Beam Energy Dependence of Strange Hadron Production from STAR at RHIC

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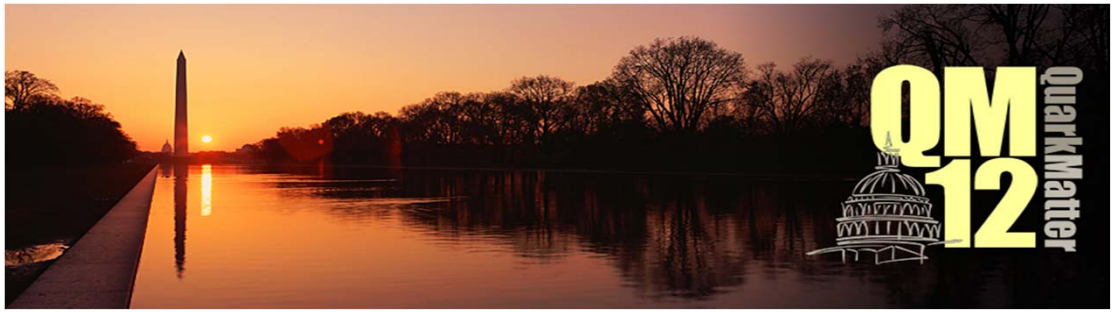
For the STAR Collaboration



Aug. 13-18, Washington, DC, USA

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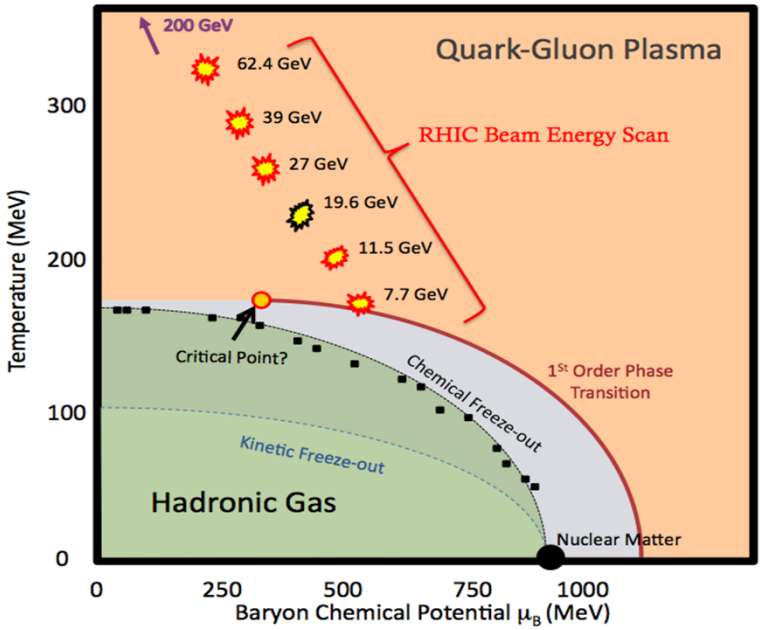
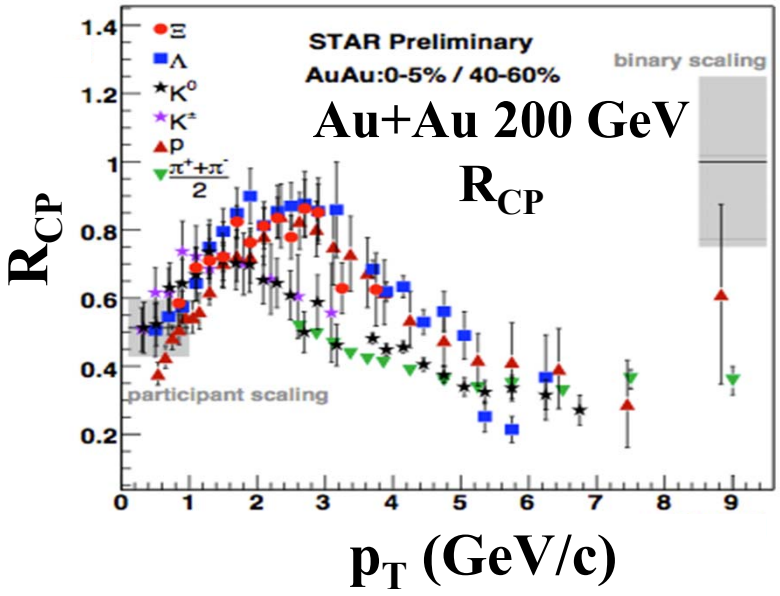
Outline

- Motivation for strangeness production measurement in STAR Beam Energy Scan (BES)
- Strangeness ($K^{\pm}$, K^{0}_{S}, ϕ, Λ, Ξ, Ω) production at mid-rapidity
  - ✓ p_T spectra
  - ✓ Particle yields and ratios
  - ✓ Mean transverse kinetic energy: $\langle m_T \rangle - m_0$
  - ✓ Central-to-peripheral nuclear modification factor: R_{CP}
  - ✓ Baryon enhancement: Ω/ϕ
- Summary

Motivation: 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, 19.6, 27, 39, 62.4 GeV

➢ Key observables on de-confinement

(1) Strangeness enhancement

(2) Baryon/meson ratio

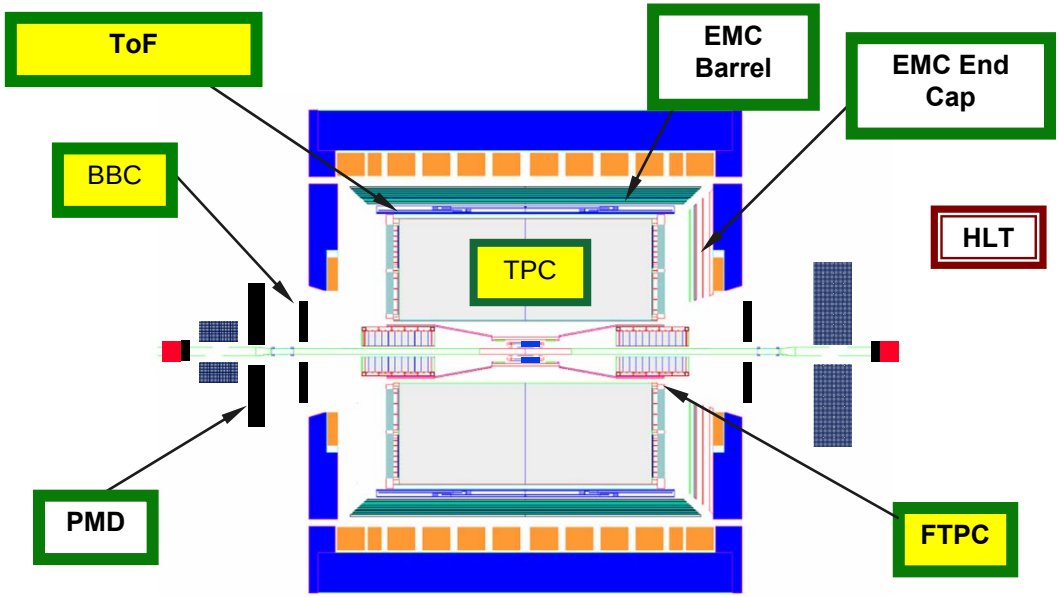
Parton recombination

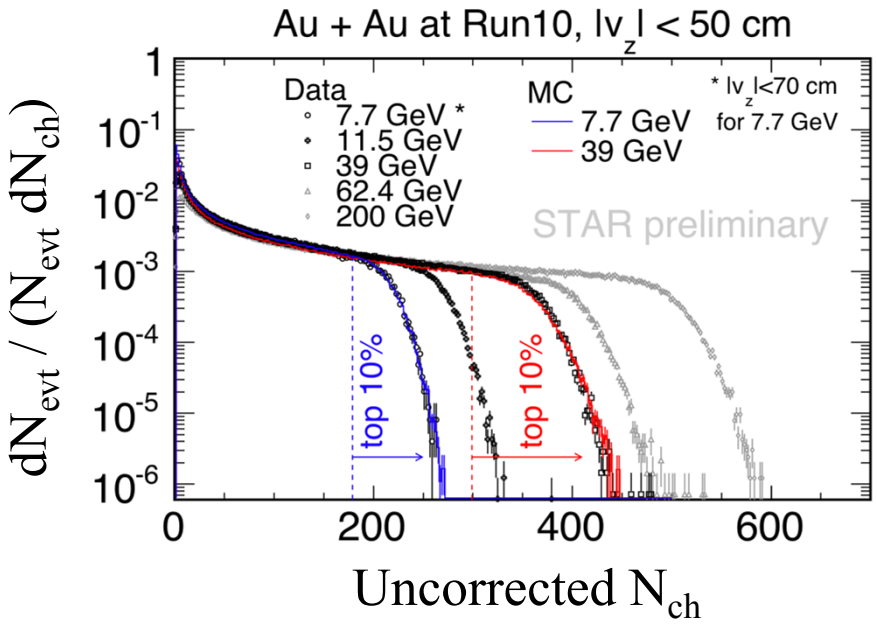
(3) Nuclear modification factor

Partonic energy loss & recombination

STAR, arXiv:1007.2613; NA49, PRC78, 034918

Detector settings during STAR BES 2010-2011

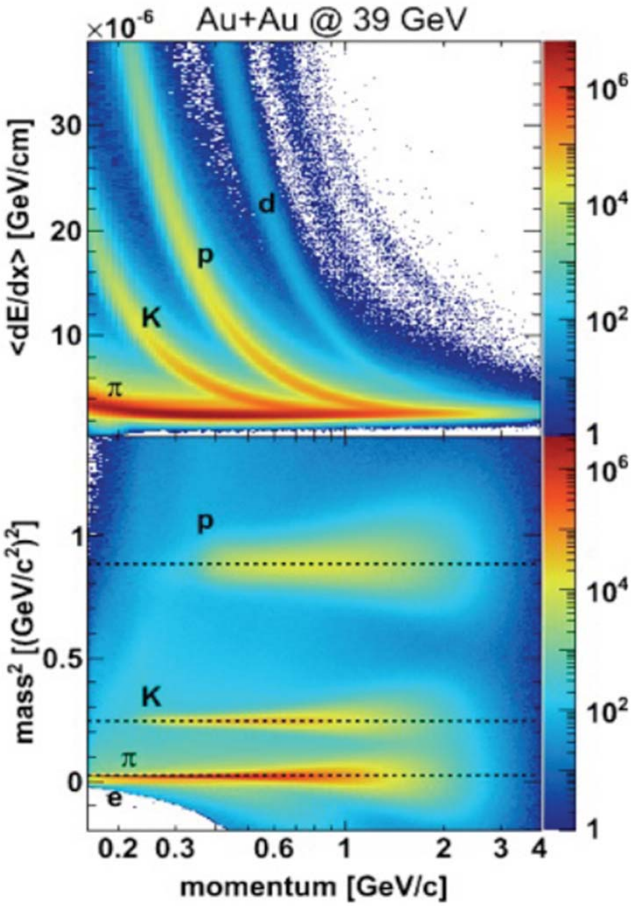


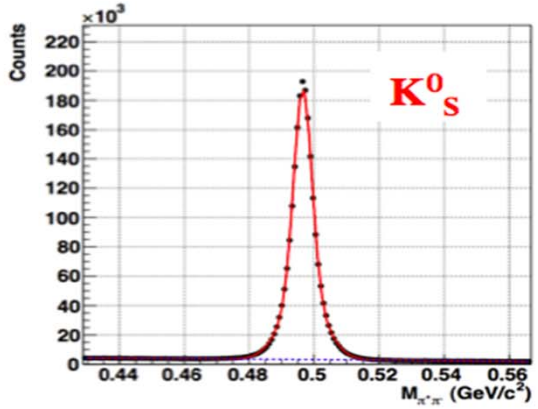


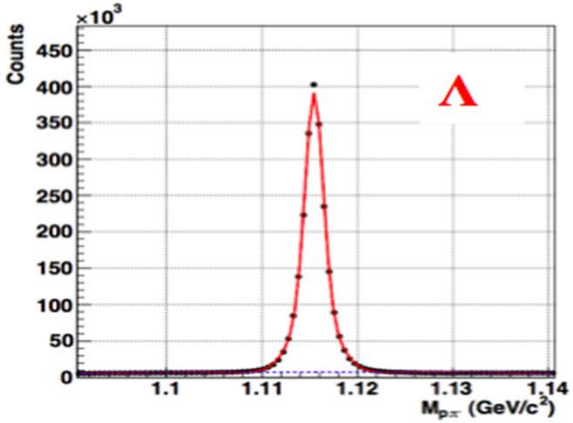
- Collisions: Au+Au
- Collisions centrality from uncorrected $dN_{ch}/d\eta$ in $|\eta| < 0.5$

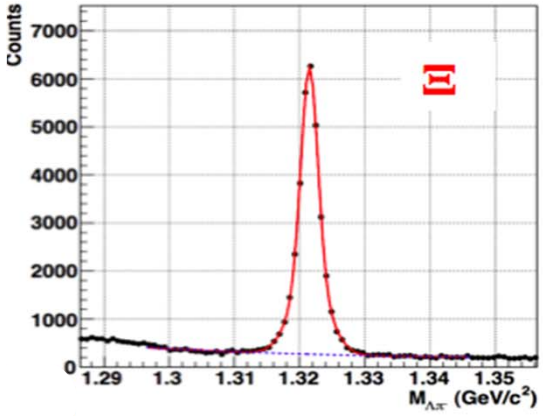
$\sqrt{s_{NN}}$ (GeV)	Good MB events in Million
7.7	~ 4 M
11.5	~ 12 M
19.6	~ 36 M
27	~ 70 M
39	~ 130 M
62.4	~ 67 M

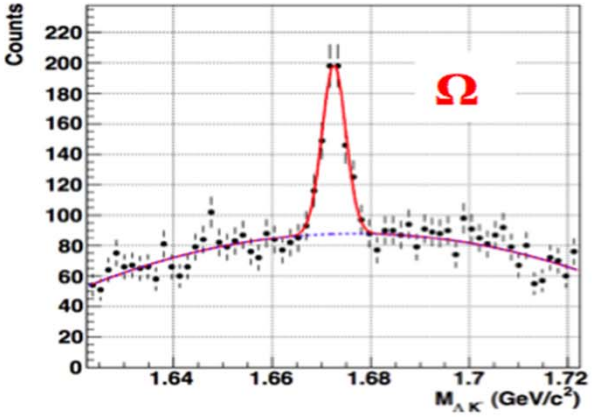
Particle identification and reconstruction

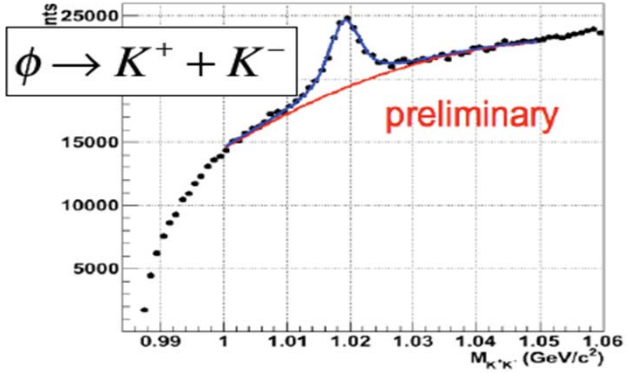






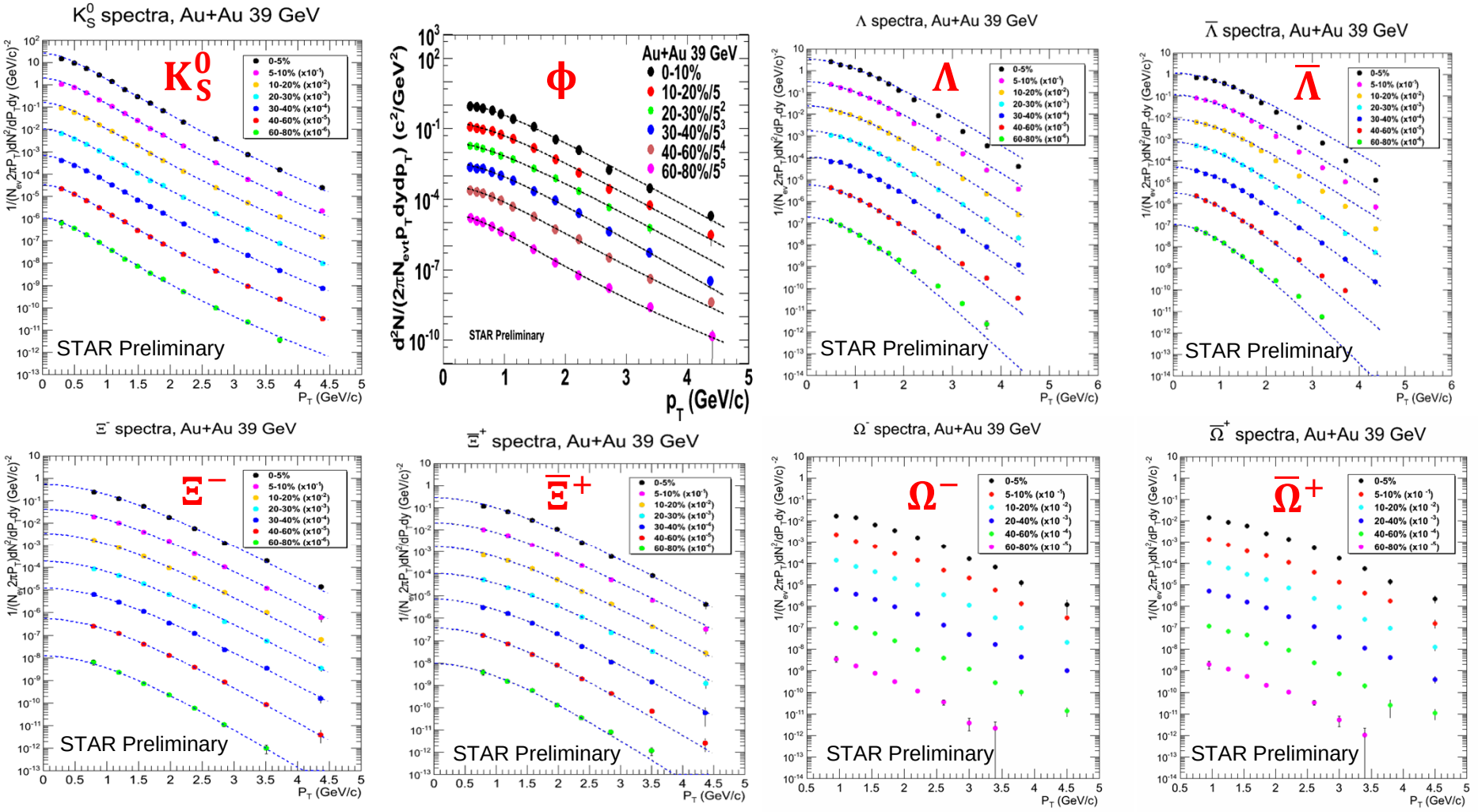






- dE/dx+TOF: π, K, p and $\phi \rightarrow K^+ + K^-$ (invariant mass)
- Weak decay particles (K^0_S, Λ, Ξ, Ω), secondary vertex + invariant mass

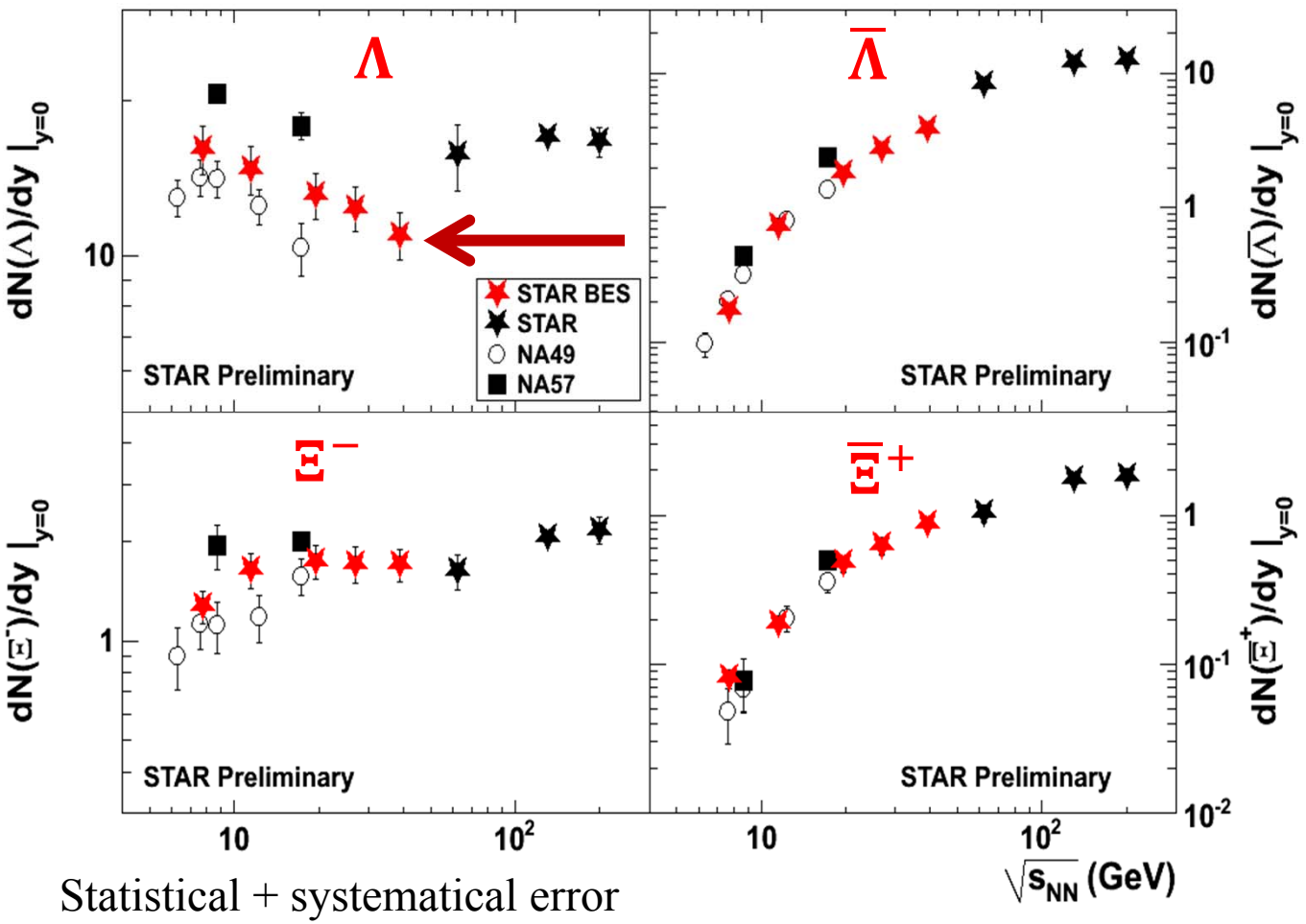
p_T spectra (39 GeV)



- 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



Statistical + systematical error

- **Central collisions**
- **Mid-rapidity**

NA49, PRC78,034918.
7% or 10% most central.
(|y|<0.4 or 0.5)

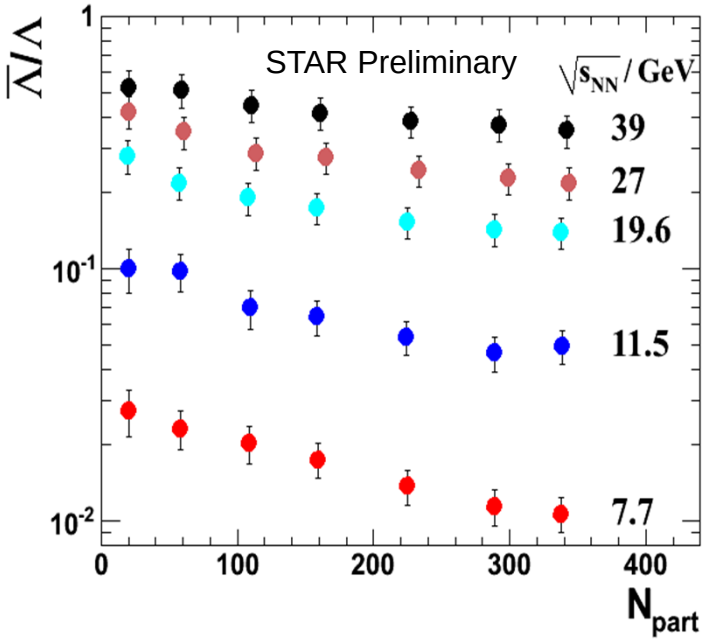
NA57, PLB595,68; JPG32, 427
0-4.5% most central,
|y|<0.5, stat. err. only

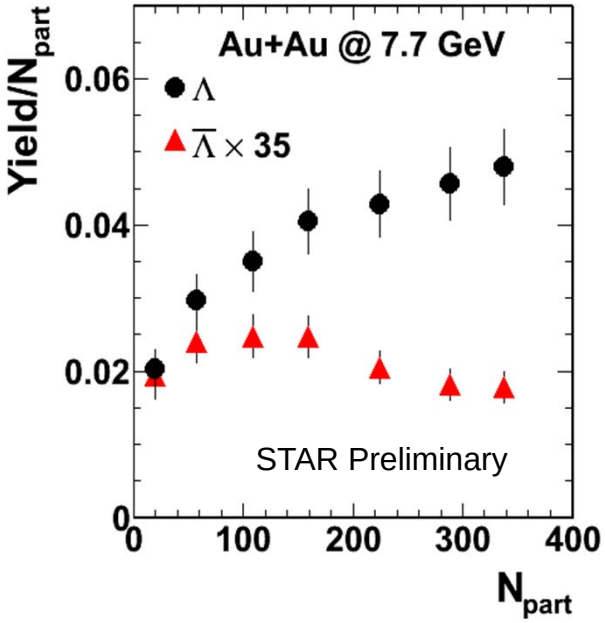
STAR, PRL86,89,92,98;PRC83
0-5% most central,
|y|<0.5

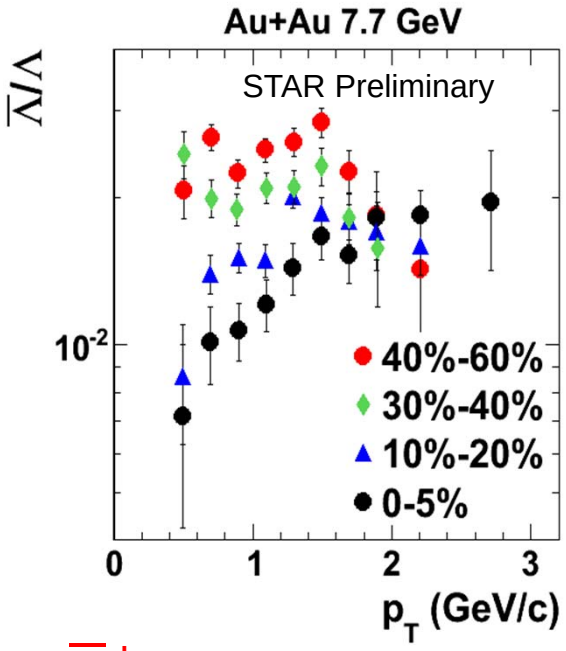
- The NA57 and NA49 yields have been scaled by the corresponding number of wounded nucleons, **STAR results closer to NA49**
- **Λ yields show dip at 39 GeV. Why? the baryon stopping at mid-rapidity may decrease with increasing energy**

$\bar{B}/B$ ratios

$\bar{\Lambda}/\Lambda$

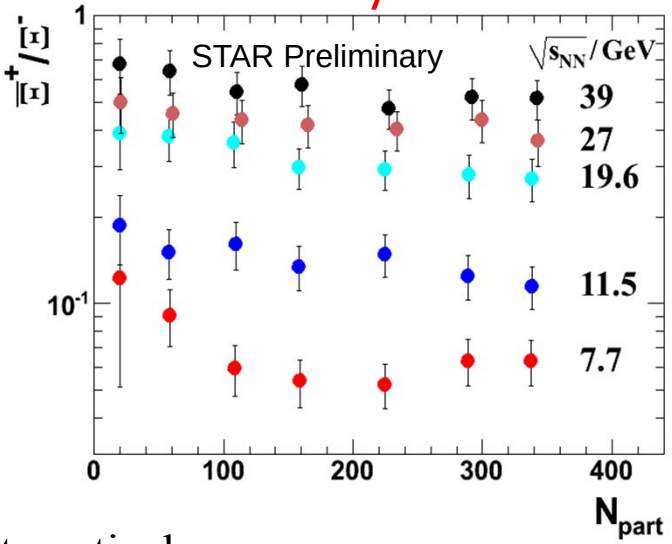






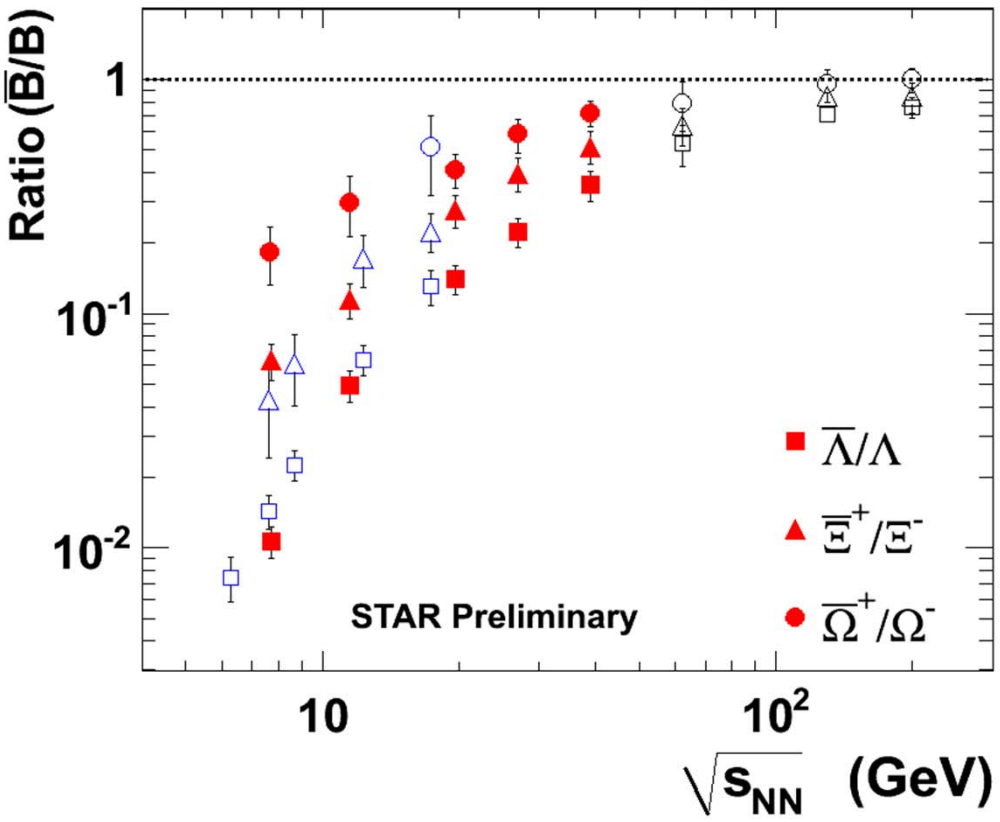
- Centrality dependence of $\bar{B}/B$ ratios:
  peripheral > central
- This effect is more prominent at lower energies.
  baryon stopping, absorption
- **Loss of low p_T $\bar{\Lambda}$ in central collisions**

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



Statistical + systematical error

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

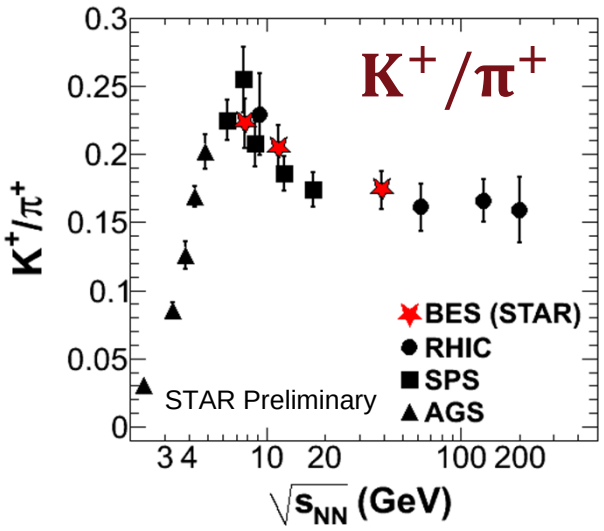


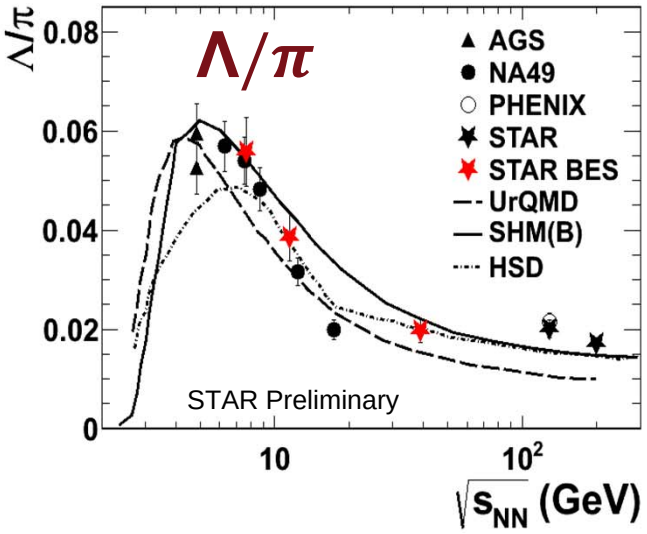
Statistical + systematical error

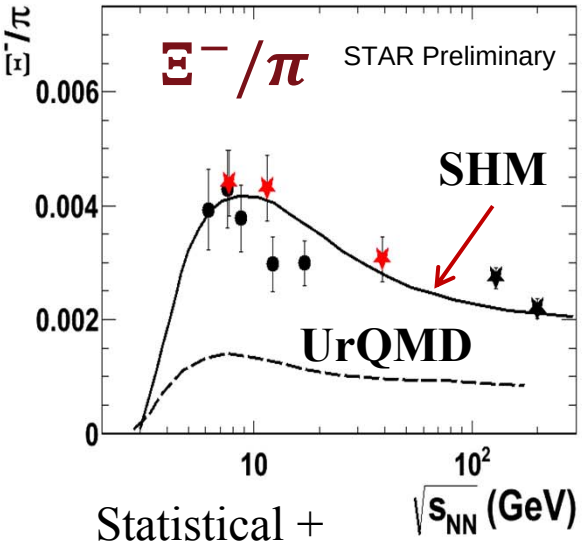
Left: Solid red: STAR BES; Solid blue: STAR published; Open blue: NA49

- STAR BES data lie in a trend with NA49 data
- $\bar{B}/B$ ratios increase with number of strange quarks at low energies $\bar{\Omega}^+/\Omega^- > \bar{\Xi}^+/\Xi^- > \bar{\Lambda}/\Lambda$: pair production v.s. baryon transport & associated production

Particle ratios

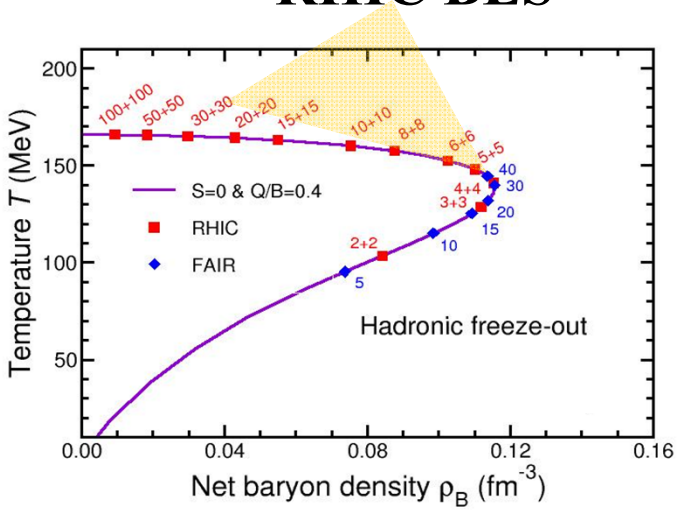






Statistical + systematical error

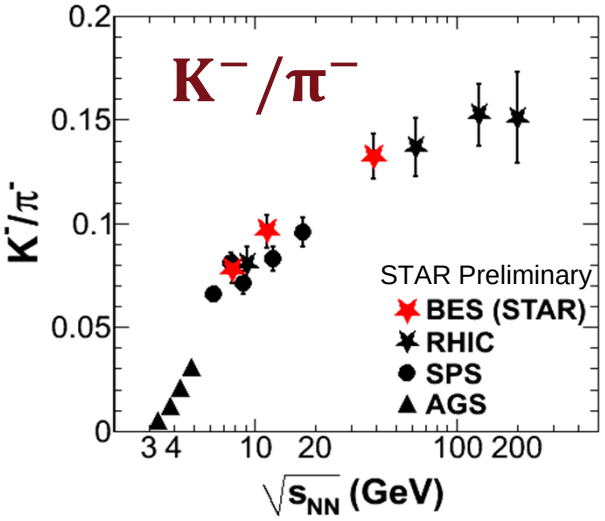
RHIC BES

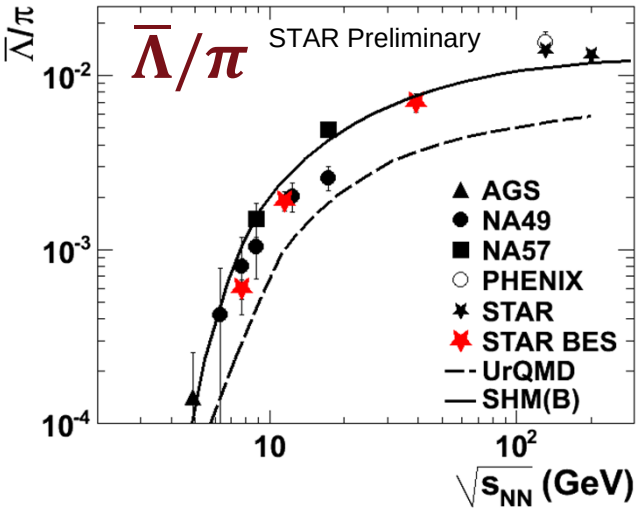


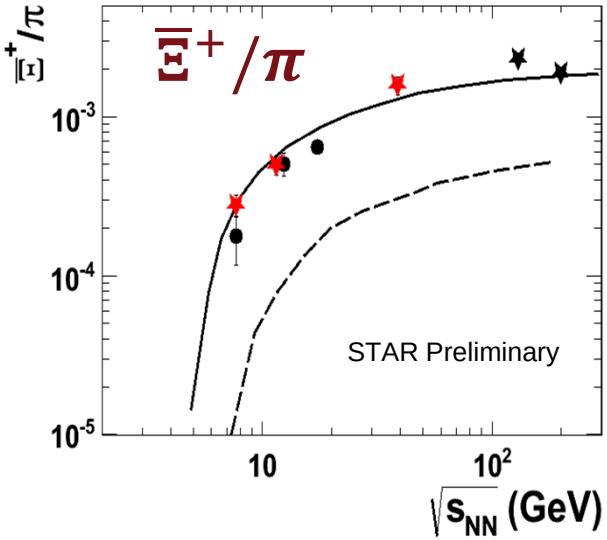
J. Randrup et al., PRC 74, 047901 (2006)

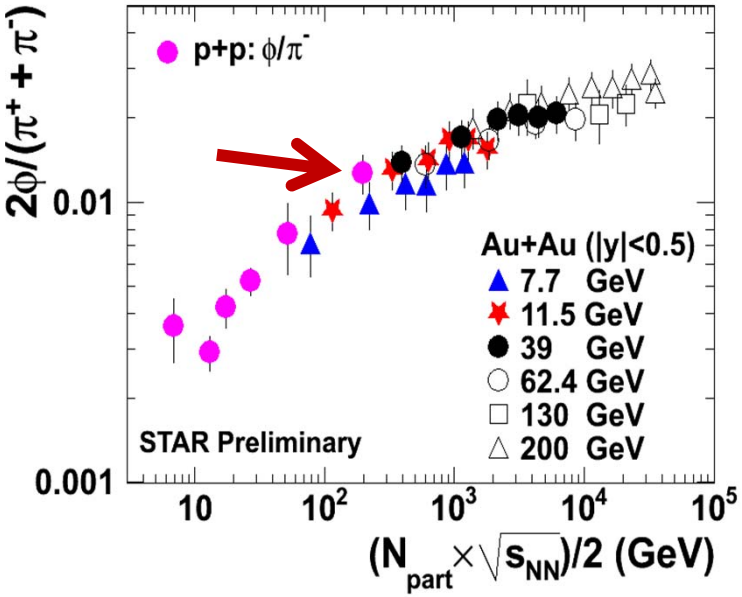
- Central, mid-rapidity
- Particle ratios consistent with NA49, consistent with the picture of a **maximum net-baryon density around $\sqrt{s_{NN}} \sim 8$ GeV at freeze-out**
- Associate production channels like $N + N \rightarrow N + \Lambda + K^+$ may be important for K^+ production, N is nucleon

Particle ratios





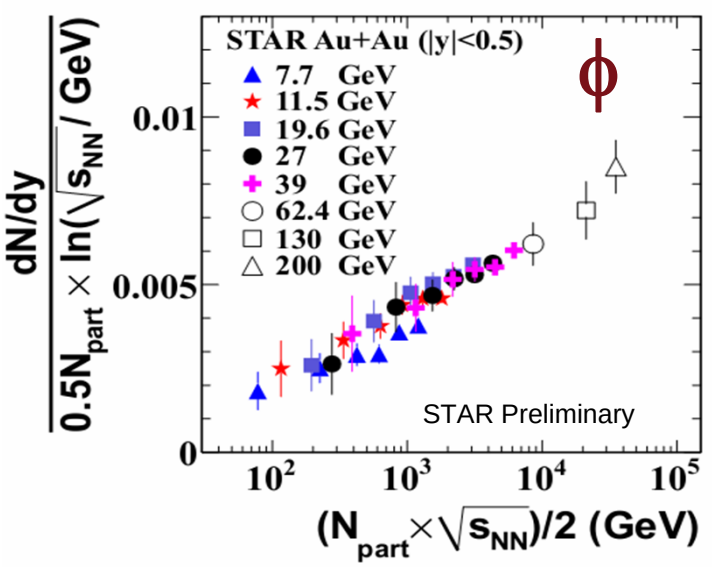




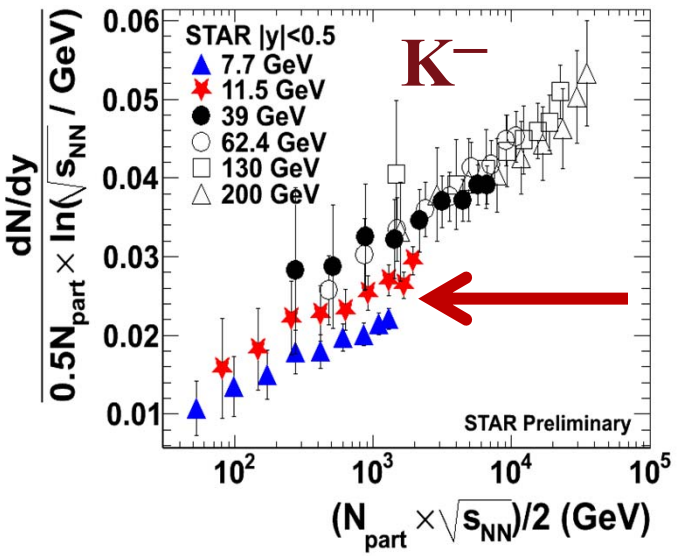
- **Clear K^-, $\bar{\Lambda}$, $\bar{\Xi}^+$ yield enhancement compared to pions with increasing collision energy**
- **Similar behavior for hidden strangeness $\phi(s\bar{s})$**
- New scaling for ϕ/π v.s. ~total collision energy, system size insensitive, initial production seems important for ϕ

Statistical + systematical error

New scaling on yields



Statistical error

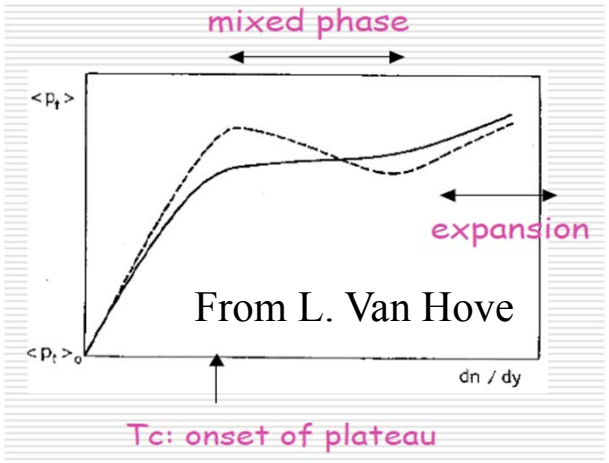


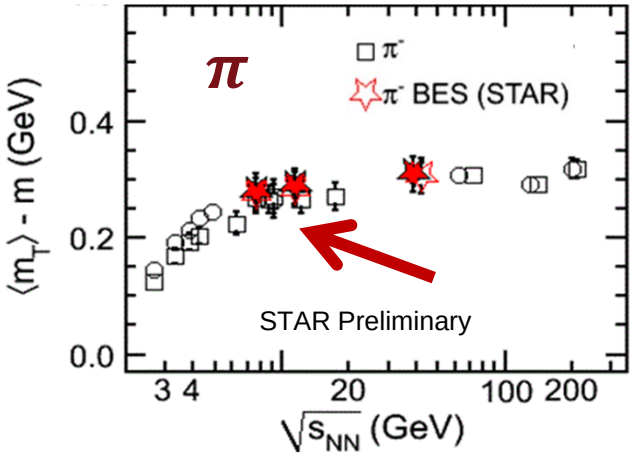
Statistical + systematical error

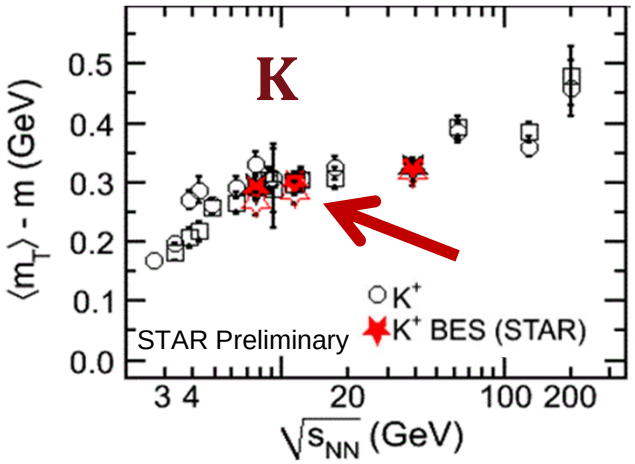
- ϕ mesons follow total participant nucleons energy scaling
- **K^- yield is lower than expected from the scaling in low beam energies**
- $\phi(s\bar{s})$: hidden strangeness K^- $(\bar{u}s)$: open strangeness
- Absorption of K^- ? no significant centrality dependence
- **Strangeness quark pairs $(s\bar{s})$ correlation scenario**, "K^- is suppressed compared to ϕ meson at small phase space", **qualitatively consistent**

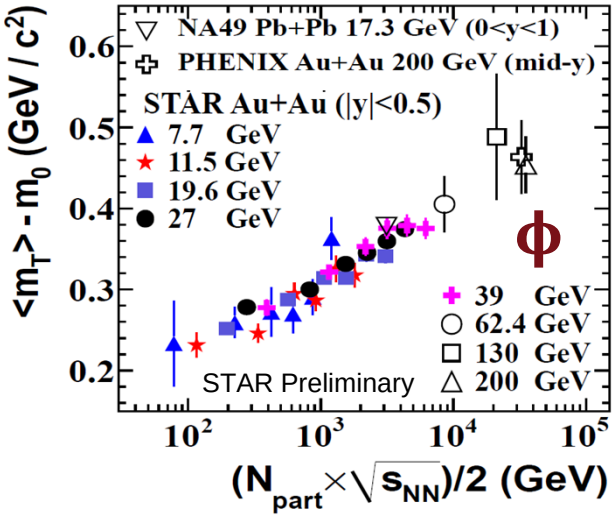
Redlich et al: Phys. Lett. B 603, 146 (2004)

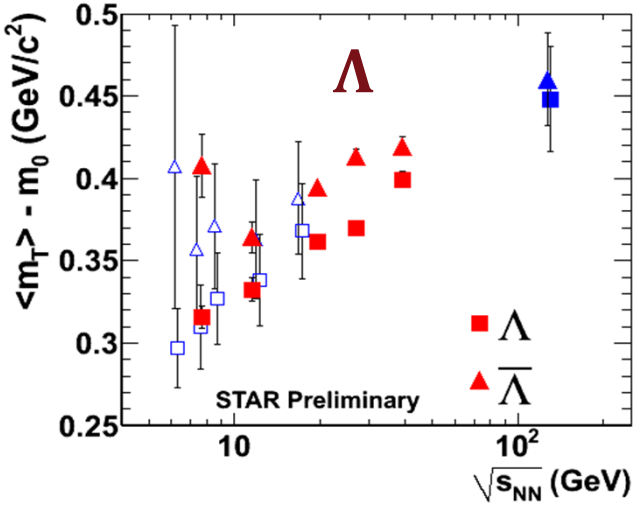
Beam energy dependence of $\langle m_T \rangle - m_0$

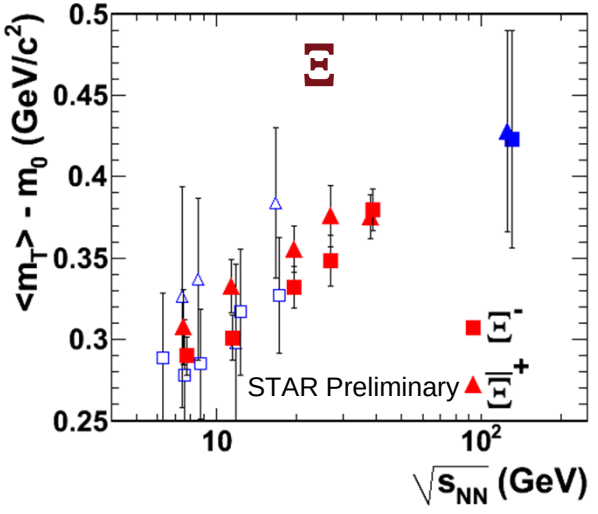










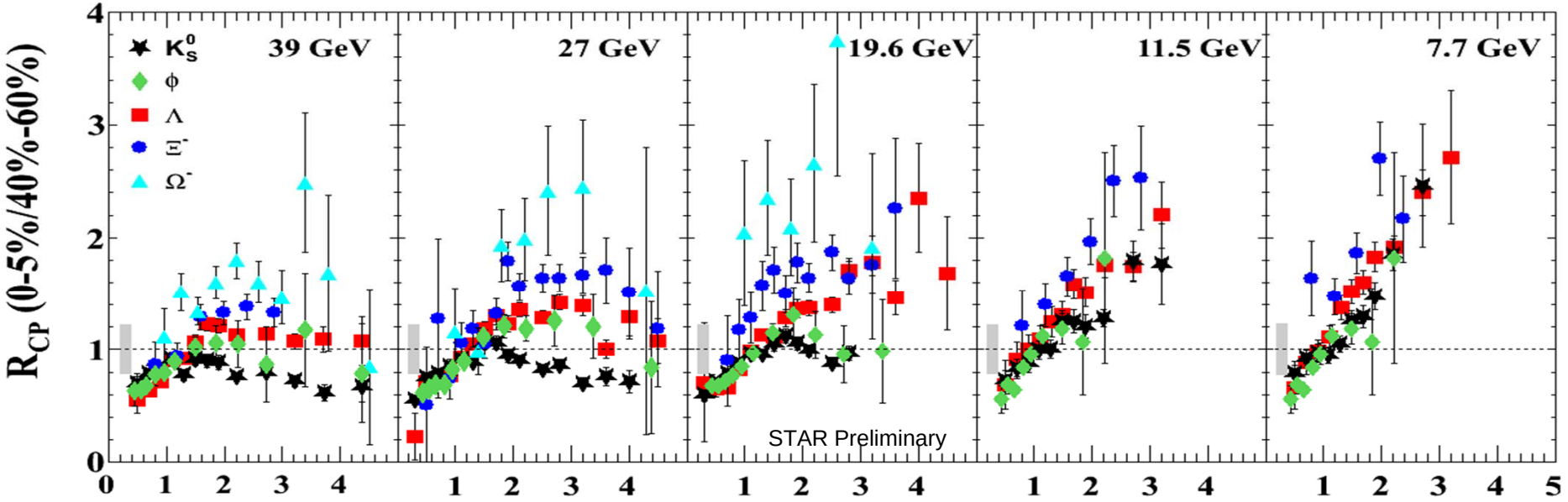


- For heavy strange hadrons ϕ, $\bar{\Lambda}$, $\bar{\Xi}$, $\langle m_T \rangle - m_0$ show increasing trend with energy, **mass matters**

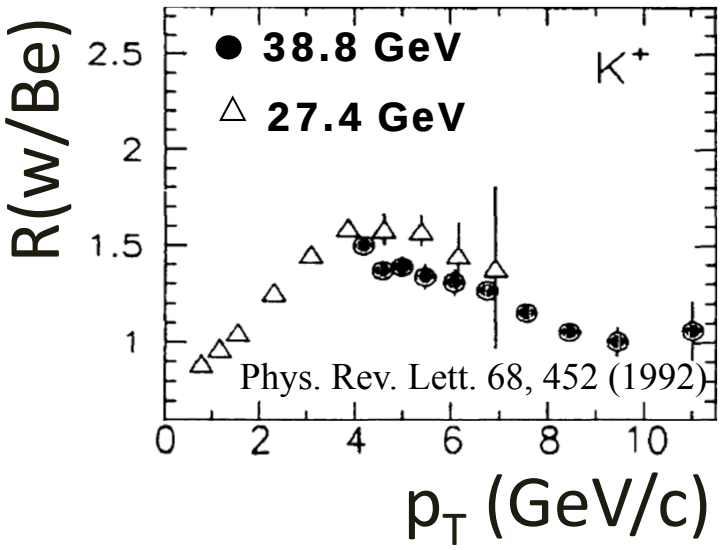
ϕ meson, statistical error

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

Nuclear modification factors R_{CP}



φ meson R_{CP}: 0-10%/40%-60%

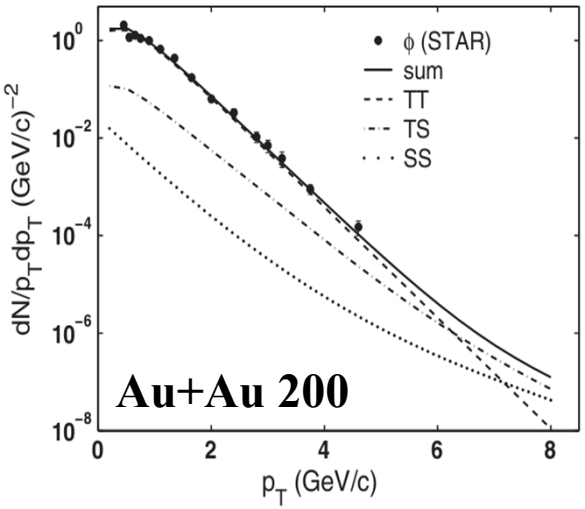


$$R_{CP}(p_T) = \frac{[d^2\sigma/(N_{\text{bin}} p_T dp_T dy)]_{\text{central}}}{[d^2\sigma/(N_{\text{bin}} p_T dp_T dy)]_{\text{peripheral}}}$$

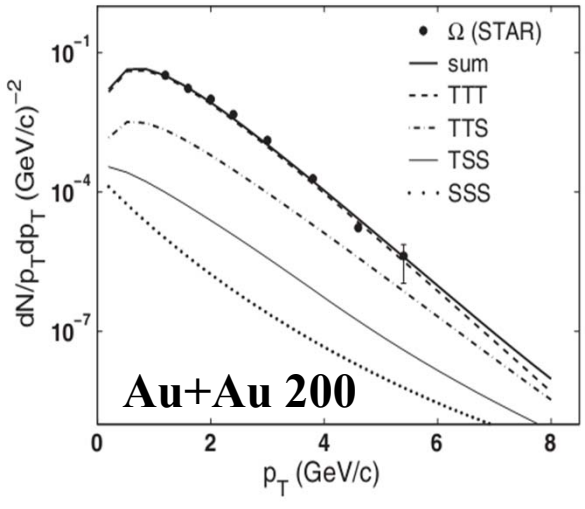
- No K^0_S suppression in Au+Au 7.7 and 11.5 GeV
- **Cronin effect takes over partonic rescatterings @ lower energies**
- Intermediate p_T, particle R_{CP} difference **becomes smaller @ 7.7 and 11.5 GeV**

Ω/ϕ ratio

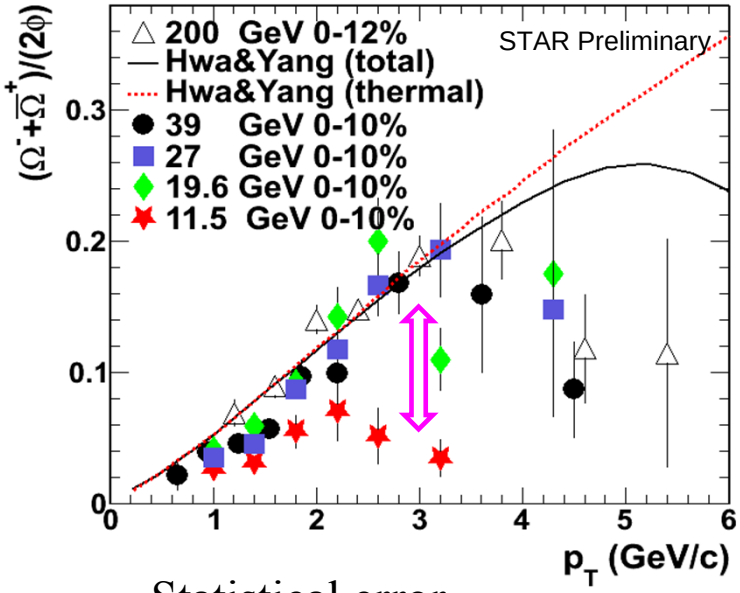
ϕ



Ω



Hwa & Yang, Phys. Rev. C 75, 054904 (2007)



Statistical error

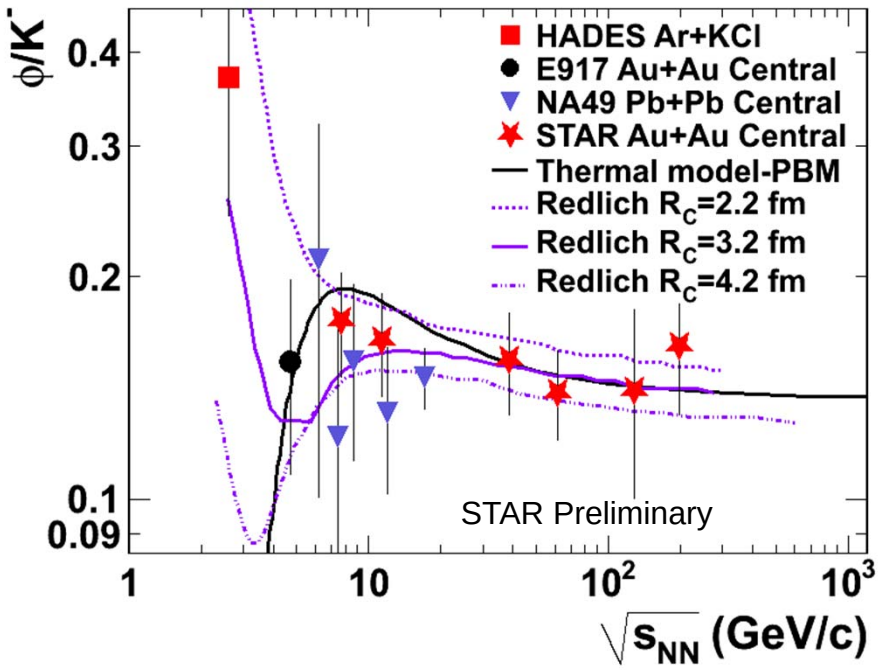
- **Ω and ϕ p_T distribution is sensitive to strange quark thermalization and recombination.** Intermediate p_T Ω yield enhancement is explained by mainly thermal *s* quark recombination @ Au+Au 200 GeV
- **Intermediate p_T Ω/ϕ ratios: clear separation between ≥ 19.6 and 11.5 GeV** (probability of same ratios in p_T 0.8—3.6 GeV/c: 11.5 & 19.6 GeV: 8.6×10^{-5}; 19.6 & 27 GeV: 0.50; preliminary systematical error included)
- Change of Ω production mechanism? **parton recombination fails at 11.5 GeV?**

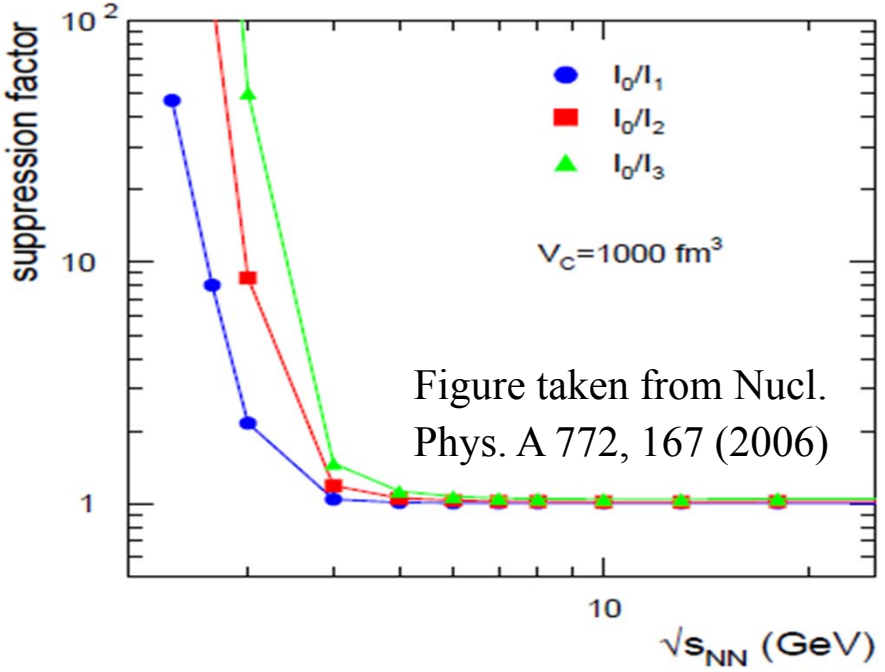
Summary

- Measurements of strange hadron production in $\sqrt{s_{NN}}$ = 7.7 - 39 GeV
- 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
- The evolution of K^- and ϕ meson yields v.s. system size and collision energies is qualitatively consistent with **strange quark pair ($s\bar{s}$) correlation** scenario
- Intermediate p_T Ω/ϕ ratios and nuclear modification factors show **clear separation between 200 – 19.6 GeV and below 11.5 GeV**, phase transition?

Backup

Different strangeness production scenarios



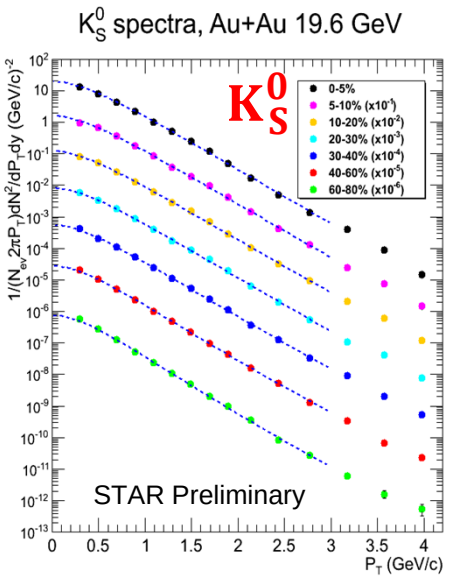


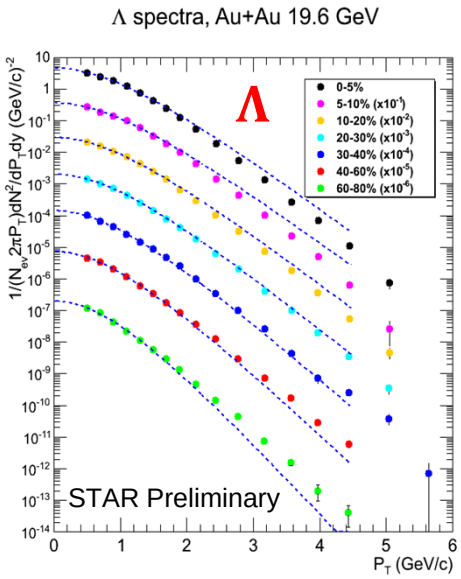
HADES: Phys. Rev. C 80, 025209 (2009) E917: Phys. Rev. C 69, 054901 (2004)
NA49: Phys. Rev. C 78, 044907 (2008) STAR 62.4, 130 & 200 GeV: Phys. Rev. C 79, 064903 (2009)
Thermal model-PBM: Nucl. Phys. A 772, 167 (2006)
Redlich model: Phys. Lett. B 603, 146 (2004)

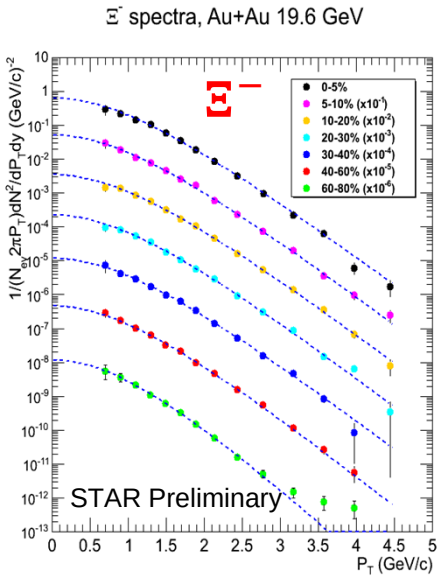
Statistical + systematical error

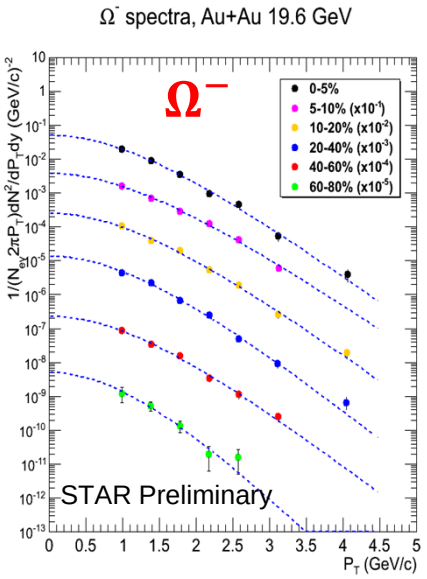
- Canonical statistical model: "**ϕ is more suppressed than K^- at small phase space**"
- Strangeness quark pairs ($s\bar{s}$) correlation, radius R_C: 2.2 ─ 4.2 fm
  "**K^- is more suppressed than ϕ at small phase space**"

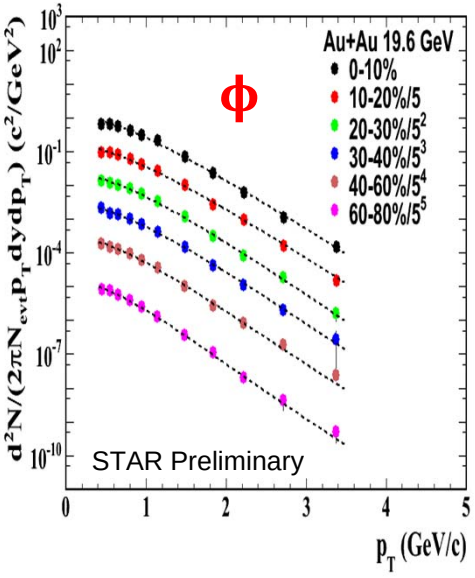
Au+Au 19.6 GeV spectra

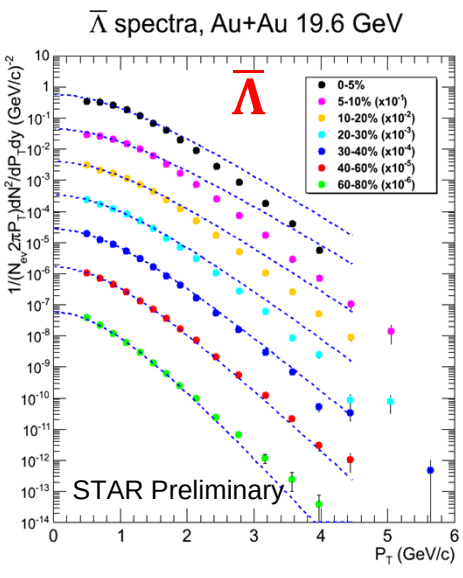


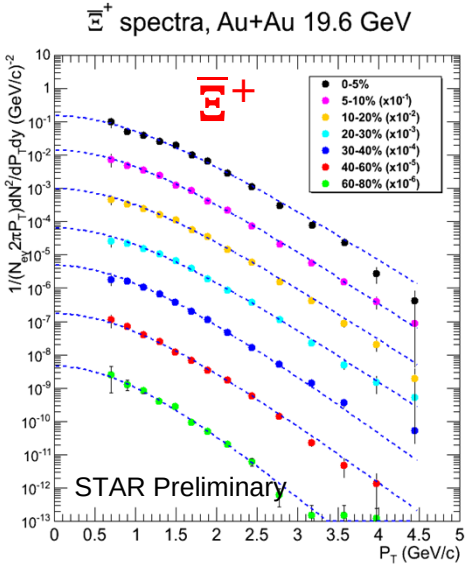


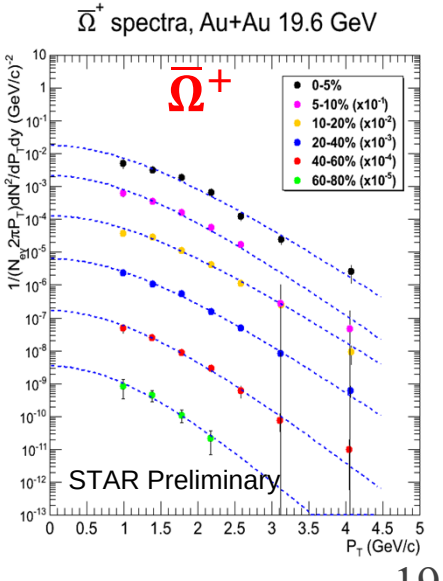




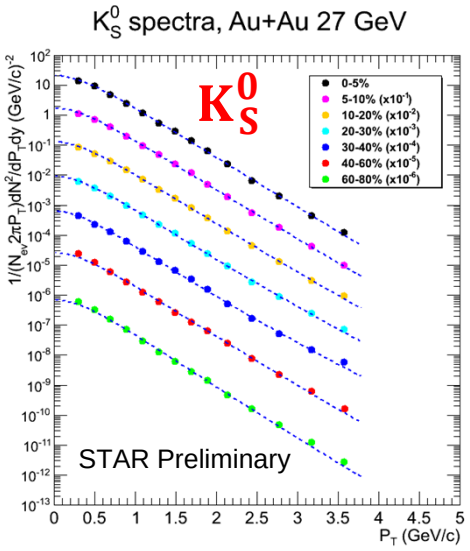


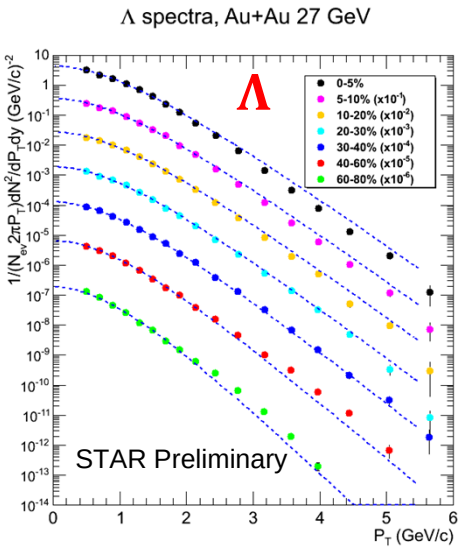


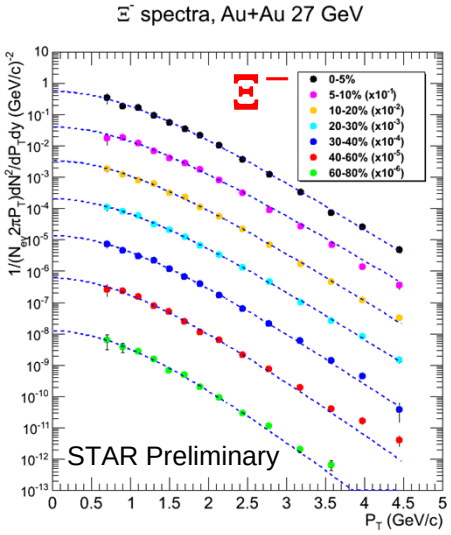


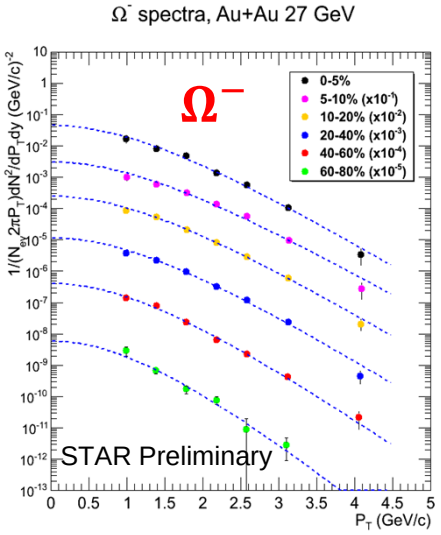


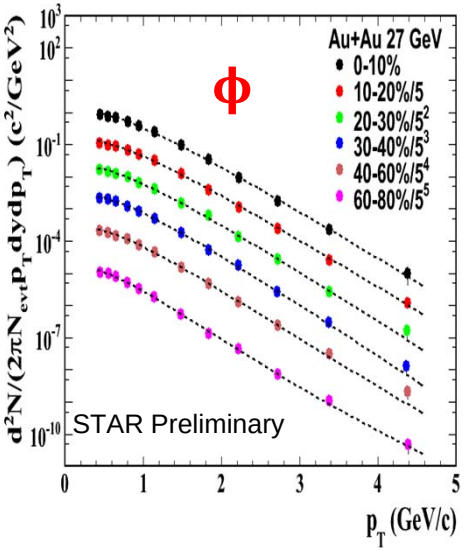
Au+Au 27 GeV spectra

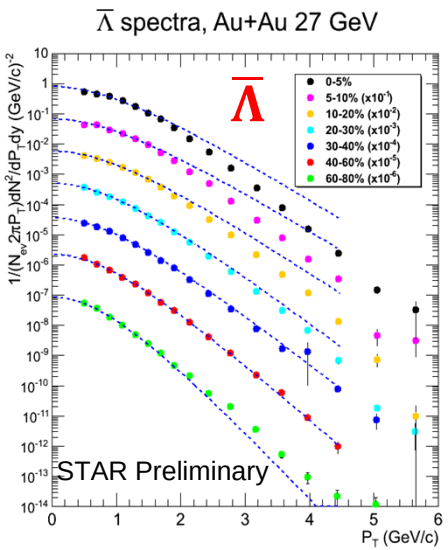


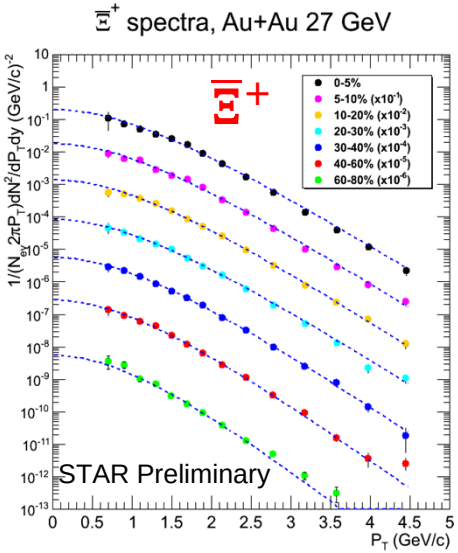


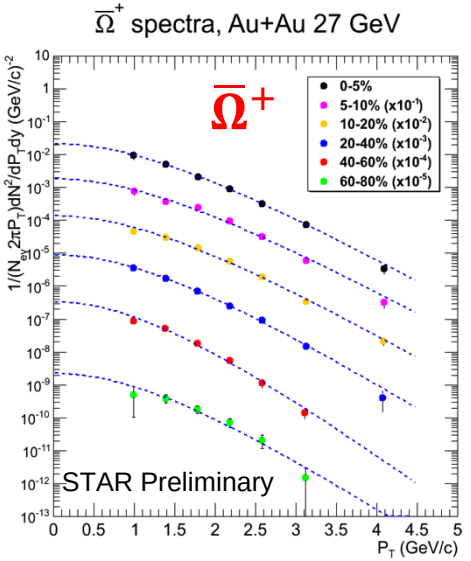






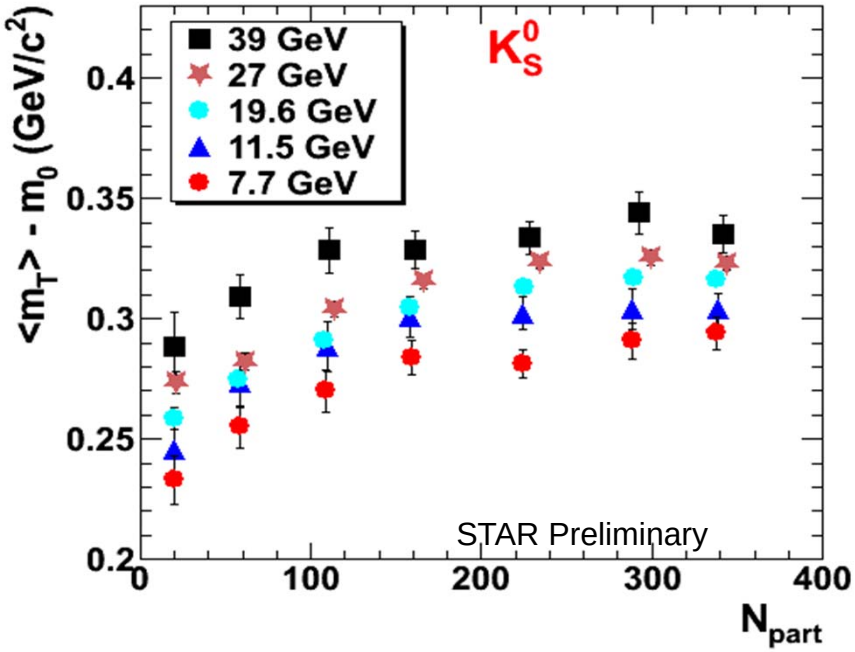


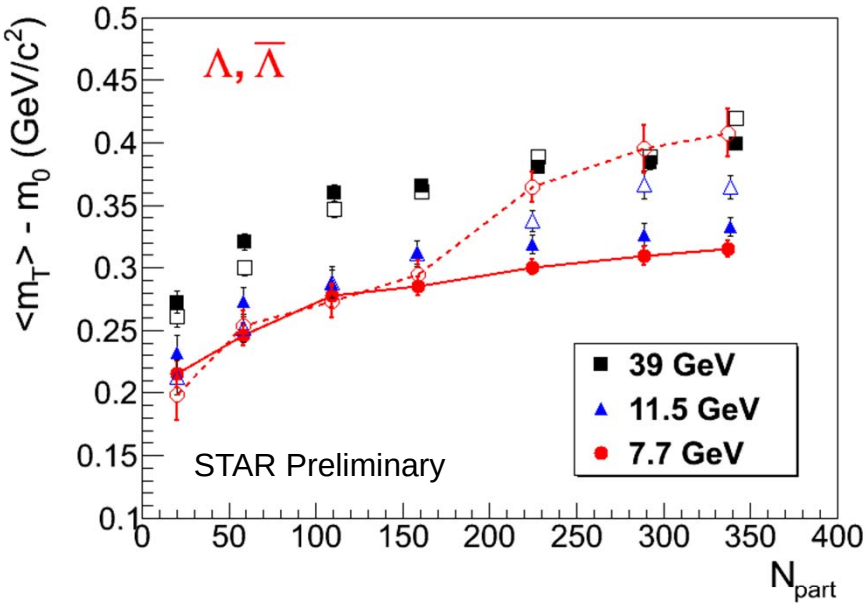


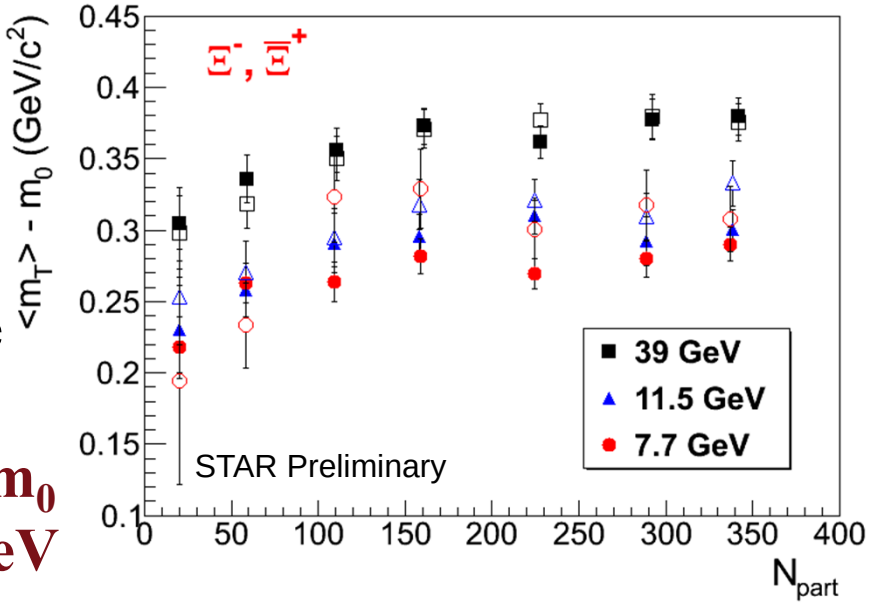


Mean transverse kinetic energy

Solid, particle;
Open, anti-particles



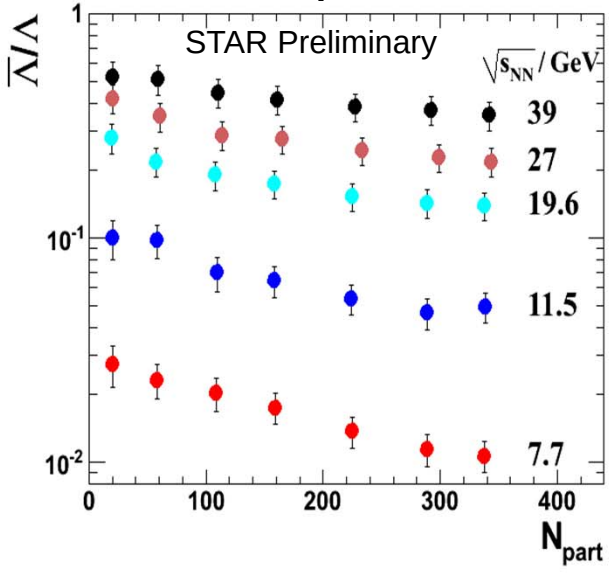




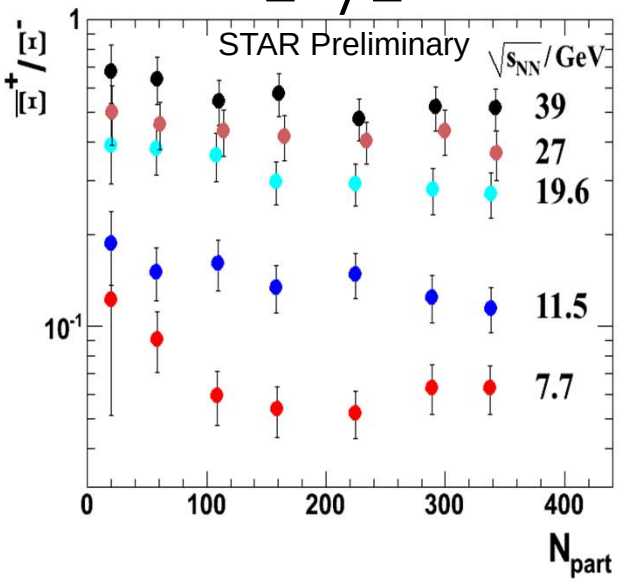
- Statistical error only!
- $<m_T> - m_0$ increases as the increase of centrality
- **$\bar{\Lambda}$: abnormal increase of $<m_T> - m_0$ versus centrality at Au+Au 7.7 GeV**

$\bar{B}/B$ ratios

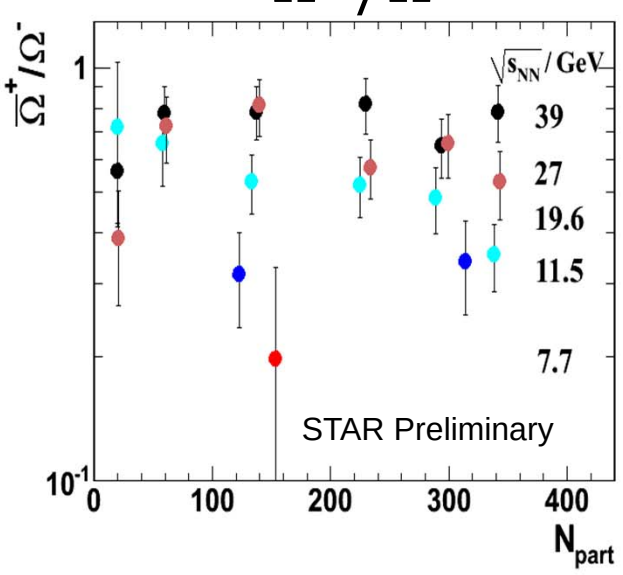
$\bar{\Lambda}/\Lambda$



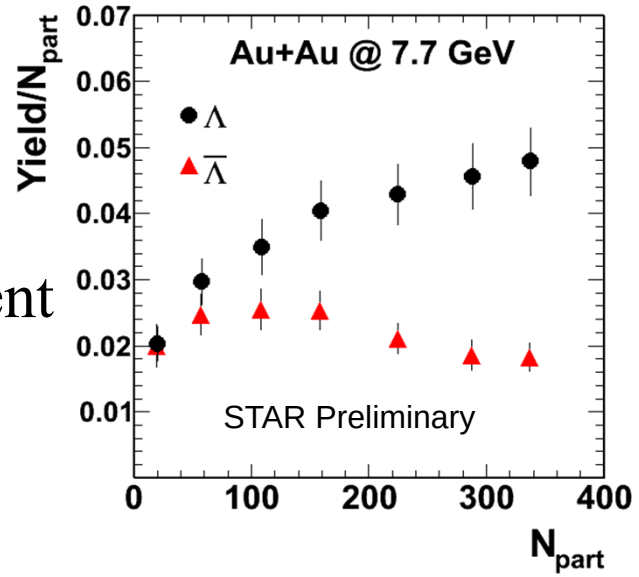
$\bar{\Xi}^+/\Xi^-$



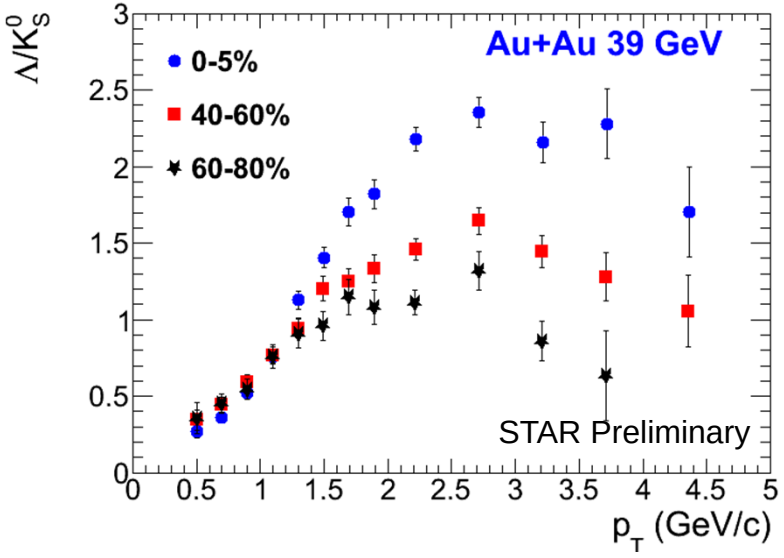
$\bar{\Omega}^+/\Omega^-$

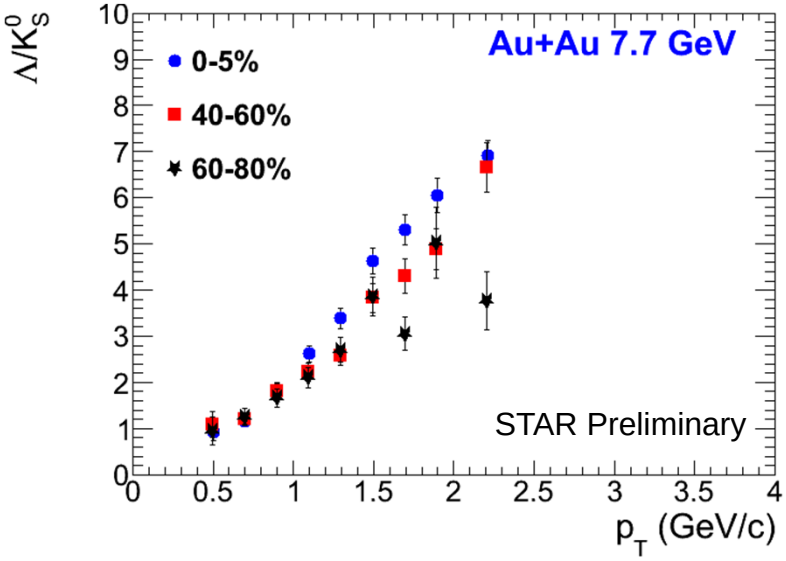


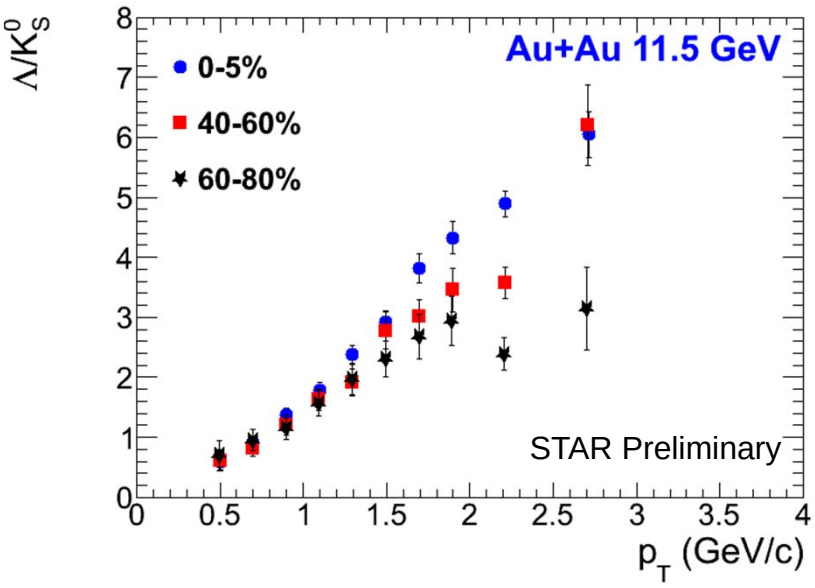
- Centrality dependence of $\bar{B}/B$ ratios: **peripheral > central**
- This effect is more prominent at lower energies, more baryon transport to mid-rapidity, absorption?



Strange baryon/meson ratios

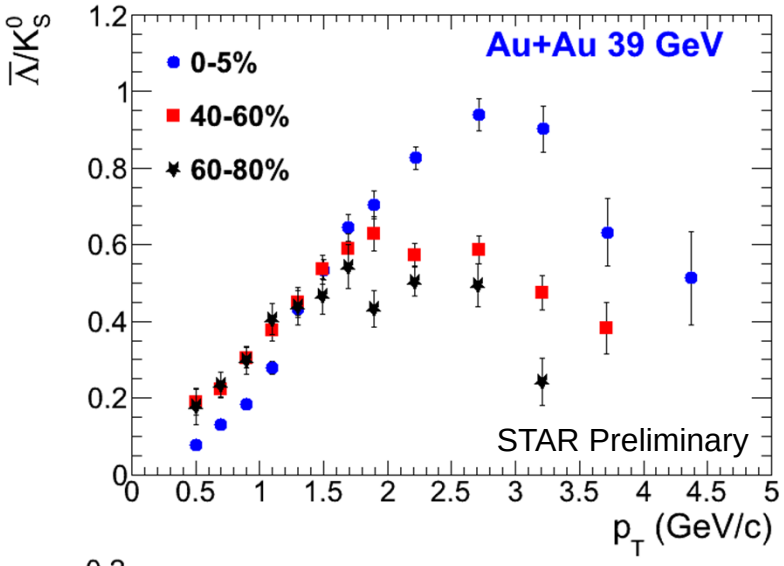


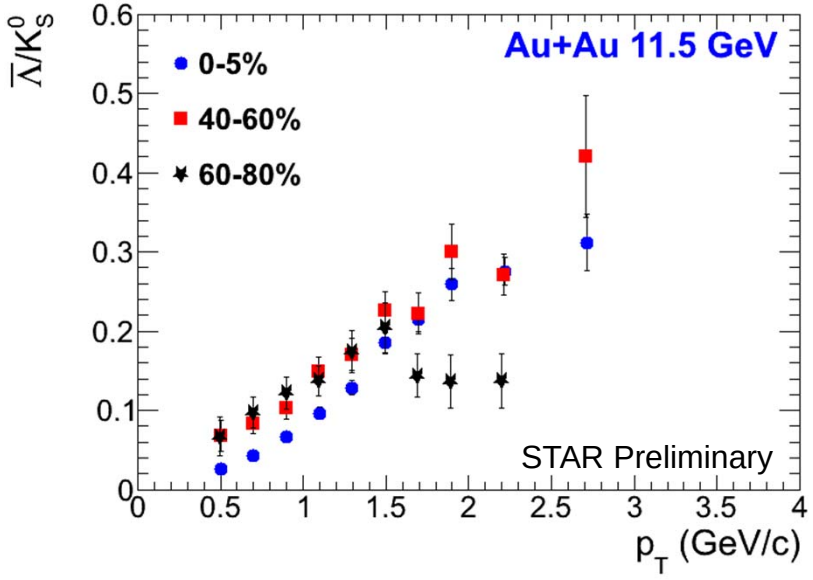


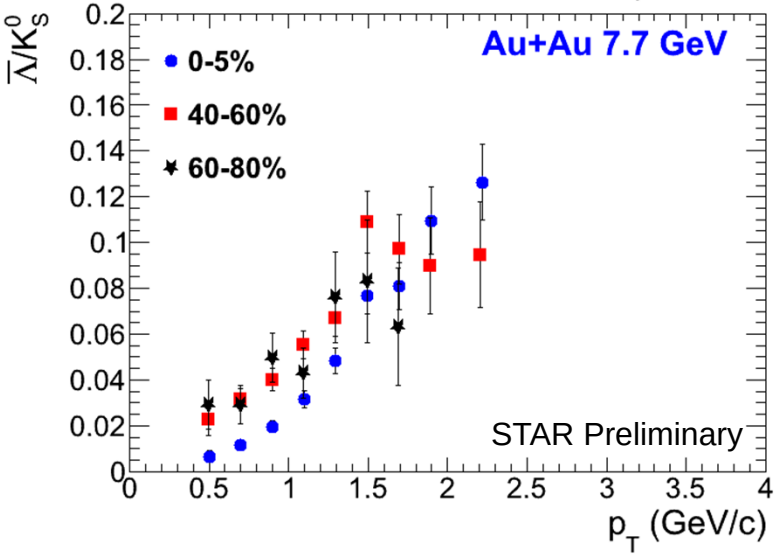


- Mid-p_T ratios get higher at lower energy
  More baryon stopping?
- Centrality dependence for Au+Au 39 GeV
  Breaks at lower energies?

Strange baryon/meson ratios

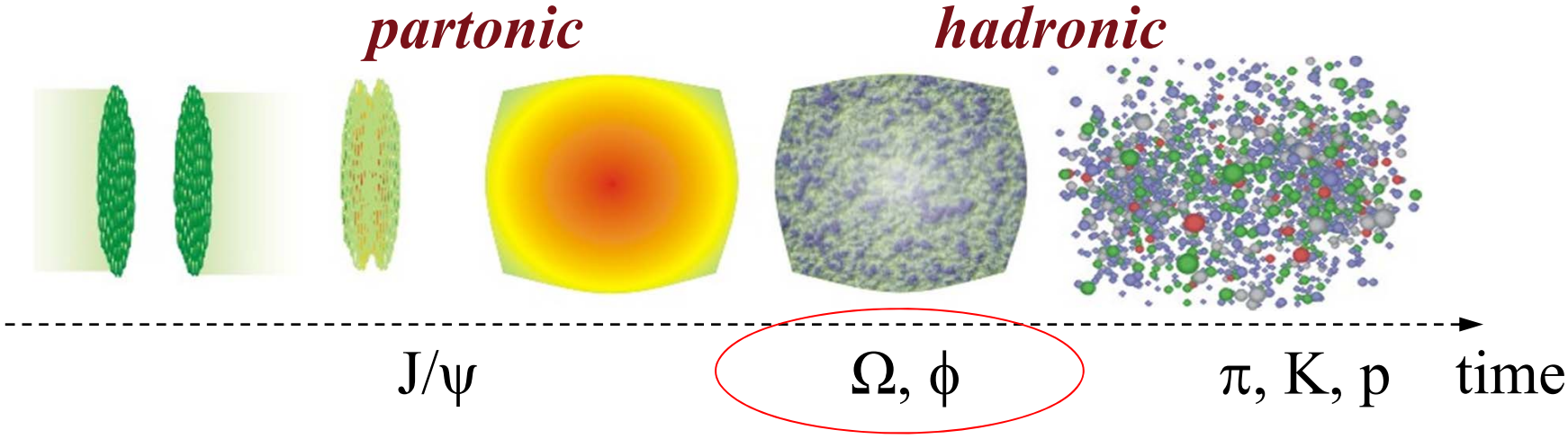


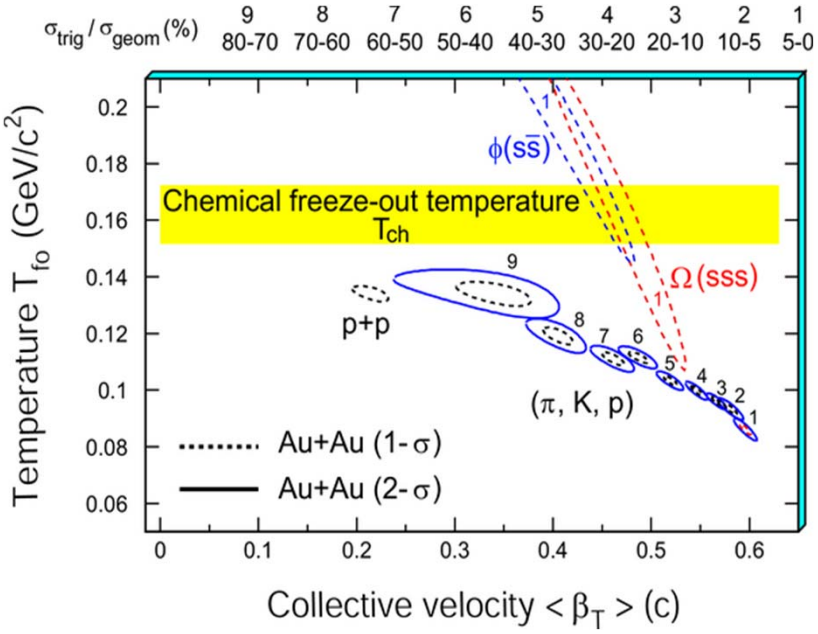




- Mid-p_T ratios get **lower** at lower energies
- Ratios still rise from low to mid-p_T at lower energies

Multi-strange hadrons?





Multi-strange hadrons

- Small hadronic cross sections, freeze-out early

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