Beam energy dependence of strangeness production

Xianglei Zhu (Tsinghua University)

QCD phase structure III,
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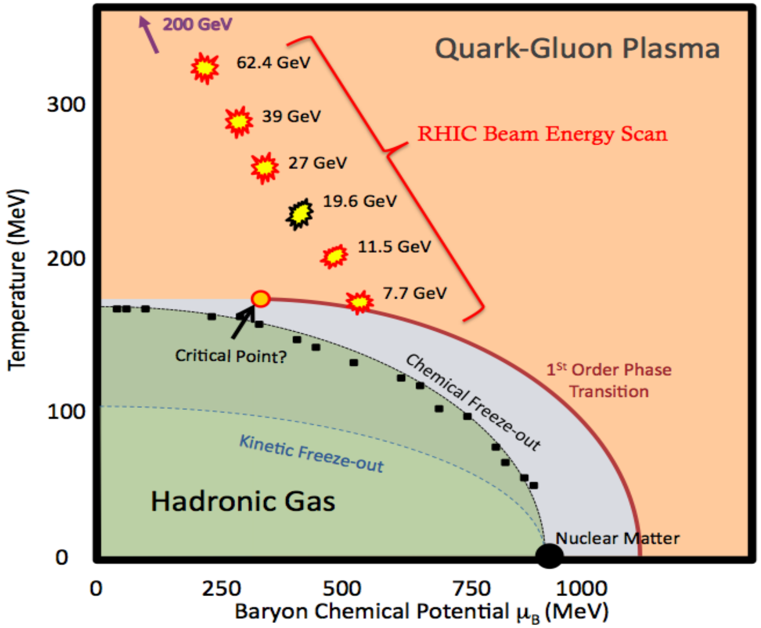
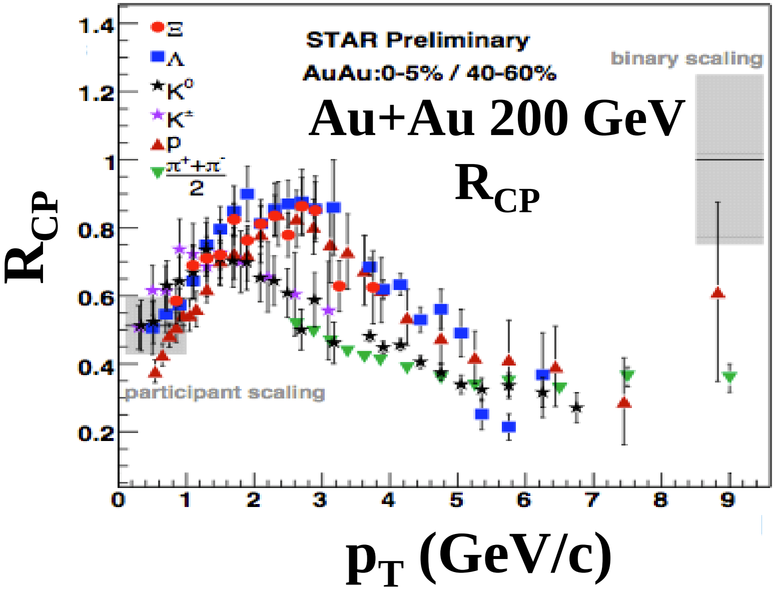
Outline

- 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

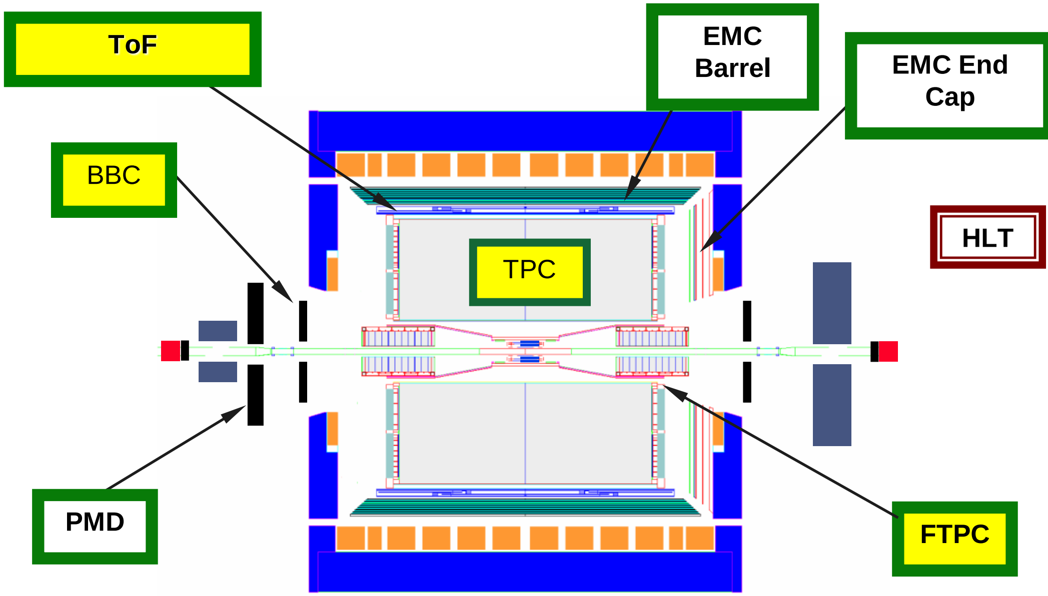


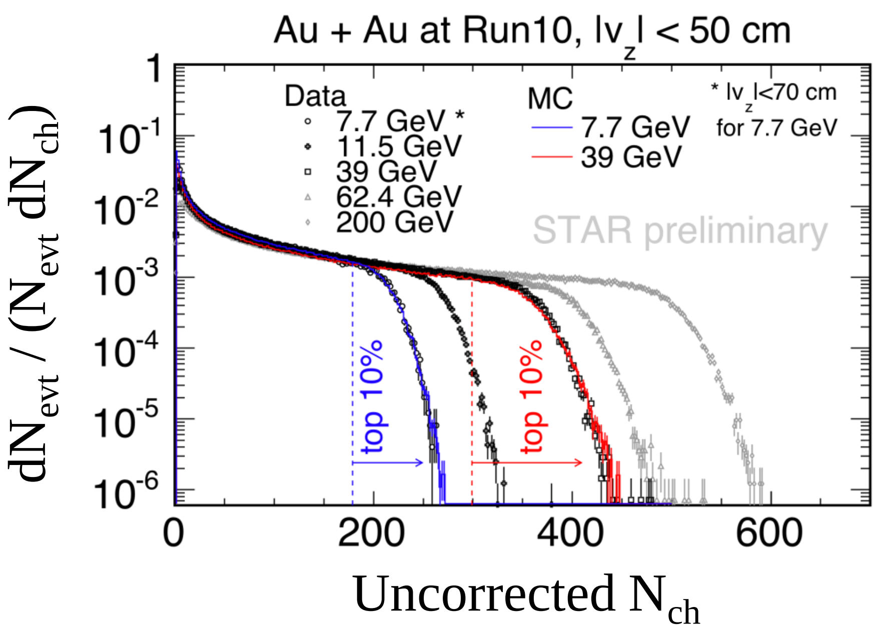


- **Beam Energy Scan at RHIC**
  Look for **onset of de-confinement, phase boundary** and critical point
  Au+Au collisions at 7.7, 11.5, 19.6, 27, 39, 62.4 GeV
- U+U collisions at 193 GeV
  System energy density dependence
- Key observables
  (1) Strangeness enhancement
  (2) Baryon/meson ratio
  Parton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

STAR, arXiv:1007.2613; NA49, PRC78, 034918

Detector settings

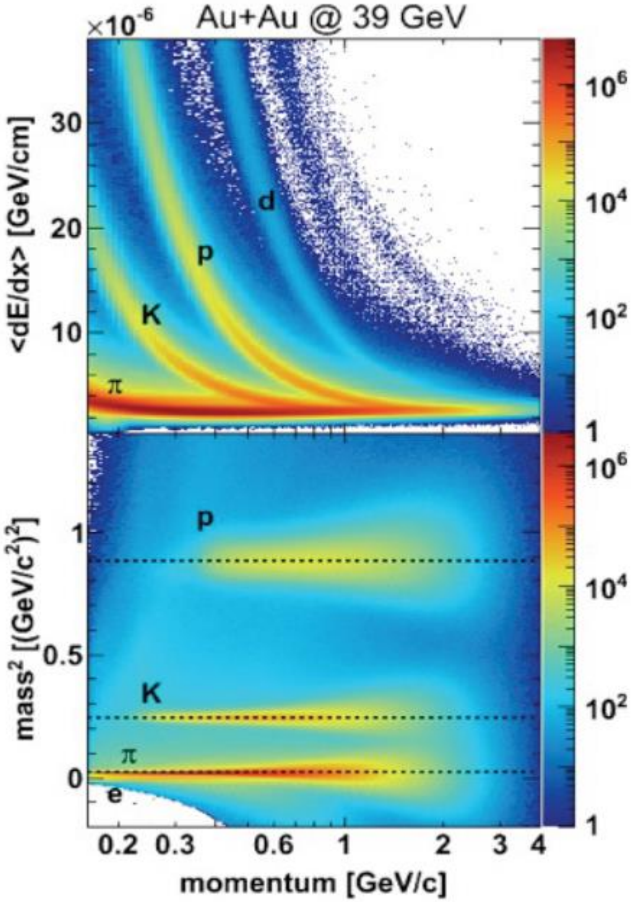


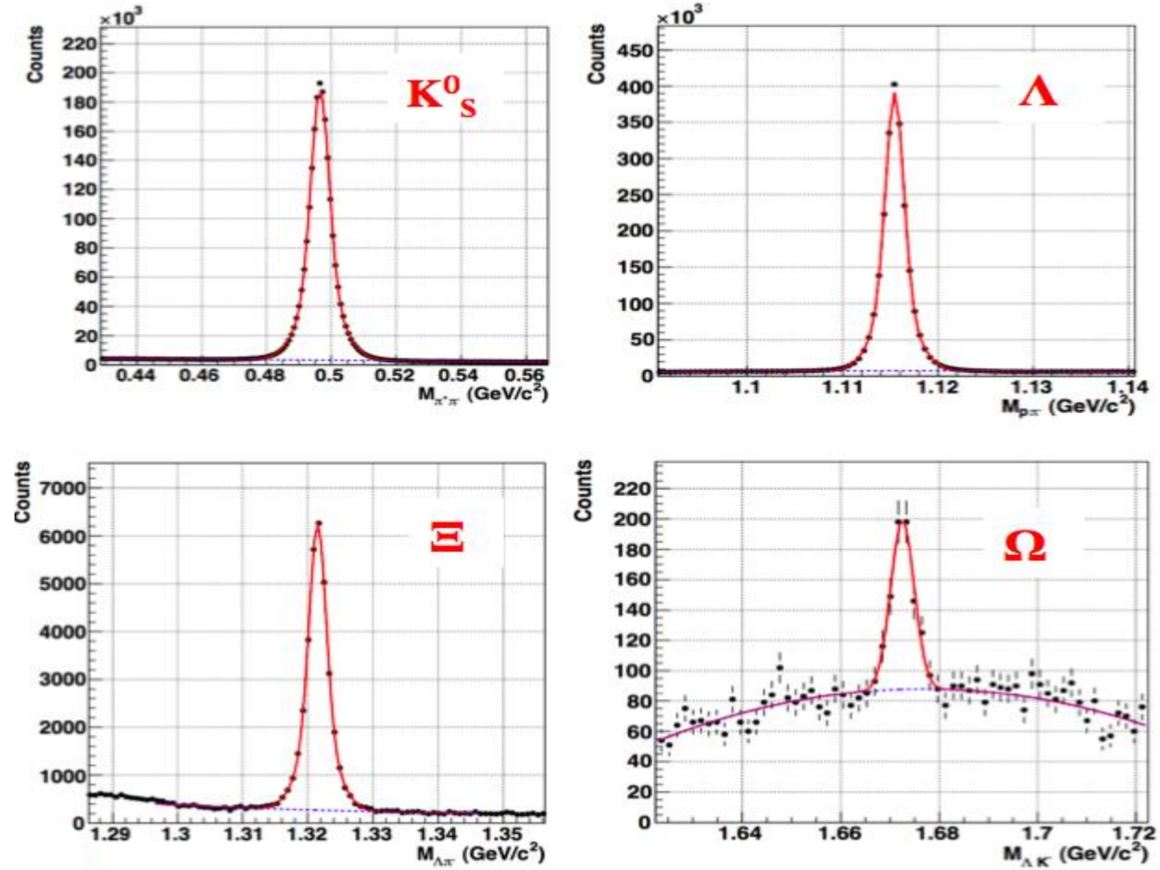


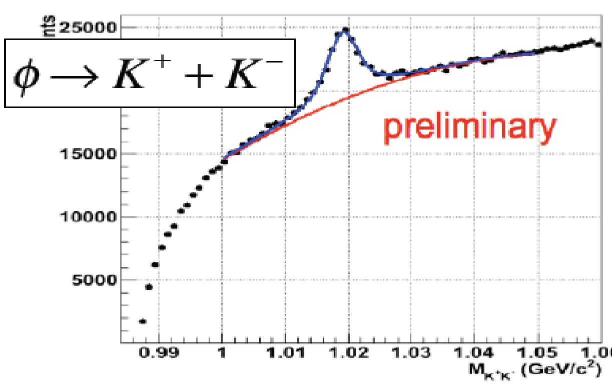
- Collisions centrality from uncorrected $dN_{ch}/d\eta$ in $|\eta| < 0.5$

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

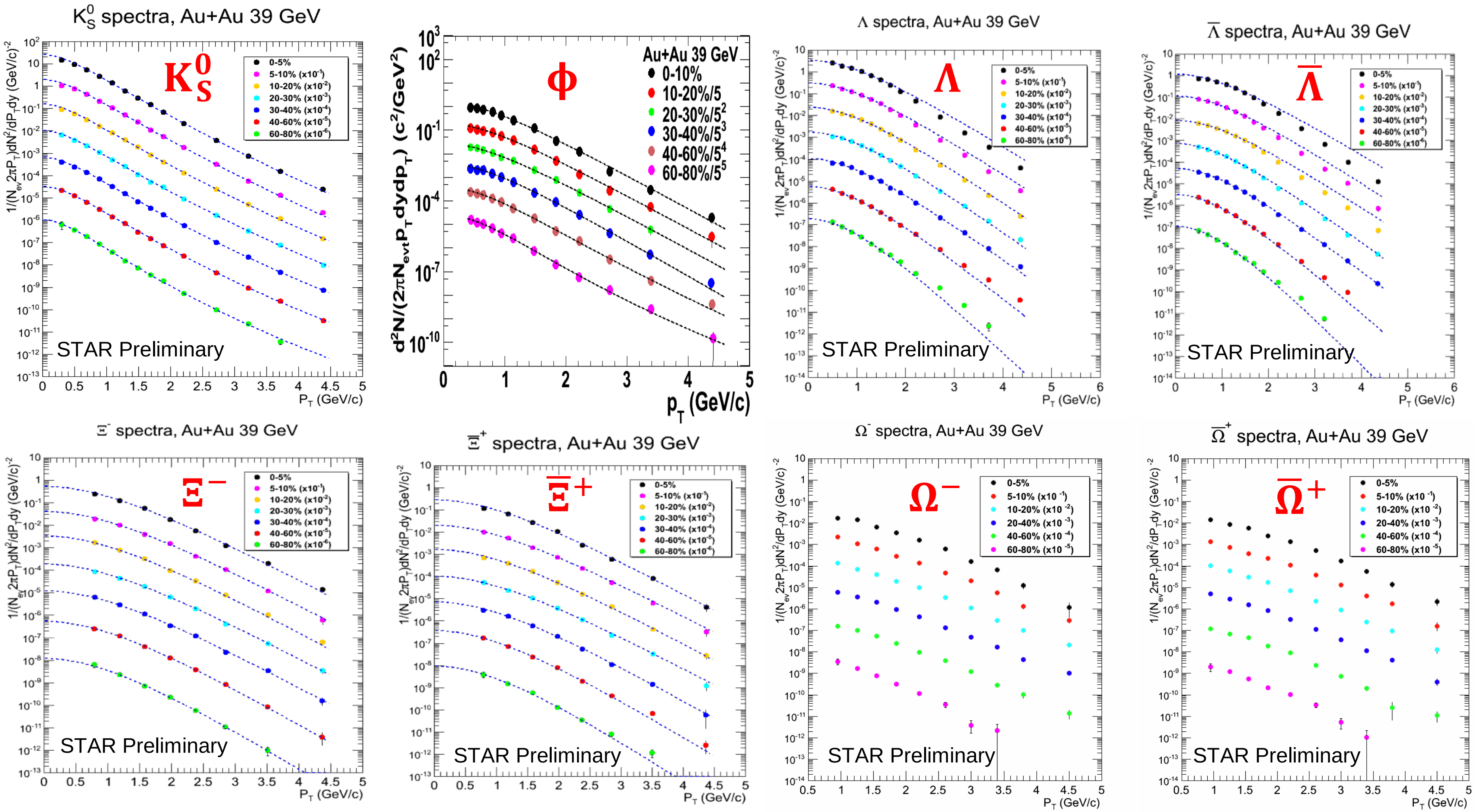






- dE/dx+TOF: π, K, p and $\phi \rightarrow K^+ + K^-$ (invariant mass)
- Weak decay particles (K^0_S, Λ, Ξ, Ω), secondary vertex + invariant mass

p_T spectra (39 GeV)



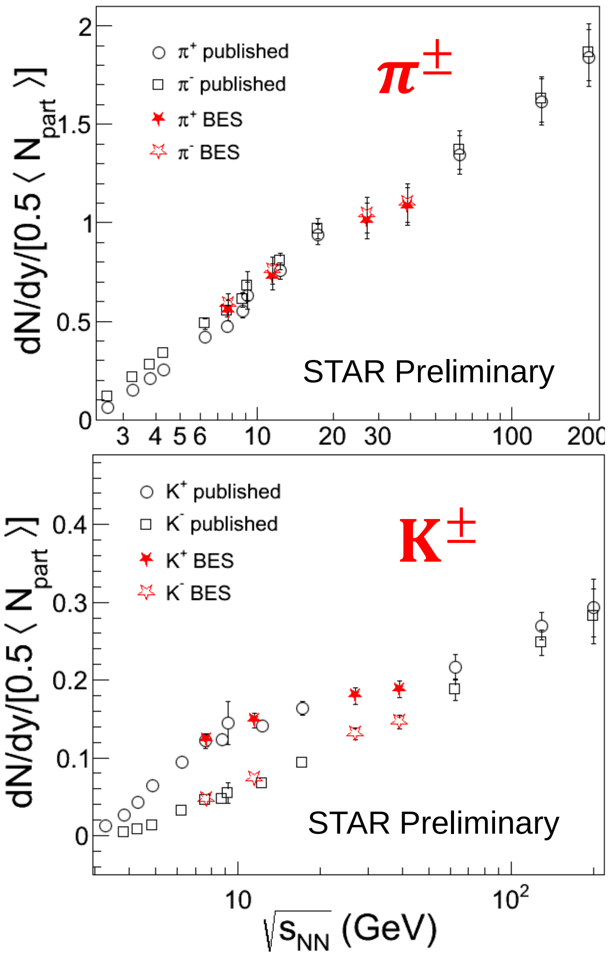
- Extensive strange particle spectra
- **$\Lambda(\bar{\Lambda})$ spectra are weak decay feed-down corrected**

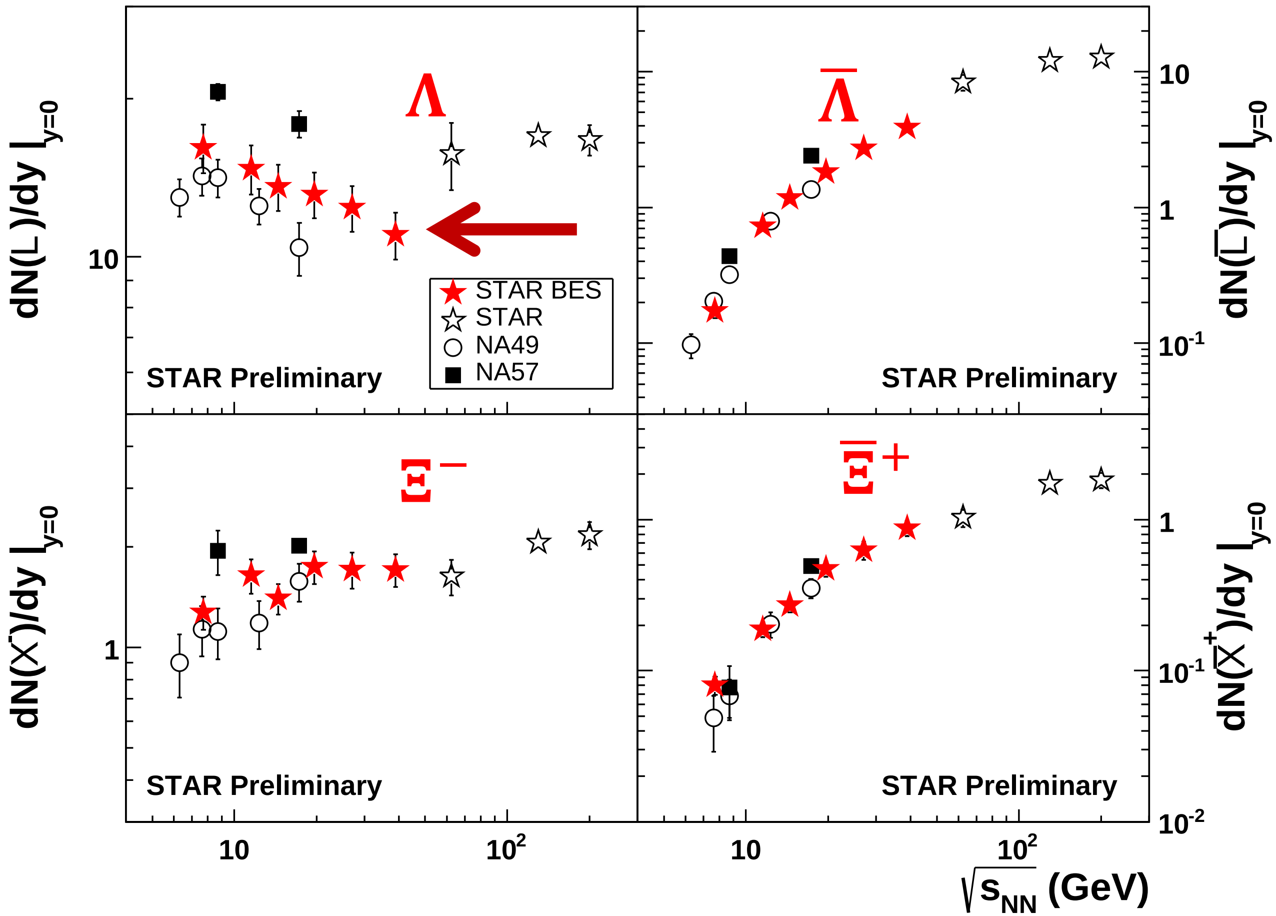
  ~ 20% for Λ; ~ 25% for $\bar{\Lambda}$

Statistical error

Particle yields

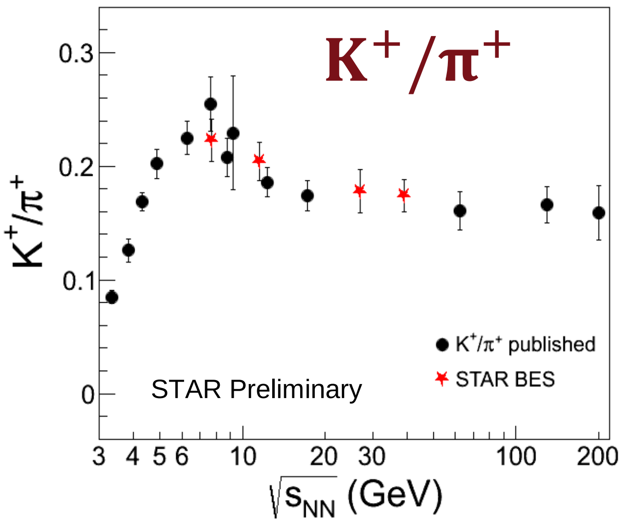
mid-rapidity, most central collisions (0-5%)

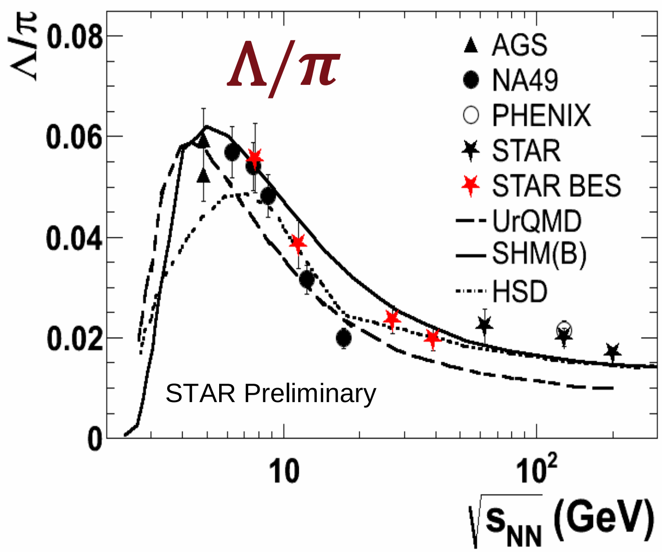


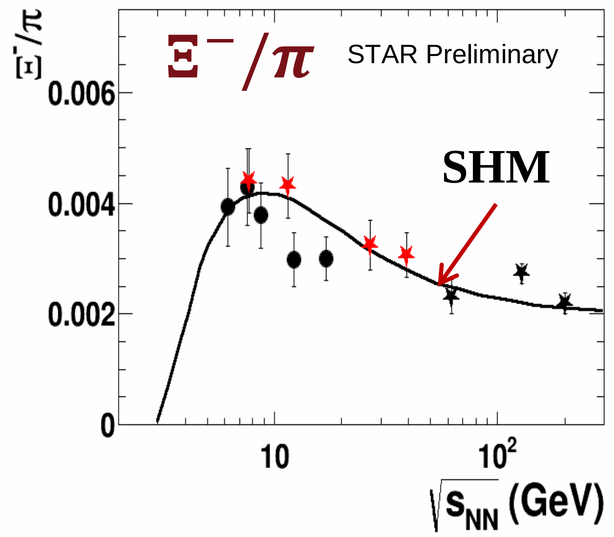


- STAR results are consistent with published data in general
- Λ yields seem to show dip around $\sqrt{s_{NN}}$ = 39 GeV. **The baryon stopping at mid-rapidity decreases with increasing energy**

Particle ratios

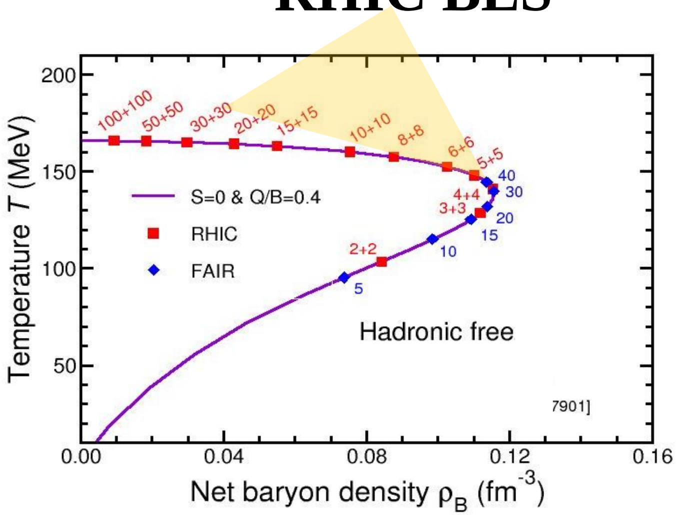






RHIC BES

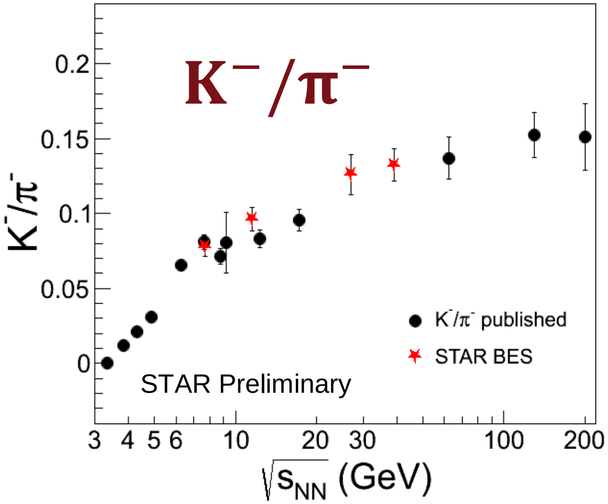
most central (0-5%), mid-rapidity, stat. + sys. error

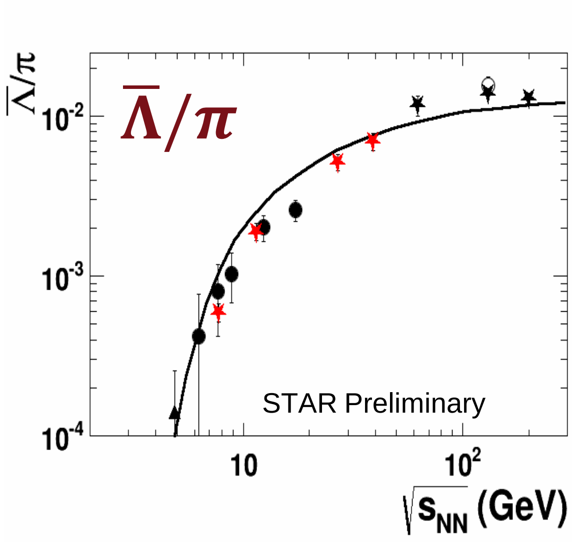


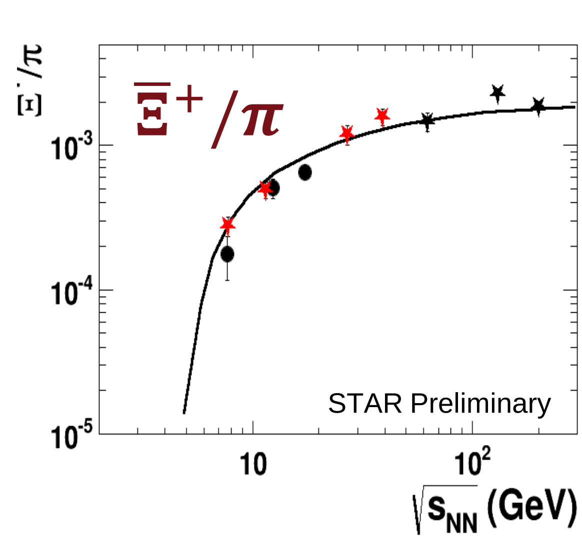
J. Randrup et al., PRC 74, 047901 (2006)

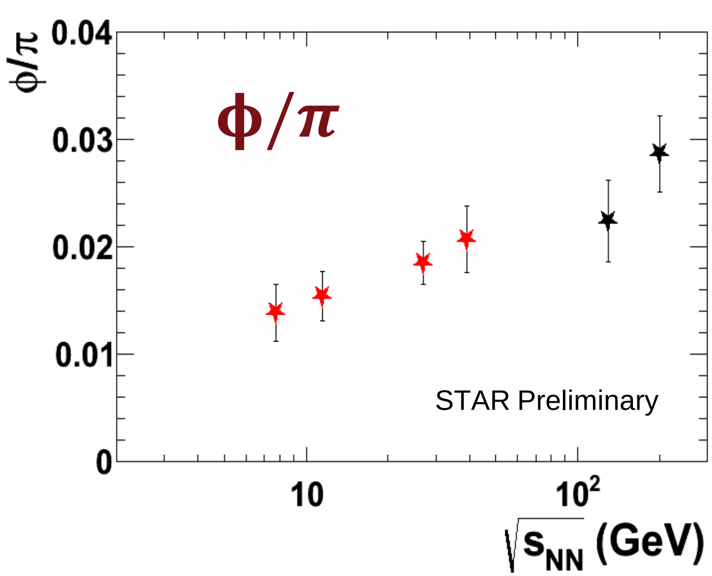
- Particle ratios consistent with NA49, consistent with the picture of a **maximum net-baryon density around $\sqrt{s_{NN}} \sim 8$ GeV at freeze-out**
- Associate production channels like $N + N \rightarrow N + \Lambda + K^+$ may be important for K^+ production, N is nucleon

Particle ratios







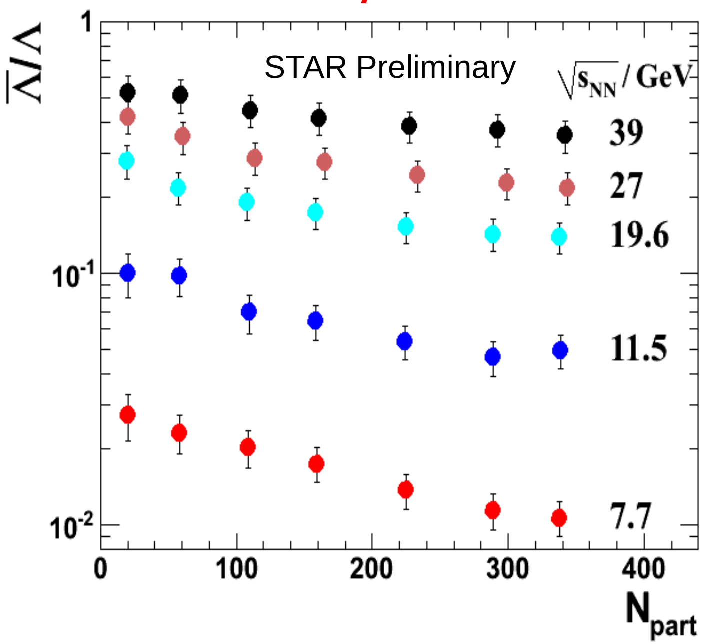


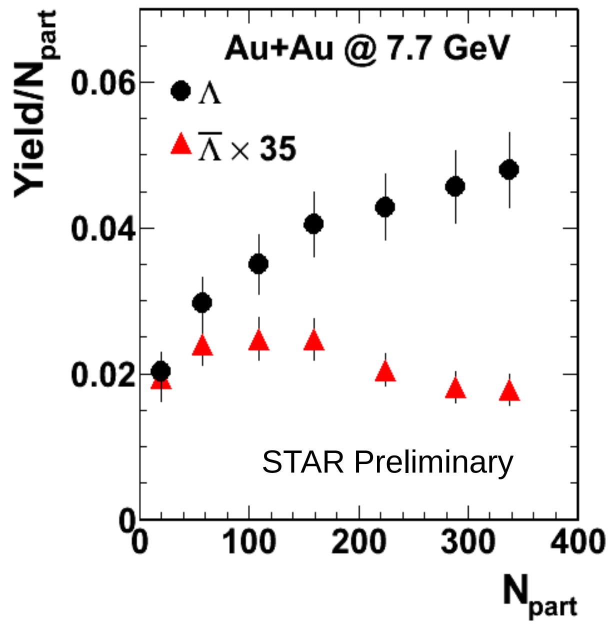
most central (0-5%)*, mid-rapidity, stat. + sys. error*

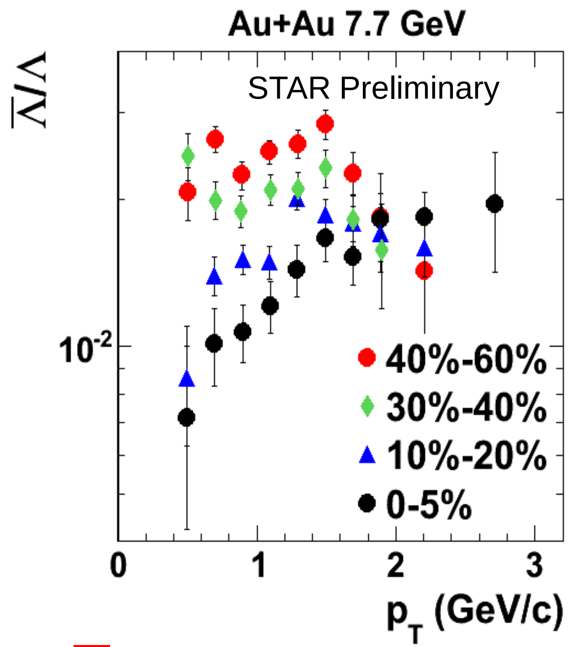
- Clear K^-, $\bar{\Lambda}$, $\bar{\Xi}^+$ yield enhancement compared to pions with increasing collision energy
- Similar behavior for hidden strangeness $\phi(s\bar{s})$

$\bar{B}/B$ ratios

$\bar{\Lambda}/\Lambda$

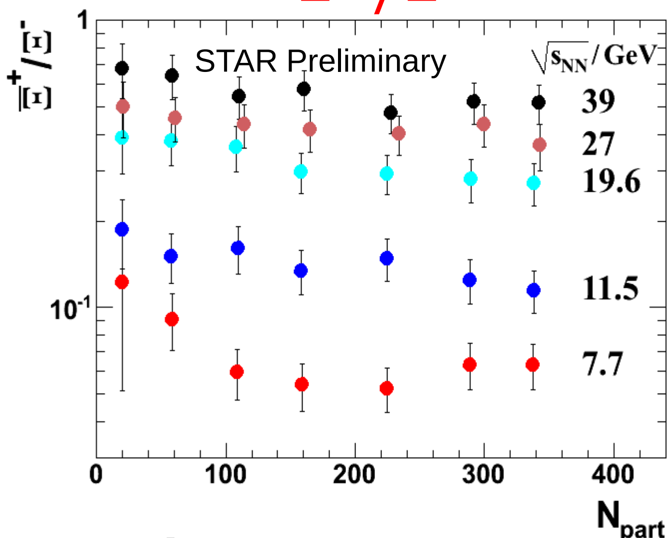






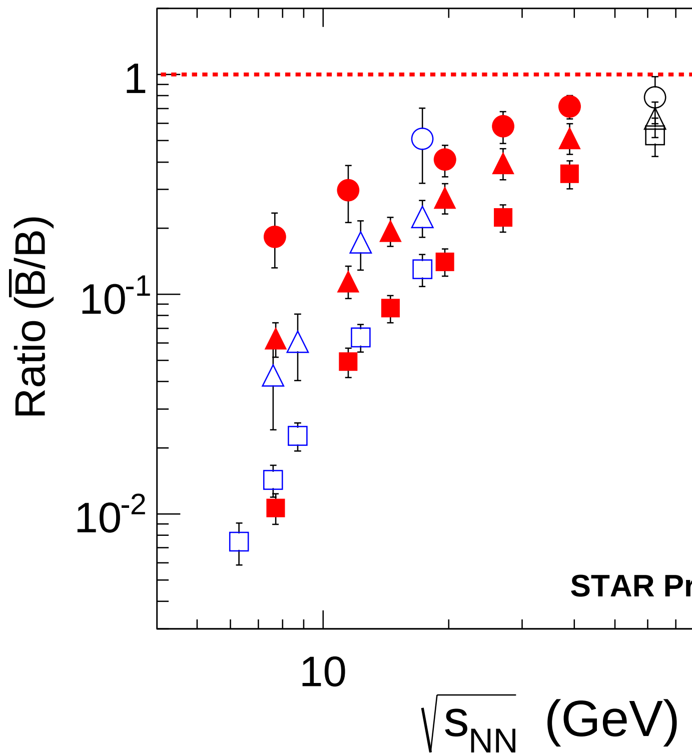
- Centrality dependence of $\bar{B}/B$ ratios: **peripheral > central**
- This effect is more prominent at lower energies. **baryon stopping, anti-baryon absorption**
- **Loss of low p_T $\bar{\Lambda}$ in central collisions**

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



Statistical + systematical error

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

Anti-baryon to baryon ratio

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

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

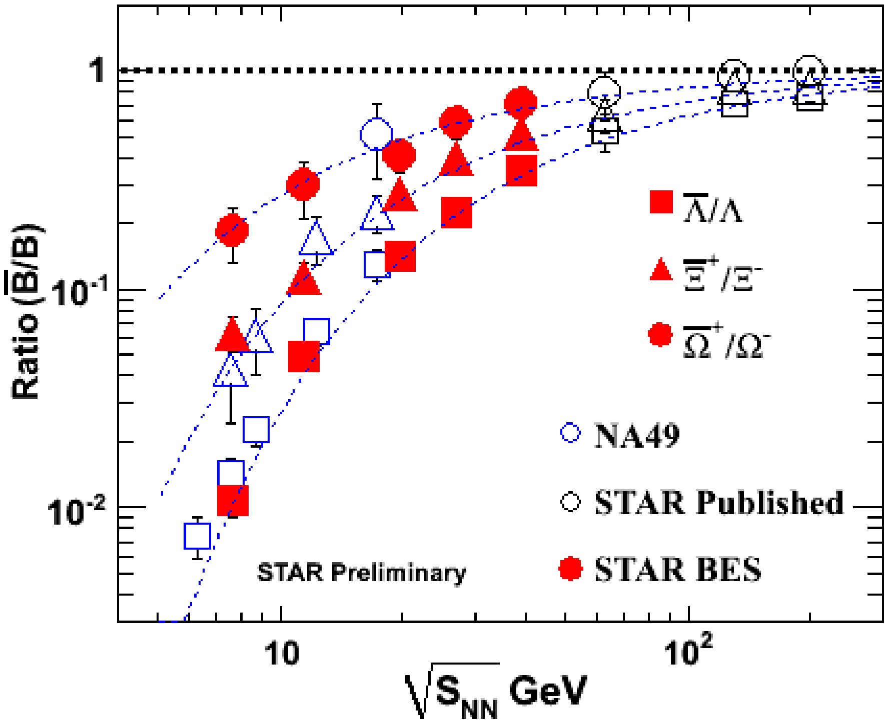
$$\frac{\overline{\Xi}^+}{\Xi^-} = \exp(-\frac{2\mu_B}{T} + \frac{4\mu_S}{T}) \quad \Rightarrow \quad \ln(\frac{\overline{\Xi}^+}{\Xi^-}) = -\frac{2\mu_B}{T} + \frac{4\mu_S}{T}$$

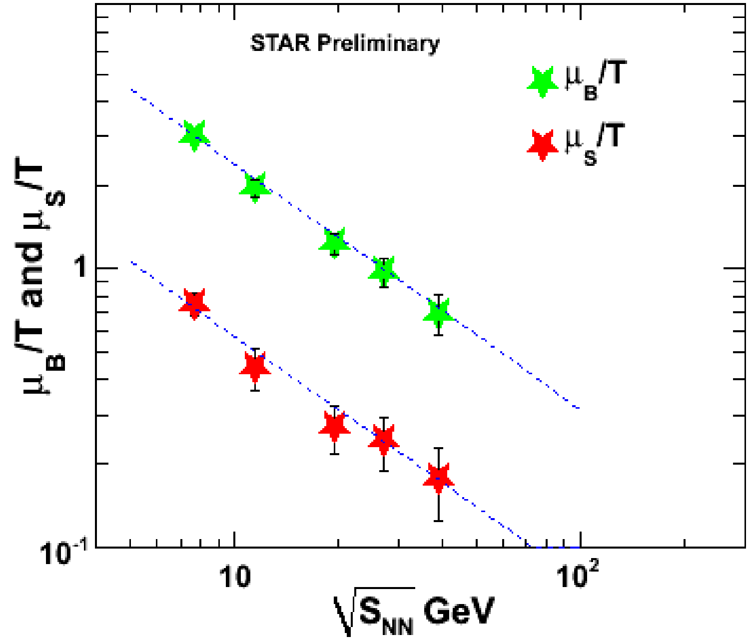
$$\frac{\overline{\Omega}^+}{\Omega^-} = \exp(-\frac{2\mu_B}{T} + \frac{6\mu_S}{T}) \quad \Rightarrow \quad \ln(\frac{\overline{\Omega}^+}{\Omega^-}) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T}$$

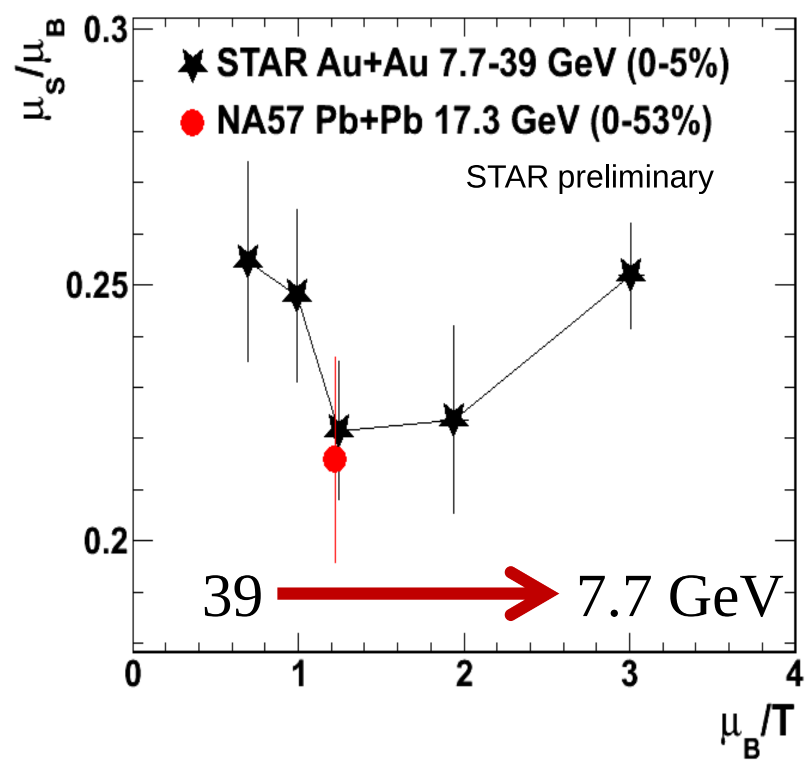
- T is the temperature.
- μ_B is the baryon chemical potential.
- μ_S is the strangeness chemical potential.

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

μ_B and μ_s correlation







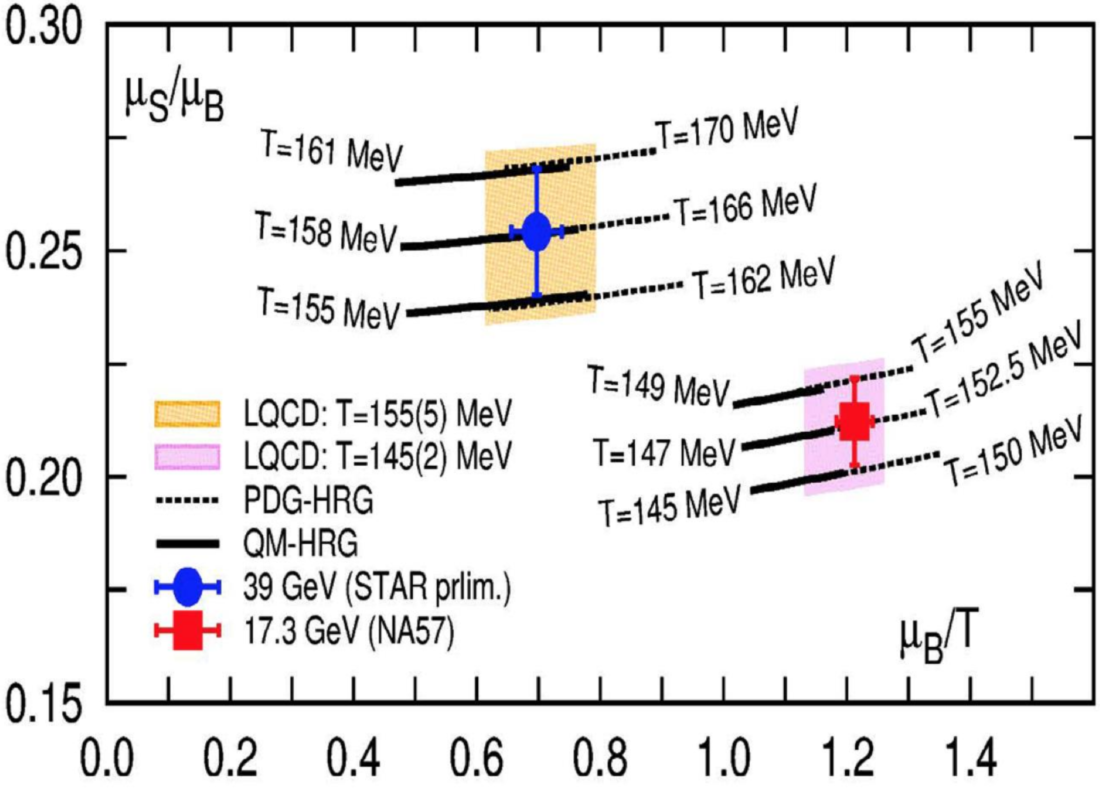
- Anti-baryon to baryon ratios are consistent with statistical thermal model
- **μ_s/μ_B seems to be smaller in 11.5 - 19.6 GeV than in 39 and 7.7 GeV**

Strangeness, LQCD and freeze-out in HIC

From Swagato Mukherjee

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

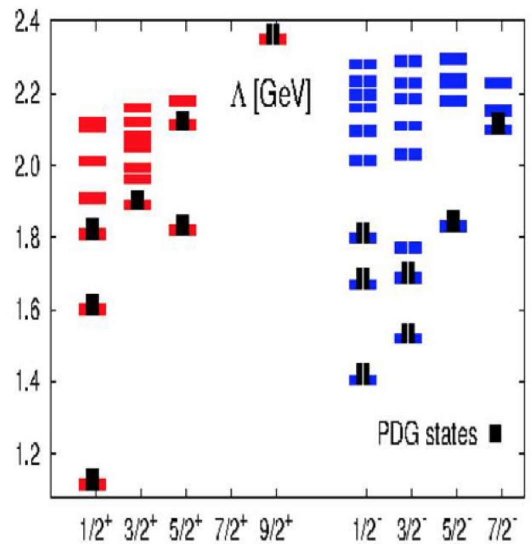
BNL-Bi-CCNU: Phys. Rev. Lett. 113 (2014) 072001



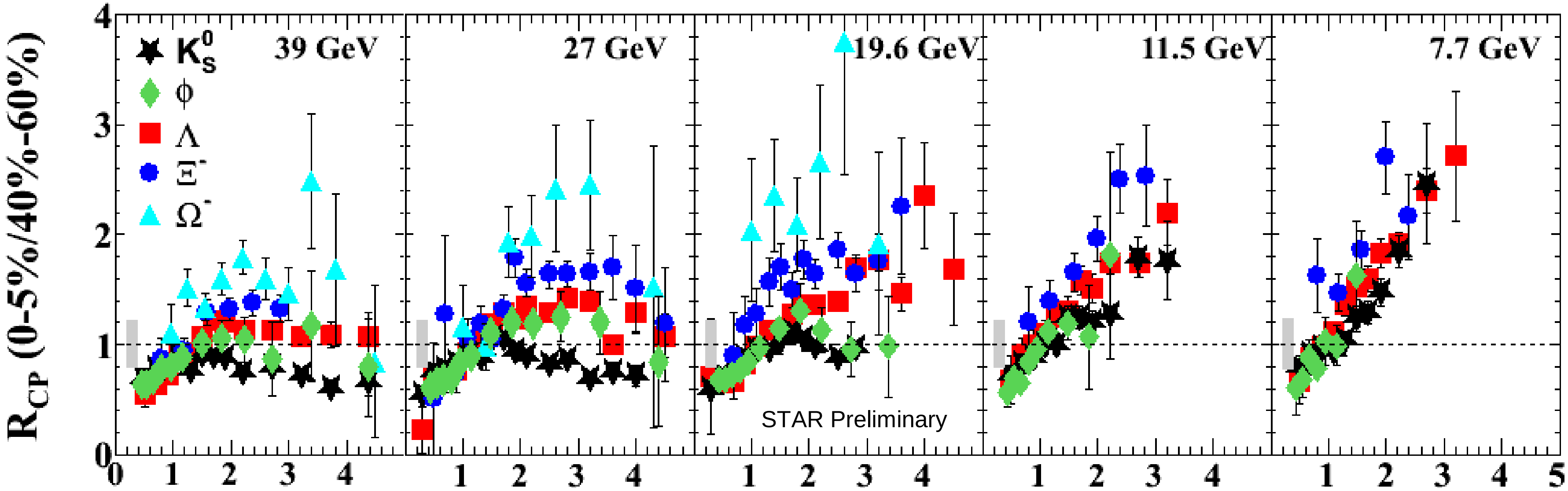
indirect evidence for so-far undiscovered strange baryons at RHIC ?

not reproduced by hadron gas with only PDG states

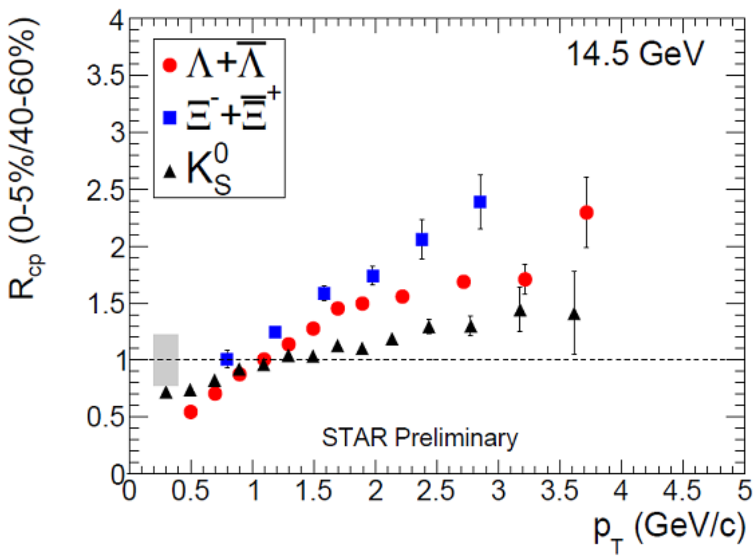
reproduced when additional Quark Model (QM) predicted strange baryons are taken into account



Nuclear modification factors R_{CP}



φ meson R_{CP}: 0-10%/40%-60%

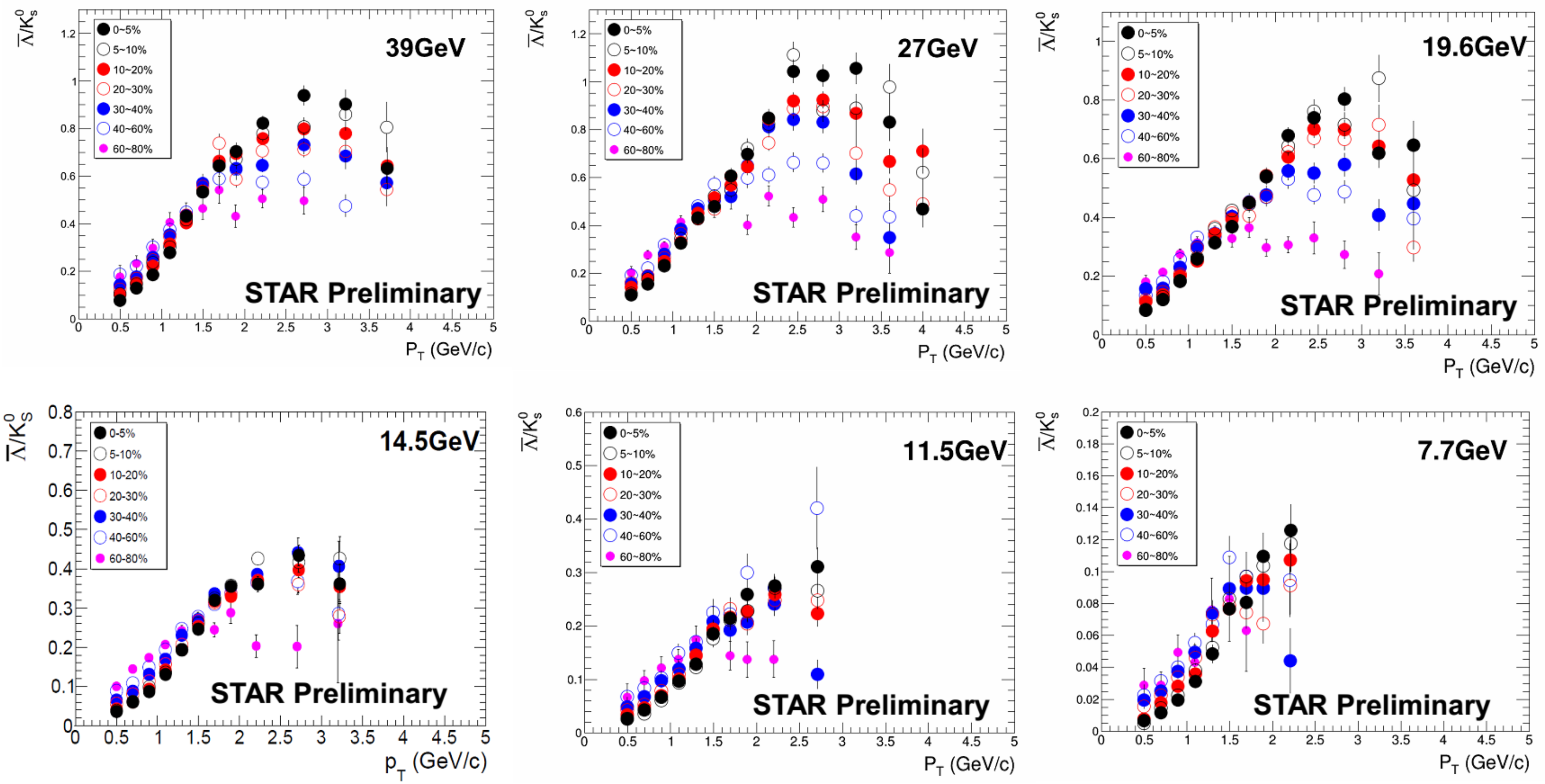


$$R_{CP}(p_T) = \frac{[d^2\sigma/(N_{\mathrm{bin}} p_T dp_T dy)]_{\mathrm{central}}}{[d^2\sigma/(N_{\mathrm{bin}} p_T dp_T dy)]_{\mathrm{peripheral}}}$$

- 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**

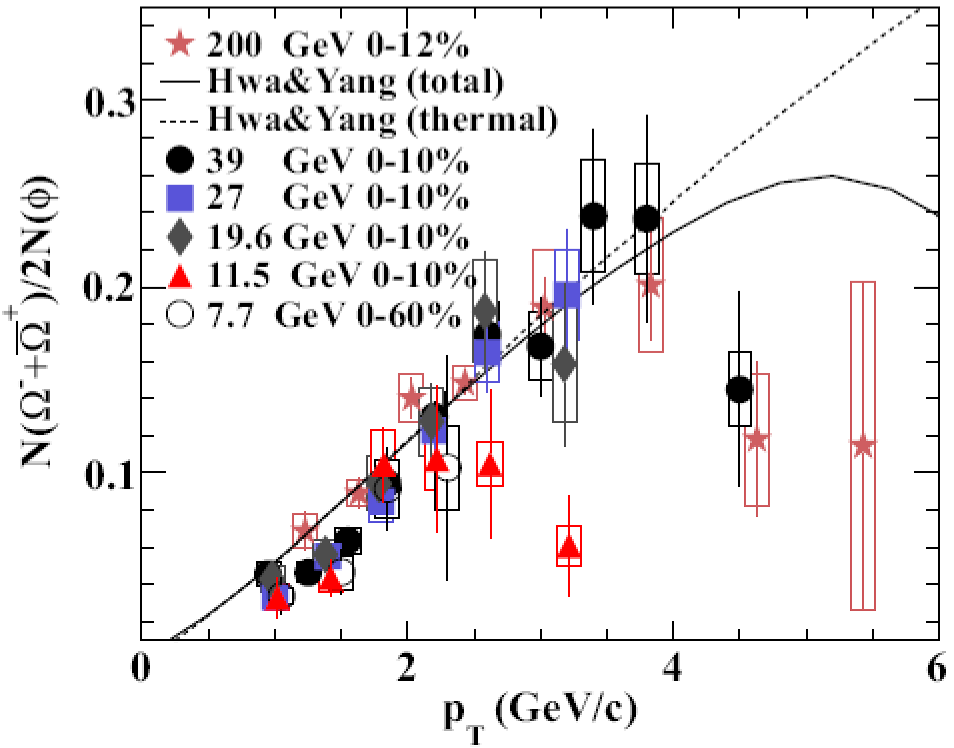
$\overline{\Lambda}$ / K^0_S ratio

statistical error only

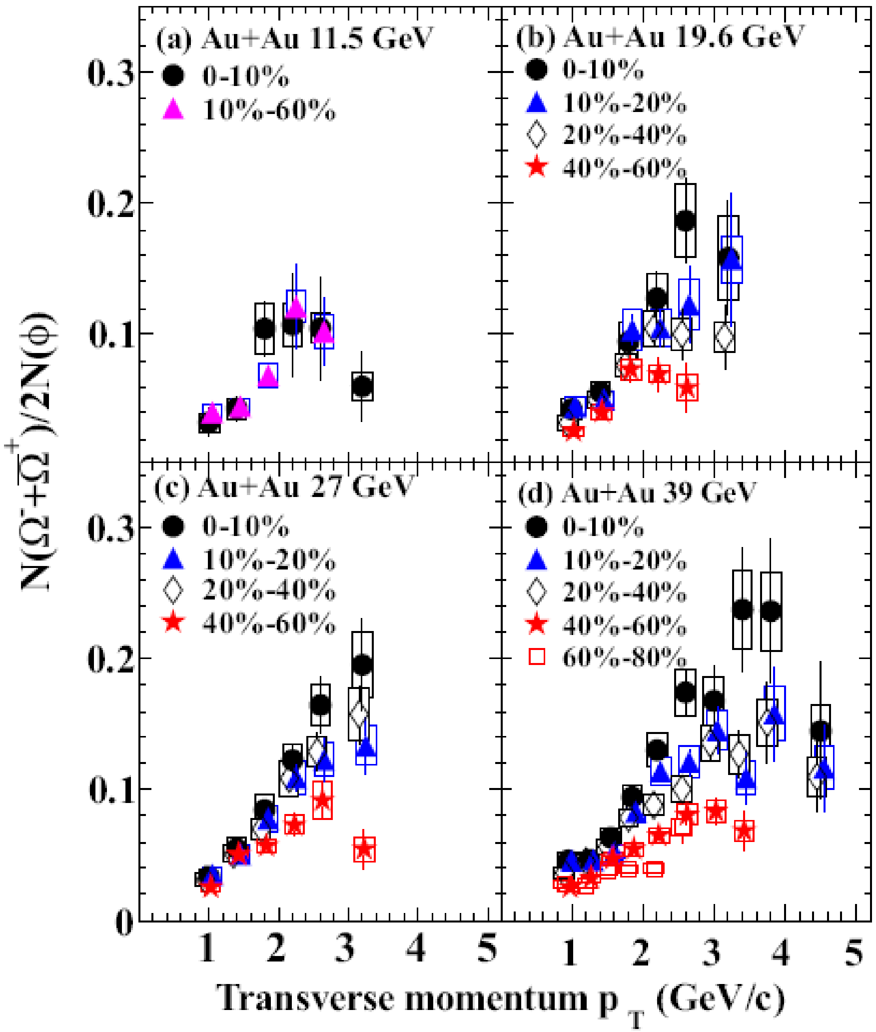


$\sqrt{s_{NN}}$ **≤ 14.5 GeV**, at p_T ~ 2GeV/c, the separation of central (0-5%) and peripheral (40-60%) collisions in $\overline{L}$ /K^0_S becomes less obvious

Ω / ϕ ratio



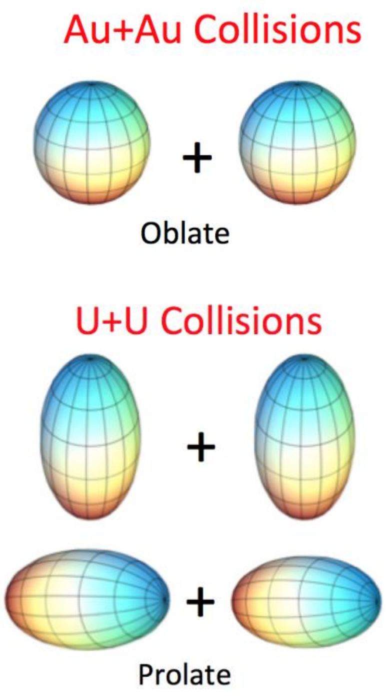
Phys. Rev. C 93, 2016, 021903 (R)

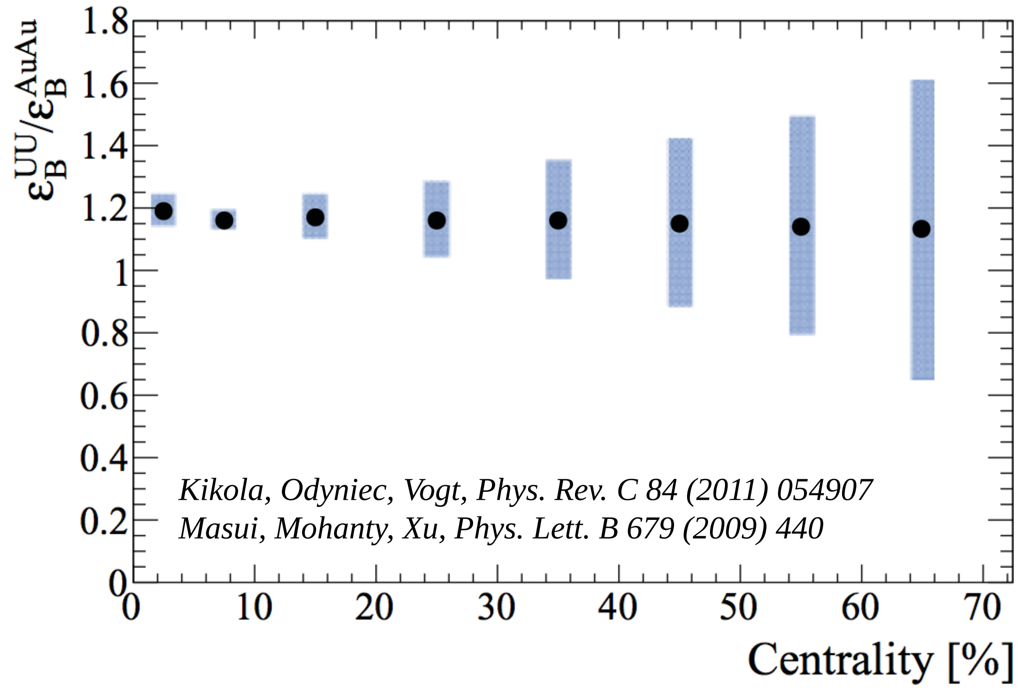


- Intermediate p_T Ω/ϕ ratios:
  Indication of separation between ≥ 19.6 and 11.5 GeV
- Ω/ϕ ratios: 40%-60% peripheral < 0-10% central for 19.6, 27 and 39 GeV

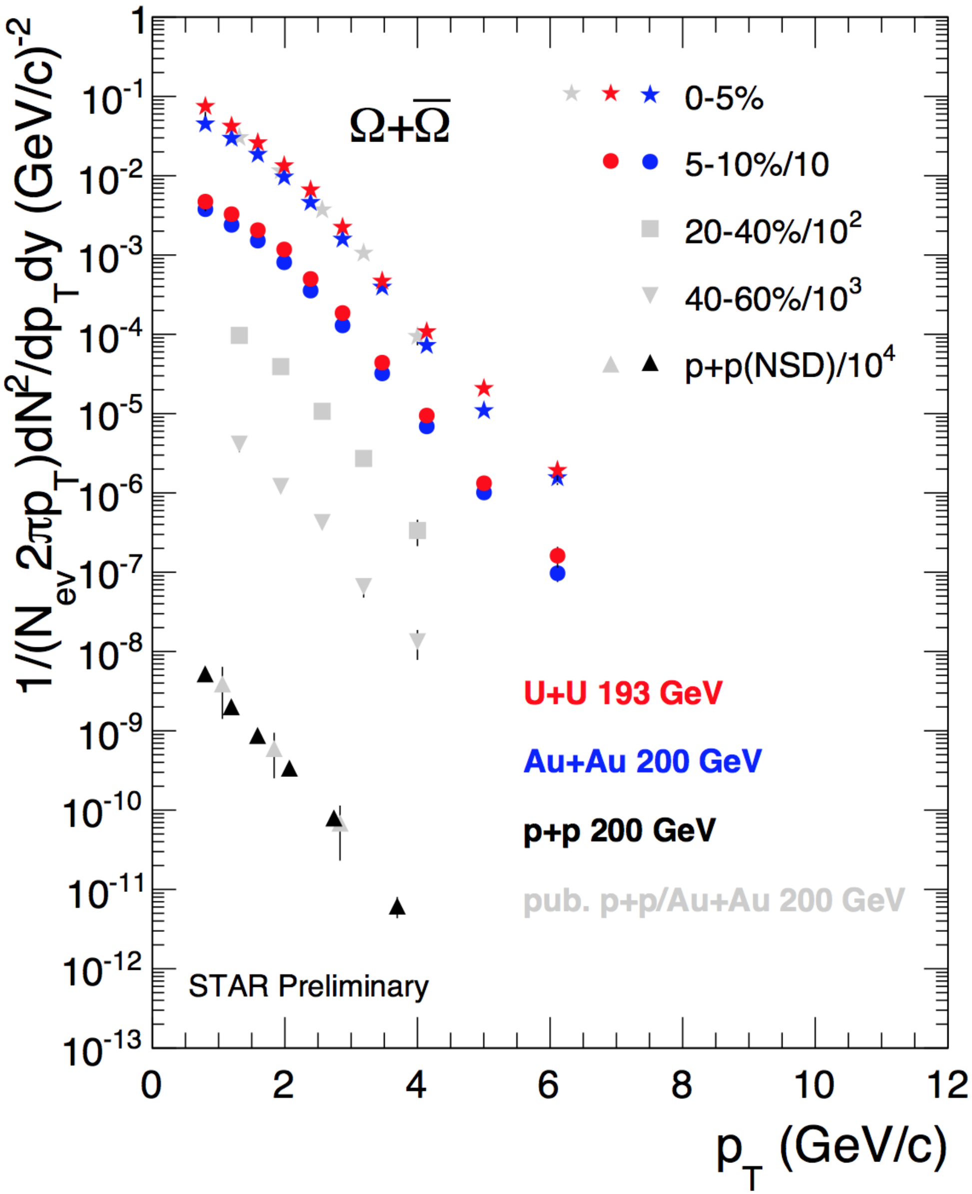
Ω in Au+Au vs in U+U at top RHIC energy

- 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?





p_T spectra



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

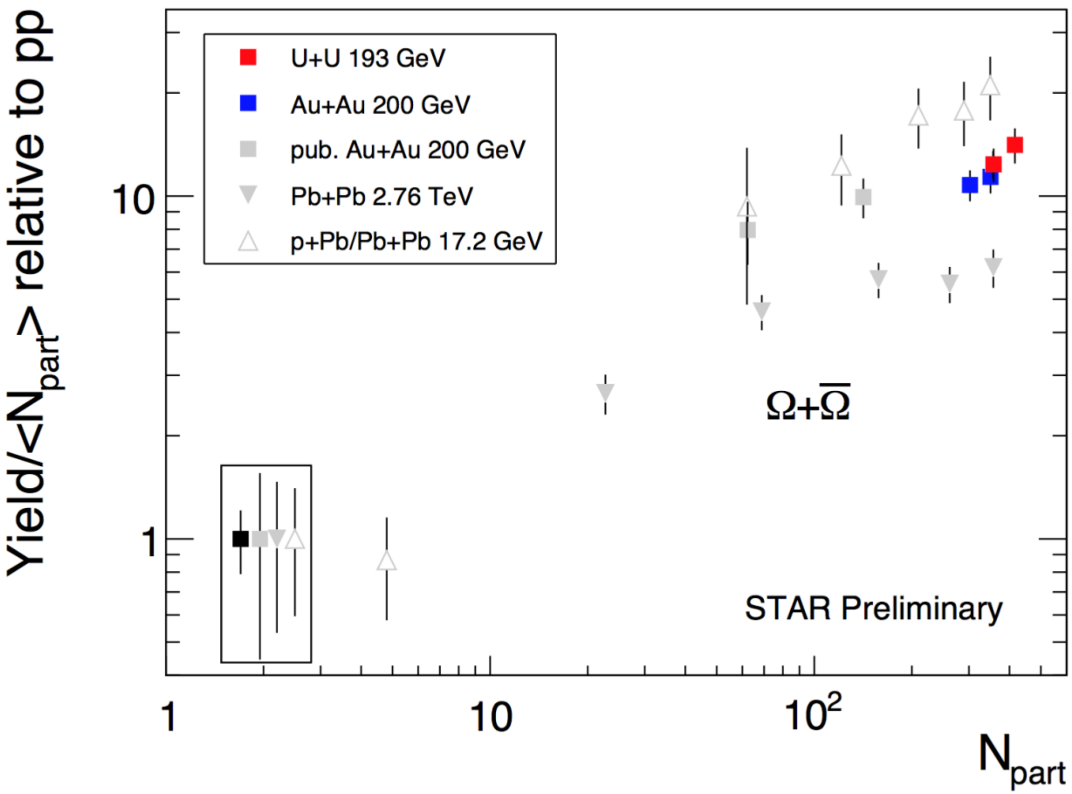
STAR, Phys. Rev. C 75 (2007) 064901

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

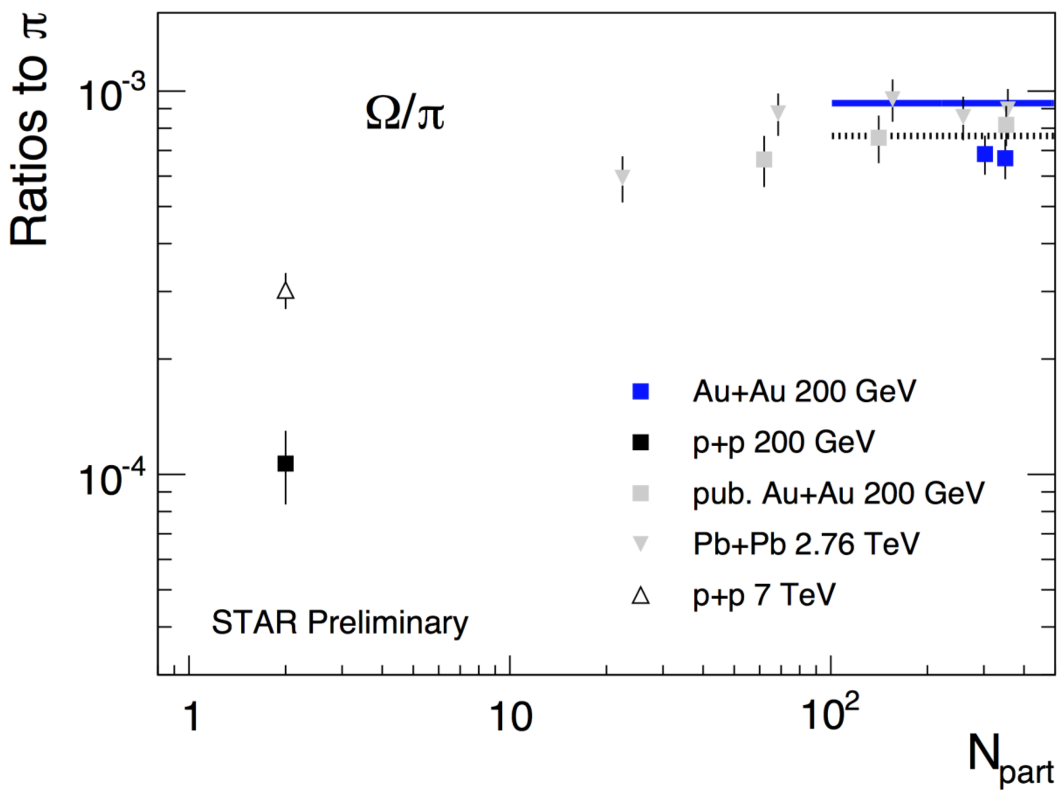
NA57, J. Phys. G 32 (2006) 427;

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



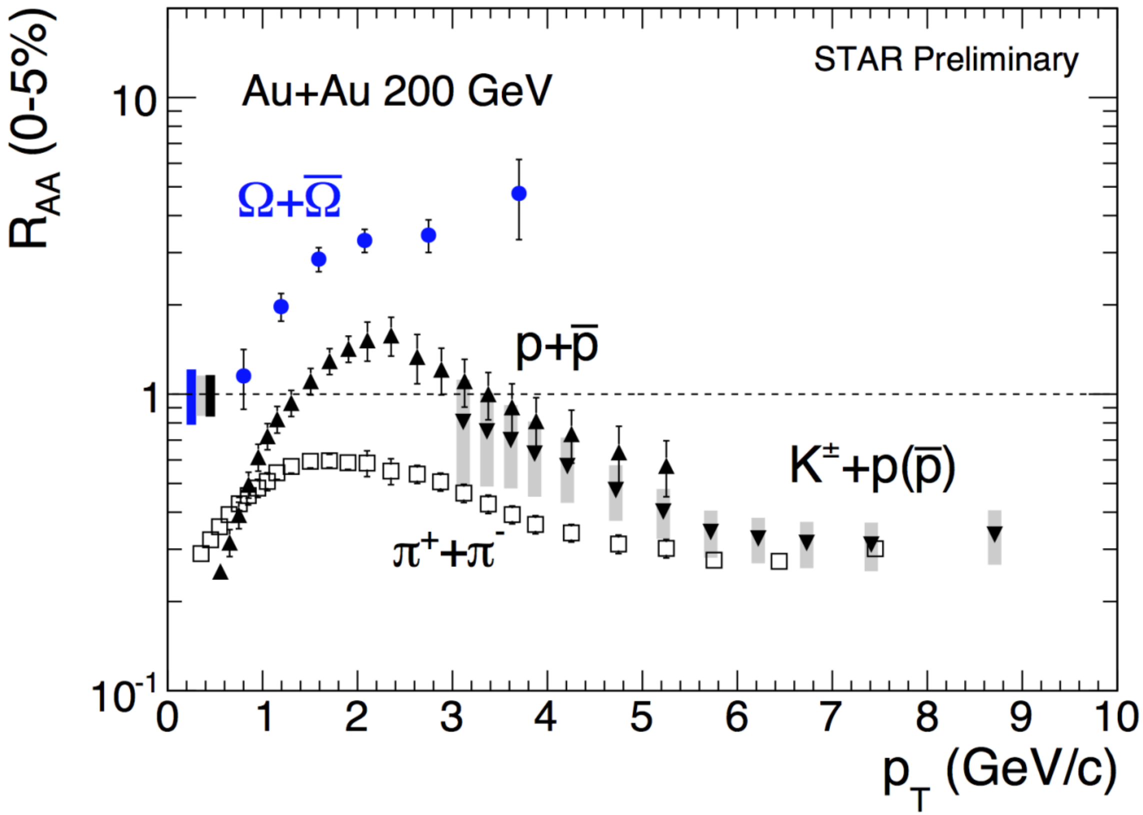
Thermal models:

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

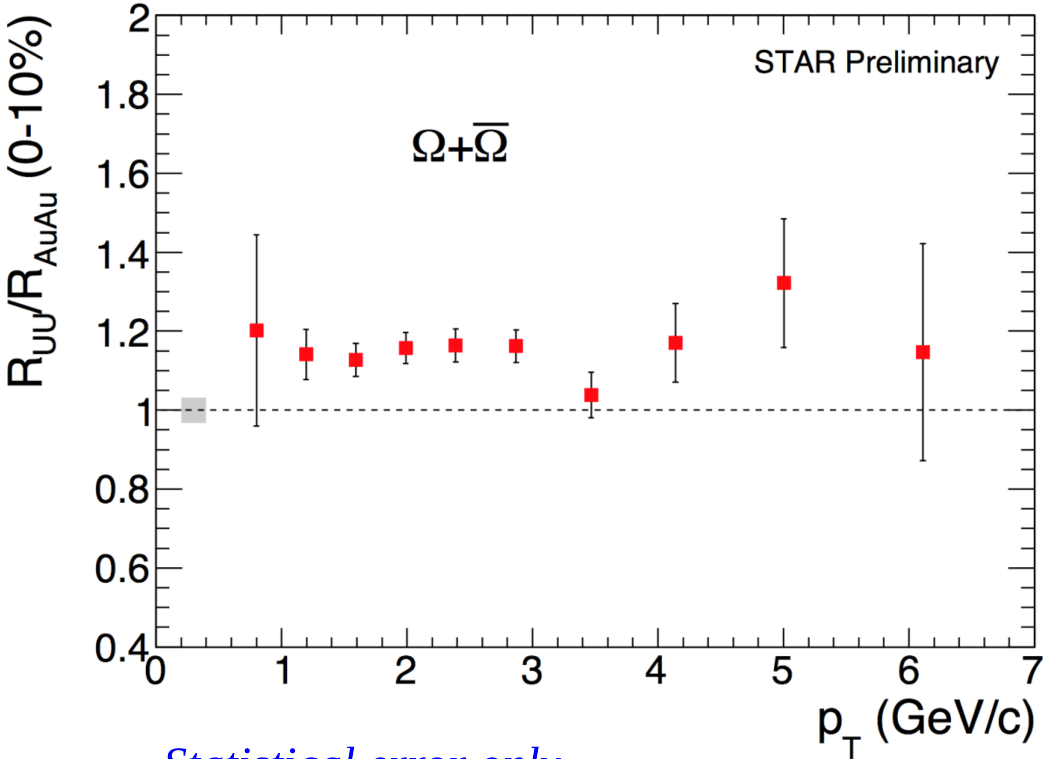
$K^{\pm} + p(\bar{p})$: *0-12%,*
STAR, Phys. Rev. Lett. 108 (2012) 072302

- 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 ± 4; N_{bin} = 941 ± 26

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

N_{part} = 387 ± 4; N_{bin} = 1151 ± 18

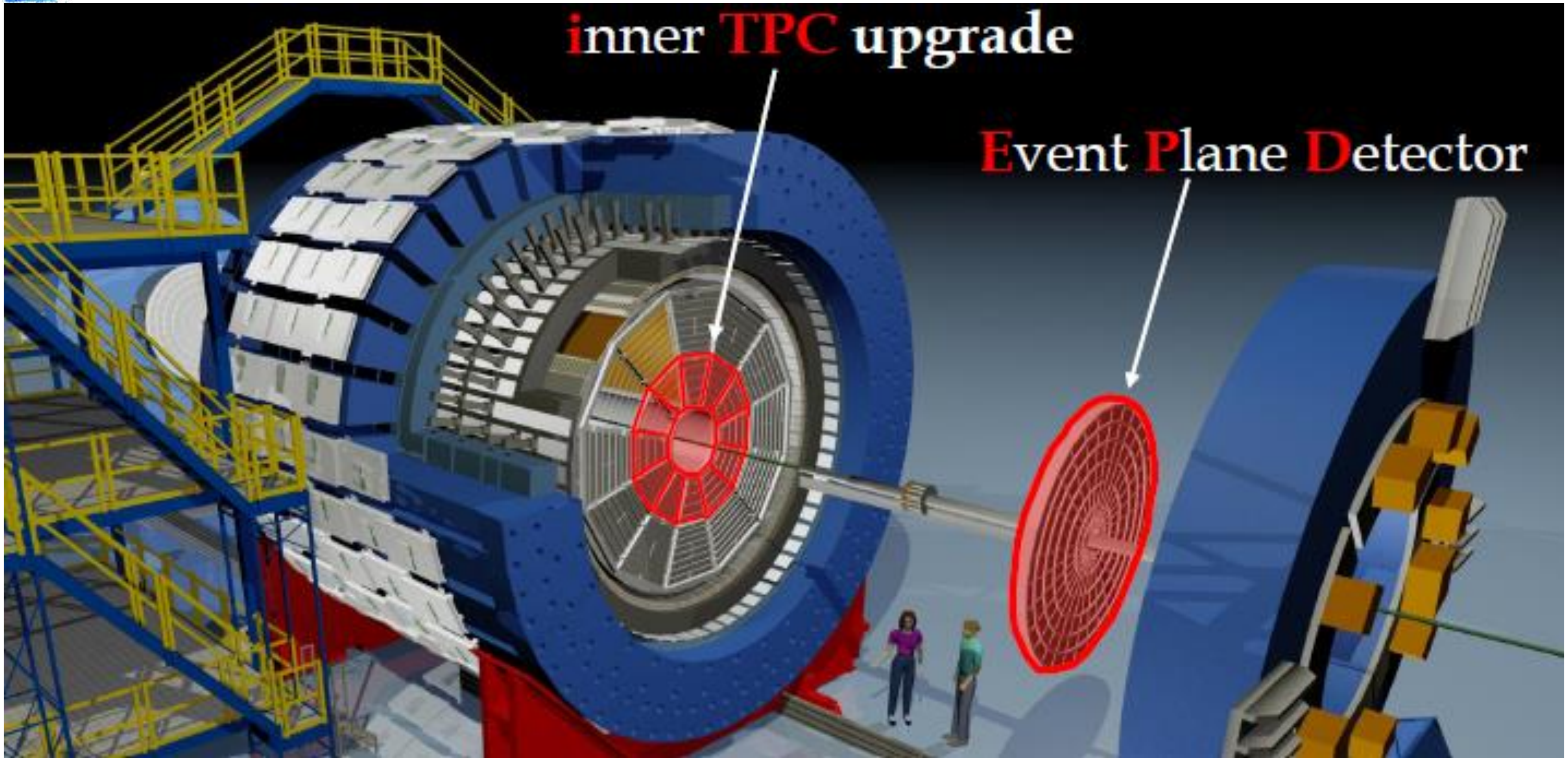
The energy density in central U+U is expected to be 20% higher, but N_{bin}-scaled high p_T Ω yield is not more suppressed

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

Summary

- STAR has measured systematically the production of various strange hadrons in $\sqrt{s_{NN}}$ = 7.7 - 200 GeV and in different collision systems
- Particle yields and ratios are consistent with the picture of a maximum net-baryon density around $\sqrt{s_{NN}}$ ~ 8 GeV at freeze-out, baryon transport to mid-rapidity is important
- Clear K^{-}, ϕ, $\bar{\Lambda}$, $\bar{\Xi}^{+}$ yield enhancement compared to pions with increasing collision energy
- Intermediate p_T Ω/ϕ ratios and nuclear modification factors show clear separation between 200 — 19.6 GeV and below 11.5 GeV, indication of **possible phase transition below 19.6 GeV**
- Ω R_{AA} (0-5%) is above 3 up to 4 GeV/c and R_{UU}/R_{AuAu} (0-10%) does not show suppression up to 6 GeV/c
  → Ω formation in central collisions may be dominated by strange quark 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

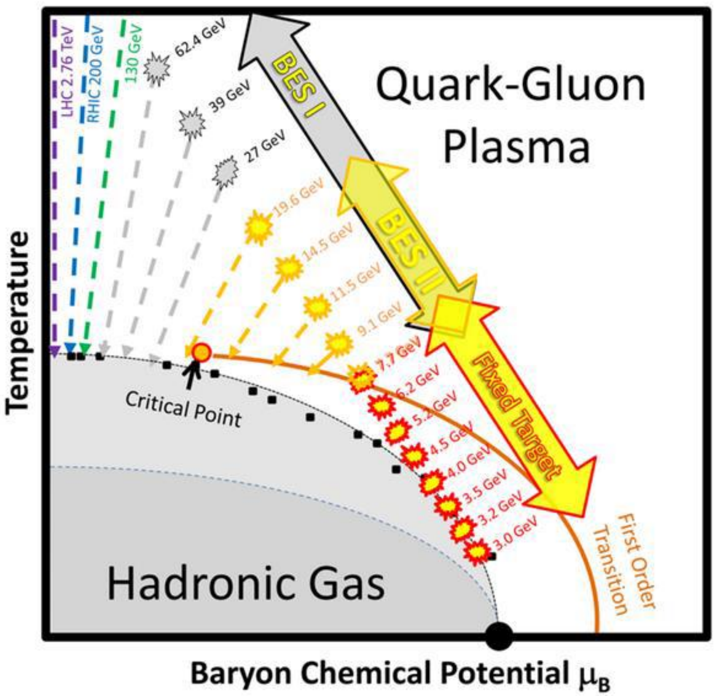
Better trigger & b/g reduction.

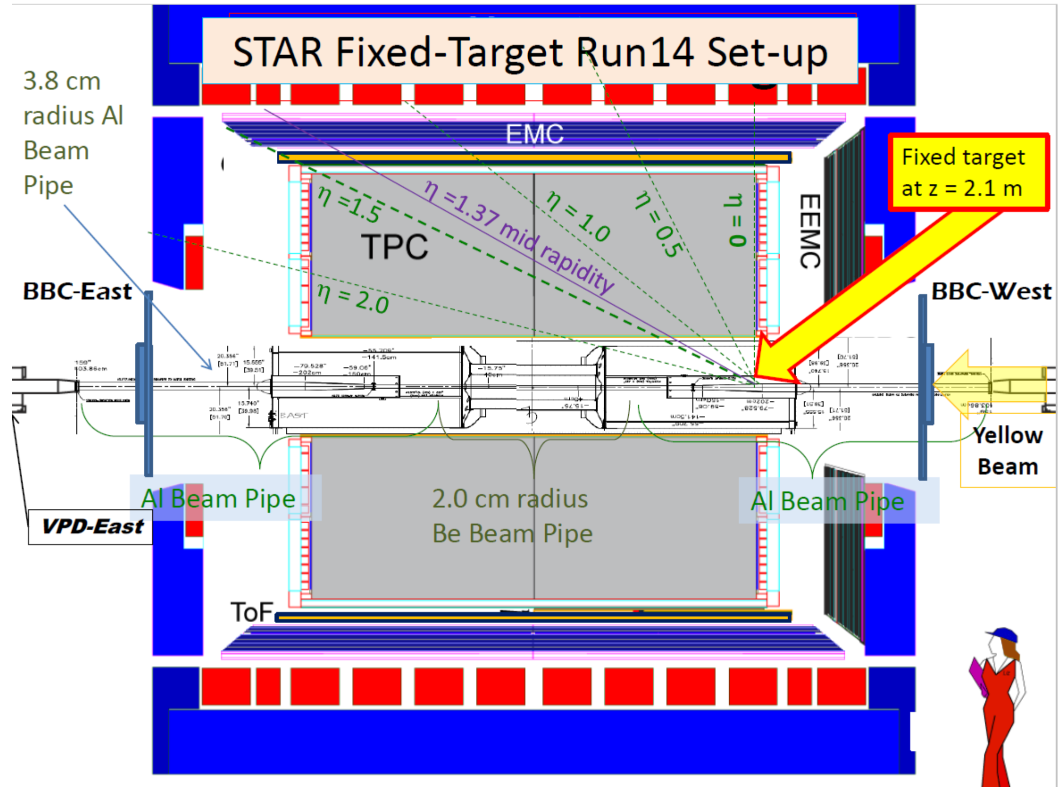
Other:

Hcal

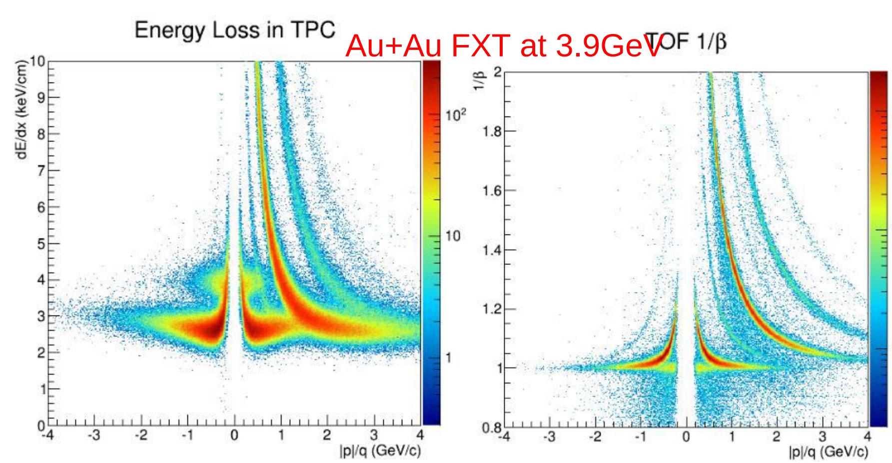
Endcap TOF

Fixed Target Program with STAR





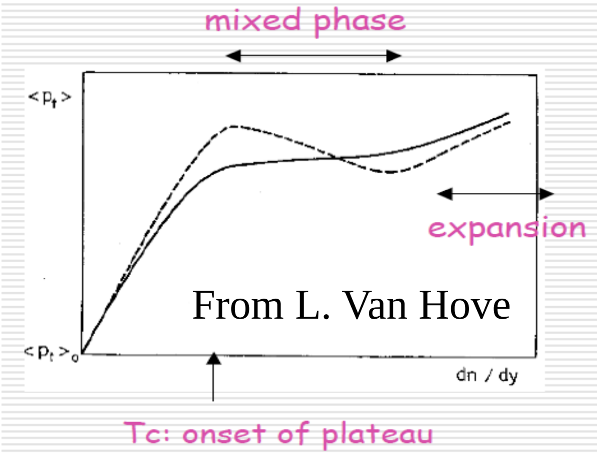
- Extend energy reach to overlap/complementary AGS/FAIR/JPARC
- Real collisions taken in run 14 and results (K. Meehan @ QM15 & WWND16)
- Upgrades (iTPC+eTOF+EPD) crucial
- Unprecedented coverage and PID for Critical Point search in BES-II
- Spectra, flow, fluctuations and correlations

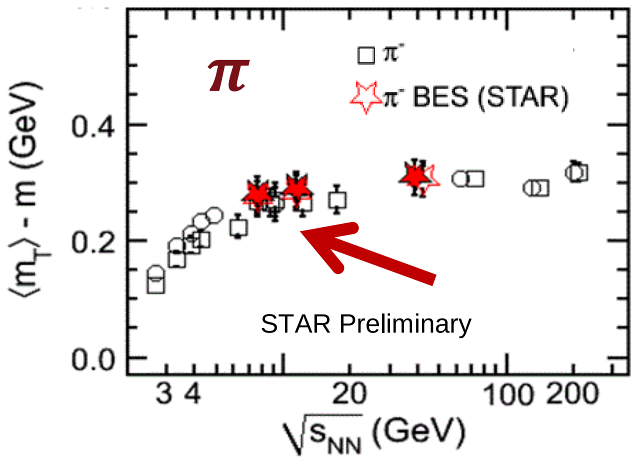


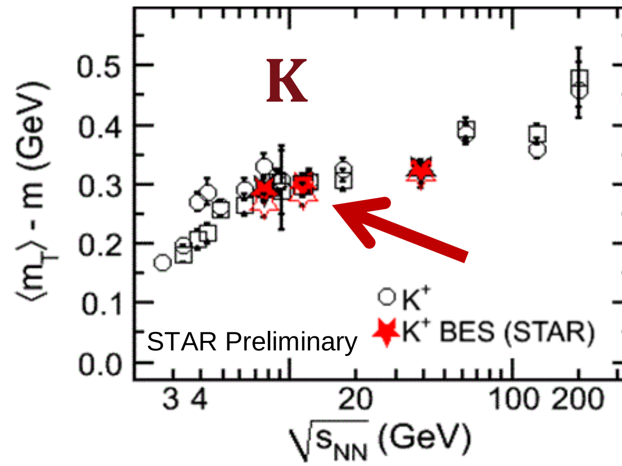
Outlook

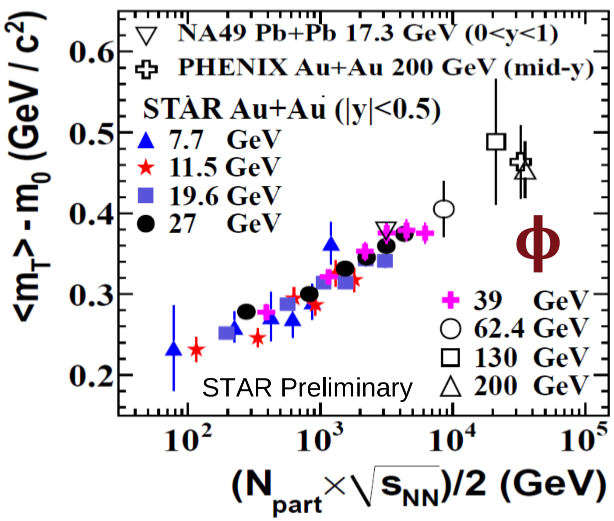
Backup

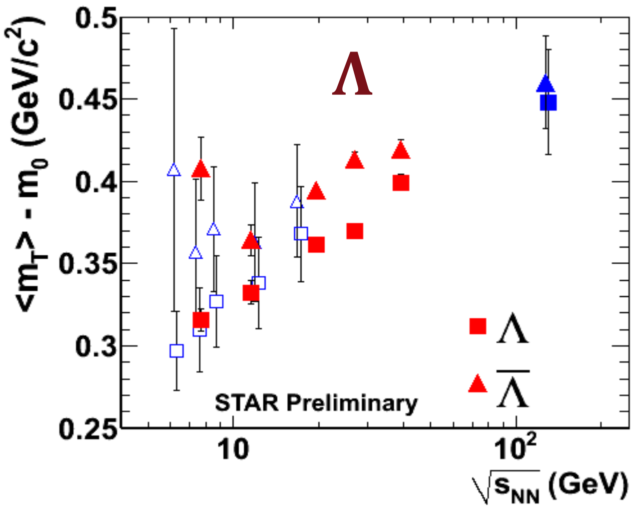
Beam energy dependence of $\langle m_T \rangle - m_0$

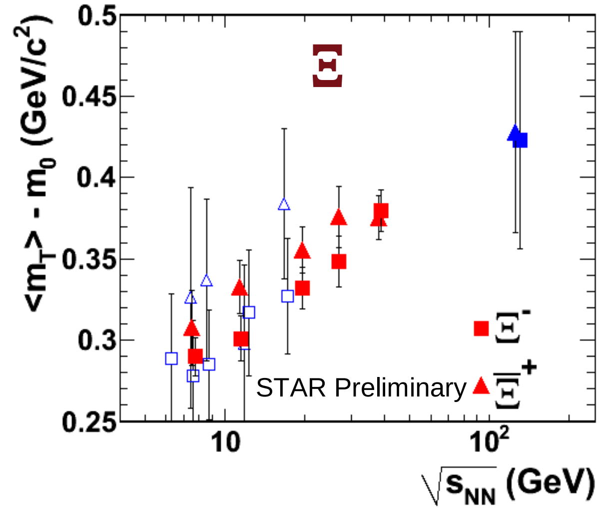












- For heavy strange hadrons ϕ, $\bar{\Lambda}$, Ξ, $\langle m_T \rangle - m_0$ show increasing trend with energy, **mass matters**

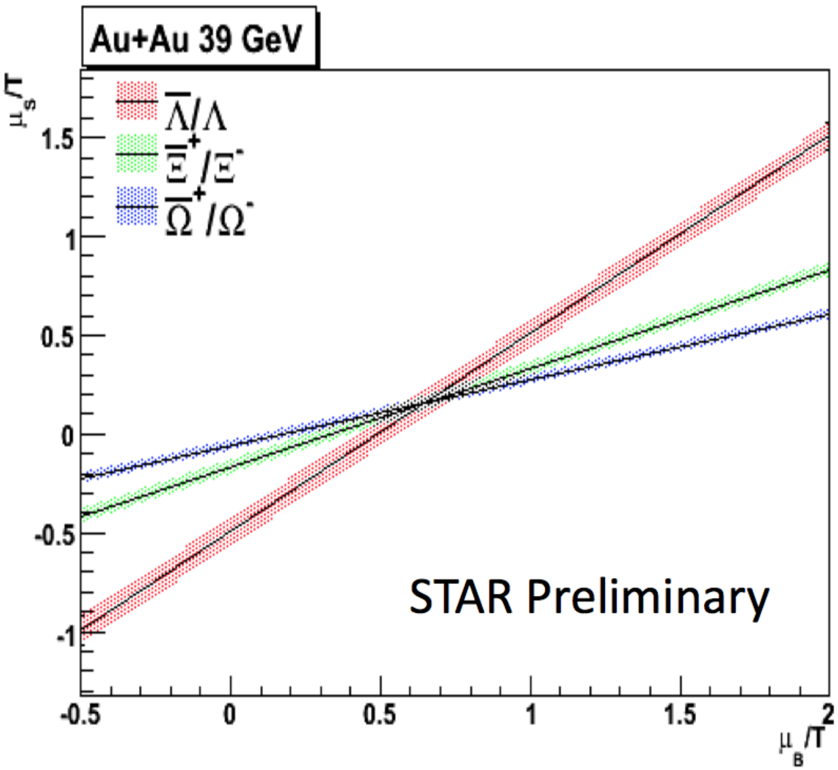
ϕ meson, statistical error

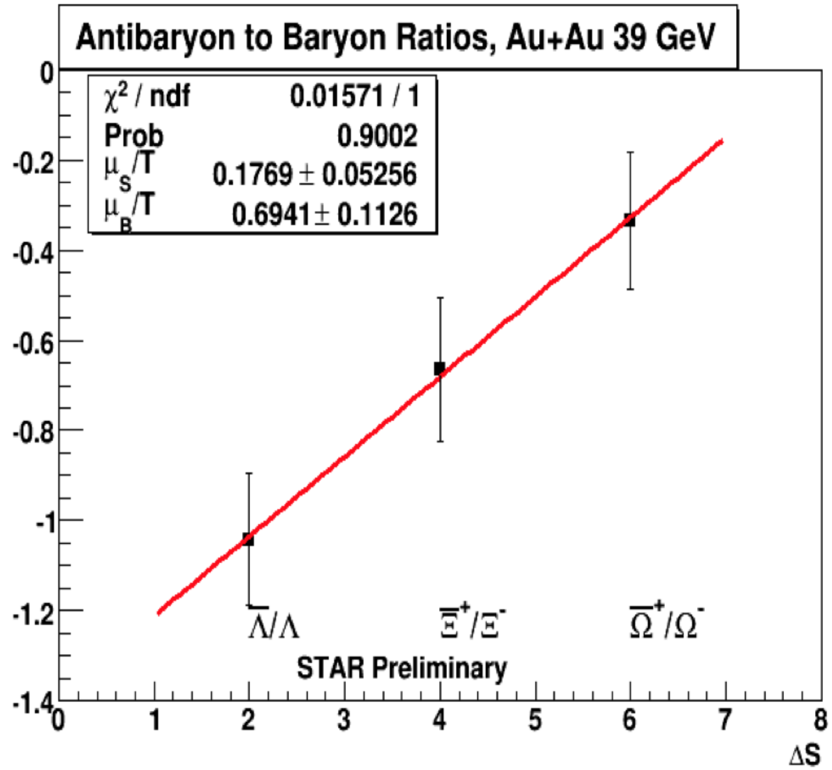
Λ, Ξ: Solid red, STAR BES, 0-5% most central, statistical error only

Solid blue, STAR published, most central, PRL 89, 092301; PRL92, 182301. Open, NA49, most central, from NA49, PRC78, 034918

Anti-baryon to baryon ratio

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

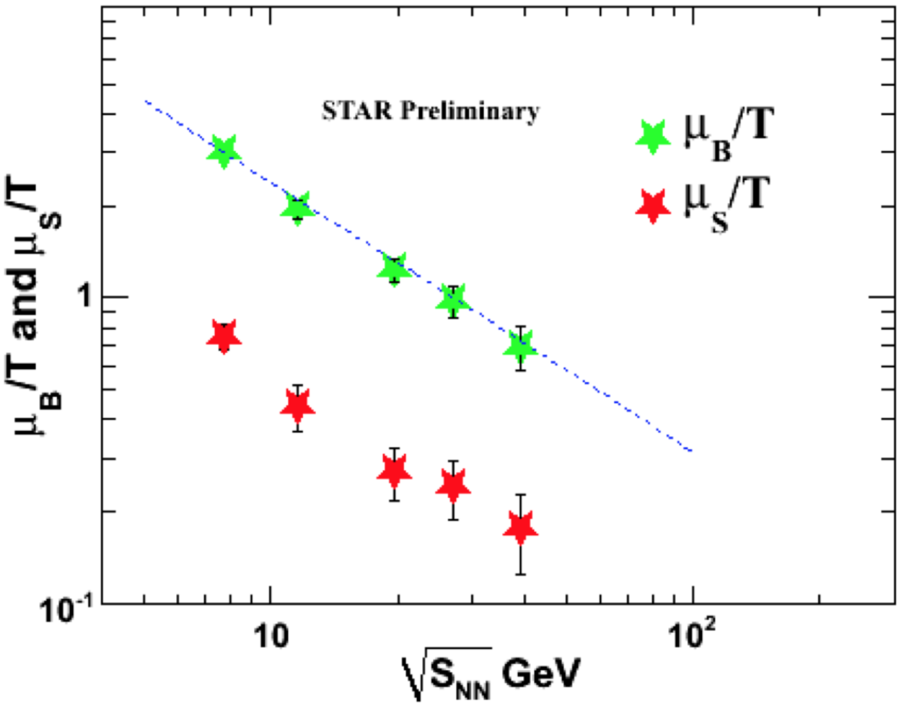




Cross the same point and straight line

→ Thermal statistical fit works!

Anti-baryon to baryon ratio



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

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

$Where:$

$T_0 = 167.5 MeV$

$b = 0.1583 GeV^{-2}$

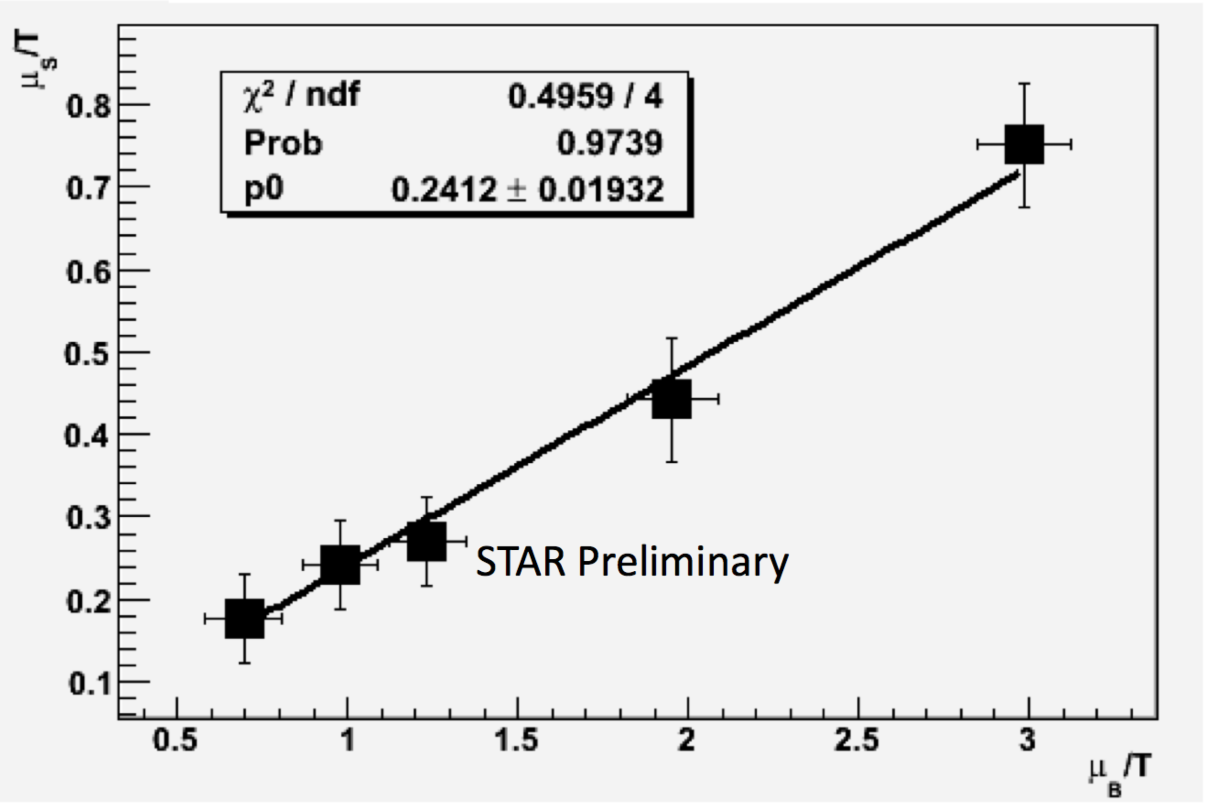
$\alpha = 2.06$

$\beta = 1.13$

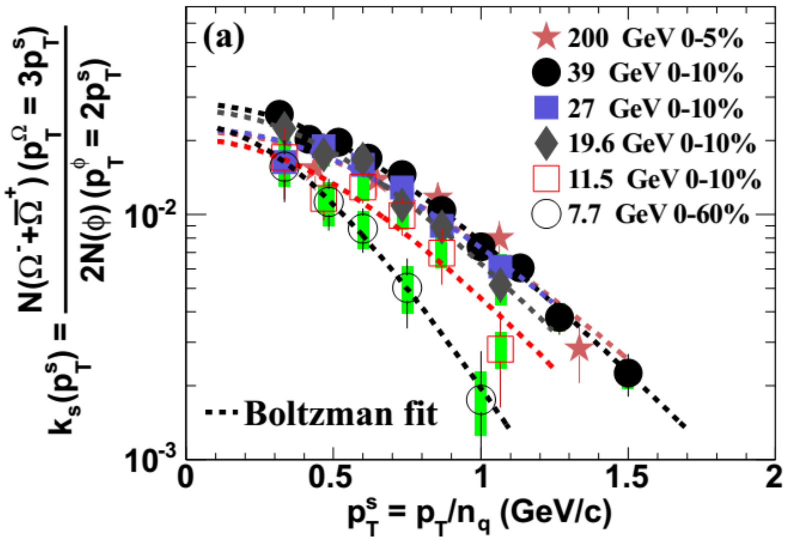
Parameters are from the fitting of published data of AGS, SPS and RHIC 130 GeV data.

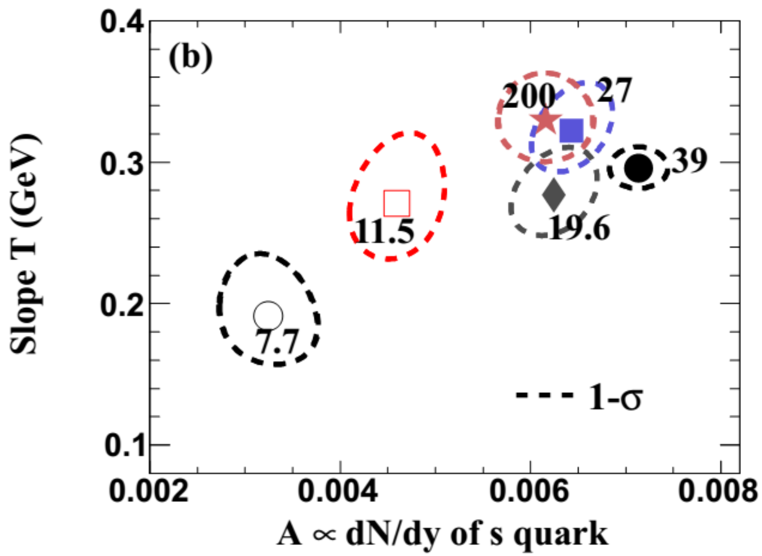
- Reference: F.Becattini et al. Phys Rev C 73, 044905 (2006)

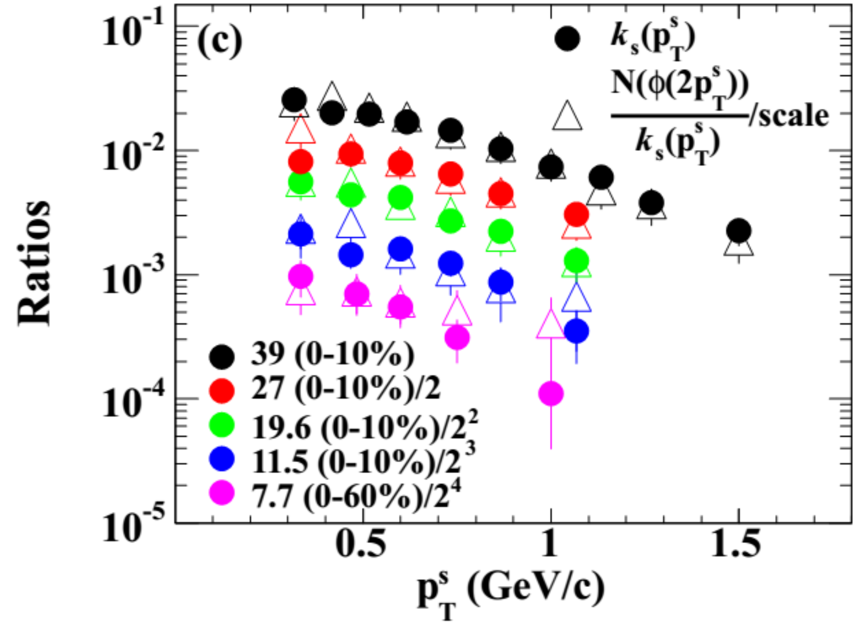
μ_s and μ_B correlation



NCQ-scaled Ω/ϕ ratio





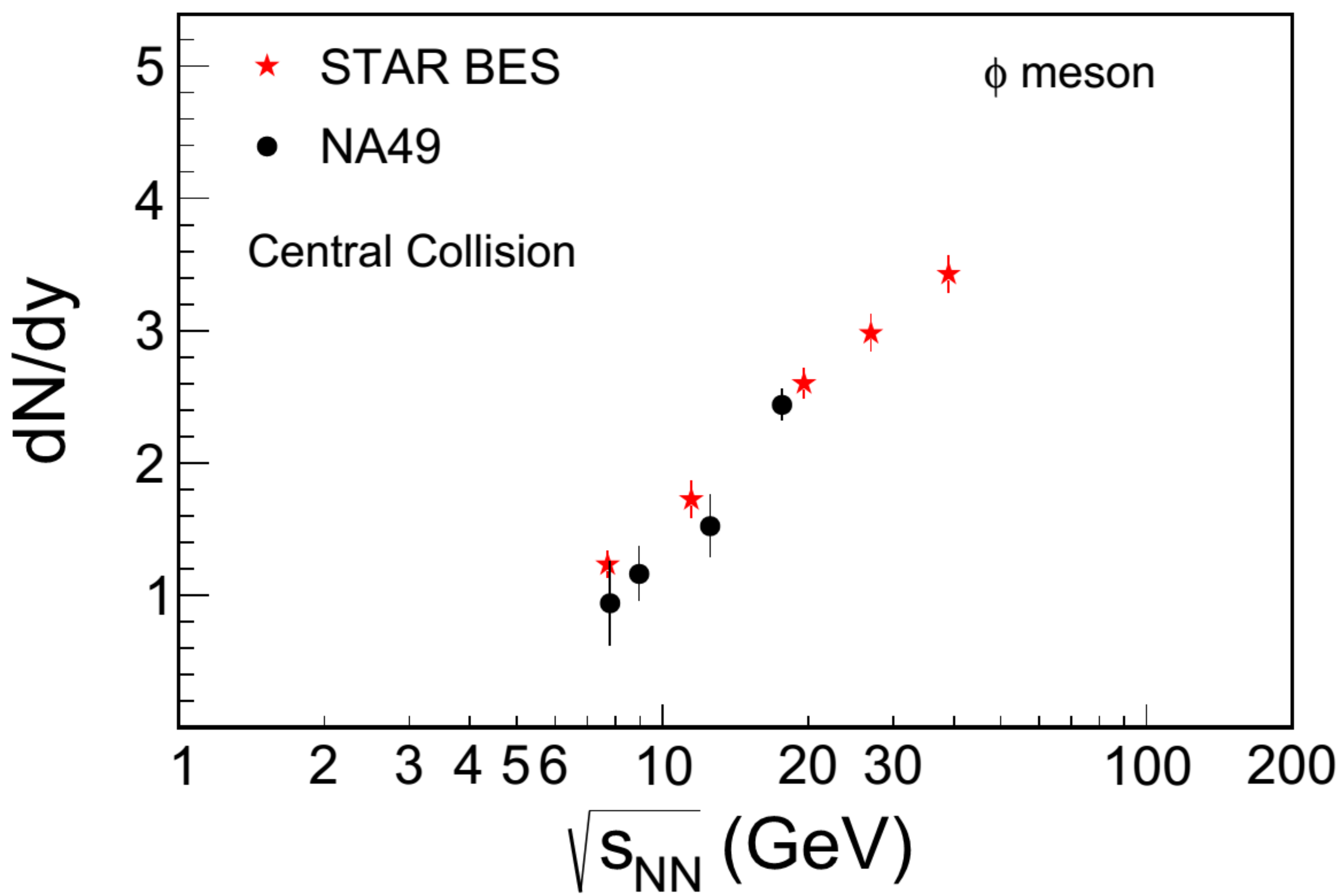


➢ **One single strange quark distribution describes both Ω and ϕ spectra**, a necessary condition for quark coalescence production

$$f_s(p_T) = \frac{g_\phi}{g_\Omega} \frac{c}{1+c^3} \frac{f(\Omega^- + \Omega^+)(3p_T)}{f(\phi)(2p_T)}$$

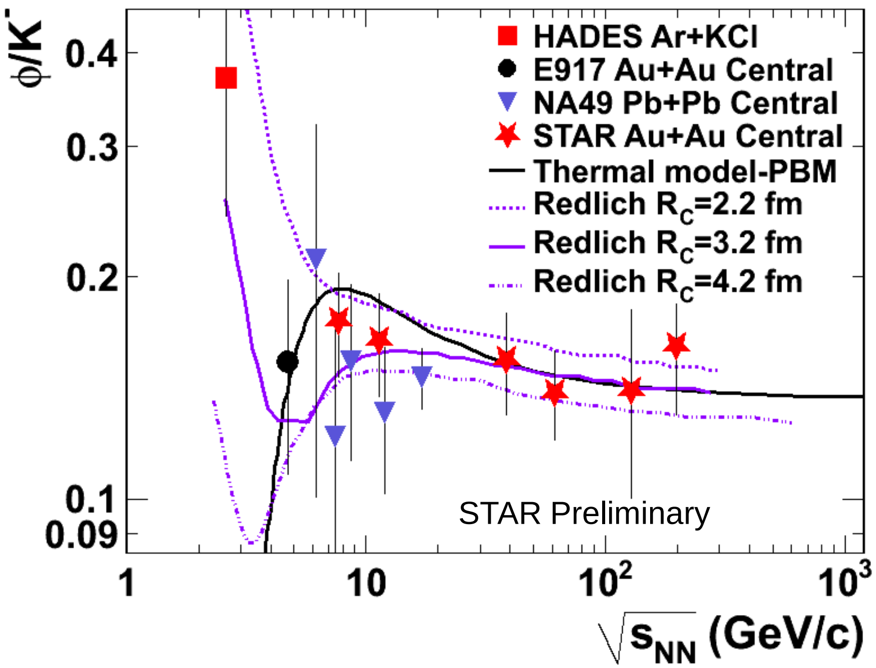
➢ Suppression of strange quark production below 19.6 GeV, slope change at 7.7 GeV. **Decreasing *s* quark density → phase transition**

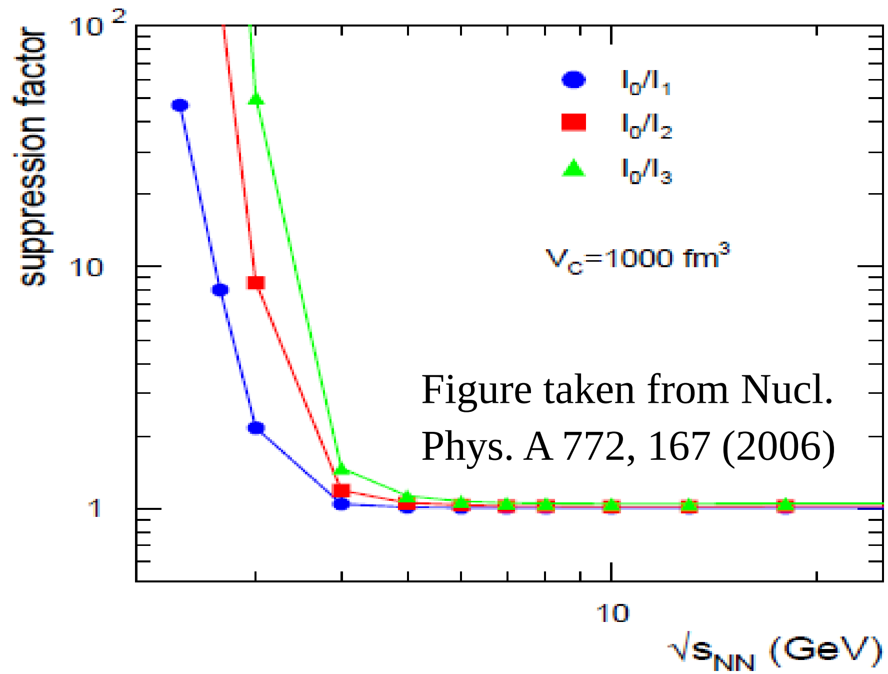
arXiv:1506.07605



STAR BES
NA49
φ meson
Central Collision
dN/dy
5
4
3
2
1
1
2
3
4
5
6
10
20
30
100
200
$\sqrt{s_{NN}}$ (GeV)

Different strangeness production scenarios





HADES: Phys. Rev. C 80, 025209 (2009) E917: Phys. Rev. C 69, 054901 (2004)
NA49: Phys. Rev. C 78, 044907 (2008) STAR 62.4, 130 & 200 GeV: Phys. Rev. C 79, 064903 (2009)
Thermal model-PBM: Nucl. Phys. A 772, 167 (2006)
Redlich model: Phys. Lett. B 603, 146 (2004)

Statistical + systematical error

- Canonical statistical model: "**ϕ is more suppressed than K^- at small phase space**"
- Strangeness quark pairs ($s\bar{s}$) correlation, radius R_C: 2.2 — 4.2 fm
  "**K^- is more suppressed than ϕ at small phase space**"

Particle yields

mid-rapidity