Strangeness production in STAR BES-II collider energies

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Why strangeness?

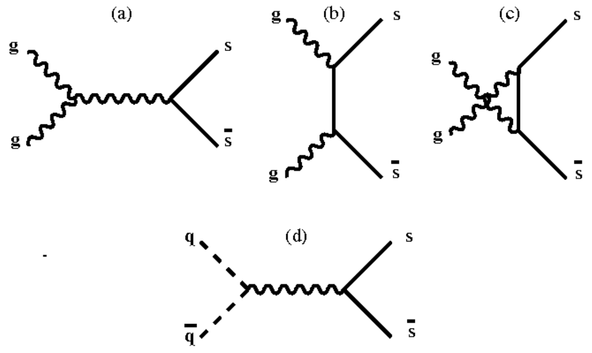
Rafelski & Müller, 1982

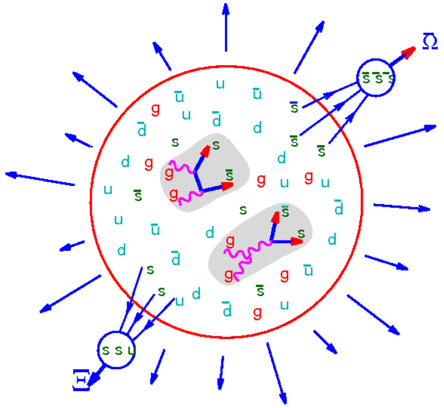
- Strange quarks
  - Not exist in colliding nuclei
  - Current mass ~100 MeV < T_c
  - Easily pair-produced in de-confined QGP medium

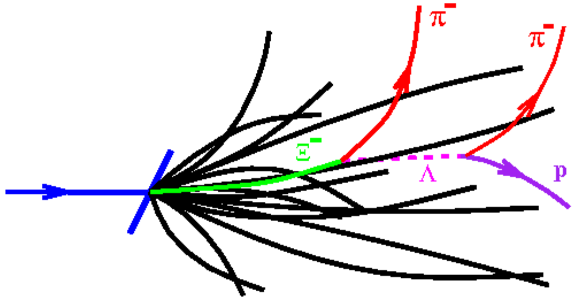
⟶ Strangeness enhancement !

- 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!



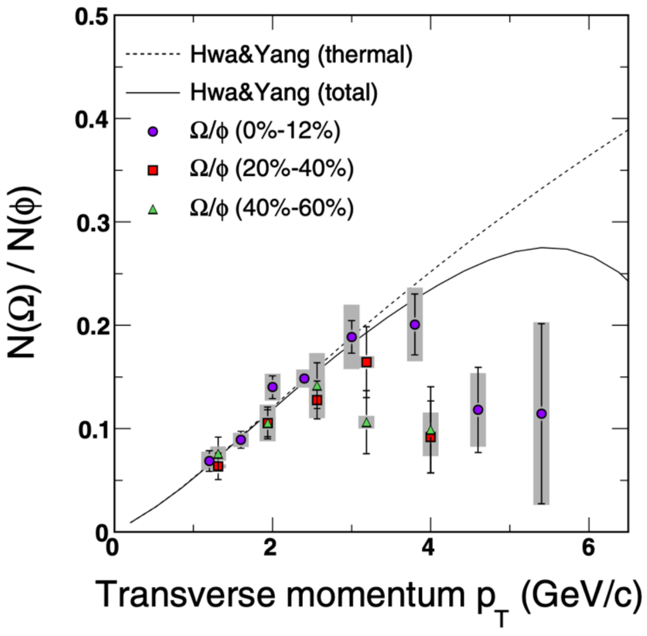




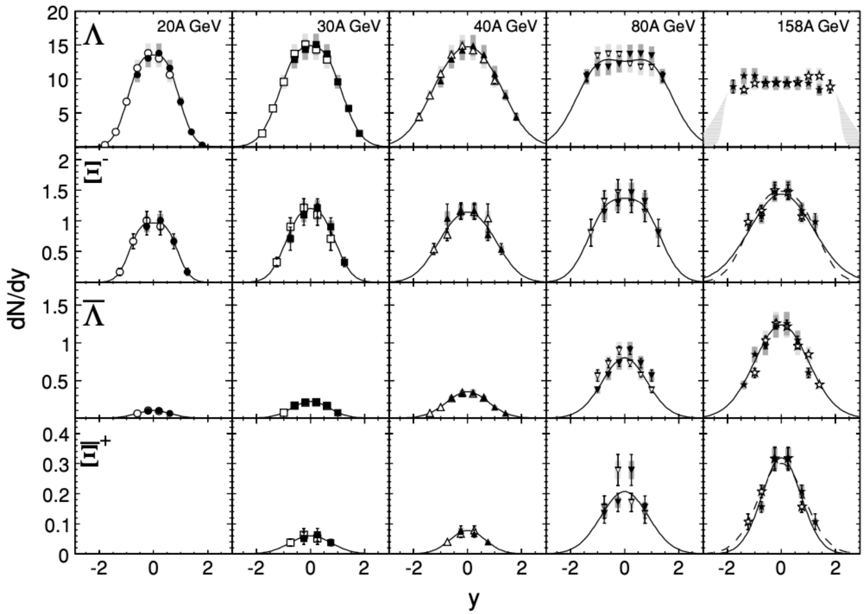
Motivation

- 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.

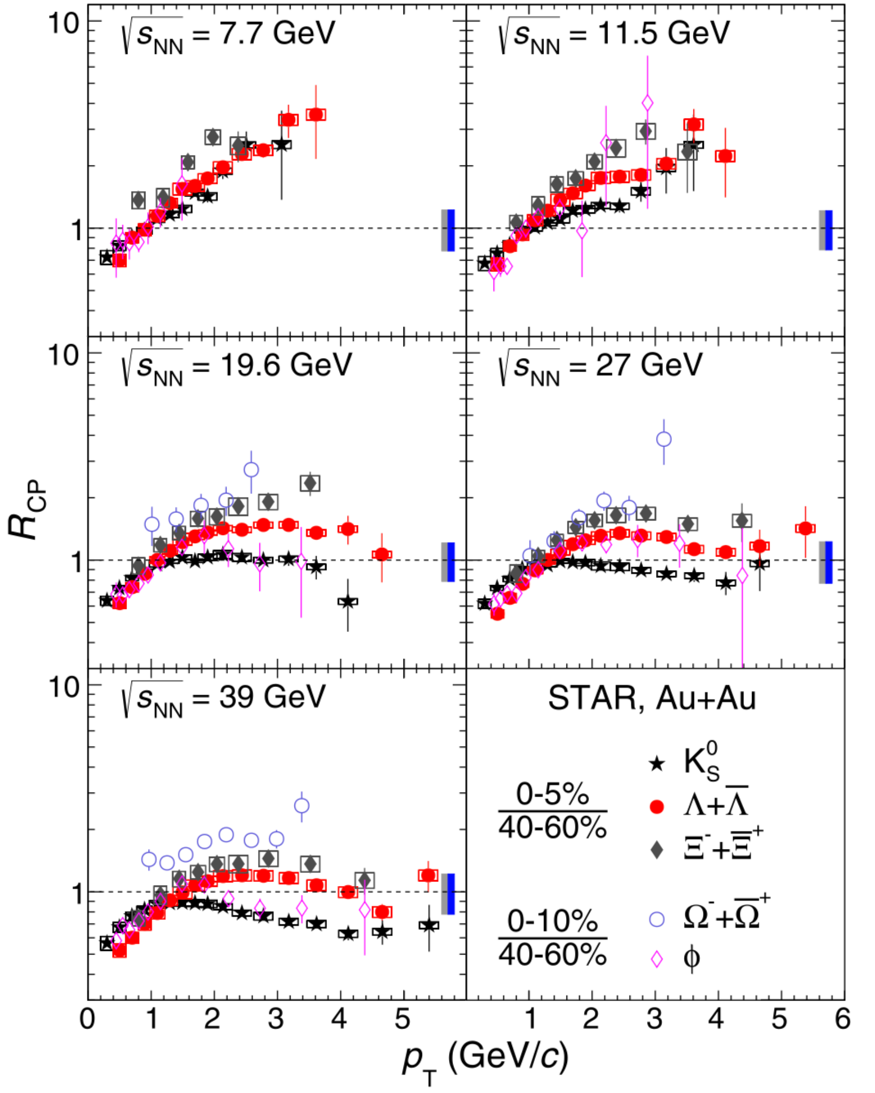
$$R_{CP} = \frac{[(dN/dp_T)/\langle N_{coll}\rangle]_{central}}{[(dN/dp_T)/\langle N_{coll}\rangle]_{peripheral}}$$



STAR, PRL 99, 112301 (2007)



NA49, PRC 78, 034918 (2008)



STAR, PRC 102, 034909 (2020)

Motivation

Heavy-ion collisions at top RHIC energy:

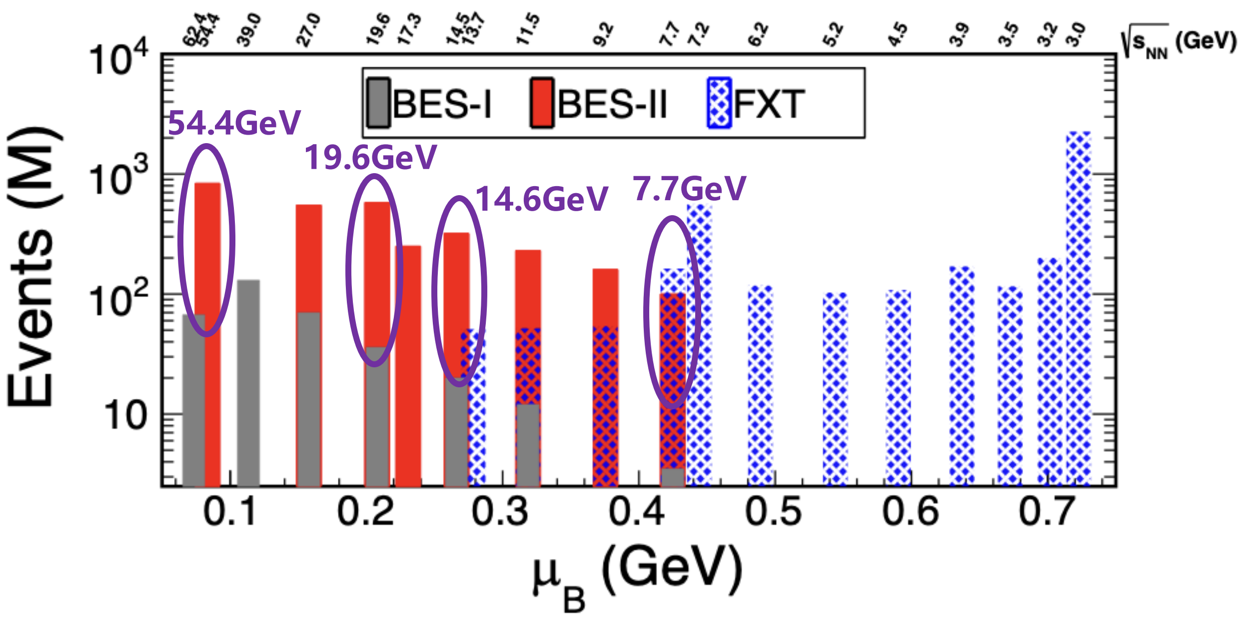
- Study QGP properties

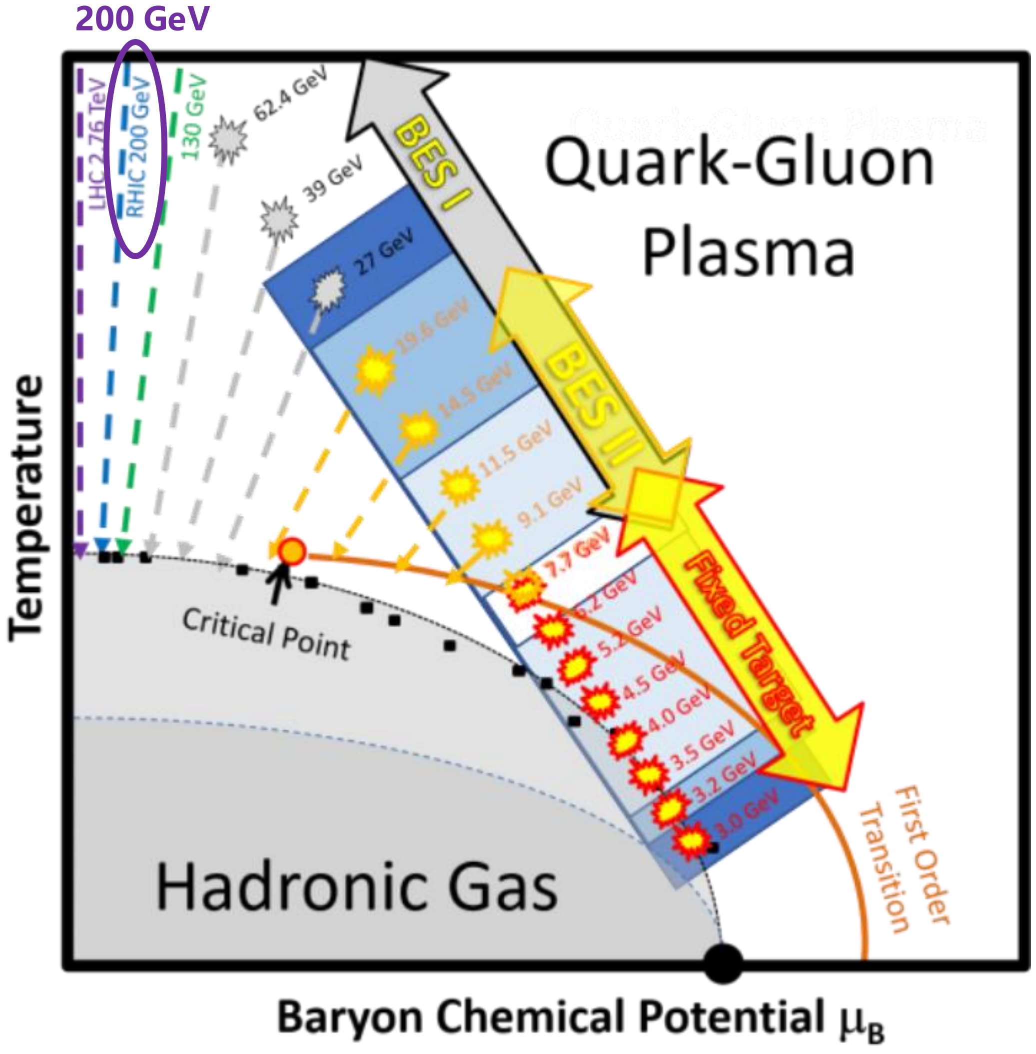
Beam Energy Scan (BES) program:

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

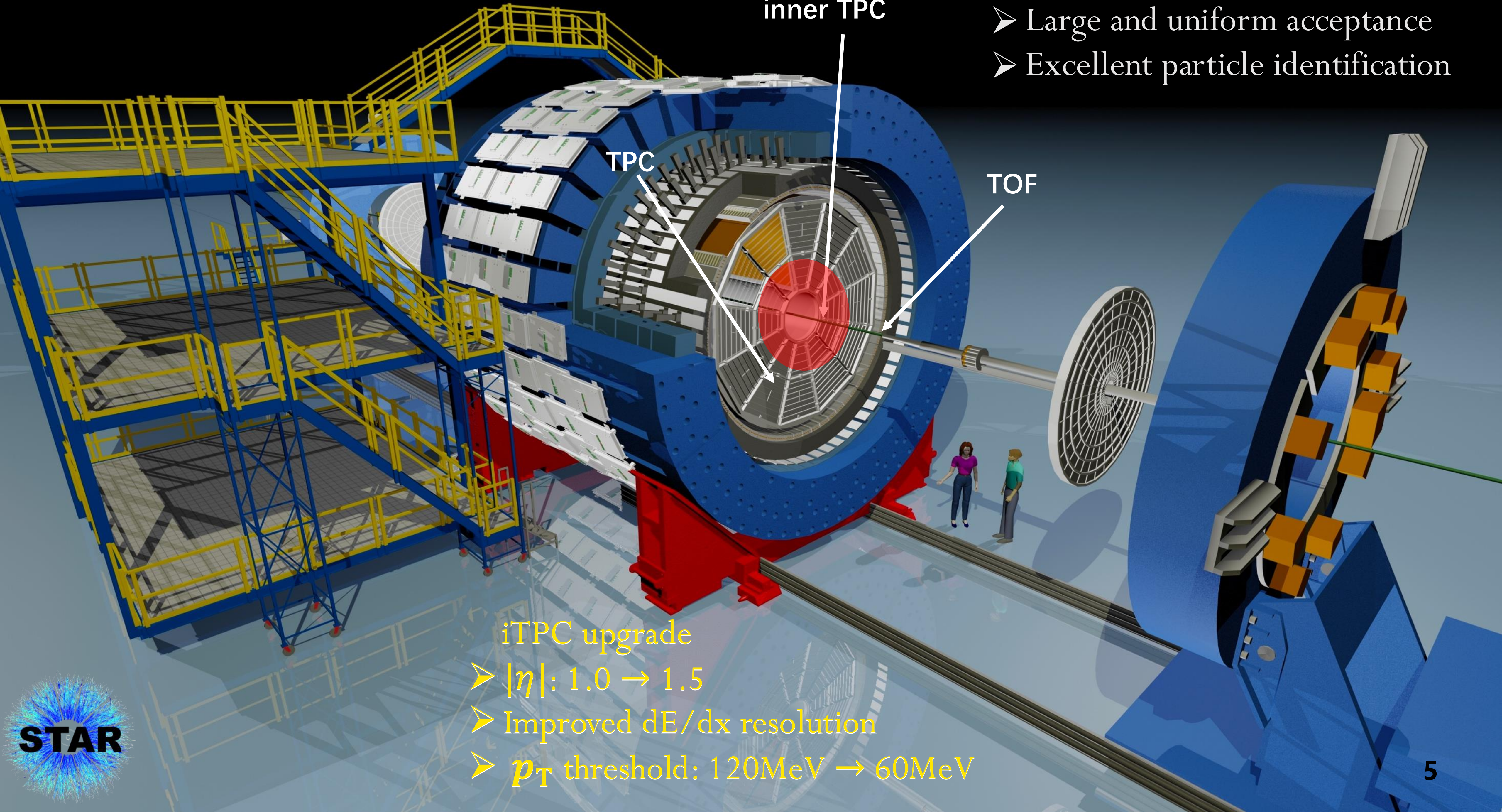
Yi Fang, Xiongxiong Xu, Weiguang Yuan, QM23/SQM24/CPS24
Yan Huang, SQM21

BES-II ~10–20 × BES-I





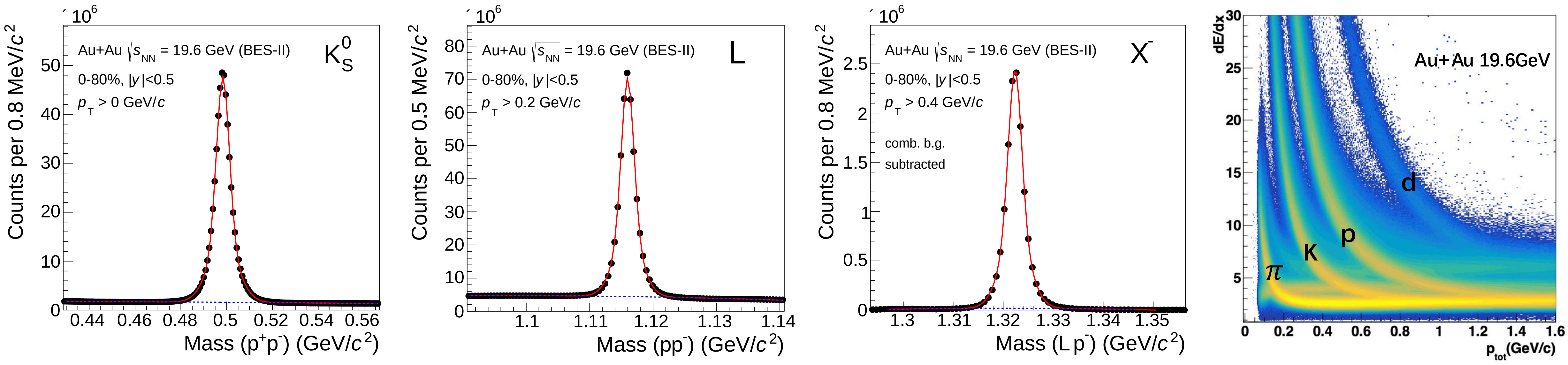
- Large and uniform acceptance
- Excellent particle identification

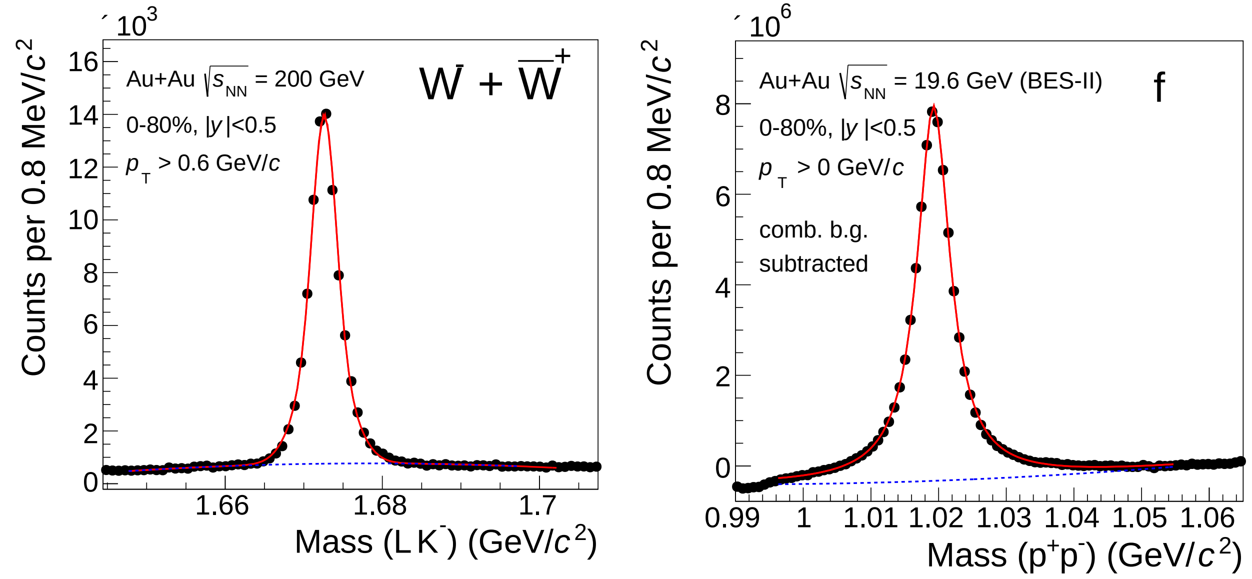


iTPC upgrade

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

Particle identification and reconstruction

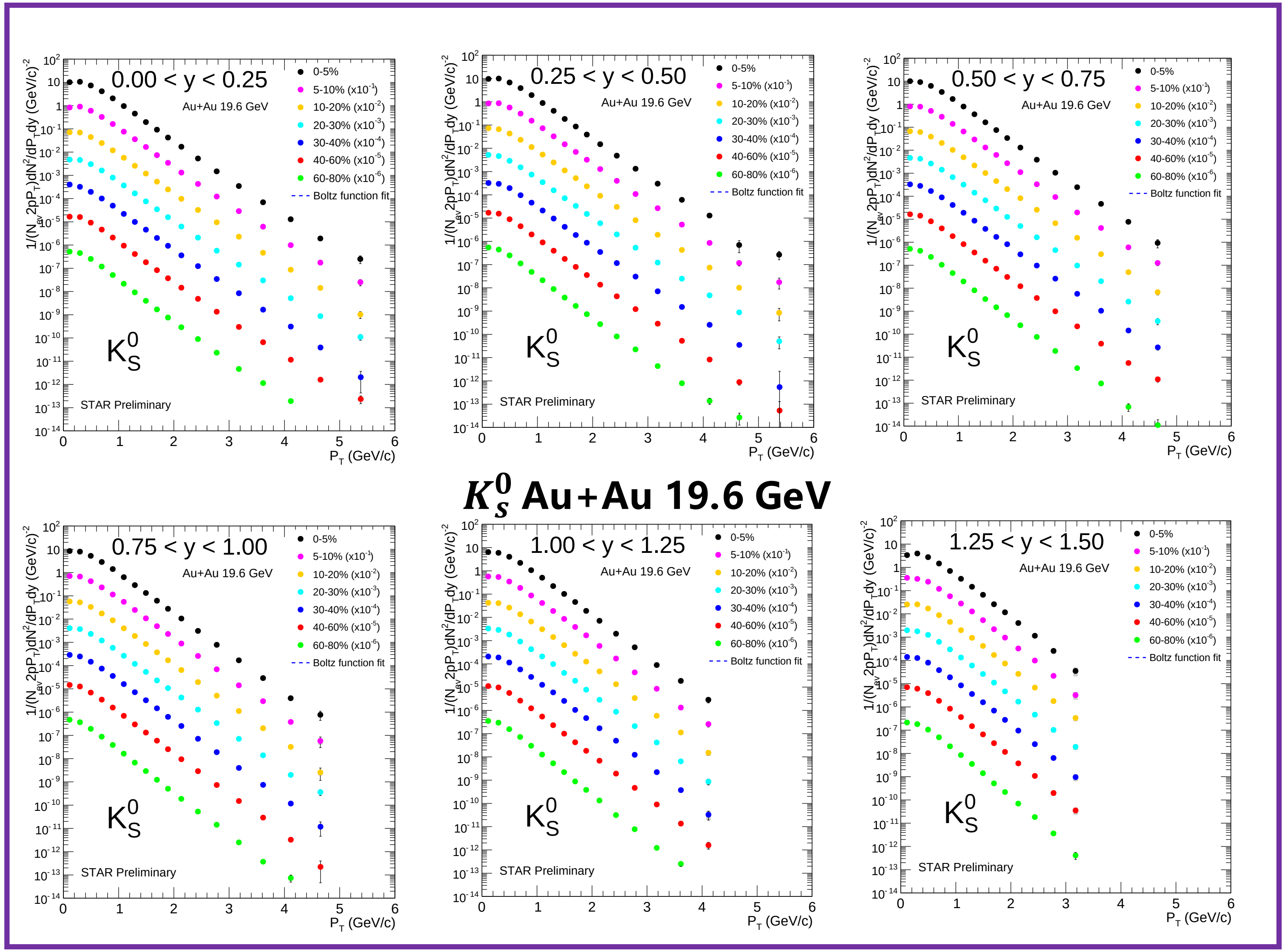


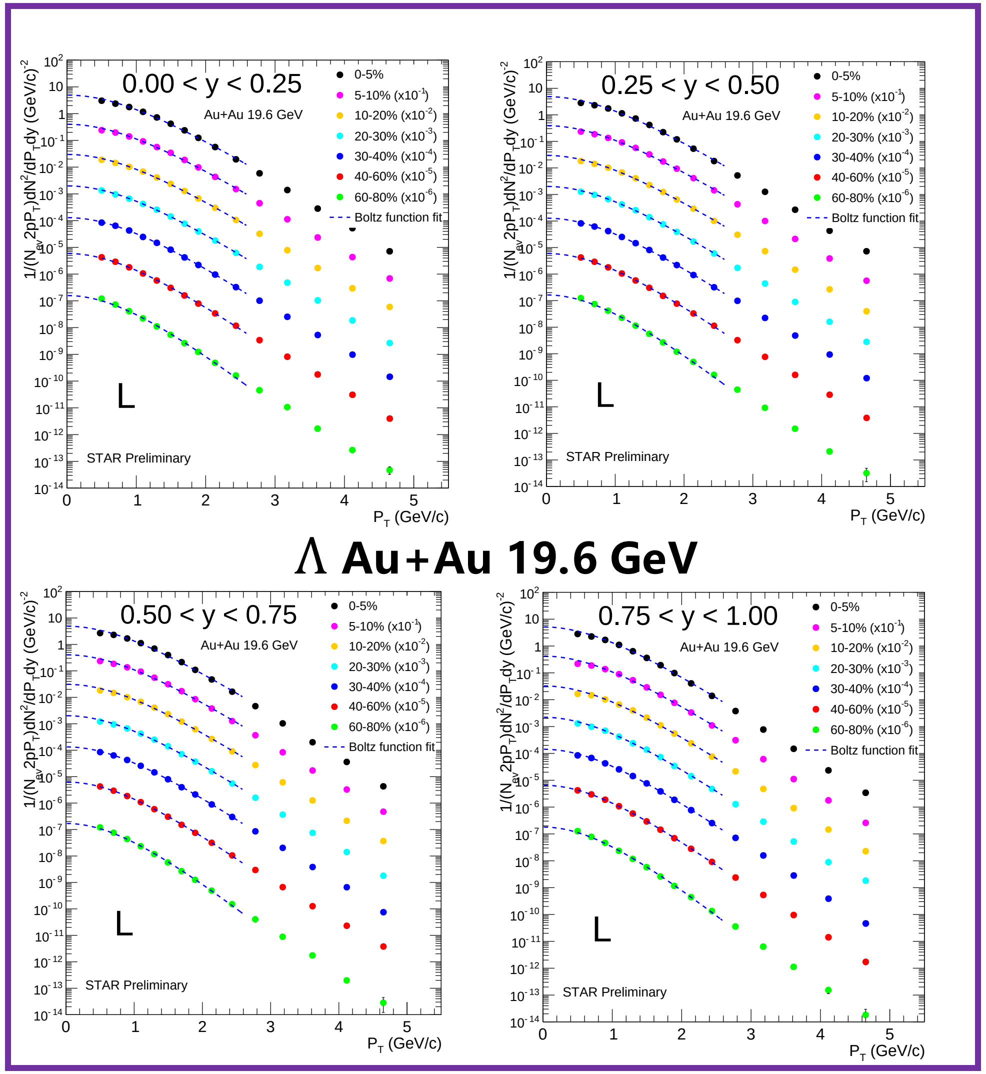


- Particle identification with dE/dx.
- π, K, p are used to reconstruct the secondary vertex of strange particles.
- TMVA optimization to improve Ω signal significance
- Large number of strange particles allow multi-differential measurements.

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

p_T spectra of K_s^0 and Λ at 19.6 GeV



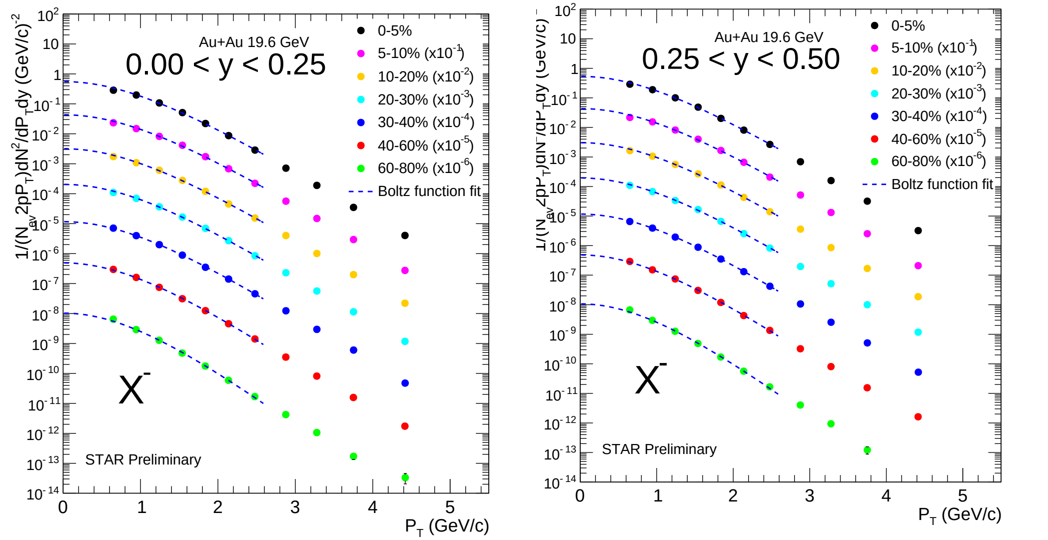


- K_s^0: measured down to p_T=0, no need for extrapolation to obtain dN/dy
- Rapidity: $|y| < 1.5$

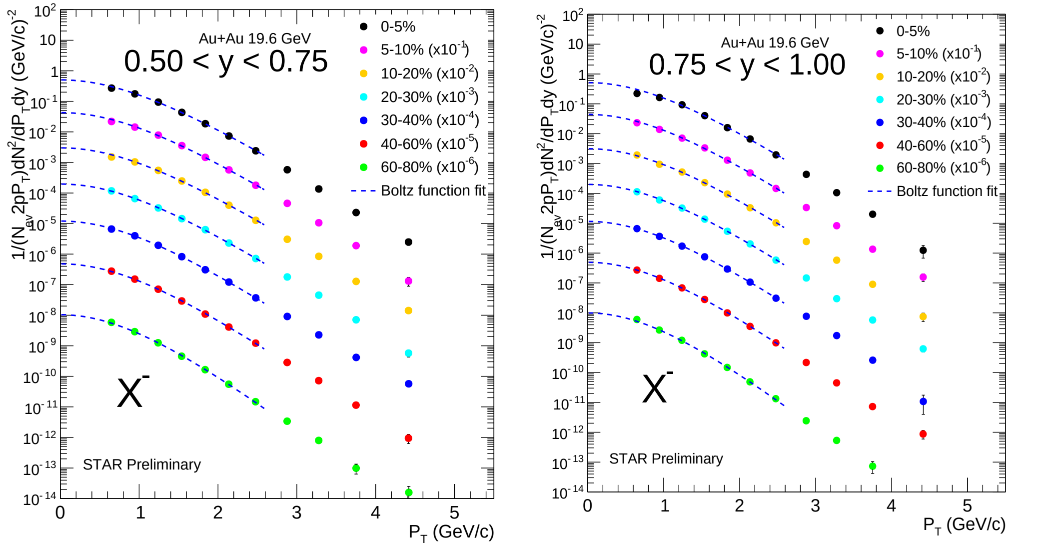
- Low p_T extrapolation: Boltzmann function
- Corrected for Ξ^- and Ξ^0 feed-down

  Rapidity: $|y| < 1$

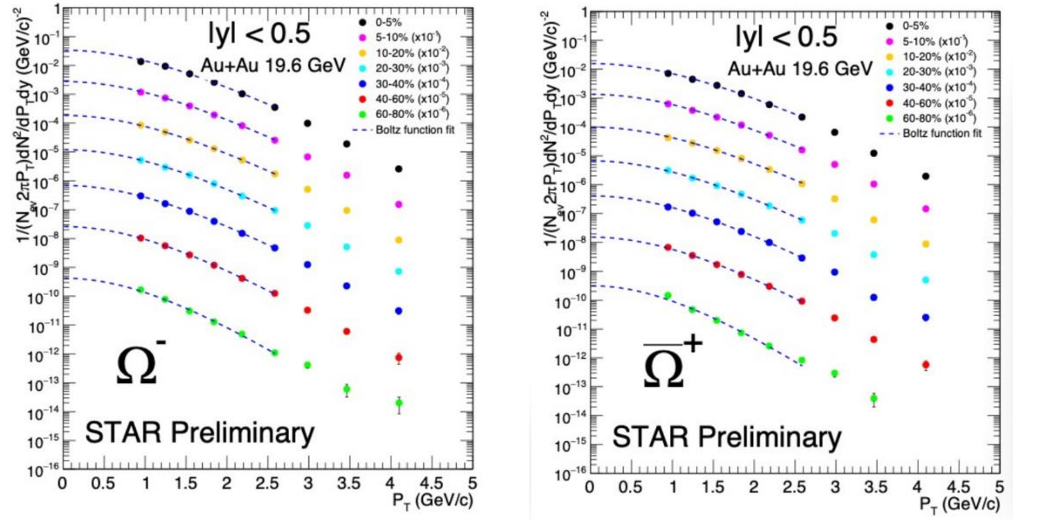
p_T spectra of Ξ^-, ϕ and $\Omega^-(\bar{\Omega}^+)$ at 19.6 GeV



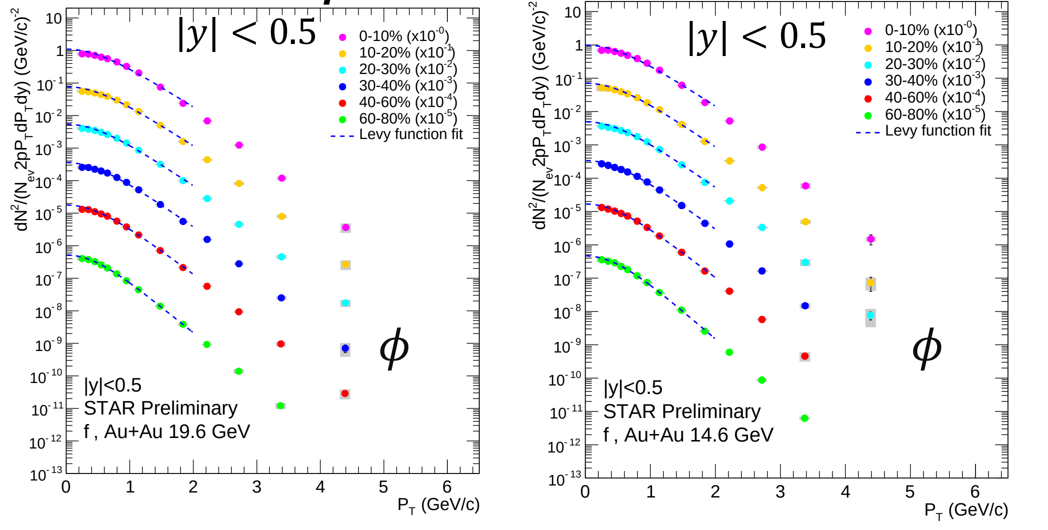
Ξ^- Au+Au 19.6 GeV



Ω^- and $\bar{\Omega}^+$ Au+Au 19.6 GeV



ϕ Au+Au 19.6 and 14.6 GeV



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

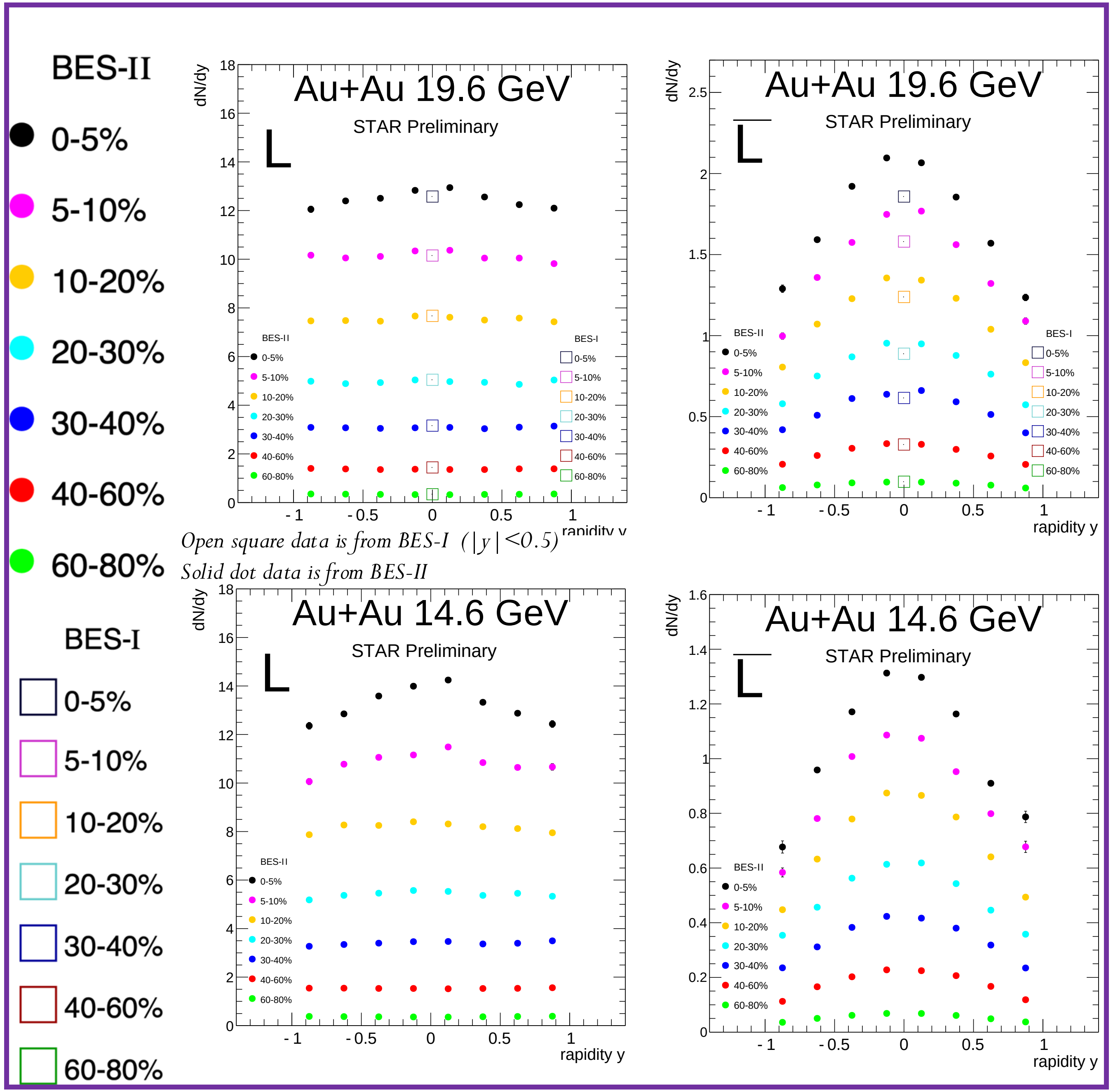
- Ω low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 0.5$

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

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

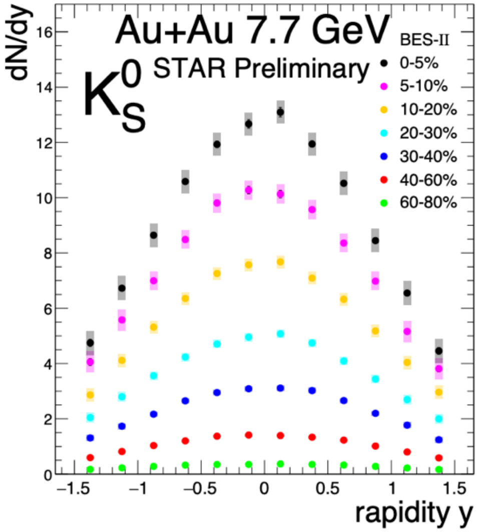
- Rapidity spectra of anti-baryons($\bar{\Lambda}$) are Gaussian-like distributions.
- Rapidity distribution of baryons(Λ) are wider than that of anti-baryons ($\bar{\Lambda}$).
  - ✓ Extra contributions from stopped baryons
- Similar trends observed by NA49.

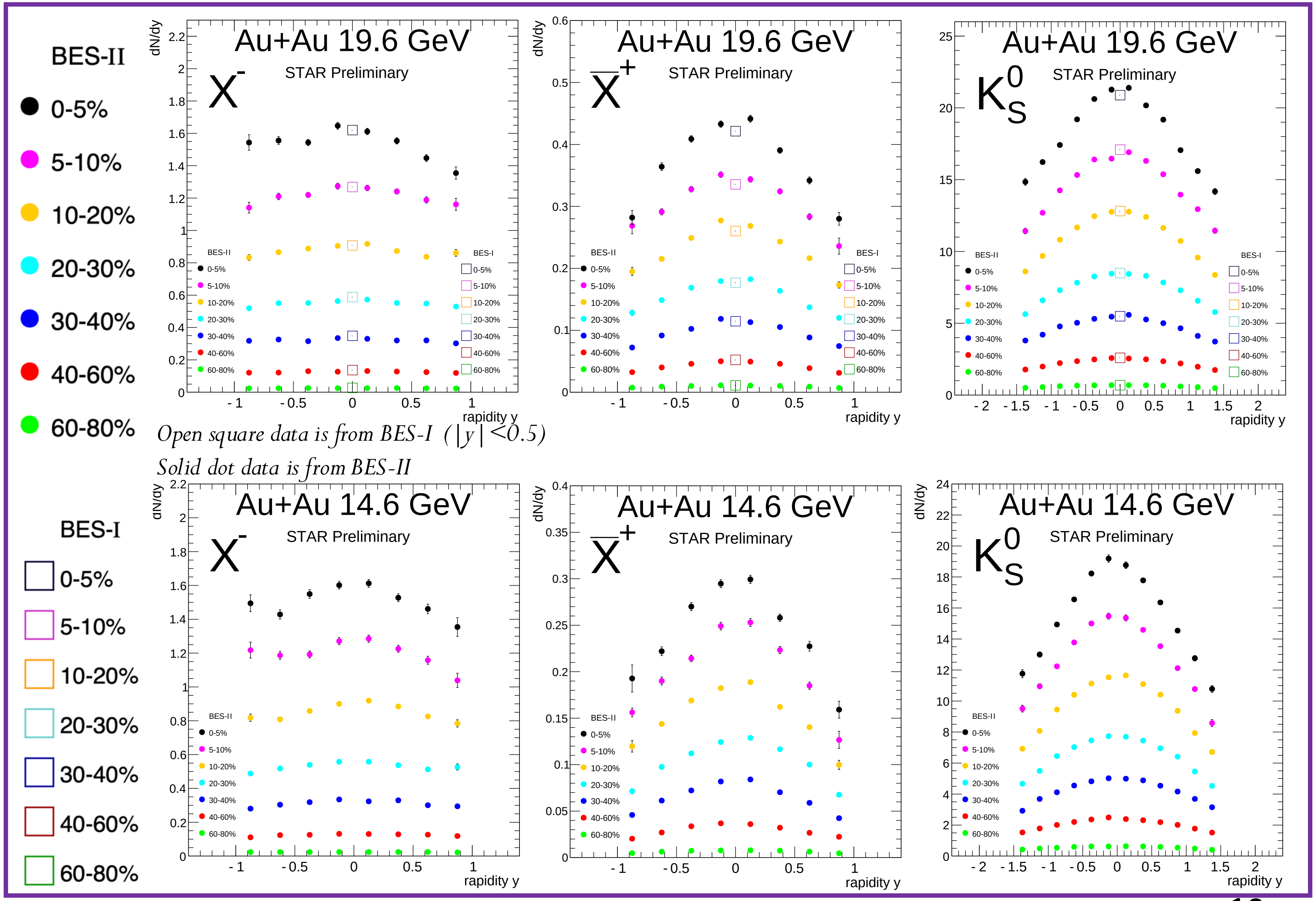
NA49, PRC 78, 034918 (2008)



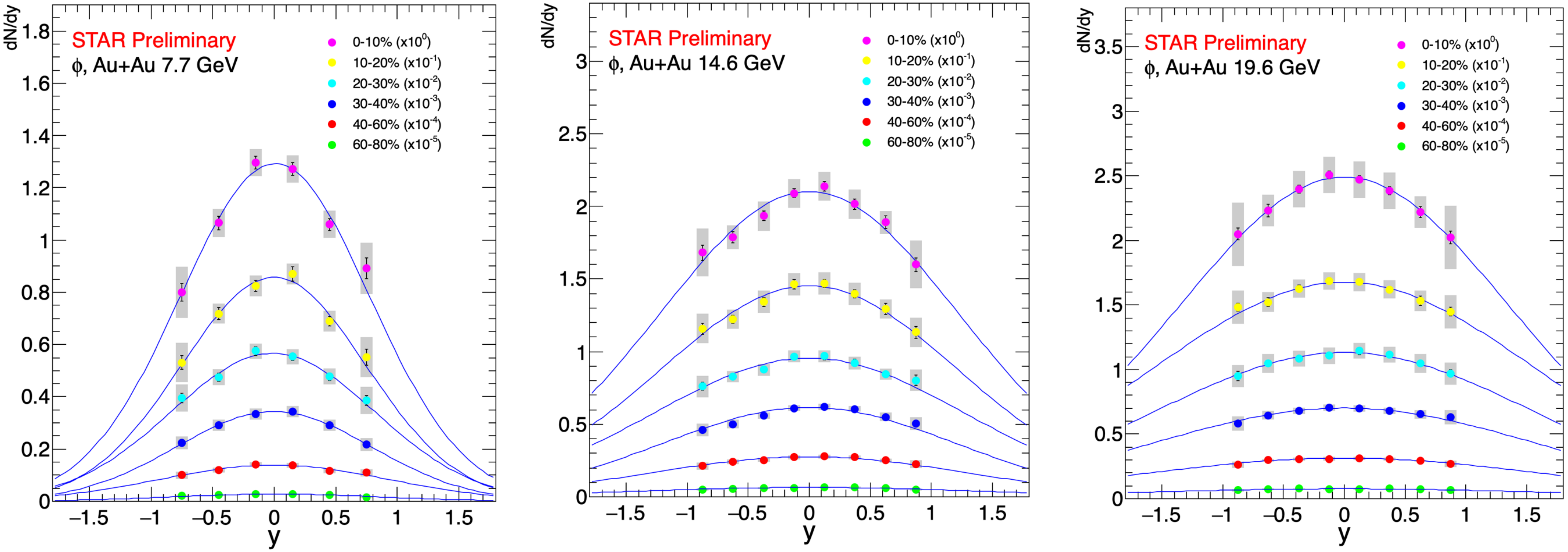
Rapidity spectra of K_s^0, Ξ^- and $\bar{\Xi}^+$ at 19.6 and 14.6 GeV

- 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.





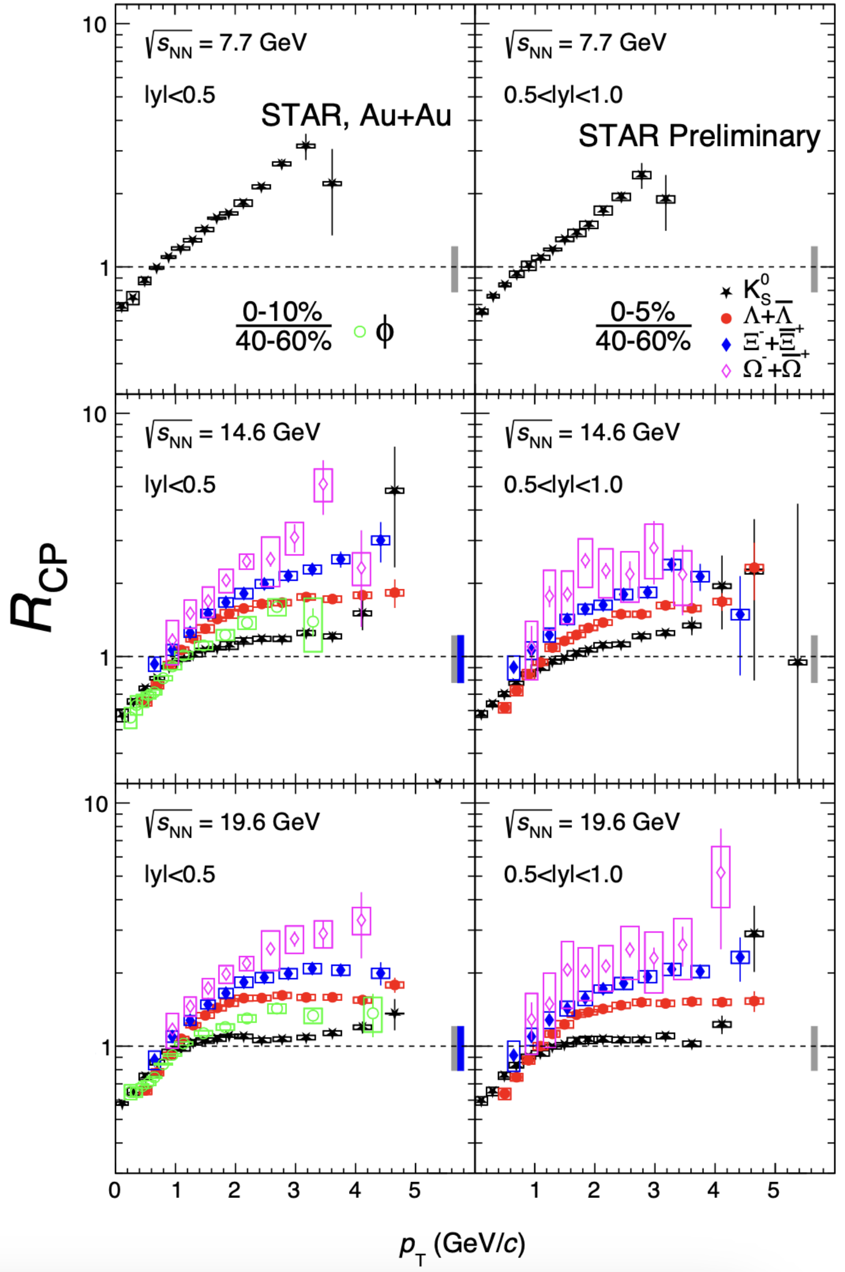
Rapidity spectra of ϕ



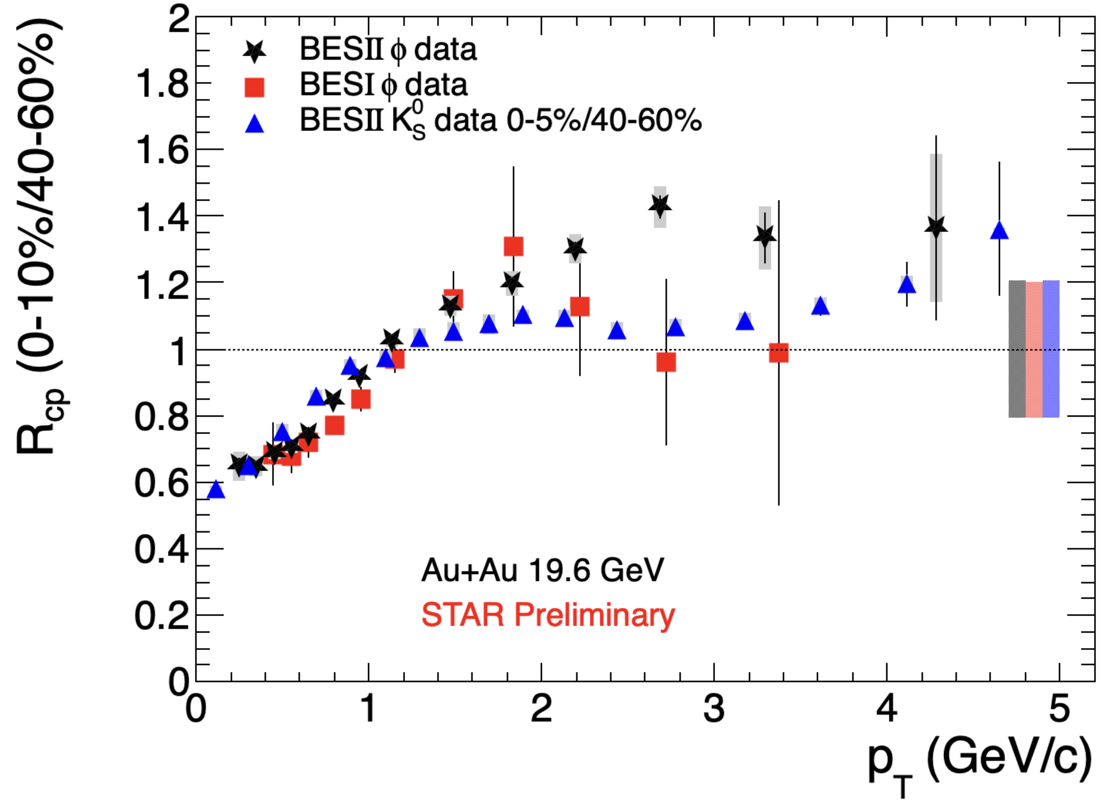
- Rapidity spectra of ϕ are Gaussian-like distributions
- Rapidity distribution become wider with increasing energy

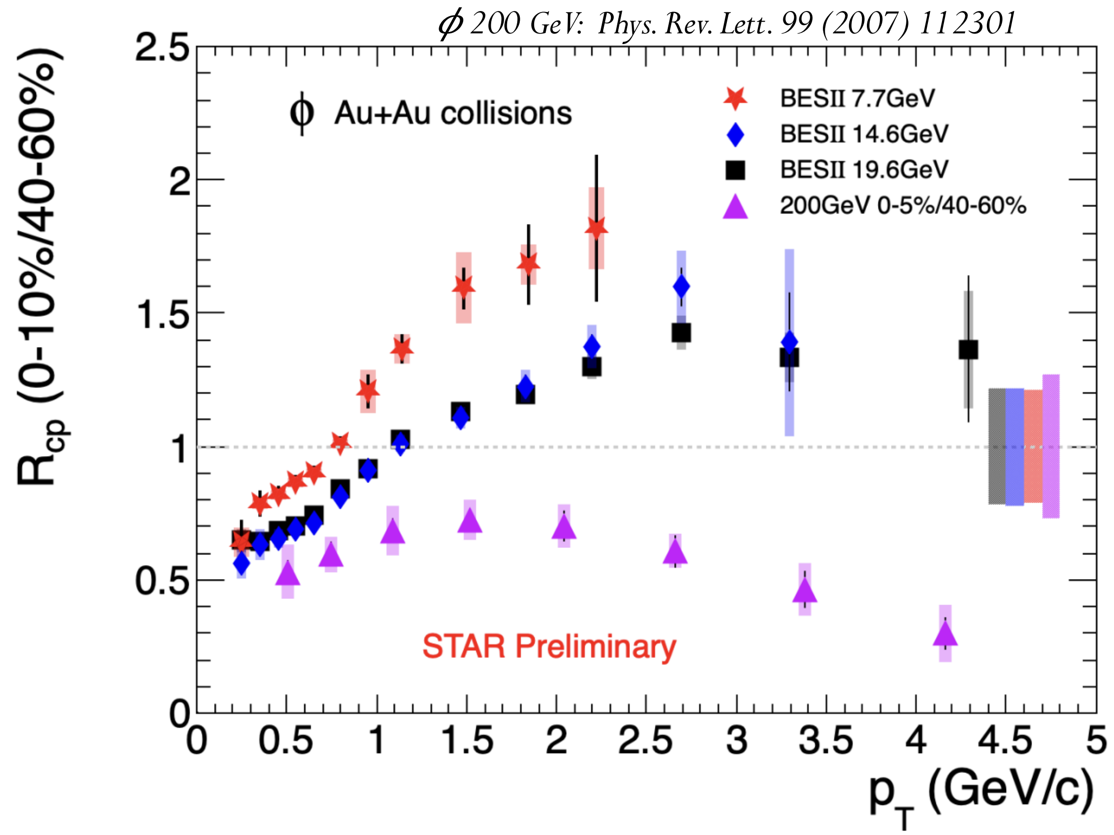
Nuclear modification factor at 19.6, 14.6 and 7.7 GeV

- 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.



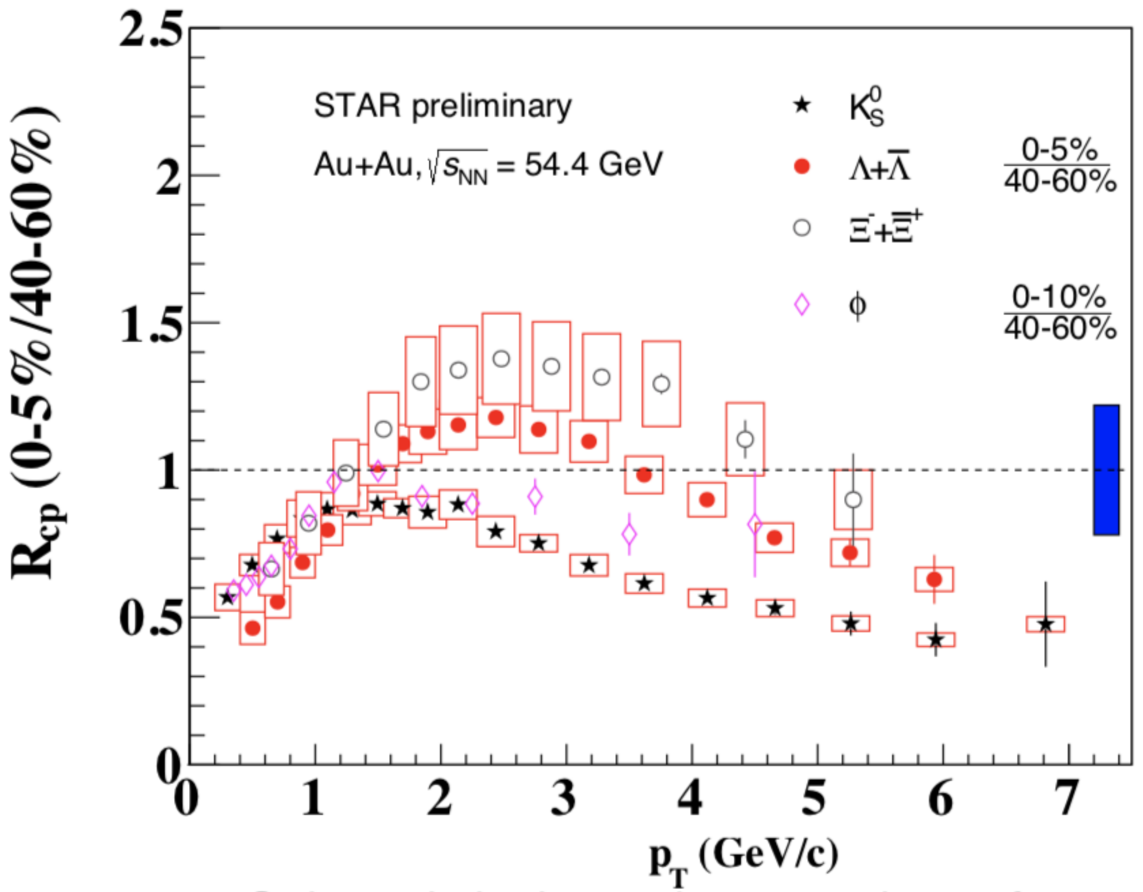
Nuclear modification factor for ϕ





- 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

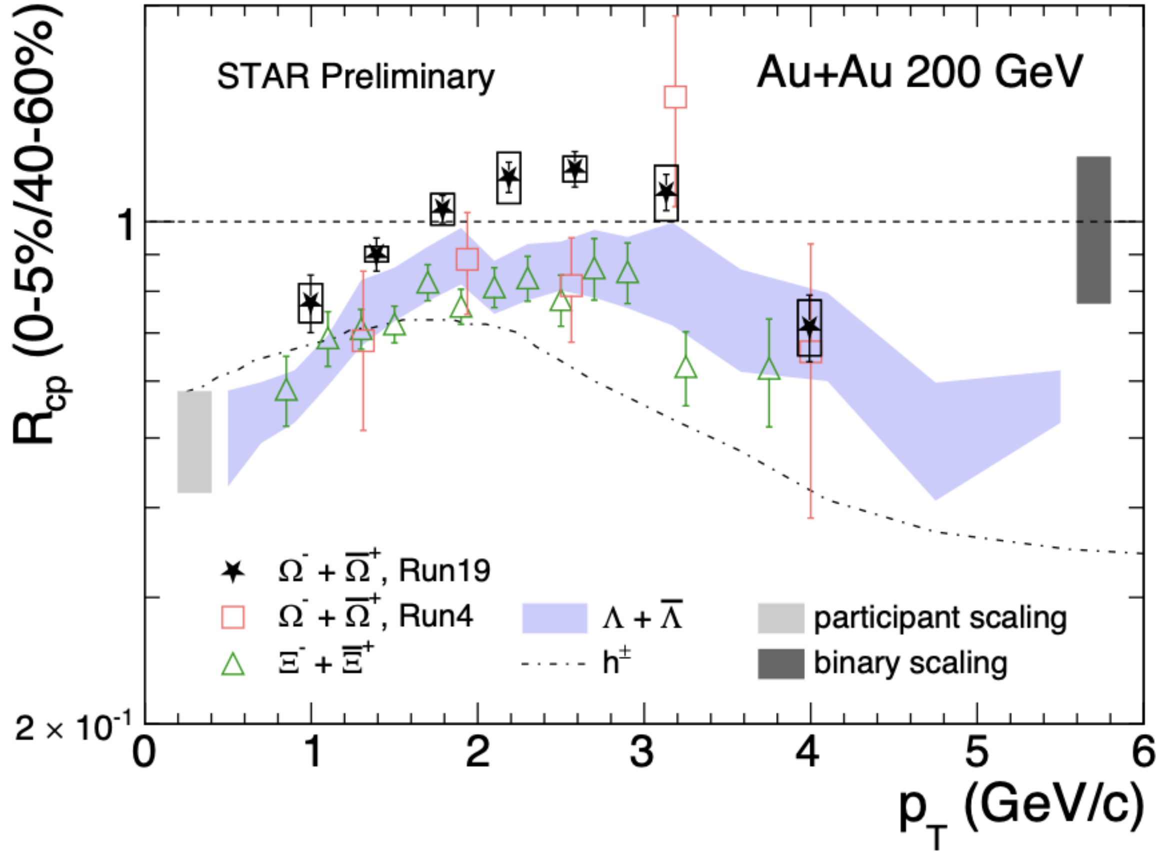
Nuclear modification factor for strange hadrons at 54.4 GeV



Only statistical error bars are shown for ϕ

- Strong suppression of K^0_S R_{CP} at high p_T
  → partonic energy loss

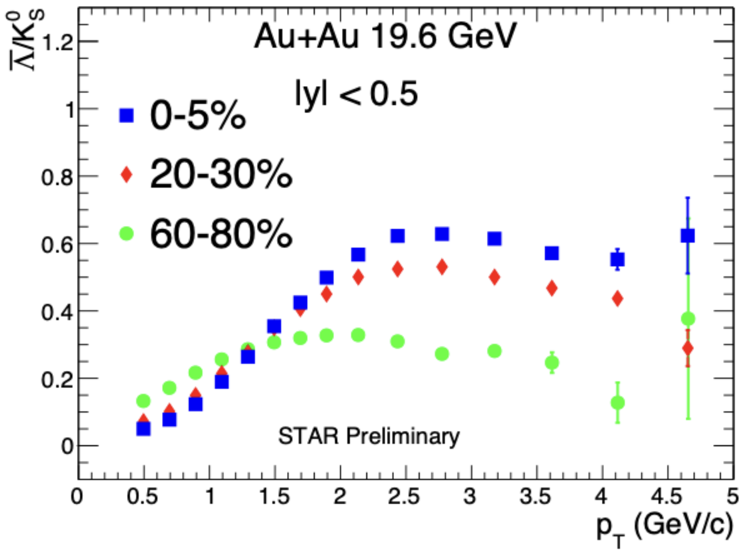
R_{CP} of strange hadrons at 200 GeV

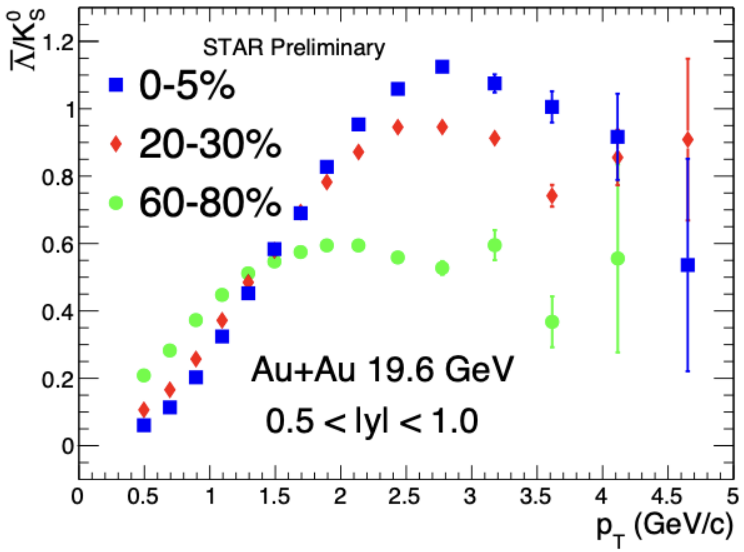


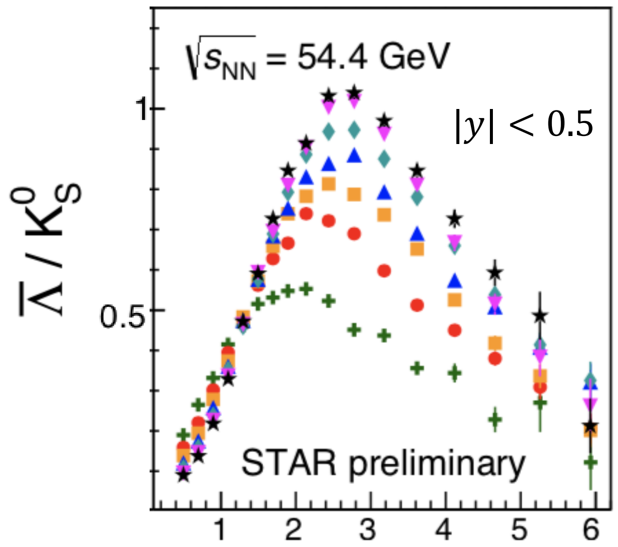
- R_{cp} of Ω follows the same trend in p_{T} as that of Λ and Ξ, as expected from recombination model.
- The higher R_{cp} of Ω implies the faster increase of Ω yields with the increasing centrality.

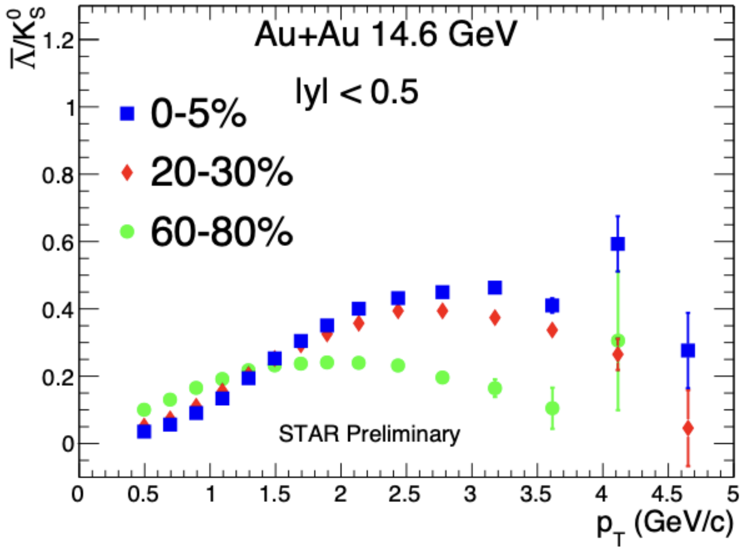
$\Omega + \bar{\Omega}$ Run4 & $\Xi + \bar{\Xi}$: STAR, Phys. Rev. Lett. 98 (2007) 062301
$\Lambda + \bar{\Lambda}$: STAR, Phys. Rev. Lett. 92 (2004) 052302
$h^{\pm}$(charged hadrons): STAR, Phys. Rev. Lett. 91 (2003) 172302

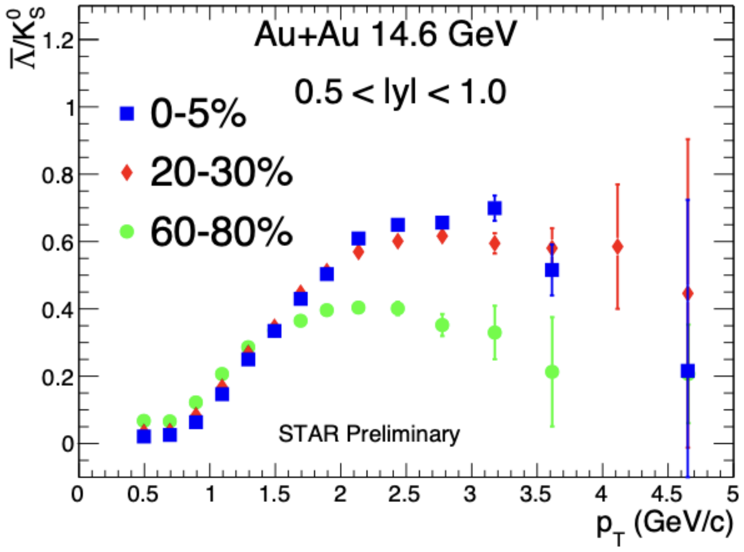
$\bar{\Lambda}/K_s^0$ ratio at 54.4, 19.6 and 14.6 GeV





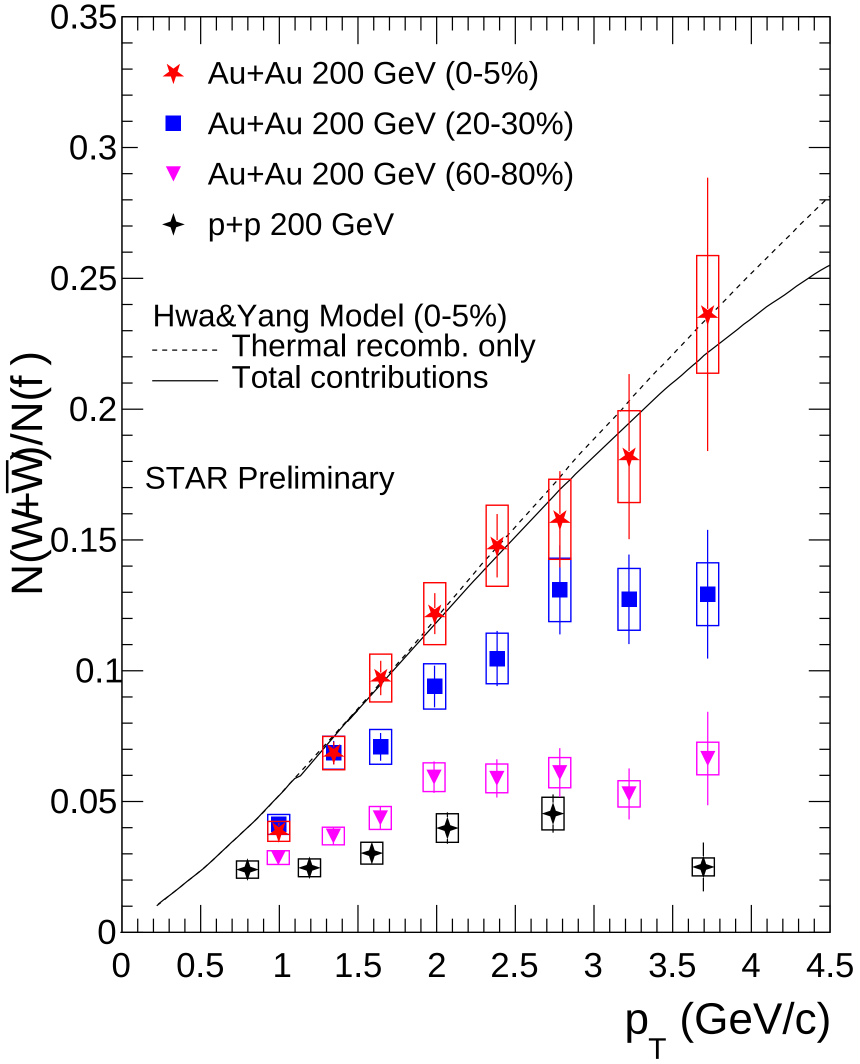






- Clear centrality and rapidity dependence of (anti-)baryon-to-meson ratio at intermediate p_T.
- Baryon enhancement is observed in all measured rapidity regions.

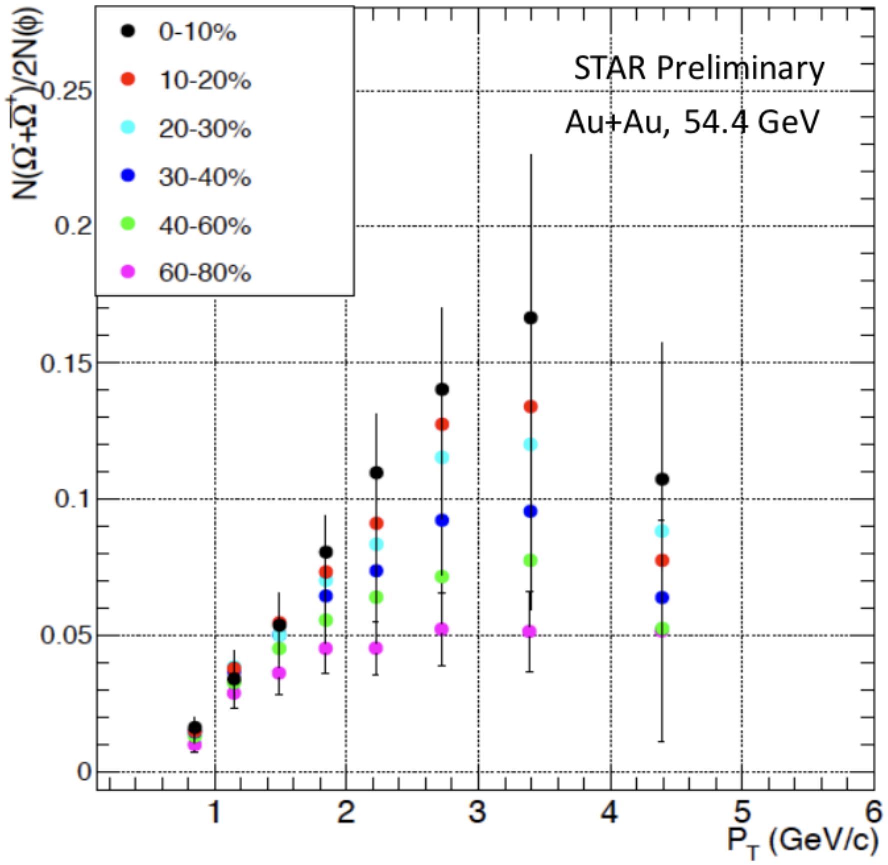
$\Omega(sss)/\phi(s\bar{s})$ ratio at 200 GeV

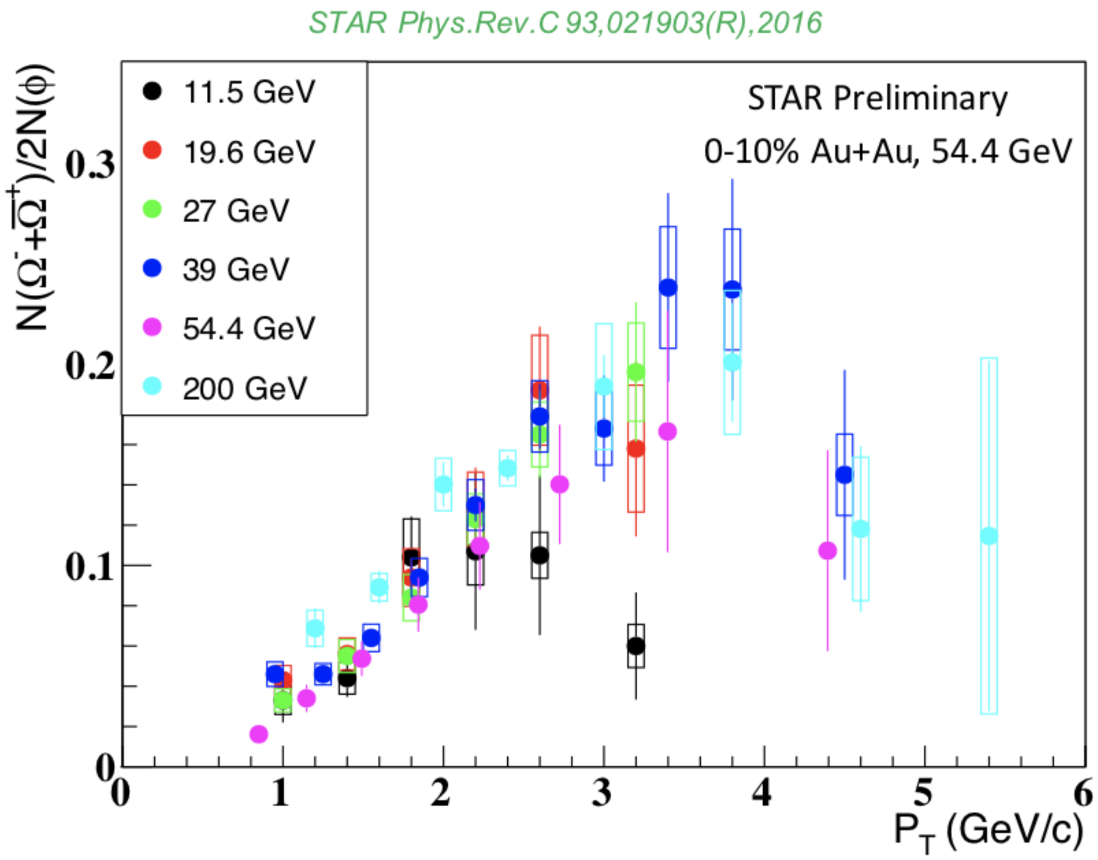


- In central collisions, good agreement between data and recombination model calculations.
  - ✓ Ω and ϕ are predominantly produced through the recombination of thermalized strange quarks in QGP.
- At intermediate p_T, ratio increases gradually with increasing system size. Significant Ω enhancement over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

Ω/ϕ ratio at 54.4 GeV



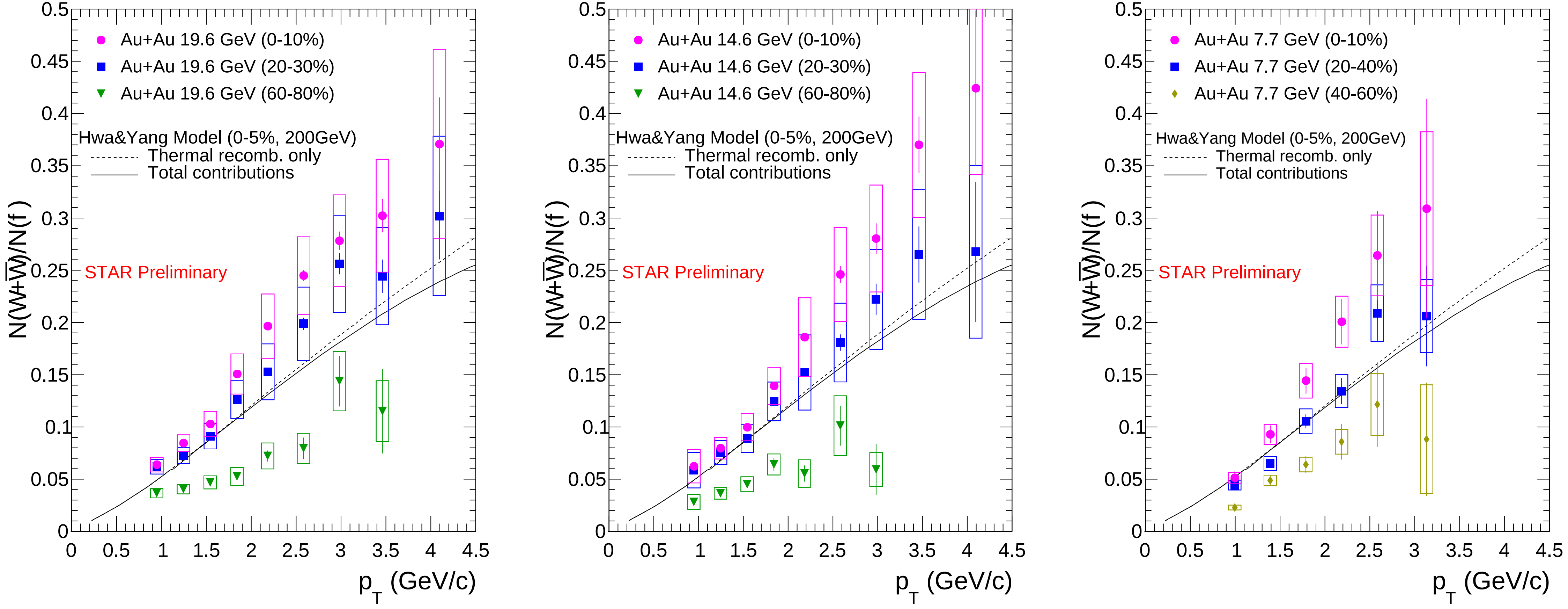


Ω/ϕ ratio enhancement at 54.4GeV

$\rightarrow$ Hadron formation through parton recombination

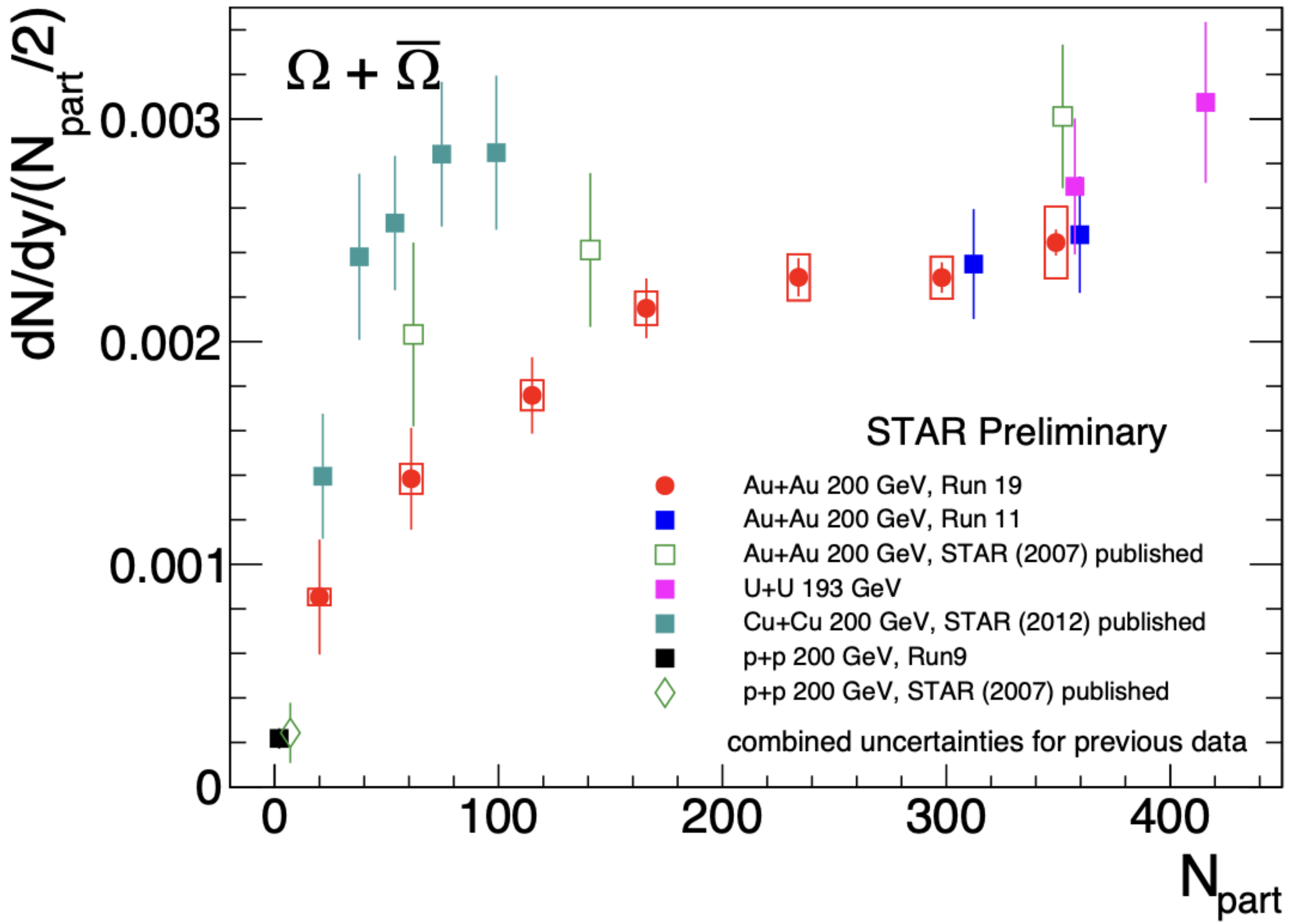
Y. Huang, SQM2021

Ω/ϕ ratio in 19.6, 14.6 and 7.7 GeV



- 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

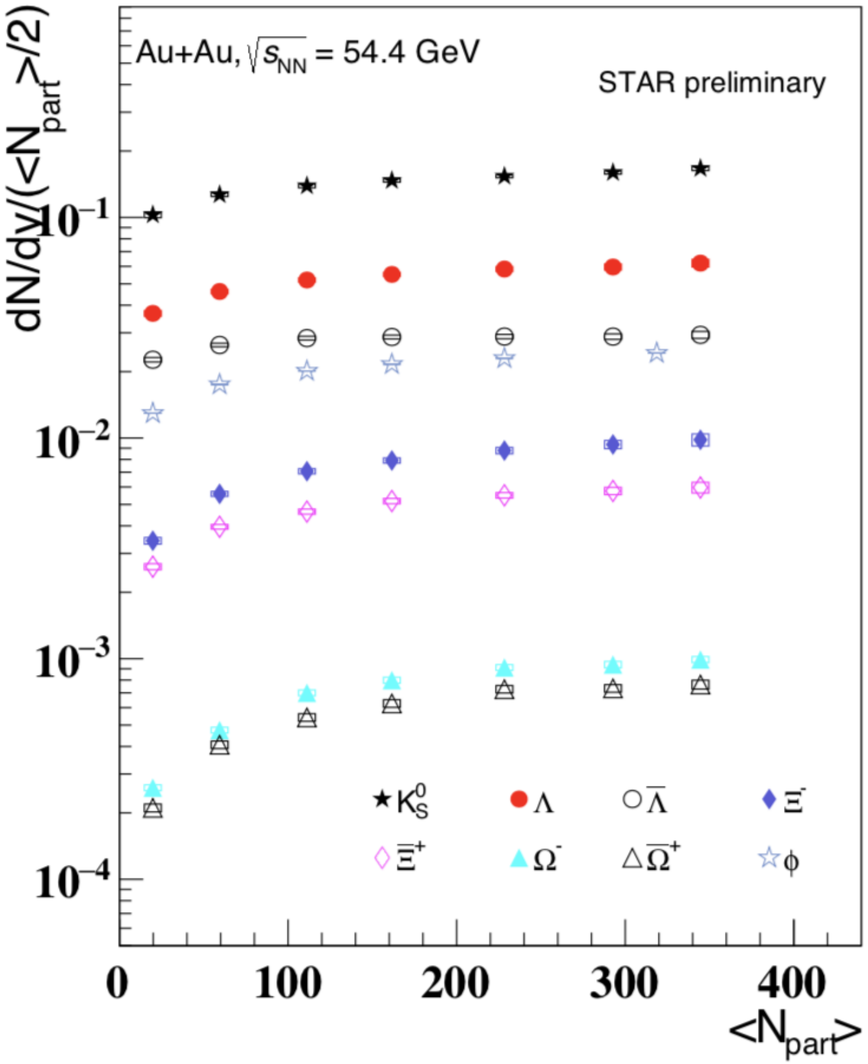
System size dependence of Ω yield at 200 GeV



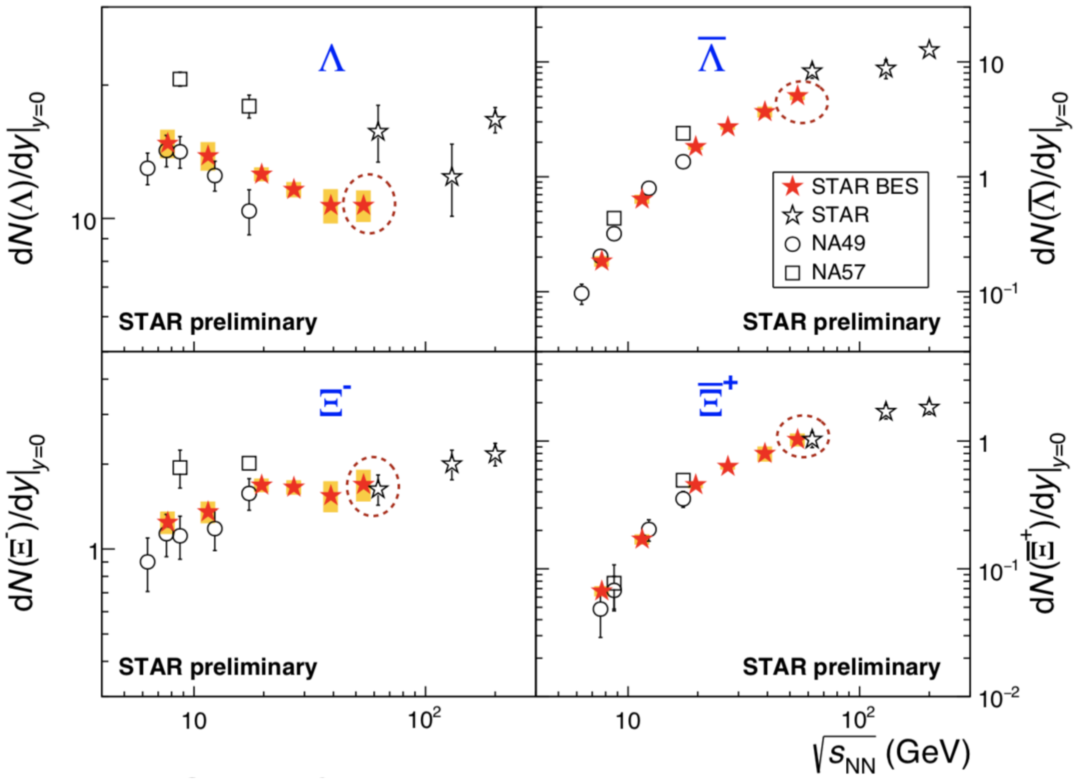
- In general, increasing Ω baryon enhancement compared to p+p collisions with increasing system size is observed.

p+p: STAR, Phys. Rev. C 75 (2007) 064901
pub. Au+Au: STAR, Phys. Rev. Lett. 98 (2007) 062301
Cu+Cu: STAR, Phys. Rev. Lett. 108 (2012) 072301
Other preliminary data, X. Zhu, QM2014

Strange hadron yields at 54.4 GeV



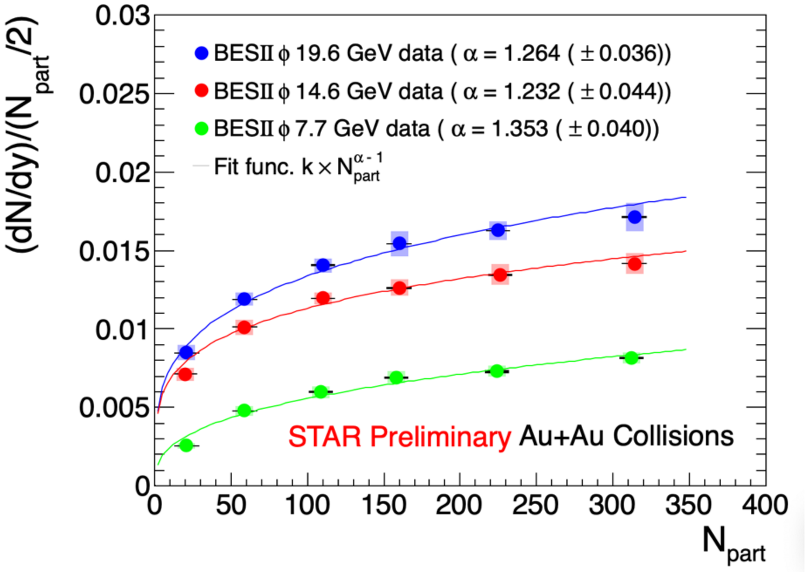
Y. Huang, SQM2021

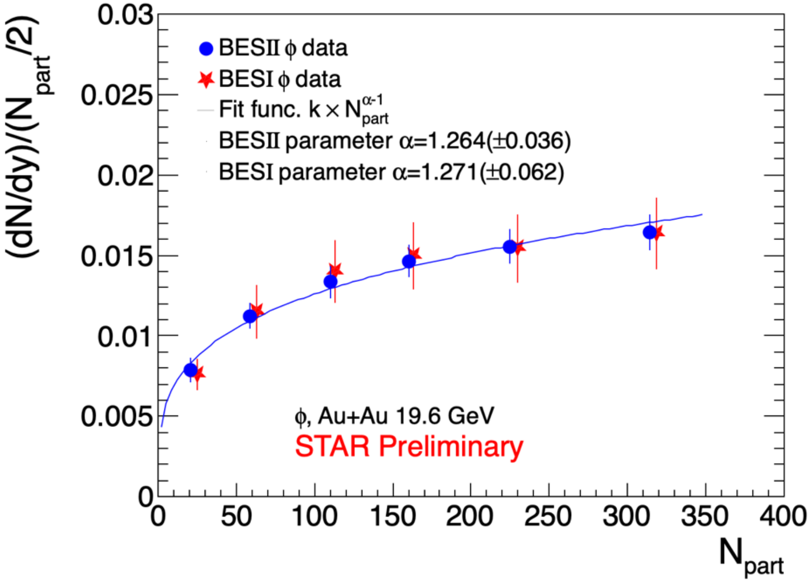


The energy dependence of Λ:

- $\Lambda\bar{\Lambda}$ pair production at higher energy
- Associated production at lower energy
- Possible cross over between two mechanisms at ~54.4 GeV

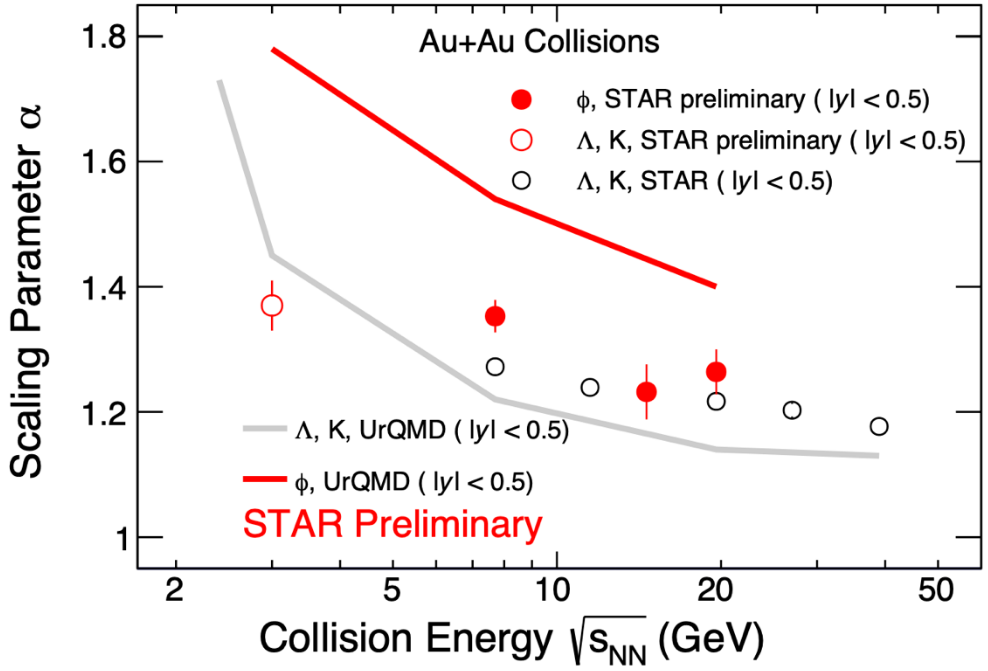
Centrality dependence of ϕ production





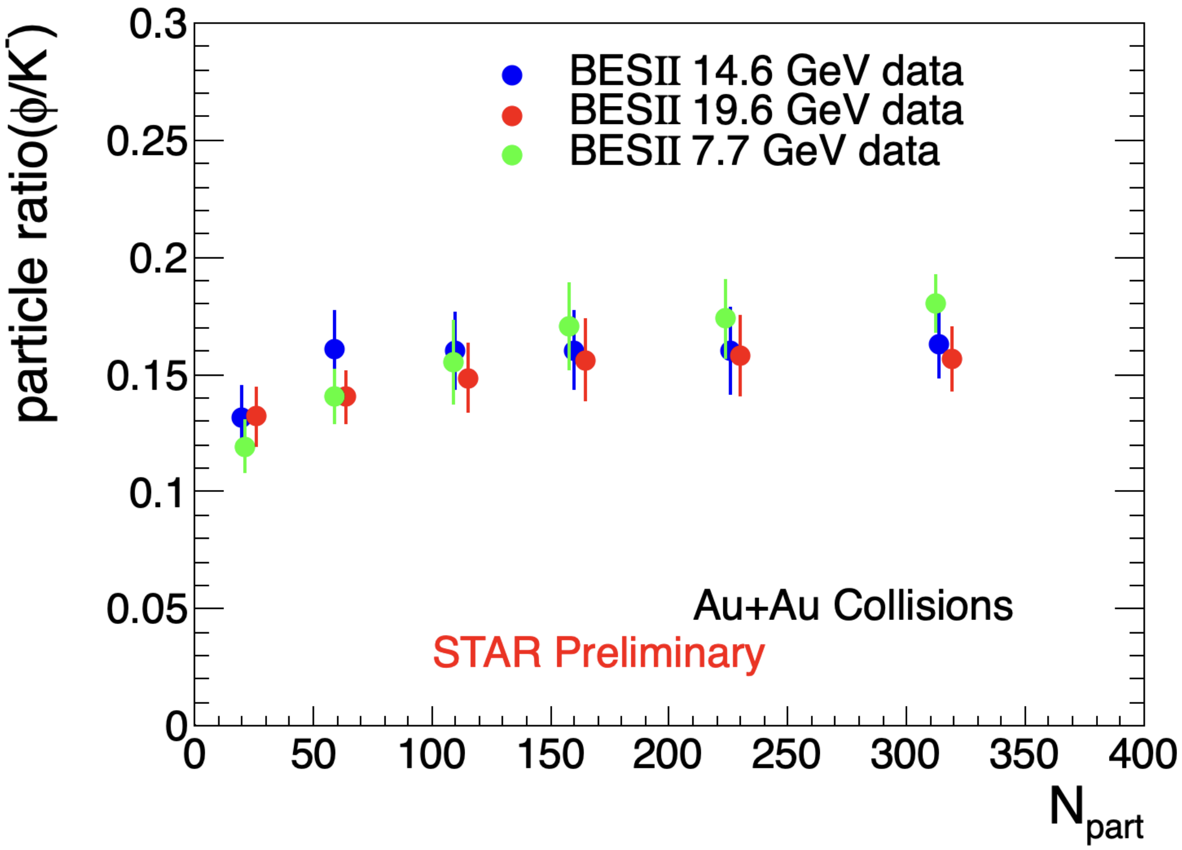
The bottom two plots show the total errors

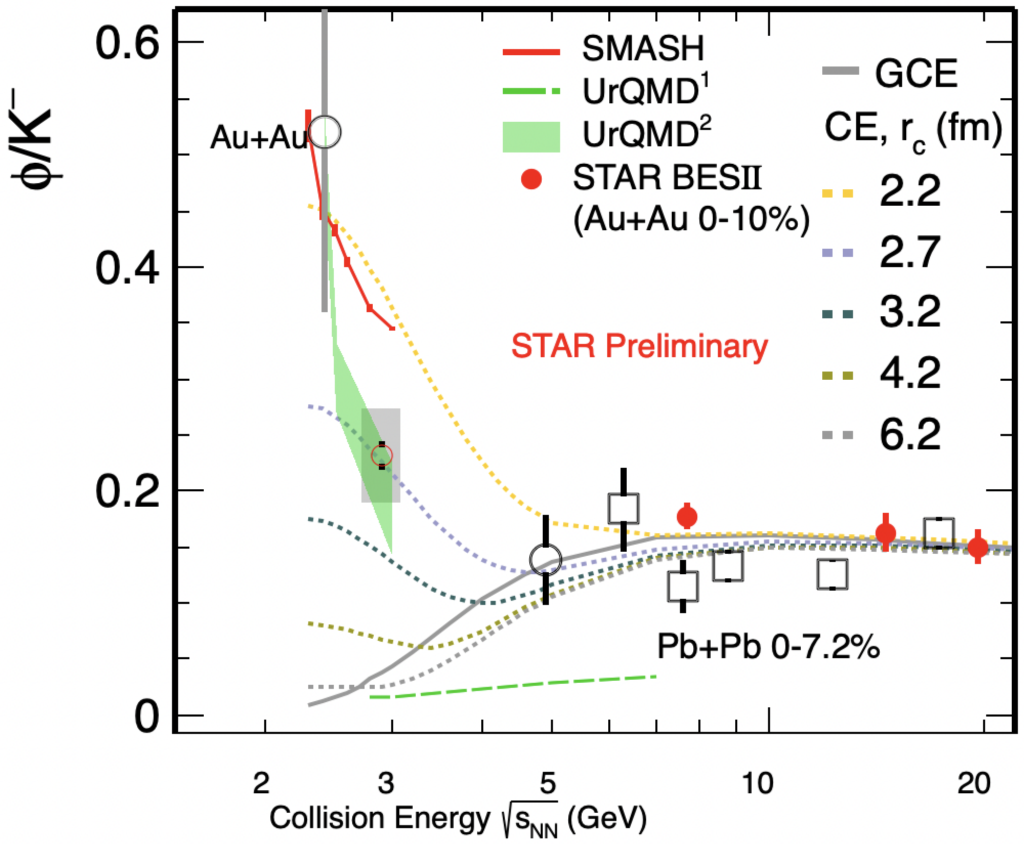
- Fit function: $\frac{dN/dy}{N_{part}/2} = k \times N_{part}^{\alpha-1}$
- Common centrality dependence for ϕ, Λ, K production at 19.6GeV.
- α parameter for ϕ is slightly larger than that for Λ, K and less than UrQMD predictions



STAR: arXiv: 2407.10110

Centrality and Energy dependence of ϕ/K^- ratio

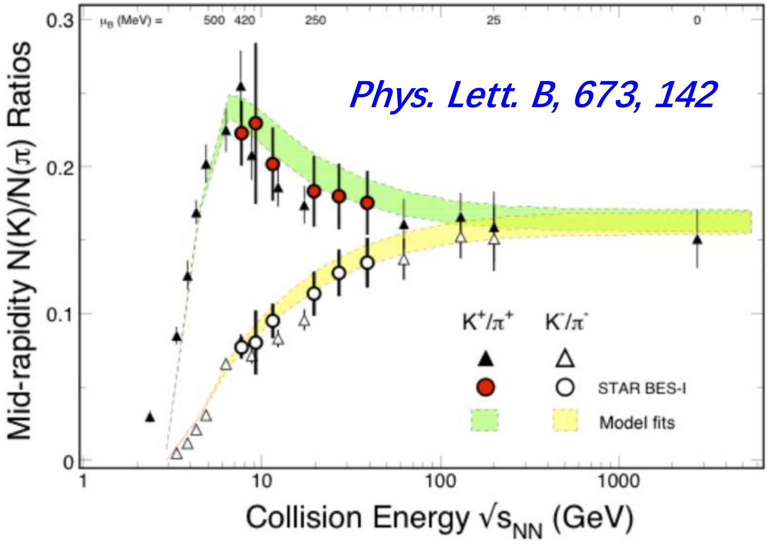




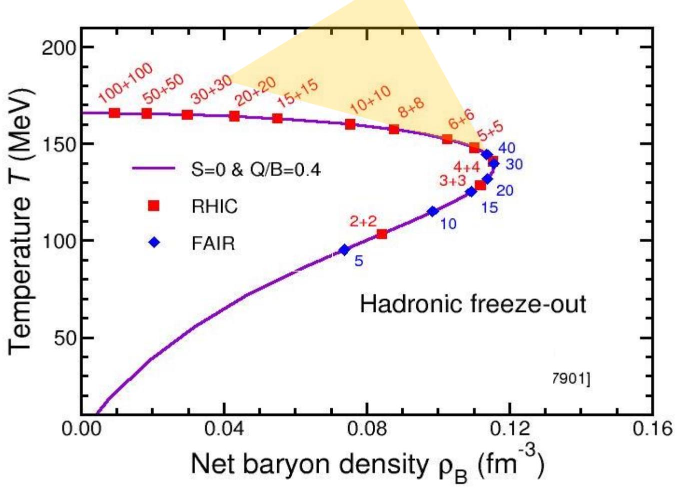
STAR: Phys. Rev. C 96 (2017) 044904
STAR: Phys. Rev. C 101 (2020) 024905
STAR: Phys. Lett. B 831 (2022) 137152

- 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

Strange hadron to pion ratio

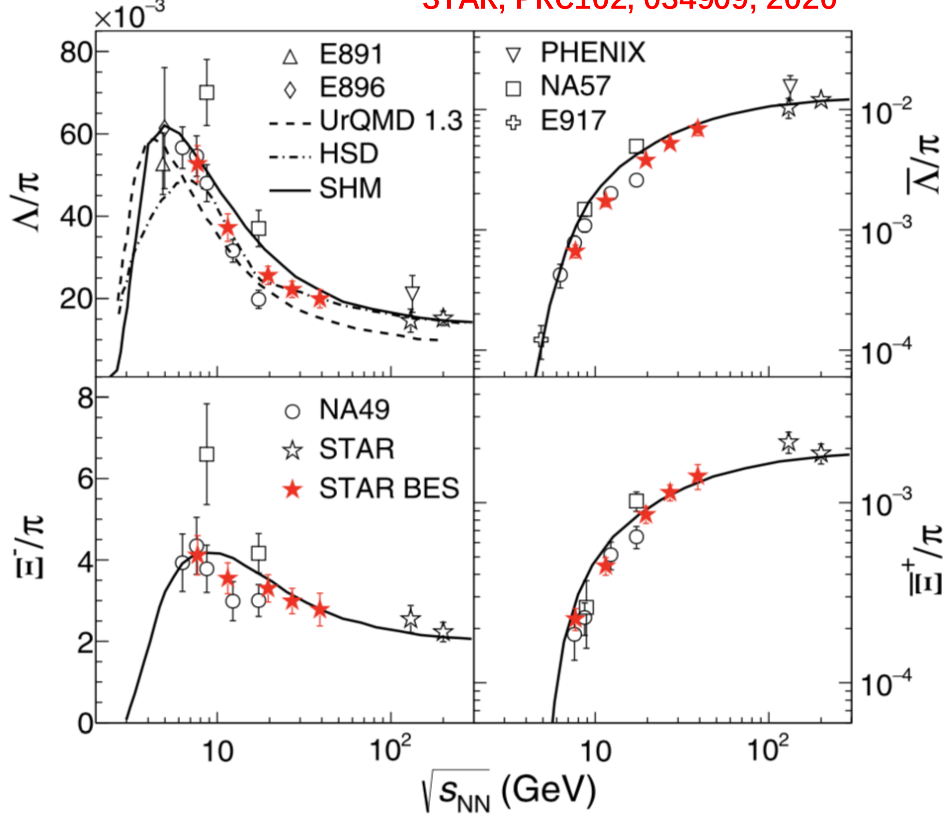


RHIC BES



J. Randrup et al., PRC 74, 047901 (2006)

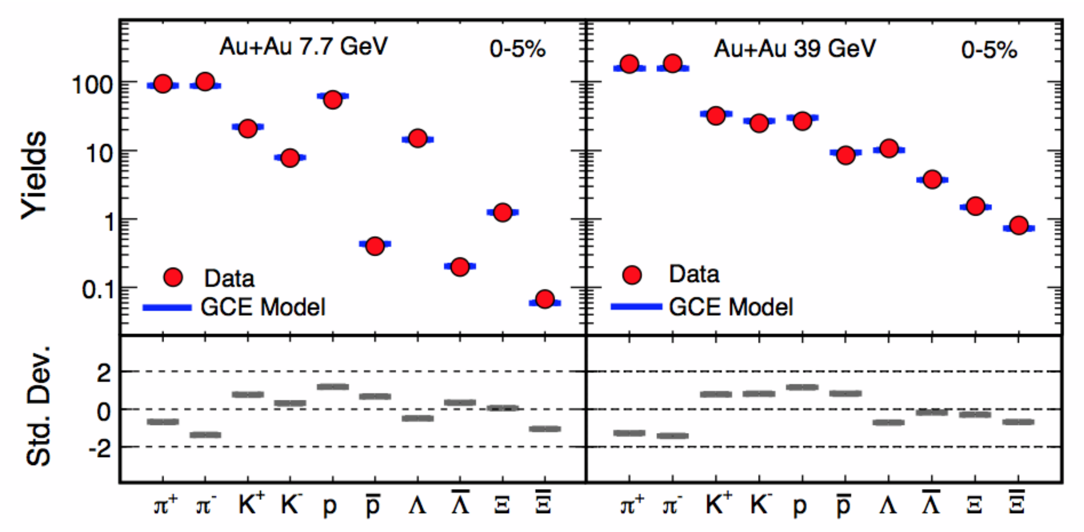
STAR, PRC102, 034909, 2020

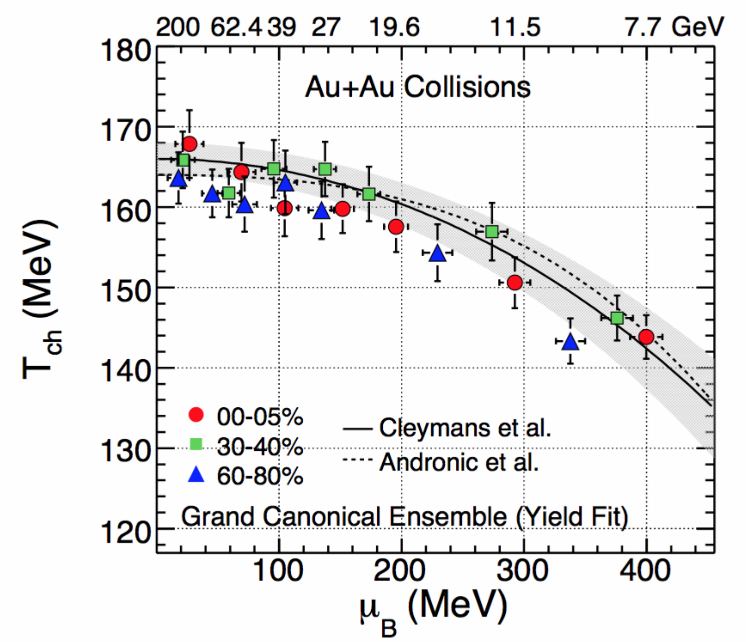


- Particle ratios consistent with NA49, consistent with the picture of a **maximum net-baryon density around $\sqrt{s_{NN}}$ ~ 8 GeV at freeze-out**

Chemical freeze-out parameters: T_{ch} vs. μ_B

STAR，Phys. Rev. C 96, 044904, 2017





✓Particles used : π, **K**, **p**, Λ, Ξ

✓ Ensemble used:

Grand canonical (GCE)

✓ Fit parameters:

T_{ch}, μ_B, μ_S and γ_S

Andronic: NPA 834 (2010) 237

Cleymans: PRC 73 (2006) 034905

Au+Au 200 GeV : Phys. Rev. C **83** (2011) 24901

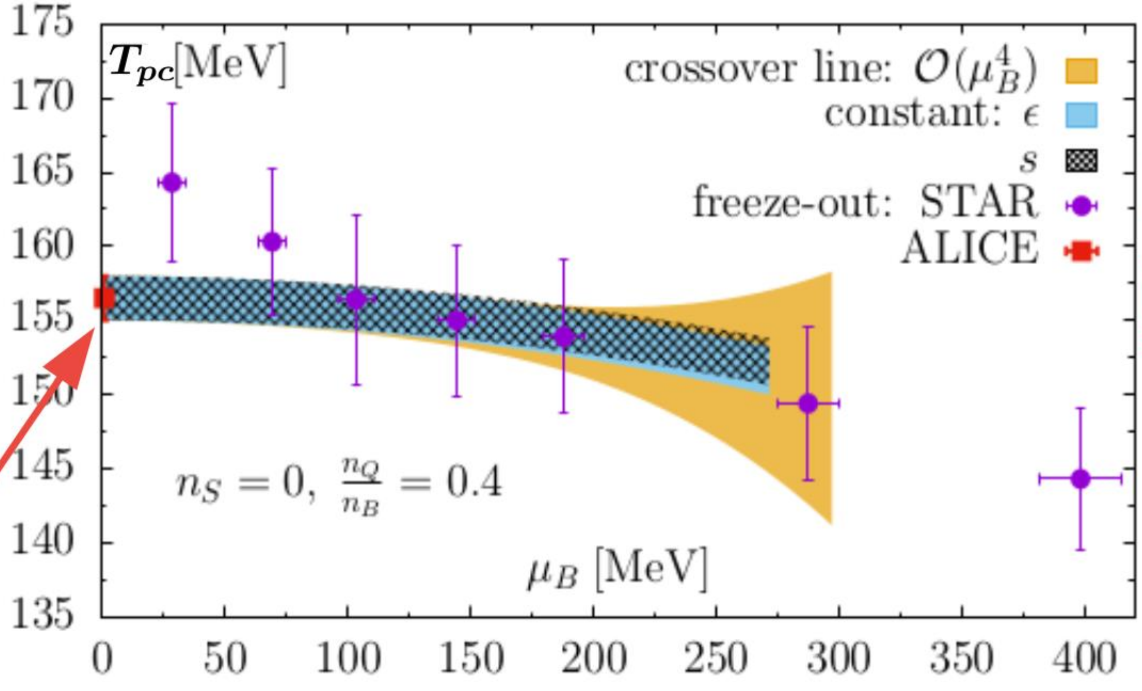
Thermus, S. Wheaton & J. Cleymans, Comput. Phys. Commun. 180: 84-106, 2009.

Pseudo-critical line for physical quark mass values

$$T_{pc}(\mu_B) = T_{pc}(0)\left(1 - \kappa_2\left(\frac{\mu_B}{T_{pc}(\mu_B)}\right)^2 - \kappa_4\left(\frac{\mu_B}{T_{pc}(\mu_B)}\right)^4 + \ldots\right)$$

phase diagram at physical values of the quark masses

F. Karsch, iHIC24



STAR: arXiv:1701.07065

A. Andronic et al., Nature 561 (2018) 321

$T_{pc} = (156.5 \pm 1.5)$ MeV

$\kappa_2 = 0.012(4)$
$\kappa_4 = 0.000(4)$

A. Bazavov et al. [HotQCD], Phys. Lett. B795 (2019), arXiv:1812.08235

$T_{pc} = (158.0 \pm 0.6)$ MeV

$\kappa_2 = 0.0153(18)$
$\kappa_4 = 0.00032(67)$

S. Borsanyi, et al, PRL 125 (2020) arXiv:2002.02821

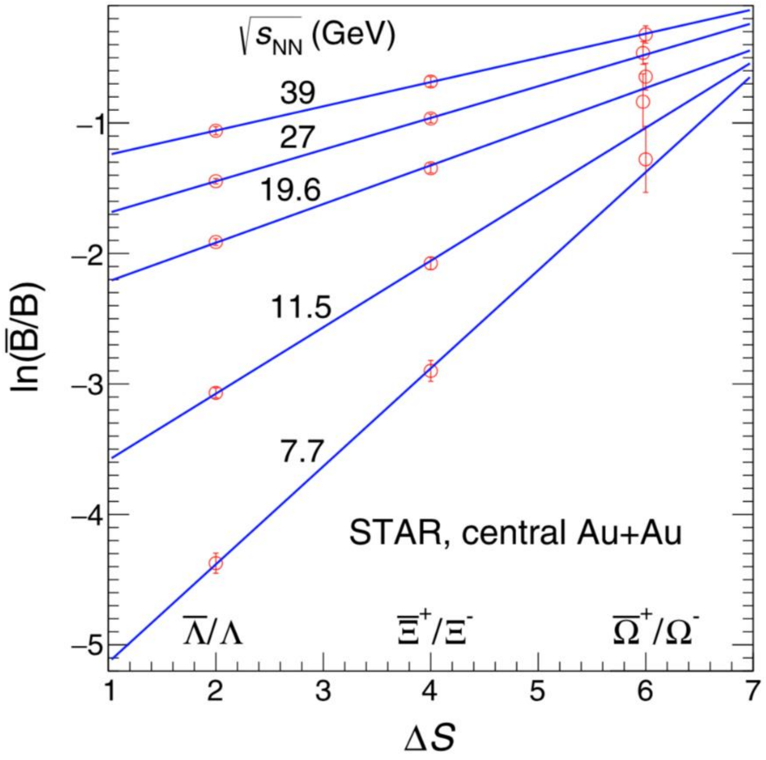
Anti-hyperon to hyperon ratios and chemical freeze-out parameters

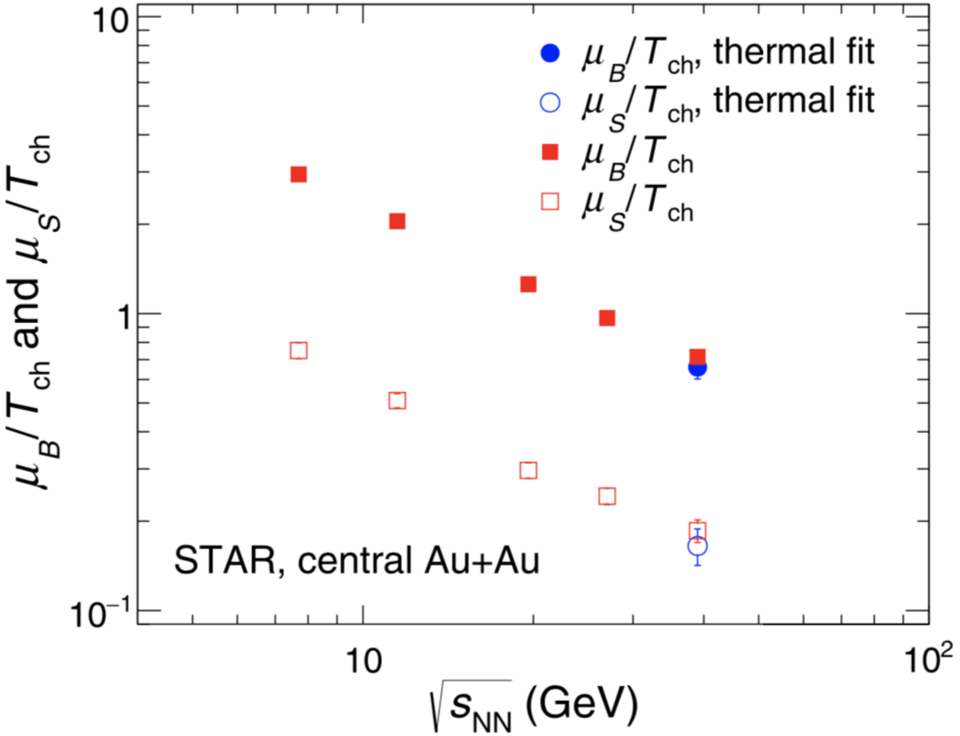
STAR, PRC102, 034909, 2020

$$\ln\left(\frac{\overline{\Lambda}}{\Lambda}\right) = -\frac{2\mu_B}{T} + \frac{2\mu_S}{T}$$

$$\ln\left(\frac{\overline{\Xi}^+}{\Xi^-}\right) = -\frac{2\mu_B}{T} + \frac{4\mu_S}{T}$$

$$\ln\left(\frac{\overline{\Omega}^+}{\Omega^-}\right) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T}$$





- Anti-hyperon to hyperon ratios are fit well with statistical thermal model
- Chemical freeze-out parameters, $\mu_S/T_{\rm ch}$ and $\mu_B/T_{\rm ch}$, are extracted

Baryon number – strangeness chemical potentials at freeze-out from strange baryon yields vs. QCD

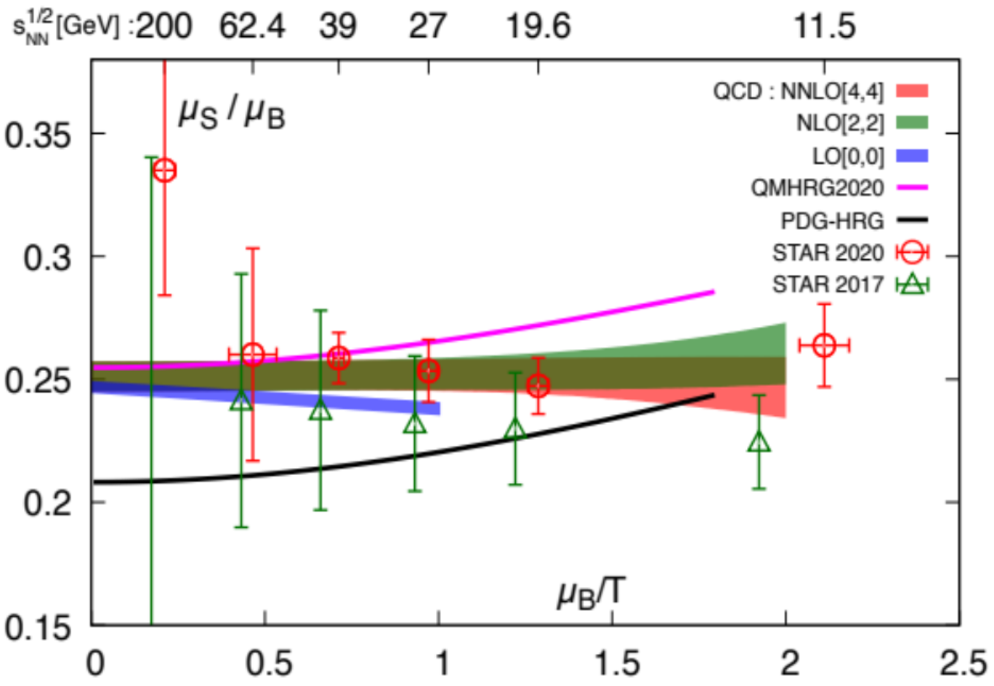
QCD:

$$\frac{\mu_S}{\mu_B} \equiv -\frac{\chi_{11}^{BS}}{\chi_2^S} - q_1 \frac{\chi_{11}^{QS}}{\chi_2^S} + \mathcal{O}(\mu_B^2)$$

STAR:

$$\ln(\overline{\mathrm{B}}/\mathrm{B}) = -2\mu_B/T_{\mathrm{ch}} + \mu_S/T_{\mathrm{ch}} \cdot \Delta S$$

F. Karsch, iHIC24



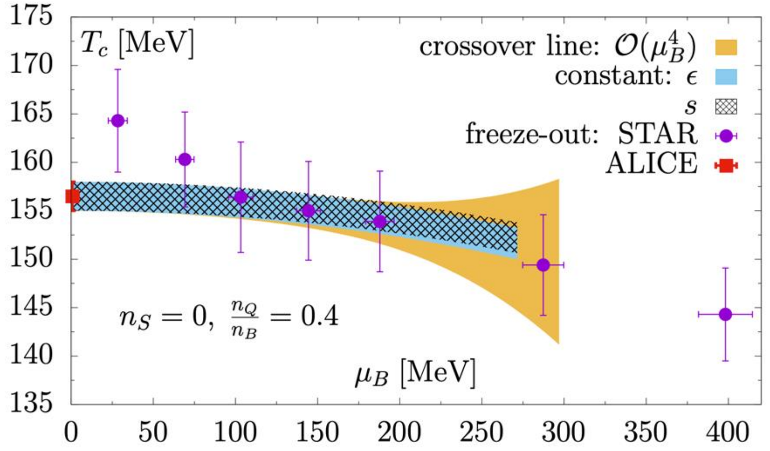
HotQCD, Phys. Rev. D 104 (2021) 074512
arXiv:2107.10011

STAR2017: Phys. Rev. C 96 (2017) 044904
STAR2020: Phys. Rev. C 102 (2020) 034909

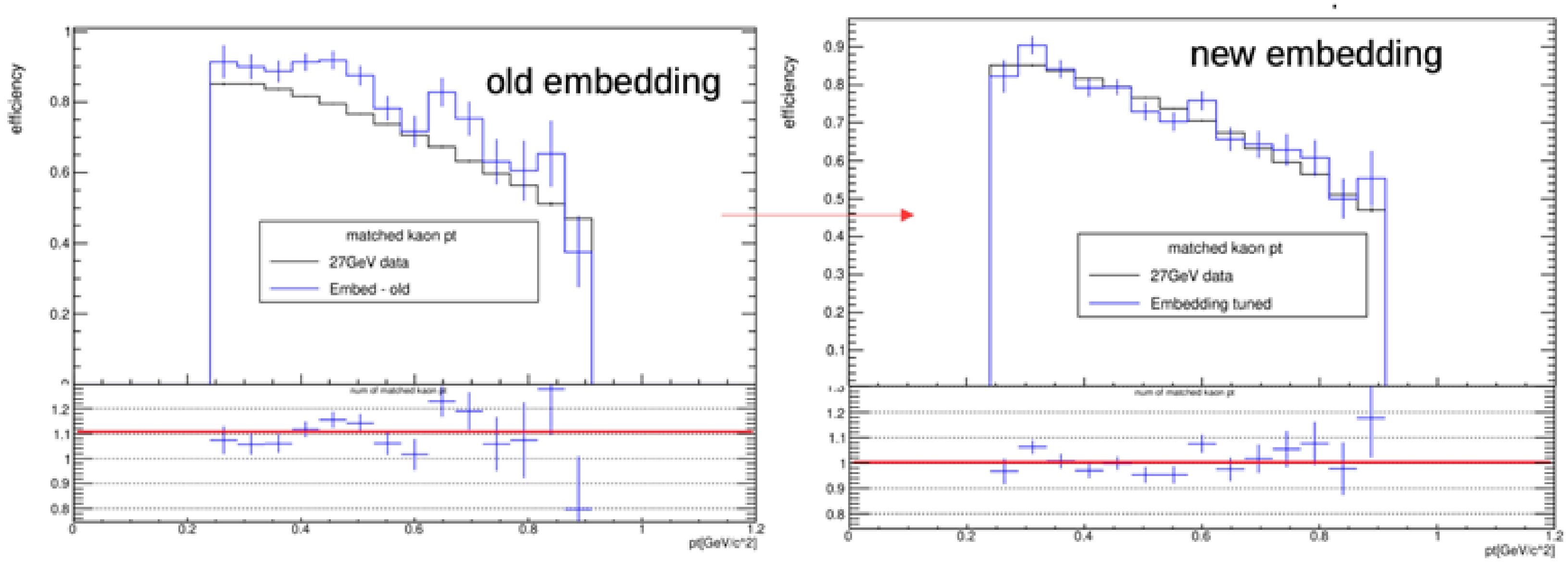
STAR multi-strange baryon yields are consistent with freeze-out at T_{pc} and a μ_S/μ_B that reflects contributions from additional strange baryons

Extracting chemical freeze-out parameters in BES-II

HotQCD, PLB 795 (2019)



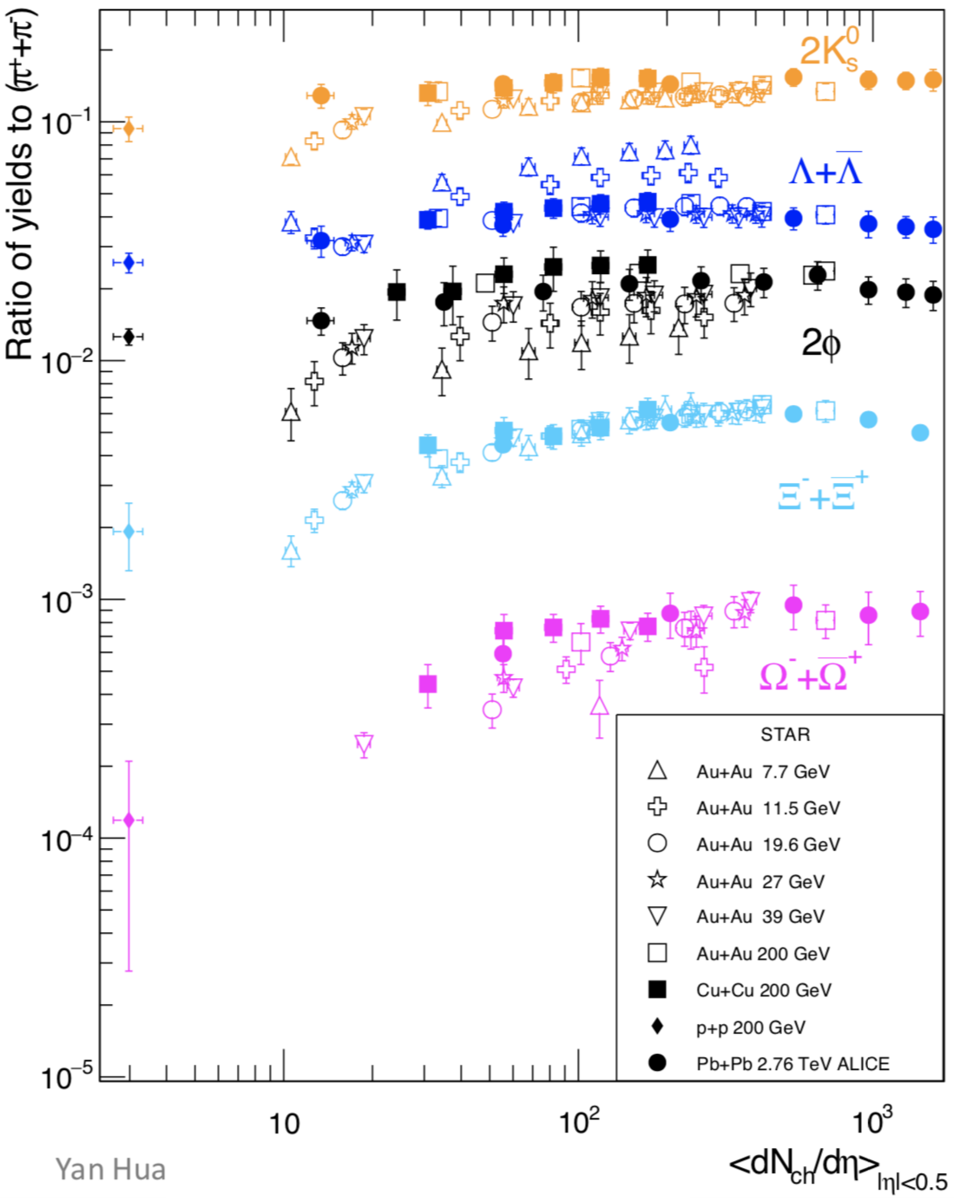
- Uncertainties dominated by systematics in yields of charged hadrons (5% tracking uncertainty in TPC)
- Pinning down these uncertainties in BES-II with iTPC and improved detector simulation.



Summary and outlook

- Comprehensive (preliminary) strangeness measurements in STAR BES-II collider energies.
- Baryon enhancement is observed from 7.7 to 200GeV → consistent with QGP formation.
- More precise measurements of hadron yields in BES-II will help constrain QCD phase boundary.

Strange hadron to pion ratio vs $dN_{ch}/d\eta$



Yan Huang, APS April Meeting 2021, SQM2021

STAR, PRC96, 044904, 2017
STAR, PRC102, 034909, 2020
ALICE, PRC88, 044910, 2013

$$\frac{dn}{dy} = \frac{\sqrt{M(1+\sinh^2 y)}}{\sqrt{1+M\sinh^2 y}}\frac{dn}{d\eta},$$

where $M = 1 + m^2/p_t^2$

$$dN_{ch}/d\eta = \sum dN_{ch}/d\eta\,(k^{\pm},\pi^{\pm},p,\bar{p})$$

$$dN_{ch}/d\eta(\eta=0) \sim dN_{ch}/d\eta(|\eta|<0.5)$$

- The ratios at different energies/centralities/systems mainly depend on charged hadrons multiplicity, except for Λ and ϕ
- The ratios saturate at large charged hadrons multiplicity