Overview of Strangeness Production and Baryon-Baryon Interactions from Heavy-Ion Collisions

Neha Shah

中国科学院上海应用物理研究所

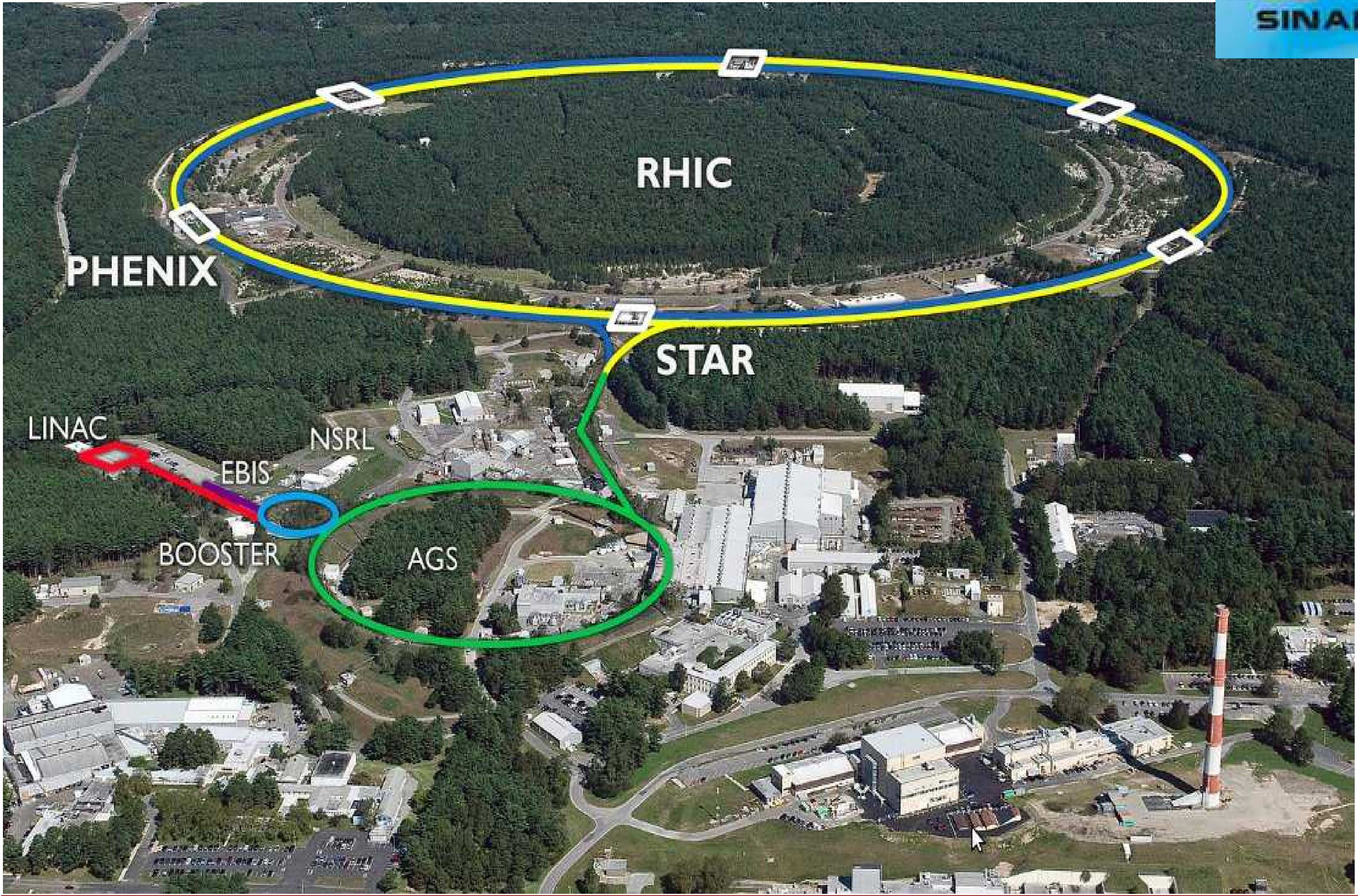
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

ExHIC Workshop
YITP

Outline

- ➔ **Strangeness production in HIC**
- ➔ **Hypertriton life time**
- ➔ **Baryon-Baryon interactions**
  - ➔ **$\Lambda\Lambda$ interactions**
  - ➔ **Antiproton-antiproton interactions**
  - ➔ **Preliminary results on Proton-Ω**

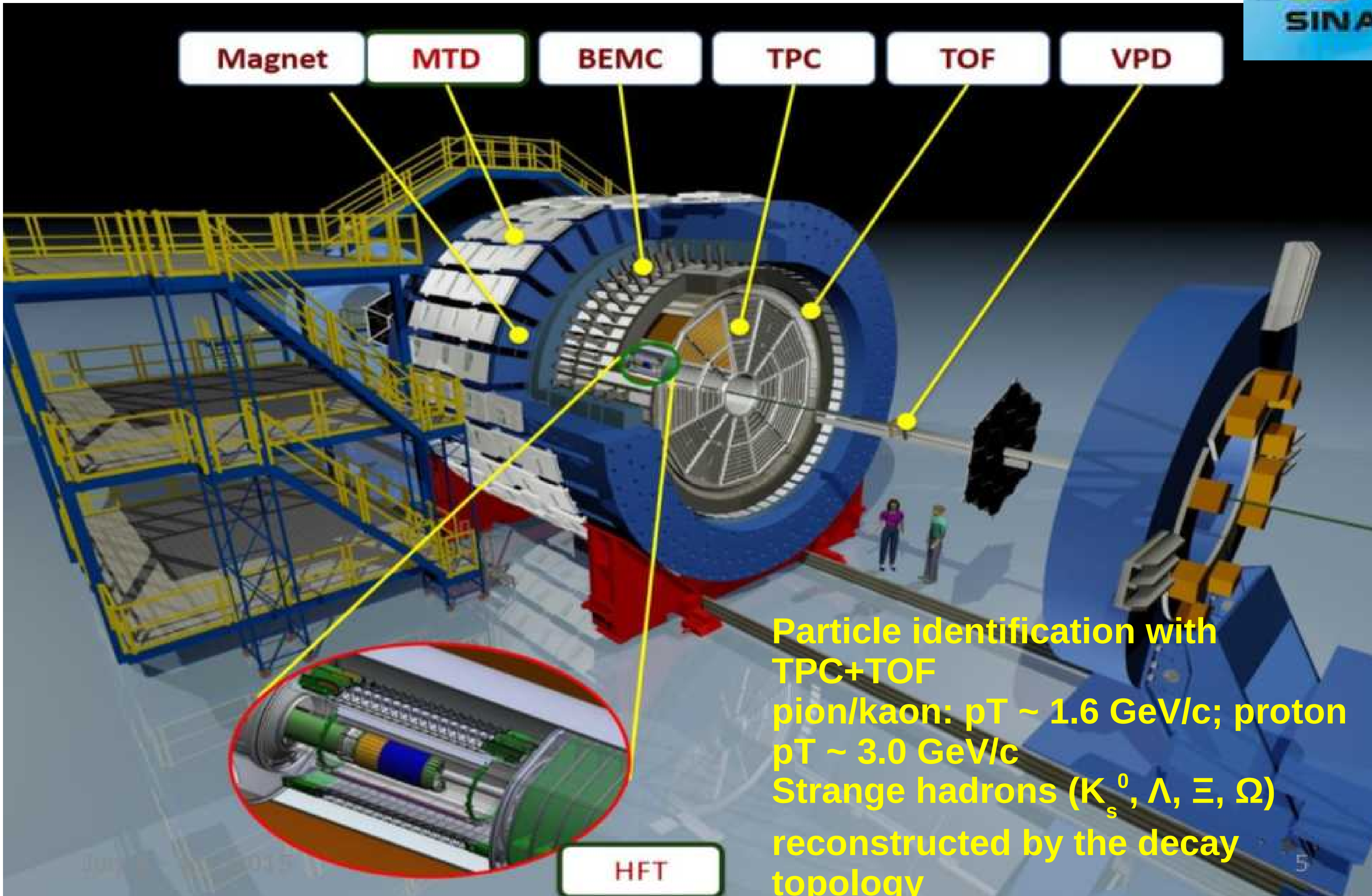
Relativistic Heavy Ion Collider (RHIC)



Relativistic Heavy Ion Collider (RHIC)

Collision species	C.M. Energy per nucleon pair (GeV)	Physics
Polarized p+p	510, 200, 150	Spin physics
Au+Au	200, 130, 62.4, 39, 27, 19.6, 14.5, 11, 7.7	Quark Gluon Plasma properties, QCD Critical point search
Cu+Cu, Cu+Au	200, 62.4, 19.6, 22.4	Study initial conditions
d+Au	200	Cold nuclear matter
U+U	193	Study initial conditions

Solenoidal tracker at RHIC (STAR)

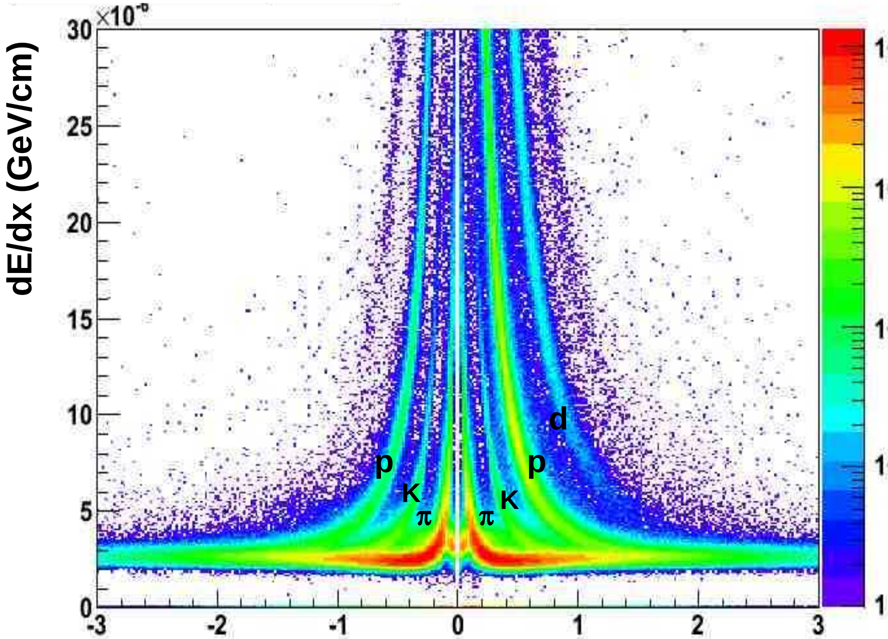


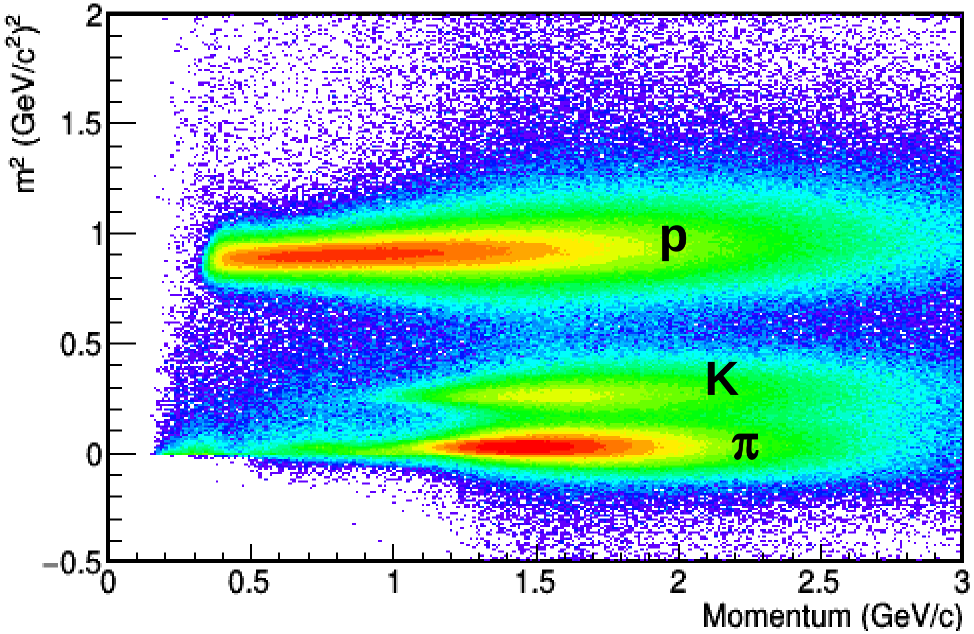
Particle identification with TPC+TOF
pion/kaon: pT ~ 1.6 GeV/c; proton pT ~ 3.0 GeV/c
Strange hadrons (K_s^0, Λ, Ξ, Ω) reconstructed by the decay topology

Particle Identification with TPC+TOF

Excellent PID with TPC+TOF

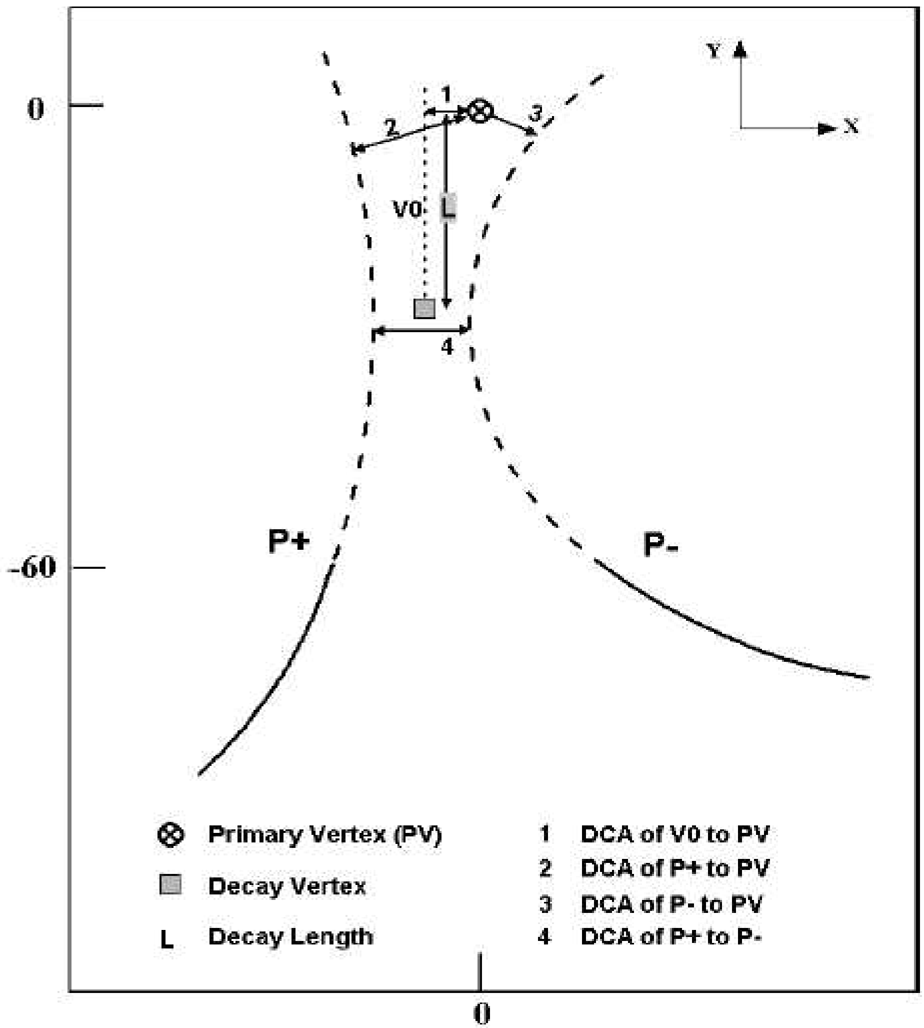
$$m^2 = (p^2/c^2)(t^2 c^2/L^2 - 1)$$



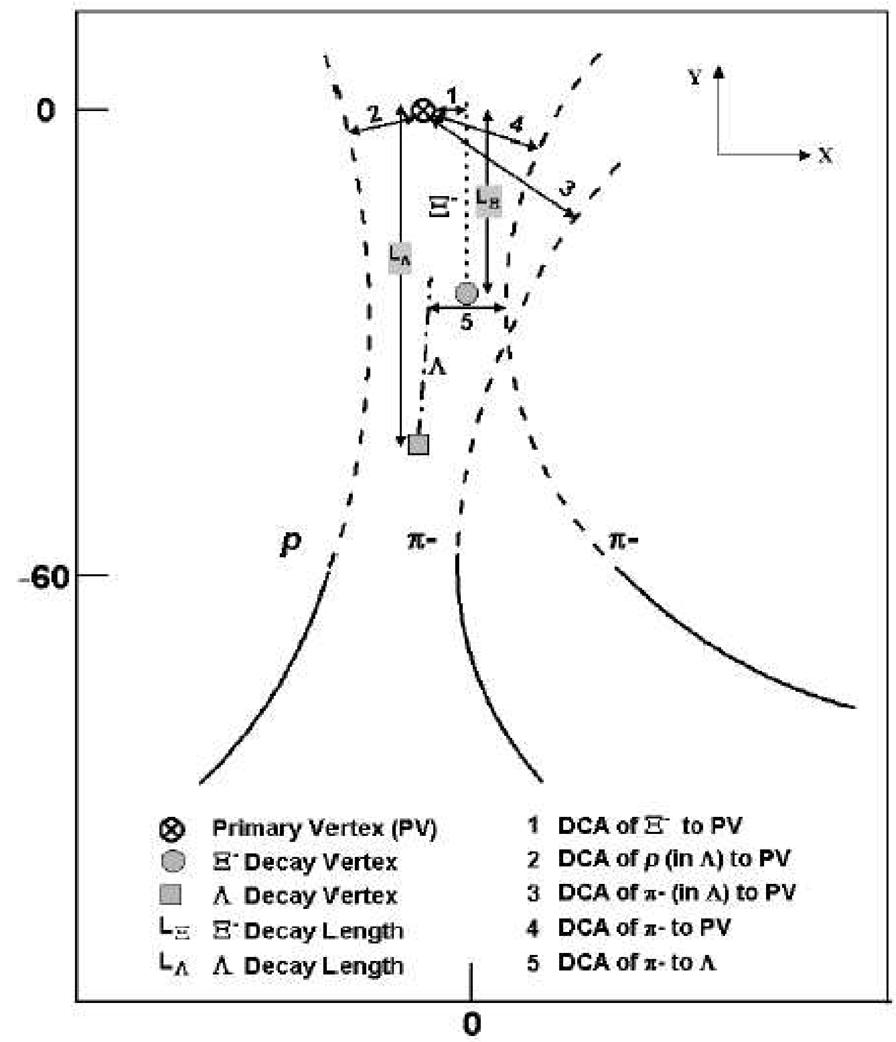


Hyperon Reconstruction

Λ reconstruction

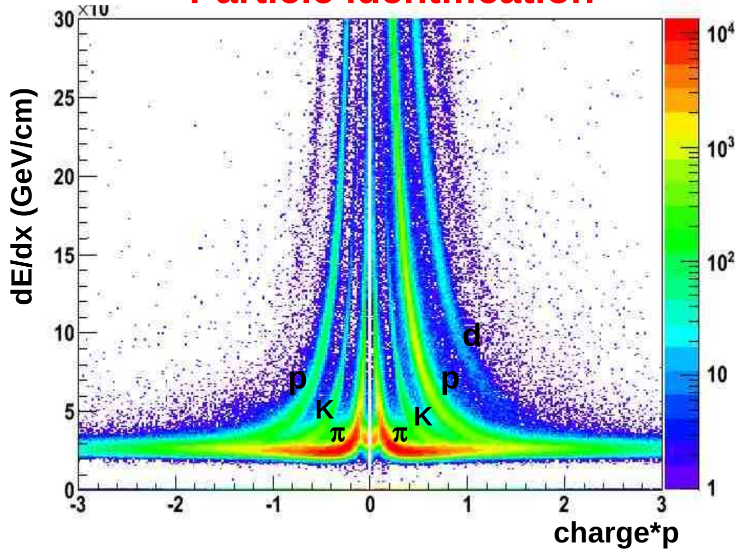


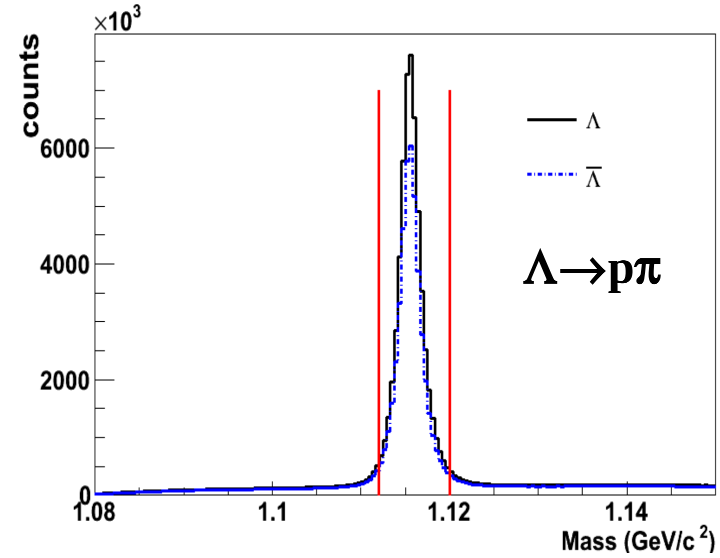
Ξ/Ω reconstruction

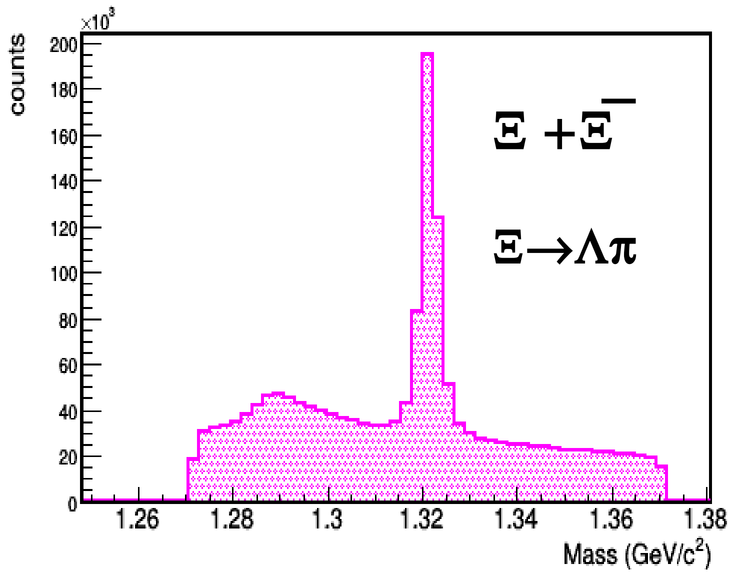


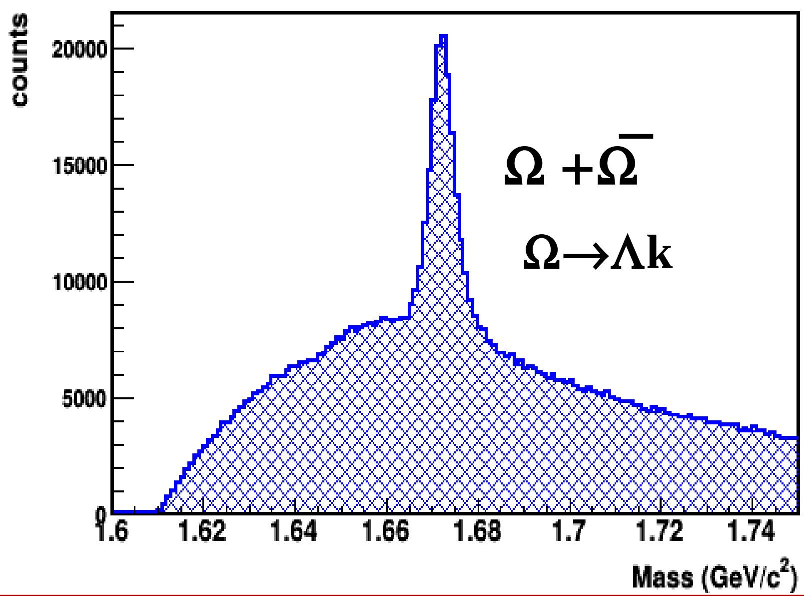
Hyperon reconstruction

Particle identification



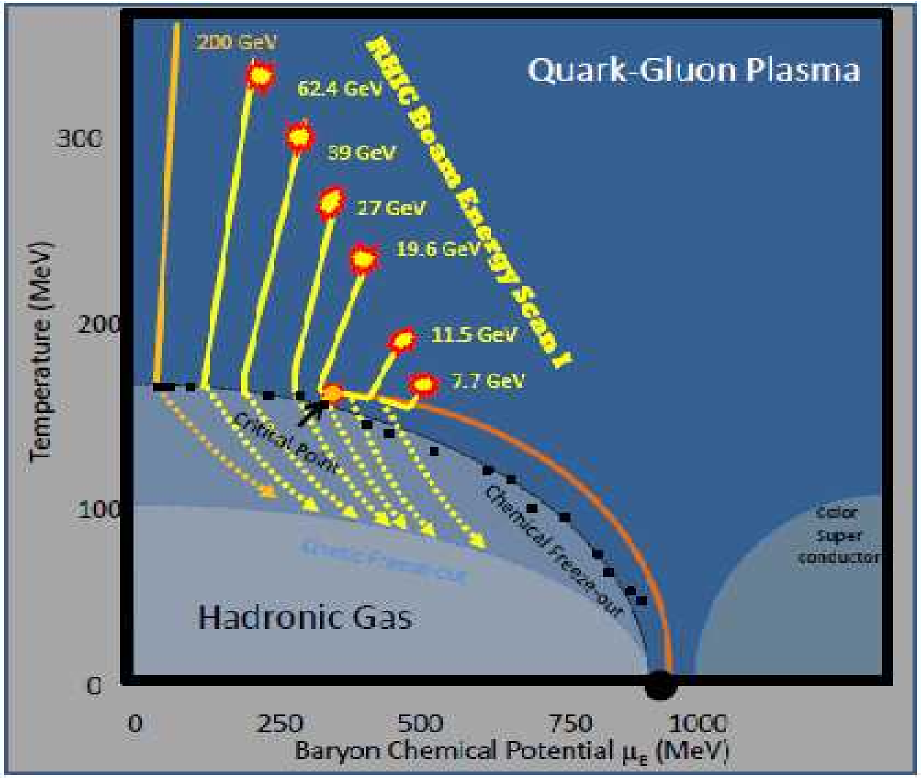






Strangeness Production

STAR BES: Study QCD Phase Diagram



Beam Energy Scan at RHIC:
Look for onset of de-confinement, identify the phase boundary and search for the QCD critical point

Systematic study of Au+Au collisions at 7.7, 11.5, 19.6, 27, 39 GeV (BES phase I)

Key Observables:

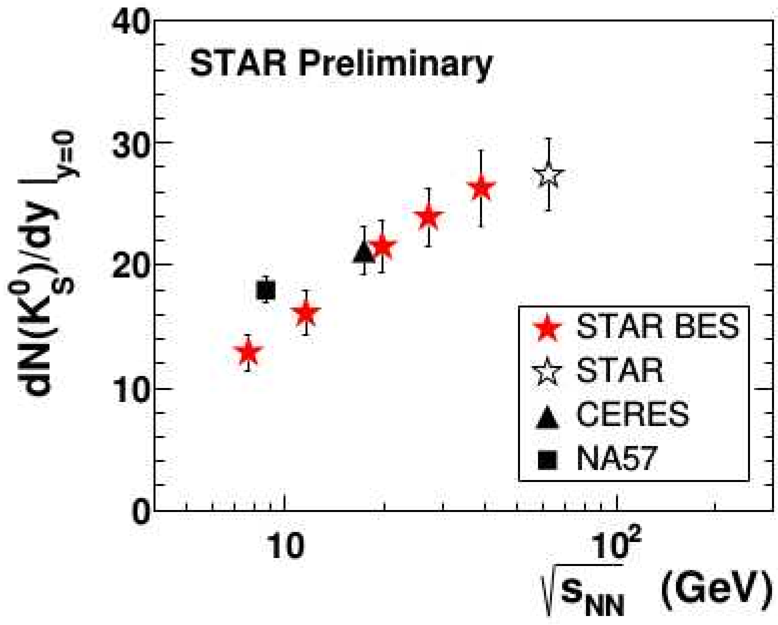
1) Strangeness enhancement

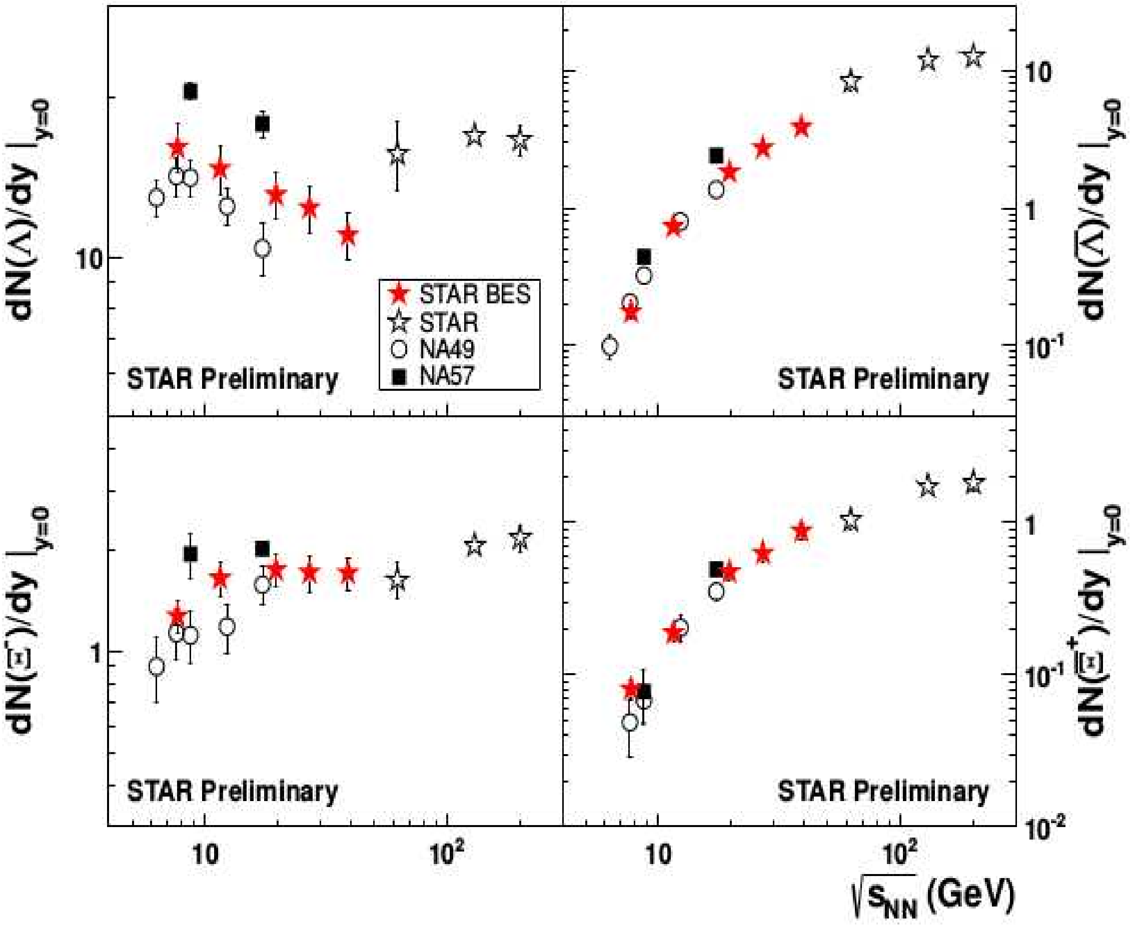
2) Baryon/meson ratio

3) Nuclear modification factor

Strange Particle Yields

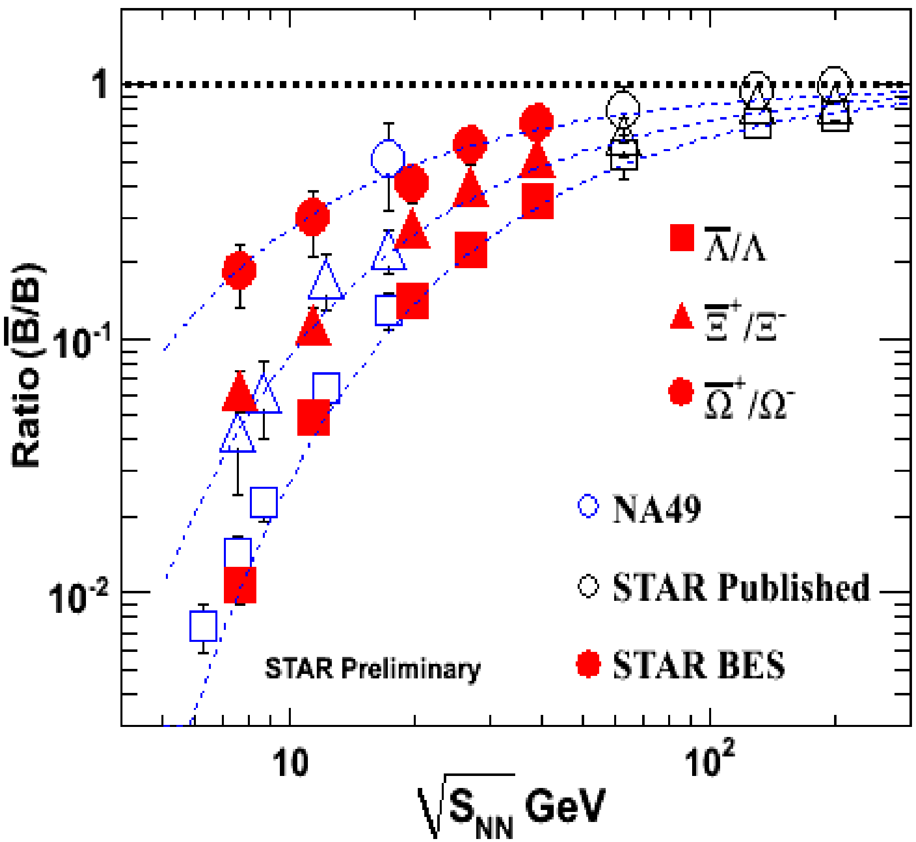
- STAR results are consistent with published data in general
- Λ yields show dip at $\sqrt{s_{NN}}$ = 39 GeV

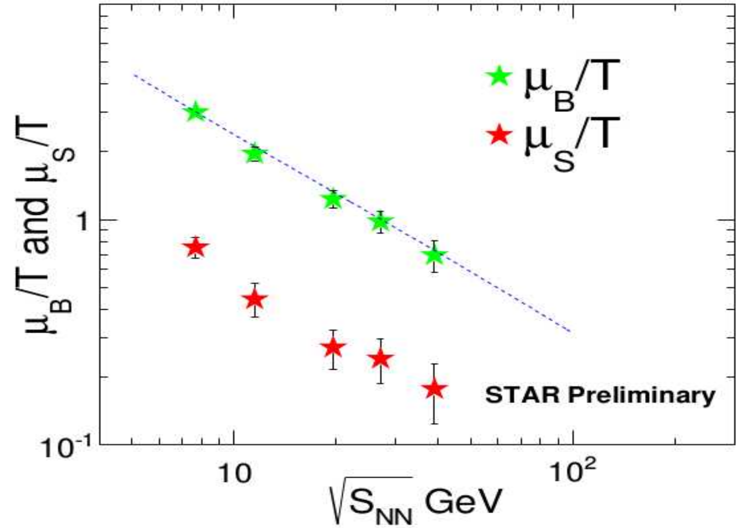


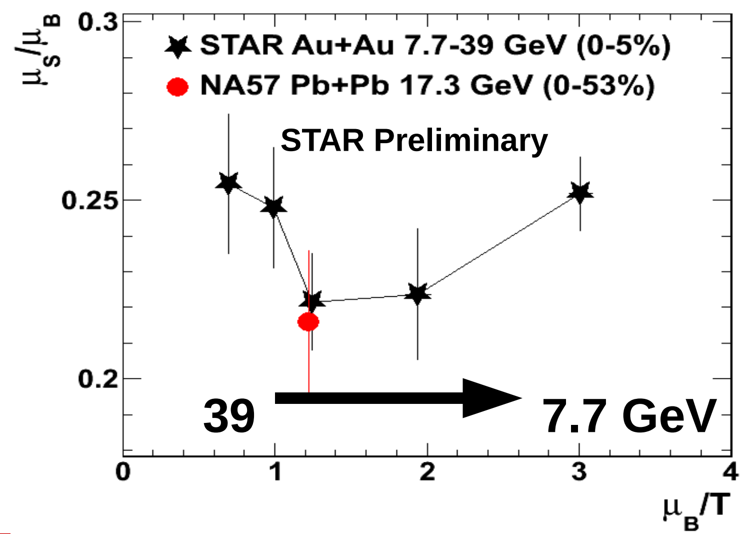


Antibaryon to Baryon Ratio

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





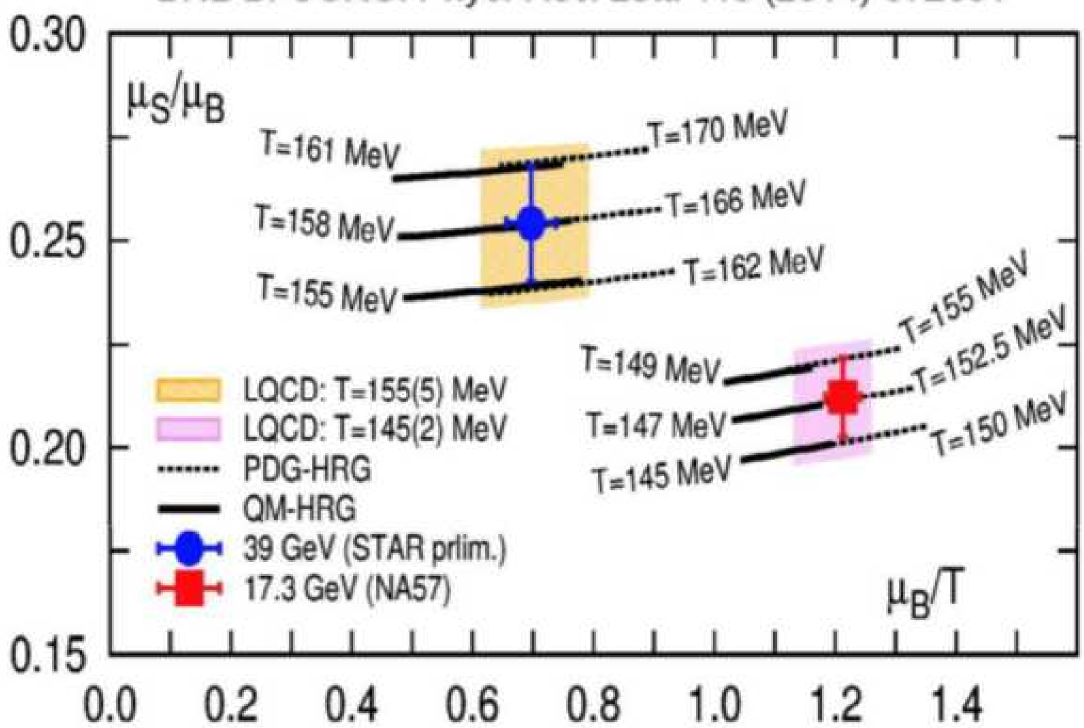


Antibaryon to Baryon Ratio

Strangeness, LQCD and freeze-out in HIC

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

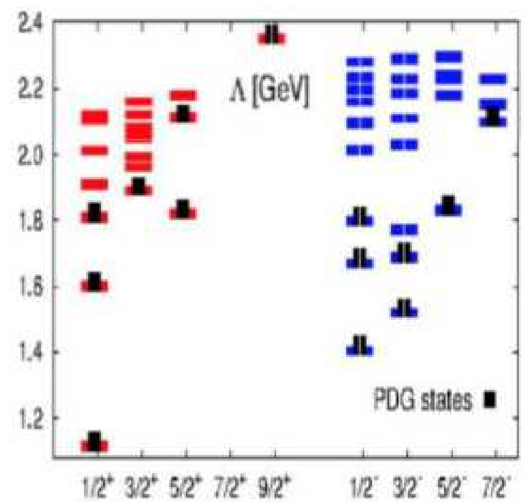
BNL-Bi-CCNU: Phys. Rev. Lett. 113 (2014) 072001



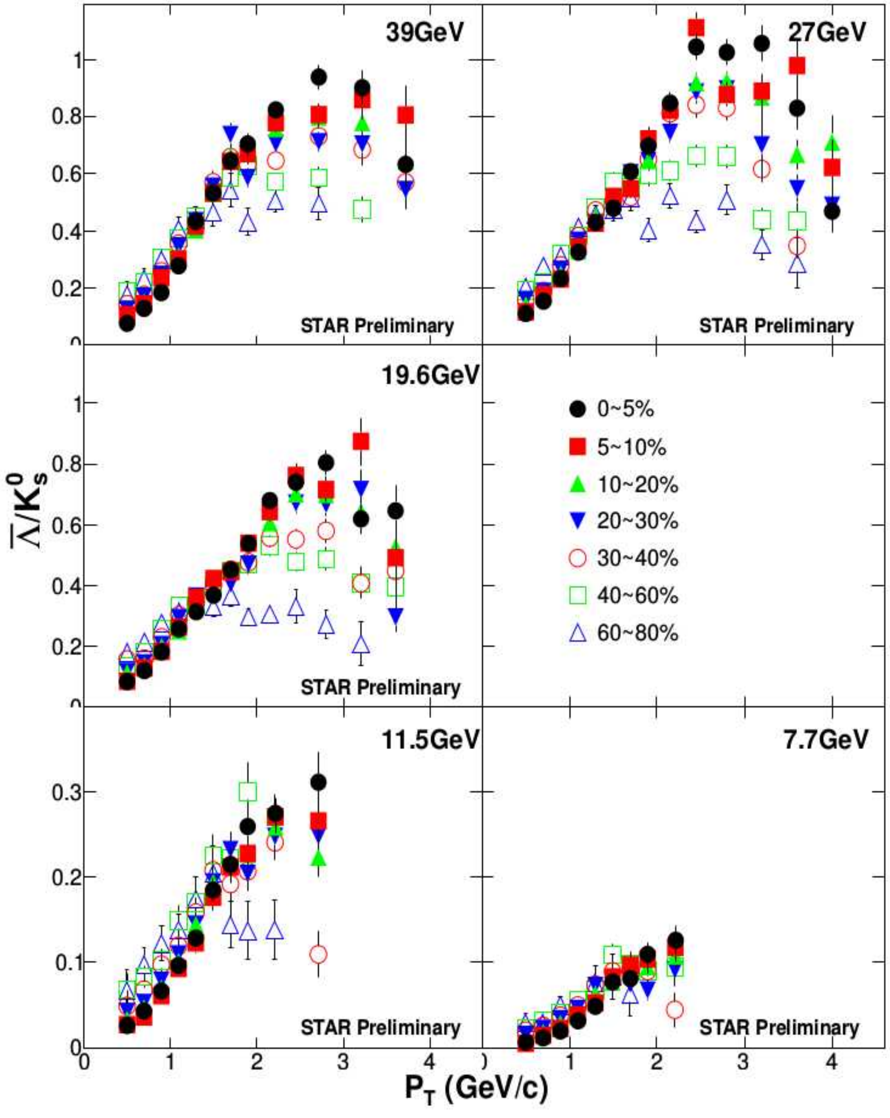
indirect evidence for so-far undiscovered strange baryons at RHIC ?

not reproduced by hadron gas with only PDG states

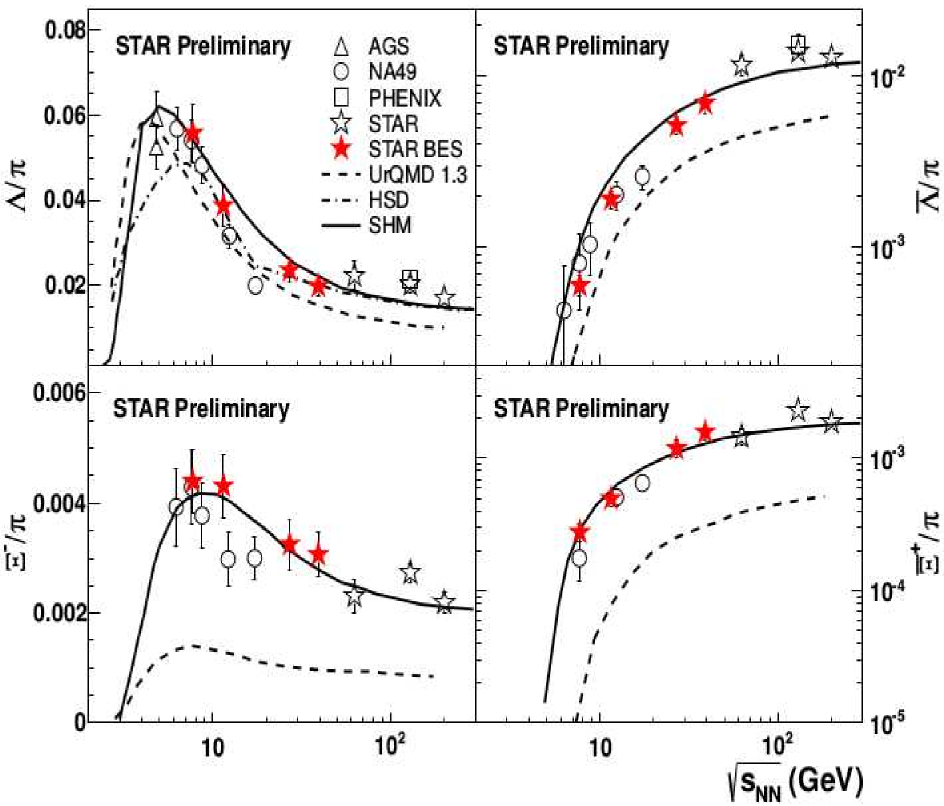
reproduced when additional Quark Model (QM) predicted strange baryons are taken into account



Baryon to Meson Ratio



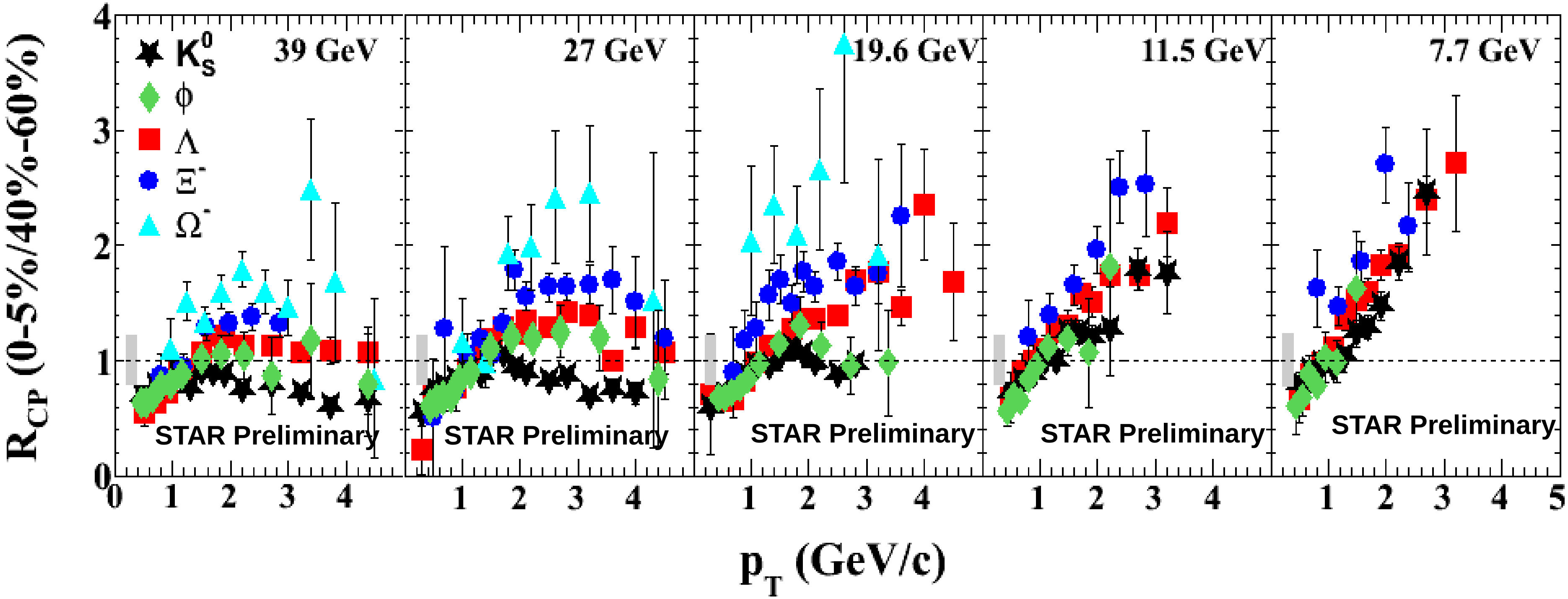
- Clear $\bar{\Lambda}$, $\bar{\Xi}$ yield enhancement compared to pion with increasing collision energy



Nuclear Modification Factor

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

- **No K_s^0 suppression in Au+Au @ 7.7, 11.5**
- **At intermediate p_T, particle R_{CP} difference becomes smaller for 7.7 and 11.5 GeV**



Summary – I: Strangeness Production

- STAR has measured systematically the production of various strange hadrons in $\sqrt{s_{NN}}$ = 7.7 - 39 GeV

- Observed clear $\overline{\Lambda}, \overline{\Xi}$ yield enhancement compared to pions with increasing collision energy

- Intermediate p_T nuclear modification factors show clear separation between different strange particles for 200 — 19.6 GeV

- Below 19.6 GeV, the separation between different strange particles becomes small → indicating possible phase transition

Hypertriton Life-time

Hypertriton Life-time Measurement

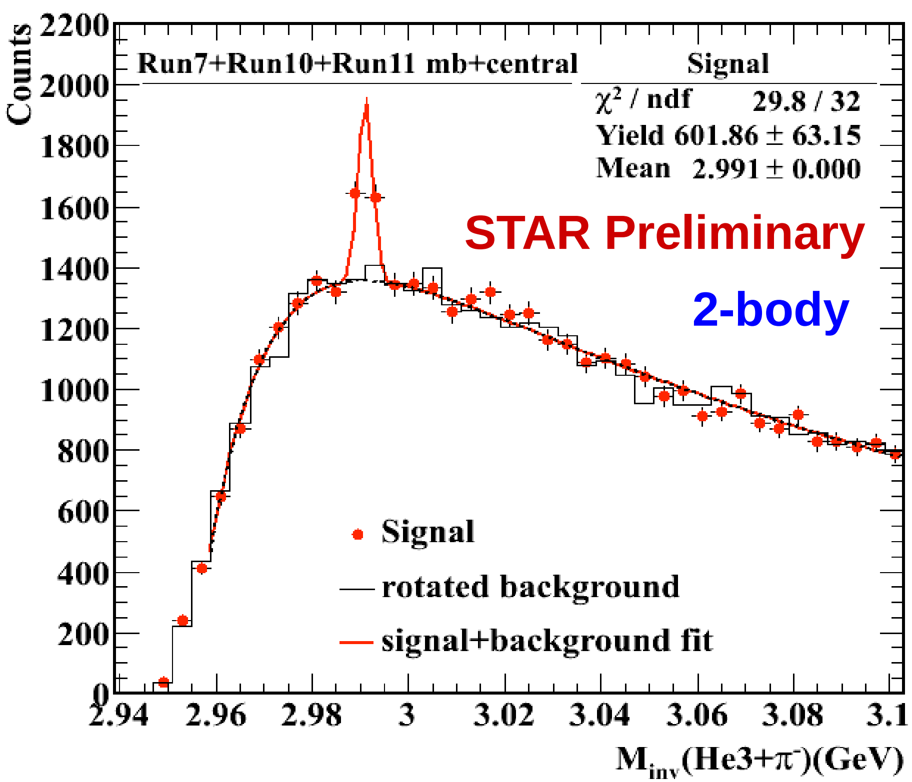
- ✔ First hyper nucleus was observed in 1952.
- ✔ Binding energy and lifetime are sensitive to YN interaction.
- ✔ The hypertriton being a loosely-bound nuclear system, its mean lifetime should be close to the free Lambda
- ✔ Life time measurements from Bubble chamber, emulsion and heavy-ion experiments are smaller than the free Λ life time.
- ✔ The hypertriton lifetime data are not accurate to distinguish between model, more precise measurements are needed.

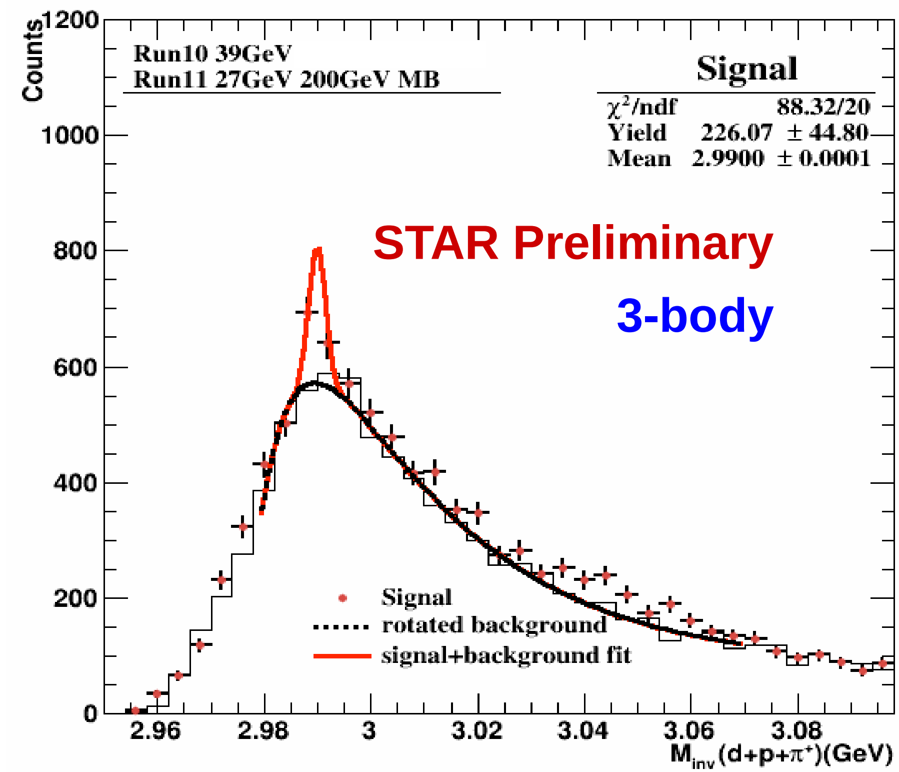
Hypertriton life-time measurement

$\tau = 182^{+89}_{-45}$ (stat) ± 27 (sys) ps (Science 328 (2010) 58)

✔ Signal from 2-body and 3-body decay

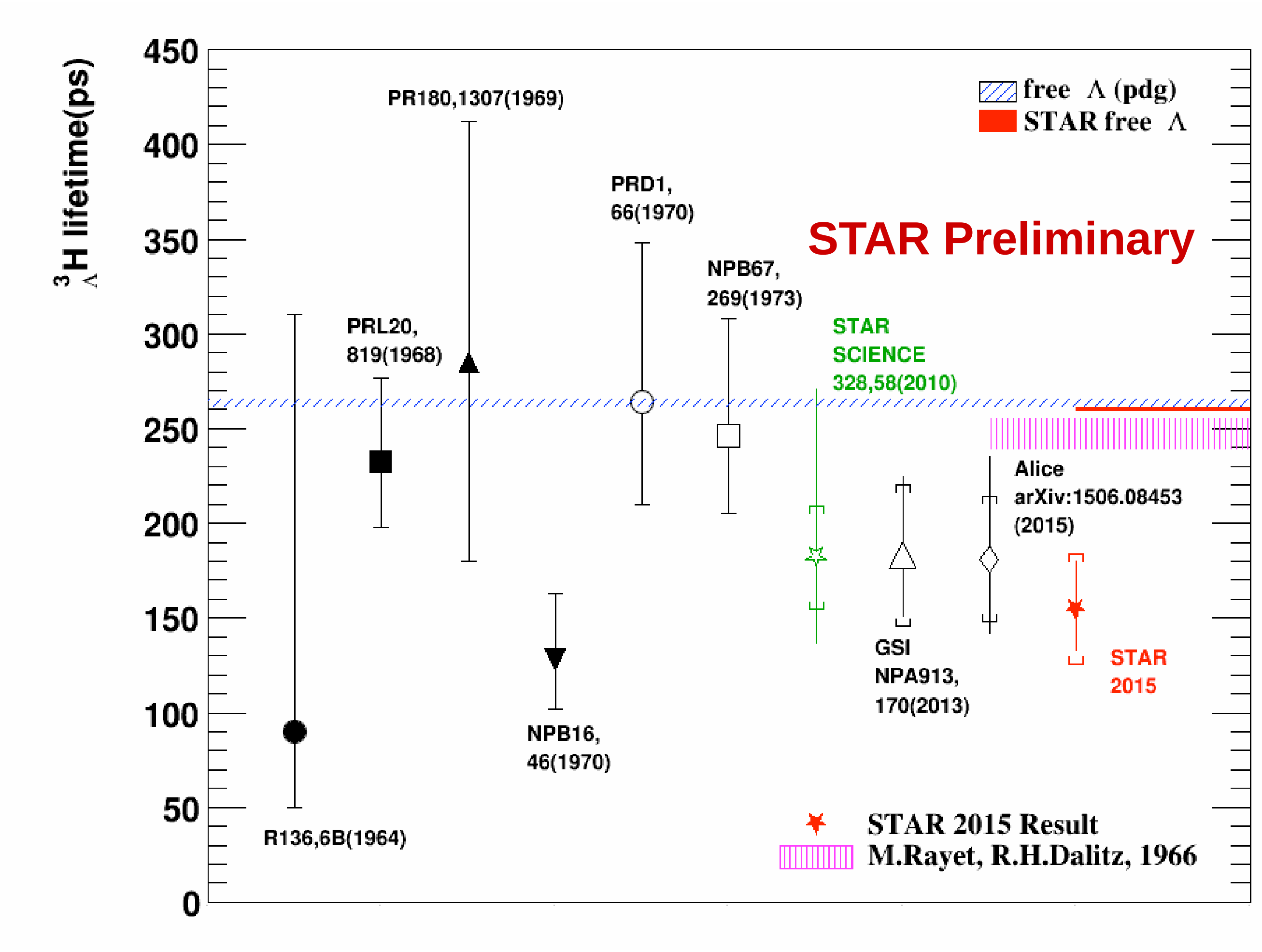
✔ Largest sample of hypertriton





Summary – II : Hypertriton Life-time

$\tau = 155^{+25}_{-22}$ (stat) ± 29 (sys) ps



Baryon-Baryon Interactions

Baryon-Baryon Interactions

- Baryon interactions are of fundamental interest in Nuclear Physics and Astrophysics
- Neutron Star puzzle
- Interactions between pair of anti-particles → examine CPT
- $\Lambda\Lambda$–ΞN Coupling is important to understand production of double-Λ hypernuclei
- Methods:
  - Scattering
  - Binding Energies
  - Two particle correlation

Correlation Function

- **Two particle correlation function**

$$C^{ab}_{\vec{K}}(\vec{q}) = \frac{d^6N^{ab}/(dp_a^3dp_b^3)}{(d^3N^a/dp_a^3)(d^3N^b/dp_b^3)} = \int d^3\vec{r'} \cdot S^{ab}_{\vec{K}}(\vec{r'}) \cdot |f(\vec{q},\vec{r'})|^2$$

$S^{ab}_{K}(r')$ – normalized separation distribution

f(q,r') – two-particle wave function, q = 2k*

(quantum statistics, FSI:Coulomb int., Strong int.)

Standard procedure:

$$C^{ab}_{\vec{K}}(\vec{k^*}) = \int d^3\vec{r'} \cdot S^{ab}_{\vec{K}}(\vec{r'}) \cdot |f(\vec{k^*},\vec{r'})|^2$$

Reversed procedure:

$$C^{ab}_{\vec{K}}(\vec{k^*}) = \int d^3\vec{r'} \cdot S^{ab}_{\vec{K}}(\vec{r'}) \cdot |f(\vec{k^*},\vec{r'})|^2$$

s-wave approximation

$$\exp(-i\vec{k}^*\vec{r}) + f\,\frac{\exp(ik^*r)}{r}$$

effective range approximation

$$f^{-1} = \frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - ik^*$$

Interaction Cross-section

At low energies, the elastic cross section, σ_e, is solely determined by the scattering length,

$$\lim_{k \to 0} \sigma_e = 4\pi f_0^2$$

where k is the wave number.

The effective range d_0 of strong interaction between two particles correspond to the range of the potential in an extremely simplified scenario - the square well potential.

The f_0 and d_0 are two important parameters in characterizing the strong interaction between two particles.

Λ–Λ interaction

ΛΛ Correlation Function

Fit function from Lednicky-Lyuboshitz analytical model:

$$C(Q)=N(1+\lambda[\sum_S \rho_S(-1)^S \exp(-r_0^2Q^2)+\Delta CF^{FSI}+a_{res}\exp(-Q^2 r_{res}^2)])$$ (SJNP 35 (1982) 770)

N- normalization, λ – suppression parameter, a_res – amplitude of residual term
r_res – width of the Gaussian

$\rho_0 = ¼(1-P^2)$ $\rho_1 = ¼(3+P^2)$ P=Polariz.=0

$$\Delta CF^{FSI} = 2\rho_0[½|f^0(k)/r_0|^2(1-d_0^0/(2r_0\sqrt{\pi})) + 2Re(f^0(k)/(r_0\sqrt{\pi}))F_1(r_0Q) - 2Im(f^0(k)/r_0)F_2(r_0Q)]$$

r_0 - emission radius, d_0 - effective radius, f_0 – scattering length

Scattering amplitude: $f^S(k)=(1/f_0^S+½d_0^S k^2 - ik)^{-1}$, k=Q/2

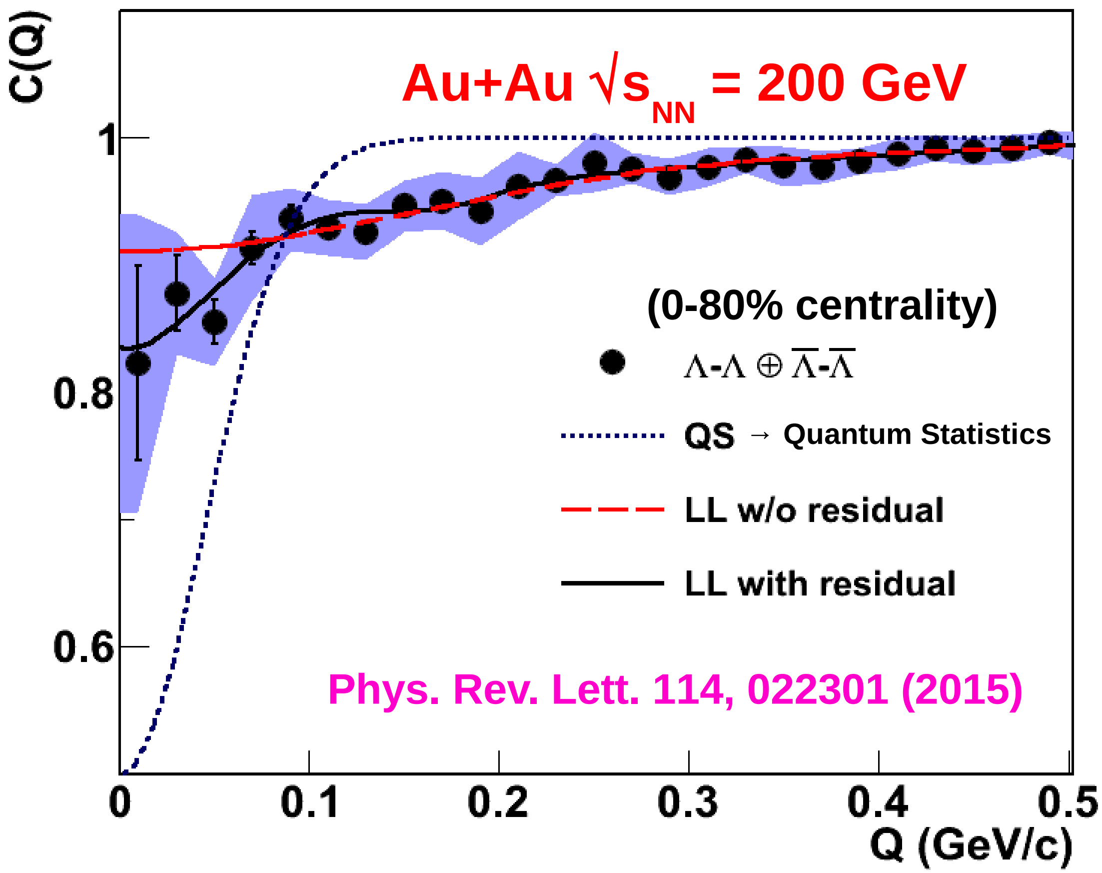
$F_1(z)=\int_0^z dx \exp(x^2-z^2)/z$ $F_2(z)=[1-\exp(-z^2)]/z$

ΛΛ Correlation Function

Fit using Lednicky-Lyuboshitz analytical model:

$$C(Q)=N(1+\lambda[\sum_S \rho_S(-1)^S \exp(-r_0^2 Q^2)+\Delta CF^{FSI}+a_{res}\exp(-Q^2 r_{res}^2)])$$ (SJNP 35 (1982) 770)

N- normalization, λ – suppression parameter



- **Interaction parameters:**

Emission radius-

$r_0 = 2.96 \pm 0.38^{+0.96}_{-0.02}$ fm

Scattering length-

$a_0 = -1.10 \pm 0.37^{+0.68}_{-0.08}$ fm

Effective range-

$r_{eff} = 8.52 \pm 2.56^{+2.09}_{-0.74}$ fm

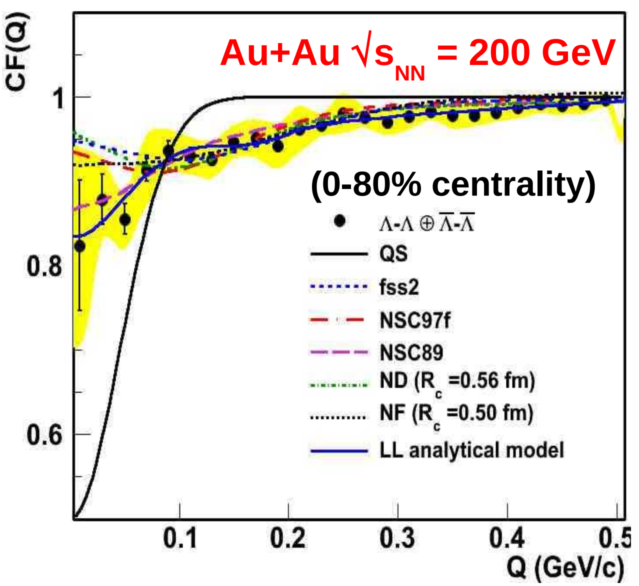
$\chi^2/NDF = 0.56$

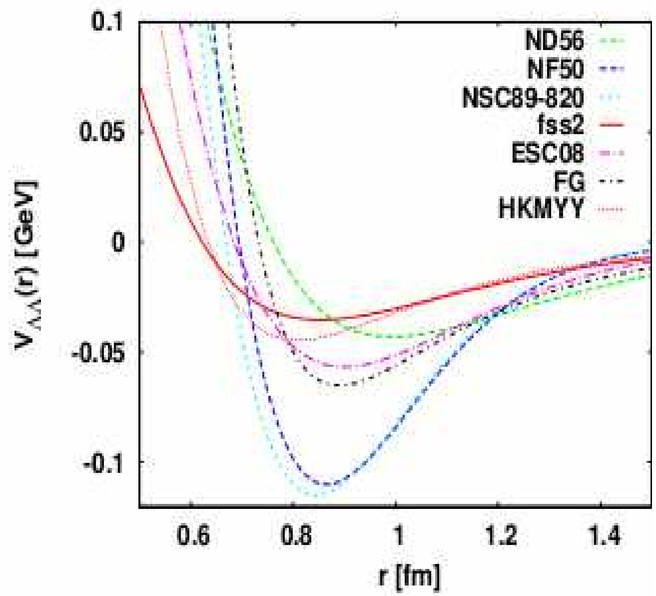
ΛΛ Interaction Parameters

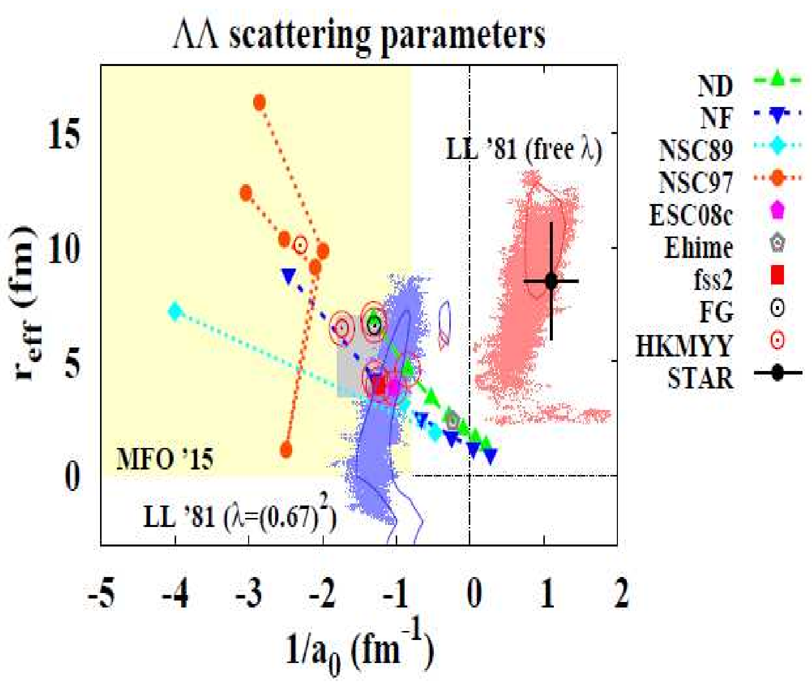
Baryon-baryon interaction model ⇒ attractive potential

A rather weak interaction exists between ΛΛ compared to NN and pΛ

$|a_{\Lambda\Lambda}| < |a_{p\Lambda}| < |a_{NN}|$







STAR Collaboration, Phys. Rev. Lett 114, 022301 (2015)
K. Morita, T. Furumoto and A. Ohnishi, Phys. Rev. C 91 024916 (2015)
A. Ohnishi, HYP2015 Proceedings

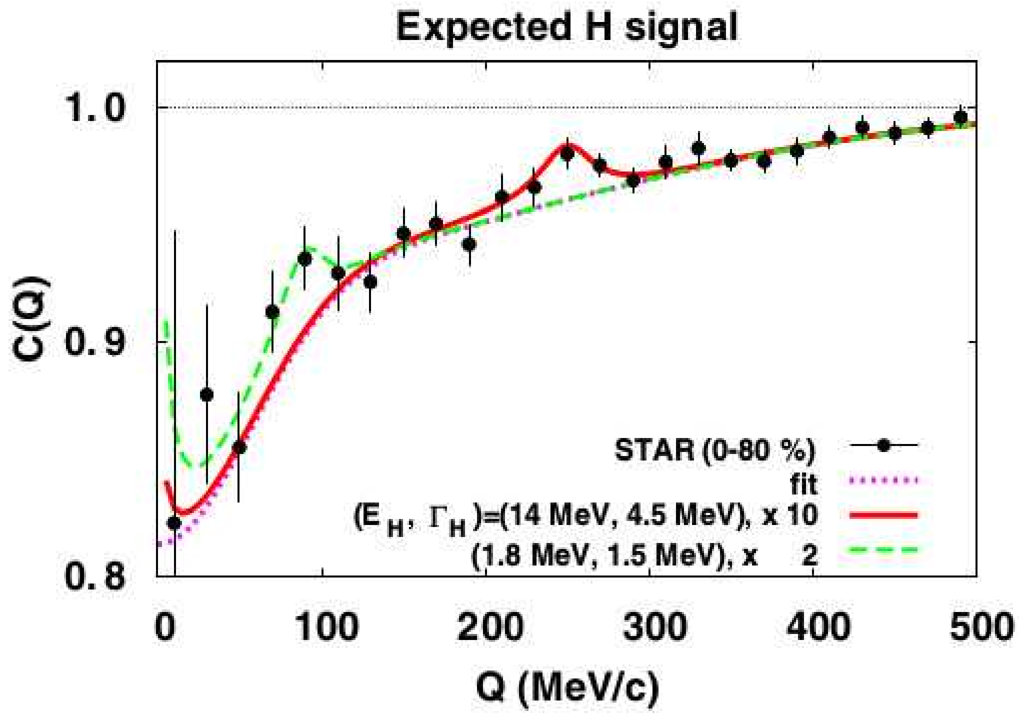
H-dibaryon Signal from Coalescence Expectation

- **Assuming H-dibaryon are stable against strong decay and are produced through coalescence of Λ pairs:**

$$(1/2\pi p_T)d^2N_H/dp_Tdy = 16B\,((1/2\pi p_T)d^2N_\Lambda/dp_Tdy)^2\ ,$$

where B is coalescence fraction. (Phys. Lett. B 350 (1995) 147)

Integrated yield (dN_H/dy) = $(1.23 \pm 0.47_{stat} \pm 0.61_{sys})\times10^{-4}$



K. Morita, T. Furumoto and A. Ohnishi, Phys. Rev. C 91 024916 (2015)

- **More experimental events are necessary to confirm or rule out the existence of resonance pole in low Q region**

Antiproton-Antiproton interaction

AntiProton-AntiProton Correlation

Correlation function:

$$C_{meas}(k^*_{pp}) = 1 + x_{pp}[C_{pp}(k^*; R_{pp}) - 1] + x_{p\Lambda}[\widetilde{C}_{p\Lambda}(k^*_{pp}; R_{p\Lambda}) - 1] + x_{\Lambda\Lambda}[\widetilde{C}_{\Lambda\Lambda}(k^*_{pp}; R_{\Lambda\Lambda}) - 1]$$

$$\widetilde{C}_{\Lambda\Lambda}(k^*_{pp}) = \sum_{k^*_{\Lambda\Lambda}} C_{\Lambda\Lambda}(k^*_{\Lambda\Lambda}) T(k^*_{\Lambda\Lambda}, k^*_{pp})$$

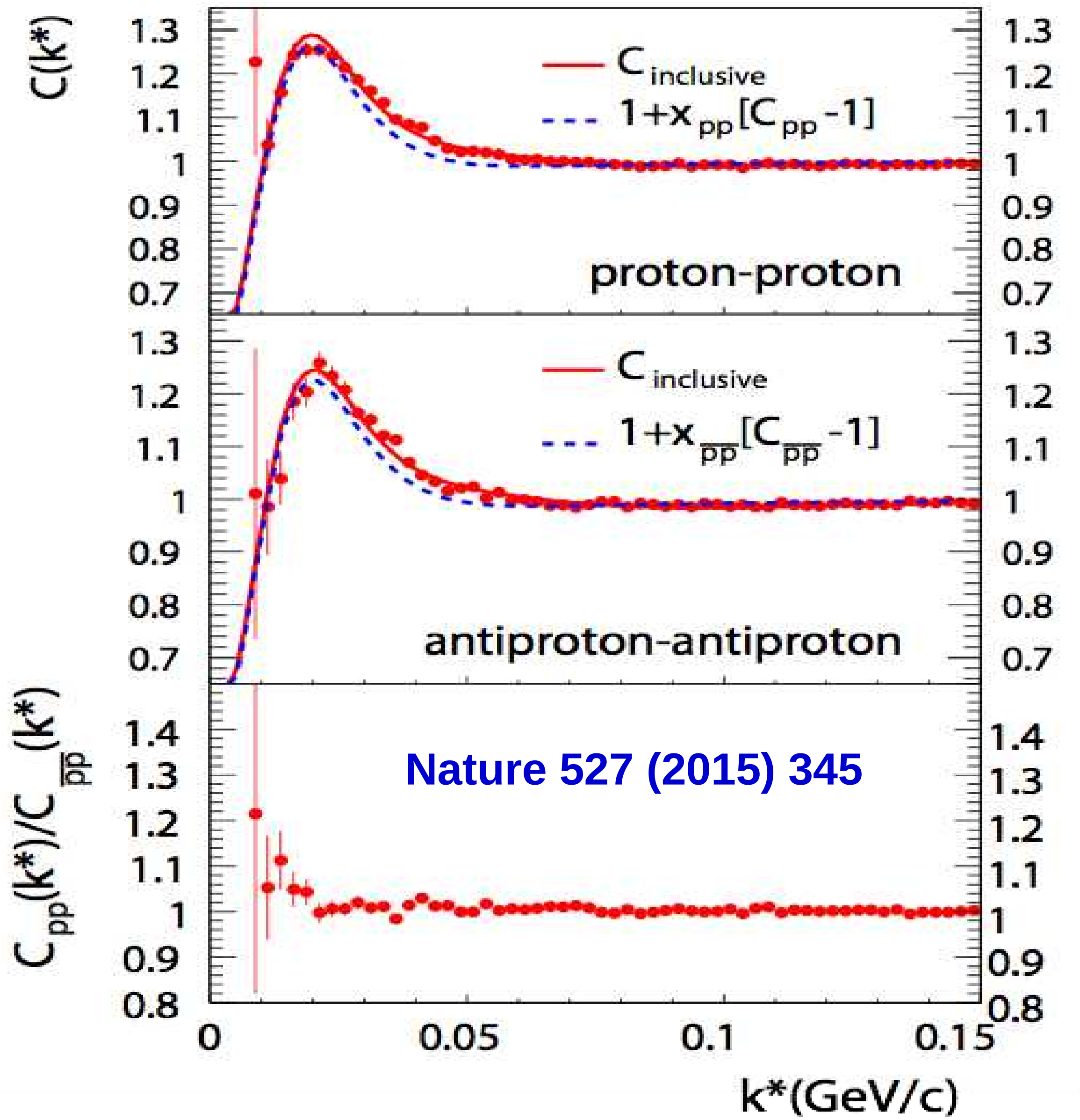
$$\widetilde{C}_{p\Lambda}(k^*_{pp}) = \sum_{k^*_{p\Lambda}} C_{p\Lambda}(k^*_{p\Lambda}) T(k^*_{p\Lambda}, k^*_{pp})$$

where $C_{pp}(k^*)$ and $C_{p\Lambda}(k^*_{p\Lambda})$ are calculated by the Lednicky-Lyuboshitz model and $C_{\Lambda\Lambda}$ $(k^*_{\Lambda\Lambda})$ is taken from STAR measurement.

$R_{p\Lambda} = R_{\Lambda\Lambda} = R_{pp}$

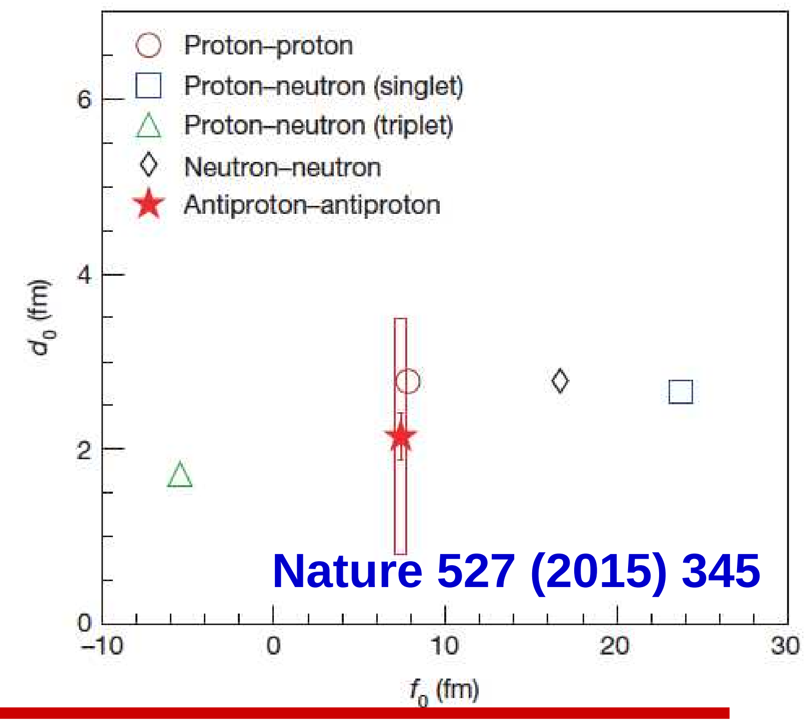
$T(k^*,k^*)$ is the corresponding transform matrices generated by THERMINATOR2 model to transform the $k^*_{p\Lambda}$ to k^*_{pp} or $k^*_{\Lambda\Lambda}$ to k^*_{pp}.

Antiproton-Antiproton Correlation



Proton-proton:
R=2.75±0.01fm; χ^2/NDF = 1.66

Antiproton-Antiproton:
R=2.80±0.02fm, f_0=7.41±0.19fm, d_0=2.14±0.27fm; χ^2/NDF=1.61

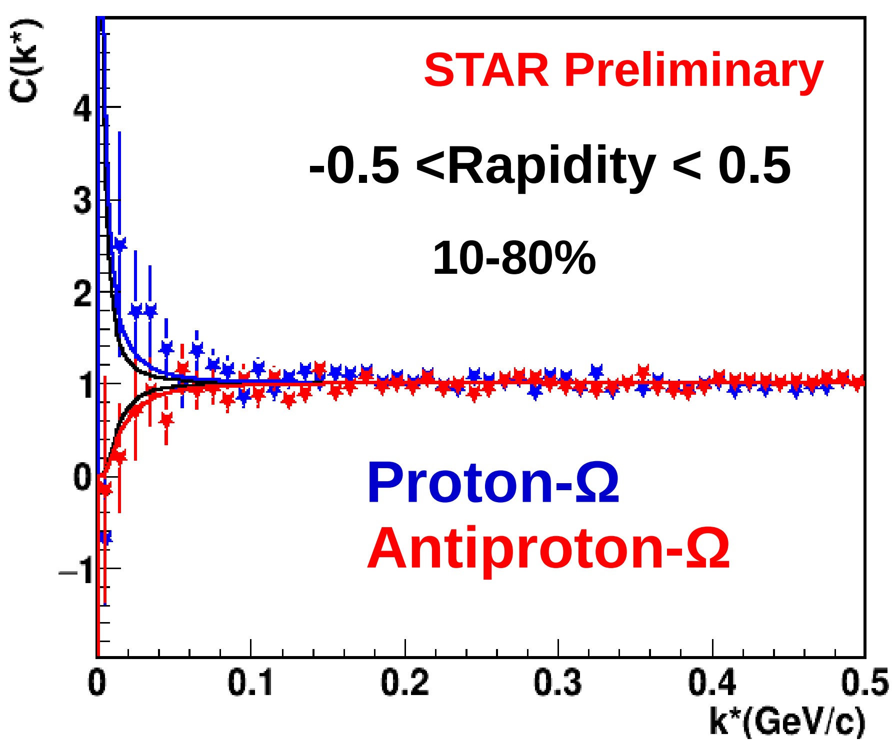


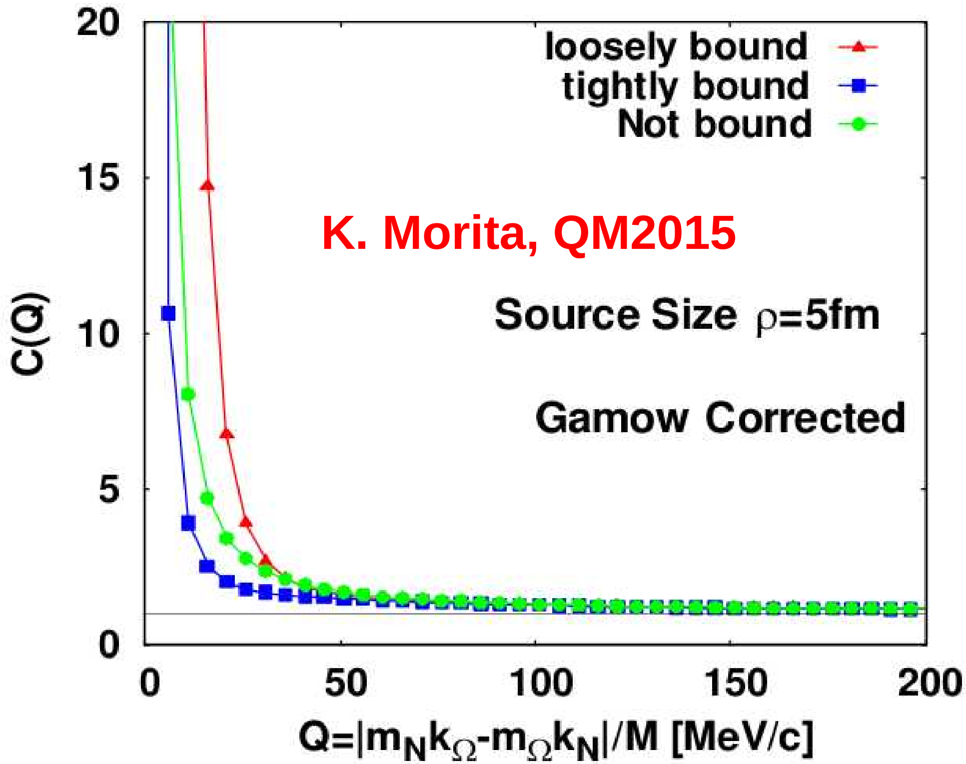
Proton-Ω Correlation Function

Proton-Ω Correlation Function

- **N-Ω potential may be attractive to form a bound state**

  Phy. Rev. Lett. 59 (1987) 627, Phy. Rev. C 69 (2004) 065207,
  Phy. Rev. C 70 (2004) 035204, Nucl. Phys. A 928 (2014) 89





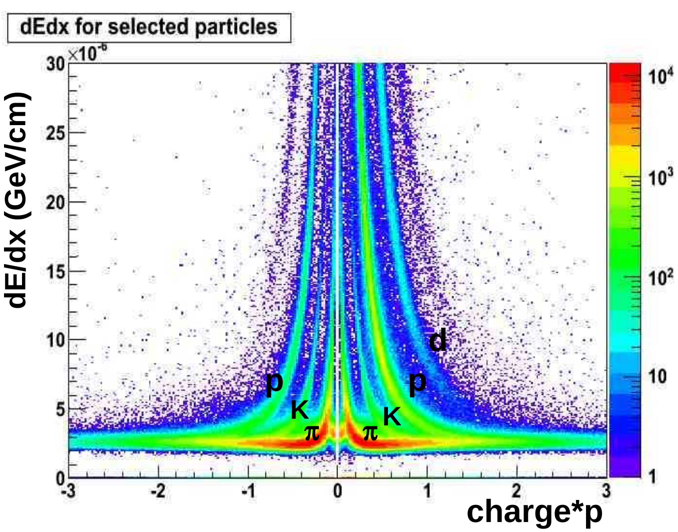
Other Correlation Function

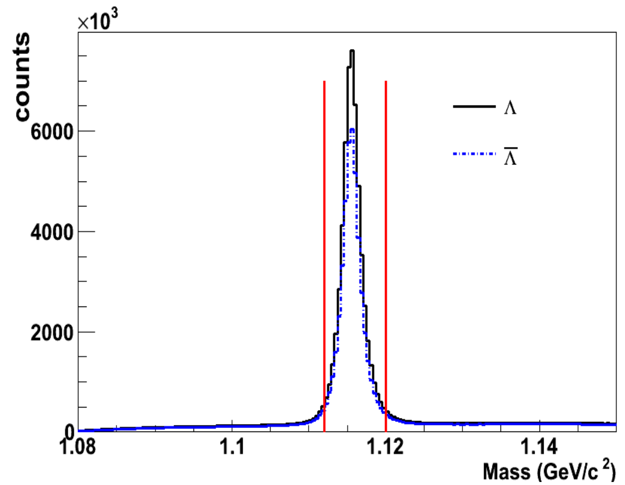
- Proton-Ξ: ΛΛ–ΞN Coupling is important to understand production of double-Λ hypernuclei
- Deuteron-Λ : Deeply bound kaonic states and to understand neutron-Λ interactions

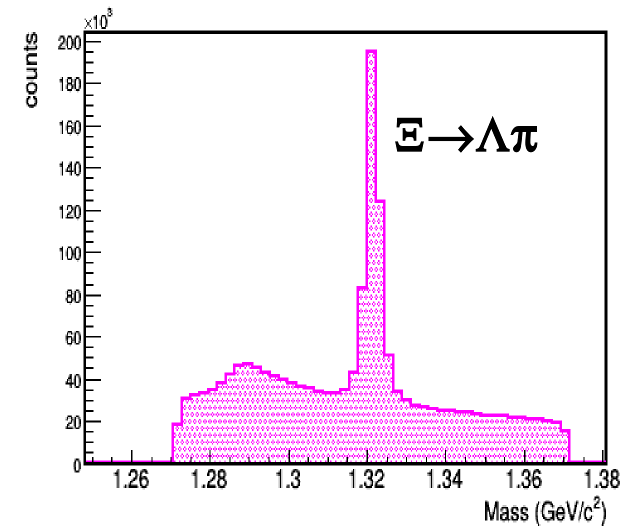
For k* < 0.5 GeV/c we have

→ 20K pair of Proton-Ξ for 0-5% centrality in 200 M MB Au+Au events

→ 26K pair of deuteron-Λ for 0-80 % centrality in 100 M MB Au+Au events



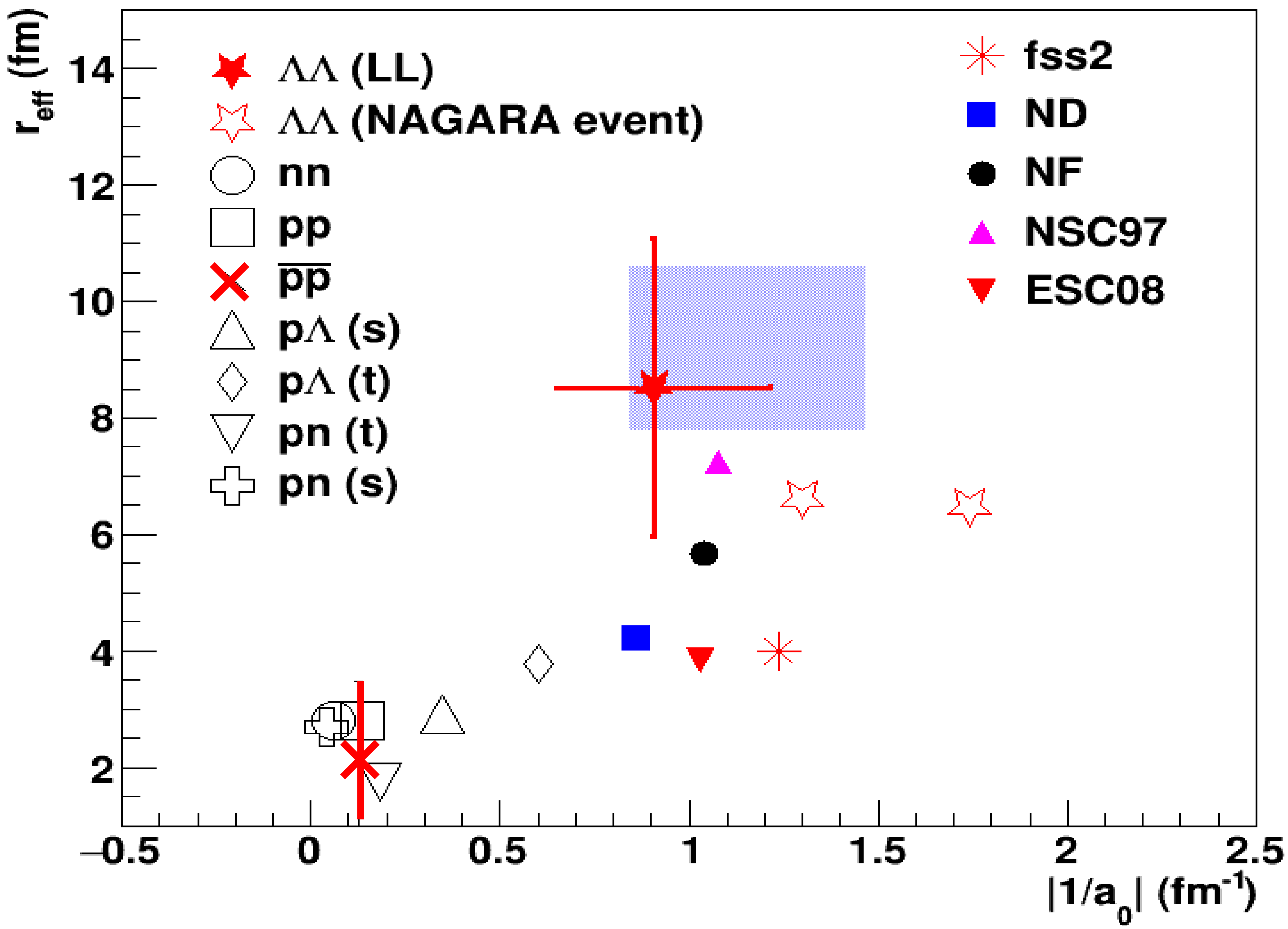




- **Work is in progress for Proton-Ξ and deuteron-Λ correlation functions**

Stay tuned for more results!

Summary – III: Interaction Parameters for Baryon-Baryon



n-n Phys. Lett B, 80 (1979) 187
p-n Phys. Rev. C 66 (2002) 047001
p-p Mod. Phys. 39 (1967) 584

p-Λ Phys. Rev. Lett. 83 (1999) 3138
ΛΛ Phys. Rev. C 66 (2002) 024007
ΛΛ Nucl. Phys. A 707 (2002) 491

Phys. Rev. Lett 114, 022301 (2015)
Phys. Rev. C 91 024916 (2015)
Nature 527 (2015) 345

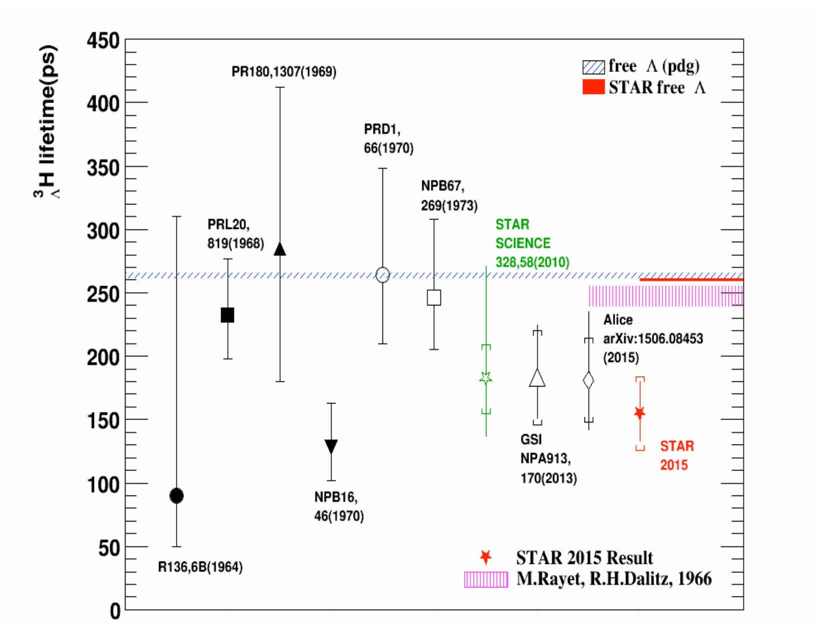
Summary

- Clear $\bar{\Lambda}$, $\bar{\Xi}$ yield enhancement compared to pions with increasing collision energy

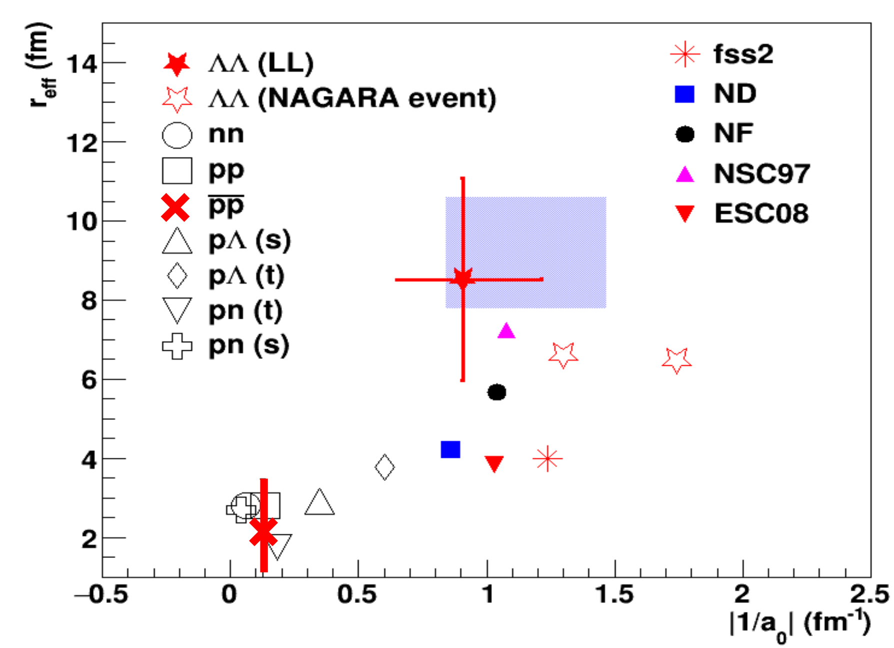
- Intermediate p_T nuclear modification factors show clear separation between different strange particles for 200 – 19.6 GeV

- Below 19.6 GeV, the separation between different strange particles becomes small → indicating possible phase transition

Hypertriton life-time



BB-Interaction Parameters




Thank you!
NS