Recent STAR results on strangeness production

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Why strangeness?

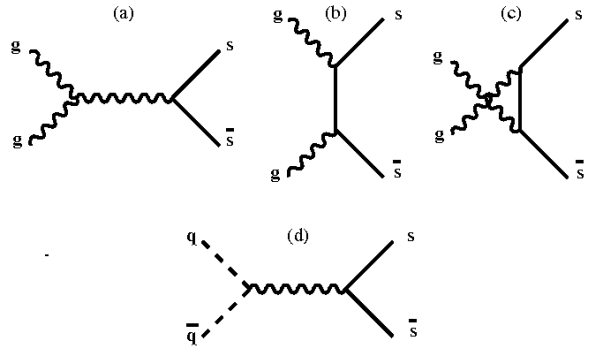
- Strange quarks
  - Not exist in colliding nuclei
  - Current mass ~100 MeV < T_c
  - Easily pair-produced in de-confined QGP medium

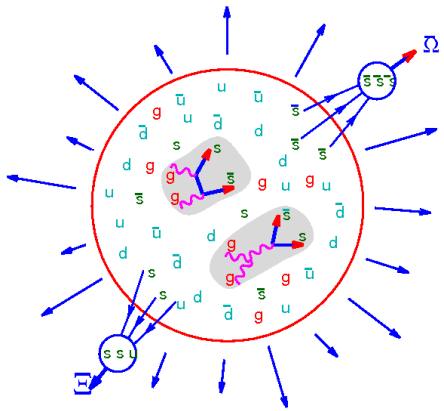
⟶ Strangeness enhancement !

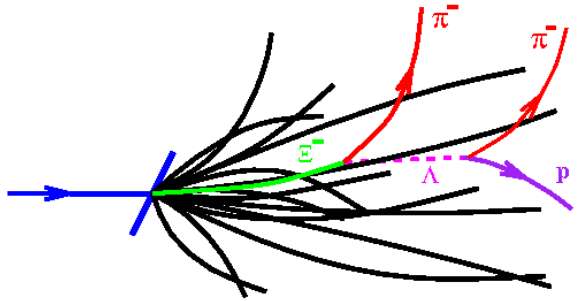
- Hadrons with (multiple) strange quarks
  - Small hadronic cross section
  - Sensitive to the early stage dynamics of the medium
  - Can be easily reconstructed and identified in experiment, up to high p_T !

⟶ Systematic study of medium properties!

Rafelski & Müller, 1982



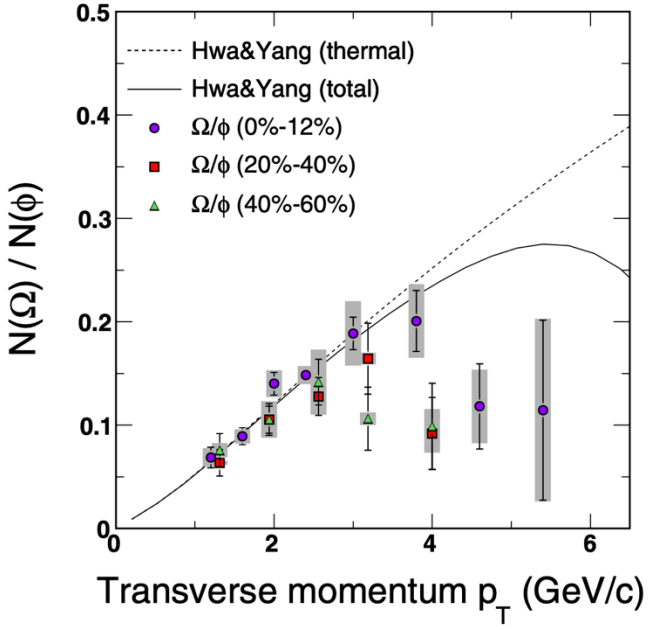




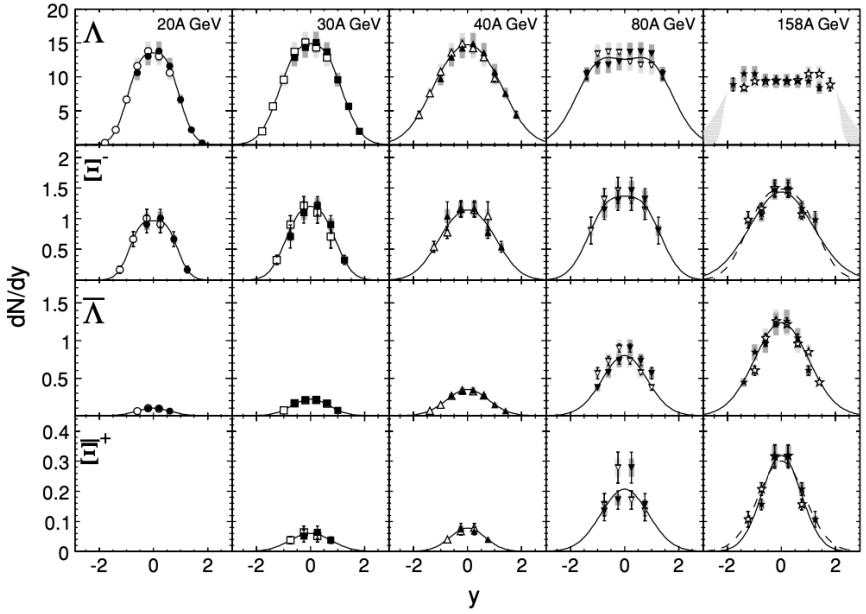
Strange hadron observables

- 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.

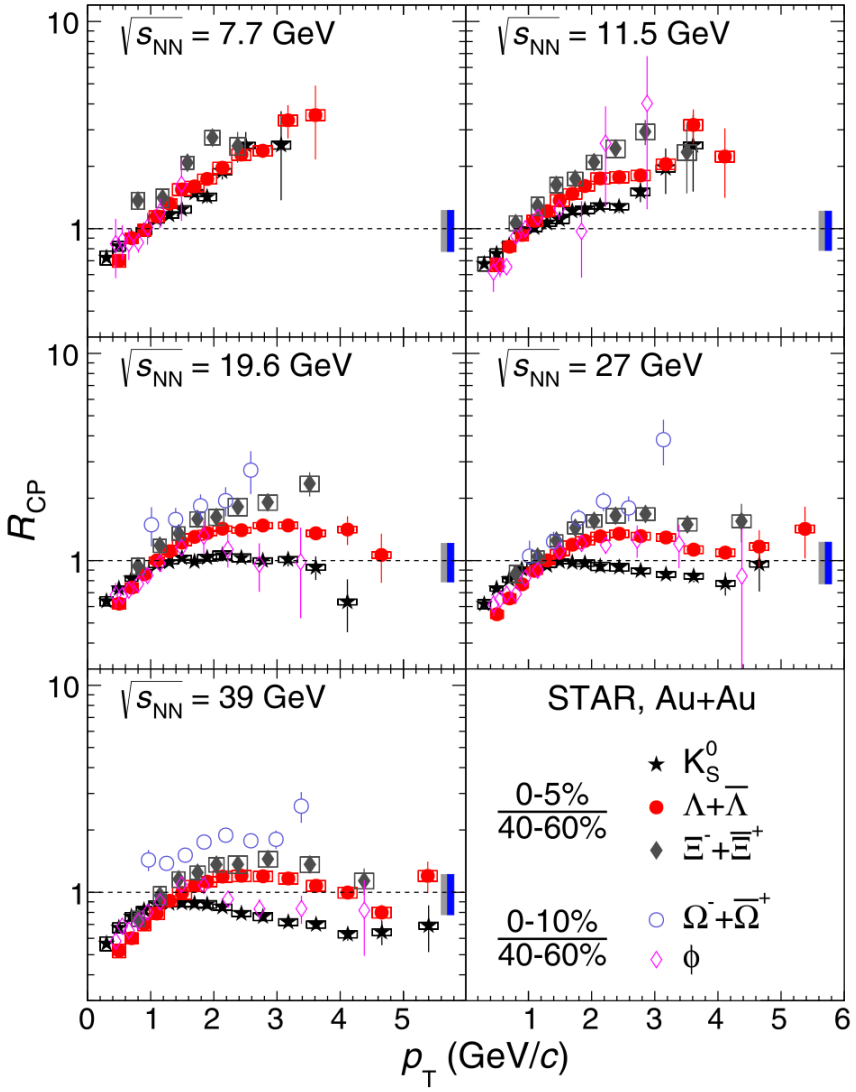
$$R_{CP} = \frac{[(dN/dp_T)/\langle N_{coll}\rangle]_{central}}{[(dN/dp_T)/\langle N_{coll}\rangle]_{peripheral}}$$



STAR, PRL 99, 112301 (2007)



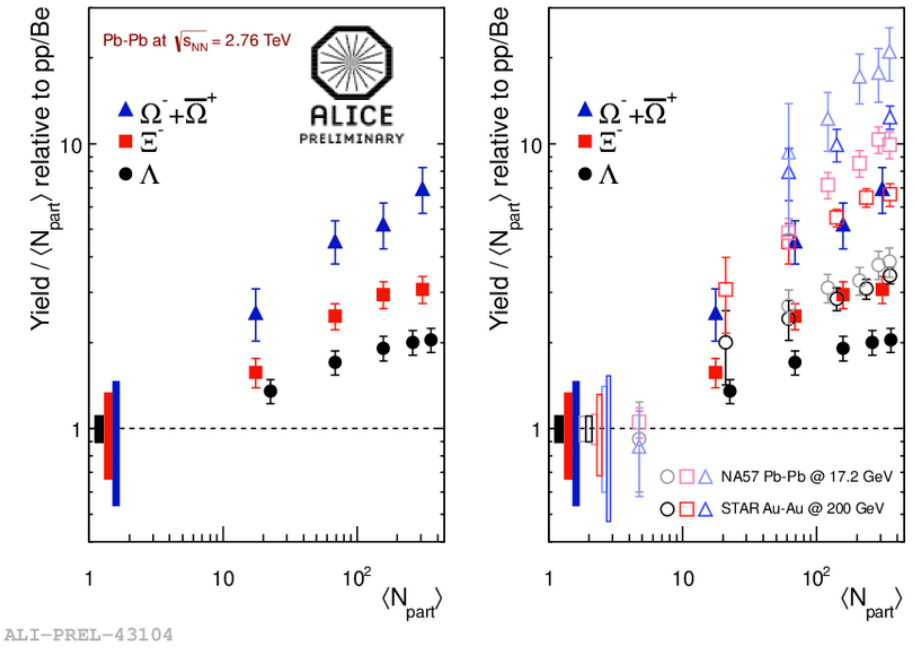
NA49, PRC 78, 034918 (2008)

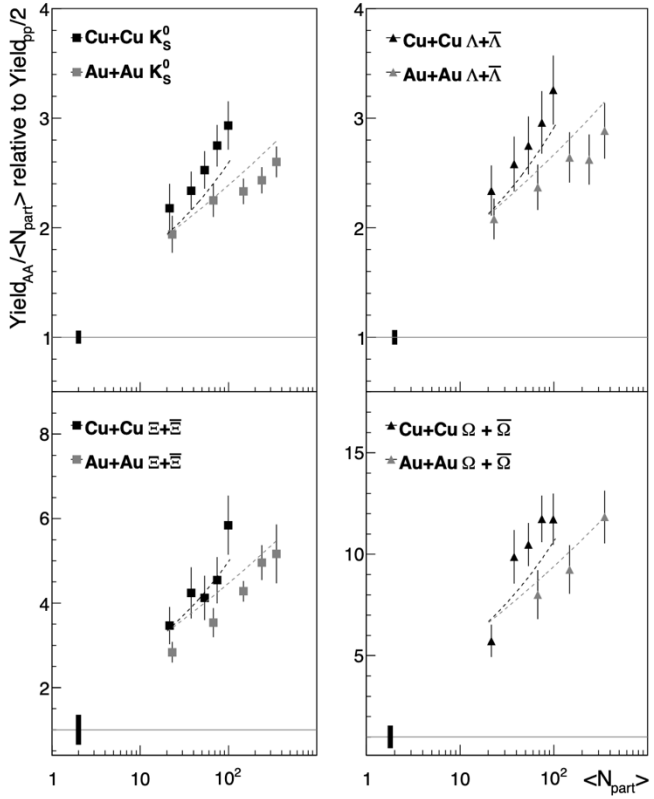


STAR, PRC 102, 034909 (2020)

Strange hadron observables

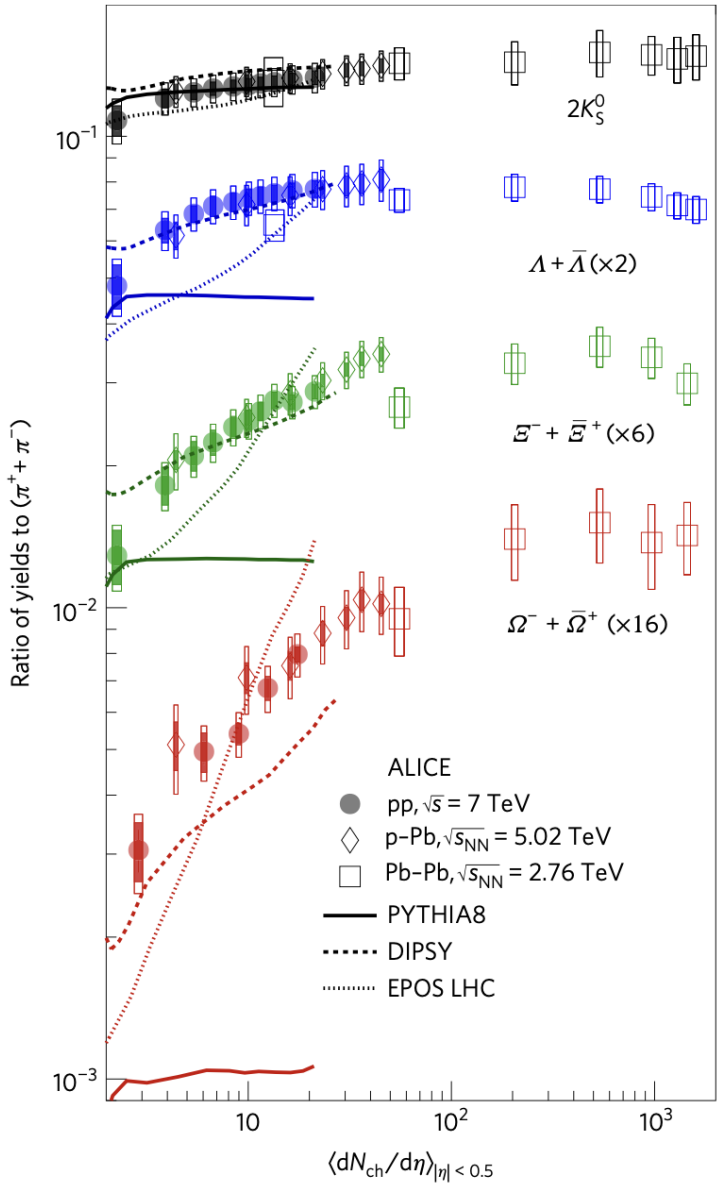
- Strange hadron yields per N_{part} relative to pp:
  - strangeness enhancement (or canonical suppression in pp/pA)
  - system size dependence (Au+Au versus Cu+Cu)
- Strange-to-pion yield ratios:
  - strangeness enhancement in small system





STAR, Phys. Rev. Lett. **108** (2012) 72301

ALICE, Nature Physics, **13**, pages535–539 (2017)



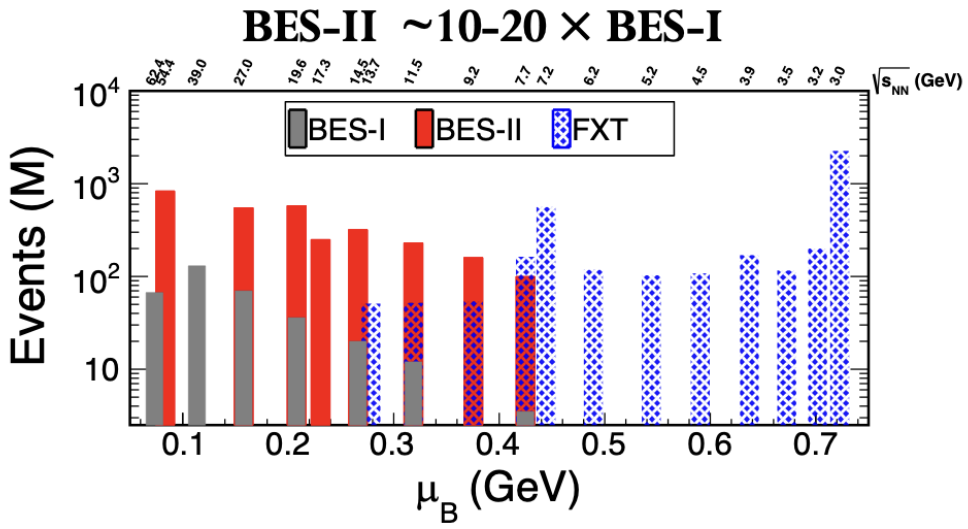
Motivation

Heavy-ion collisions at top RHIC energy:

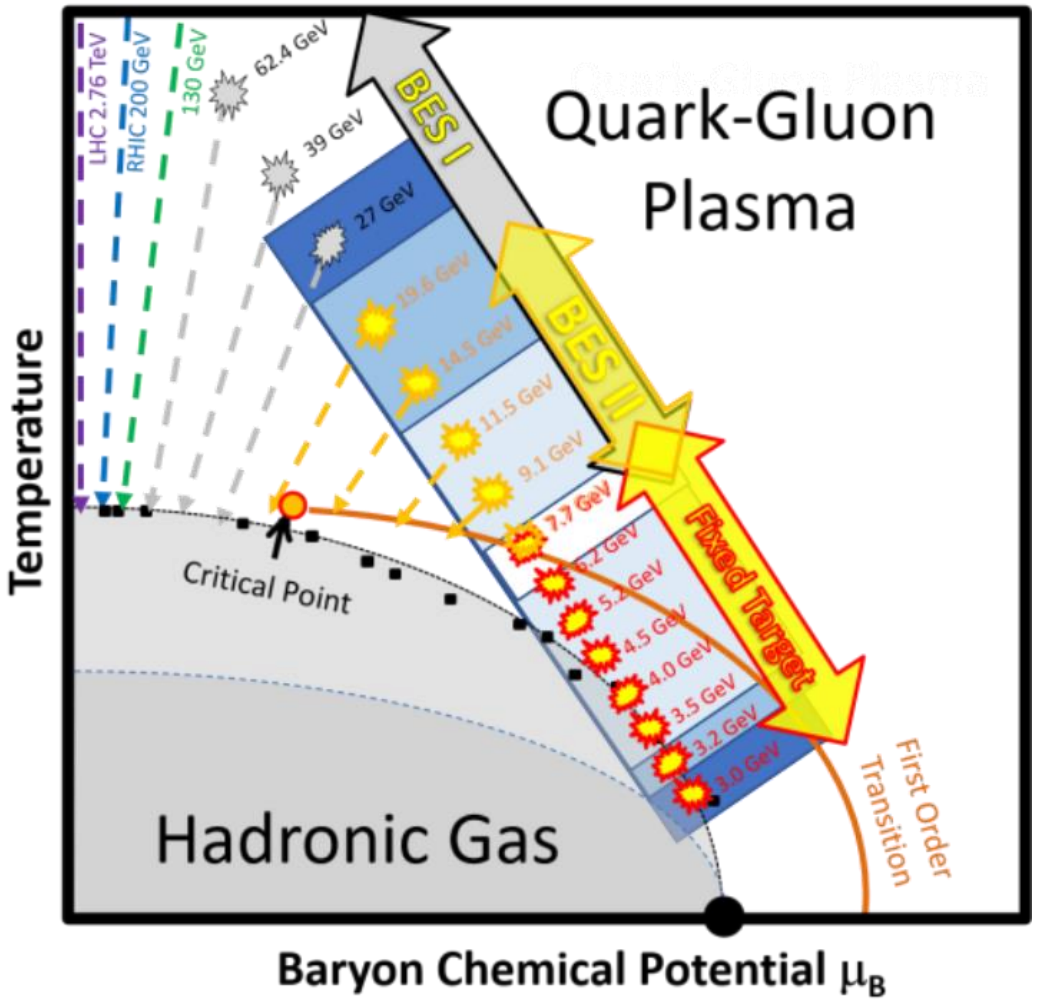
- Study QGP properties (AuAu)
- System size dependence (pp/dAu/OO/Isobar/AuAu)

Beam Energy Scan (BES) program:

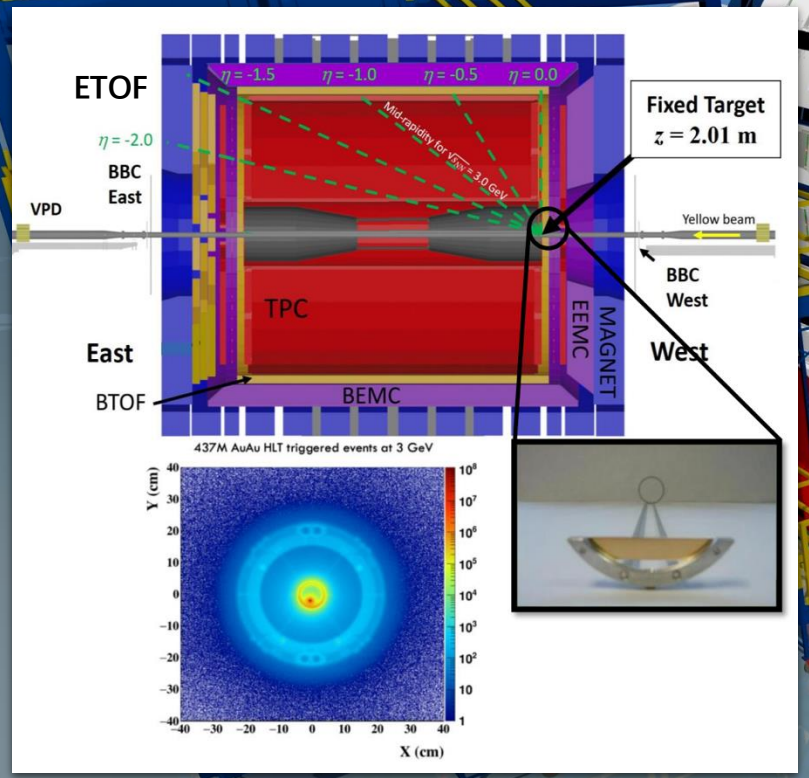
- Search for the onset of deconfinement
- Search for the first-order phase transition
- Search for the critical point



Yi Fang, Xiongxiong Xu, Weiguang Yuan, QM23/SQM24/CPS24
Yan Huang, SQM21
Hongcan Li, Dongsheng Li, Ishu Aggarwal, SQM24
Yingjie Zhou, iHIC24, Iris Ponce, DNP24



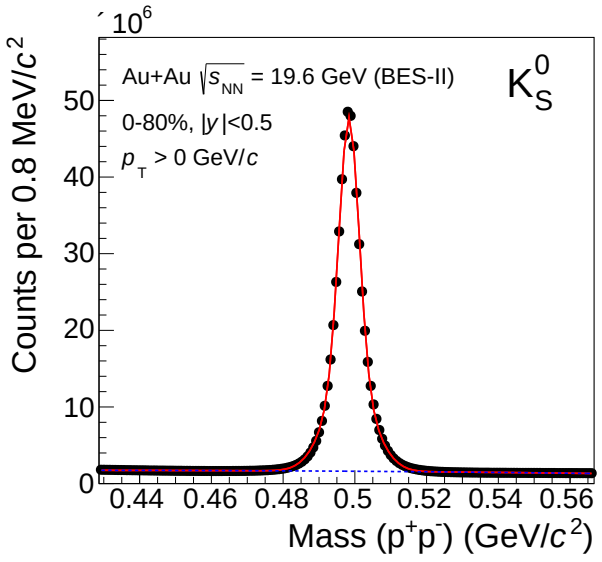
- Large and uniform acceptance
- Excellent particle identification

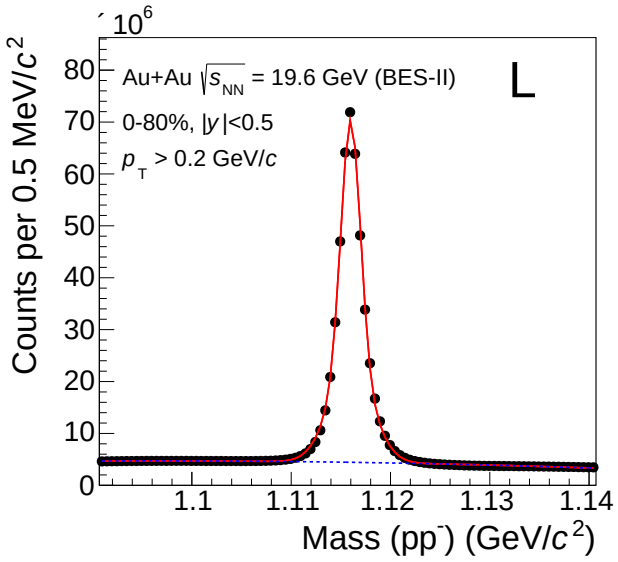


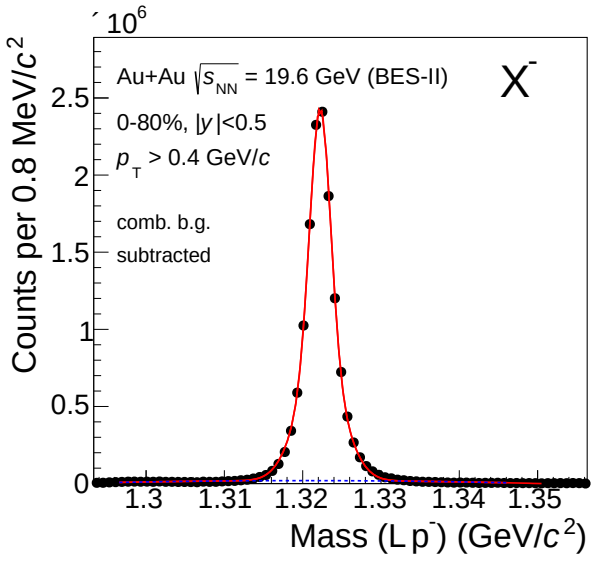
iTPC upgrade

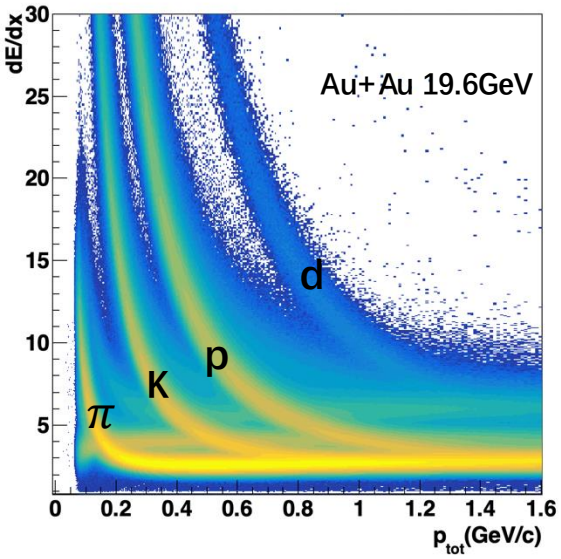
- $|\eta|$: 1.0 → 1.5 ;
  FXT: $y_{c.m.} \in [y_{beam}, 0]$
- Improved dE/dx resolution
- $\boldsymbol{p_T}$ threshold: 120MeV → 60MeV

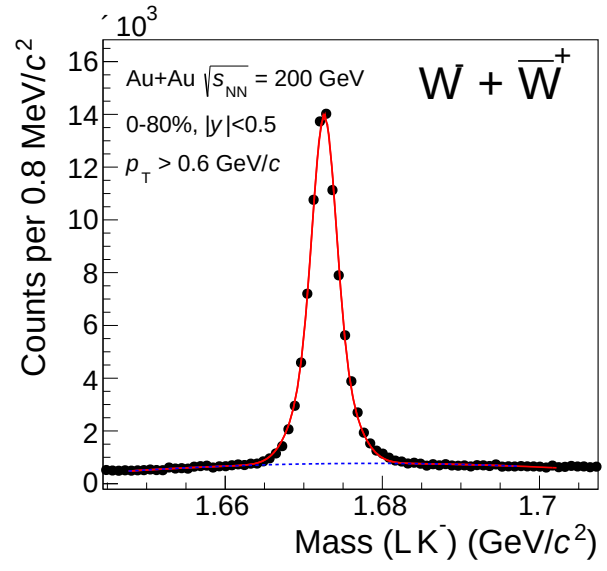
Particle identification and reconstruction

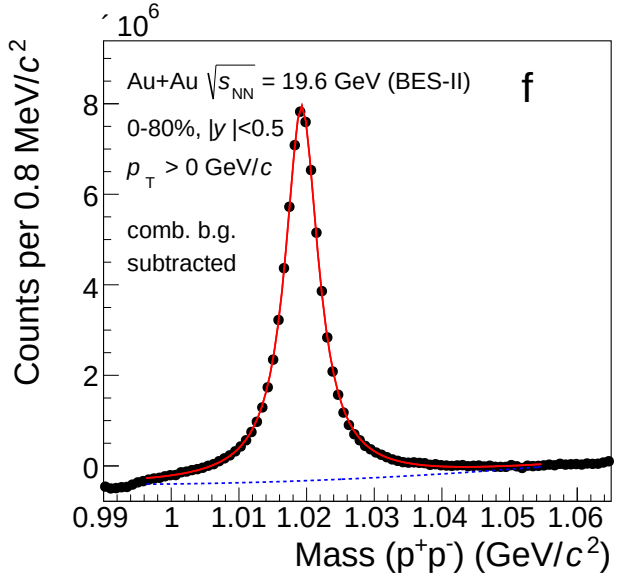








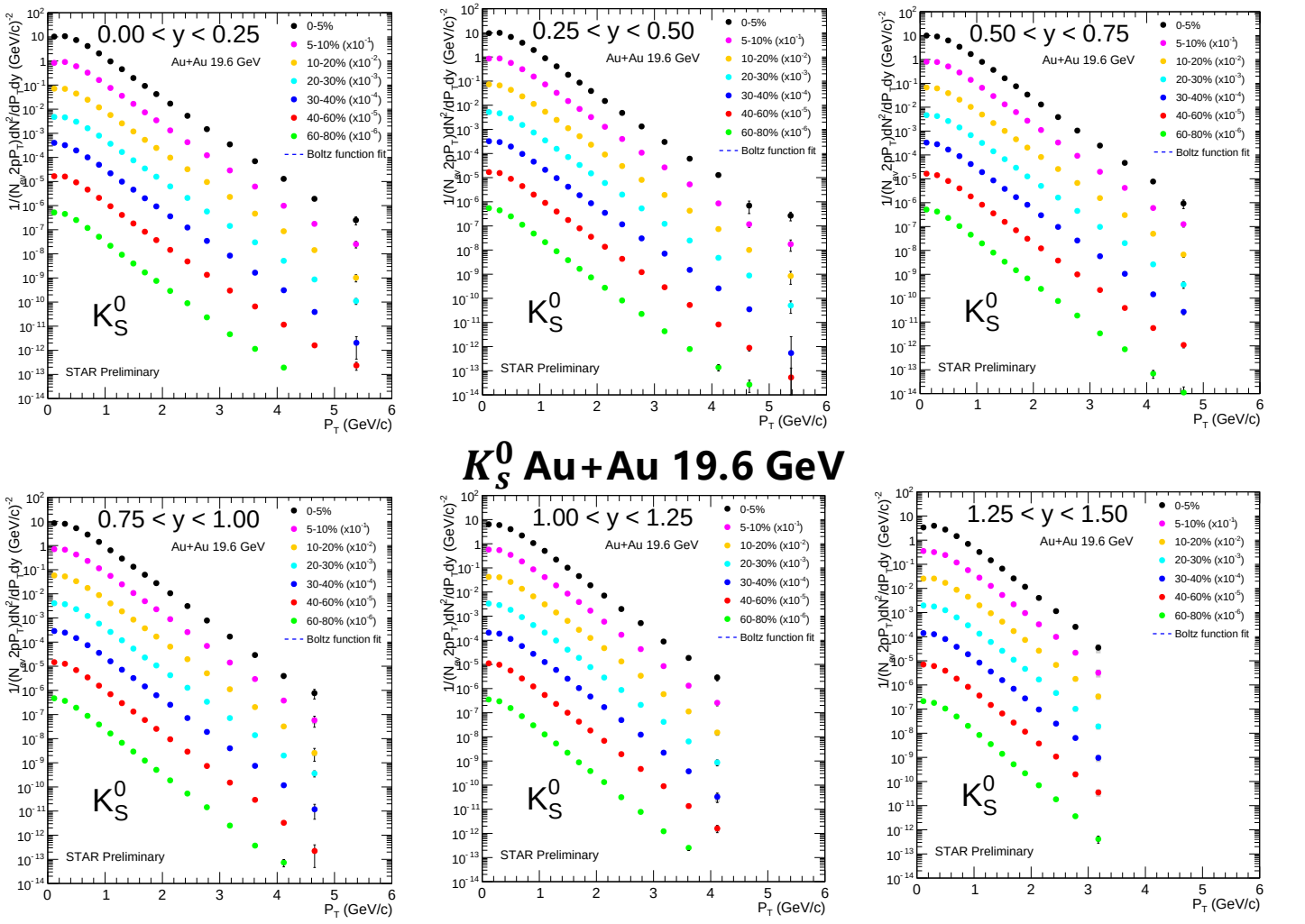




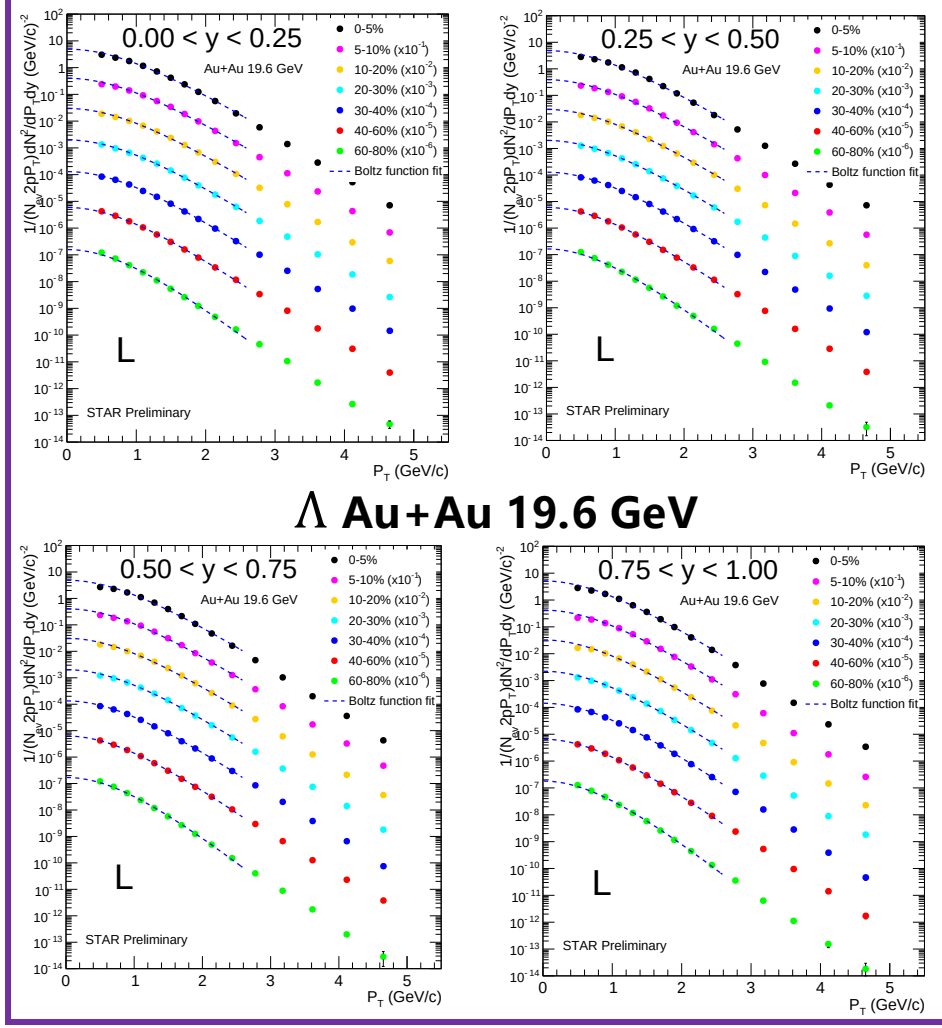
- Particle identification with dE/dx.
- π, K, p are used to reconstruct the secondary vertex of strange particles.
- TMVA optimization to improve Ω signal significance
- Large number of strange particles allow multi-differential measurements.

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

p_T spectra of K_s^0 and Λ at 19.6 GeV



K_s^0 Au+Au 19.6 GeV



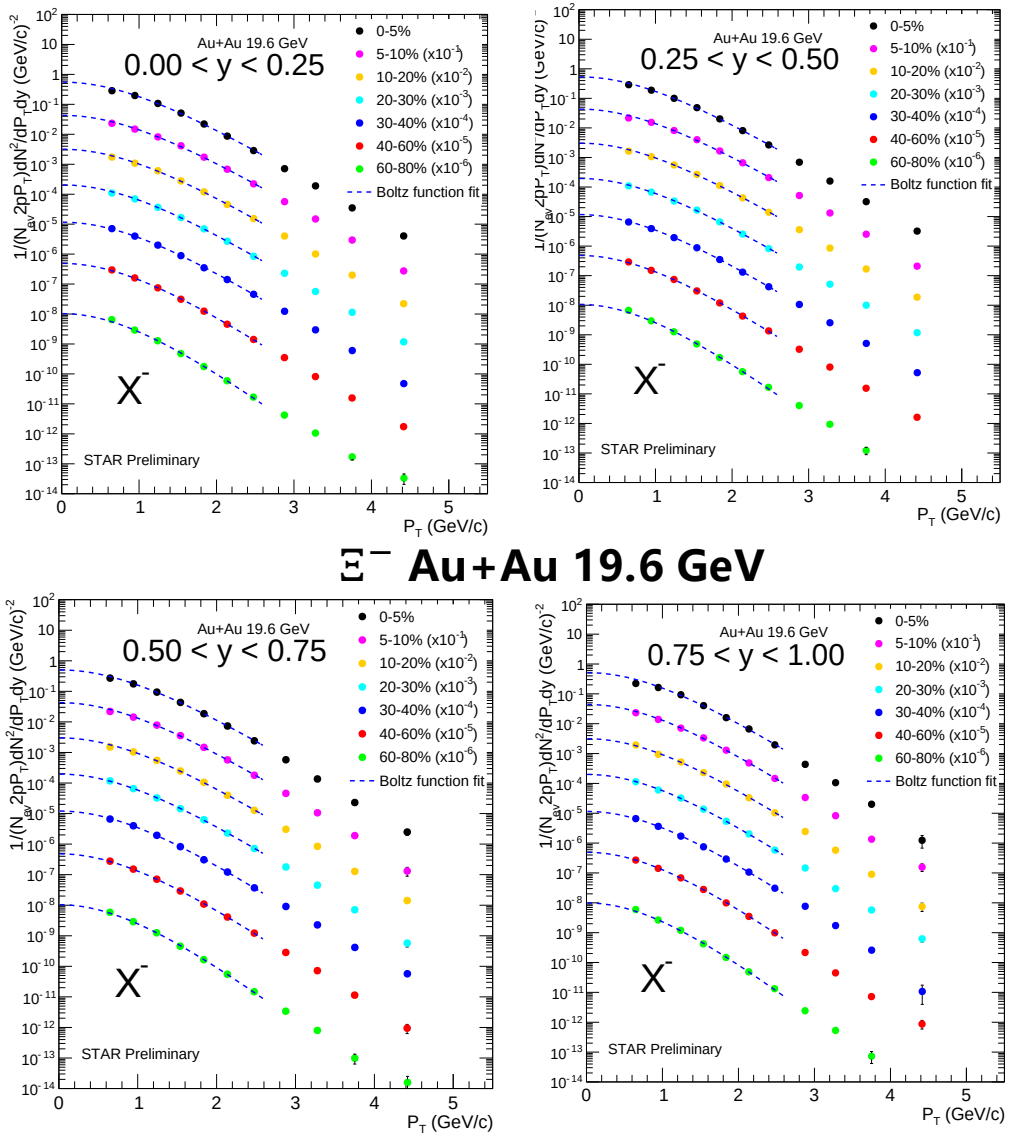
Λ Au+Au 19.6 GeV

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

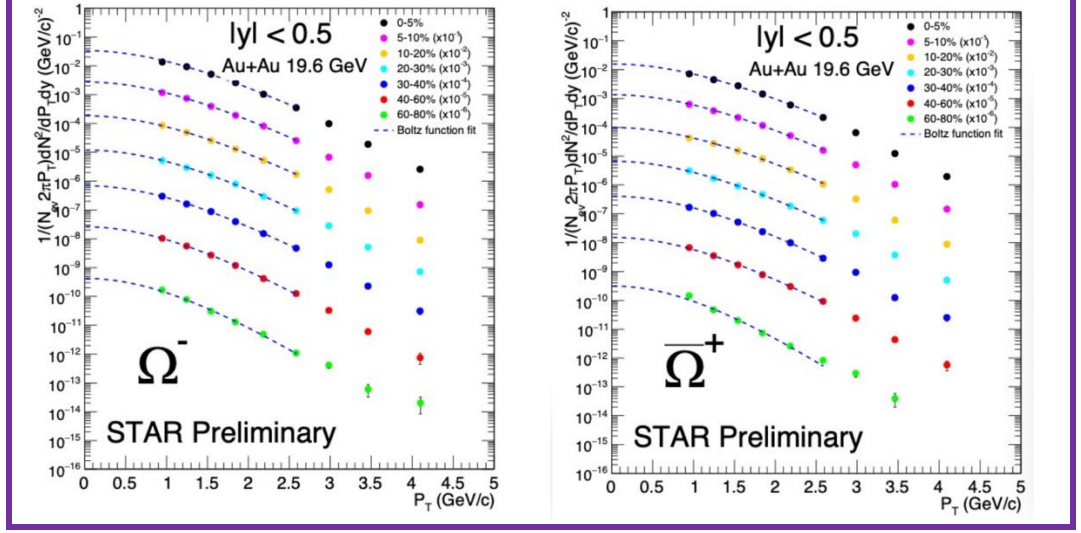
- Low p_T extrapolation: Boltzmann function
- Corrected for Ξ^- and Ξ^0 feed-down

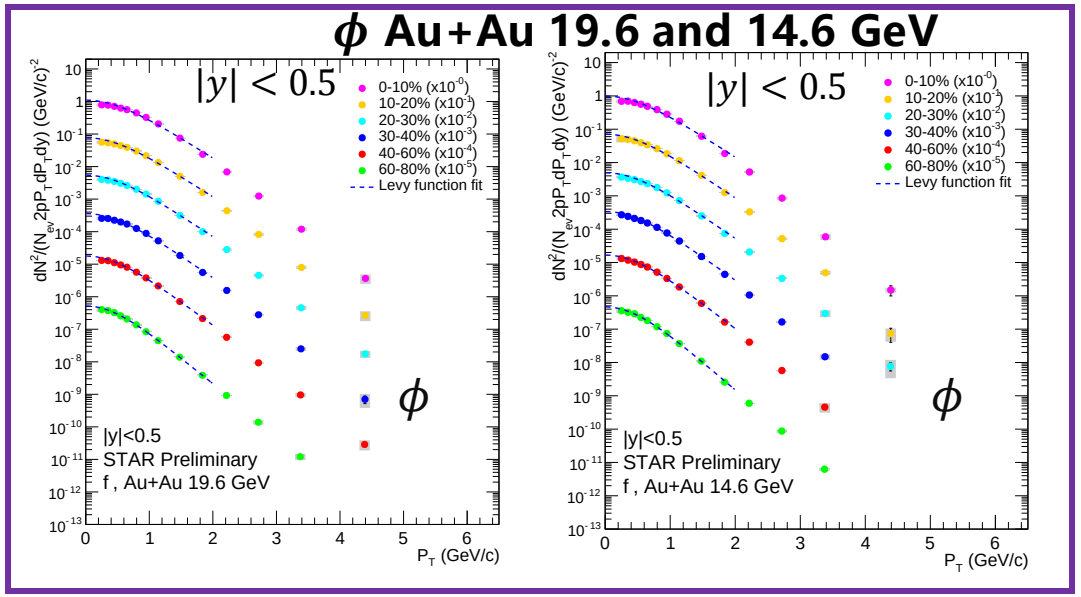
Rapidity: $|y| < 1$

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



Ξ^- Au+Au 19.6 GeV



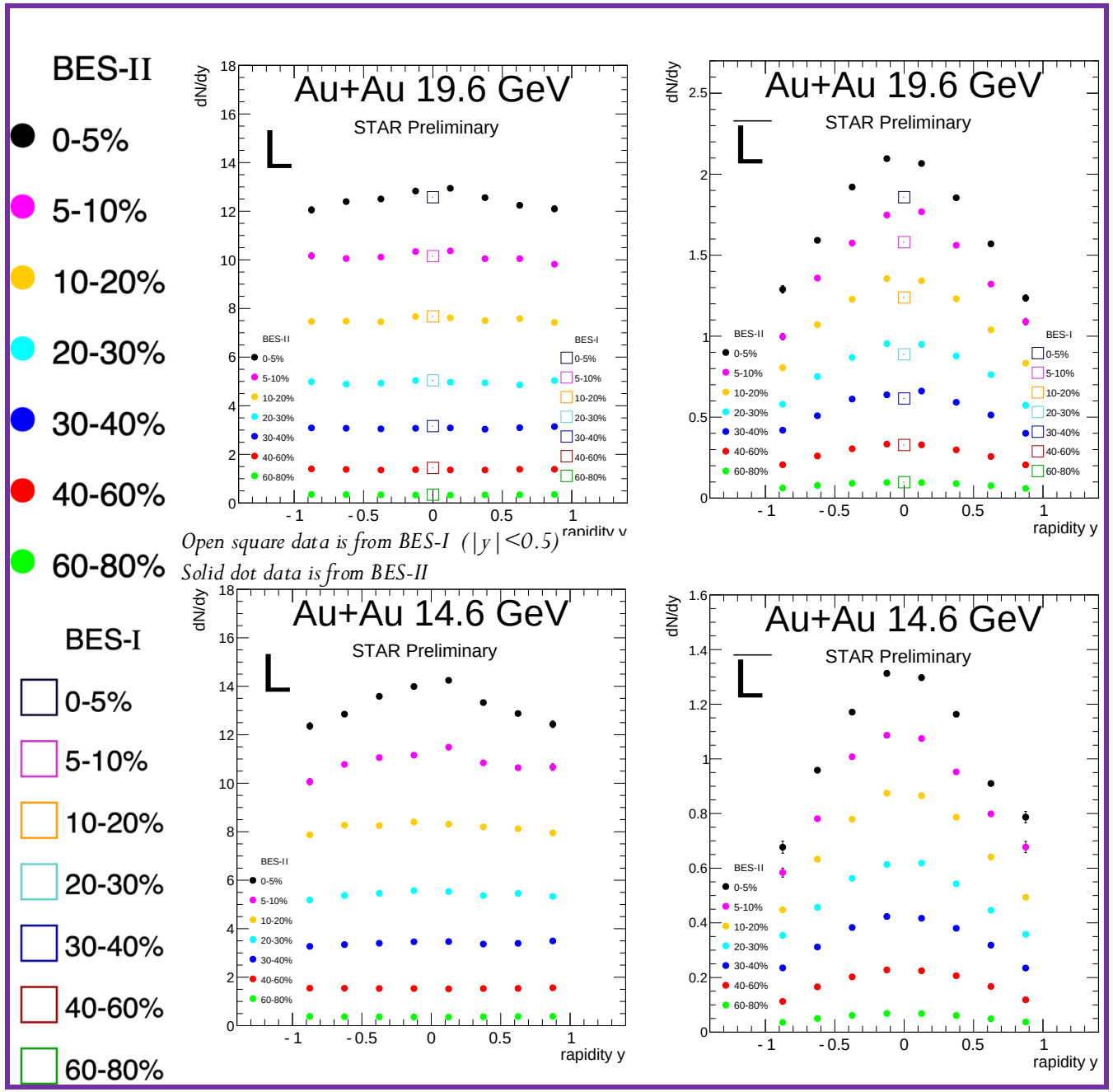


- Ξ^- Low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 1.0$
- Ω low p_T extrapolation: Boltzmann function
- Rapidity: $|y| < 0.5$
- ϕ low p_T extrapolation: Levy function
- Rapidity: $|y| < 0.5$

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

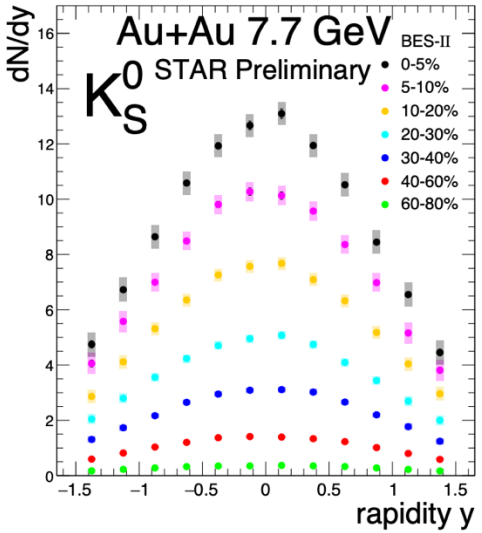
- Rapidity spectra of anti-baryons($\bar{\Lambda}$) are Gaussian-like distributions.
- Rapidity distribution of baryons(Λ) are wider than that of anti-baryons ($\bar{\Lambda}$).
  - ✓ Extra contributions from stopped baryons
- Similar trends observed by NA49.

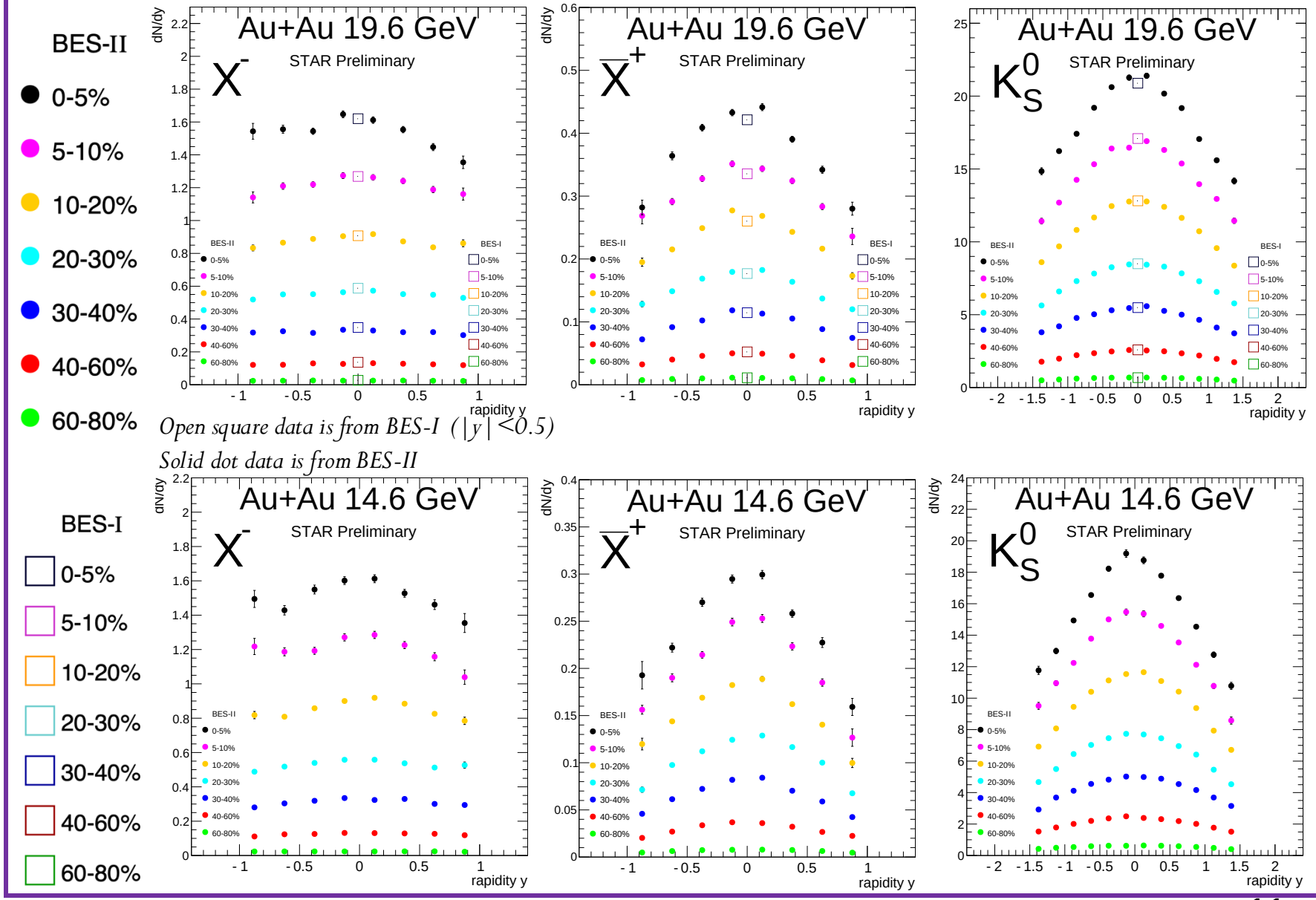
NA49, PRC 78, 034918 (2008)



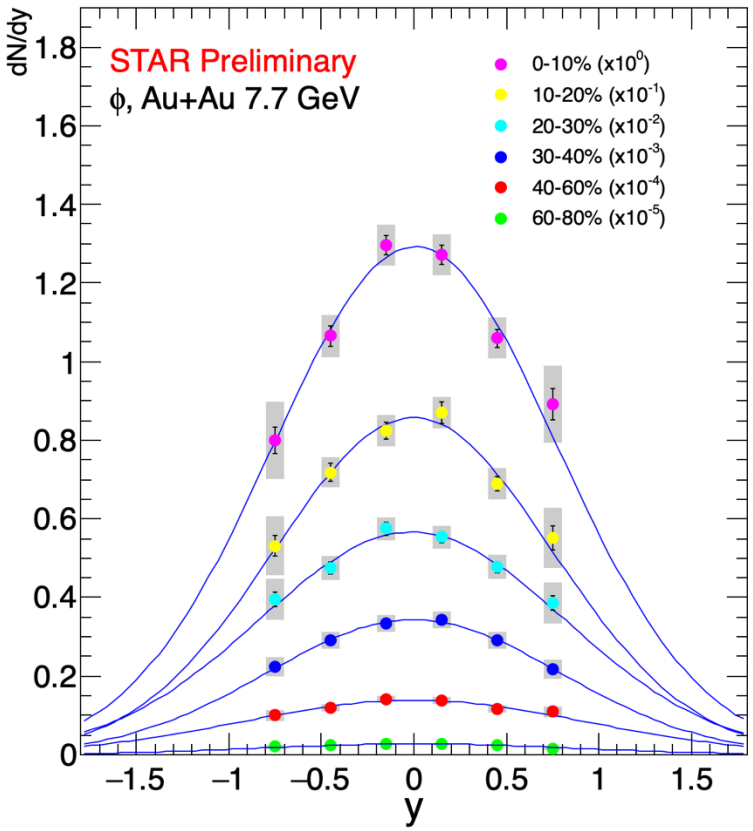
Rapidity spectra of K_s^0, Ξ^- and $\bar{\Xi}^+$ at 19.6 and 14.6 GeV

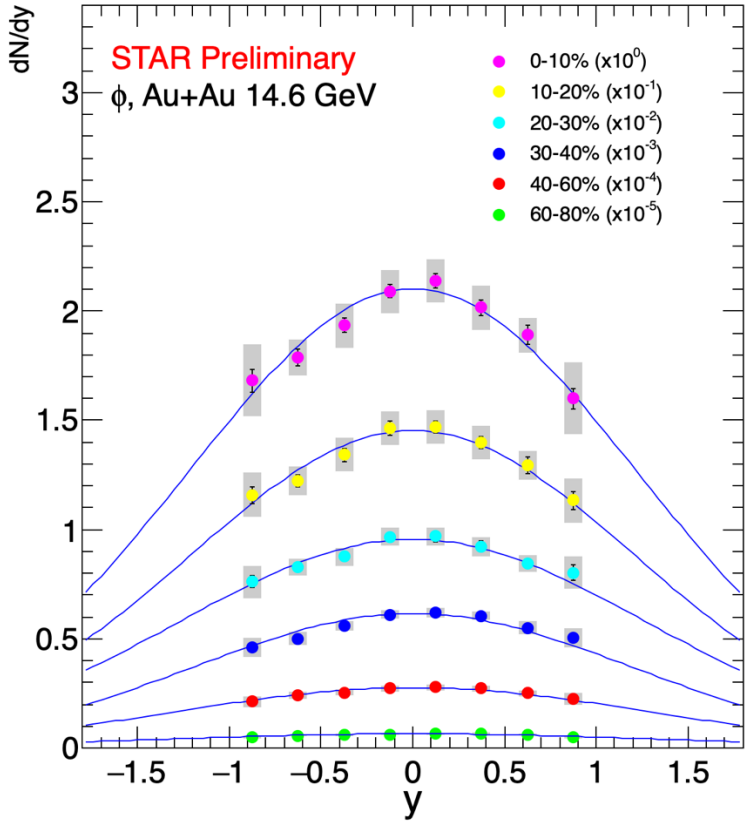
- Rapidity spectra of mesons (K_s^0) and anti-baryons($\bar{\Xi}^+$) are Gaussian-like distributions.
- Rapidity distribution of baryons(Ξ^-) are wider than the distributions of the anti-baryons($\bar{\Xi}^+$) in Au+Au collisions.

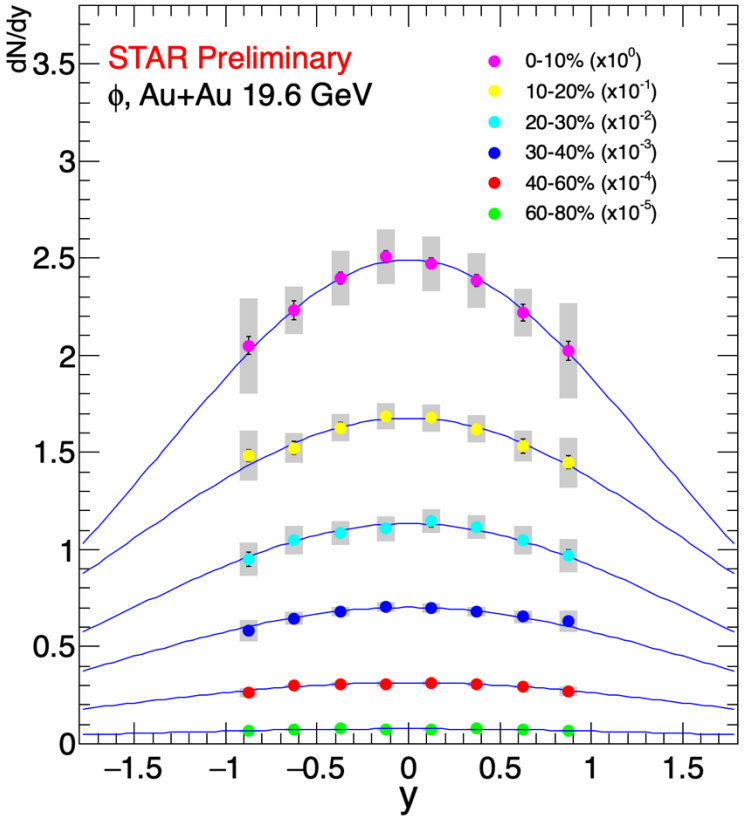




Rapidity spectra of ϕ

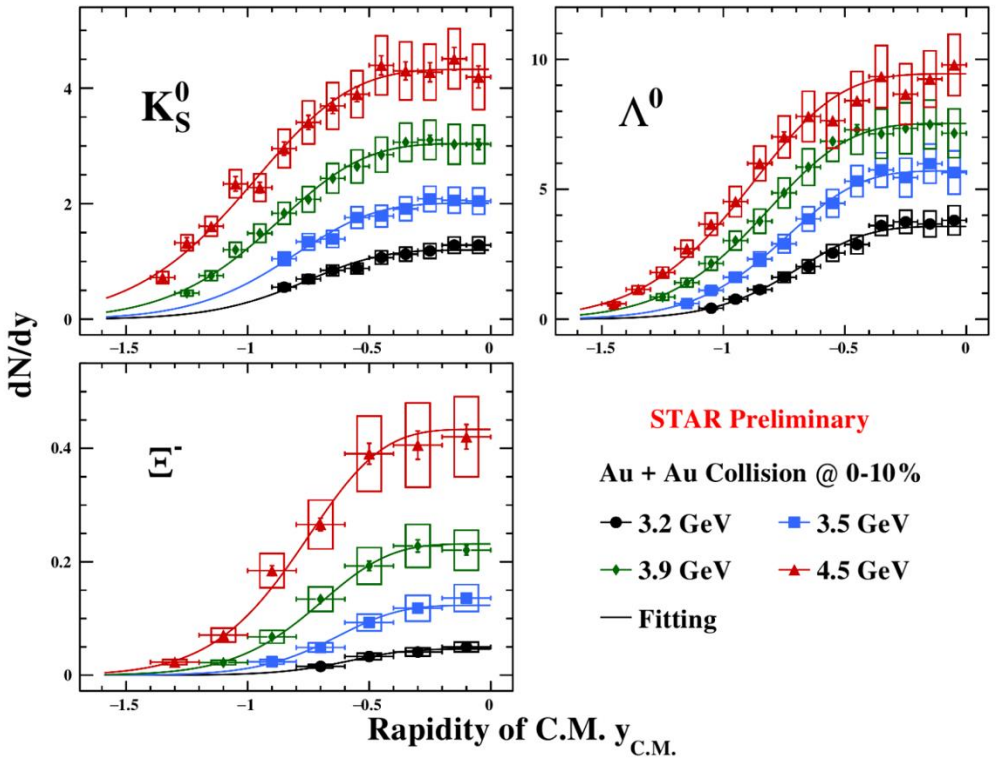




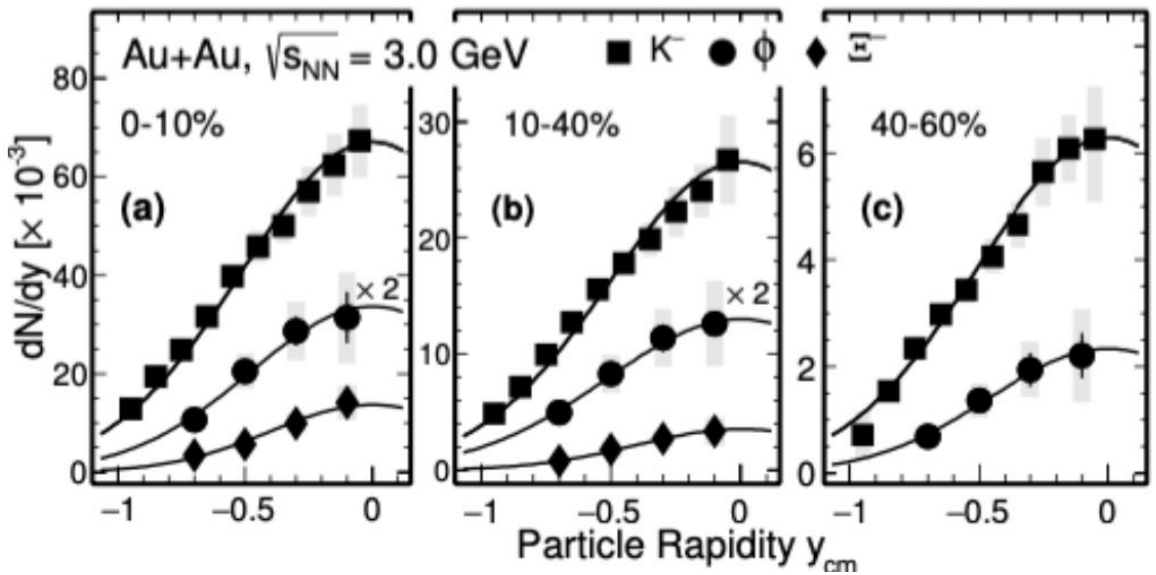


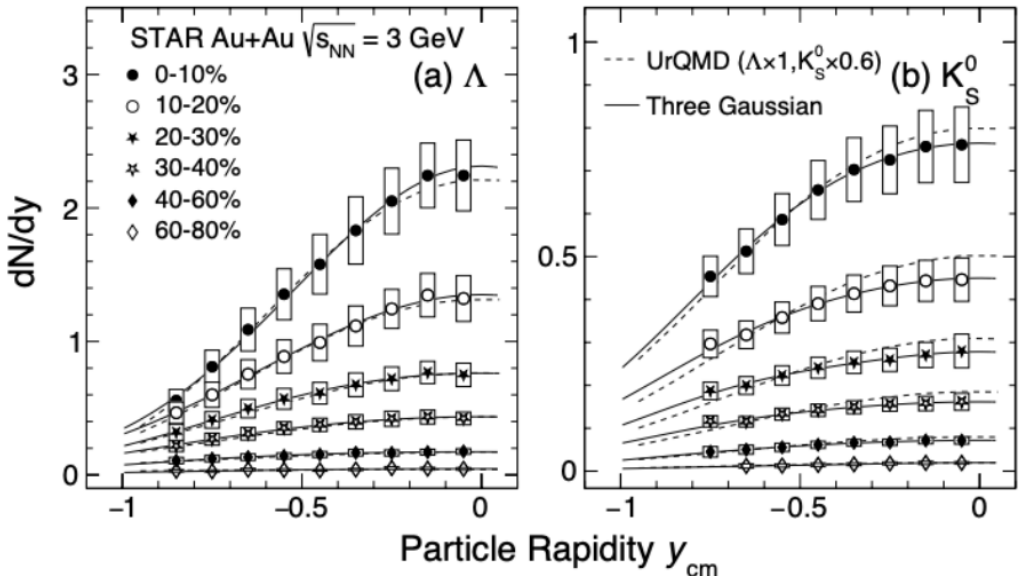
- Rapidity spectra of ϕ are Gaussian-like distributions
- Rapidity distribution become wider with increasing energy

Rapidity spectra of K^-, K_s^0, ϕ, Λ and Ξ^- at 3.0-4.5 GeV (FXT)



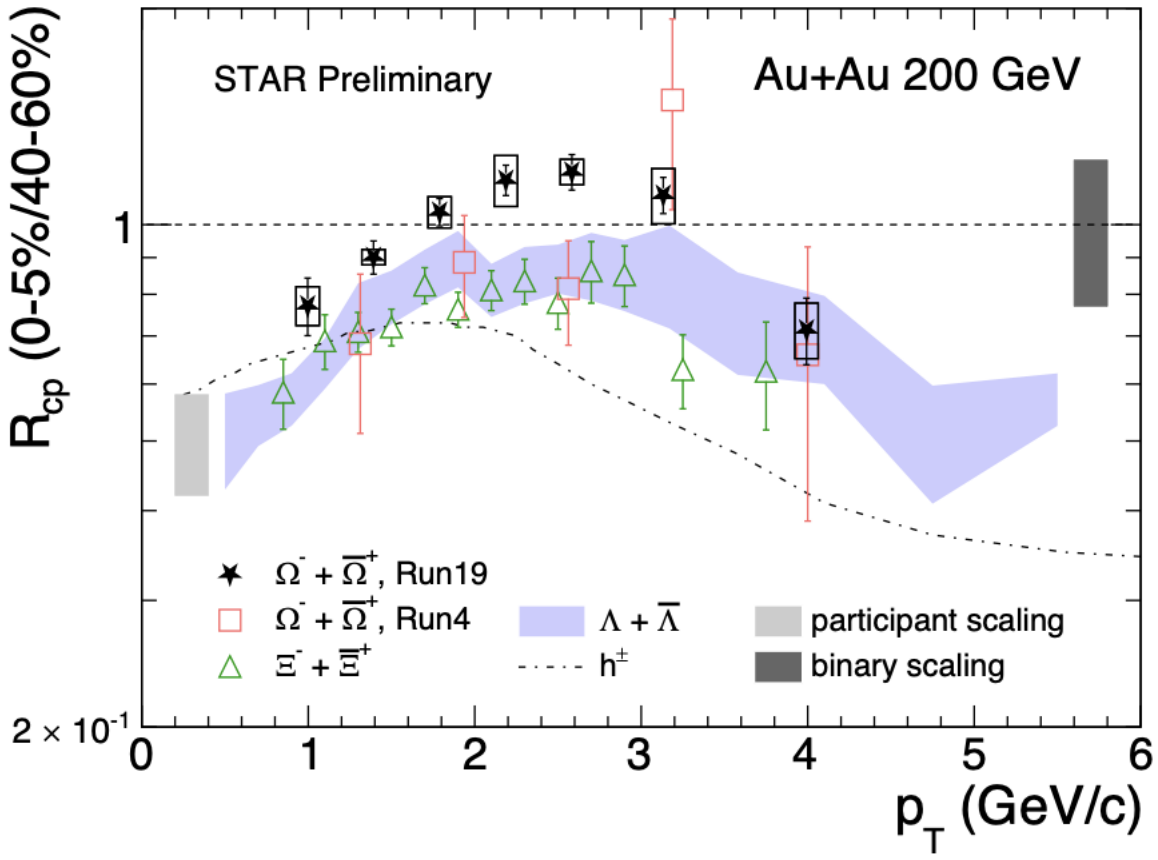
STAR: Phys. Lett. B 831 (2022) 137152; arXiv: 2407.10110





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

R_{CP} of strange hadrons at 200 GeV

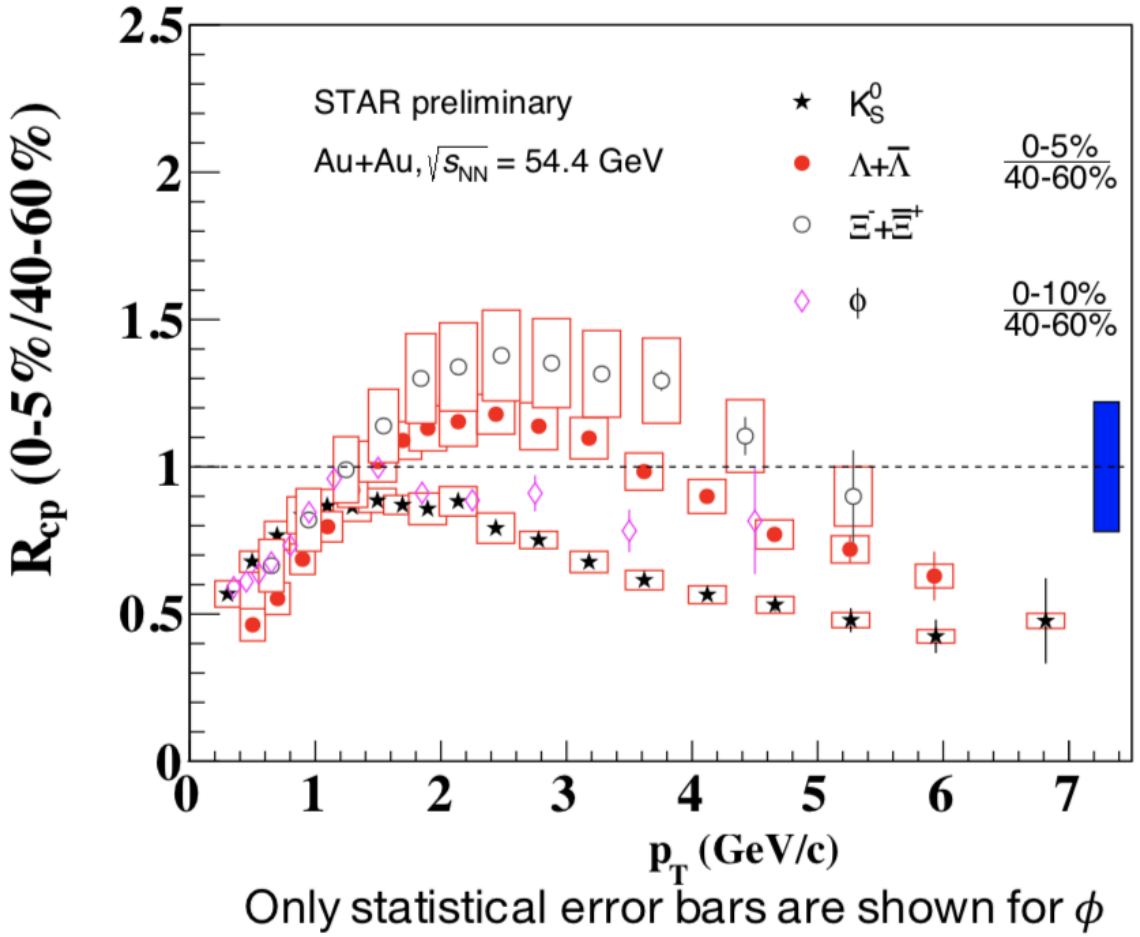


$$R_{\mathrm{CP}} = \frac{[(dN/dp_T)/\langle N_{\mathrm{coll}}\rangle]_{\mathrm{central}}}{[(dN/dp_T)/\langle N_{\mathrm{coll}}\rangle]_{\mathrm{peripheral}}}$$

- 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

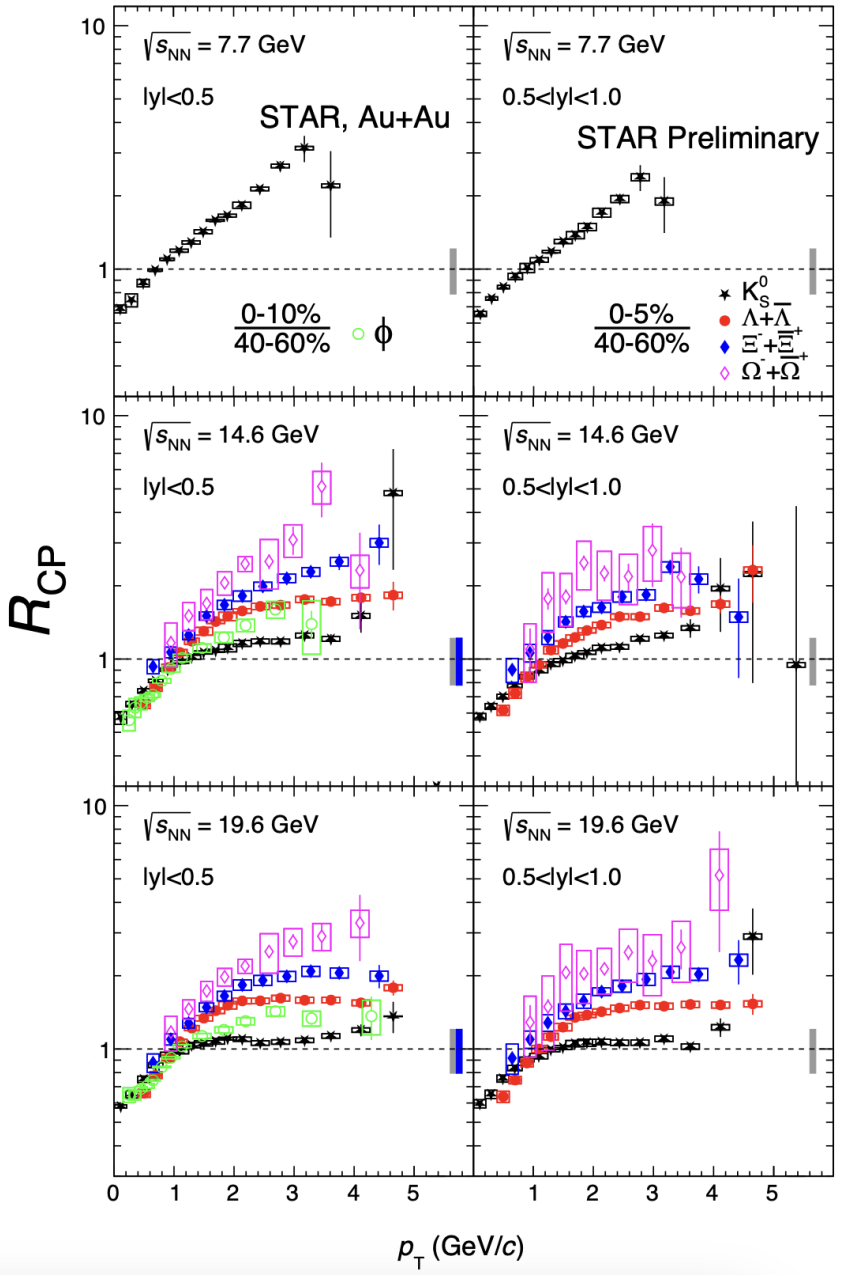
Nuclear modification factor for strange hadrons at 54.4 GeV



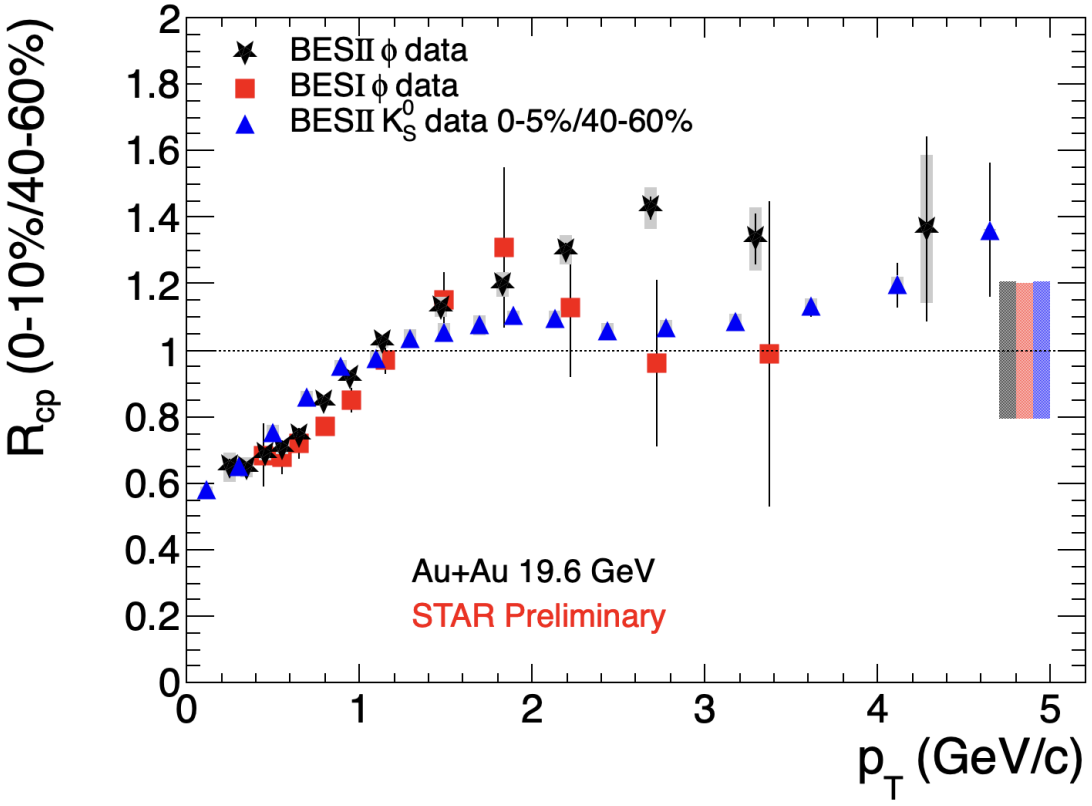
- Strong suppression of K^0_S R_{CP} at high p_T
  → partonic energy loss

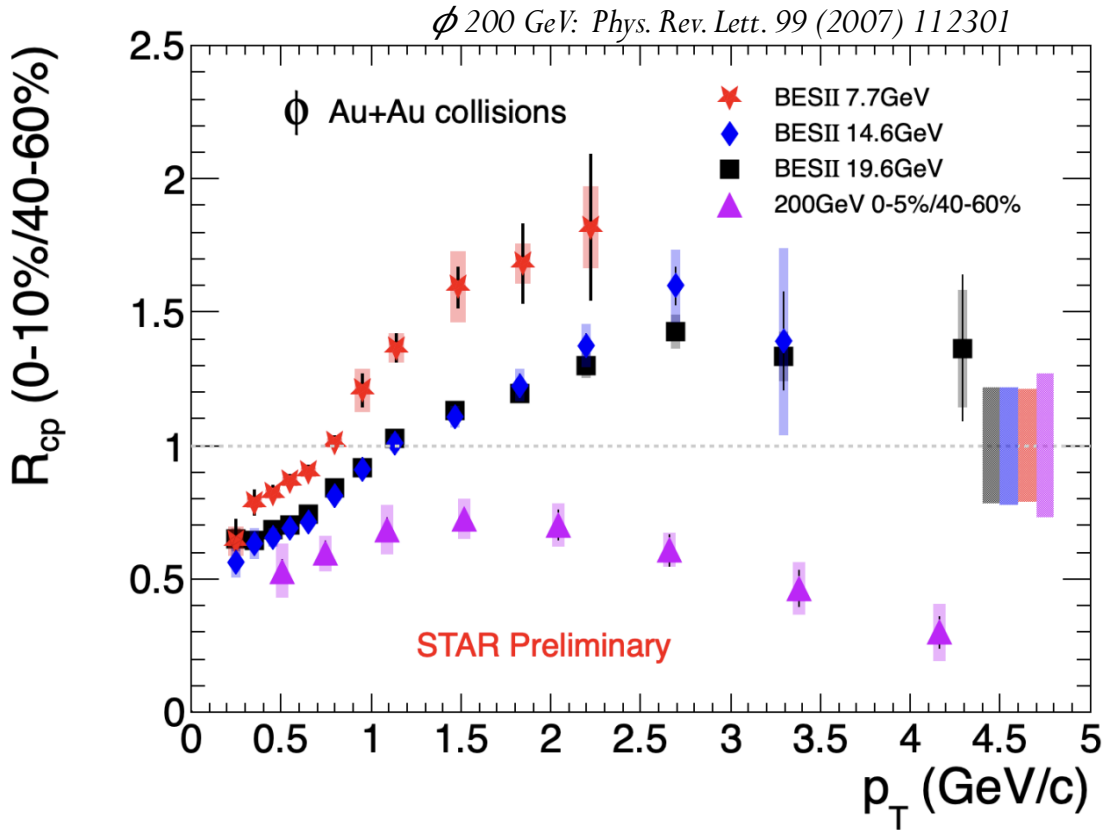
Nuclear modification factor at 19.6, 14.6 and 7.7 GeV

- 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.



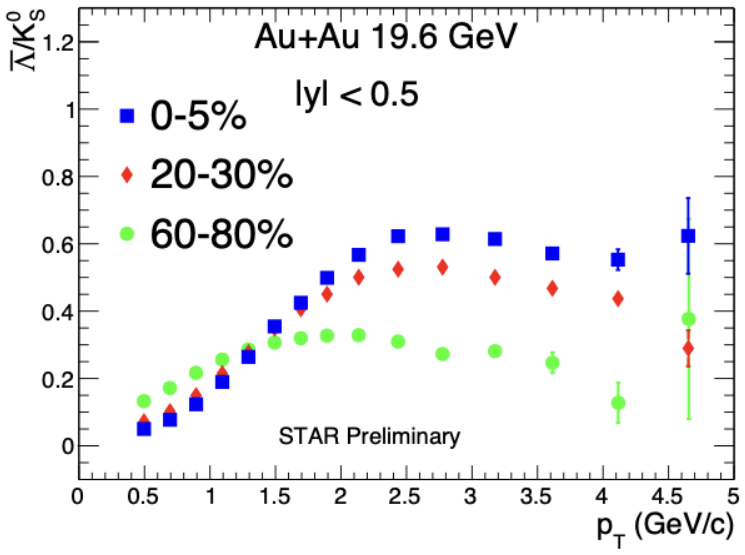
Nuclear modification factor for ϕ

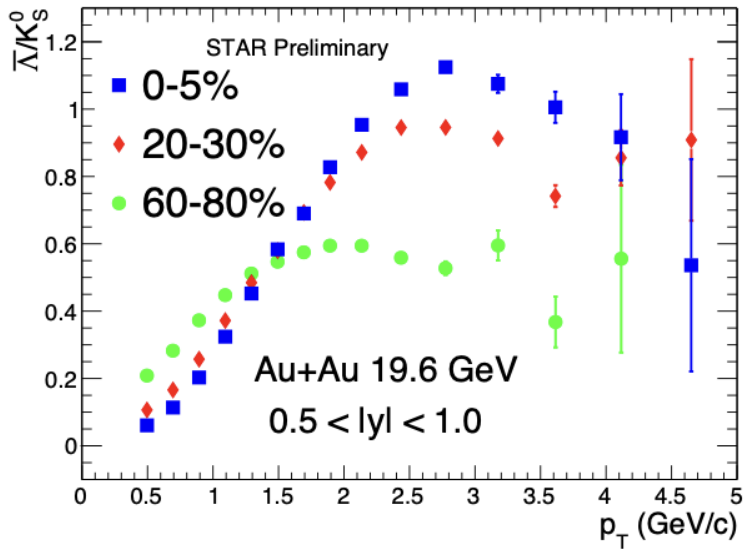


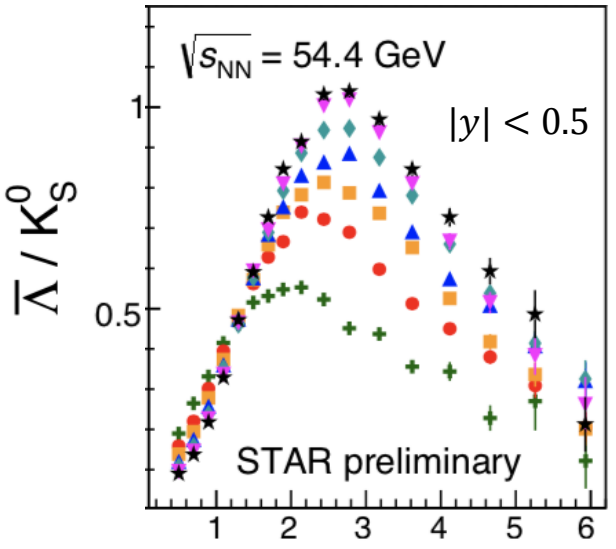


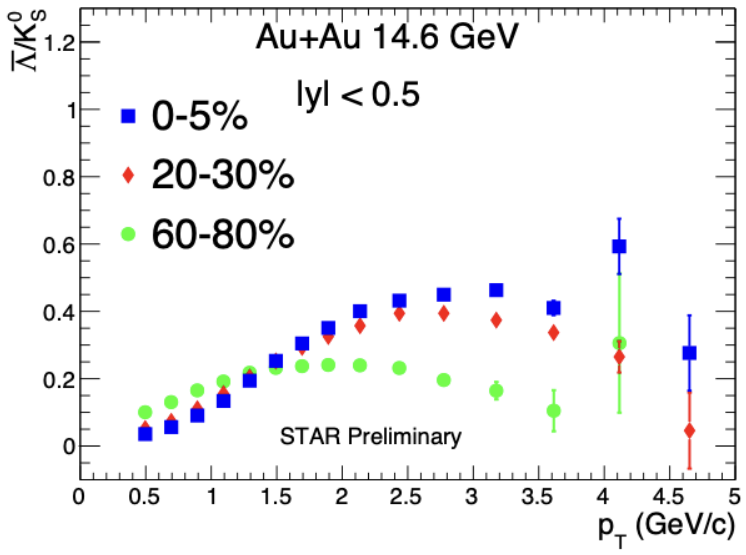
- BES-II result is consistent with BES-I with greatly improved precision
- $R_{CP}(\phi) > R_{CP}(K^0_S)$ at $2 < p_T < 4$ GeV/c
- $R_{CP} < 1$ for higher p_T at 200 GeV → Partonic energy loss in the QGP medium
- $R_{CP} > 1$ for higher p_T at 19.6 GeV and lower energies → Cronin-type interactions, radial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

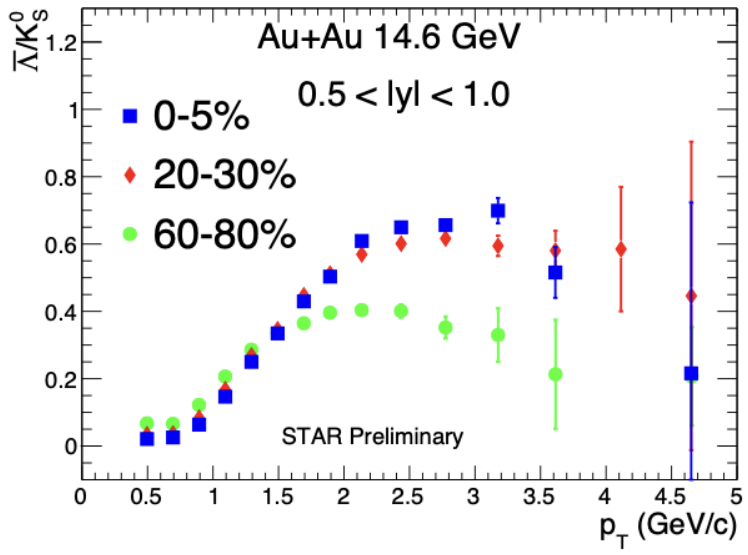
$\overline{\Lambda}/K_s^0$ ratio at 54.4, 19.6 and 14.6 GeV





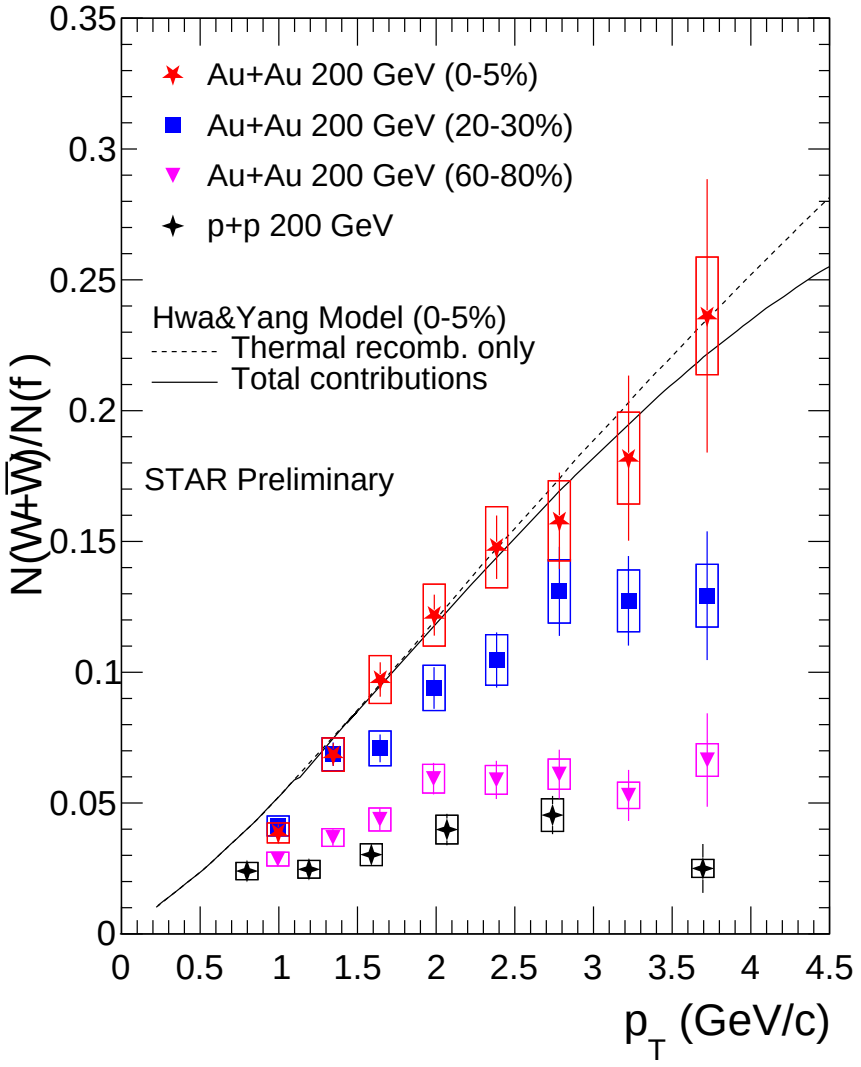






- Clear centrality and rapidity dependence of (anti-)baryon-to-meson ratio at intermediate p_T.
- Baryon enhancement is observed in all measured rapidity regions.

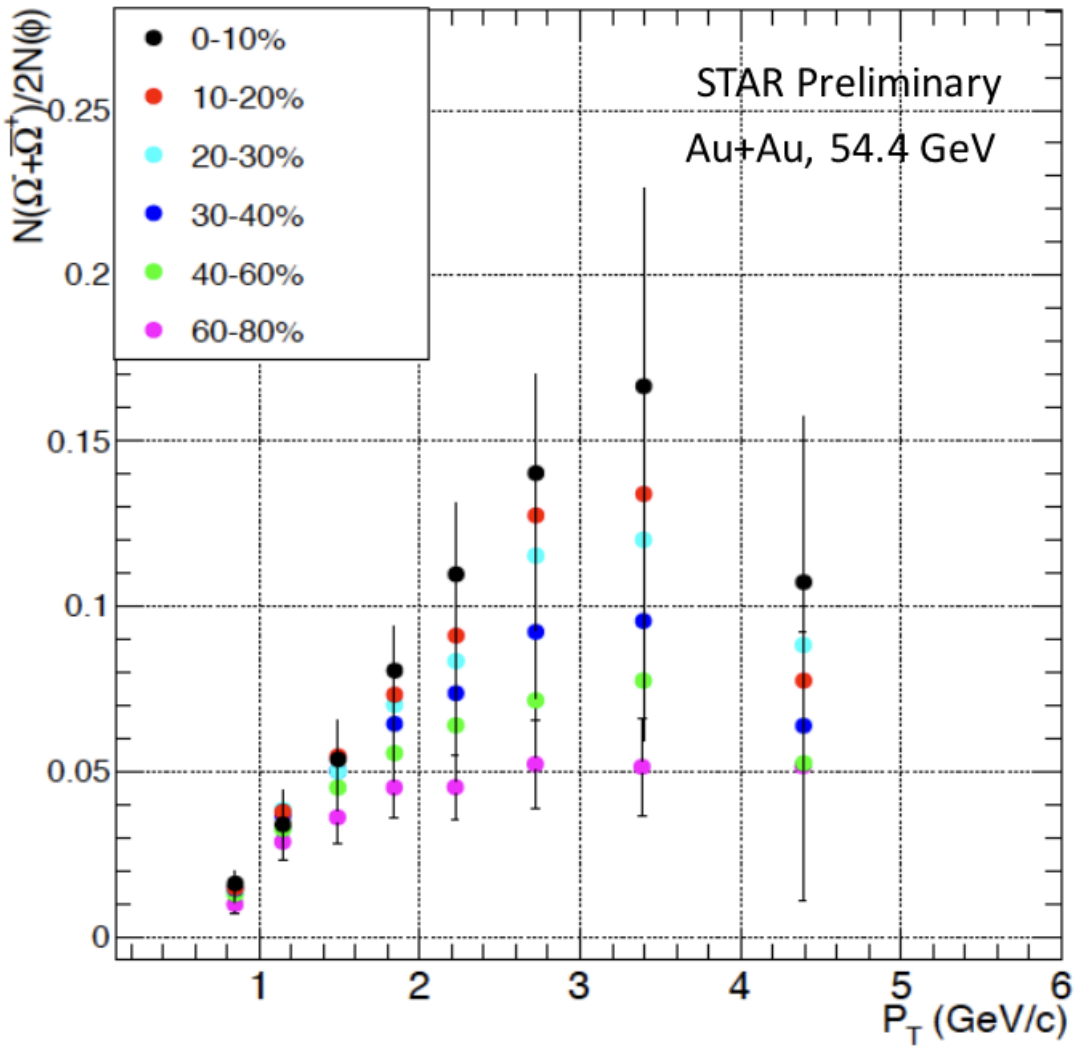
$\Omega(sss)/\phi(s\bar{s})$ ratio at 200 GeV



- 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

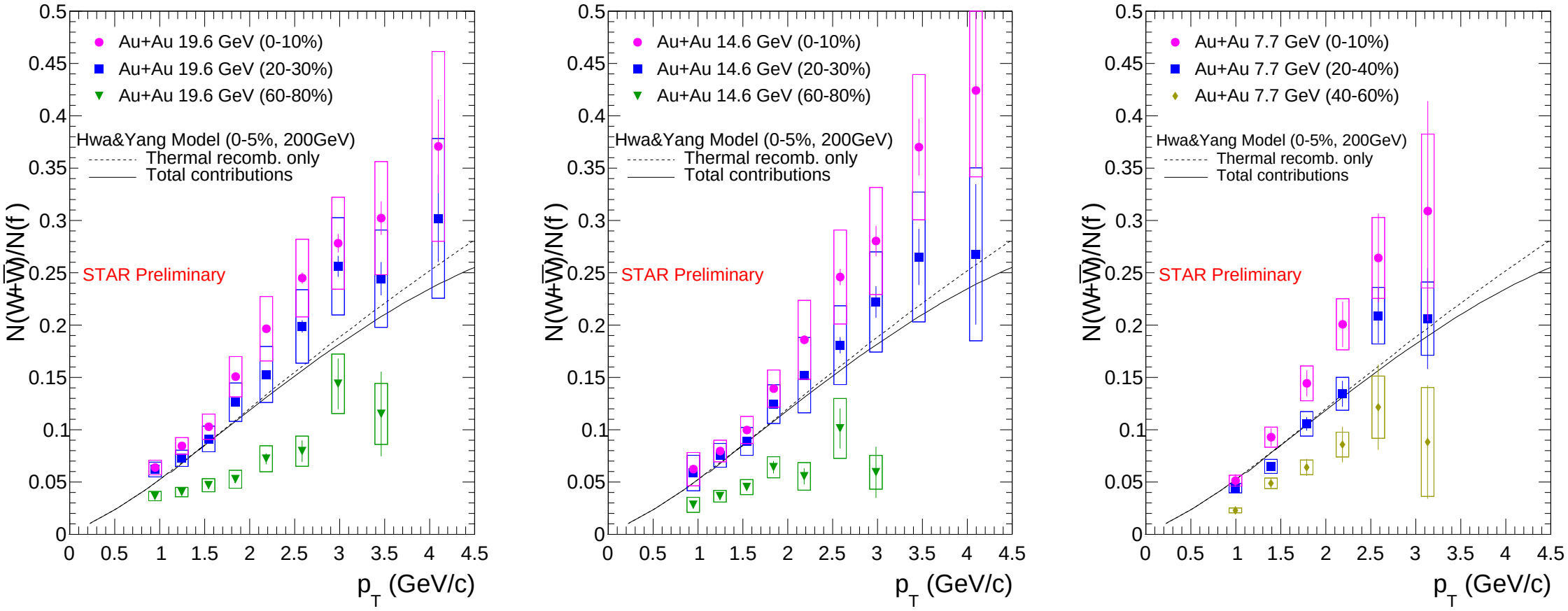
Ω/ϕ ratio at 54.4 GeV



Ω/ϕ ratio enhancement at 54.4GeV

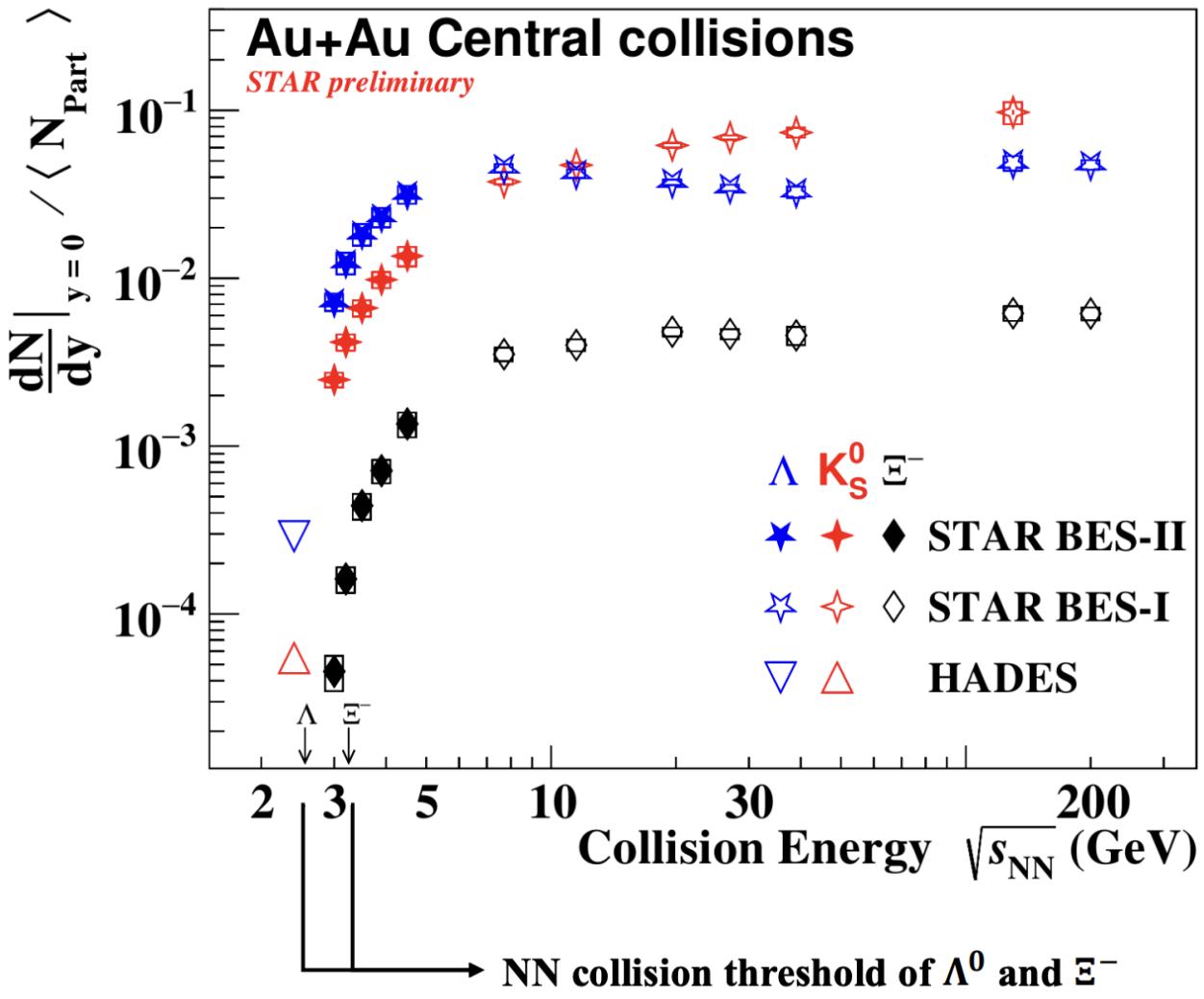
→ Hadron formation through parton recombination

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

Energy dependence of mid-rapidity yields



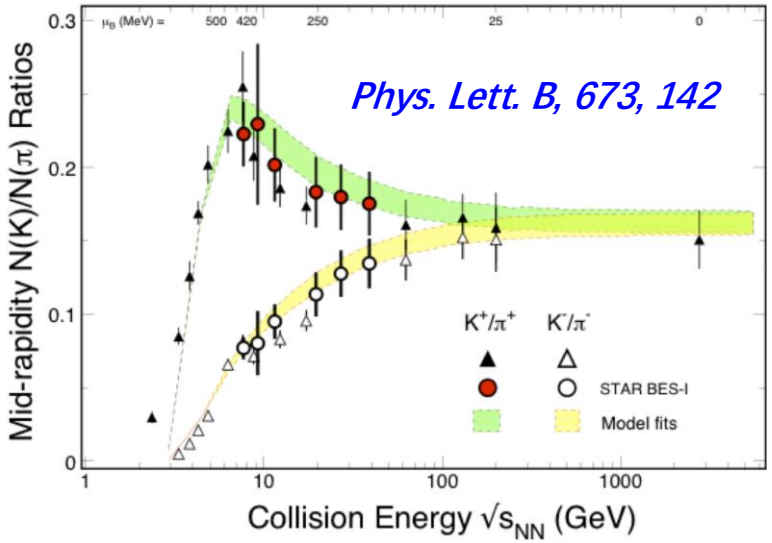
- **Rich structure in strangeness excitation functions**
  - **Production mechanisms is different at low and high energies (high and low baryon density)**
    - **Partonic interaction (pair production)**

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

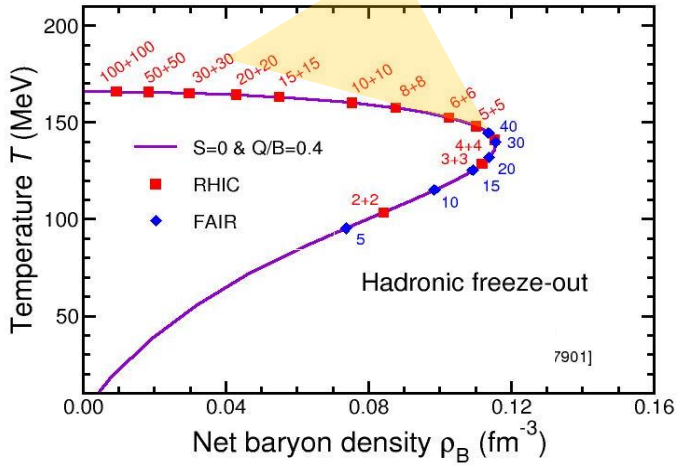
      $BB \rightarrow BYK$ or $BB \rightarrow B\Xi KK$

      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**

Strange hadron to pion ratio

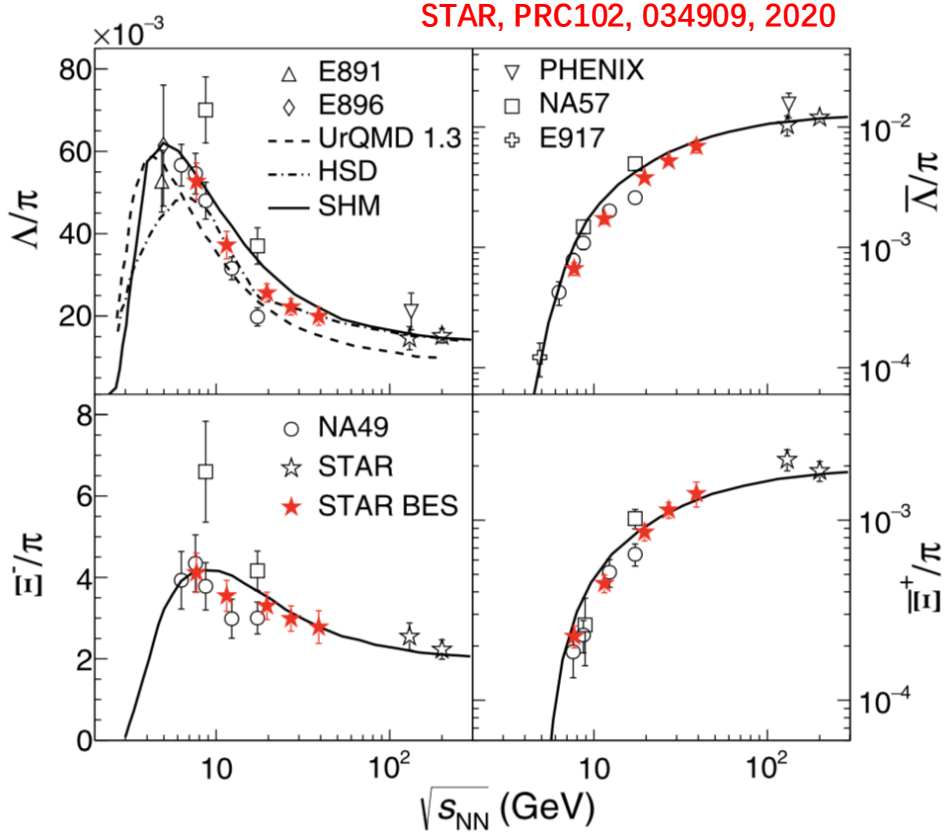


RHIC BES



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

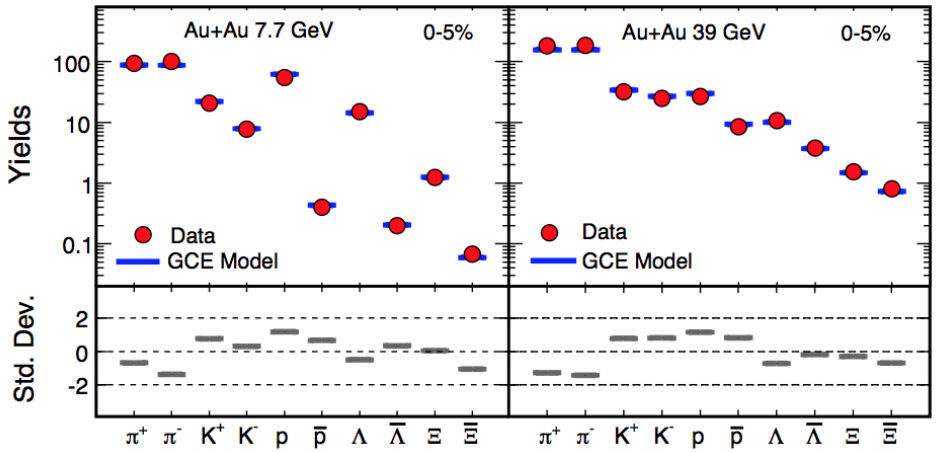
STAR, PRC102, 034909, 2020

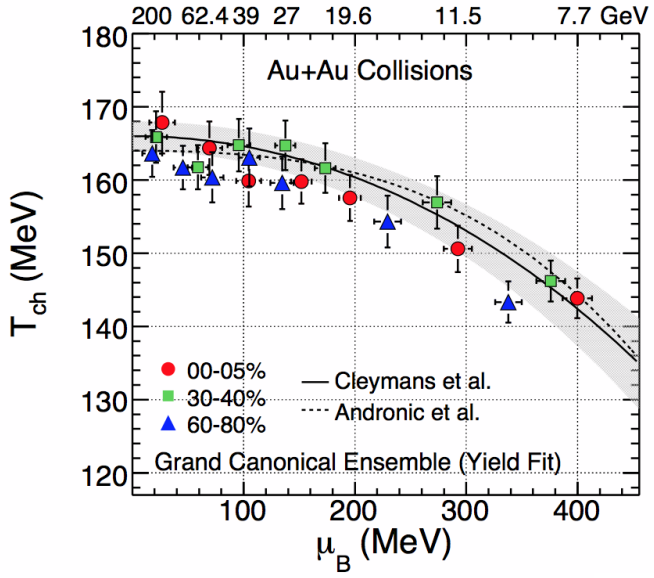


- Particle ratios consistent with NA49, consistent with the picture of a **maximum net-baryon density around $\sqrt{s_{NN}}$ ~ 8 GeV at freeze-out**

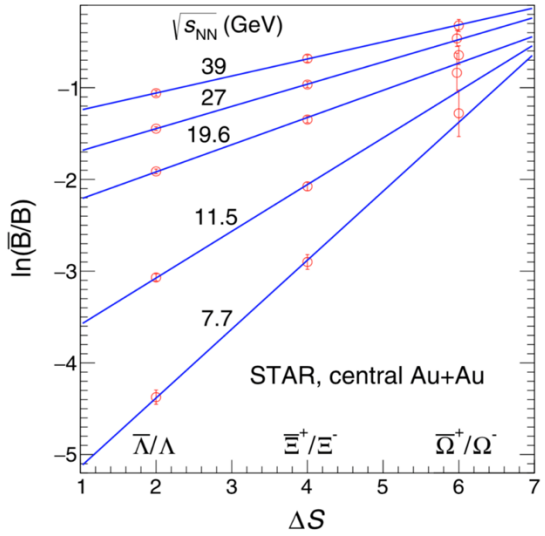
Chemical freeze-out parameters: T_{ch} vs. μ_B

STAR, Phys. Rev. C 96, 044904, 2017





STAR, PRC102, 034909, 2020

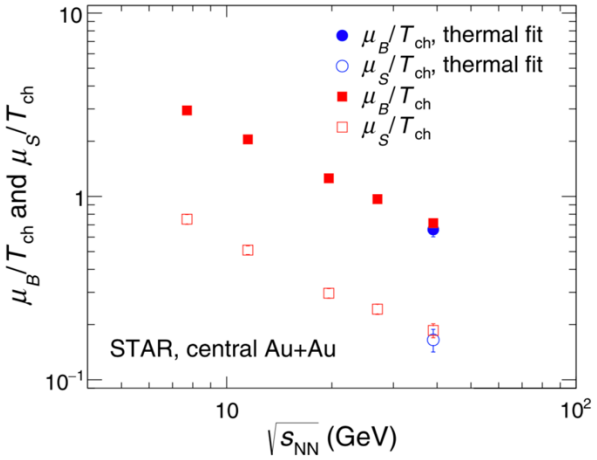


✓Particles used : **π, K, p, Λ, Ξ**

✓ 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



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

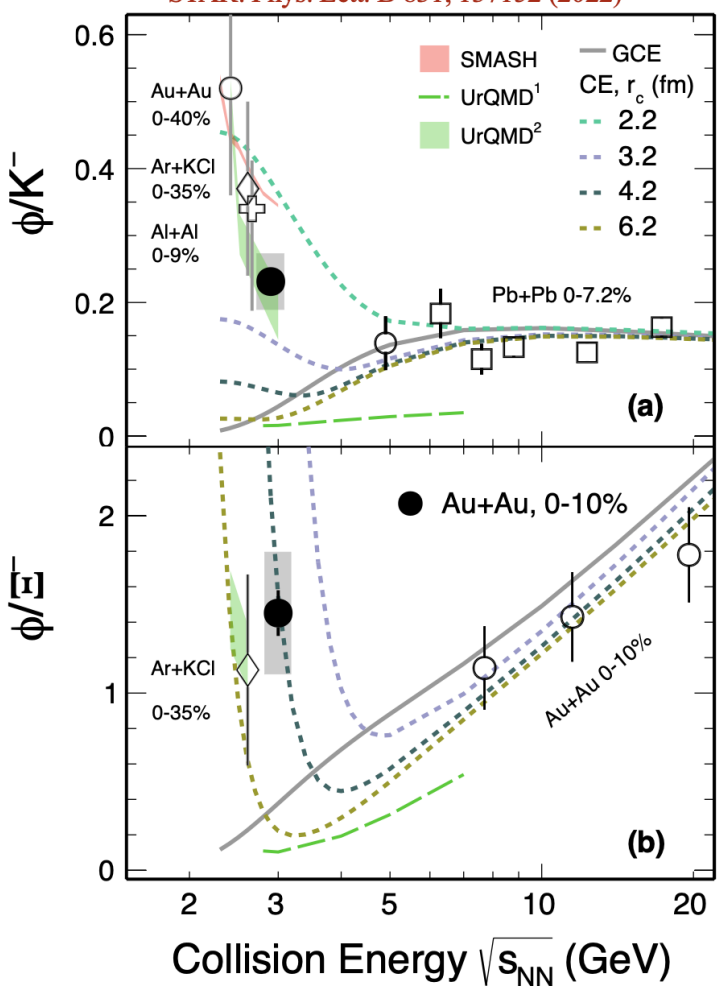
$$\ln\left(\frac{\bar{\Xi}^+}{\Xi^-}\right) = -\frac{2\mu_B}{T} + \frac{4\mu_S}{T}$$

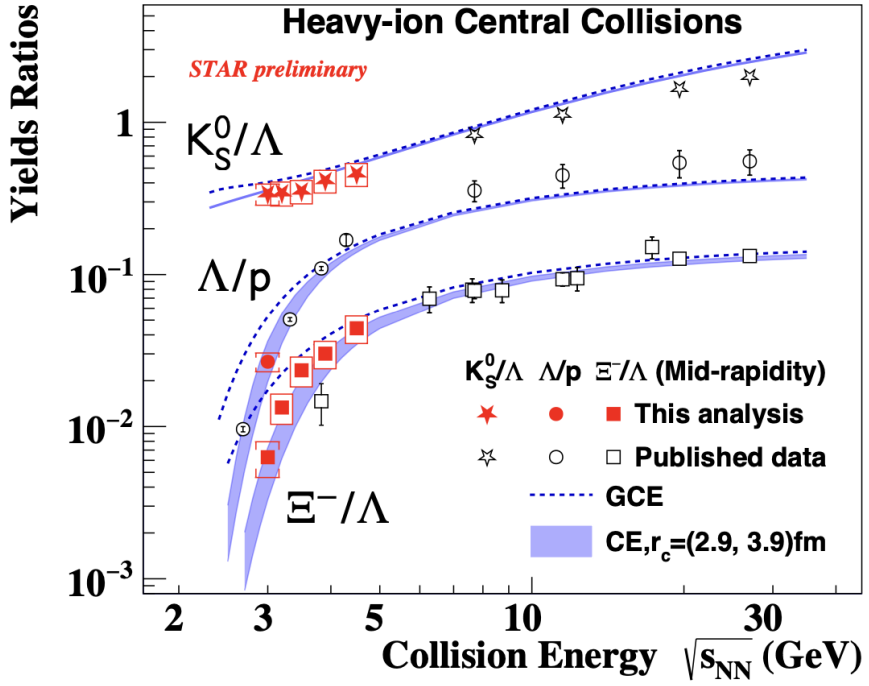
$$\ln\left(\frac{\bar{\Omega}^+}{\Omega^-}\right) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T}$$

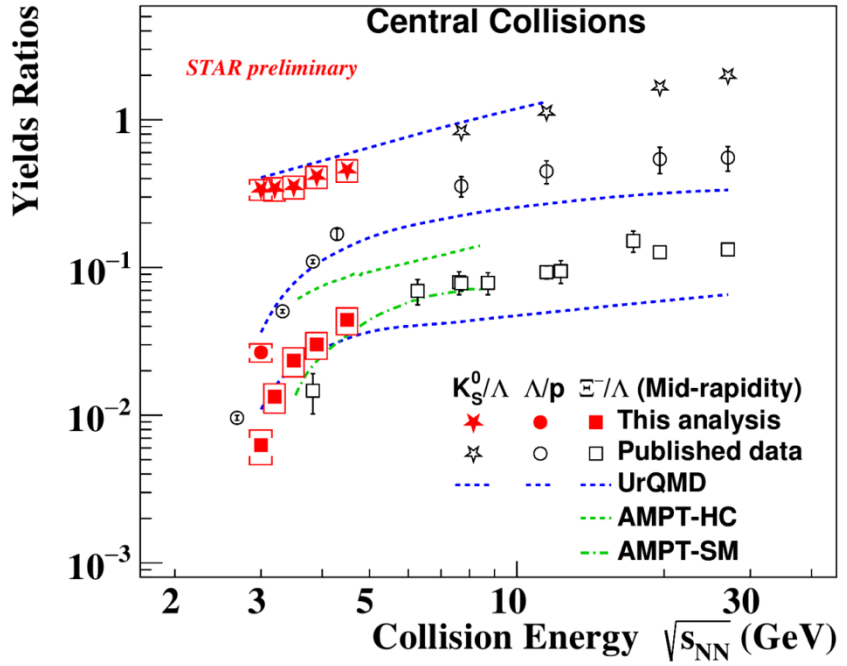
Thermus, S. Wheaton & J. Cleymans, Comput. Phys. Commun. 180: 84-106, 2009.

Energy dependence of mid-rapidity yield ratios

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







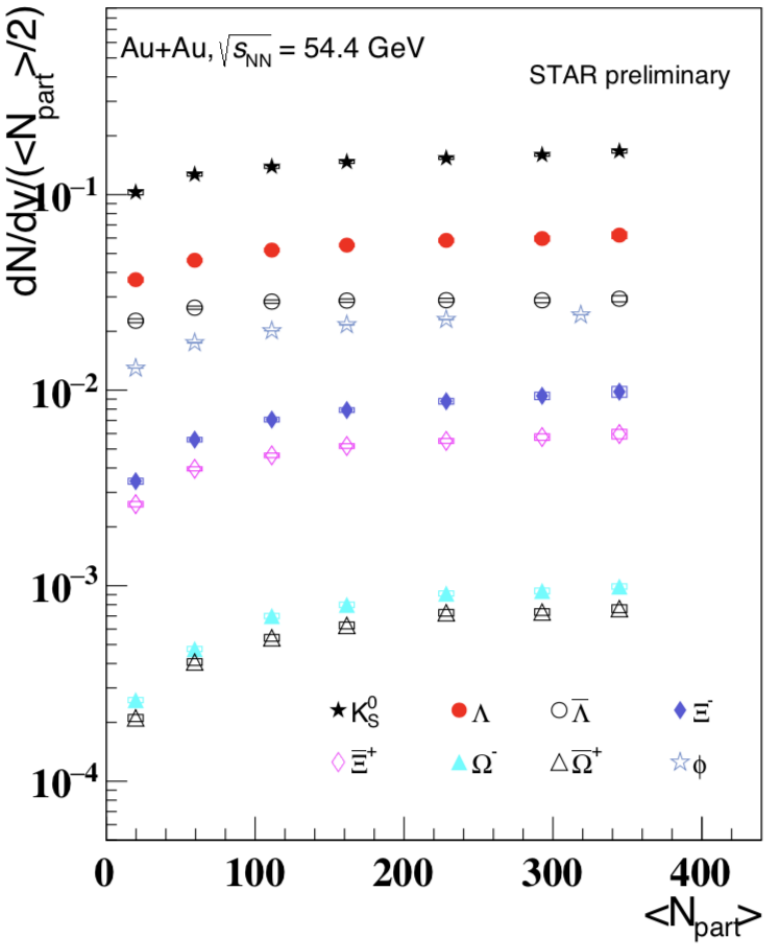
1) Canonical Ensemble (CE) with strangeness correlation length 2.9 – 3.9 fm, simultaneously describes K^0_S/Λ, Λ/p, and Ξ^-/Λ in the measured energy range, GCE fails at low energies

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

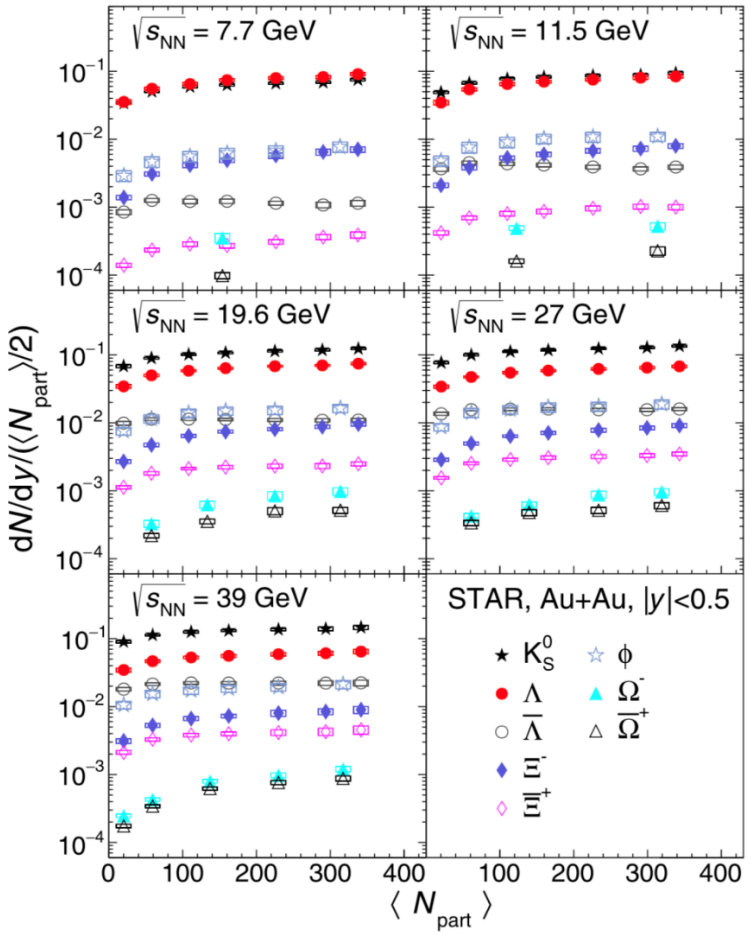
➡Change of medium properties at the high-density region

UrQMD: cascade mode, hard EOS

Centrality dependence of mid-rapidity yields



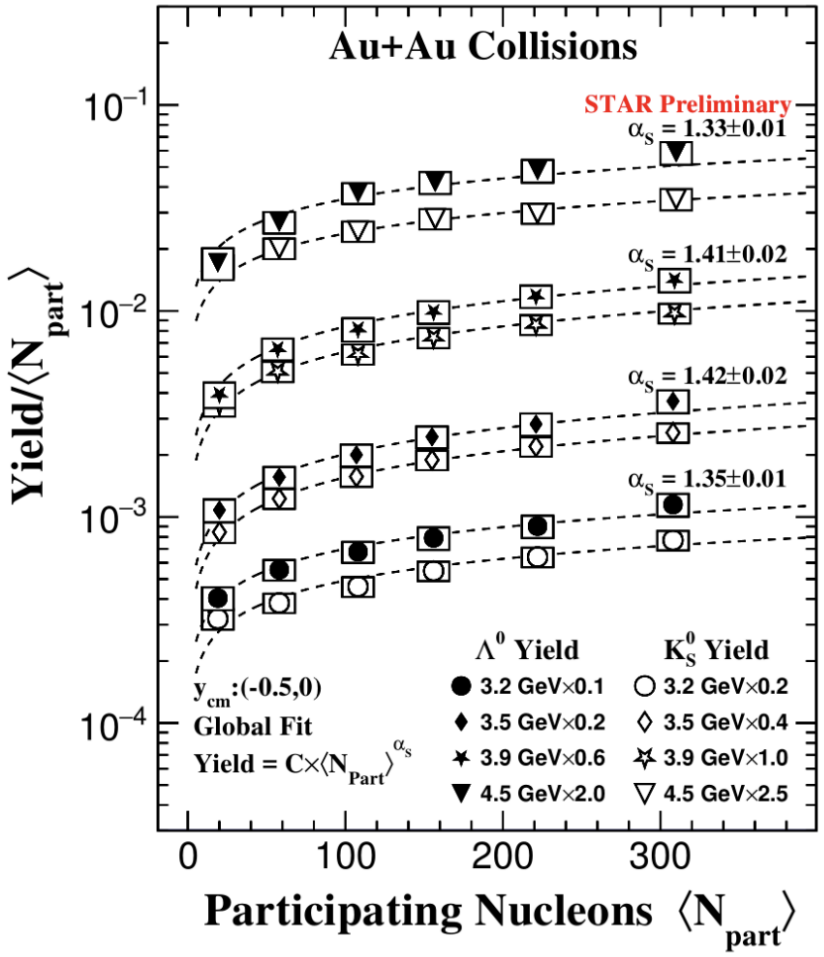
Y. Huang, SQM2021

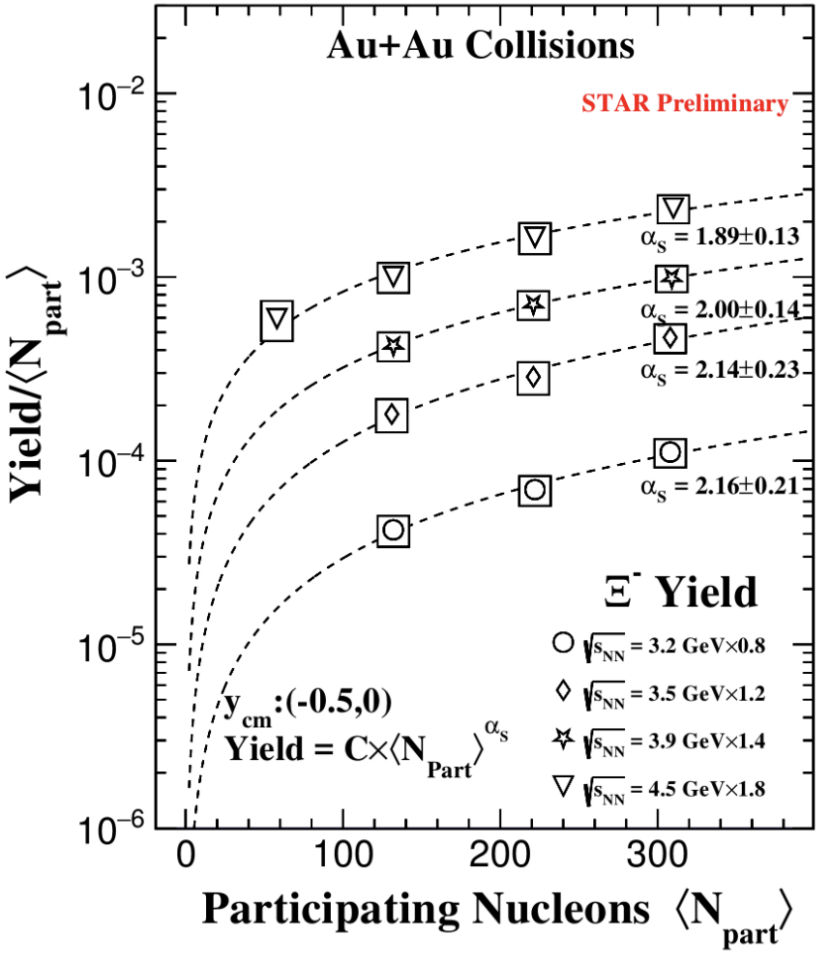


STAR, PRC102, 034909, 2020

- Yield per participating pair increases towards central and higher energies in general, except that $\bar{\Lambda}$ has weak centrality dependence

Centrality dependence of mid-rapidity yields



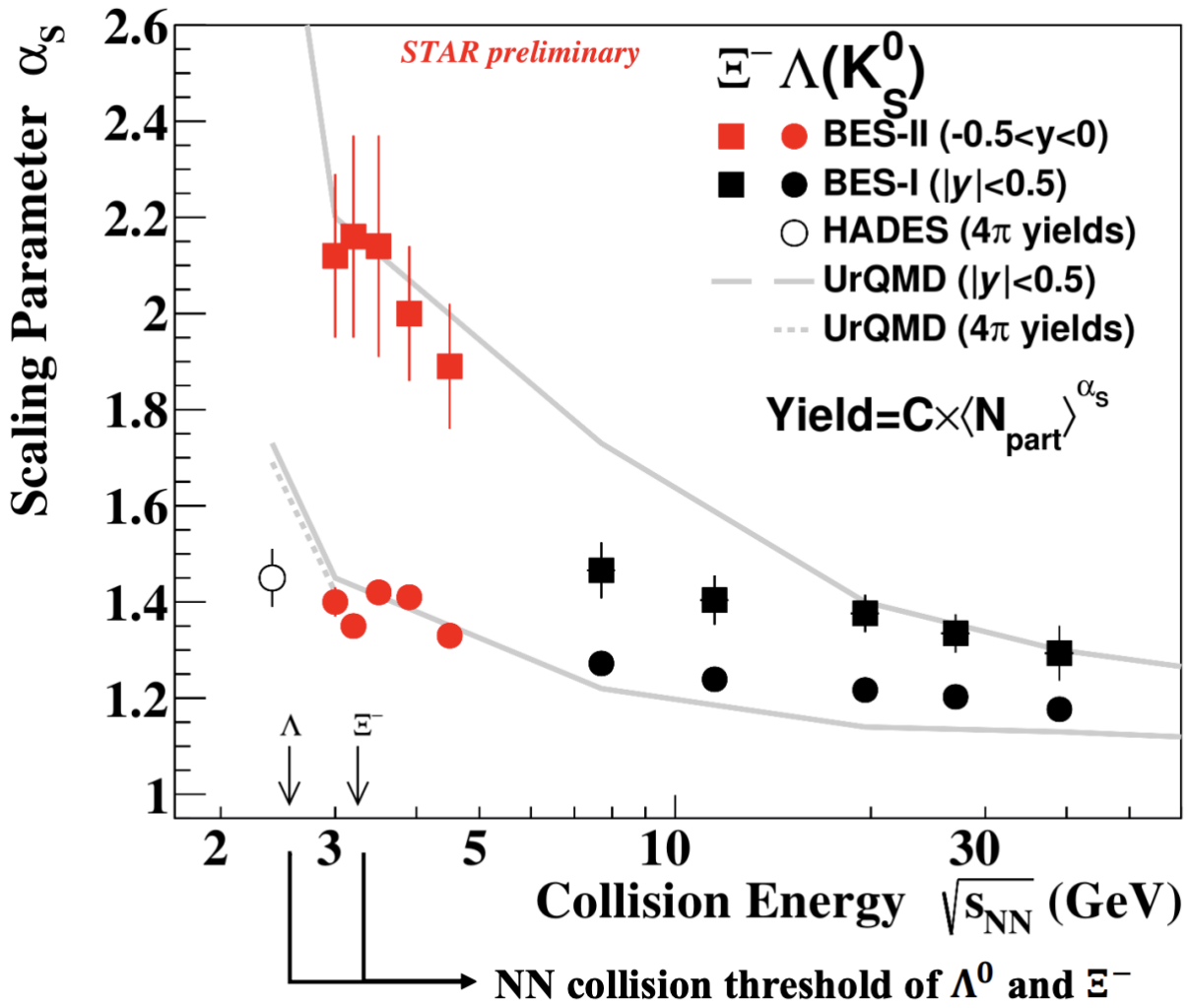


- **Scaling formula:**

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

- **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



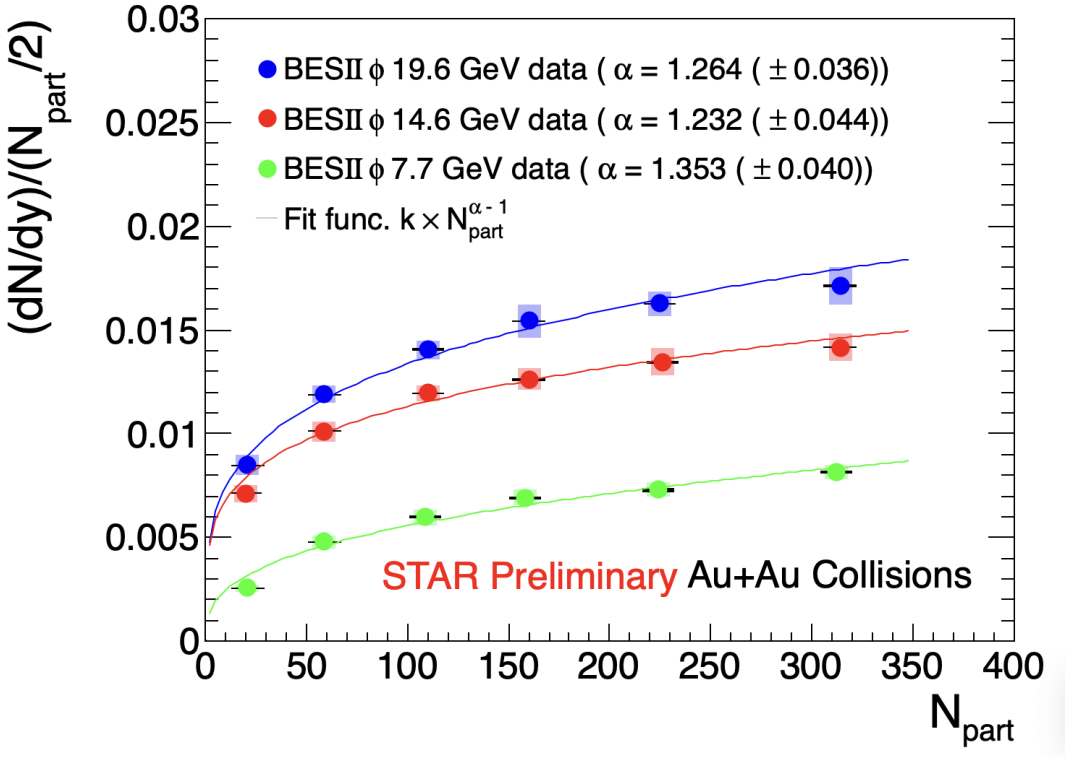
- **Rapid decrease of scaling parameter α_S for Ξ^- from 4.5 to 7.7 GeV, and saturate at high energy**
  - **The mechanism of strange hadron production may change**
  - **Strange hadron production predominantly from hadronic interactions at $\sqrt{s_{NN}} < 4.5$ GeV**

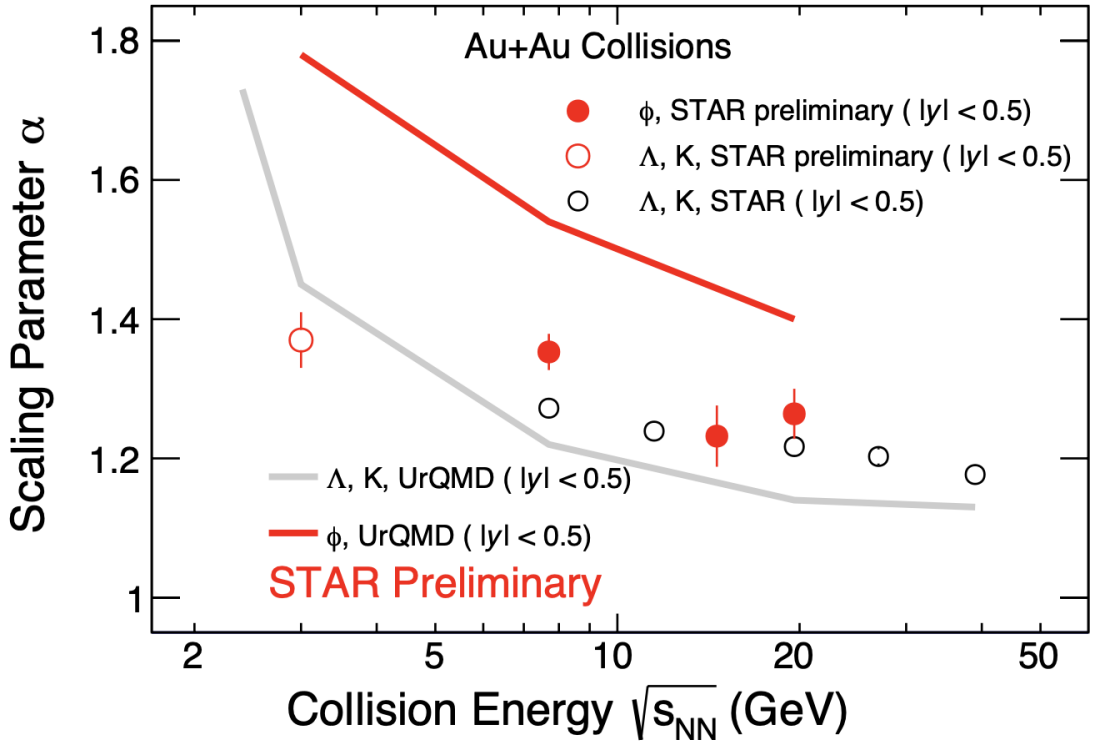
- **UrQMD qualitatively reproduces the energy dependence, but cannot quantitatively describe all energies**
  - **likely due to missing medium effects**

UrQMD: cascade mode, hard EOS

S.A. Bass, et.al. Prog. Part. Nucl. Phys. 41 (1998)

Centrality dependence of ϕ production

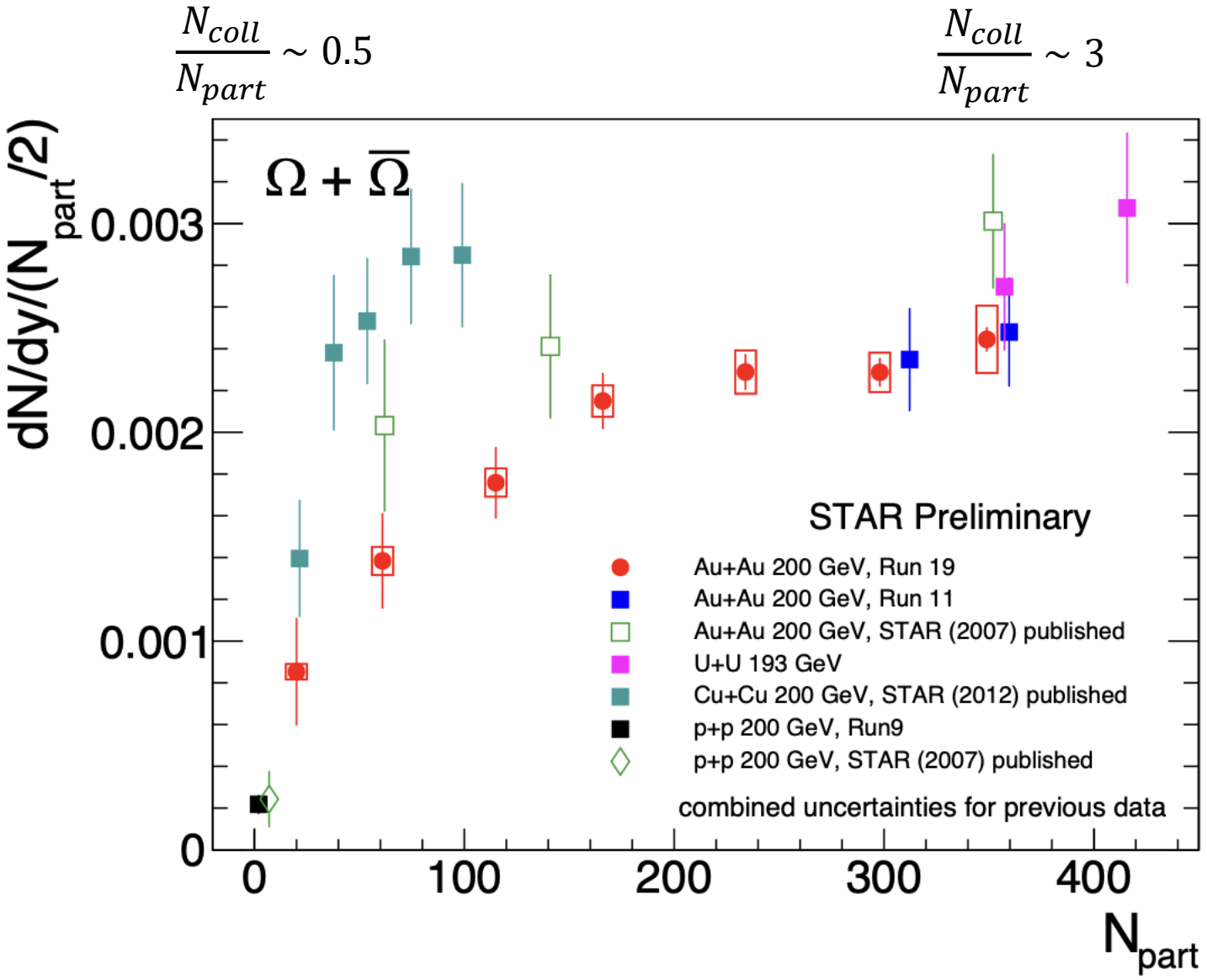


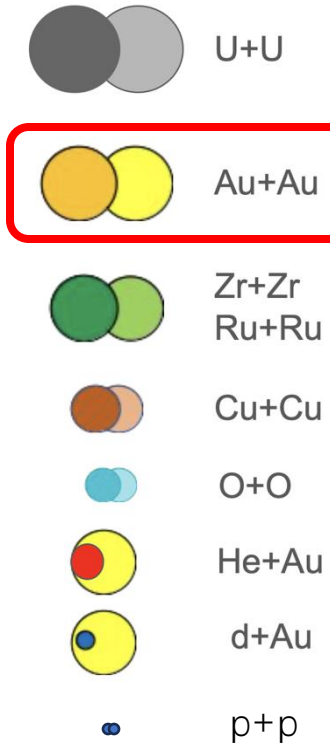


STAR: arXiv: 2407.10110

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

System size dependence of Ω yield at 200 GeV

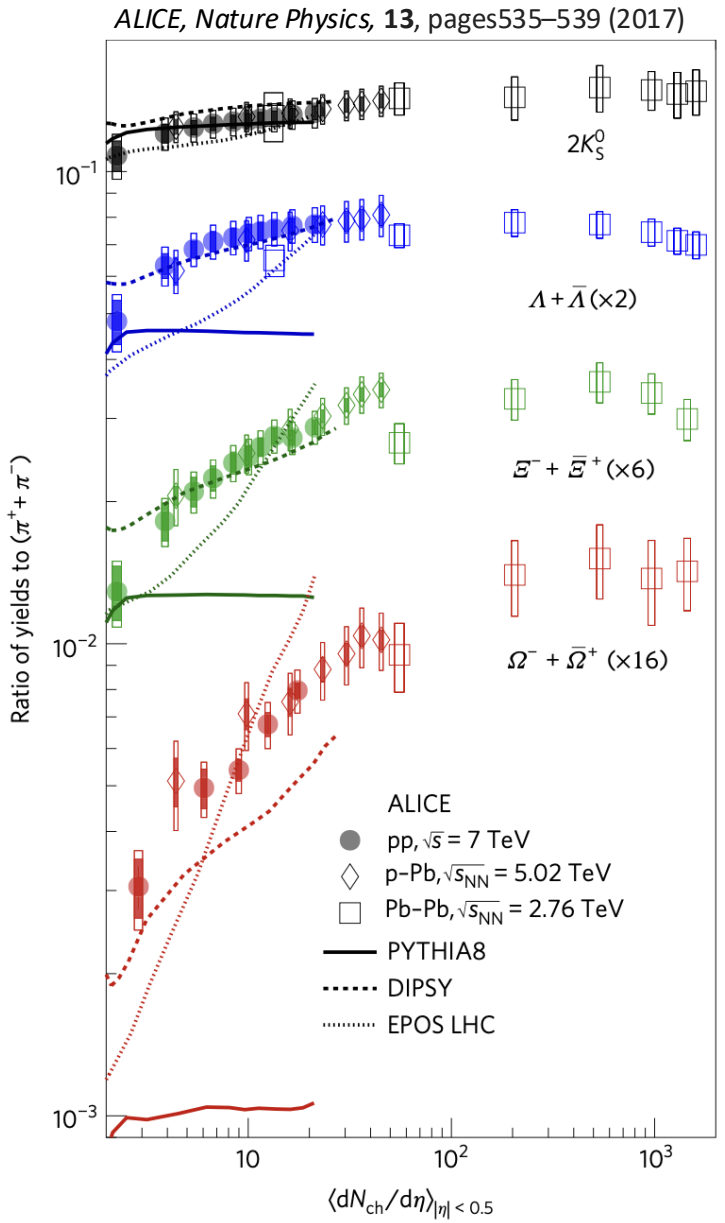


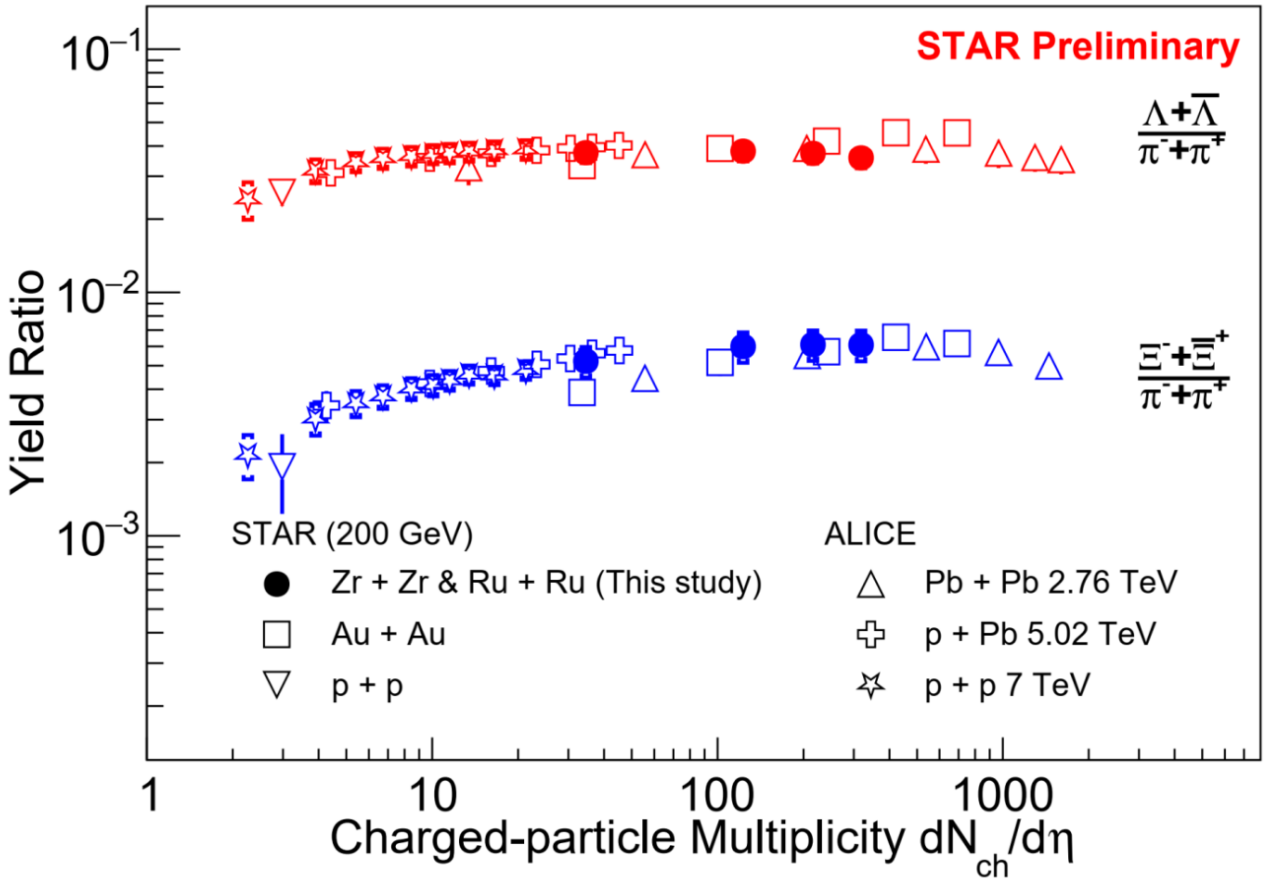


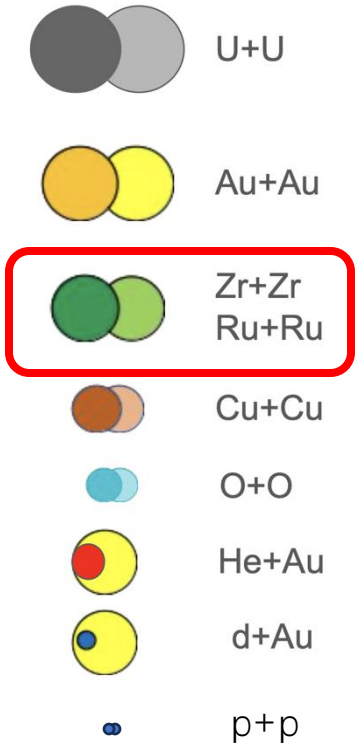
- In general, increasing Ω baryon enhancement compared to p+p collisions with increasing system size is observed.
- Multi-strange hadron production sensitive to multiple collisions.

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

System size dependence of strange-to-pion yield ratios

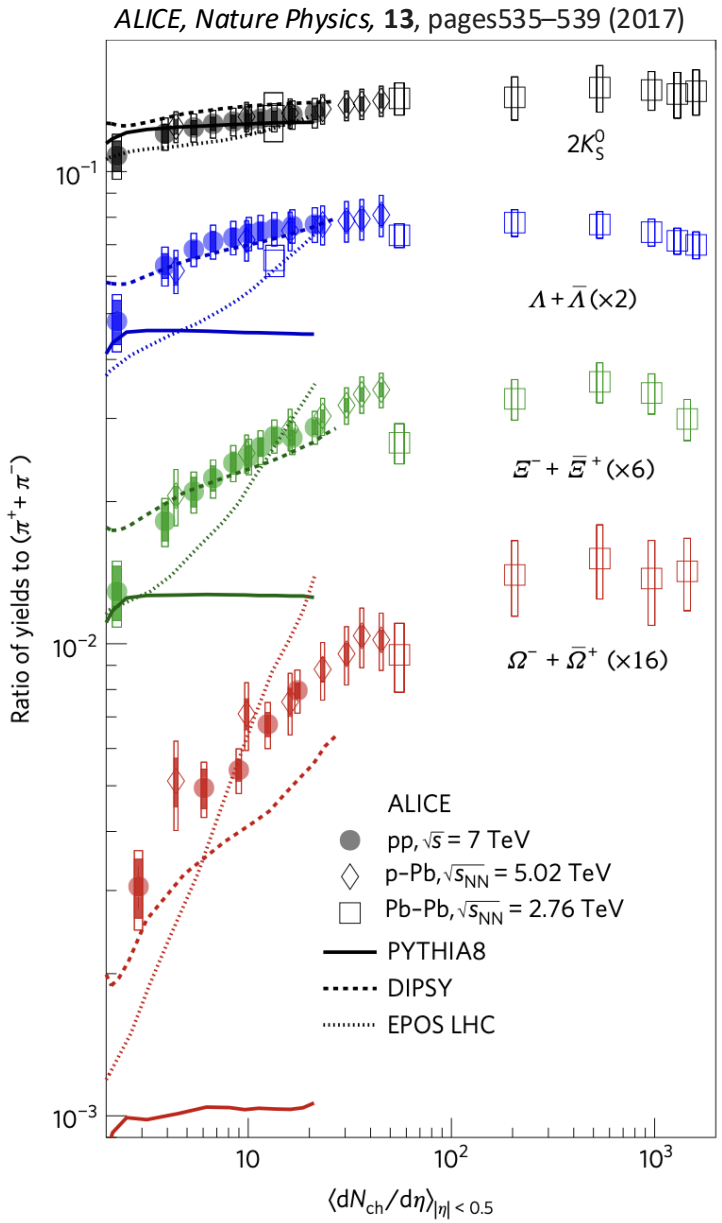


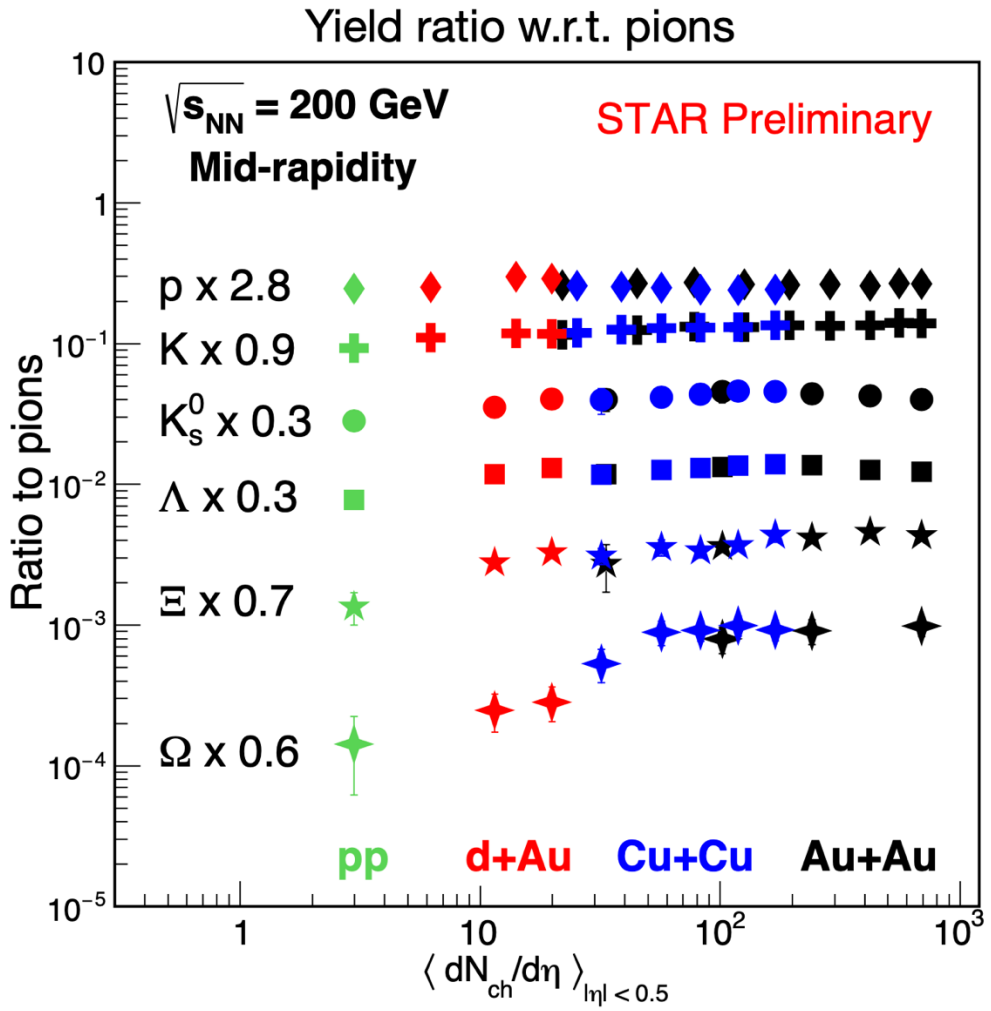


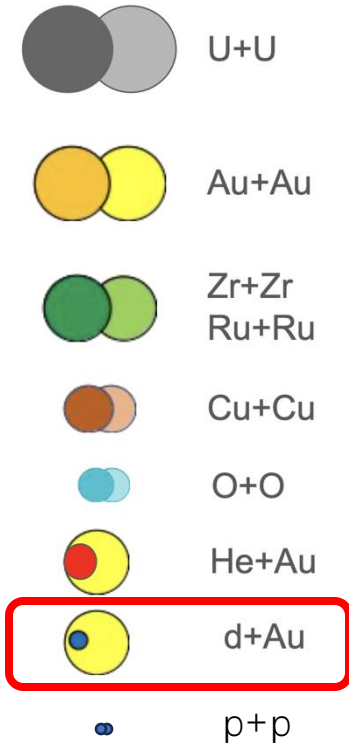


- Isobar hyperon-to-pion ratios follow the trend.
- Similar hyperon production mechanism for systems with same multiplicity despite differences in collision energy or system.

System size dependence of strange-to-pion yield ratios





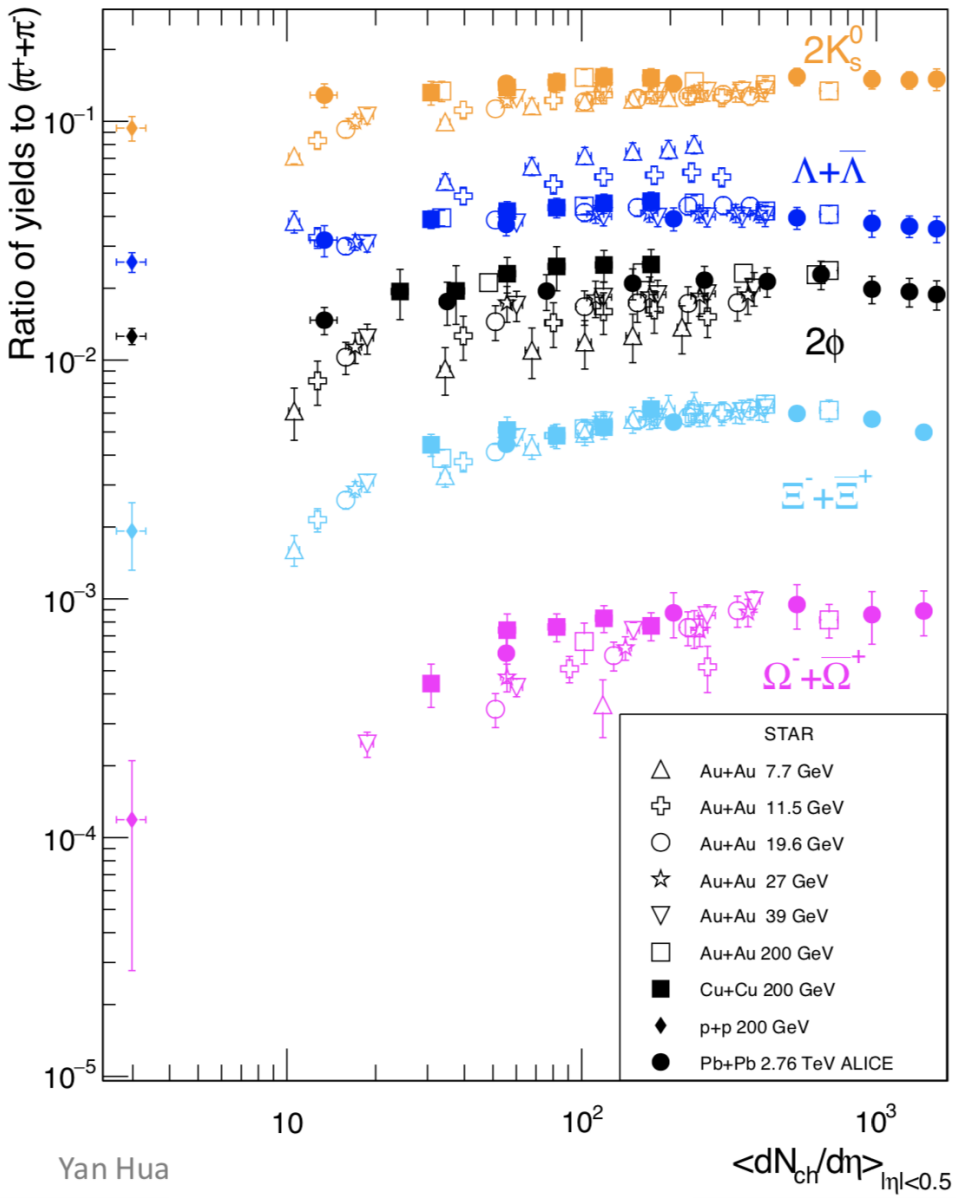


- Smooth transition from p+p to A+A.
- O+O and p+p analysis on-going.

Summary and outlook

- Comprehensive strangeness measurements in STAR BES and top energy collisions.
- Baryon enhancement is observed from 7.7 to 200GeV → consistent with QGP formation.
- Strange hadron yields at central collisions cannot be described by GCE thermal model in FXT collisions, while hadron transport models work better.
- Multi-strange hadron production show strong system-size dependence, sensitive to multiple hadronic/partonic collisions.
- More strangeness measurements and model comparisons in STAR BES-II and top energies will help study the medium properties at almost-zero to high baryon densities, and at different system sizes.

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



Yan Hua

Yan Huang, APS April Meeting 2021, SQM2021

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

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

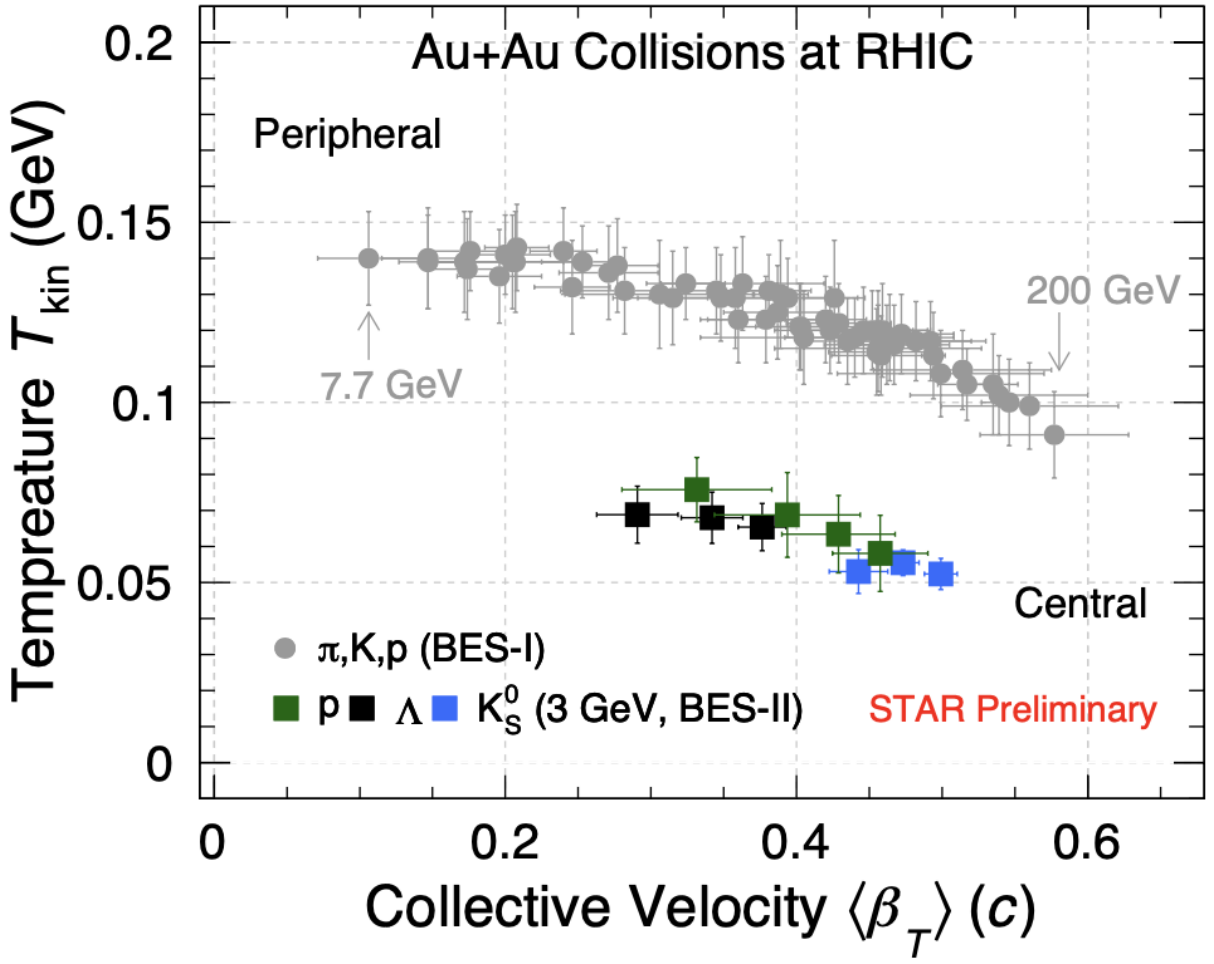
where $M = 1 + m^2/p_t^2$

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

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

- 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

Kinetic freeze-out properties at 3 GeV



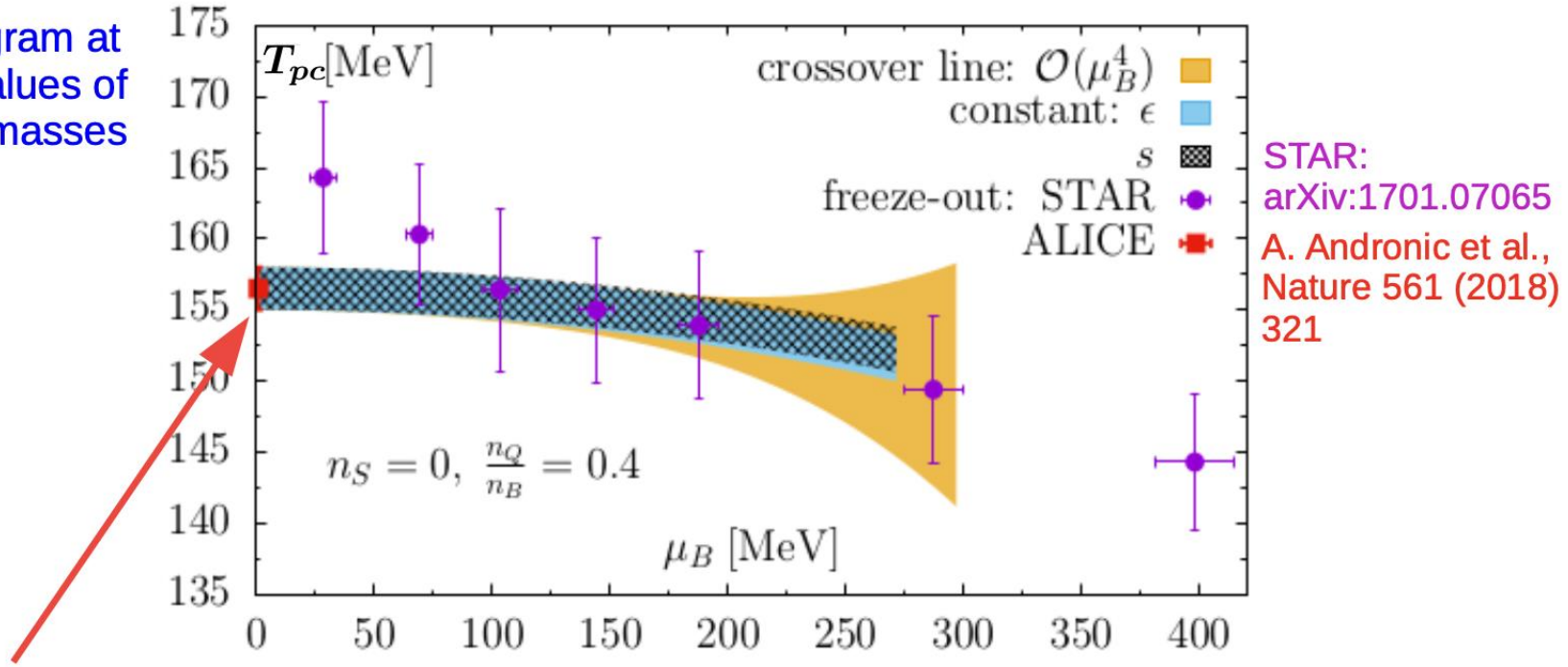
- T_{kin} of Λ and K^0_S at 3 GeV is lower than π, K, p at higher energy collisions
- Similar observations for protons and deuterons, implying different EOS at freeze-out

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

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

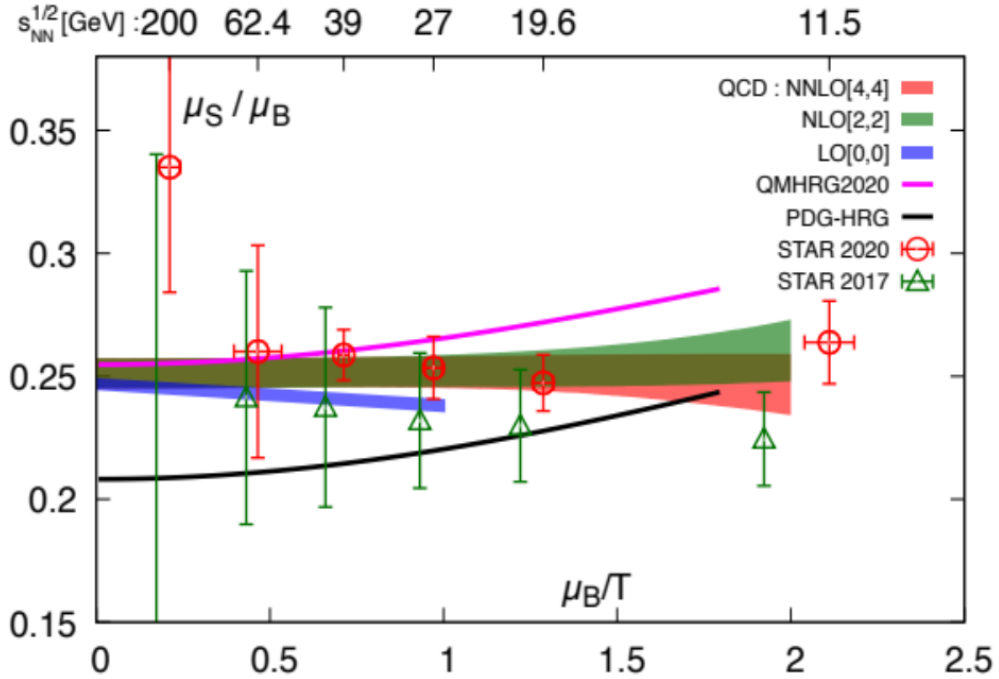
QCD:

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

STAR:

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

F. Karsch, iHIC24



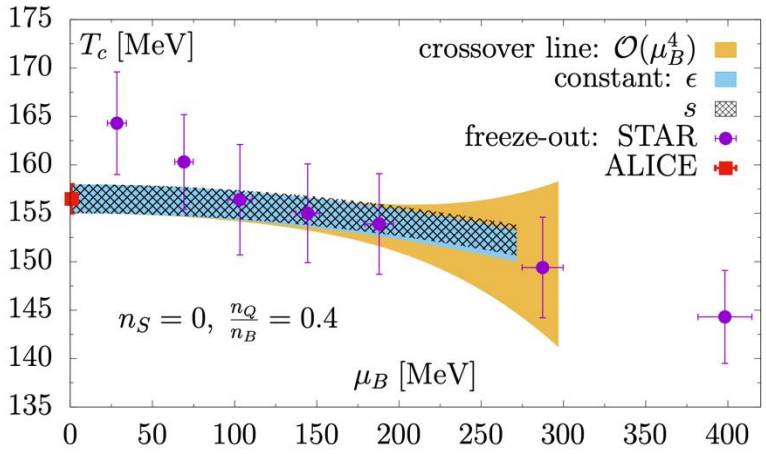
HotQCD, Phys. Rev. D 104 (2021) 074512
arXiv:2107.10011

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.