Study of Hyperon Interactions from Heavy-Ion Collisions using STAR Detector at RHIC

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Outline

- ➔ ΛΛ Correlation Function
  - H-dibaryon (|S| = 2)
  - H-dibaryon and two particle correlations
  - Summary of H-dibaryon search
- ➔ Hypertriton life-time
- ➔ Future plans

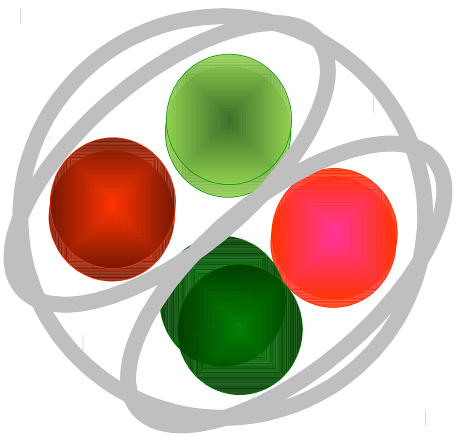
Introduction

- **Standard Model: Baryons – 3 quarks and Mesons – pair of quark-antiquark**

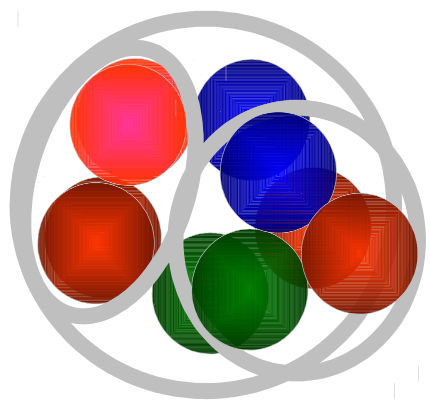
- **1977: within Quark Bag Model, Jaffe predicted H-dibaryon made of six quarks (uuddss)** (Phys. Rev. Lett. 38,195 (1977); 38, 617(E)(1977))

- **Exotic hadrons – long standing challenge in hadron physics**

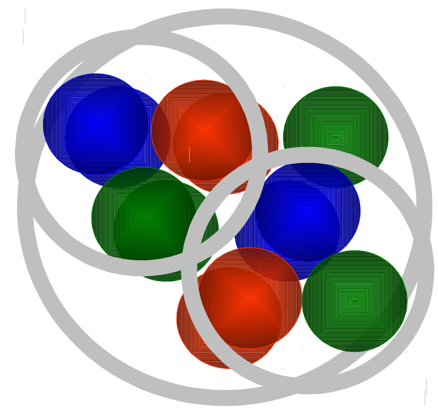
Tetraquark
Meson-Meson molecule



Pentaquark
Meson-Baryon molecule

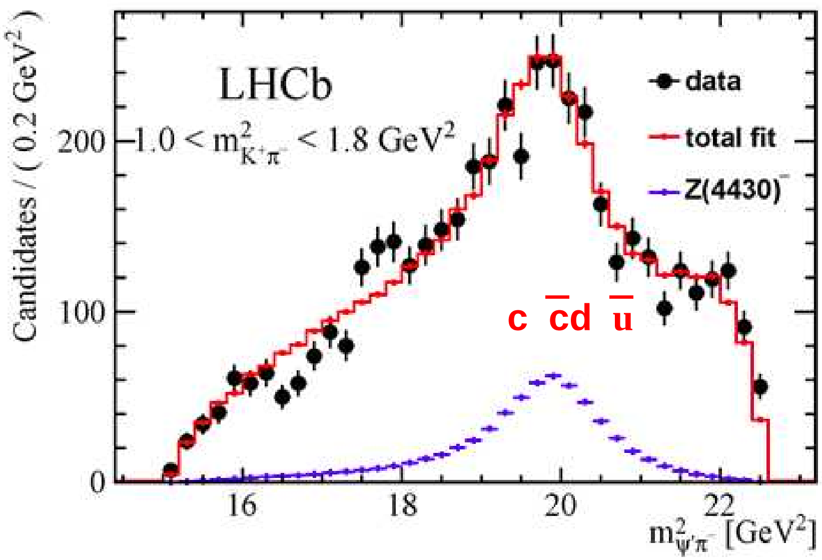


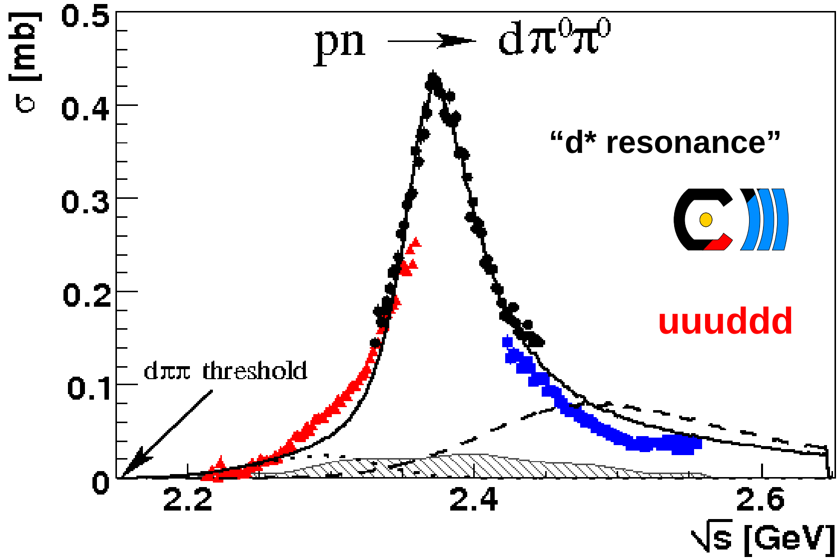
Hexaquark
Baryon-Baryon molecule

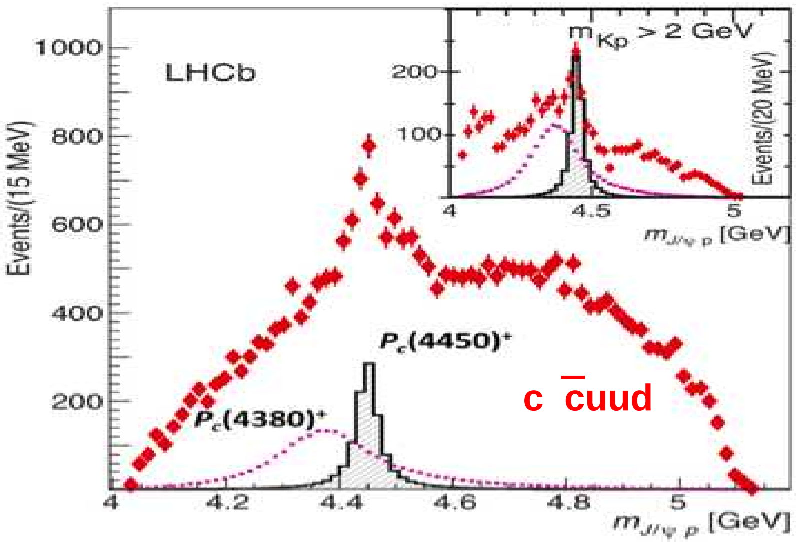


Introduction

➢ **Observation of exotic states @ WASA-at-COSY, LHCb**







Multi-quark states/molecular states?

Phys. Rev. Lett 115 (2015) 072001

Phys. Rev. Lett 112 (2014) 222002

Phys. Rev. Lett. 106 (2011) 242302

Exotics

Quark content, decay modes and mass of exotic states in strangeness sector:

particle	Mass (MeV)	Quark composition	Decay mode
f_0	980	$q\bar{q}s\bar{s}$	$\pi\pi$
a_0	980	$q\bar{q}s\bar{s}$	$\pi\eta$
K(1460)	1460	$q\bar{q}q\bar{s}$	$K\pi\pi$
$\Lambda(1405)$	1405	$qqqs\bar{q}$	$\pi\Sigma$
$\Theta^+(1530)$	1530	$qqqq\bar{s}$	KN
H	2245	uuddss	$\Lambda\Lambda$
$N\Omega$	2573	qqqsss	$\Lambda\Xi$
$\Xi\Xi$	2627	qqssss	$\Lambda\Xi$
$\Omega\Omega$	3228	ssssss	$\Lambda K^-+\Lambda K^-$

H-dibaryon (Theory-I)

Properties : $J^{\pi} = 0^{+}$, mass : (1.9-2.8) GeV/c^2

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

Decay Modes:

Channel	Threshold mass (GeV/c2)	ΔS
ΛΛ	2.231	0
pΞ	2.249	0
Λpπ	2.192	1
ppππ	2.152	2
nn	1.9	2

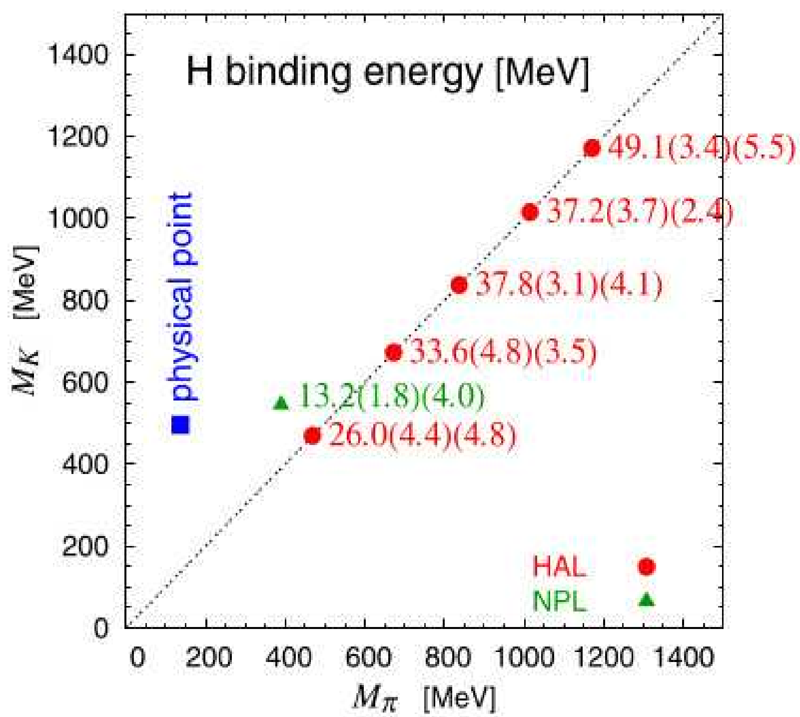
Phys. Rev. Lett. 38 (1977) 195
Phys. Rev. C 40 (1989) 115
Phys. Rev. C 85 (2012) 045202

H-dibaryon (Theory-II)

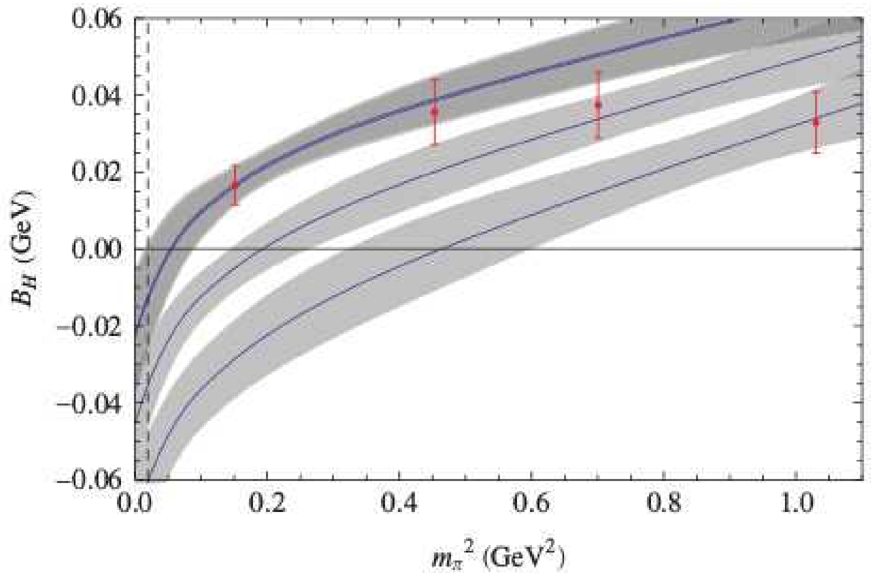
- **Lattice calculation – a bound state above the physical pion mass**
  Phys. Rev. Lett. 106 (2011) 162001, Phys. Rev. Lett. 106 (2011) 162002

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



H-dibaryon (Experiment)

- NAGARA event – Measurement of $_{\Lambda\Lambda}{}^{6}H \rightarrow \Lambda\Lambda + {}^{4}He$

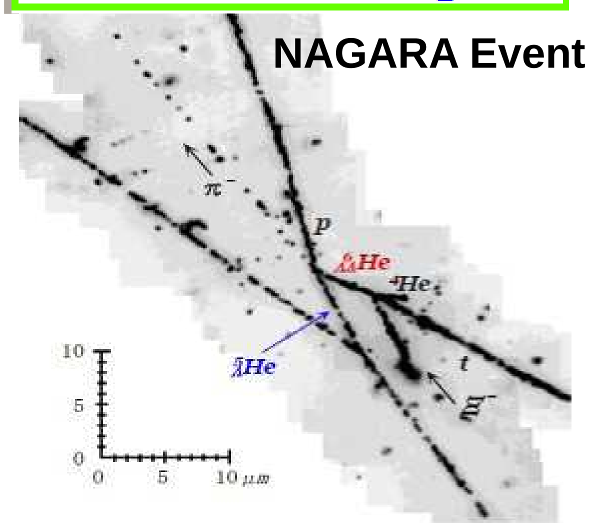
  $\Rightarrow$ **BE ~ 6.91 MeV**

- KEK-E522 observation of 2.6σ enhancement for ΛΛ invariant mass spectra – resonance!

KEK-E373 experiment

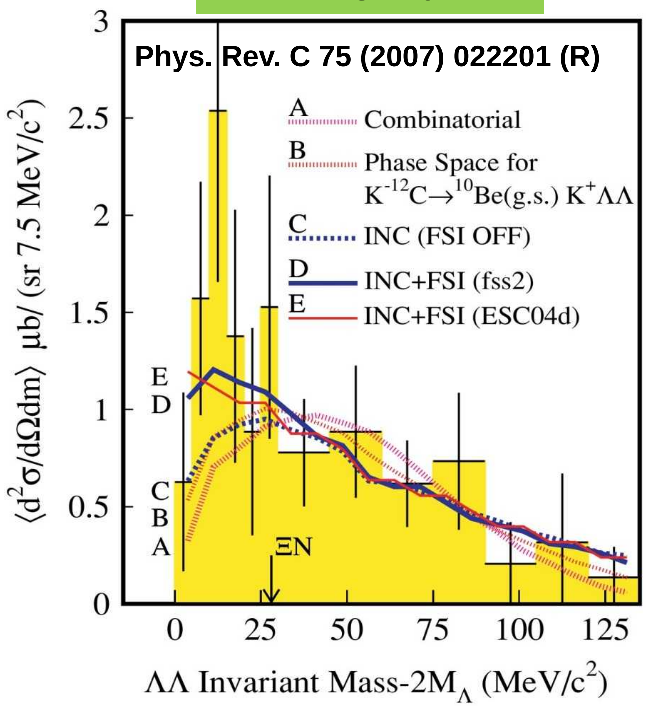
$\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$

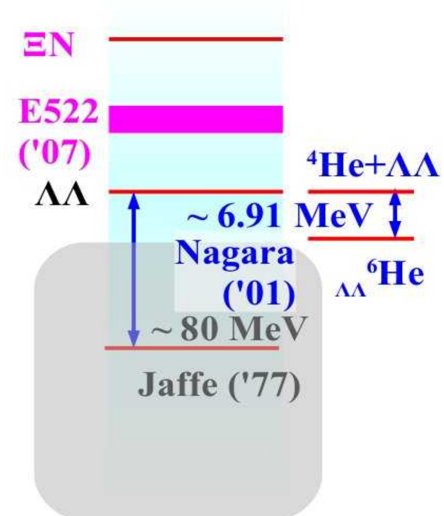
${}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$



Phys. Rev. Lett. 87 (2001) 212502

KEK-PS E522



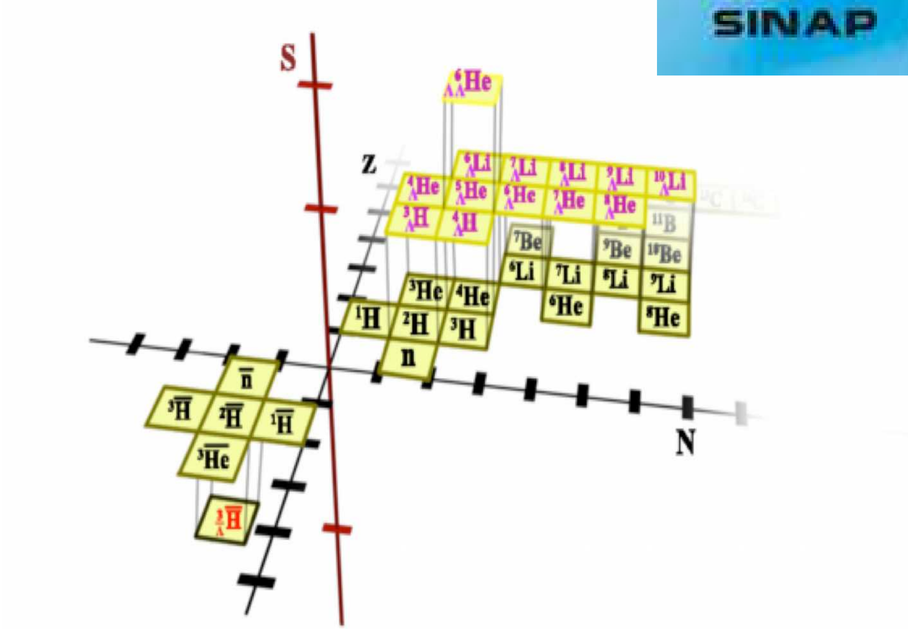


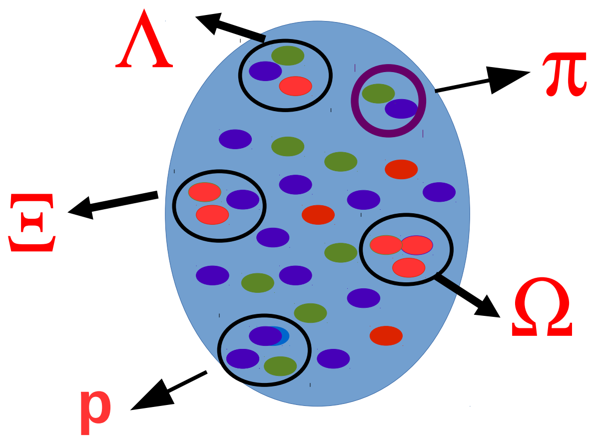
Other Experimental searches:

BNL E810, E836, E885, E888, E896, KEK E224, kTeV@Fermilab, NA49, Belle, ALICE

Venues for Dibaryon Search

- Systematic study of BE for various hypernuclei
  - Experiments at J-PARC, KEK





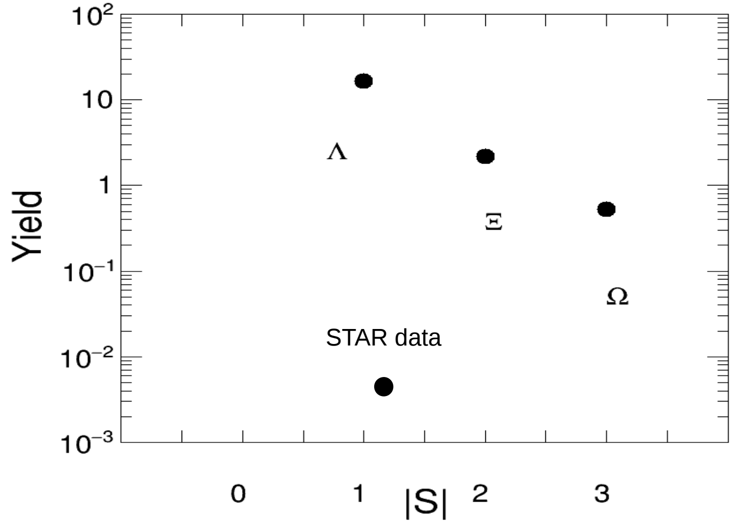
- Heavy Ion Collisions

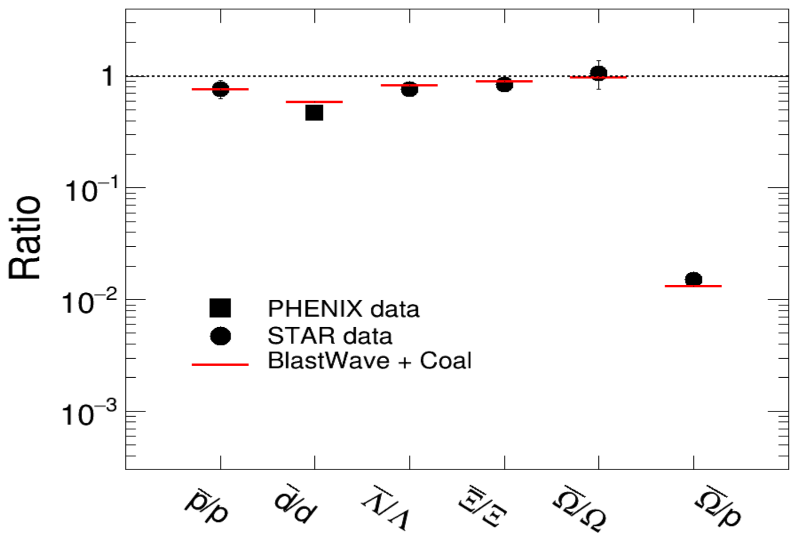
➢ Hot and dense, strongly interacting partonic matter

➢ Environment suitable to form exotic hadrons through coalescence or phase space correlations

Why Heavy Ion Collisions?

Central Au+Au Collision (0-5%) mid-rapidity dN/dy @ 200 GeV :





Phys. Rev. Lett 98 (2007) 062301, Phys. Rev. C 83(2011) 24901, arXiv:0909.0566, Phys. Rev. C 85 (2012) 064912

Coalescence Model: Integrated yield of H in Au+Au @ 200 GeV in central collisions ~10^{-3}–10^{-5}

- **Invariant mass**
  - ✔ **Significant combinatorial background in central Au+Au collisions makes search difficult**

- **Two particle correlations**
  - ✔ **Information about Quantum statistics, Final state interaction, exotic particles**

Two Particle Correlation Function

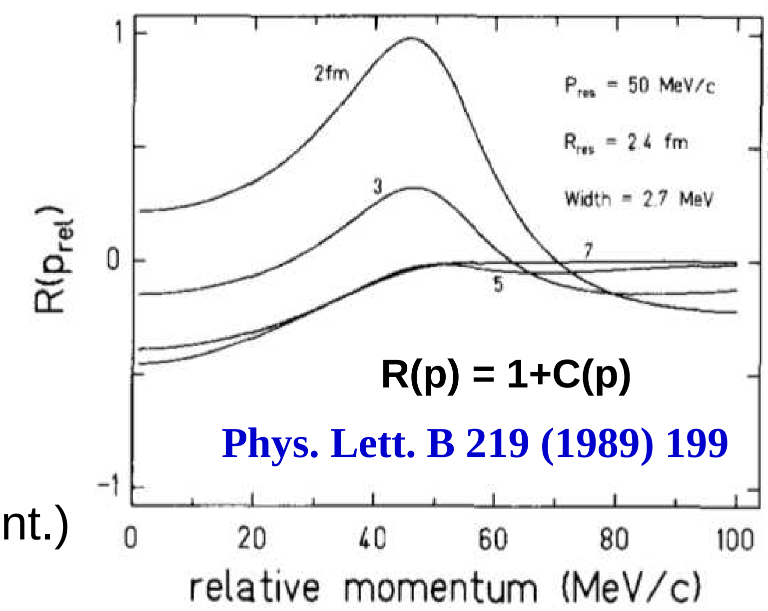
- **Two particle correlation function**

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

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

$f(q,r')$ – two-particle wave function

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

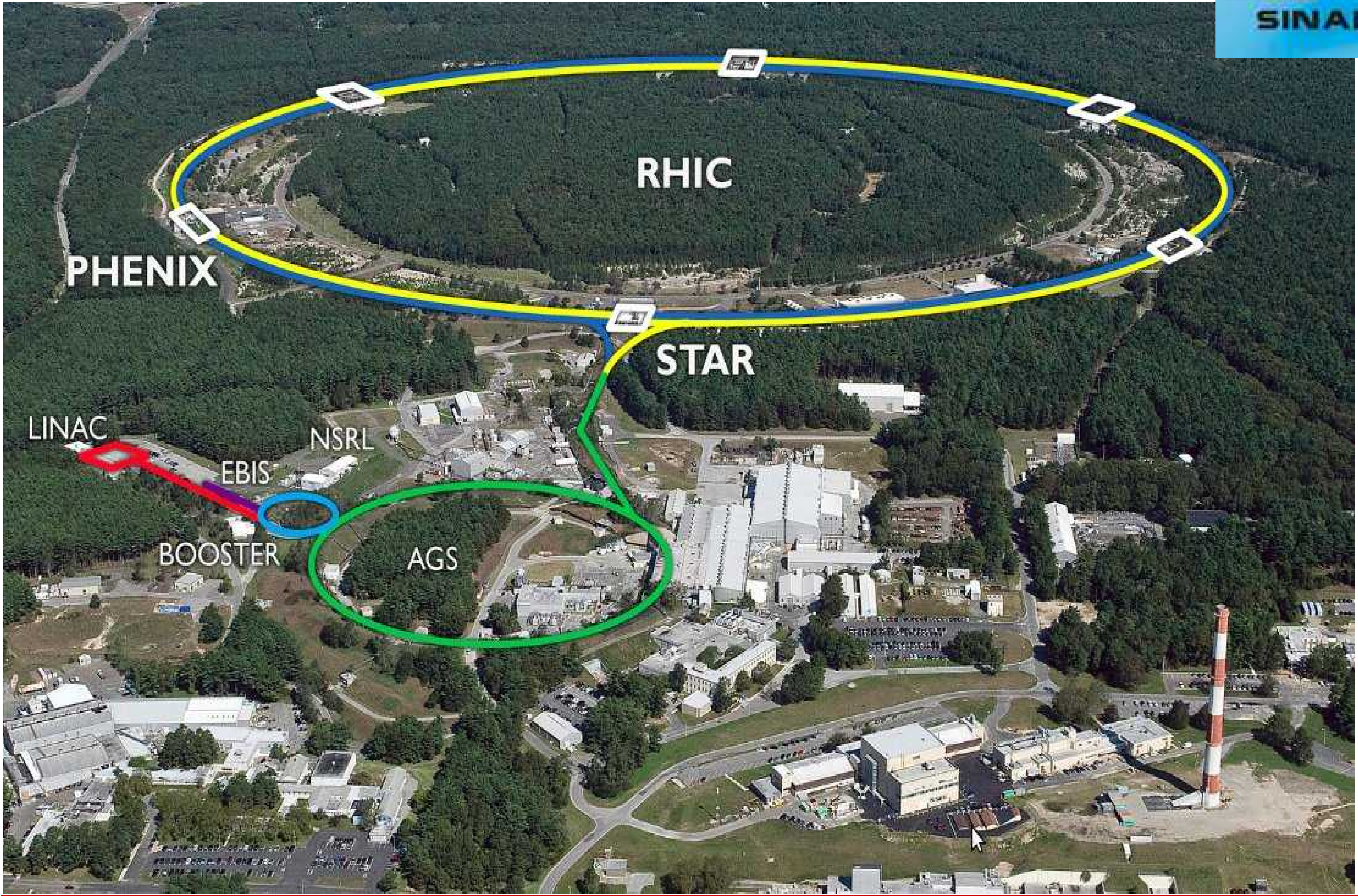


R(p) = 1+C(p)

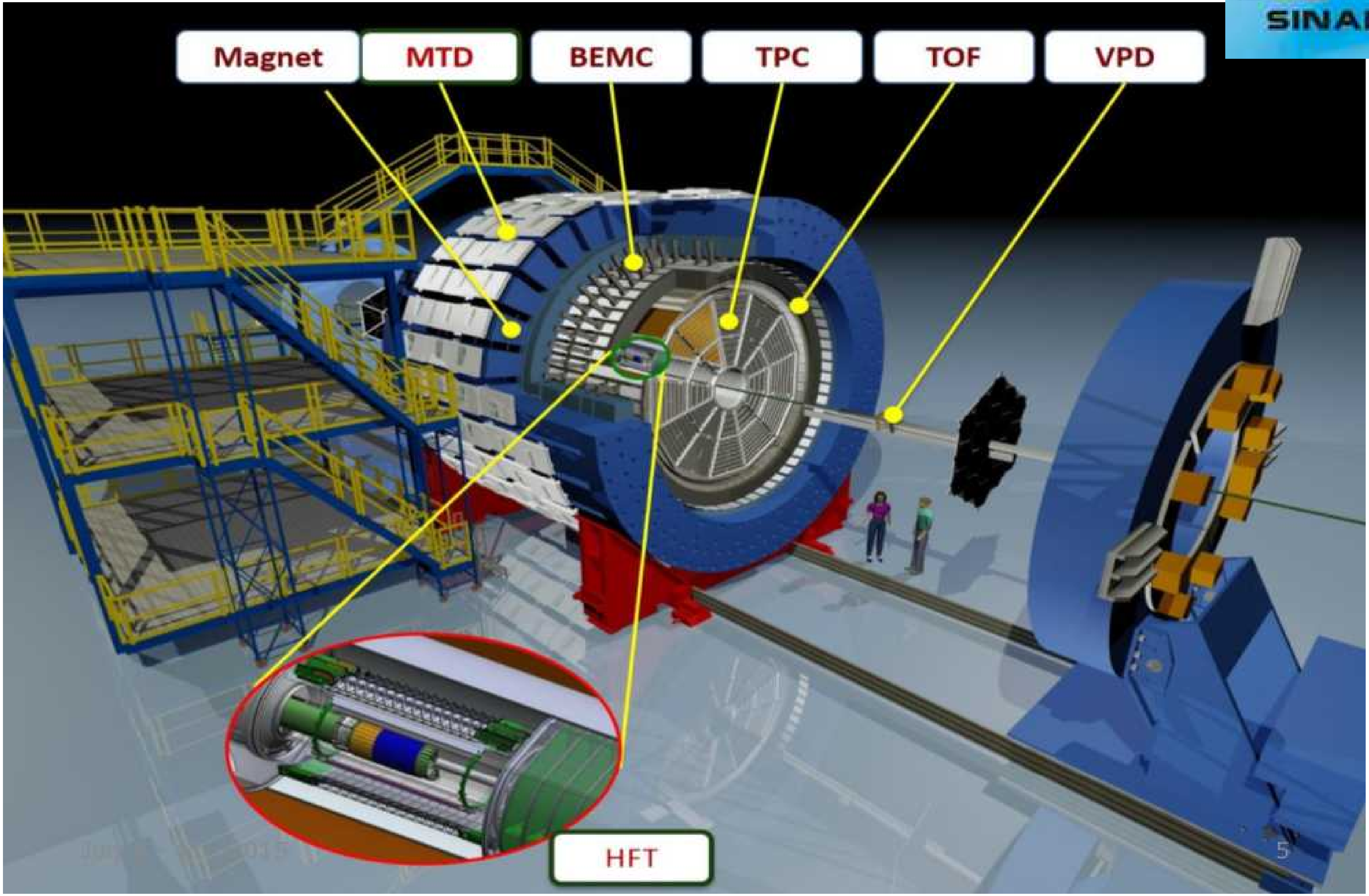
Phys. Lett. B 219 (1989) 199

- **Depletion in two particle correlation function if there is a bound H-dibaryon as it would exhaust Λ pairs at low momentum**

Relativistic Heavy Ion Collider (RHIC)

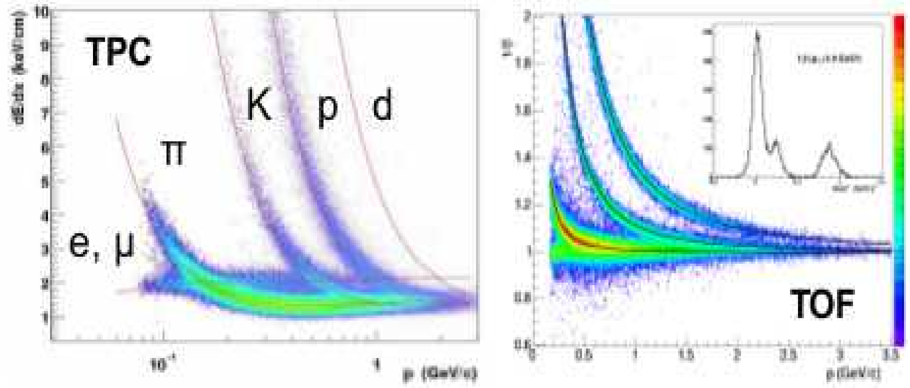


Solenoidal tracker at RHIC (STAR)

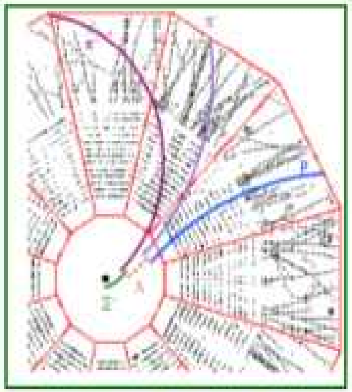


STAR: Excellent PID and tracking

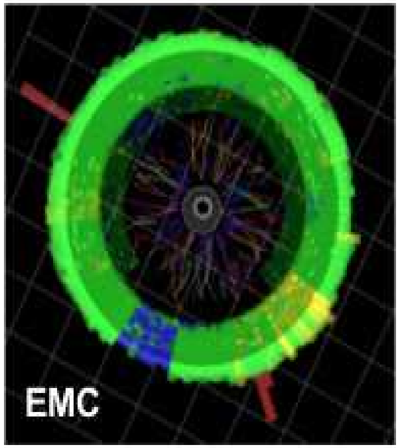
- More than a billion minimum bias events for Au+Au @ 200 GeV



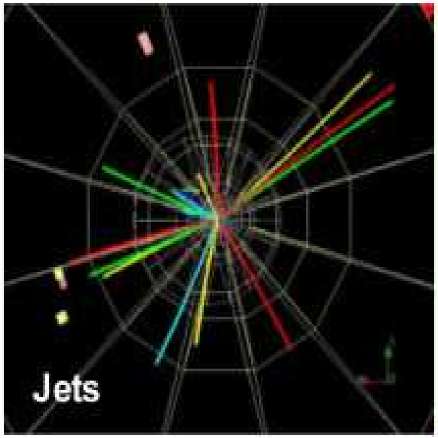
Charged hadrons



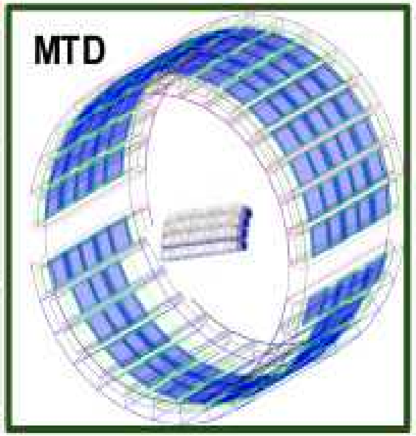
Hyperons & Hyper-nuclei



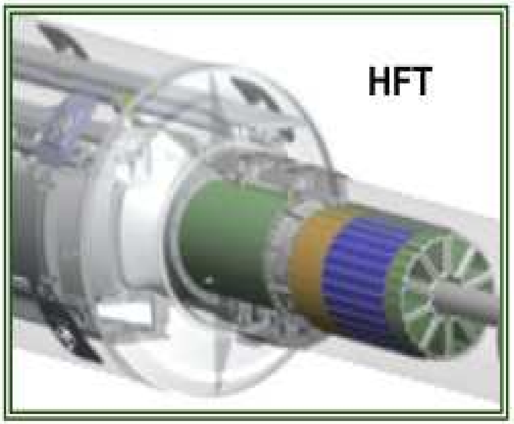
Neutral particles



Jets & Correlations



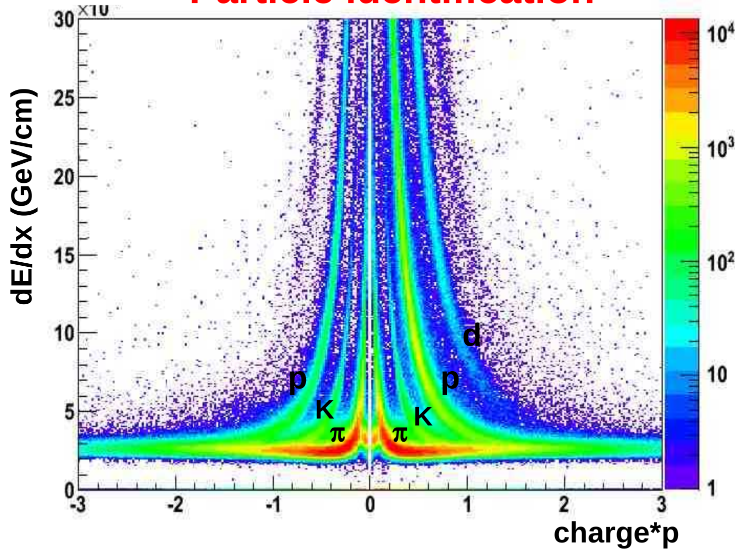
High p_T muons

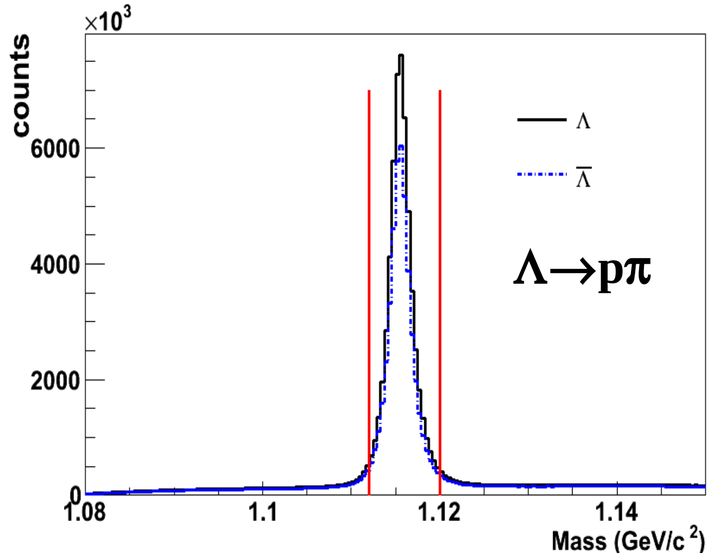


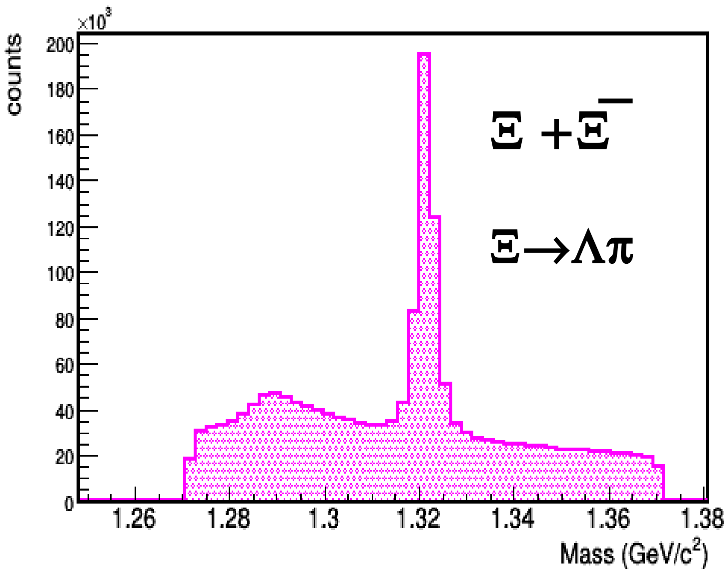
Heavy-flavor hadrons

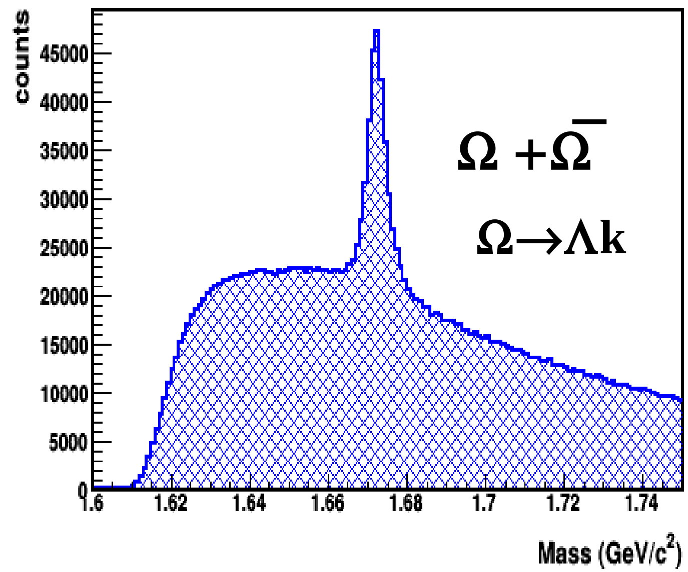
Hyperon reconstruction

Particle identification

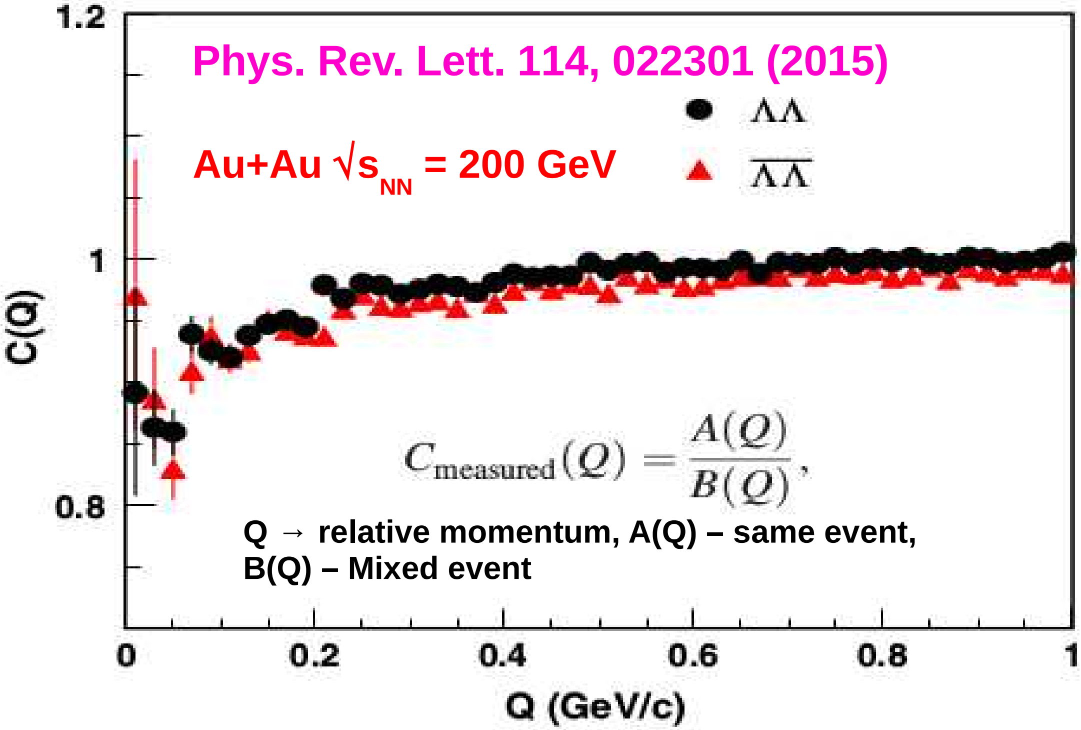


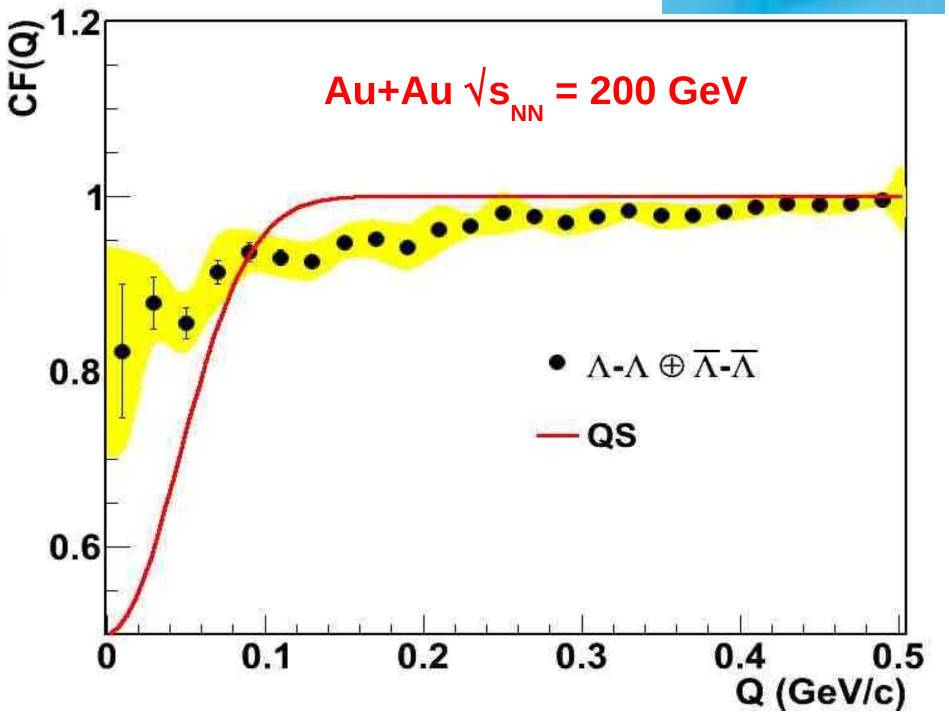






ΛΛ Correlation Function





- ΛΛ and their anti-particle correlation function are nearly equal
- CF(Q=0) > CF_{QS}(Q=0) ⇒ interaction is attractive, QS → Quantum Statistics
- High Q tail → residual correlations from Σ, Ξ

ΛΛ Correlation Function

Fit function from 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, a_res – amplitude of residual term
r_res – width of the Gaussian

$$\rho_0 = \tfrac{1}{4}(1-P^2) \quad \rho_1 = \tfrac{1}{4}(3+P^2) \quad P=\text{Polariz.}=0$$

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

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

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

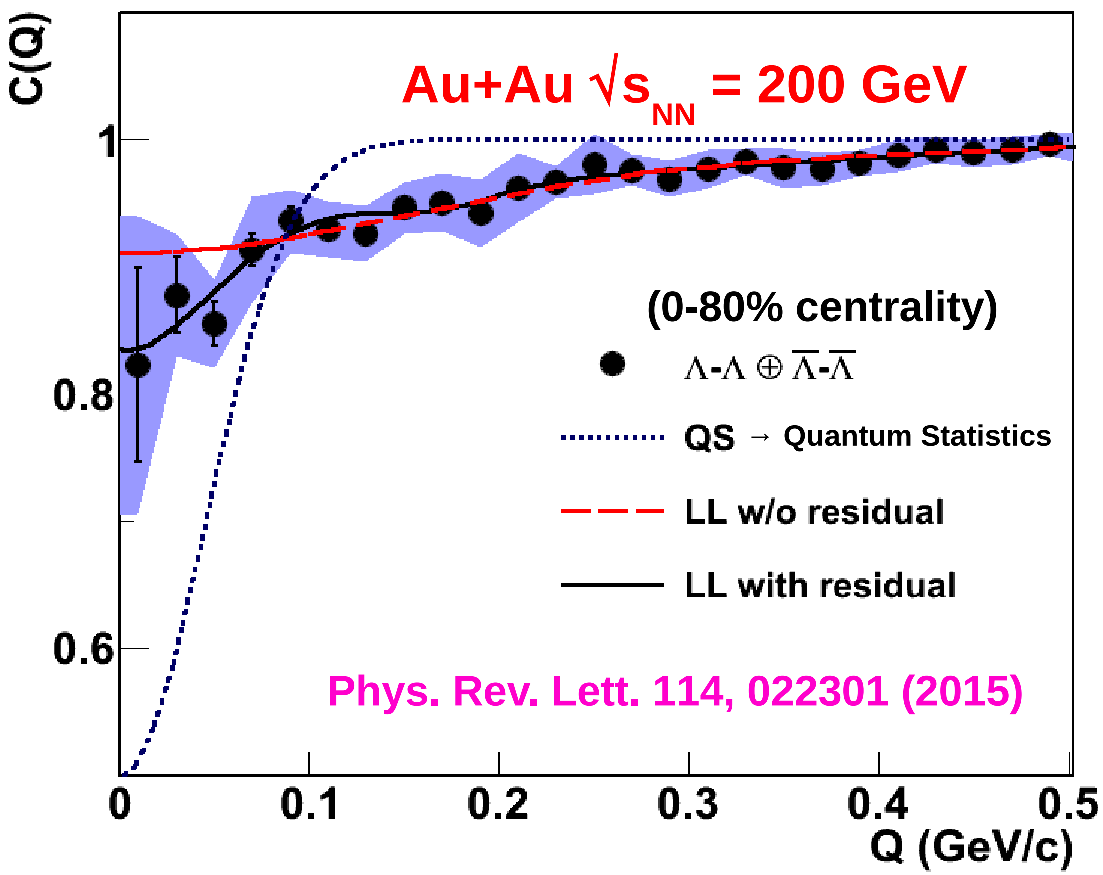
$$F_1(z)=\int_0^z dx\, \exp(x^2-z^2)/z \quad F_2(z)=[1-\exp(-z^2)]/z$$

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

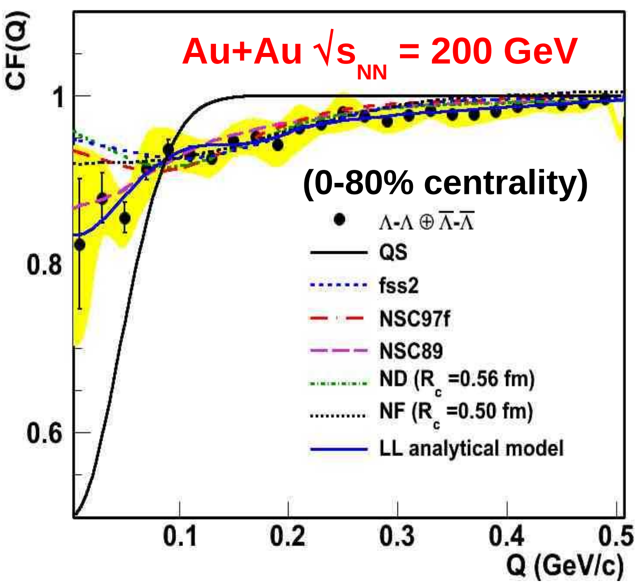
Effective range-
$r_{eff} = 8.52 \pm 2.56^{+2.09}_{-0.74}$ fm

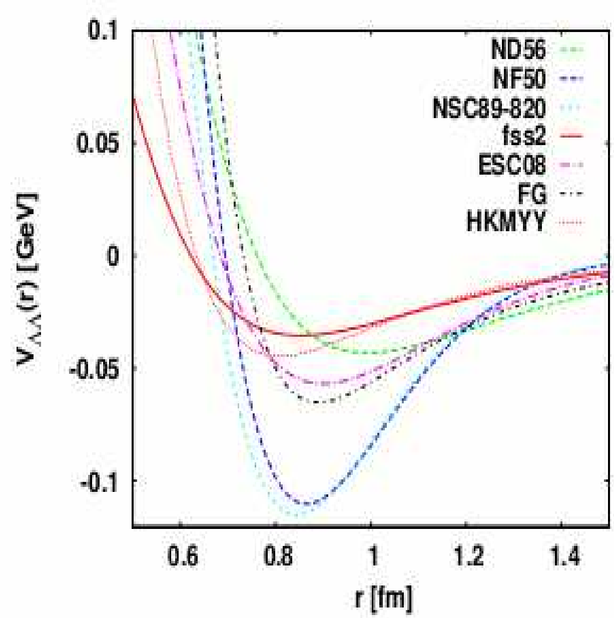
$\chi^2/NDF = 0.56$

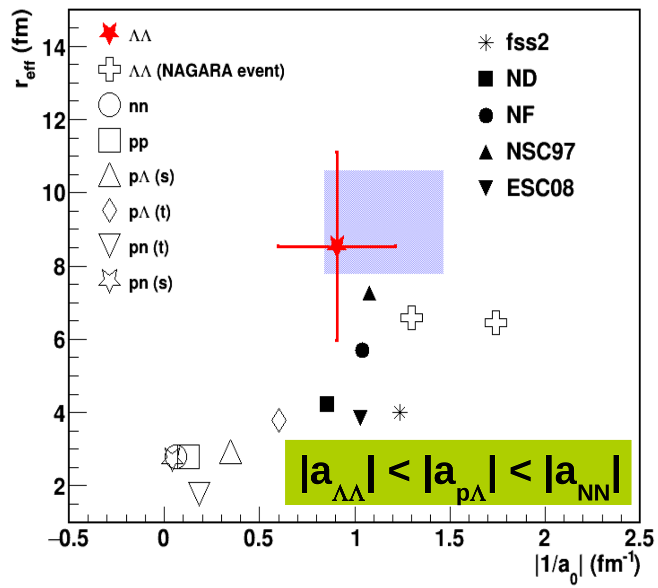
ΛΛ Correlation Function

Baryon-baryon interaction model ⇒ attractive potential

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







STAR Collaboration, Phys. Rev. Lett 114, 022301 (2015)
K. Morita, T. Furumoto and A. Ohnishi, Phys. Rev. C 91 024916 (2015) (parallel: 6a-1)

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

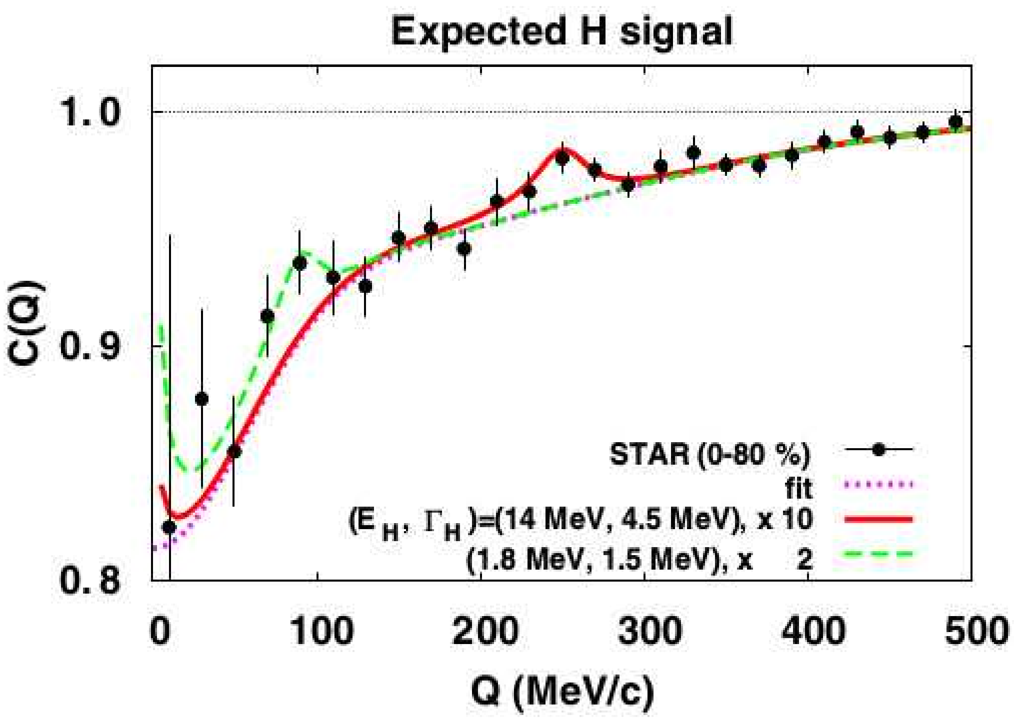
H-dibaryon Signal from Coalescence Expectation

- 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)

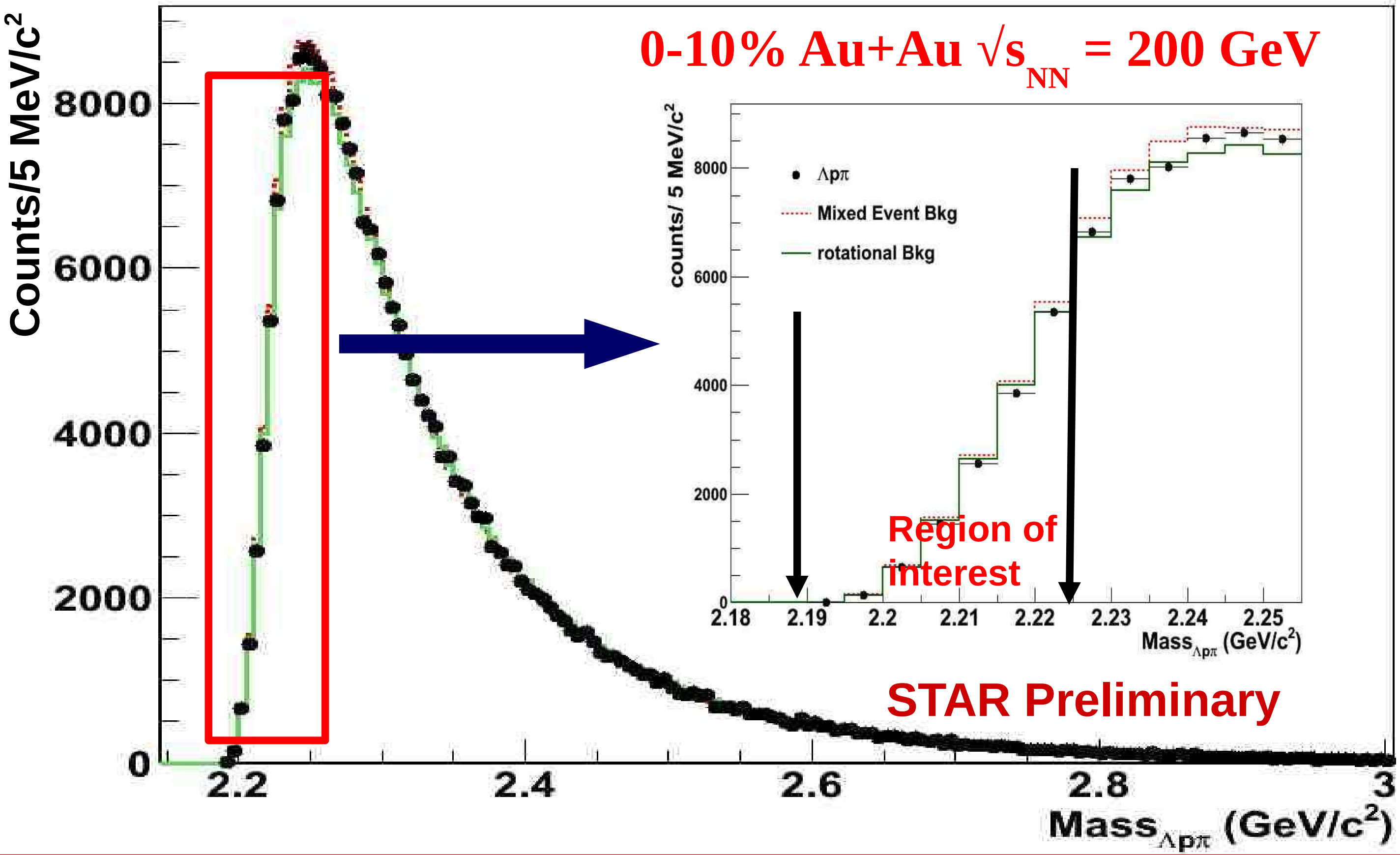
- More experimental events are necessary to confirm or rule out the existence of resonance pole in low Q region

- Measured $a_0 = -1.10 \pm 0.37^{+0.68}_{-0.08}$ fm, $r_{eff} = 8.52 \pm 2.56^{+2.09}_{-0.74}$ fm suggests non-existence of H-dibaryon as bound state of ΛΛ

H-dibaryon Weak Decay

Topological reconstruction of weak decay: H→Λpπ

- Mass range: 2.2 GeV/c^2 < m_H < 2.231 GeV/c^2
- No significant signal observed with respect to mixed event and rotational background



Summary of H-dibaryon search

- ✔ **ΛΛ interaction is attractive**
- ✔ **Attraction is not strong enough to form stable H-dibaryon**
- ✔ **Interaction parameters: $|1/a_0| > 0.5\ fm^{-1}$ and $r_{eff} \geq 3$ fm**
- ✔ **Measured interaction parameter gives indication towards non-existence of bound H below the NΞ and ΣΣ threshold.**

Hypertriton life-time measurement

Parallel 4c-3
Talk: Yifei Xu

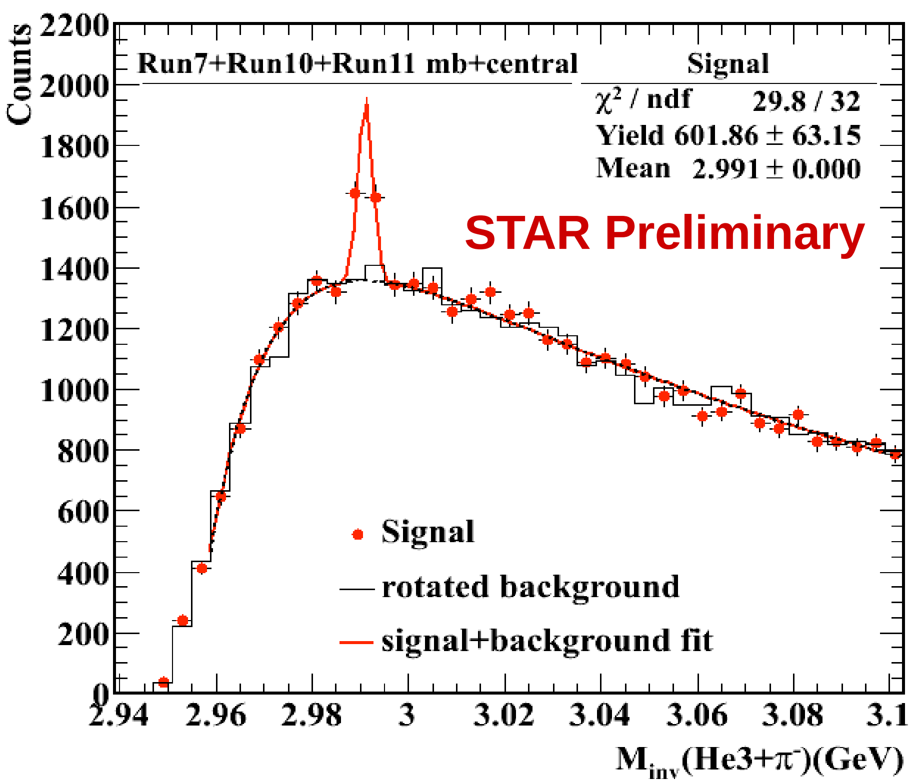
- ✔ First hyper nucleus was observed in 1952.
- ✔ Binding energy and lifetime are sensitive to YN interaction.
- ✔ The hypertriton being a loosely-bound nuclear system, its mean lifetime should be close to the free Lambda life time.
- ✔ Life time measurements from Bubble chamber, emulsion and heavy-ion 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.

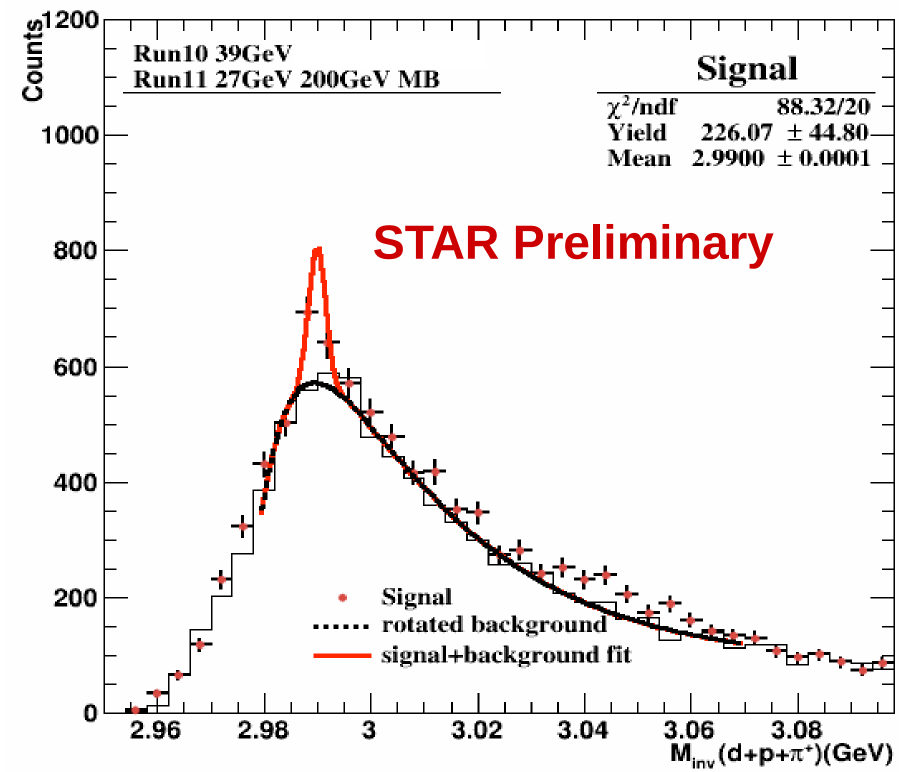
Hypertriton life-time measurement

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

Parallel 4c-3
Talk: Yifei Xu

- ✔ Signal from 2-body and 3-body decay
- ✔ Largest sample of hypertriton

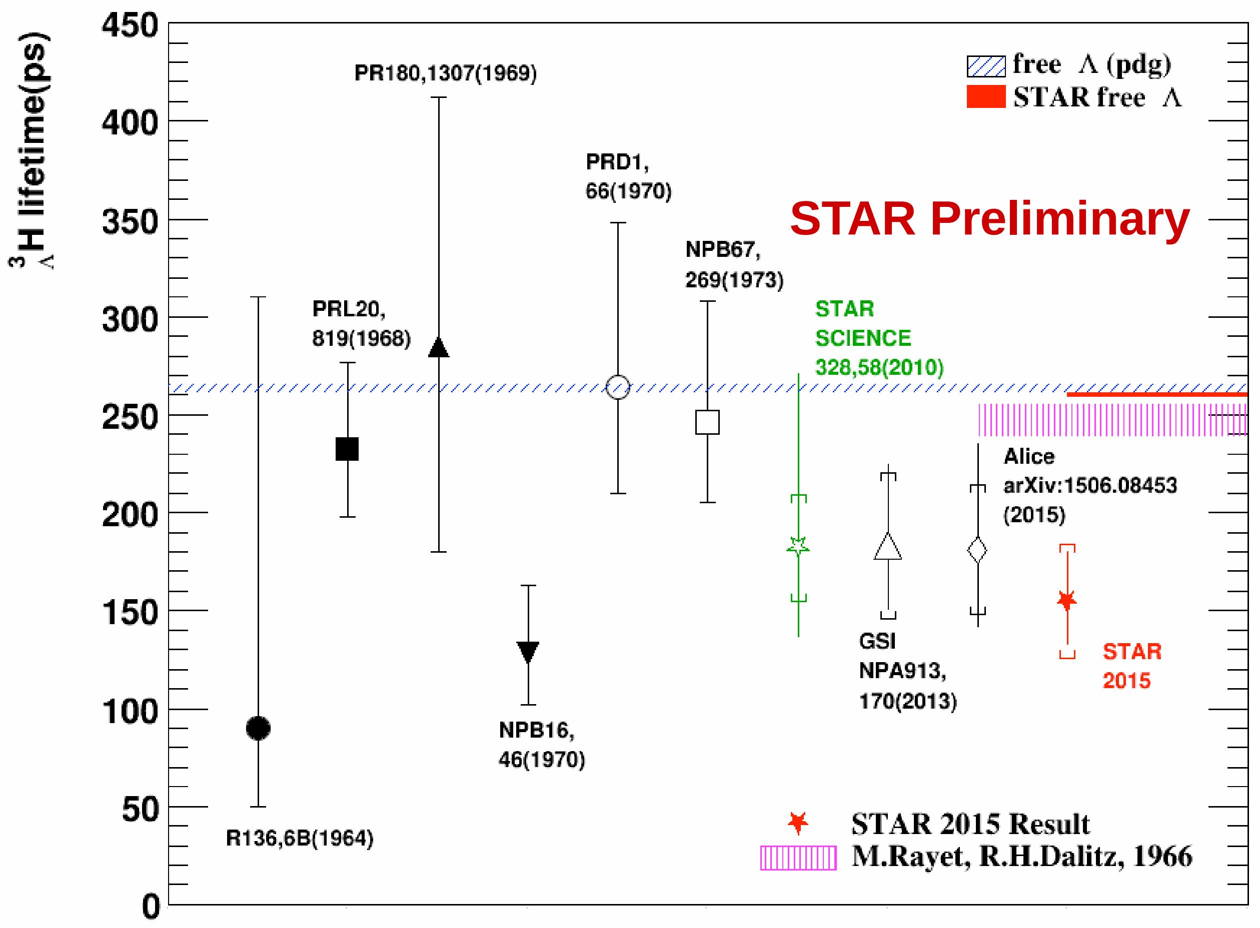




Hypertriton life-time measurement

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

Parallel 4c-3
Talk: Yifei Xu



Future plans

- **Observation of di-baryon in Δ-Δ system from WASA-at-COSY ⇒ renewed interest in di-baryon structure within the QCD** (Phys. Rev. Lett. 106 (2011) 242302, Phys. Lett. B721 (2013) 229, Phys.Lett. B743 (2015) 325)

  - **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)

  - **ΞΞ -a bound state analogous to deuteron** (G. A. Miller, Chin. J. Phys. 51 (2013) 466)

- **STAR has collected more than billion minimum bias events for Au+Au @ 200 GeV, which will allow us to extend measurement to NΩ and ΞΞ and provide precise measurement of hypertriton life time.**

- **A unique opportunity at RHIC for hyperon physics!**

Thank you!