Strangeness production in heavy ion collisions at RHIC

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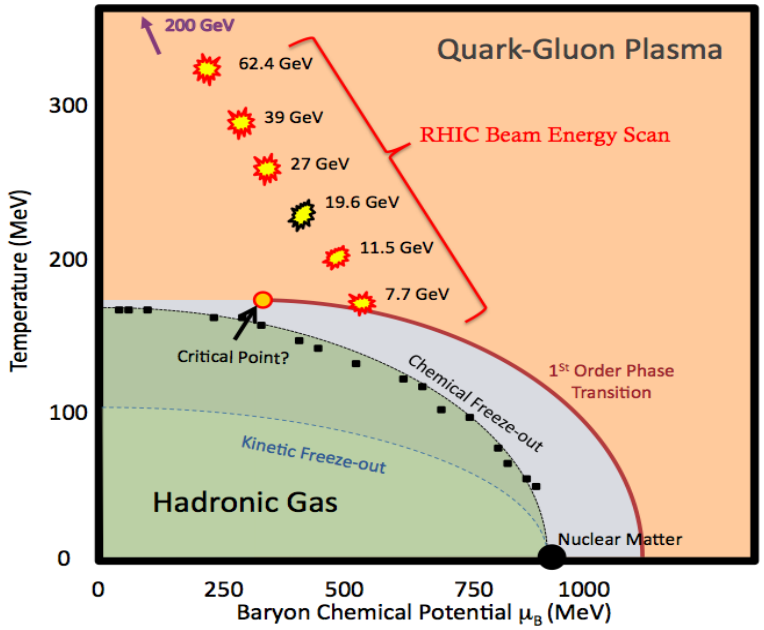
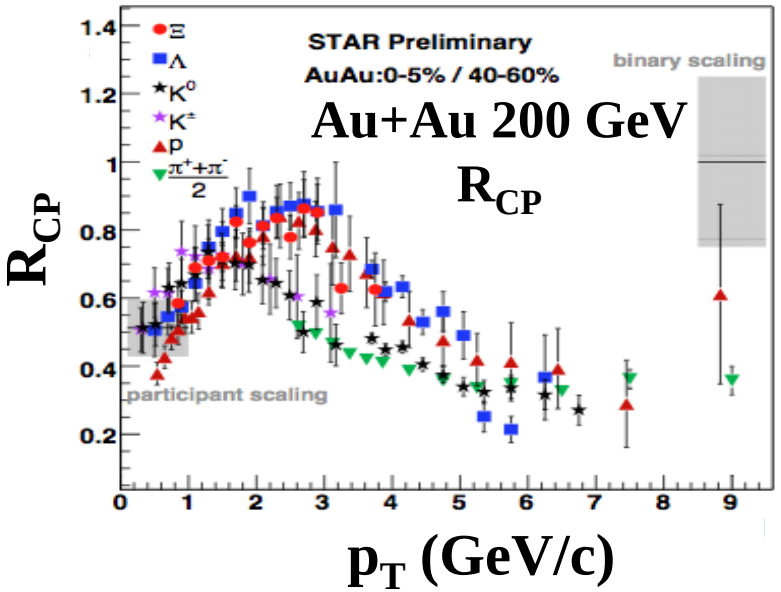
中国物理学会高能物理分会
第十二届全国粒子物理学术会议
2016.8.22-26
中国科学技术大学

Outline

- Strangeness production in heavy ion collisions
- Strangeness measurements in STAR
  - ✓Beam energy scan: Au+Au 7.7 – 39 GeV
  - ✓Top RHIC energy: p+p, Au+Au 200 GeV, U+U 193 GeV
- Summary

s quarks: good probe for QCD phase transition & QGP properties

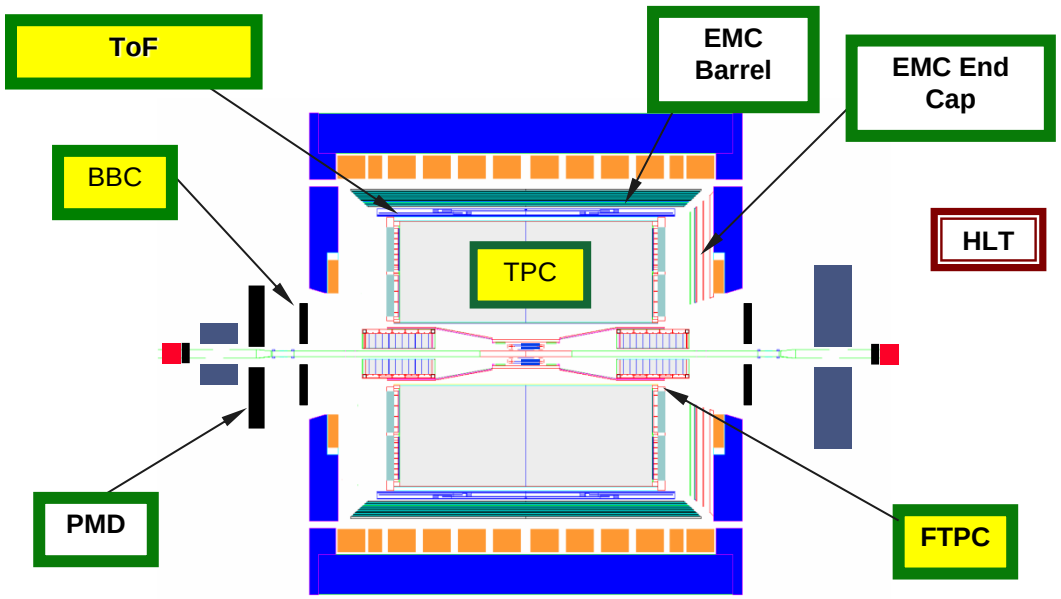




- **Beam Energy Scan at RHIC**
  Au+Au collisions at 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 GeV
  Look for **onset of de-confinement, phase boundary** and critical point
- U+U collisions at 193 GeV
  System energy density dependence
- Key observables
  (1) Strangeness enhancement
  (2) Baryon/meson ratio
  Parton recombination
  (3) Nuclear modification factor
  Partonic energy loss & recombination

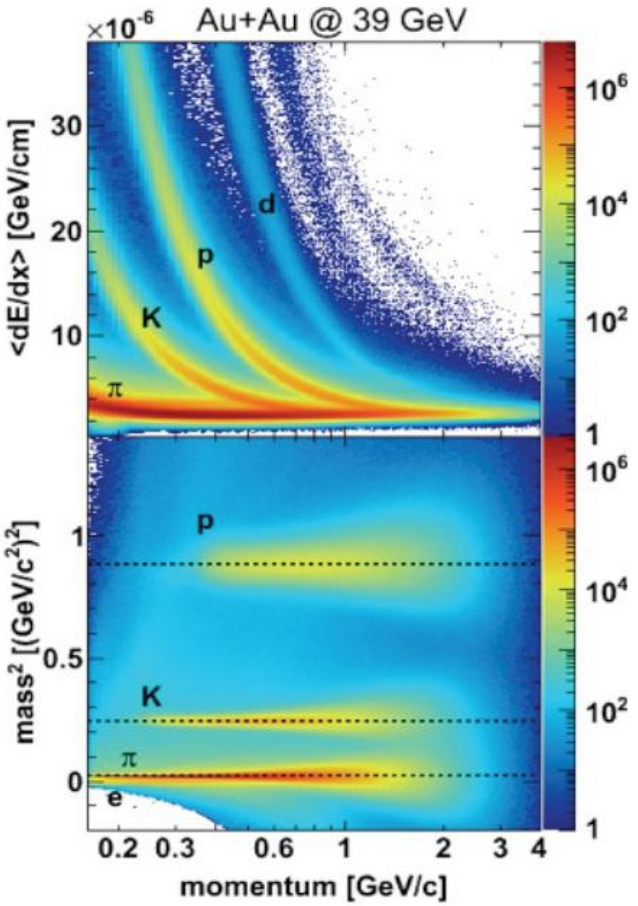
STAR, arXiv:1007.2613; NA49, PRC78, 034918

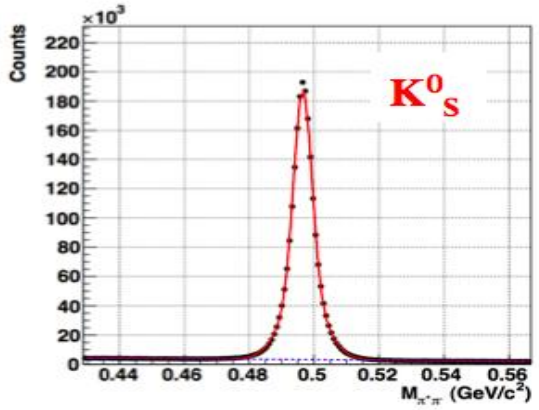
Detector settings and data sets

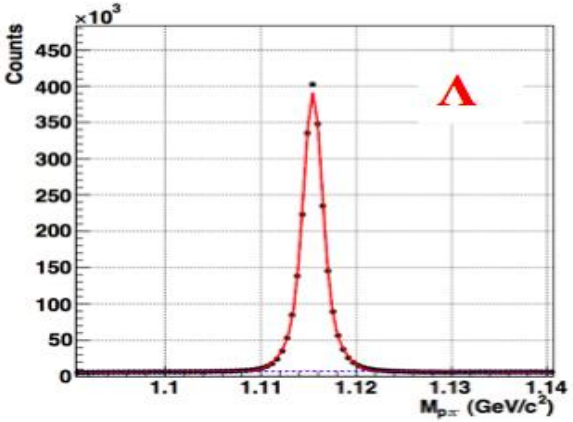


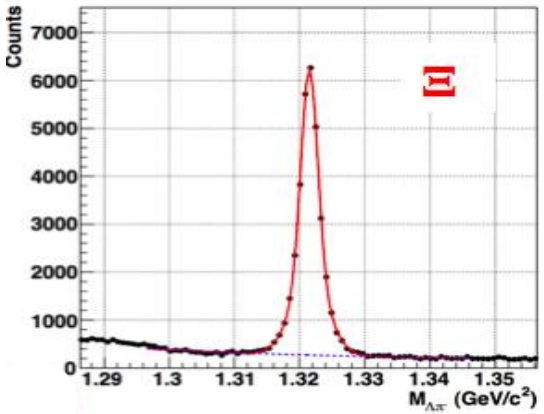
Year	*Collisions*	$\sqrt{s_{NN}}$ (GeV)	MB events in Million
2010	Au+Au	7.7	~ 4 M
2010	Au+Au	11.5	~ 12 M
2014	Au+Au	14.5	~ 18 M
2011	Au+Au	19.6	~ 36 M
2011	Au+Au	27	~ 70 M
2010	Au+Au	39	~ 130 M
2011	Au+Au	200	~ 480 M
2012	U+U	193	~ 270 M
2009	p+p	200	~ 107 M

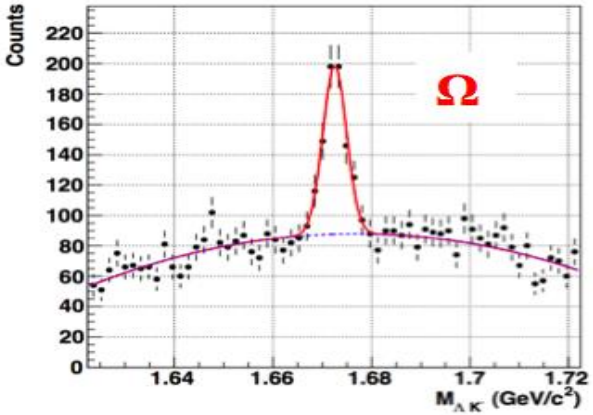
Particle identification and reconstruction

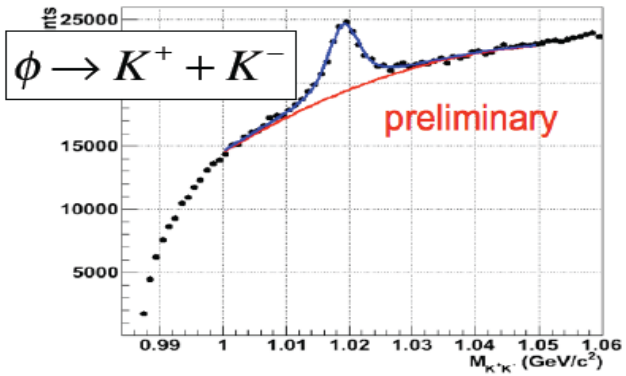






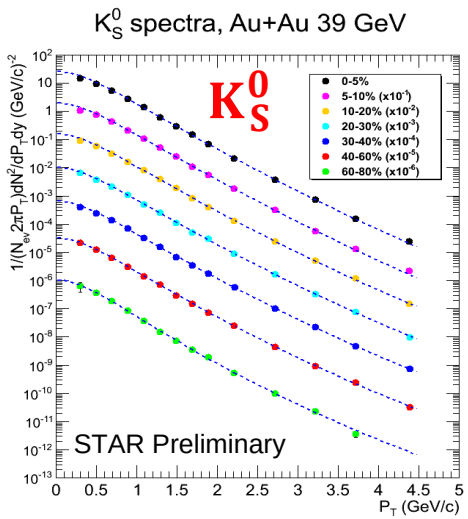


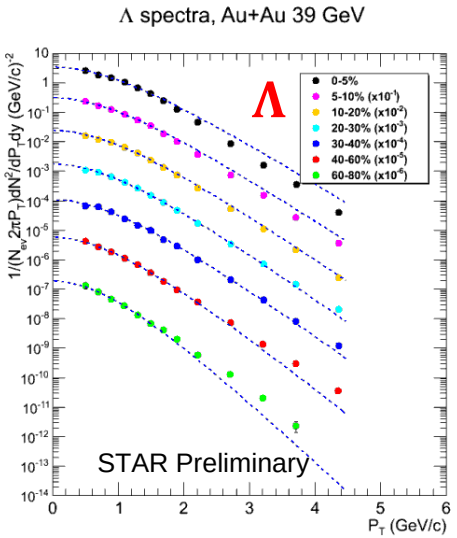


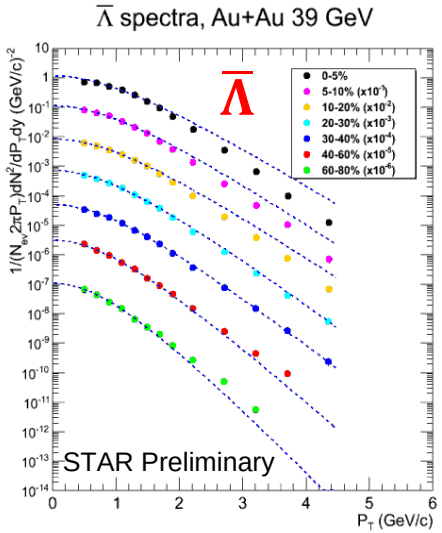


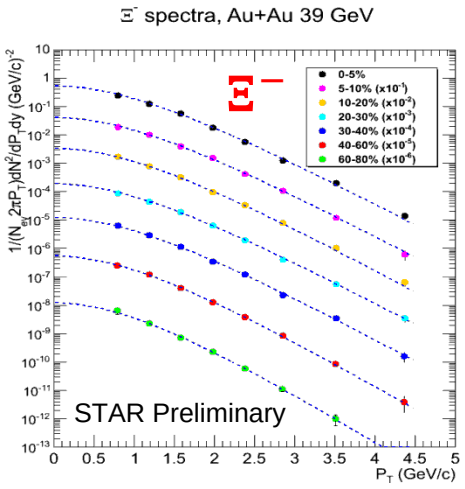
- dE/dx+TOF: π, K, p and $\phi \rightarrow K^+ + K^-$ (invariant mass)
- Weak decay particles (K^0_S, Λ, Ξ, Ω), secondary vertex + invariant mass

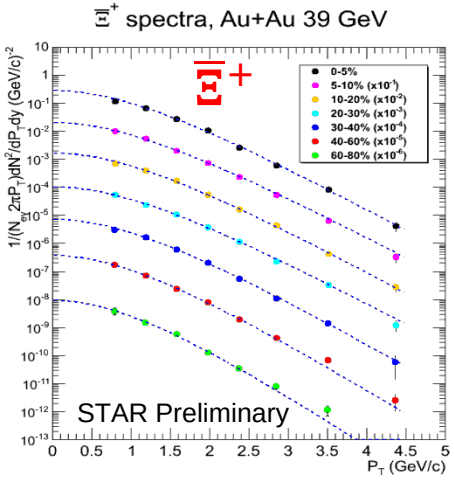
p_T spectra (K^0_S, Λ, Ξ at 39 GeV)







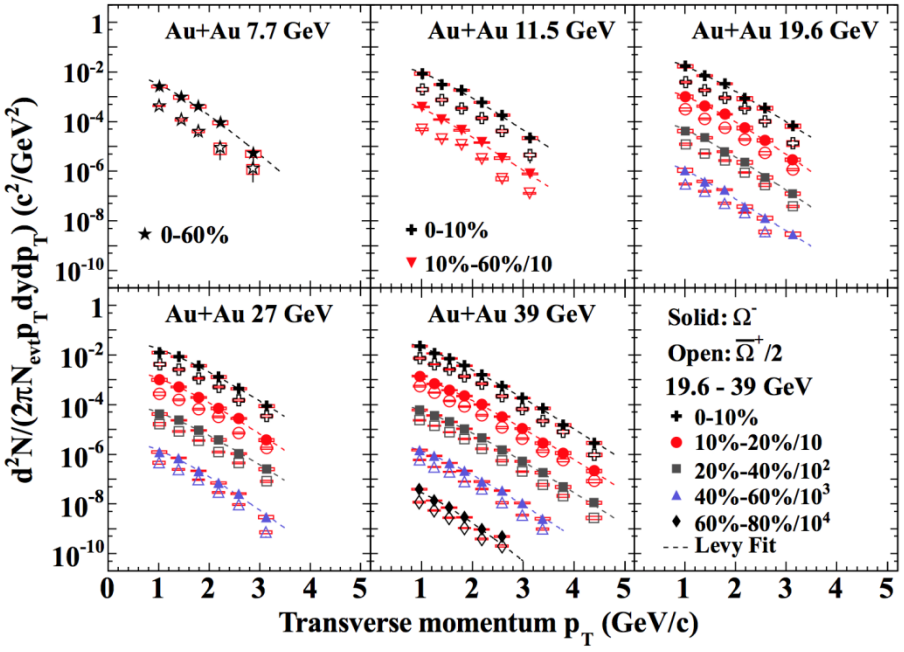


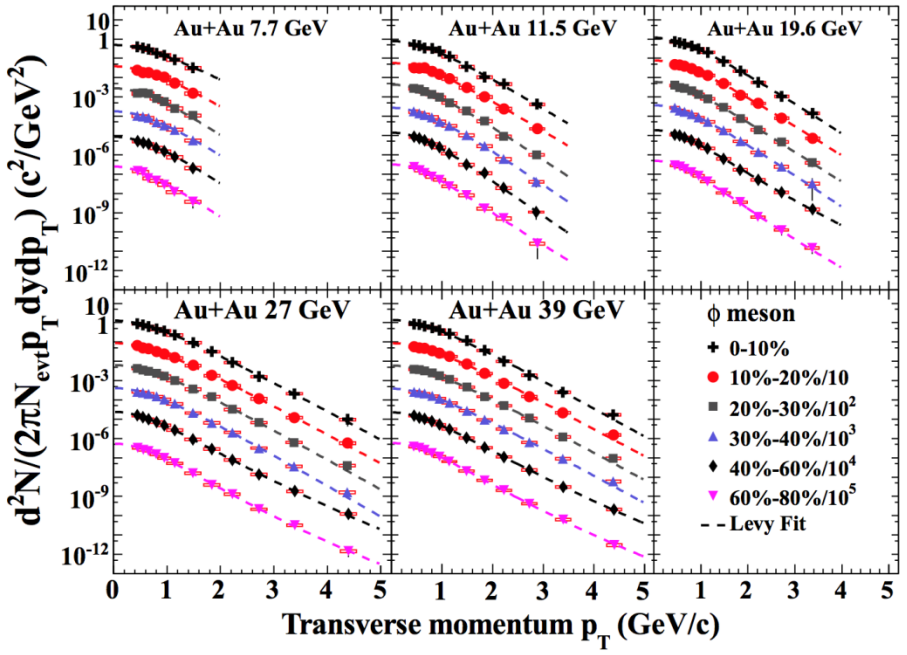


- Extensive strange particle spectra — Statistical error
- **$\Lambda(\bar{\Lambda})$ spectra are weak decay feed-down corrected**

  ~ 20% for Λ; ~ 25% for $\bar{\Lambda}$

p_T spectra (Ω and ϕ)



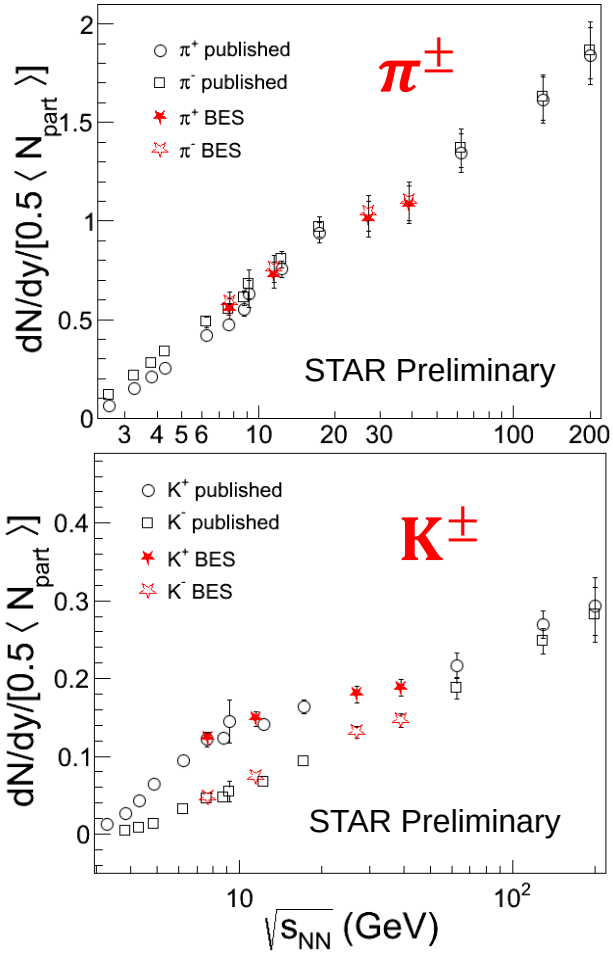


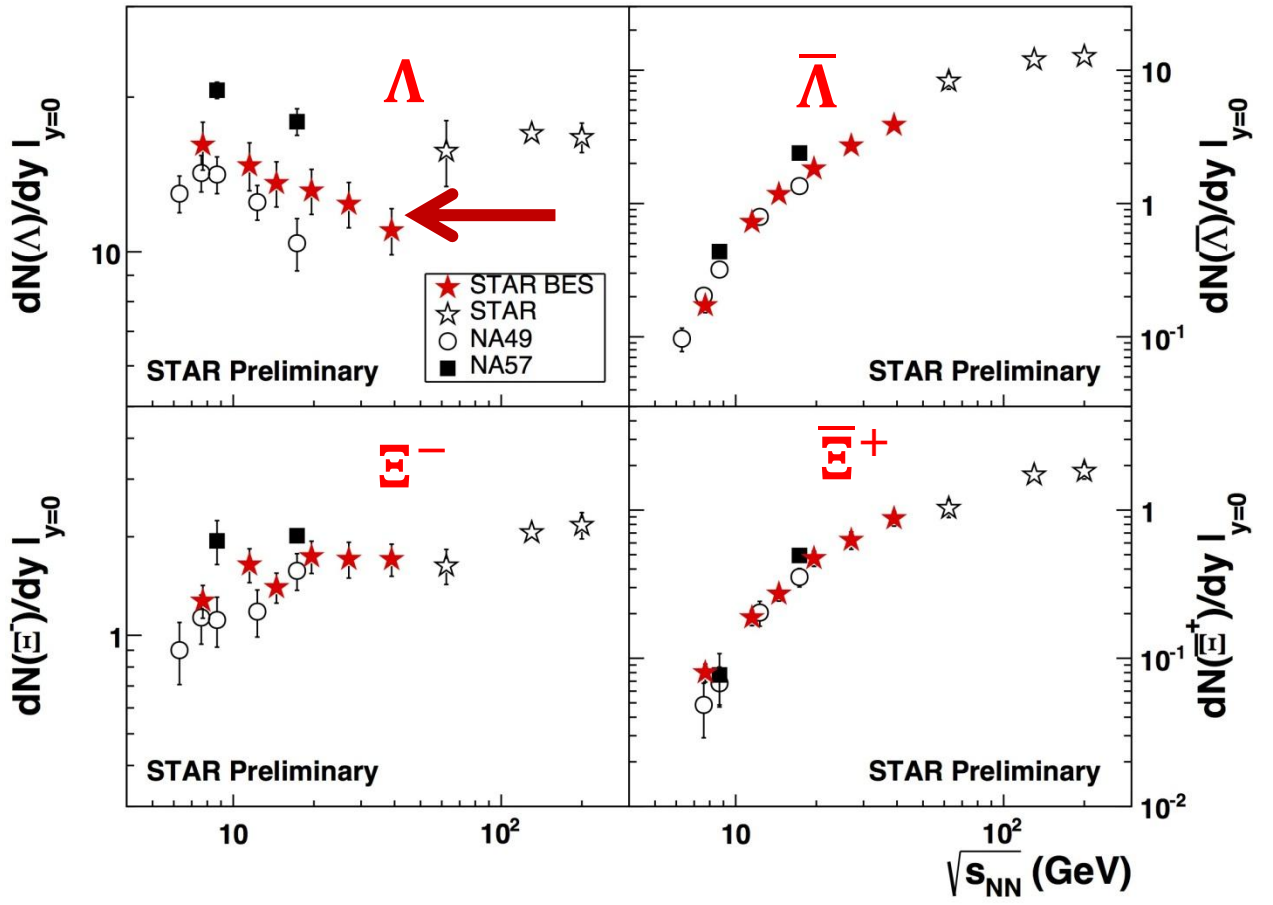
Phys. Rev. C 93, 2016, 021903 (R)

- Extensive strange particle spectra

Particle yields

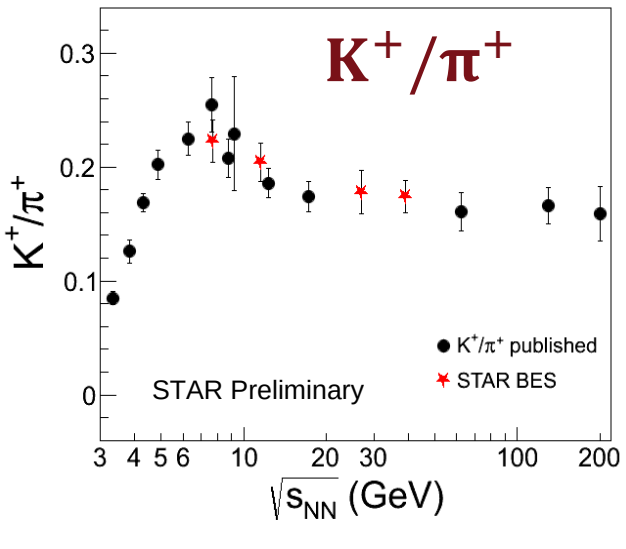
mid-rapidity, most central collisions (0-5%)

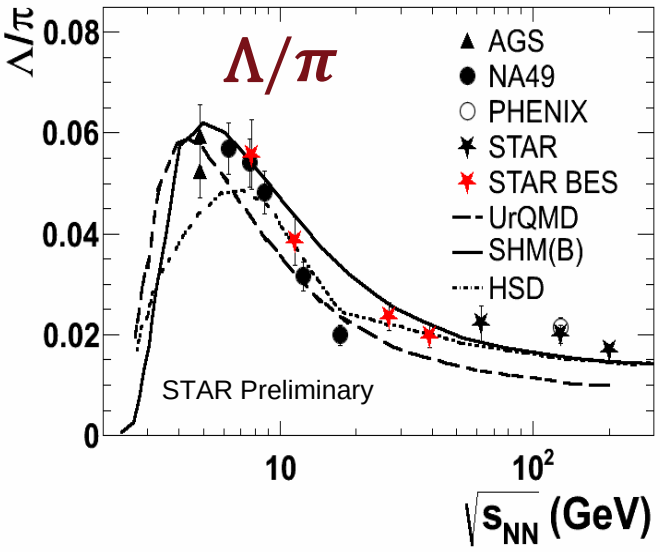


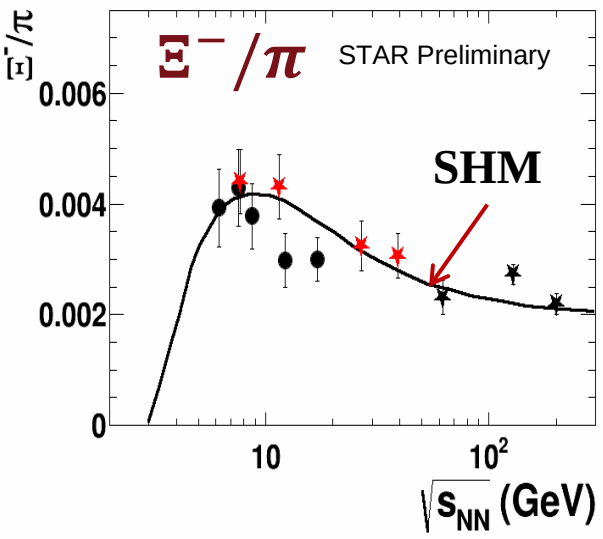


- STAR results are consistent with published data in general
- Λ yields seem to show dip around $\sqrt{s_{NN}}$ = 39 GeV. **The baryon stopping at mid-rapidity decreases with increasing energy**

Particle ratios

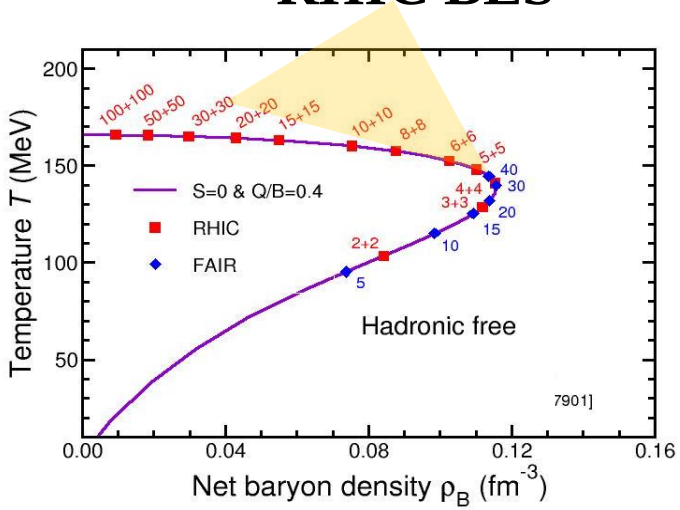






RHIC BES

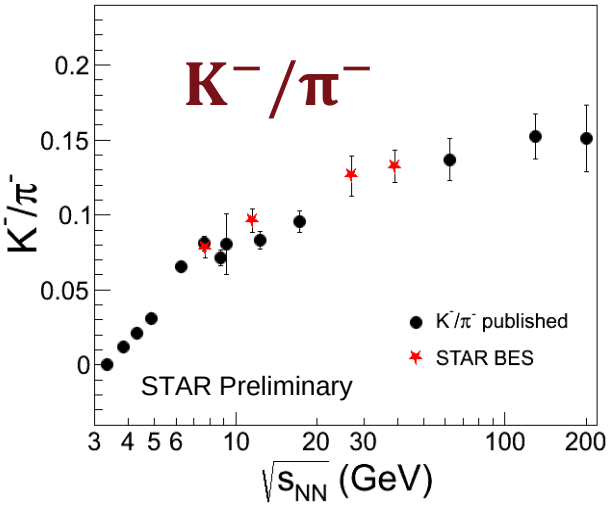
most central (0-5%), *mid-rapidity, stat. + sys. error*

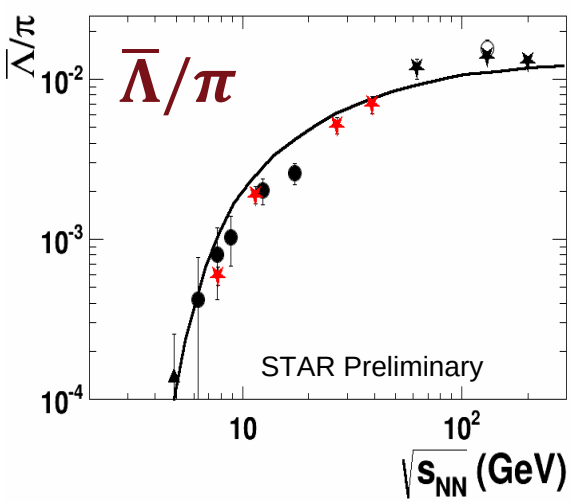


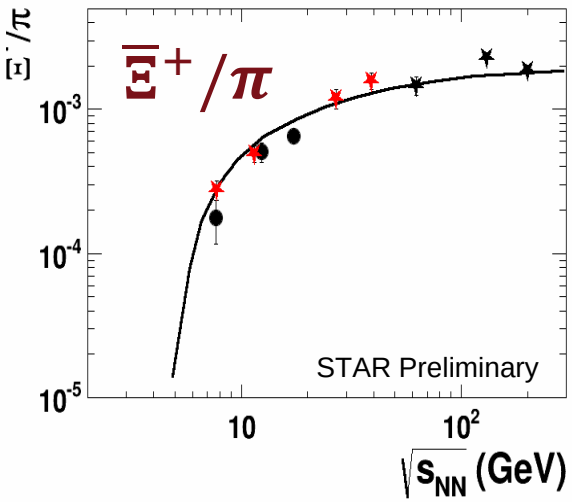
J. Randrup et al., PRC 74, 047901 (2006)

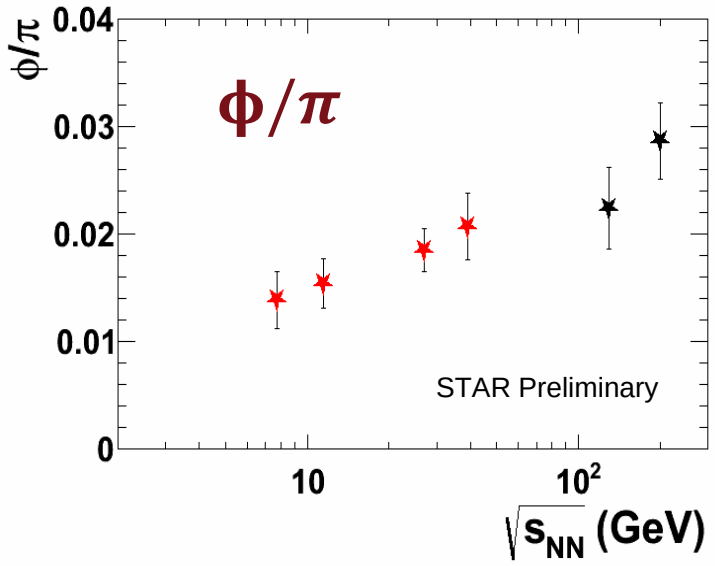
- Particle ratios consistent with NA49, consistent with the picture of a **maximum net-baryon density around $\sqrt{s_{NN}} \sim 8$ GeV at freeze-out**

Particle ratios







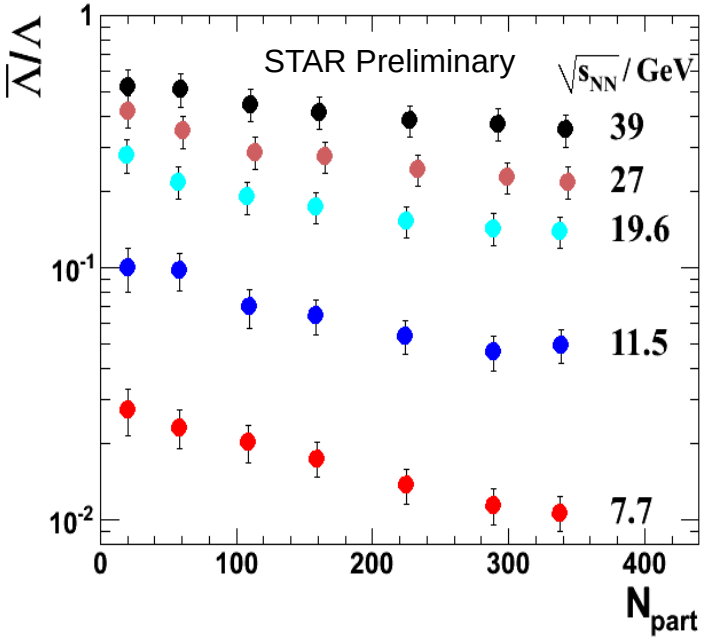


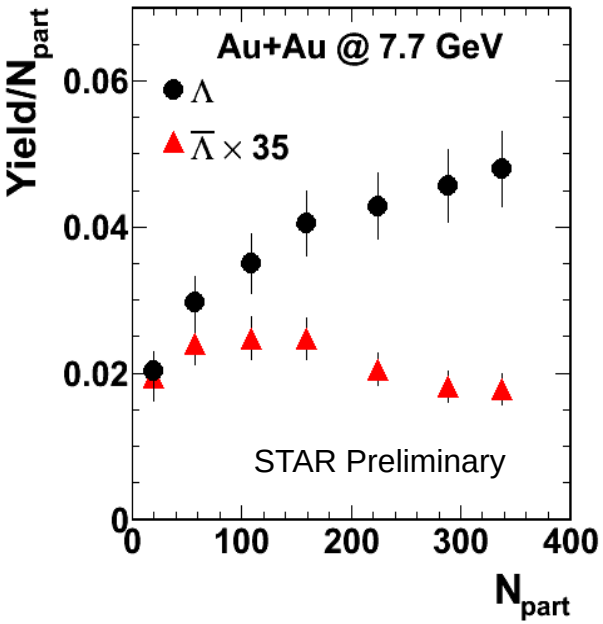
***most central (0-5%)**, mid-rapidity, stat. + sys. error*

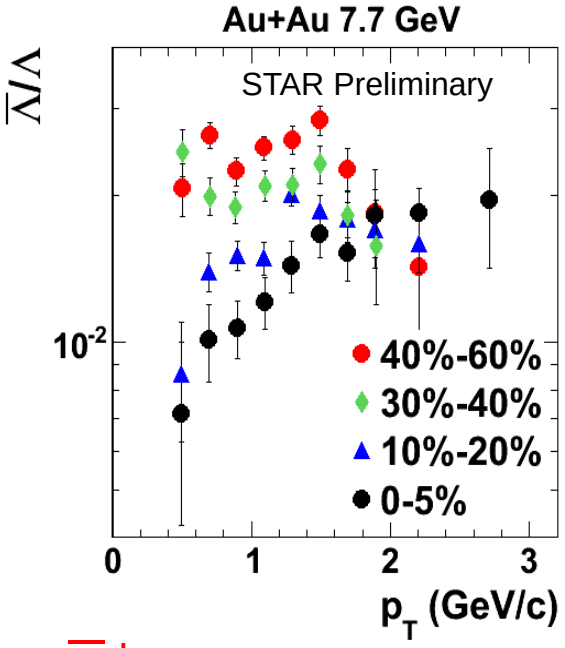
- Clear $\mathbf{K^-}$, $\bar{\mathbf{\Lambda}}$, $\bar{\mathbf{\Xi}}^+$ yield enhancement compared to pions with increasing collision energy
- Similar behavior for hidden strangeness $\boldsymbol{\phi}(s\bar{s})$

$\bar{B}/B$ ratios

$\bar{\Lambda}/\Lambda$

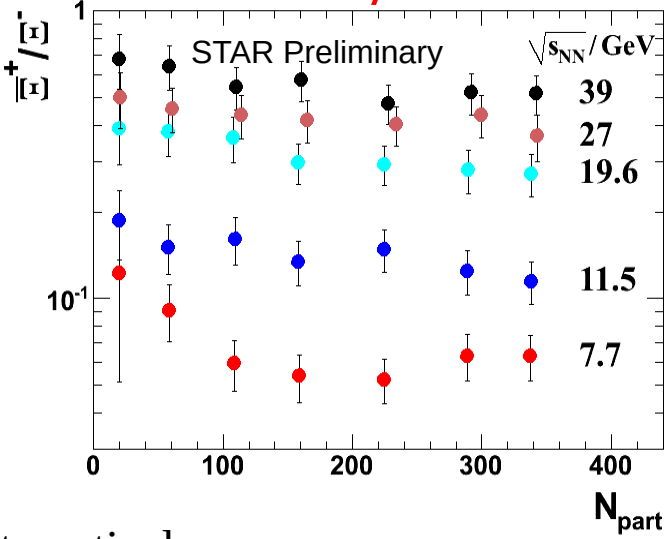






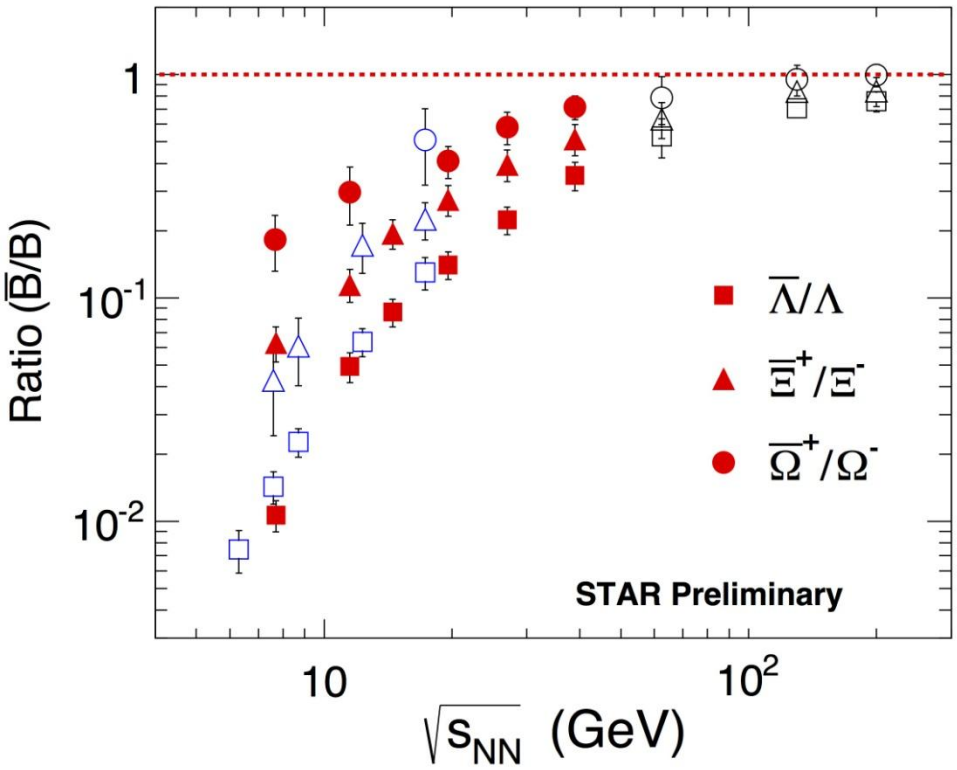
- Centrality dependence of $\bar{B}/B$ ratios:
  peripheral > central
- This effect is more prominent at lower energies.
  baryon stopping, anti-baryon absorption
- **Loss of low p_T $\bar{\Lambda}$ in central collisions**

$\bar{\Xi}^+/\Xi^-$



Statistical + systematical error

Excitation function of $\bar{B}/B$ ratios



Statistical + systematical error

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

- 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

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

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

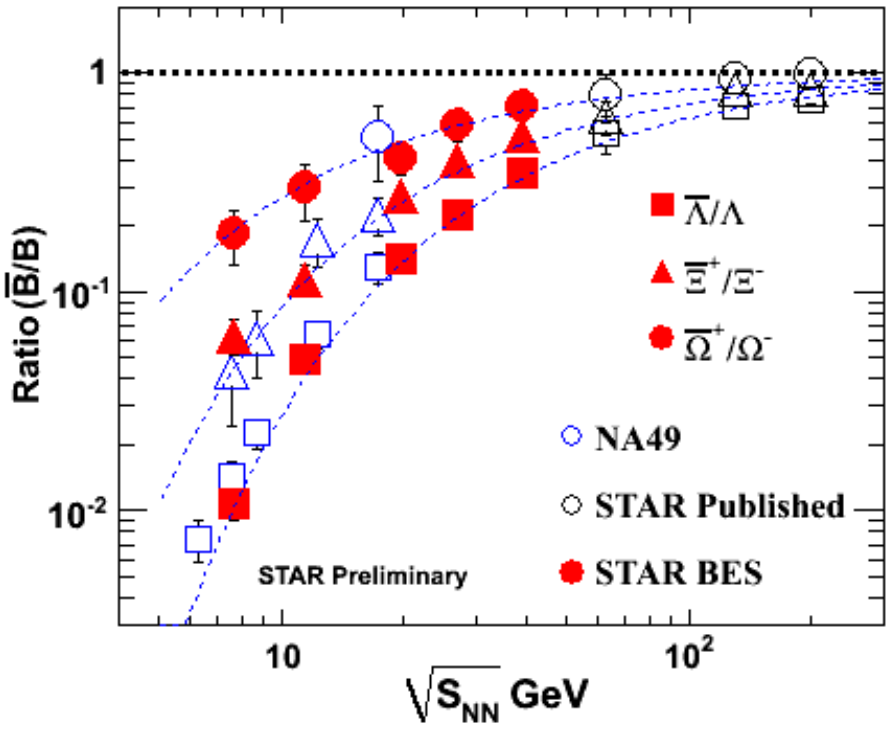
$$\frac{\bar{\Xi}^+}{\Xi^-} = \exp(-\frac{2\mu_B}{T} + \frac{4\mu_S}{T}) \qquad \ln(\frac{\bar{\Xi}^+}{\Xi^-}) = -\frac{2\mu_B}{T} + \frac{4\mu_S}{T}$$

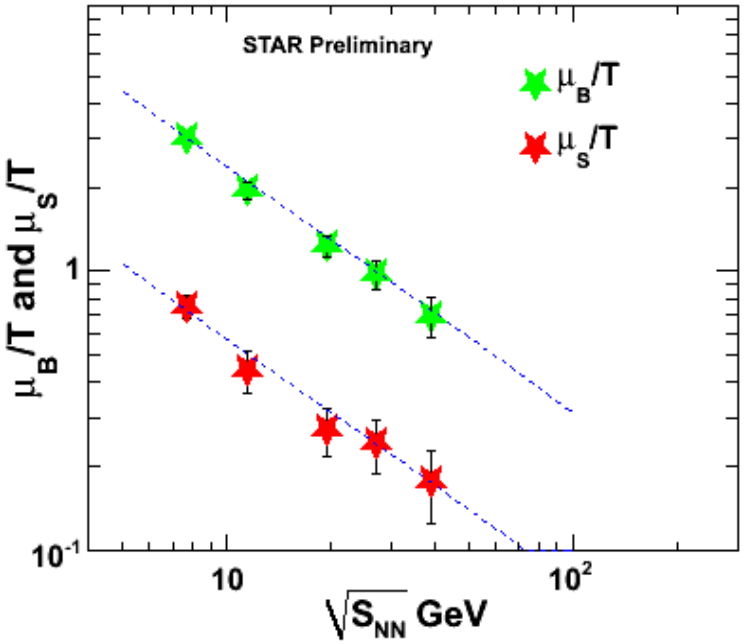
$$\frac{\bar{\Omega}^+}{\Omega^-} = \exp(-\frac{2\mu_B}{T} + \frac{6\mu_S}{T}) \qquad \ln(\frac{\bar{\Omega}^+}{\Omega^-}) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T}$$

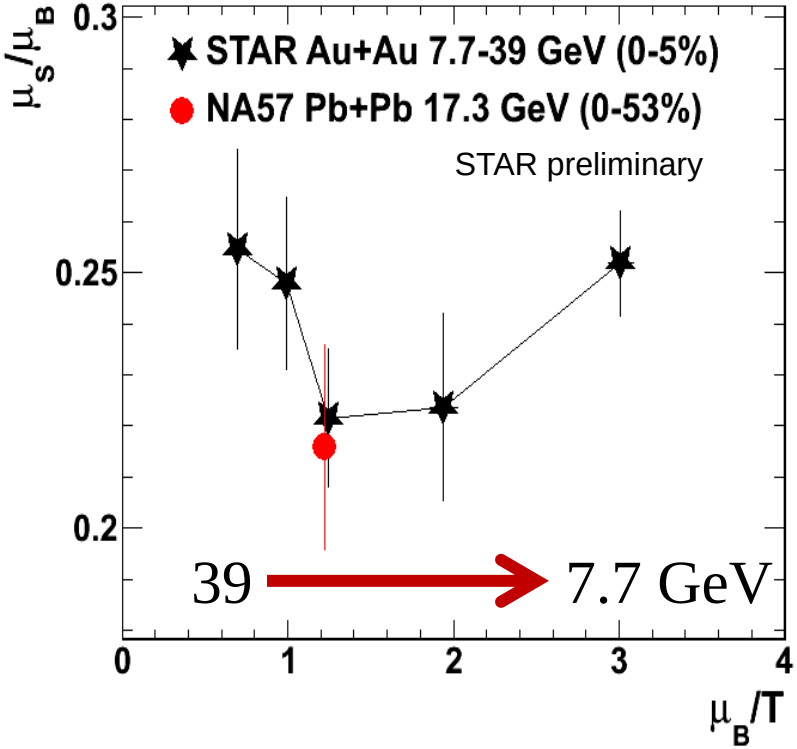
- T is the temperature.
- μ_B is the baryon chemical potential.
- μ_S is the strangeness chemical potential.

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

μ_B and μ_s correlation





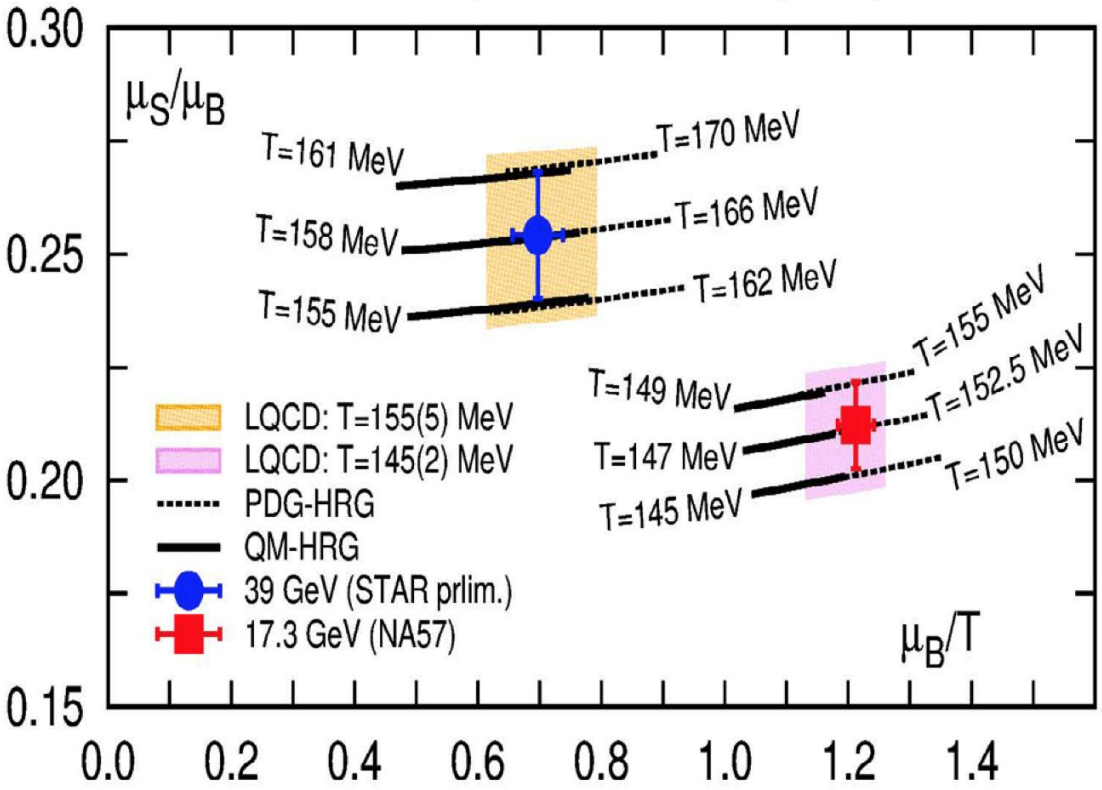


- Anti-baryon to baryon ratios are consistent with statistical thermal model
- **μ_s/μ_B seems to be smaller in 11.5 - 19.6 GeV than in 39 and 7.7 GeV**

Strangeness, LQCD and freeze-out in HIC

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

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

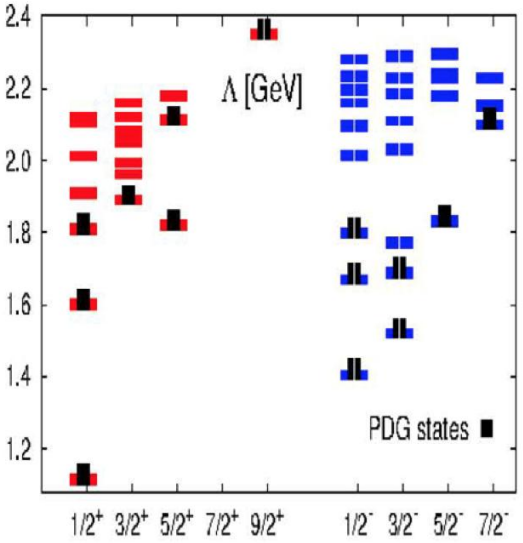


indirect evidence for so-far undiscovered strange baryons at RHIC ?

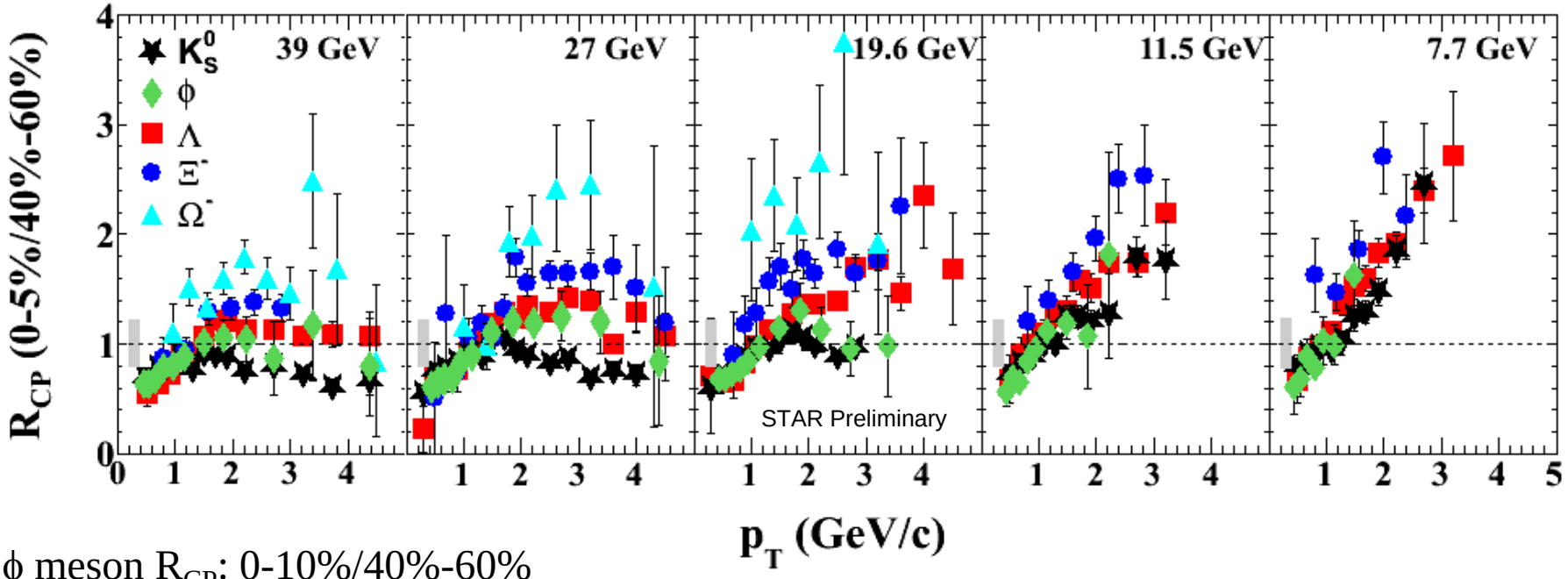
From Swagato Mukherjee

not reproduced by hadron gas with only PDG states

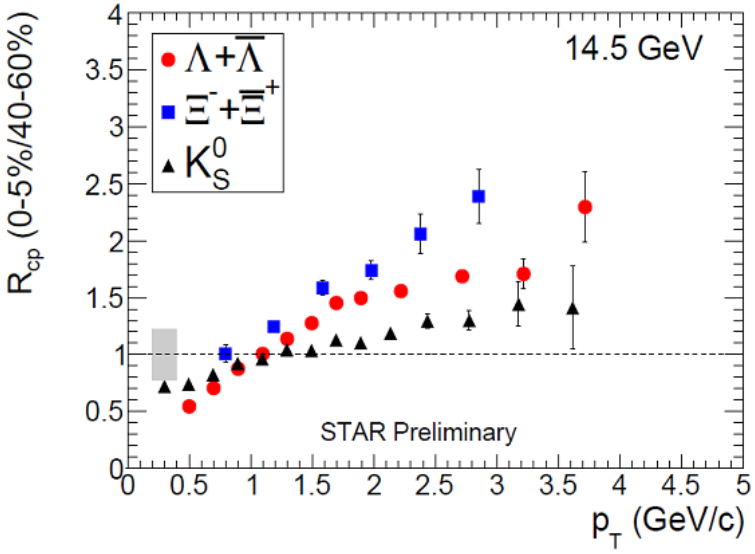
reproduced when additional Quark Model (QM) predicted strange baryons are taken into account



Nuclear modification factors R_{CP}



ϕ meson R_{CP}: 0-10%/40%-60%

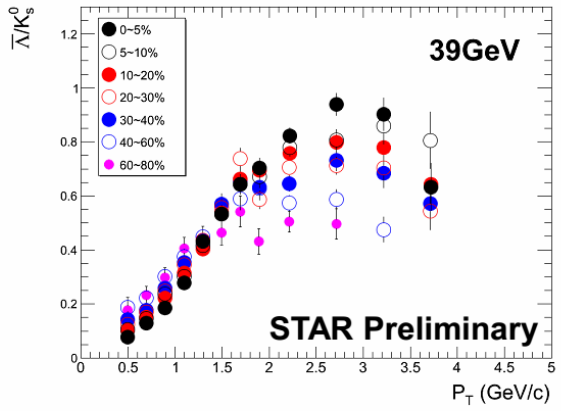


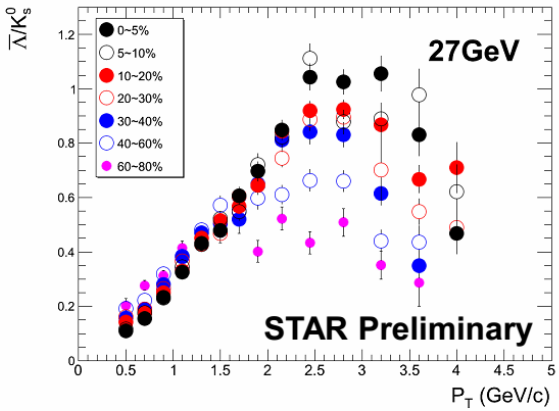
$$R_{CP}(p_T) = \frac{[d^2\sigma/(N_{\text{bin}} p_T dp_T dy)]_{\text{central}}}{[d^2\sigma/(N_{\text{bin}} p_T dp_T dy)]_{\text{peripheral}}}$$

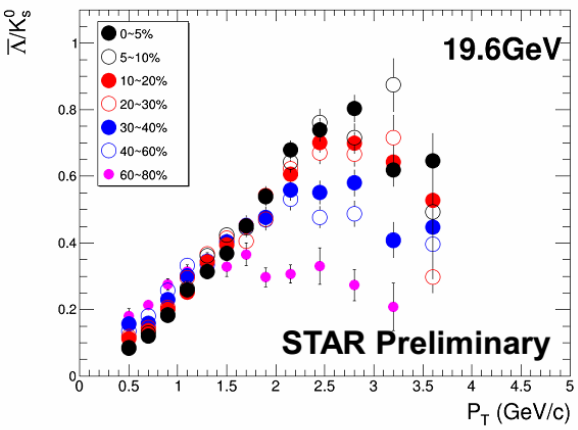
- No K^0_S suppression in Au+Au 7.7, 11.5 and 14.5 GeV
- **Cronin effect takes over partonic rescatterings @ lower energies**
- Intermediate p_T, particle R_{CP} difference **becomes smaller @ 7.7 and 11.5 GeV**

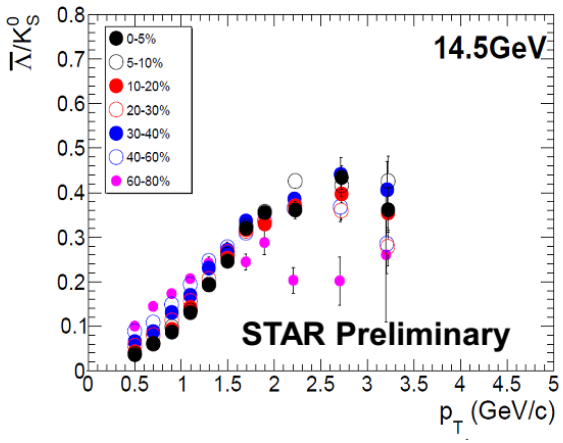
$\overline{\Lambda}$ / K^0_S ratio

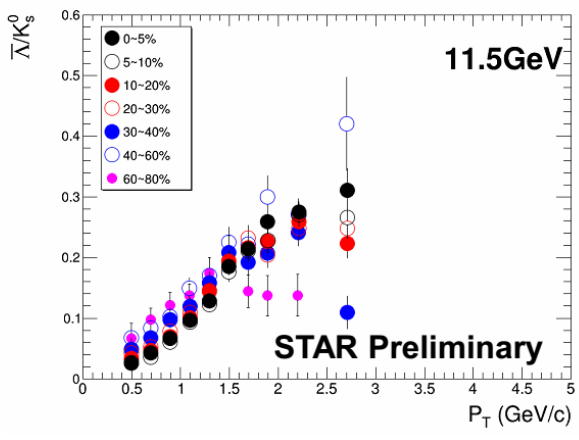
statistical error only

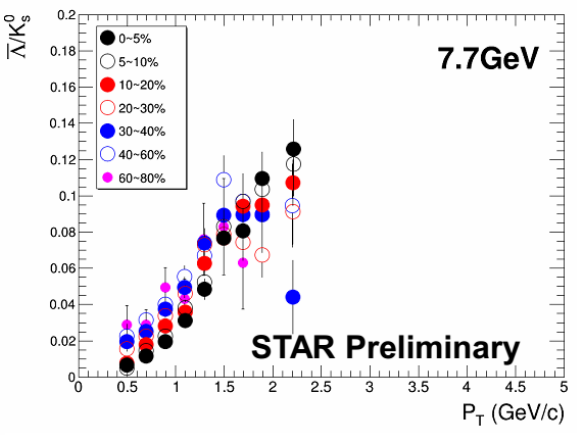






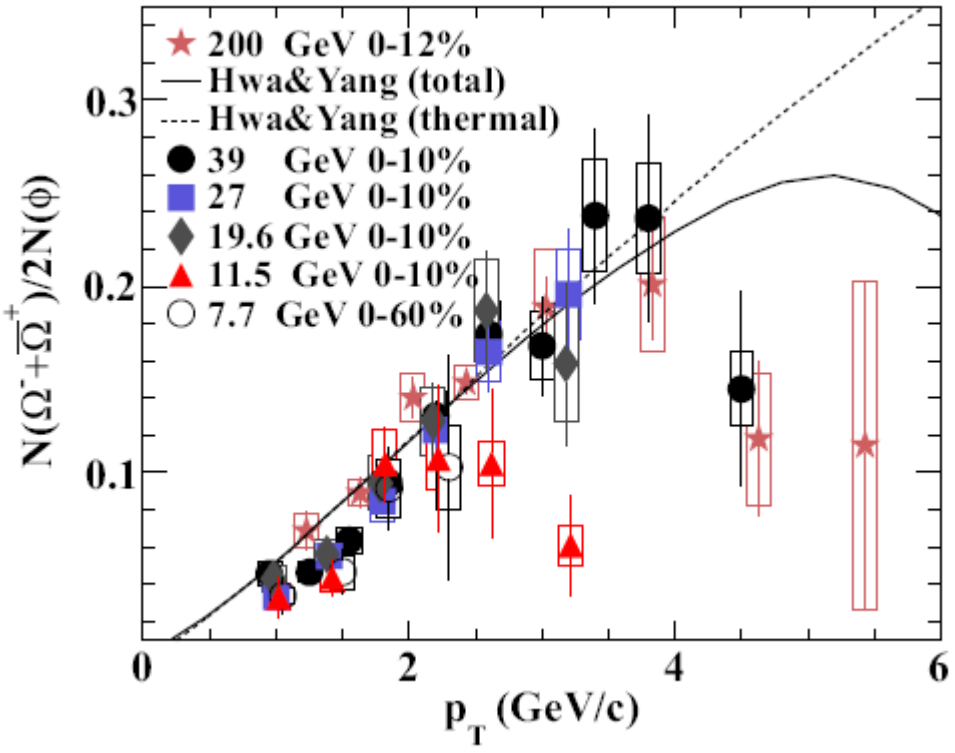


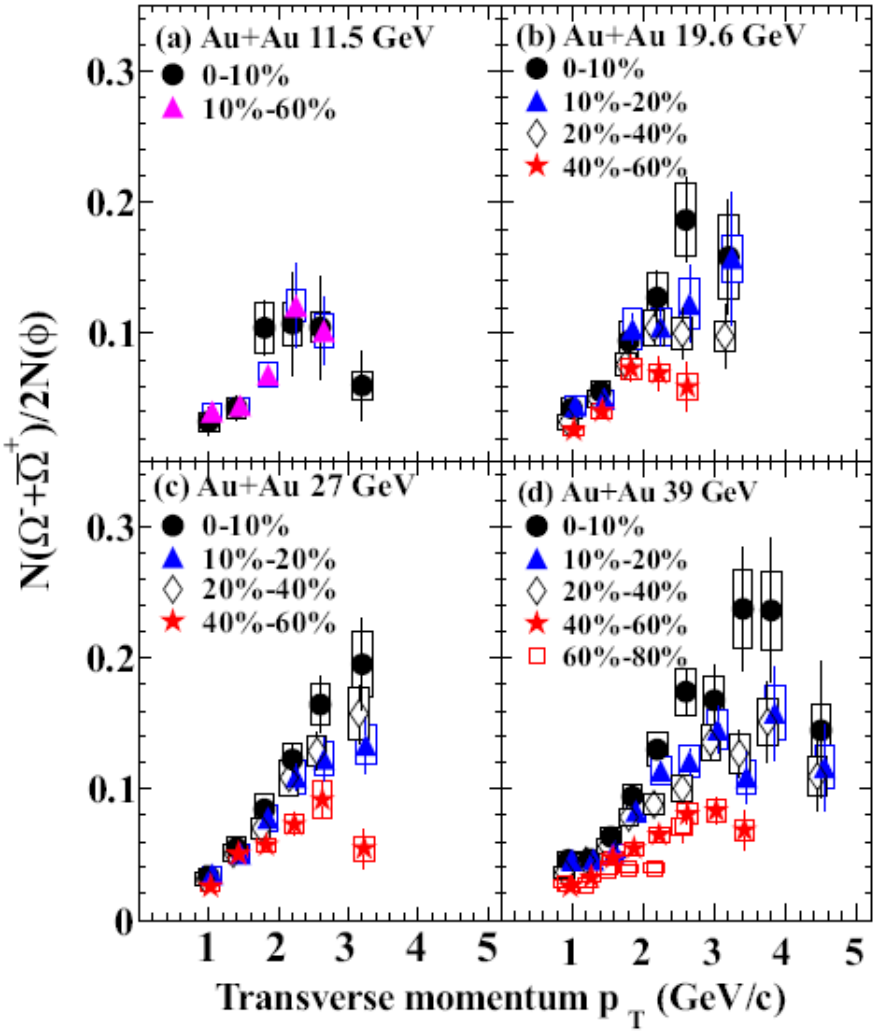




$\sqrt{s_{NN}} \leq$ **14.5 GeV**, at $p_T \sim 2$GeV/c, the separation of central (0-5%) and peripheral (40-60%) collisions in $\overline{\Lambda}$ / K^0_S becomes less obvious

Ω / ϕ ratio





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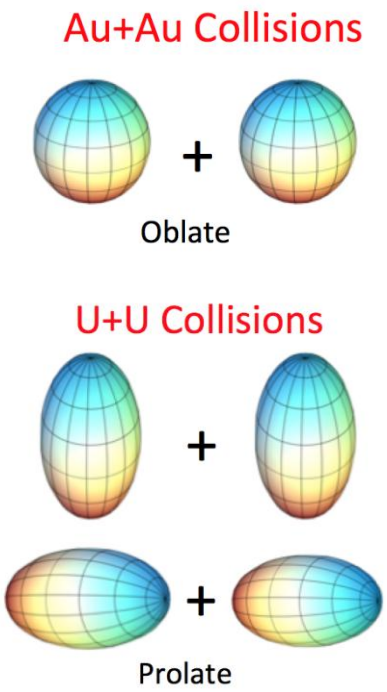
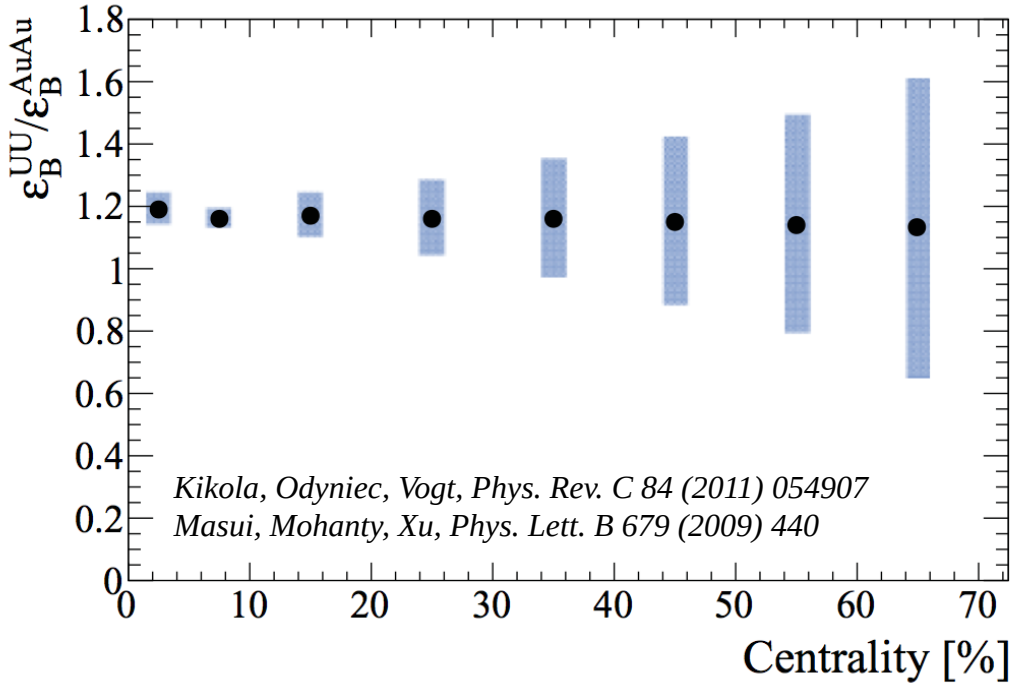
- Intermediate p_T Ω/ϕ ratios:
  Indication of separation between ≥ 19.6 and 11.5 GeV
- Ω/ϕ ratios: 40%-60% peripheral < 0-10% central for 19.6, 27 and 39 GeV

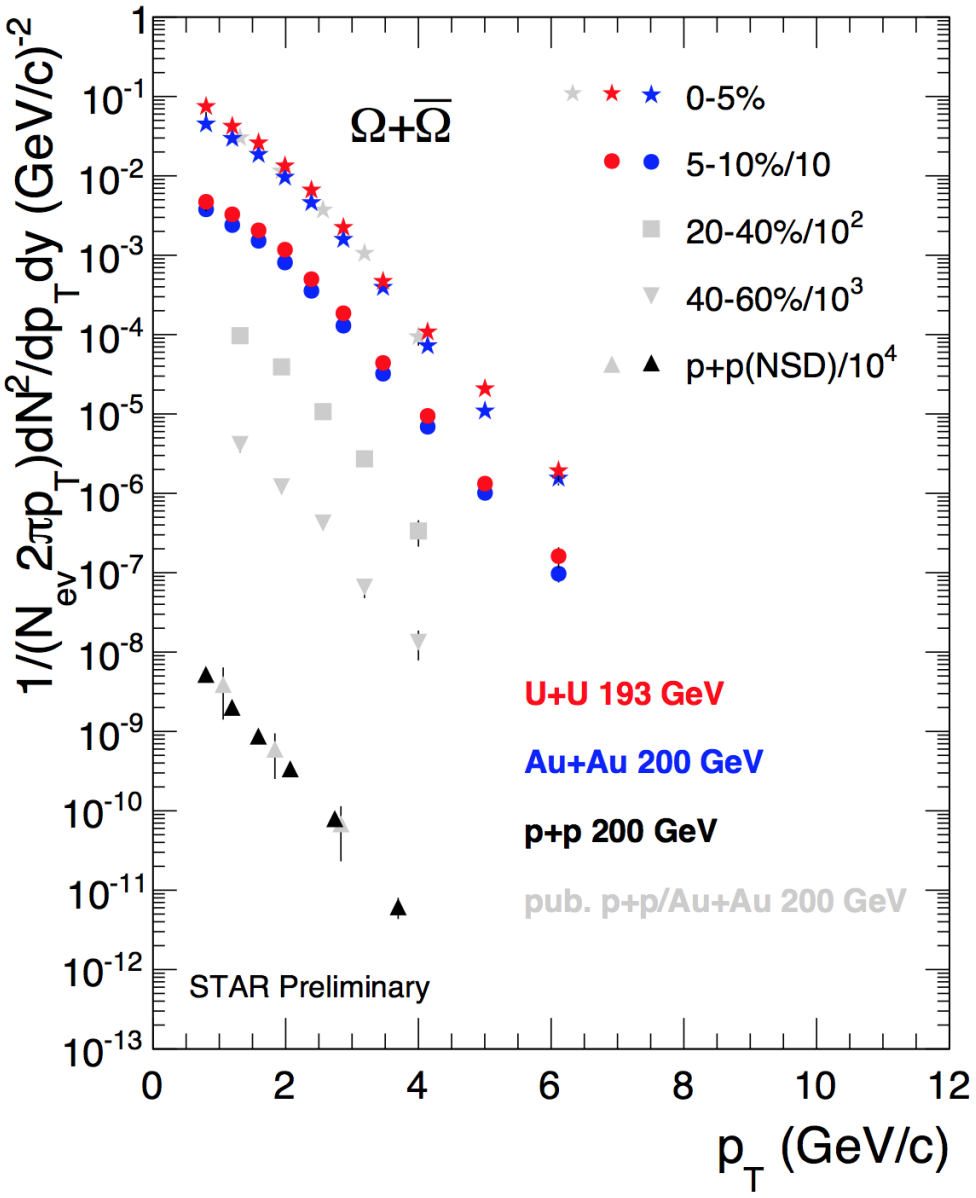
Ω in Au+Au vs in U+U at top RHIC energy

- U+U collisions expected to have **20% higher** energy density
- How is the Ω enhancement in U+U?
- Ω yield suppressed at high p_T in Au+Au?
  and even more suppressed in U+U?
- Fully explore the Ω production mechanism with **high statistics** Au+Au, U+U data taken in 2011-2012, and p+p data in 2009.





p_T spectra



* *|y|<0.5, statistical error only*

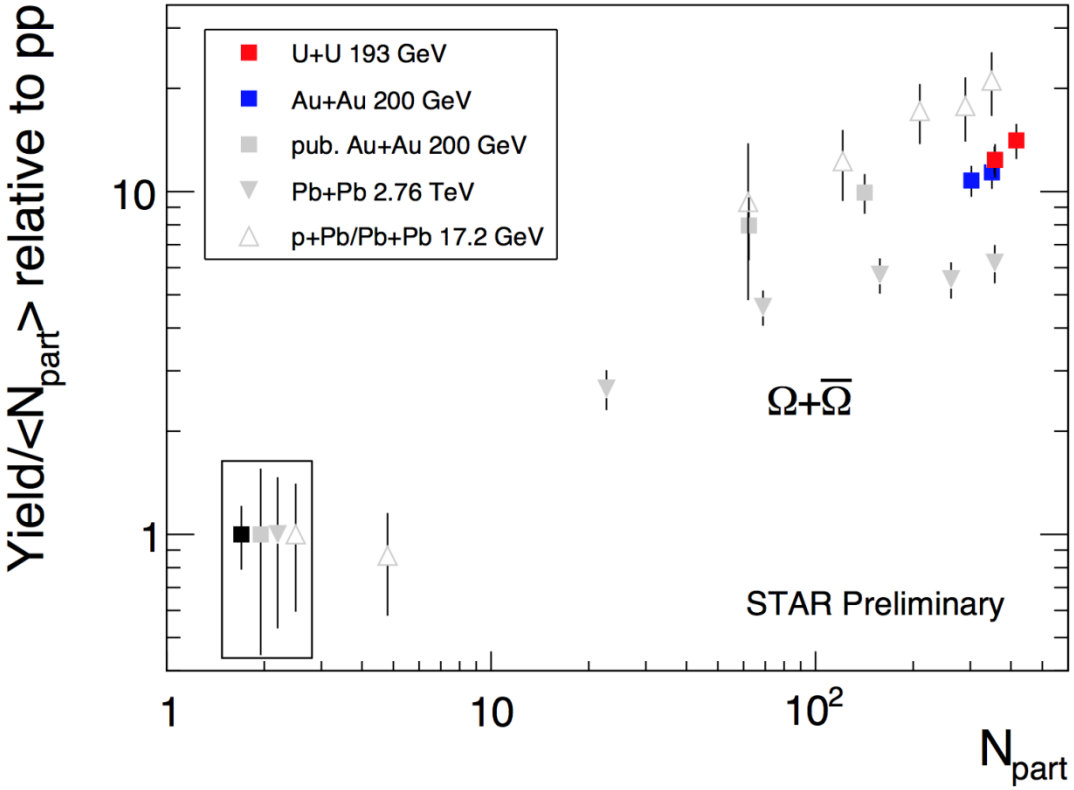
STAR, Phys. Rev. C 75 (2007) 064901

STAR, Phys. Rev. Lett. 98 (2007) 062301

* *only central (0-5, 5-10%) new Au+Au and U+U data available so far*

- Maximum p_T ~ 6 GeV/c for both Au+Au and U+U central collisions
- Yields (U+U > Au+Au)

Strangeness enhancement factor



New p+p 200 GeV data as reference for both new Au+Au 200 GeV and U+U 193 GeV

ALICE, Phys. Lett. B 728 (2014) 216

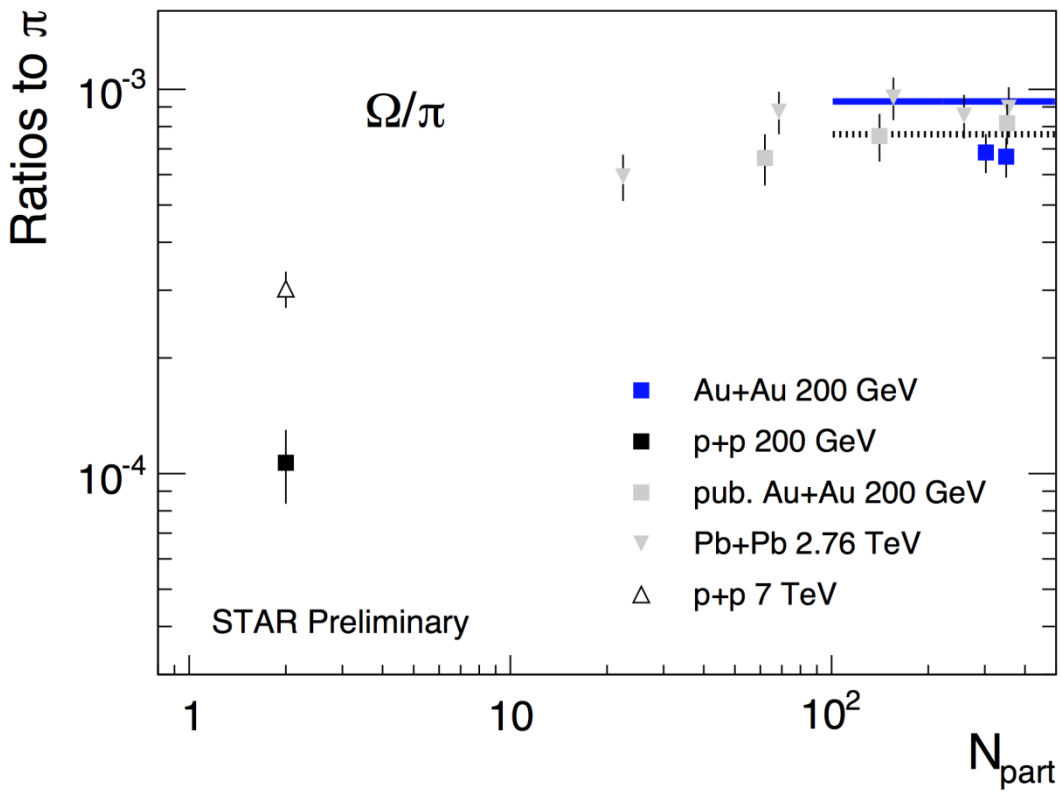
NA57, J. Phys. G 32 (2006) 427;

NA57, J. Phys. G 37 (2010) 045105

STAR, Phys. Rev. C 77 (2008) 044908

- Significantly reduced reference uncertainty at RHIC
- Larger enhancement than LHC, lower than SPS
- Larger enhancement in central (0-5%) U+U than in central (0-5%) Au+Au (strangeness enhancement not saturated)

Ratios to pion



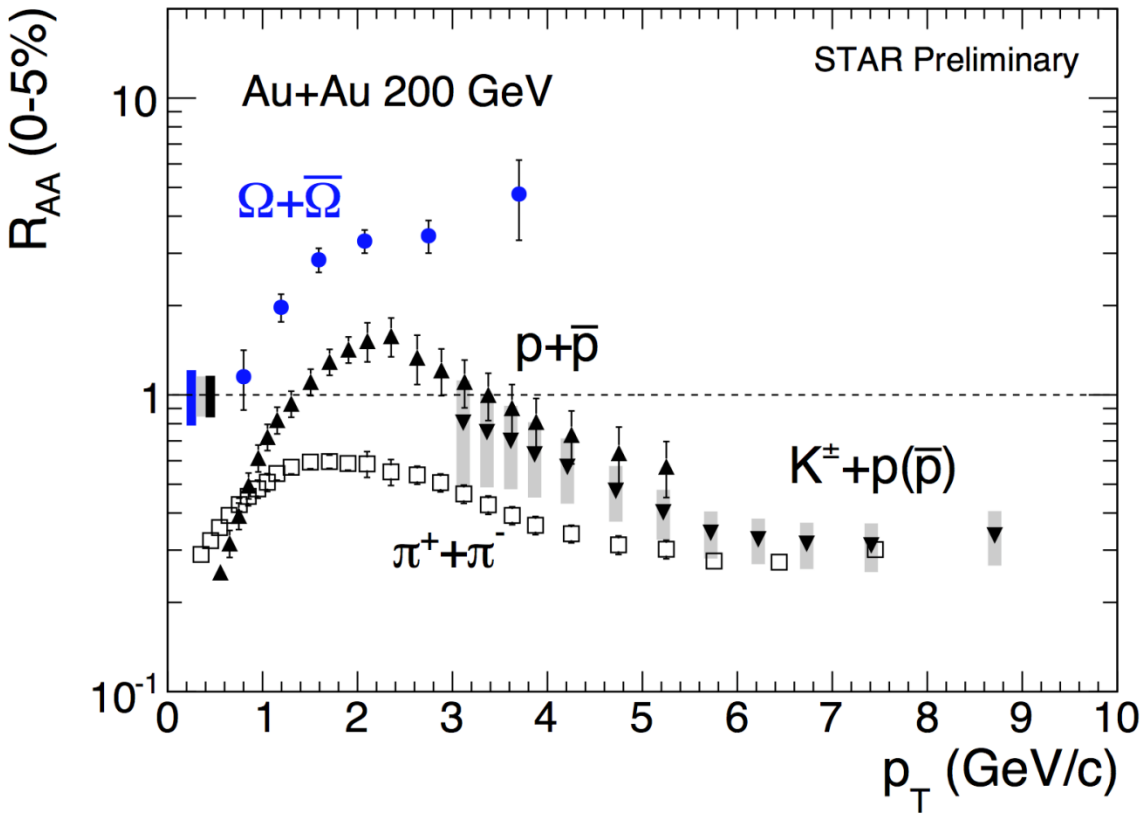
Thermal models:

Fitting to RHIC, *Andronic, et al., Phys. Lett. B 673 (2009) 142; Phys. Lett. B 678 (2009) 516*

Fitting to LHC, Stachel, et al., arXiv: 1311.4662

- RHIC data are lower than LHC
- Ω/π (LHC>RHIC) in p+p, canonical suppression

Nuclear modification factor (R_{AA})



$$R_{AA} = \frac{\sigma_{NN}^{\text{inel}}}{N_{\text{bin}}^{AA}} \frac{d^2N_{AA}/dyd\,p_T}{d^2\sigma_{pp}/dyd\,p_T}$$

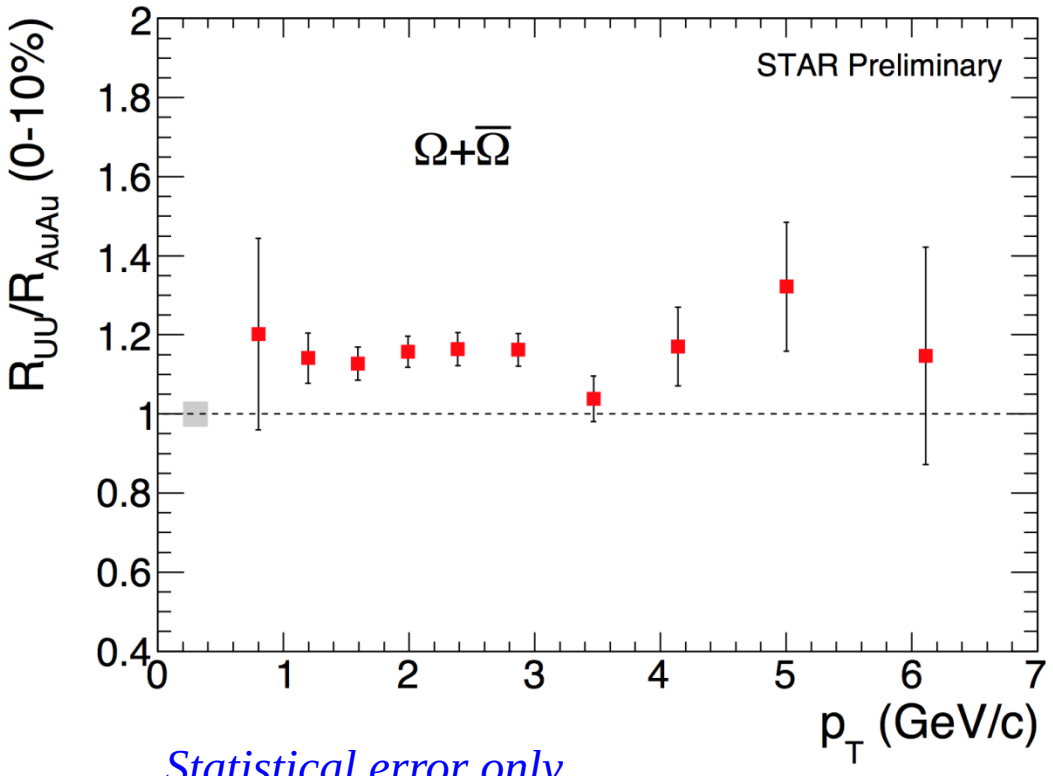
Statistical error only for Ω

$\pi^+ + \pi^-$ and p + p̄: *0-12%,*
STAR, Phys. Rev. Lett. 97 (2006) 152301
STAR, Phys. Lett. B 637 (2006) 161
STAR, Phys. Rev. C 81 (2010) 054907

$K^{\pm}$ + p(p̄): *0-12%,*
STAR, Phys. Rev. Lett. 108 (2012) 072302

- Ω baryon R_{AA} much larger than proton/pion up to 4 GeV/c
  → Ω suppression in p+p
  → Interplay of strange quark energy loss and coalescence or recombination in Au+Au

Ratio of nucl. mod. factors (R_{UU}/R_{AuAu})



Statistical error only

Higher energy density

→ *Jet more quenched*

$R_{UU}/R_{AuAu} < 1$ *at high* p_T

→ *Strangeness enhancement*

(Coalescence?)

$R_{UU}/R_{AuAu} > 1$ *at intermediate* p_T

* *Au+Au 200 GeV 0-10%*

$N_{part} = 325 \pm 4$; $N_{bin} = 941 \pm 26$

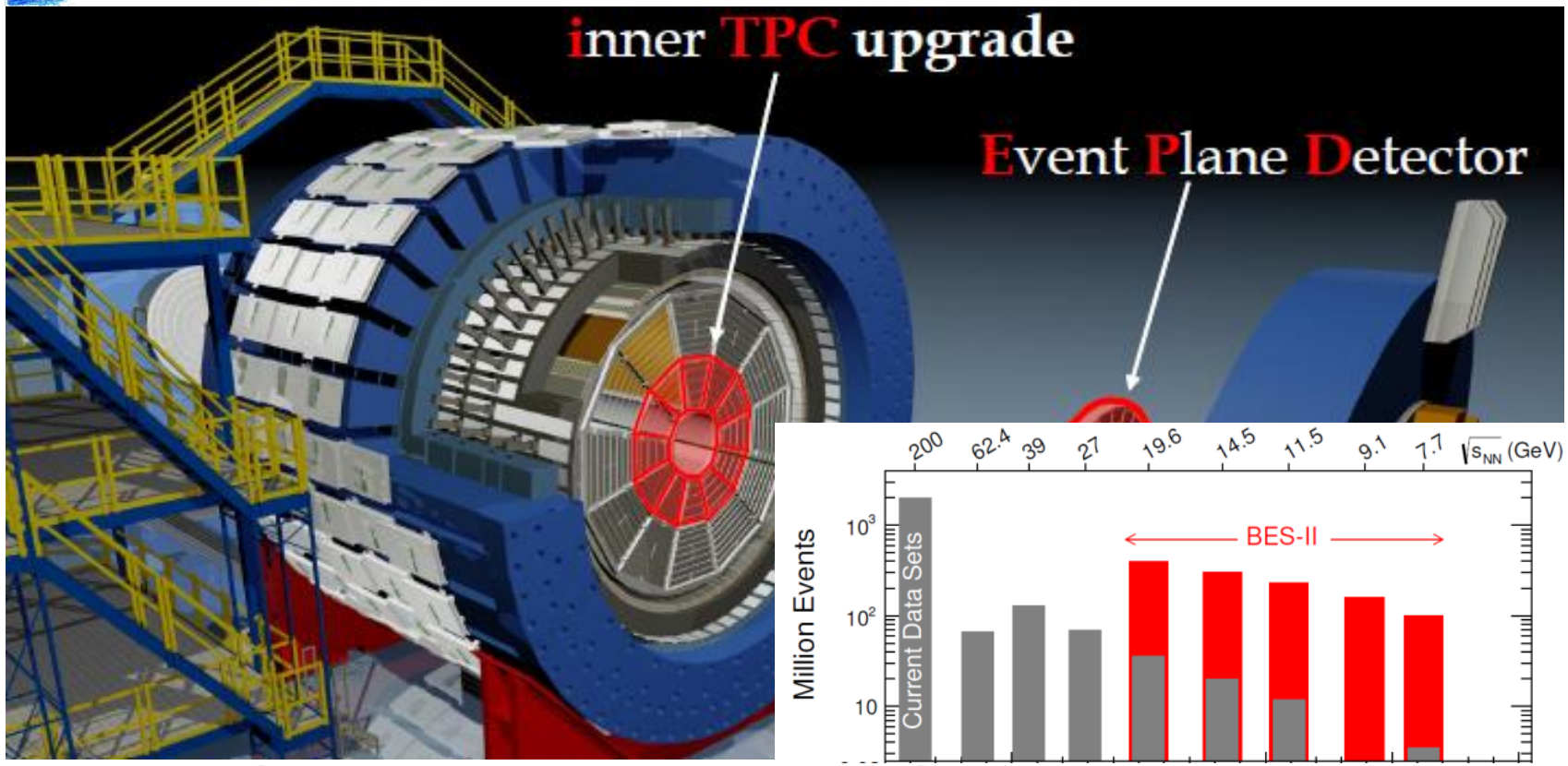
* *U+U 193 GeV 0-10%*

$N_{part} = 387 \pm 4$; $N_{bin} = 1151 \pm 18$

The energy density in central U+U is expected to be 20% higher, but N_{bin}-scaled high p_T Ω yield is not more suppressed

→ Ω formed through coalescence/recombination up to p_T ~ 6 GeV/c ?

Plans for Beam Energy Scan II



iTPC upgrade:

Replace ageing wires;

Sparse pads ➡ cover full area;

➡ better *dE/dx*;

$-1 < \eta < 1$ ➡ $-1.5 < \eta < 1.5$;

p_T >125 MeV ➡ p_T >60 MeV/*c*.

EPD upgrade:

Replaces ageing BBC, which wasn't designed for BES phys.

Greatly improved Event Plane info (esp. 1st-order EP);

Alternative Centrality definition

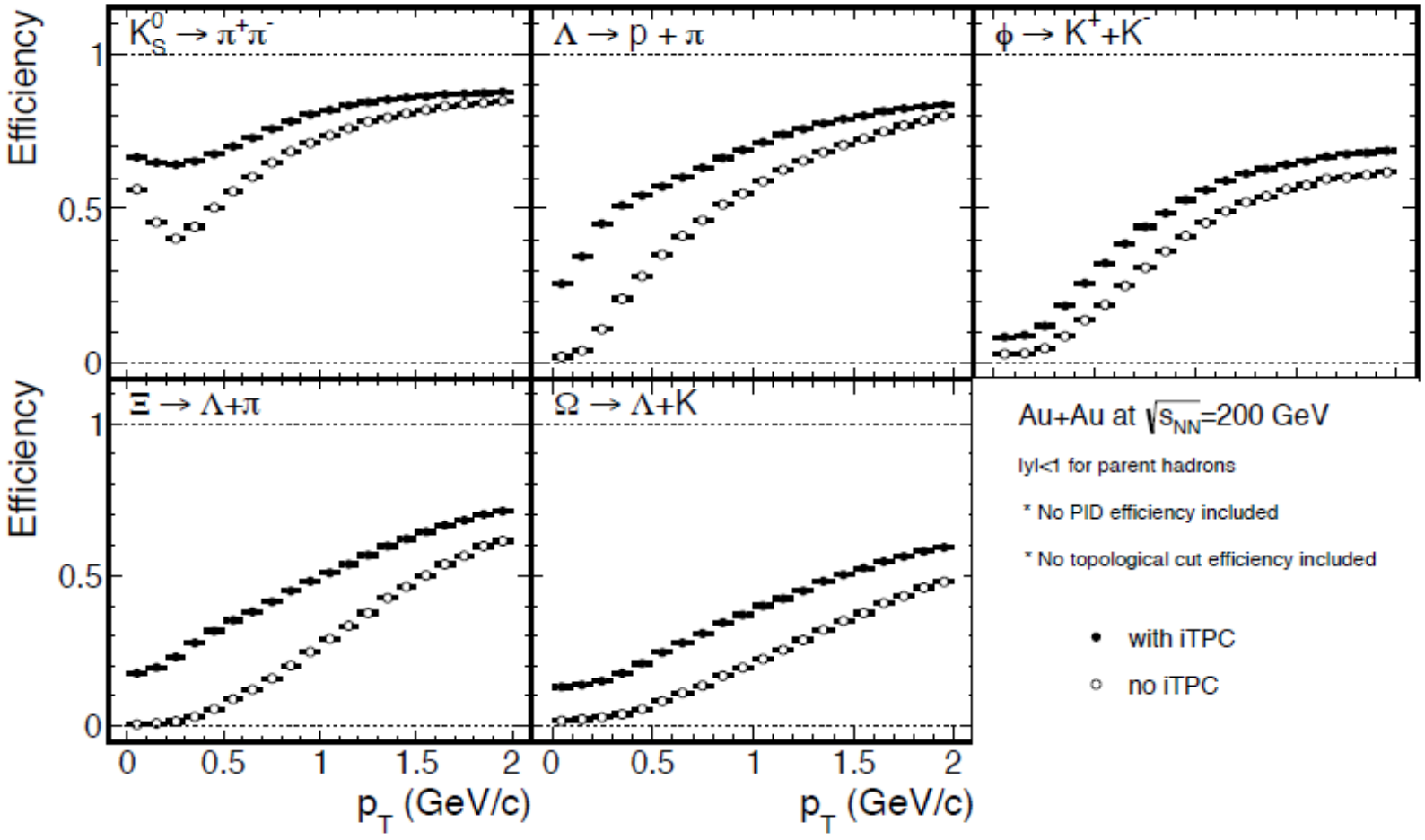
Better trigger & b/g reduction.

Other:

Hcal

Endcap TOF

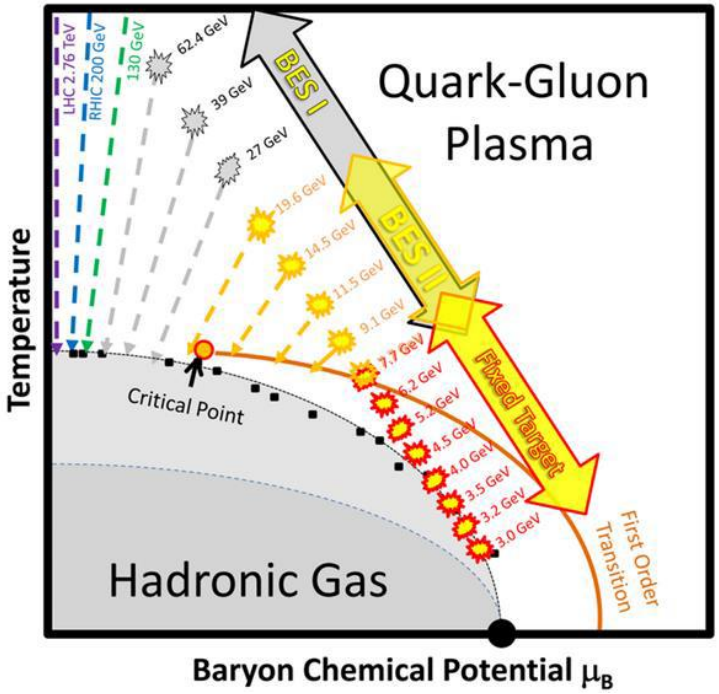
iTPC improves strangeness reconstruction in BES II

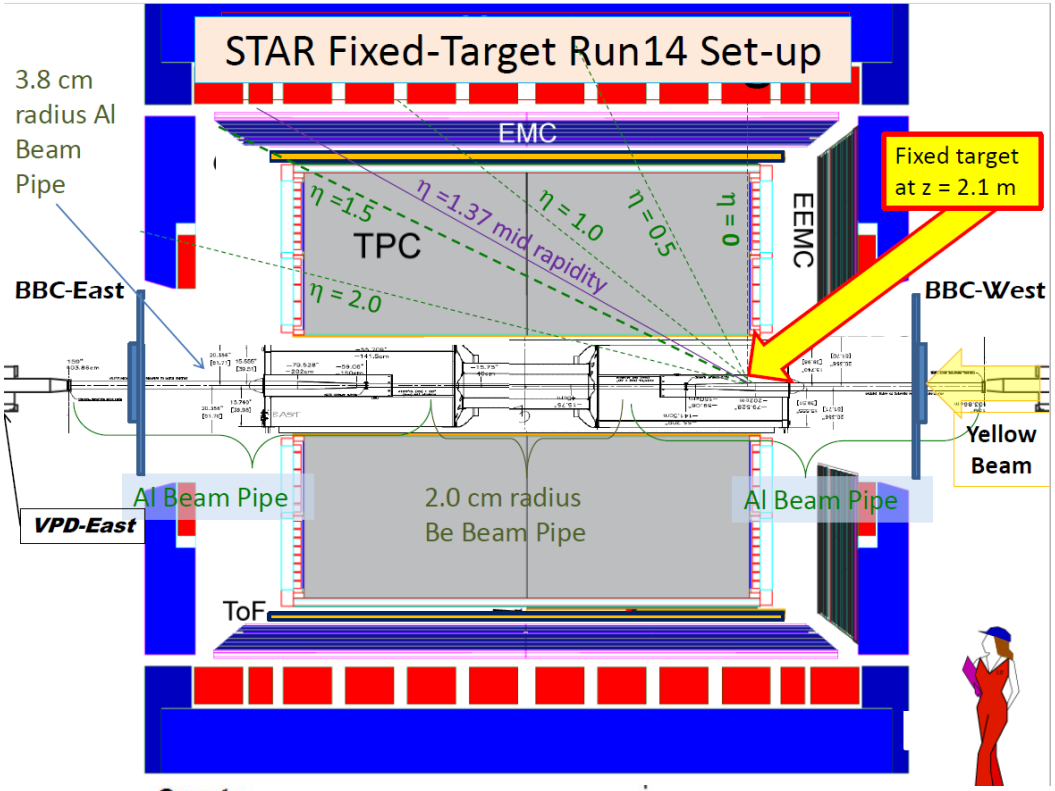


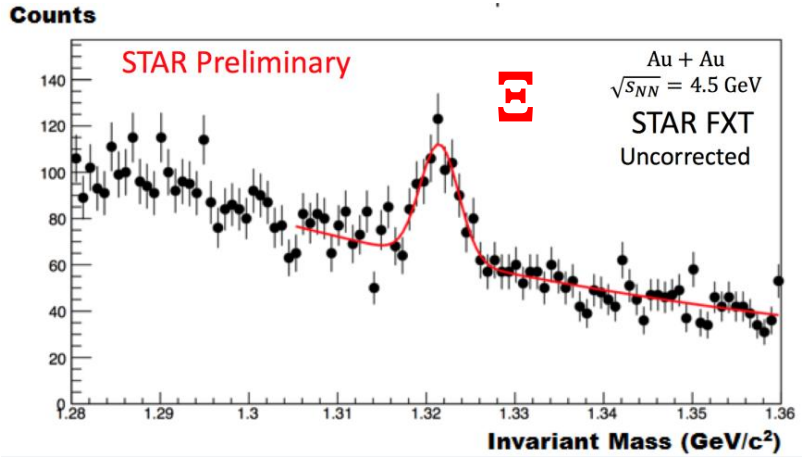
- Significant improvement of efficiency especially for Ξ, Ω

H. Masui, A. Schmah / LBNL

Fixed Target Program with STAR







- Extend energy reach to overlap/complementary AGS/FAIR/JPARC
- Real collisions taken in run 14 and results (K. Meehan @ QM15 & WWND16)
- Upgrades (iTPC+eTOF+EPD) crucial
- Unprecedented coverage and PID for Critical Point search in BES-II
- Spectra, flow, fluctuations and correlations

Summary

- STAR has measured systematically the production of various strange hadrons in $\sqrt{s_{NN}}$ = 7.7 - 200 GeV and in different collision systems
- Chemical freeze-out parameters μ_S/T, μ_B/T were extracted with anti-baryon to baryon ratios ($\bar{\Omega}^+/\Omega^-$, $\bar{\Xi}^+/\Xi^-$, $\bar{\Lambda}/\Lambda$)
- Intermediate p_T Ω/ϕ ratios, nuclear modification factors, $\bar{\Lambda}/K_S$, show clear separation between 200 ─ 19.6 GeV and below 11.5 GeV, indication of possible onset of deconfinement below 19.6 GeV.
- High statistics Ω R_{AA} (0-5%) and R_{UU}/R_{AuAu} (0-10%) measurements at top RHIC energies shows that Ω formation is dominated by strange quark coalescence up to p_T ~ 6 GeV/c
- Future RHIC BES-II with STAR detector upgrade (iTPC, eTOF, EPD) will allow precise measurements of QCD phase transition.