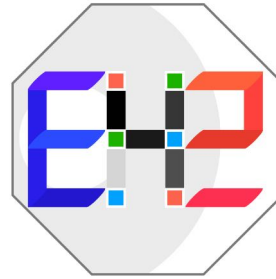


HaPhy2021-1, Online, 24 Sep 2021



# Hadron physics program with **E42** with an emphasis on *H*-Dibaryon

Shin Hyung Kim  
(Korea University)

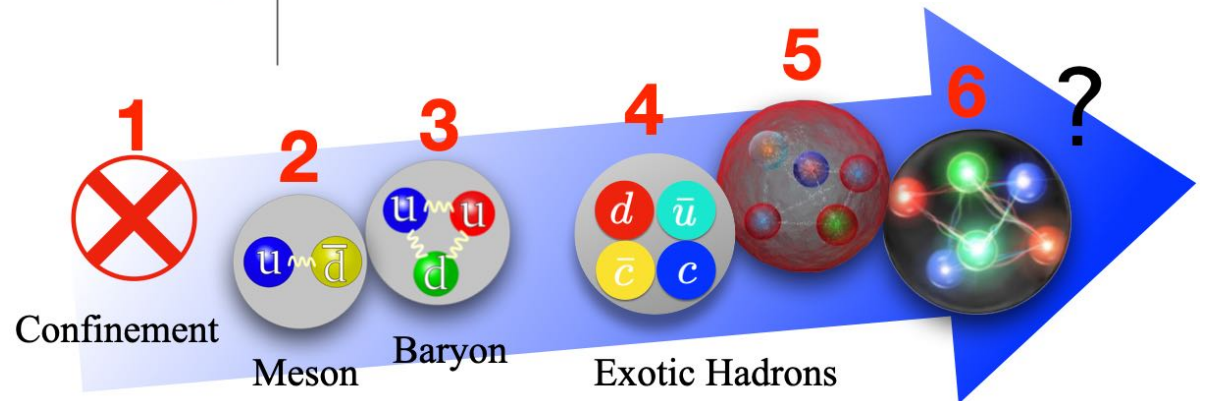
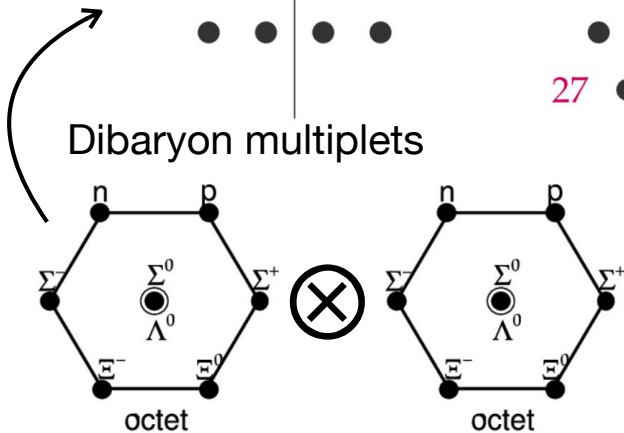
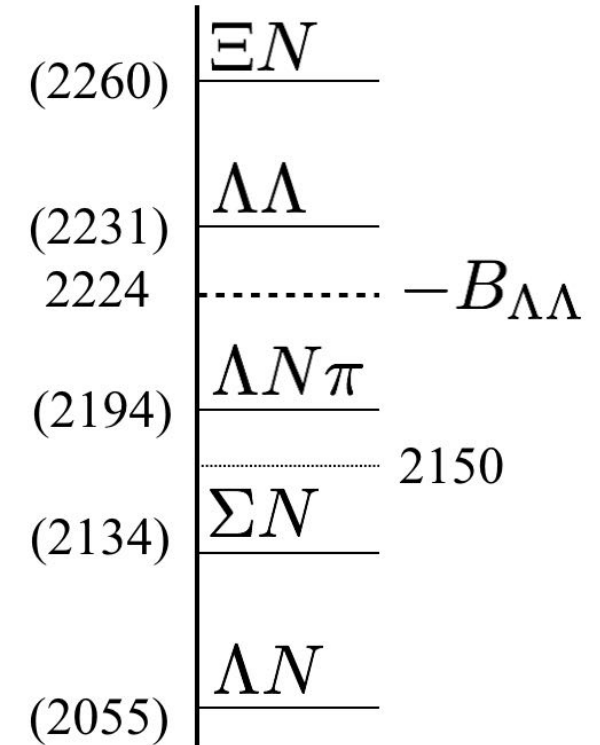
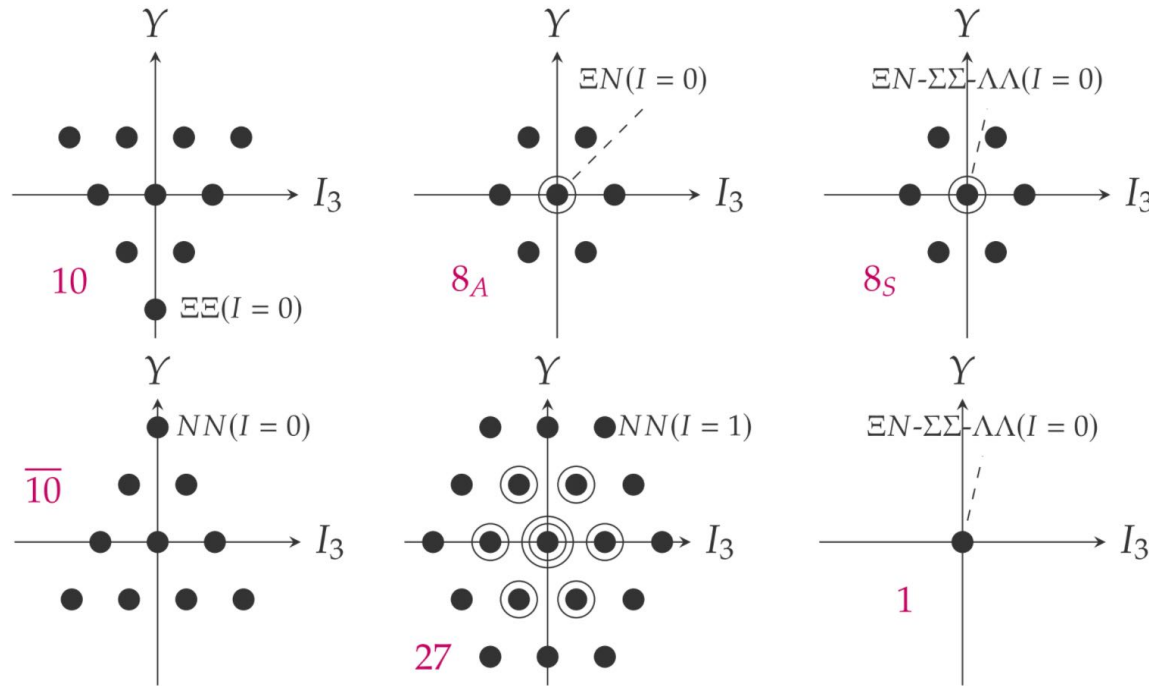
- Physics Motivation of E42
  - History of  $H$ -Dibaryon Search
- J-PARC E42 Experiment
  - Experimental setup
  - Run Summary
  - Analysis Status
- E42 Byproducts
  - $^{12}\text{C}(\text{K}^-, \text{K}^+)$ ,  $\text{p}(\text{K}^-, \text{K}^+)$ ,  $^{12}\text{C}(\text{K}^-, \pi^+)$ ,  $^{12}\text{C}(\text{K}^-, \text{p})$
- Summary

# Physics Motivation

---

# H-Dibaryon?

- SU(3) flavor singlet state ( $I=0, J^{\pi}=0^+$ )
- Quark composition of  $uuddss$



# Brief History of $H$ -Dibaryon Search

1977 ● First proposed by Jaffe “Deeply bound state”  
81 MeV lighter than the  $\Lambda\Lambda$  threshold

VOLUME 38, NUMBER 5      PHYSICAL REVIEW LETTERS      31 JANUARY 1977

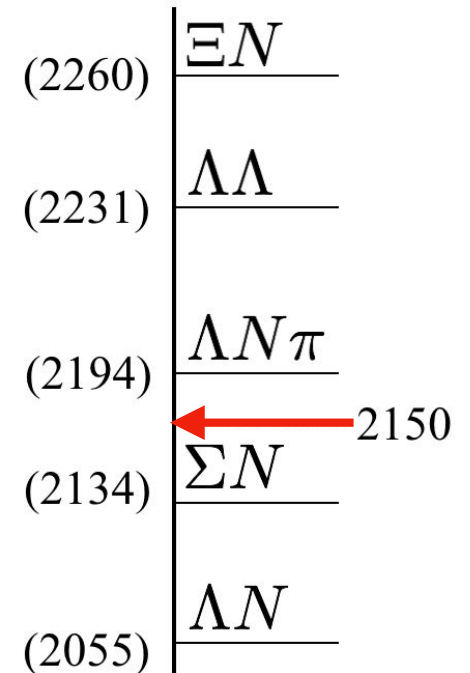
## Perhaps a Stable Dihyperon\*

R. L. Jaffe†

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Department of Physics and Laboratory of Nuclear Science, ‡ Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

(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.



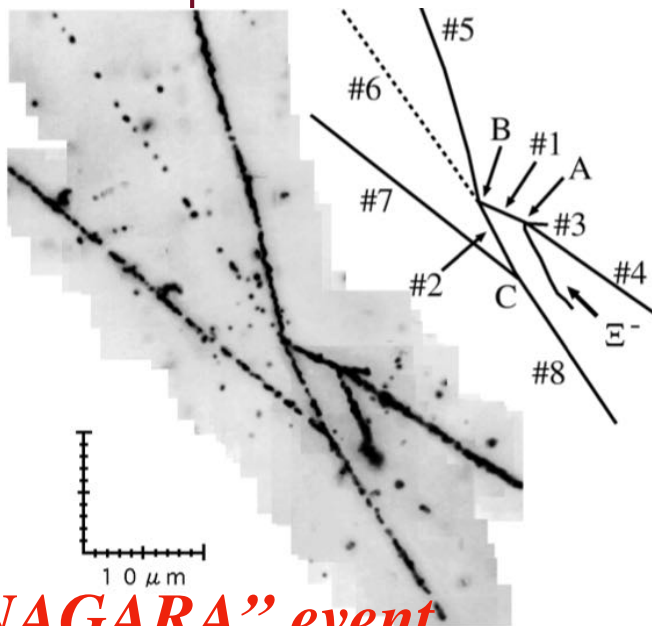
⋮

Many **experimental** attempts to find  $H$   
Many **theoretical** model calculations  
to predict the  $H$  mass

# Brief History of $H$ -Dibaryon Search

1977 ● First proposed by Jaffe “Deeply bound state”

2001 ● Mass constraint from  $\Lambda^6\text{He}$  ( $B_{\Lambda\Lambda} \sim 7$  MeV)



“NAGARA” event

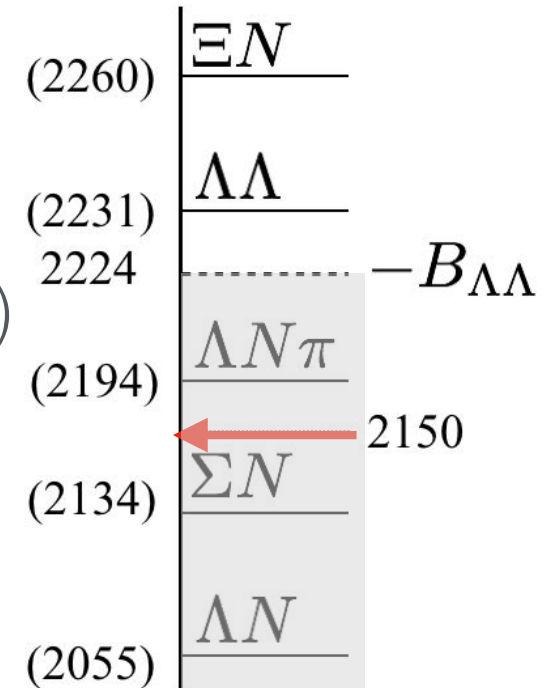
Phys. Rev. Lett. 87 (2001) 212502

$$M_H > 2M_\Lambda - B_{\Lambda\Lambda}$$

Lower limit of  $M_H$   
 $2223.7 \text{ MeV}/c^2$  (90% CL)

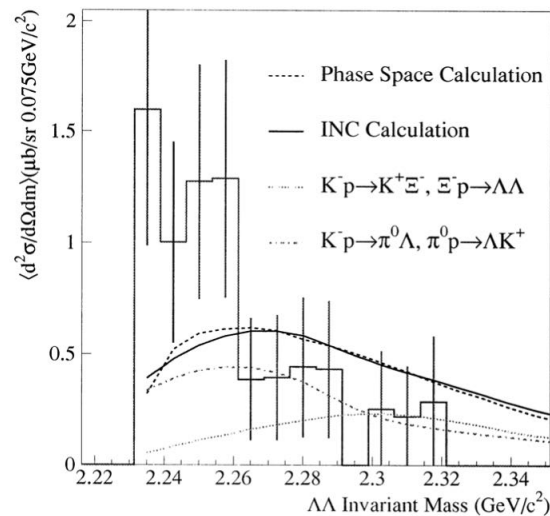
Weakly bound state?  
 Resonance?

J-PARC E07 (2017)  
 x10 data coming soon!



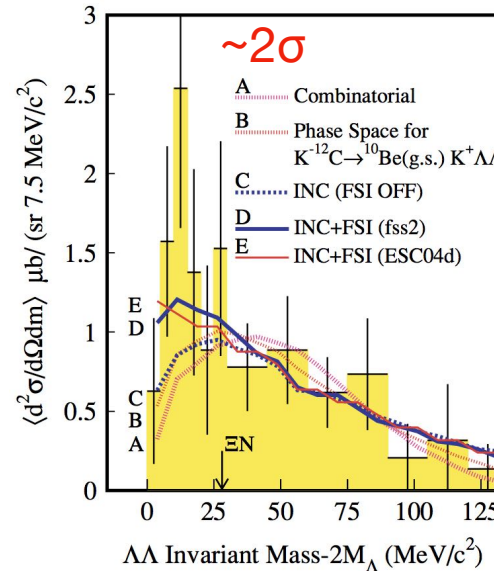
# Brief History of $H$ -Dibaryon Search

- 1977 ● First proposed by Jaffe “Deeply bound state”
- 2001 ● Mass constraint from  $\Lambda^6\text{He}$  ( $B_\Lambda \sim 7$  MeV)
- 1998,2007 ● Observed enhancement near  $\Lambda\Lambda$  threshold



Phys. Lett. B444 (1998) 267

2.1  $\mu\text{b/sr}$  (90% CL)



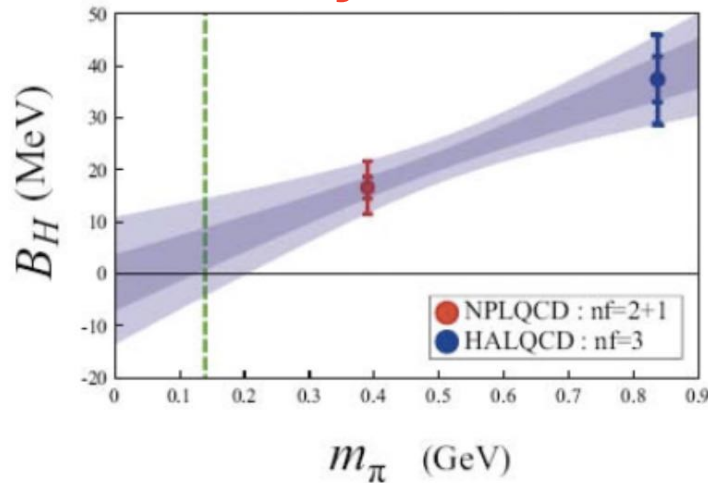
Phys. Rev. C75 (2007) 022201

|        |                  |
|--------|------------------|
| (2260) | $\Xi N$          |
| (2231) | $\Lambda\Lambda$ |
| 2224   | -----            |
| (2194) | $\Lambda N \pi$  |
| (2134) | $\Sigma N$       |
| (2055) | $\Lambda N$      |

# Brief History of $H$ -Dibaryon Search

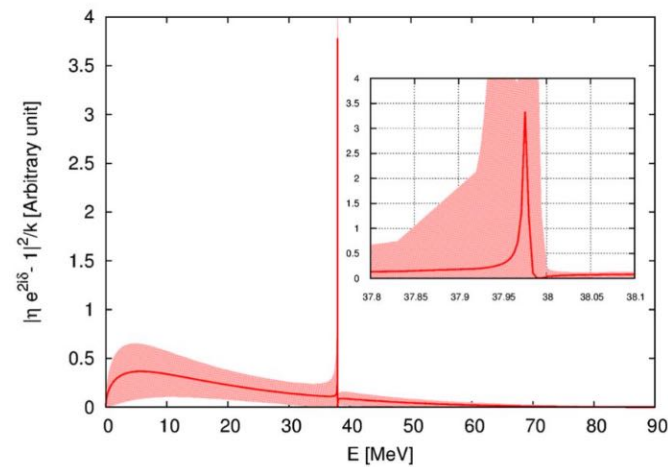
- 1977 ● First proposed by Jaffe “Deeply bound state”
- 2001 ● Mass constraint from  $\Lambda^6\text{He}$  ( $B_\Lambda \sim 7$  MeV)
- 1998,2007 ● Observed enhancement near  $\Lambda\Lambda$  threshold
- 2011,2018 ● LQCD predictions

**Loosely bound state?**

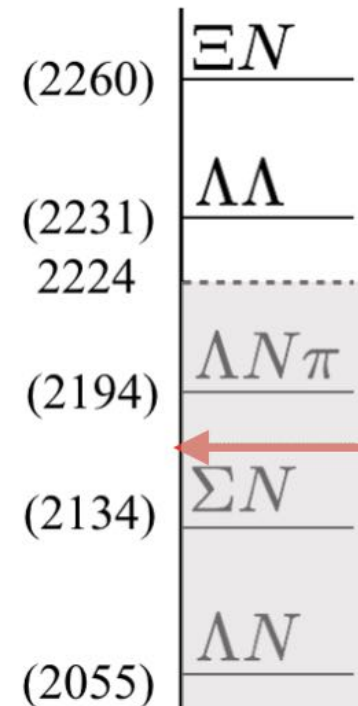


Phys. Rev. Lett. 106 (2011) 162001

**Sharp peak just before  $\Xi N$  threshold?**

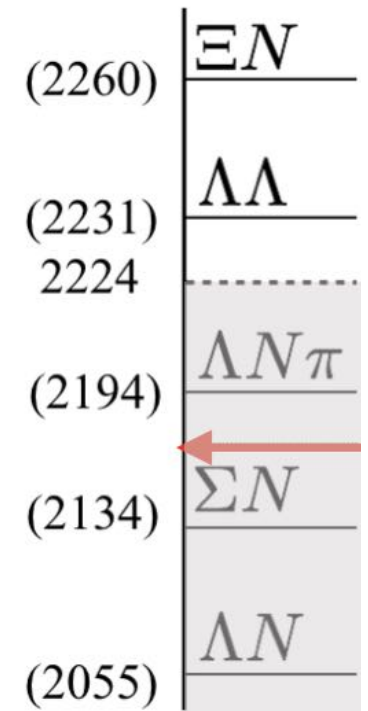
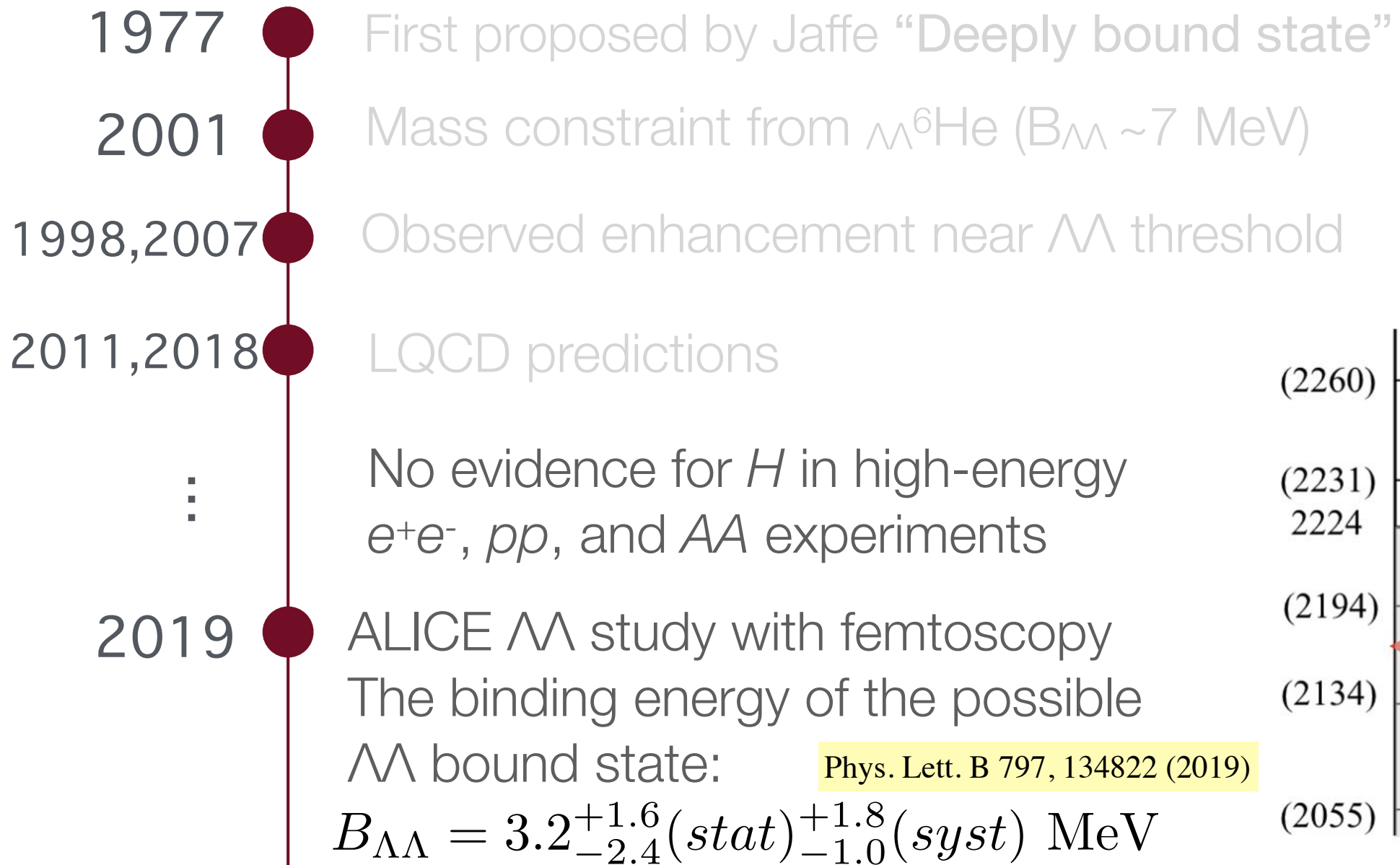


K. Sasaki for the HAL Collab. (2018)



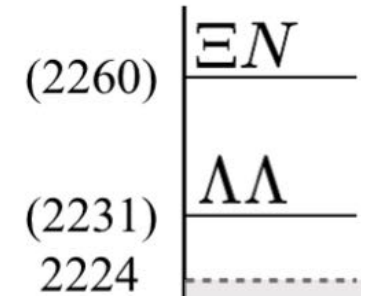


# Brief History of $H$ -Dibaryon Search



# Brief History of $H$ -Dibaryon Search

- 1977 ● First proposed by Jaffe “Deeply bound state”
- 2001 ● Mass constraint from  $\Lambda^6\text{He}$  ( $B_\Lambda \sim 7$  MeV)
- 1998,2007 ● Observed enhancement near  $\Lambda\Lambda$  threshold
- 2011,2018 ● LQCD calculations
- ⋮ No evidence for  $H$  in high-energy  $e^+e^-$ ,  $pp$ , and  $AA$  experiments
- 2019 ● ALICE  $\Lambda\Lambda$  study with femtoscopy
- 2021 ● **E42 @J-PARC**

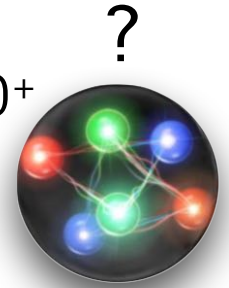


# J-PARC E42 Experiment

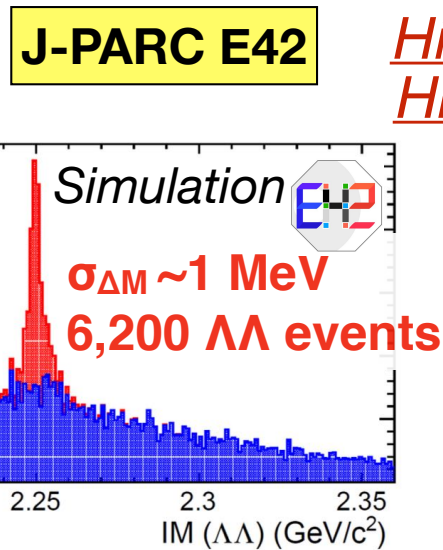
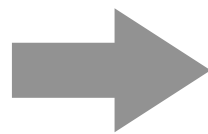
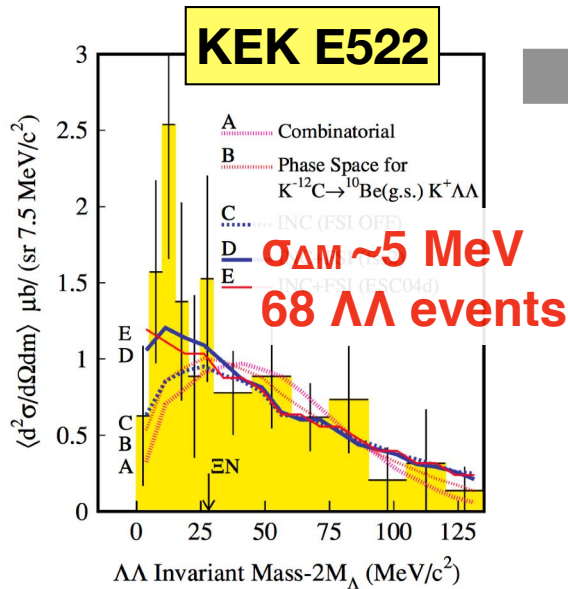
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# J-PARC E42 Experiment

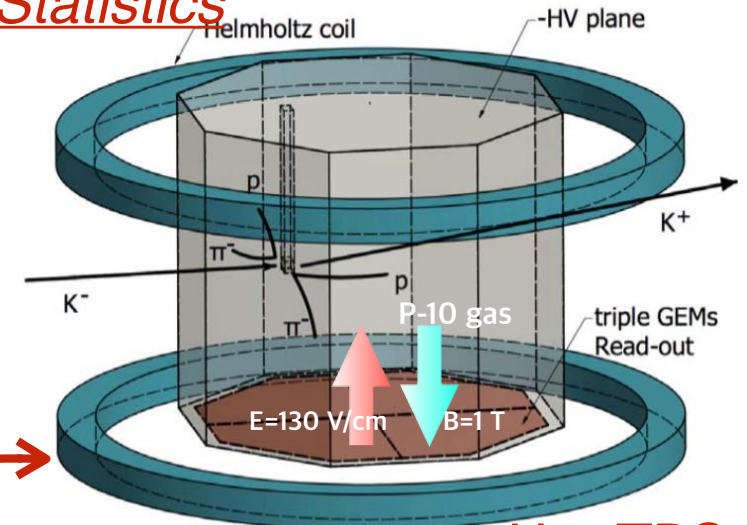
$uuddss$   
 $I=0, J^\pi=0^+$



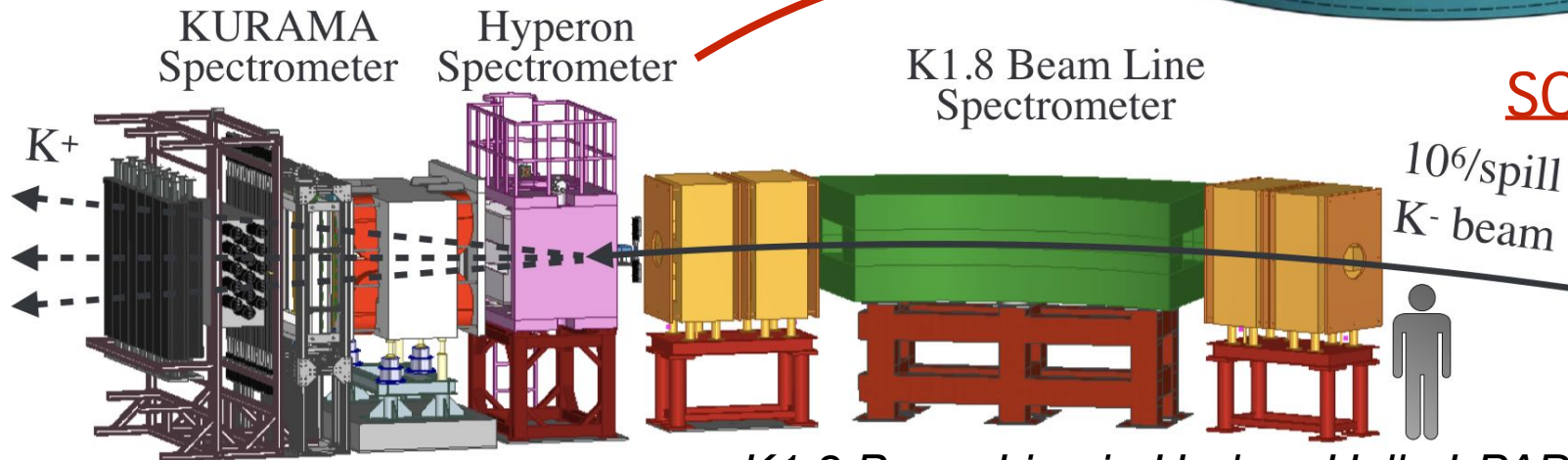
- Search for  $H$ -dibaryon via  $^{12}\text{C}(K^-, K^+)$  reactions



High Resolution  
High Statistics



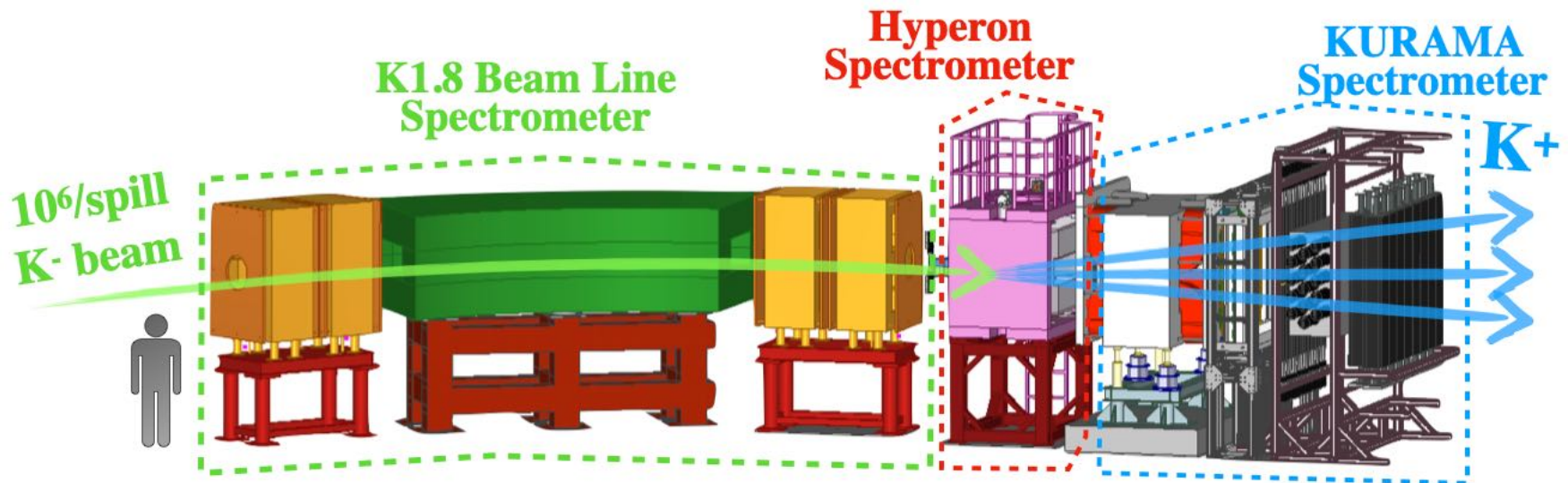
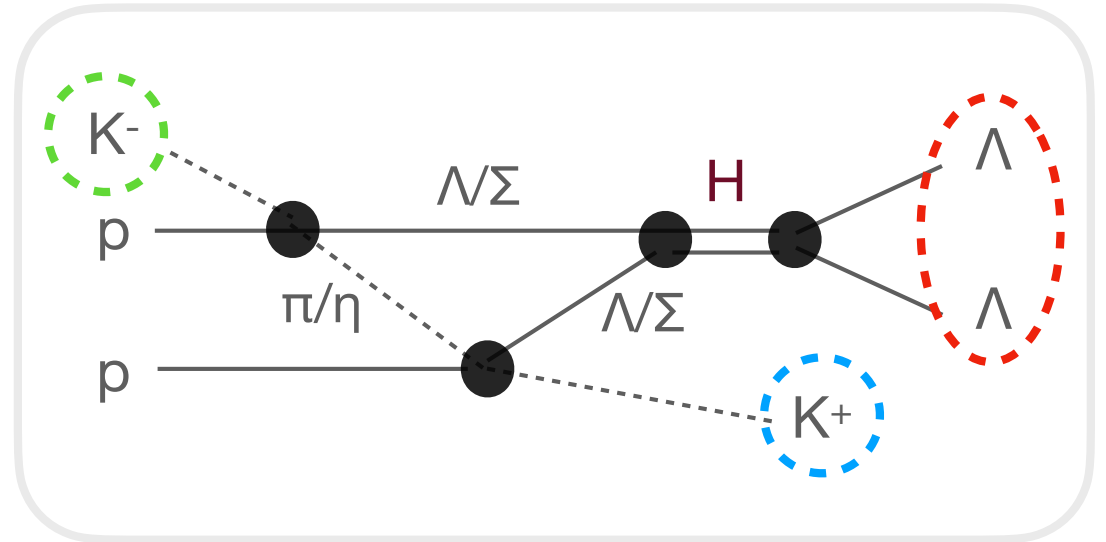
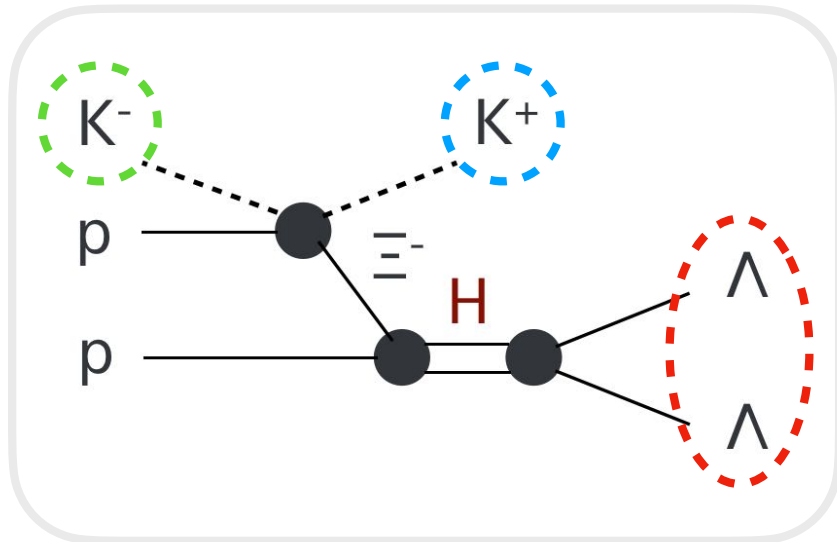
HypTPC  
SC Magnet



K1.8 Beam Line in Hadron Hall, J-PARC

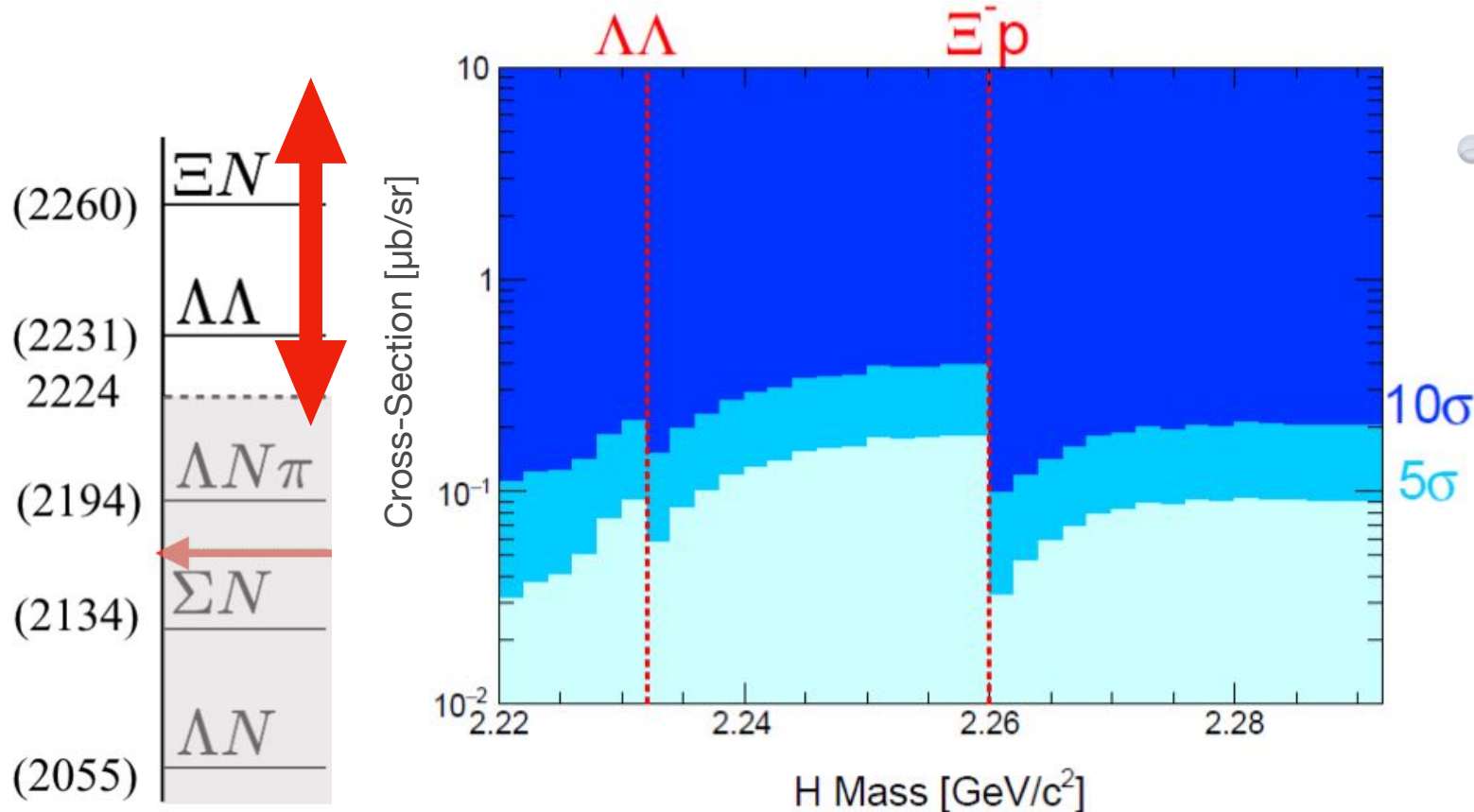
# $H$ Production via $(K^-, K^+)$ Reactions

- Possible  $H$  processes on a diproton pair via the  $^{12}\text{C}(K^-, K^+)$  reactions



# Experimental Sensitivity to $H$ Mass

- The sensitivity is good enough to cover a broad range of the  $H$ -dibaryon mass from the  $\Lambda\Lambda$  bound state to the unbound region above the  $\Xi^-p$  mass threshold.



- Significance:

$$\frac{S}{\sqrt{S+B}}$$

- $B$ : INC model, Phase Space w/ 7.6  $\mu\text{b/sr}$

# E42 Collaboration

J.K. Ahn (*spokesperson*), S.H. Kim, S.W. Choi, W.S. Jung, B.M. Kang, J.W. Lee, S.B. Yang, M. Fujita, S. Hasegawa, Y. Ichikawa (*co-spokesperson*), K. Imai, H. Sako, S. Sato, K. Tanida, T. Takahashi, M. Ukai, T. Yamamoto, S. Hayakawa, Y. Ishikawa, S. Kajikawa, K. Kamada, T. Kitaoka, T. Morino, F. Oura, T. Sakao, M. Saito, H. Tamura, S. Wada, T. Harada, S.H. Hwang, K. Hicks

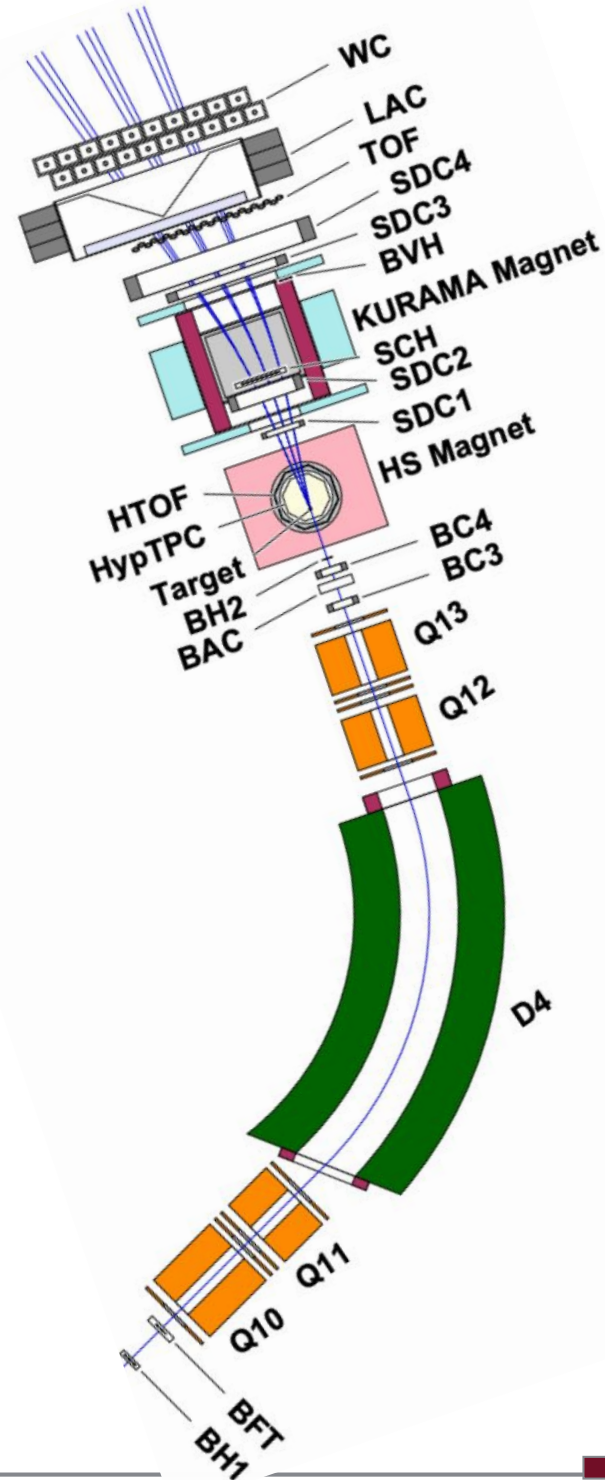
Ph.D. candidates and core members

*Korea Univ / JAEA / KEK / Tohoku Univ / Kyoto Univ / KRISS / Ohio Univ*



# E42 Detectors

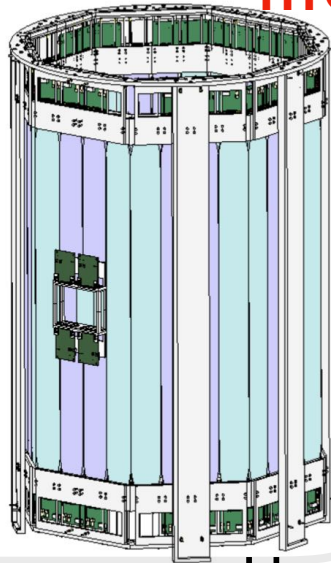
| Beamline                    |
|-----------------------------|
| BH1                         |
| BFT                         |
| BC3                         |
| BAC                         |
| BC4                         |
| BH2                         |
| <b>Hyperon Spectrometer</b> |
| SHS Magnet                  |
| HypTPC                      |
| HTOF                        |
| <b>KURAMA</b>               |
| SDC1                        |
| SDC2                        |
| SCH                         |
| BVH                         |
| SDC3                        |
| SDC4                        |
| TOF                         |
| LAC                         |
| WC                          |



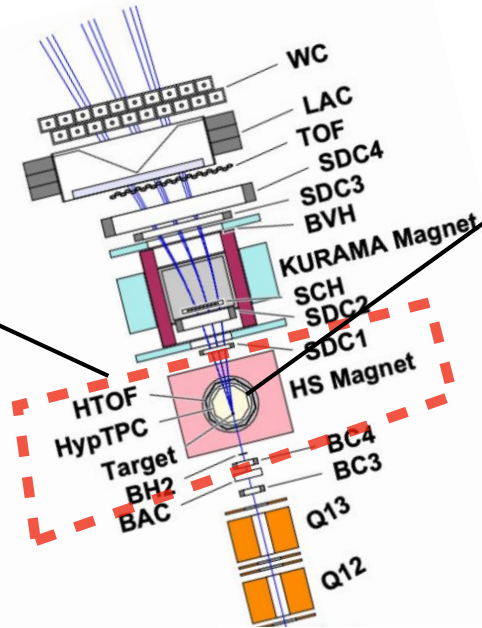


# Hyperon Spectrometer

## Trigger Counters HTOF

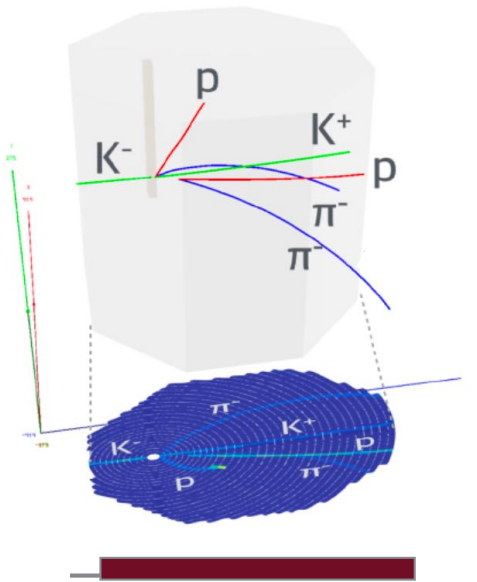
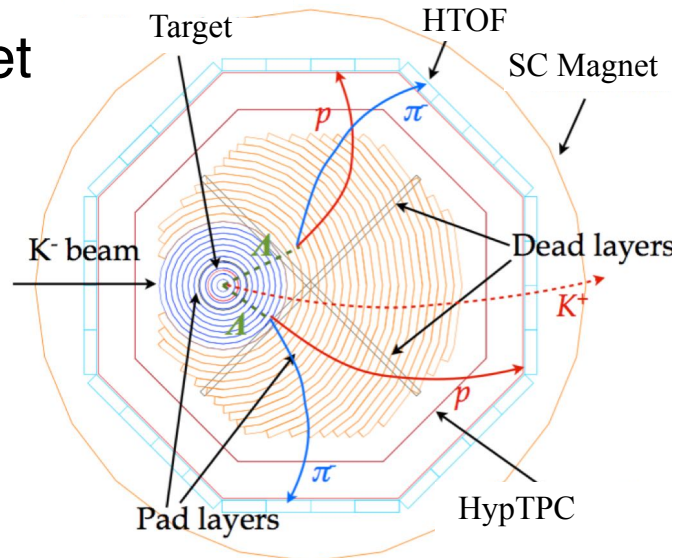
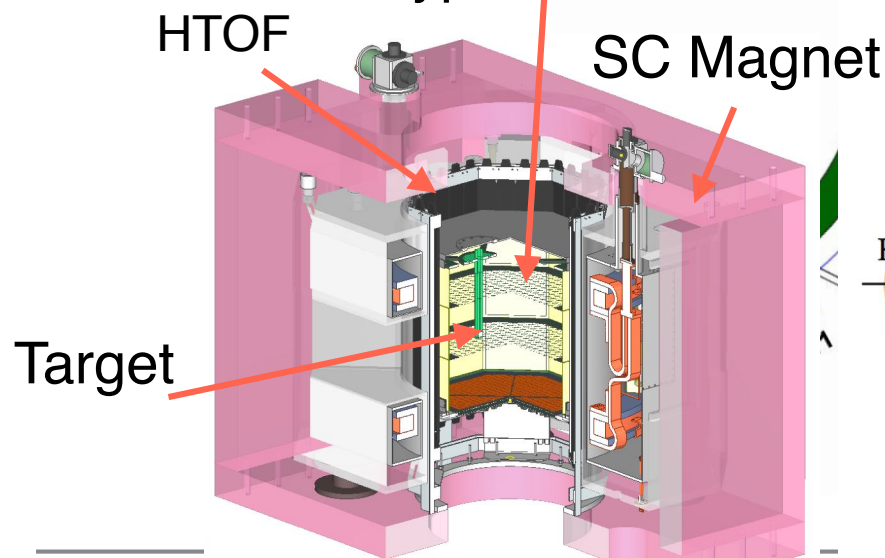
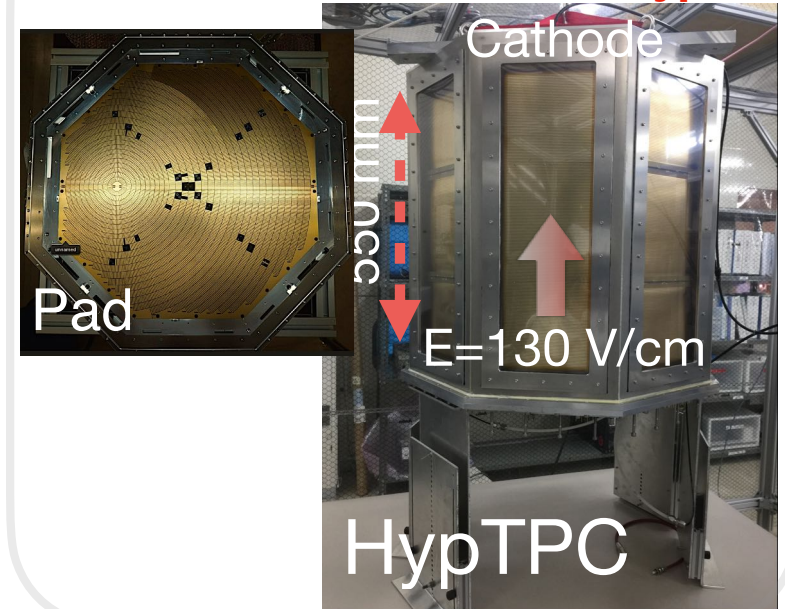


HypTPC



## Tracking devices

HypTPC

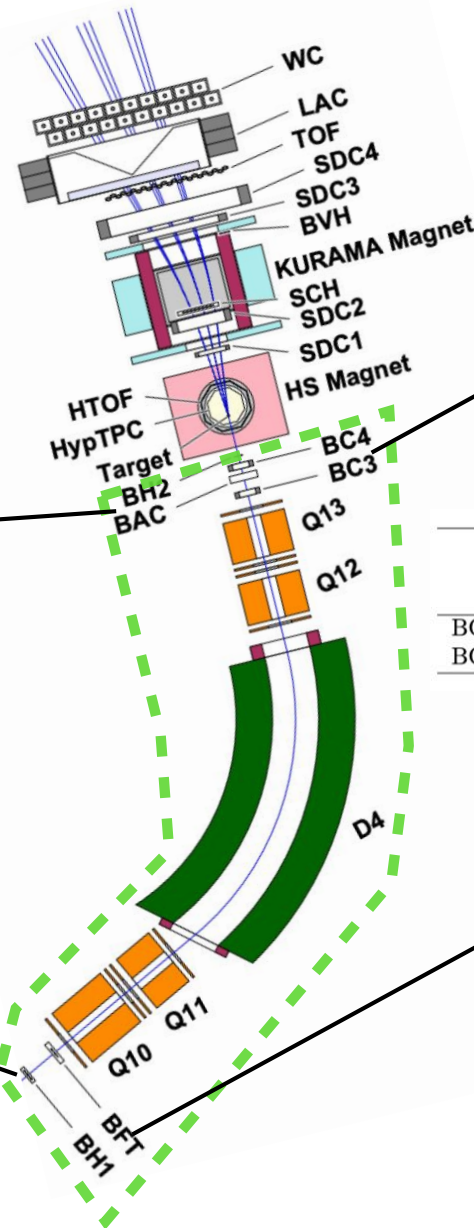
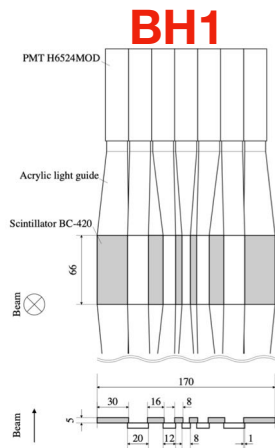
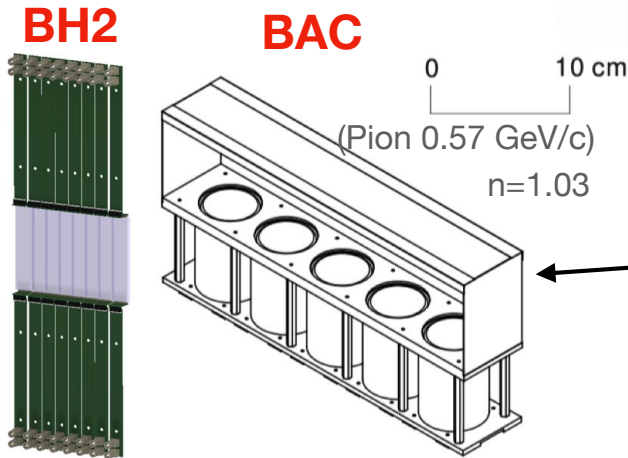


# K1.8 Beam line Spectrometer

## Trigger Counters

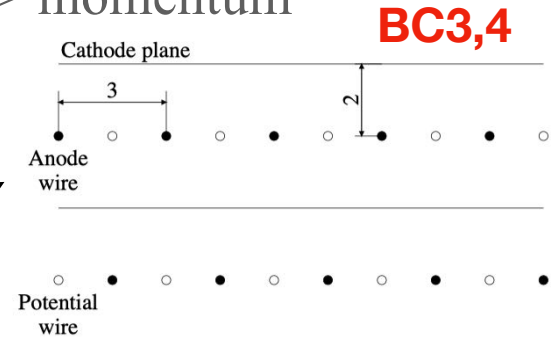
$$K_{\text{Beam}} = BH1 \otimes BH2 \otimes \overline{BAC}$$

Beam ToF : BH1~BH2

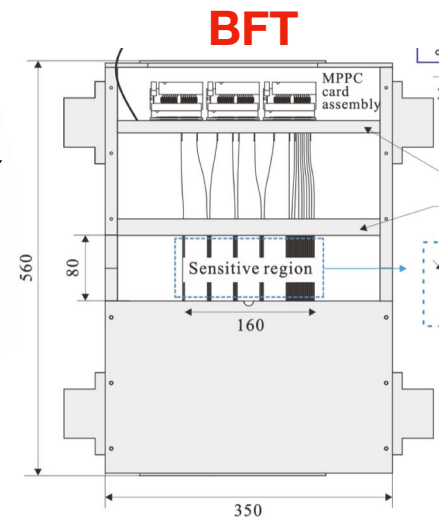


## Tracking devices

3rd order transfer matrix  
-> momentum



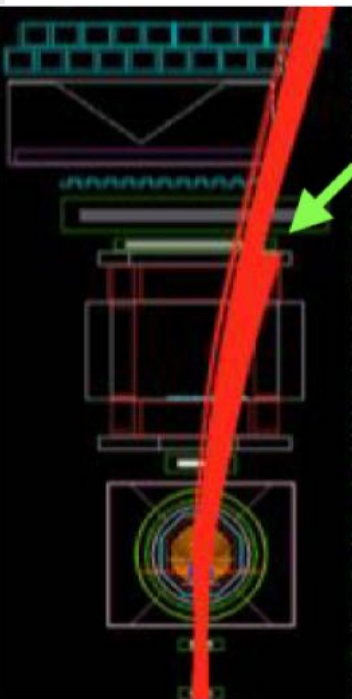
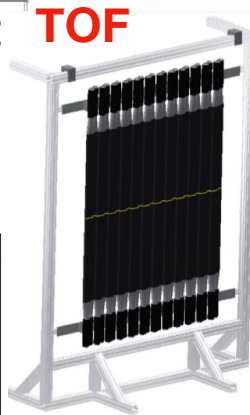
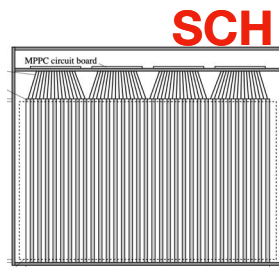
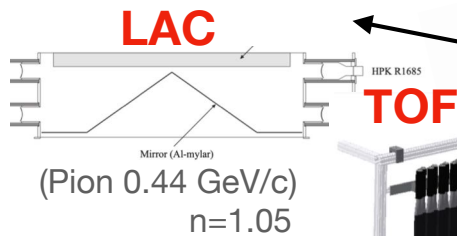
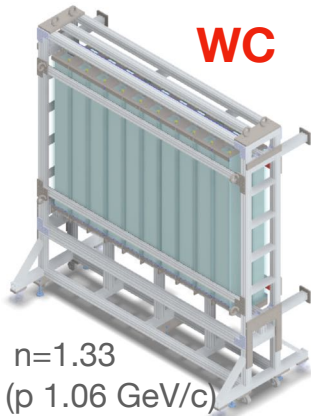
|     | Sensitive area<br>(W×H [mm]) | Wire spacing [mm] |                    | Orientation | Tilt angle<br>[deg] |
|-----|------------------------------|-------------------|--------------------|-------------|---------------------|
|     |                              | Anode             | -Anode<br>-Cathode |             |                     |
| BC3 | 192 × 100                    | 3                 | 2                  | $xx'vv'uu'$ | 0, -15, 15          |
| BC4 | 192 × 100                    | 3                 | 2                  | $uu'vv'xx'$ | 15, -15, 0          |



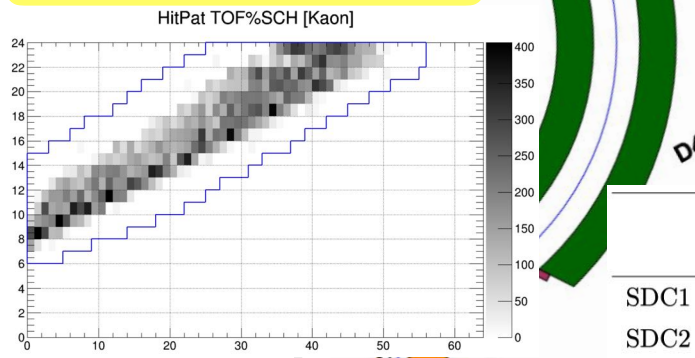
# KURAMA Spectrometer

## Trigger Counters

$$KScat = TOF(7-24) \otimes LAC \otimes WC$$



2DMtx : SCH, TOF



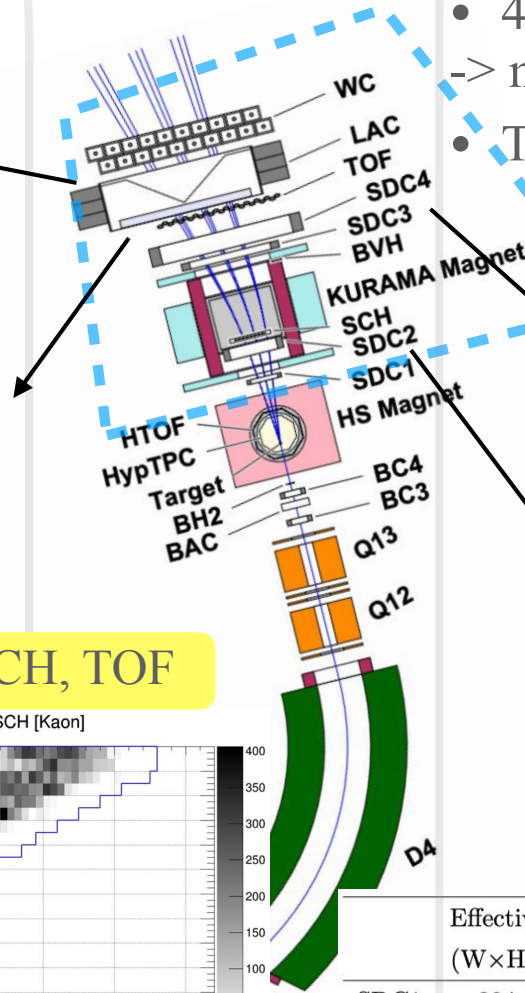
3DMtx : BH2, SCH, TOF+BVH

## Tracking devices

- 4th order Runge-Kutta method  
-> momentum(p), path length(L)
- ToF(T) : BH2~TOF

$$\beta = \frac{L}{Tc}$$

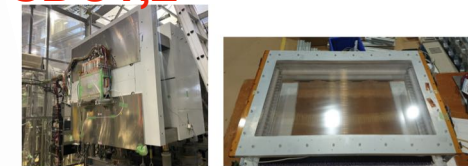
$$M^2 = \left(\frac{p}{\beta}\right)^2 (1 - \beta^2)$$



SDC3,4

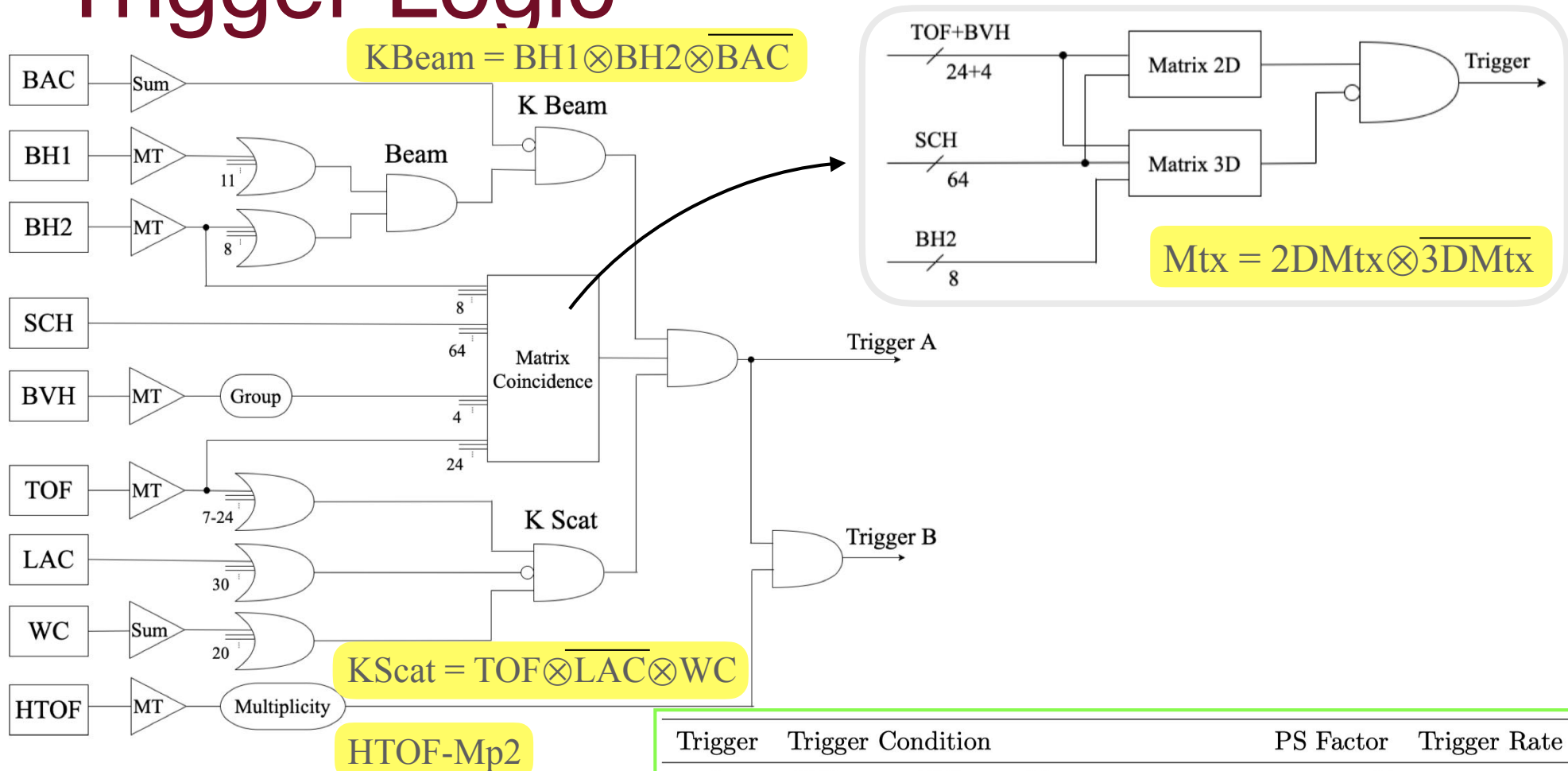


SDC1,2



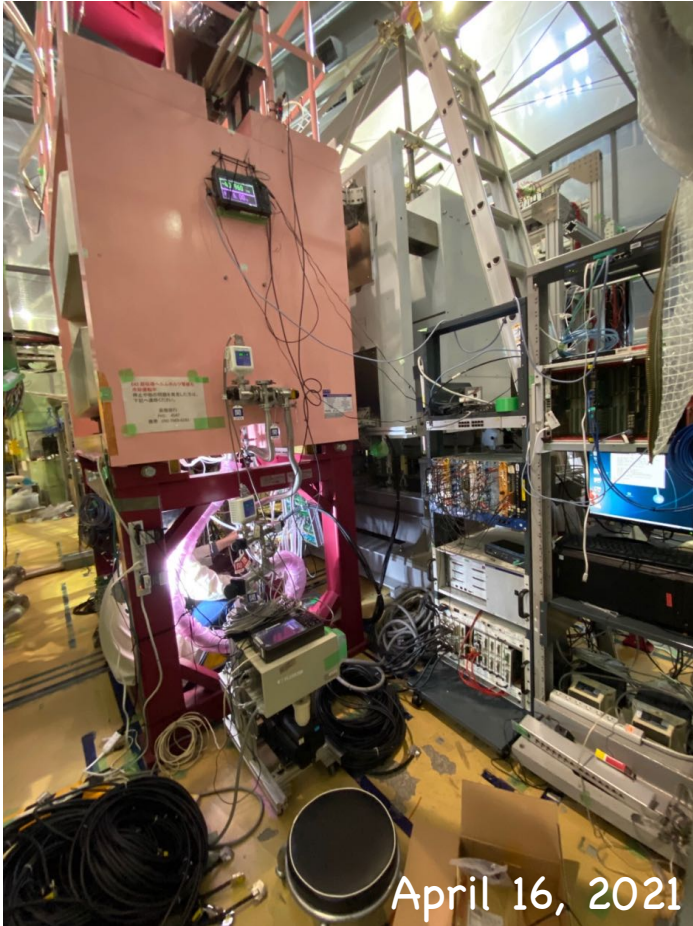
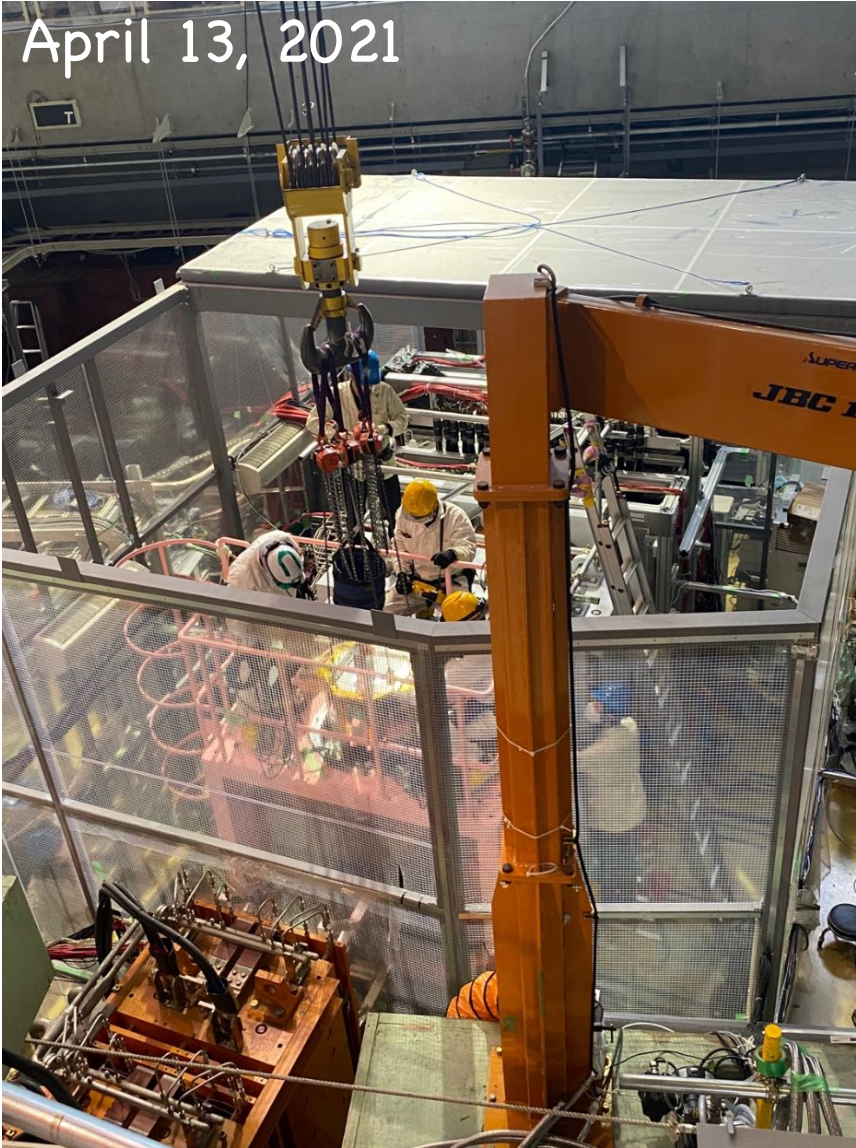
|      | Effective area<br>(W×H [mm]) | Wire spacing<br>[mm] | Orientation | Tilt angle<br>[deg] |
|------|------------------------------|----------------------|-------------|---------------------|
| SDC1 | 384×264                      | 6                    | $u'x'v'$    | 15, 0, -15          |
| SDC2 | 700×400                      | 10                   | $x'y'$      | 0, 90               |
| SDC3 | 1152×1152                    | 9                    | $x'y'$      | 0, 90               |
| SDC4 | 1920×1280                    | 20                   | $yy'x'$     | 90, 0               |

# Trigger Logic

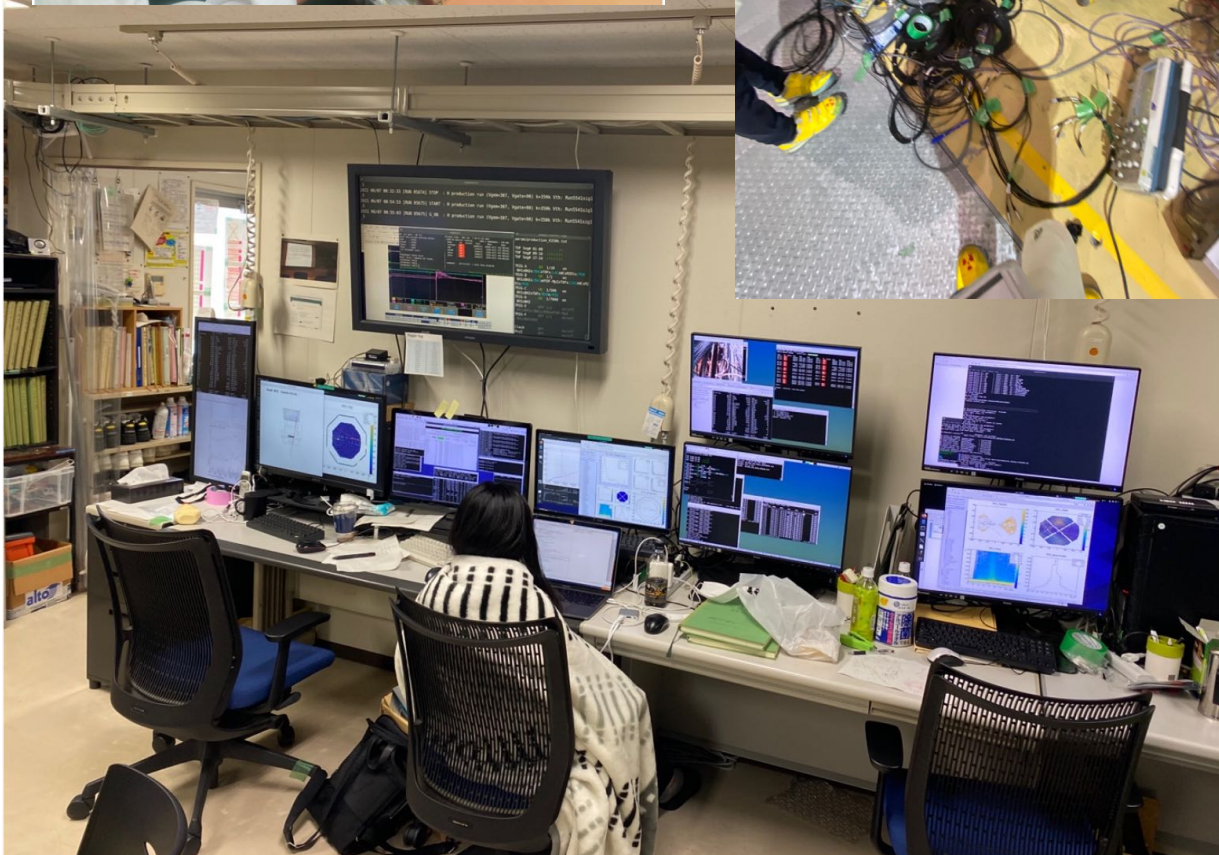
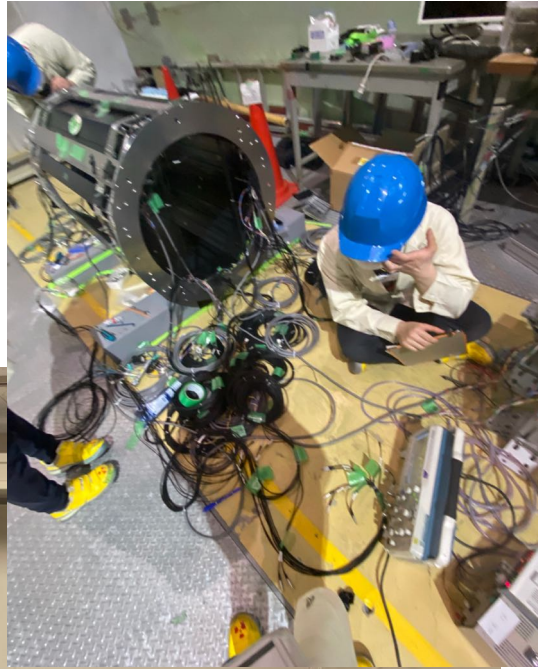
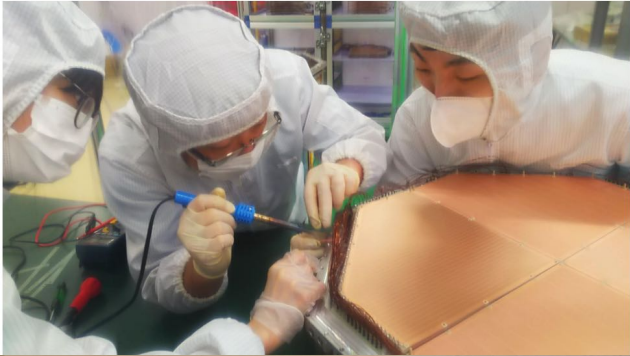


| Trigger                  | Trigger Condition   | PS Factor | Trigger Rate [/spill] |
|--------------------------|---|-----------|-----------------------|
| A                        | $K_{Beam} \otimes K_{Scat} \otimes Mtx$   | 7         | 340                   |
| B                        | $K_{Beam} \otimes K_{Scat} \otimes Mtx \otimes HTOF-Mp2$                            | 1         | 715                   |
| C                        | $BH1 \otimes BH2 \otimes TOF(7-24) \otimes \overline{BVH} \otimes \overline{Mtx3D}$ | 600       | 50                    |
| D                        | $BH1 \otimes BH2$   | 13200     | 50                    |
| Trigger Request [/spill] |   |           | 1,030                 |
| Trigger Accept [/spill]  |   |           | 950                   |
| DAQ efficiency           |   |           | 92%                   |

# Hyperon Spectrometer at K1.8 Beam Line



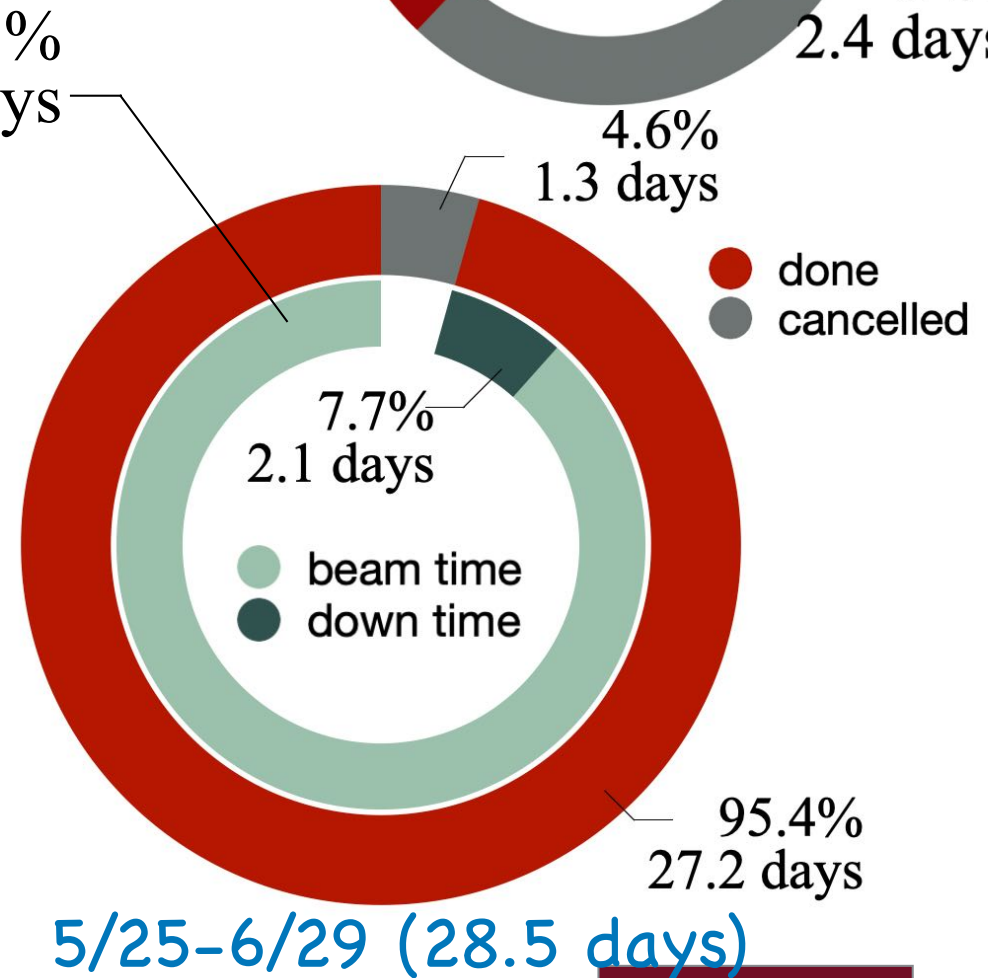
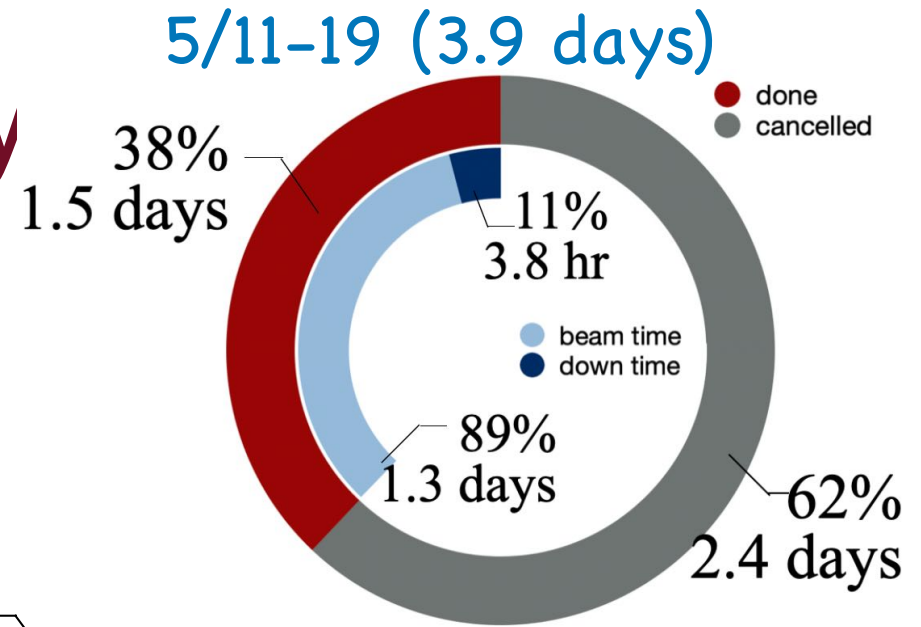
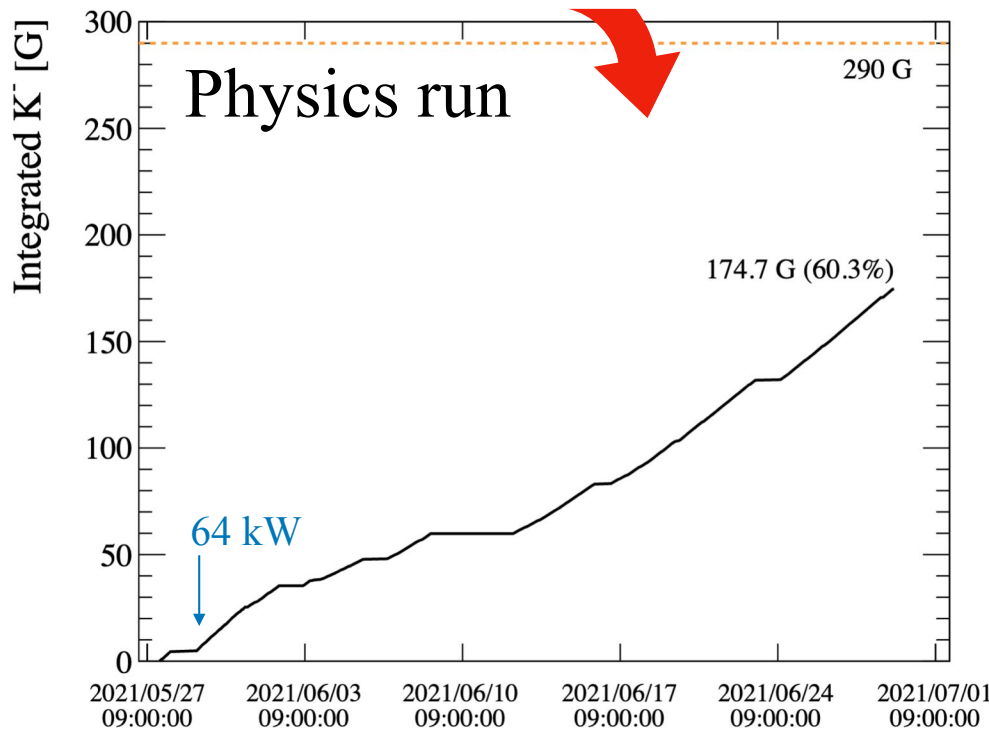
# E42 Underway



# Beam Time Summary

- Request to PAC
  - Commissioning run: 4.5 days
  - Physics run: 29 days (60 kW)

Calibration run : 2.4 days  
 Physics run : 22.7 days } 25.1 days (92.3%)

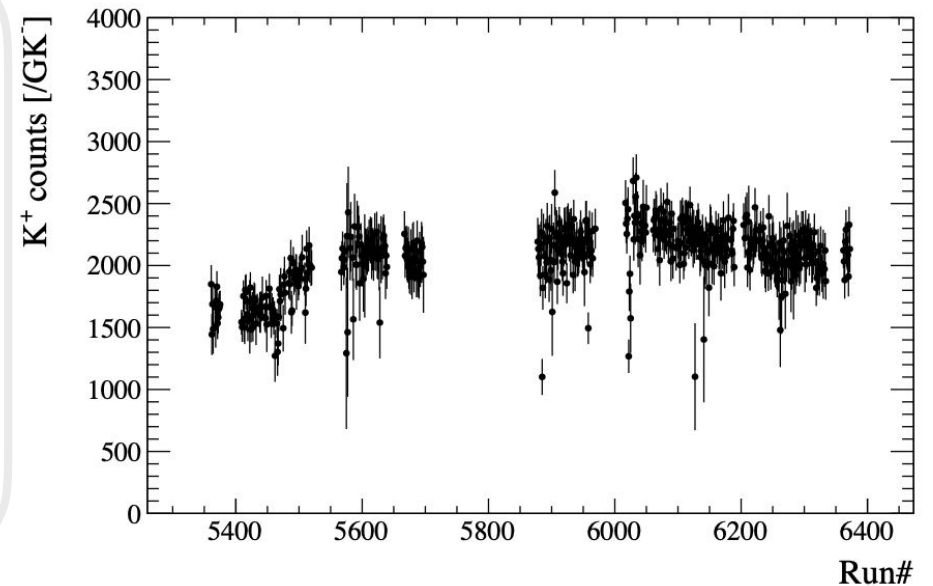


# Run Summary

| Target       | $V_{\text{GEM}}$ | Beam momentum<br>[GeV/c] | Number of beam particles |         |
|--------------|------------------|--------------------------|--------------------------|---------|
|              | [V]              |                          | $K^-$                    | $\pi^-$ |
| Diamond      | 285–306          | 1.82                     | 38.5G                    | 15.1G   |
| Diamond      | 307              | 1.82                     | 139.3G                   | 25.6G   |
| Polyethylene | 307              | 1.82                     | 6.2G                     | 0.77G   |

## +Calibration runs

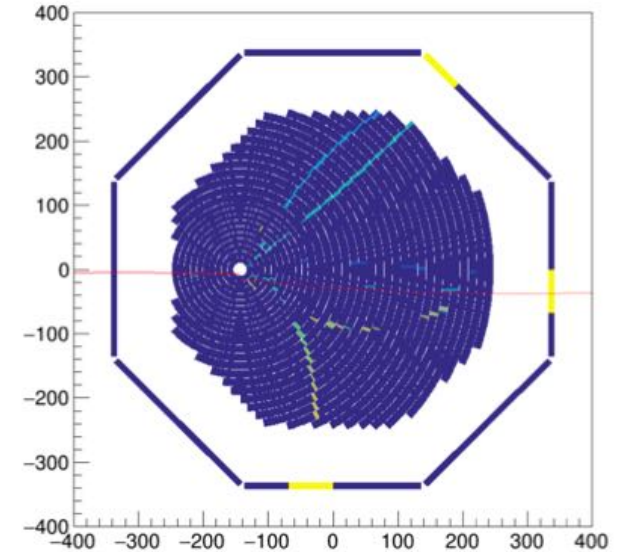
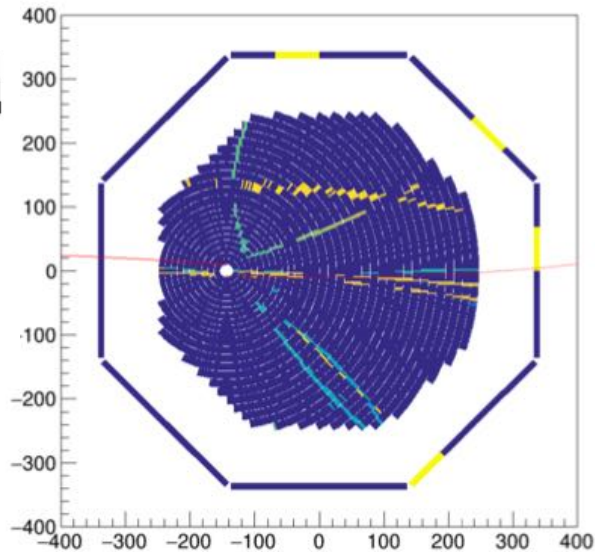
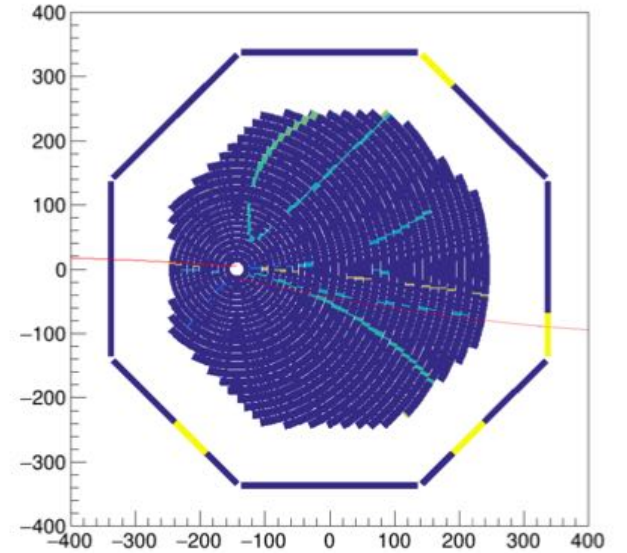
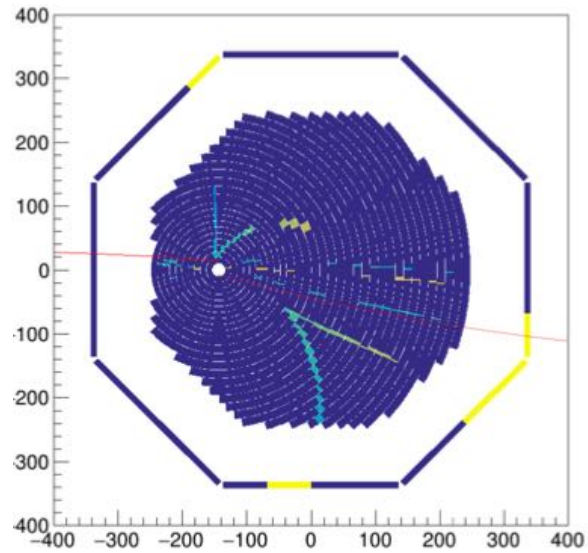
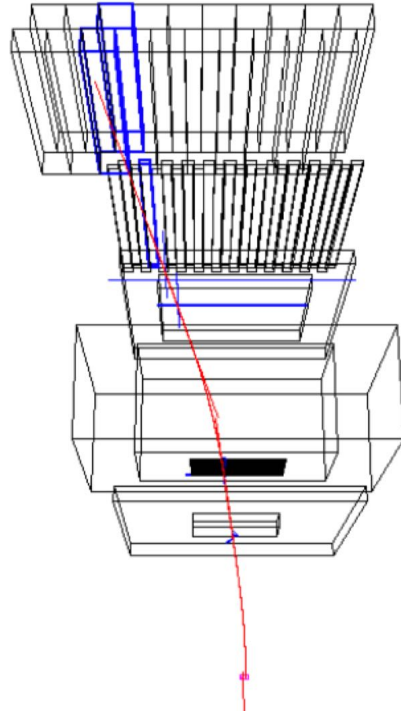
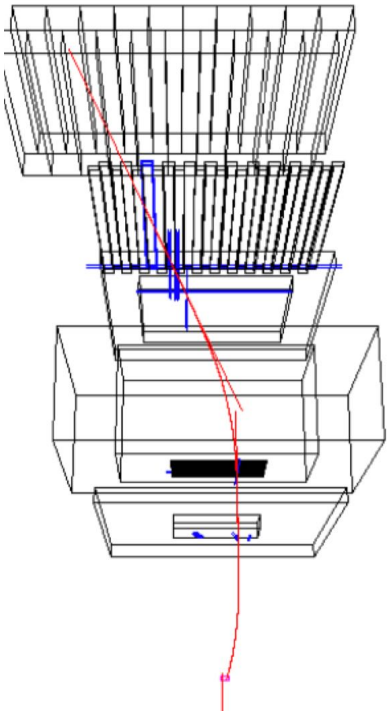
- TPC defocus run w/ and w/o B field
- Beam through K -1.8 GeV/c, p/pi +1.4 GeV/c
- Beam through p/pi  $\pm 0.8, 0.6, 0.5, 0.4, 0.3$  GeV/c
- KURAMA tracking pi +1.2 GeV/c (only KURAMA on)
- TOF calibration run
- **HTOF calibration run**  
(trig: HTOF-Mp4, beam: -1.8 GeV/c pi, target: C)



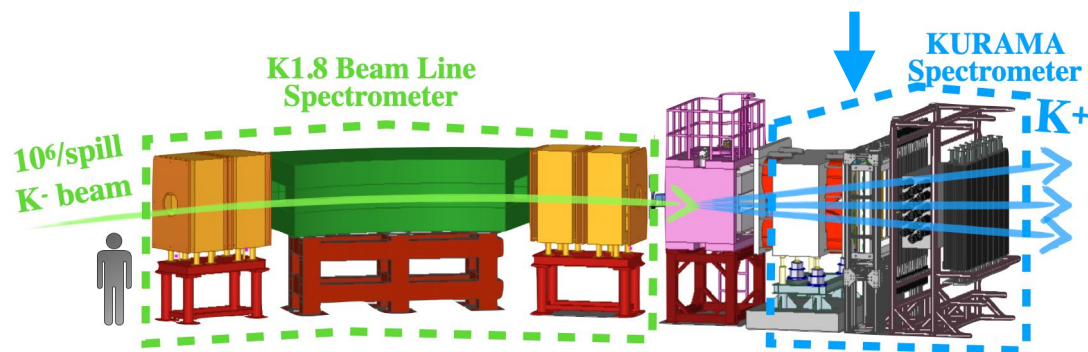
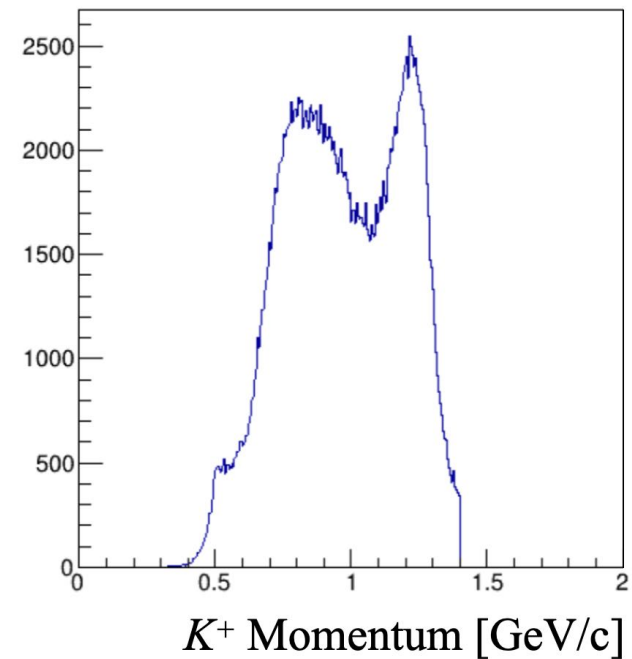
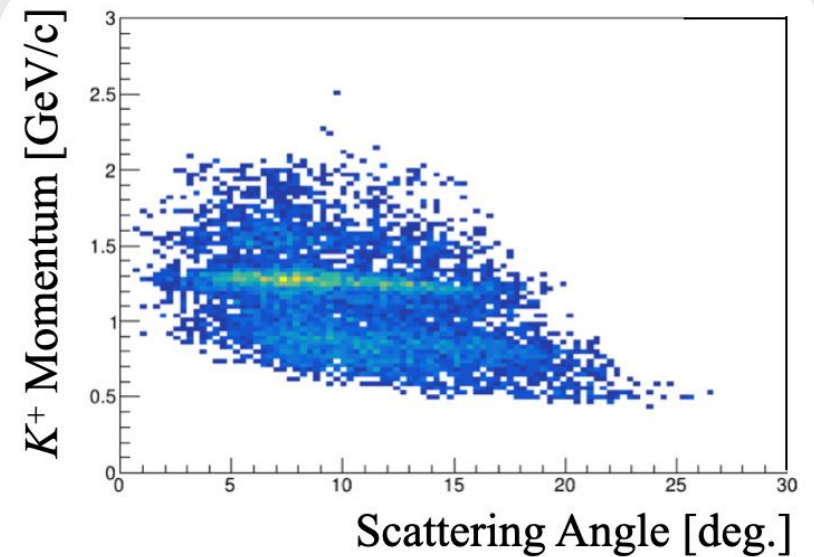
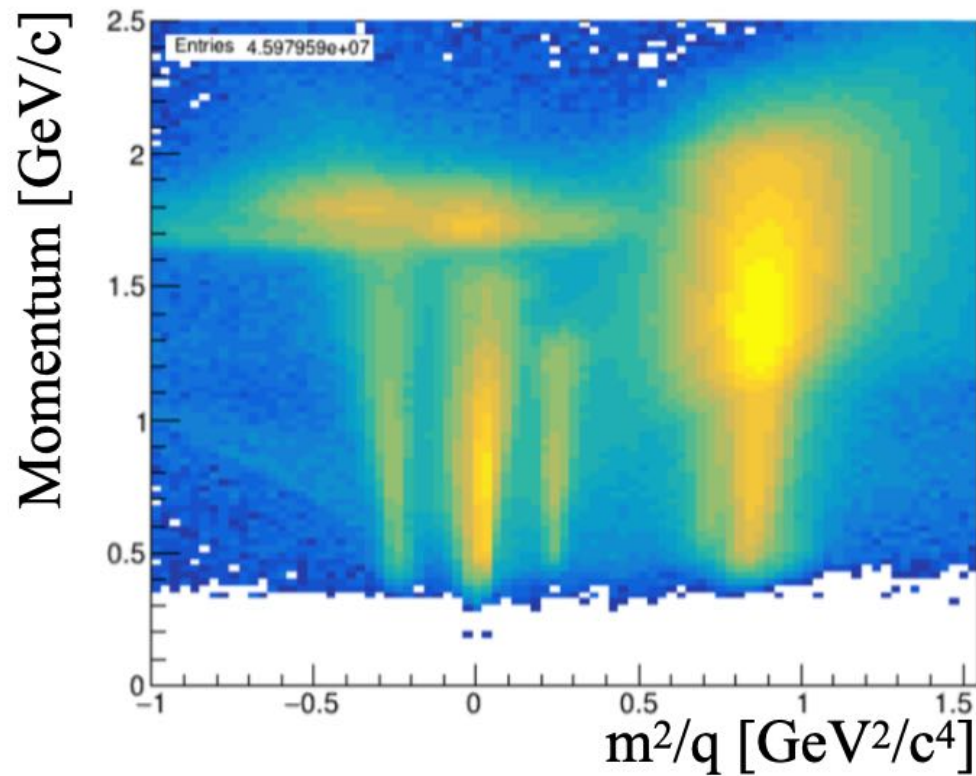
~300k  $^{12}\text{C}(K^-,K^+)$  events



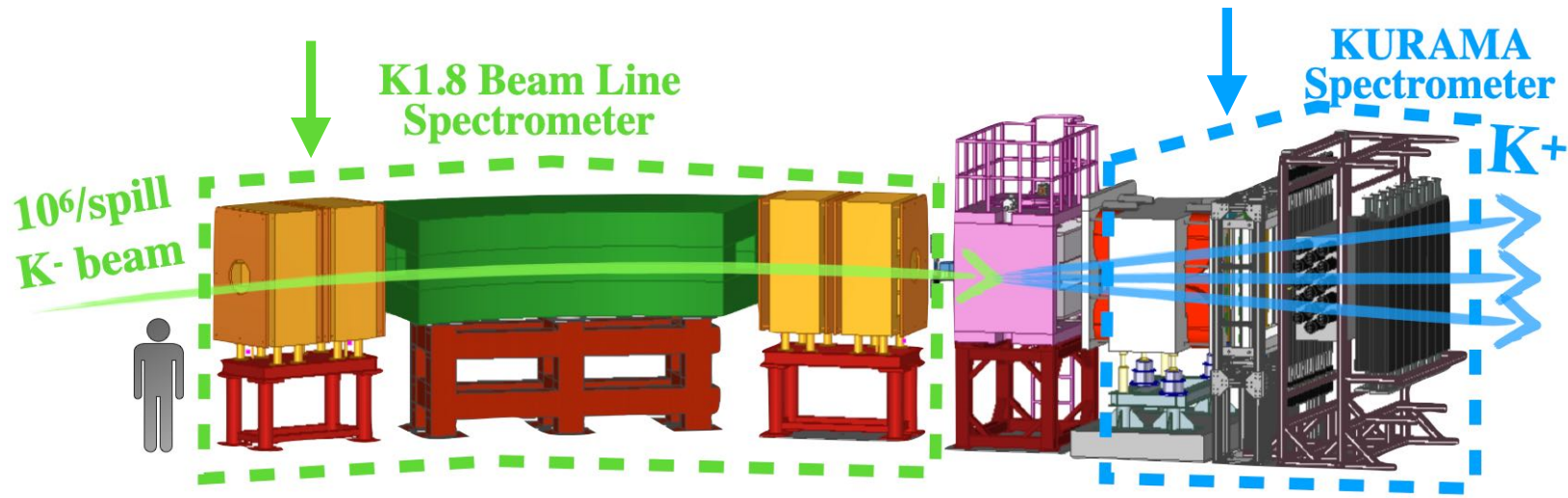
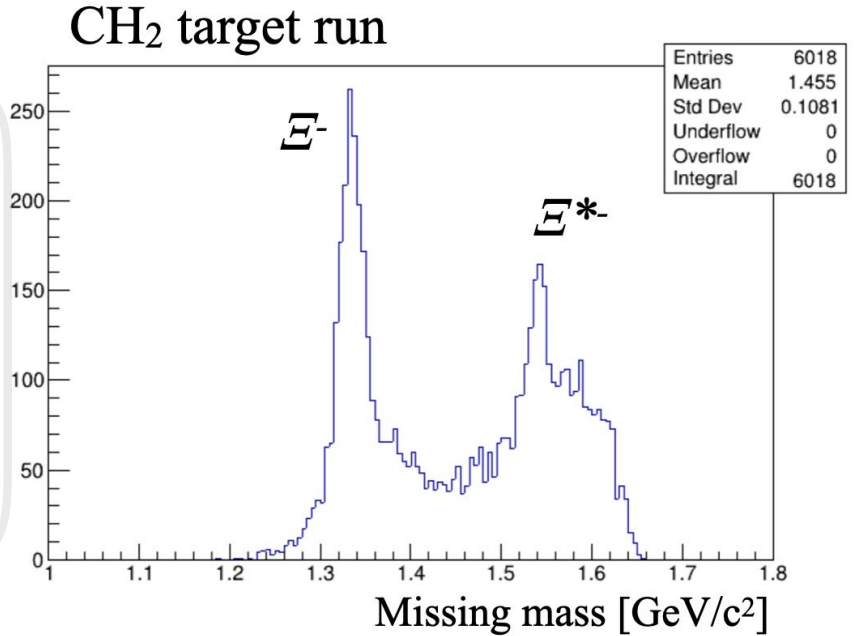
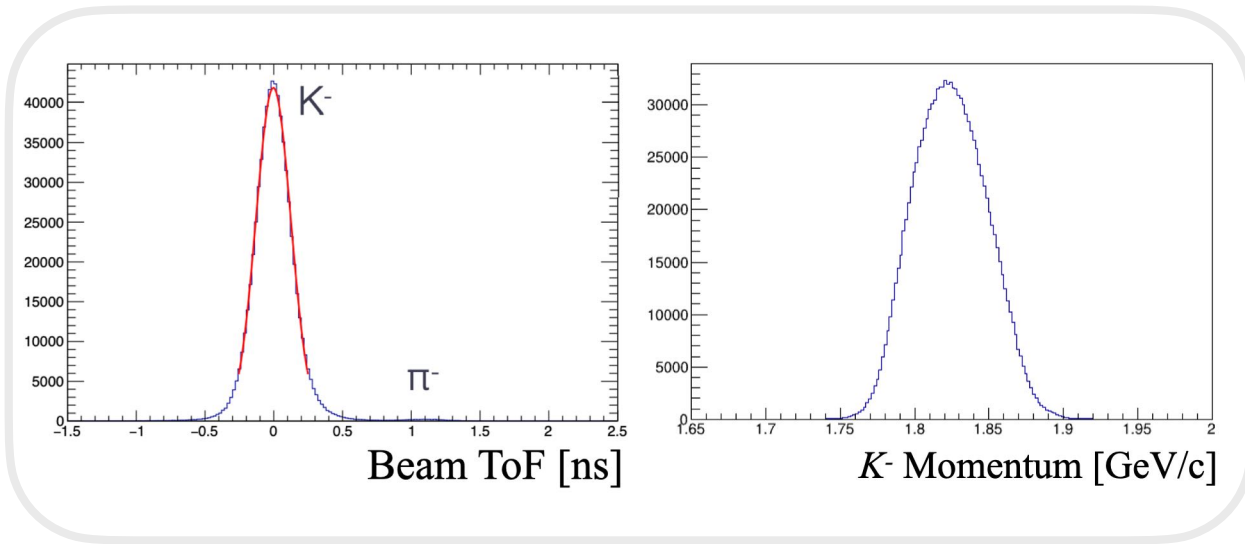
# Online Event Displays



# Online Analysis - $K^+$ Part

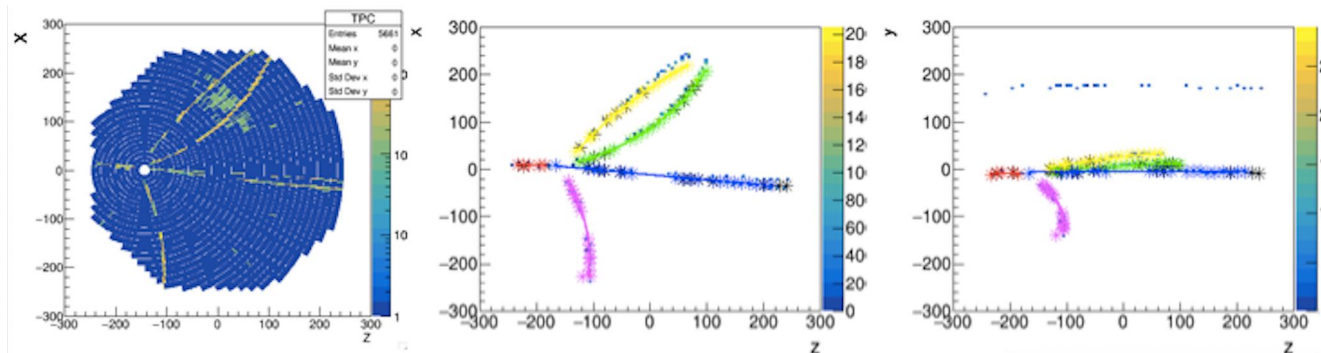
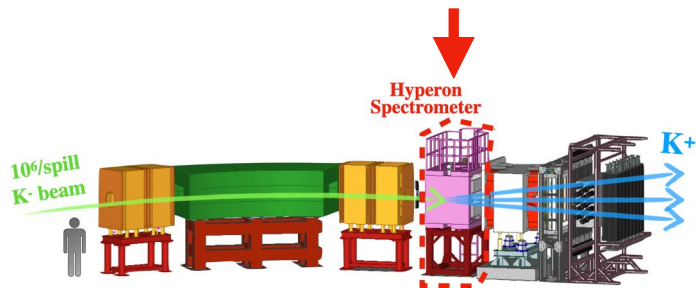
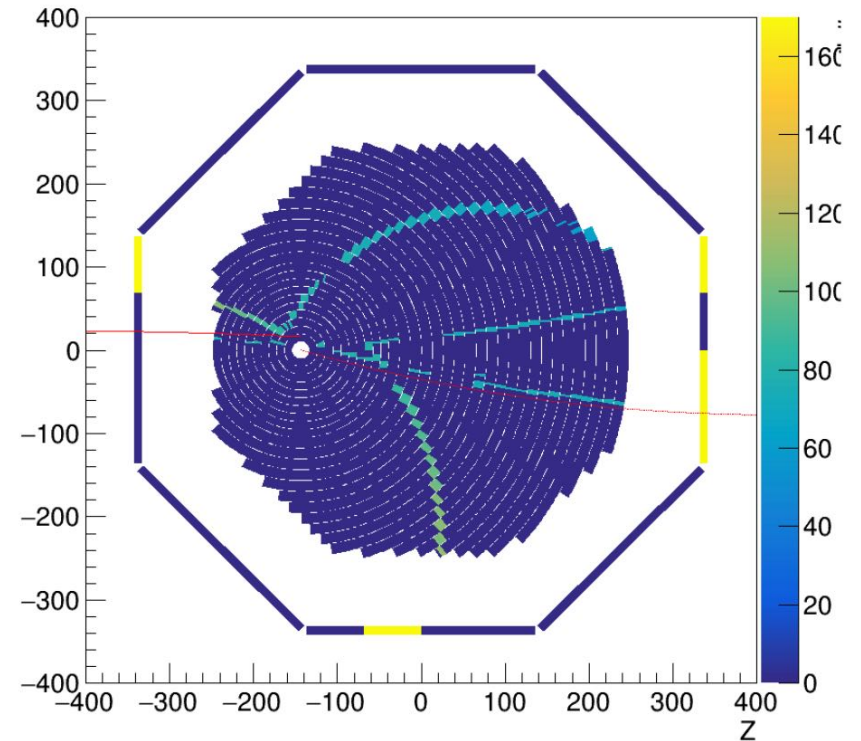


# Online Analysis - ( $K^-$ , $K^+$ ) Part



# Online Analysis - HypTPC Part

- New detector -> analyzer from scratch
- Position calibration (due to field distortion) for momentum/vertex
- Gain calibration (due to GEM sag?) for dE/dx
- Large data size (~200 GB/hr) -> takes time to analyze data



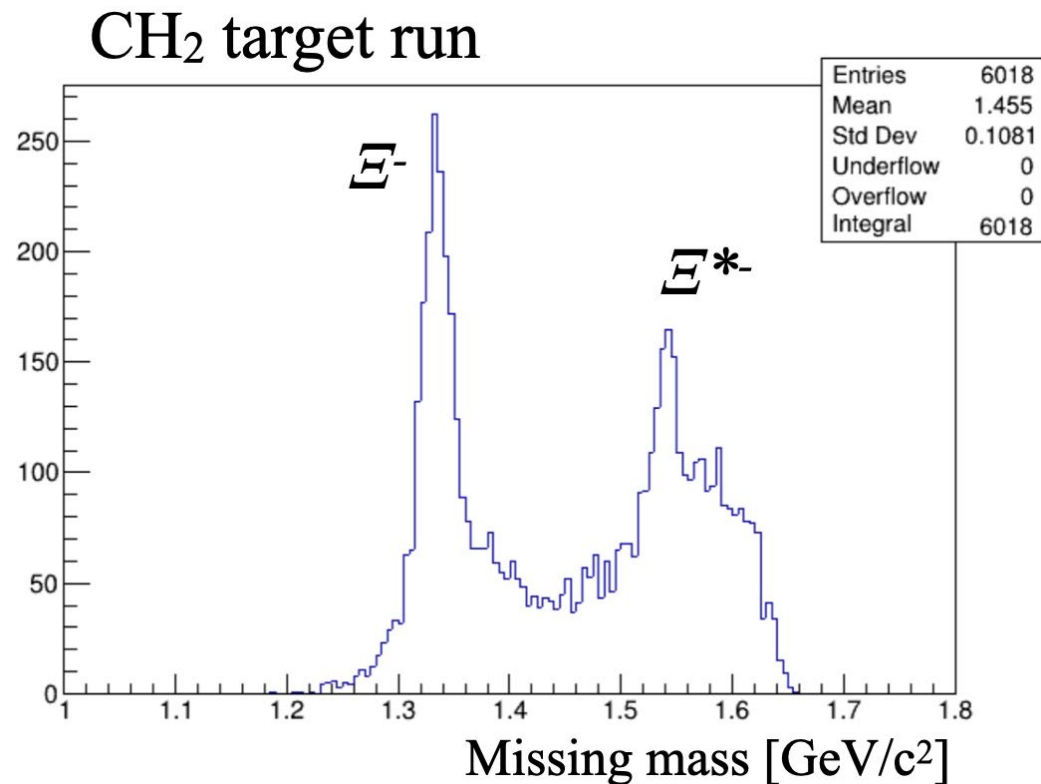
# E42 Byproducts

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# $\Xi^- / \Xi^{*-}(1530)$

p(K<sup>-</sup>,K<sup>+</sup>)

- $\Xi^-$  Polarization ( $P_{\Xi}$ )
- $\Xi^- \rightarrow p\pi^-\pi^-$  rare decay ( $\Delta S=2$ )
- Secondary  $\Xi^-$  interactions:  $\Xi^-p \rightarrow \Lambda$ ,  $\Xi^-p \rightarrow \Xi^-p$
- $d\sigma/d\Omega$  for  $K^-p \rightarrow K^+\Xi^{*-}(1530)$



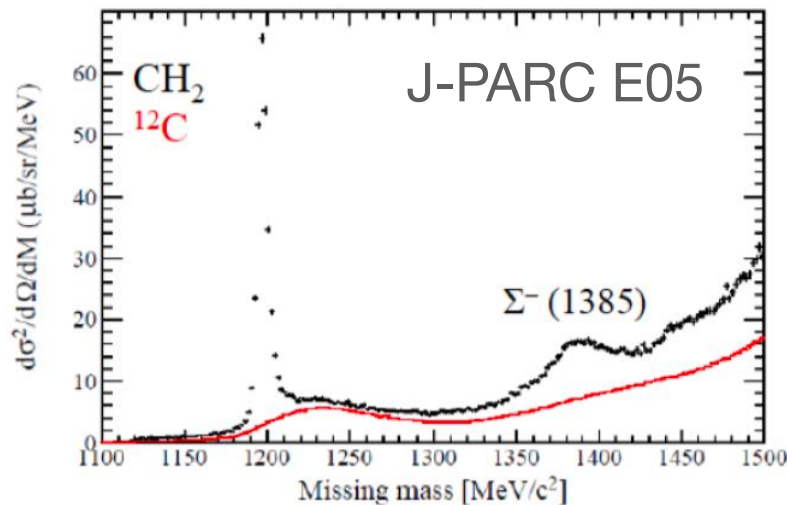
# $K^{*-}(892)/\Sigma^{*-}(1385)$ In-Medium Mass Shift

- $^{12}\text{C}(K^-, p)K^{*-}(892) X$ ,  
 $K^{*-}(892) \rightarrow K^0 \pi^-, K_S^0 \rightarrow \pi^+ \pi^-$
- $^{12}\text{C}(K^-, \pi^+)\Sigma^{*-}(1385) X$ ,  
 $\Sigma^{*-}(1385) \rightarrow \Lambda \pi^-, \Lambda \rightarrow p \pi^-$

$^{12}\text{C}(K^-, p)$

$^{12}\text{C}(K^-, \pi^+)$

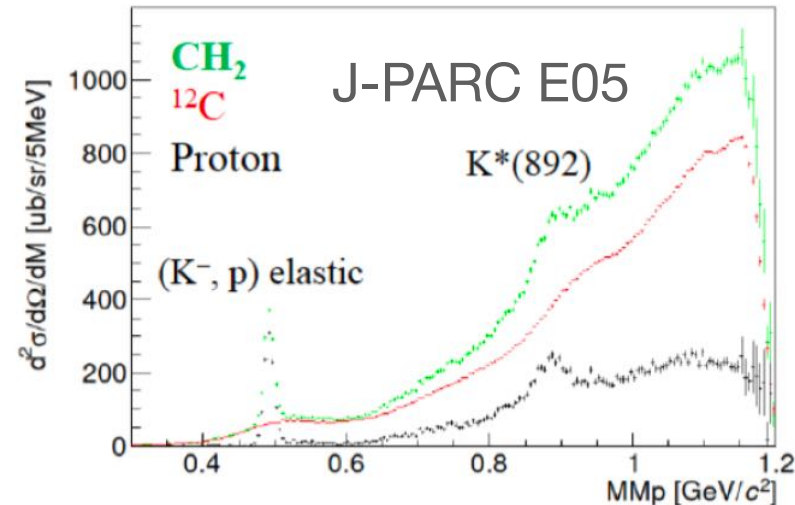
The  $(K^-, \pi^+)$  spectra for  $\text{CH}_2$  and carbon targets.  
 (Assuming that proton at reset is a target.)



PDG value  $\Sigma^- (1385)$

- Mean:  $1386.2 \pm 0.5 \text{ MeV}/c^2$
- $\Gamma$ :  $39.4 \pm 2.1 \text{ MeV}$

The  $(K^-, p)$  spectra for  $\text{CH}_2$  and carbon targets.  
 (Assuming that proton at reset is a target.)



PDG value  $K^*(892)$

- Mean:  $891.6 \pm 0.26 \text{ MeV}/c^2$
- $\Gamma$ :  $50.8 \pm 0.9 \text{ MeV}$

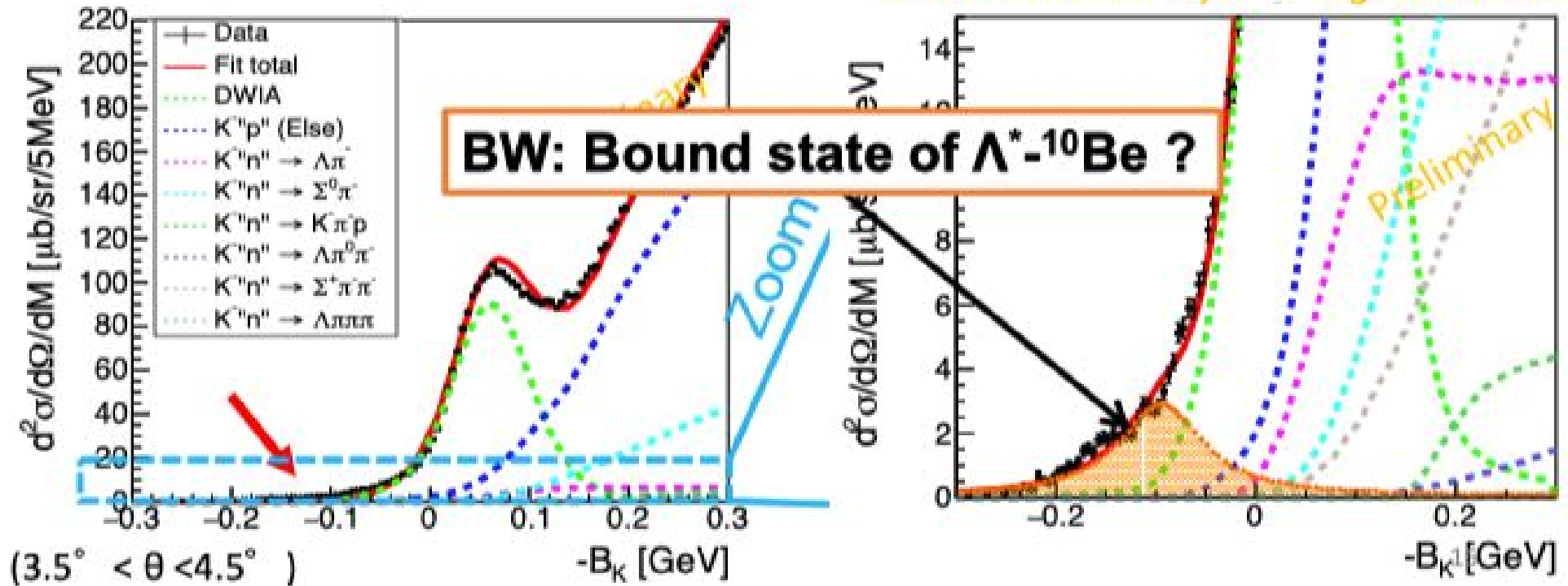
# KN Interaction with Kaonic Nuclei

- $K^-$   $^{12}\text{C} \rightarrow p$   $^{11}\text{K}^- \text{Be} (^{11}\Lambda^* \text{Be}),$   
 $^{11}\text{K}^- \text{Be} \rightarrow \Lambda$   $^{10}\text{Be}$

$^{12}\text{C}(K^-, p)$

J-PARC E05

DWIA Calculation by J. Yamagata-Sekihara



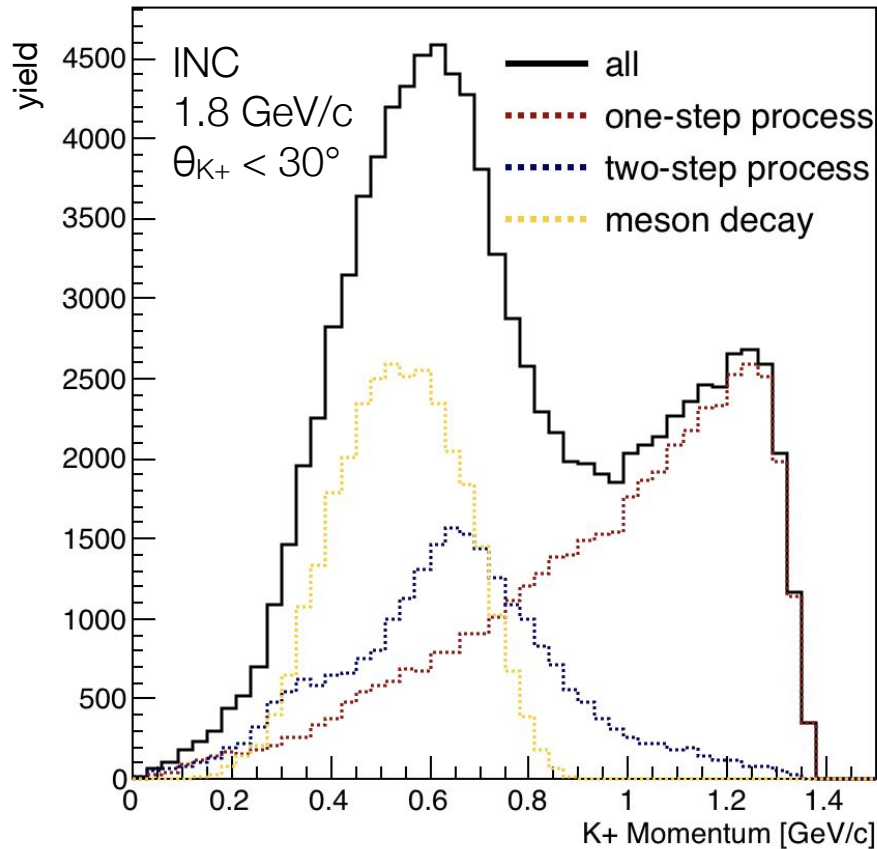
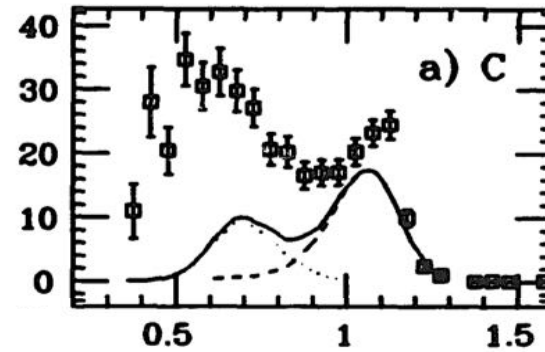
Y. Ichikawa et al. Prog. Theor. Exp. Phys. 12, 123D01 (2020).



# K<sup>+</sup> Momentum with INC Model

<sup>12</sup>C(K<sup>-</sup>,K<sup>+</sup>)

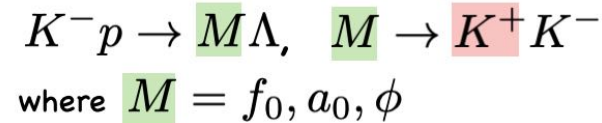
- <sup>12</sup>C(K<sup>-</sup>,K<sup>+</sup>)
- <sup>12</sup>C(K<sup>-</sup>,K<sup>+</sup>Λ)
- <sup>12</sup>C(K<sup>-</sup>,K<sup>+</sup>K<sup>-</sup>)



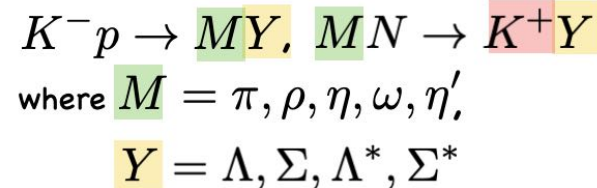
1. One-step double-strangeness exchange reaction



2. Heavy meson production and their decay

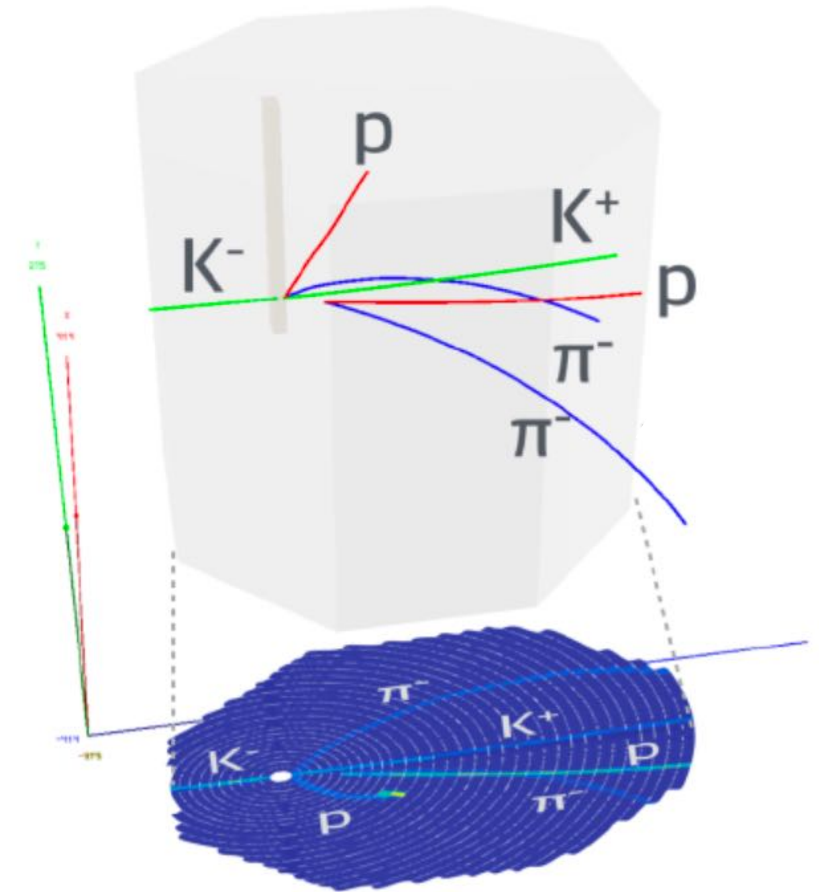


3. Two-step strangeness exchange and production reaction



# Summary

- The J-PARC E42, which was dedicated to search for the H-dibaryon, was just completed in June of 2021.
- We have collected two orders of magnitude more statistics for  $\Lambda\Lambda$  production in  $(K^-,K^+)$  reaction than measured ever before.
- The E42 opens many other physics opportunities such as  $\Xi^*$  and  $\Phi$  production processes in the  $(K^-,K^+)$  reaction, and secondary  $\Xi^-$  induced reactions.



**Any physics ideas are welcome!**