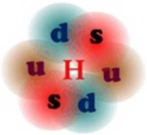
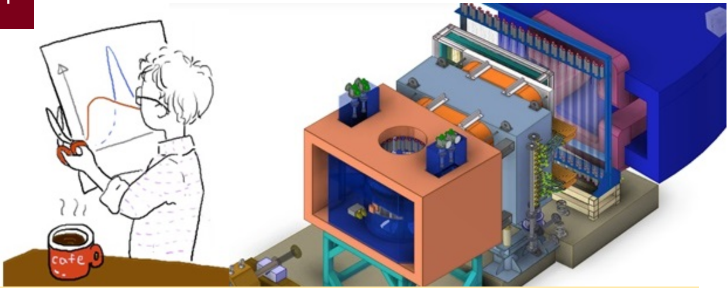
고려대학교
KOREA UNIVERSITY

Hadron & Nuclear Physics Lab




# EXPERIMENTAL ATTEMPTS TO Multi-Strangeness Hyperon Spectroscopy

**Jung Keun Ahn (Korea University)**

# Outline (Last July)

- $\Xi(1530)$, $\Xi(1690)$, and $\Omega$
- $K^- p \rightarrow \Xi^* K^+$ and $K^- p \rightarrow \Omega^- K^0 K^+$ reactions
- $\Xi^- p$ and $\Xi^0 p$ Interactions

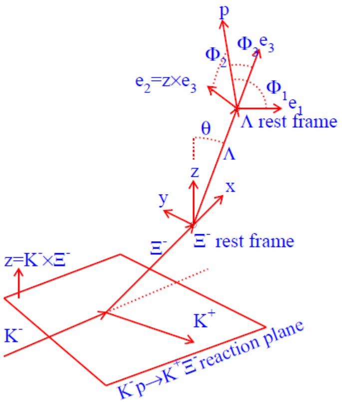
based on [1].

[1] Note on $\Xi^*$ spectroscopy, Note on $\Xi 1690)$ by K. Imai

# Outline

- Polarization of $\Xi$ (Low-energy hyperon beam?)
- Exclusive measurement of charged and neutral particles in the final state ($\Lambda$ and $\Sigma^0$).
- Resonances from Experiments and Theories (Invariant masses of the $mB$ system and poles in the scattering plane)
- Isospin mass splitting of charmed baryons.

# Polarization of Hyperons




Parity conservation requires the $\Xi^-$ polarization to be normal to the production plane:

$$I(\theta) = 1 + \alpha_{\Xi^-} P_{\Xi^-} \cos\theta, \quad \cos\theta = \hat{n} \cdot \hat{k}_\Lambda,$$

where $\hat{n} = \hat{k}_{K^-} \times \hat{k}_{\Xi^-}$. The decay parameter $\alpha_{\Xi^-}$ is $-0.456 \pm 0.014$.

# Polarization of Hyperons

For a fixed angle $\theta$, the protons of the subsequent $\Lambda$ obeys distributions

$$I(\phi_i) = 1 + \alpha_\Lambda P_{\Lambda_i} \cos\phi_i, \qquad \cos\phi_i = \hat{k}_p \cdot \hat{P}_\Lambda,$$

with respect to the $\Lambda$ polarization components, $P_{\Lambda_i} \cos\phi_i$ defined as:

$$P_{\Lambda_1} = \frac{-P_{\Xi^-}\gamma_{\Xi^-} \sin\theta}{(1 + \alpha_{\Xi^-}P_{\Xi^-} \cos\theta)}, \quad P_{\Lambda_2} = \frac{P_{\Xi^-}\beta_{\Xi^-} \sin\theta}{(1 + \alpha_{\Xi^-}P_{\Xi^-} \cos\theta)}, \quad P_{\Lambda_3} = \frac{(P_{\Xi^-} \cos\theta + \alpha_{\Xi^-})}{(1 + \alpha_{\Xi^-}P_{\Xi^-} \cos\theta)}.$$

# Polarization of Hyperons

Averaging $I(\phi_i)$ over all $\Xi^-$ decay angle $\theta$ gives the resulting distribution, $I(\phi_i) = 1 + \alpha_\Lambda < P_{\Lambda_i} > \cos\phi_i$, where $< P_{\Lambda_i} >$ is given by

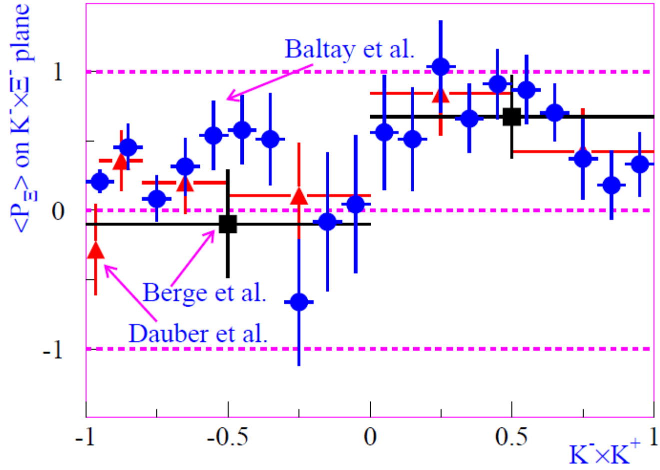
$$< P_{\Lambda_i} >= \int P_{\Lambda_i}(\theta) I(\theta) d\Omega / \int I(\theta) d\Omega,$$

where $\int I(\theta) d\Omega$ is normalized to $4\pi$. Therefore, the decay-proton distributions of the $\Lambda$ decays are explicitly

$$I(\phi_1) = 1 - \frac{\pi}{4} P_{\Xi^-} \gamma_{\Xi^-} \alpha_\Lambda \cos\phi_1, \quad I(\phi_2) = 1 + \frac{\pi}{4} P_{\Xi^-} \beta_{\Xi^-} \alpha_\Lambda \cos\phi_2, \quad I(\phi_3) = 1 + \alpha_{\Xi^-} \alpha_\Lambda \cos\phi_3,$$

where $\cos\phi_1 = \hat{k}_p \cdot \hat{e}_1$, $\cos\phi_2 = \hat{k}_p \cdot \hat{e}_2$, $\cos\phi_3 = \hat{k}_p \cdot \hat{e}_3$,

# Polarization of Hyperons



# Branching ratios of the $\Sigma(1385)$

- Br($\Lambda\pi^0$)$= 87.0 \pm 1.5\%$
- Br($\Sigma\pi^0$)$= 11.7 \pm 1.5\%$

**$\Sigma$(1385) BRANCHING RATIOS**

**$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$** $\Gamma_2/\Gamma_1$

| VALUE | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|
| **0.135±0.011 OUR AVERAGE** | | | | | |
| 0.20 ±0.06 | DIONISI | 78B | HBC | ± | $K^- p \to Y^* K \overline{K}$ |
| 0.16 ±0.03 | BERTHON | 74 | HBC | + | $K^- p$ 1.26–1.84 GeV/$c$ |
| 0.11 ±0.02 | BERTHON | 74 | HBC | − | $K^- p$ 1.26–1.84 GeV/$c$ |
| 0.21 ±0.05 | BORENSTEIN | 74 | HBC | + | $K^- p \to \Lambda\pi^+\pi^-$, $\Sigma^0\pi^+\pi^-$ |
| 0.18 ±0.04 | MAST | 73 | MPWA | ± | $K^- p \to \Lambda\pi^+\pi^-$, $\Sigma^0\pi^+\pi^-$ |
| 0.10 ±0.05 | THOMAS | 73 | HBC | − | $\pi^- p \to \Lambda K\pi$, $\Sigma K\pi$ |
| 0.16 ±0.07 | AGUILAR-... | 72B | HBC | + | $K^- p$ 3.9, 4.6 GeV/$c$ |
| 0.13 ±0.04 | COLLEY | 71B | DBC | −0 | $K^- N$ 1.5 GeV/$c$ |
| 0.13 ±0.04 | PAN | 69 | HBC | + | $\pi^+ p \to \Lambda K\pi$, $\Sigma K\pi$ |
| 0.08 ±0.06 | LONDON | 66 | HBC | + | $K^- p$ 2.24 GeV/$c$ |
| 0.163±0.041 | ARMENTEROS | 65B | HBC | ± | $K^- p$ 0.95–1.20 GeV/$c$ |
| 0.09 ±0.04 | HUWE | 64 | HBC | ± | $K^- p$ 1.2–1.7 GeV |

# A Puzzle in the $\Sigma(1670)(D13)$

- Formation experiments observe one $\Sigma$ resonance in the 1660 MeV mass region with $J^p = 3/2^-$ and decaying primarily to $N\overline{K}$, $\Lambda\pi$, and $\Sigma\pi$.

- Production experiments have found evidence suggestive of two $\Sigma$ resonances in this mass region, based on a difference in the production angular distributions of $\Sigma(1660)$ decaying into $\Sigma\pi$ and $\Sigma\pi\pi$.

# Four-star Rating from $\Sigma(1670)$ PWA

## $\Sigma(1670)$ ****

### $\Sigma(1670)$ MASS

| DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|
| KOISO | 85 | DPWA | $K^- p \to \Sigma\pi$ |
| GOPAL | 80 | DPWA | $\overline{K}N \to \overline{K}N$ |
| ALSTON-... | 78 | DPWA | $\overline{K}N \to \overline{K}N$ |
| GOPAL | 77 | DPWA | $\overline{K}N$ multichannel |
| HEPP | 76B | DPWA | $K^- N \to \Sigma\pi$ |
| BAILLON | 75 | IPWA | $\overline{K}N \to \Lambda\pi$ |
| VANHORN | 75 | DPWA | $K^- p \to \Lambda\pi^0$ |
| KANE | 74 | DPWA | $K^- p \to \Sigma\pi$ |
| [1] MARTIN | 77 | DPWA | $\overline{K}N$ multichannel |
| DEBELLEFON | 76 | IPWA | $K^- p \to \Lambda\pi^0$ |
| PONTE | 75 | DPWA | $K^- p \to \Lambda\pi^0$ |

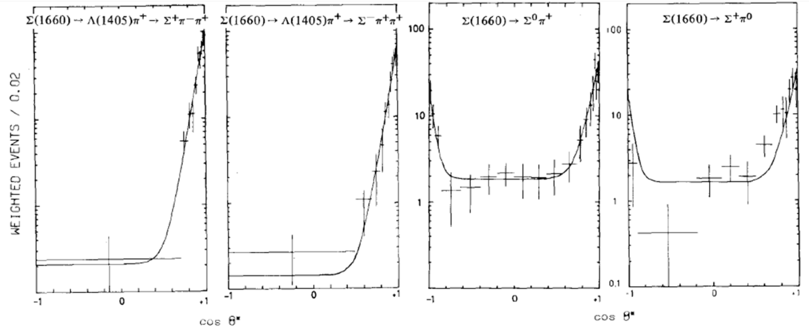
### $\Sigma(1670)$ (PRODUCTION EXPERIMENTS)

| DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|
| [1] CARROLL | 76 | DPWA | | Isospin-1 total $\sigma$ |
| [2] HEPP | 76 | DBC | − | $K^- N$ 1.6–1.75 GeV/$c$ |
| APSELL | 74 | HBC | | $K^- p$ 2.87 GeV/$c$ |
| BERTHON | 74 | HBC | 0 | Quasi-2-body $\sigma$ |
| AGUILAR-... | 70B | HBC | | $K^- p \to \Sigma\pi\pi$ 4 GeV |
| AGUILAR-... | 70B | HBC | | $K^- p \to \Sigma 3\pi$ 4 GeV |
| ALVAREZ | 63 | HBC | + | $K^- p$ 1.51 GeV/$c$ |
| [3] FERRERSORIA | 81 | OMEG | − | $\pi^- p$ 9,12 GeV/$c$ |
| TIMMERMANS | 76 | HBC | + | $K^- p$ 4.2 GeV/$c$ |
| BUGG | 68 | CNTR | | $K^- p$, $d$ total $\sigma$ |
| PRIMER | 68 | HBC | + | See BARNES 69E |
| ALEXANDER | 62C | HBC | −0 | $\pi^- p$ 2–2.2 GeV/$c$ |

# Decay Angular Distributions of the $\Sigma(1670)$ [2]

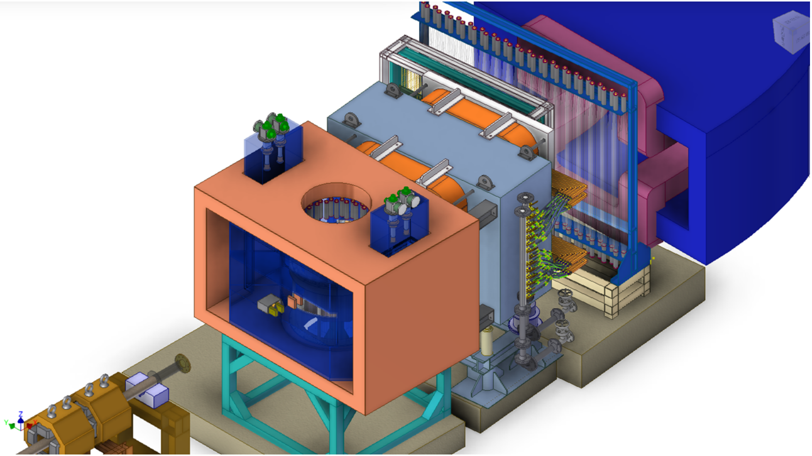
$\Lambda(1405)\pi^+$

$\Sigma^+\pi^-\pi^+$ $\Sigma^-\pi^+\pi^+$ $\Sigma^0\pi^+$ $\Sigma^+\pi^0$

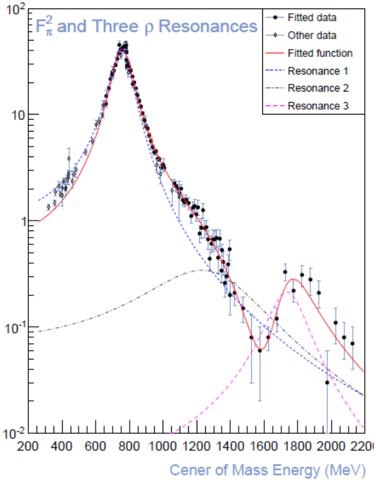



[2]Timmermans *et al.*, Nucl. Phys. B112, (1976) 77

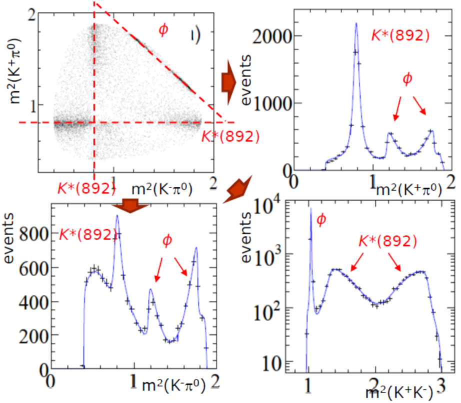
# Ideal Spectrometer with EMcal?



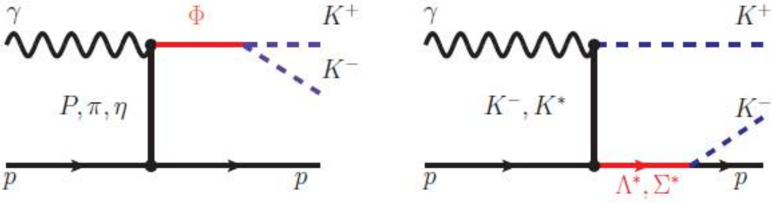
# Amplitude Interference in N-Body Final States




- Dalitz plot of $D_s^+ \to K^+K^-\pi^0$

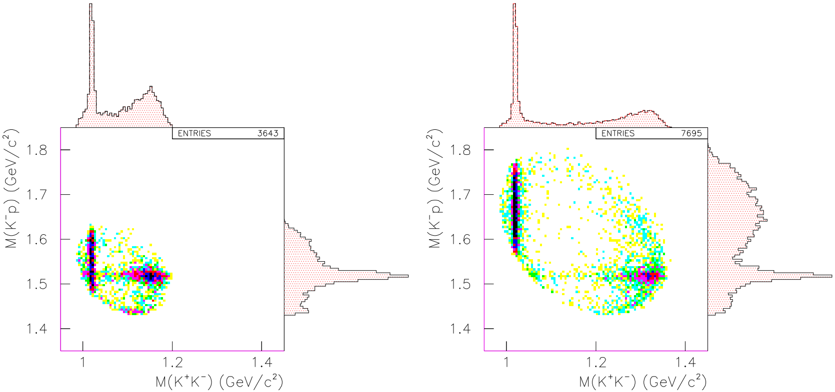


# $\gamma p \to K^+ K^- p$



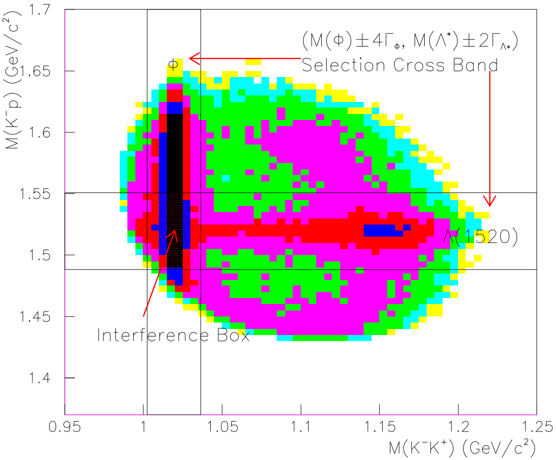
# $K^-K^+$ and $K^-p$ Masses from $\gamma p \to K^+K^-p$ [3]

- Scatter plots of the $K^-K^+$ and the $K^-p$ invariant masses from SPring-8/LEPS.




[3] from Ph.D analysis by S.Y. Ryu (RCNP)

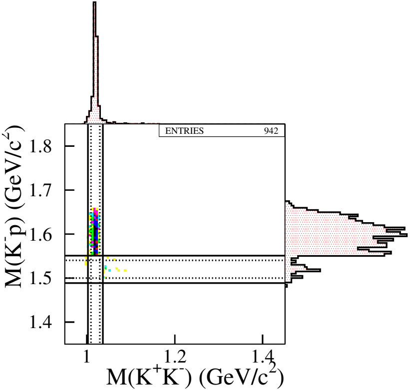
# The M($K^-K^+$)-M($K^-p$) Mass Bands



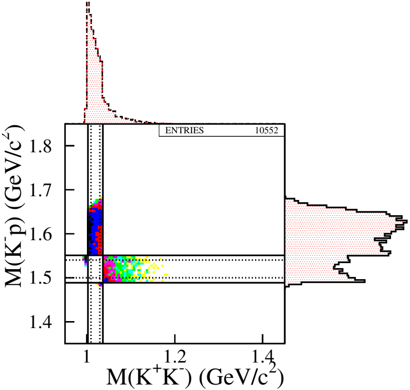

- Events were further selected in the cross band region.

# Scatter Plots w/o the Interference Box (I)

Real data




Simulated S-wave data

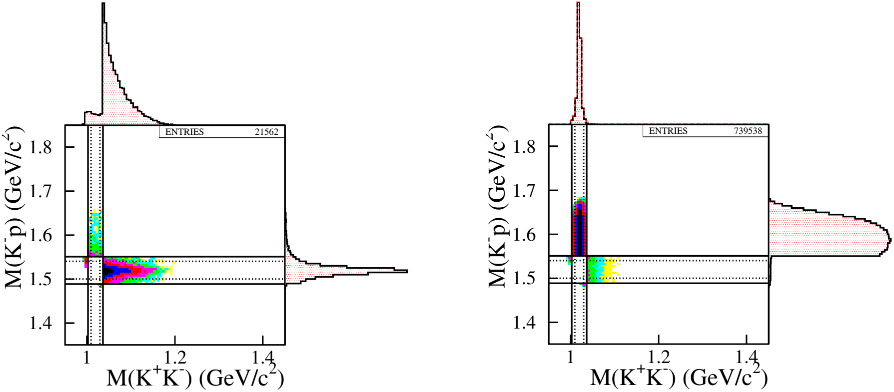



- Events in the interference box were also removed from the scatter plot.

# Scatter Plots w/o the Interference Box (II)

Simulated $\Lambda(1520)$ data

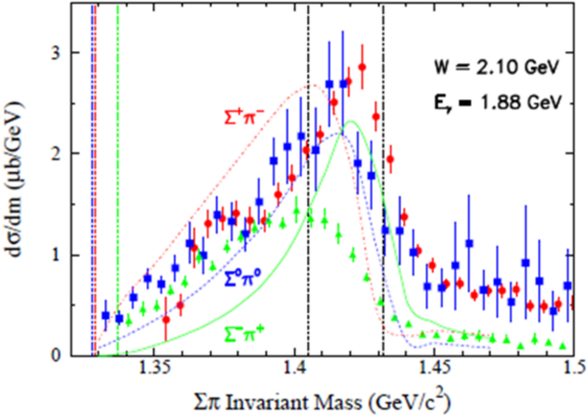
Simulated $\phi$ data




- Data without events in the interference box were fit to the lineshapes of simulated data.

# $\Lambda(1405)$ and the $\pi\Sigma$ Systems (I) [4]

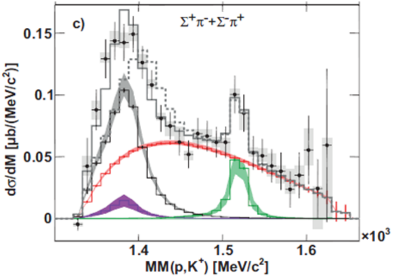
- $\gamma p \to K^+ \Sigma\pi$ from CLAS/JLab

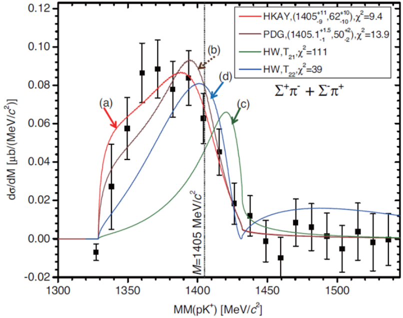



[4] K. Moriya *et al.* (CLAS), Phys. Rev. C87, 035206 (2013)

# $\Lambda(1405)$ and the $\pi\Sigma$ Systems (II) [5] [6]

- $pp \to K^+ p \Sigma \pi$ at 3.5 GeV from HADES/GSI

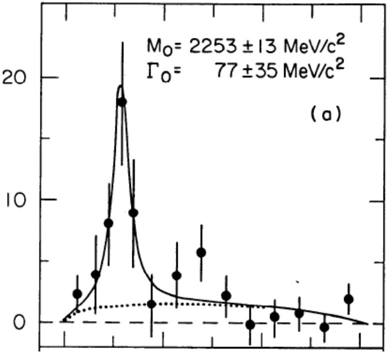


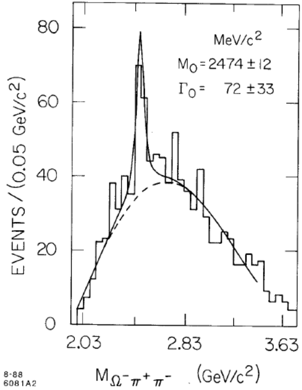




[5] G. Agkishiev *et al.* (HADES), Phys. Rev. C87, 025201 (2013)
[6] M. Hassanvand *et al.*, Phys. Rev. C88, 019905 (2013)

# Triply Strange Baryons [7]

- $\Omega^-$, $\Omega(2250)^-$, $\Omega(2380)^-$, and $\Omega(2470)^-$.
- $K^- p \to K^+ K^0 \Omega^{*-}$ at 11 GeV/c, followed by $\Omega^{*-} \to \Xi\pi K^-$ or $\Omega^-\pi^+\pi^-$.

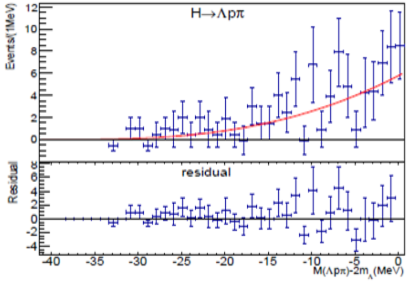


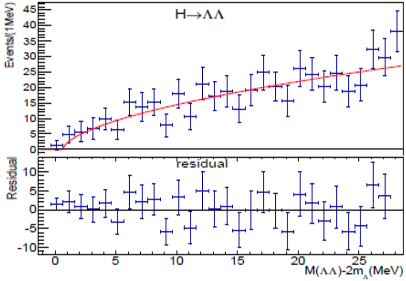




[7] D. Aston *et al.*, Phys. Lett. B194 (1987) 579

# H-Dibaryon Search at Belle [8]

- The Belle searched for the H-dibaryon in $\Upsilon$ decays $(Br(\Upsilon \to HX)/Br(\Upsilon \to \bar{d}X) < 10^{-2})$.
- Needs to measure $\Upsilon \to H\bar{H}$ or $H\overline{\Lambda\Lambda}$
- Needs to identify $\Lambda\Lambda$ excluding $\Lambda\Sigma^0$ and/or $\Sigma^0\Sigma^0$.

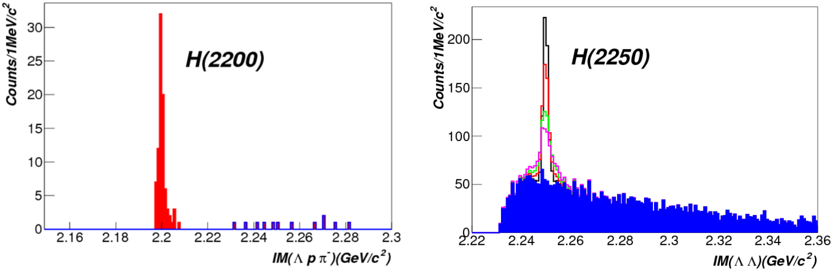



[8] B.H. Kim *et al.*, Phys. Rev. Lett. 110 (2013)

# H-Dibaryon Search at J-PARC

- The J-PARC-E42 experiment searches for the H-dibaryon in $\Sigma^- p$, $\Lambda p \pi^-$, $\Lambda\Lambda$, and $\Xi^- p$ channels by tagging the $S = -2$ system production via $(K^-, K^+)$ reactions with a diamond ($^{12}$C) target.



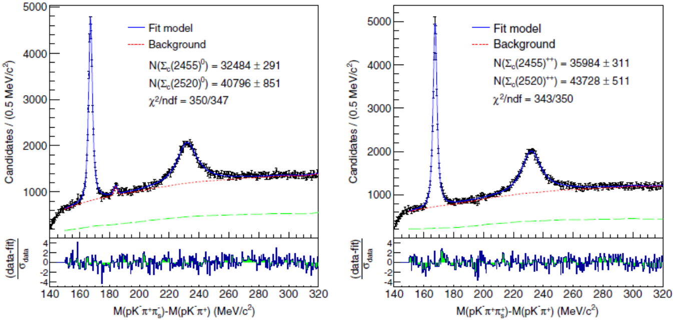
# More Strange Dibaryons [9]

- $N\Omega^-$(2549) dibaryon $(J^p = 2^+, I = 1/2)$ decaying into $\Lambda\Xi$ (deeply bound)
- $\Omega\Omega$(3300) dibaryon $(J = I = 0)$ (weakly bound?)

[9] Y-X. Liu *et al.*, Phys. Lett. B544 (2002) 280 ; N. Sawado, Phys. Lett. B524 (2002) 289; F. Wang, Phys. Rev. C69 (2004) 065207

# Mass difference ($\Sigma_c^0(2455)$ and $\Sigma_c^{++}(2455)$) [10]

| $(\mathrm{MeV}/c^2)$ | $\Delta m(m(\Sigma_c) - m(\Lambda_c^+))$ | Mass |
|---|---|---|
| $\Sigma_c(2455)^0$ | $167.29 \pm 0.01 \pm 0.02$ | $2453.75 \pm 0.01 \pm 0.02 \pm 0.14$ |
| $\Sigma_c(2455)^{++}$ | $167.51 \pm 0.01 \pm 0.02$ | $2453.97 \pm 0.01 \pm 0.02 \pm 0.14$ |




[10] S.-H. Lee (Belle) *et al.*, Phys. Rev. D 89, 091102R (2014)

# Isospin Mass Splitting of Baryons

| | |
|---|---|
| $\Delta^{++} - \Delta^0$ | $-2.86 \pm 0.30$ MeV [11] |
| $\Sigma_c(2455)^{++} - \Sigma_c(2455)^0$ | $0.22 \pm 0.01 \pm 0.01$ MeV |

- The mass hiearchy from the $u/d$-quark mass difference.
- Isospin mass splitting from electromagnetic interaction (the smaller baryon wave function, the stronger electromagnetic interaction) [12].
- The ρ-mode excitation in the diquark picture can account for this mass splitting (longer spatial distance with a $uu$ pair than with a $dd$ pair)?

[11] A.B. Gridnev *et al.*, Phys. Atom. Nucl. 69 (2006) 1542
[12] S. Capstick, Phys. Rev. D36, 2800 (1987)