STAR results on strangeness production and properties of sQGP

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For the STAR Collaboration

SQM

DUBNA 2015

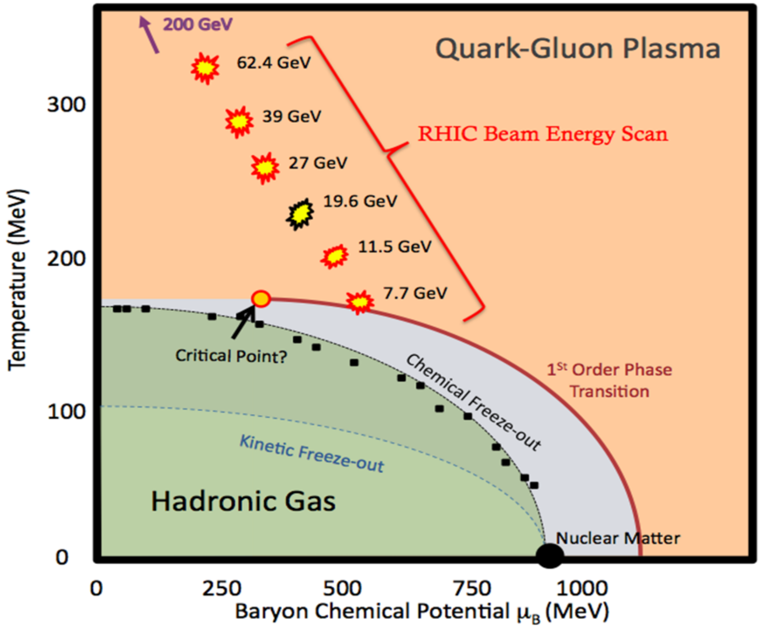
Outline

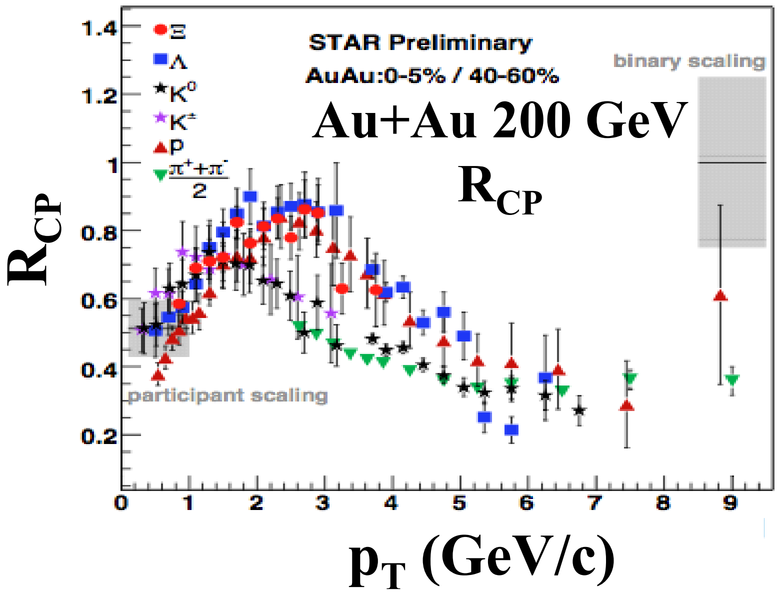
- Strangeness production in heavy ion collisions

- Strangeness measurements in STAR
  - ✓ Beam energy dependence
    (Beam energy scan: Au+Au 7.7 – 200 GeV)
  - ✓ System size dependence (p+p, Au+Au 200 GeV, U+U 193 GeV)

- Summary

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

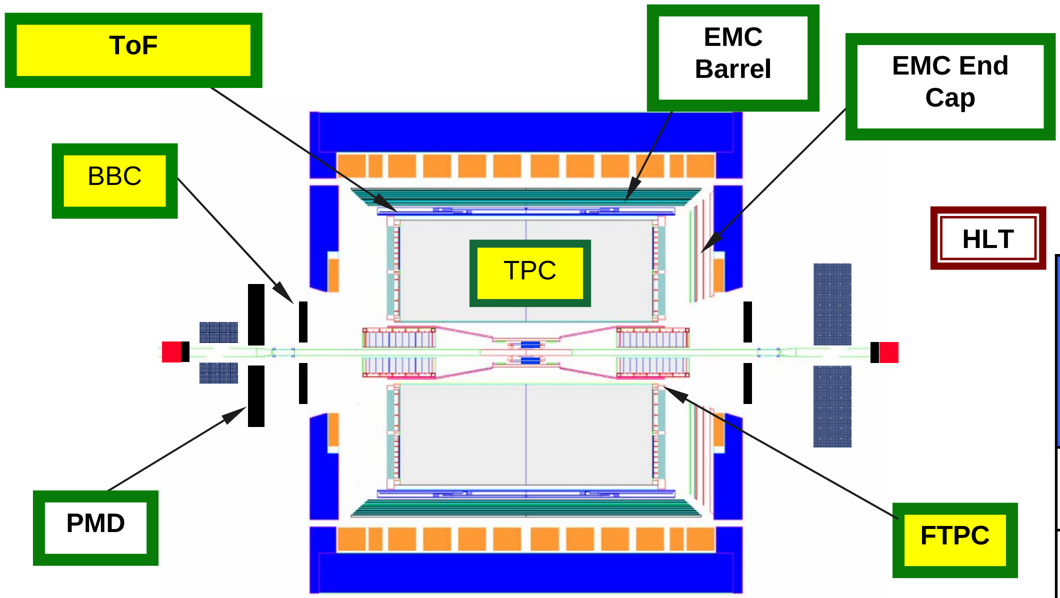


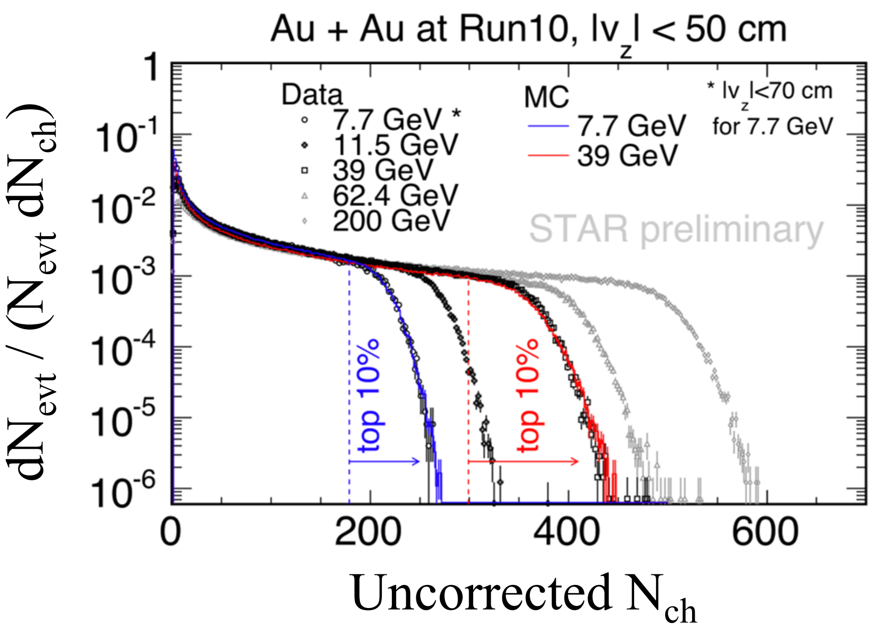


- **Beam Energy Scan at RHIC**
  Look for **onset of de-confinement, phase boundary** and critical point
  Au+Au collisions at 7.7, 11.5, 19.6, 27, 39, 62.4 GeV
- U+U collisions at 193 GeV
  System energy density dependence
- Key observables
  (1) Strangeness enhancement
  (2) Baryon/meson ratio
  Parton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

STAR, arXiv:1007.2613; NA49, PRC78, 034918

Detector settings

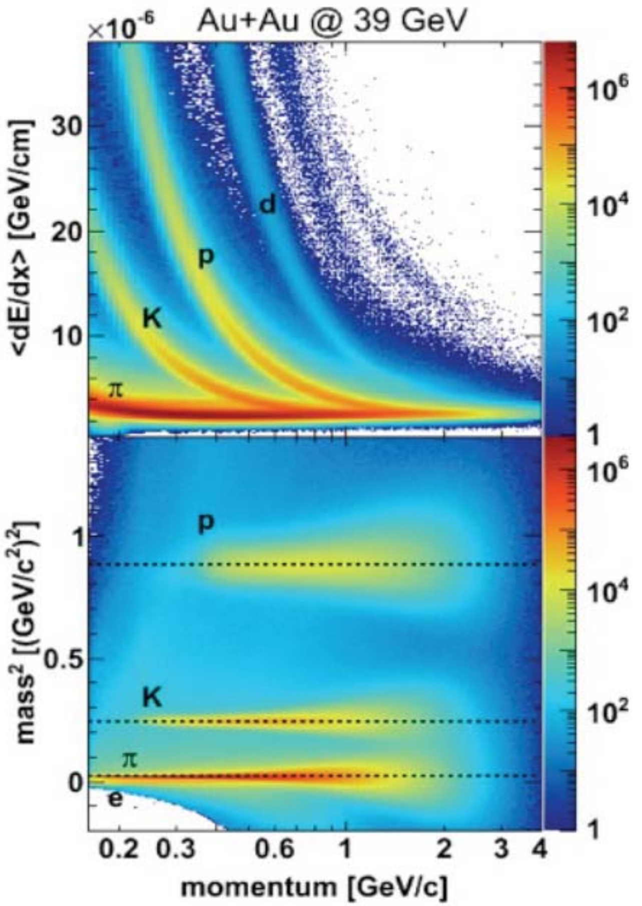


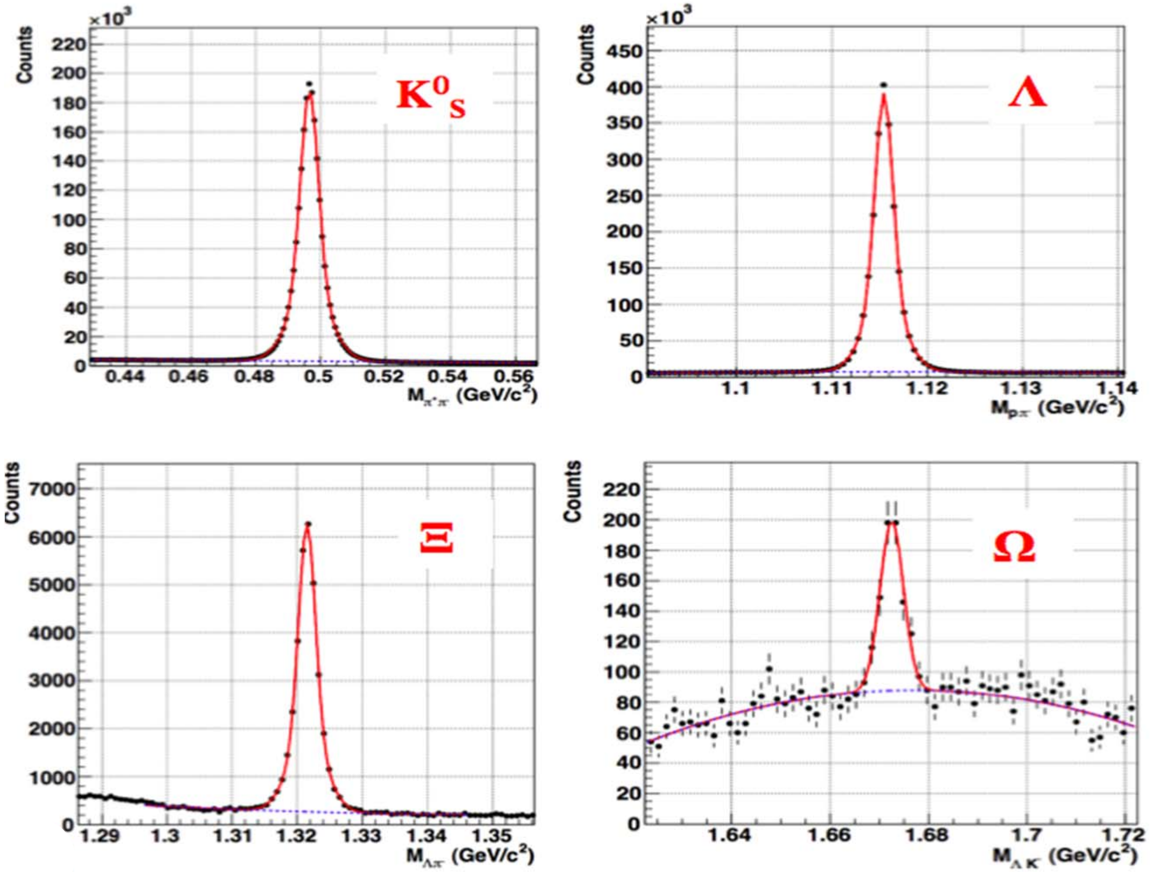


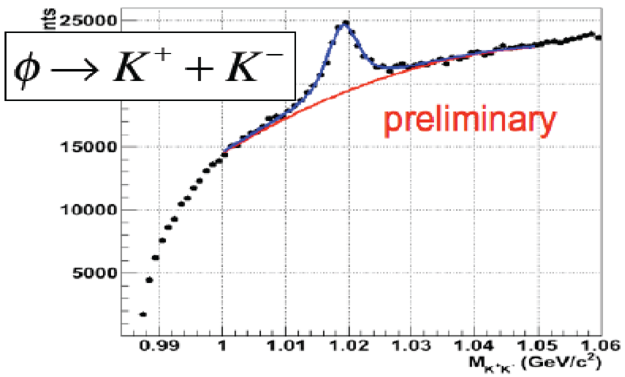
- Collisions centrality from uncorrected $dN_{ch}/d\eta$ in $|\eta| < 0.5$

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 (new)
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

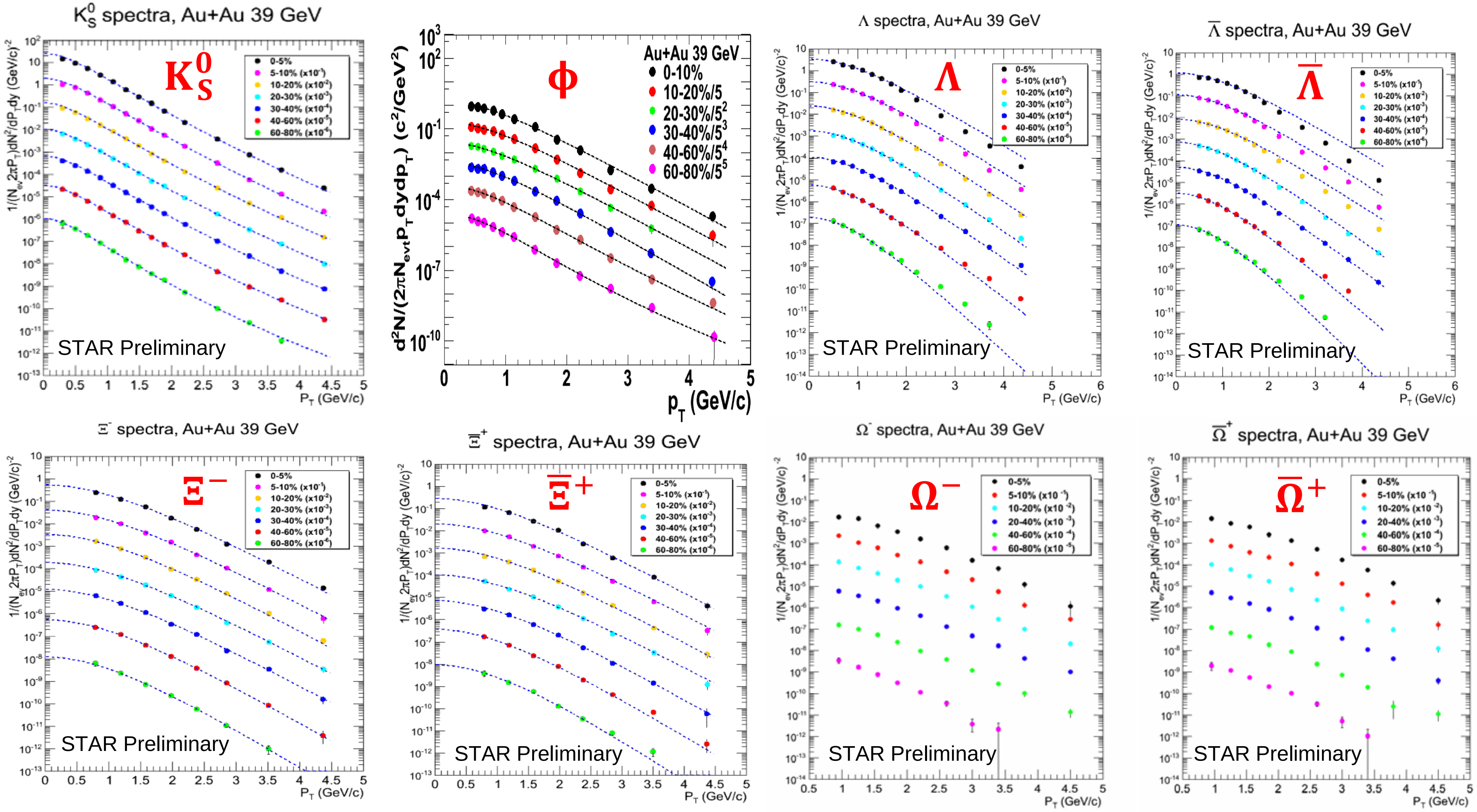






- dE/dx+TOF: π, K, p and $\phi \rightarrow K^{+} + K^{-}$ (invariant mass)
- Weak decay particles (K^0_S, Λ, Ξ, Ω), secondary vertex + invariant mass

p_T spectra (39 GeV)



- Extensive strange particle spectra

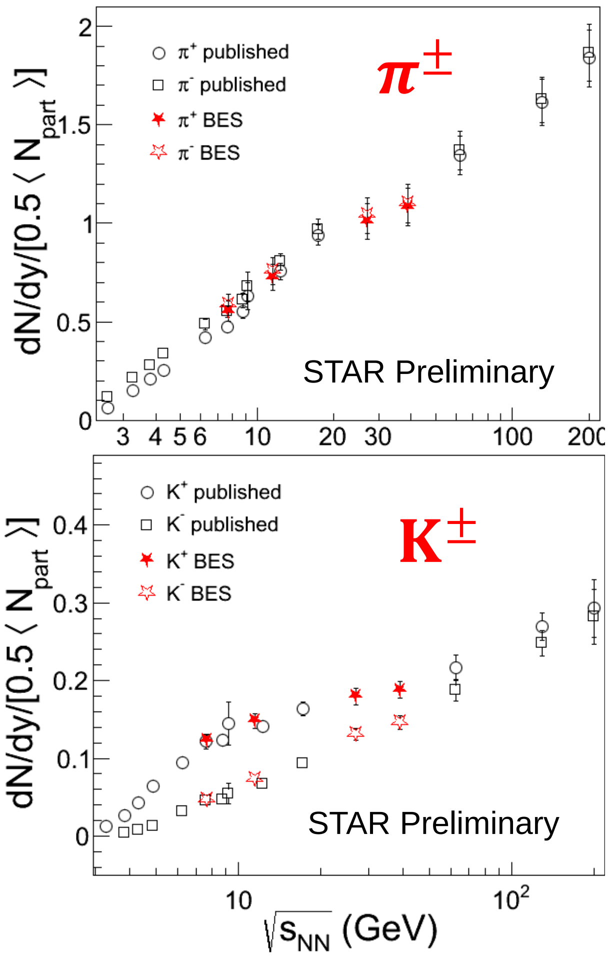
Statistical error

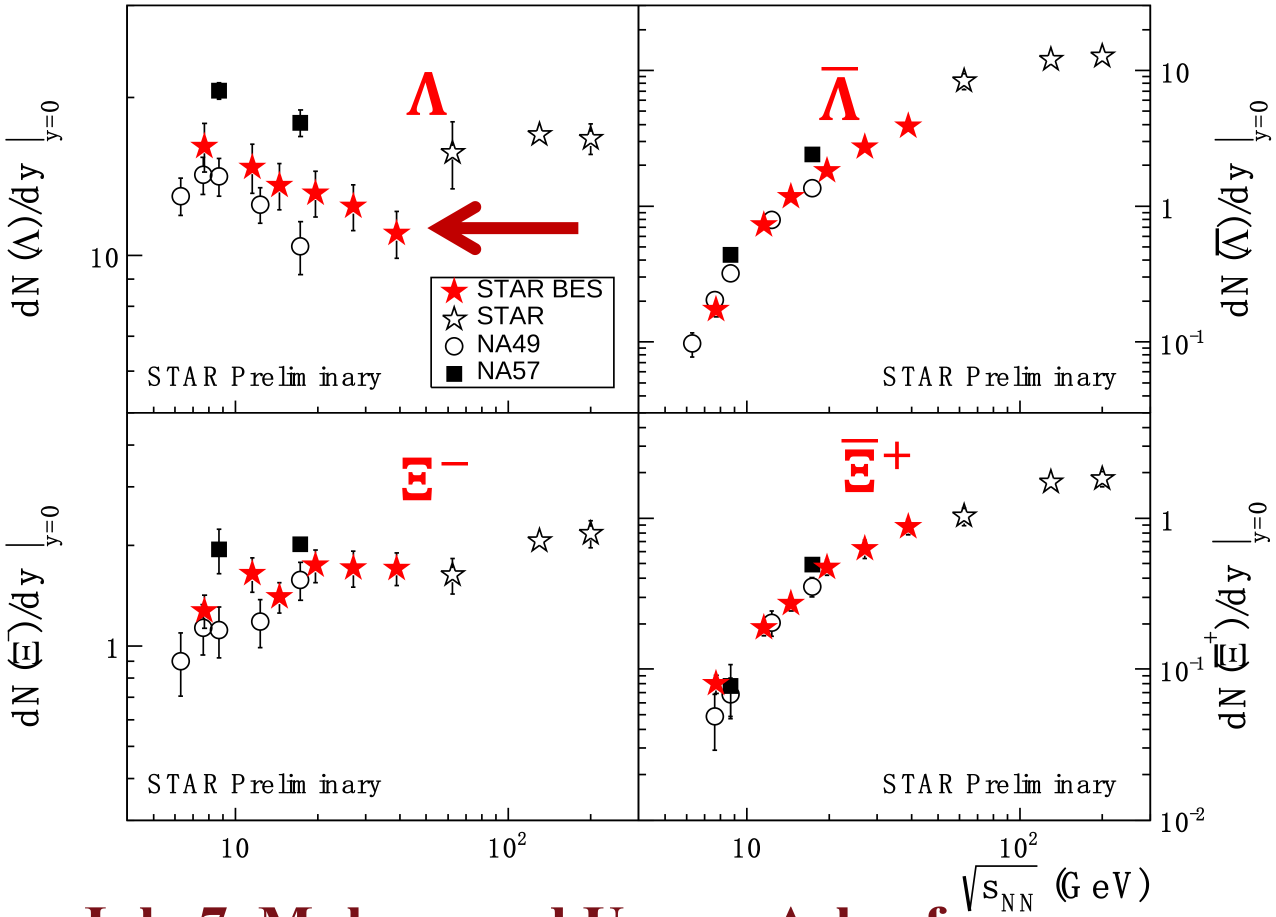
- **$\Lambda(\bar{\Lambda})$ spectra are weak decay feed-down corrected**

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

Particle yields

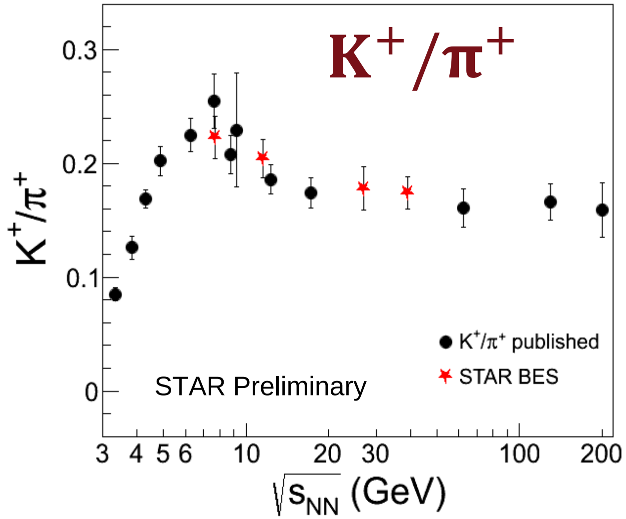
mid-rapidity, most central collisions (0-5%)

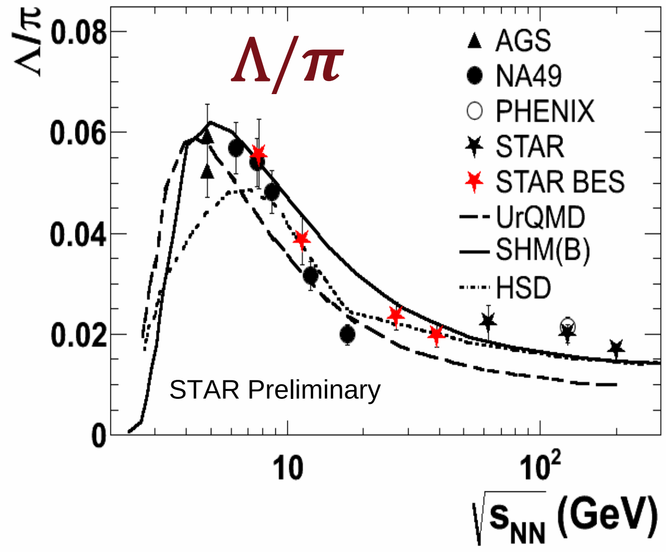


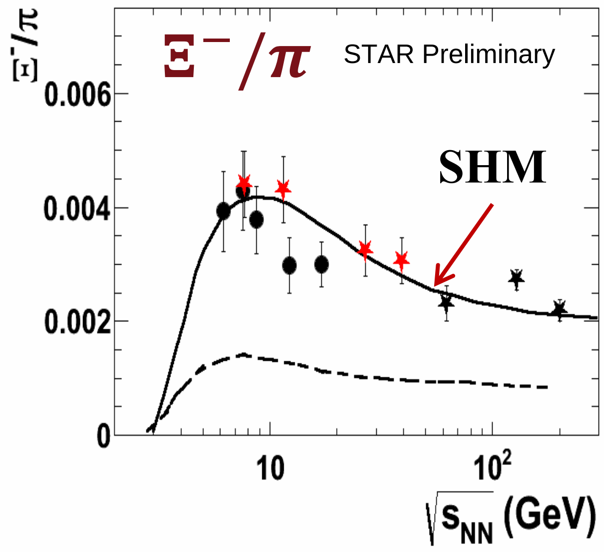


- STAR results are consistent with published data in general
- Λ yields seem to show dip around $\sqrt{s_{NN}}$ = 39 GeV. **The baryon stopping at mid-rapidity decreases with increasing energy**

Particle ratios

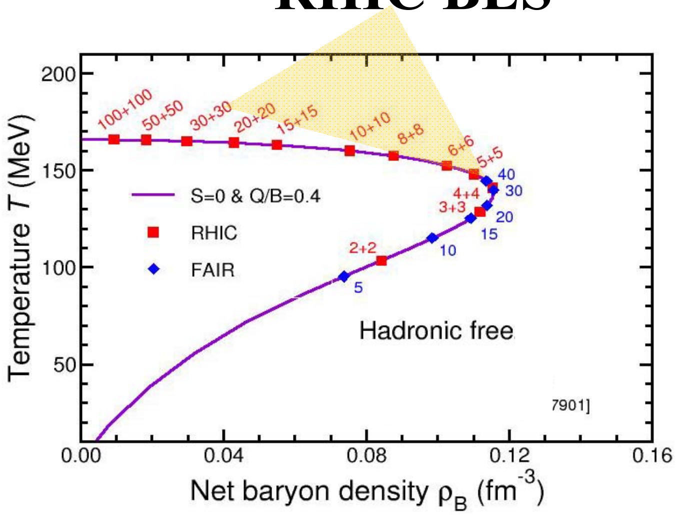






***most central (0-5%)**, mid-rapidity, stat. + sys. error*

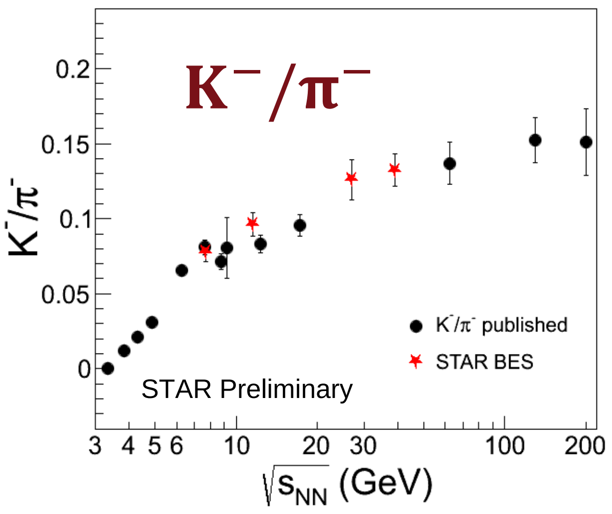
RHIC BES

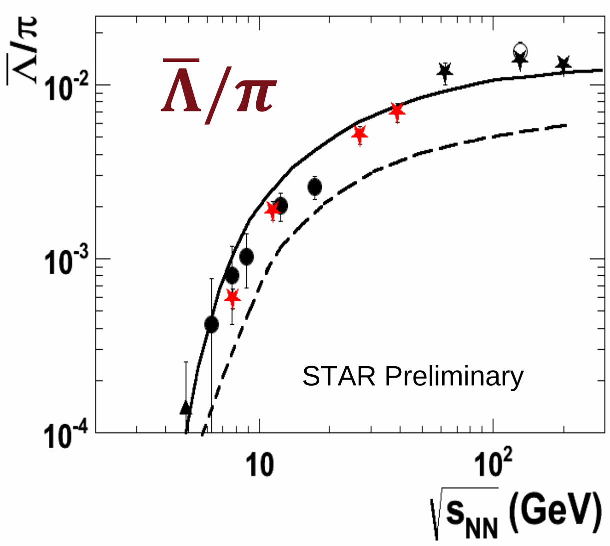


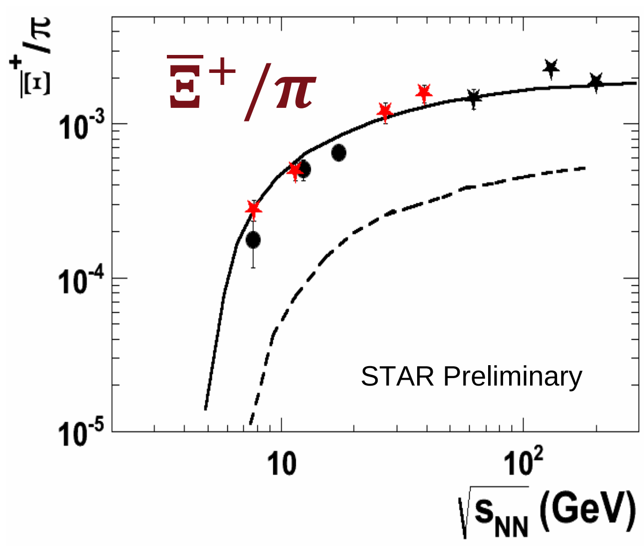
J. Randrup et al., PRC 74, 047901 (2006)

- 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**
- Associate production channels like $N + N \rightarrow N + \Lambda + K^+$ may be important for K^+ production, N is nucleon

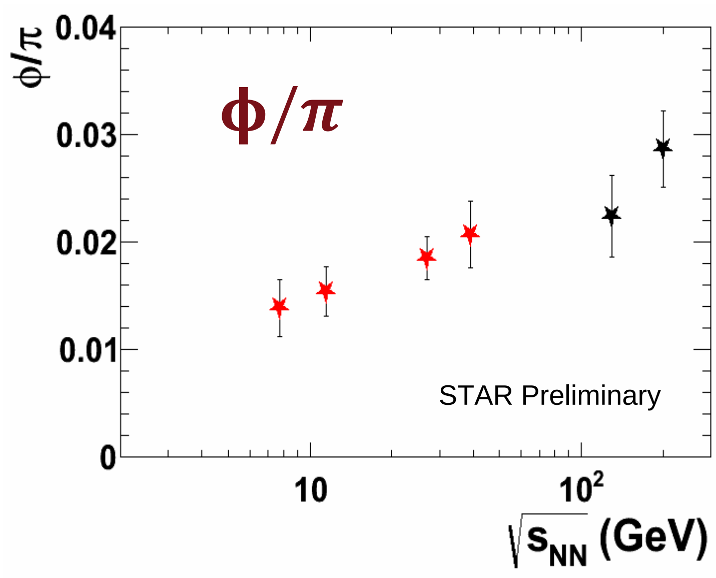
Particle ratios







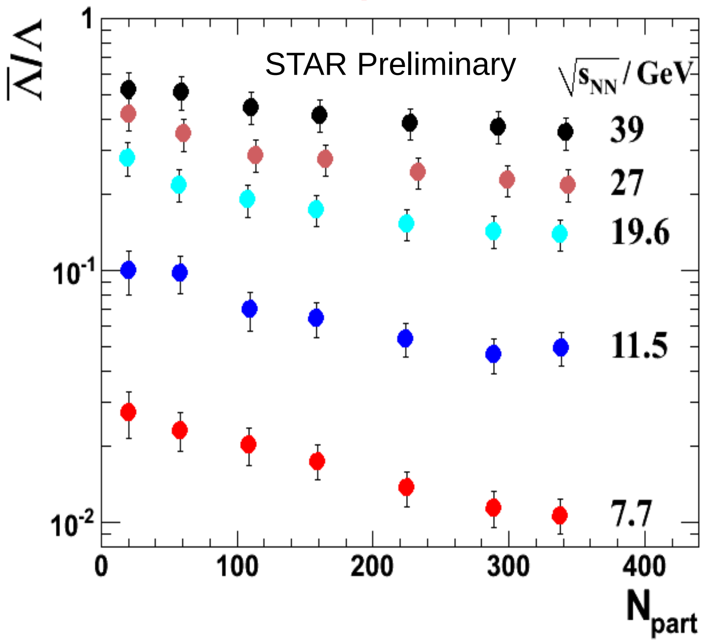
most central (0-5%)*, mid-rapidity, stat. + sys. error*

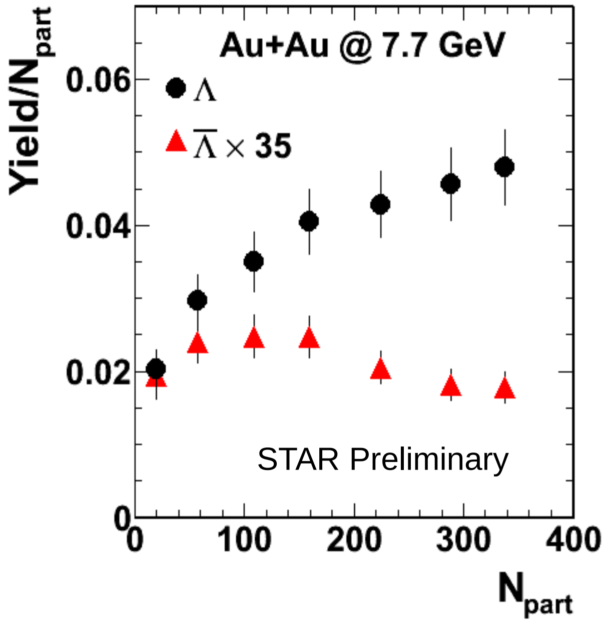


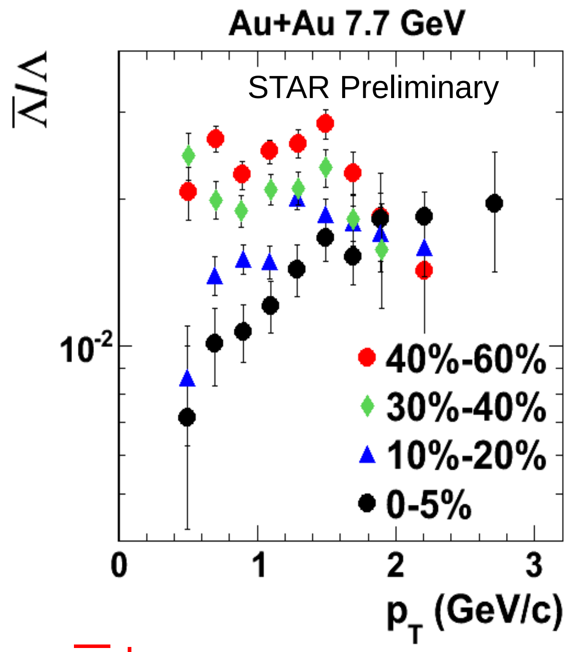
- ❑ Clear $\mathbf{K^-}$, $\bar{\mathbf{\Lambda}}$, $\bar{\mathbf{\Xi}}^+$ yield enhancement compared to pions with increasing collision energy
- ❑ Similar behavior for hidden strangeness $\boldsymbol{\phi}(s\bar{s})$

$\bar{B}/B$ ratios

$\bar{\Lambda}/\Lambda$

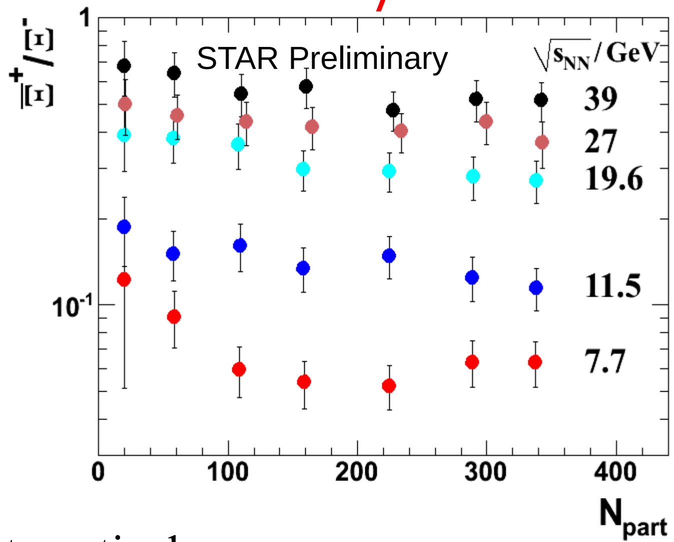






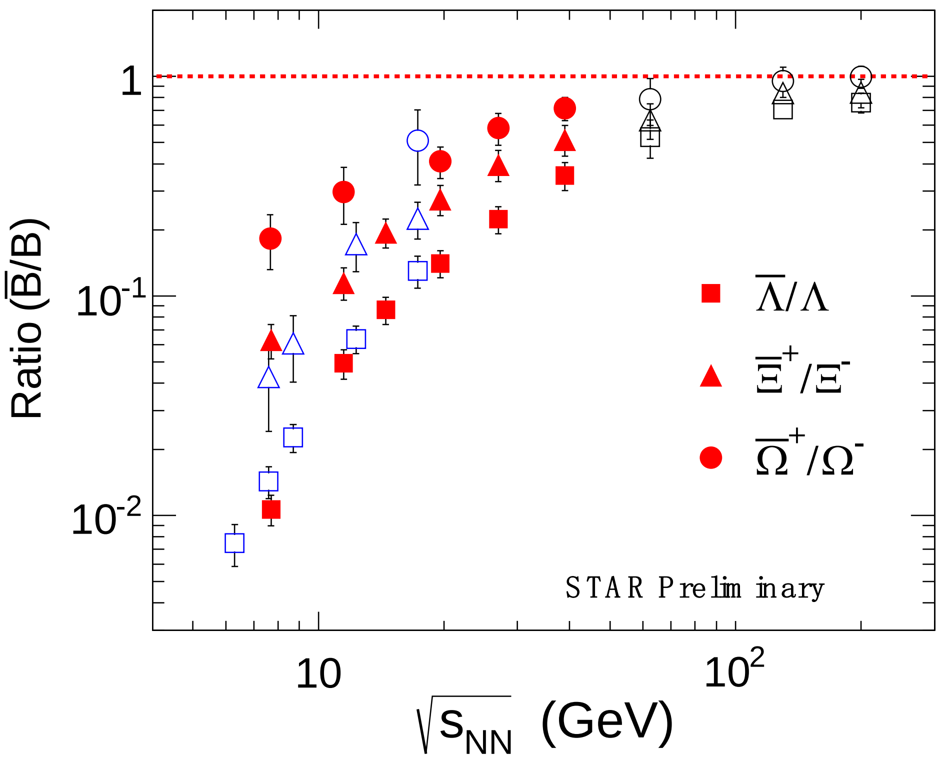
- Centrality dependence of $\bar{B}/B$ ratios:
  peripheral > central
- This effect is more prominent at lower energies.
  baryon stopping, anti-baryon absorption
- **Loss of low p_T $\bar{\Lambda}$ in central collisions**

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



Statistical + systematical error

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



Statistical + systematical error

July 7, Muhammad Usman Ashraf

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 **$\overline{\Omega}^{+}/\Omega^{-} > \overline{\Xi}^{+}/\Xi^{-} > \overline{\Lambda}/\Lambda$**: pair production v.s. baryon transport & associated production

Anti-baryon to baryon ratio

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

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

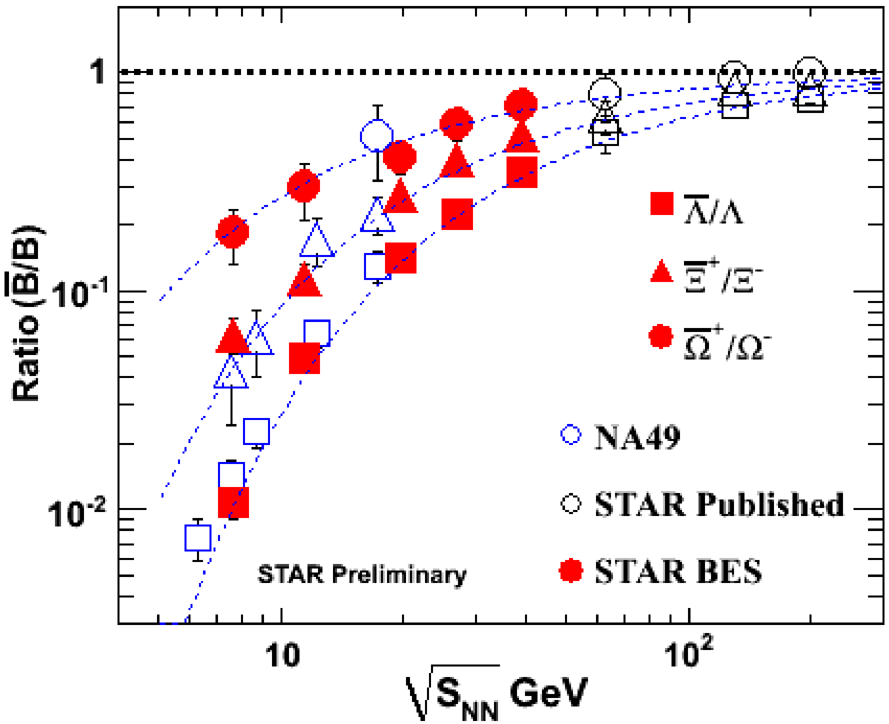
$$\frac{\overline{\Xi}^+}{\Xi^-} = \exp(-\frac{2\mu_B}{T} + \frac{4\mu_S}{T}) \quad \Rightarrow \quad \ln(\frac{\overline{\Xi}^+}{\Xi^-}) = -\frac{2\mu_B}{T} + \frac{4\mu_S}{T}$$

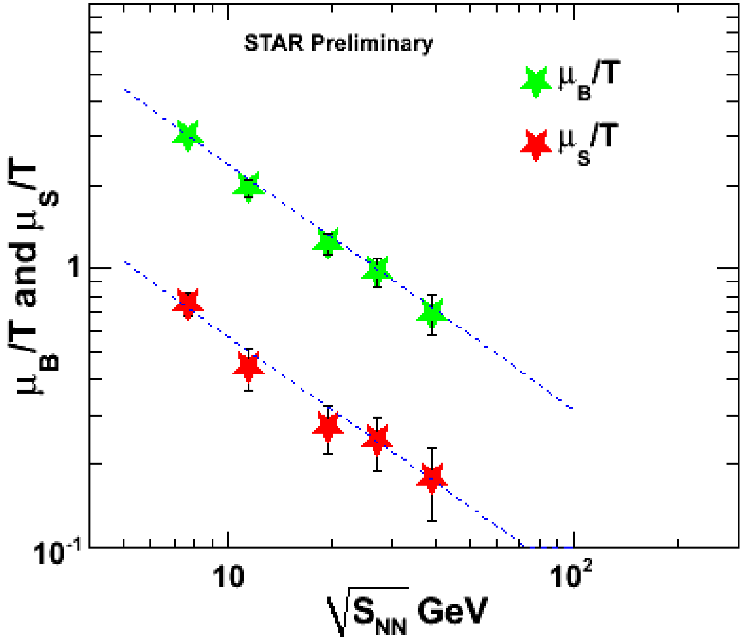
$$\frac{\overline{\Omega}^+}{\Omega^-} = \exp(-\frac{2\mu_B}{T} + \frac{6\mu_S}{T}) \qquad \ln(\frac{\overline{\Omega}^+}{\Omega^-}) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T}$$

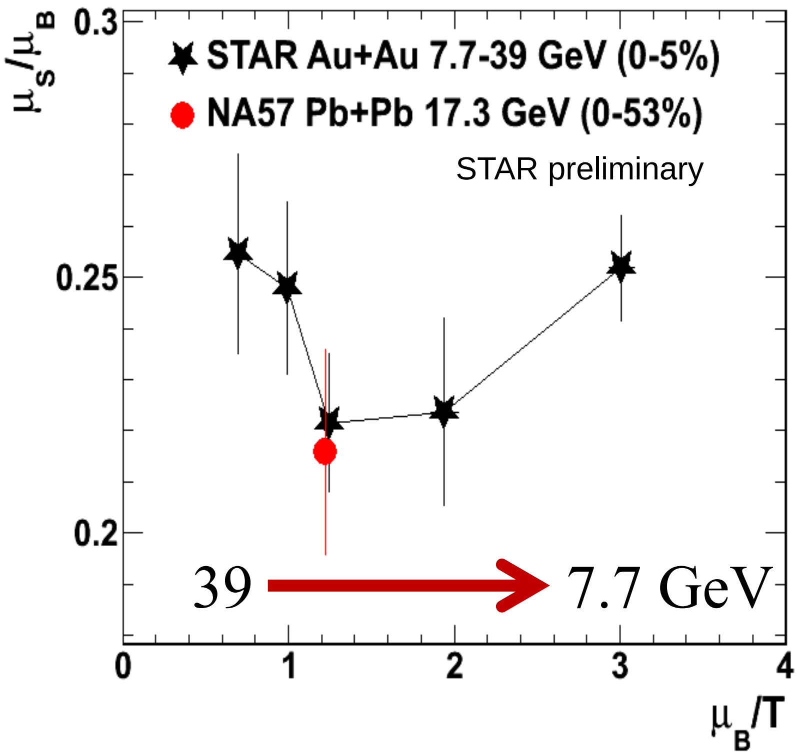
- T is the temperature.
- μ_B is the baryon chemical potential.
- μ_S is the strangeness chemical potential.

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

μ_B and μ_s correlation







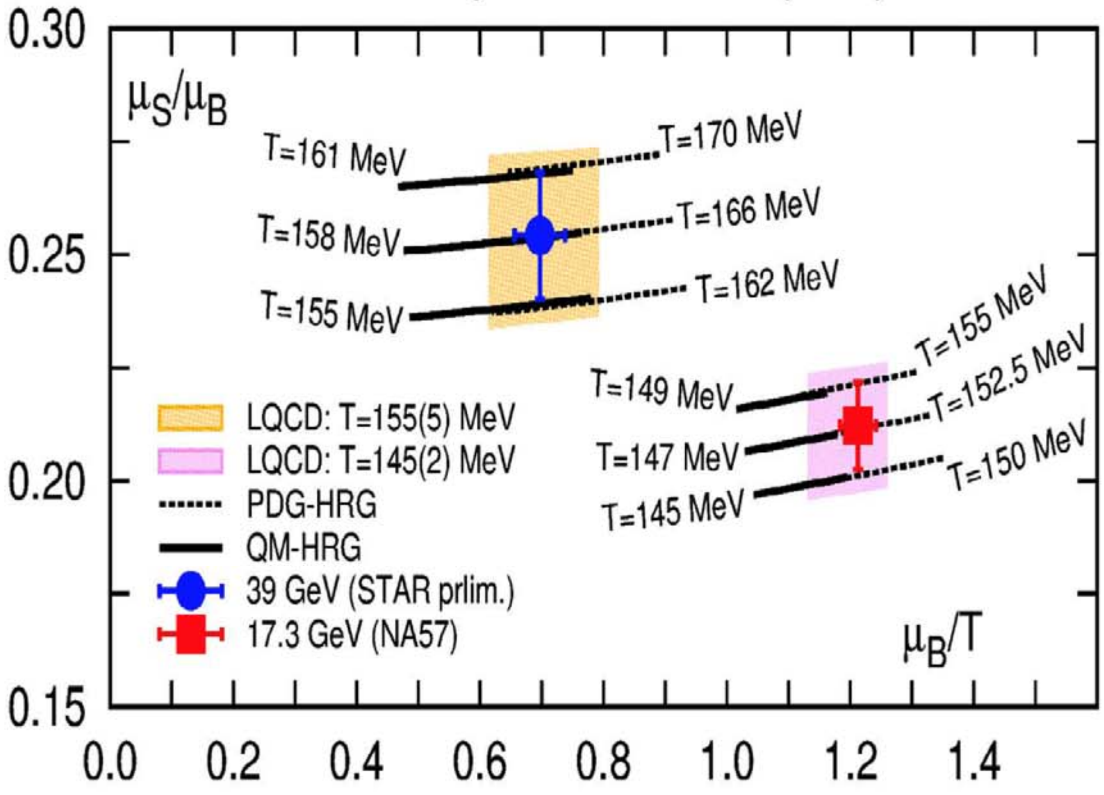
- Anti-baryon to baryon ratios are consistent with statistical thermal model
- **μ_s/μ_B seems to be smaller in 11.5 - 19.6 GeV than in 39 and 7.7 GeV**

Strangeness, LQCD and freeze-out in HIC

Swagato Mukherjee, Mon

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

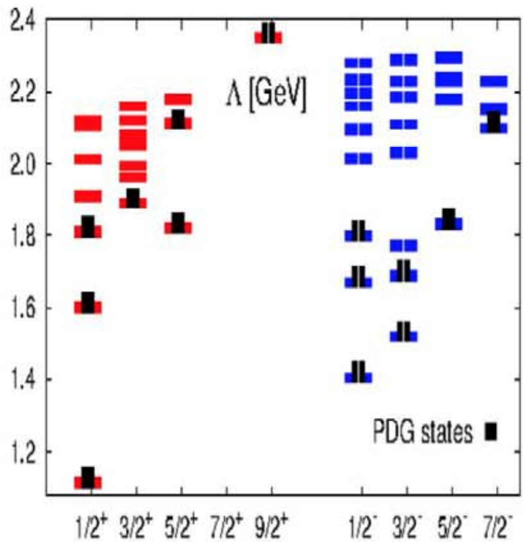
BNL-Bi-CCNU: Phys. Rev. Lett. 113 (2014) 072001



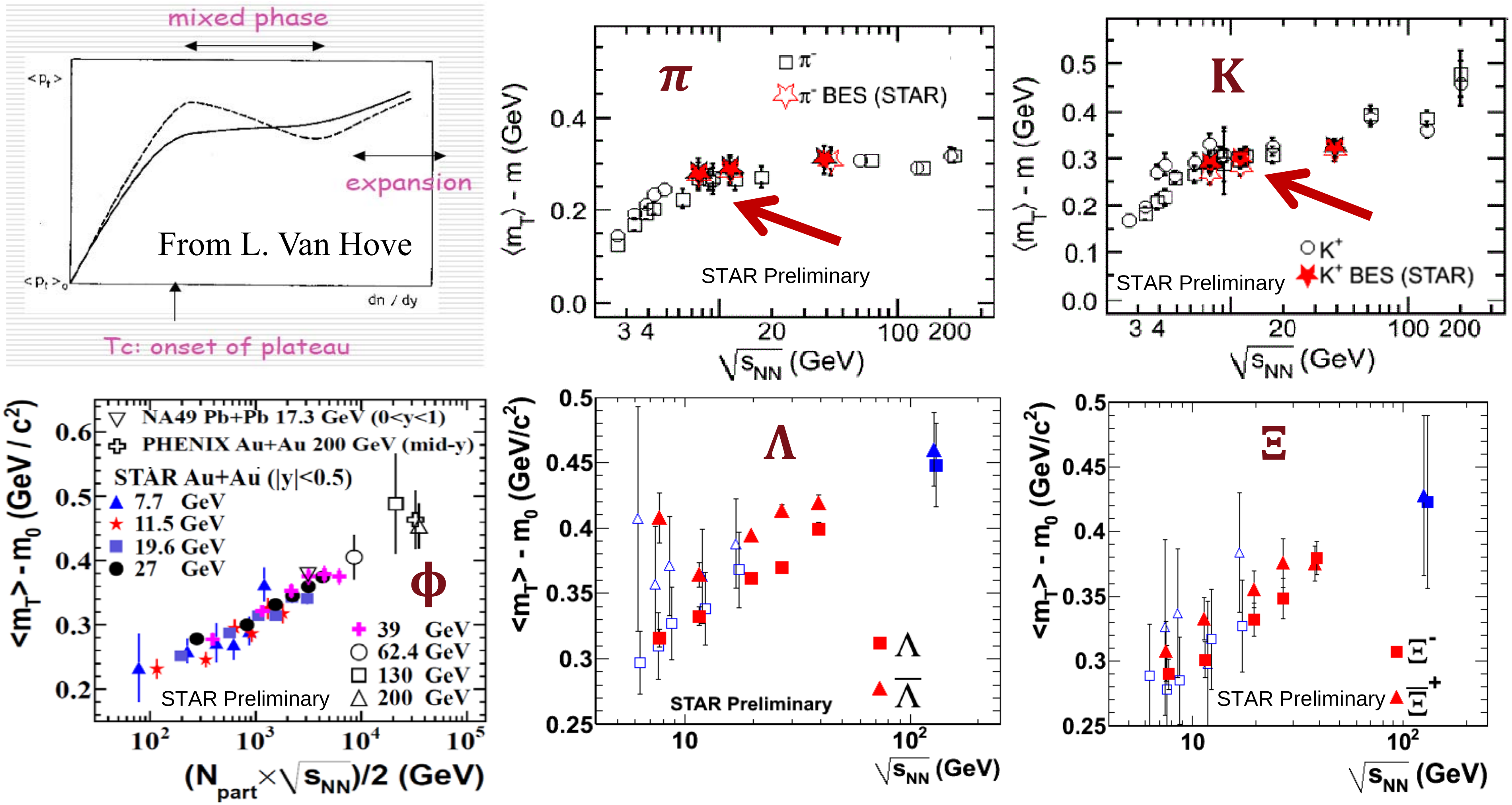
indirect evidence for so-far undiscovered
strange baryons at RHIC ?

not reproduced by
hadron gas with
only PDG states

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



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

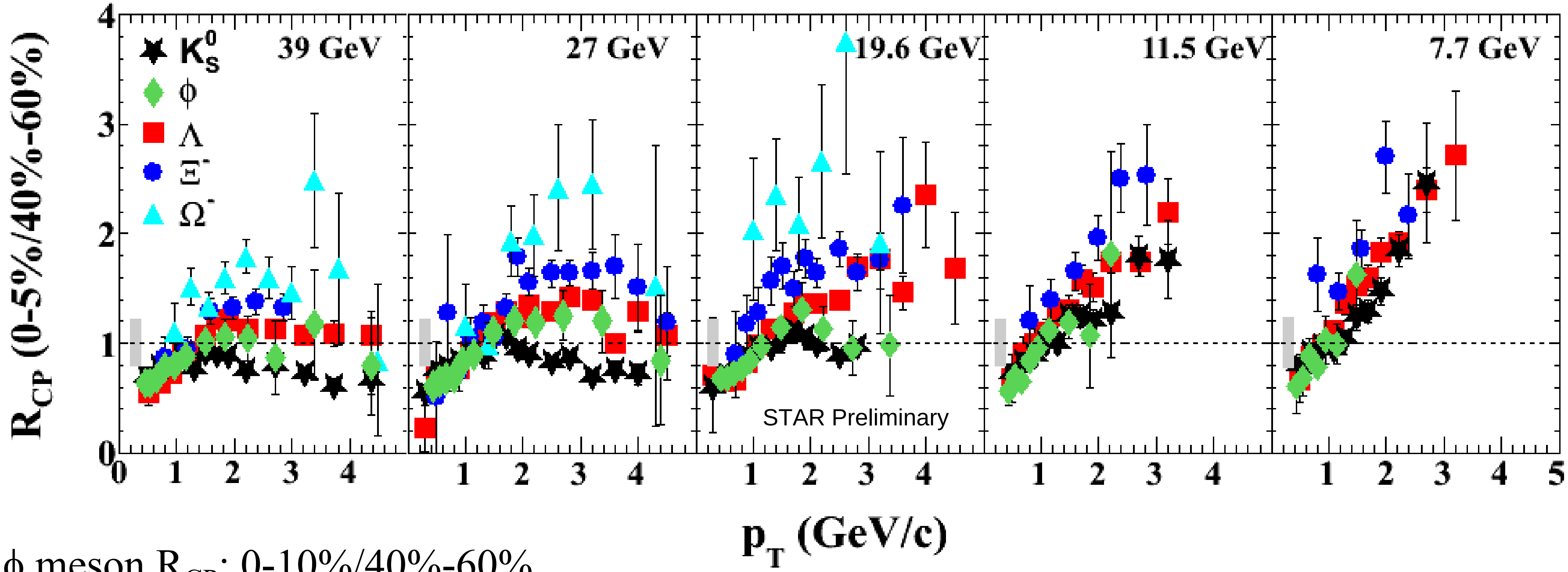


- For heavy strange hadrons ϕ, $\bar{\Lambda}$, Ξ, $\langle m_T \rangle - m_0$ show increasing trend with energy, **mass matters**

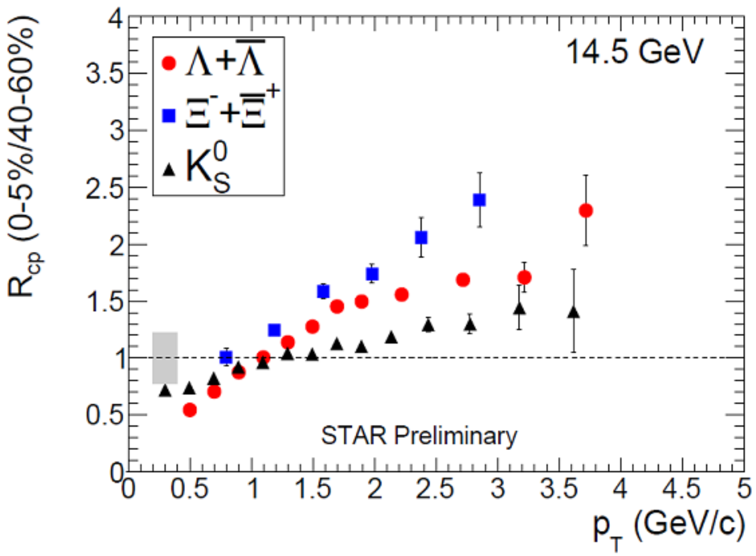
Λ, Ξ: Solid red, STAR BES, 0-5% most central, statistical error only
Solid blue, STAR published, most central, PRL 89, 092301; PRL92, 182301. Open, NA49, most central, from NA49, PRC78, 034918

ϕ meson, statistical error

Nuclear modification factors R_{CP}



ϕ meson R_{CP}: 0-10%/40%-60%

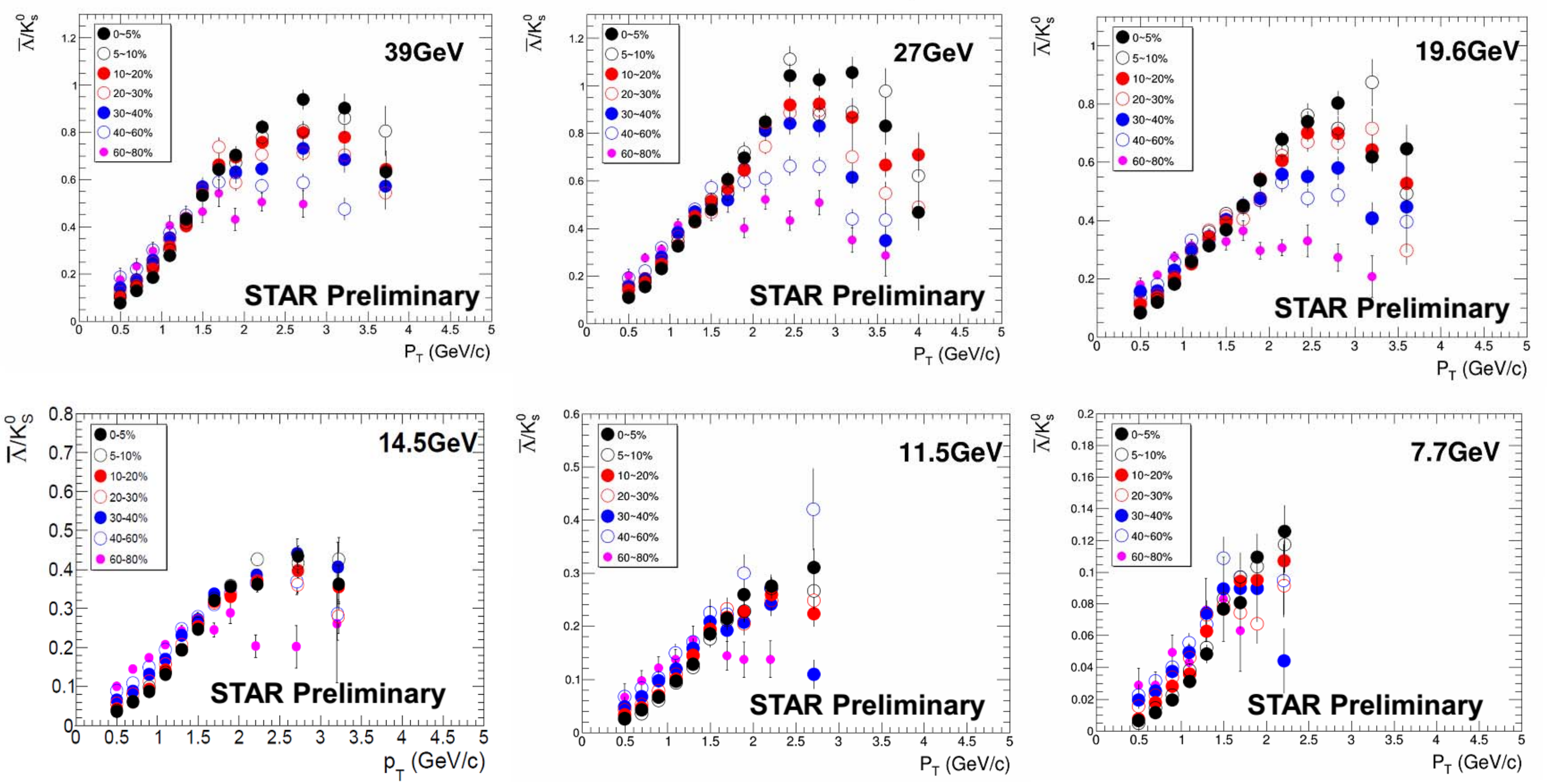


$$R_{CP}(p_T) = \frac{[d^2\sigma/(N_{bin} p_T dp_T dy)]_{central}}{[d^2\sigma/(N_{bin} p_T dp_T dy)]_{peripheral}}$$

- 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**

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

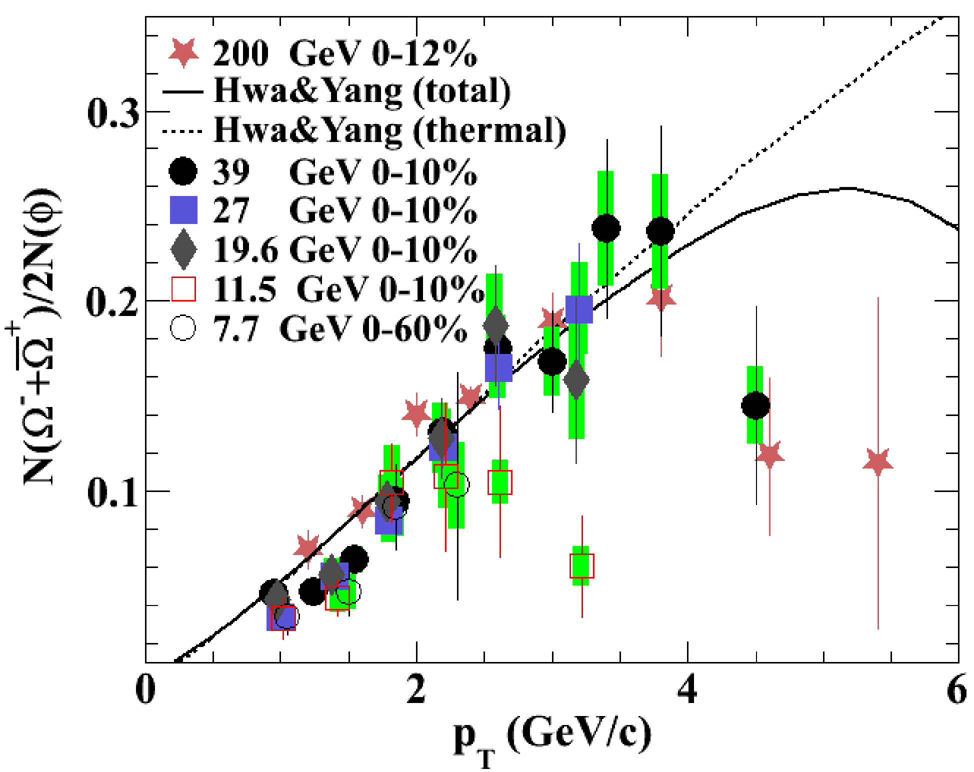
statistical error only

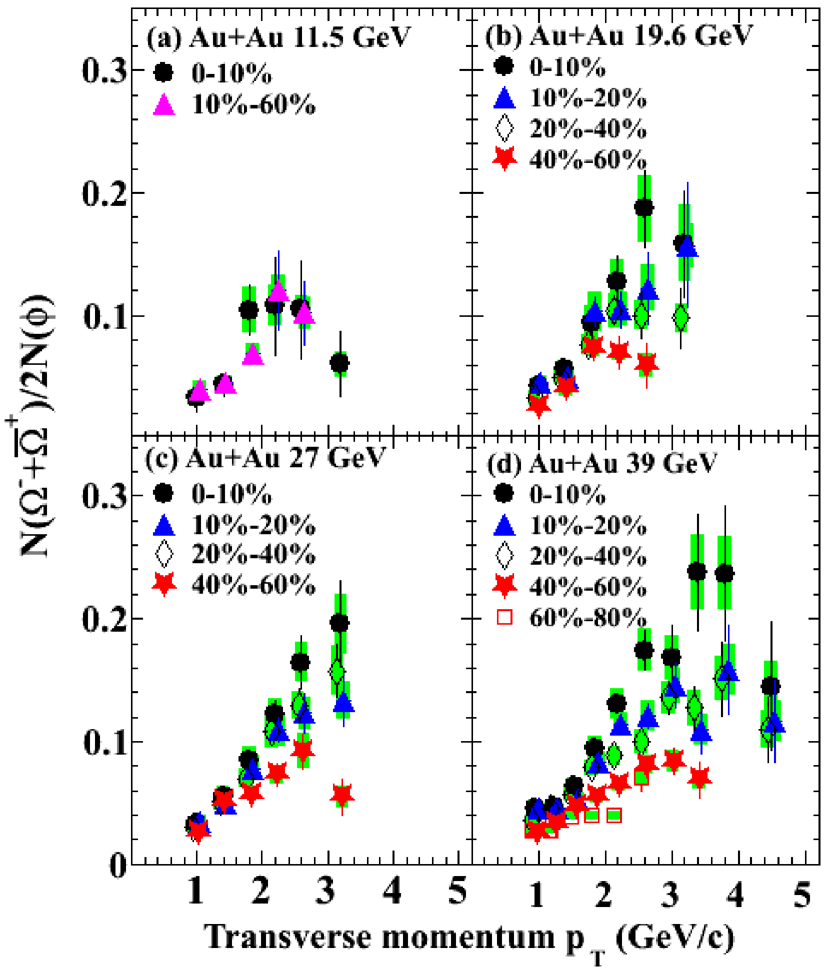


$\sqrt{s_{NN}}$ **≤ 14.5 GeV**, at $p_T \sim$ 2GeV/c, the separation of central (0-5%) and peripheral (40-60%) collisions in $\bar{\Lambda}/K^0_S$ becomes less obvious

July 7, Muhammad Usman Ashraf

Ω / ϕ ratio

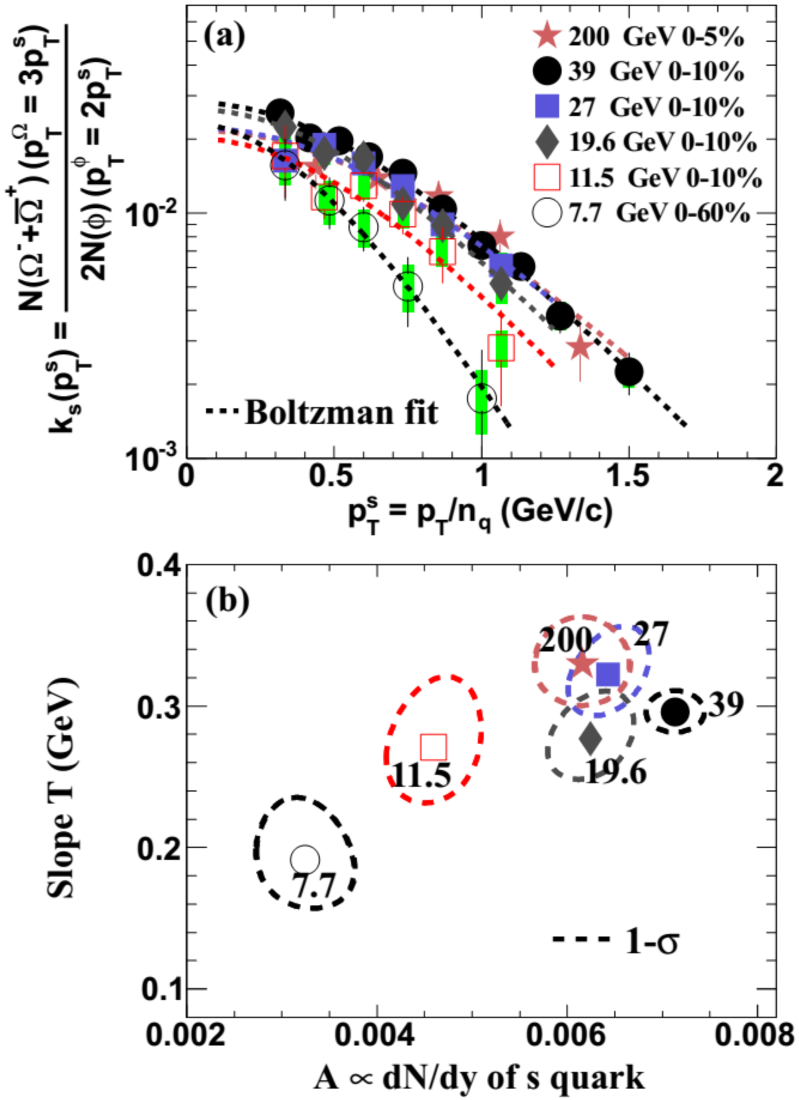


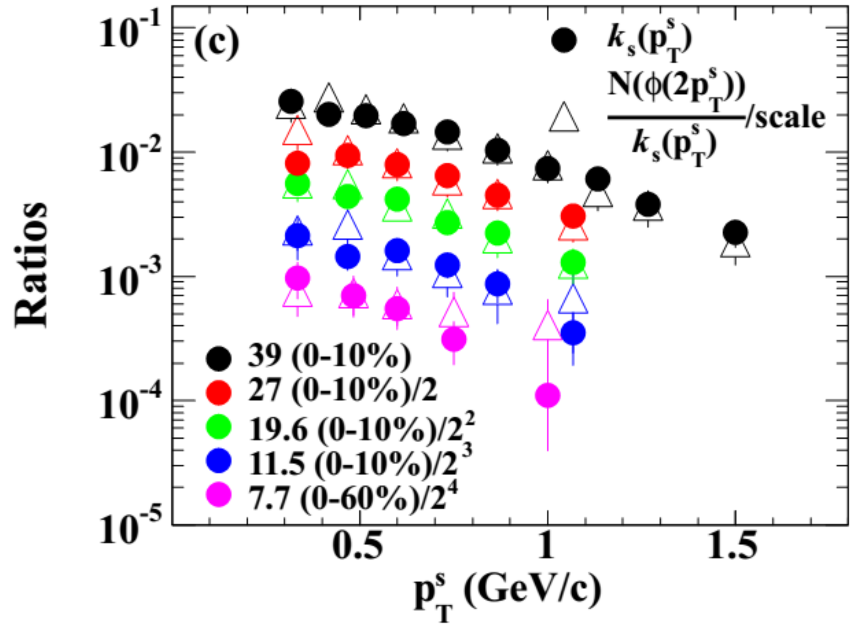


arXiv:1506.07605

- 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

NCQ-scaled Ω/ϕ ratio





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

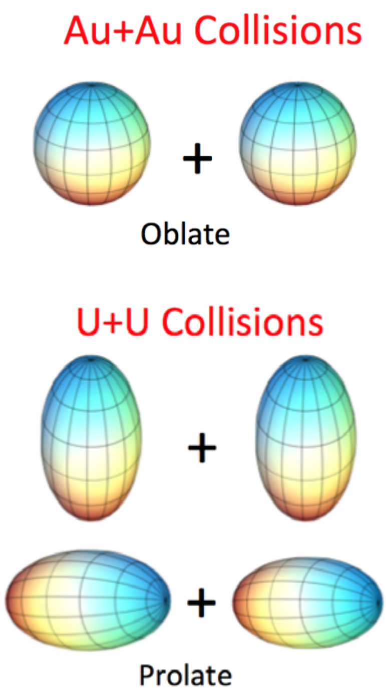
$$f_s(p_T) = \frac{g_\phi}{g_\Omega}\frac{c}{1+c^3}\frac{f(\Omega^- + \Omega^+)(3p_T)}{f(\phi)(2p_T)}$$

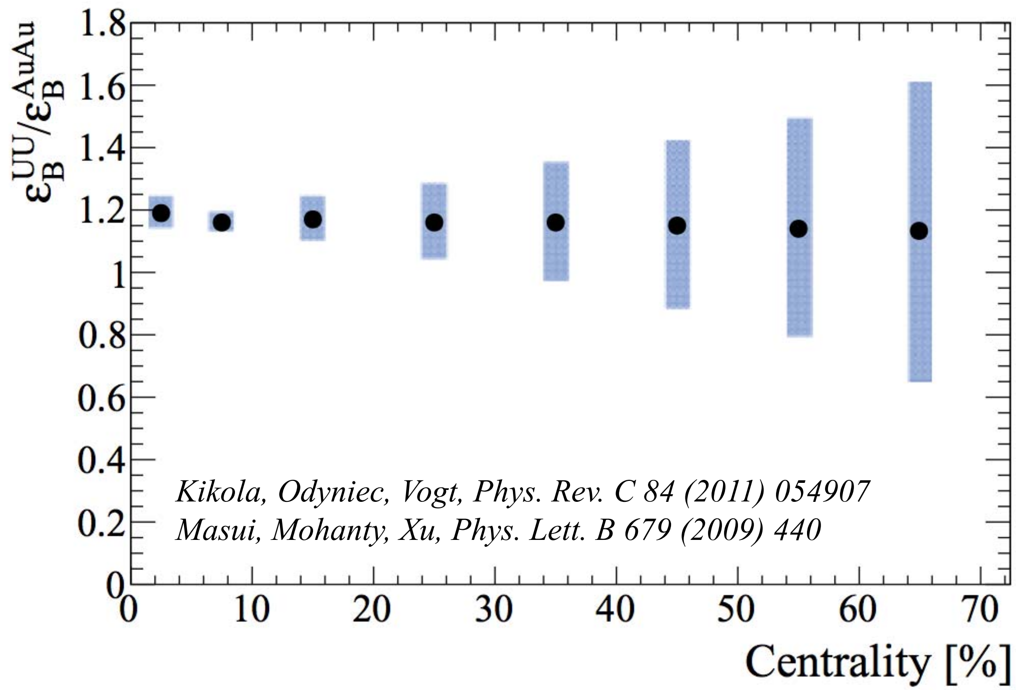
- Suppression of strange quark production below 19.6 GeV, slope change at 7.7 GeV. **Decreasing *s* quark density → phase transition**

arXiv:1506.07605

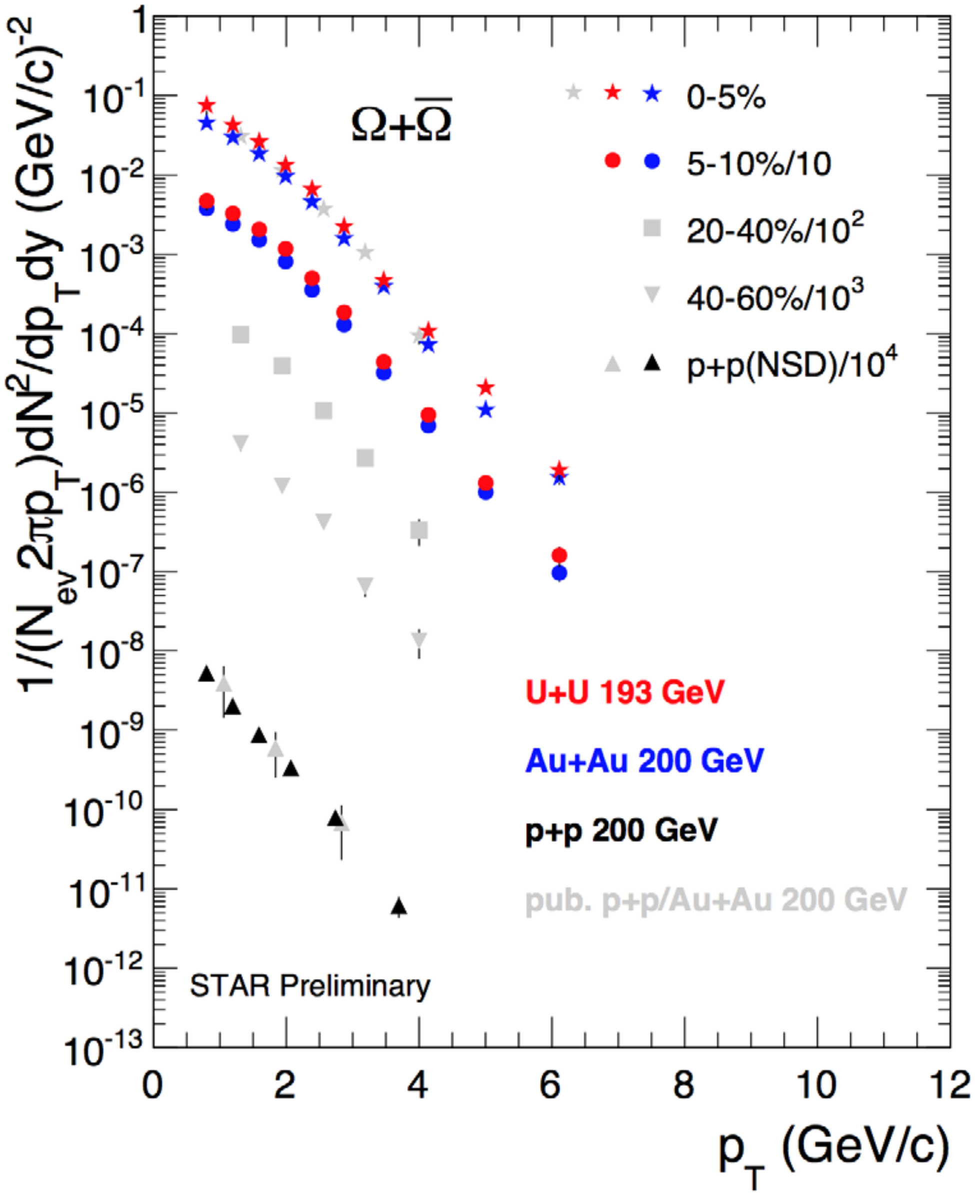
Ω in Au+Au vs in U+U

- 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*

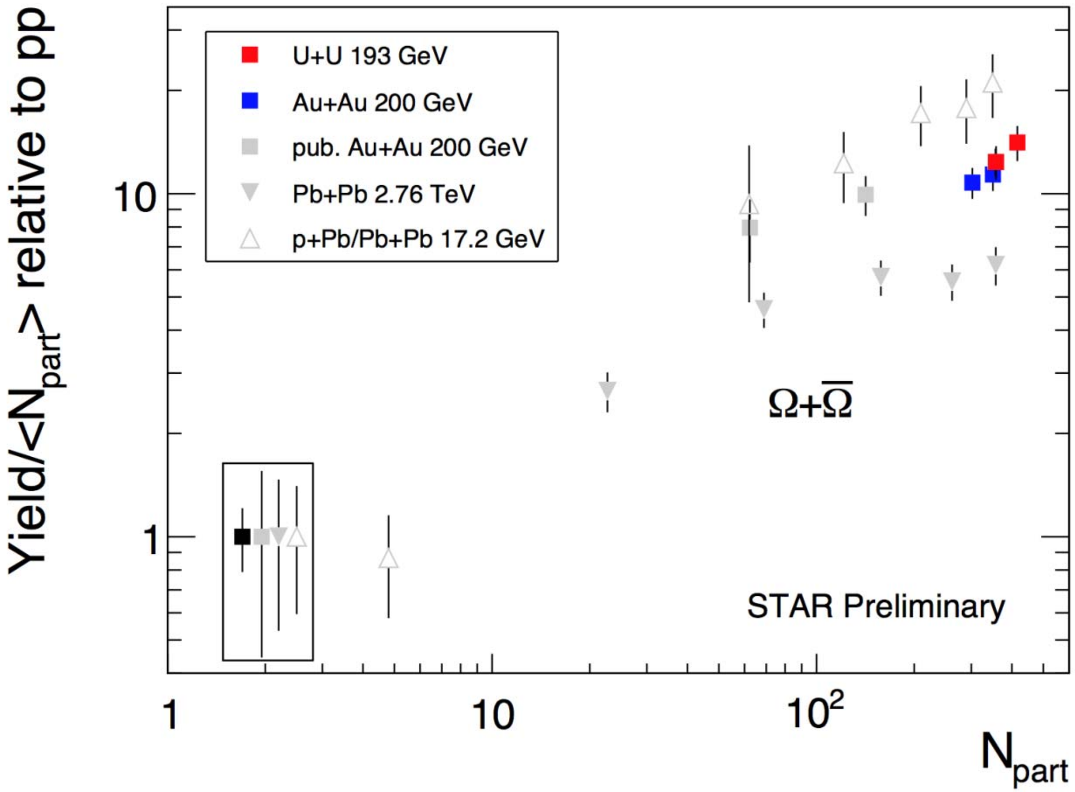
STAR, Phys. Rev. C 75 (2007) 064901

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

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

- Maximum $p_T \sim 6$ 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

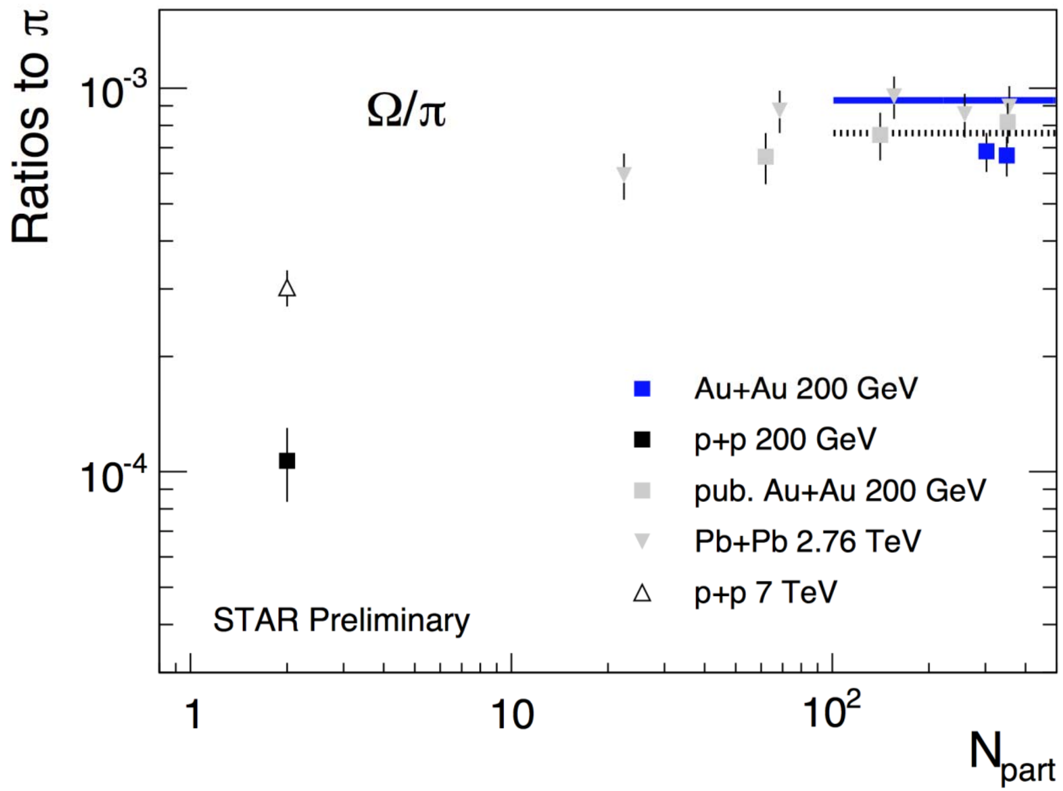
NA57, J. Phys. G 32 (2006) 427;

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



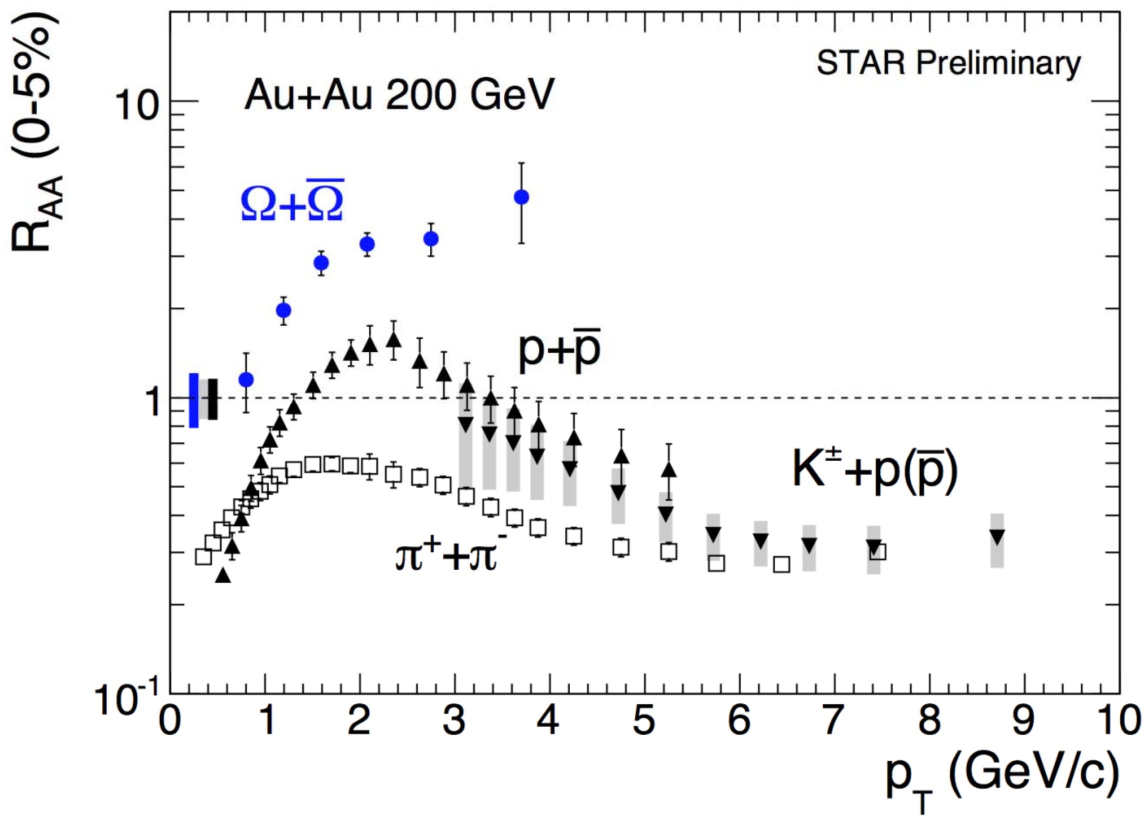
<u>*Thermal models:*</u>

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})



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

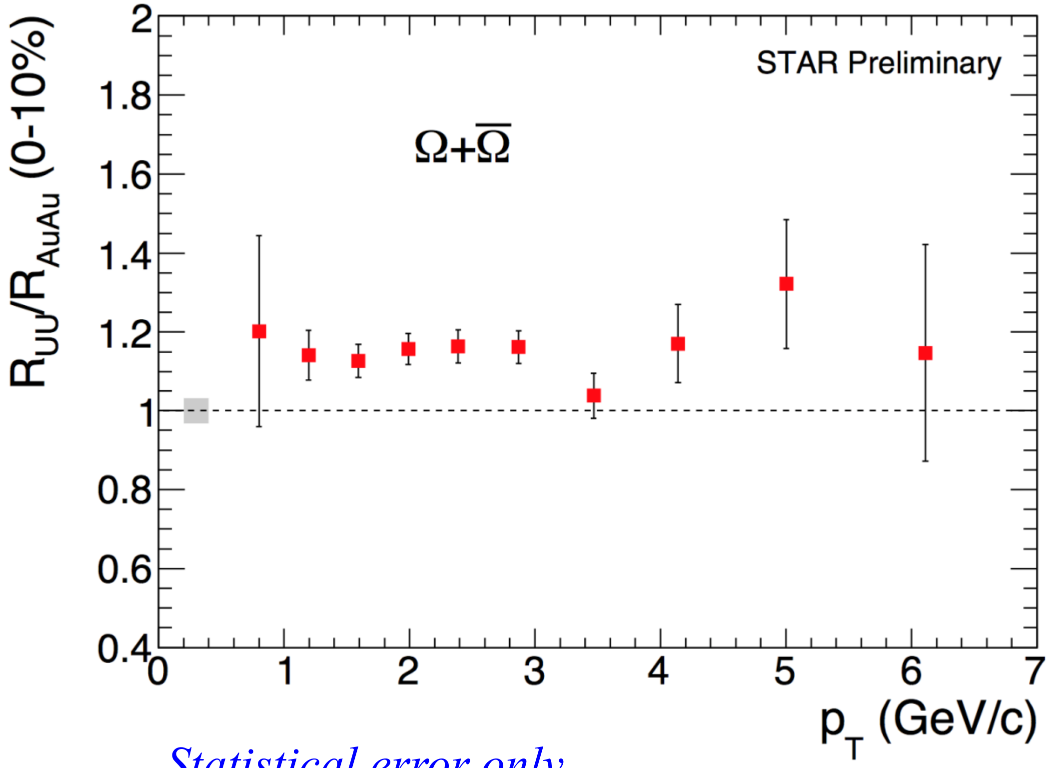
Statistical error only for Ω

$\pi^+ + \pi^-$ 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%*

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

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

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

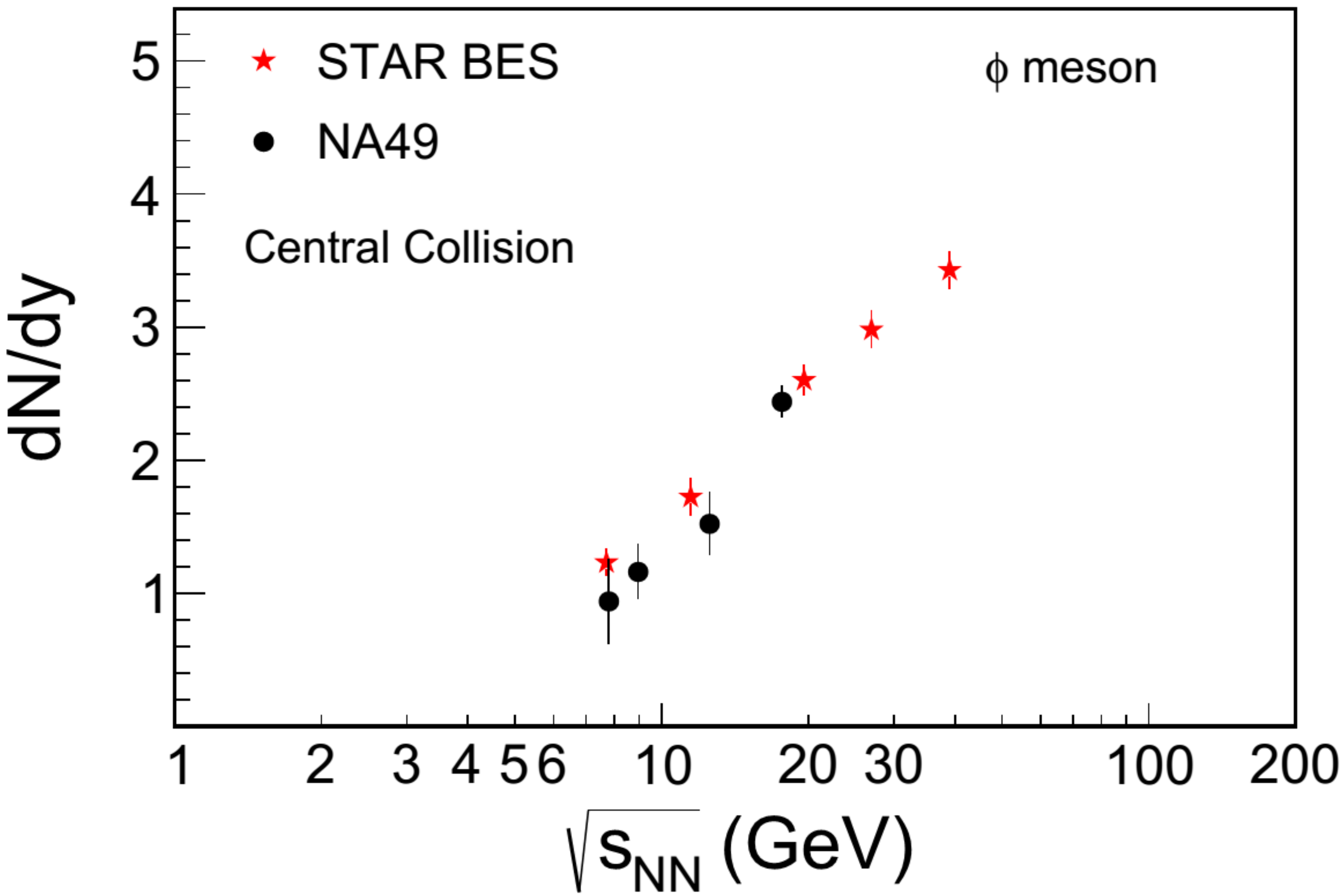
The energy density in central U+U is expected to be 20% higher, but N_{bin}-scaled high p_T Ω yield is not more suppressed

→ Ω formed through coalescence/recombination up to $p_T \sim 6$ GeV/c ?

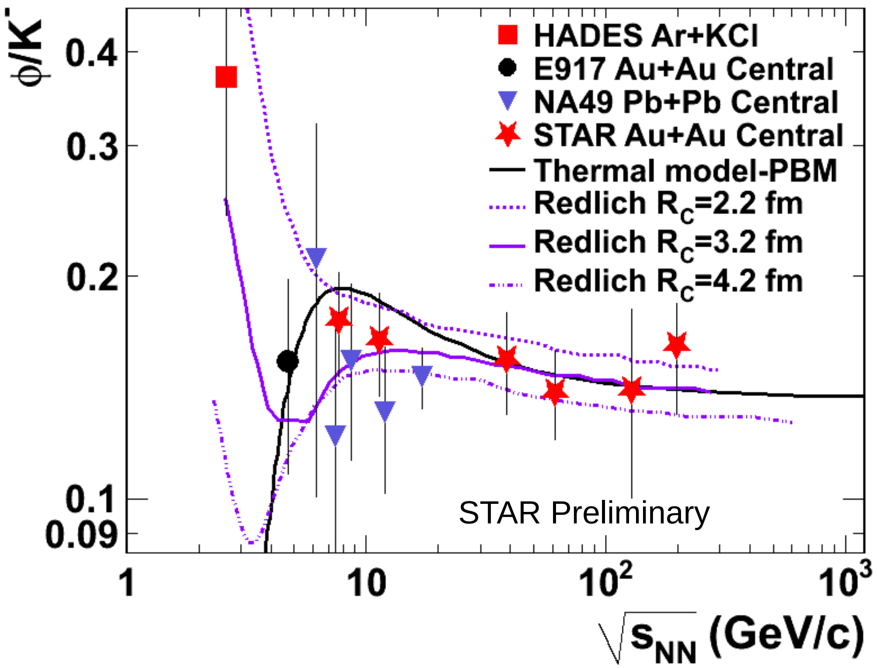
Summary

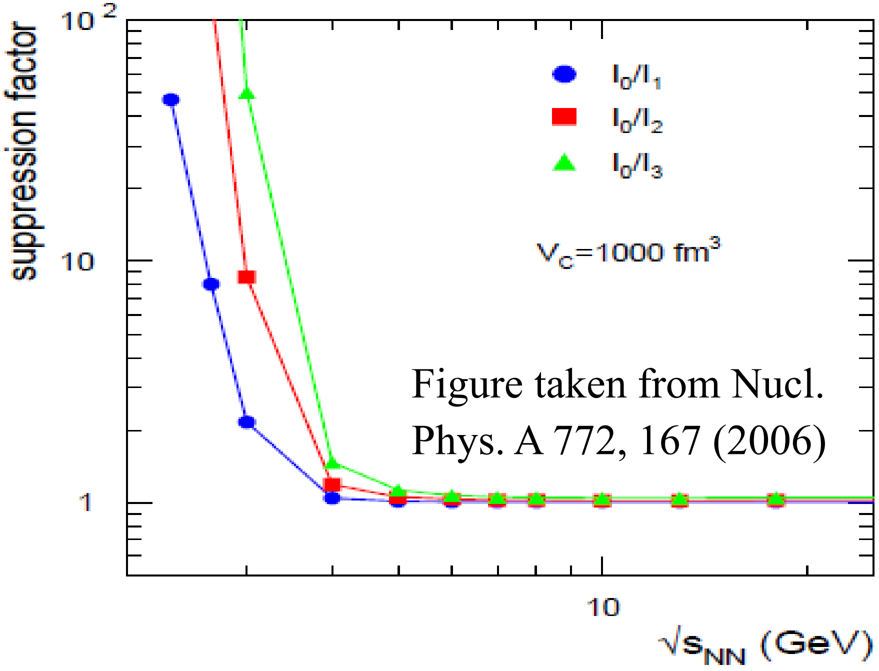
- STAR has measured systematically the production of various strange hadrons in $\sqrt{s_{NN}}$ = 7.7 - 200 GeV and in different collision systems
- Particle yields and ratios are consistent with the picture of a maximum net-baryon density around $\sqrt{s_{NN}} \sim 8$ GeV at freeze-out, baryon transport 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 $p_T \sim 6$ GeV/c

Backup


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

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