Strangeness Production in STAR Beam Energy Scan

Xianglei Zhu, Tsinghua University

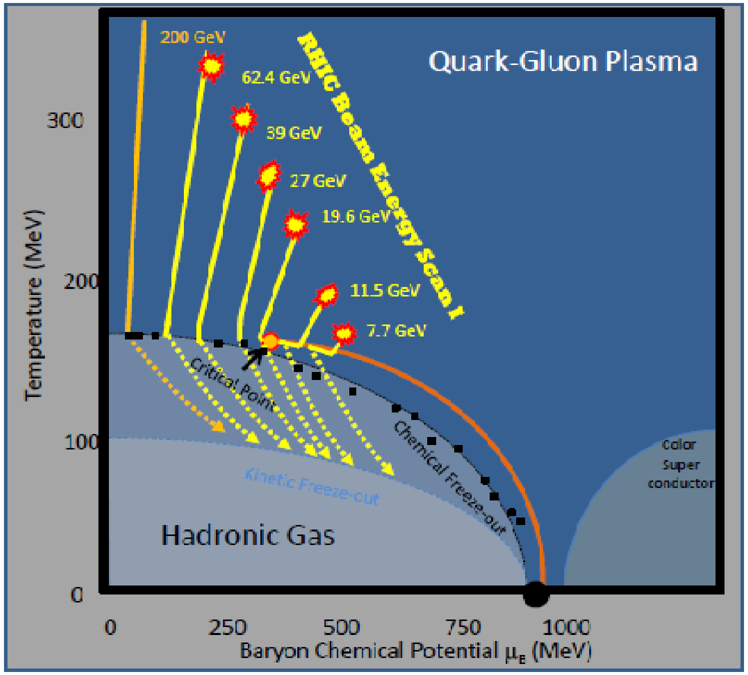
For the STAR Collaboration

11/17/2014

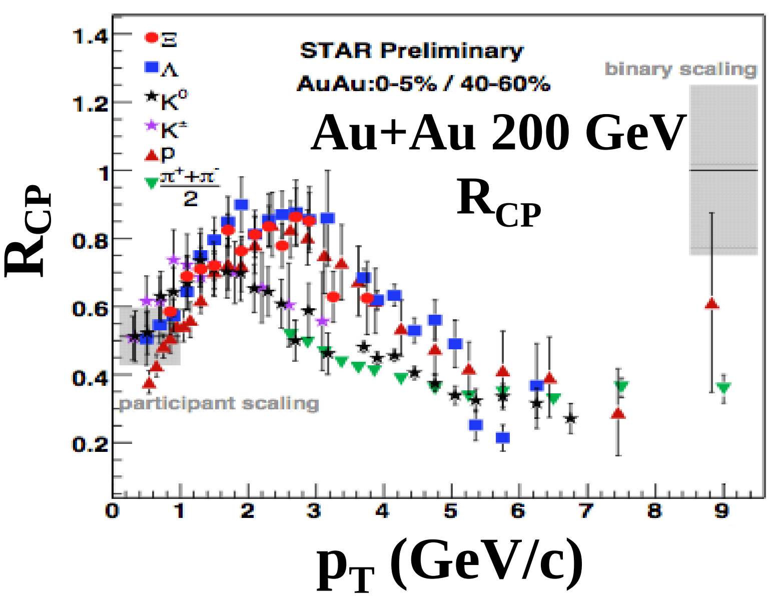
Outline

- STAR beam energy scan (BES)
- Chemical freeze-out parameters
- Turn-off of QGP signatures
  - Nuclear modification factors
  - Baryon/meson enhancement
- Summary

STAR BES: study QCD phase diagram

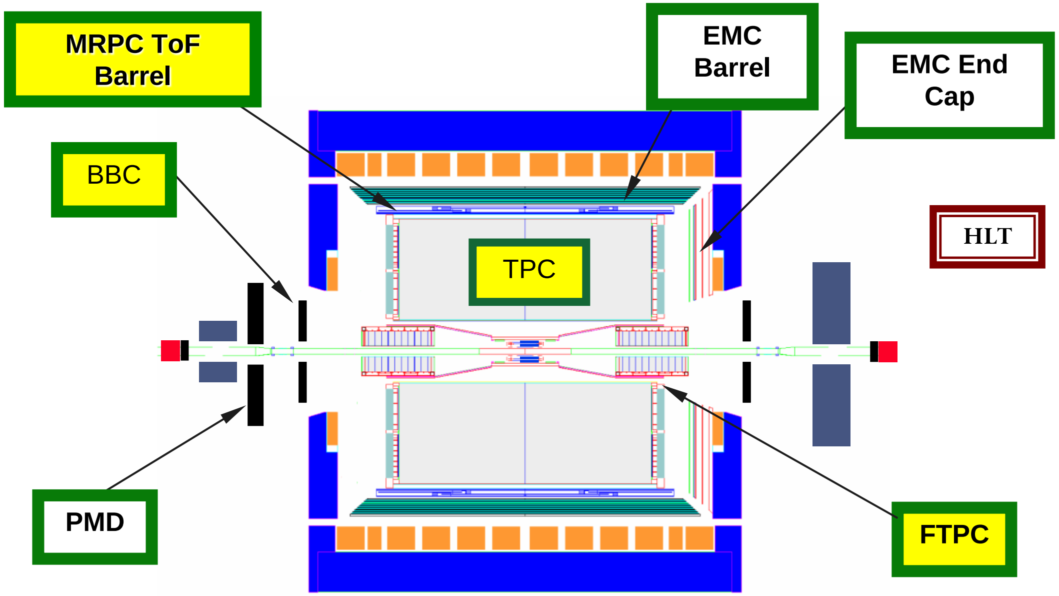


- **Beam Energy Scan at RHIC**
  Look for **onset of de-confinement, phase boundary** and critical point
  Systematic study of Au+Au collisions at 7.7, 11.5, 14.5, 19.6, 27, 39 GeV (BES phase I)

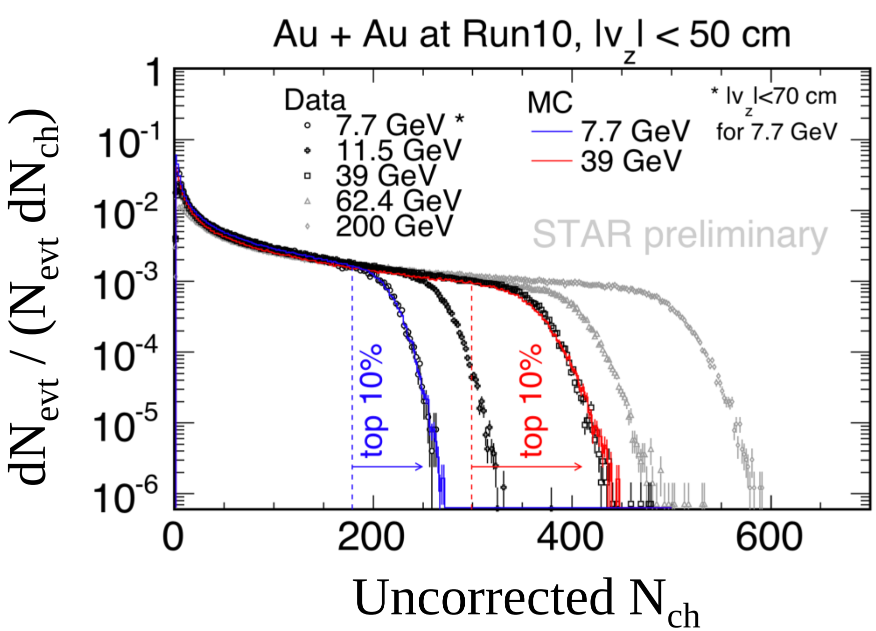


- Key observables on de-confinement
  (1) Baryon/meson ratio
  Parton recombination
  (2) Nuclear modification factor
  Partonic energy loss & recombination
  STAR, arXiv:1007.2613

Detector settings during STAR BES 2010-2011



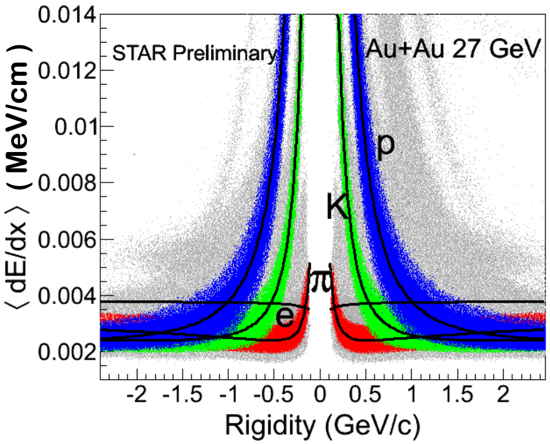
- Collisions: Au+Au
- Collisions centrality from uncorrected $dN_{ch}/d\eta$ in $|\eta| < 0.5$

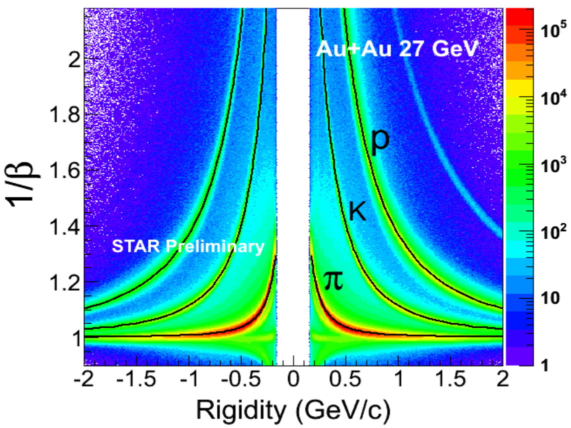


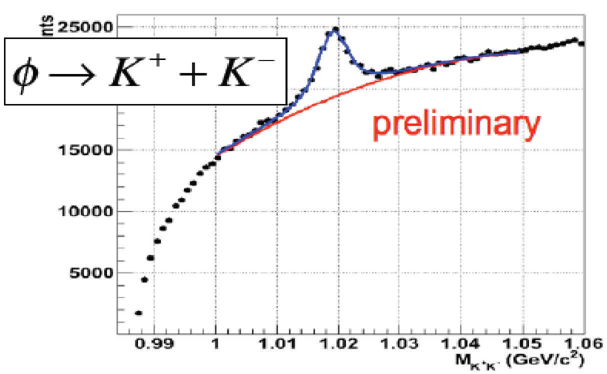
Year	$\sqrt{s_{NN}}$ (GeV)	Minimum bias events in Million
2010	7.7	~ 4 M
2010	11.5	~ 12 M
2011	19.6	~ 36 M
2011	27	~ 70 M
2010	39	~ 130 M
2014*	14.5	~ 20 M

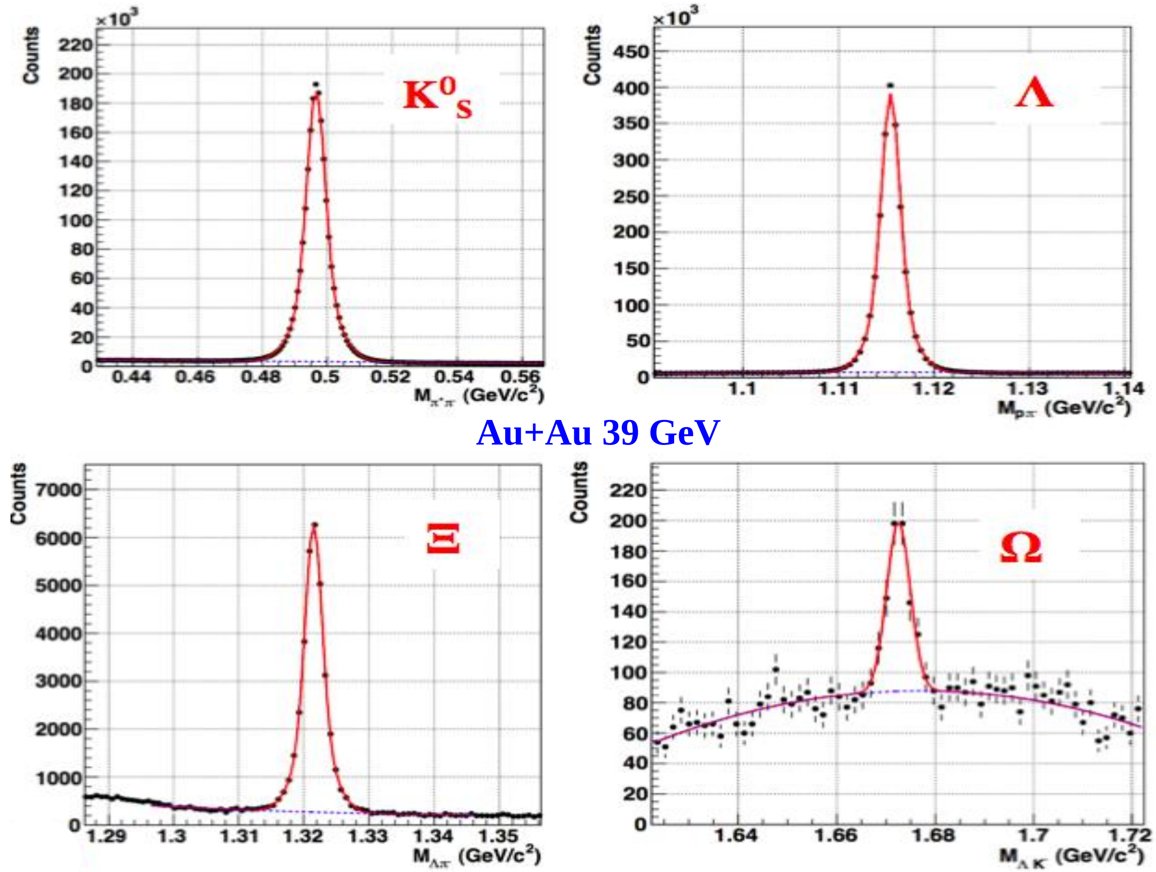
* *not analyzed yet*

Particle identification and reconstruction



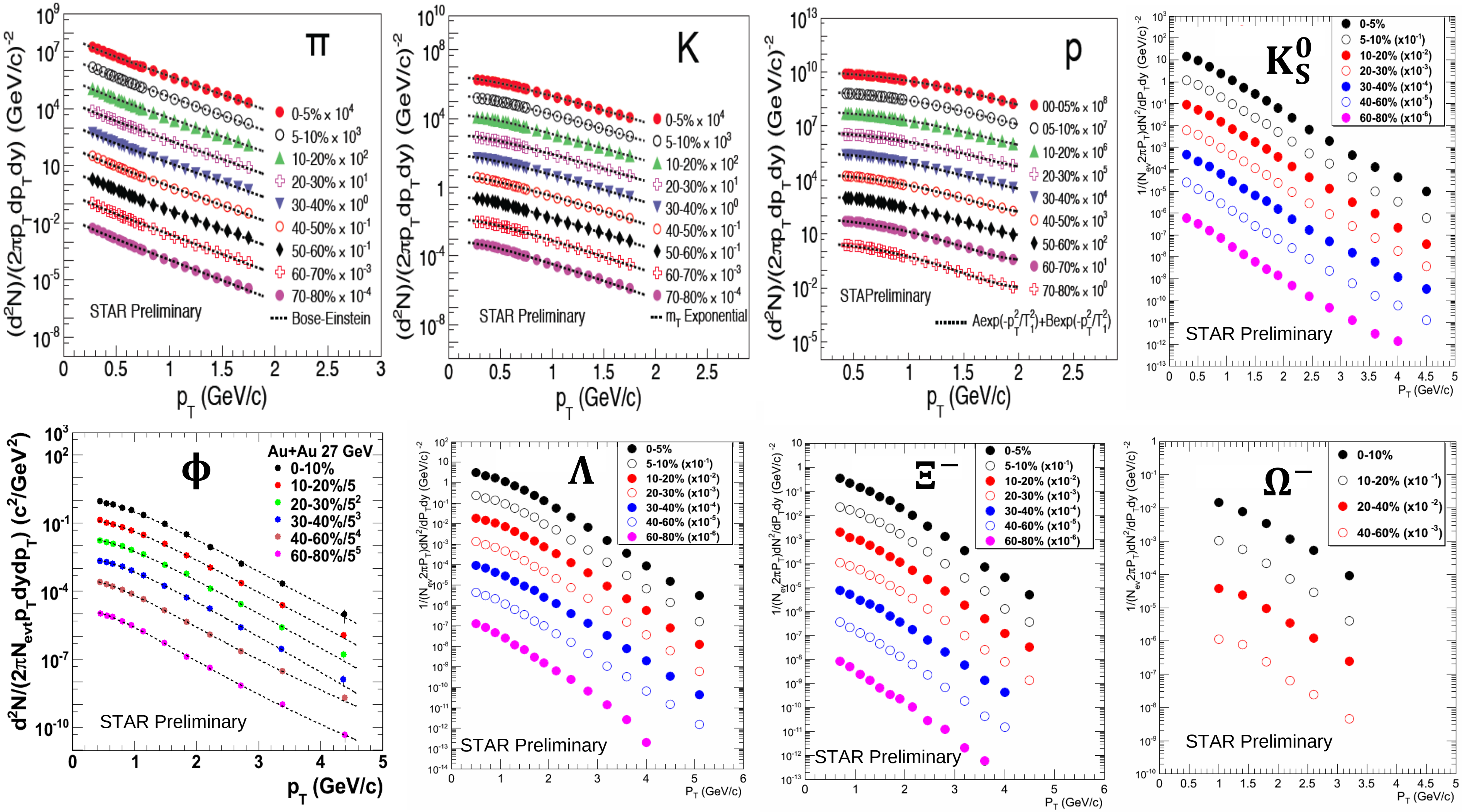






- dE/dx+TOF: π, K, p and $\phi \to K^+ + K^-$ (invariant mass)
- Weak decay particles (K^0_S, Λ, Ξ, Ω), secondary vertex + invariant mass

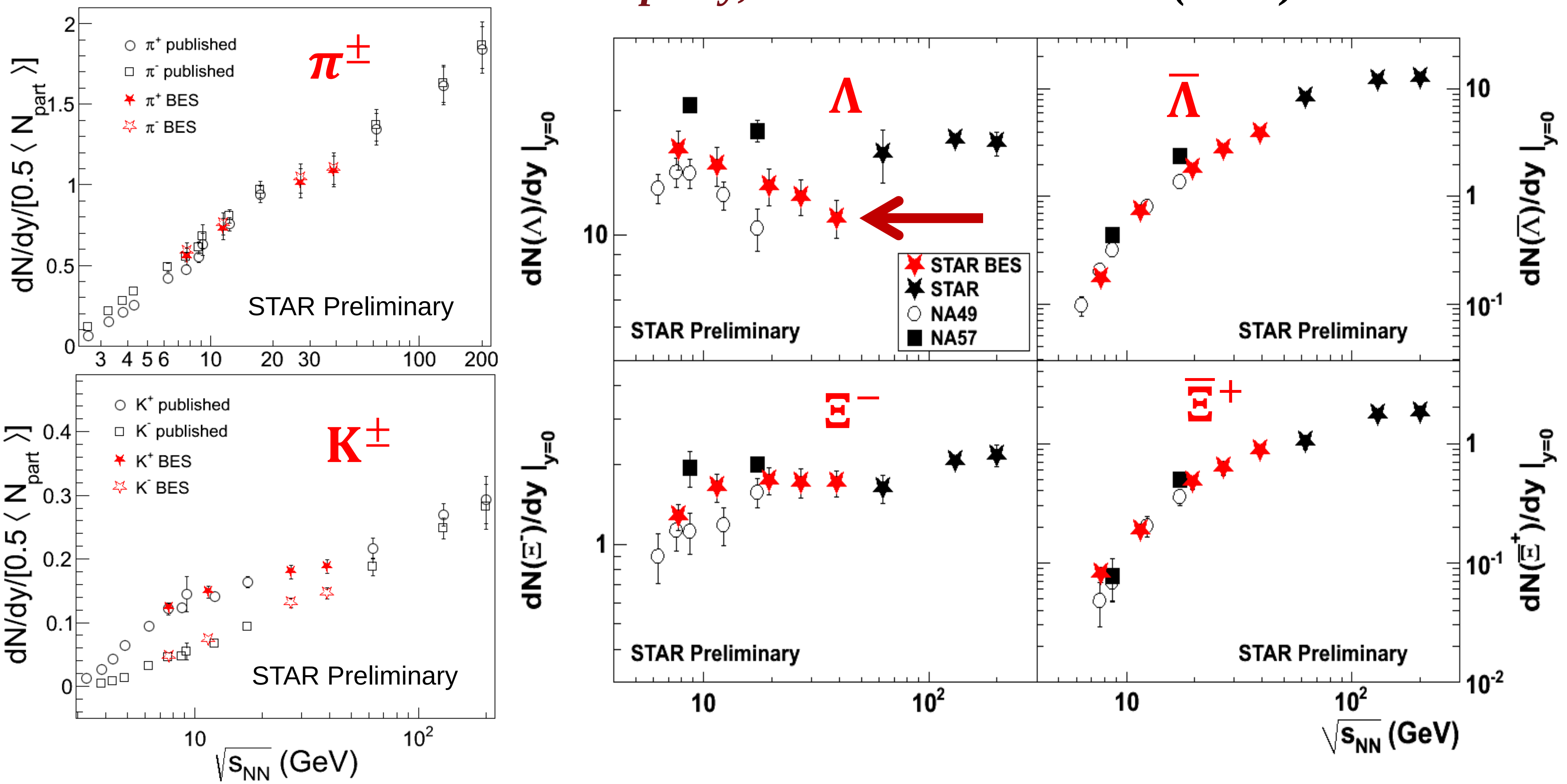
p_T spectra (27 GeV)



- Extensive particle spectra
- $\Lambda(\bar{\Lambda})$ spectra are weak decay feed-down corrected

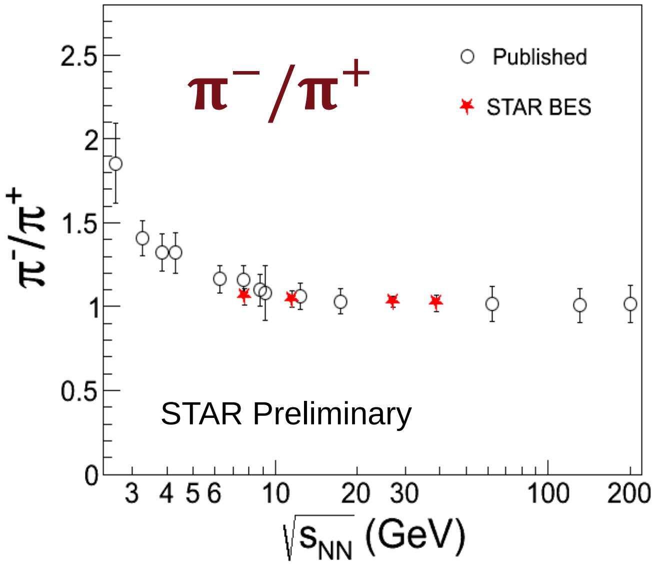
Particle yields

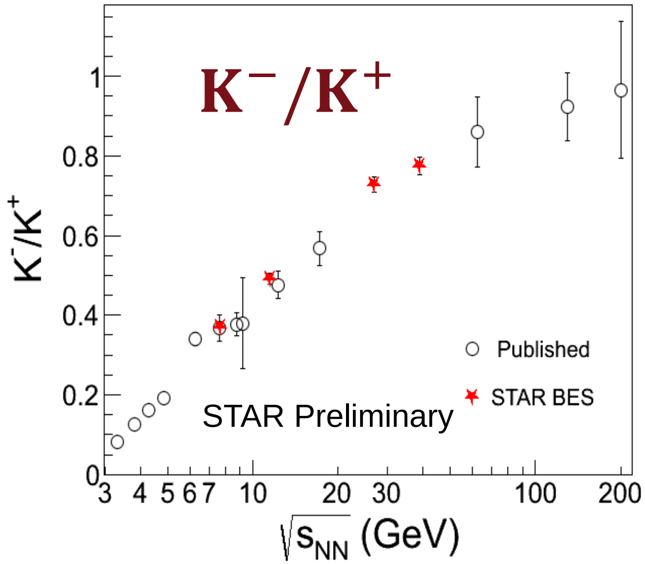
mid-rapidity, most central collisions (0-5%)

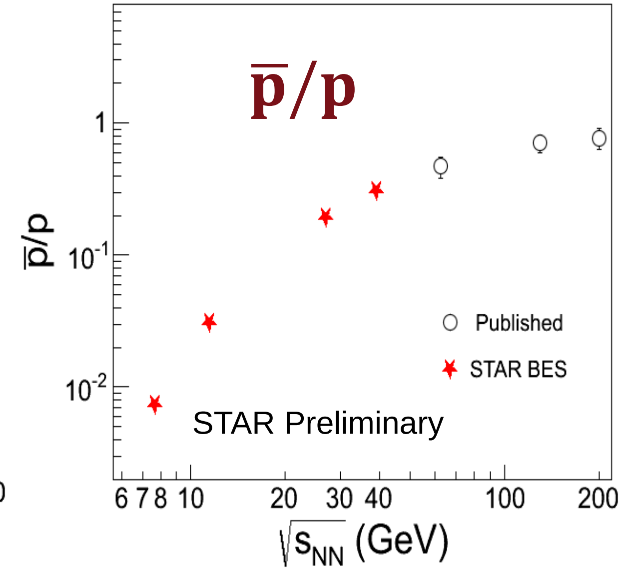


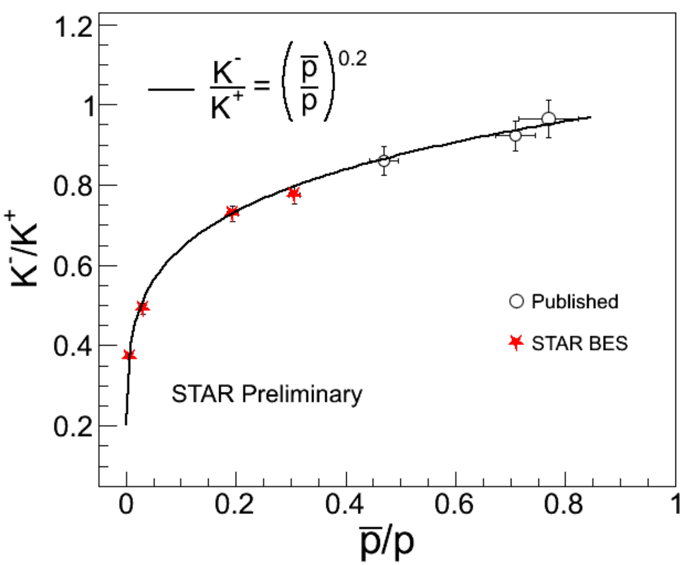
- STAR results are consistent with published data in general
- Λ yields show dip at $\sqrt{s_{NN}}$ = 39 GeV

Particle ratios









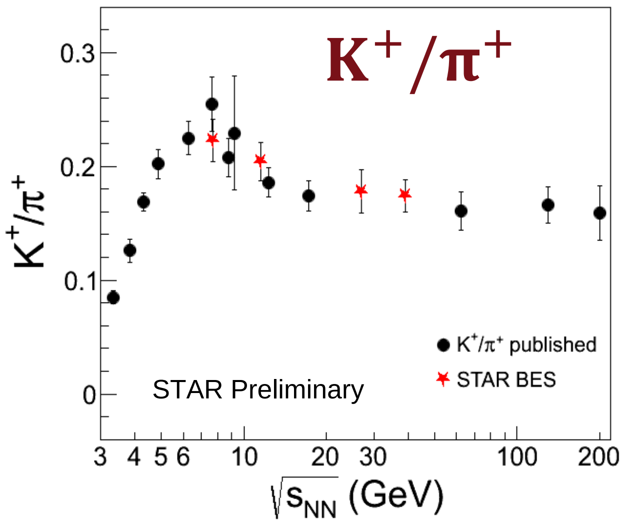
most central (0-5%)

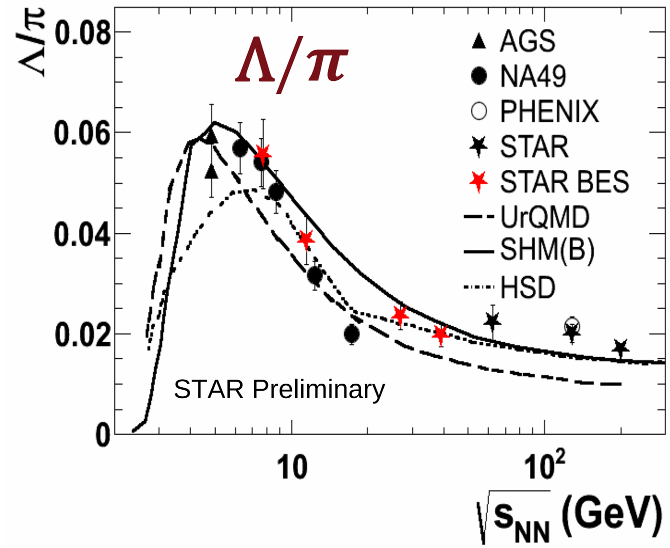
statistical and systematic errors added in quadrature

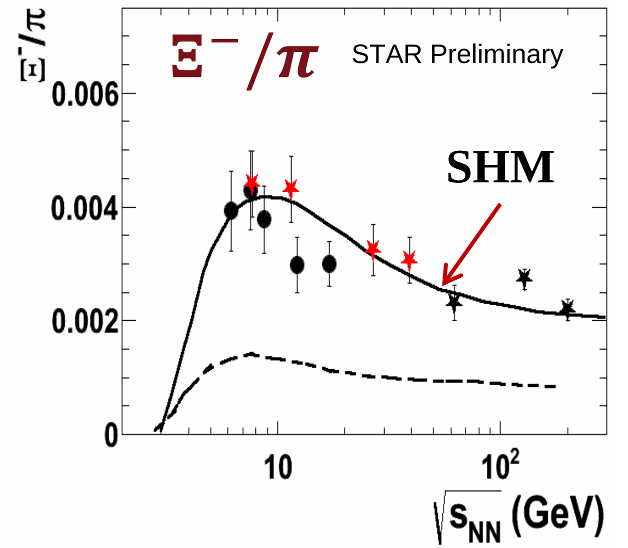
- Anti-particle to particle ratios at BES energies follows a systematic trend with beam energy.

BRAHMS: PRL 90, 102301 (2003)
Becattini et al. PRC 64, 024901 (2001)

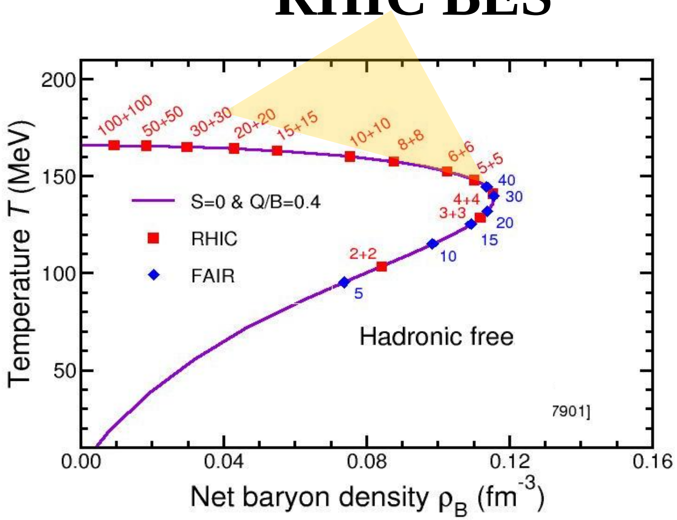
Particle ratios







RHIC BES

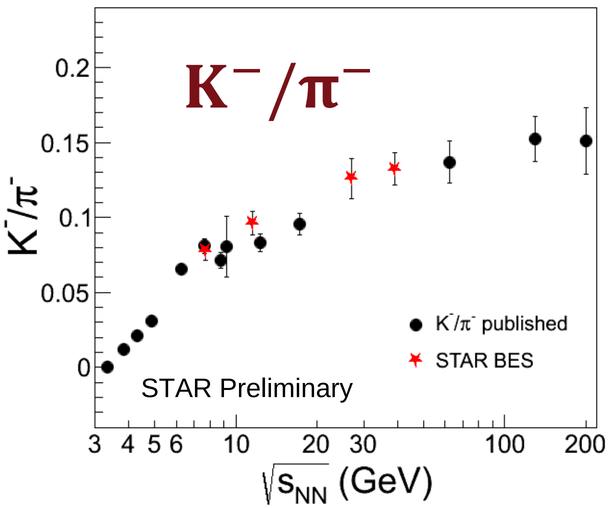


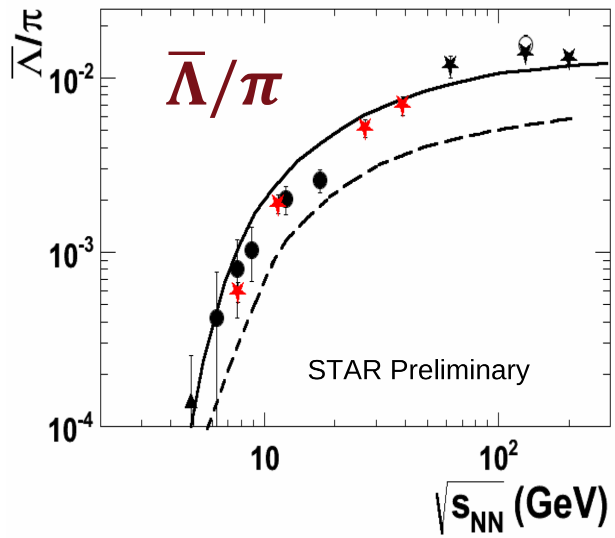
J. Randrup et al., PRC 74, 047901 (2006)

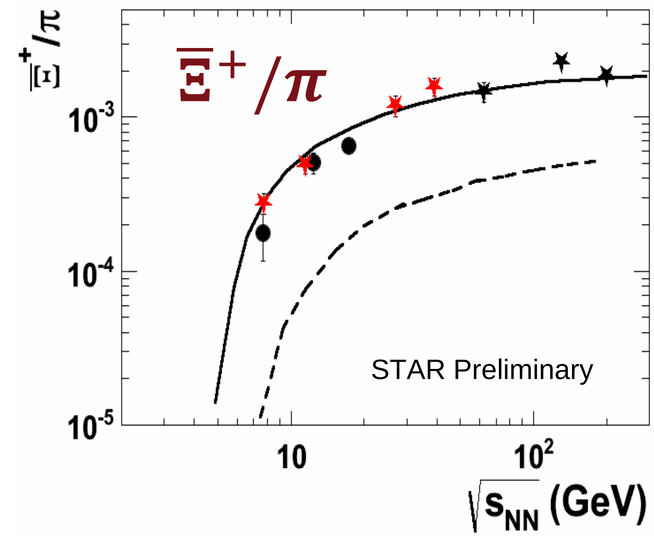
most central (0-5%), *mid-rapidity*, *stat. + sys. error*

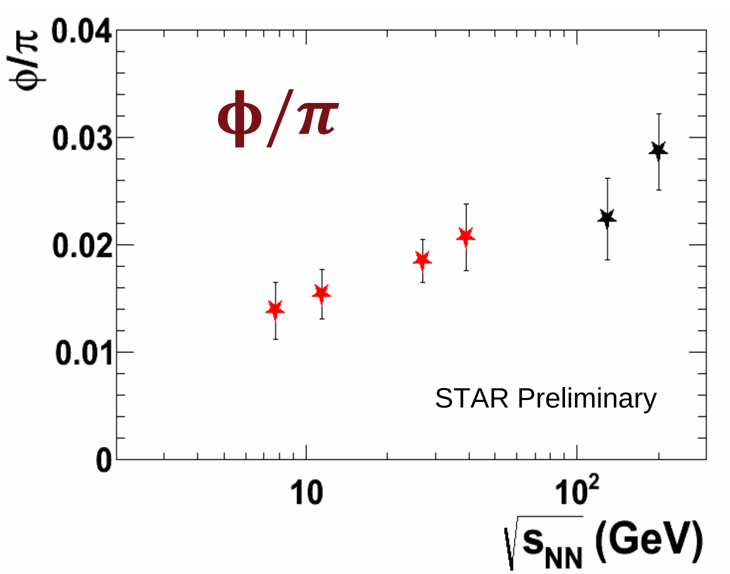
- Particle ratios consistent with NA49, consistent with the picture of a **maximum net-baryon density around $\sqrt{s_{NN}}$ ~ 8 GeV at freeze-out**
- Associate production channels like $N + N \rightarrow N + \Lambda + K^+$ may be important for K^+ production, N is nucleon

Particle ratios





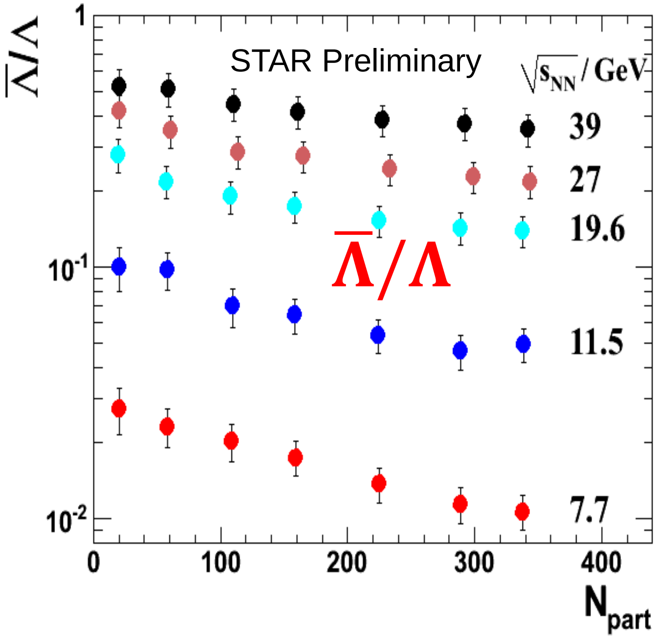


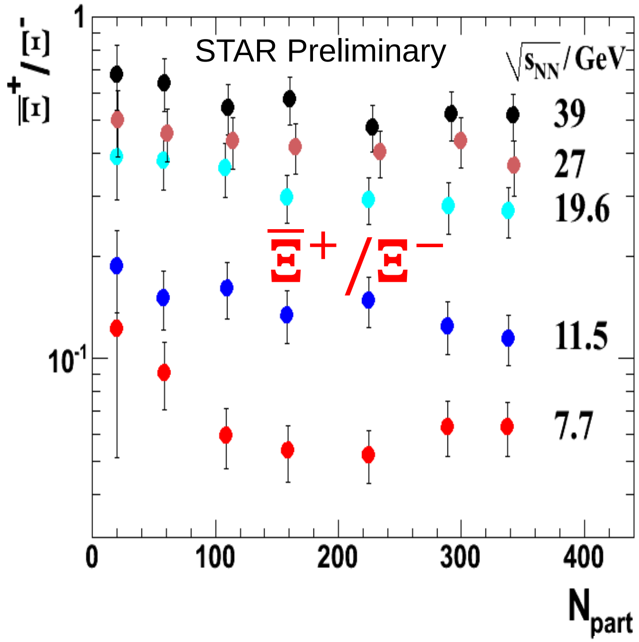


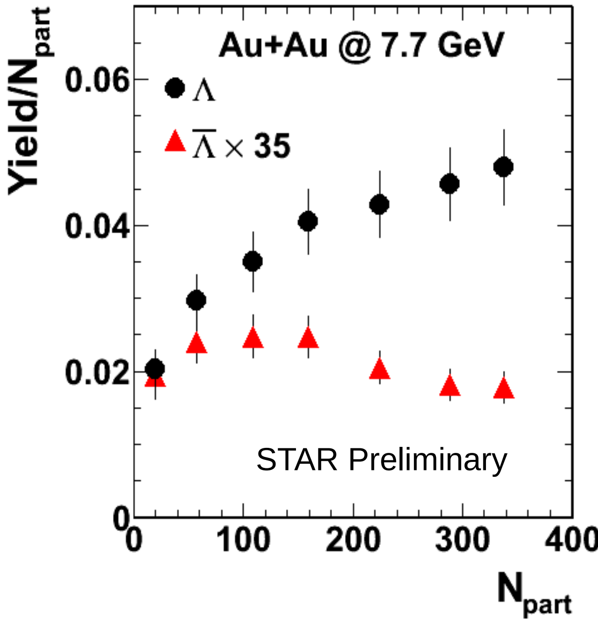
***most central (0-5%)**, mid-rapidity, stat. + sys. error*

- ❑ Clear $\mathbf{K^-}$, $\bar{\mathbf{\Lambda}}$, $\bar{\mathbf{\Xi}}^+$ yield enhancement compared to pions with increasing collision energy
- ❑ Similar behavior for hidden strangeness $\boldsymbol{\phi}(s\bar{s})$

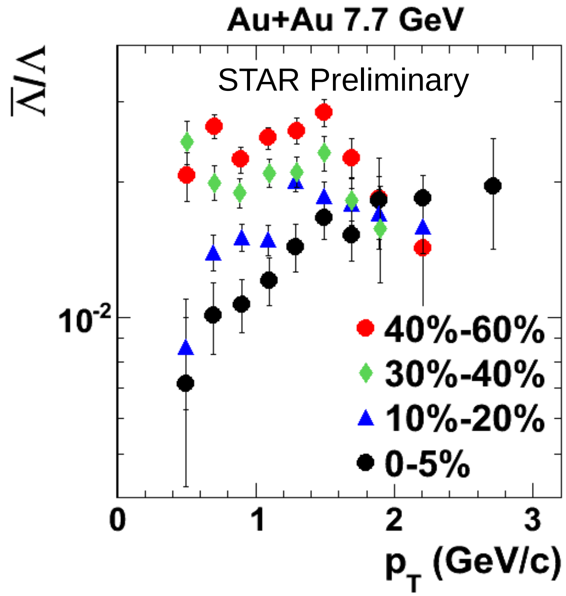
Anti-baryon to baryon ratio (centrality dependence)



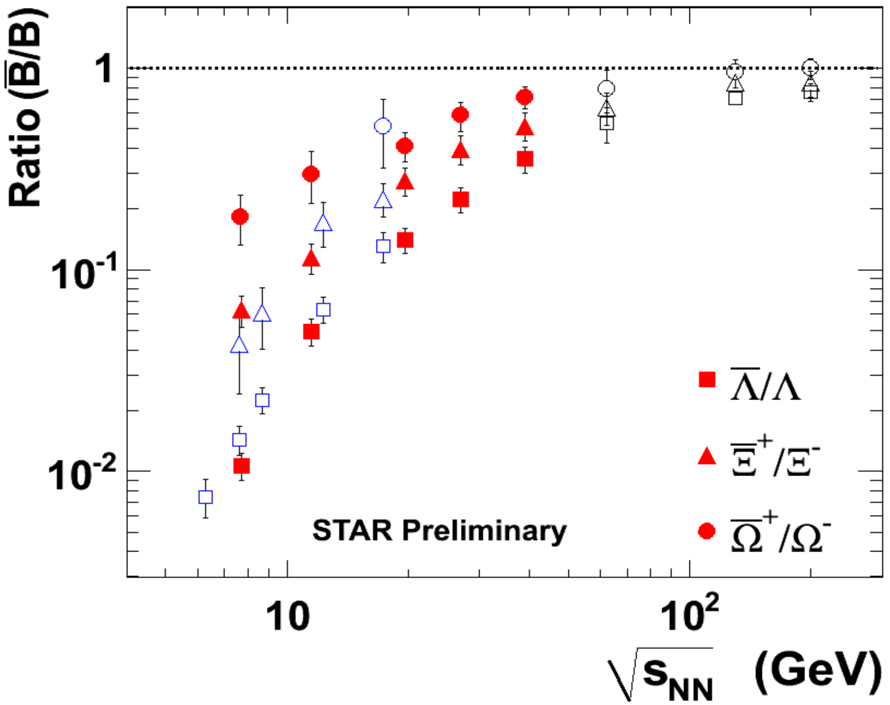




- Centrality dependence of $\overline{B}/B$ ratios:
  peripheral > central
- This effect is more prominent at lower energies.
  baryon stopping, absorption
- **Absorption: loss of low p_T $\overline{\Lambda}$ in central collisions**



Anti-baryon to baryon ratio (excitation function)



Solid red: STAR BES;
Open black: STAR published;
Open blue: NA49

central collisions (0-5%)

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

Anti-baryon to baryon ratio

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

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

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

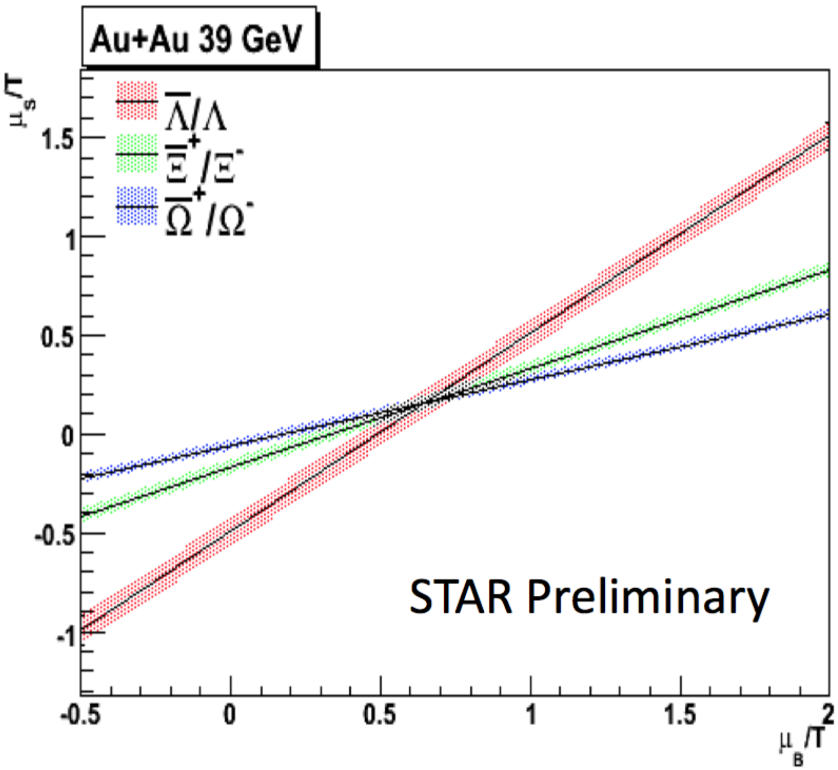
$$\frac{\overline{\Omega}^+}{\Omega^-} = \exp(-\frac{2\mu_B}{T} + \frac{6\mu_S}{T}) \qquad \ln(\frac{\overline{\Omega}^+}{\Omega^-}) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T}$$

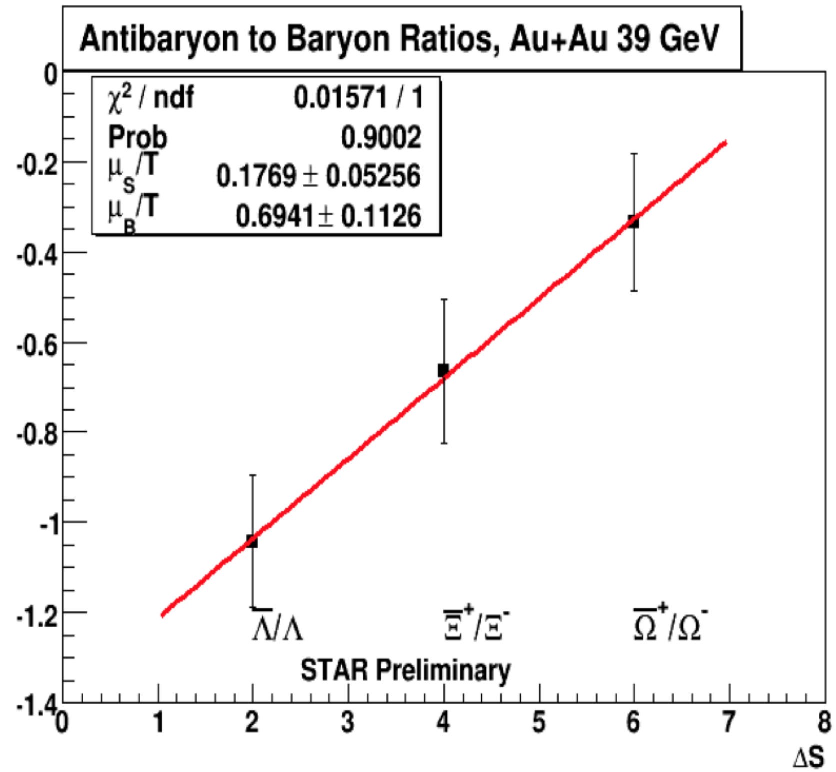
- T is the temperature.
- μ_B is the baryon chemical potential.
- μ_S is the strangeness chemical potential.

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

Anti-baryon to baryon ratio

$$\ln(Ratio) = -\frac{2\mu_B}{T} + \frac{\mu_S}{T} \times \Delta S$$

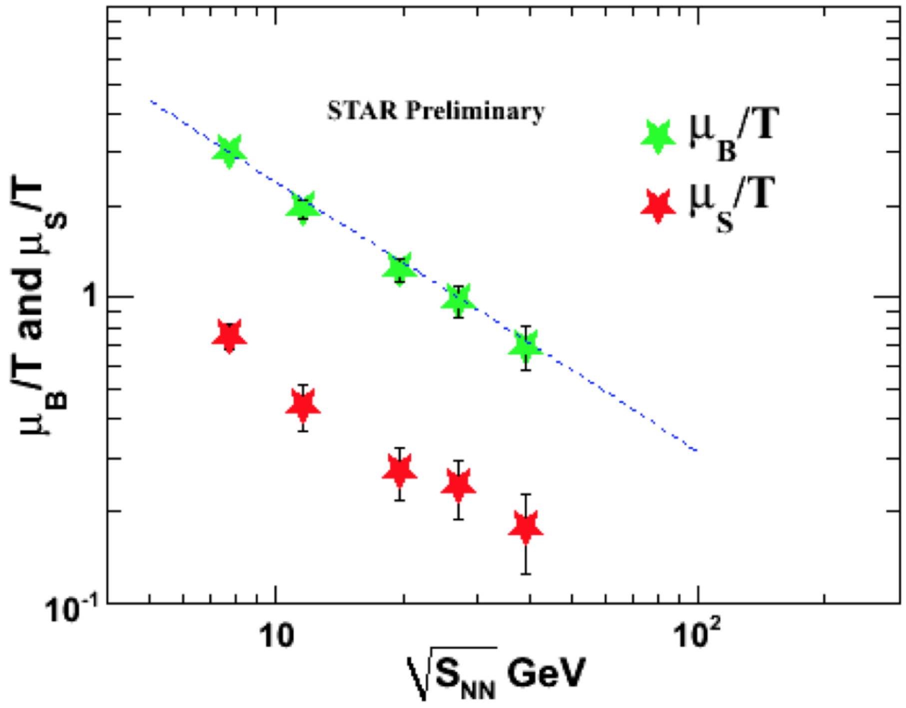




Cross the same point and straight line

→ Thermal statistical fit works!

Anti-baryon to baryon ratio



$$T \approx T_0 - b\mu_B^2$$

$$\mu_B = \alpha \frac{\log \sqrt{S_{NN}}}{(\sqrt{S_{NN}})^{\beta}}$$

$Where:$

$T_0 = 167.5 MeV$

$b = 0.1583 GeV^{-2}$

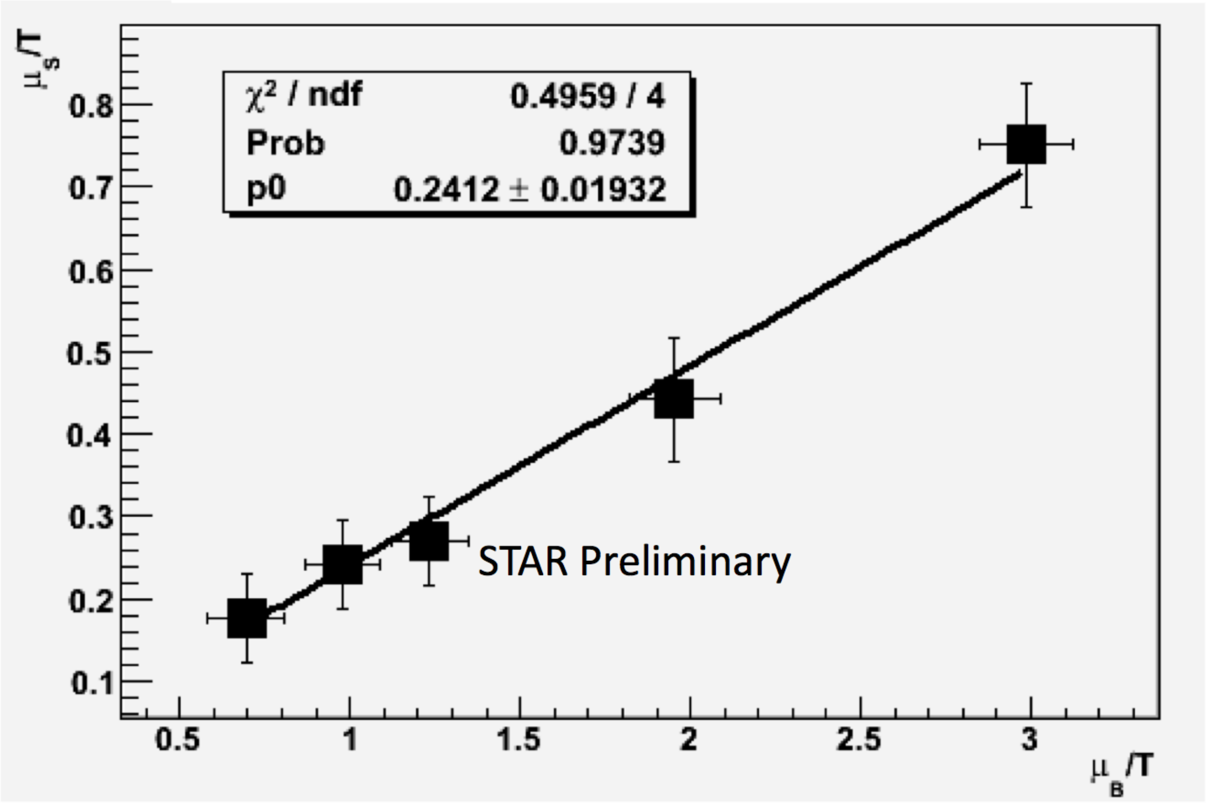
$\alpha = 2.06$

$\beta = 1.13$

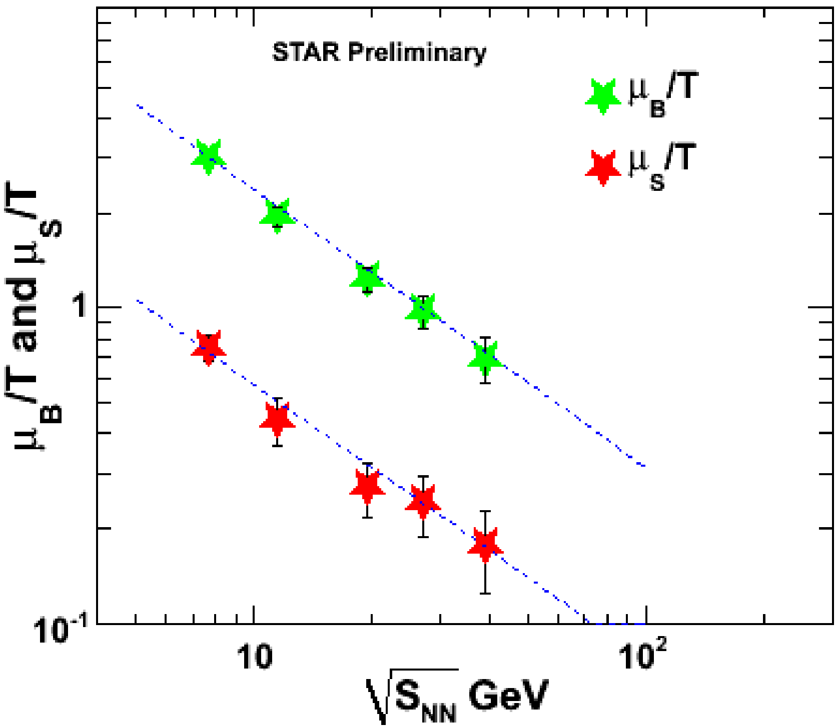
Parameters are from the fitting of published data of AGS, SPS and RHIC 130 GeV data.

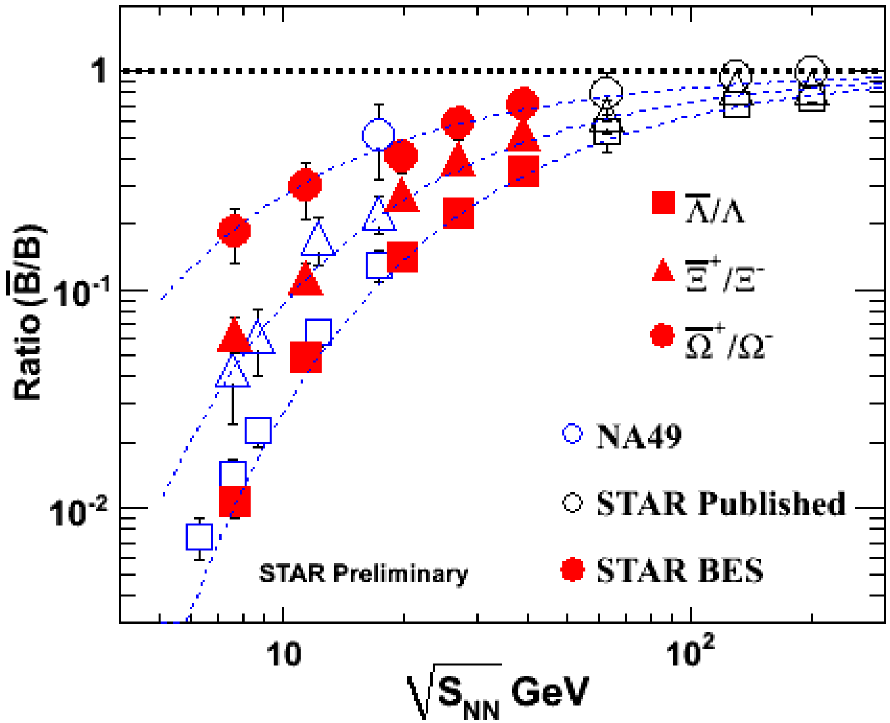
- Reference: F.Becattini et al. Phys Rev C 73, 044905 (2006)

μ_s and μ_B correlation



Anti-baryon to baryon ratio





$T(\mu_B)$ parameterization is from the fitting of published data of AGS, SPS and RHIC 130 GeV data.
F.Becattini et al. Phys Rev C 73, 044905 (2006)

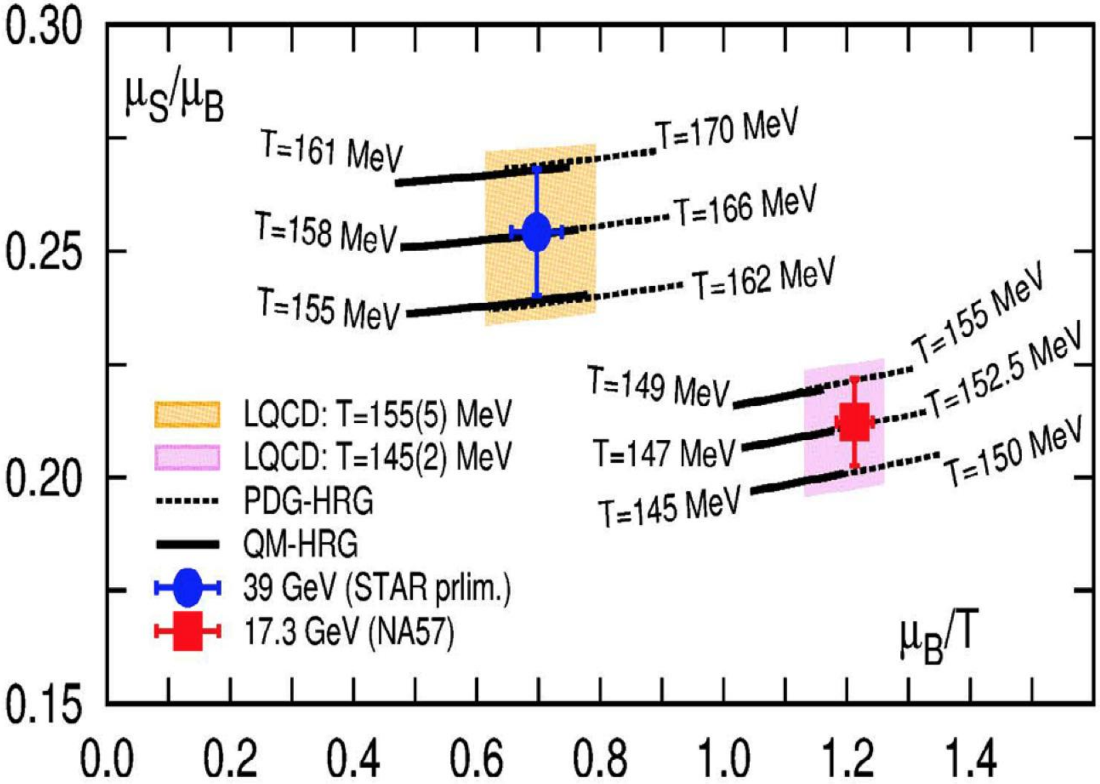
- Anti-baryon to baryon ratios are consistent with statistical thermal model

Strangeness, LQCD and freeze-out in HIC

Swagato Mukherjee, Mon

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

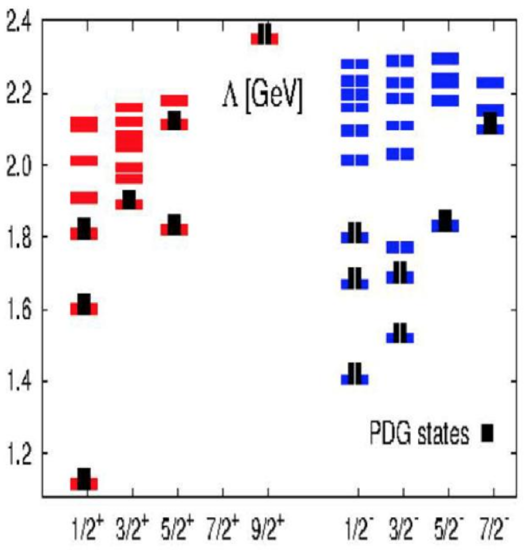
BNL-Bi-CCNU: Phys. Rev. Lett. 113 (2014) 072001



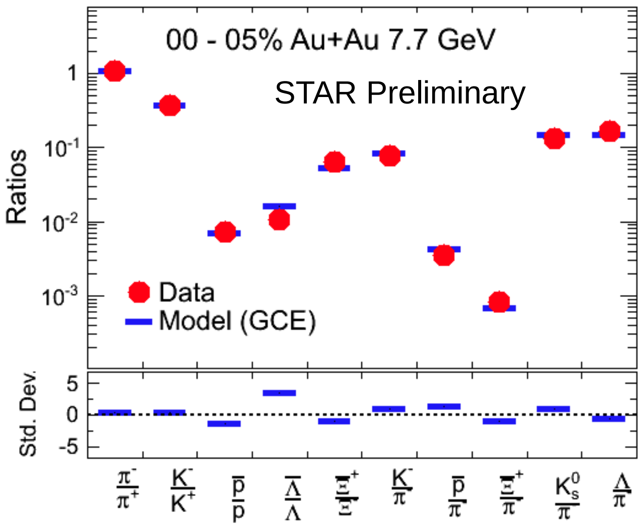
indirect evidence for so-far undiscovered strange baryons at RHIC ?

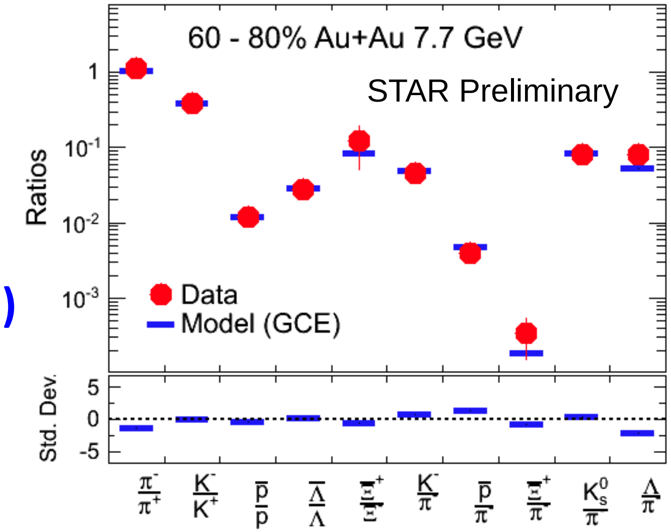
not reproduced by hadron gas with only PDG states

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



Chemical freeze-out parameters



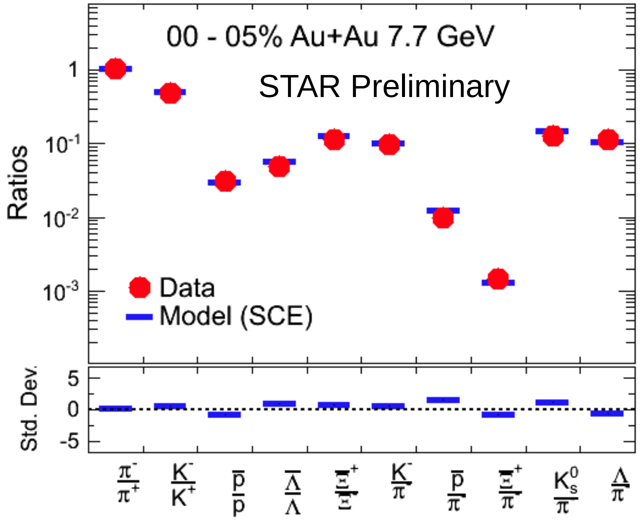


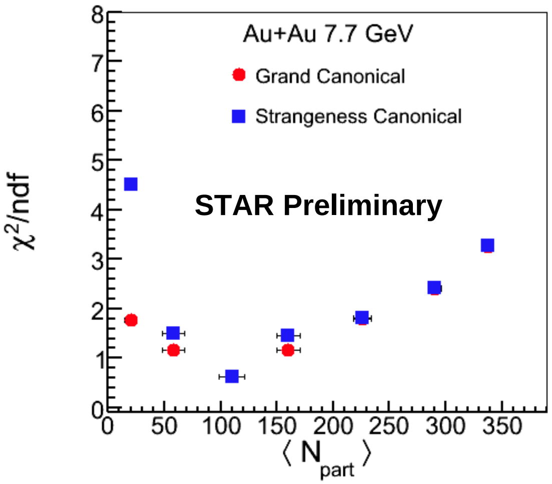
✓Particles used :
π, K, p, Λ, Ξ and K^0_s

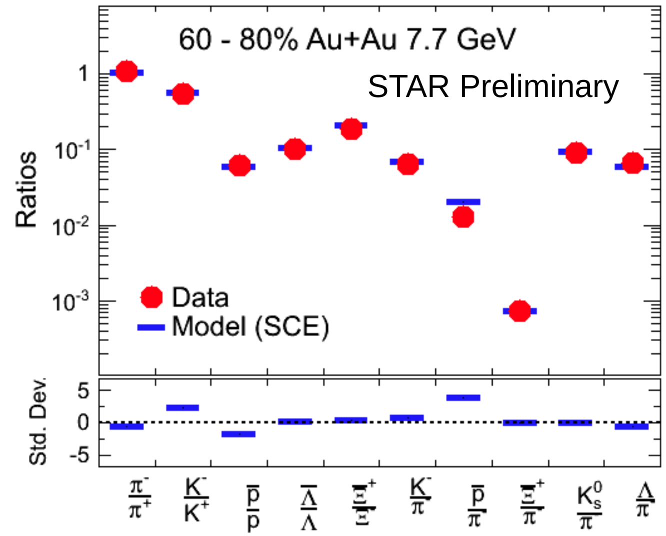
✓ Ensemble used:
Grand canonical (GCE), Strangeness canonical (SCE)

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

✓BES energies:
39, 27, 11.5, and **7.7** GeV

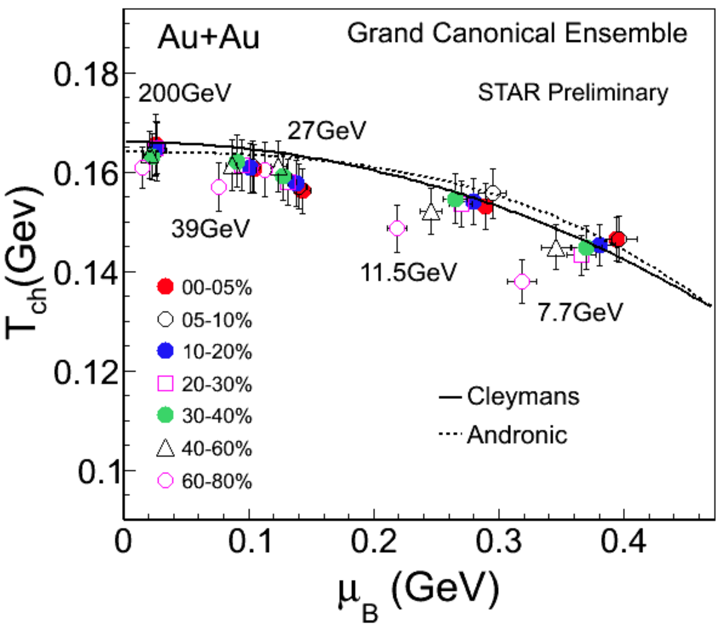






Thermus, S. Wheaton & J. Cleymans, Comput. Phys. Commun. 180: 84-106, 2009.

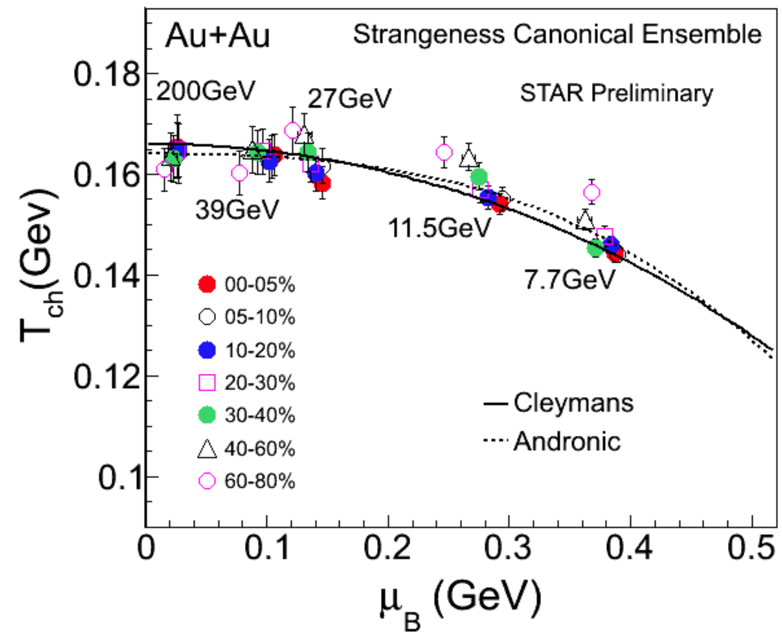
Chemical freeze-out parameters: T_{ch} vs. μ_B



✓Particles used :
π, K, p, Λ, Ξ
and K^0_s

✓ Ensemble used:
Grand canonical (GCE), Strangeness canonical (SCE)

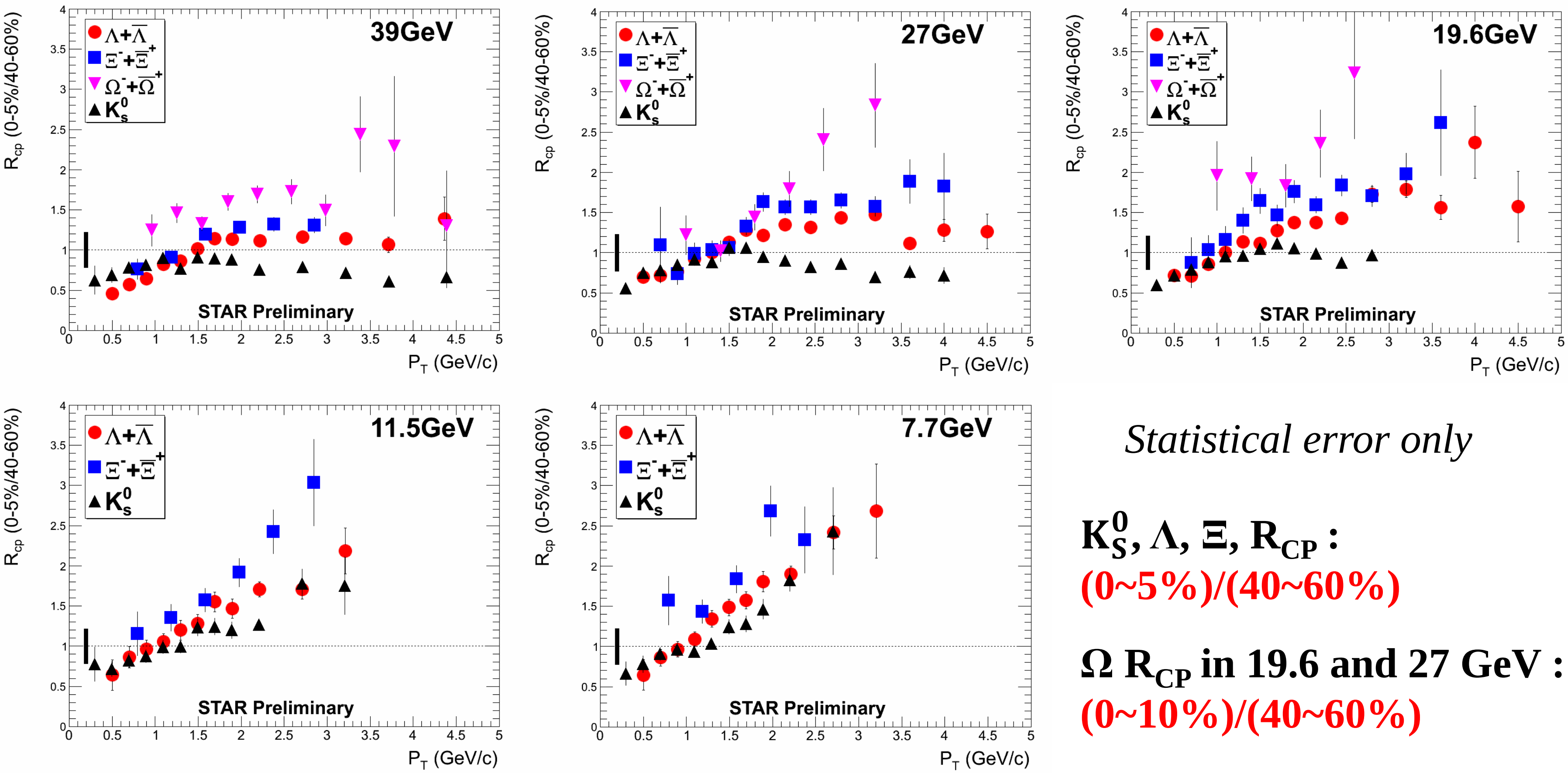
✓ Fit parameters:
T_{ch}, μ_B, μ_S and γ_S



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

- Central collisions: Grand canonical (GCE) and Strangeness canonical (SCE) provide consistent results on chemical freeze-out parameters.
- Peripheral collisions: GCE and SCE results not consistent, more detailed study is on-going.

Open strange hadrons R_{CP}



Statistical error only

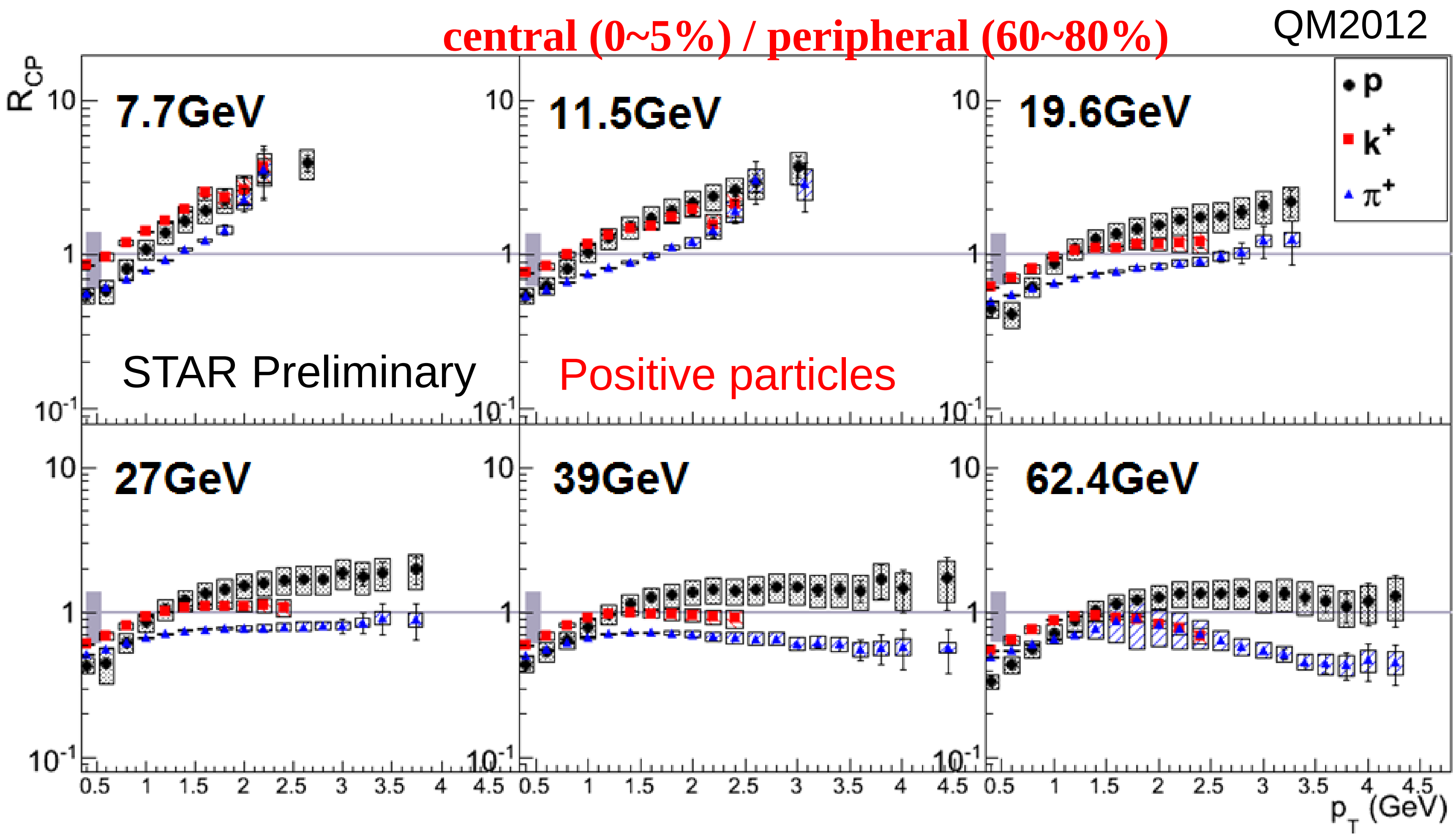
K_S^0, Λ, Ξ, R_{CP} :
(0~5%)/(40~60%)

Ω R_{CP} in 19.6 and 27 GeV :
(0~10%)/(40~60%)

$\sqrt{s_{NN}} \leq$ **11.5 GeV,**

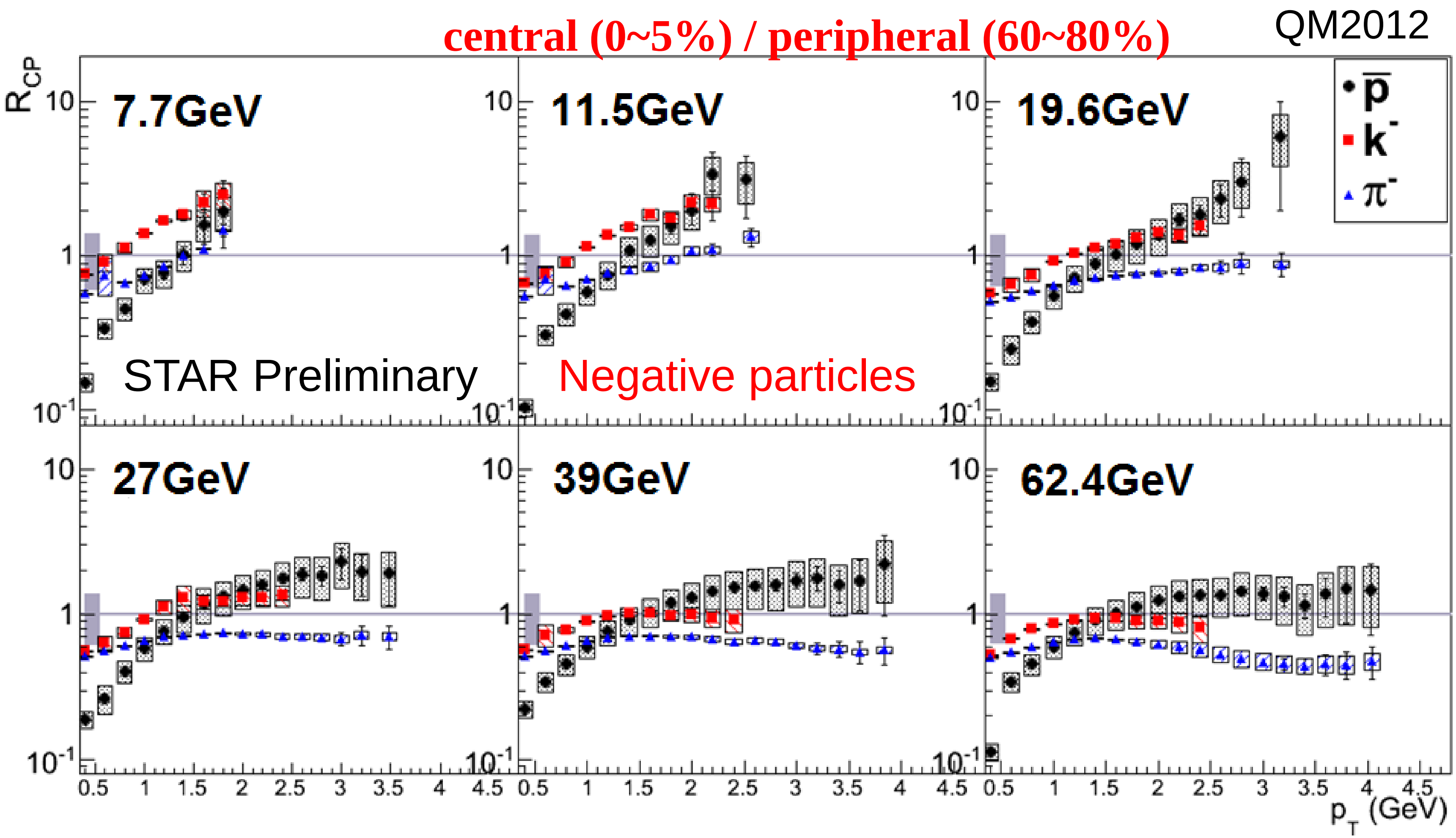
- K_S^0 R_{CP} larger than unity for p_T > 1.5 GeV/c
- R_{CP} particle type (baryon/meson) difference at intermediate p_T (2~3 GeV/c) becomes less obvious

Charged particles R_{CP}



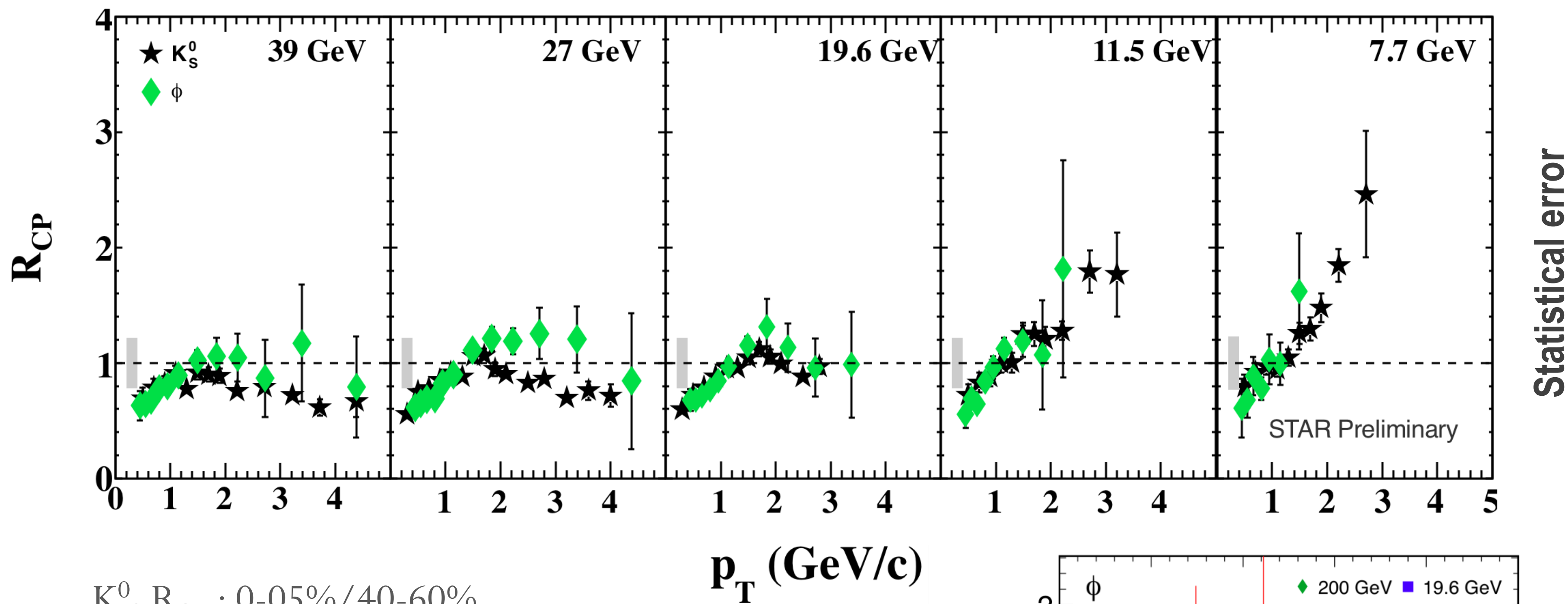
- $K^{\pm}$ and $\pi^{\pm}$ R_{CP} larger than unity (for p_T>2 GeV/c) at $\sqrt{s_{NN}} \leq 11.5$ GeV

Charged particles R_{CP}



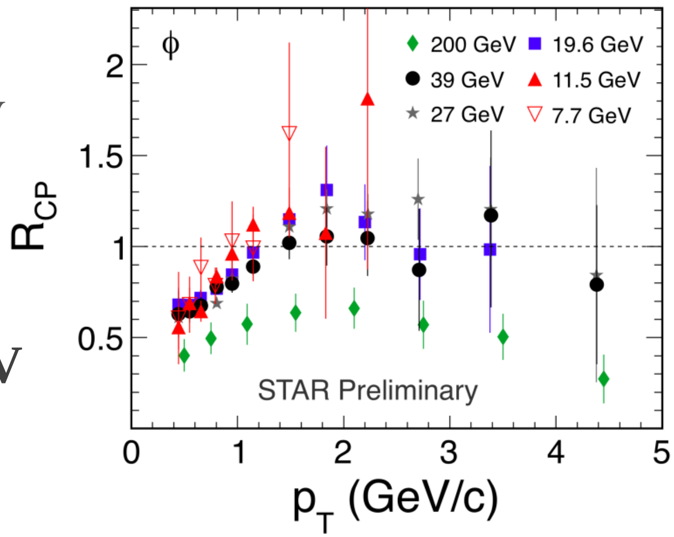
- $K^{\pm}$ and $\pi^{\pm}$ R_{CP} larger than unity (for p_T>2 GeV/c) at $\sqrt{s_{NN}} \leq 11.5$ GeV

ϕ meson R_{CP}



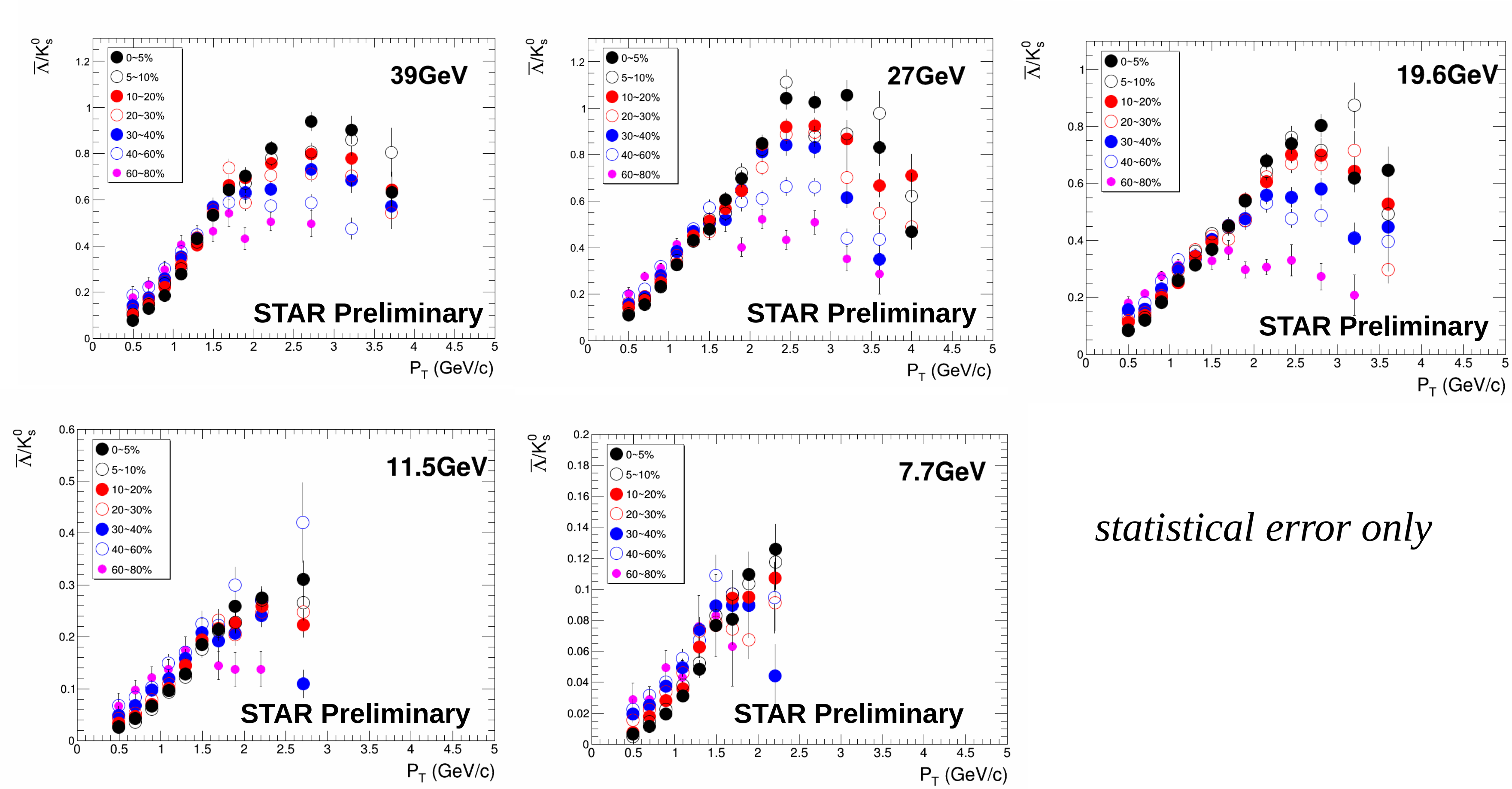
$K^0{}_S$ R_{CP} : 0-05%/40-60%

ϕ R_{CP}: 0-10%/40-60% and 0-05%/40-60% for 200 GeV



- $R_{CP} \geq 1$ at intermediate p_T for $\sqrt{s_{NN}} \leq 39$ GeV

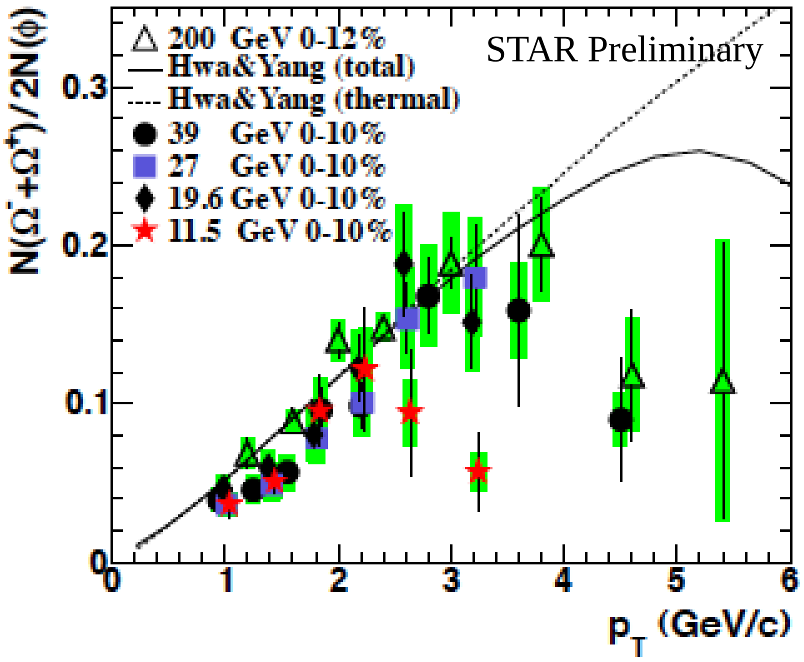
$\bar{\Lambda}/K_S^0$ ratio

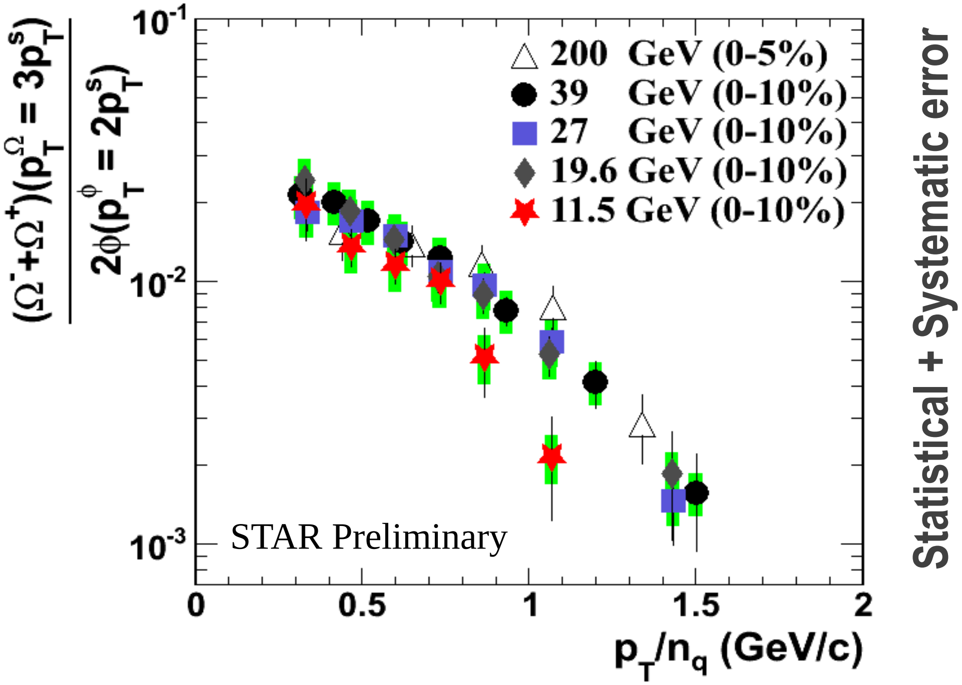


statistical error only

At $p_T \sim$ 2GeV/c, the $\bar{\Lambda}/K_S^0$ magnitude decreases with decreasing energy, the separation of central and peripheral decreases as well

Ω / ϕ ratio





- Intermediate p_T Ω/ϕ ratios:
  Indication of separation between ≥ 19.6 and 11.5 GeV.
  χ^2/ndf for deviation between 11.5 and 19.6 GeV (p_T > 2.4 GeV/c) is 8.3/2

- Derived strange quark p_T distributions show a trend of separation between ≥ 19.6 and 11.5 GeV.

Summary & outlook

- Measurements of strange hadron production in STAR beam energy scan.
- Chemical freeze-out parameters extracted with thermal statistical model
- K^0_S, $K^{\pm}$ and $\pi^{\pm}$ R_{CP} larger than unity at intermediate p_T for $\sqrt{s_{NN}} \leq 11.5$ GeV
- At $p_T \sim 2$GeV/c, the $\overline{\Lambda}/K^0_S$ ratio decreases with decreasing energy, the separation of central and peripheral decreases as well
- $\sqrt{s_{NN}} = 14.5$ GeV Au+Au collisions data have been taken in 2014, to complete BES phase I
- BES phase II is planned for 2018-2019!