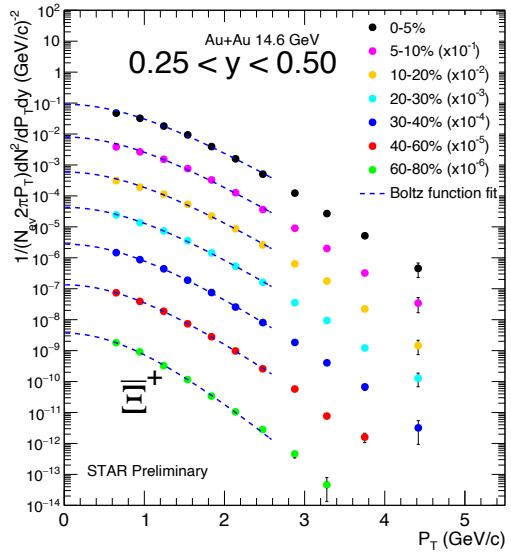


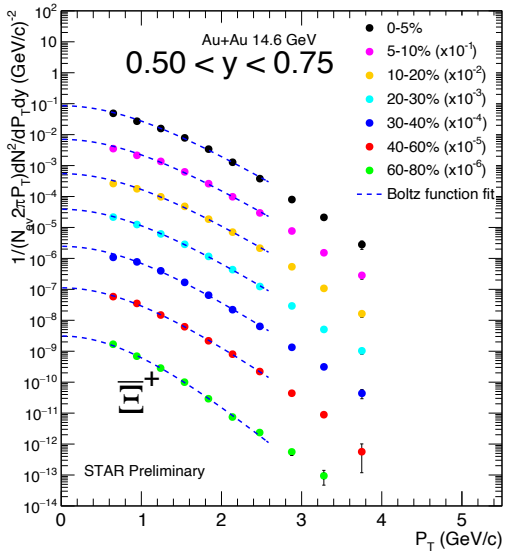


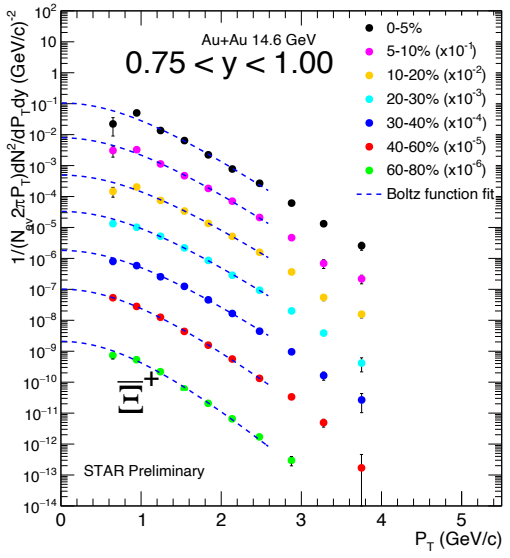












- Low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 1.0$