Light flavor production in STAR BES and QCD phase transition

Xianglei Zhu（朱相雷）
Tsinghua University

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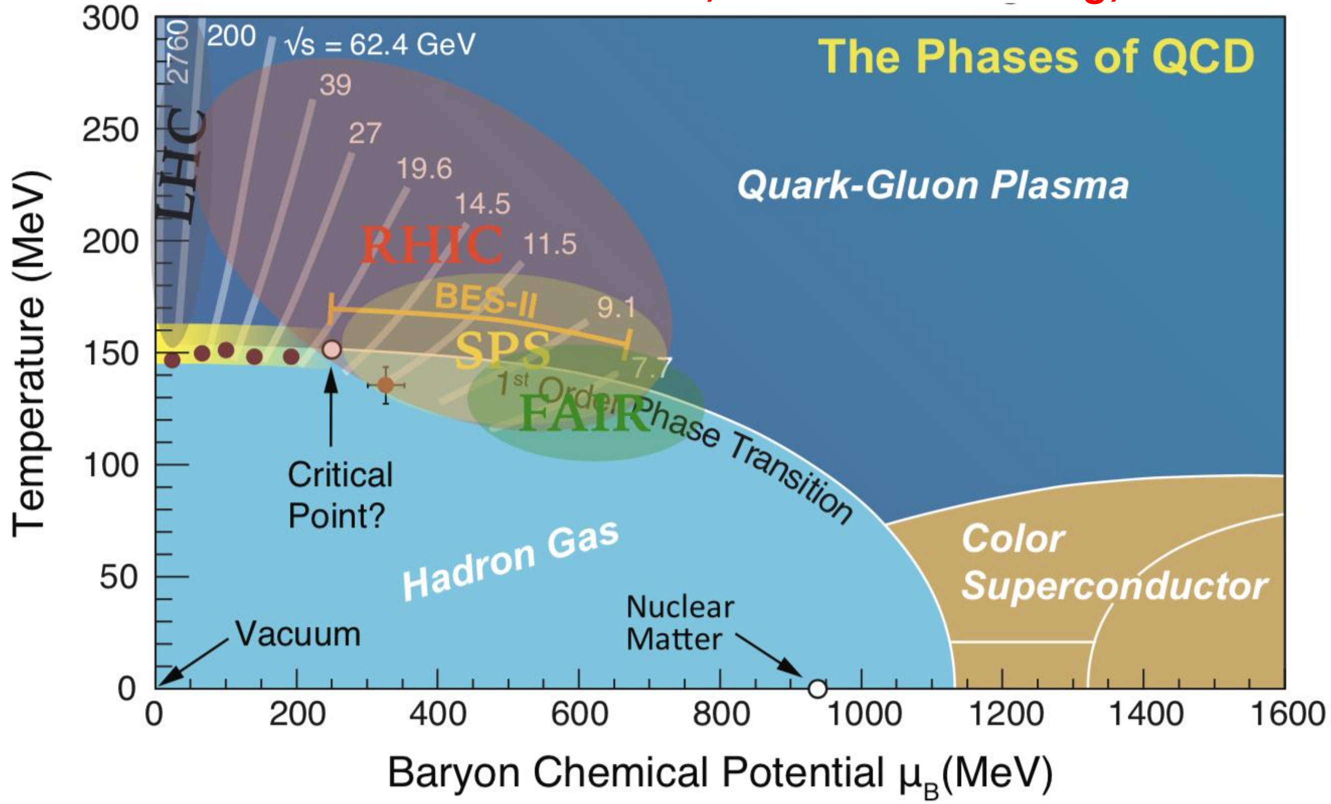
Workshop on QCD Physics & Study of the QCD Phase Diagram and New-type Topologic Effect

Weihai, July 17-25, 2019

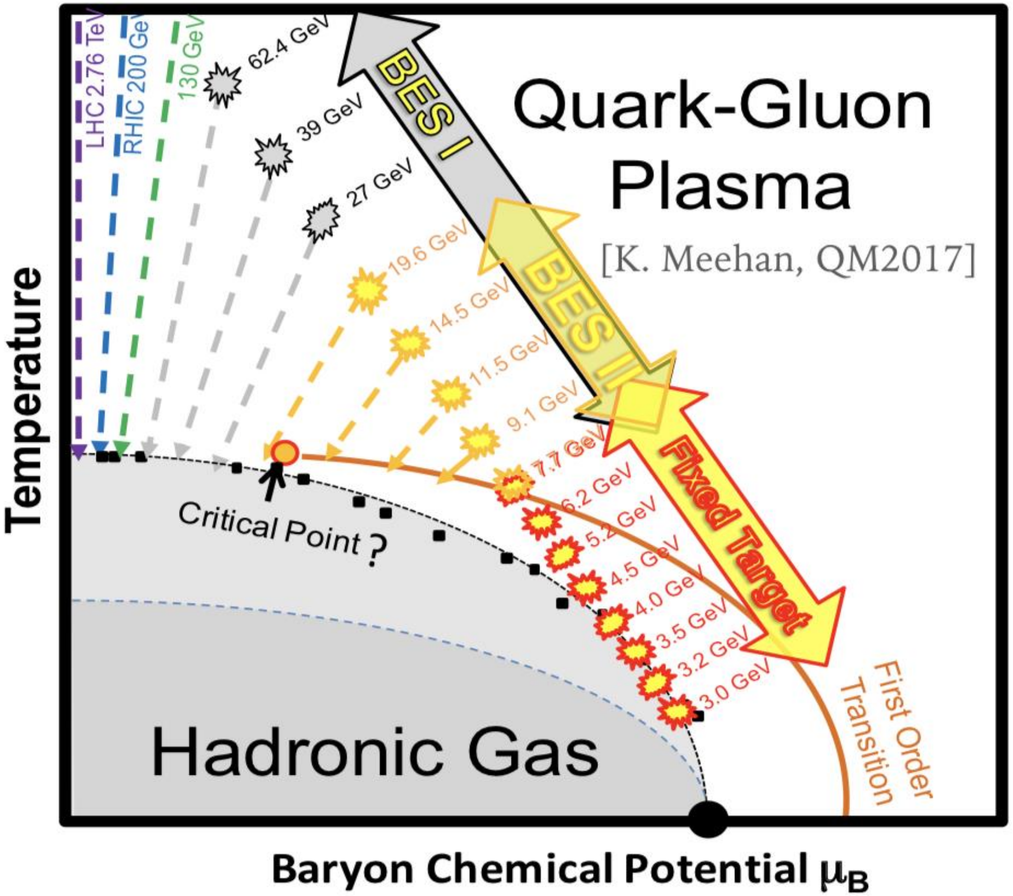
QCD phase diagram

B. Müller, BEST Col. Meeting, 2016



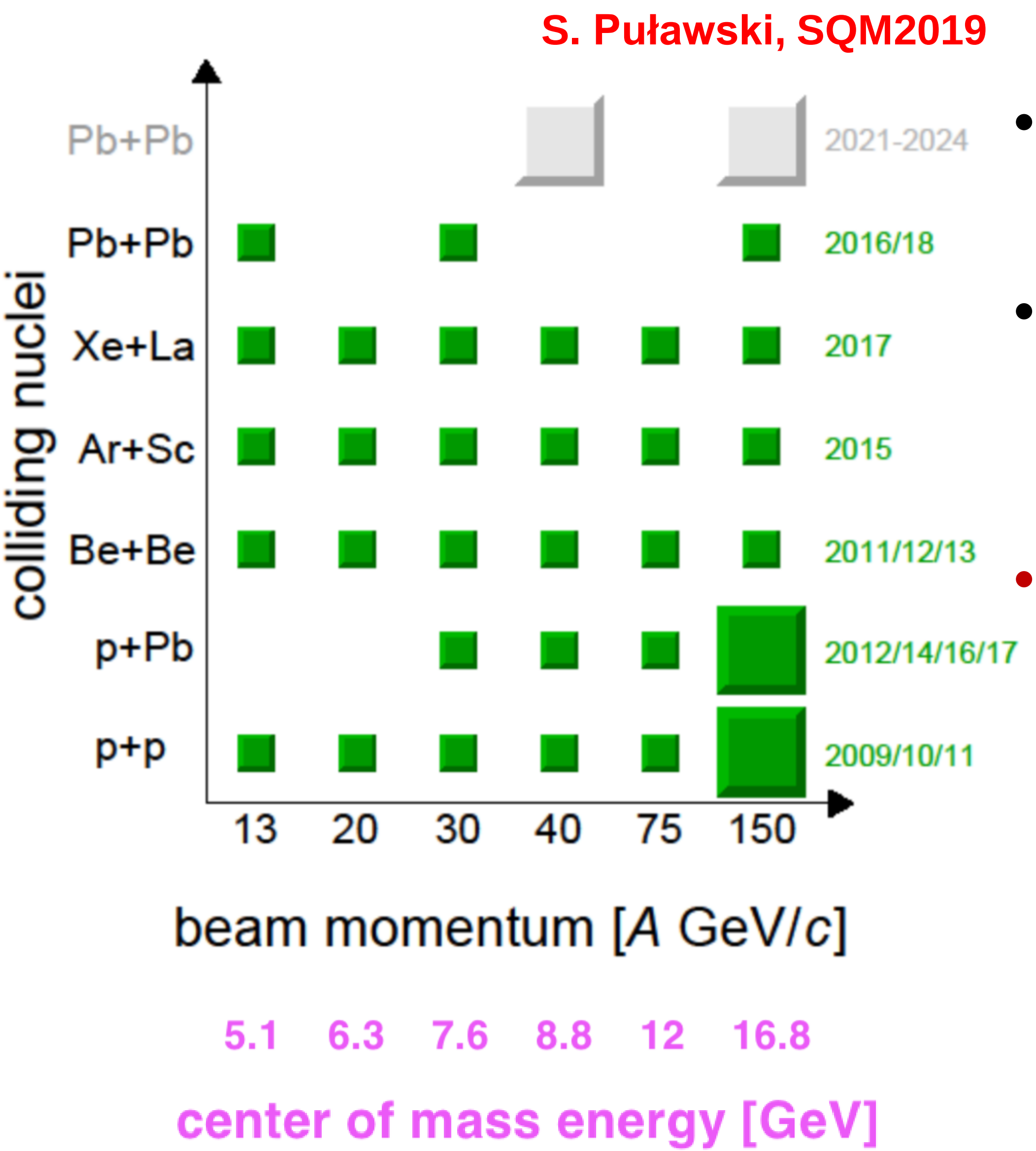
- **RHIC BES & SPS**
  Cover the intermediate baryon density region
  Look for **onset of de-confinement, phase boundary** and critical point

STAR BES



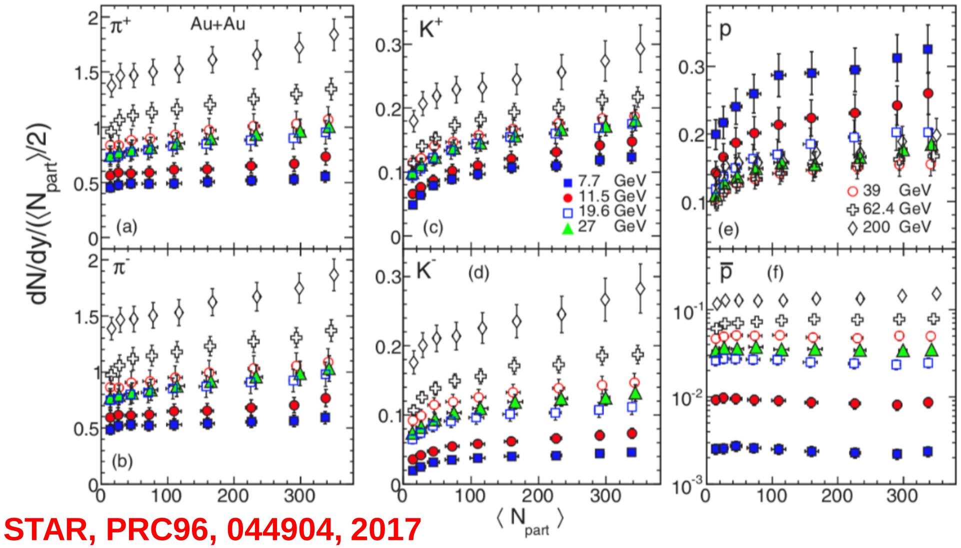
- Collider experiment at RHIC
- full azimuthal coverage at mid-rapidity
- BES-I (completed)
  Au+Au $\sqrt{s_{NN}}$ = 62.4 – 7.7 GeV
- BES-II (on-going)
  Au+Au $\sqrt{s_{NN}}$ = 19.6 – 7.7 GeV
- Fixed-target (on-going)
  Au+Au $\sqrt{s_{NN}}$ = 7.7 – 3.0 GeV
  μ_B up to 721 MeV

NA61/SHINE

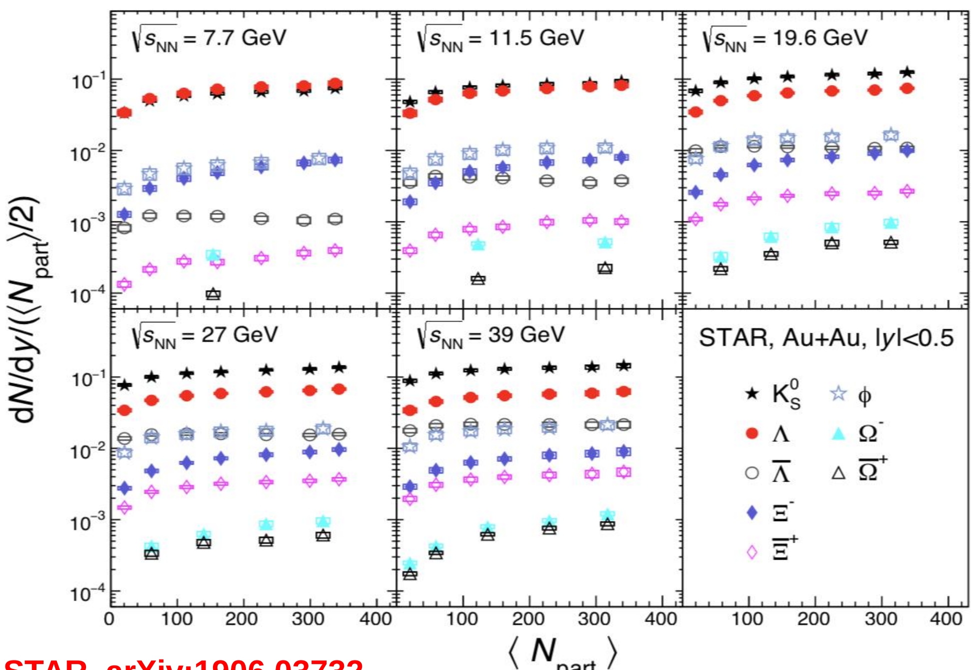


- Fixed target experiment at SPS
- Large acceptance: full forward hemisphere down to p_T=0
- Performed 2D scan in collision energy and system size

Particle yields (STAR BES-I)



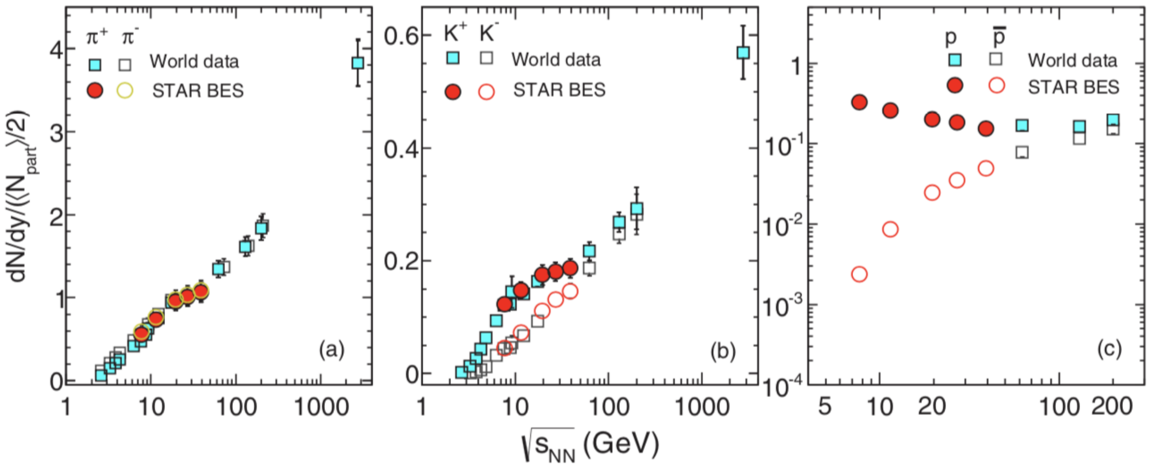
STAR, PRC96, 044904, 2017



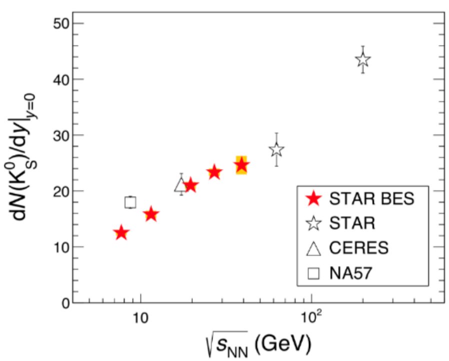
STAR, arXiv:1906.03732

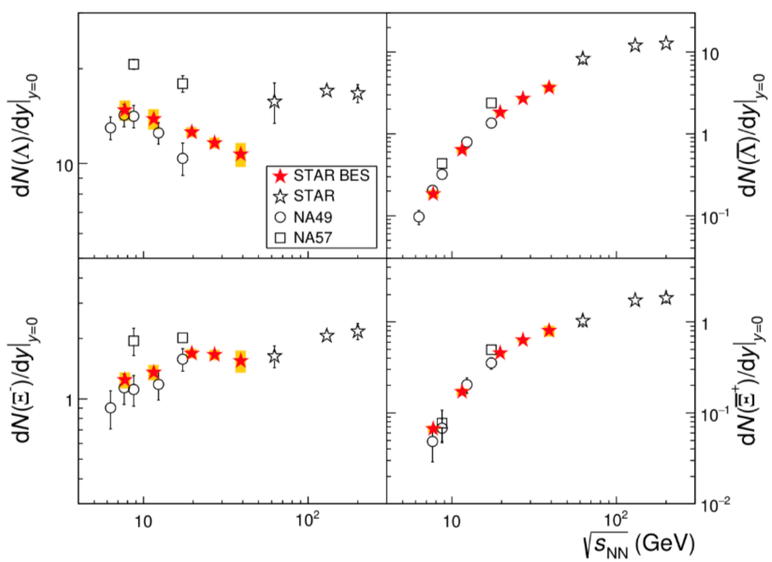
- dN/dy at mid-y for all species vs centrality and energy
- Yield per participating pair increases towards central and higher energies in general
- Exceptions:
  - p and Λ yields decrease towards higher energy
  - $\bar{p}$ and $\overline{\Lambda}$ has weak centrality dependence

Particle yields in central collisions



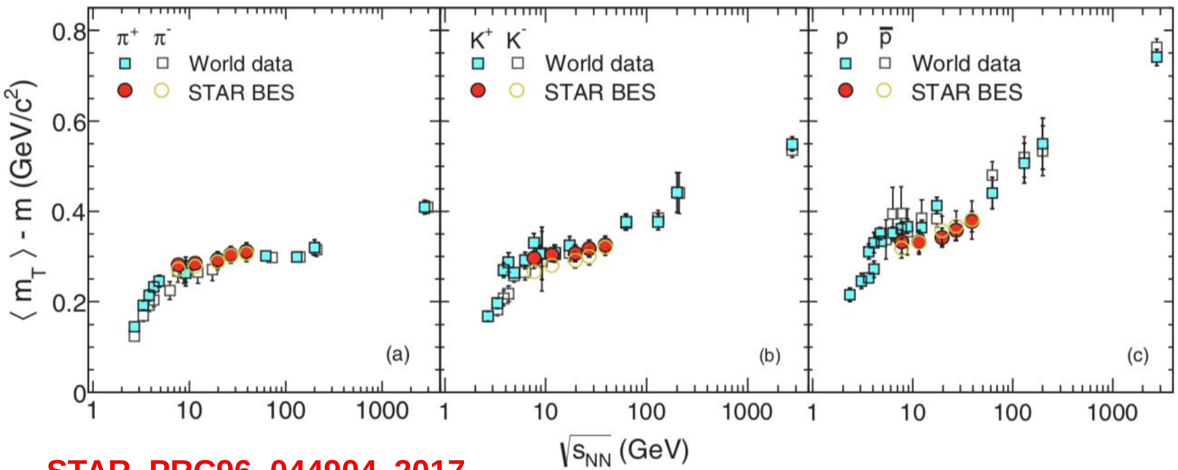
STAR, PRC96, 044904, 2017
STAR, arXiv:1906.03732



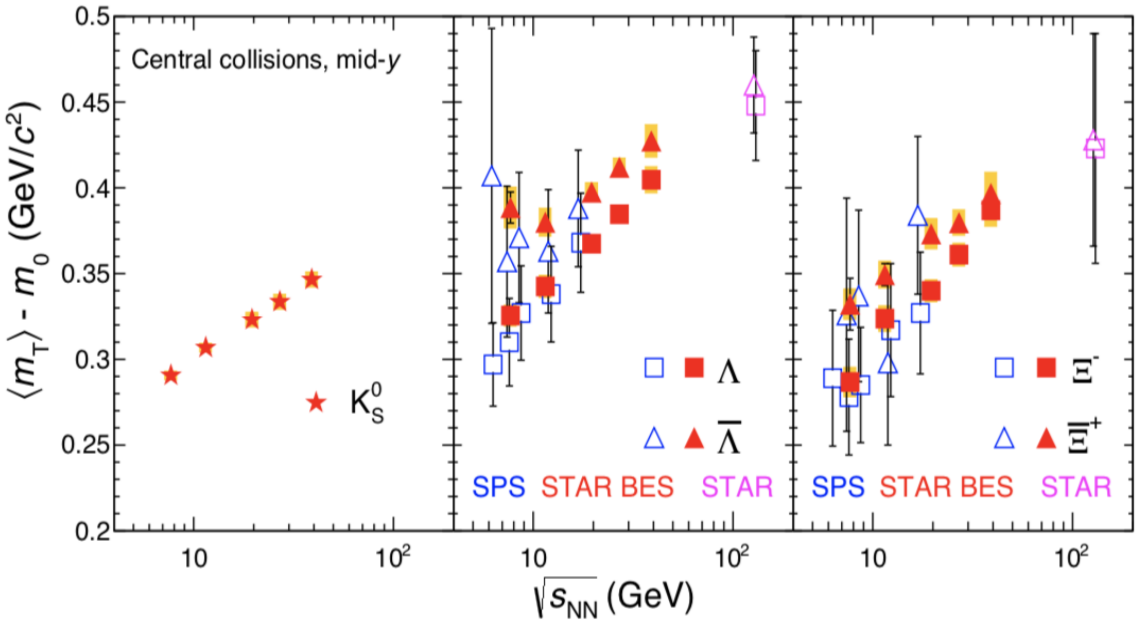


- STAR BES-I data consistent with published data in general
- Rich structure in these excitation functions
- p and Λ yields reach minimum at 39 GeV: interplay of baryon transport and pair production

Average transverse mass



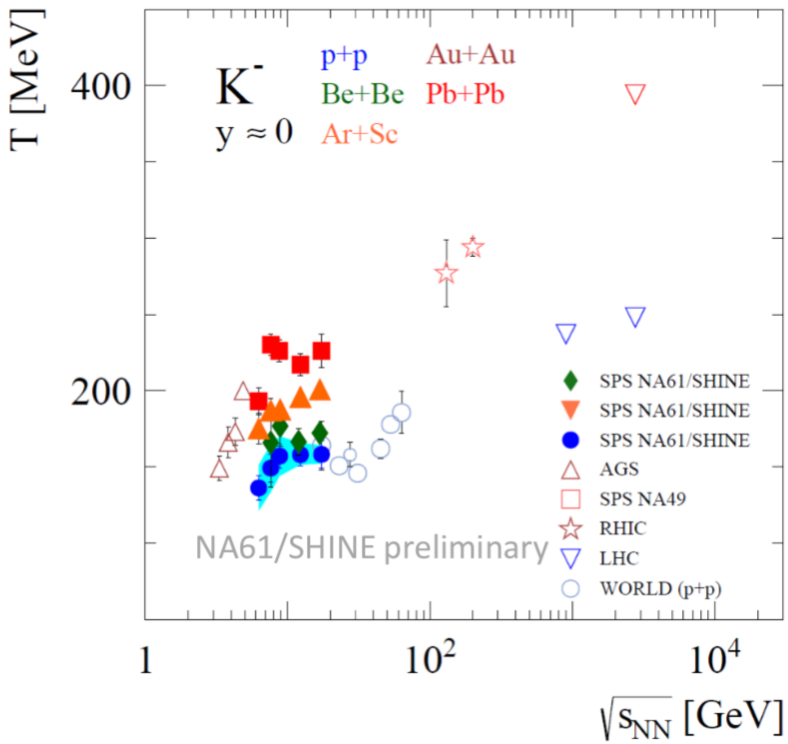
STAR, PRC96, 044904, 2017
STAR, arXiv:1906.03732

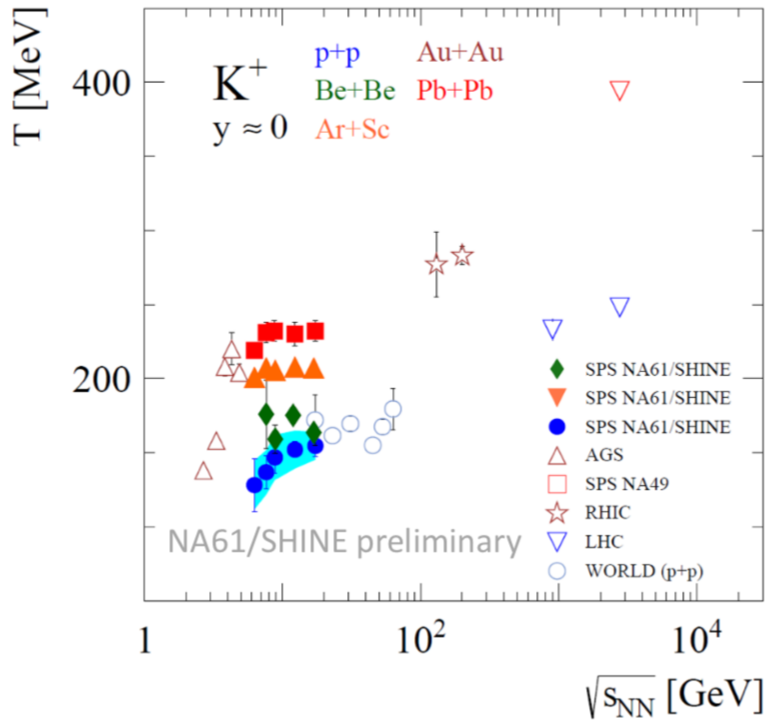


- A step-like structure can be seen in the energy dependence first-order phase transition?
- Λ and $\bar{\Lambda}$ show split at lower energies might be due to baryon-antibaryon annihilations at high baryon density

T slope (NA61/SHINE)

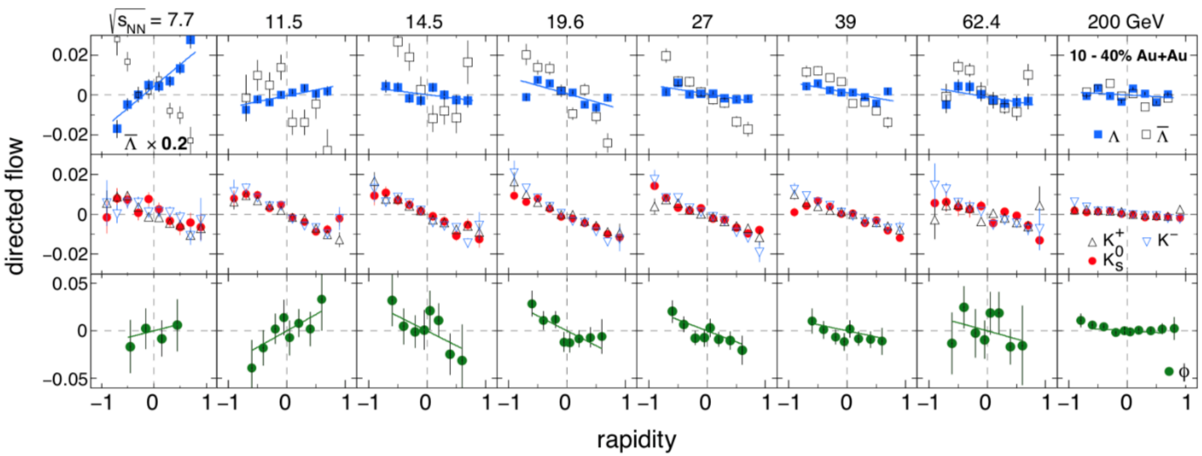
P. Podlaski, SQM2019

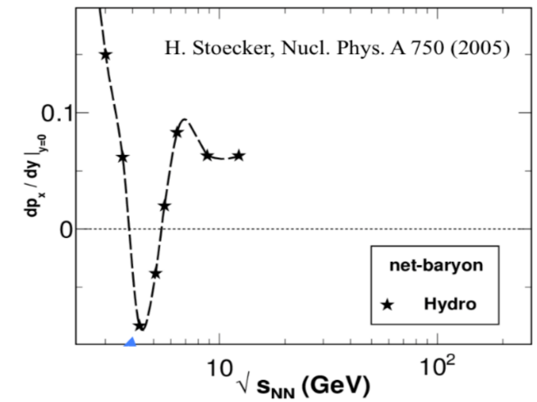




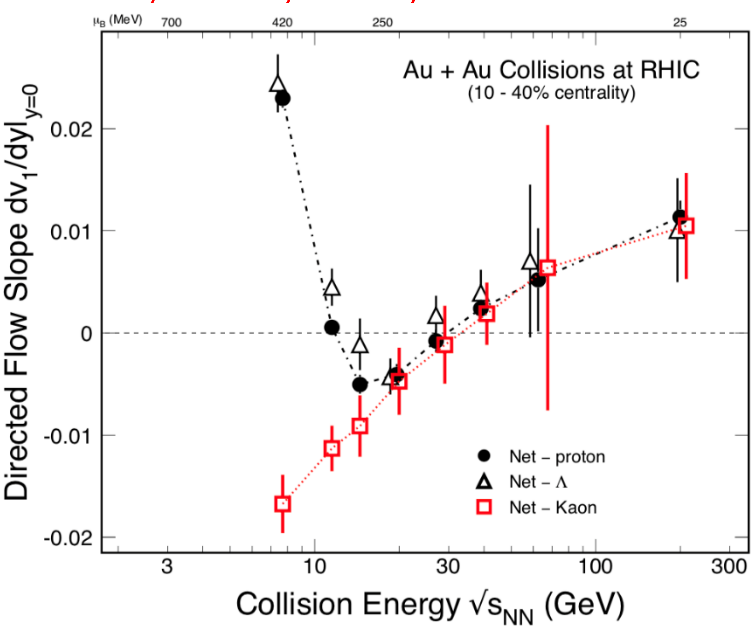
- Qualitatively similar energy dependence is seen in p+p, Be+Be and Pb+Pb collisions
- Magnitude of T in Be+Be slightly higher than in p+p
- Ar+Sc results between p+p/Be+Be and Pb+Pb

Directed flow (STAR BES-I)





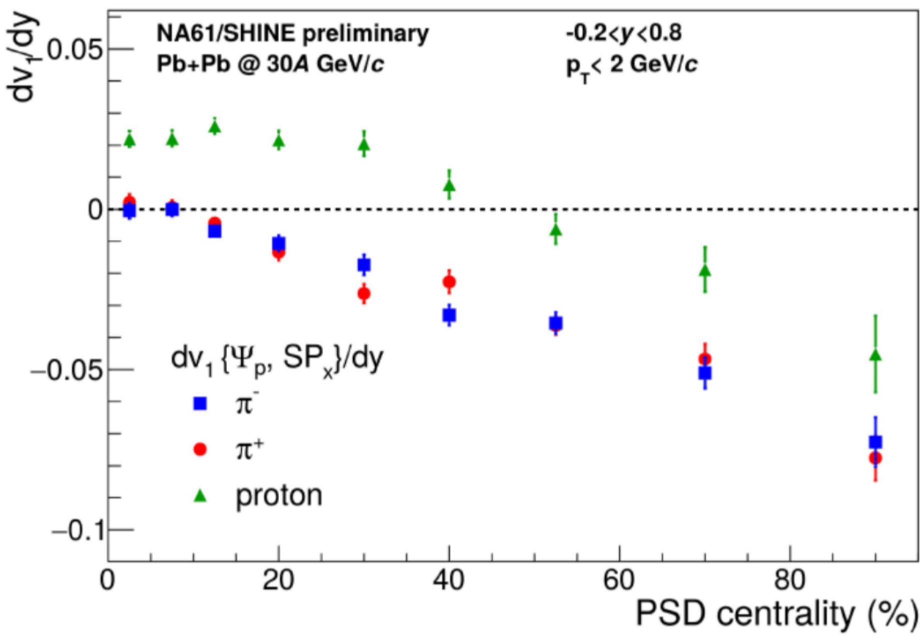
STAR, PRL112, 162301, 2014
STAR, PRL120, 062301, 2018

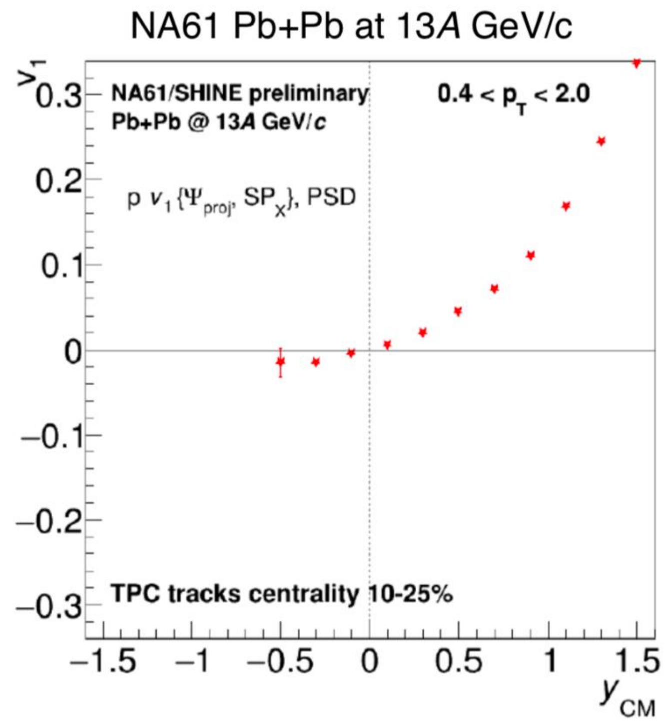


- Sign change of proton dv_1/dy, softening of EOS, first-order phase transition
- Double sign change seen in net-proton, net-Λ, not seen in net-kaon
- Need theory to explain

Directed flow (NA61/SHINE)

S. Puławski, SQM2019

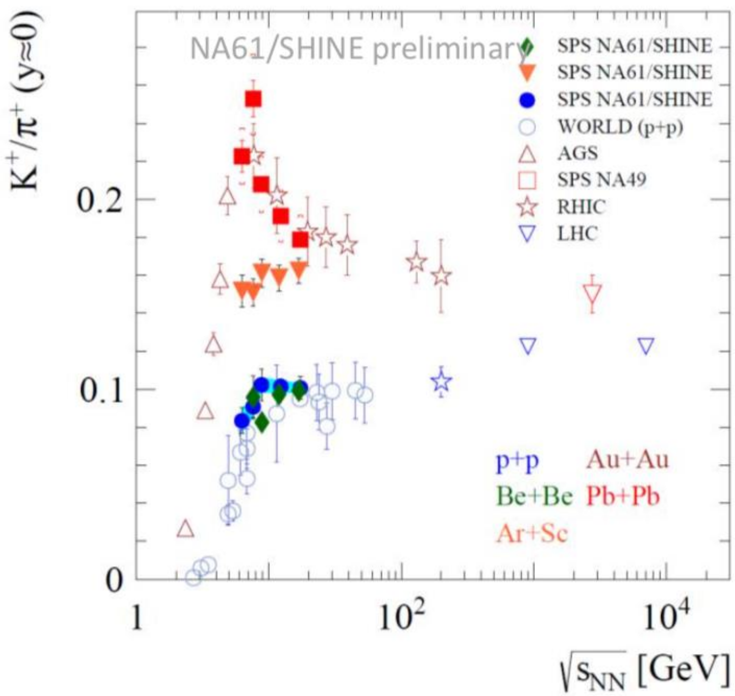


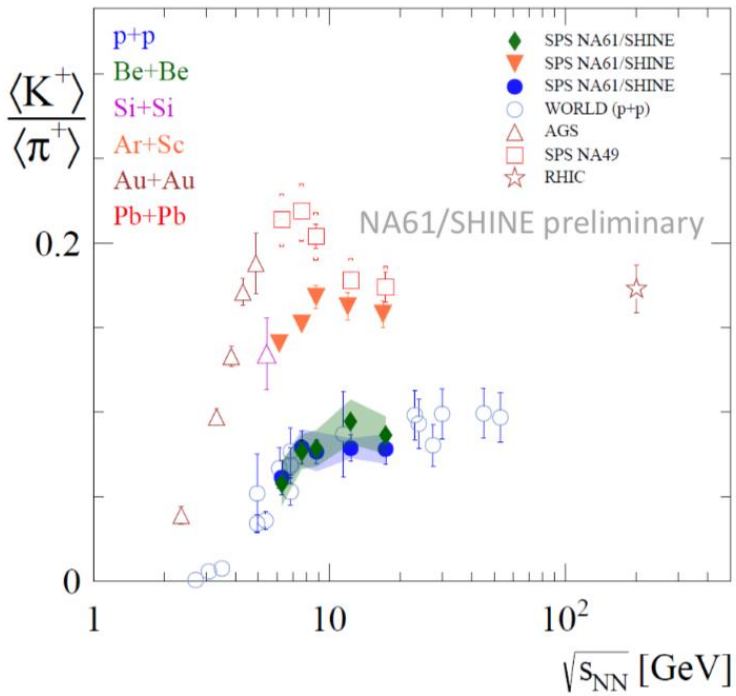


- At 30A GeV/c, close to mid-rapidity, slope of pion v_1 is negative for all centralities; slope of proton v_1 changes sign at centrality of about 50%
- At 13A GeV/c, no evidence for the collapse of proton v_1

K^+/π^+ ratio (NA61/SHINE)

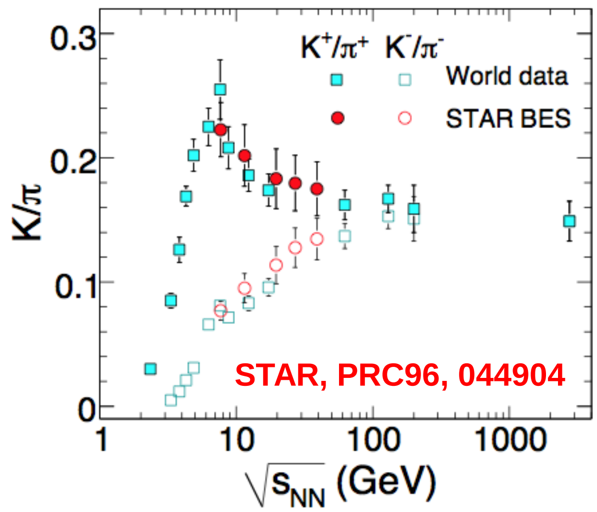
P. Podlaski, SQM2019



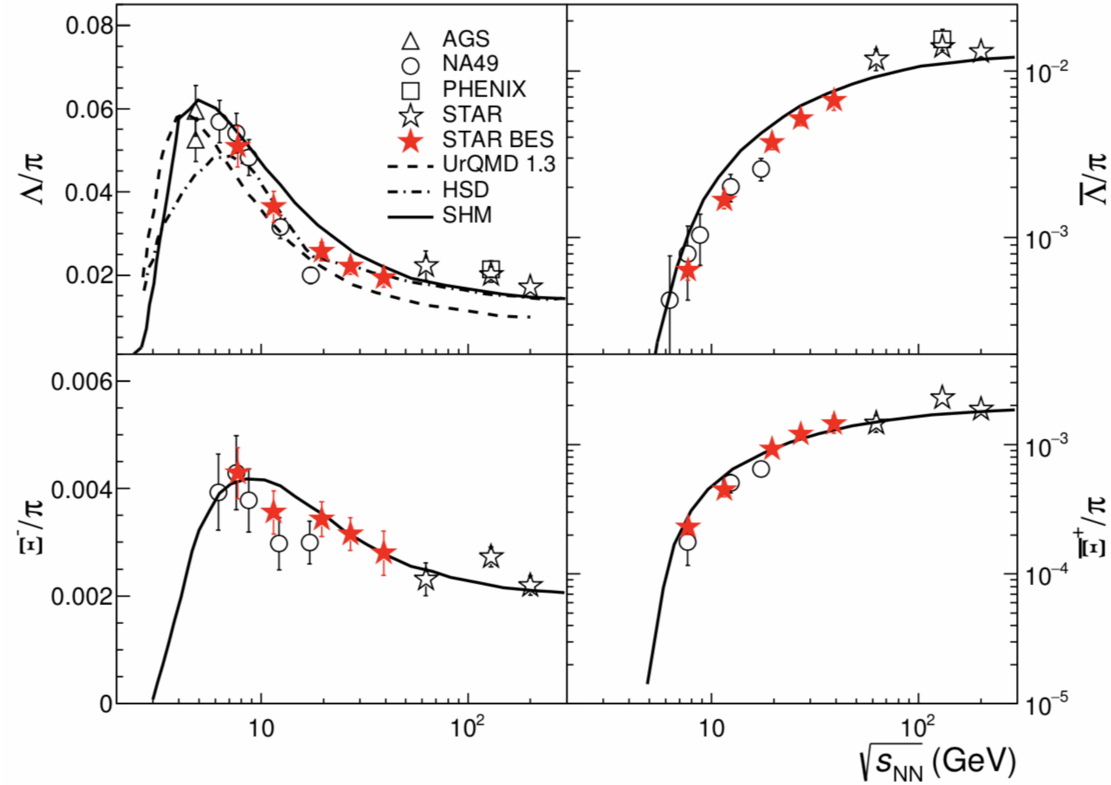


- Plateau like structure visible in p+p
- Be+Be close to p+p
- Ar+Sc is higher than p+p but form of energy dependence is similar to p+p (no horn)

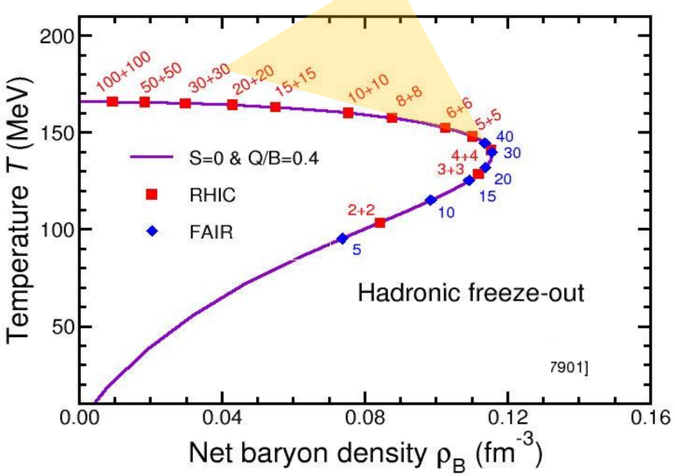
Strange hadron to pion ratio (STAR BES-I)



STAR, arXiv:1906.03732



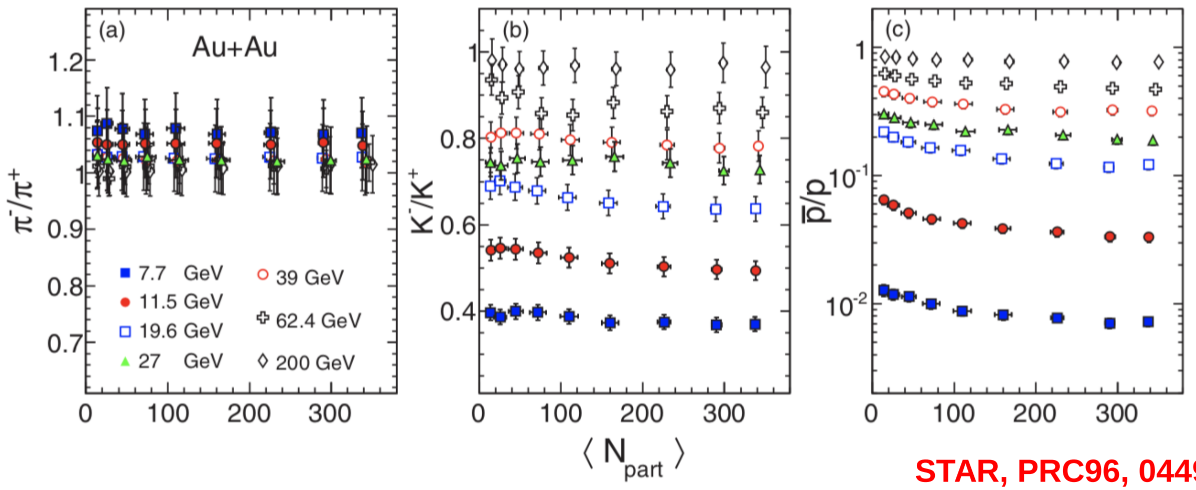
RHIC BES

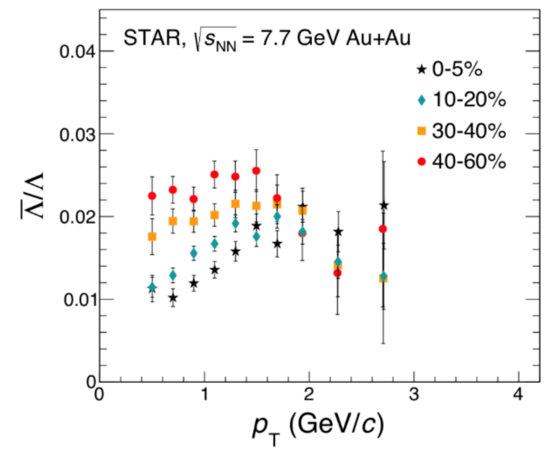


J. Randrup et al., PRC 74, 047901 (2006)

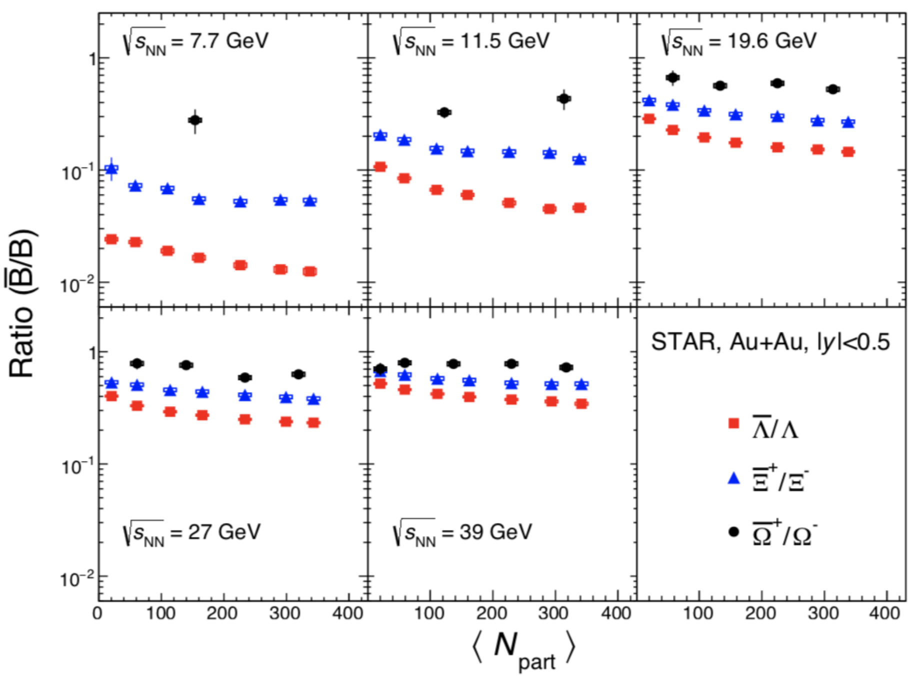
- Particle ratios consistent with NA49, consistent with the picture of a **maximum net-baryon density around $\sqrt{s_{NN}}$ ~ 8 GeV at freeze-out**

Anti-hadron to hadron ratio



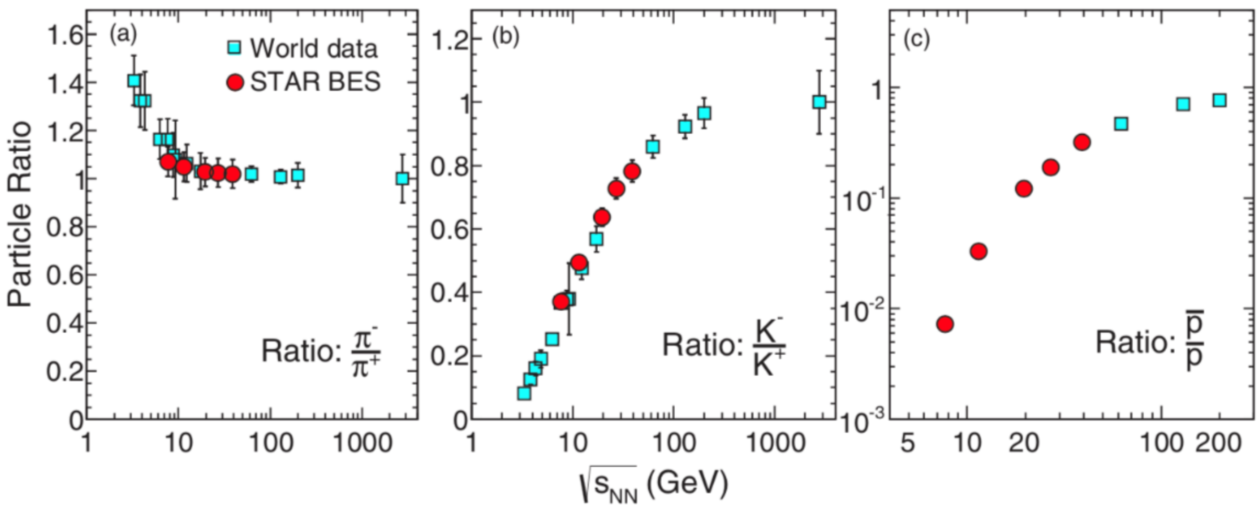


STAR, PRC96, 044904, 2017
STAR, arXiv:1906.03732

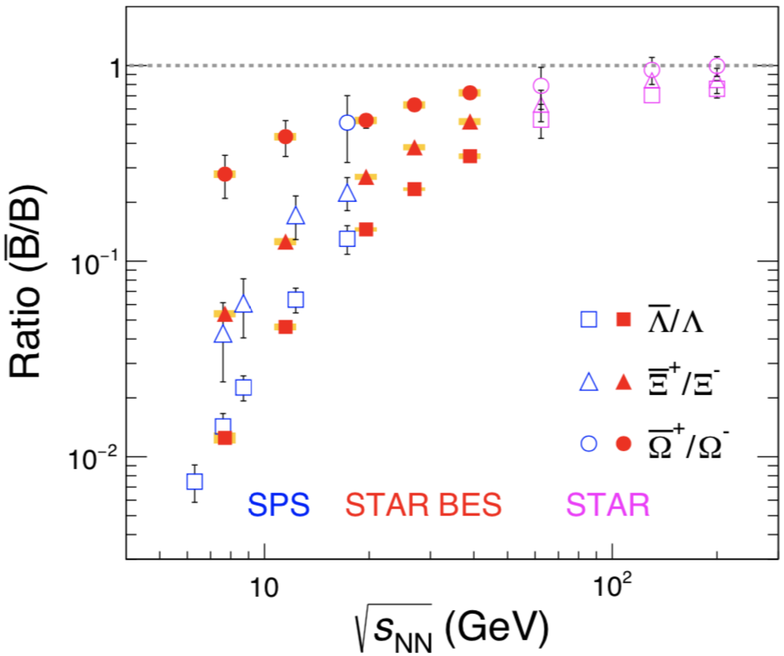


- Centrality dependence of $\bar{B}/B$ ratios: **peripheral > central**
- This effect is more prominent at lower energies. **baryon stopping and/or anti-baryon absorption**
- **Loss of low p_T $\bar{\Lambda}$ in central collisions**

Anti-hadron to hadron ratio



STAR, PRC96, 044904, 2017
STAR, arXiv:1906.03732



- STAR BES data lie in a trend with NA49 data
- $\bar{\mathbf{B}}/\mathbf{B}$ ratios increase with number of strange quarks at low energies
  $\bar{\Omega}^+/\Omega^- > \bar{\Xi}^+/\Xi^- > \bar{\Lambda}/\Lambda > \bar{p}/p$

Anti-hyperon to hyperon ratio

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

$$\frac{\overline{\Lambda}}{\Lambda} = \exp(-\frac{2\mu_B}{T} + \frac{2\mu_S}{T}) \quad \Rightarrow \quad \ln(\frac{\overline{\Lambda}}{\Lambda}) = -\frac{2\mu_B}{T} + \frac{2\mu_S}{T}$$

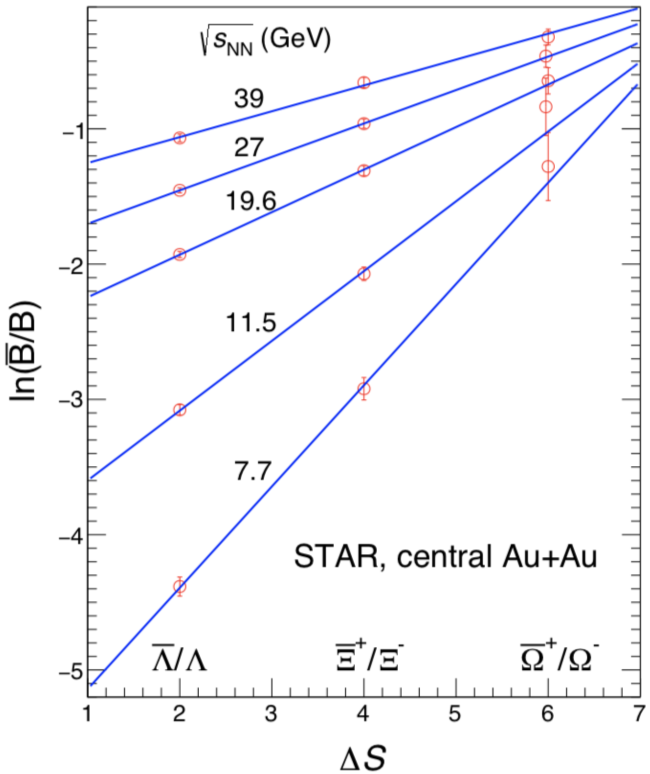
$$\frac{\overline{\Xi}^+}{\Xi^-} = \exp(-\frac{2\mu_B}{T} + \frac{4\mu_S}{T}) \quad \Rightarrow \quad \ln(\frac{\overline{\Xi}^+}{\Xi^-}) = -\frac{2\mu_B}{T} + \frac{4\mu_S}{T}$$

$$\frac{\overline{\Omega}^+}{\Omega^-} = \exp(-\frac{2\mu_B}{T} + \frac{6\mu_S}{T}) \quad \Rightarrow \quad \ln(\frac{\overline{\Omega}^+}{\Omega^-}) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T}$$

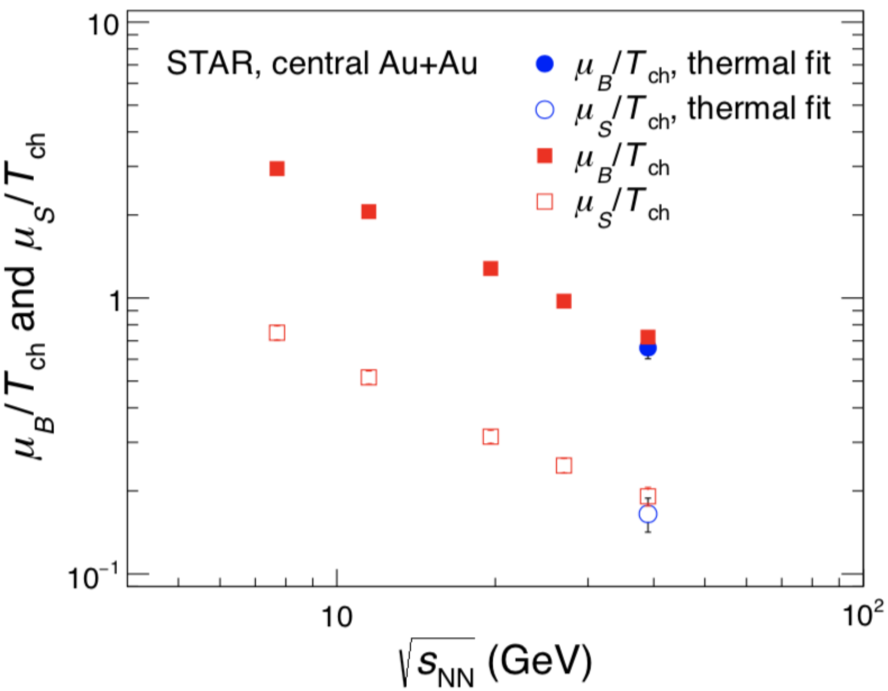
- T is the temperature.
- μ_B is the baryon chemical potential.
- μ_S is the strangeness chemical potential.

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

$\mu_S/T_{\rm ch}$ and $\mu_B/T_{\rm ch}$



STAR, arXiv:1906.03732



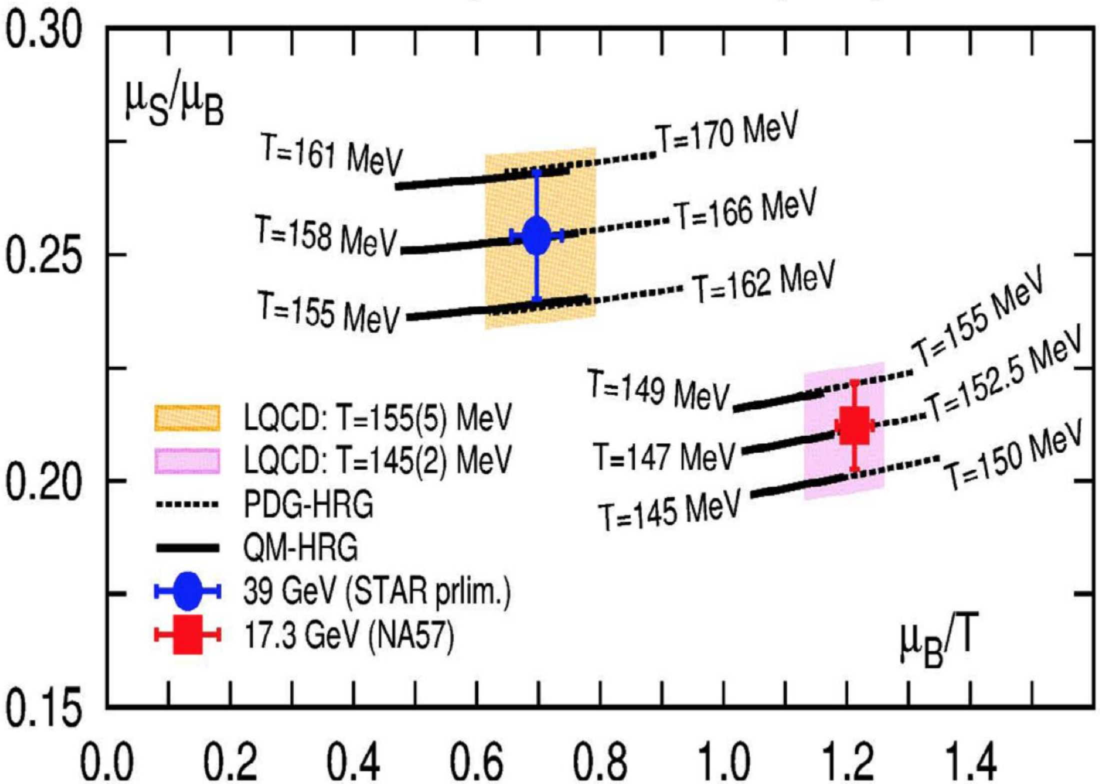
- Anti-hyperon to hyperon ratios are fit well with statistical thermal model
- Chemical freeze-out parameters, $\mu_S/T_{\rm ch}$ and $\mu_B/T_{\rm ch}$, are extracted

Strangeness, LQCD and freeze-out in HIC

From Swagato Mukherjee

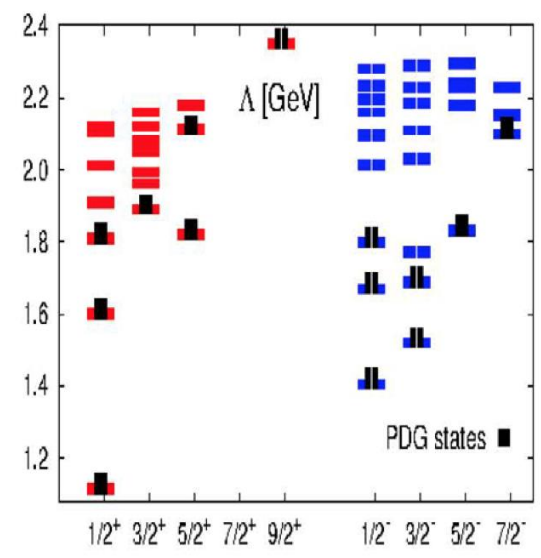
freeze-out T by comparing
μ_S/μ_B from LQCD and expt.

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



not reproduced by hadron gas with only PDG states

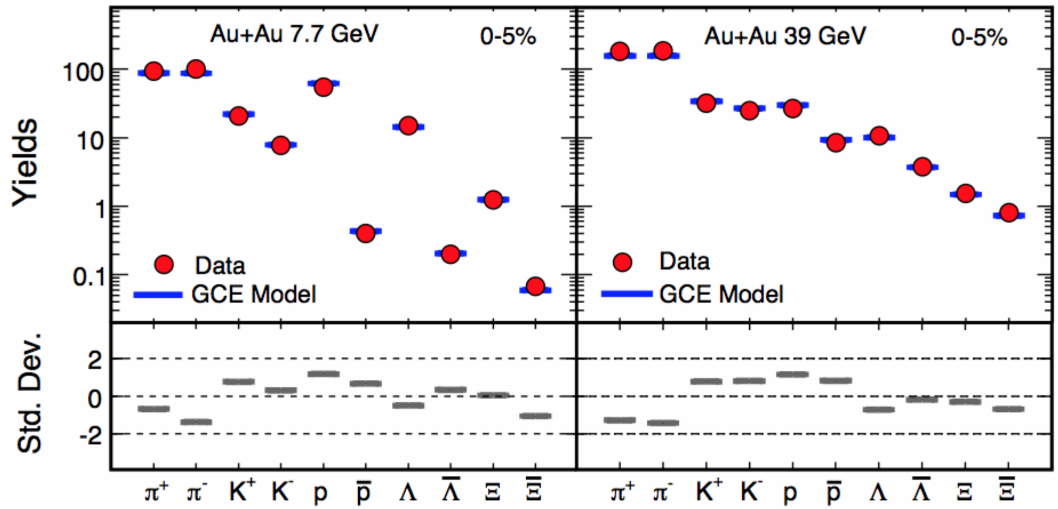
reproduced when additional Quark Model (QM) predicted strange baryons are taken into account

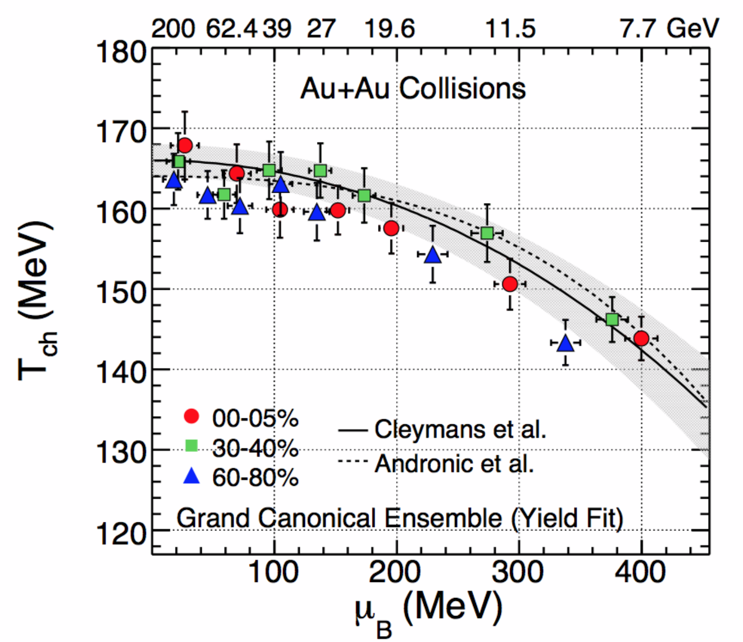


indirect evidence for so-far undiscovered strange baryons at RHIC ?

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

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



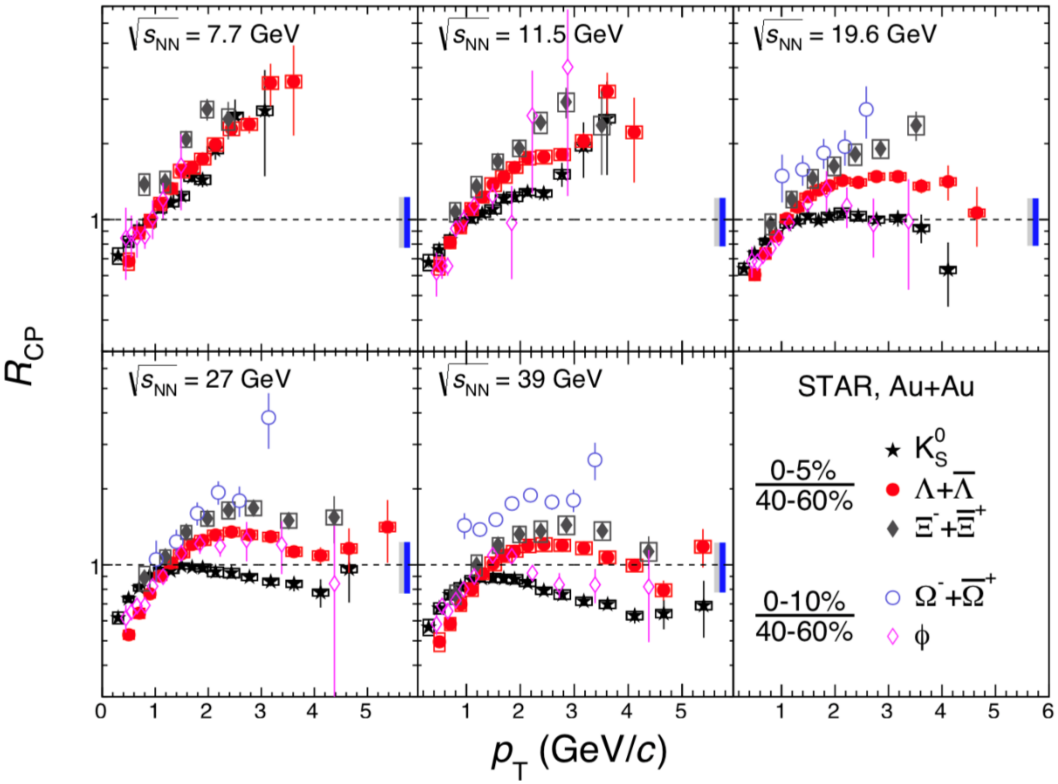


Andronic: NPA 834 (2010) 237
Cleymans: PRC 73 (2006) 034905
Au+Au 200 GeV : Phys. Rev. C **83** (2011) 24901

- ✓ Particles used : π, K, p, Λ, Ξ
- ✓ Ensemble used: **Grand canonical (GCE)**
- ✓ Fit parameters: T_{ch}, μ_B, μ_s and γ_s

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

Nuclear modification factors R_{CP}

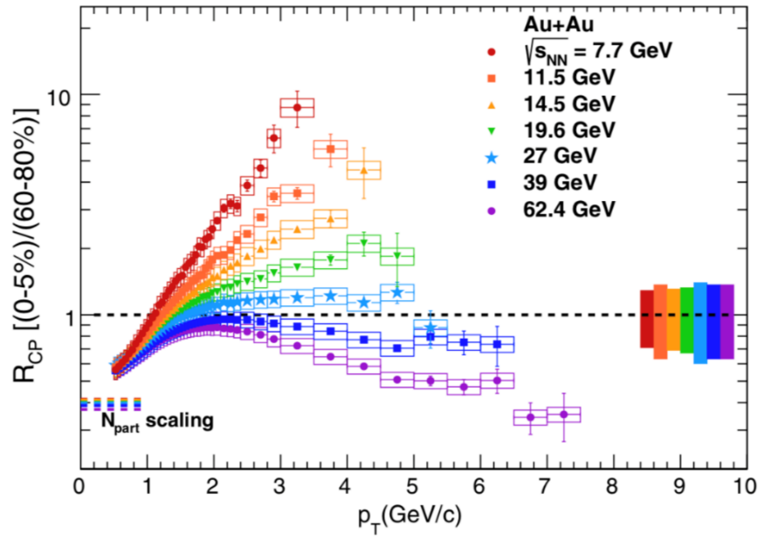


$$R_{CP}(p_T) = \frac{[d^2\sigma/(N_{bin}p_T dp_T dy)]_{central}}{[d^2\sigma/(N_{bin}p_T dp_T dy)]_{peripheral}}$$

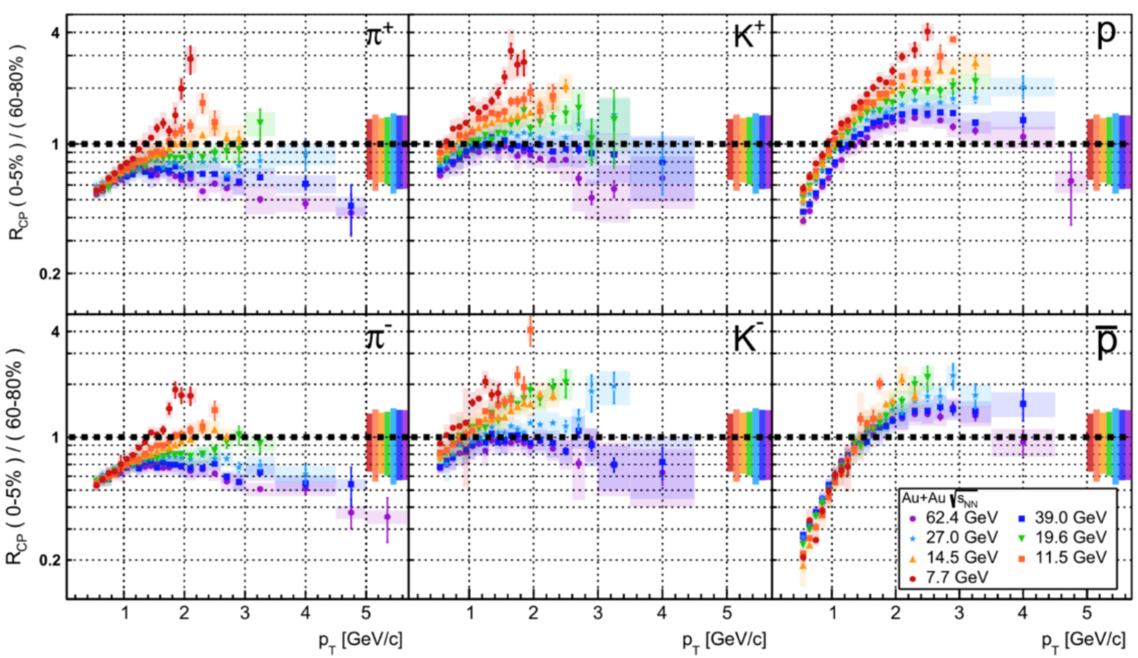
STAR, arXiv:1906.03732

- No K^0_S 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

Nuclear modification factors R_{CP}

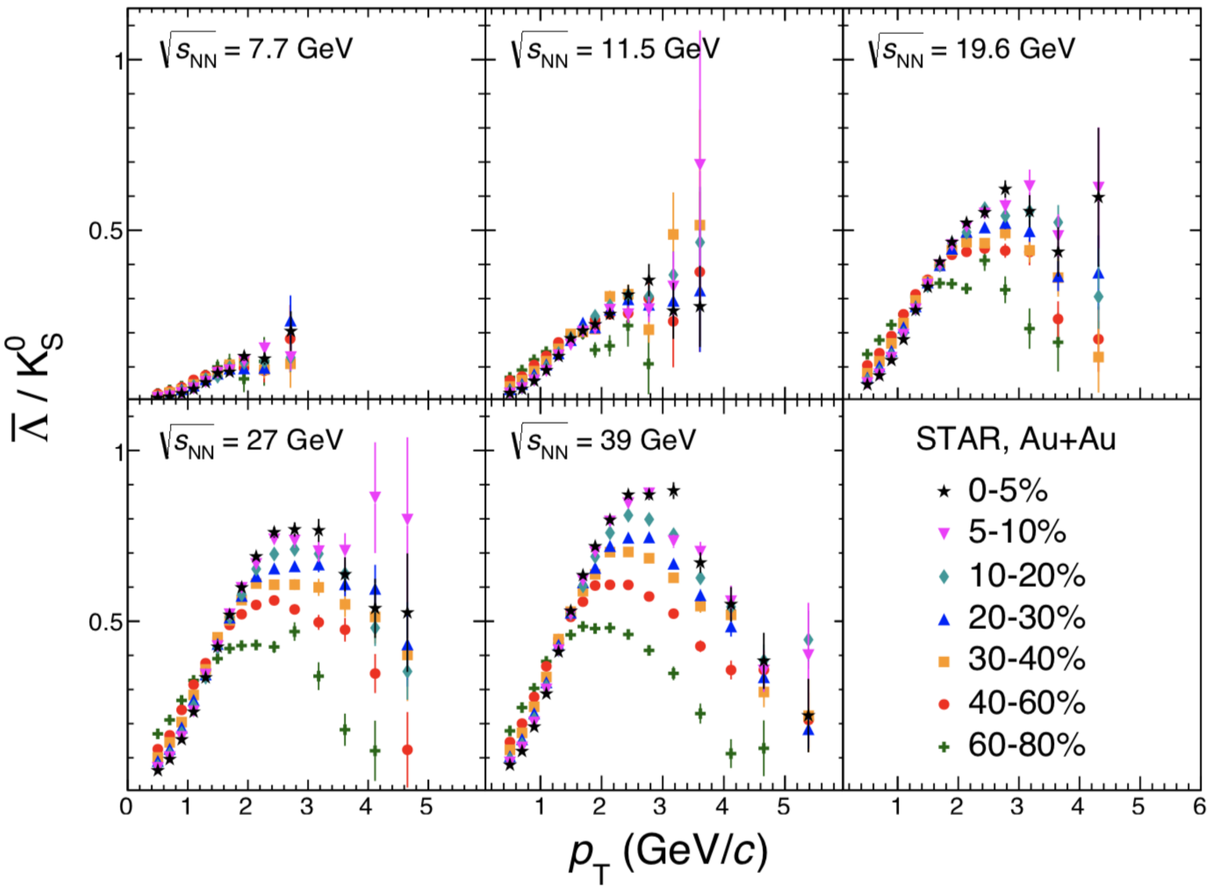


- No suppression for lower energies
- Cronin effect and other effects (radial flow) compete with partonic energy loss



STAR, PRL121, 032301, 2018

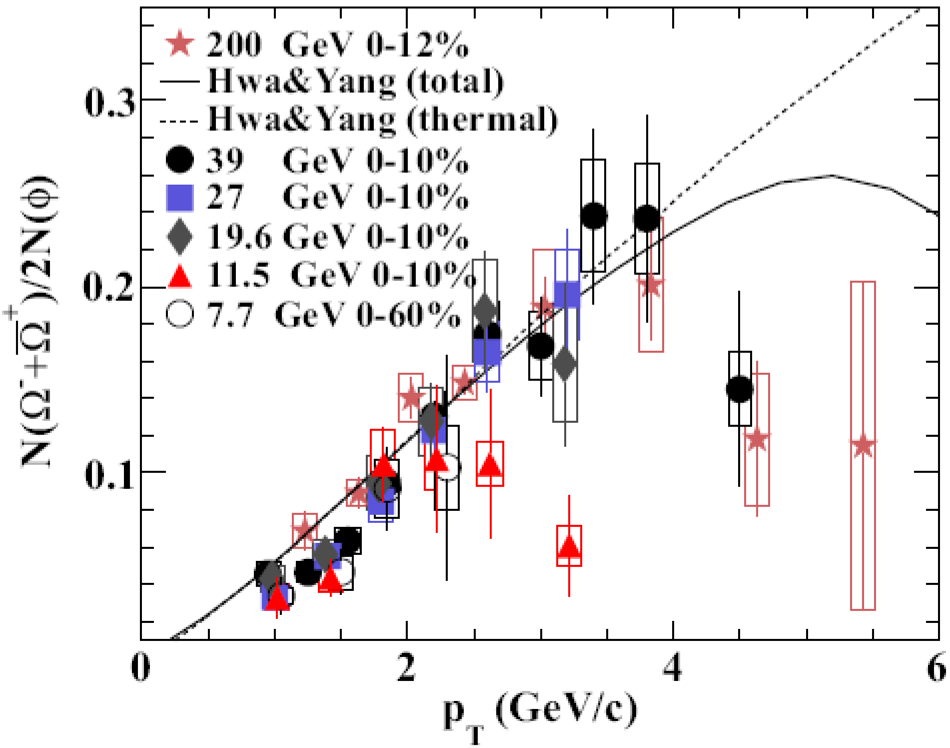
Baryon to meson ratio: $\bar{\Lambda}/K^0_S$

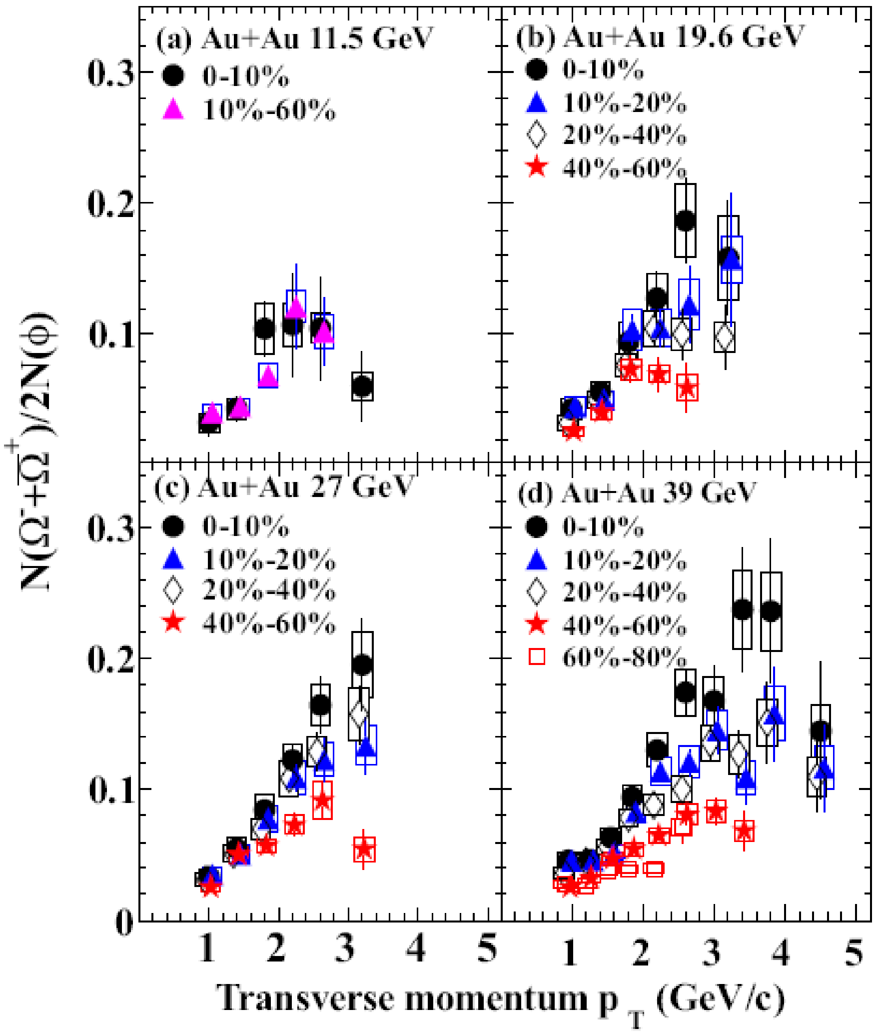


STAR, arXiv:1906.03732

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

Ω / ϕ ratio

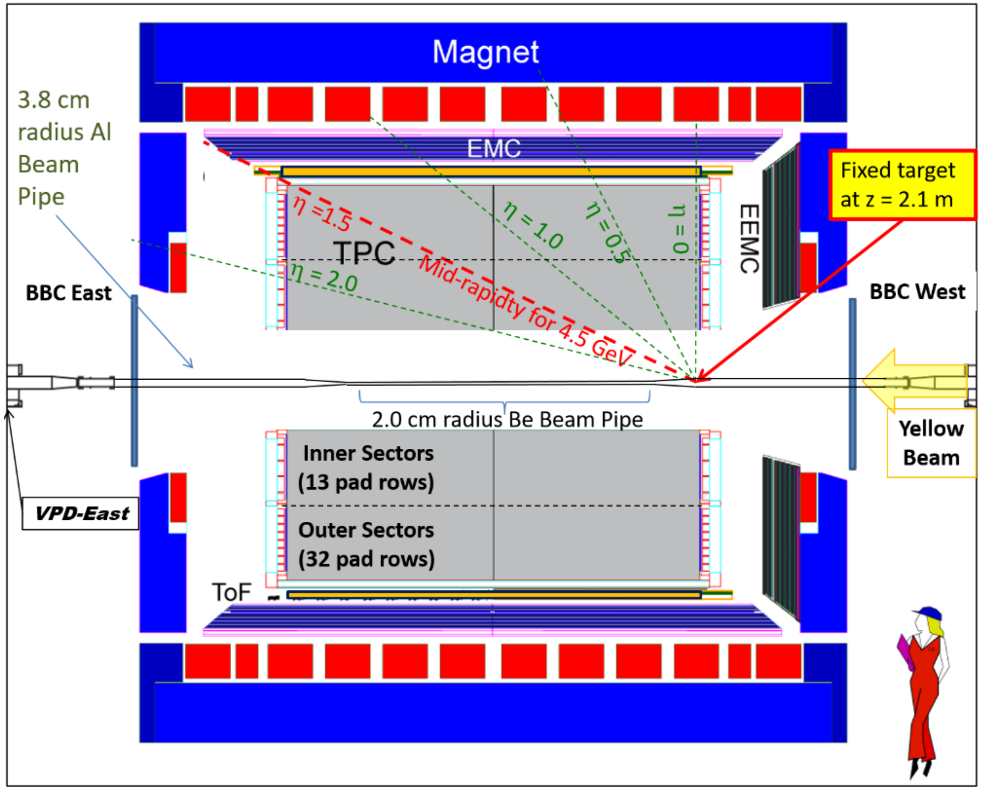




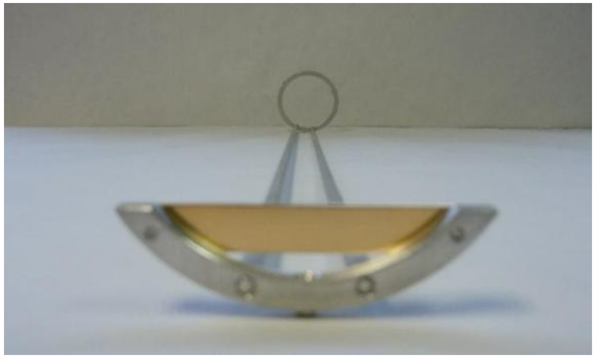
STAR, Phys. Rev. C 93, 021903 (R), 2016

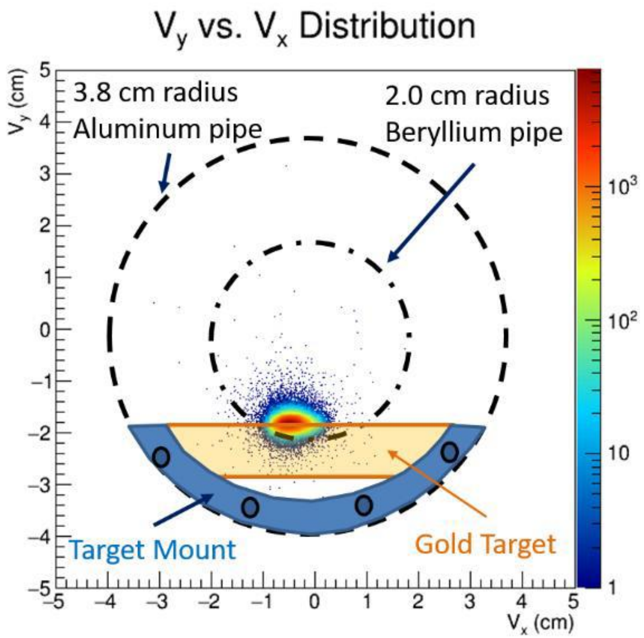
- Intermediate p_T Ω/ϕ ratios:
  Indication of separation between ≥ 19.6 and 11.5 GeV
- Ω/ϕ ratios: 40%-60% peripheral < 0-10% central for 19.6, 27 and 39 GeV

The STAR fixed-target program



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

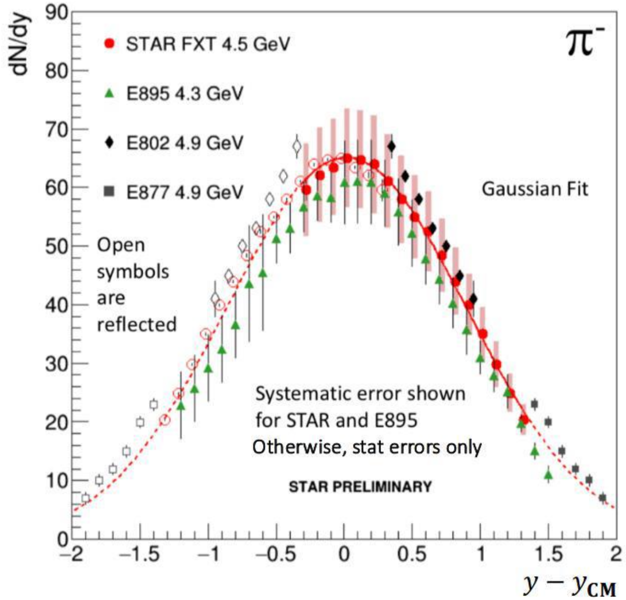




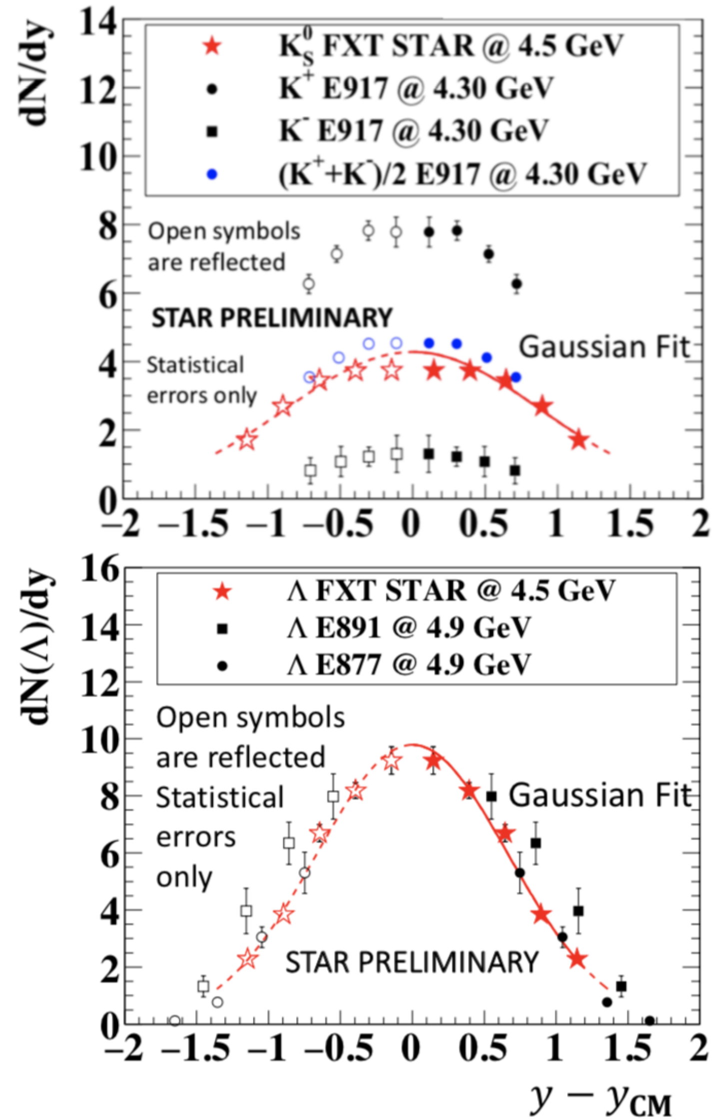
1.3M events from half hour test run, top 30% central trigger, Au+Au $\sqrt{s_{NN}}$=4.5 GeV

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



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

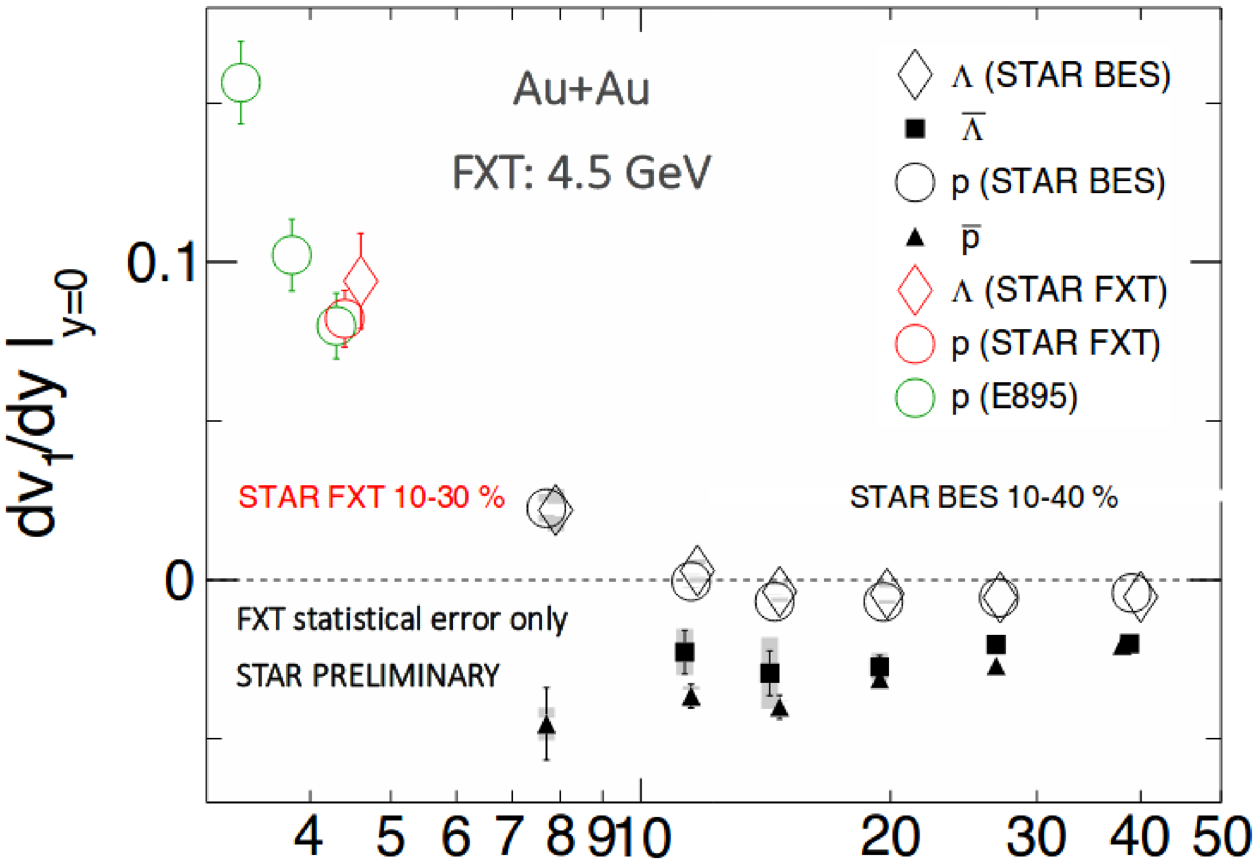


Y. Wu, QM2018
Top 5%

- 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

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

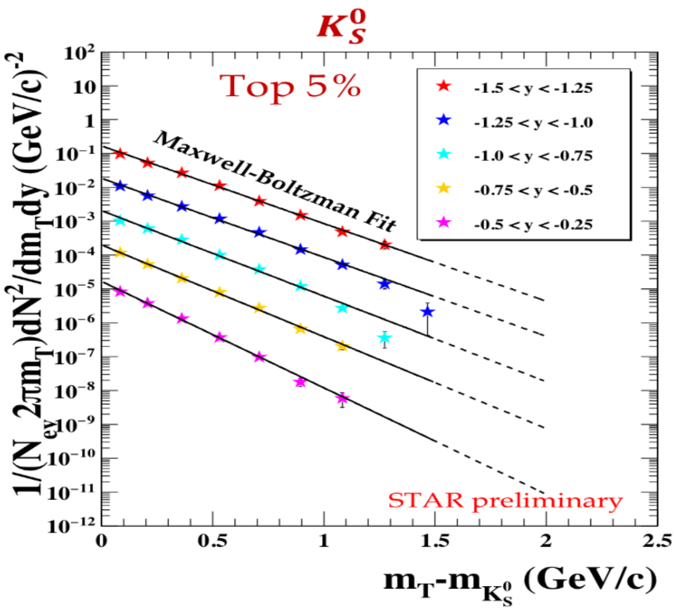
E895. Phys. Rev. Lett. 84 (2000) 005488
STAR . Phys. Rev. Lett. 112 (2014) 162301

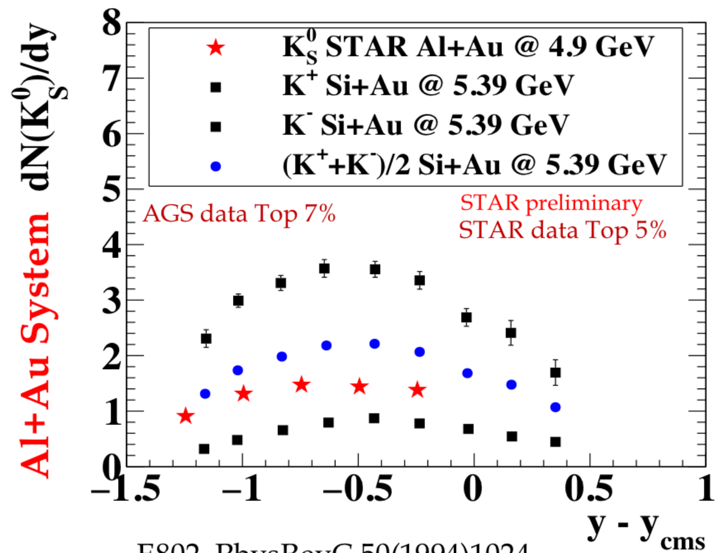


Y. Wu, QM2018

Baryon v_1 slope is consistent with E895 at 4.3GeV

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

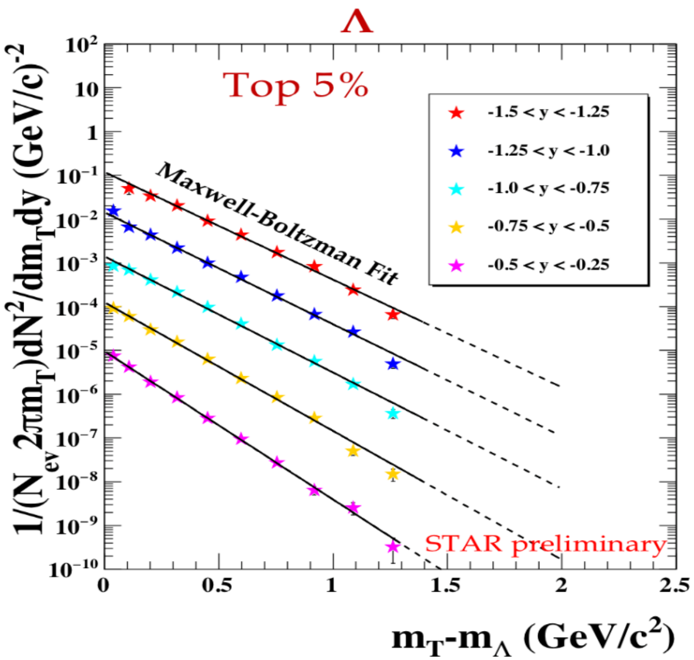


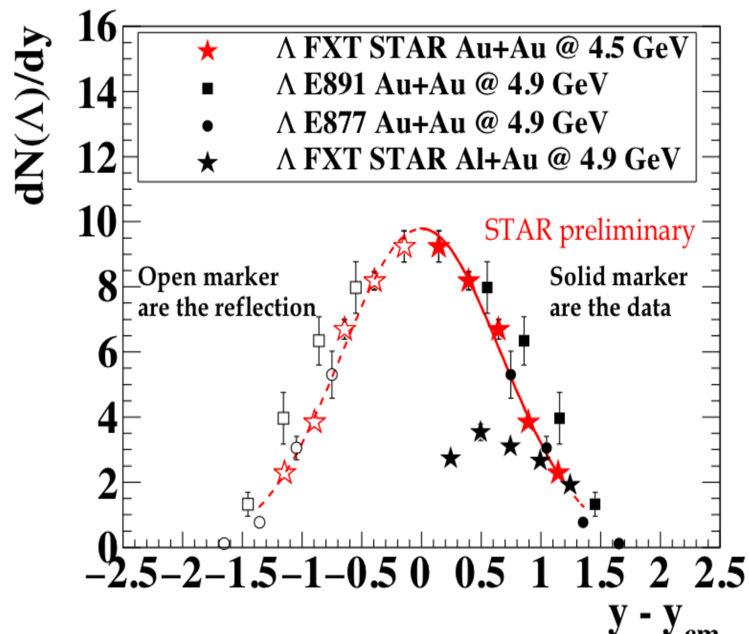


E802, PhysRevC.50(1994)1024

M.-U. Ashraf, ATHIC2018

Top 5%





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…