Study of hyperon interaction via heavy-ion collisions from STAR Exp.

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Outline

- Introduction
  exotic hadrons - strangeness (S) sector

- H-dibaryon search from STAR Exp.

  – H-dibaryon and two particle correlations
    – Strong decay: correlation function for $\Lambda\,\Lambda$

  – Weak decay: $H \rightarrow \Lambda + p + \pi$ mass spectrum

- STAR other effort on the Y-N interaction measurement

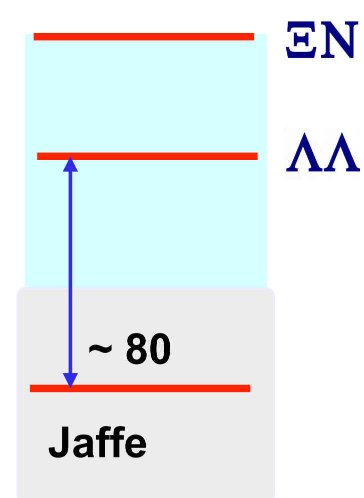
- Summary and Outlook

Introduction on Exotic Hadrons

- Hadron with multi quark components is a long-standing challenge in hadronic physics

- In 1977, Jaffe predicted that double strange dibaryon made of six quark (*uuddss*) may be deeply bound below the Lambda-Lambda threshold due to strong attraction from color magnetic interaction based on the bag model calculation

Phys. Rev. D **15**, 267 (1977);
Phys. Rev. D **15**, 281 (1977)
Phys. Rev. Lett. **38**,195 (1977); **38**, 617(E)(1977)



- Properties : $J^P = 0^+$, mass : (1.9-2.8) GeV/c^2

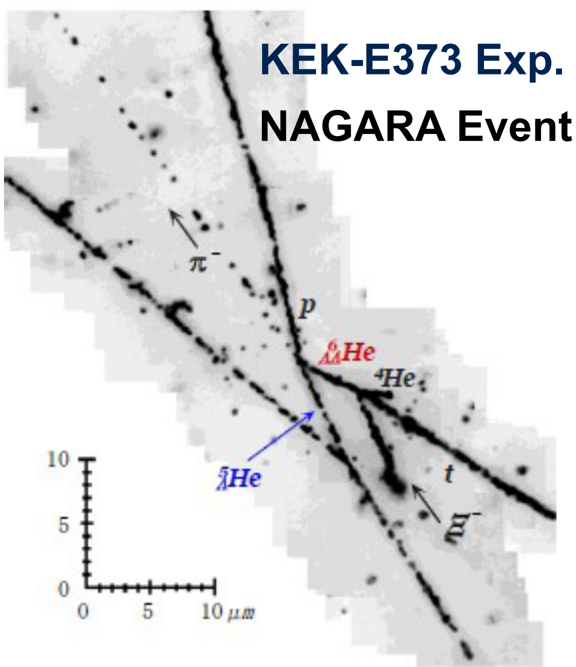
$$\psi(\mathrm{H}) = \sqrt{\frac{1}{8}}\psi(\Lambda\Lambda) + \sqrt{\frac{4}{8}}\psi(N\Xi) - \sqrt{\frac{3}{8}}\psi(\Sigma\Sigma)$$

- Since prediction, dedicated measurements have been performed to look for the H dibaryon signal, but its existence remains an open question

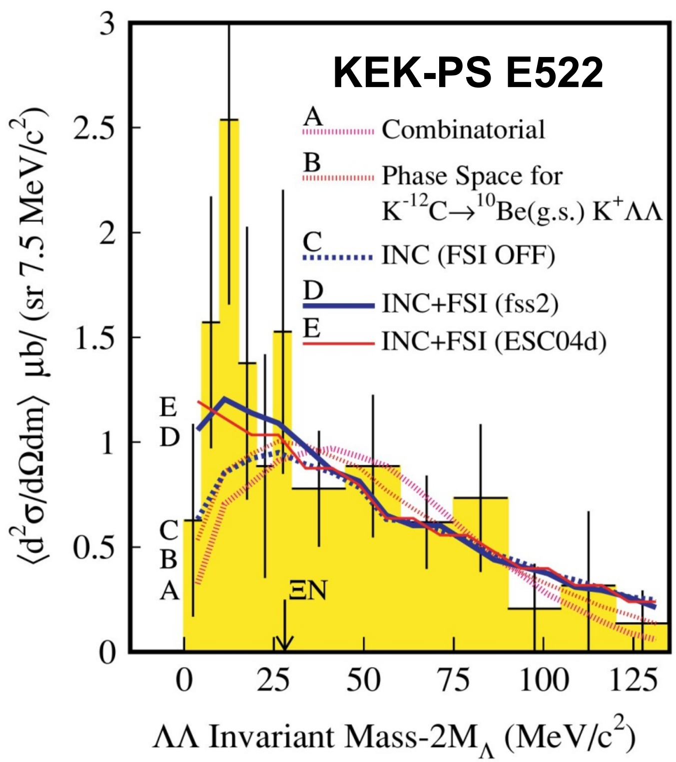
H-dibaryon (1)

- ☑ **NAGARA event – measurement of $_{\Lambda\Lambda}{}^{6}$H—>ΛΛ+^{4}He (BE ~ 6.91 MeV)**
- ☑ **KEK-E522 observation of 2.6σ enhancement for ΛΛ invariant mass spectra – resonance!**

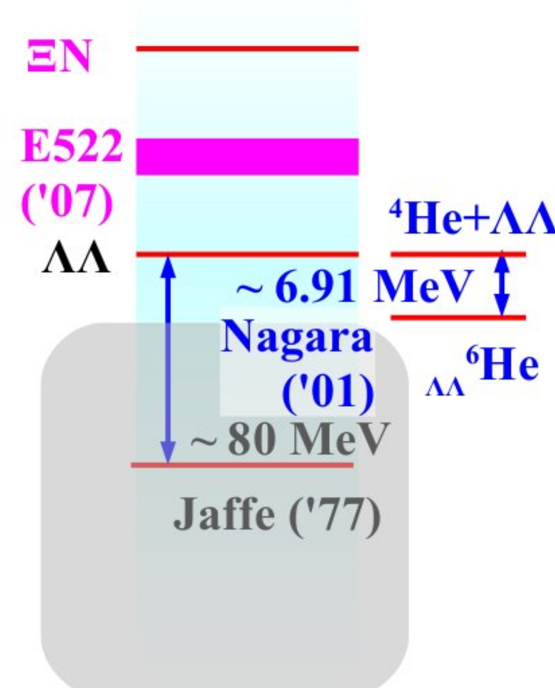
$$^{12}\mathrm{C} + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$
$$^{6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$$



Phys. Rev. Lett. 87,212502 (2001)



Phys. Rev. C 75, 022201(R) (2007)

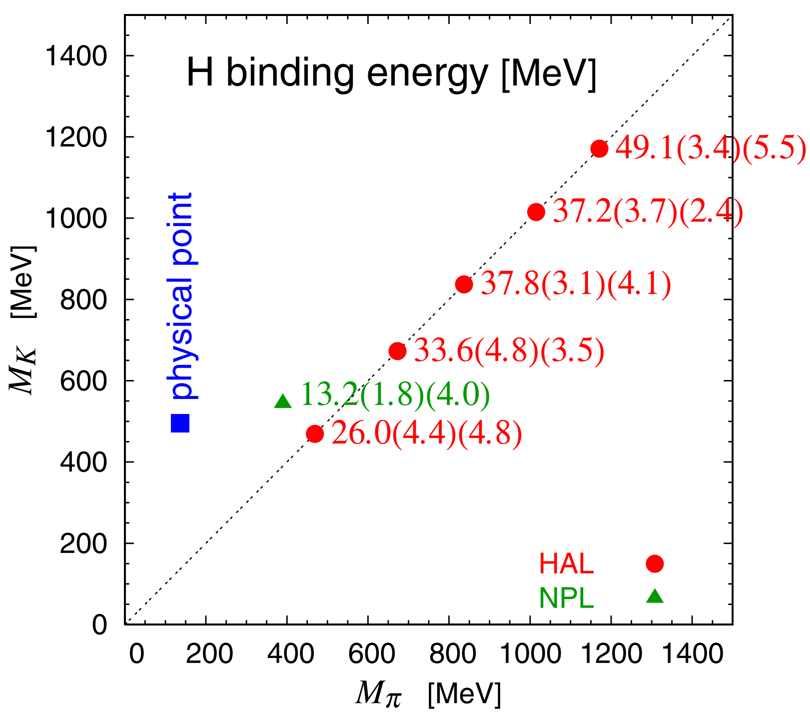


H-dibaryon (2)

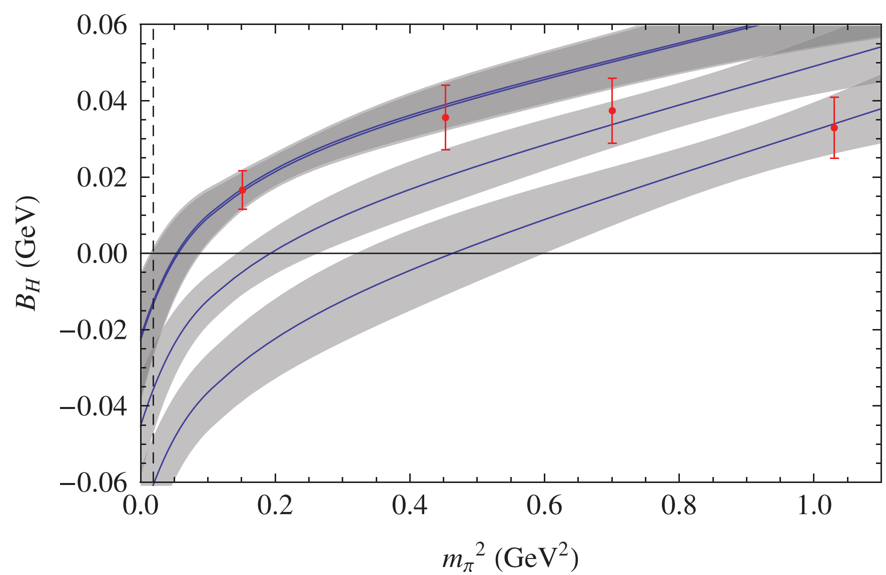
- ☑ Lattice QCD calculations – H-particle is indeed bound at quark mass above the physics range
  NPLQCD: Phys. Rev. Lett. 106,162001 (2011), HALQCD: Phys. Rev. Lett. 106, 162002 (2011)…

- ☑ Chiral extrapolation to physical pion mass leads to unbound H
  Phys. Rev. Lett. 107, 092004 (2011), Phys. Lett. B 706 (2011) 100

HALQCD, Nucl. Phys. A 881 (2012) 28



P.E. Shanahan, A.W. Thomas and R.D. Young, Phys. Rev. Lett. 107, 092004 (2011)



Possible venues for H-dibaryon search

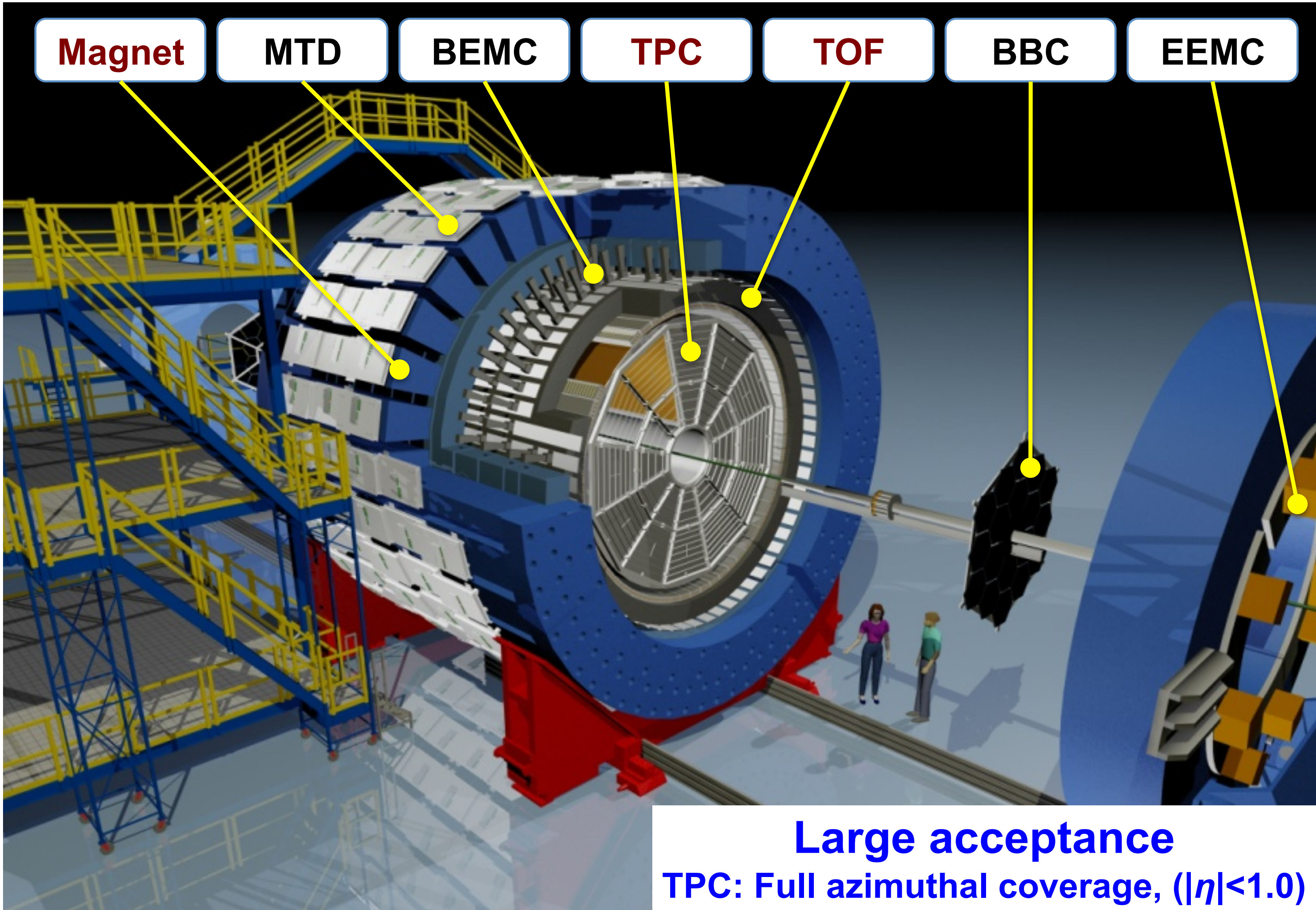
- Systematic study of double strangeness systems
  - Binding energies

    Future experiments at J-PARC, KEK

- Heavy Ion Collisions
  - Study two particle correlations
  - Invariant mass

    High statistics data from Relativistic Heavy Ion Collider (RHIC) & Large Hadron Collider (LHC)

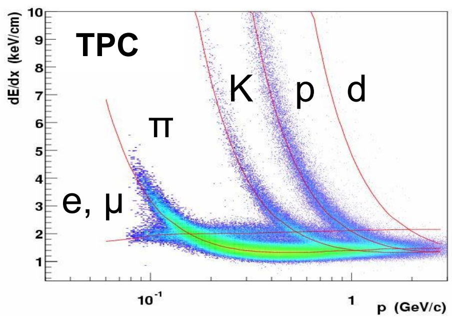
The STAR detector

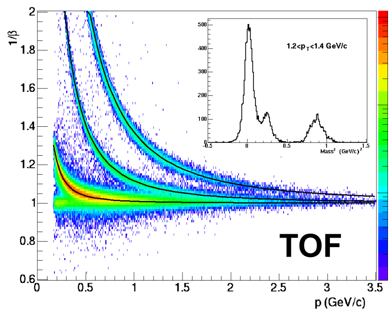


Large acceptance

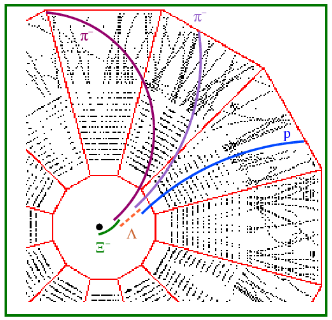
TPC: Full azimuthal coverage, ($|\eta|$<1.0)

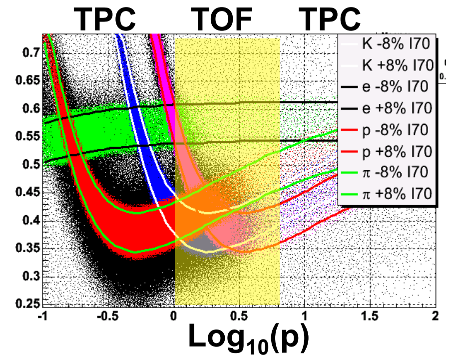
STAR : Excellent PID and Tracking



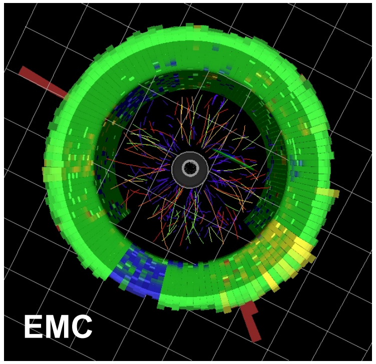


Charged hadrons

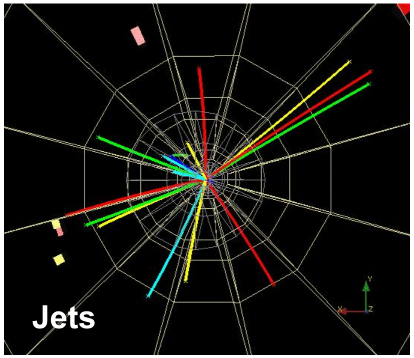




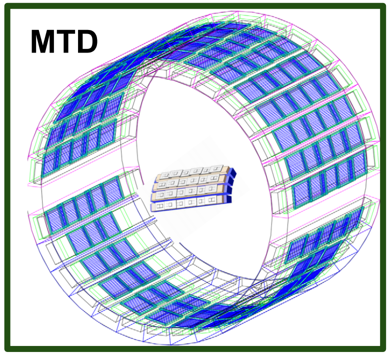
Hyperons & Hyper-nuclei



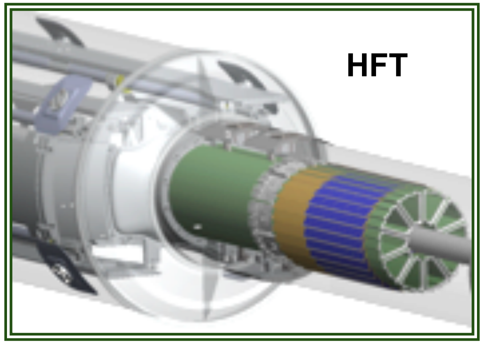
Neutral particles



Jets & Correlations



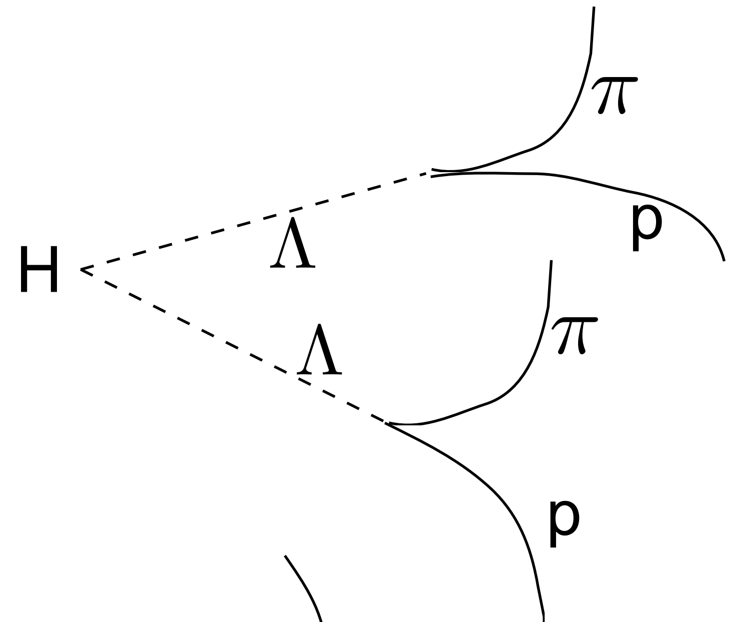
High p_T muons



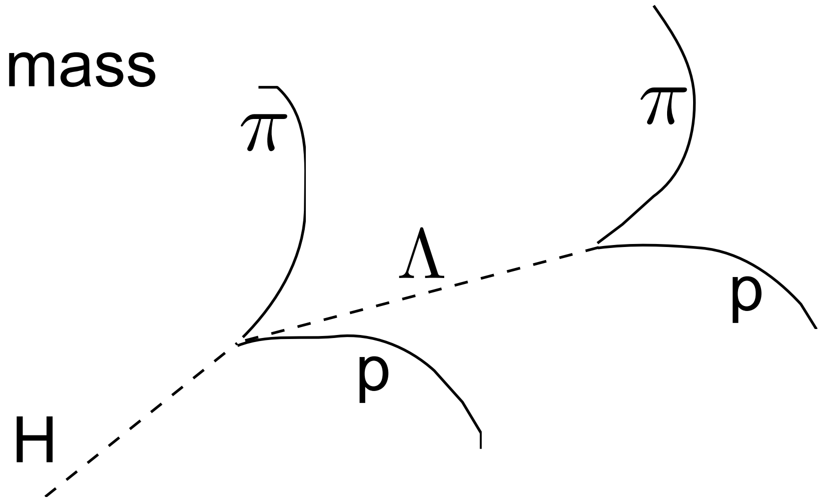
Heavy-flavor hadrons

The observable in STAR:

☑ Correlation function



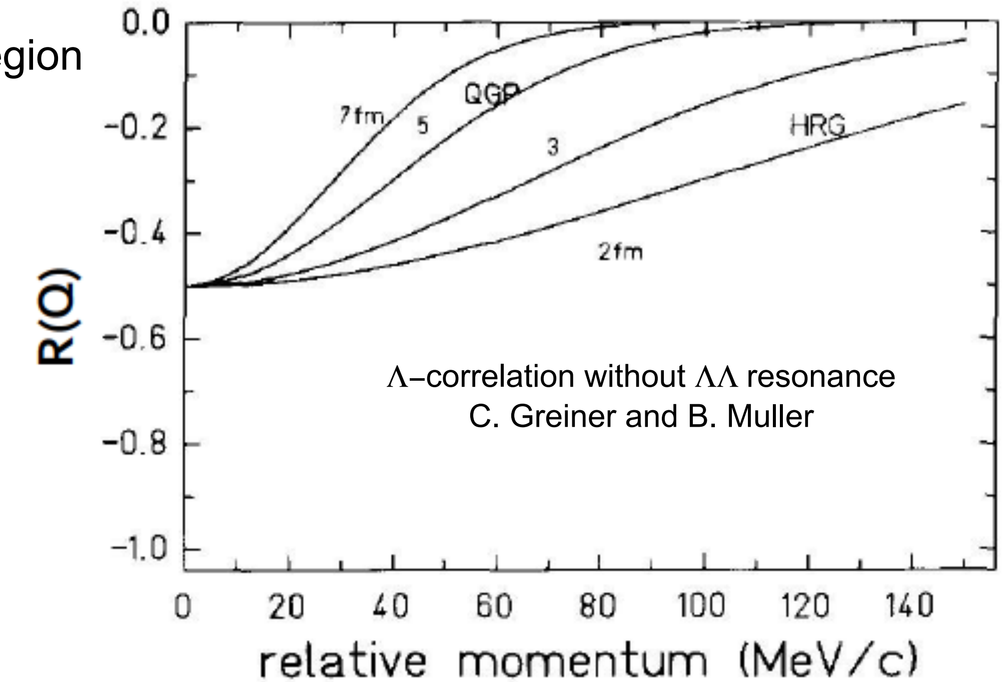
☑ Invariant mass



Correlation function

Measurement of $\Lambda\Lambda$ correlation functions:

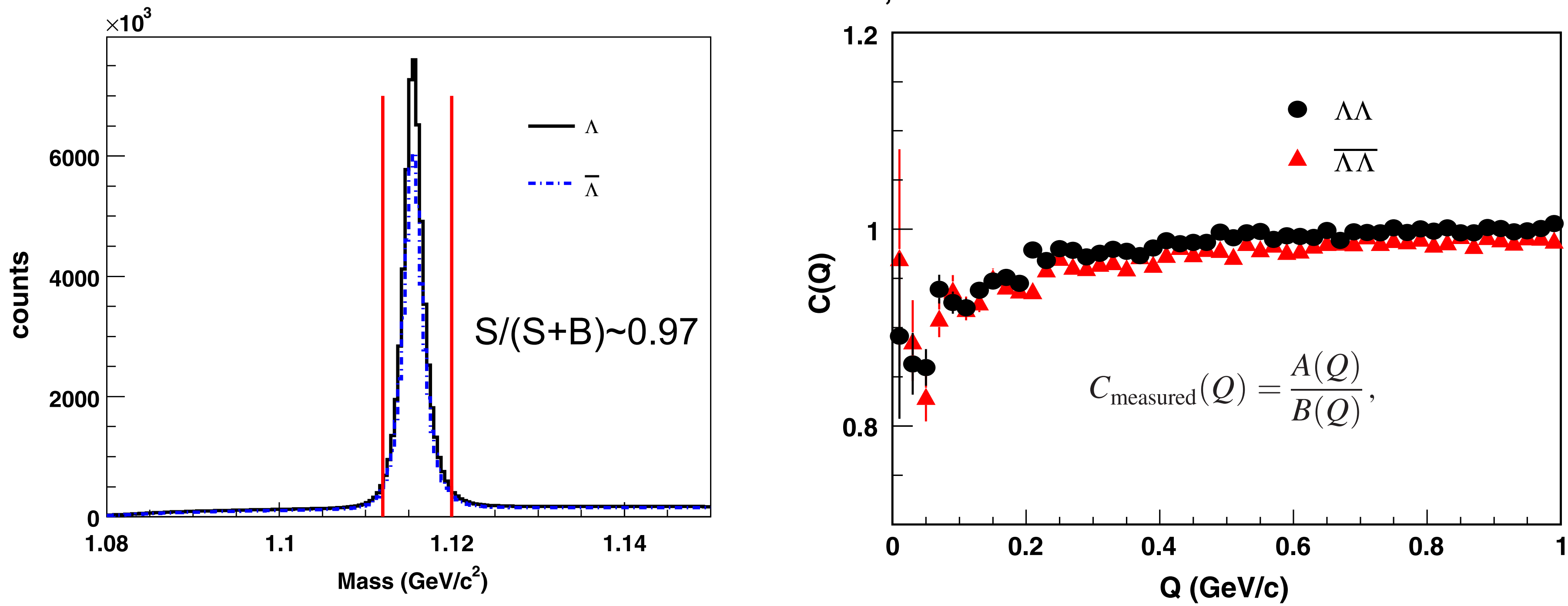
- related to the size r_0 of the emitting region
- no Coulomb interactions
- the two particle correlation function
  (C. Greiner and B. Muller
  Phys. Lett. B **219** (1989) 199)
- $R(Q)=\lambda*\exp(-Q^2r^2)$
- Q: relative momentum between two particles
- λ: degree of incoherence of the source
- search for H-dibaryon



The pair correlation function of the Λ depends sensitively on the source radius r_0 of the spacial volume.

Measurements from STAR detector

Au+Au at 200GeV, 0-80%



STAR Col. Phys. Rev. Lett. **114**, 022301(2015)

- ☑ STAR measure a clean Lambda signal with excellent signal to background ratio.
- ☑ Lambda-Lambda correlation function and its anti-particle's are found to be nearly identical.
- ☑ The following slides show combined results of Lambda and anti-Lambda to increase the statistics.

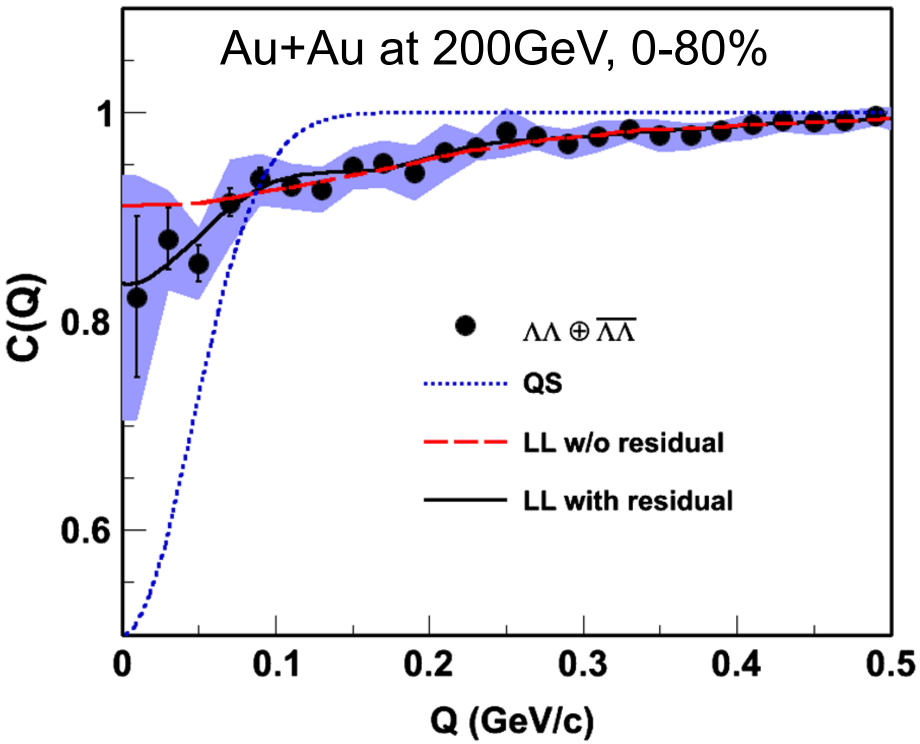
$\Lambda\,\Lambda$ correlation function

Fit using Lednicky-Lyuboshitz analytical model

$$CF = N(1+\lambda[\Sigma_S \rho_S (-1)^S \exp(-r_0^2 Q^2) + \Delta CF^{FSI} + a_{res} \exp(-Q^2 r_{res}^2)])$$

N- normalization, λ - suppression parameter

SJNP 35 (1982) 770



STAR Col. Phys. Rev. Lett. 114, 022301(2015)

- CF(Q=0) > CF_{QS}(Q=0)
  - – interaction is attractive
- High Q tail -> residual correlations from Σ^0, Ξ
- Interaction parameters:

$$\chi^2/\text{NDF} = 0.56$$

– Emission radius-

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

– Scattering length-

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

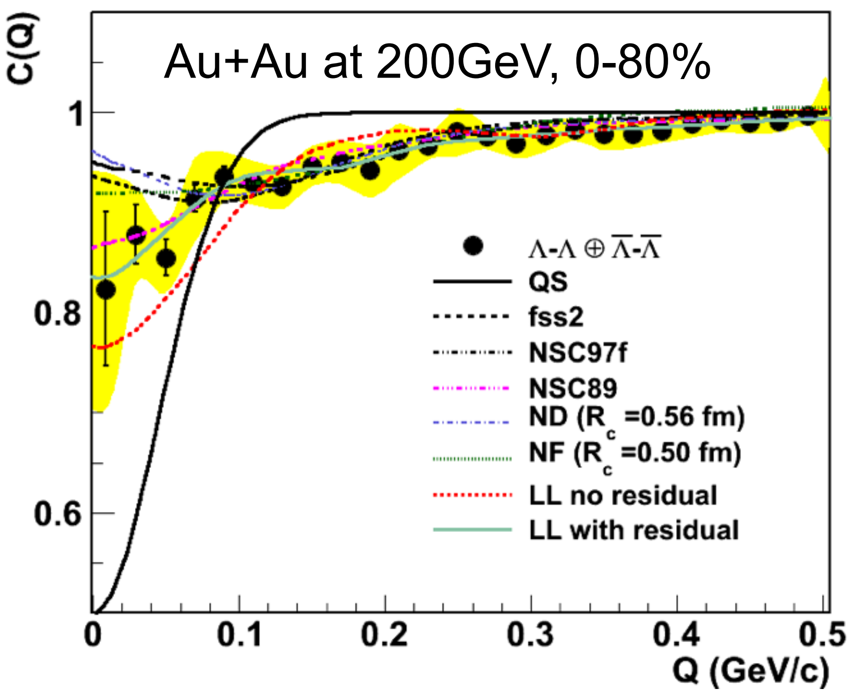
– Effective range-

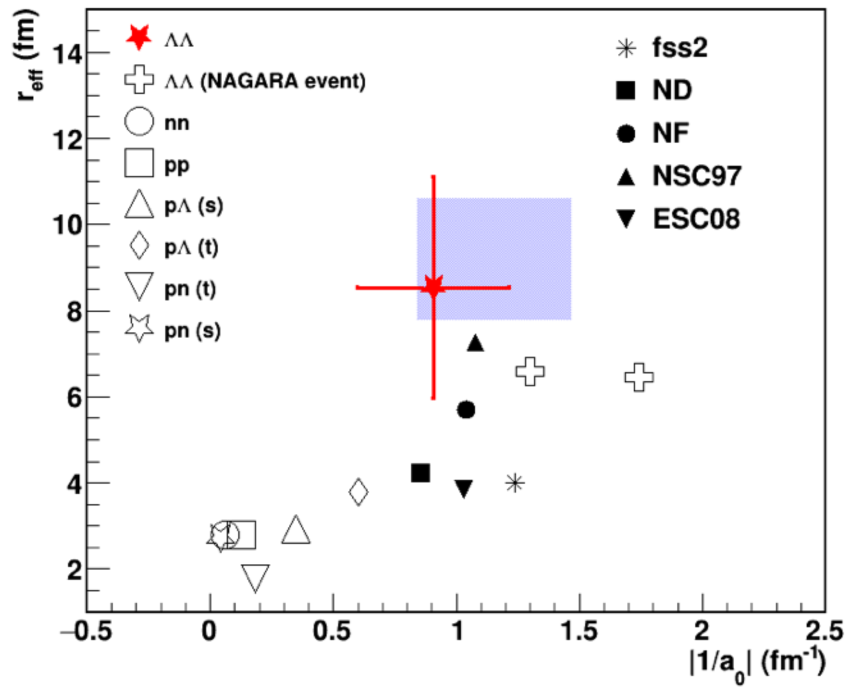
$$r_{\text{eff}} = 8.52 \pm 2.56^{+2.09}_{-0.74} \text{ fm},$$

$\Lambda\,\Lambda$ interaction potential

STAR Col. Phys. Rev. Lett. **114**, 022301(2015)

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





t → for triplet state
s → for singlet state

n-n → Phys. Lett B, 80 (1979) 187
p-n → Phys. Rev. C 66, 047001(2002)
p-p → Mod. Phys. 39 (1967) 584
p-Λ→ Phys. Rev. Lett. 83, 3138(1999)
ΛΛ→ Phys. Rev. C 66, 024007(2002)
ΛΛ→ Nucl. Phys. A 707 (2002) 491

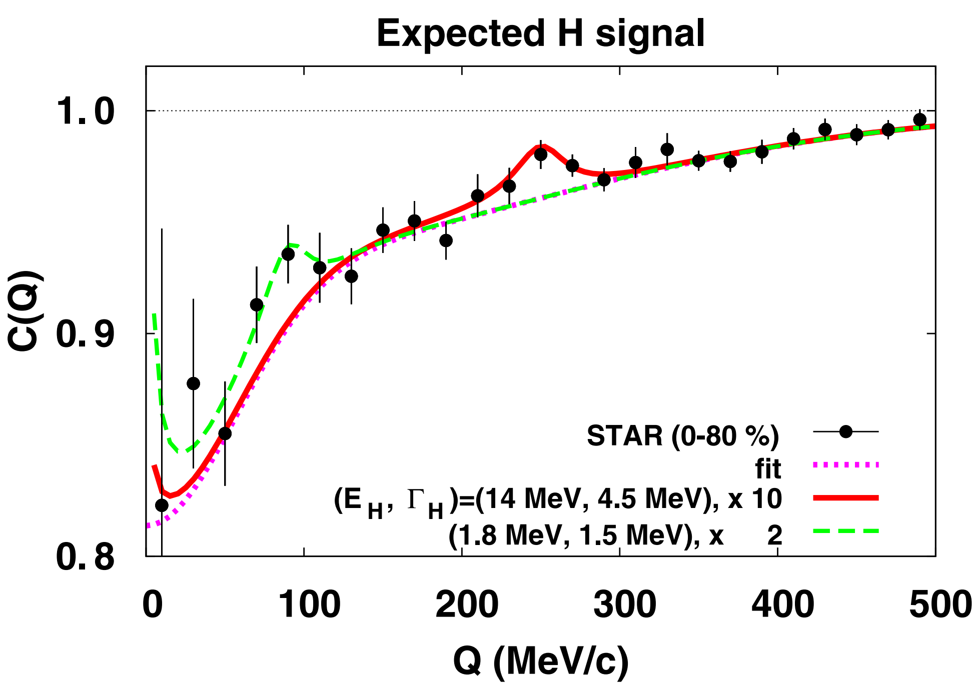
☑ All model fits to data suggest that a rather weak interaction is present between $\Lambda\,\Lambda$ pairs

Discussion on H-signal from model

- Assuming that H dibaryons are stable against strong decay of Lambda, and are produced through coalescence of Lambda-Lambda pairs:

$$d^2N_H/2\pi p_T dp_T dy = 16B(d^2N_\Lambda/2\pi p_T dp_T dy)^2$$

The integrated yield: $dN_H/dy = (1.23 \pm 0.47_{stat} \pm 0.61_{syst}) \times 10^{-4}$



- On the basis of (a_0,r_{eff}) from current data, the existence of H-particle as bound state of Lambda-Lambda is not preferred.

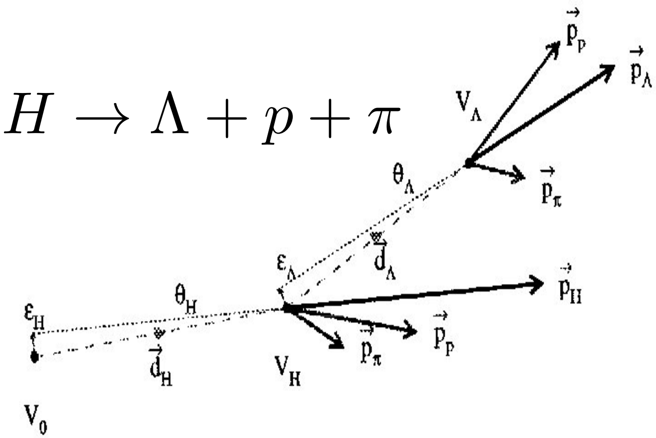
- On the resonance pole: high statistics is necessary to confirm or rule out the existence at low Q region.

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

H-dibaryon invariant mass distribution

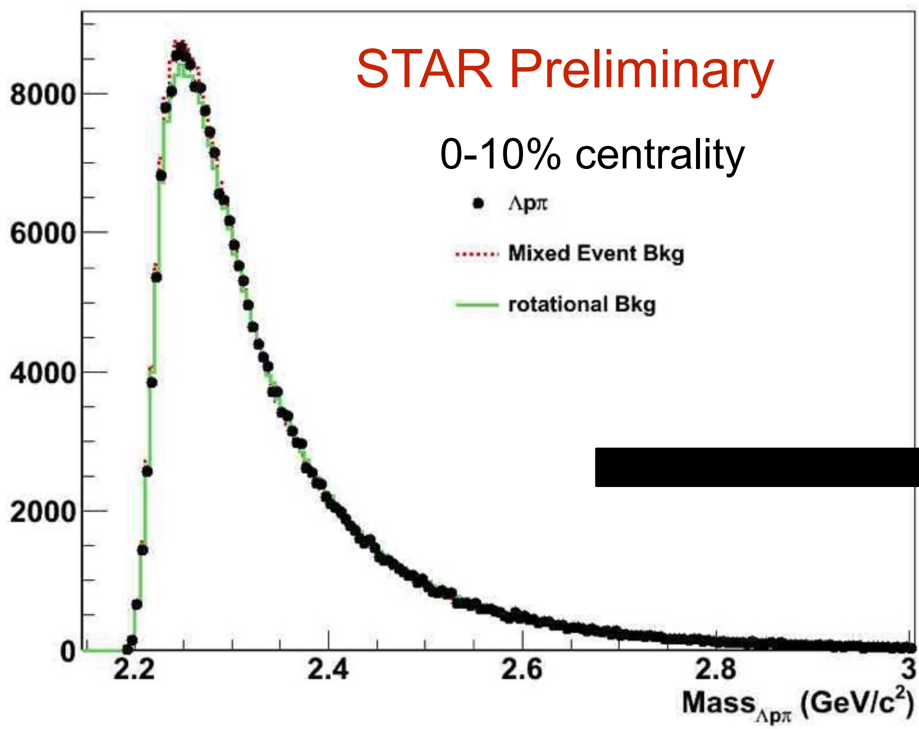
- ☑ Topological reconstruction of $\Lambda p \pi$ to look for H
  - Mass range: $2.2 < m_H < 2.231$ GeV/c^2

$$H \rightarrow \Lambda + p + \pi$$

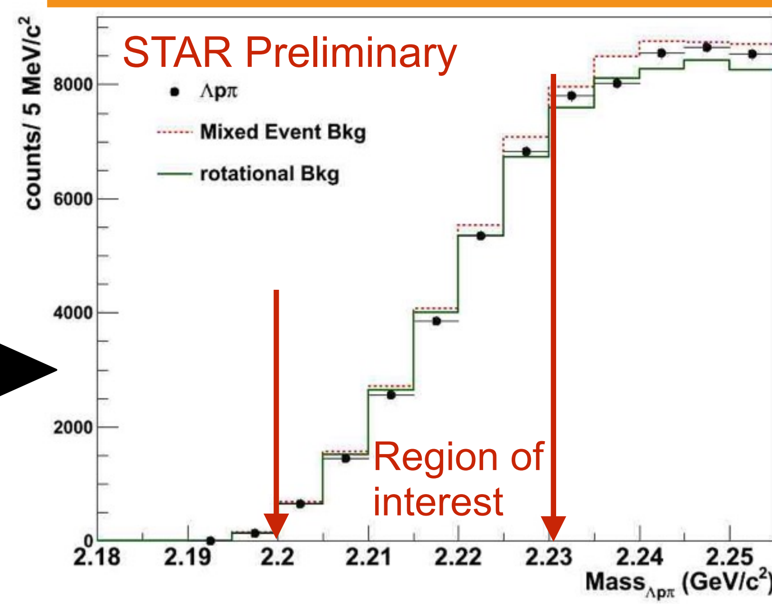


N. Shah for STAR Col. Nucl. Phys. A 914 (2013) 410

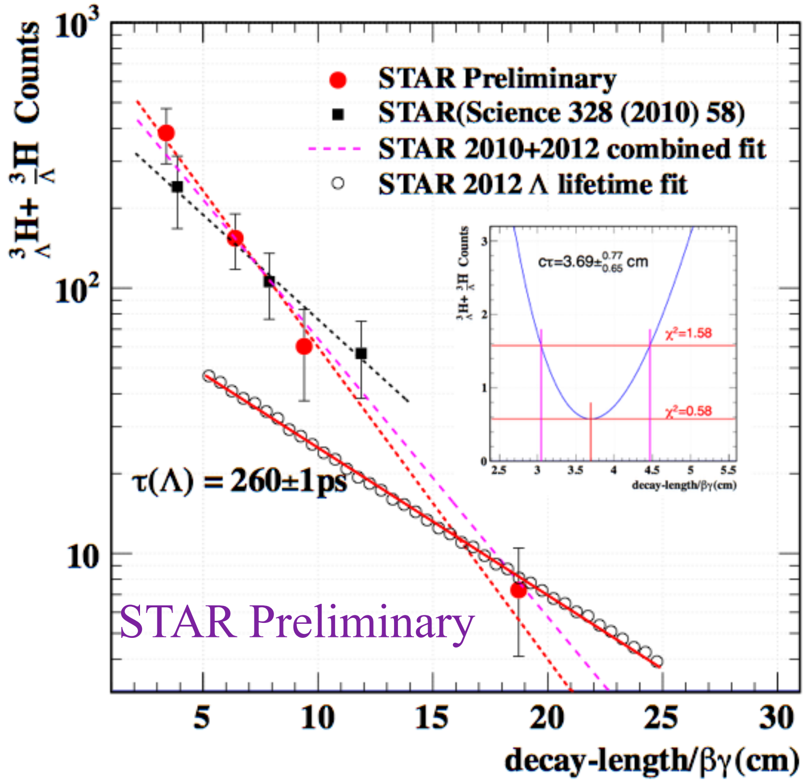
Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

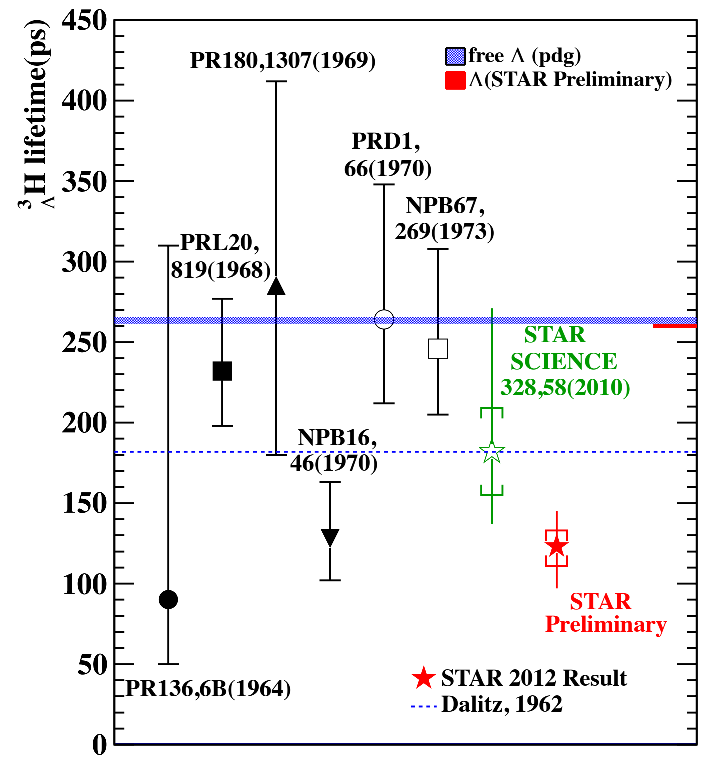


- No visible signal with respect to mixed event or rotational background



STAR effort on the Y-N interaction measurement





Decay mode: ${}^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$ and ${}^3_{\bar\Lambda}\bar{\mathrm{H}} \rightarrow {}^3\overline{\mathrm{He}} + \pi^+$ Y. Zhu for STAR Col. Nucl. Phys. A 904 (2013) 551

- ☑ A precise determination of the lifetime of hyper triton provides direct information on the Y-N interaction strength
- ☑ High statistics data from STAR show a short lifetime compared with the free Lambda’s

Summary

- ☑ $\Lambda\Lambda$ interaction is indeed attractive
- ☑ Attraction is not strong enough to form stable H-dibaryon
- ☑ Interaction parameters: $1/a_0 < -0.5\ fm^{-1}$ and $r_{eff} > 3$ fm
- ☑ Measured interaction parameter gives indication towards non-existence of $\Lambda\Lambda$ resonance below the $N\Xi$ and $\Sigma\Sigma$ threshold
- ☑ On the hypertriton part: $\tau = 123 \pm^{26}_{22} \pm 10\, ps$ is obtained, which is significantly shorter than the value from free Lambda's

Outlook

- Observation of di-baryon in Delta-Delta system from WASA-at-COSY : stimulated new interest in di-baryon structure within the QCD framework

- N-Omega potential may be attractive for a bound state (HAL QCD Col. Nucl. Phys. A 928 (2014) 89)
- Xi-Xi: a bound state analogous to deuteron (G.A. Miller, Chin. J. Phys. 51 (2013) 466)

- Extend correlation measurement to these systems

- Shed light on hyperon-interactions, which is important to constrain the equation of state for nuclear matter including strange quark degree of freedom which is essential to understand the neutron stars

Thank you!

Back-up slide

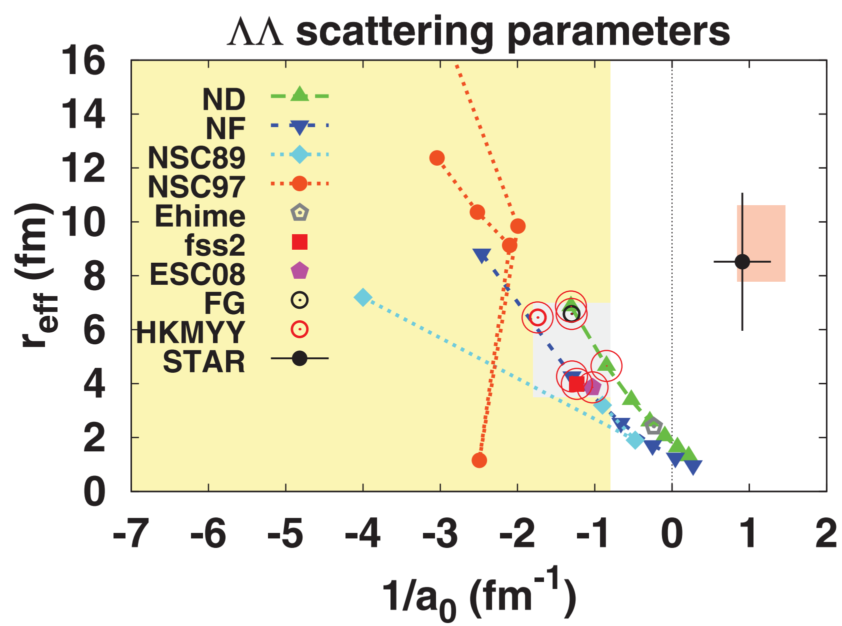


FIG. 1. (Color online) $\Lambda\Lambda$ interactions and scattering parameters in the $(1/a_0, r_{\rm eff})$ plane. The $\Lambda\Lambda$ interactions favored by the $\Lambda\Lambda$ correlation data without feed-down correction are marked with big circles. The thin big and thick small shaded areas correspond to the favored regions of scattering parameters with and without feed-down correction, respectively, which show stable and small χ^2 minimum (see text). The results of the analysis by the STAR Collaboration is shown by the filled circle [15], together with systematic error represented by the surrounding shaded region.