Where is the H-Dibaryon?

J-PARC E42

Jung Keun Ahn (Korea University)

(HaPhy Meeting, November 25-26, 2016)

Outline

1. Introduction
2. Experimental Review
3. J-PARC E42

Introduction

Perhaps a Stable Dihyperon

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Perhaps a Stable Dihyperon*

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(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the $\Delta(1236)$ bind six quarks to form a stable, flavor-singlet (with strangeness of -2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in $\Lambda\Lambda$ invariant-mass plots. Production and decay systematics of the H are discussed.

- MIT bag model predicts di-hyperon state (H) with

$$I = 0, \quad S = -2, \quad J^p = 0^+$$

  and a mass of $m_H = 2150$ MeV (by 80 MeV relative to $2m_\Lambda$).
- H^* with $J^p = 1^+$ appears as a 2335-MeV bump in $\Lambda\Lambda$ mass distribution.

One Gluon Exchange Interaction

The one gluon exchange interaction potential is given by

$$
\begin{aligned}
V^{\mathrm{OGEP}}(\vec{r}_i, \vec{r}_j) &= \frac{\alpha_s}{4}(\vec{\lambda}_i \cdot \vec{\lambda}_j)\Big\{\frac{1}{r} \\
&- \frac{\pi}{m_q^2}(1 + \frac{2}{3}\vec{\sigma}_i \cdot \vec{\sigma}_j)\delta(\vec{r}) \quad \text{(color – magnetic)} \\
&- \frac{1}{4m_q^2}(3\vec{\sigma}_i \cdot \hat{r}\vec{\sigma}_j \cdot \hat{r} - \vec{\sigma}_i \cdot \vec{\sigma}_j) \\
&- \frac{3}{2m_q^2}\frac{1}{r^3}(\vec{r} \times \frac{1}{2}(\vec{p}_i - \vec{p}_j)) \cdot \frac{1}{2}(\vec{\sigma}_i + \vec{\sigma}_j) \\
&+ \frac{1}{2m_q^2}\frac{1}{r^3}(\vec{r} \times \frac{1}{2}(\vec{p}_i + \vec{p}_j)) \cdot \frac{1}{2}(\vec{\sigma}_i - \vec{\sigma}_j)
\end{aligned}
$$

The color-magnetic interaction energy for the n-quark state in SU(3) representation $[f]$ is given by

$$E_{cm} = E_0\Big[n(n-10) + C_2[f] + \frac{4}{3}S(S+1)\Big],$$

where S is the total spin and $C_2[f]$ denotes the value of the quadratic Casimir operator ($C_2 = 0$ for the singlet, $C_2 = 12$ for the octet, and C_2 for the decuplet). The overall constant E_0 is given by a spatial integration of the quark wave functions.

[1] M. Oka, *QCD analysis of the H-dibaryon* arXiv:hep9510354v1 (1995).

Color Magnetic Interaction [2]

$$E_{cm} = E_0\left[n(n-10) + C_2[f] + \frac{4}{3}S(S+1)\right],$$

- $E_0 \approx 18$ MeV from the $N-\Delta$ mass splitting ($C_2 = 12$ for N and 24 for Δ, and $4/3 \cdot S(S+1) = 1$ for N and 5 for Δ, so $E_0 = (M_\Delta - M_N)/16 \approx 18$ MeV.)
- The minimum E_{cm} for $S = 0$ and $C_2 = 0$ ($J = 0$ and flavor singlet):

$$E_{cm}^{\min} = -24E_0$$

- $E_{cm}(H) = -450$ MeV ???

[2] M. Oka, *QCD analysis of the H-dibaryon* arXiv:hep9510354v1 (1995).

Phenomenological Fit to Hadron Spectrum [3]

COLOR-MAGNETIC INTERACTION FOR qq AND $q\bar{q}$

$$V_{q_1q_2} = C_M \vec{s}_1 \cdot \vec{s}_2 \frac{1}{m_1 m_2}, \qquad V_{q\bar{q}} = C_B \vec{s}_q \cdot \vec{s}_{\bar{q}} \frac{1}{m_q m_{\bar{q}}},$$

where $C_M \approx 3C_B = 635 m_u^2$.

Diquark	(ud)	(us)	(ds)
V_{qq}	A	$\frac{3}{5}A$	$\frac{3}{5}A$

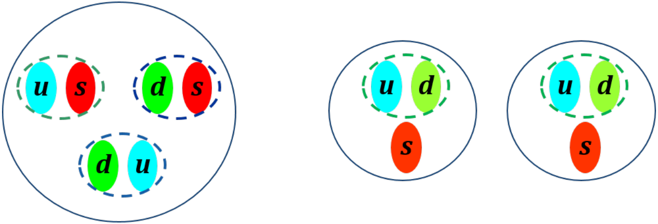
$$A = \frac{3}{4}\frac{C_B}{m_u^2} = 145 \text{ MeV}$$

$$m_u = m_d = 300 \text{ MeV}$$

$$m_s = 500 \text{ MeV}$$

[3] S.H. Lee, *Few ideas on Hadronic Physics at RHIC/LHC*.

H-Dibaryon : (ud)(us)(ds)



- H-dibaryon : $\Delta V = -29$ MeV

$$V = -\frac{3}{4}\frac{C_B}{m_u^2} - 2\cdot\frac{3}{4}\frac{C_B}{m_u m_s} = -145 - 2\cdot 145\frac{3}{5} = -319 \text{ MeV},$$

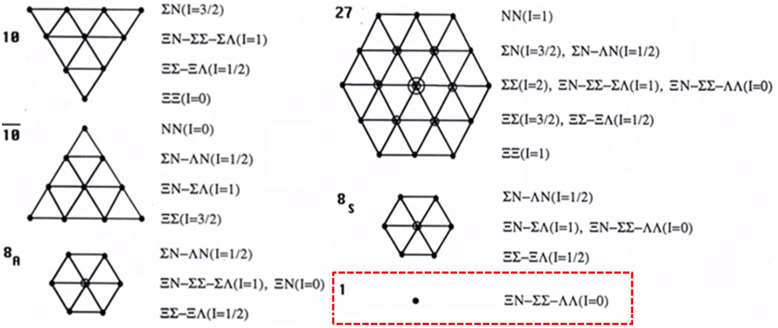
where $m_u \approx m_s$ and $m_s \approx 5/3 m_u$.

- Λ+Λ :

$$V = \frac{3}{4}\frac{C_B}{m_u^2} - \frac{3}{4}\frac{C_B}{m_u^2} = -290 \text{ MeV}$$

H-Dibaryon (Hexaquark State)

- A stable $SU(3)_f$ singlet hexaquark state consisting of $uuddss$ quarks due to QCD color magnetic force : H-Dibaryon.



Baryon-Baryon System [4]

- The flavor-singlet two-baryon state:

$$|H\rangle \approx \frac{\mathscr{A}}{\sqrt{8}}\Big(|\Lambda\Lambda\rangle + \sqrt{4}|N\Xi\rangle - \sqrt{3}|\Sigma\Sigma\rangle\Big),$$

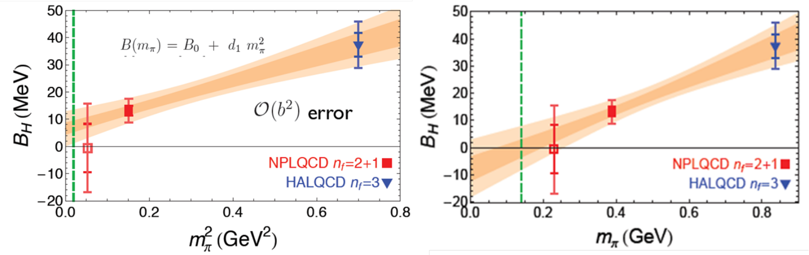
  where $\mathscr{A}$ is the antisymmetrization operator for the six quarks.

- H couples most strongly to $N\Xi$ and that a $N\Xi$ bound state will appear in the $\Lambda\Lambda$ spectrum as a sharp resonance state.

[4] M. Oka, *QCD analysis of the H-dibaryon* arXiv:hep9510354v1 (1995).

H-Dibaryon from Lattice QCD in 2011[5]

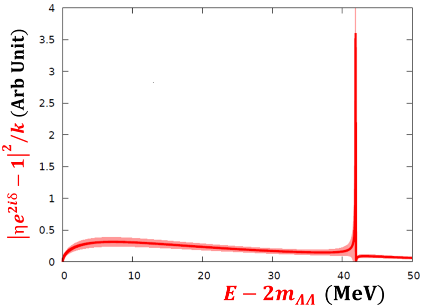
- Recent LQCD calculations seem to point to a weekly bound H or resonant state although we have got to wait for definite results with physical quark masses.

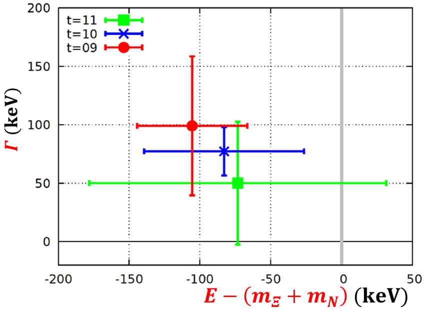


[5] HAL Collab., PRL 106 (2011)/ NPLQCD Collab. PRL 106 (2011)/ Shanahan, Thomas, Young, PRL 107 (2011)

Recent Lattice QCD Calculation Result

- Preliminary results with $L = 8$ fm and $m_\pi = 145$ MeV.
- $\Lambda\Lambda$ and $N\Xi$ $(I = 0)$ $^1S_0$ phase shifts [6]





- Deuteron-like $N\Xi$ bound system from ESC model.[7]

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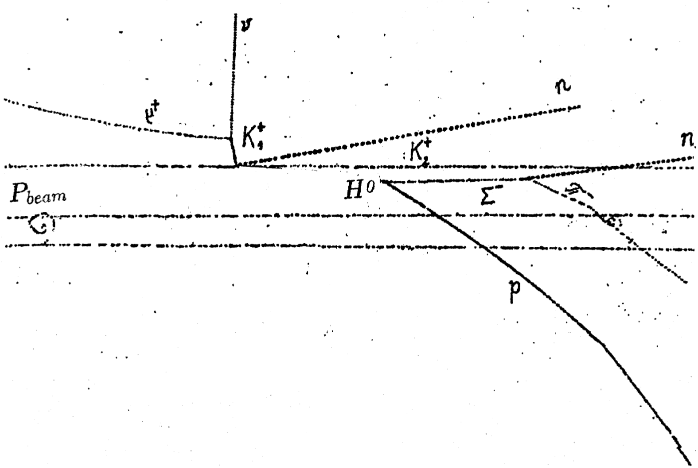
[6] K. Sasaki for the HAL Collab., Reimei 2016, Inha (2016).

[7] Y. Yamamoto, NSMAT2016

Experimental Review

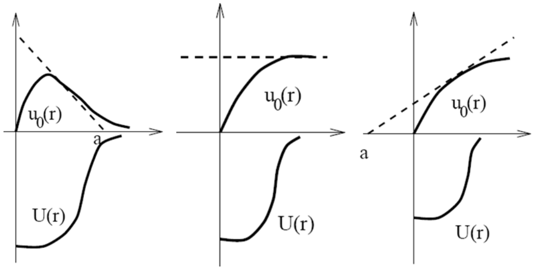
Candidate for $H \to \Sigma^- p$ in a Propane Bubble Chamber [8]



[8]B.A. Shahbazian, *et al.*, Z. Phys. C 39, 151 (1988).

Bound, Virtual State ($a_{\Lambda\Lambda} = \infty$), or Resonance?

- The existence of the H-dibaryon still awaits definitive experimental confirmation or exclusion.

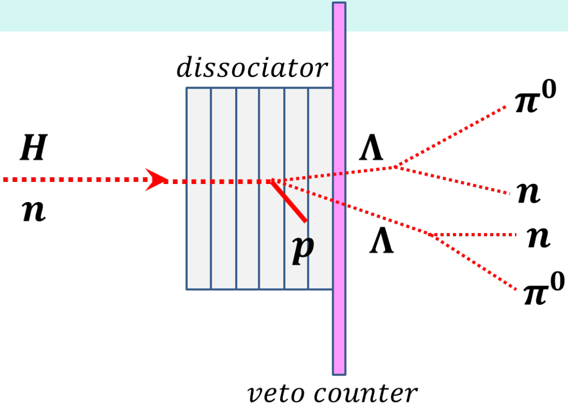


- Weakly-bound : $H \to \Lambda p \pi^-$
- Virtual state : $\Lambda\Lambda$ threshold effect
- Resonance : Breit-Wigner peak in the $\Lambda\Lambda$ mass spectrum

H-Dibaryon Searches

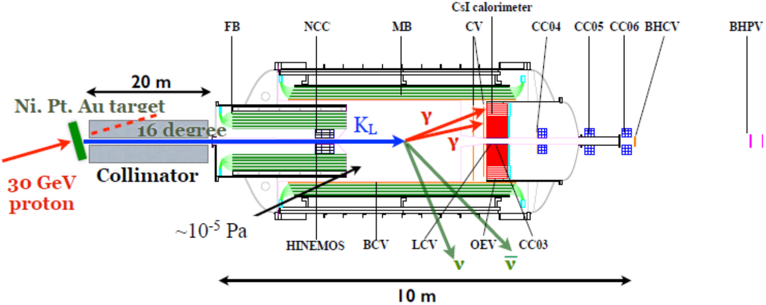
1. H search in (K^-, K^+) reactions from J-PARC E42.
2. Long-lived H search in the $H \to \Lambda n \pi^0$ decay at J-PARC E14.
3. H production in the $\gamma d \to K^+ K^0 H$ reaction at SPring-8 ($E_\gamma^{\mathrm{th}} = 1.83$ GeV for $m_H = 2m_\Lambda$).
4. H search in $\Lambda\Lambda$ at Belle-II.

- $p + Pt \to H + X$ and $H \to \Lambda\Lambda$



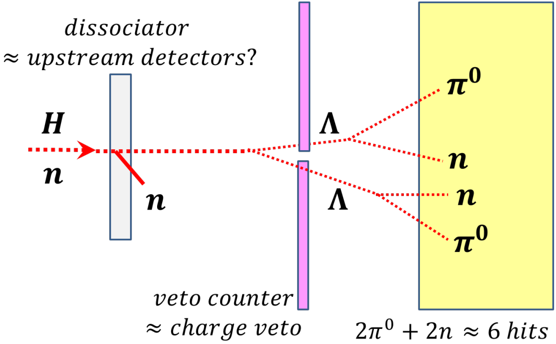
[9] J. Belz, *et al.* (BNL-E888 Collaboration), Phys. Rev. D 53, R3487 (1996).

- Search for the $K_L \to \pi^0 \nu \overline{\nu}$ with a CsI calorimeter and hermetric veto detectors.



[10] KOTO Collaboration, J-PARC E14

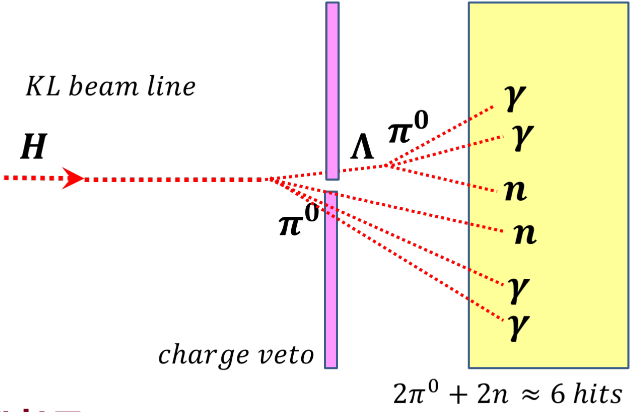
○ Search for the $H \to \Lambda\Lambda$ decays.



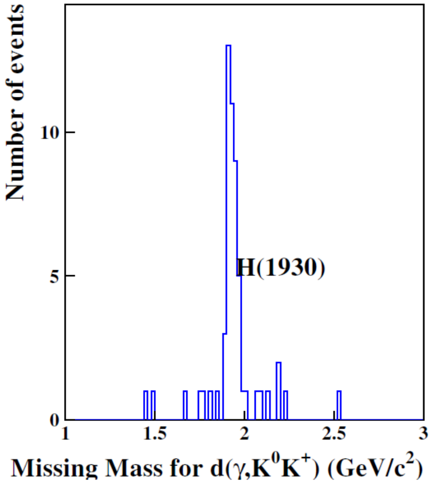
[11] KOTO Collaboration, J-PARC E14

H-Dibaryon Search with J-PARC-E14 KOTO

○ $p + Pt \rightarrow H + X$ and $H \rightarrow \Lambda n \pi^0$



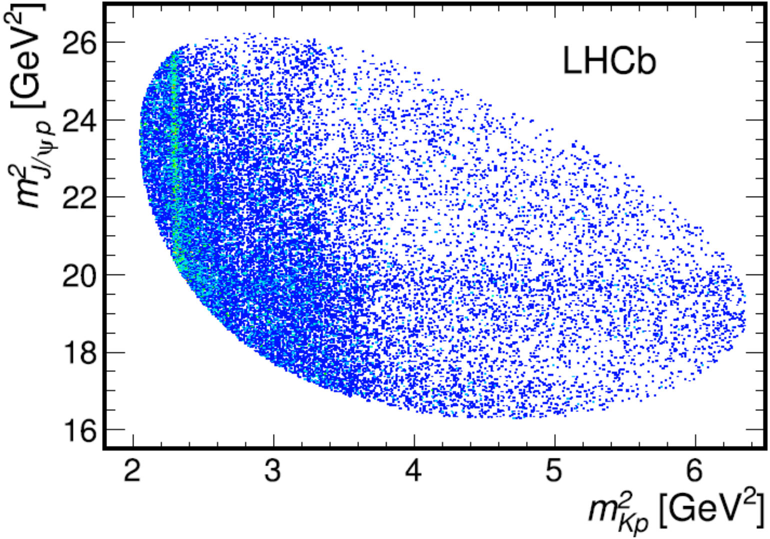
H-Dibaryon Search from Photoproduction [12]



- $\gamma d \rightarrow K^+ K^0 H$ reaction ($E_\gamma^{th} = 1.83$ GeV for $m_H = 2m_\Lambda$)
- $\gamma p \rightarrow K^+ \overline{K}^0 n$ ($a_0^+ \rightarrow K^+ \overline{K}^0$)

[12] LEPS Collaboration, SPring-8

LHCb Observation Revived Pentaquarks!



$S = -2$ Dibaryons in Particle Data Book (1982)

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S=−2 DIBARYON Status: *

→ **108 BARYON NUMBER 2, STRANGENESS -2 STATES**

IN THIS SECTION WE USE THE FOLLOWING ABBREVIATIONS FOR MEASURED QUANTITIES--

LLIM	LAMBDA-LAMBDA INVARIANT MASS
LLPI	LAMBDA-LAMBDA-PI INVARIANT MASS
XPIM	XI-P INVARIANT MASS

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108 B=2, S=-2 -- MASS (MEV)

M	A	(2367.0)	(4.0)	BEILLIERE 72 LLIM Q=0 GAUSSIAN FIT
M	B	(2365.3)	(9.6)	SHAHBAZIA 73 LLIM Q=0
M	C	(2480.0)		GOYAL 80 XPIM Q=0
M	B	(3568.3)		SHAHBAZIA 82 LPPI Q=1

M

M A K- D TO XI- P K0.

M B N P TO LAMBDA LAMBDA X AND PI- P TO LAMBDA LAMBDA X FOR P IN C12.

M C GOYAL 80 ALSO SEES A SHOULDER AT 2360 MEV.

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108 B=2, S=0 -- WIDTH (MEV)

W	A	(15.0)	(4.0)	BEILLIERE 72 LLIM Q=0 GAUSSIAN FIT
W	B	(47.0)	(15.7)	SHAHBAZIA 73 LLIM Q=0

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40 Year History since the H-Dibaryon Prediction

- 1977 — Deeply-bound di-hyperon predicted by R. Jaffe
- 1980-2000 — No evidence for the deeply-bound H from KEK, BNL,
- and CERN experimental efforts by more than 80 MeV
- 2001 — Mass constraint from observation of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ (E373)
- 1998,2007 — Enhanced $\Lambda\Lambda$ production near threshold was
- reported from E224 and E522 at KEK-PS.
- 2013-2015 — No evidence for $H \rightarrow \Lambda p \pi^-$ and $H \rightarrow \Lambda\Lambda$
- in high-energy e^+e^-, pp and AA experiments
- 2011-2016 — LQCD calculations predict the H-dibaryon
- to appear near (just above) threshold
- Present — **J-PARC E42 under preparation**

J-PARC E42

H-Dibaryon Search at J-PARC : E42

The existence of the H-dibaryon still awaits definitive experimental confirmation or exclusion.

- Weakly-bound : $H \rightarrow \Lambda p \pi^-$
- Virtual state : $\Lambda\Lambda$ threshold effect
- Resonance : Breit-Wigner peak in the $\Lambda\Lambda$ mass spectrum

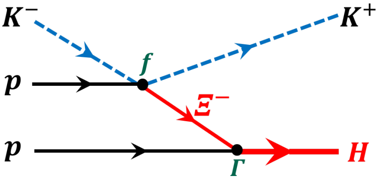
J-PARC-E42 EXPERIMENT

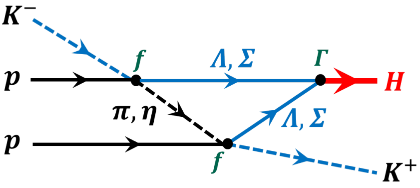
1. in $(\Sigma^- p)$, $\Lambda p \pi^-$, $\Lambda\Lambda$ and $\Xi^- p$ channels
2. by tagging the $S = -2$ system production
3. via (K^-, K^+) reactions at 1.7 GeV/c with a diamond target.
4. Hyperon Spectrometer : 1 MeV $\Lambda\Lambda$ mass resolution!

H Production from (K^-, K^+) Reactions

$$K^- + (pp)^1S_0 \rightarrow K^+ + (\Xi^- p)^1S_0 \rightarrow K^+ + H(J^\pi = 0^+)$$

- Possible H production processes on a diproton pair via the (K^-, K^+) reaction[13] [14] :

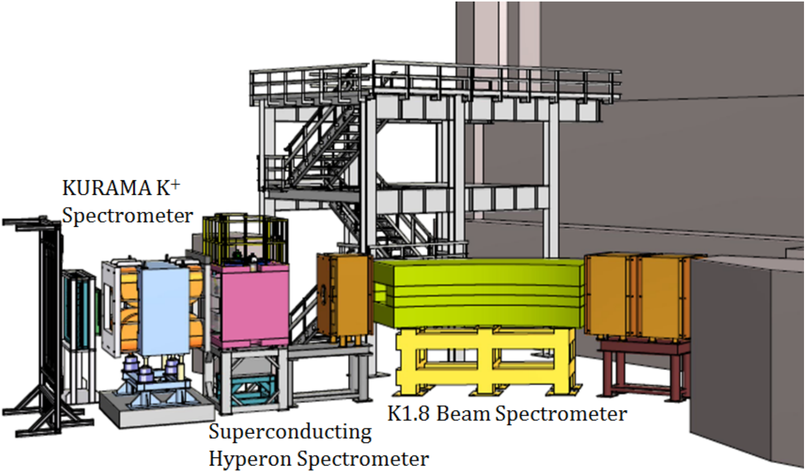




[13] N. Aizawa and M. Hirata, Z. Phys. A 343, 103 (1992)

[14] A.T.M. Aerts and C.B. Dover, Phys. Rev. D28, 450 (1983)

Hyperon Spectrometer at K1.8 Beam Line of J-PARC



- The Hyperon spectrometer consists of a time projection chamber (HypTPC) and the superconducting Helmholtz magnet.

Superconducting Dipole Magnet

- Helmholtz-type dipole magnet[a]
- B field at center : 1.5 T (1.0 T for E42)
- Conduction cooling with two GM refrigerators
- Field uniformity $B_r/B_y < 1\%$ over the inner volume ($\phi = 500$ mm)

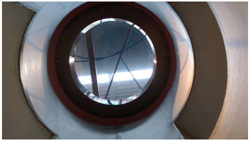
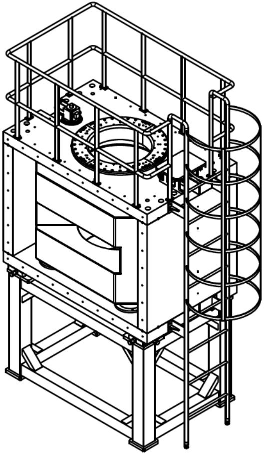


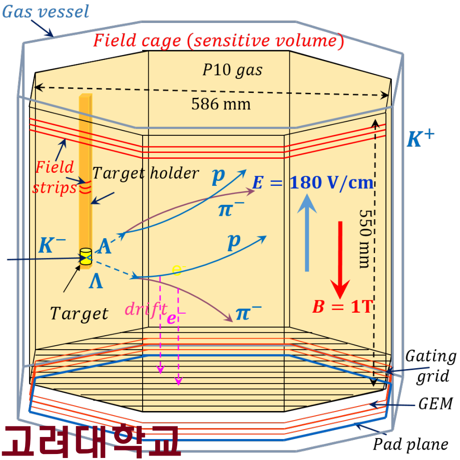
Photo of inner volume ($\phi = 800$ mm)

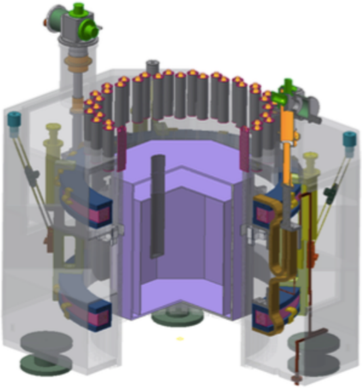
Photo of the Helmholtz magnet for field measurement



[a] KR-tech, Daegu, Korea

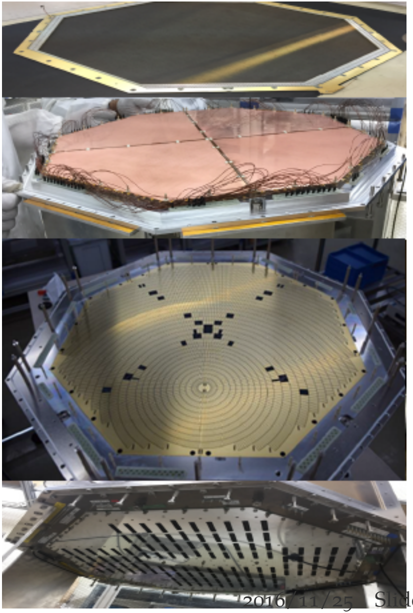
- Octagonal prism field cage and a readout chamber consisting of a gating-grid, a triple GEM layer and a concentric pad plane (5768 pads)





HypTPC Structure

- Four GEM (250×250 mm^2) sheets per layer
- Triple GEM layers (50 μm + 50 μm + 100 μm)
- Gain ~ 10^4
- 10 inner pad rows with $2.1\text{-}2.7 \times 9$ mm^2.
- 22 outer pad rows with $2.3\text{-}2.4 \times 12.5$ mm^2.
- Position resolution < 300 μm
- $\Delta p/p$ = 1-3% for π and p.



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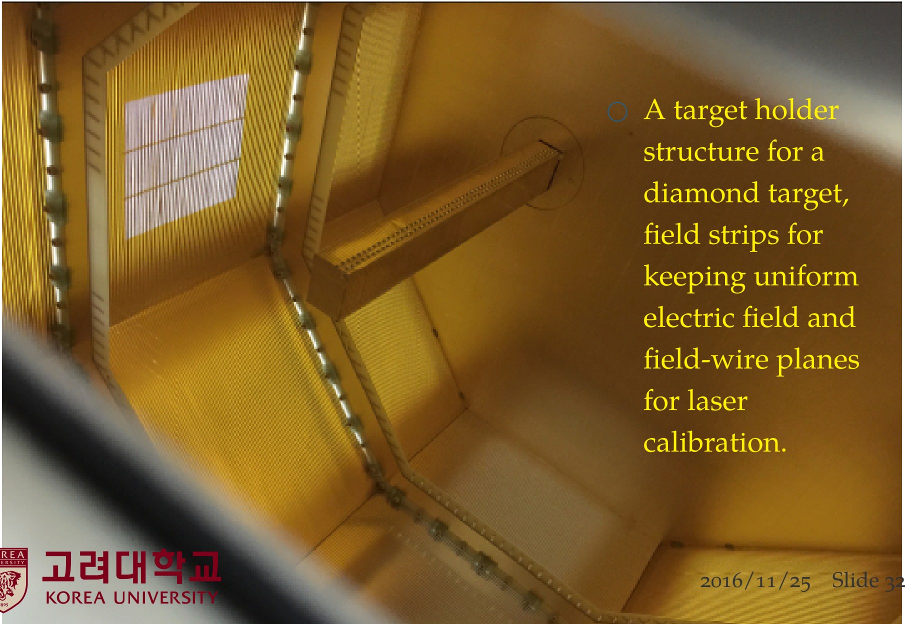
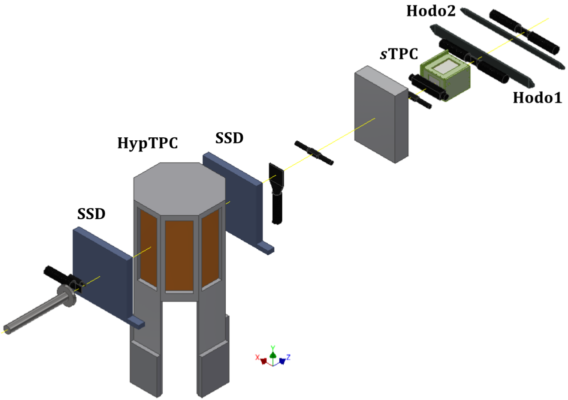
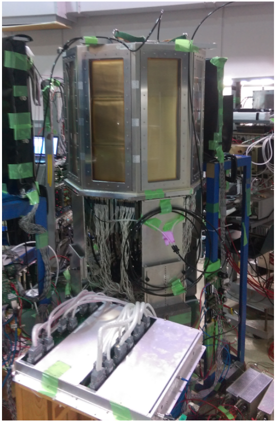
Inside the HypTPC



- A target holder structure for a diamond target, field strips for keeping uniform electric field and field-wire planes for laser calibration.

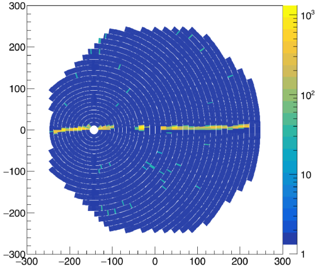
First Beam Test with HypTPC at ELPH

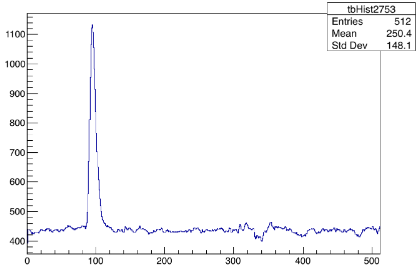




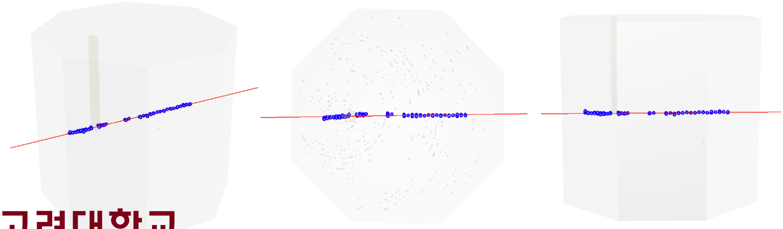
- A 460-MeV/c positron beam was exposed to HypTPC on November 7-9, 2016 at ELPH, Tohoku University.

Preliminary ELPH Test Results





- A positron beam track is clearly reconstructed.



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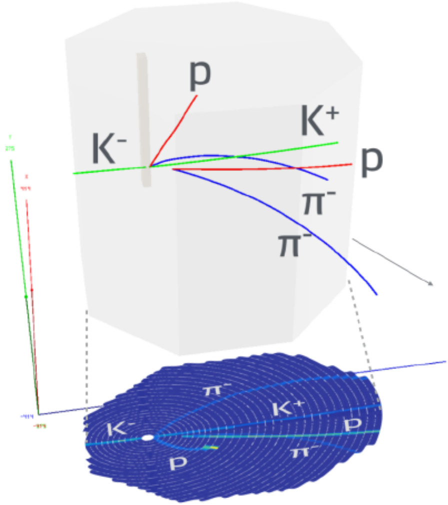
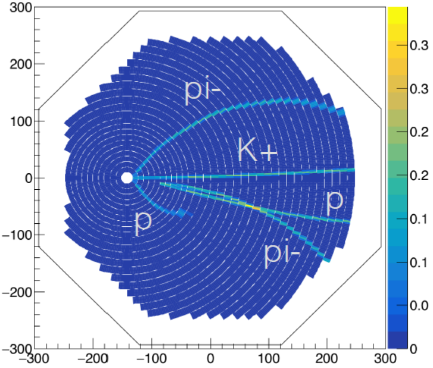
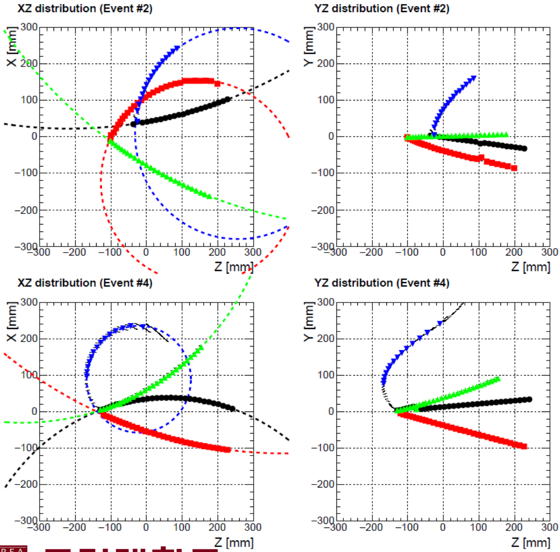
A Full Simulation on the HypTPC Performance



- $\Lambda\Lambda$ Production in the (K^-, K^+) Reaction.



Progressive Tracking Finding



- ΛΛ Production in the (K^-, K^+) Reaction.
- Progressive track finding algorithm with cluters in first three active downstream layers.

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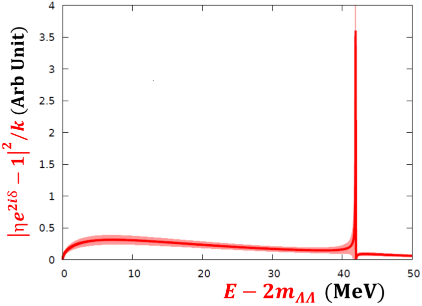
Yield Estimate

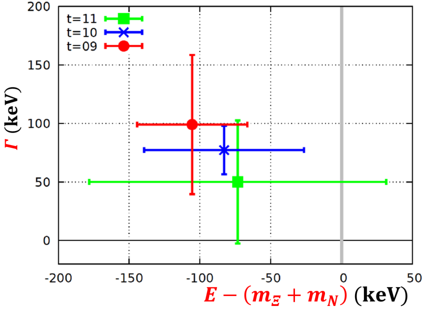
Parameters	Value
K^- beam	6×10^5 K^-/ spill (5.5 s)
Target length	20 mm
Number of nuclei	$2.65 \times 10^{23}/\mathrm{cm}^2$
$d\sigma/d\Omega_L^C(\Lambda\Lambda)$	7.6 μb/sr
$\Delta\Omega(K^+)$	0.16 sr
$\mathrm{Br}(\Lambda \to p\pi^-)^2$	0.41
K^+ Reconstruction	0.5
$\Lambda\Lambda$ Reconstruction	0.4 – 0.6
Yield	0.03 event / spill

- 1.5×10^4 $\Lambda\Lambda$ events for 100 shifts at the current beam power.

Recent Lattice QCD Calculation Result

- Preliminary results with $L = 8$ fm and $m_\pi = 145$ MeV.
- $\Lambda\Lambda$ and $N\Xi$ $(I = 0)$ $^1S_0$ phase shifts [15]





- Deuteron-like $N\Xi$ bound system from ESC model.[16]

[15] K. Sasaki for the HAL Collab., Reimei 2016, Inha (2016).

[16] Y. Yamamoto, NSMAT2016

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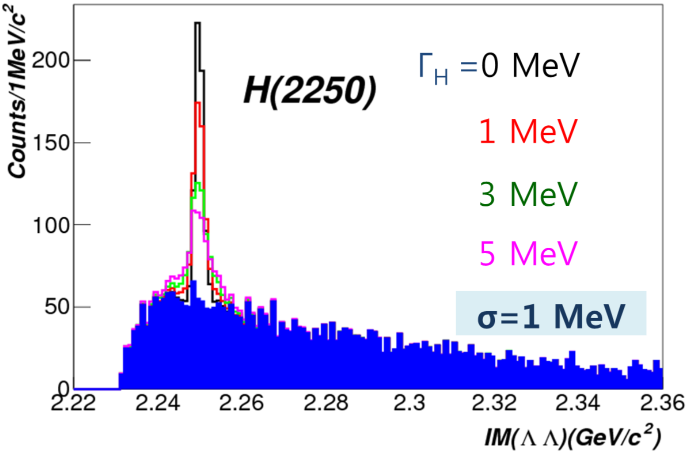
Simulated $\Lambda\Lambda$ Spectrum from E42 [17]

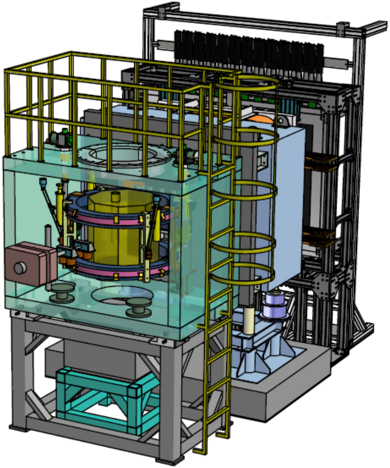
- Lineshapes with respect to Γ_H (assuming σ_m = 1 MeV).



[17] Y. Nara, A. Ohnishi, T. Harada and A. Engel, Nucl. Phys. A614 (1997) 433.

Summary

- We welcome you to join us on the journey for hunting the H-dibaryon (E42) and also for studying baryon resonances (E45) with the HypTPC at J-PARC.



Schematic view of the E42 setup