H-dibaryon Search

J-PARC E42 and Future Opportunities with HypTPC

Jung Keun Ahn
(Korea University)

Multiquark States

- An exotic hadron is a state that cannot be classified in terms of standard qqq or $q\bar{q}$ configurations according to $\mathrm{SU}_f(3)$ irreducible representations: multiquark states ($qq\overline{qq}$, $qqqq\bar{q}$, $6q$, and so on).

- The existence of multiquark hadrons is now firmly established in the meson sector: tetraquark states such as XYZ states.
- Recently, the LHCb collaboration claims on the observation of three hidden-charm pentaquark P_c states.
- The observation of such many multiquark candidates poses a question on the dripline of further multiquark states: hexaquark state.

The Most Promising Candidate in the Strange Sector

H-dibaryon

- : The H-Dibaryon ($J = 0, I = 0$) is a stable $SU(3)_f$ singlet hexaquark state consisting of $uuddss$ quarks due to QCD color magnetic force.

- H is named after Hexa-quark states.

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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.

QCD Color Magnetic Interaction

Effective Hamiltonian

- The QCD color magnetic interaction can be summarized by an effective Hamiltonian acting on the quarks' spin and color indices;

$$\mathcal{H}_{\text{eff}} \propto -\sum_{i\neq j} \vec{\lambda}_i \cdot \vec{\lambda}_j \vec{\sigma}_i \cdot \vec{\sigma}_j$$

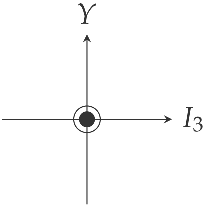
- For N quarks,

$$\mathcal{H}_{\text{eff}} \propto -\sum_{i\neq j}^{N} \{\vec{\lambda}\vec{\sigma}\}_i \cdot \{\vec{\lambda}\vec{\sigma}\}_j = 8N - \frac{1}{2}C_6^N + \frac{4}{3}S_N(S_N+1).$$

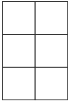
- For 6 quarks, the color-spin interaction energies are

$$\langle\mathcal{H}_{\text{eff}}\rangle_1 = -24, \quad \langle\mathcal{H}_{\text{eff}}\rangle_8 = -28/3, \quad \langle\mathcal{H}_{\text{eff}}\rangle_{\overline{10}} = +8/3, \quad \langle\mathcal{H}_{\text{eff}}\rangle_{27} = +3,$$

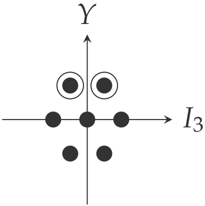
Dibaryon Multiplets in SU(3)$_f$



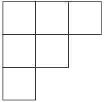
H-dibaryon



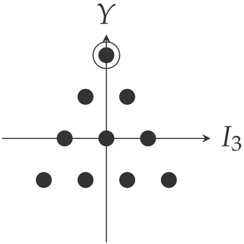
1_f



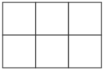
$\Lambda N / \Sigma N$



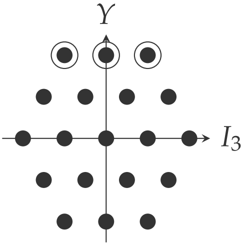
8_f



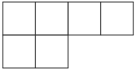
Deuteron



$\overline{10}_f$

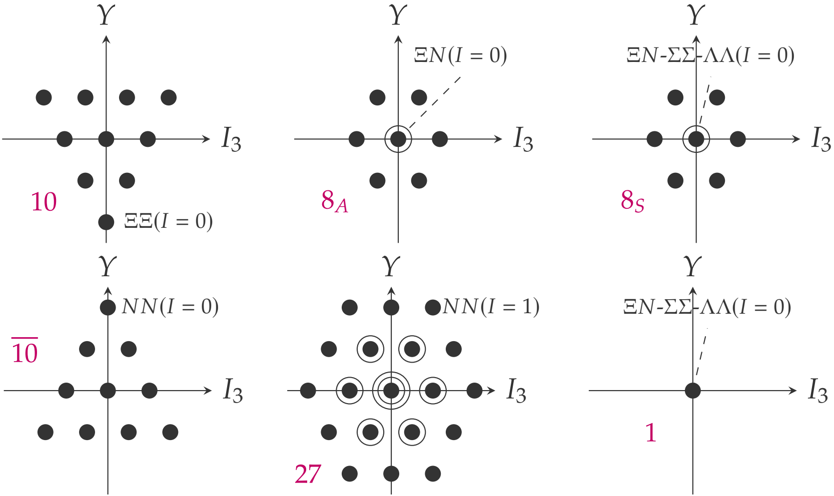


$I = 1\ NN$



27_f

Dibaryon Multiplets in $SU(3)_f$



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Brief Summary of the History of H-Dibaryon Searches

- 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 ${}^{6}_{\Lambda\Lambda}$He (E373)
- 1998,2007 — Enhanced $\Lambda\Lambda$ production near threshold was reported from E224 and E522 at KEK-PS.
- 2011 — LQCD calculations predict the H-dibaryon near $m_{\Lambda\Lambda}$
- 2013-2015 — No evidence for $H \to \Lambda p \pi^-$ and $H \to \Lambda\Lambda$ in high-energy e^+e^-, pp and AA experiments
- 2021 — LQCD calculations point to the mass the H-dibaryon very close to ΞN threshold ($m_\pi \approx 146$ MeV)
- 2021 — J-PARC E42 has successfully completed with HypTPC.
- 2022 — We are about to see what we would see in the E42 dataset.

H-Dibaryon Search at J-PARC : E42

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

- Weakly-bound : $H \longrightarrow \Lambda p \pi^-$
- Virtual state : $\Lambda\Lambda$ or $\Xi^- p$ threshold effect
- Resonance : Breit-Wigner peak in $\Lambda\Lambda$ and $\Xi^- p$ masses

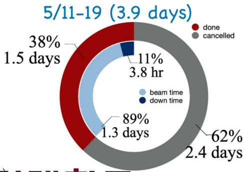
J-PARC-E42 EXPERIMENT

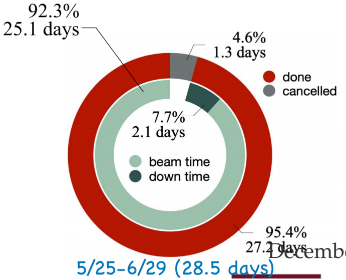
1. in $\Lambda p \pi^-$, $\Lambda\Lambda$ and $\Xi^- p$ channels
2. by tagging the $S = -2$ system production
3. via (K^-, K^+) reactions at 1.8 GeV/c with a diamond target
4. with Hyperon Spectrometer : 1 MeV $\Lambda\Lambda$ mass resolution

E42 (H-Dibaryon Search) Run Summary

E42 completed the physics run from May 11 through June 29, 2021, successfully operating the new superconducting hyperon spectrometer (SHS).

Commissioning (May 11–19)	• 1.5 days running out of 3.9 days available. • 2.4 days canceled due to the HypTPC trouble.
Beam time Physics (May 25–Jun 29)	• 28.5 days available. • 27.2 days running including 2.4 day calibration. • 1.25 days canceled due to the HypTPC trouble.
Accelerator	• 92.65% operation for the E42 available days.





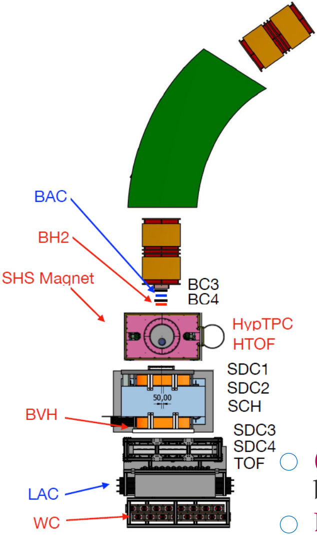
The J-PARC E42 Collaboration

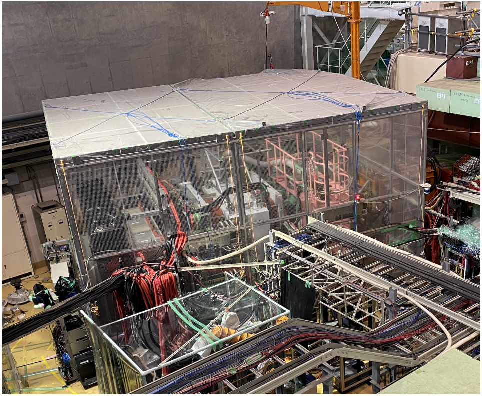
J.K. Ahn (*spokesperson*), **S.H. Kim**, S.W. Choi, W.S. Jung, B.M. Kang, J.W. Lee, S.B. Yang, M. Fujita, S. Hasegawa, **Y. Ichikawa** (*co-spokesperson*), K. Imai , H. Sako, S. Sato, K. Tanida, T. Takahashi, M. Ukai, T. Yamamoto, **S. Hayakawa**, Y. Ishikawa, S. Kajikawa, K. Kamada, T. Kitaoka, T. Morino, 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 Detector for the H-Dibaryon Search





- (K^-, K^+) reaction events are tagged by the K1.8 beam line and the KURAMA spectrometers.
- Decays of the $S = -2$ system are reconstructed using the Superconducting Hyperon Spectrometer.

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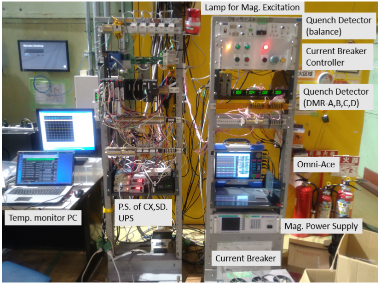
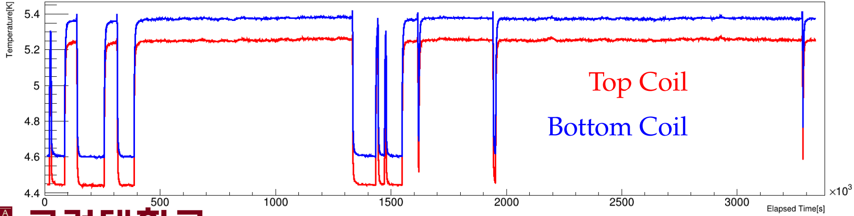
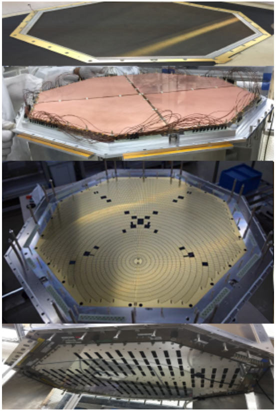
Superconducting Hyperon Spectrometer Magnet

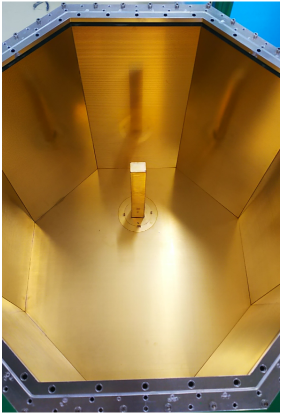


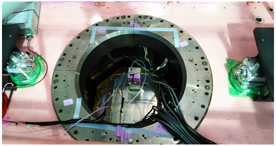
- The 1-T SHS magnet operated stably, 30 cm apart from the 0.7-T KURAMA magnet.

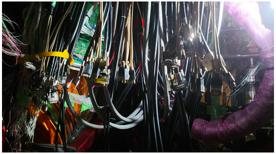


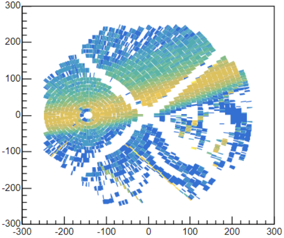
Hyperon Time Projection Chamber (HypTPC)











- The HypTPC operation was relatively stable except two events stopping the E42 run shortly.
- Event display for 0.4 GeV/c π^+ beam tracks accumulated in the calibration run.

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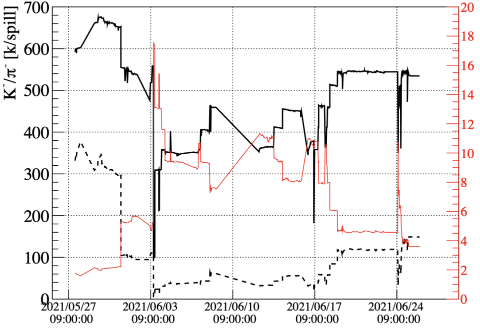
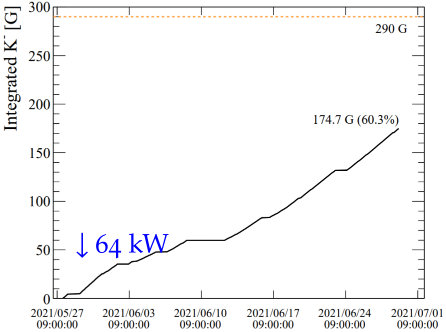
E42 Operation Summary

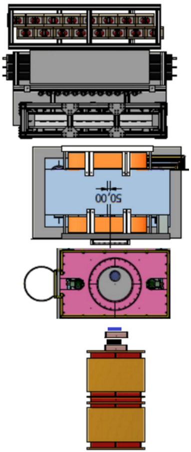


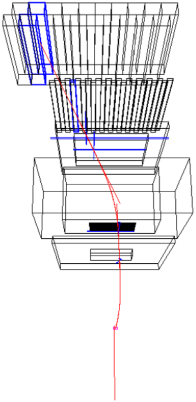


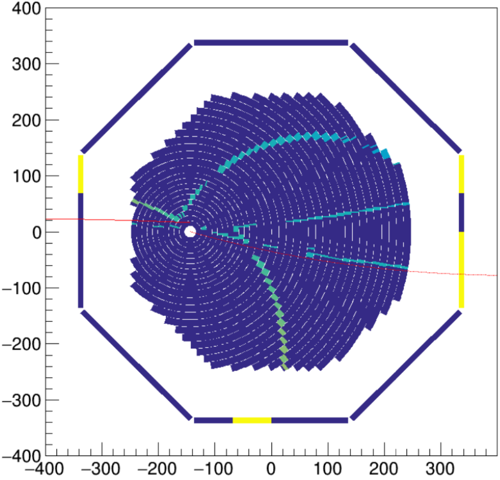
- The accumulated beam yield is 175G K^-, which is approximately 60% of the level we intended to achieve.
- The K^- beam intensity was gradually increased and finally was set to 550 k/spill for the stable HypTPC operation[a]

[a] We operated the HypTPC below the 6/h spark rate limit, which was sufficiently low for safe GEM operation. We operated the HypTPC without the GEM damage during the E42 run.

$^{12}C(K^-, K^+)$ Reaction Event







- Reconstructed K^- beam and outgoing K^+ tracks share the vertex at the diamond target position.
- Two Vs are seen in the HypTPC and four decay particles hit the HTOF.

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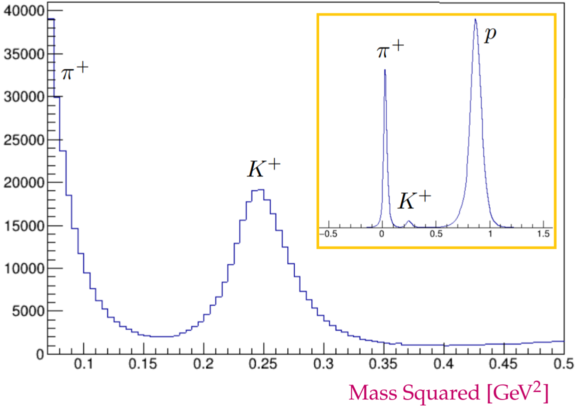
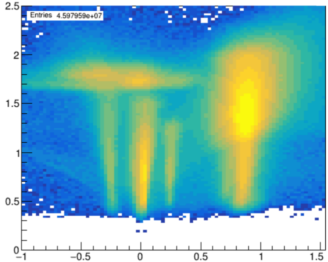
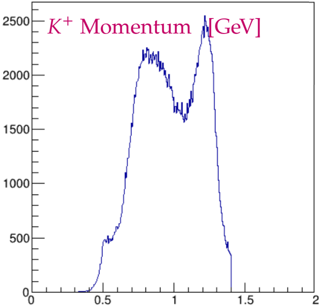
Reconstructed Mass and K^+ Momentum







- Very preliminary offline analysis reconstructs masses and momenta for scattered particles from the E42 target.

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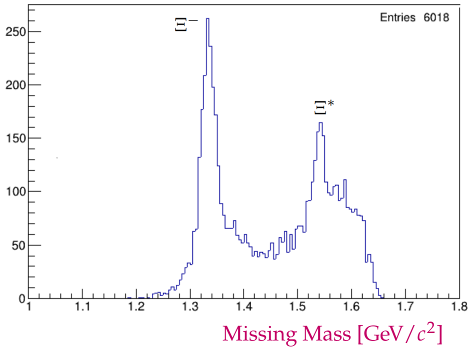
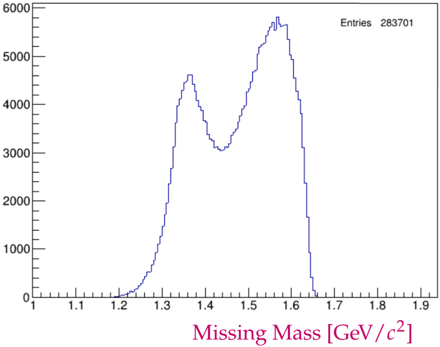




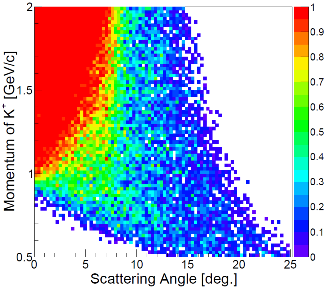
- Ξ^- and $\Xi(1535)^-$ peaks are identified in the missing-mass spectrum for (K^-, K^+) reactions with a polyethylene target (left).
- High mass region is enhanced in the missing mass spectrum for $C(K^-, K^+)$ reactions with a diamond target (right), which includes the contribution from two-step processes.

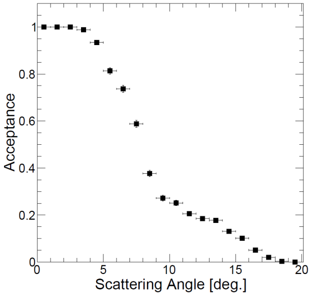
Expected Yields for $\Lambda\Lambda$ and H-Dibaryon Events

	KEK-E224[a]	KEK-E522[b]	J-PARC E42
$p_{K^-}(\mathrm{GeV}/c)$	1.65	1.65	1.8
$p_{K^+}(\mathrm{GeV}/c)$	$0.95 < p_{K^+} < 1.3$	$0.90 < p_{K^+} < 1.3$	$0.50 < p_{K^+}$
$\Lambda\Lambda$ yield	35 events	68 events	**6200 events**
H yield		4.8 events	**940 events**

[a] J.K. Ahn *et al.* (E224), Phys. Lett. **B444** (1998) 267.

[b] C.J. Yoon *et al.* (E522), Phys. Rev. **C75** (2007) 022201.





Simulated $\Lambda\Lambda$ and $\Xi^- p$ Mass Spectra

- Simulated invariant-mass spectra for $H(2250) \to \Lambda\Lambda$ [a] and $H(2265) \to \Xi^- p$ decays. [b]

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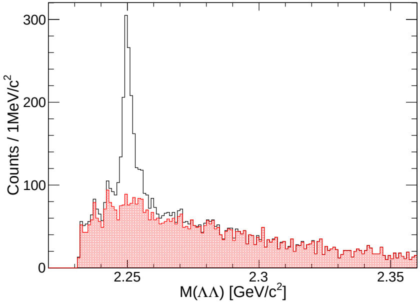
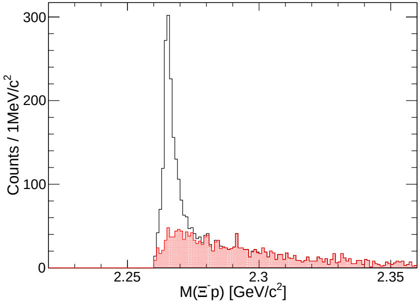
[a] Simulation on two-step processes is based on INC calculation by Y. Nara, A. Ohnishi, T. Harada and A. Engel, Nucl. Phys. A614 (1997) 433.

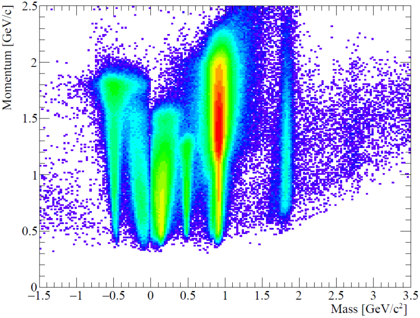


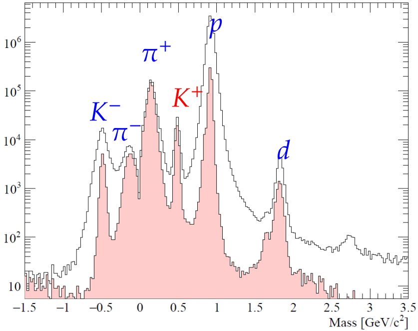
Simulated $\Lambda\Lambda$ Spectrum for $H(2250)$ assuming $d\sigma/d\Omega = 1.0\ \mu$b/sr.

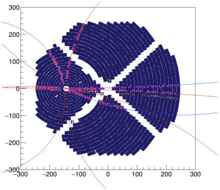


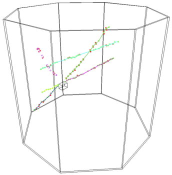
Simulated $\Xi^- p$ Spectrum for $H(2265)$ assuming $d\sigma/d\Omega = 1.0\ \mu$b/sr.

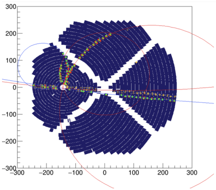
Current Analysis Progress

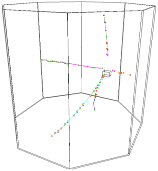












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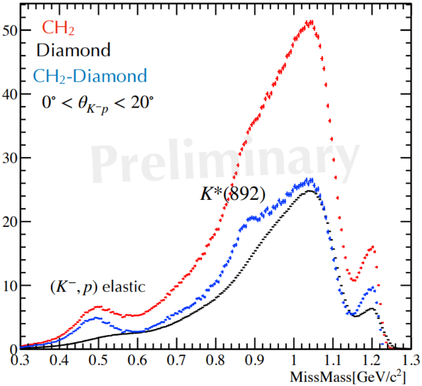
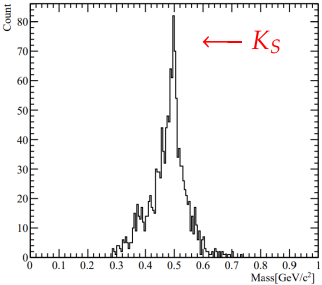
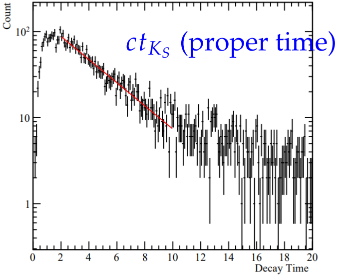
(K^-, p) and $K^{*-} \to K_S \pi^-$







- Most K^* particles decay inside ^{12}C by tagging high-momentum protons in (K^-, p) reactions.
- E42 will look for a possible change in mass and/or width of K^* in ^{12}C.

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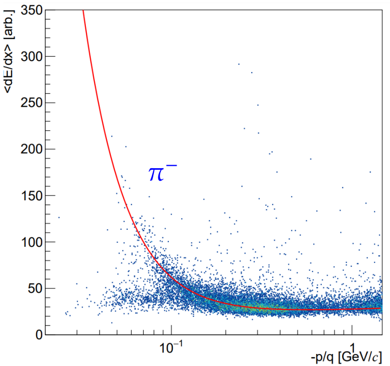
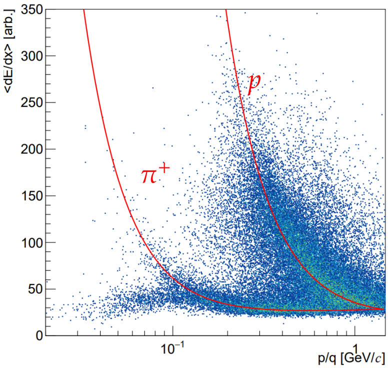
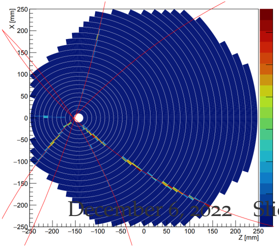
Particle Identification with HypTPC





- $\langle dE/dx \rangle_{20\%\ \mathrm{truncated}}$ vs p/q with (π^-, >= 4ch) datasets.



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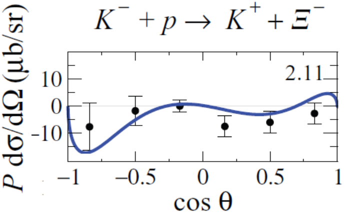
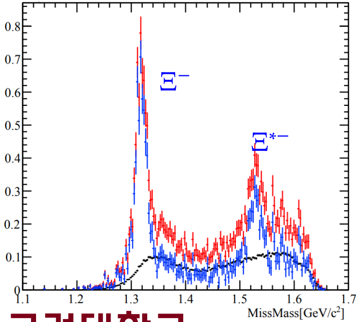
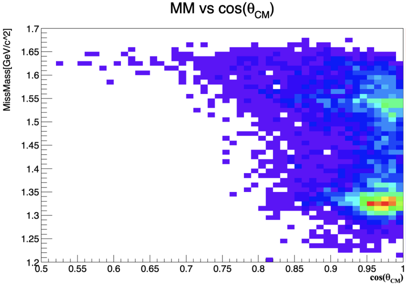
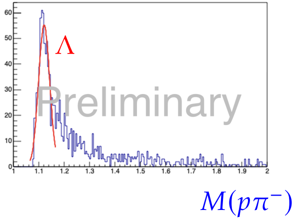
$K^- p \to K^+ \Xi^-$ Reaction









- $P d\sigma / d\Omega$ measurements in $0.85 < \cos\theta^* < 1.0$.

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Physics Opportunities with HypTPC

- E72 : $K^- p \to \eta\Lambda, \pi^0\Lambda, \pi^0\Sigma^0, \pi^\pm\Sigma^\mp, \overline{K}^0 n, \pi^+\pi^-\Lambda, \pi^+\pi^-\Sigma^0$ near $W = 1.67$ GeV.
- E45 : $\pi^\pm p \to \pi\pi N$ in $W = 1.50$–2.15 GeV.
- E90 : $d(K^-, \pi^-)$ for $\Sigma N(I = 1/2, S = 1)$ interaction at threshold.
- P95 : $\pi^- p \to \phi n, \Lambda K^{*0}, \Sigma^0 K^{*0}$.
- ^{3}He$(K^-, \pi^\pm)$ for $^3_\Sigma$n, ^{4}He(K^-, π^-) for $^4_\Sigma$He, ^{4}He(K^-, π^0) for $^4_\Sigma$H.
- Kaonic nuclei via ^{12}C$(K^-, p)X$ in coincidence with Λp.
- Θ^+ search via $K^+ d \to K^0 pp$ at 0.5 GeV$/c$.

- This workshop would be a watershed moment to enrich the physics program with HypTPC.