# Study baryon interactions via hyperon correlation analysis at RHIC-STAR

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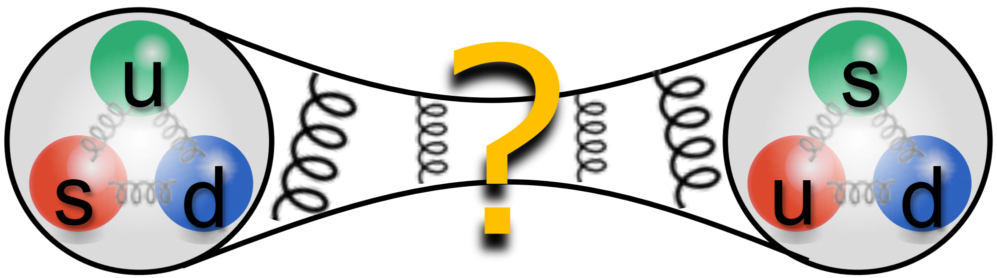
# Outline

- Introduction
  - Exotic hadrons - strangeness (S) sector
- Measurements from STAR
  - H-dibaryon analysis
  - Preliminary results on NΩ dibaryon analysis
- Summary

# Motivation

- Baryon-baryon interaction including strangeness




  - Possible hyperon matter in the core of a neutron star
  - Exotic hadrons (non-$q\bar{q}$, non-qqq)

- Inputs from theory

  - Lattice QCD: physical point results coming soon?

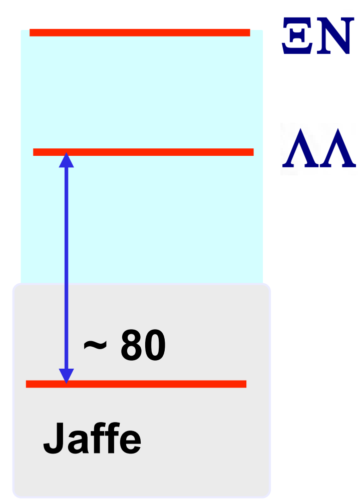
# Introduction on H-dibaryon

- 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/$c^2$

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

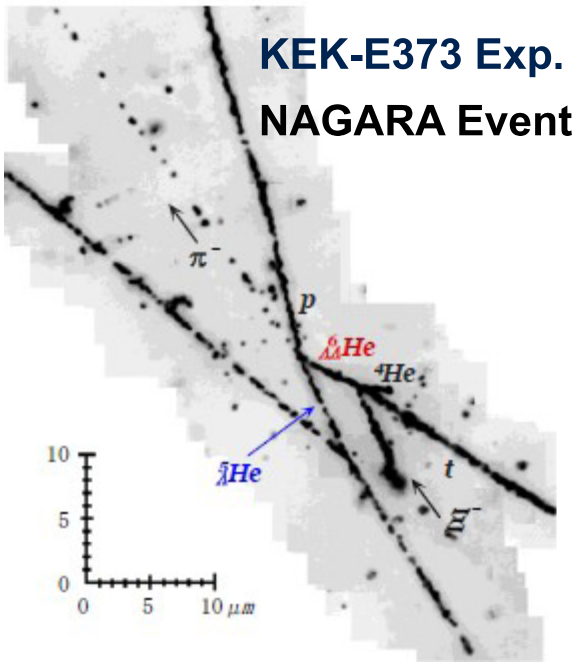



- Since prediction, dedicated measurements have been performed to look for the H dibaryon signal, but its existence remains an open question

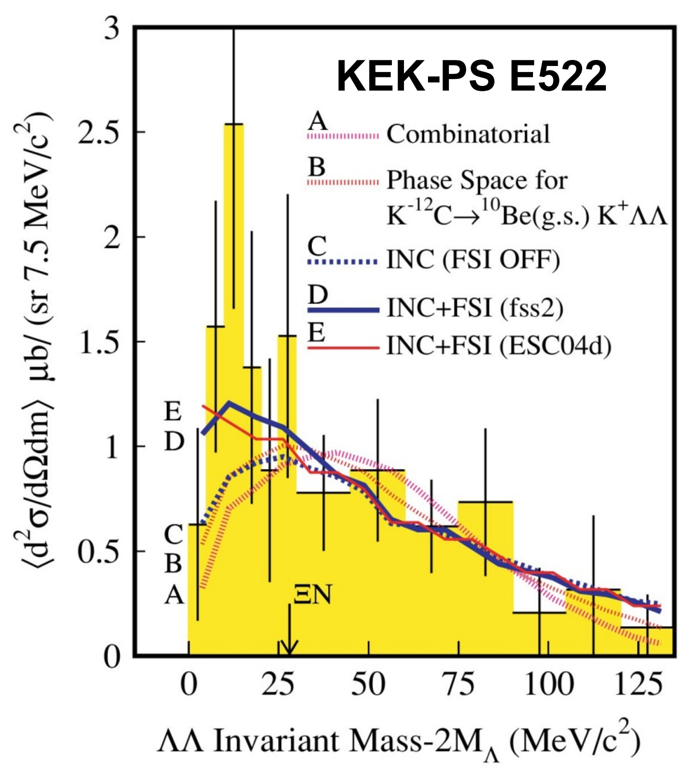
# H-dibaryon (1)

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

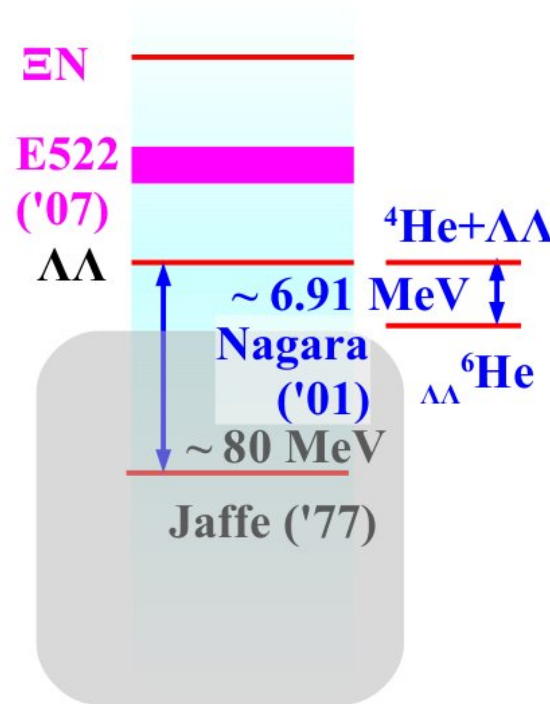
$$ {}^{12}C + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t $$
$$ {}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^- $$




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




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

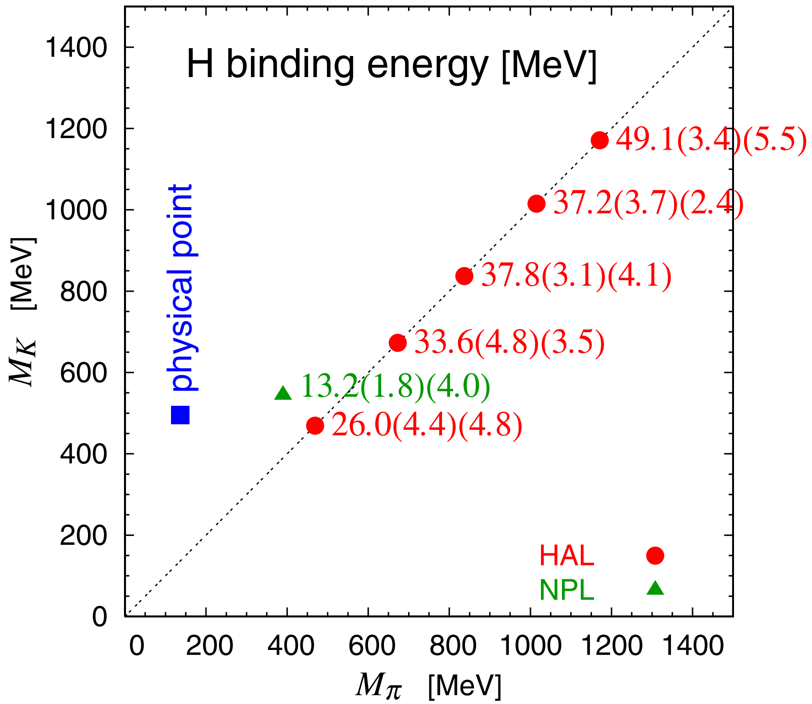


# H-dibaryon (2)

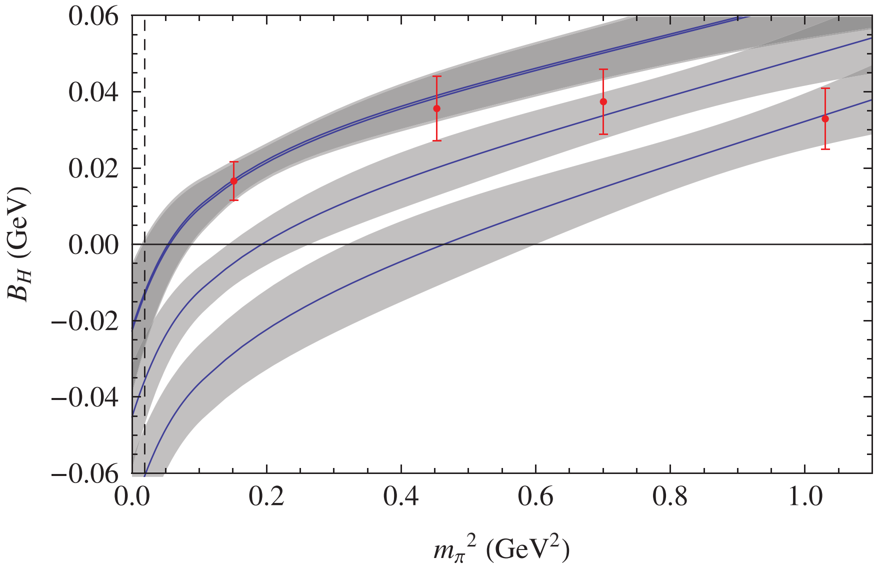
- Lattice QCD calculations – H-particle is indeed bound at quark mass above the physics range
  NPLQCD: Phys. Rev. Lett. 106,162001 (2011), HALQCD: Phys. Rev. Lett. 106, 162002 (2011)…

- 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

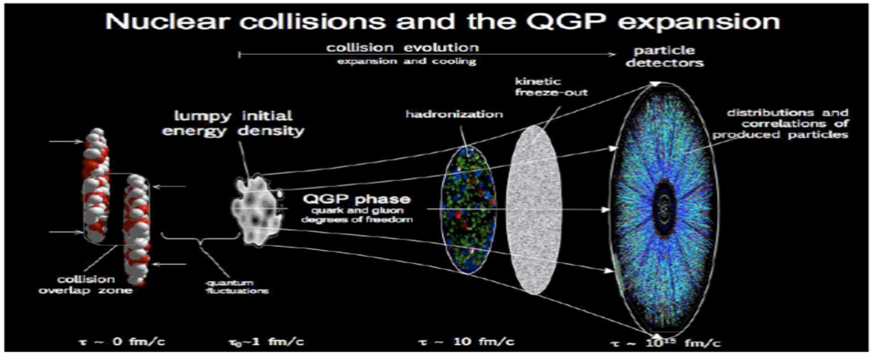
- Systematic study of double strangeness systems
  - Binding energies

    Future experiments at J-PARC, KEK

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

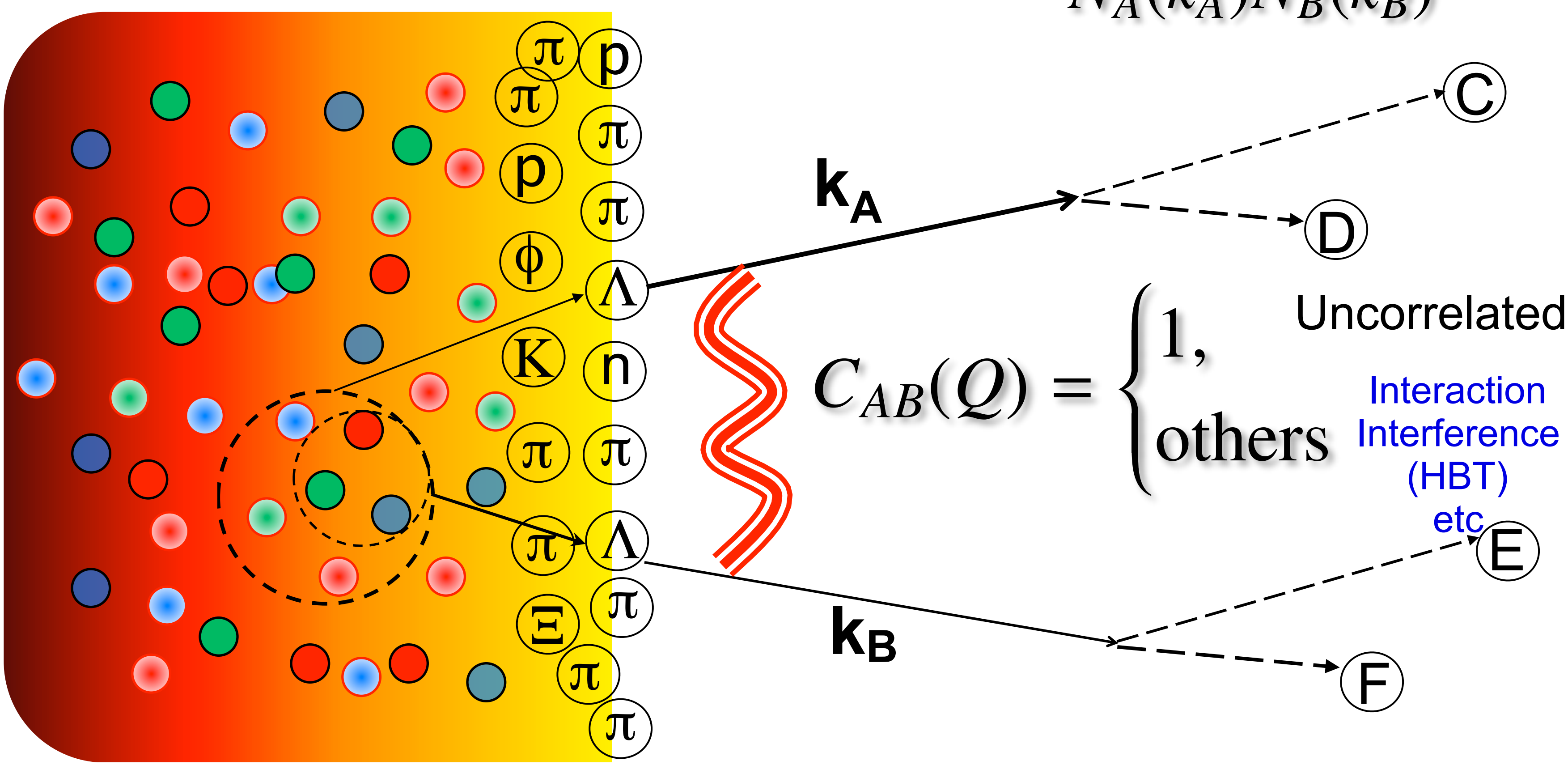
    High statistics data from Relativistic Heavy Ion Collider (RHIC) & Large Hadron Collider (LHC)

# Particle correlation in HIC



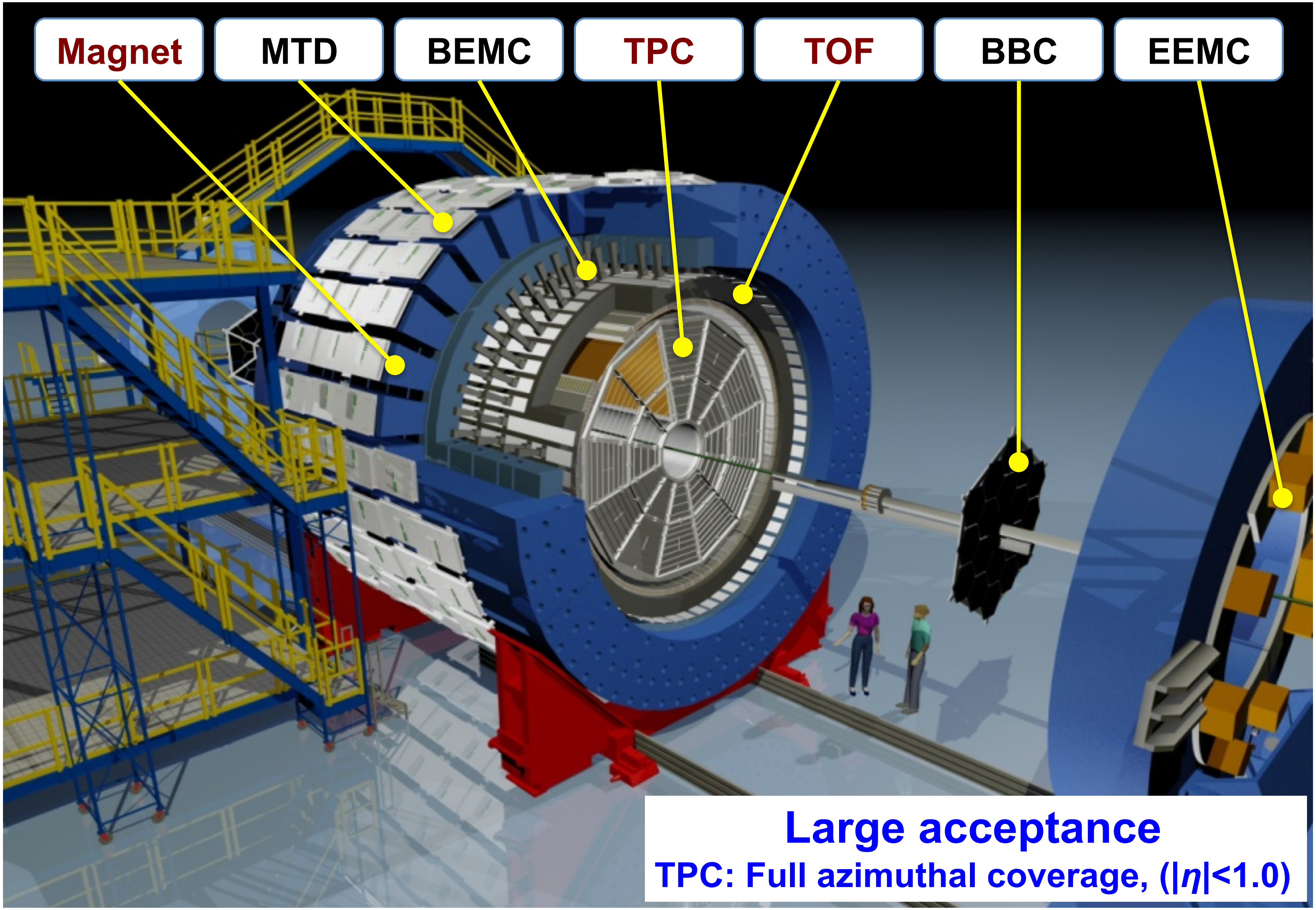

- ☑ HIC as a hyperon factory
- ☑ Baryon interaction via hyperon correlation

$$C_{AB}(Q) = \frac{N^{\text{pair}}_{AB}(k_A, k_B)}{N_A(k_A)N_B(k_B)}$$




$$C_{AB}(Q) = \begin{cases} 1, & \text{Uncorrelated} \\ \text{others} & \text{Interaction, Interference (HBT), etc} \end{cases}$$

# The STAR detector at RHIC

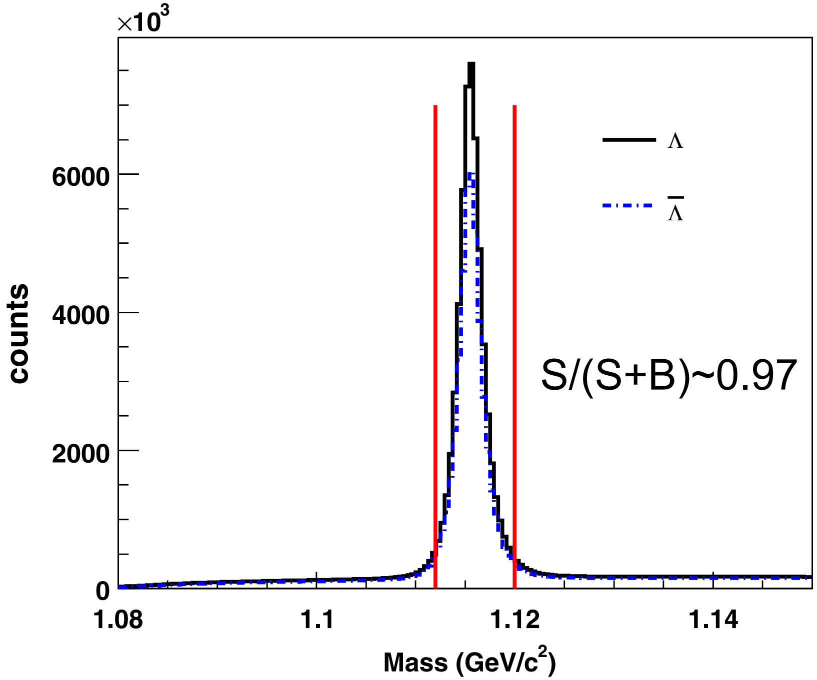


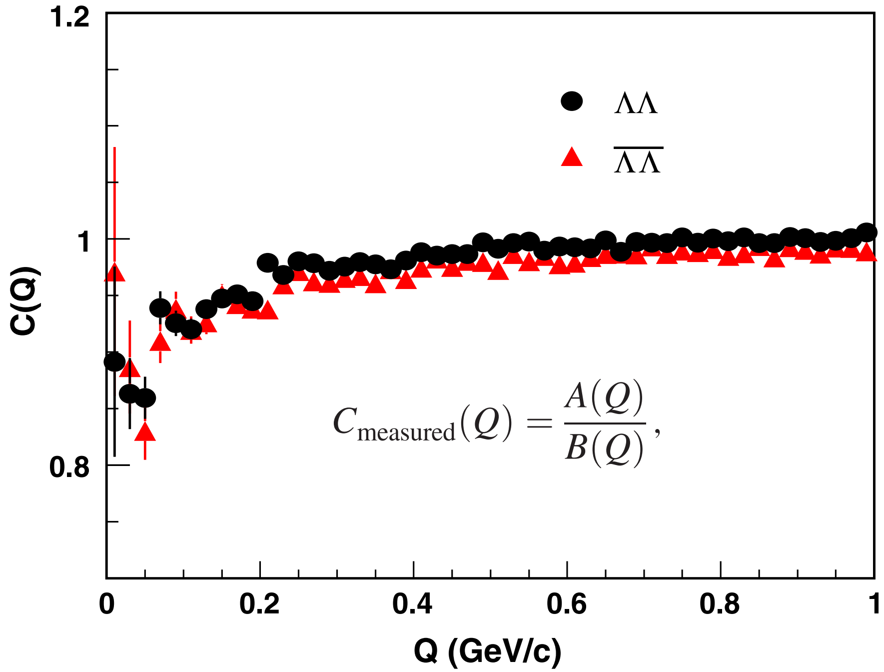

**Large acceptance**

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

# 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.

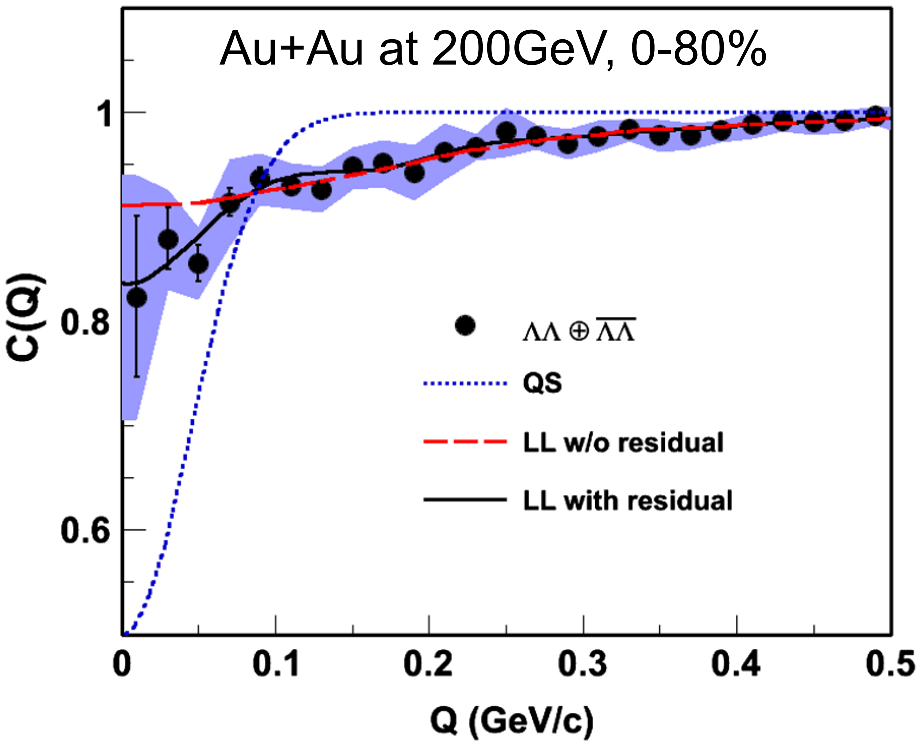
# Lambda-Lambda correlation function

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, $\lambda$ - 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 $\Sigma^0, \Xi$
- ☑ Interaction parameters:

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

– Emission radius-

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

– Scattering length-

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

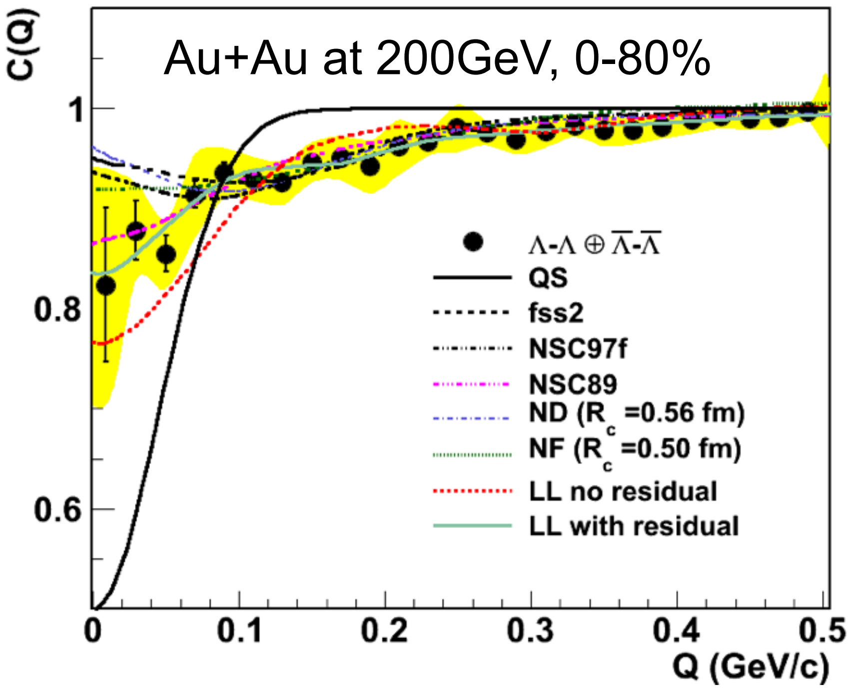
– Effective range-

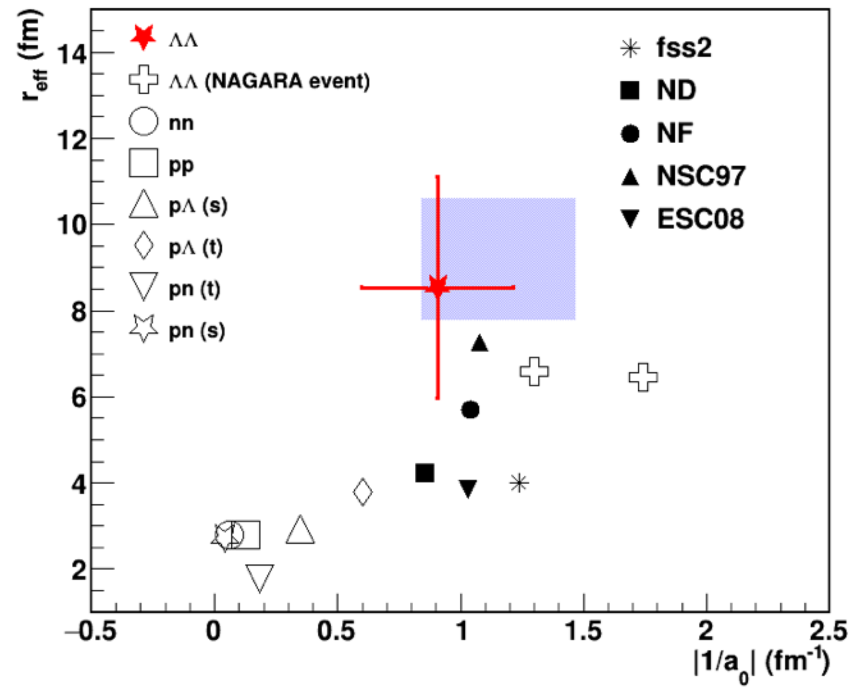
$$r_{\mathrm{eff}} = 8.52 \pm 2.56^{+2.09}_{-0.74}\ \mathrm{fm},$$

# 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**

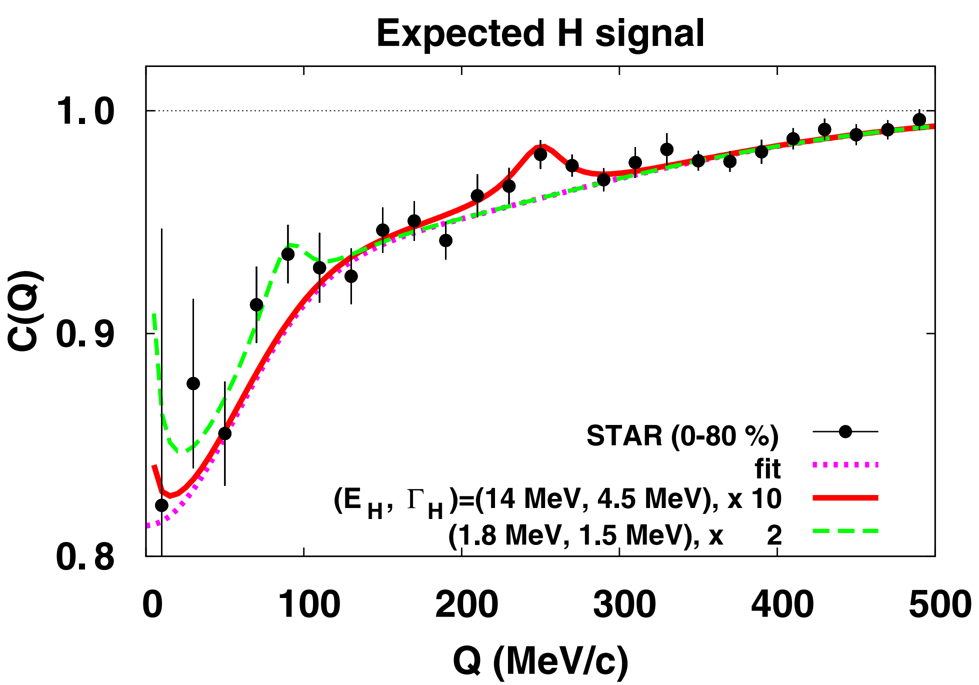
☑ All model fits to data suggest that a rather weak interaction is present between ΛΛ pairs

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



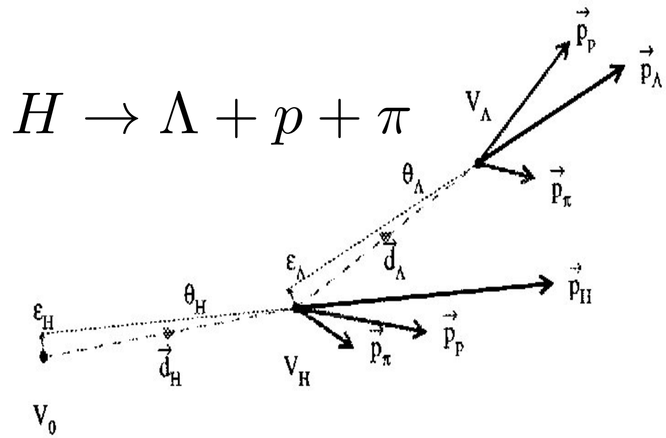

☑ On the basis of ($a_0$,$r_{eff}$) from current data, the existence of H-particle as bound state of Lambda-Lambda is not preferred.

☑ 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)

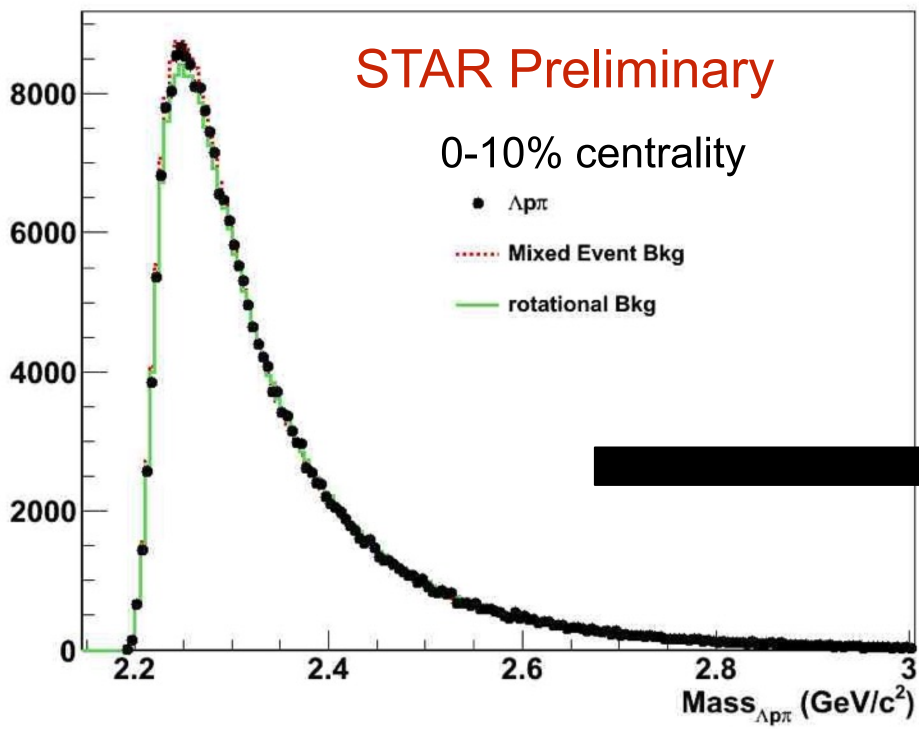
# H-dibaryon invariant mass distribution

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

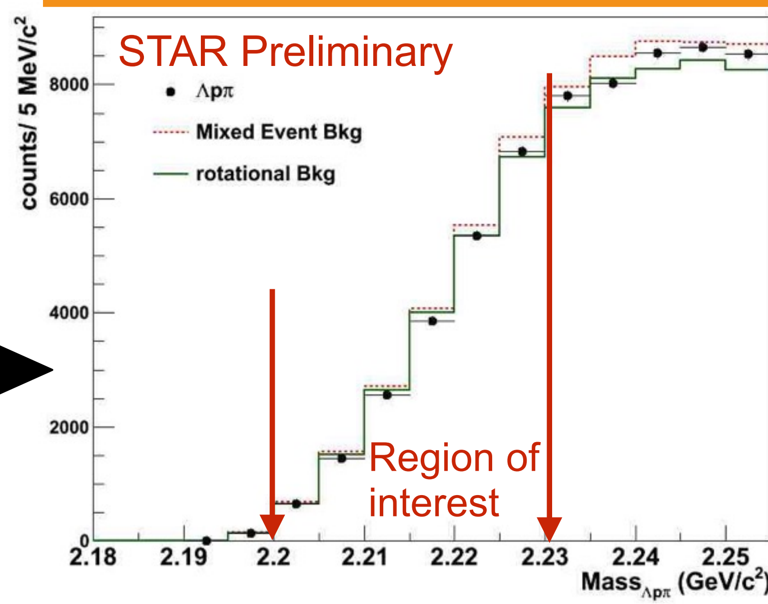



N. Shah for STAR Col. Nucl. Phys. A 914 (2013) 410

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

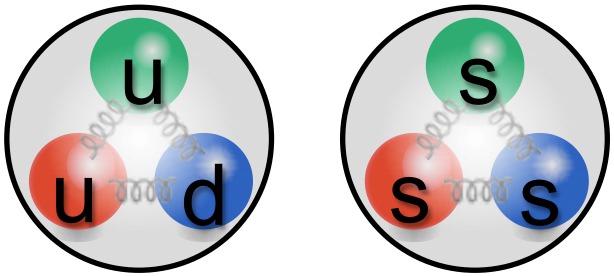



- No visible signal with respect to mixed event or rotational background



# Move onto the Strangeness = -3 dibaryon

- ☑ Strangeness -3 is stable against strong decay, from MIT bag and potential model calculation, N-Omega with I=1/2, *J*=2, $E_B$=140-250MeV




F. Wang et al., : PRL 59,627(1987); PRC 69, 065207(2004); 83, 015202(2011); 92,065202(2015)

- ☑ HAL-QCD calculation find a bound state of N-Omega system, potential through Nambu-Bethe-Salpeter wave function NPA 928, 89(2014)

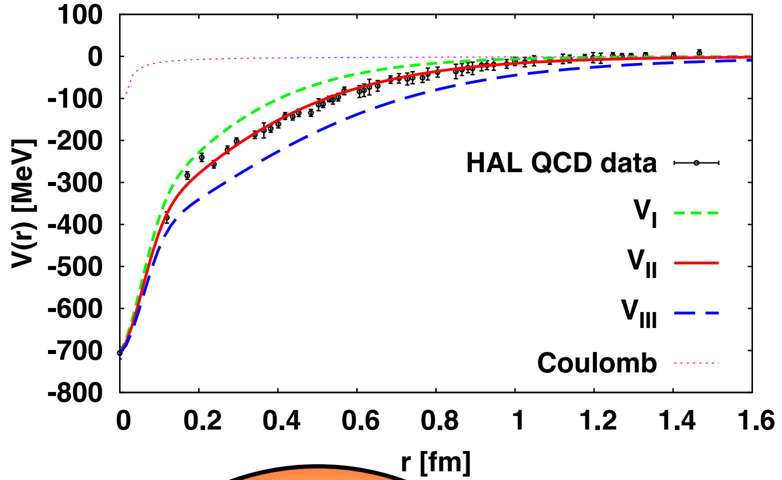
$$\begin{aligned} B_{N\Omega} &= 18.9(5.0)(^{+12.1}_{-1.8})\ \mathrm{MeV}, \\ a_{N\Omega} &= -1.28(0.13)(^{+0.14}_{-0.15})\ \mathrm{fm}, \\ (r_e)_{N\Omega} &= 0.499(0.026)(^{+0.029}_{-0.048})\ \mathrm{fm}. \end{aligned}$$

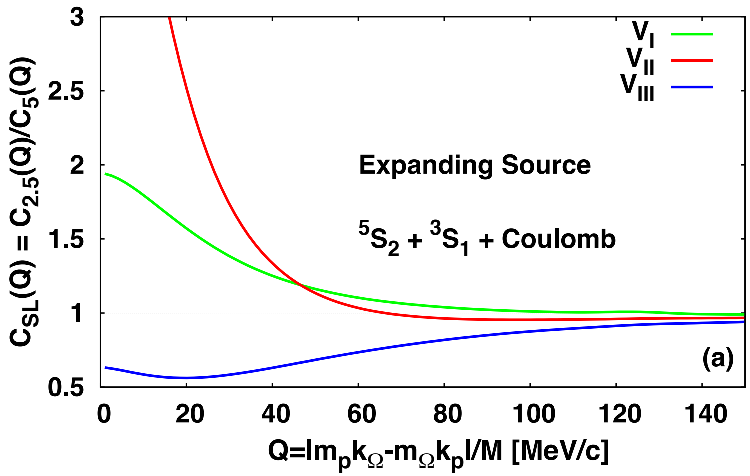
# Proposal on source size dependence analysis

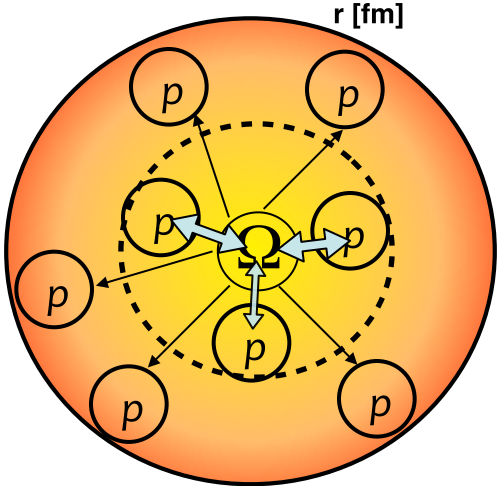
- Starting from the N-Omega potential from HAL QCD data, Morita etc. propose a source size analysis of C(Q) to extract the strong p-Omega interaction w/o much contamination from Coulomb attraction.

$$V(r) = b_1 e^{-b_2 r^2} + b_3 (1 - e^{-b_4 r^2})^n (e^{-b_5 r}/r)^2$$

Morita etc. arXiv:1605.06765

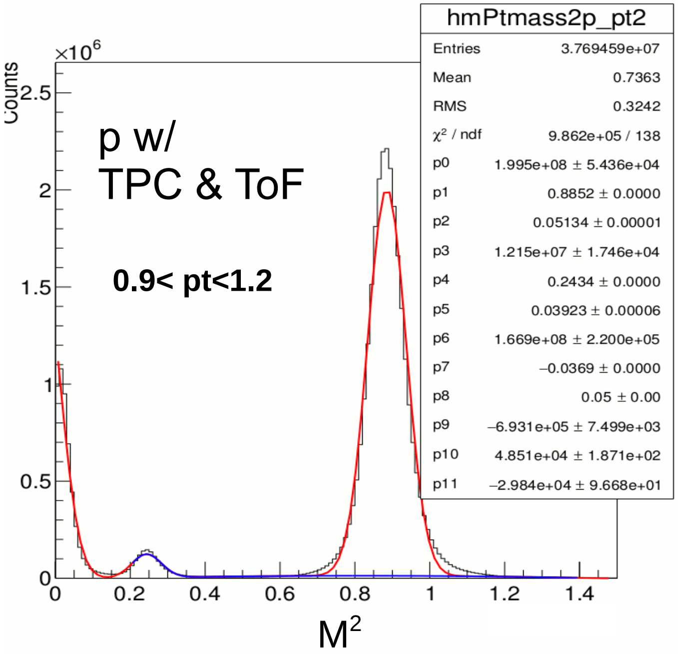


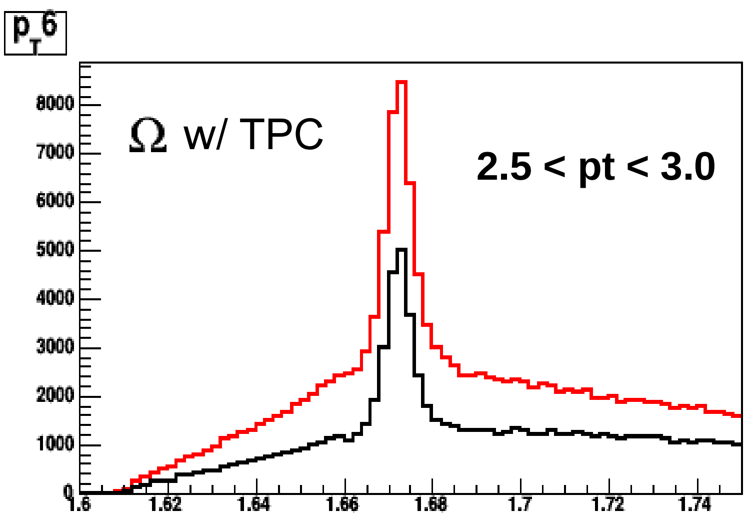



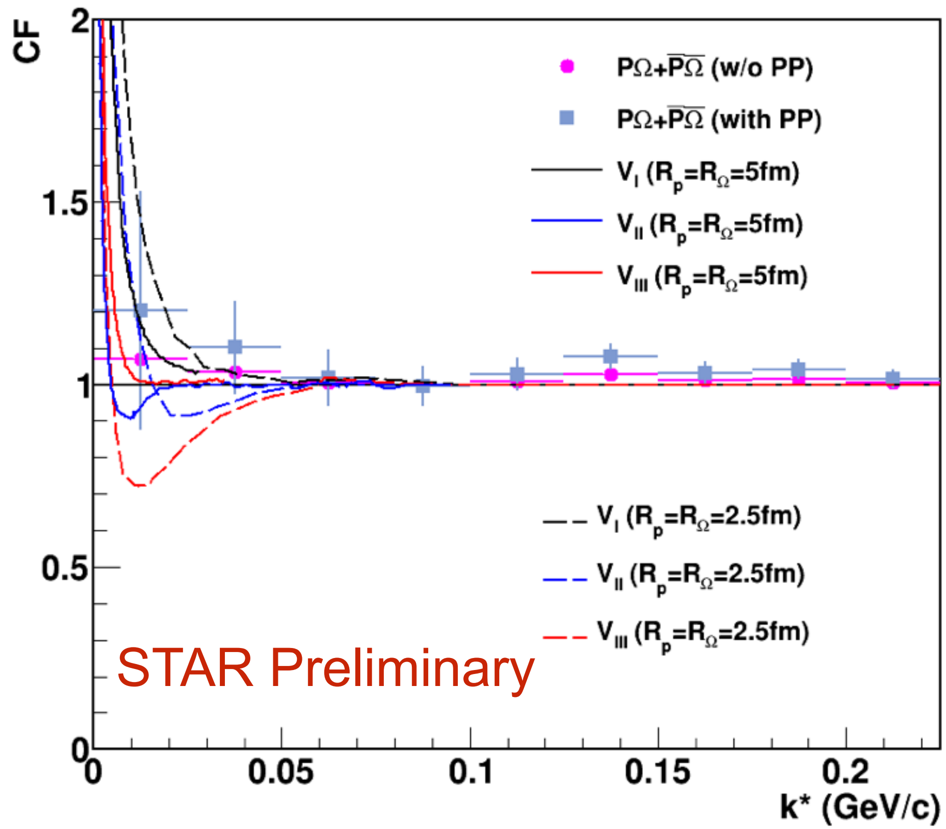




Ratio of C(Q): small/large system:
- Loose : Enhancement at low Q
- Tight : C(Q) < 1
- No Bound: Slightly above 1

# How to measure experimentally?




- ☑ Preliminary results with larger stat. uncertainty
- ☑ System size analysis (40-80% vs. 0-40%) is on going

# 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
- ☑ Systematic study on S=-3 NΩ system is ongoing

Thank you!