The 2nd CENuM Workshop for Hadron Physics

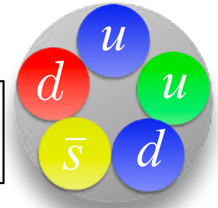
Inha University, Dec 18-19, 2023

Search for a Θ^+ pentaquark at J-PARC

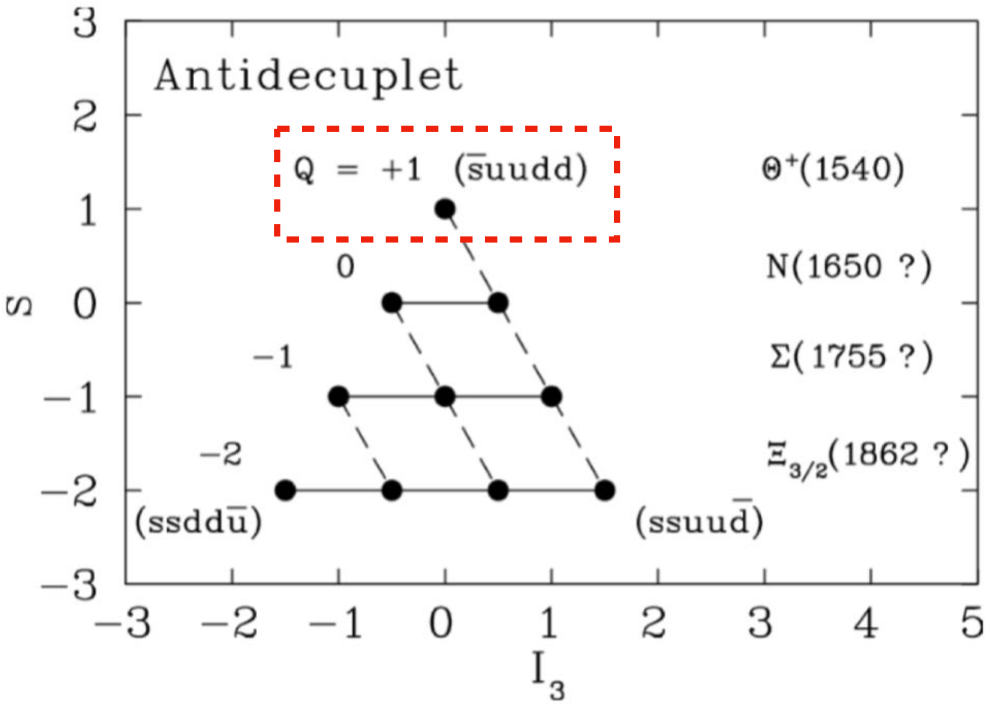
Shin Hyung Kim
(Korea University)

Θ+ Pentaquark

Exotic flavor quantum number S=+1 with a **minimal** quark content of $uudd\bar{s}$

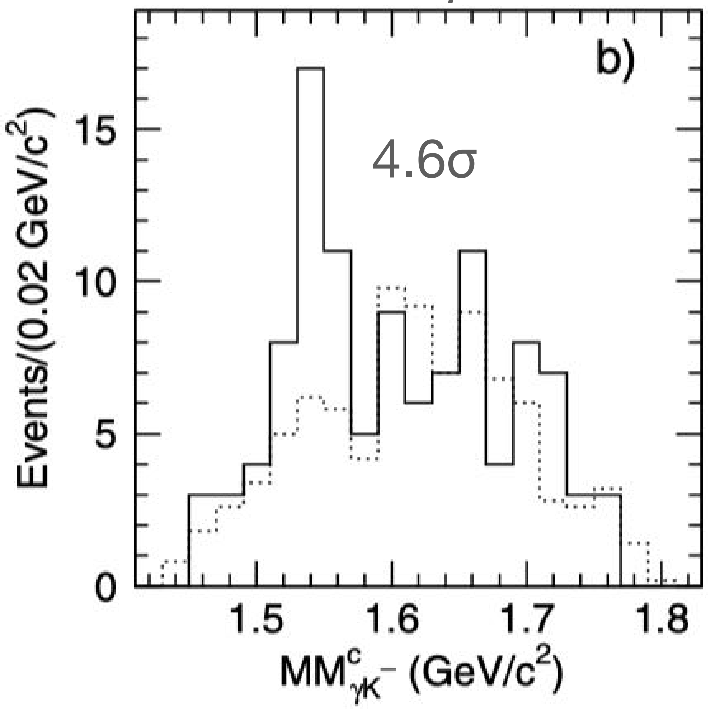


- Predicted by Diakonov et al.
  chiral soliton model
  M~1540 MeV/c², Γ<15 MeV/c²



D. Diakonov, V. Petrov, and M. Polyakov, Z., Phys. A 359, 305 (1997).

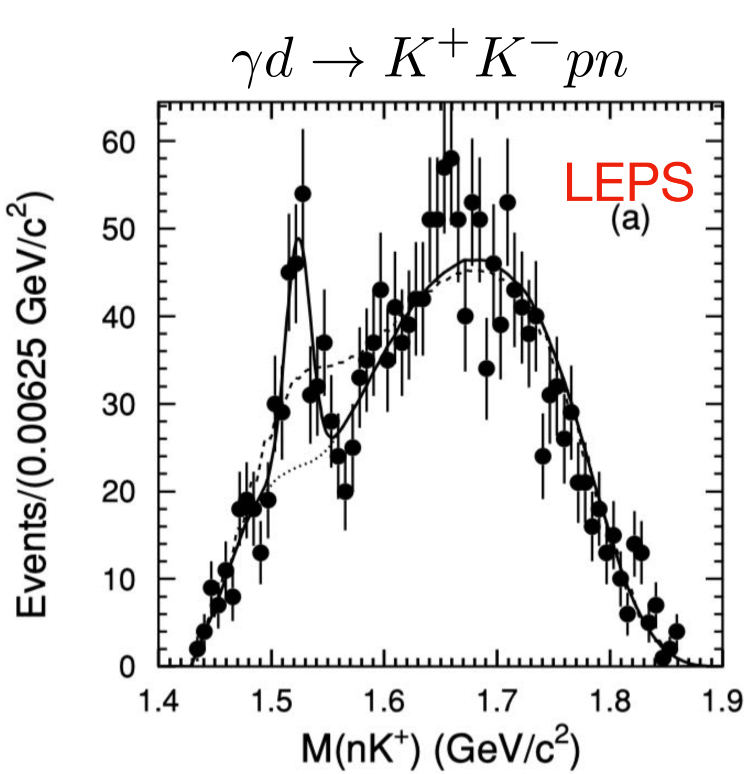
- First reported by LEPS Collaboration
  $\gamma n \rightarrow K^- \Theta^+ \rightarrow K^- K^+ n$ on ^{12}C
  M=1540±10 MeV/c², Γ<25 MeV/c²

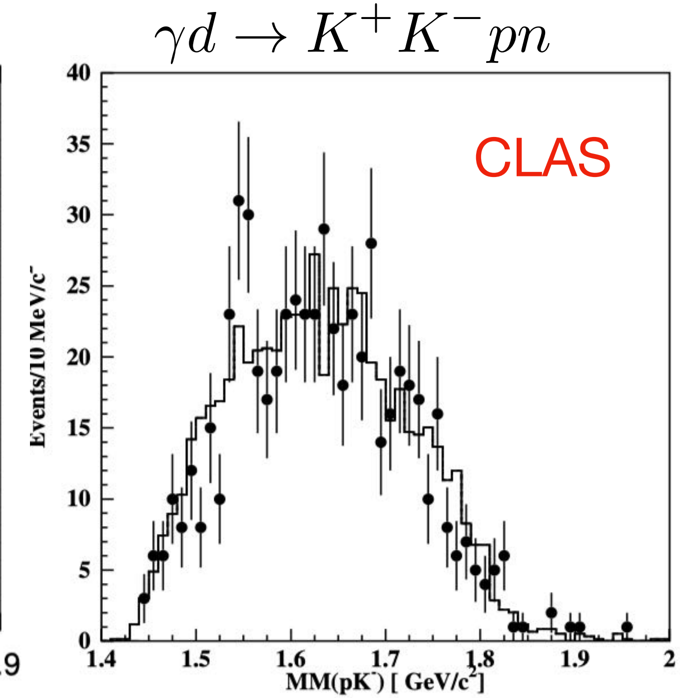


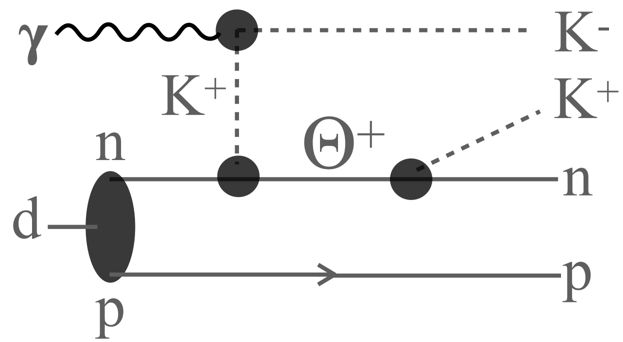
T. Nakano et al., Phys. Rev. Lett., 91, 012002 (2003).

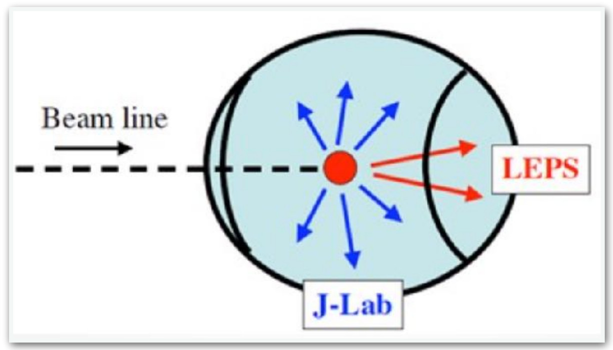
➔ Good agreement between theory and experiment triggered investigation of the Θ+ pentaquark.

Photoproduction of Θ+







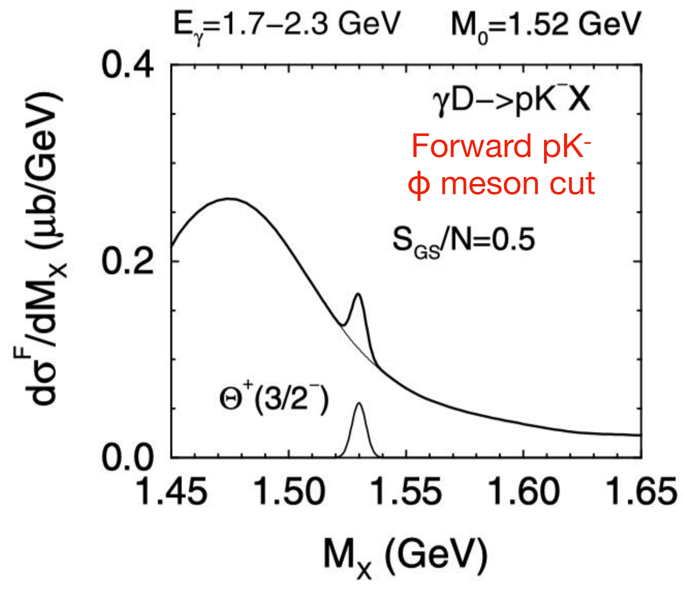


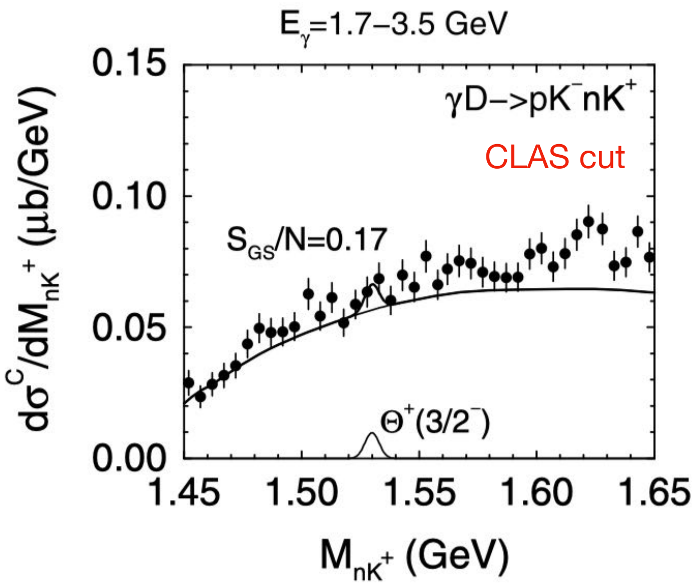
T. Nakano et al., Phys. Rev. C, 79, 025210 (2009).

B. McKinnon et al., Phys. Rev. Lett., 96, 212001 (2006).

- LEPS and CLAS observed the peak near 1.54 GeV/c^2 at first but showed disagreement with higher statistics data later.
- Their experimental setups differed in K$^-$ emission angle that ensures the production of S=+1 systems in photoproduction.

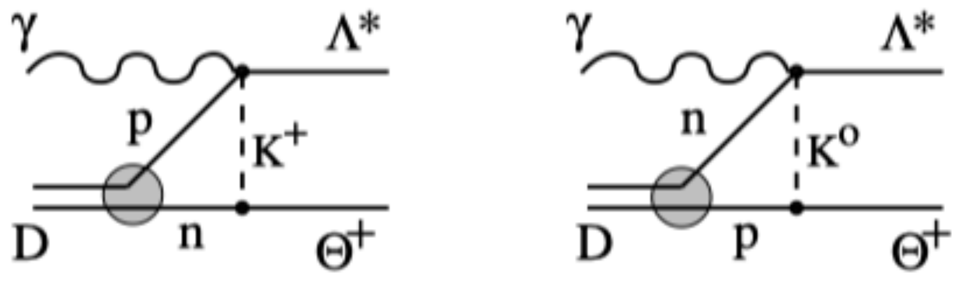
Null Results in CLAS?



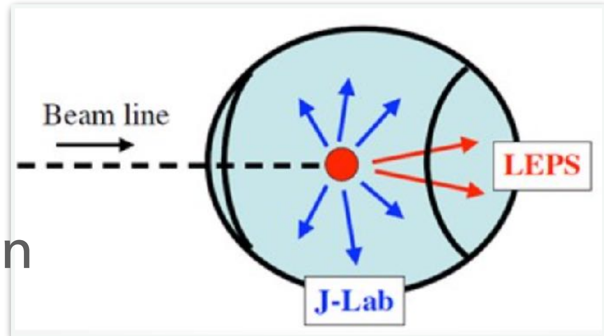


$\gamma d \to K^+ K^- pn$

A. I. Titov et al., Phys. Rev. C, 74, 055206 (2006).



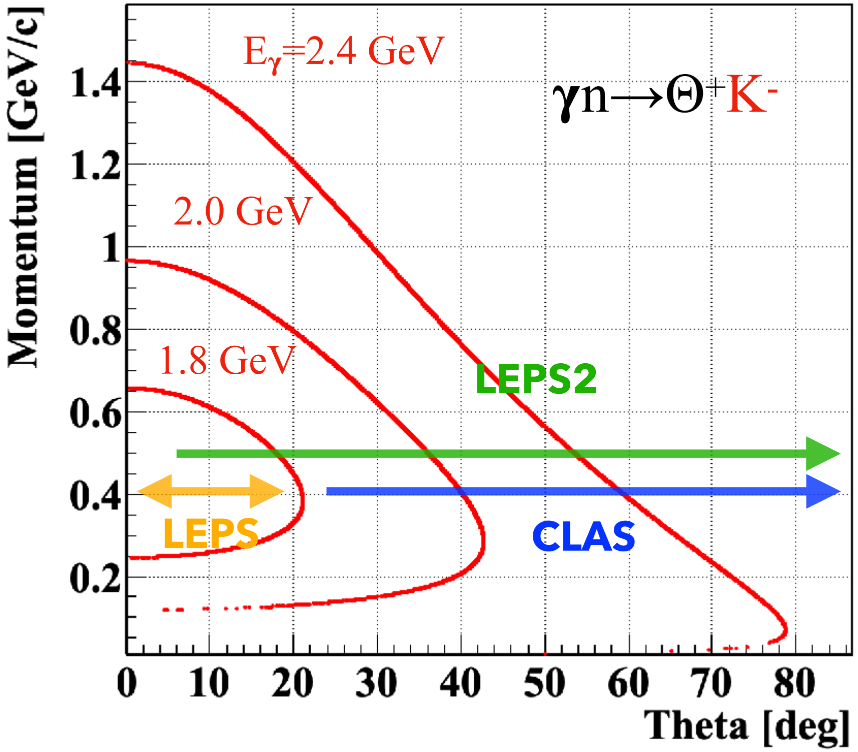
- Interference for two subprocesses
  ➔ Θ^+ signal enhanced by $\Lambda^*(1520)$
- Forward pK- pair
  ➔ slow *K* can merge with a spectator *N* to produce a Θ^+
- CLAS:
  - $\Lambda^*(1520)$ cut
  - K- in central region

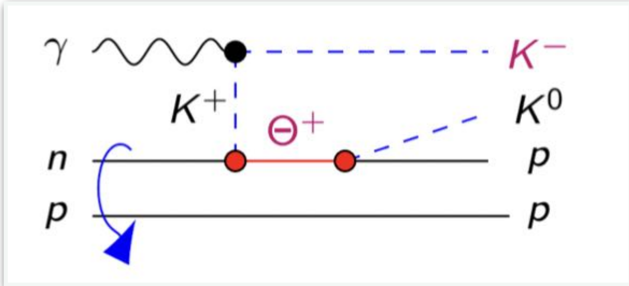


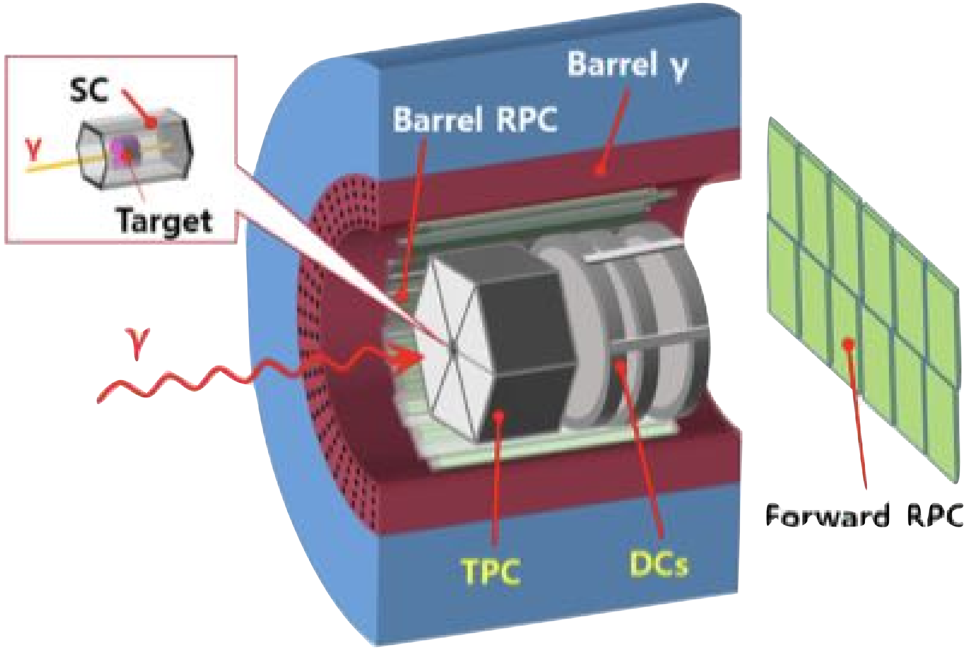
New Attempt for Θ^+ Search at LEPS2

M. Yosoi, EPJ Web Conf. 199, 01020 (2019).

- $\gamma n \rightarrow K^- \Theta^+$ ($\Theta^+ \rightarrow K^0 p$; $K^0 \rightarrow \pi^+\pi^-$)
- $\gamma p \rightarrow \overline{K}^{*0} \Theta^+$ ($\overline{K}^{*0} \rightarrow K^- \pi^+$)







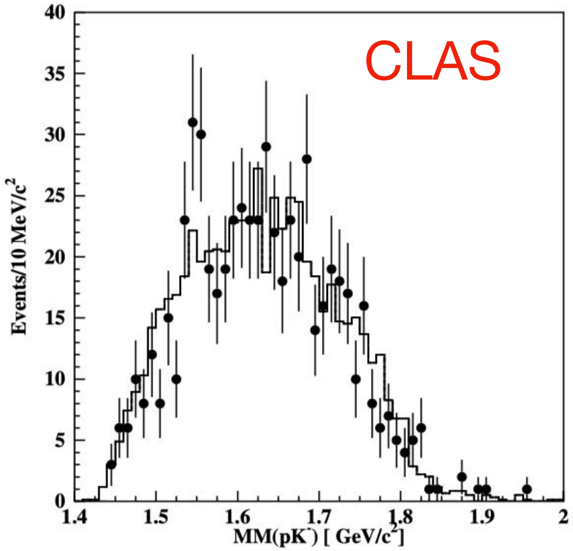
- LEPS2 spectrometer has a wider angular coverage for K^- detection, covering both of LEPS and CLAS acceptances.
- All final state particles can be reconstructed by LEPS2 detector.
  ➔ No Fermi-motion correction is necessary.

Recent Review on CLAS data

M. Amaryan, Eur. Phys. J. Plus 137, 684 (2022).

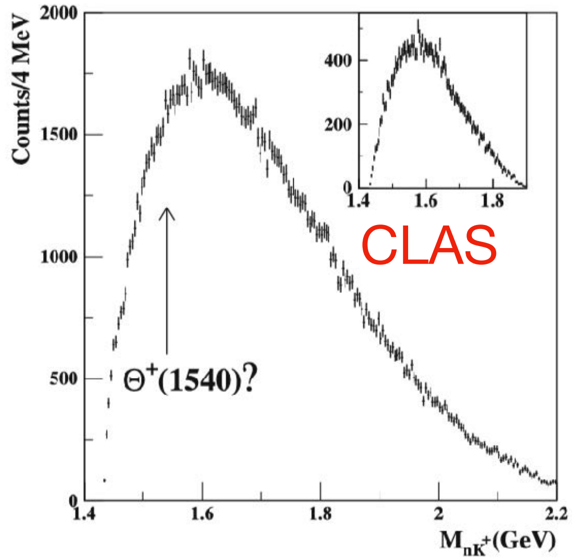
- Current status of non-observation doesn't allow to dismiss its existence

$\gamma d \to K^+ K^- p n$



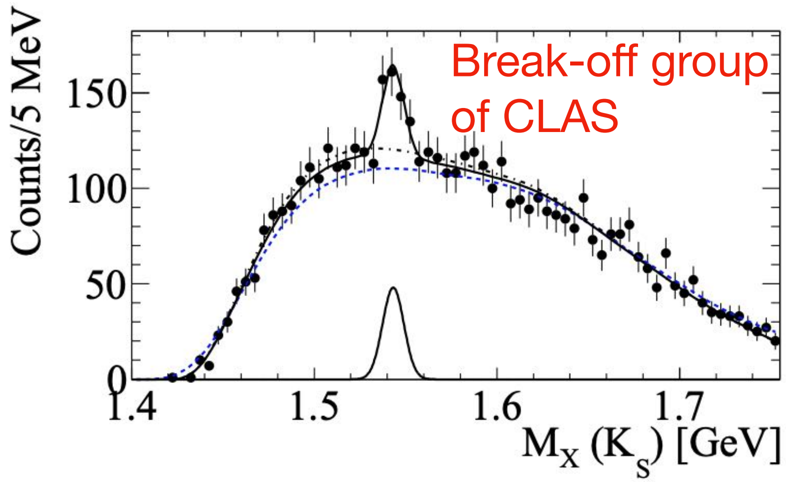
Phys. Rev. Lett., 96, 212001 (2006).

$\gamma p \to K^0_s K^+ n$



Phys. Rev. Lett., 96, 042001 (2006).

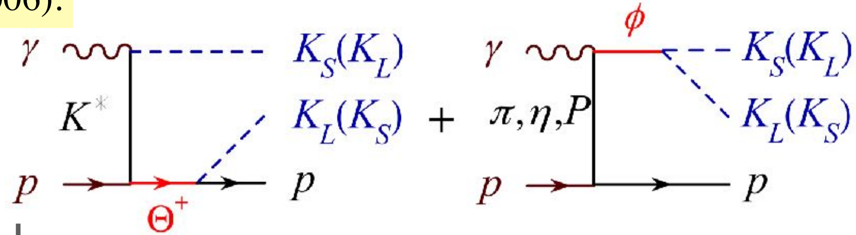
$\gamma p \to K^0_s K^0_l p$



Phys. Rev. C, 85, 035209 (2012).

- $\gamma d \to K^+ n K^- p$
- $K^+ p \to K^+ n K^- p$
- Λ*s, Σ*s background : not well established which may result in a large uncertainty on reflections

- $\gamma p \to K^0_s K^+ n$
- $\gamma p \to K^0_s K^+ n$



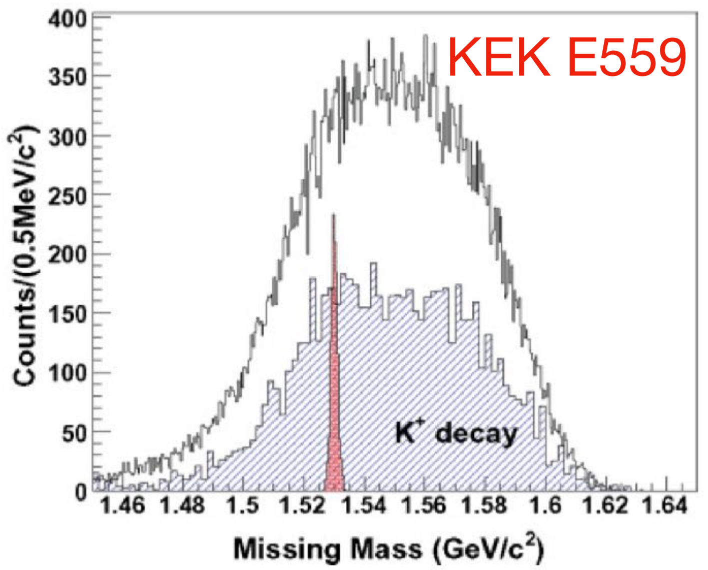
- Interference for two subprocesses
- Θ^+ signal enhanced by ϕ

- Direct formation: $K_L p \to K^+ n$ in Hall D at JLab

Hadronic Production of Θ+

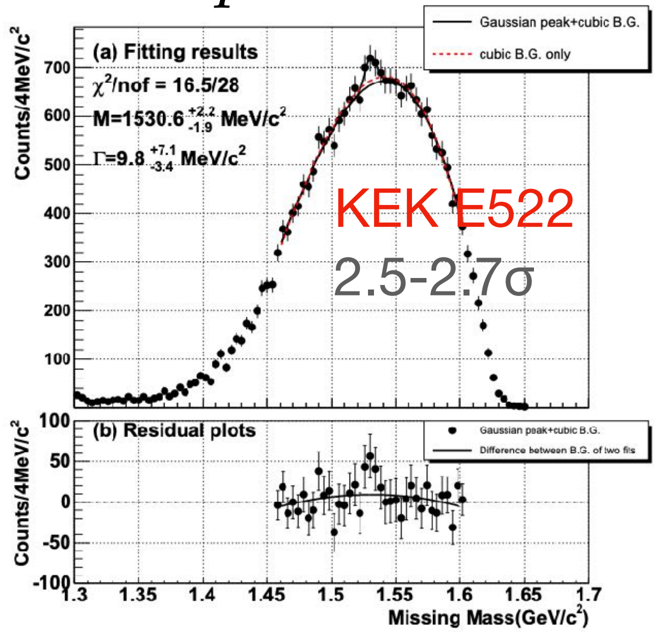
- Hadron-induced reaction has larger production cross-section and production mechanism is more straightforward over photo-induced reaction.

$K^+ p \rightarrow \Theta^+ \pi^+$



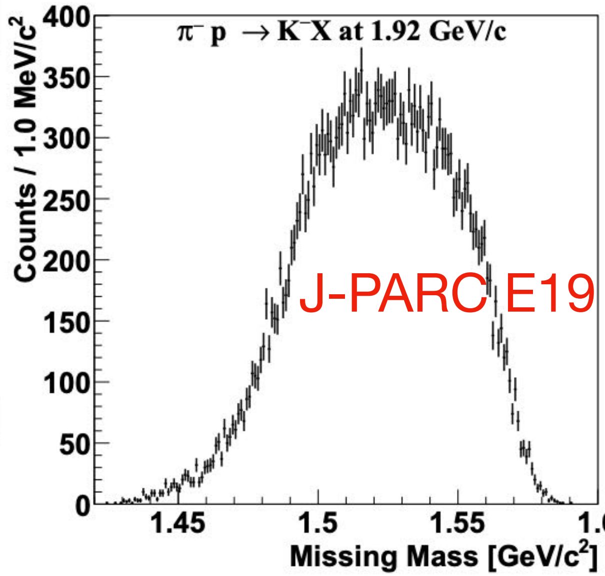
K. Miwa et al.,
Phys. Rev. C, 77, 045203 (2008).

$\pi^- p \rightarrow \Theta^+ K^-$



K. Miwa et al.,
Phys. Lett. B, 635, 72 (2006).

$\pi^- p \rightarrow \Theta^+ K^-$

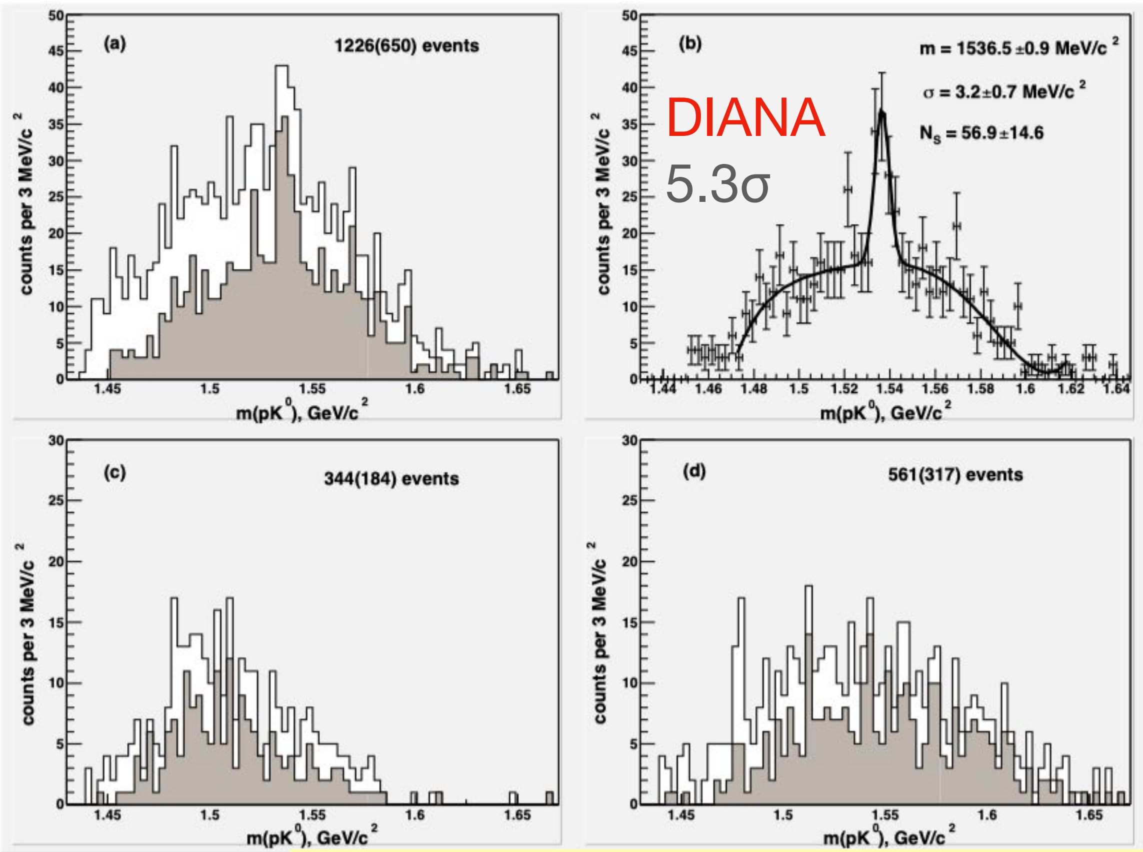


K. Shirotori et al.,
Phys. Rev. Lett., 109, 132002 (2012).

- $K^+p \rightarrow K^+n\pi^+$ or $K^0p\pi^+$
- $K^+p \rightarrow K^+n\pi^+$ or $K^0p\pi^+$
  - Δ^+, Δ^{++} background
- $\pi^-p \rightarrow K^+nK^-$ or K^0pK^-
- $\pi^-p \rightarrow K^+K^-n$
  - $a_0(980)$ or ϕ background

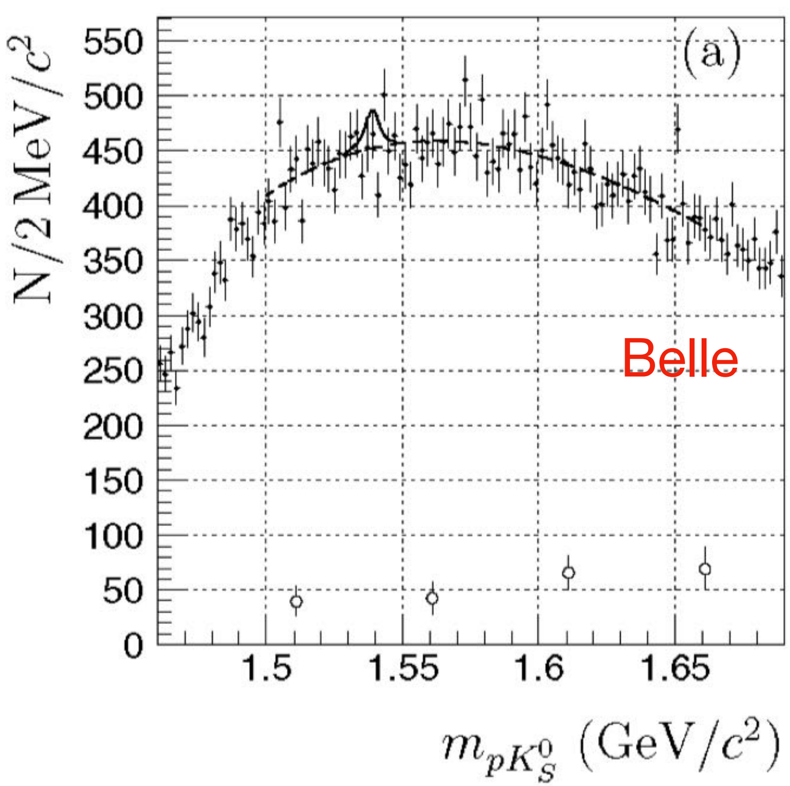
Direct Formation of Θ^+ on Nuclei

$K^+\mathrm{Xe} \to K_s^0 pX$



V. V. Barmin et al., Phys. Atom. Nucl. 70, 35-43 (2007).

$K^+n \to pK_S$



R. Mizuk et al., Phys. Lett. B 632, 173–180 (2006).

- Kinematic cuts to remove the effect of the rescattering of reaction products in nuclear matter.
- kaon secondary interactions in the detector material

- M_Θ = 1537 ± 2 MeV
- Γ_Θ = 0.36 ± 0.11 MeV

- Γ_Θ < 0.64 MeV at the 90% C.L. for M_Θ = 1.539 MeV

Θ^+ Search History Summary

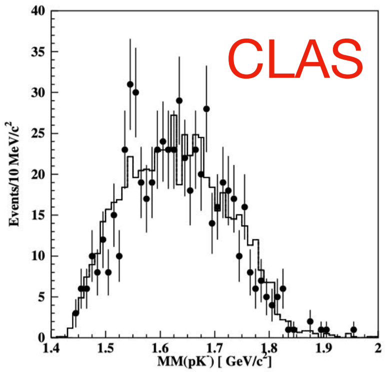
Photoproduction

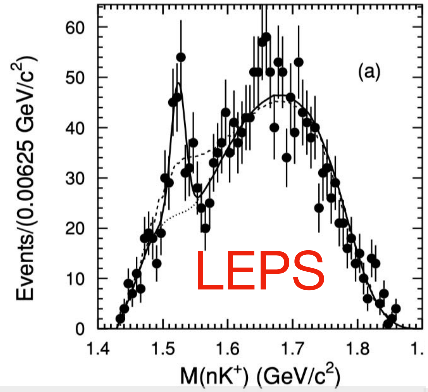
$\gamma d \rightarrow K^+ n K^- p$

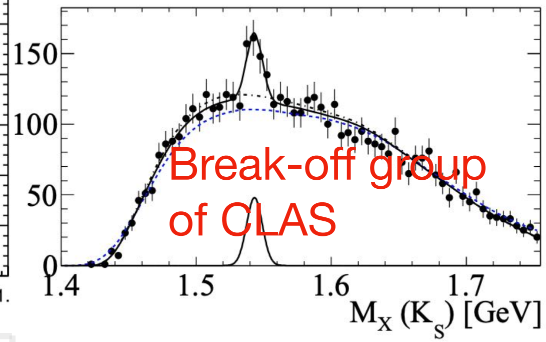
$\gamma p \rightarrow K^0_S K^+ n$

$\gamma p \rightarrow K^0_S K^0_L p$

$\gamma d \rightarrow K^0 p K^- p$



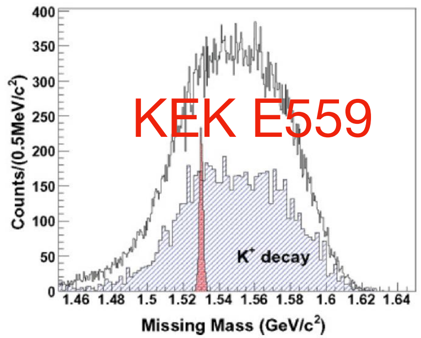


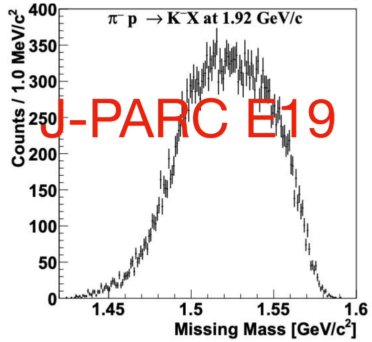


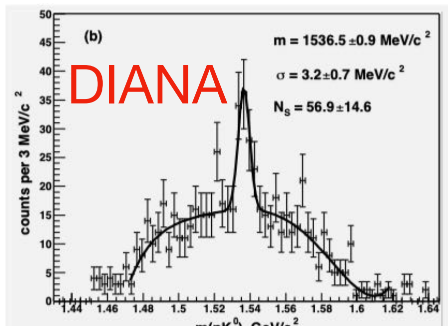
Hadronic production

$K^+ p \rightarrow \Theta^+ \pi^+$

$\pi^- p \rightarrow \Theta^+ K^-$







$K^+ n$(in nuclei) $\rightarrow \Theta^+ \rightarrow K^0 p$

huge background

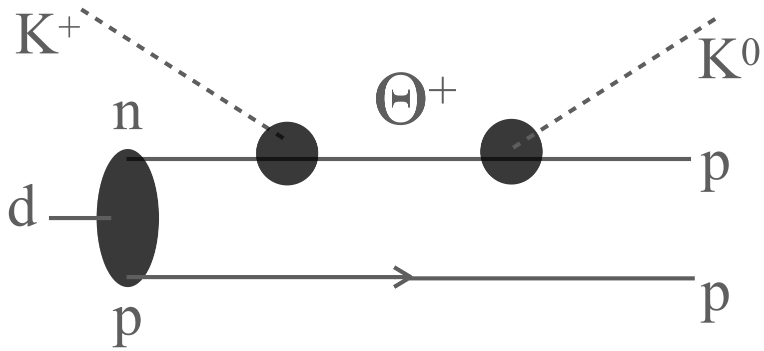
K^- angle acceptance

VS. with a kinematic cut

- A final attempt should be made for a definitive exclusion.

Direct Formation of Θ^+ in KN Interaction

- K^0p reaction
  ◯ liquid hydrogen target: Free from the Fermi motion
  × K^0 beam: Hardly determine the momentum
- ➔ K^+n reaction with deuterium target



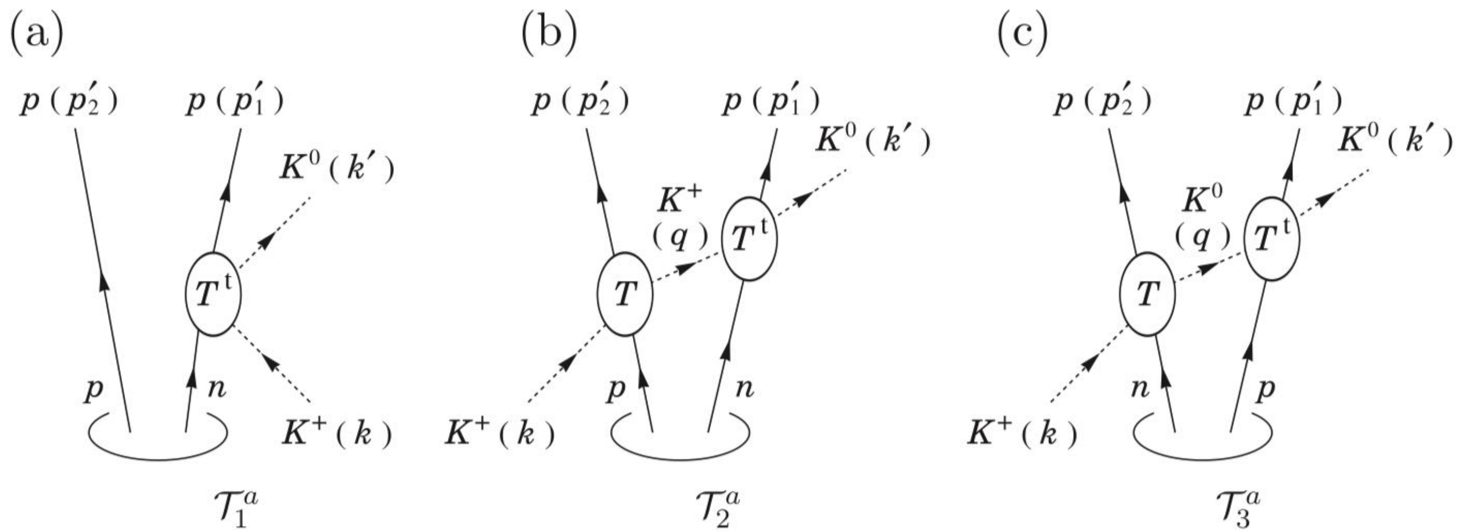
- The Θ^+ lies 110 MeV above KN threshold & 25 MeV below KNπ threshold.
  ➔ A pion can barely be produced near the Θ^+ production threshold.
- ➔ For K^+d reaction near threshold, only the following processes are available:
  (1) $K^+d \rightarrow K^+d$ (coherent elastic scattering)
  (2) $K^+d \rightarrow K^+np$ (incoherent breakup reaction)
  (3) $K^+d \rightarrow K^0pp$ (incoherent charge-exchange breakup reaction)

$K^+d \to K^0pp$ for the Θ^+ Production

Prog. Theor. Exp. Phys., 2020, 063D03 (2020).

Feasibility study of the $K^+d \to K^0pp$ reaction for the Θ^+ pentaquark

Takayasu Sekihara[1,2,3,*], Hyun-Chul Kim[1,4,5], and Atsushi Hosaka[1,2]

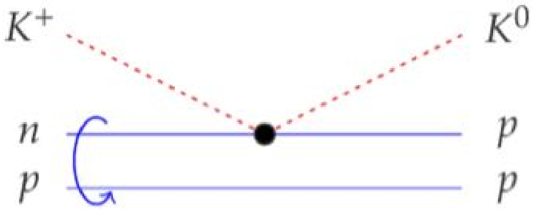


- They predicts that the Θ^+ (M_Θ=1524 MeV, Γ_Θ=0.5 MeV) production cross section is of the order of a few hundred μb to 1 mb at p_{K+}≈0.40 GeV/c where impulse scattering process is dominant, and drops to ≤ 1 μb at p_{K+}≈0.85 GeV/c at which two-step processes overtake the impulse one.

$K^+d \to K^0pp$ at 0.5 GeV/c Simulation

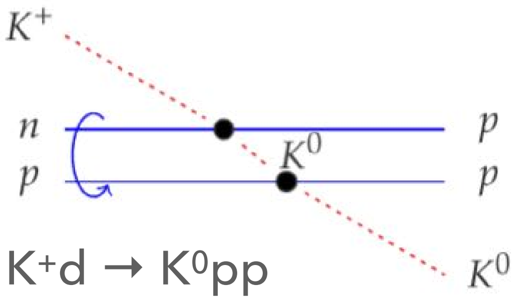
- Impulse scattering process

  $K^+n \to K^0p$

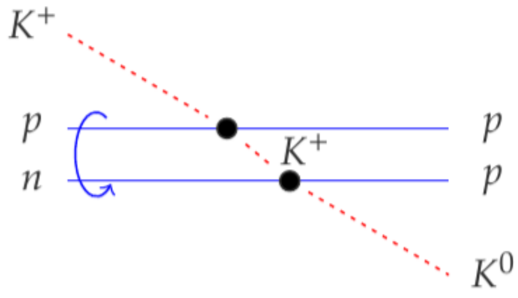


- Two-step processes

  $K^+n \to K^0p$; $K^0p \to K^0p$



  $K^+p \to K^+p$; $K^+n \to K^0p$



- Non-resonant breakup reaction: $K^+d \to K^0pp$
- Θ^+ production: $K^+d \to \Theta^+p$ (Θ^+ mass: relativistic BW with M_0=1.524 GeV, Γ=1 MeV)

- Fermi momentum of nucleons in a deuteron:

$$f(k) = ae^{-\alpha k} + be^{-\beta k}$$

where a=13 [GeV/c]$^{-3}$, α=8 GeV/c]$^{-1}$,
b=3 × 10^4 [GeV/c]$^{-3}$, and β = 37 [GeV/c]$^{-1}$

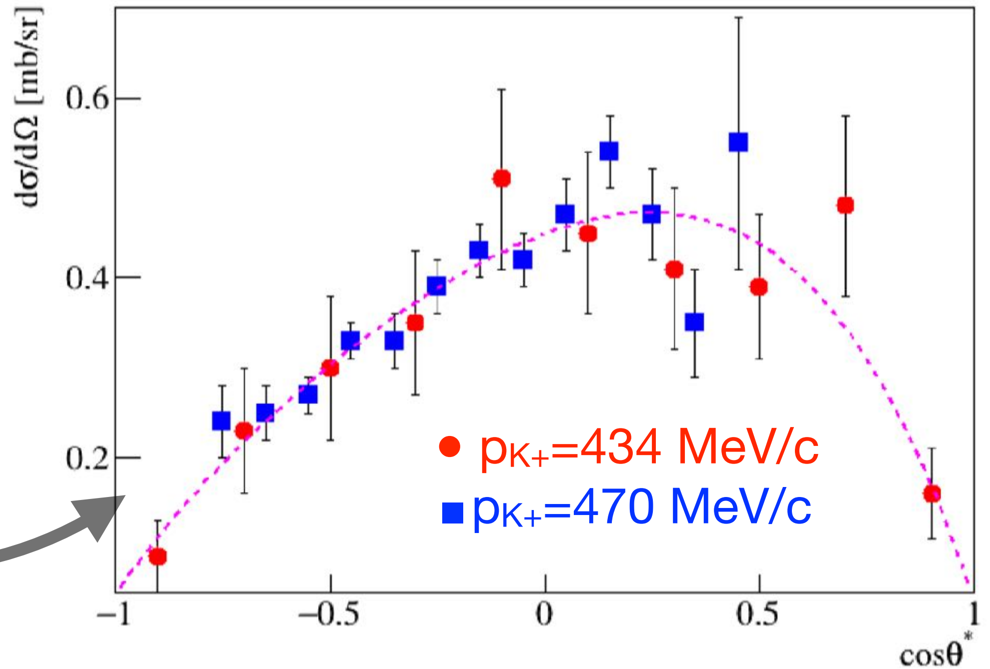
M. Bernheim et al., Nucl. Phys. A 365, 349 (1981).

- Differential Cross Section for $K^+n \to K^0p$:

$$\frac{d\sigma}{d\Omega} = \sum_{n=0}^{n=4} c_n P_n(\cos\theta^*)$$

C.J.S. Damerell et al., Nucl. Phys. B 94, 374 (1975).
R.G. Glasser et al., Phys. Rev. D 15 1200 (1977).

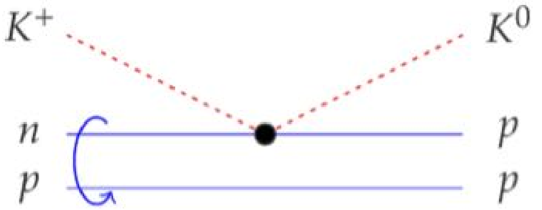
J.K. Ahn and S.H. Kim, JKPS 82, 579 (2023).



$K^+d \rightarrow K^0pp$ at 0.5 GeV/c Simulation

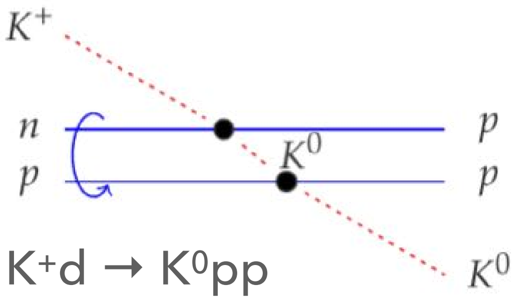
- Impulse scattering process

  $K^+n \rightarrow K^0p$

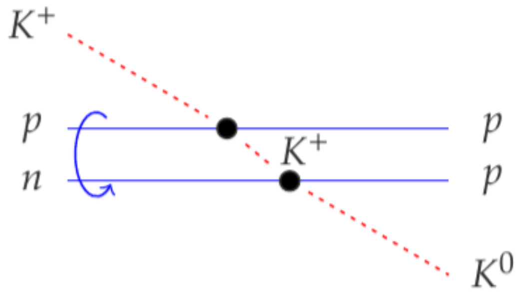


- Two-step processes

  $K^+n \rightarrow K^0p$; $K^0p \rightarrow K^0p$



  $K^+p \rightarrow K^+p$; $K^+n \rightarrow K^0p$



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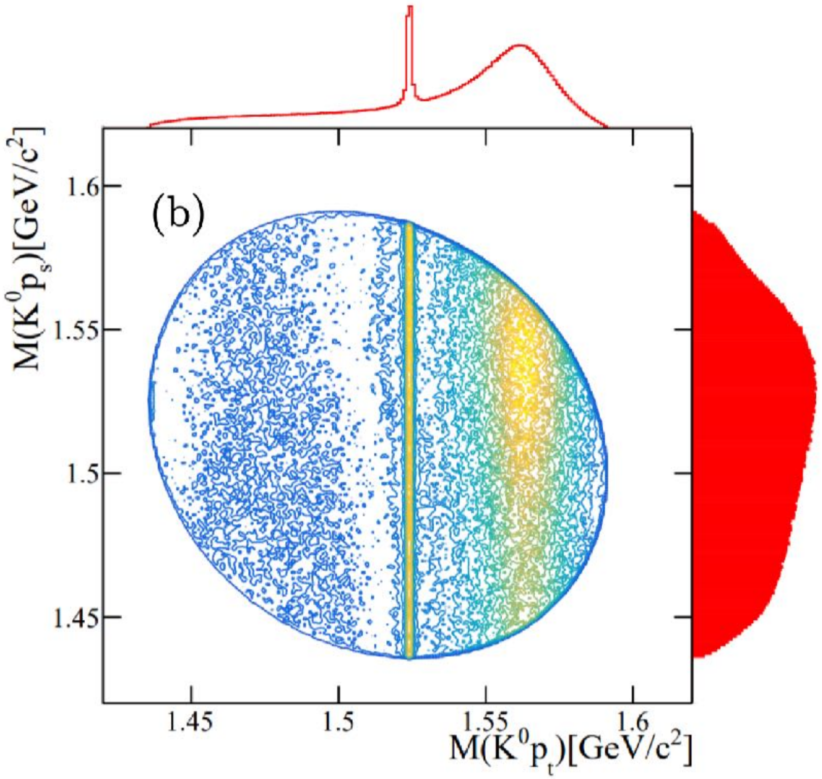
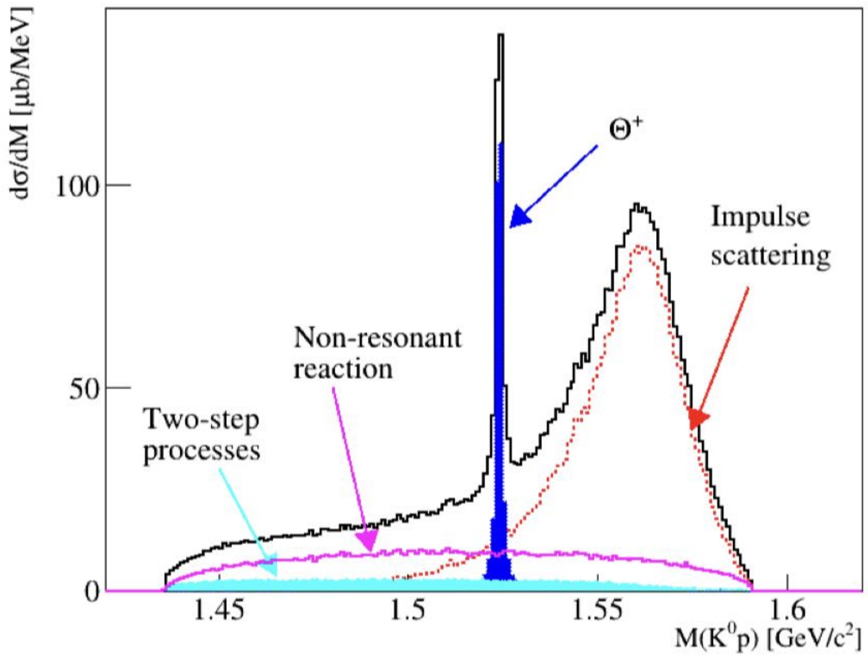
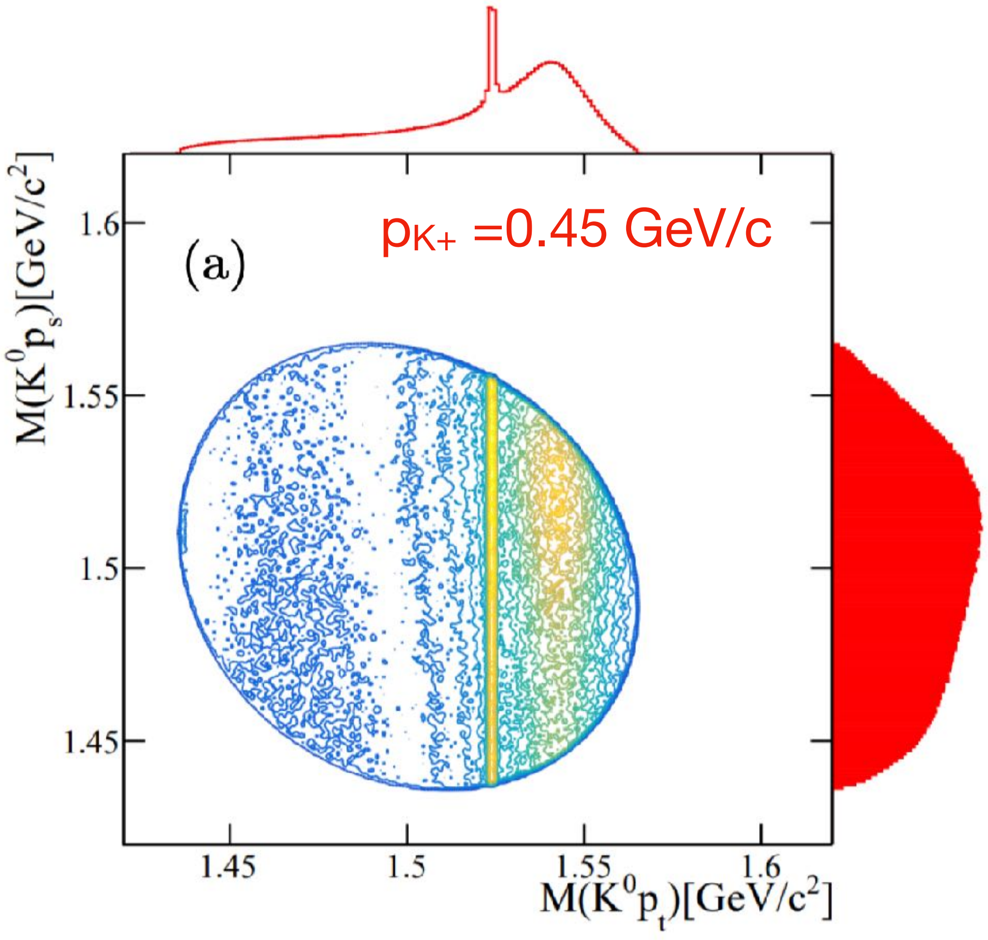


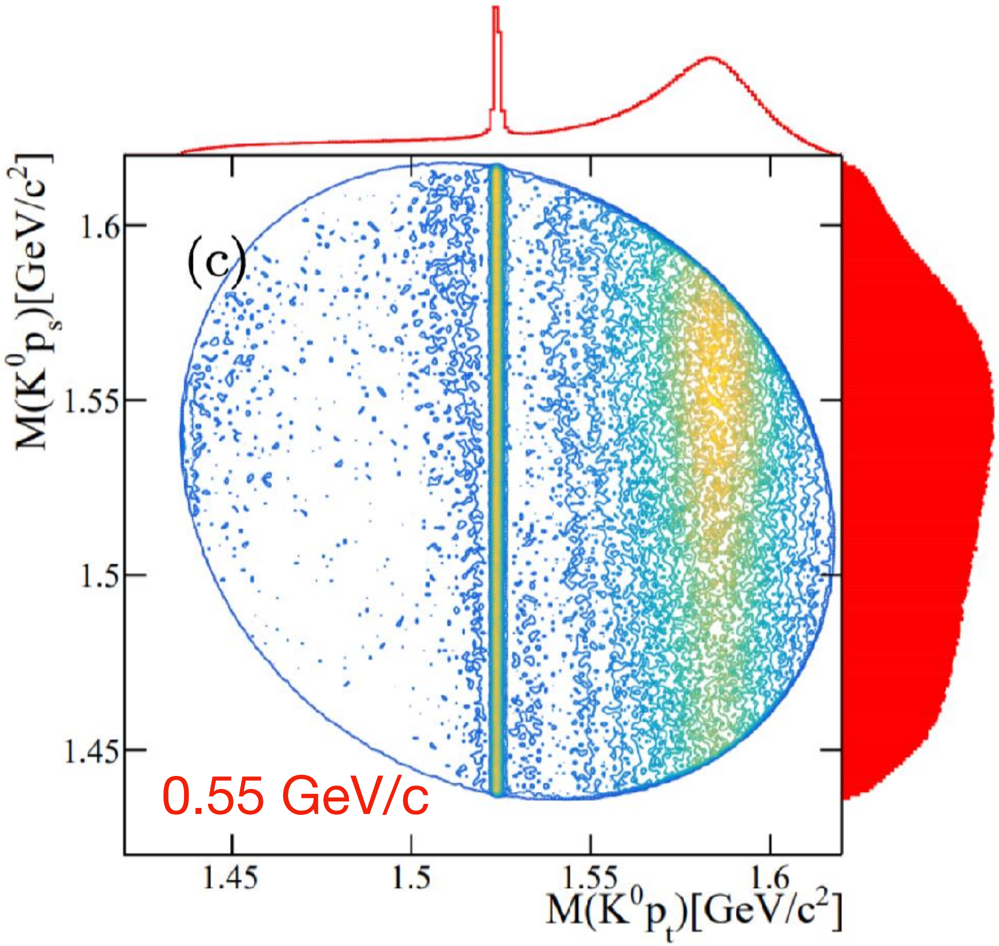


J.K. Ahn and S.H. Kim, JKPS 82, 579 (2023).

$K^+d \rightarrow K^0pp$ at 0.45 & 0.55 GeV/c

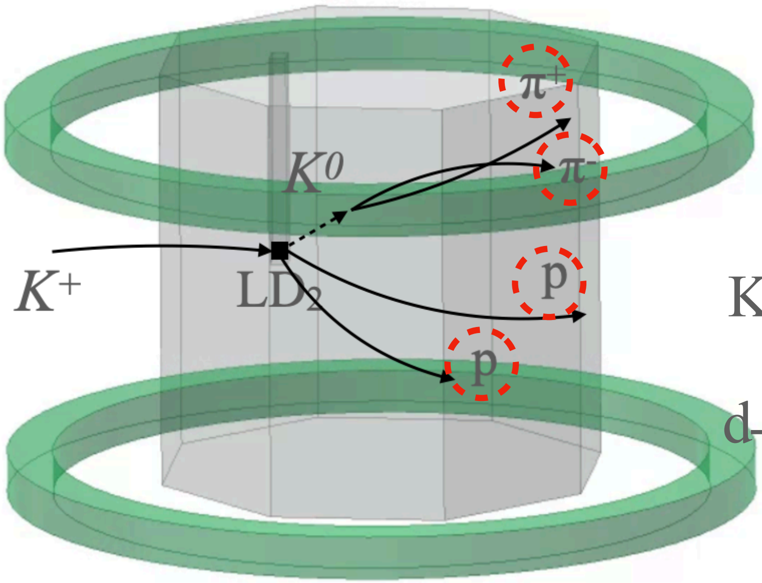
- The lower K^+ beam momentum,
  ➔ the closer the Θ^+ peak moves to the quasifree scattering peak.
- The higher K^+ beam momentum,
  ➔ the smaller chance the K^+n center-of-mass energy has for the Θ^+ formation.

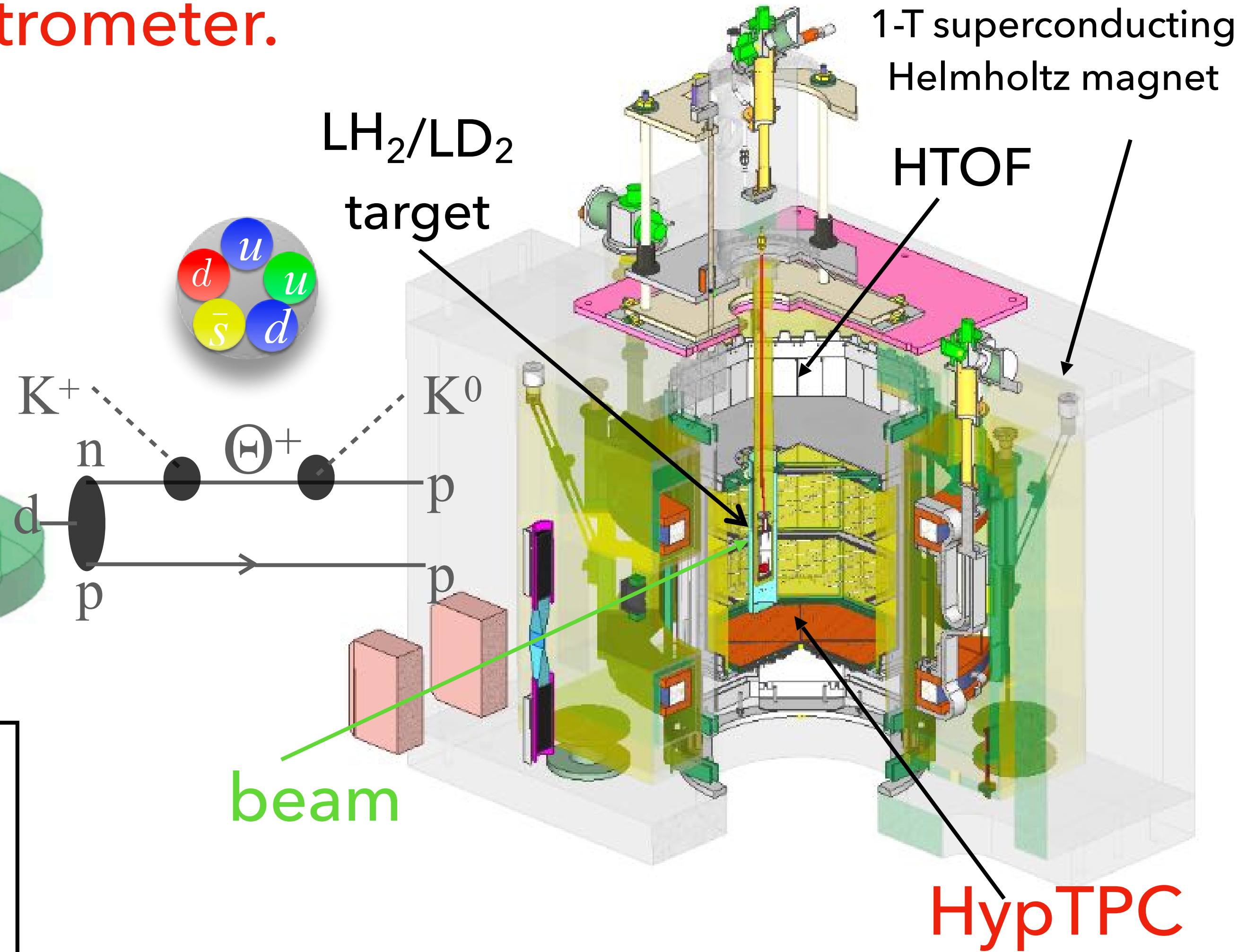




New Proposal at J-PARC

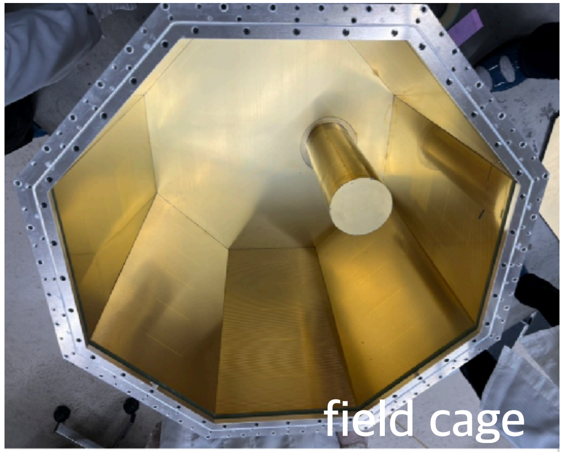
- A dedicated experiment to search for Θ^+ in $K^+d \rightarrow K^0pp$ at p_{K+}=0.5 GeV/c (at J-PARC K1.8BR or K1.1BR) with Hyperon Spectrometer.

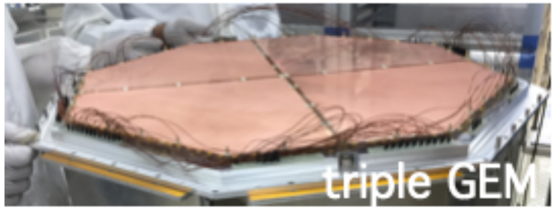


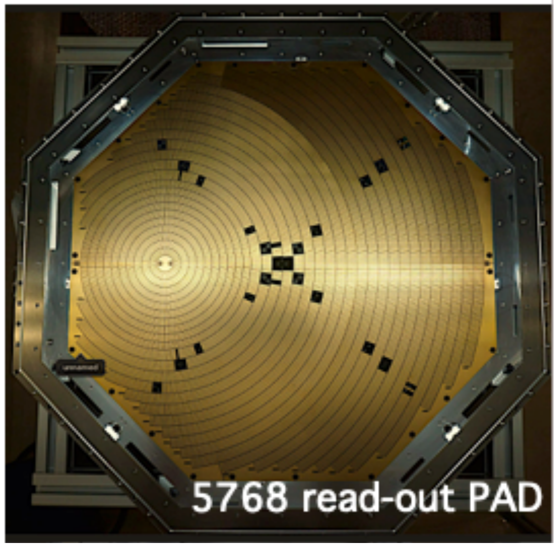


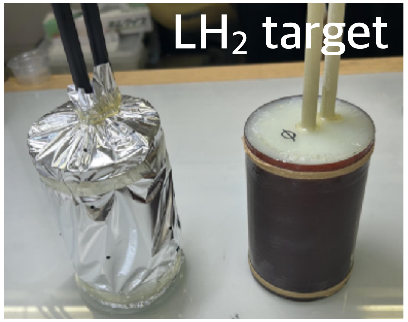
- High statistics
- High resolution
- Large acceptance

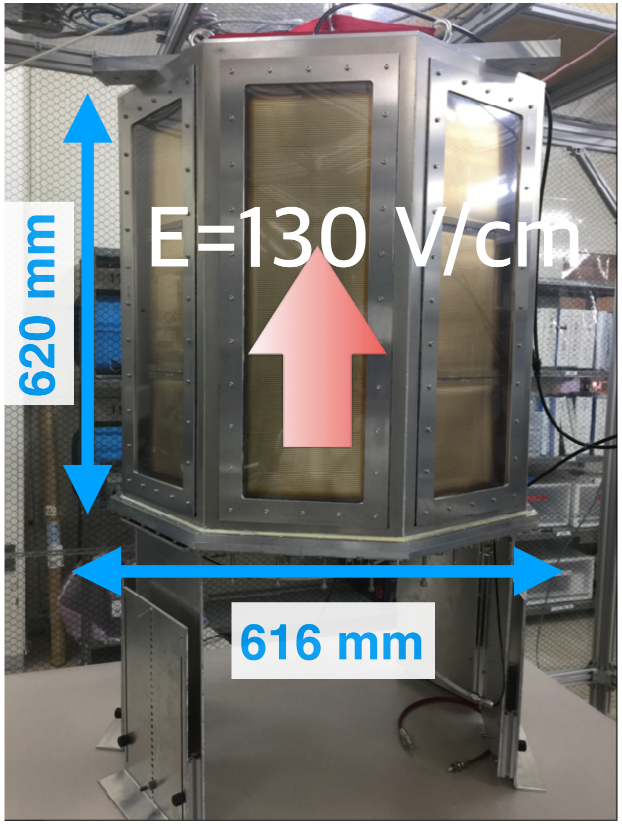
Hyperon Spectrometer



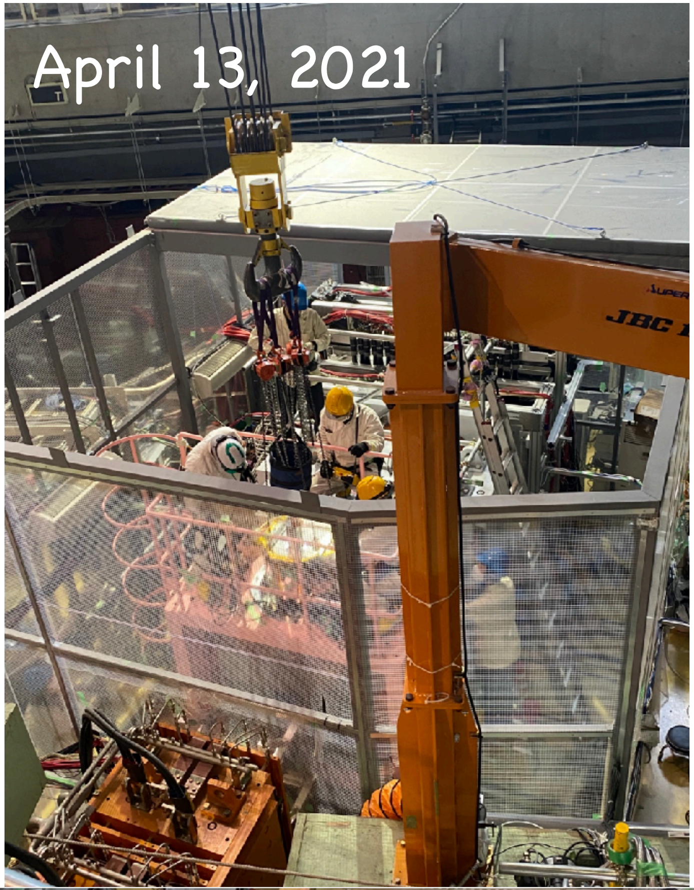


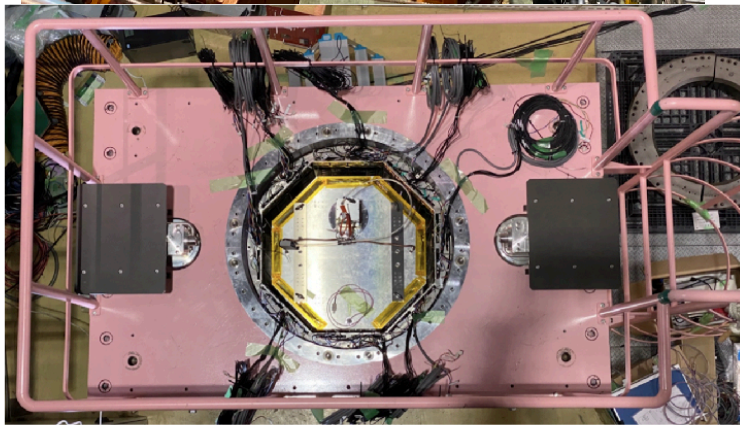






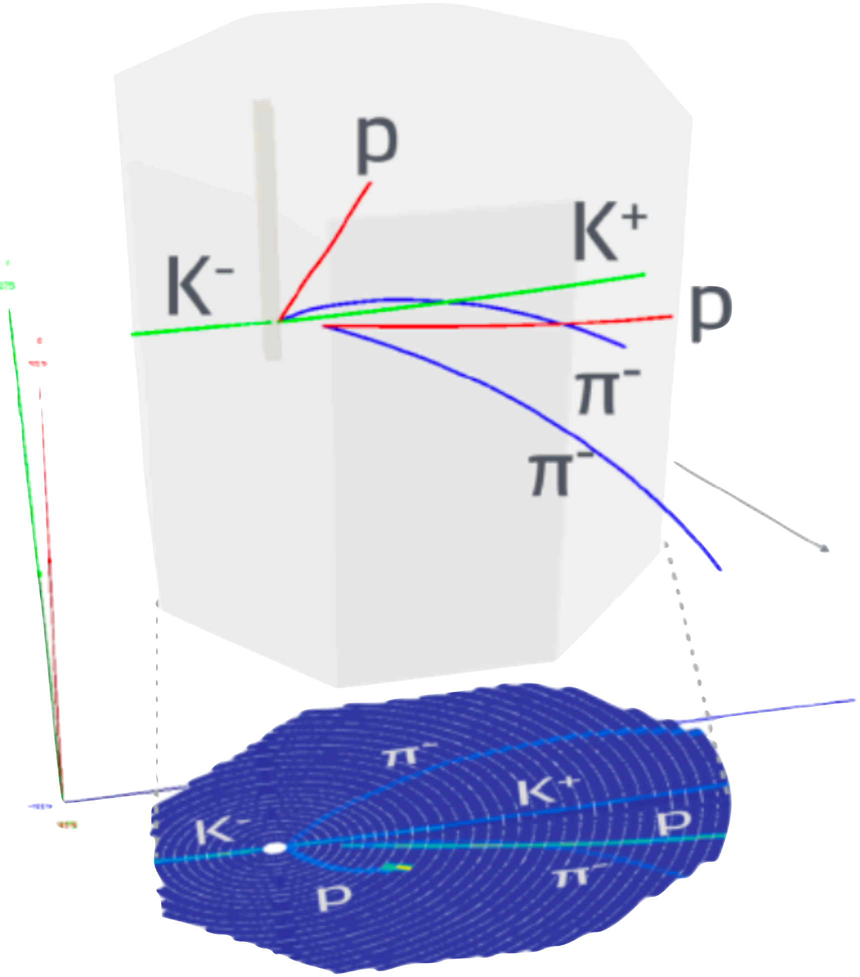
- *HypTPC*



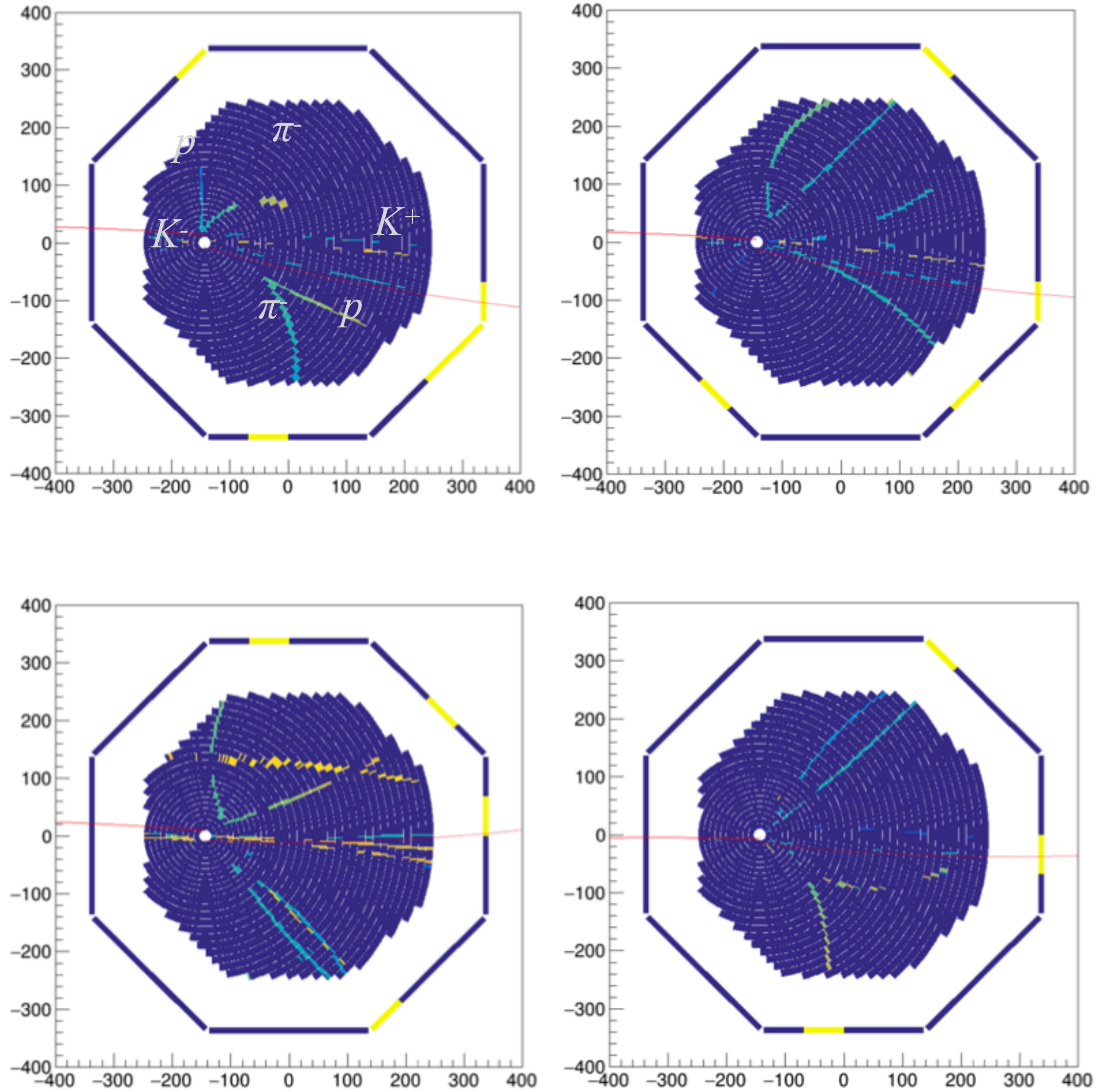


Hyperon Spectrometer

- *Simulation (J-PARC E42)*

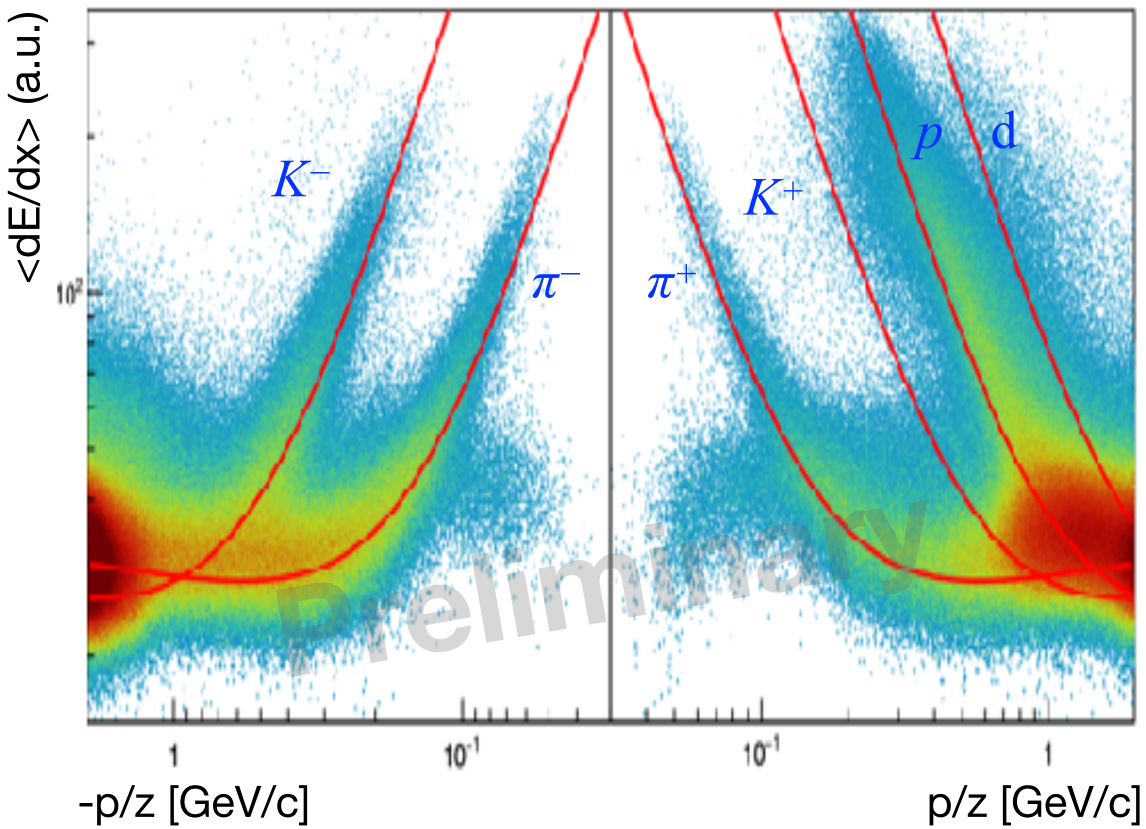


- *Event Display (J-PARC E42)*

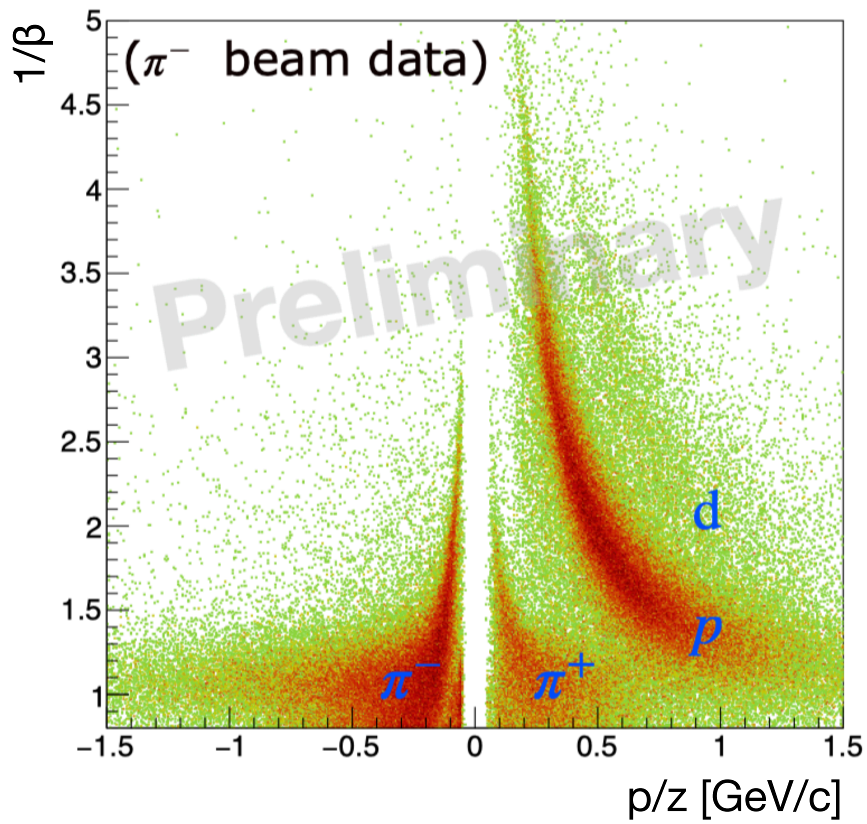


PID by Hyperon Spectrometer

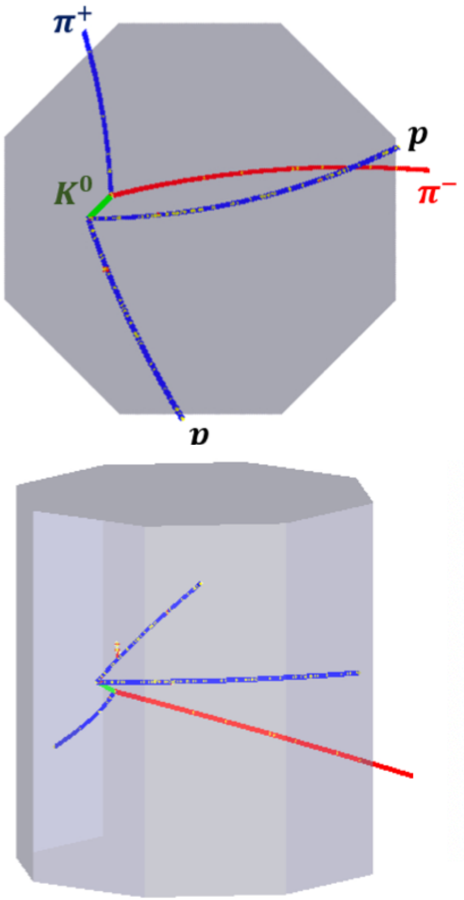
- HypTPC dE/dx
  - $\sigma_{<dE/dx>}$/<dE/dx> ~ 20%
  at $0.4 < p_T < 0.45$ GeV/c

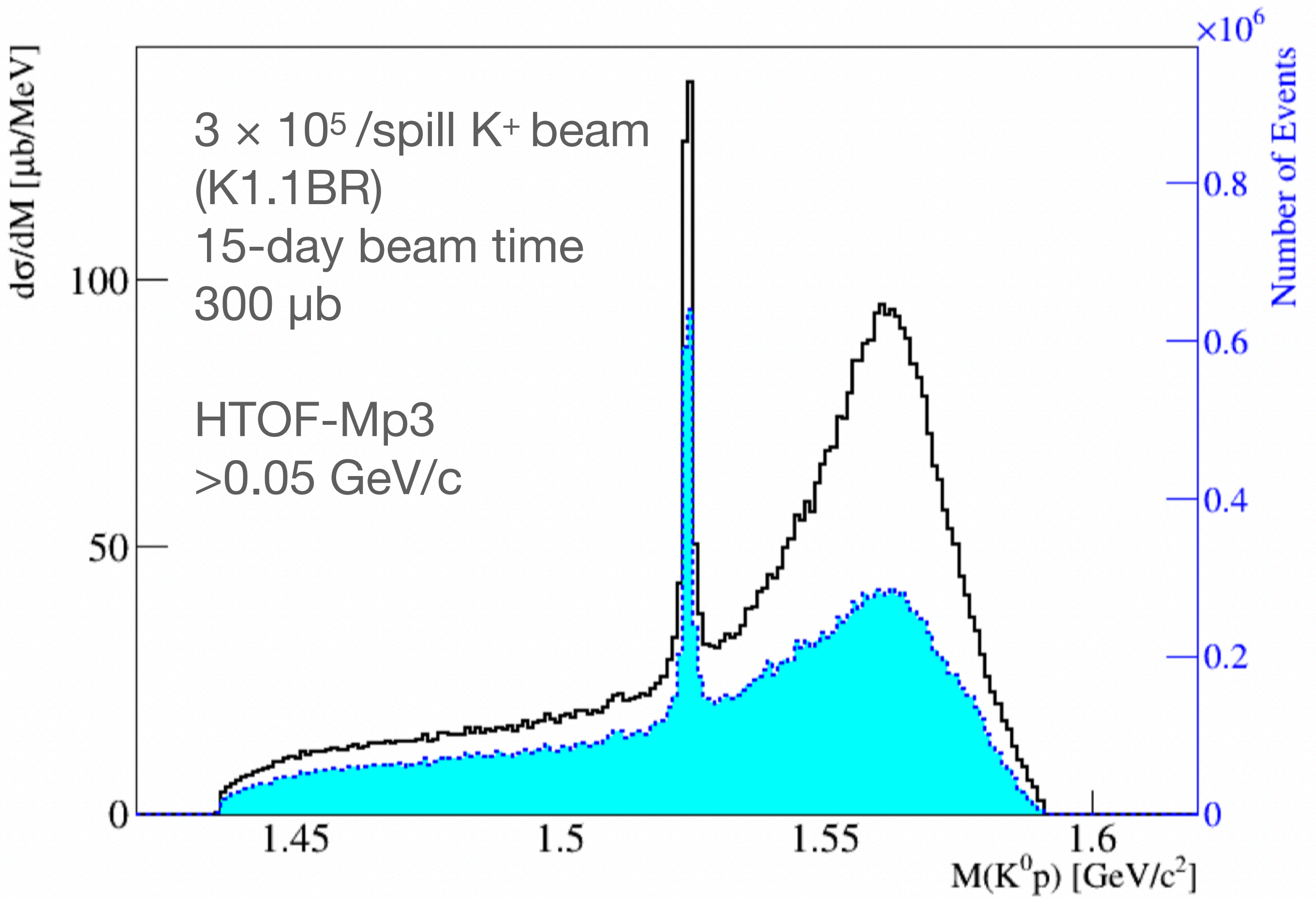


- HTOF Time-of-Flight
  flight length: 200~500 mm
  σ_t ~ 120 ps for π^-



Expected results



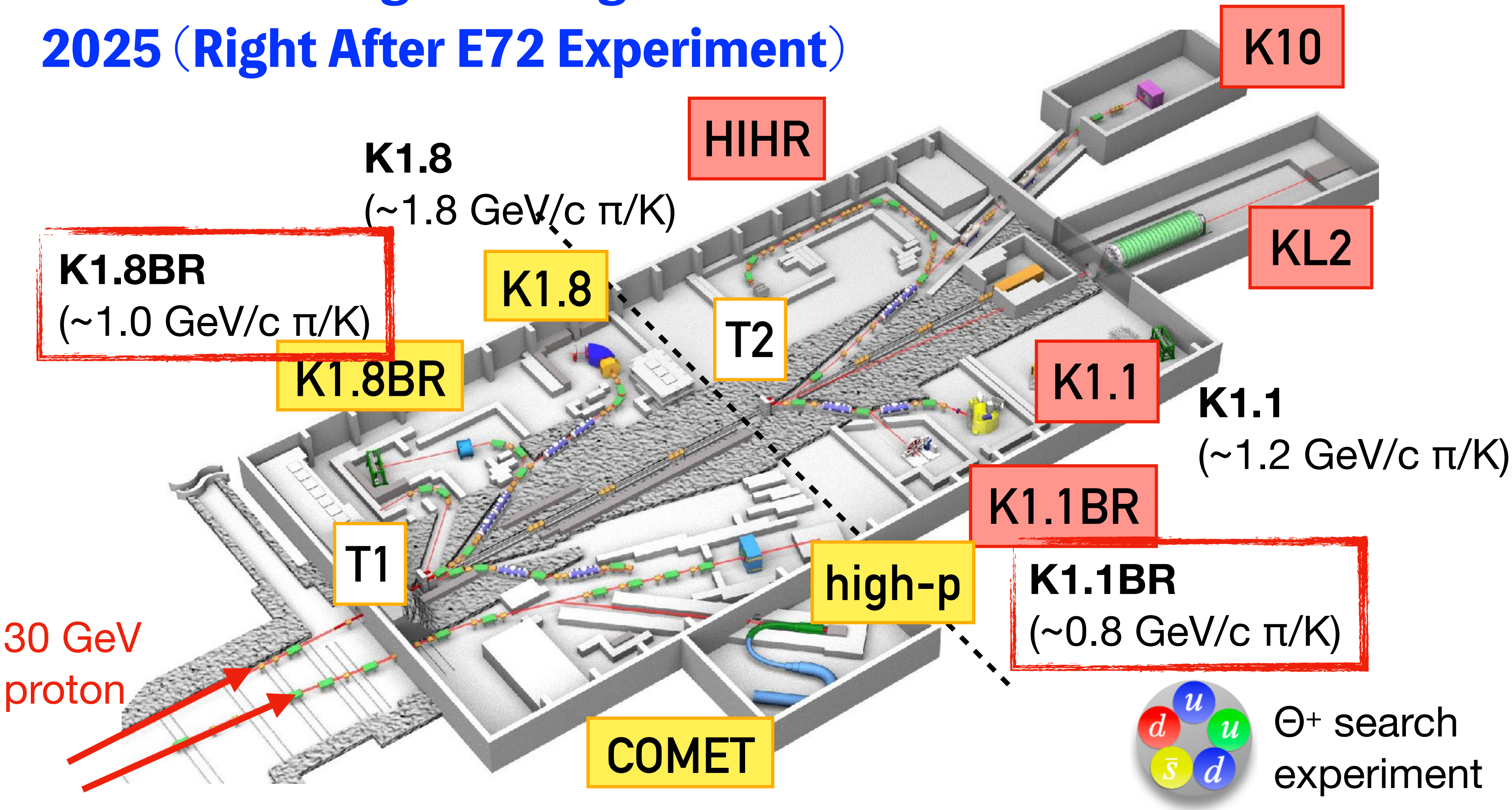


J.K. Ahn and S.H. Kim, JKPS (2023)

- We expect to collect hundreds of thousands of Θ^+ events, assuming a cross section of 300 μb in 15-day beam time at J-PARC.

Target Timeline

Commissioning Run Target:
2025 (Right After E72 Experiment)



Physics Run Target:
7+ Years Later (After the Extension)

Yield Estimation

$$N = \sigma \times \frac{\rho \times L \times N_A}{A} \times N_{beam} \times Acc \times decay$$

- LD_2 Target: ρL=1.03 g/cm^2, N_A=6.022×10^{23}, A=2
- K^+ Beam: N_{beam}=7 k/spill* (measured at 0.7 GeV/c at K1.8BR beamline)
- Detector Acceptance: Acc=0.5
- K^0_S Decay: $decay$=0.5 (K^0-K_S conversion) × 0.692 ($K_S \to \pi^+\pi^-$)

	σ	N [/spill]	N [/1 hr]	N [/1 day]
$K^+d \to K^0pp$	6 mb	2.25	1.56k	34.4k
Θ^+	300 μb	0.11	78	1.87k

- *Beam intensity drops by an order of magnitude at 0.5 GeV/c. We are considering using a degrader. ➔ Background effects?

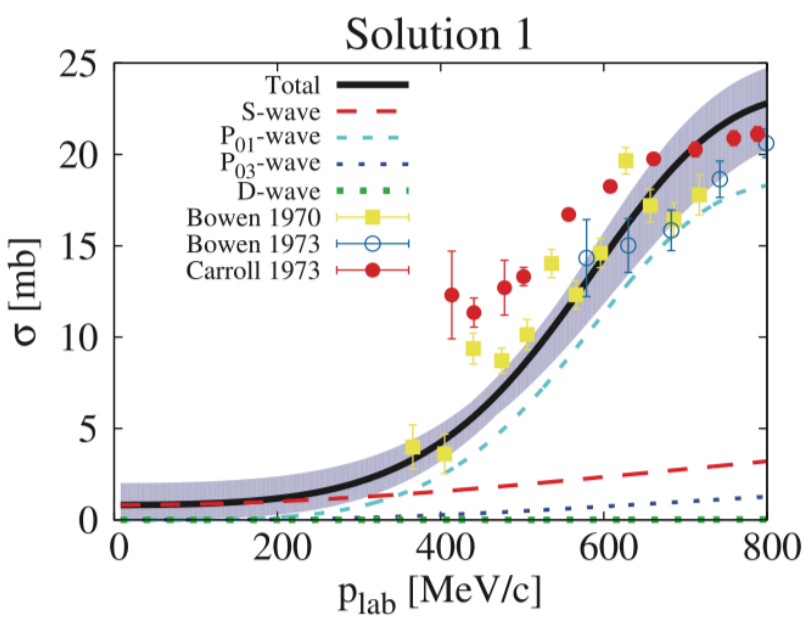
Recent Calculation of K^+N Scattering

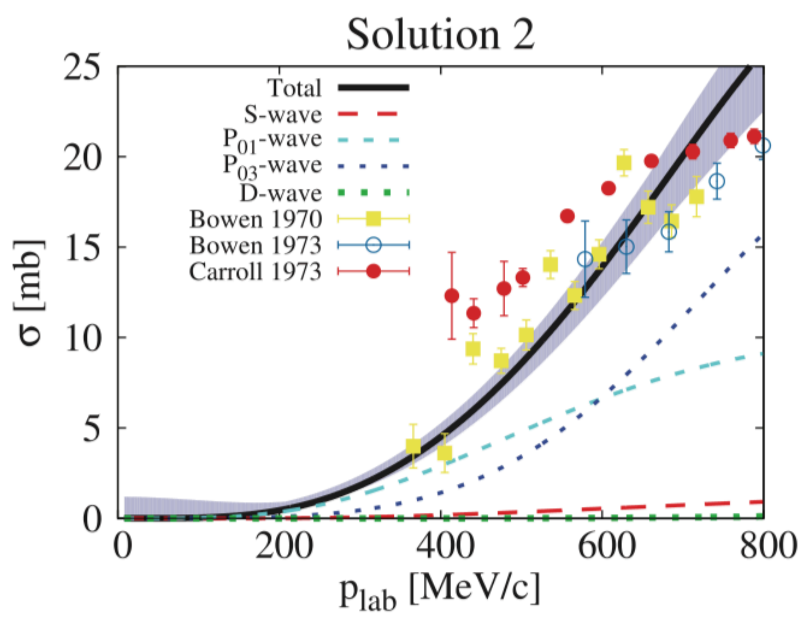
- KN scattering amplitude at low energies was revisited based on the chiral unitary approach to investigate the possibility of the existence of a S=+1 broad resonance in the I = 0 channel (Z*).

K. Aoki and D. Jido, Prog. Theor. Exp. Phys. 2019, 013D01

Y. Iizawa, D. Jido, and S. Hübsch, arXiv:2308.09397

- The I=0 total cross sections

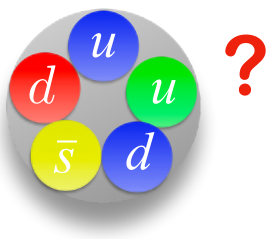


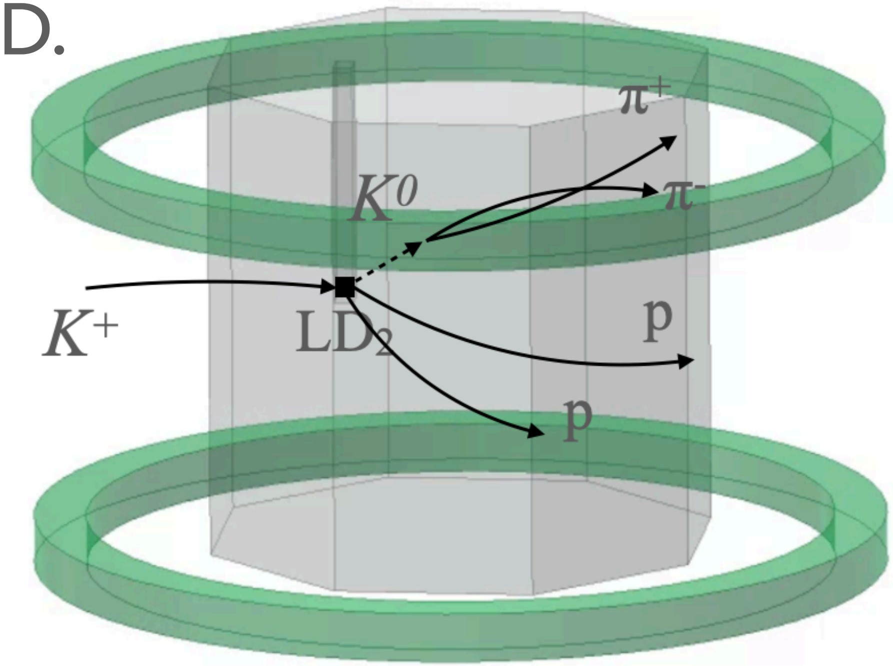


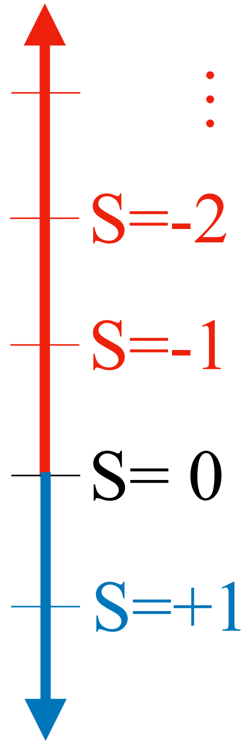
- Solution 1 supports a dominant P_{01} (1/2$^+$, M=1617, Γ=305) amplitude, whereas Solution 2 predicts a large contribution from P_{03} (3/2$^+$, M=1678, Γ=403).

Summary

- We propose a direct formation of Θ^+ in $K^+d \rightarrow K^0pp$ reactions at 0.5 GeV/c at J-PARC using the new Hyperon Spectrometer.
- Low energy K^+N system is free from the resonances, so it will provide a good playground to study the non-perturbative QCD.







Any ideas are welcome!