Strangeness and LF at intermediate baryon density (RHIC BES + SPS)

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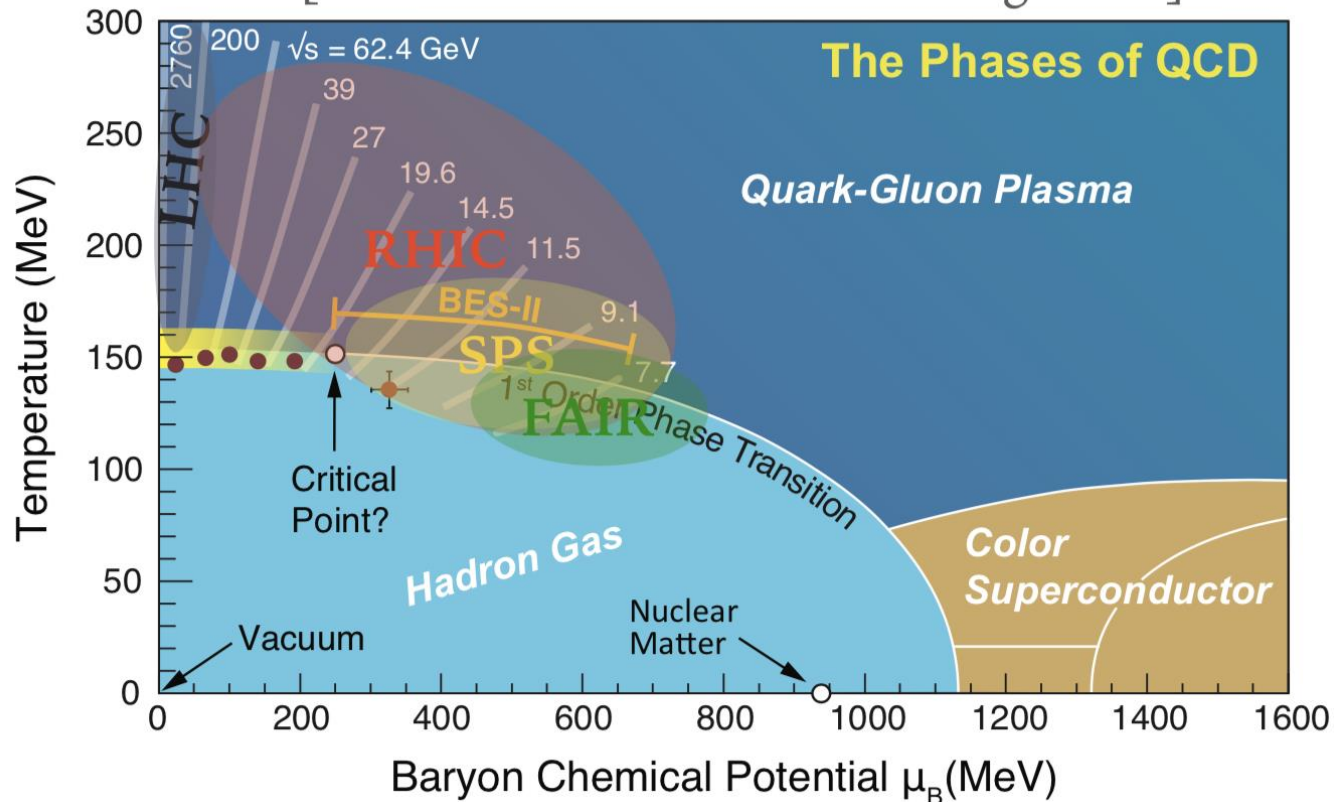
6/12/2019

The 18th International Conference on
Strangeness in Quark Matter (SQM 2019)
10-15 June 2019, Bari (Italy)

QCD phase diagram

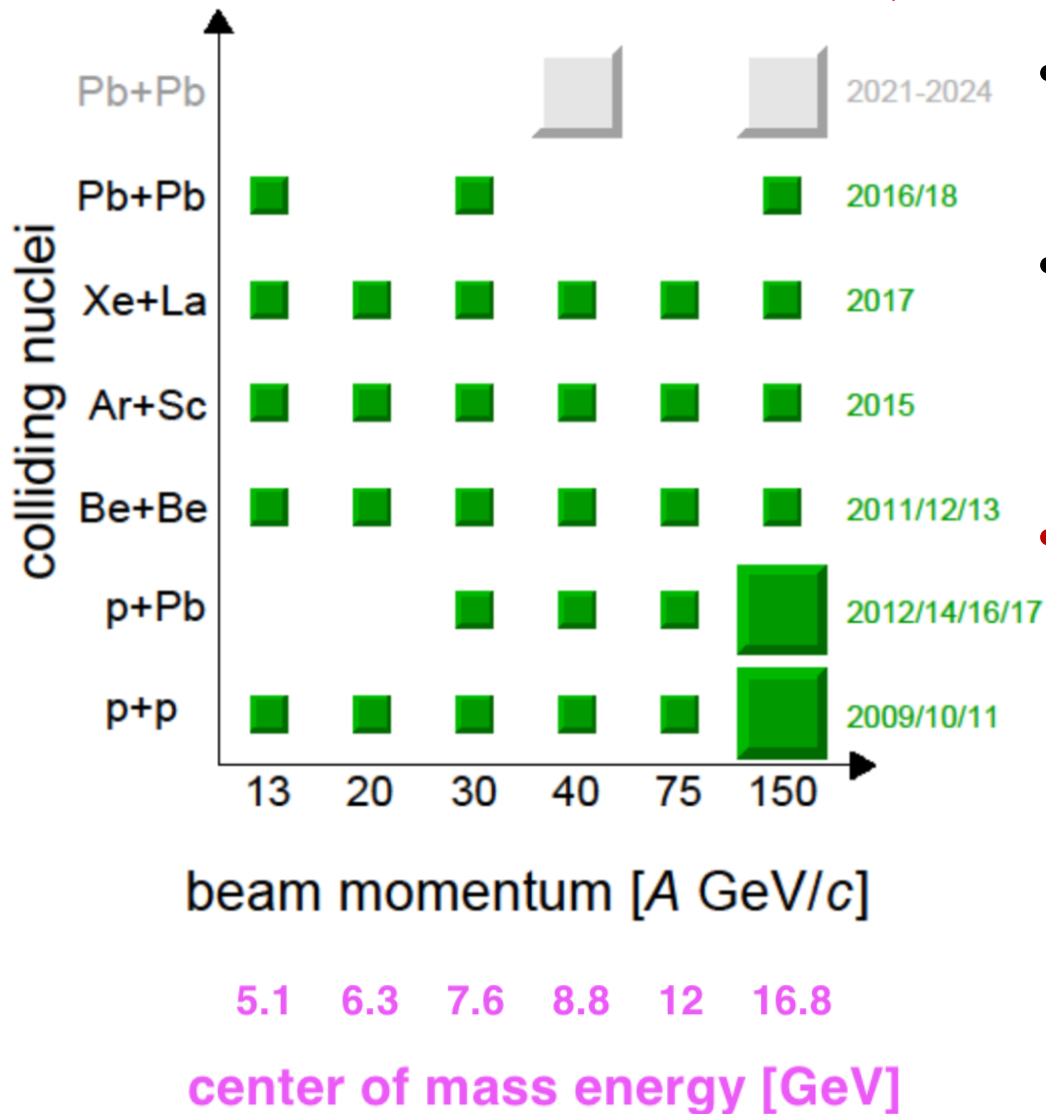[B. Müller: BEST Col. Meeting 2016] D. Tlusty, SQM2017

- **RHIC BES & SPS**
  Cover the intermediate baryon density region
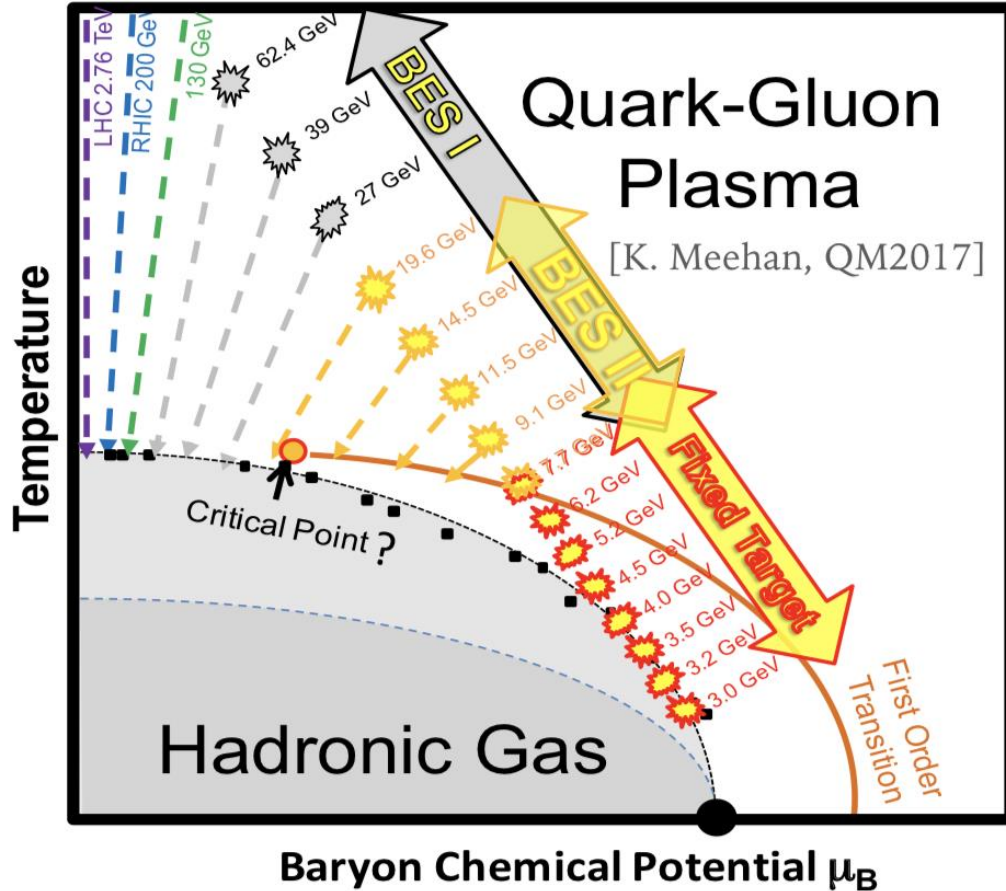 Look for **onset of de-confinement, phase boundary** and
 critical point

NA61/SHINE

- Fixed target experiment at SPS

- Large acceptance: full forward hemisphere down to $p_T=0$

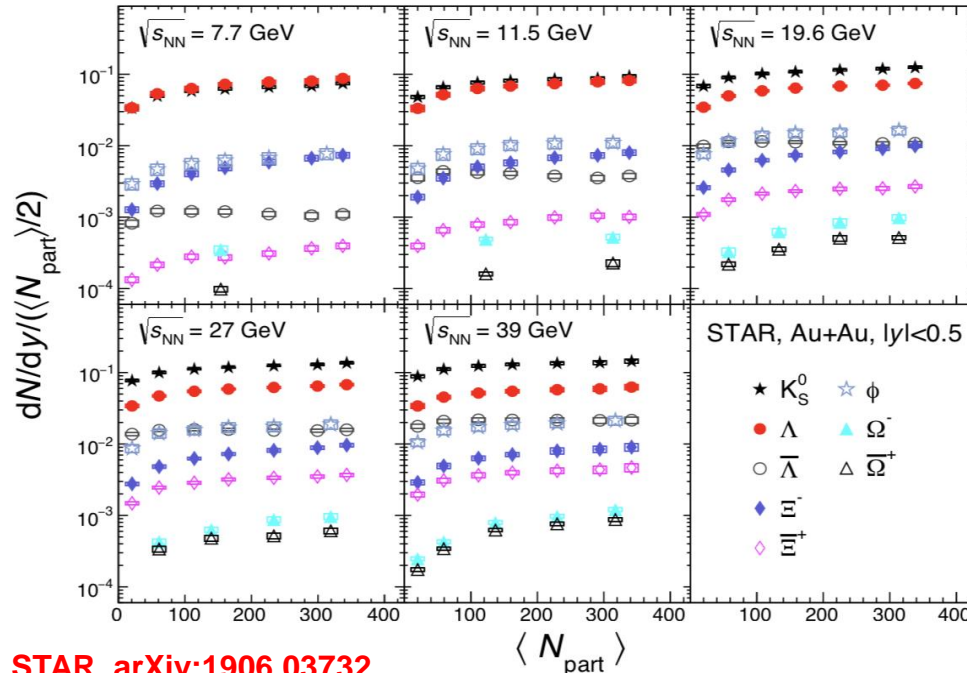- Performed 2D scan in collision energy and system size

STAR BES

[K. Meehan, QM2017]

- Collider experiment at RHIC

- full azimuthal coverage at mid-rapidity

- BES-I (completed) Au+Au $\sqrt{s_{NN}} = 62.4 - 7.7$ GeV

- BES-II (on-going) Au+Au $\sqrt{s_{NN}} = 19.6 - 7.7$ GeV

- Fixed-target (on-going) Au+Au $\sqrt{s_{NN}} = 7.7 - 3.0$ GeV

  μ_B up to 721 MeV

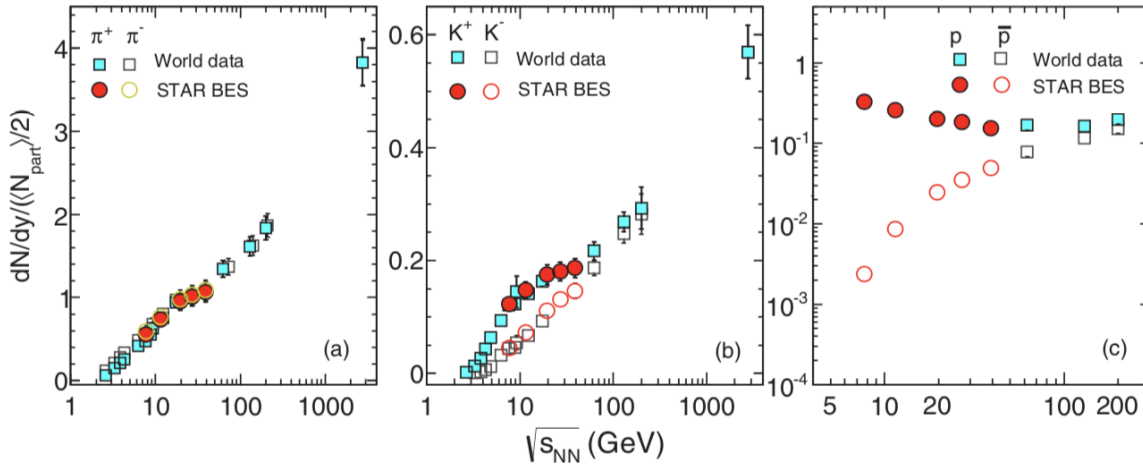# Particle yields (STAR BES-I)
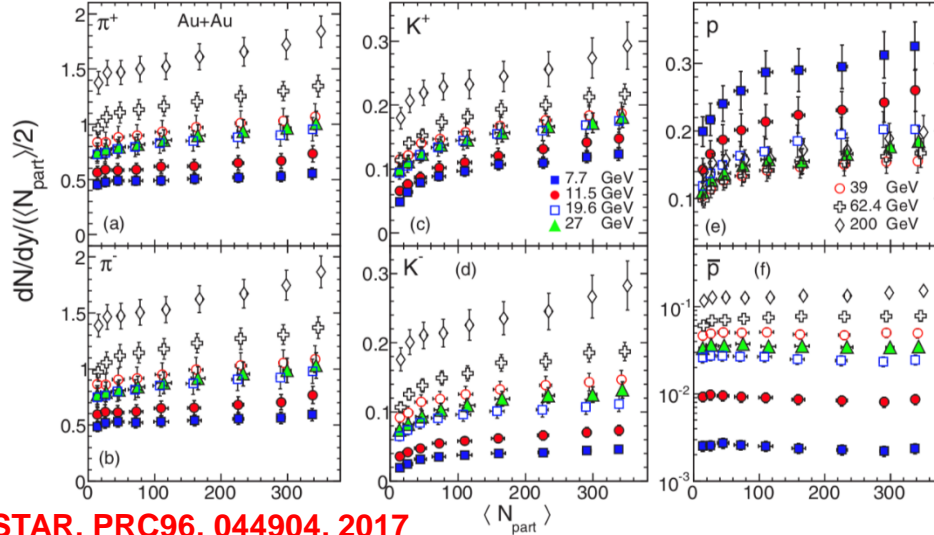

STAR, PRC96, 044904, 2017

STAR, arXiv:1906.03732

- dN/dy at mid-y for all species vs centrality and energy

- Yield per participating pair increases towards central and higher energies in general

- Exceptions:

  - p and Λ yields decrease towards higher energy

  - $\bar{p}$ and $\bar{\Lambda}$ has weak centrality dependence

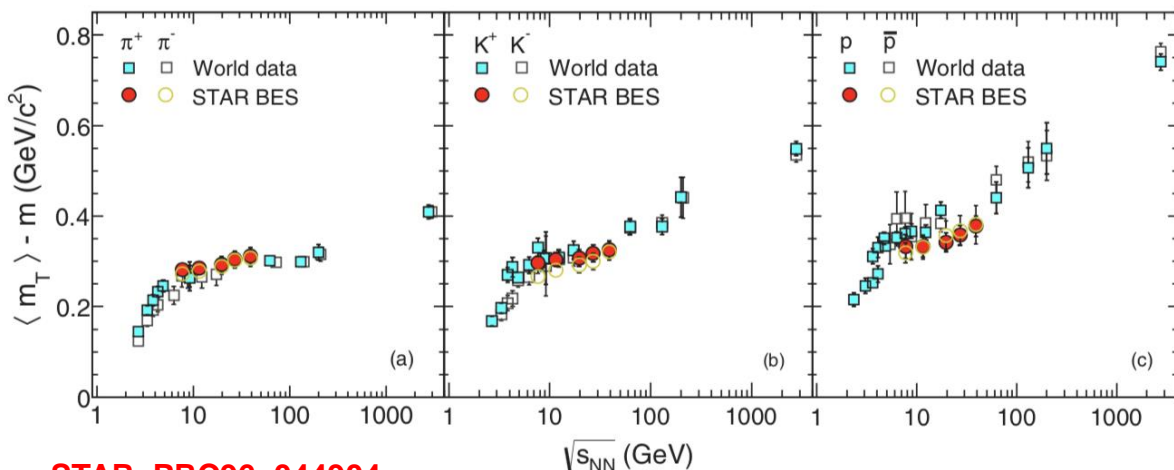# Particle yields in central collisions (STAR BES-I)
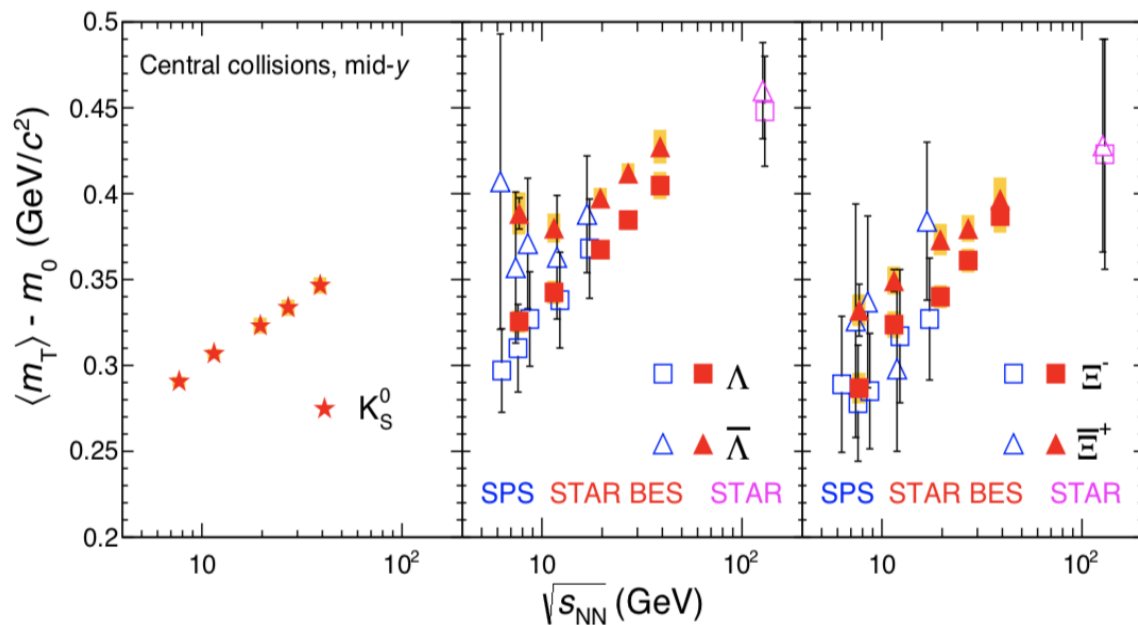

STAR, PRC96, 044904
STAR, arXiv:1906.03732
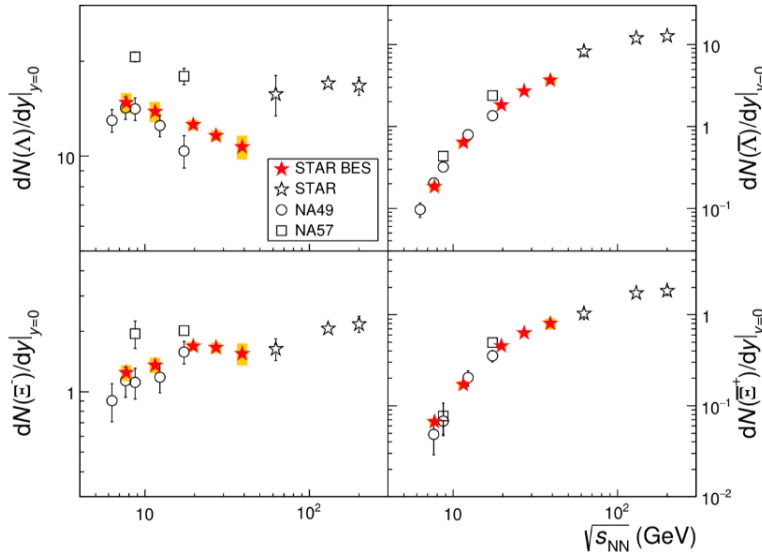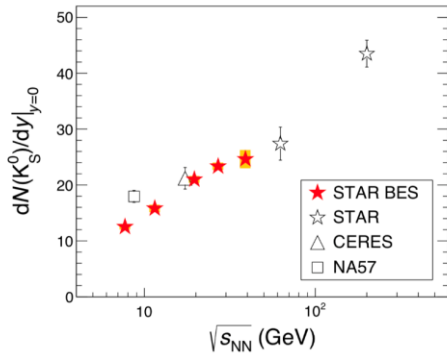
- STAR BES-I data consistent with published data in general

- Rich structure in these excitation functions

- p and Λ yields reach minimum at 39 GeV: interplay of baryon transport and pair production

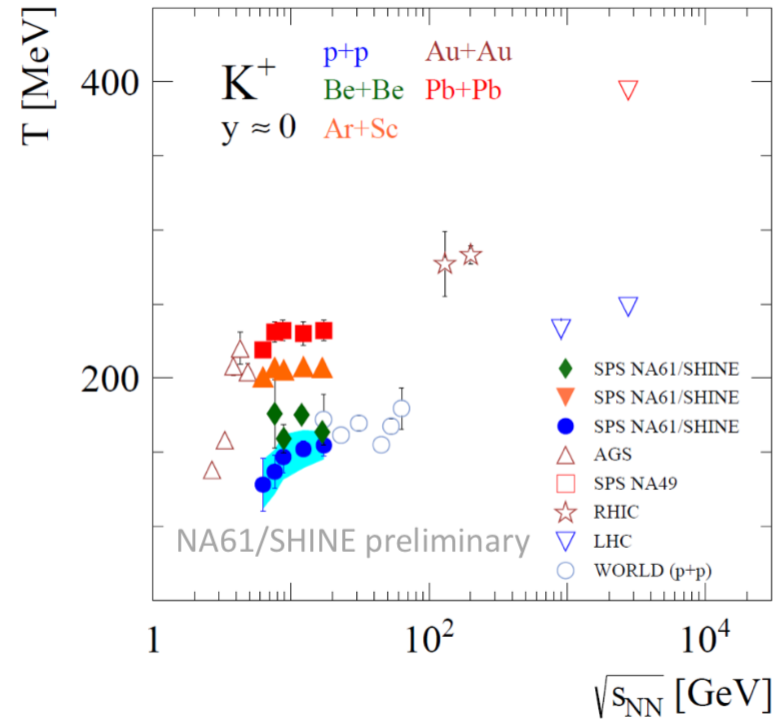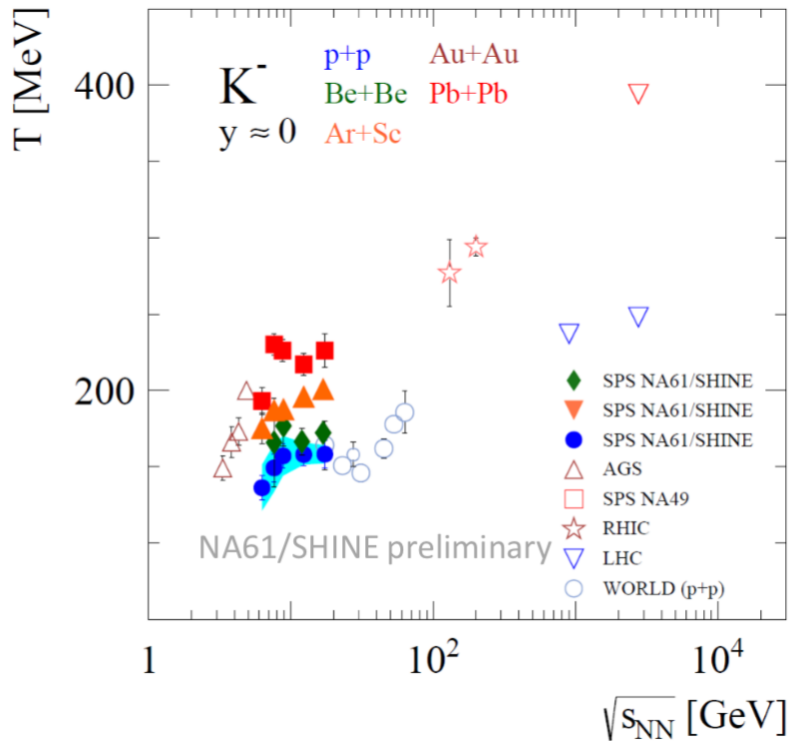# Average transverse mass (STAR BES-I)

STAR, PRC96, 044904
STAR, arXiv:1906.03732

- A step-like structure can be seen in the energy dependence first-order phase transition?

- Λ and $\overline{\Lambda}$ show split at lower energies might be due to baryon-antibaryon annihilations at high baryon density
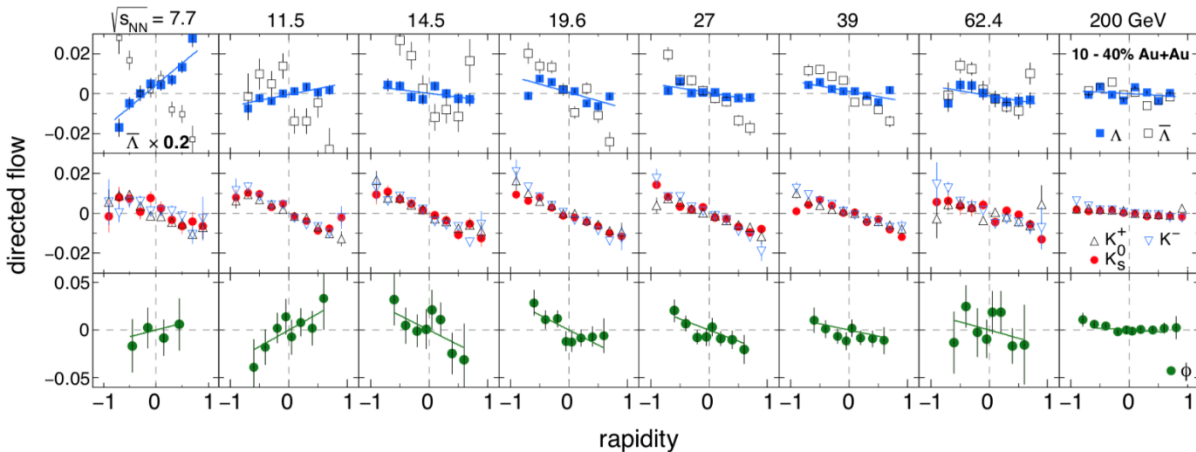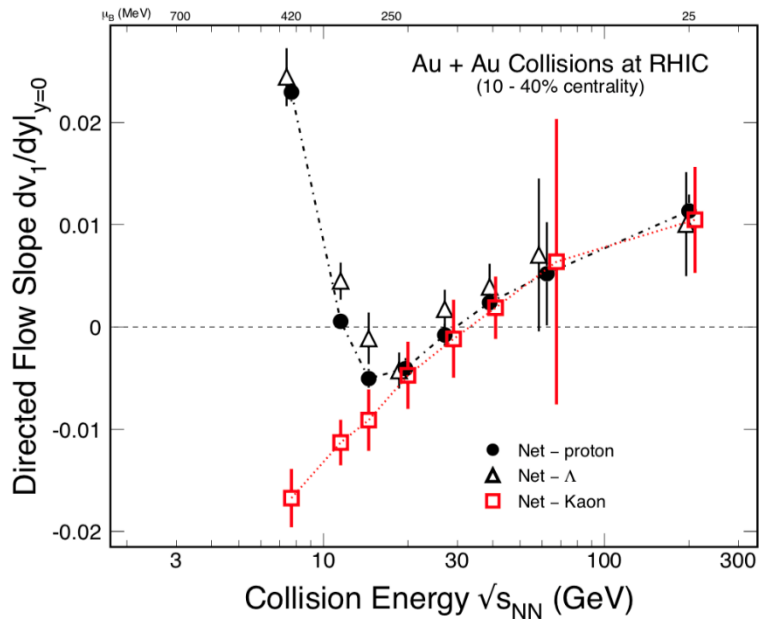
7

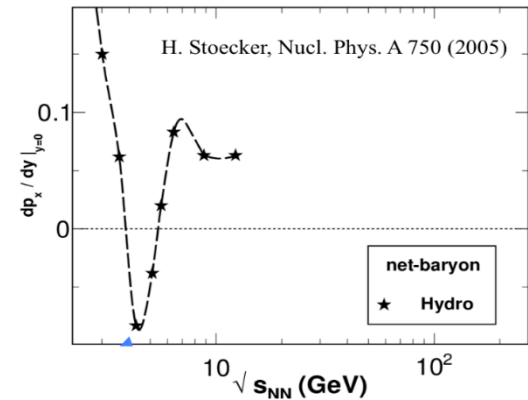# T slope (NA61/SHINE)

P. Podlaski, Tue

- Qualitatively similar energy dependence is seen in p+p, Be+Be and Pb+Pb collisions

- Magnitude of T in Be+Be slightly higher than in p+p

- Ar+Sc results between p+p/Be+Be and Pb+Pb
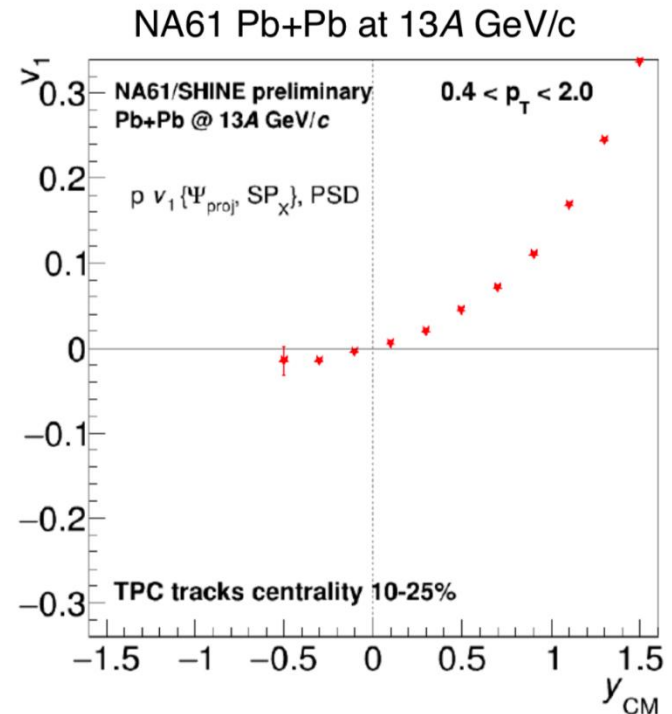
Directed flow (STAR BES-I)

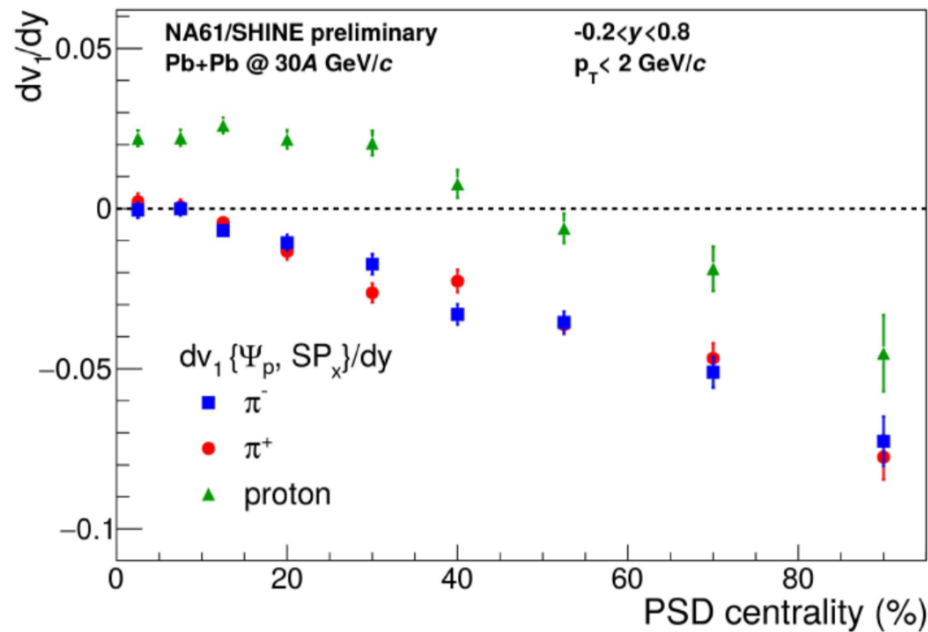**STAR, PRL112, 162301 (2014)**
STAR, PRL120, 062301 (2018)

- Sign change of proton dv_1/dy, softening of EOS, first-order phase transition

- Double sign change seen in net-proton, net-Λ, not seen in net-kaon

- Need theory to explain
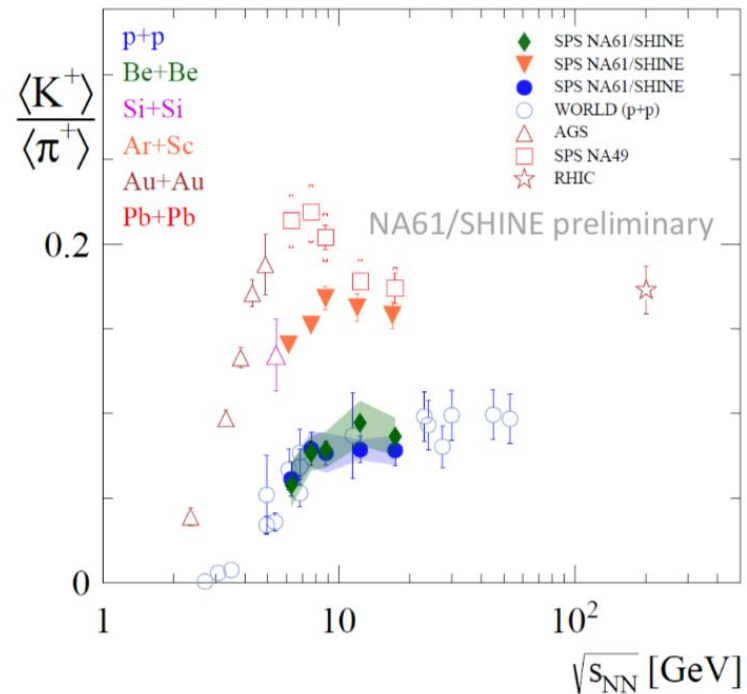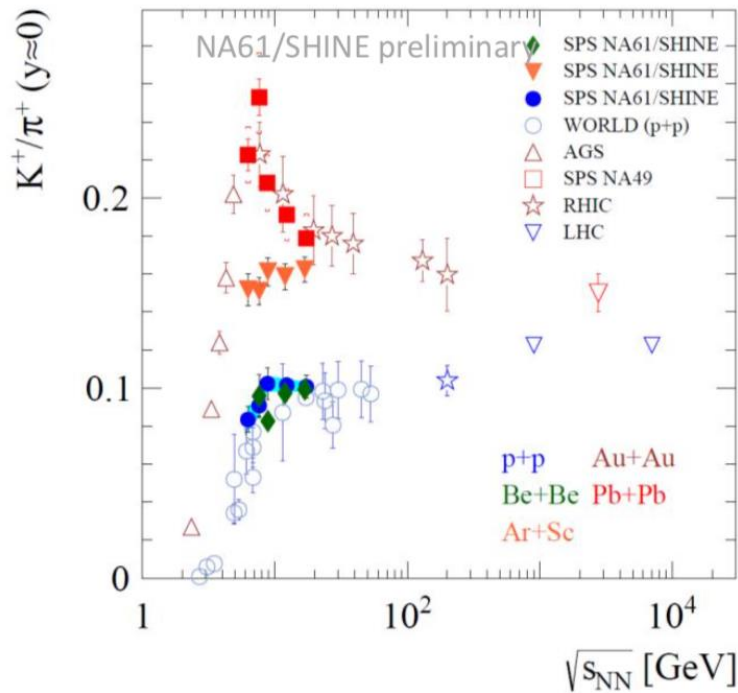
9

Directed flow (NA61/SHINE)

S. Puławski, Mon

- At 30A GeV/c, close to mid-rapidity, slope of pion v_1 is negative for all centralities; slope of proton v_1 changes sign at centrality of about 50%

- At 13A GeV/c, no evidence for the collapse of proton v_1
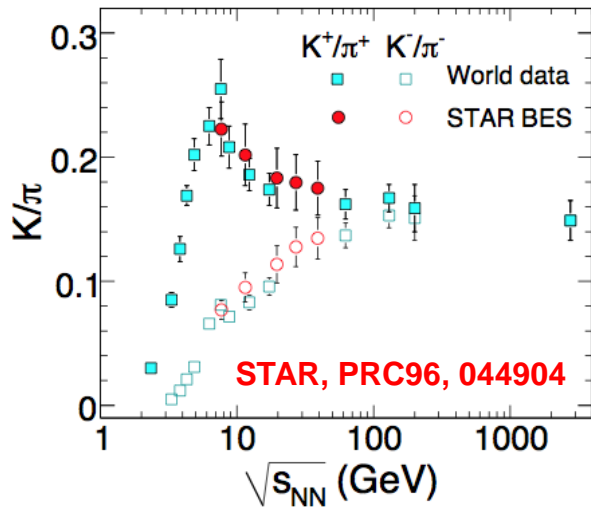
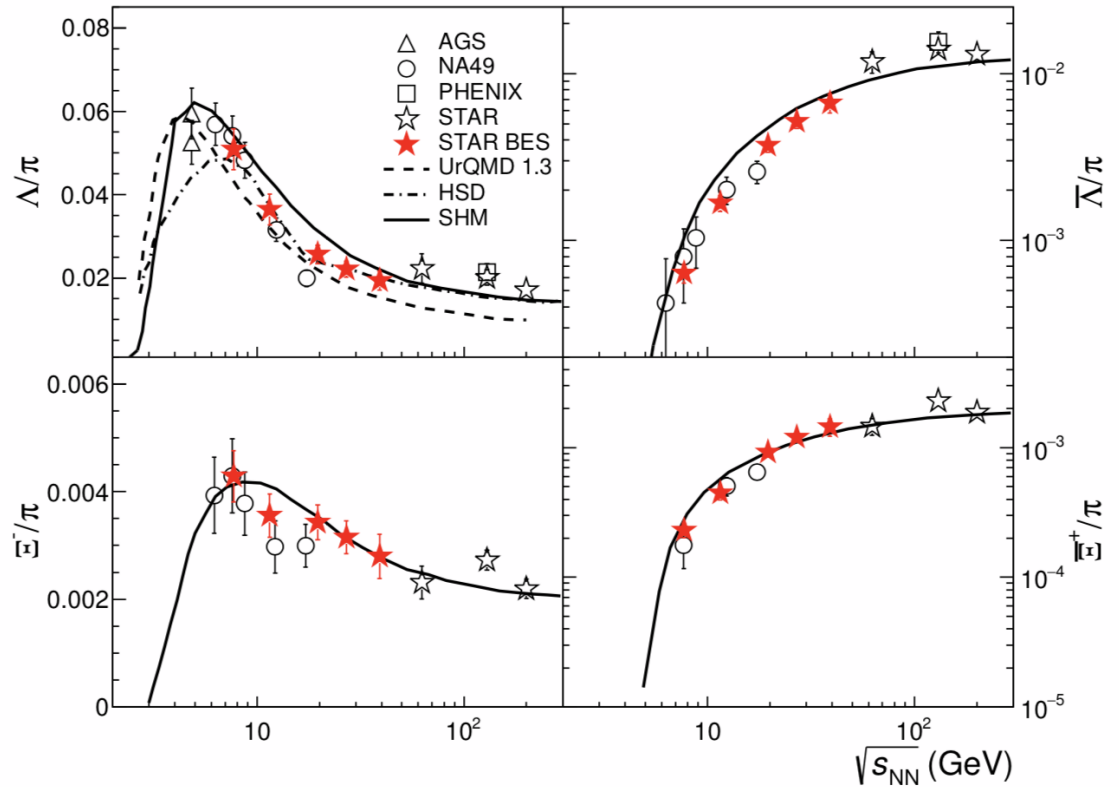# K⁺/π⁺ ratio (NA61/SHINE)

P. Podlaski, Tue

- Plateau like structure visible in p+p
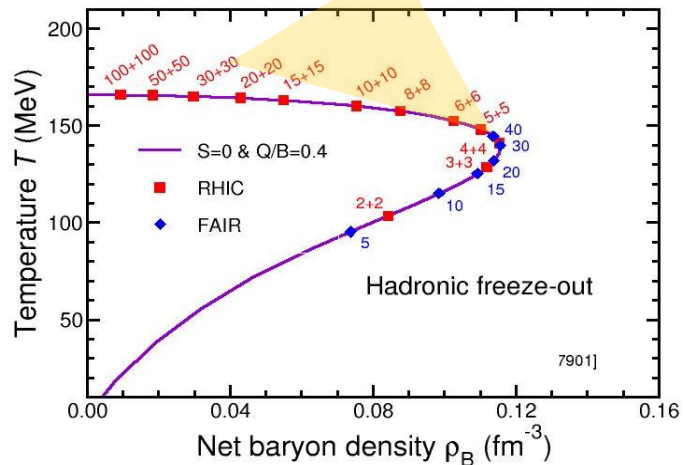
- Be+Be close to p+p

- Ar+Sc is higher than p+p but form of energy dependence is similar to p+p (no horn)

Strange hadron to pion ratio (STAR BES-I)

STAR, PRC96, 044904

RHIC BES

J. Randrup et al., PRC 74, 047901 (2006)
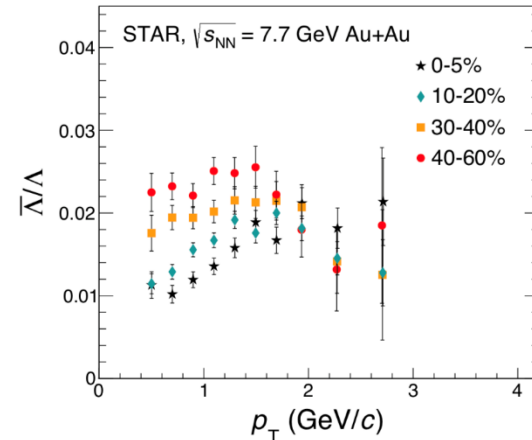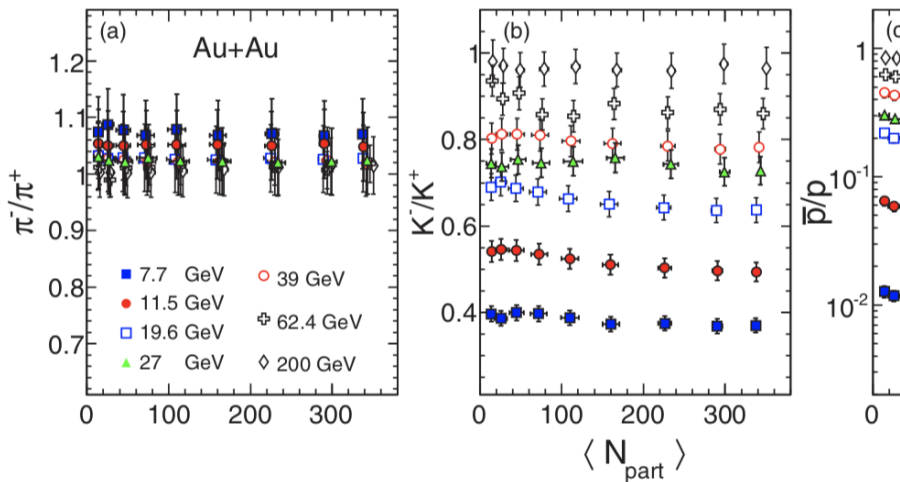
➤ Particle ratios consistent with NA49, consistent with the picture of a **maximum net-baryon density around $\sqrt{s_{NN}} \sim 8$ GeV at freeze-out**

12

Anti-hadron to hadron ratio (STAR BES-I)

STAR, PRC96, 044904
STAR, arXiv:1906.03732
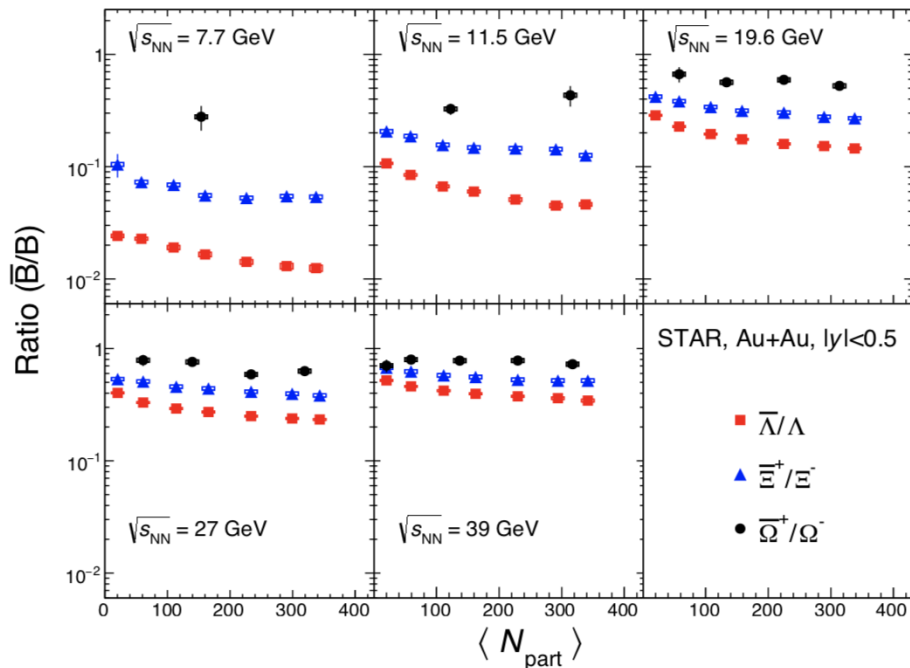
- Centrality dependence of $\overline{B}/B$ ratios: **peripheral > central**

- This effect is more prominent at lower energies.
  baryon stopping and/or anti-baryon absorption

- **Loss of low p_T $\overline{\Lambda}$ in central collisions**

Anti-hadron to hadron ratio (STAR BES-I)

STAR, PRC96, 044904
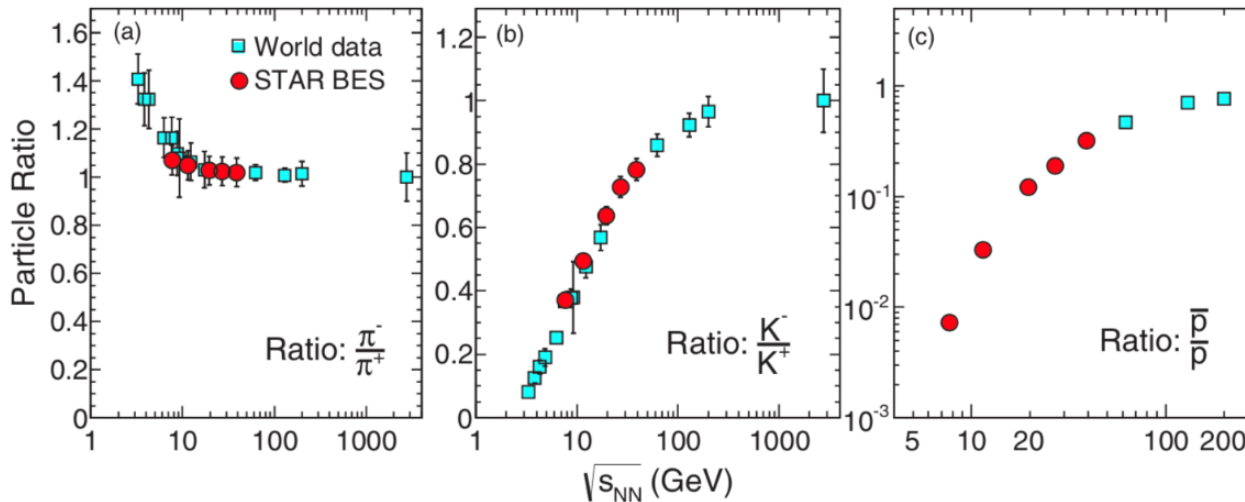STAR, arXiv:1906.03732
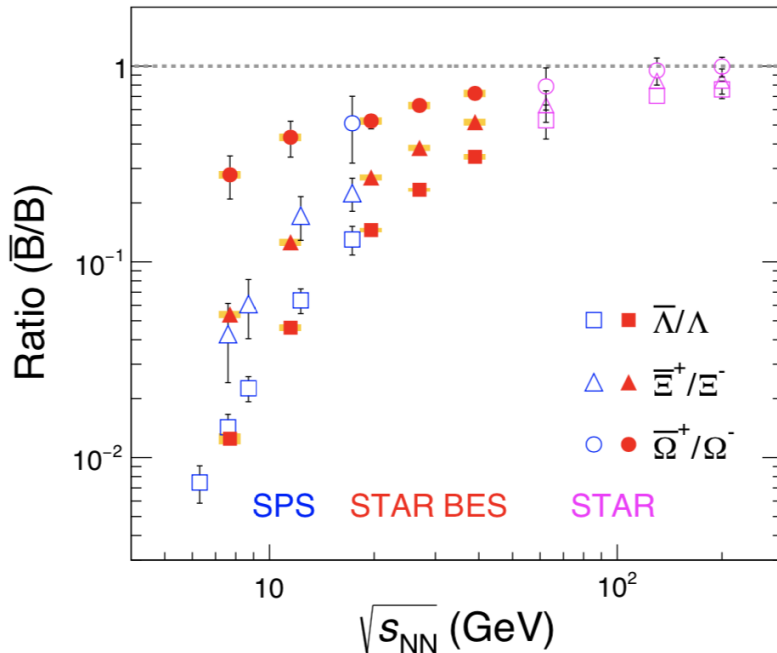
- STAR BES data lie in a trend with NA49 data

- $\overline{\mathbf{B}}/\mathbf{B}$ ratios increase with number of strange quarks at low energies
$$\overline{\Omega}^+/\Omega^- > \overline{\Xi}^+/\Xi^- > \overline{\Lambda}/\Lambda > \overline{p}/p$$

Anti-hyperon to hyperon ratio

$$n_i = \frac{g_i}{(2\pi^2)} \gamma_S^{|S_i|} m_i^2 T K_2(m_i/T) \exp(\mu_i/T)$$

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

$$\frac{\overline{\Xi}^+}{\Xi^-} = \exp\left(-\frac{2\mu_B}{T} + \frac{4\mu_S}{T}\right) \qquad \ln\left(\frac{\overline{\Xi}^+}{\Xi^-}\right) = -\frac{2\mu_B}{T} + \frac{4\mu_S}{T}$$
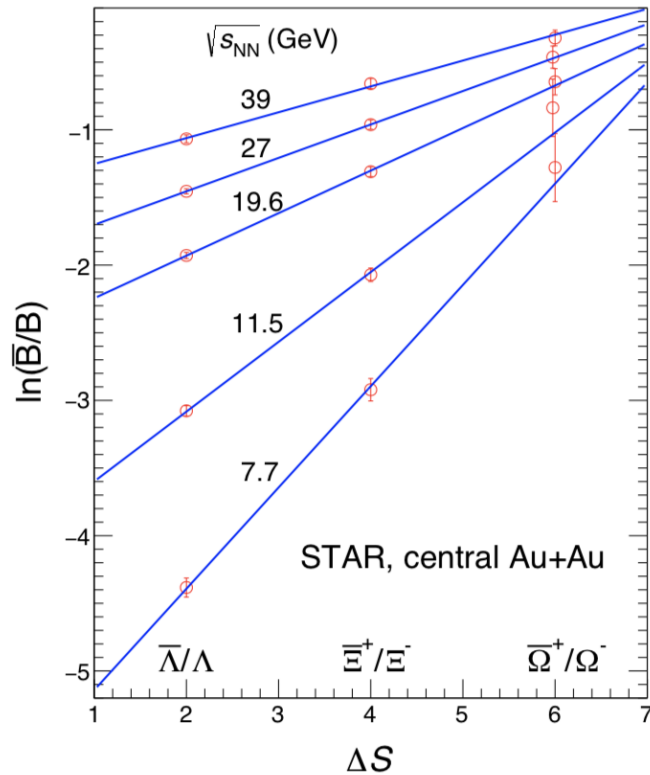
$$\frac{\overline{\Omega}^+}{\Omega^-} = \exp\left(-\frac{2\mu_B}{T} + \frac{6\mu_S}{T}\right) \qquad \ln\left(\frac{\overline{\Omega}^+}{\Omega^-}\right) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T}$$
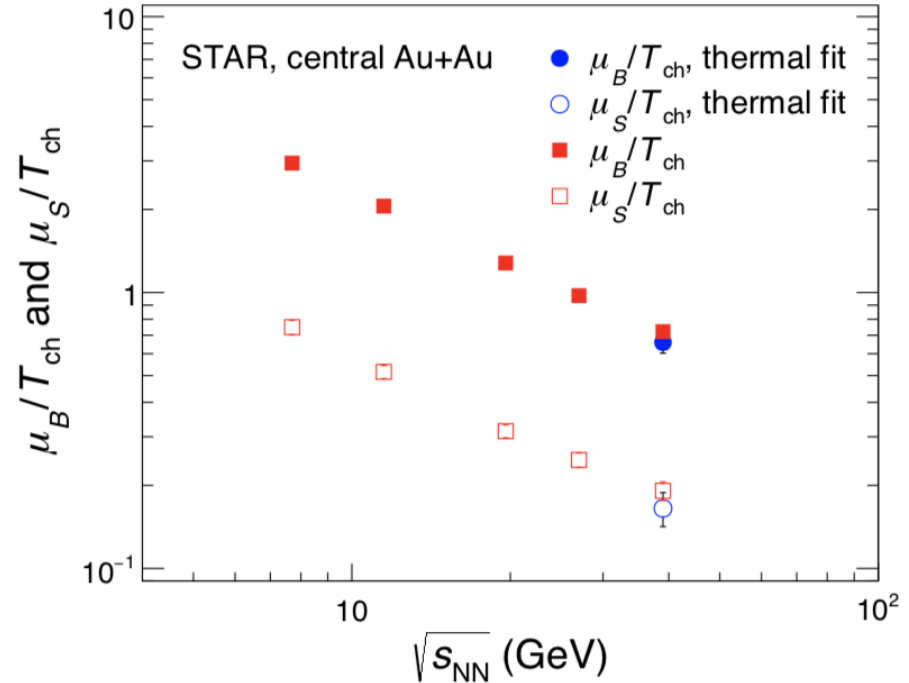
- T is the temperature.
- μ_B is the baryon chemical potential.
- μ_S is the strangeness chemical potential.

(arXiv:nucl-th/9704046v1 by J.Cleymans & Phys. Rev. C 71(2005)054901)

μ_S/T_{ch} and μ_B/T_{ch}
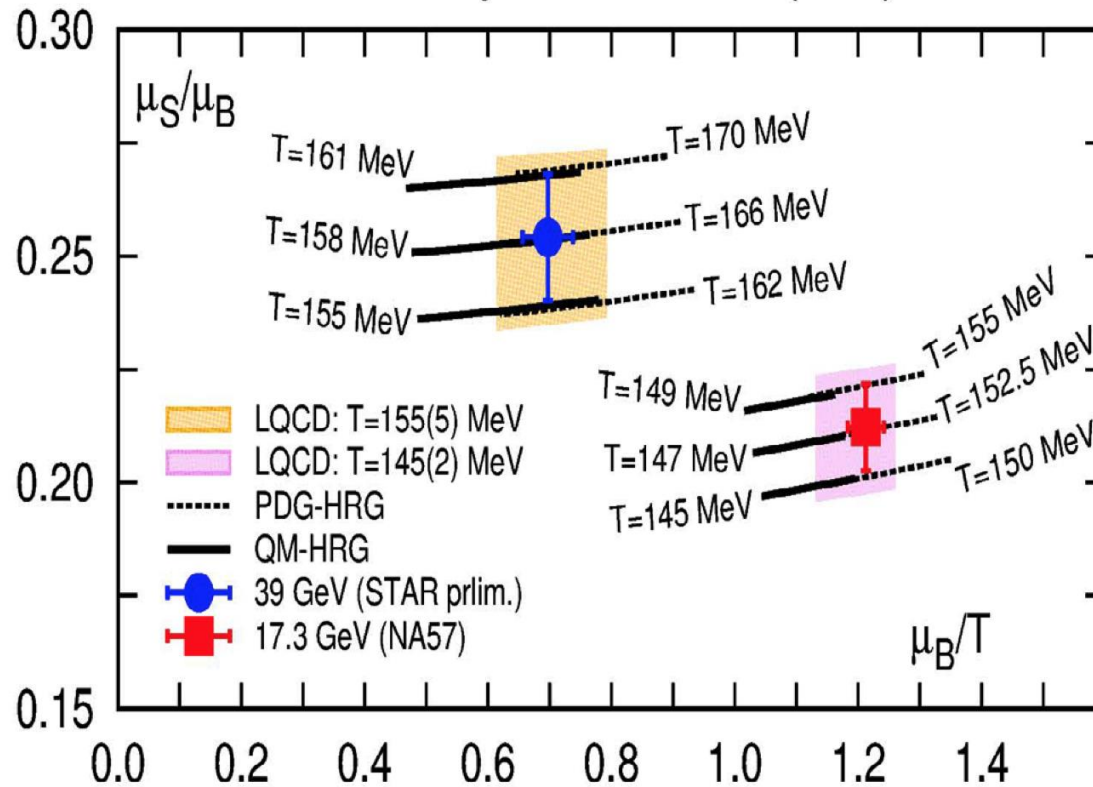

STAR, arXiv:1906.03732

- Anti-hyperon to hyperon ratios are fit well with statistical thermal model
- Chemical freeze-out parameters, μ_S/T_{ch} and μ_B/T_{ch}, are extracted

Strangeness, LQCD and freeze-out in HIC

freeze-out T by comparing
μ_S/μ_B from LQCD and expt.

From Swagato Mukherjee

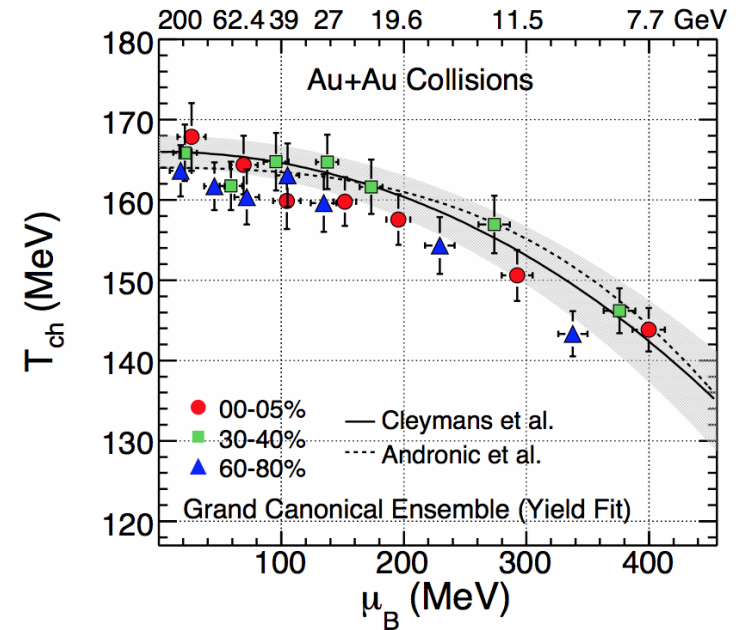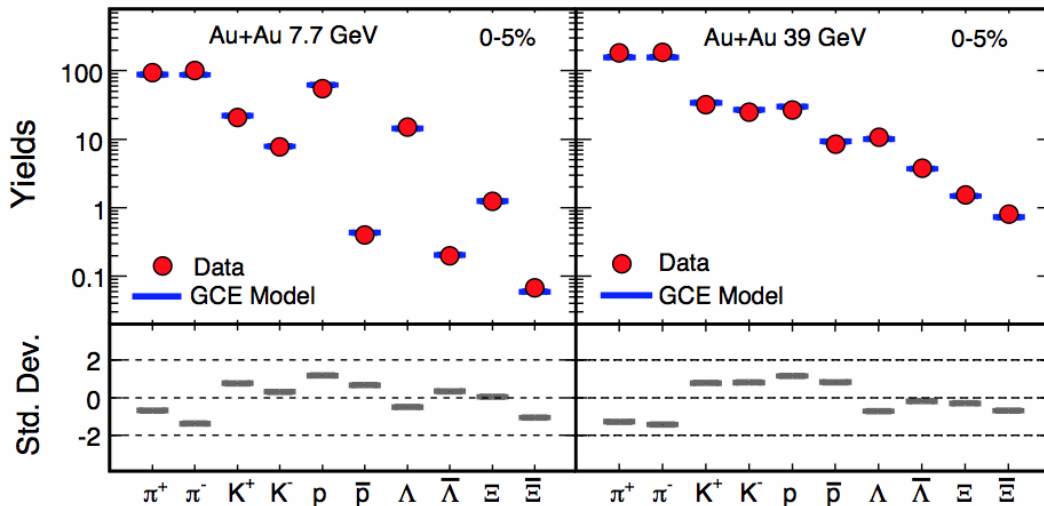not reproduced by hadron gas with only PDG states

reproduced when additional Quark Model (QM) predicted strange baryons are taken into account

BNL-Bi-CCNU: Phys. Rev. Lett. 113 (2014) 072001

indirect evidence for so-far undiscovered strange baryons at RHIC ?
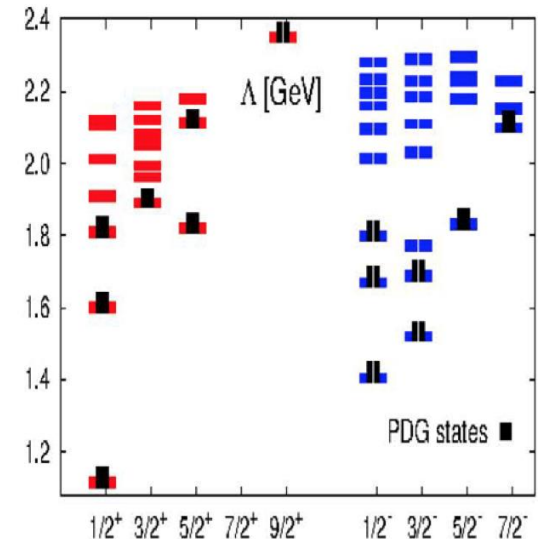
Chemical freeze-out parameters: T_{ch} vs. μ_B

STAR，Phys. Rev. C 96, 044904, 2017

✓Particles used : **π, K, p, Λ, Ξ**

✓ Ensemble used:
   Grand canonical (GCE)

✓ Fit parameters:
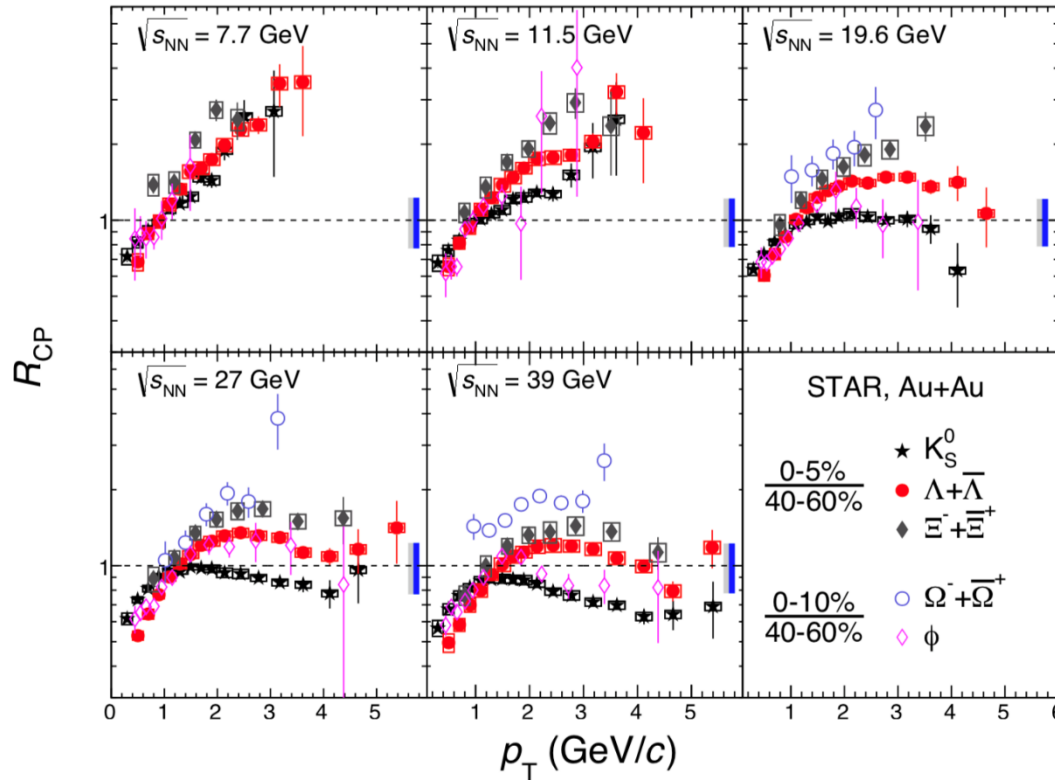   **T_{ch}, μ_B, μ_s** and **γ_s**

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.
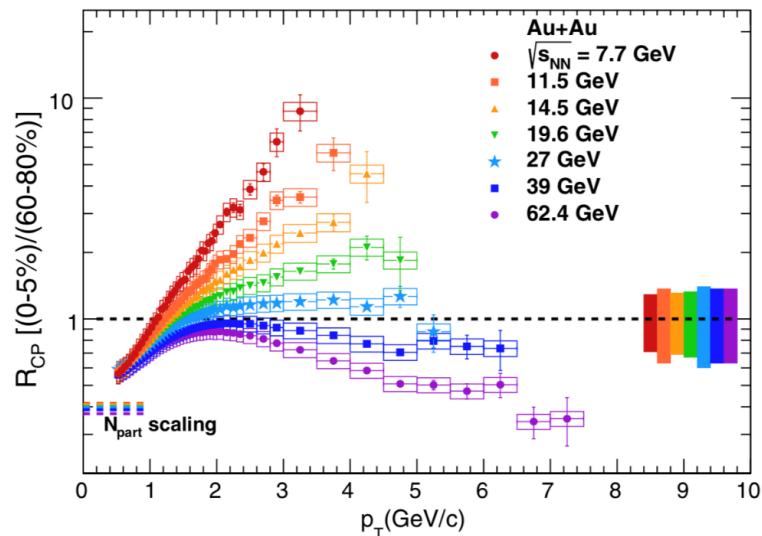
Nuclear modification factors R_{CP}

$$R_{CP}(p_T) = \frac{[d^2\sigma/(N_{bin}p_T dp_T dy)]_{central}}{[d^2\sigma/(N_{bin}p_T dp_T dy)]_{peripheral}}$$
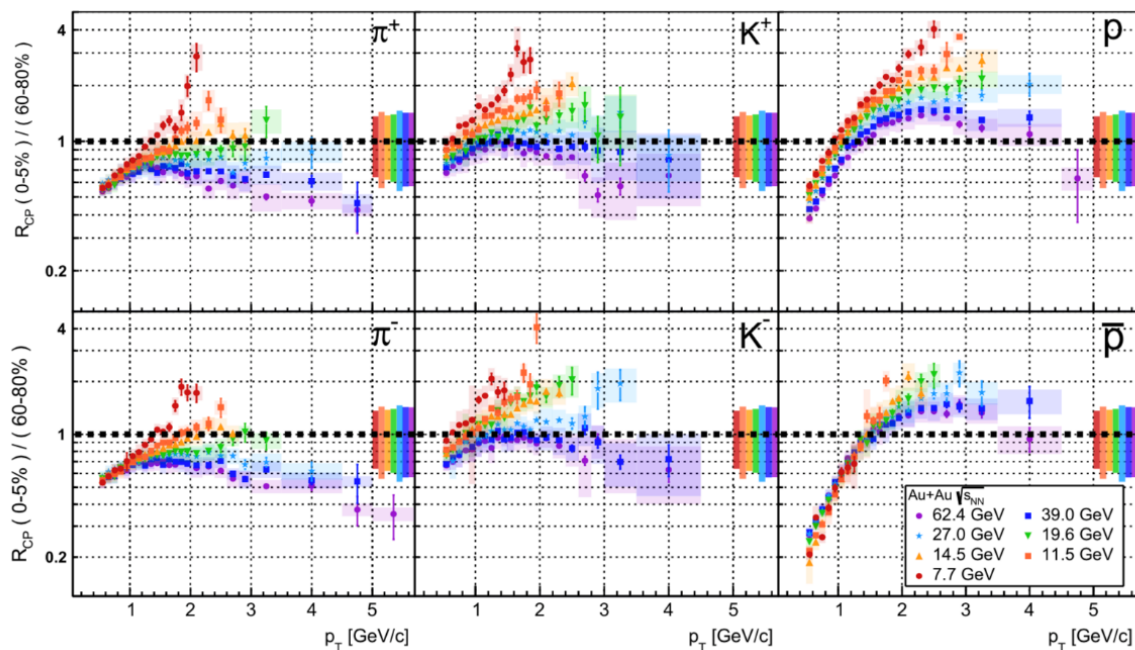
STAR, arXiv:1906.03732

- No K_S^0 suppression in Au+Au 7.7 and 11.5 GeV
- Cronin effect and other effects (radial flow) compete with partonic energy loss
- Intermediate p_T, particle R_{CP} difference becomes smaller @ 7.7 and 11.5 GeV
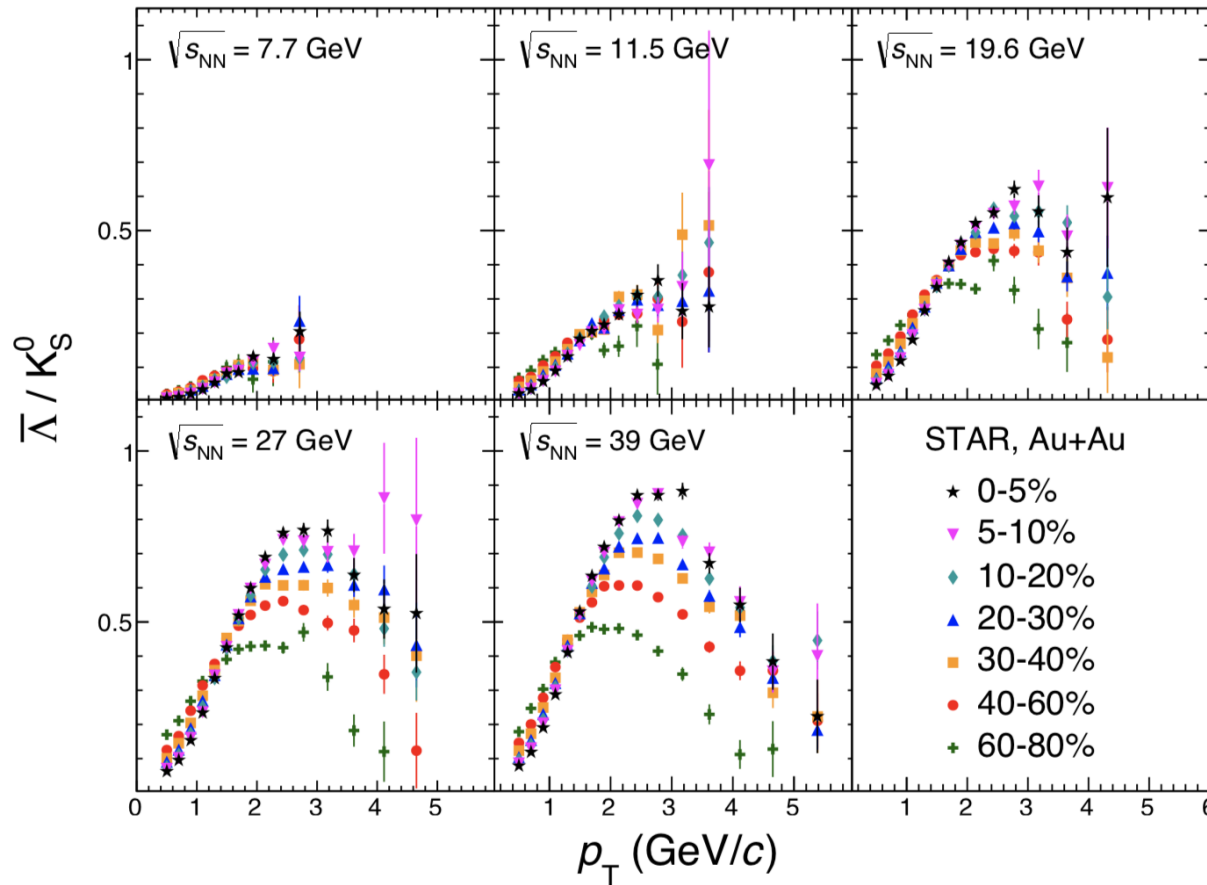
19

Nuclear modification factors R_{CP}

- No suppression for lower energies
- Cronin effect and other effects (radial flow) compete with partonic energy loss
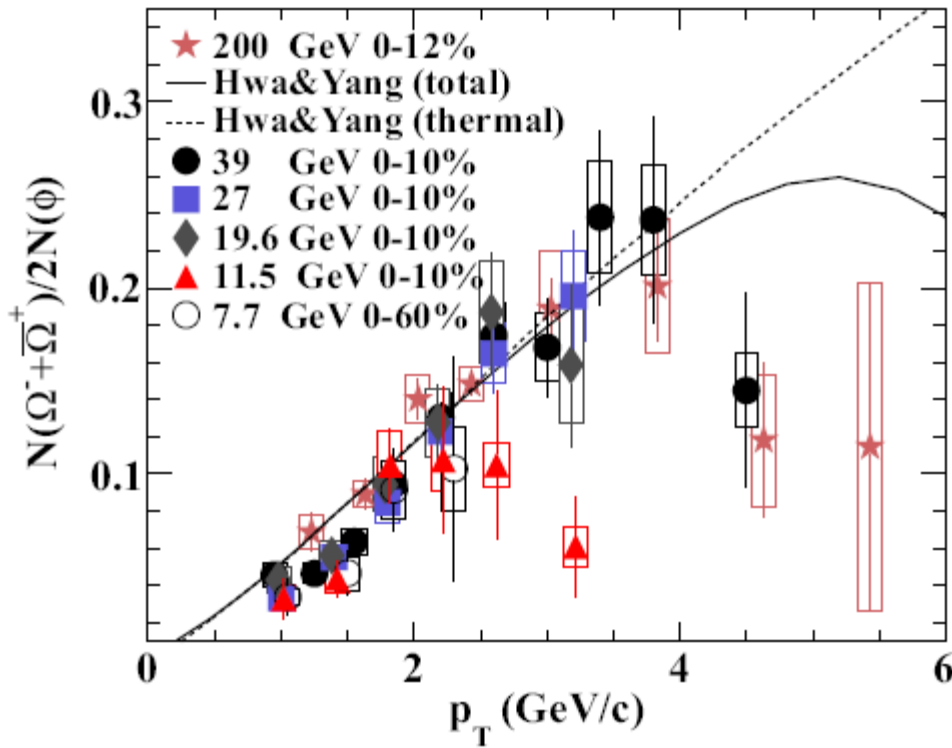
STAR, PRL121, 032301, 2018

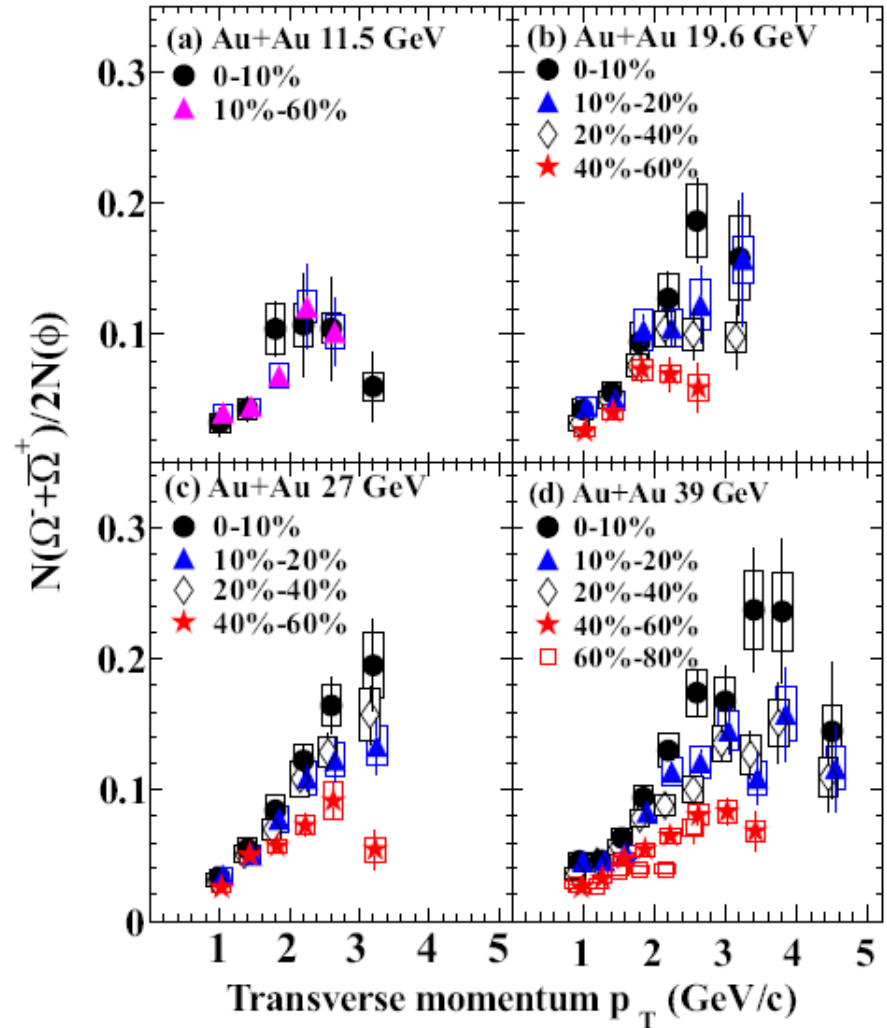# Baryon to meson ratio: $\overline{\Lambda}/K_S^0$

STAR, arXiv:1906.03732

$\sqrt{s_{NN}} < $ **19.6 GeV**, at intermediate p_T, the separation of central (0-5%) and peripheral (40-60%) collisions in $\overline{\Lambda}/K_S^0$ becomes less significant
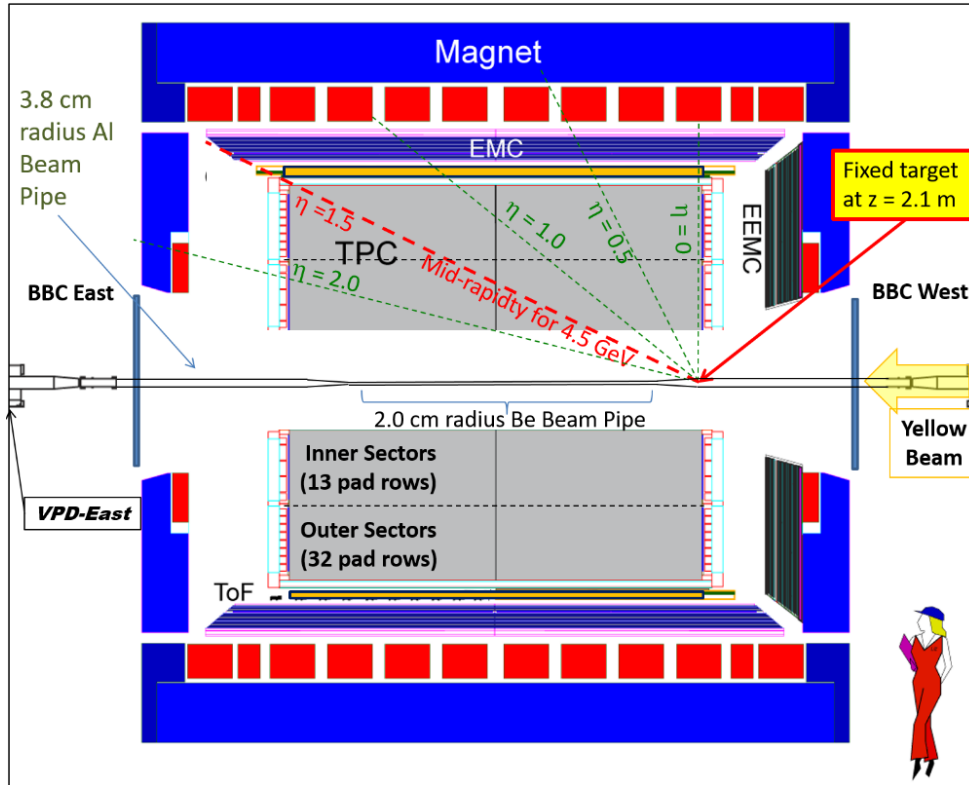
21

Ω / φ ratio

➤ Intermediate p_T Ω/φ ratios:
Indication of separation between ≥ 19.6 and 11.5 GeV

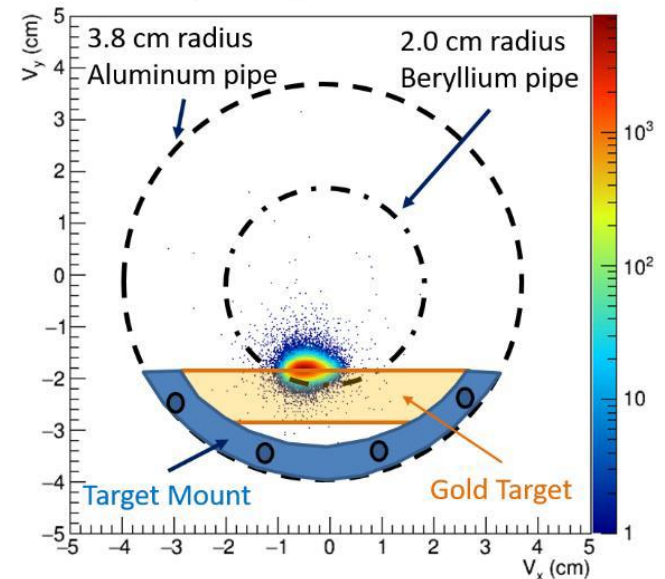➤ Ω/φ ratios: 40%-60% peripheral < 0-10% central for 19.6, 27 and 39 GeV

The STAR fixed-target program
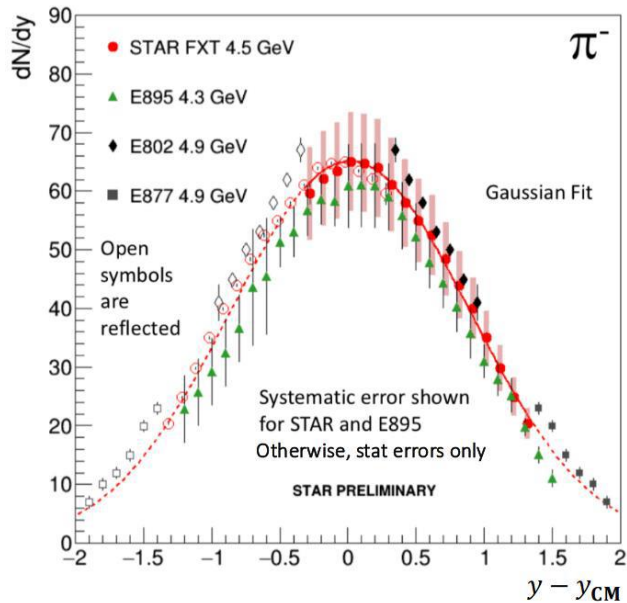

A 1 mm thick (4% inter. prob.) gold target

V_y vs. V_x Distribution

1.3M events from half hour test run, top 30% central trigger, Au+Au $\sqrt{s_{NN}}$=4.5 GeV
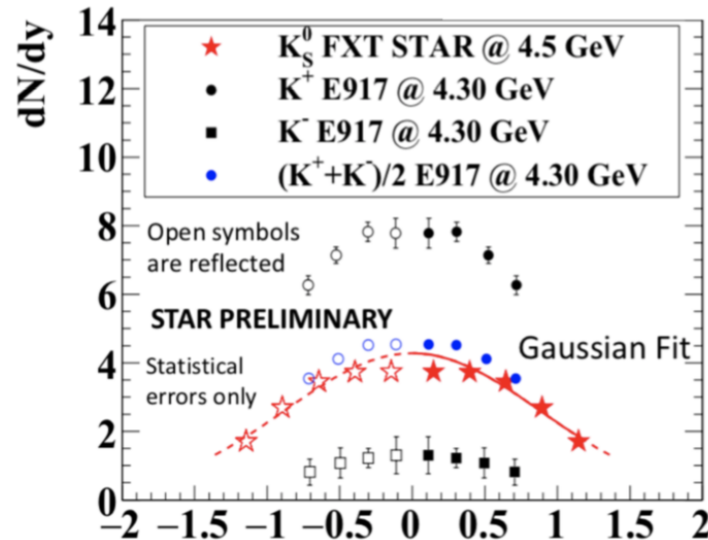
3.4M events from two hour test run, top 30% central trigger, Al+Au $\sqrt{s_{NN}}$=4.9 GeV

Hadron spectra and dN/dy in Au+Au $\sqrt{s_{NN}}$=4.5 GeV
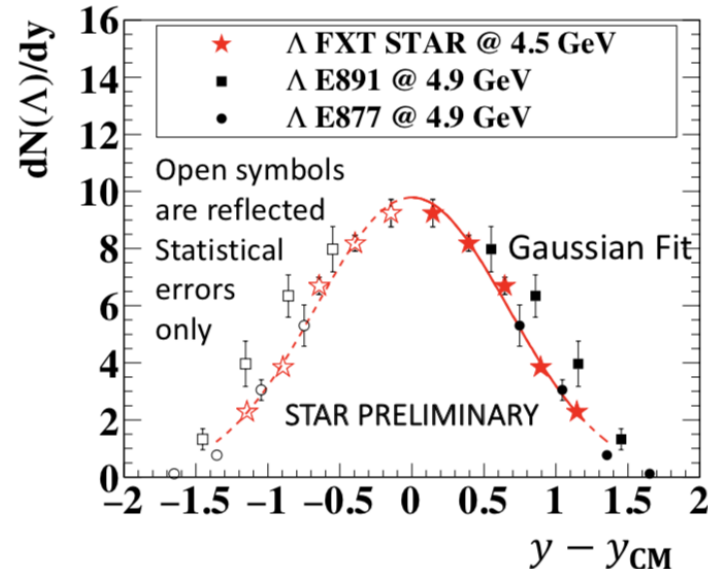

Y. Wu, QM2018
Top 5%

E895. Phys. Rev. C 68 (2003) 054905
E802. Phys. Rev. C 57 (1998) R466
E877. Phys. Rev. C 62 (2000) 024901

- Amplitude and width of rapidity densities are consistent with AGS experiments
- $m_T - m_0$ and y range will be extended by eTOF and iTPC upgrades
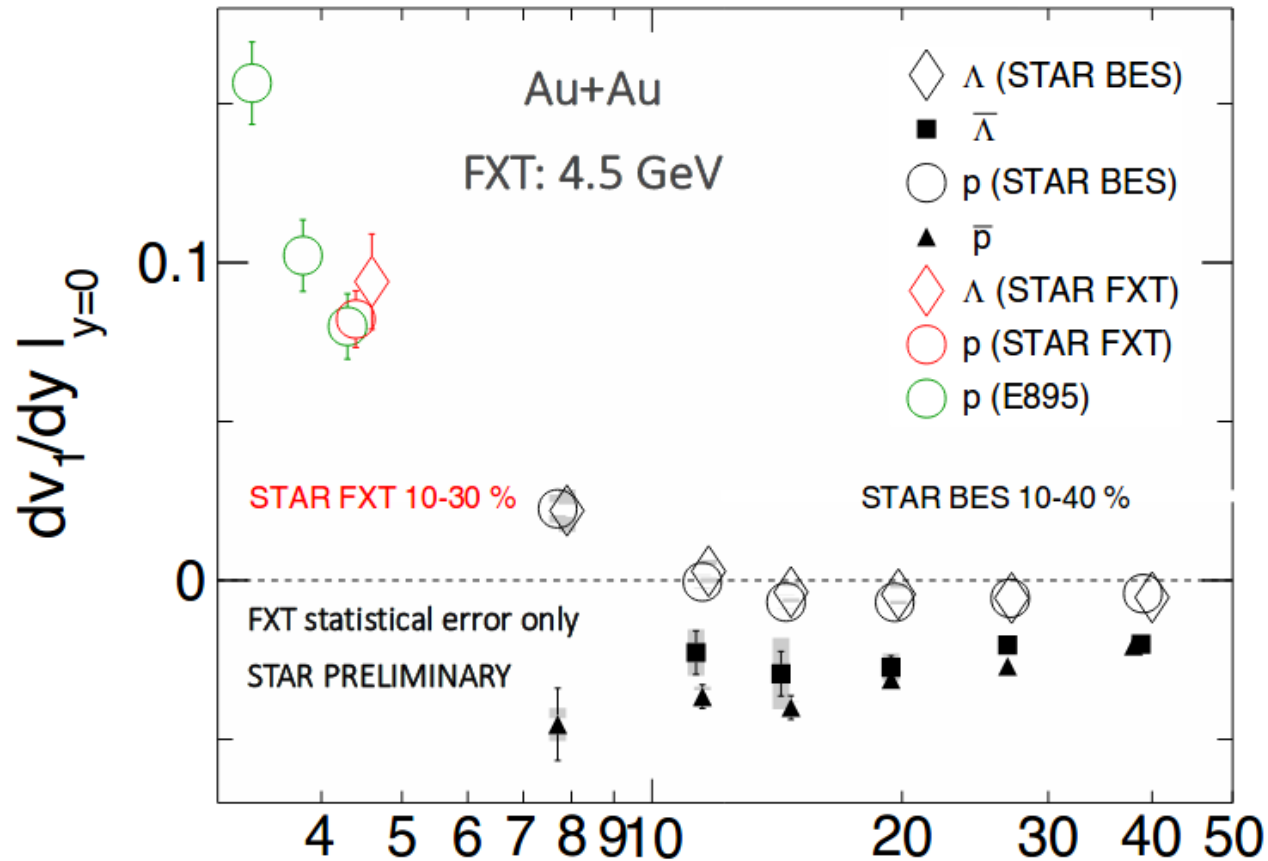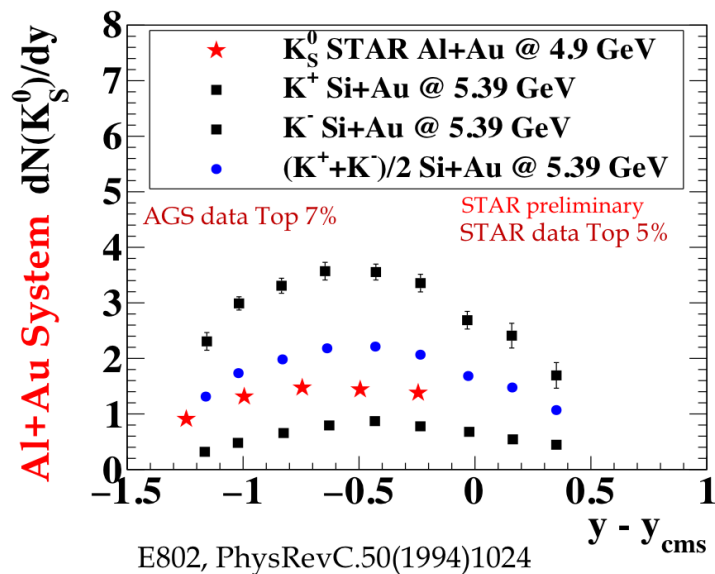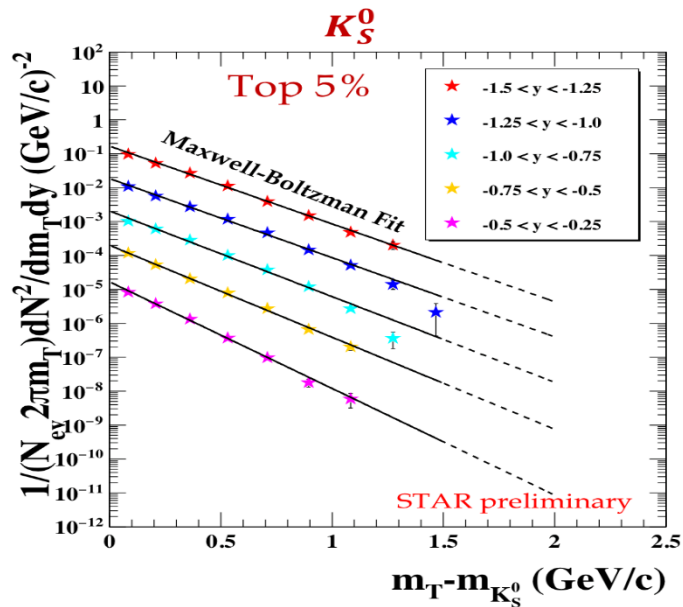
24

Directed flow in Au+Au $\sqrt{s_{NN}}$=4.5 GeV

Y. Wu, QM2018

Baryon v_1 slope is consistent with E895 at 4.3GeV

25

K_S^0 and Λ spectra/yield from $\mathbf{Al}$ + Au $\sqrt{s_{NN}} = 4.9$ GeV

M.-U. Ashraf, ATHIC2018

Top 5%

E802, PhysRevC.50(1994)1024
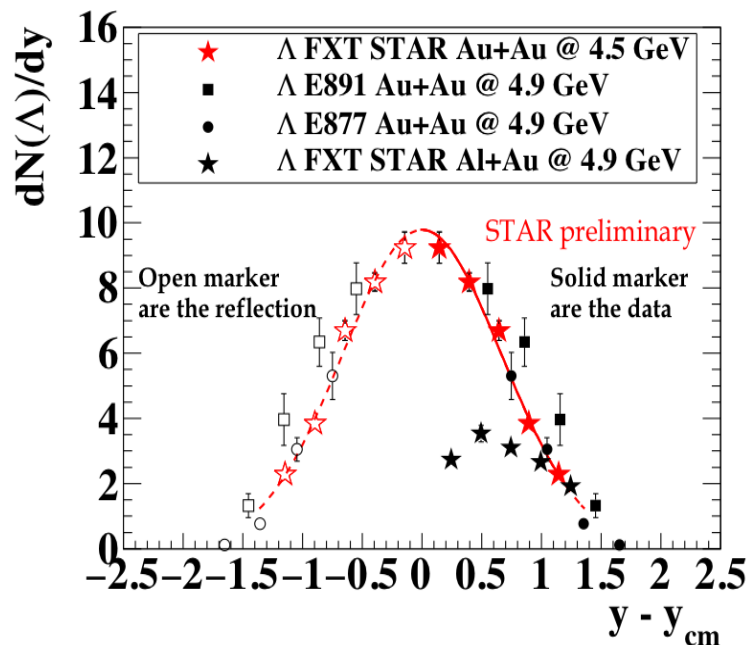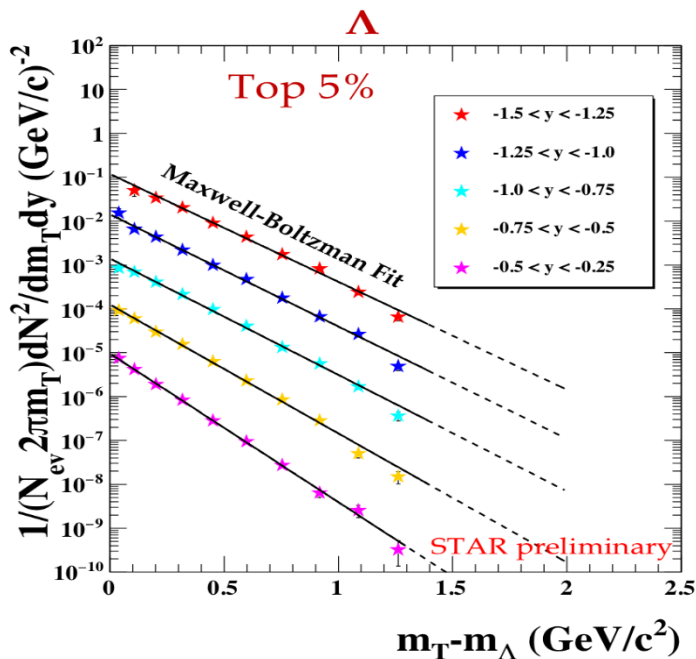
Summary & outlook

➢ STAR BES-I and NA61/SHINE have measured systematically the production of strangeness and LF at intermediate baryon density

➢ Step/horn structures are now investigated at different system sizes

➢ Double sign change seen in directed flow of net-baryons, but not in net-kaons

➢ QGP signatures appear to turn off at lower collision energies, but need more statistics to confirm

➢ The ongoing STAR BES-II with detector upgrade (iTPC, eTOF, EPD) and larger luminosity allow precise measurement of the matter properties at intermediate baryon density (μ_B up to 721 MeV)

➢ More results from SPS NA61/SHINE 2D scan are expected to fully explore the onset of deconfinement, onset of fireball…