Recent strangeness results from the RHIC beam energy scan

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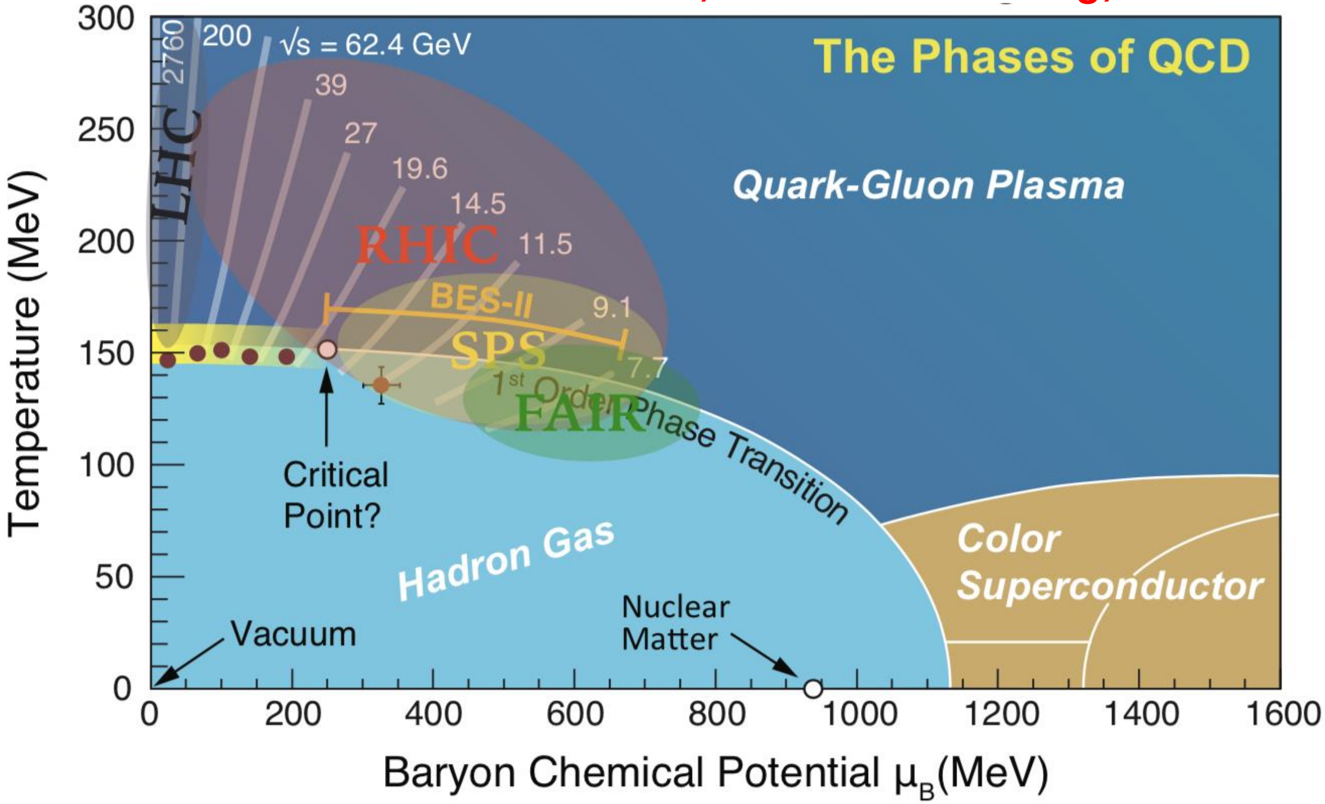
5/11/2021

BNL nuclear physics seminar

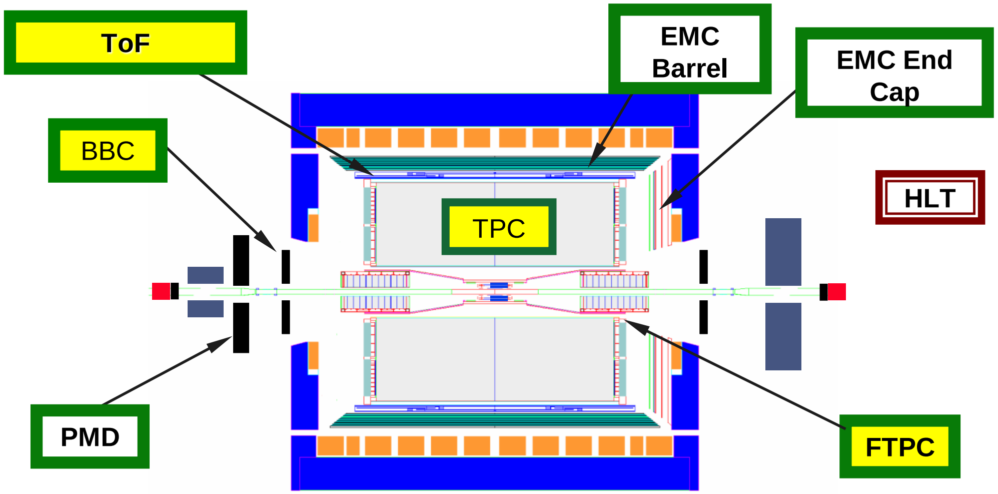
QCD phase diagram

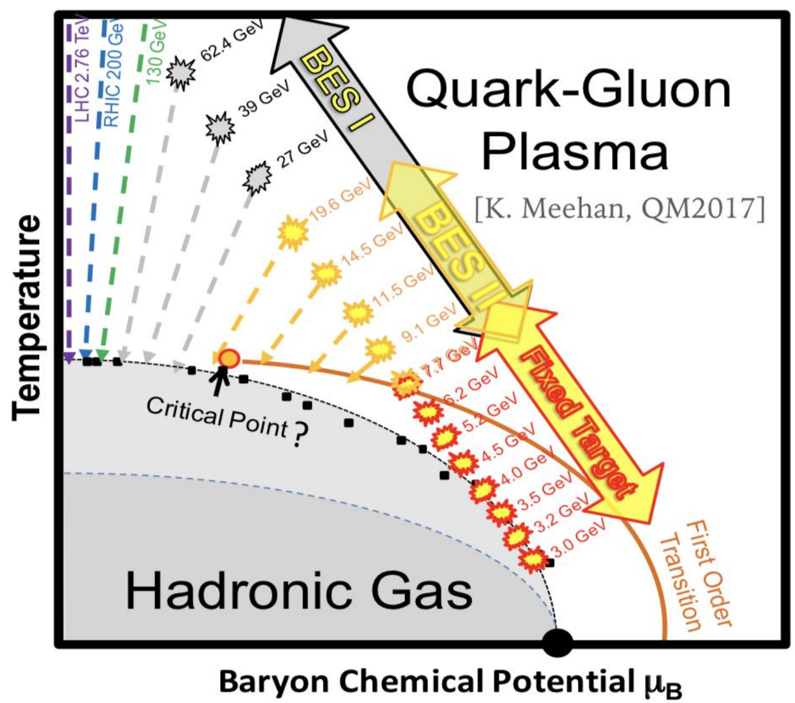
B. Müller, BEST Col. Meeting, 2016



- **RHIC Beam Energy Scan**
  Cover the intermediate baryon density region
  Look for **onset of de-confinement, phase boundary** and critical point

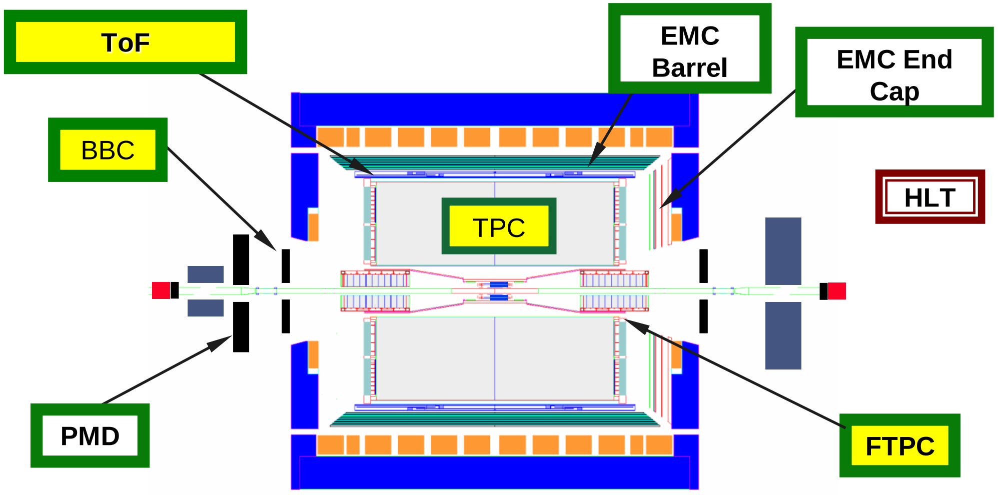
STAR BES





- STAR: 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

STAR BES-I datasets

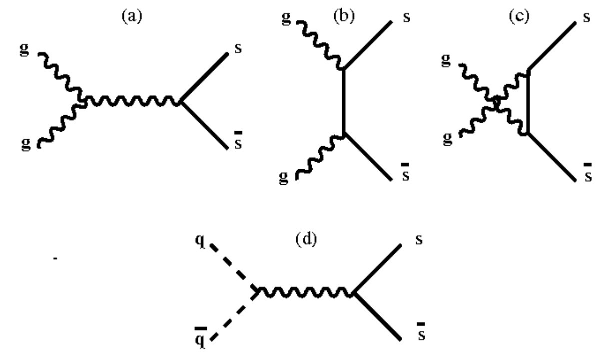


- STAR:
  Collider experiment at RHIC
- full azimuthal coverage at mid-rapidity
- BES-I (completed)
  Au+Au $\sqrt{s_{\mathrm{NN}}} = 62.4 – 7.7$ GeV

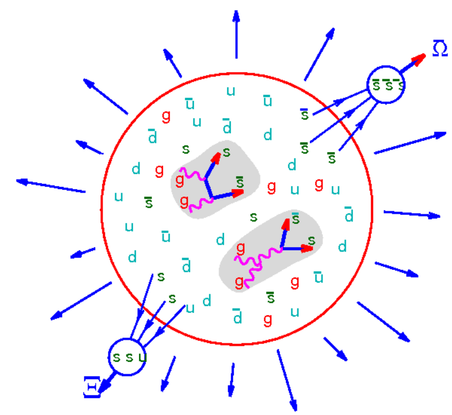
Year	*Collisions*	$\sqrt{s_{NN}}$ (GeV)	MB events
2010	Au+Au	7.7	~ 4 M
2010	Au+Au	11.5	~ 12 M
2014	Au+Au	14.5	~ 13 M
2011	Au+Au	19.6	~ 36 M
2011 / 2018	Au+Au	27	~ 70 M / ~ 560 M
2010	Au+Au	39	~ 130 M
2017	Au+Au	54.4	~ 556 M
2010	Au+Au	62.4	~ 46 M

Why strangeness?

Rafelski & Müller, 1982

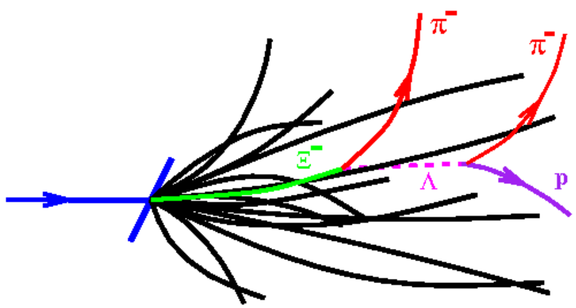


- Strange quarks
  - Not exist in colliding nuclei
  - Current mass ~100 MeV < T_c
  - Easily pair-produced in de-confined QGP medium

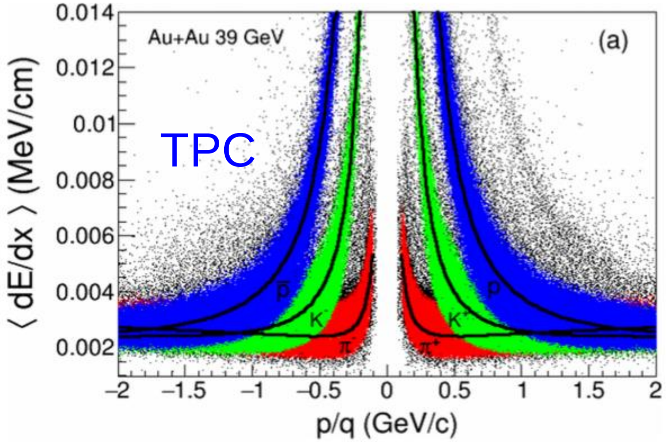


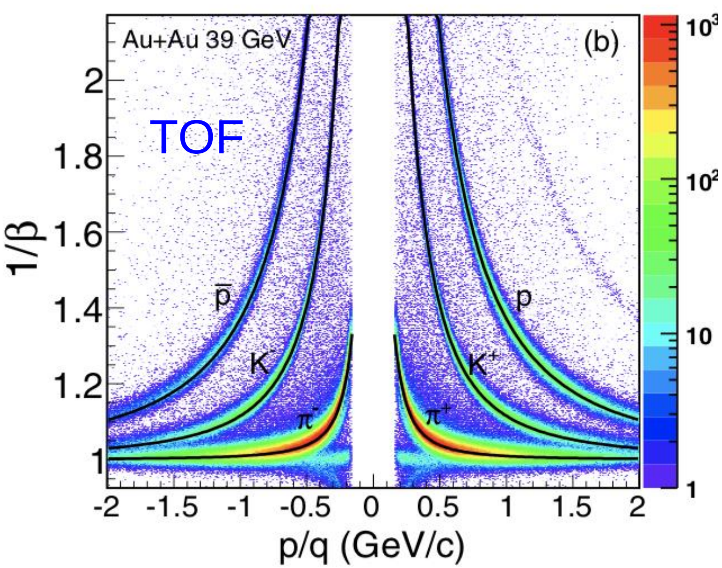
→ Strangeness enhancement !

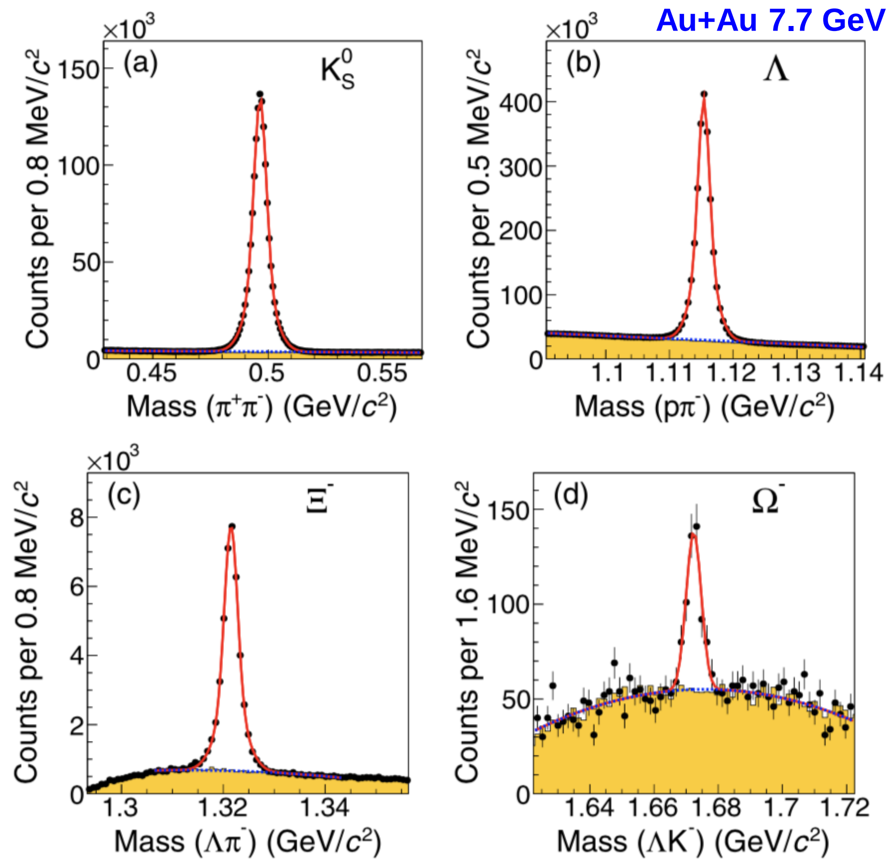
- Hadrons with (multiple) strange quarks
  - Small hadronic cross section
  - Sensitive to the early stage dynamics of the medium
  - Can be easily reconstructed and identified in experiment, up to high p_T !

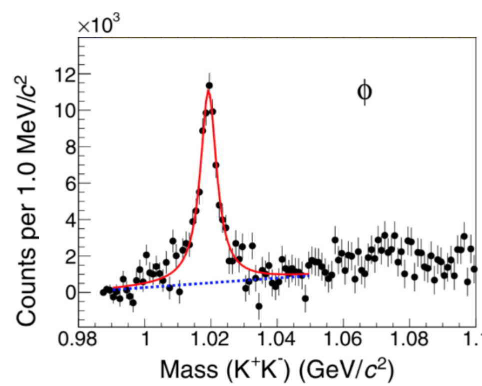


Particle identification and reconstruction



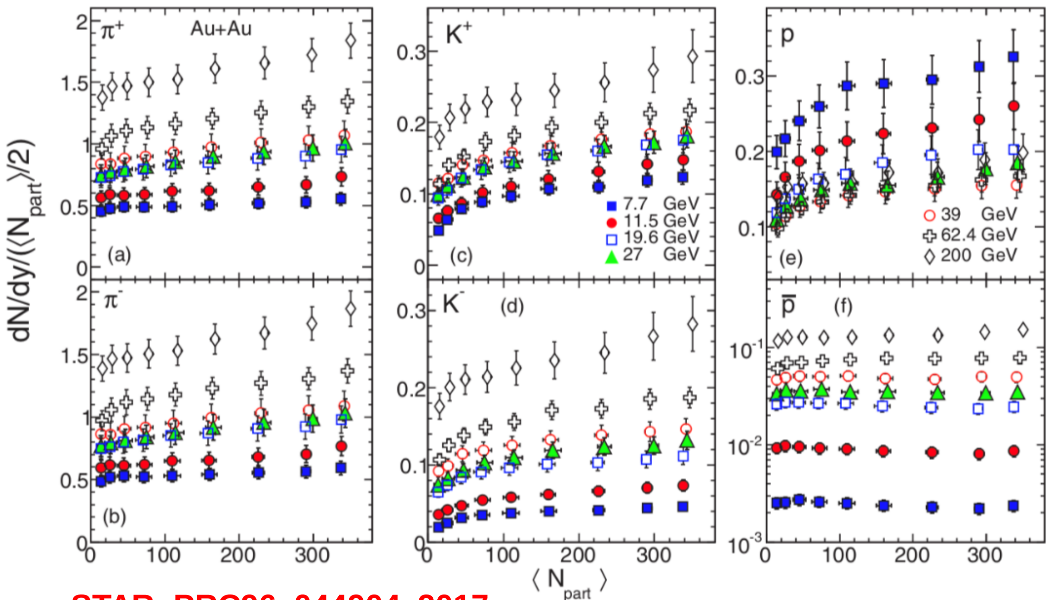




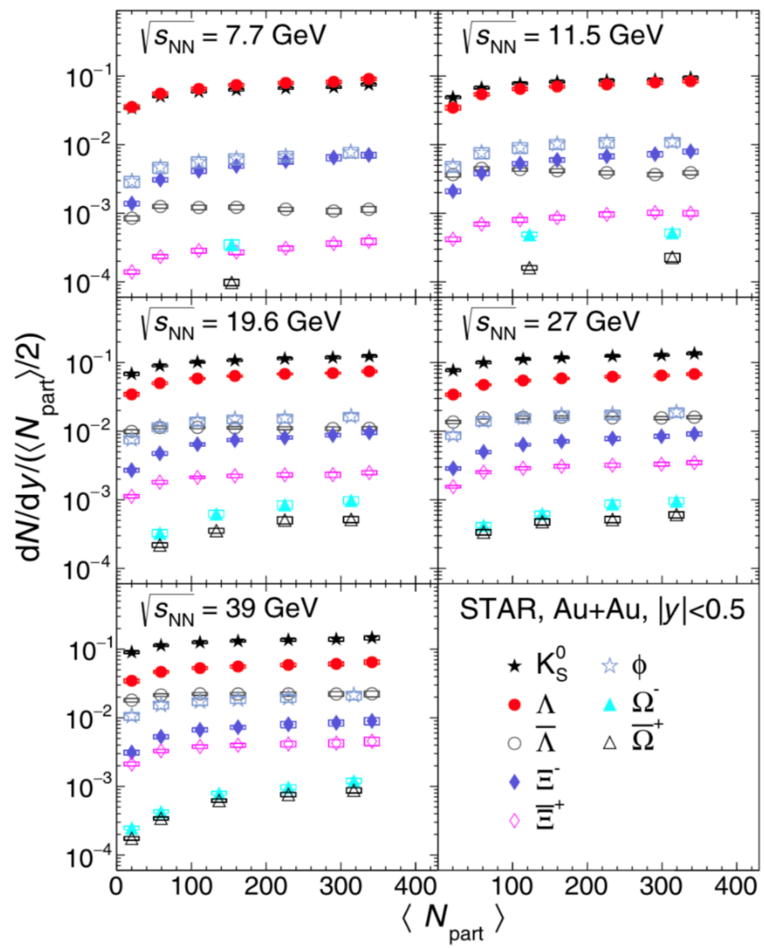


STAR, PRC96, 044904, 2017
STAR, PRC102, 034909, 2020

Particle yields, d*N*/dy, at mid-*y*



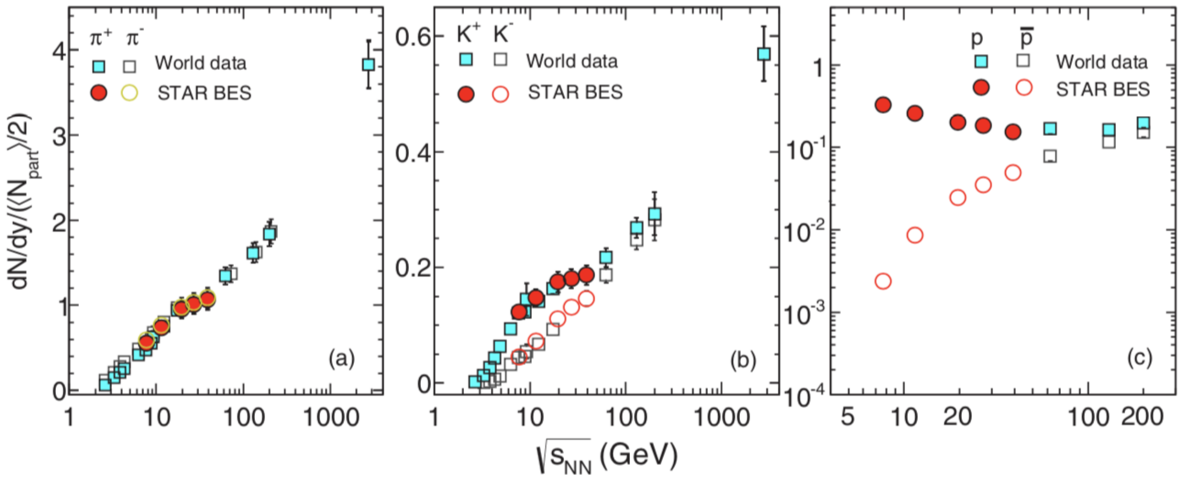
STAR, PRC96, 044904, 2017



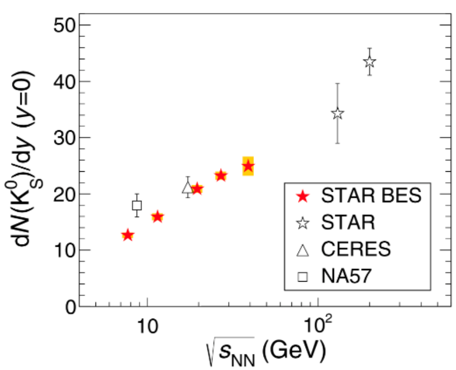
STAR, PRC102, 034909, 2020

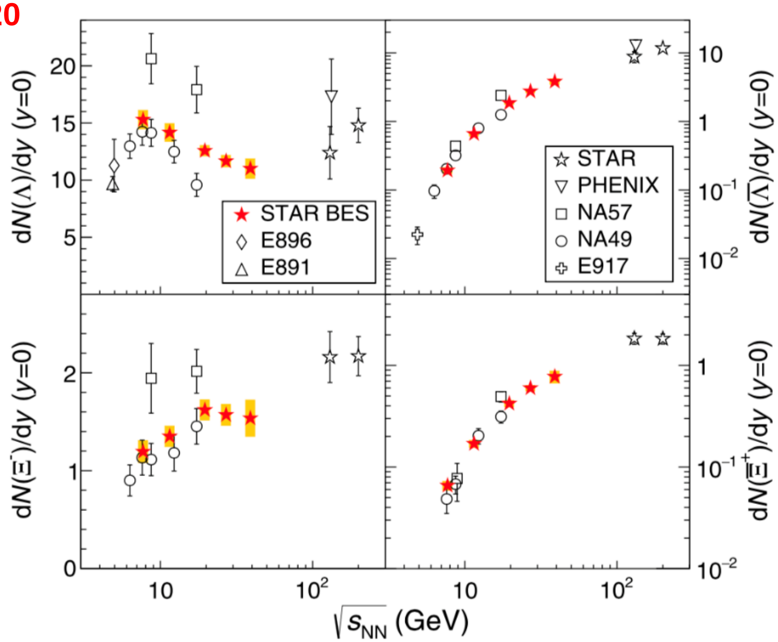
- Yield per participating pair increases towards central and higher energies in general
- Exceptions:
  - p and Λ yields decrease towards higher energy
  - $\bar{p}$ and $\overline{\Lambda}$ has weak centrality dependence

Particle yields in central collisions



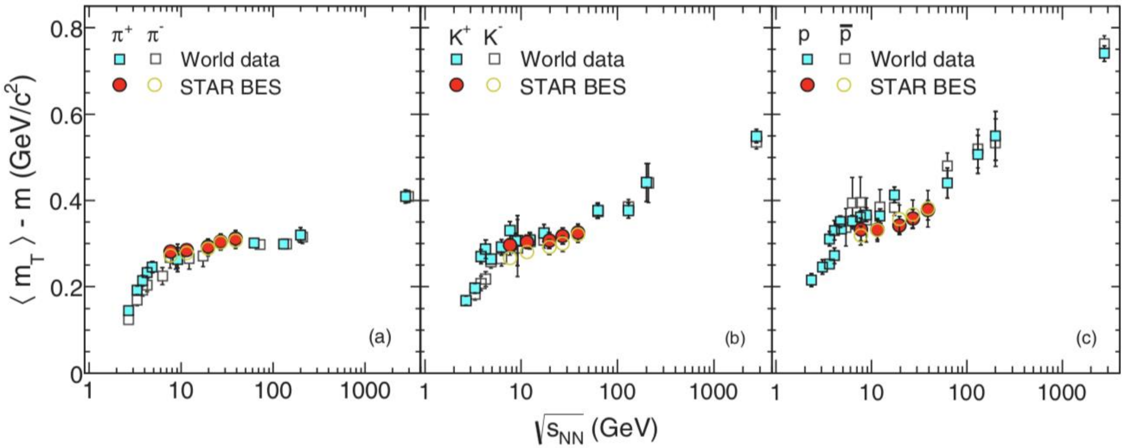
STAR, PRC96, 044904, 2017
STAR, PRC102, 034909, 2020

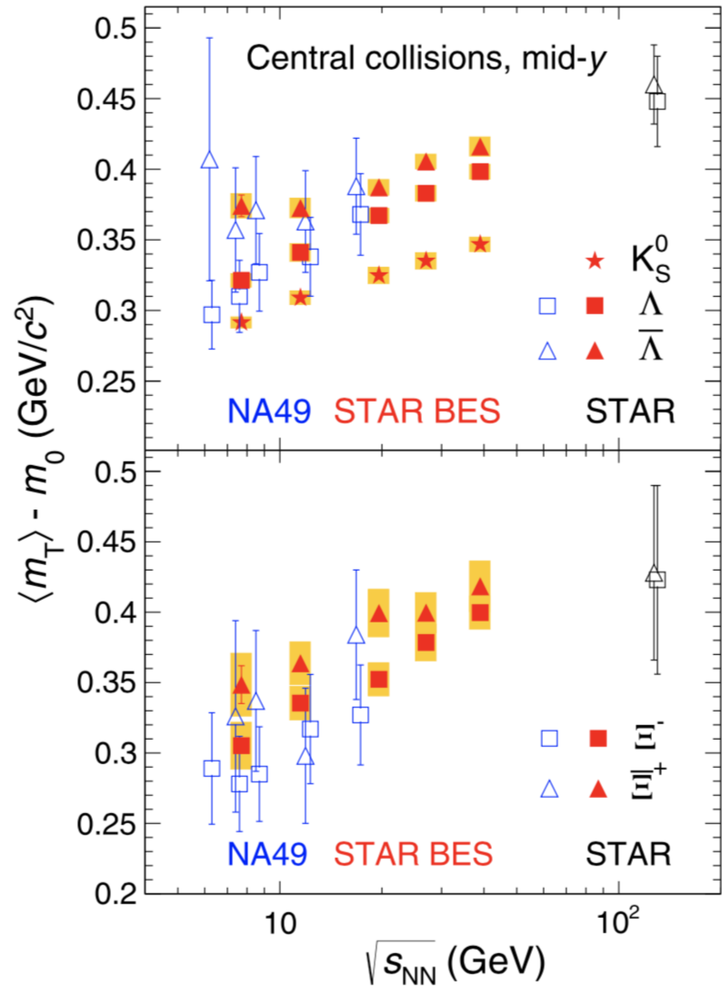




- STAR BES-I data consistent with published data in general
- Rich structure in these excitation functions
- p and Λ yields reach minimum at 39 GeV: interplay of baryon transport and pair production

Average transverse mass

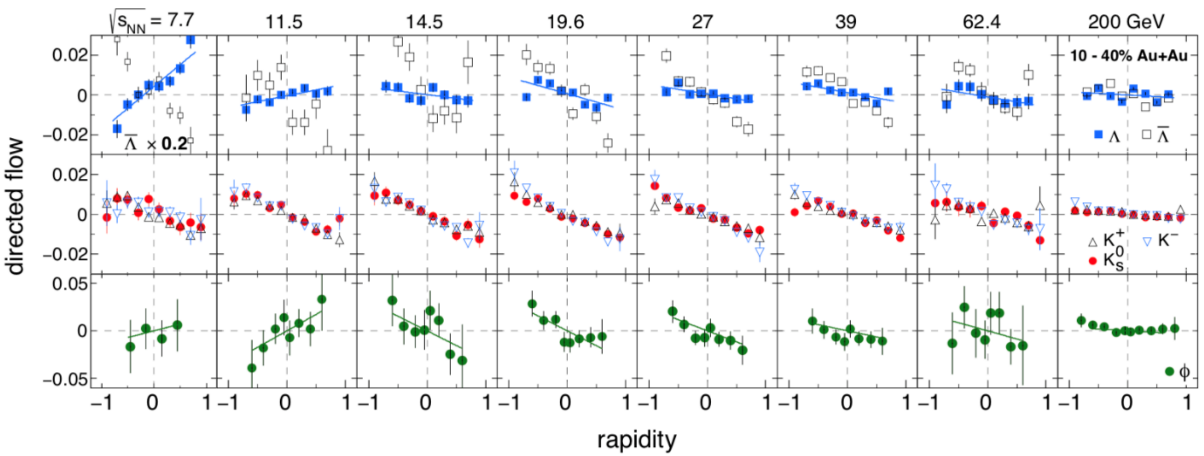


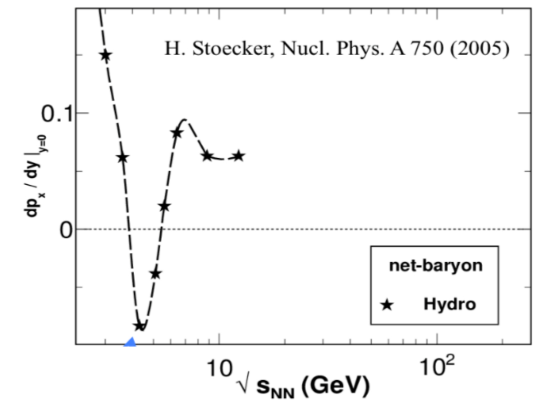


STAR, PRC96, 044904, 2017
STAR, PRC102, 034909, 2020

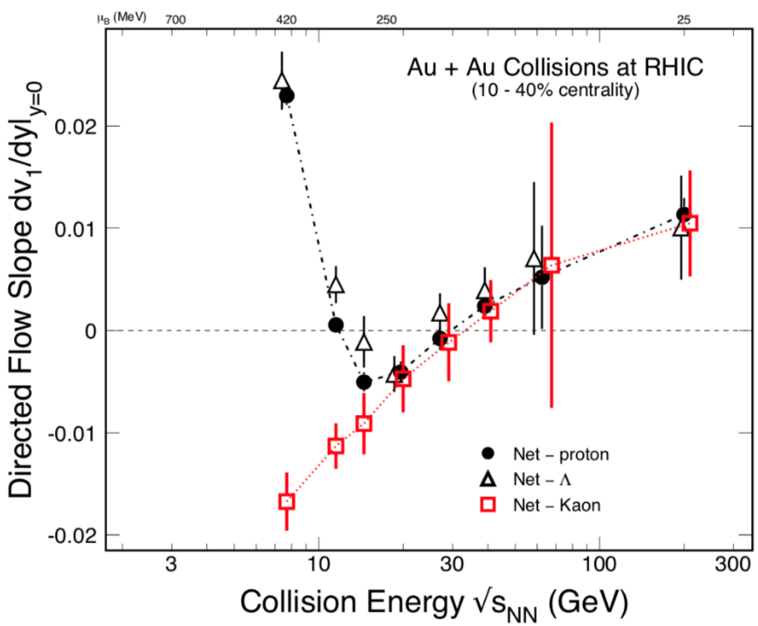
- A step-like structure can be seen in the energy dependence
- Λ and $\bar{\Lambda}$ show split at lower energies might be due to baryon-antibaryon annihilations at high baryon density

Directed flow



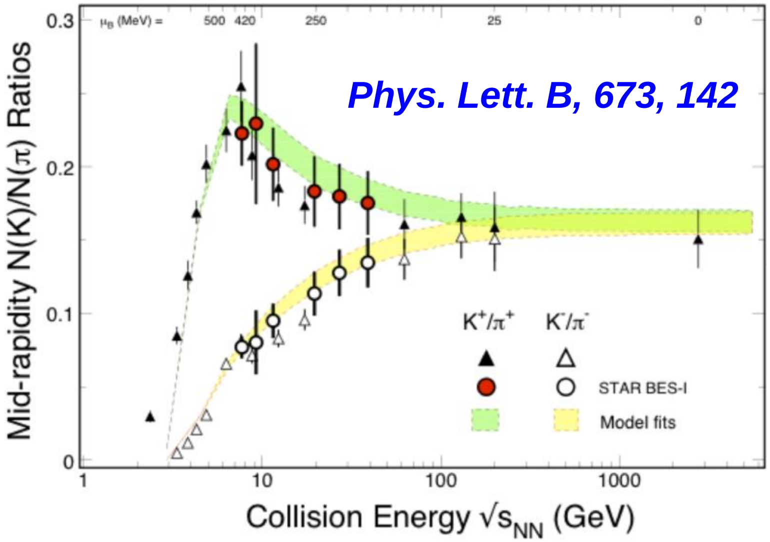


STAR, PRL112, 162301, 2014
STAR, PRL120, 062301, 2018

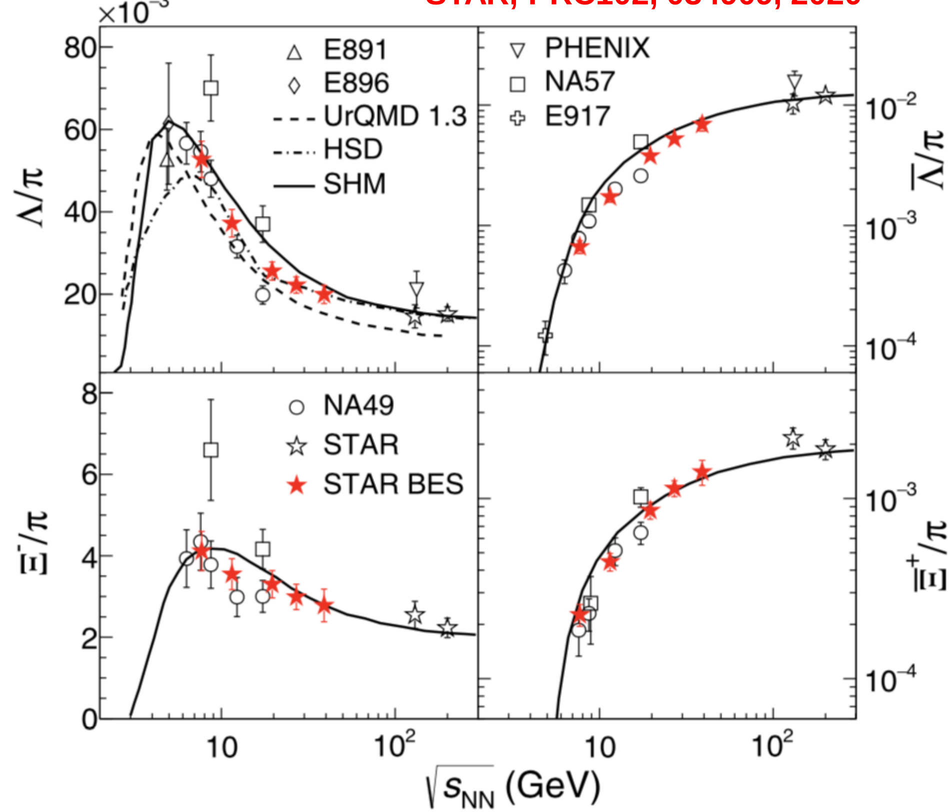


- Sign change of proton dv_1/dy, softening of EOS, first-order phase transition
- Double sign change seen in net-proton, net-Λ, not seen in net-kaon
- Need theory to explain

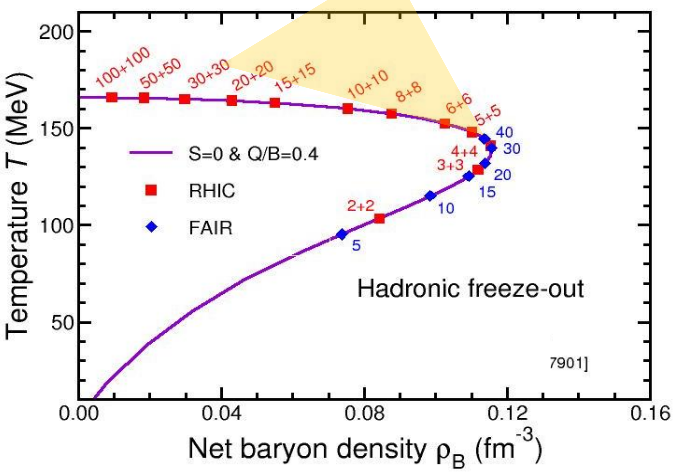
Strange hadron to pion ratio



STAR, PRC102, 034909, 2020



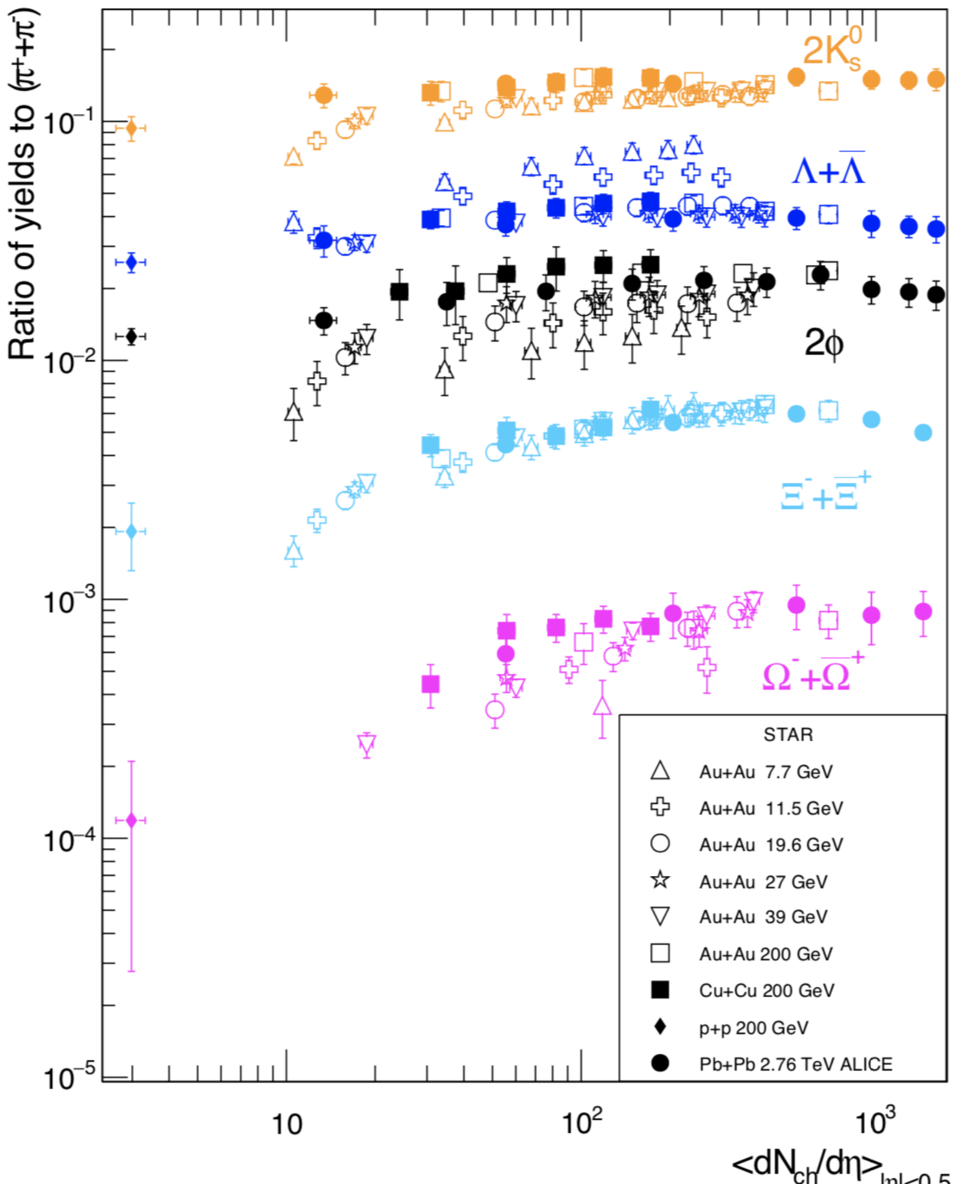
RHIC BES



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**

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

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

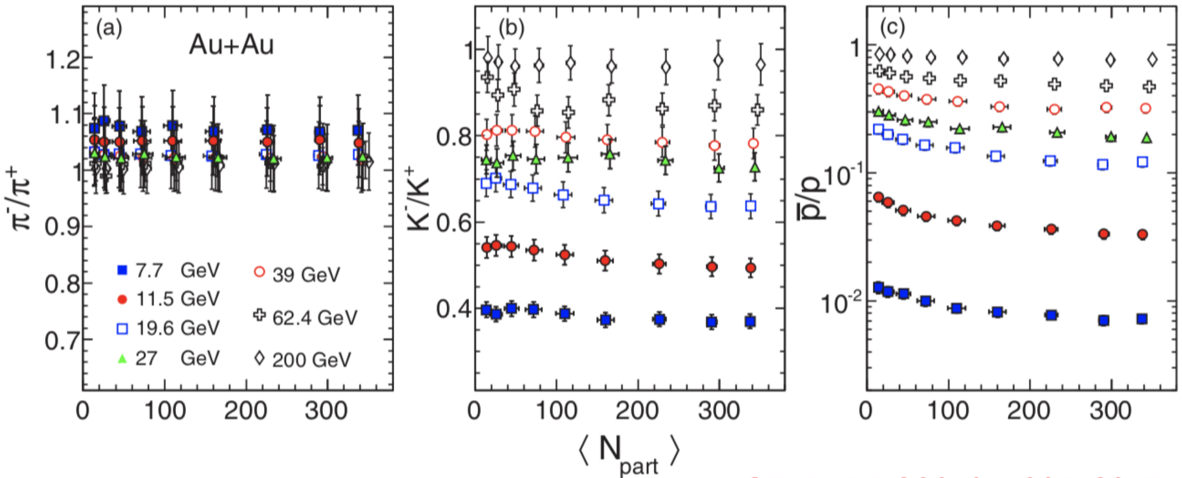
where $M = 1 + m^2/p_t^2$

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

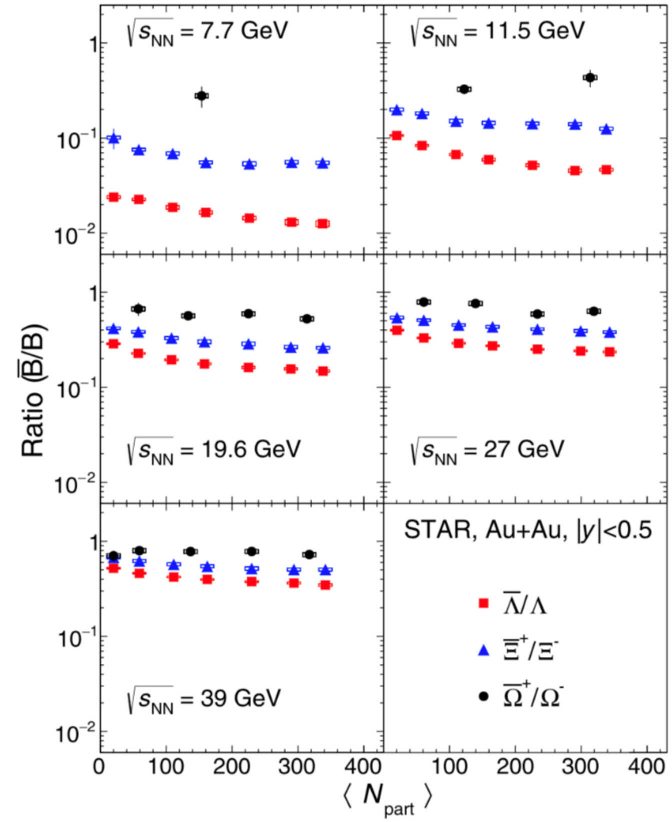
$$dN_{ch}/d\eta(\eta = 0) \sim dN_{ch}/d\eta(|\eta| < 0.5)$$

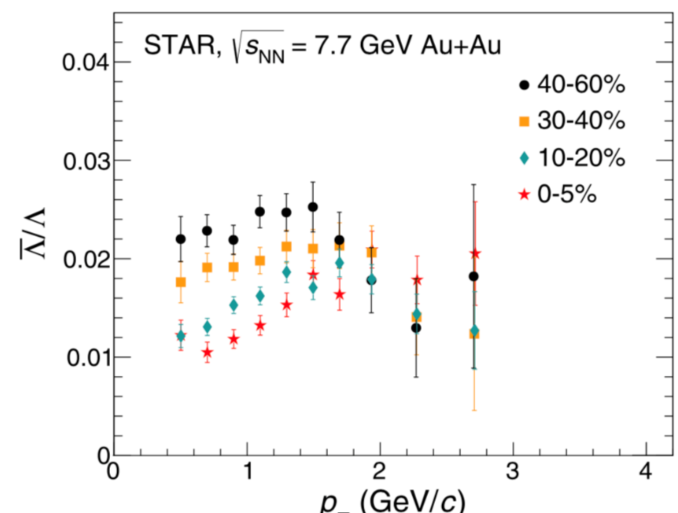
- The ratios at different energies/centralities/systems mainly depend on charged hadrons multiplicity, except for Λ and ϕ
- The ratios saturate at large charged hadrons multiplicity

Anti-hadron to hadron ratio



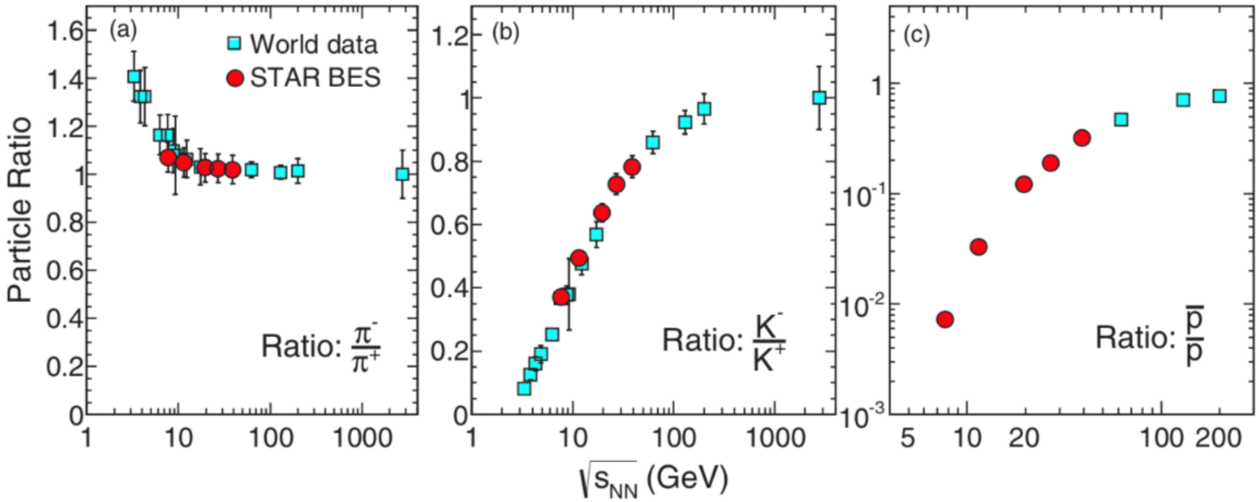
STAR, PRC96, 044904, 2017
STAR, PRC102, 034909, 2020



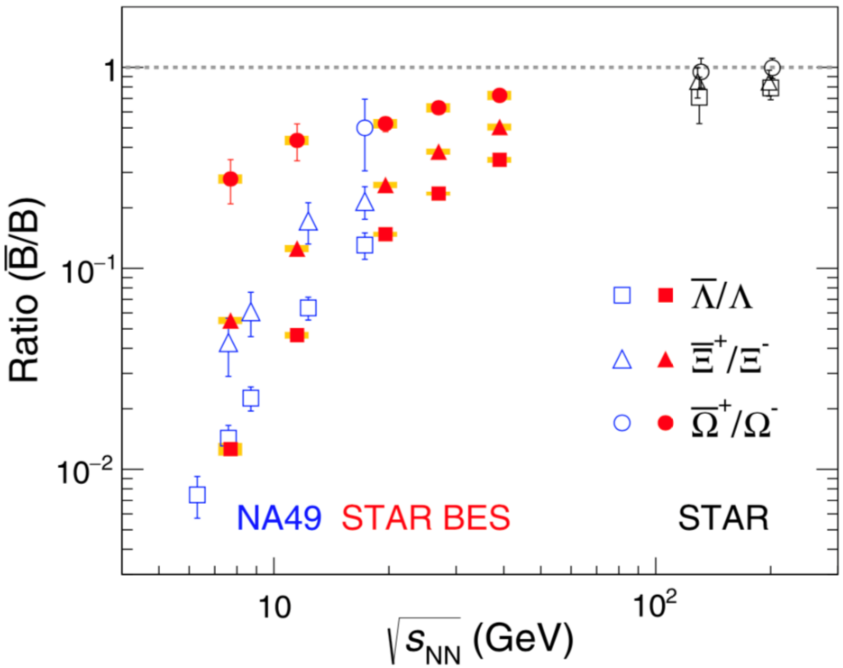


- Centrality dependence of $\overline{\mathrm{B}}/\mathrm{B}$ ratios: **peripheral > central**
- This effect is more prominent at lower energies. **baryon stopping and/or anti-baryon absorption**
- **Loss of low p_T $\bar{\Lambda}$ in central collisions**

Anti-hadron to hadron ratio



STAR, PRC96, 044904, 2017
STAR, PRC102, 034909, 2020



- STAR BES data lie in a trend with NA49 data
- $\bar{B}/B$ 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

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

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

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

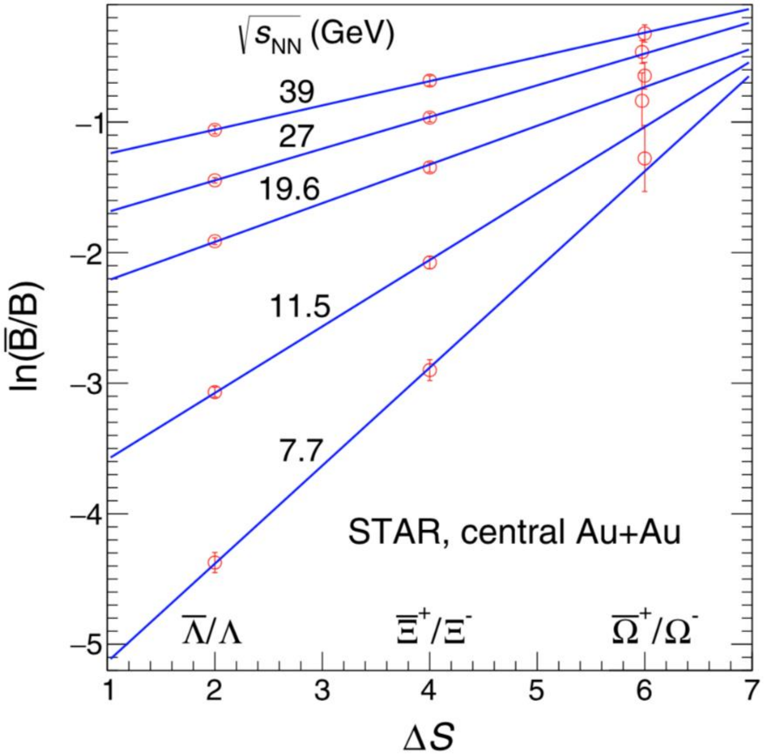
$$\frac{\overline{\Omega}^+}{\Omega^-} = \exp(-\frac{2\mu_B}{T} + \frac{6\mu_S}{T}) \qquad \Rightarrow \qquad \ln(\frac{\overline{\Omega}^+}{\Omega^-}) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T}$$

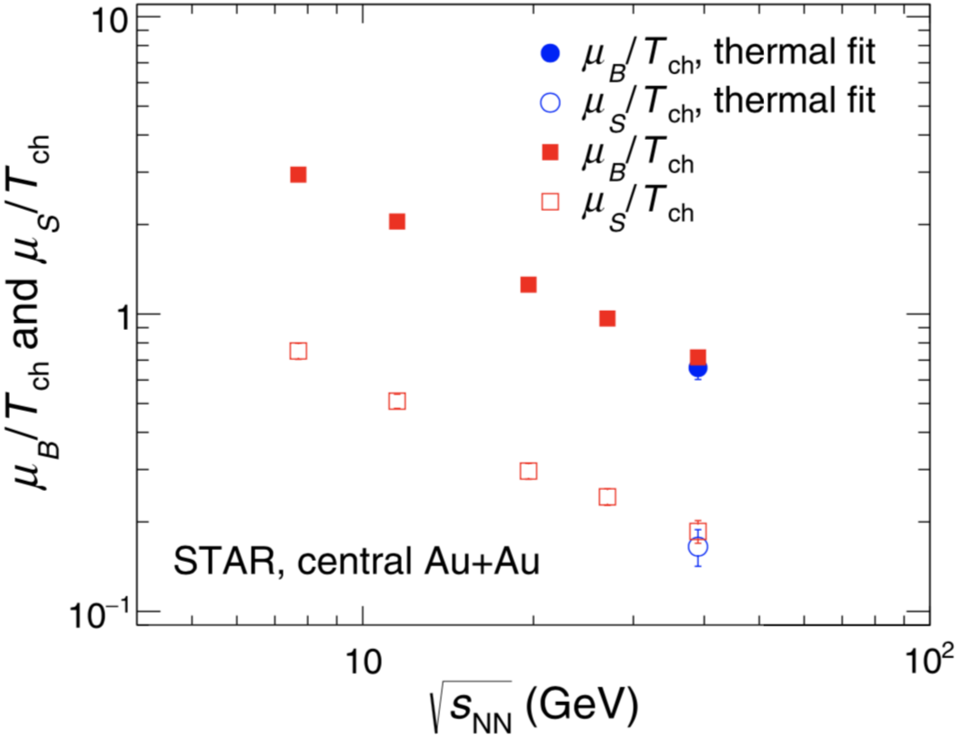
- T is the temperature.
- μ_B is the baryon chemical potential.
- μ_S is the strangeness chemical potential.

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

μ_S/T_{ch} and μ_B/T_{ch}

STAR, PRC102, 034909, 2020

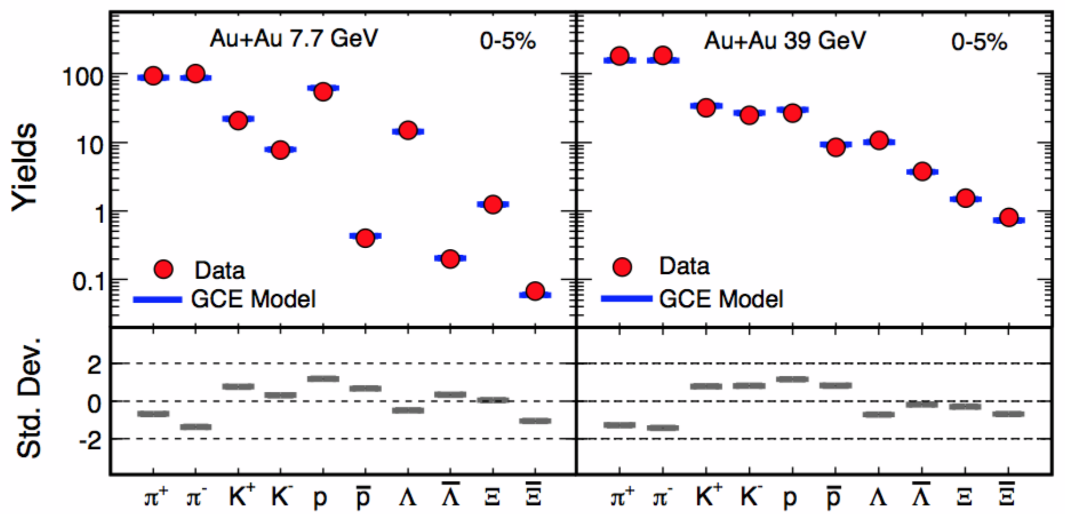


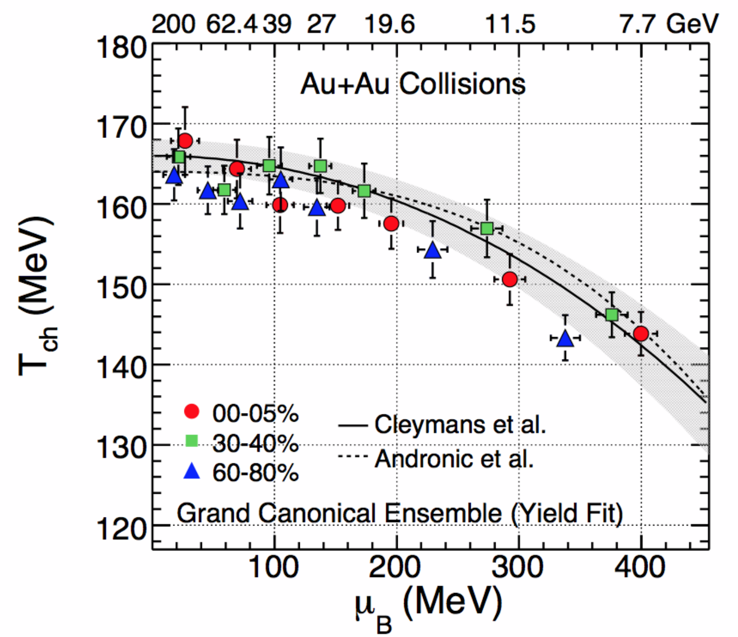


- Anti-hyperon to hyperon ratios are fit well with statistical thermal model
- Chemical freeze-out parameters, μ_S/T_{ch} and μ_B/T_{ch}, are extracted

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

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



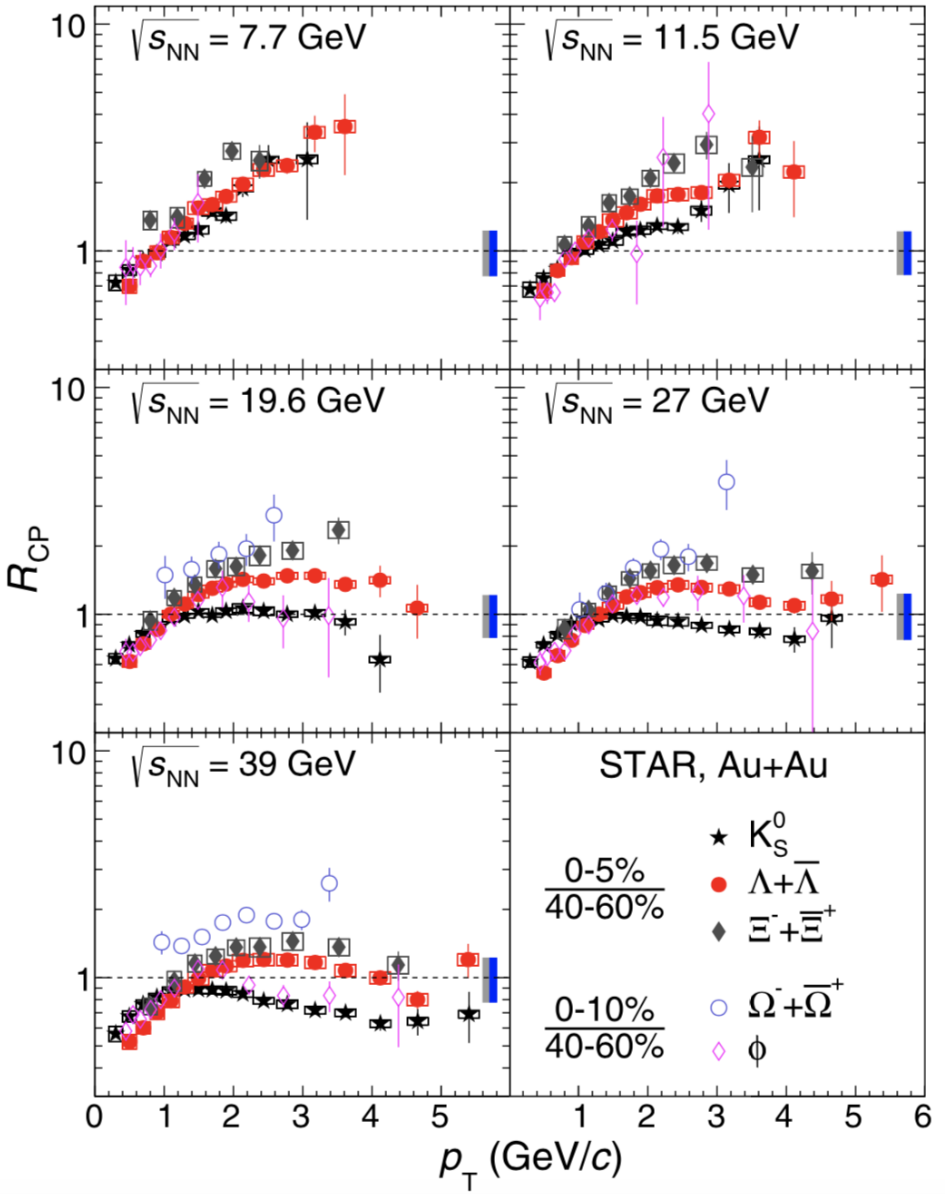


Andronic: NPA 834 (2010) 237
Cleymans: PRC 73 (2006) 034905
Au+Au 200 GeV : Phys. Rev. C **83** (2011) 24901

- ✓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}

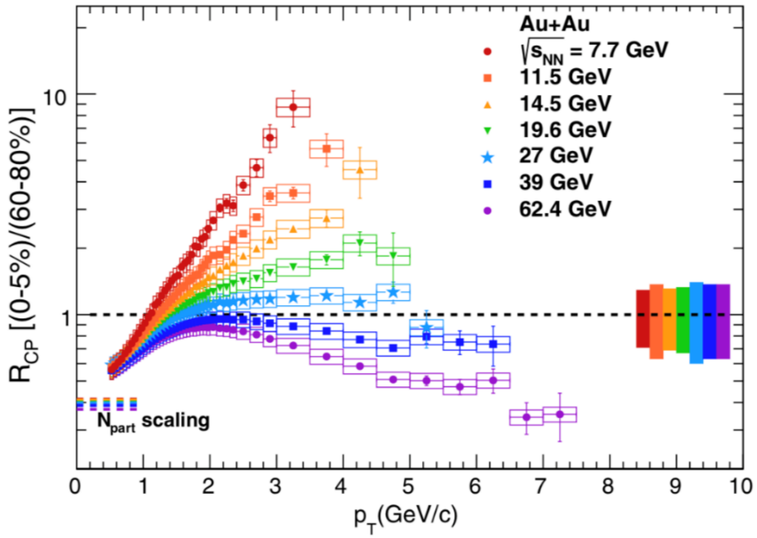


$$R_{CP}(p_T) = \frac{[d^2\sigma/(N_{\rm bin}p_T dp_T dy)]_{\rm central}}{[d^2\sigma/(N_{\rm bin}p_T dp_T dy)]_{\rm peripheral}}$$

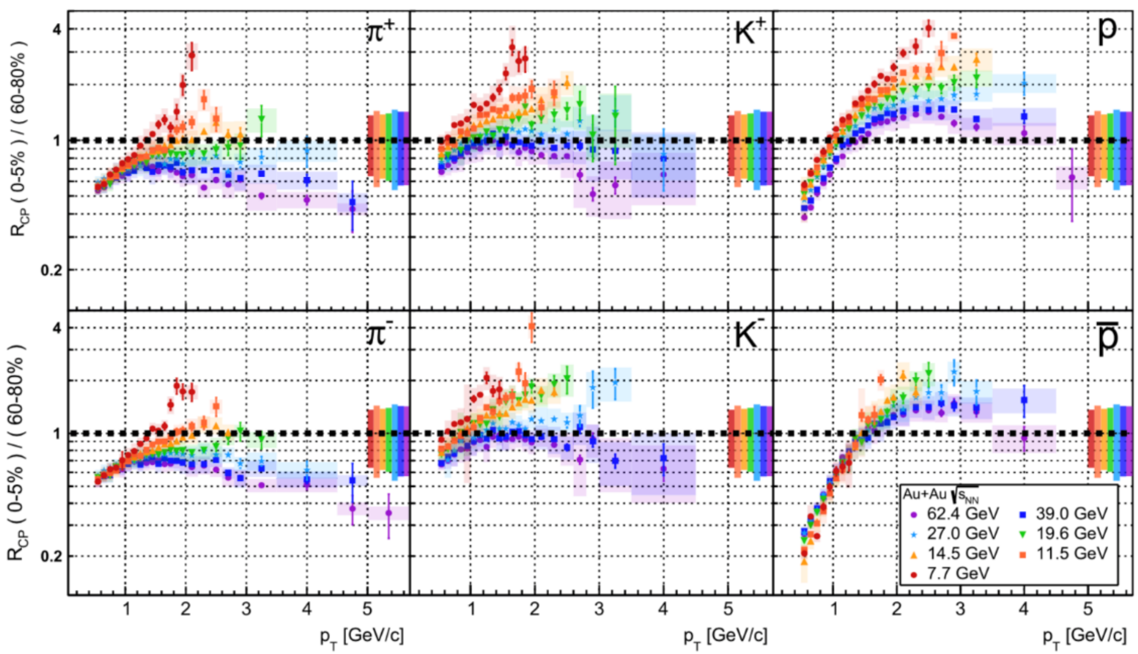
- No K^0_S suppression in Au+Au 7.7 and 11.5 GeV
- Cronin effect and other effects (radial flow) compete with partonic energy loss
- Intermediate p_T, particle R_{CP} difference becomes smaller @ 7.7 and 11.5 GeV

STAR, PRC102, 034909, 2020

Nuclear modification factors R_{CP}

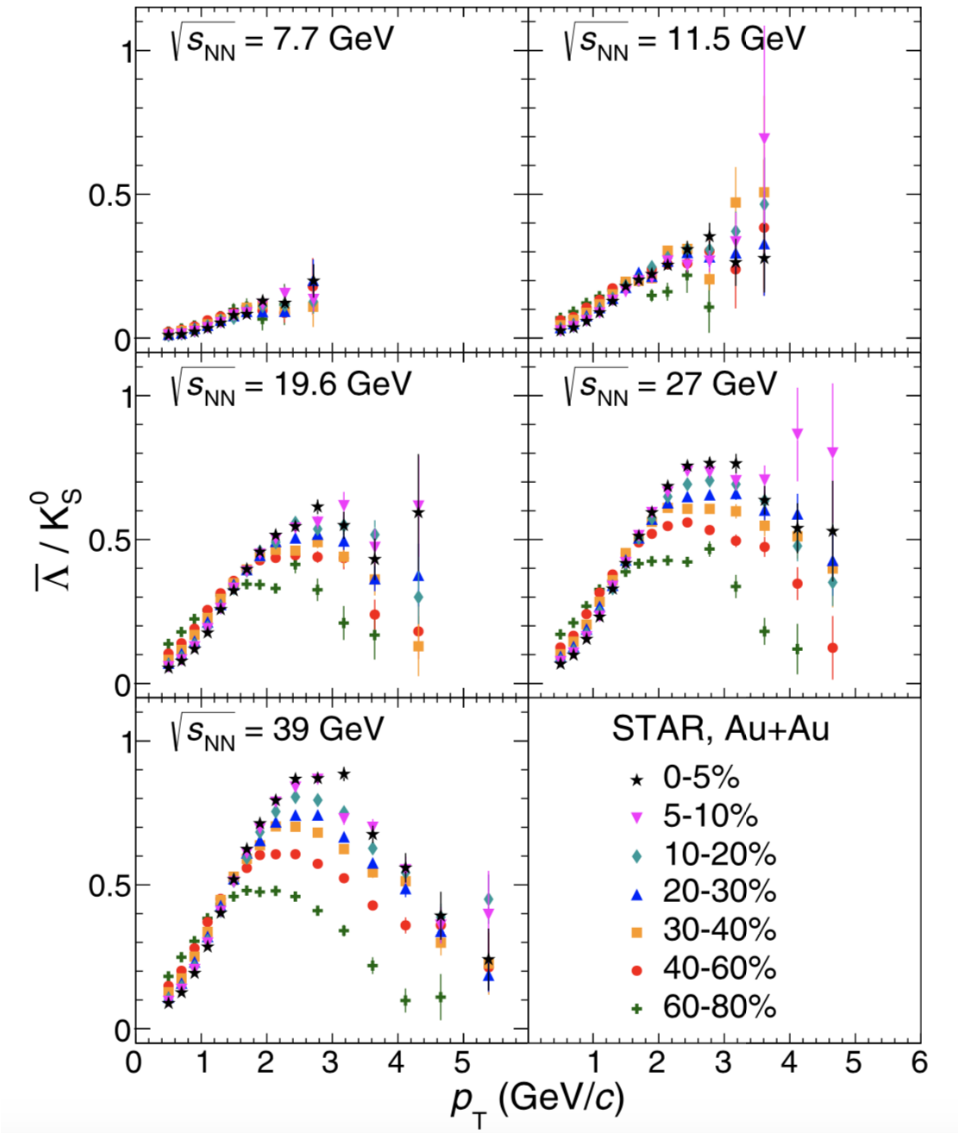


- No suppression for lower energies
- Cronin effect and other effects (radial flow) compete with partonic energy loss



STAR, PRL121, 032301, 2018

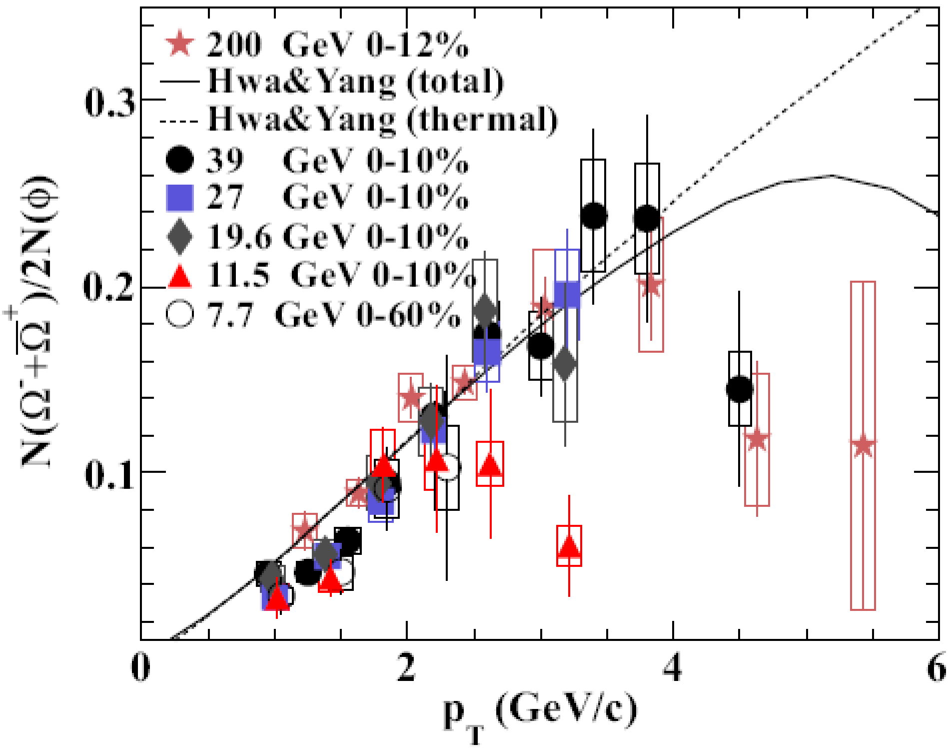
Baryon to meson ratio: $\overline{\Lambda}/K_S^0$

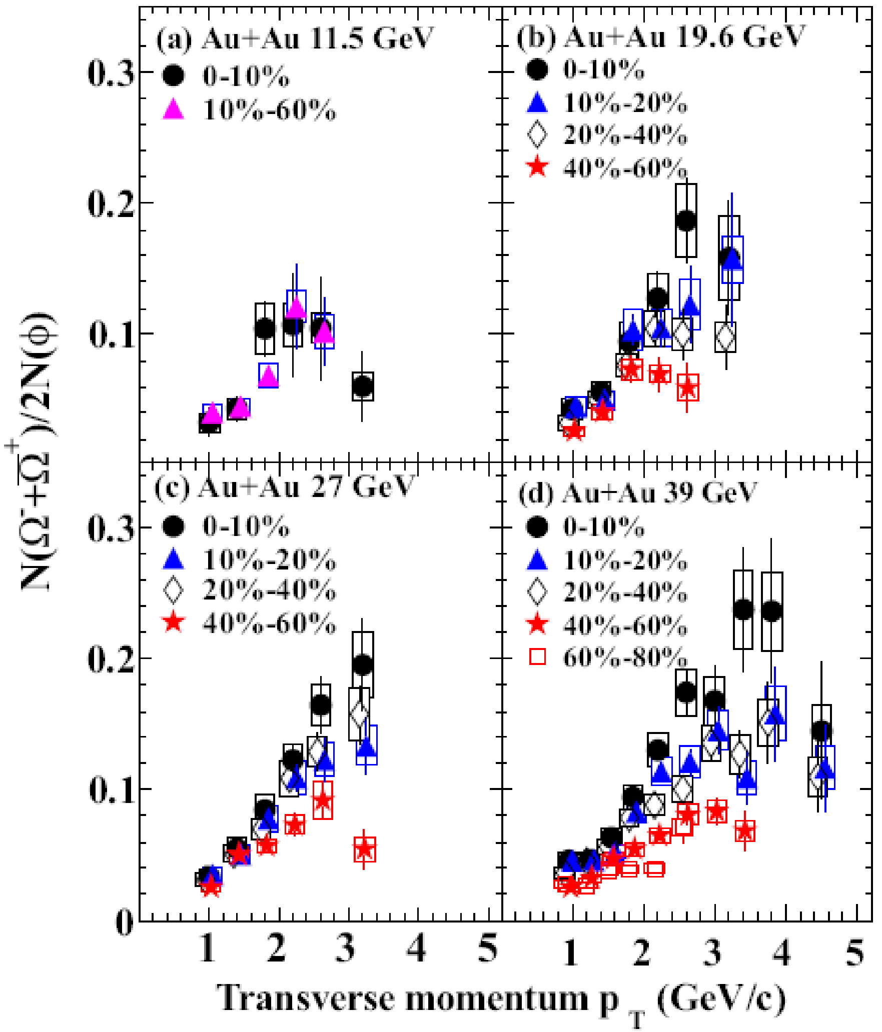


STAR, PRC102, 034909, 2020

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

Ω / ϕ ratio

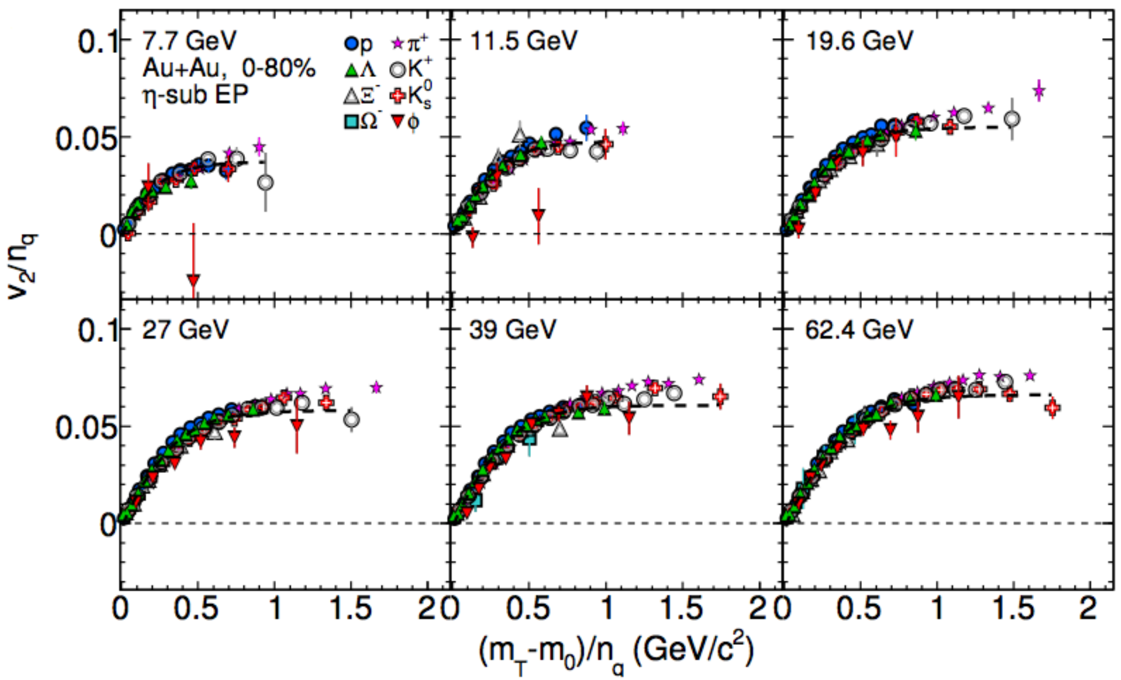


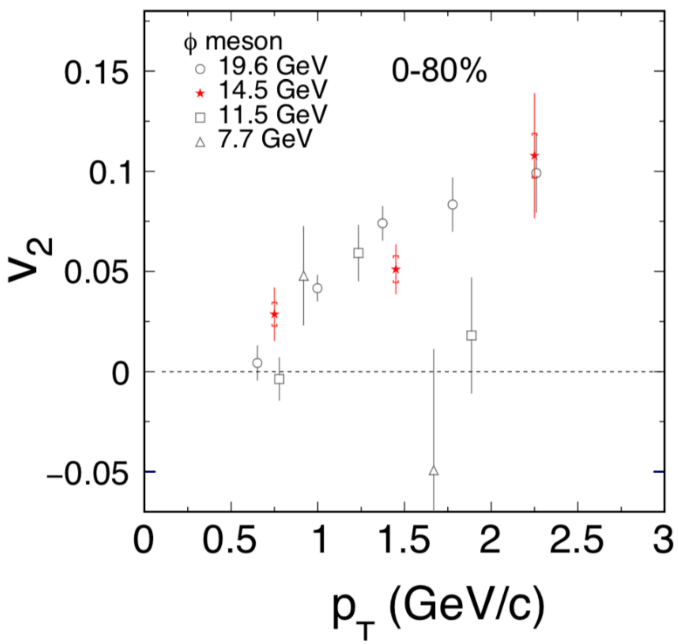


STAR, Phys. Rev. C 93, 021903 (R), 2016

- 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

Elliptic flow

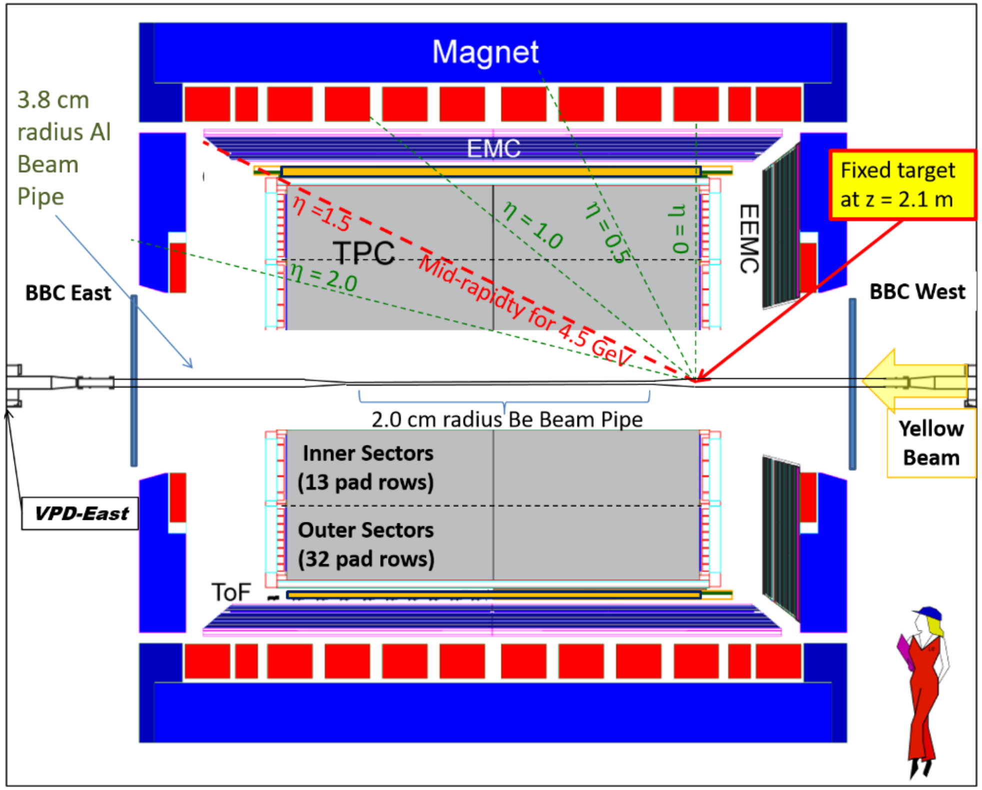




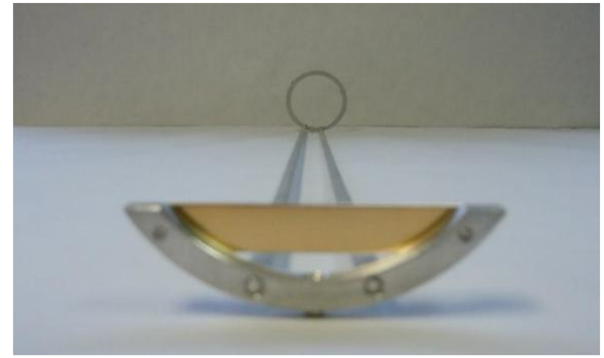
STAR, Phys. Rev. C88 (2013) 014902; Phys. Rev. C93 (2016) 014907

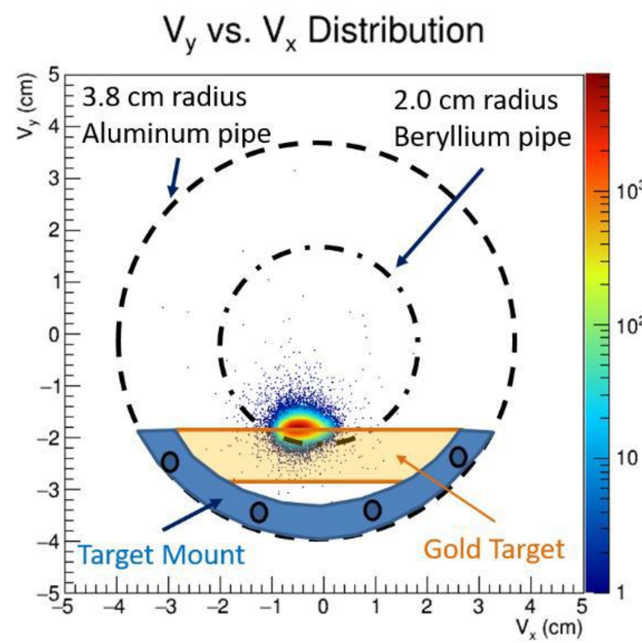
- NCQ scaling holds with 10% for selected particles in all energies
- 14.5 GeV: Sizable ϕ meson v_2, comparable to 19.6 GeV
- High statistics and more collision energies below 20 GeV needed!

The STAR fixed-target program



1 mm thick (4% inter. prob.) gold target (2015)
→ 1/4 mm thick gold target in FXT phys. program

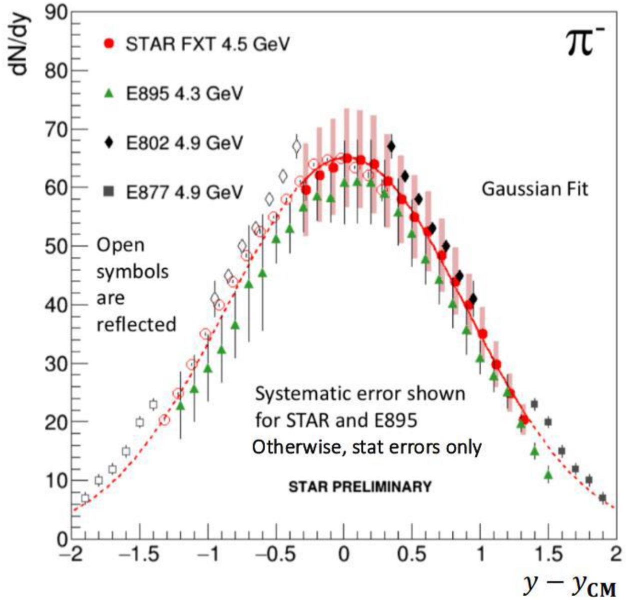




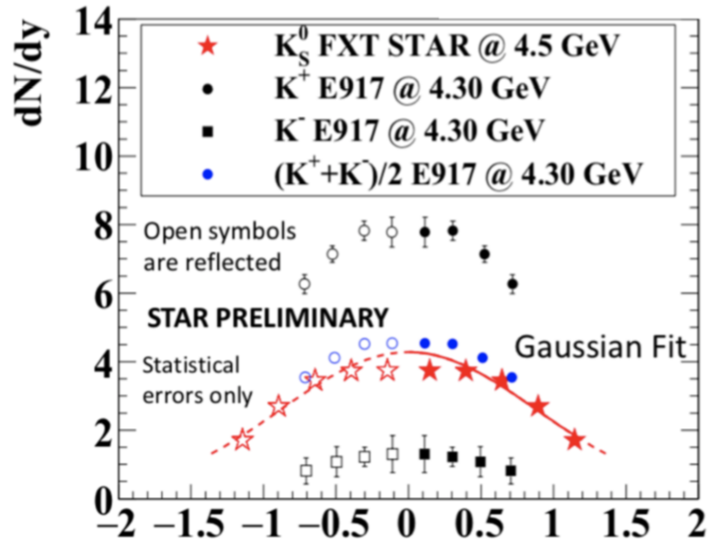
1.3M events from half hour test run, top 30% central trigger, Au+Au $\sqrt{s_{NN}}$=4.5 GeV

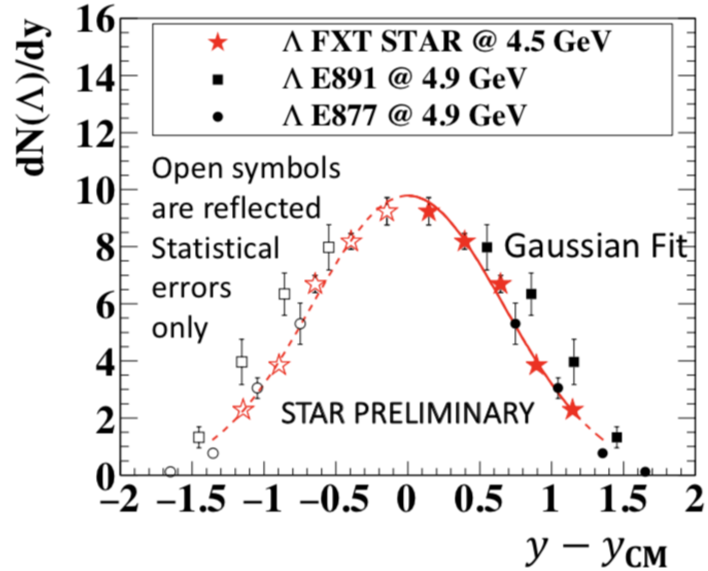
3.4M events from two hour test run, top 30% central trigger, Al+Au $\sqrt{s_{NN}}$=4.9 GeV

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





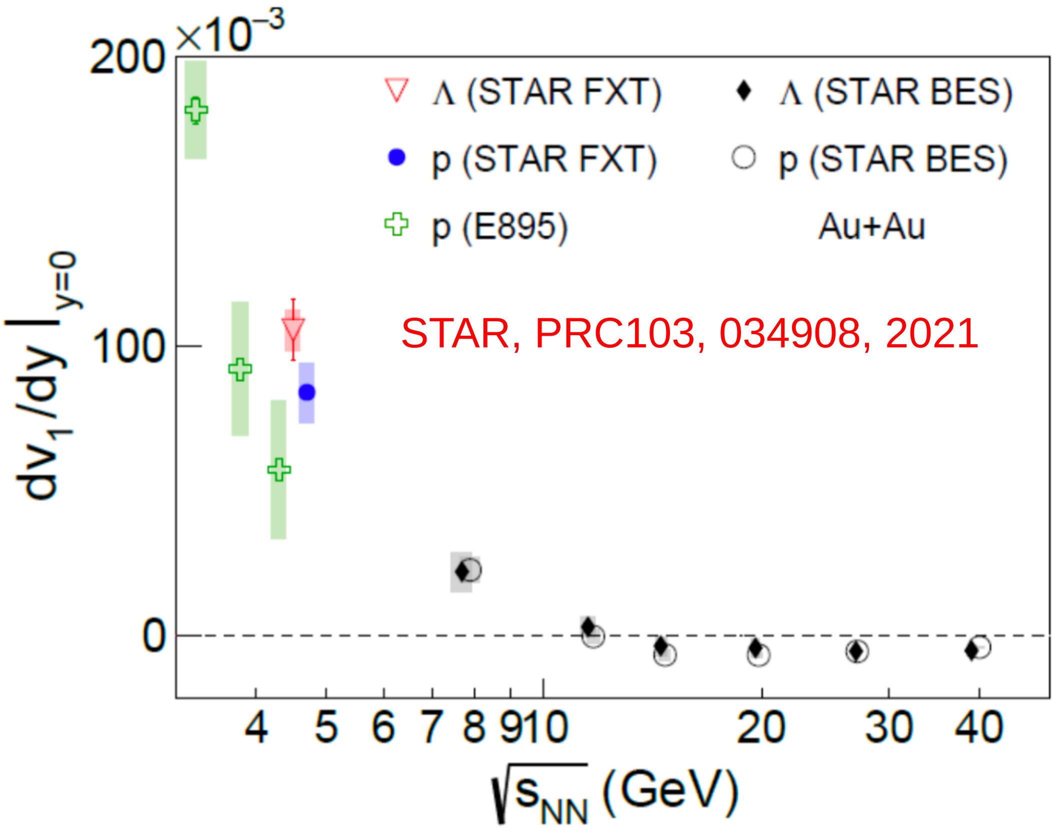
Y. Wu, QM2018
Top 5%

M.-U. Ashraf, QM2019

- Amplitude and width of rapidity densities are consistent with AGS experiments
- $m_T - m_0$ and y range can 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



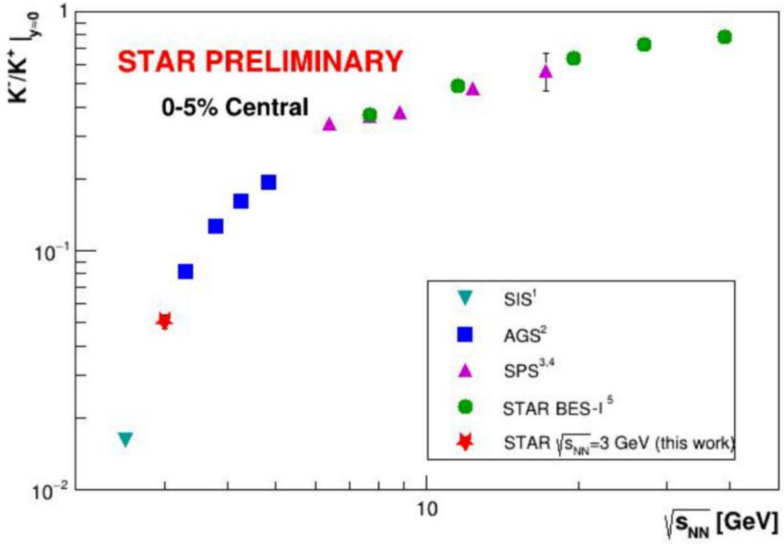
Baryon v_1 slope is consistent with E895 at 4.3GeV

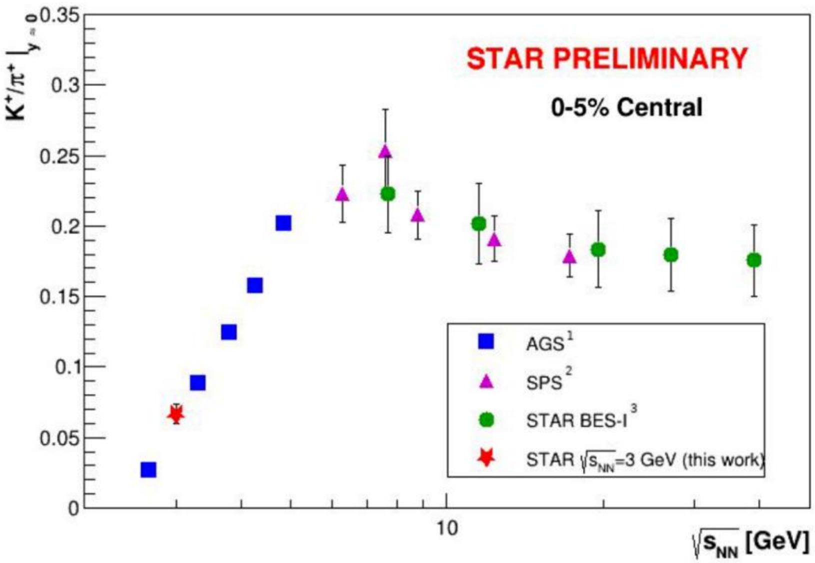
The STAR fixed-target physics program (2018-2021)

Year	*Collisions*	$\sqrt{s_{NN}}$ (GeV)	Good events
2018	Au+Au	3.0	~ 258 M
2018	Au+Au	7.2	~ 155 M
2019	Au+Au	3.9	~ 53 M
2019	Au+Au	3.2	~ 200 M
2019 / 2020	Au+Au	7.7	~ 164 M
2020	Au+Au	4.5	~ 108 M
2020	Au+Au	6.2	~ 118 M
2020	Au+Au	5.2	~ 103 M
2020	Au+Au	3.9	~ 117 M
2020	Au+Au	3.5	~ 116 M
2021	Au+Au	3.0, 9.2, 11.5,13.7…	On-going

D. Cebra, APS April Meeting, 2021

Charged kaon production in Au+Au $\sqrt{s_{NN}}$=3.0 GeV



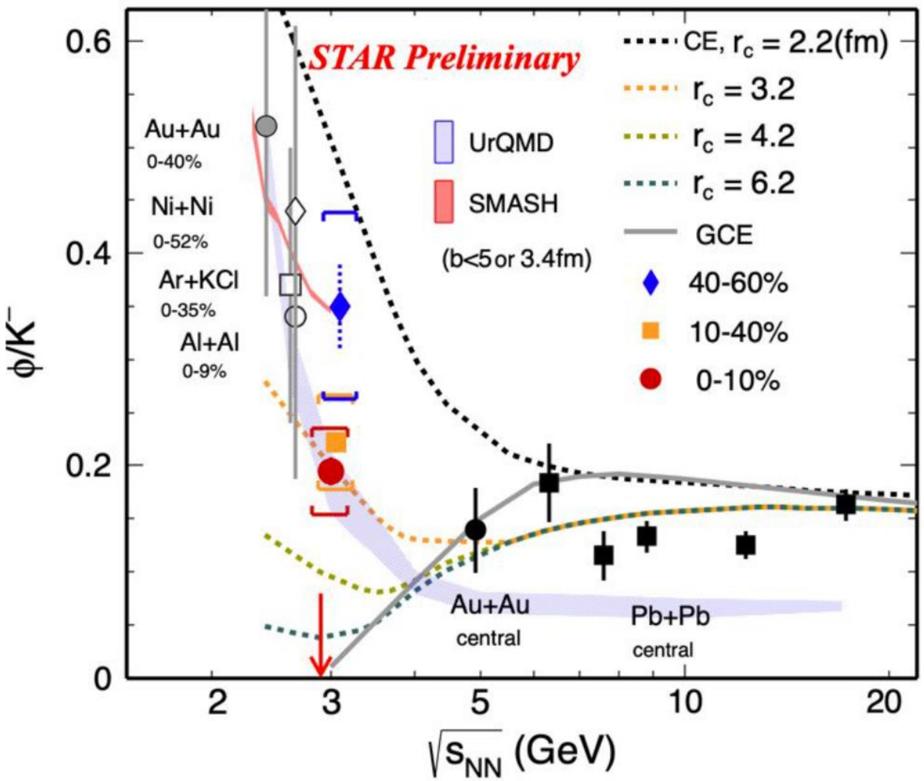


B. Kimelman, CPOD2021

SIS: J. Phys. G 28, 2011
AGS: Phys. Lett. B 490, 53;
Phys. Lett. B 476, 1
SPS: Phys. Rev. C 77, 024903;
Phys. Rev. C 66, 054902;
Phys. Rev. C 77, 024903
STAR: Phys. Rev. C 96, 044904

- K^+/π^+ and K^-/K^+ ratios follow world trend
- K^-/K^+ ratio drops at lower energies from associated production of K^+ (NN→ NΛK)

ϕ production in Au+Au $\sqrt{s_{NN}}$=3.0 GeV



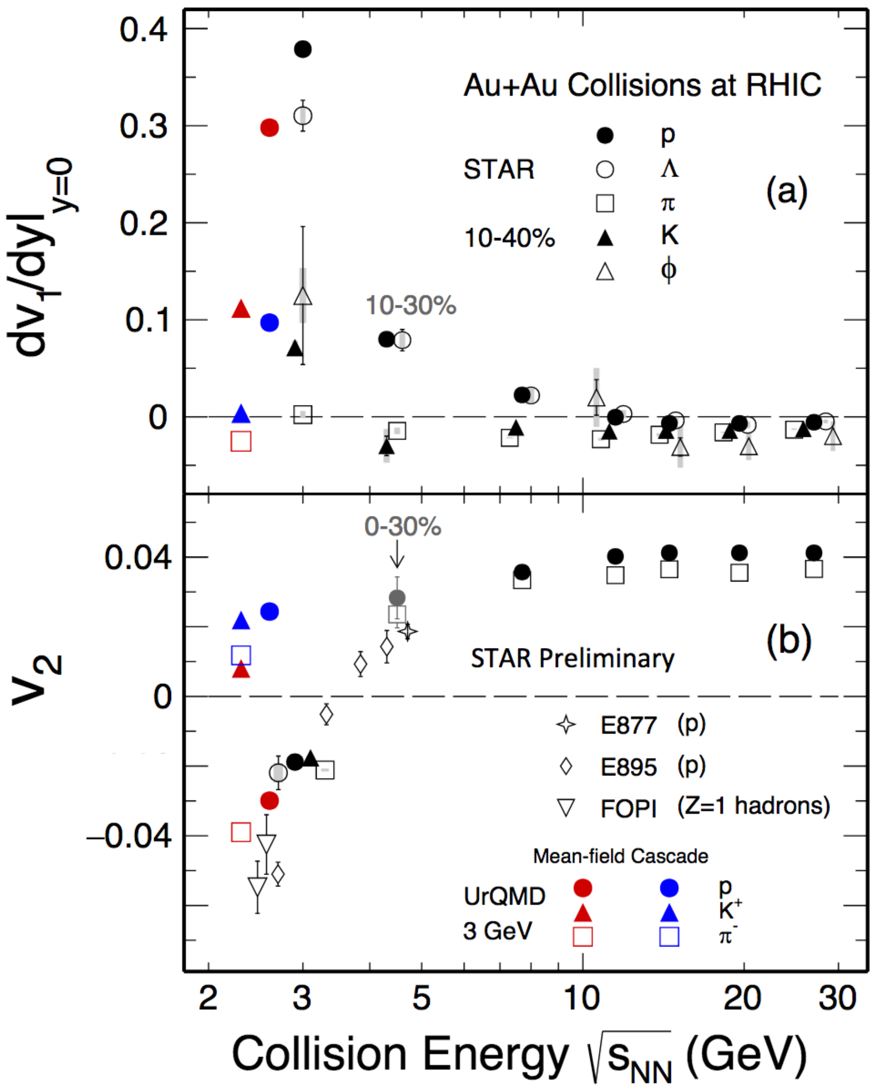
World data: Phys. Lett. B 778, 403-407, Phys. Rev. C. 80.025209; Phys. Rev. C. 69.054901; Phys. Rev. C 78, 044907; Phys. Rev. C 77, 024903, Phys. Rev. C 66, 054902

Models: Nucl. Phys. A 772, 167; Phys. Lett. B 603, 146
J. Phys. G: Nucl. Part. Phys. 43 (2016) 015104
Phys. Rev, C 99, 064908

G. Xie, S. Radhakrishnan, APS April Meeting, 2021

- Low energies, small systems: local strangeness conservation
- Canonical instead of Grand Canonical Ensemble describe statistical production → reduced phase space → "Canonical suppression"
- Data favors a CE calculation with a correlation length r_c = 3.2 fm in 0-10%
- Data strongly disfavors GCE, results ~5σ away from zero (for 0-10%)

v_1 and v_2 in Au+Au $\sqrt{s_{NN}}$=3.0 GeV

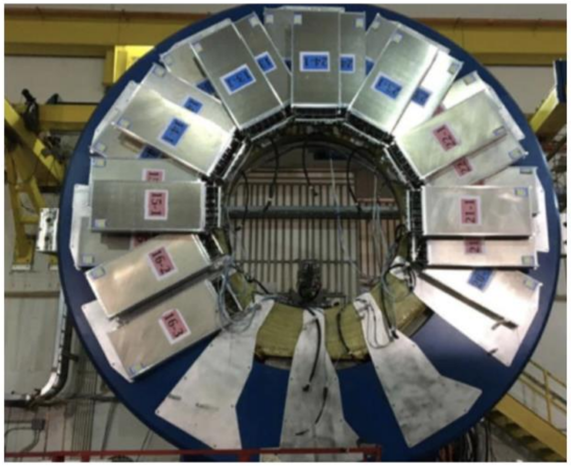


S. Radhakrishnan, APS April Meeting, 2021

- Negative v_1 slope and large positive v_2 at high energy collisions
- Positive v_1 slope and negative v_2 for all measured particles in 3 GeV collisions
- Positive v_1 slope observed for kaons and ϕ mesons for the first time
- Results from UrQMD with baryonic mean-field interactions qualitatively describe the data

E877: Phys. Rev. C 56, 3254-3264
E895: Phys. Rev. Lett.85, 940
FOPI: Phys. Lett. B612, 173

STAR detector upgrades for BES-II



iTPC:
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c
- Ready in 2019

EndCap TOF:
- Forward rapidity coverage is critical
- PID at η = 0.9 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR
- Ready in 2019

EPD:
- Improves trigger
- Reduces background
- Allows a better centrality and reaction plane measurement

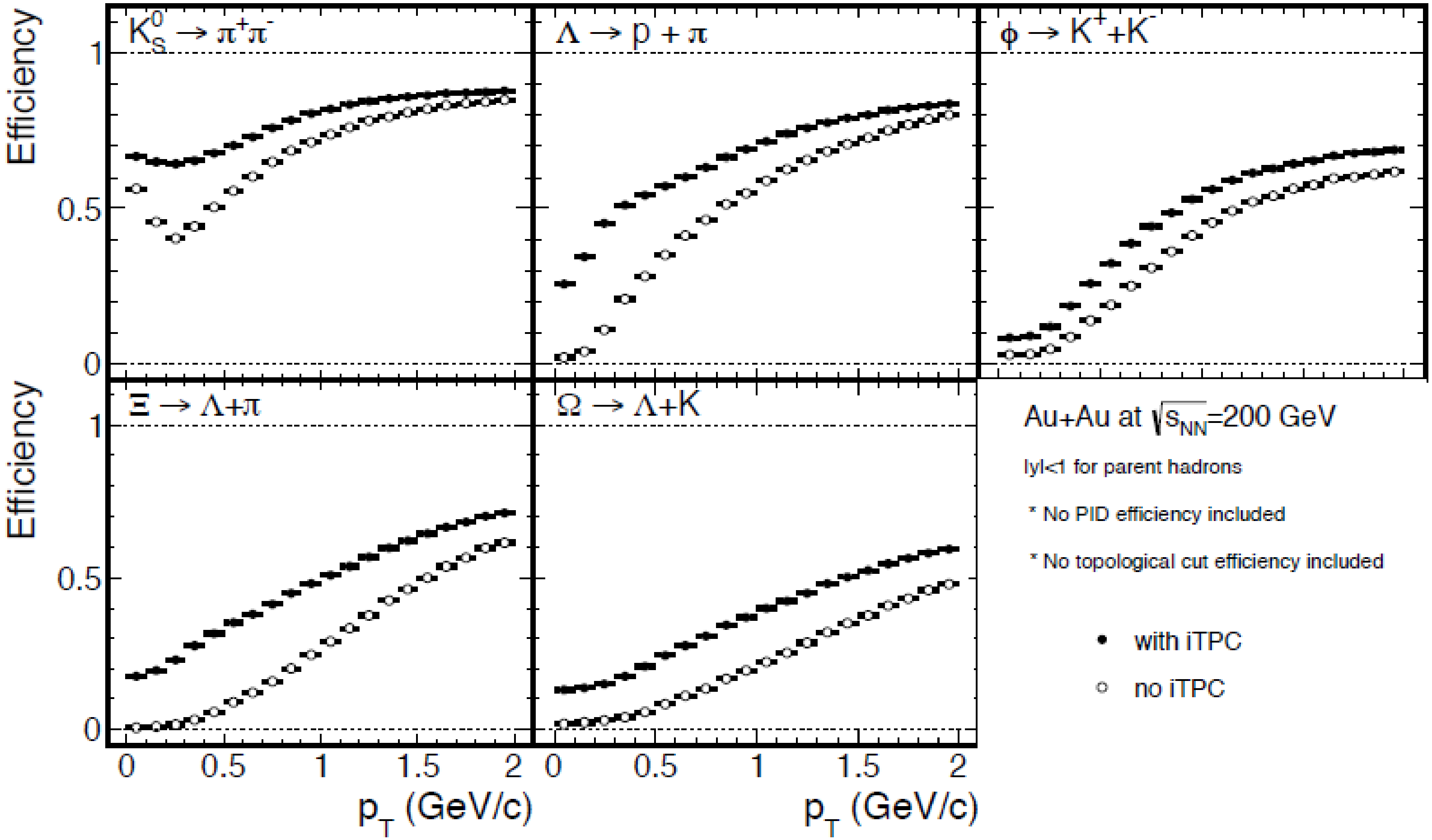
Ready in 2018

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. Nucl. Instr. Meth. A 968, 163970 (2020)

1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/EP resolution

All 3 detectors fully installed before Run-19.

iTPC improves strangeness reconstruction in BES II



- Significant improvement of efficiency especially for Ξ, Ω

H. Masui, A. Schmah / LBNL

STAR BES-II data samples

Year	*Collisions*	$\sqrt{s_{NN}}$ (GeV)	Good events
2019	Au+Au	19.6	~ 582 M
2019	Au+Au	14.5	~ 324 M
2020	Au+Au	11.5	~ 235 M
2020	Au+Au	9.2	~ 162 M
2021	Au+Au	7.7	~ 100 M (goal)
2021	Au+Au	17.1	~ 250 M (goal)

Data taking goes smoothly and reached the goal of statistics.

Summary & outlook

- STAR BES-I have measured systematically the production of strangeness at intermediate baryon density.
- Many structures are visible in strangeness related observables in this energy range.
- In particular, QGP signatures appear to turn off at lower collision energies (<20GeV), but need more statistics to confirm
- The almost completed STAR BES-II with detector upgrade (iTPC, eTOF, EPD) and larger data samples allow precise measurement of the matter properties at intermediate to high baryon density (μ_B up to 721 MeV)