QNP 2024
10th International Conference on Quarks and Nuclear Physics
Universitat de Barcelona, July 8-12, 2024

Final Attempt to Search for the S=+1 Pentaquark at J-PARC

HypTPC Collaboration

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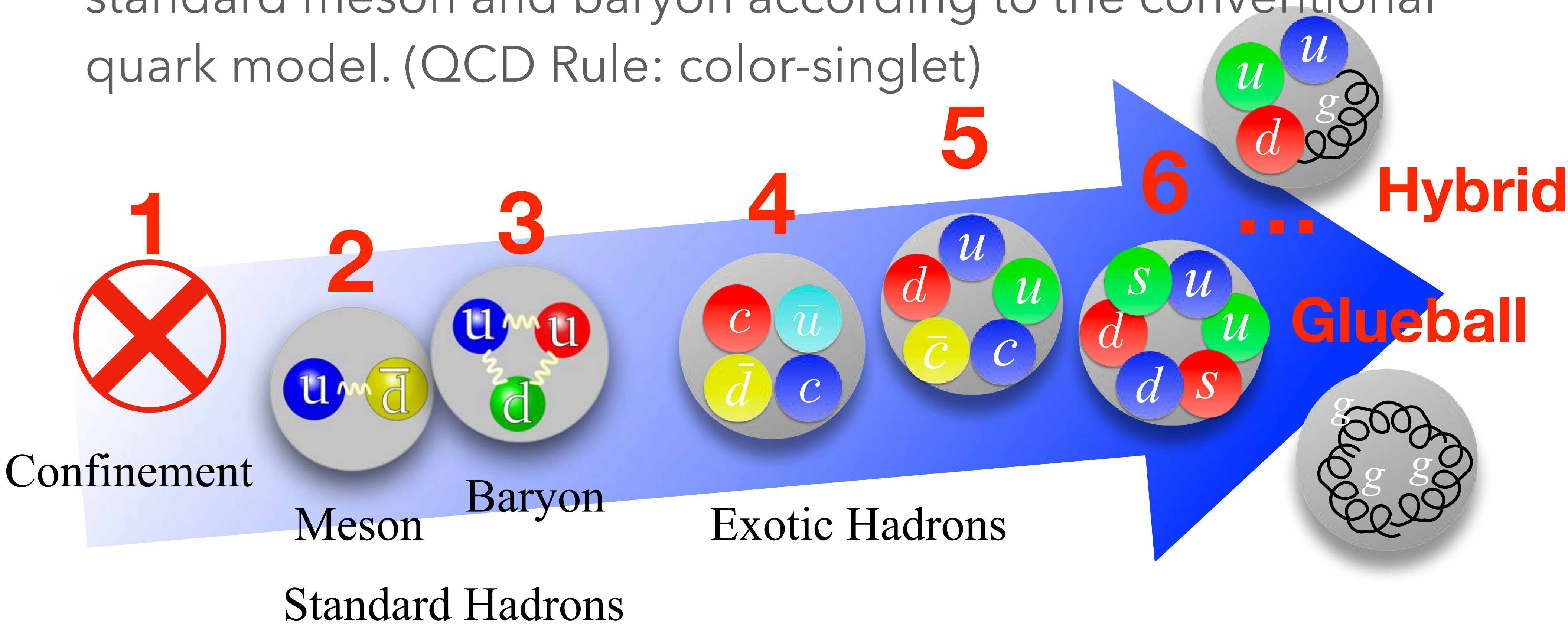
Exotic Hadrons

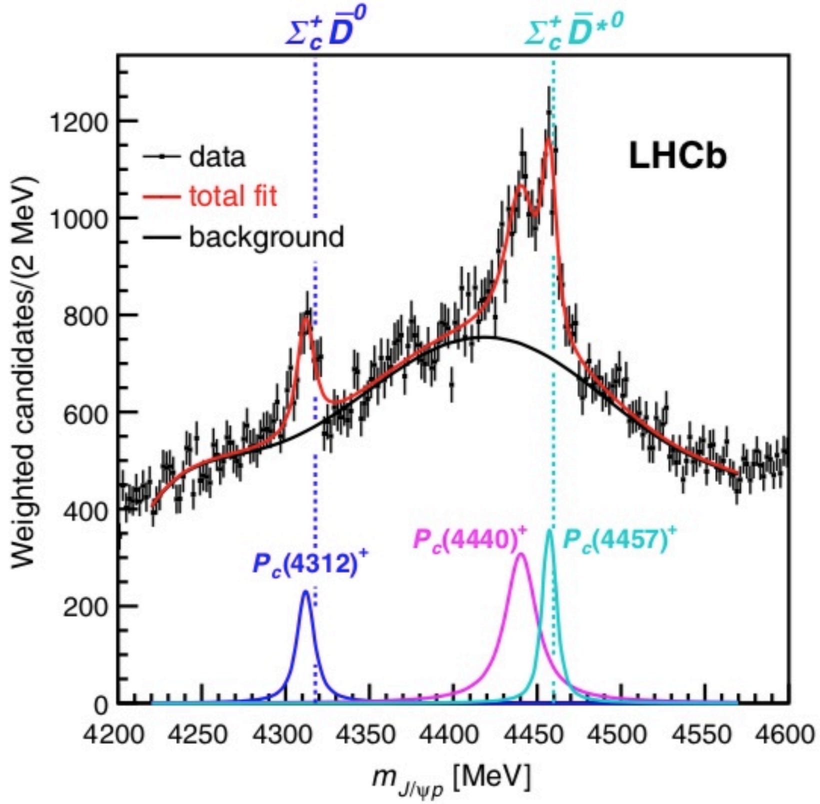
- Exotic hadrons are states that cannot be classified in terms of standard meson and baryon according to the conventional quark model. (QCD Rule: color-singlet)



- QCD allows exotic hadrons to exist, so discovery of exotic hadrons will give a deeper understanding of non-perturbative QCD.

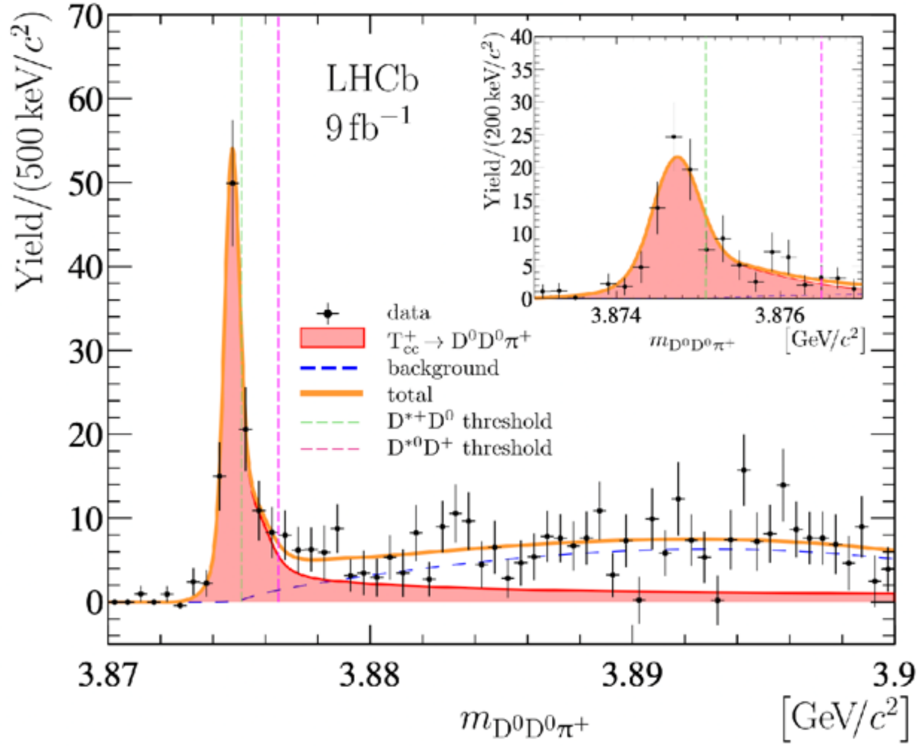
Candidates in the Heavy-Quark Sector

- The charmonium-pentaquark P_cs



LHCb, Phys. Rev. Lett. 122, 222001 (2019)

- The doubly charmed tetraquark T_{cc}

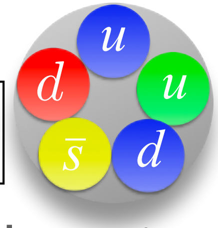


LHCb, Nature Commun. 13, 3351 (2022)

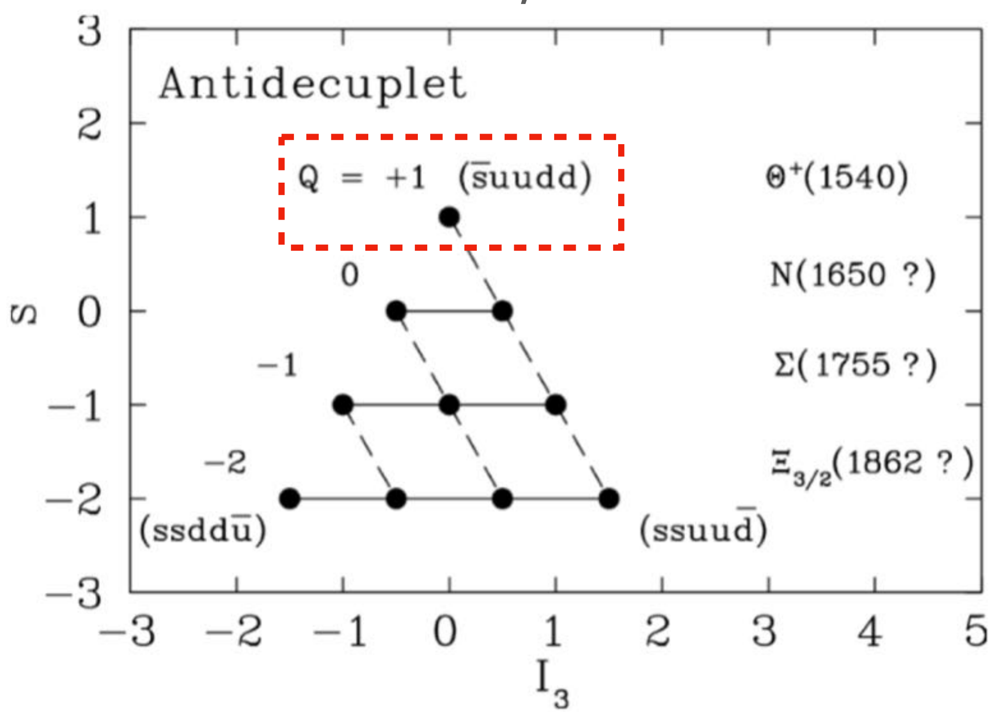
- How about exotic hadrons in the **light-quark** sector?

Θ+ Pentaquark

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

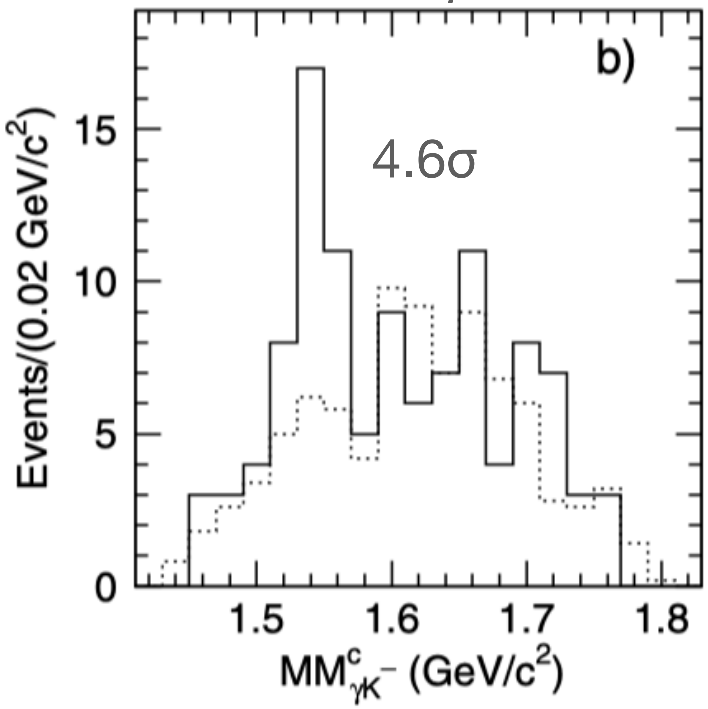


- Predicted by Diakonov et al.
  chiral soliton model
  M~1540 MeV/c², Γ<15 MeV/c²



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

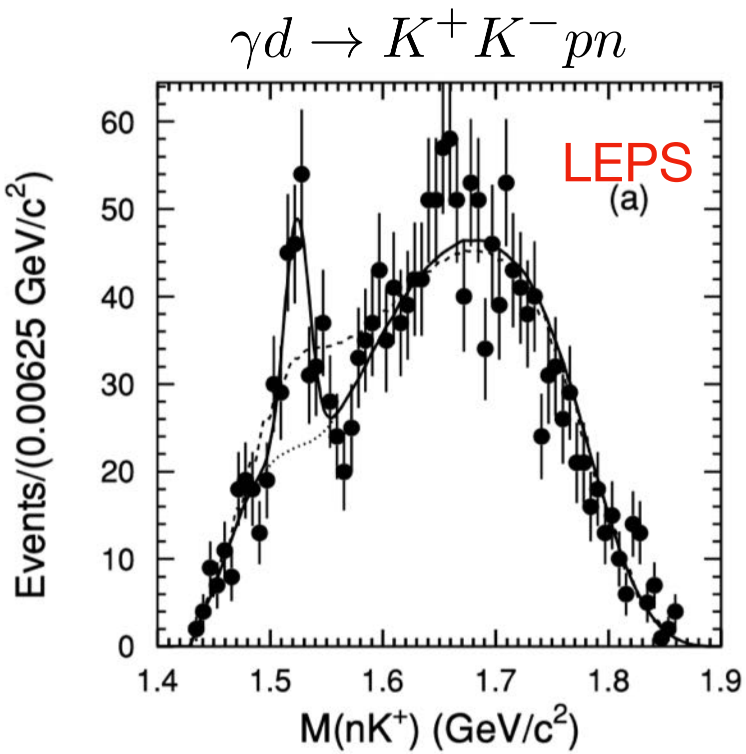
- First reported by LEPS Collaboration
  $\gamma n \rightarrow K^- \Theta^+ \rightarrow K^- K^+ n$ on ^{12}C
  M=1540±10 MeV/c², Γ<25 MeV/c²



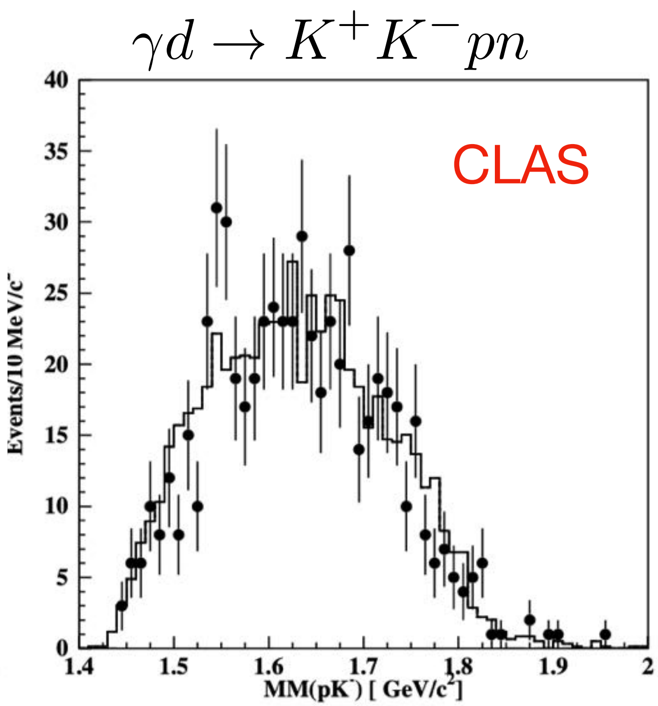
T. Nakano et al., Phys. Rev. Lett., 91, 012002 (2003).

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

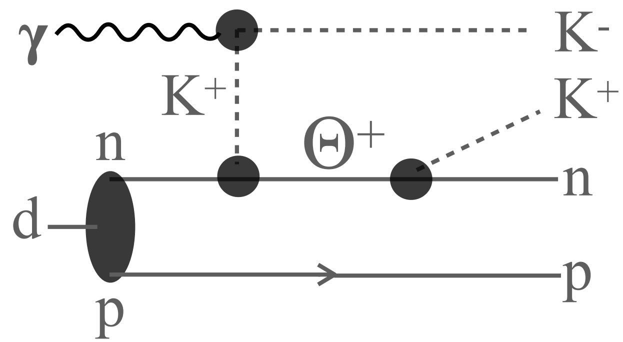
Photoproduction of Θ⁺

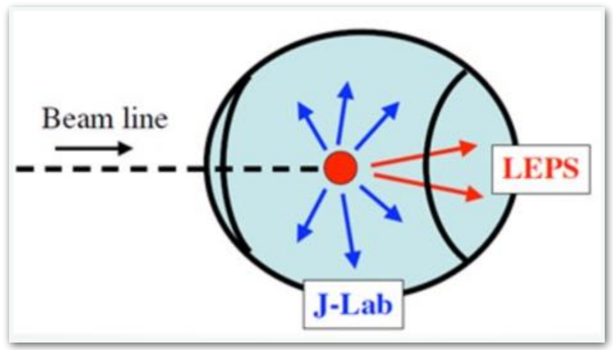


T. Nakano et al., Phys. Rev. C, 79, 025210 (2009).



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



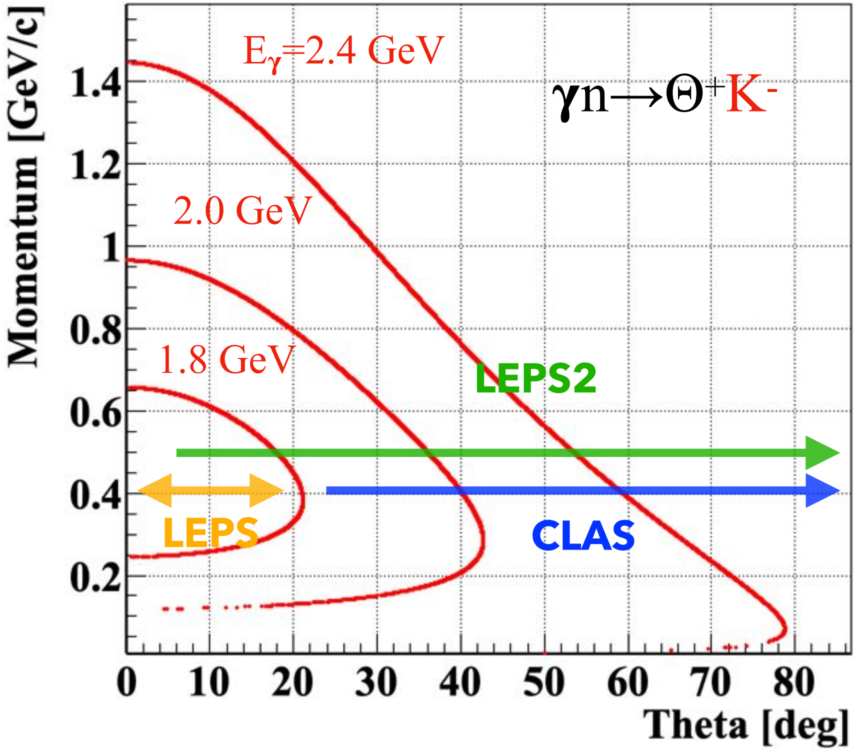


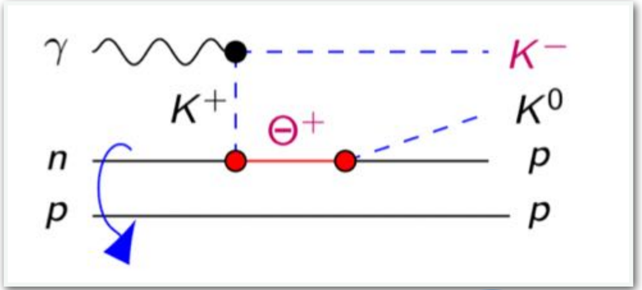
- LEPS and CLAS observed the peak near 1.54 GeV/c² at first but showed disagreement with higher statistics data later.
- Their experimental setups differed in K⁻ emission angle that ensures the production of S=+1 systems in photoproduction.

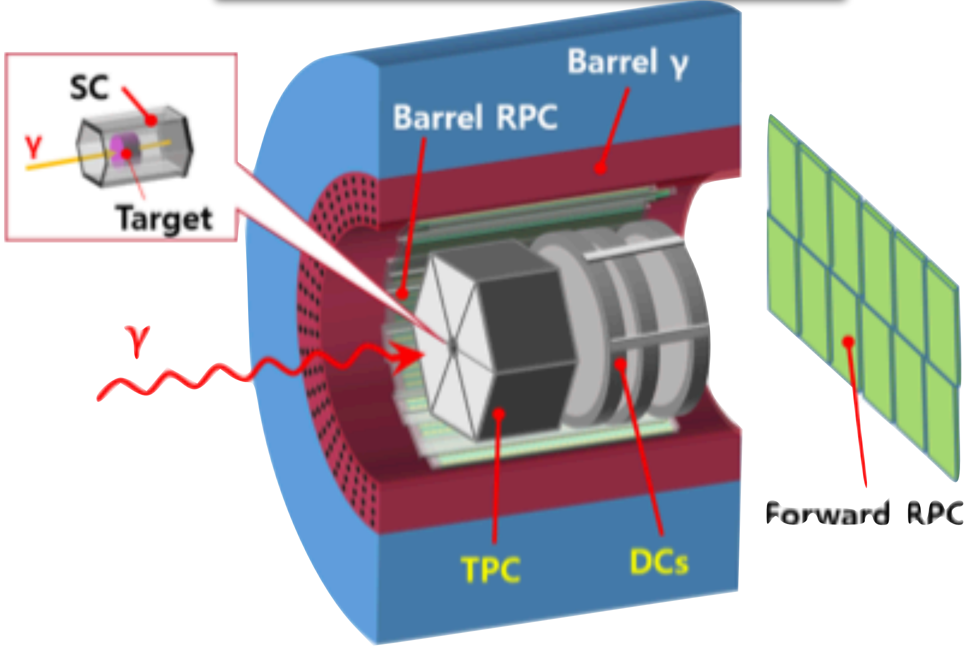
New Attempt for Θ⁺ Search at LEPS2

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

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





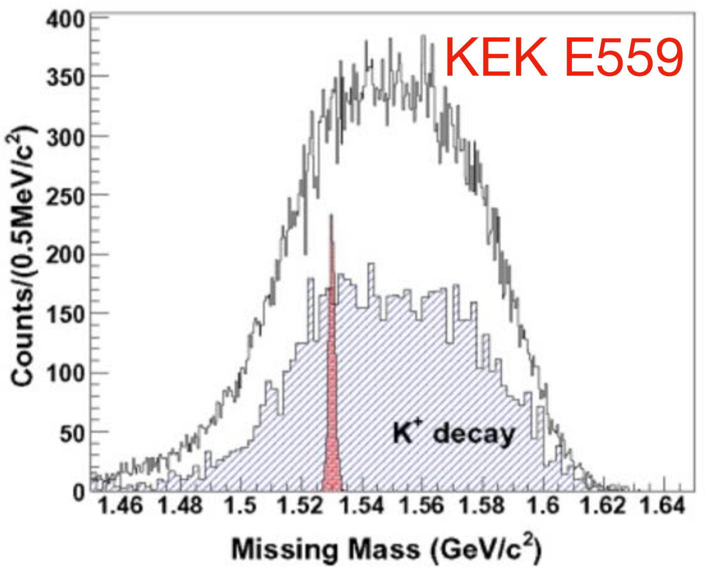


- LEPS2 spectrometer has a wider angular coverage for K⁻ detection, covering both of LEPS and CLAS acceptances.
- All final state particles can be reconstructed by LEPS2 detector.
  ➔ No Fermi-motion correction is necessary.

Hadronic Production of Θ+

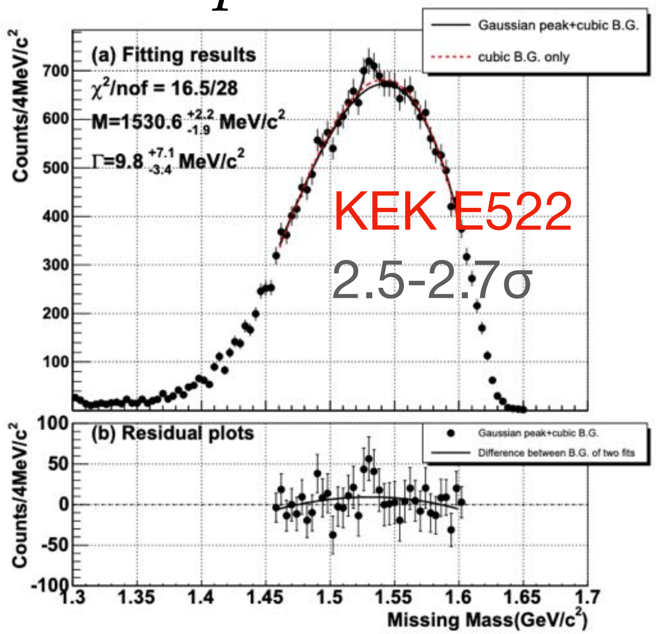
- Hadron-induced reaction has larger production cross-section and production mechanism is more straightforward over photo-induced reaction.

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



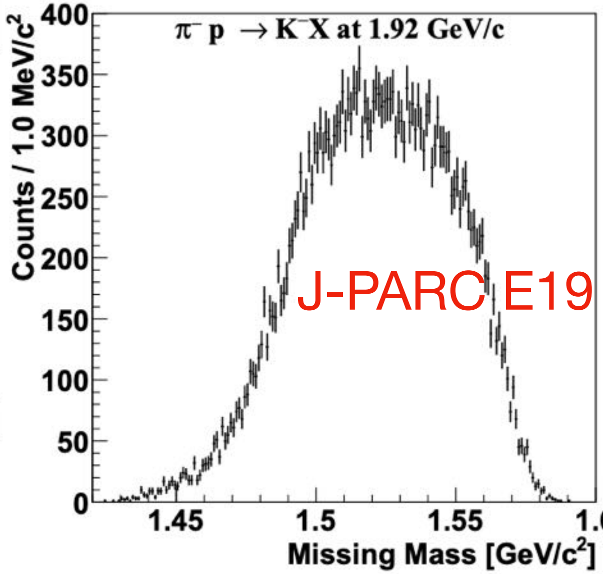
K. Miwa et al.,
Phys. Rev. C, 77, 045203 (2008).

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



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

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

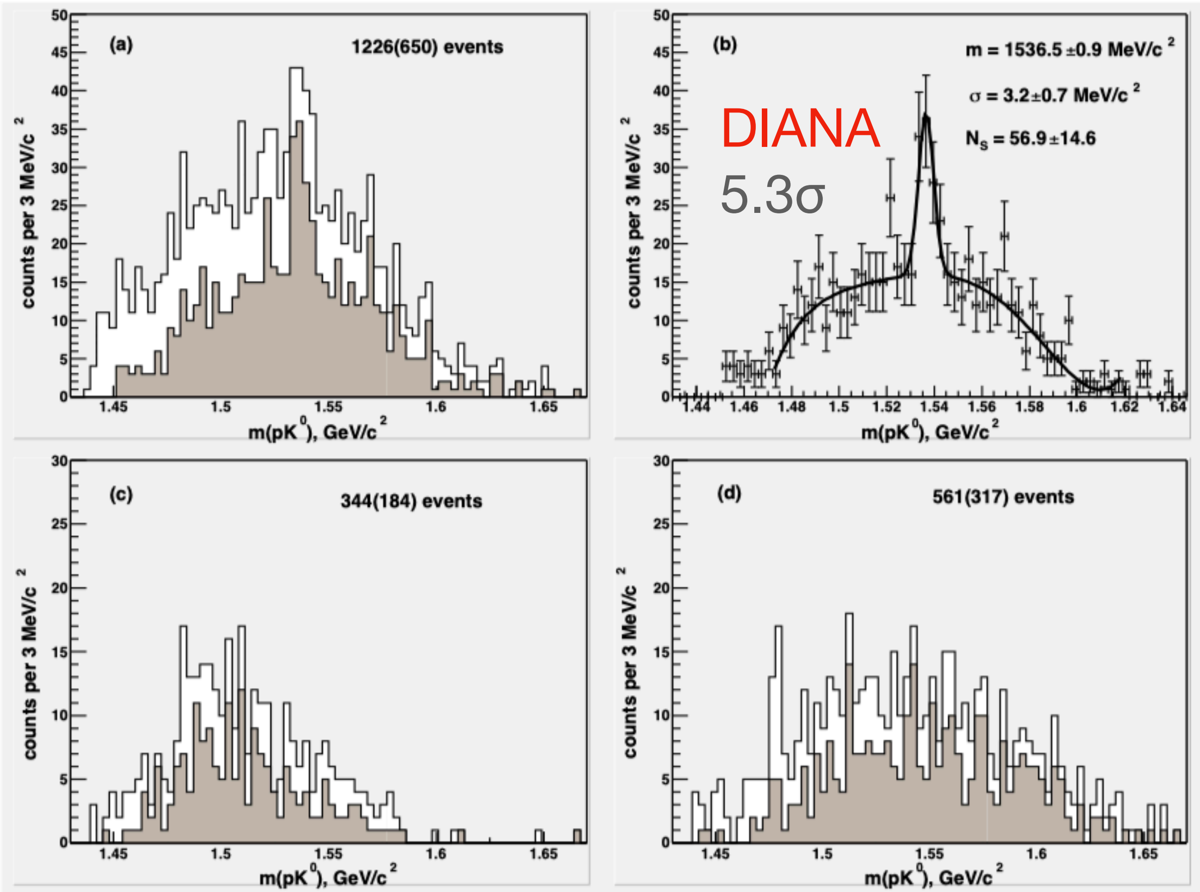


K. Shirotori et al.,
Phys. Rev. Lett., 109, 132002 (2012).

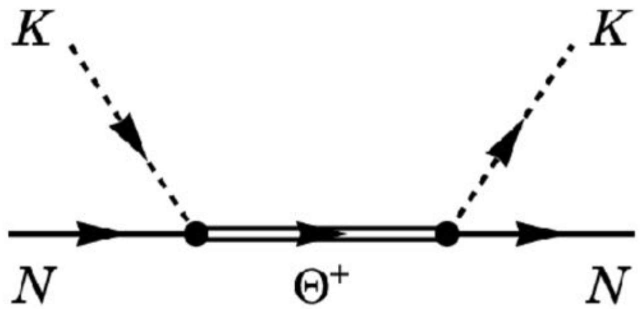
- $K^+p \to K^+n\pi^+$ or $K^0p\pi^+$
- $K^+p \to K^+n\pi^+$ or $K^0p\pi^+$
  - Δ^+, Δ^{++} background
- $\pi^-p \to K^+nK^-$ or K^0pK^-
- $\pi^-p \to K^+K^-n$
  - $a_0(980)$ or ϕ background

Direct Formation of Θ^+ on Nuclei

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



$$K^+\mathrm{Xe} \rightarrow K^0_s p X$$



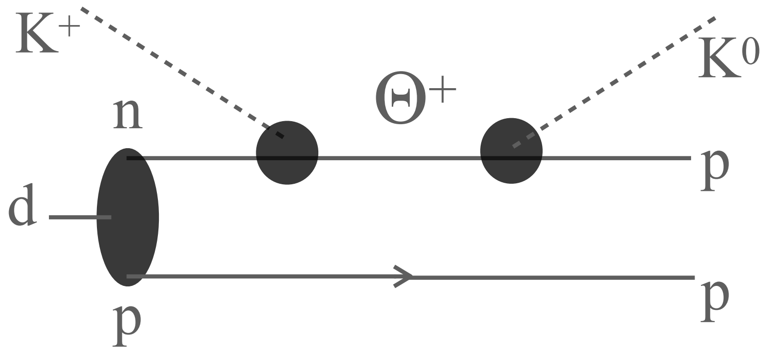
- M_Θ= 1537 ± 2 MeV
- Γ_Θ = 0.36 ± 0.11 MeV

- Kinematic cuts to remove the effect of the rescattering of reaction products in nuclear matter.

Direct Formation of Θ+ in KN Interaction

Modern Physics Letters A 39:14 (2024)

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



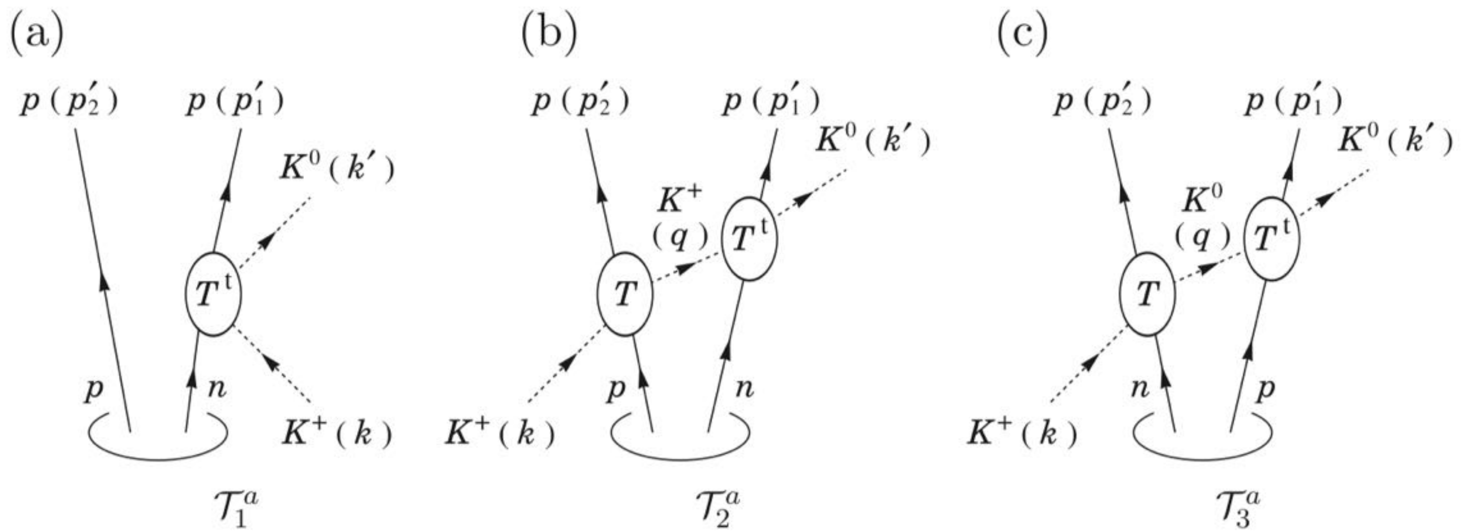
- $K^+d \rightarrow K^0pp$ is the simplest way to perform the KN (I=0) scattering.
- The Θ^+ lies 110 MeV above KN threshold & 25 MeV below KNπ threshold.
  ➔ A pion can barely be produced near the Θ^+ production threshold.

$K^+d \to K^0pp$ 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]

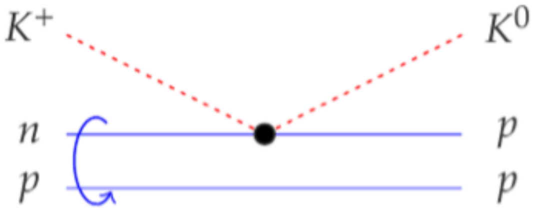


- They predicts that the Θ^+ (M_Θ=1524 MeV, Γ_Θ=0.5 MeV) production cross section is of the order of a few hundred μb to 1 mb at p_{K+}≈0.40 GeV/c where impulse scattering process is dominant, and drops to ≤ 1 μb at p_{K+}≈0.85 GeV/c at which two-step processes overtake the impulse one.

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

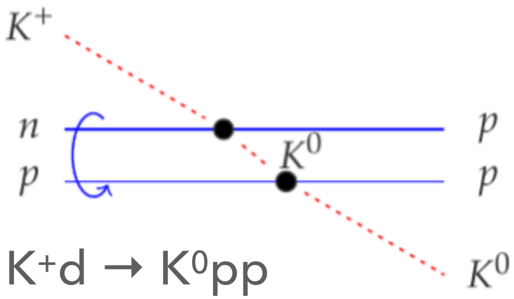
- Impulse scattering process

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

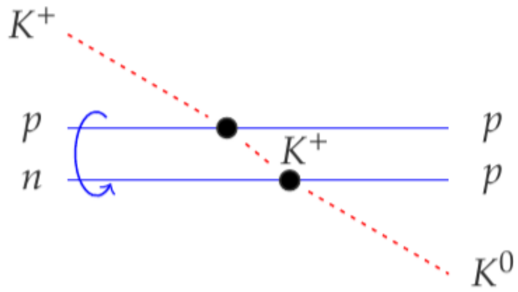


- Two-step processes

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



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



- Non-resonant breakup reaction: $K^+d \rightarrow K^0pp$
- Θ^+ production: $K^+d \rightarrow \Theta^+p$ (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 $[\mathrm{GeV/c}]^{-3}$, α=8 GeV/c]$^{-1}$,
b=3×10^4 $[\mathrm{GeV/c}]^{-3}$, and β = 37 $[\mathrm{GeV/c}]^{-1}$

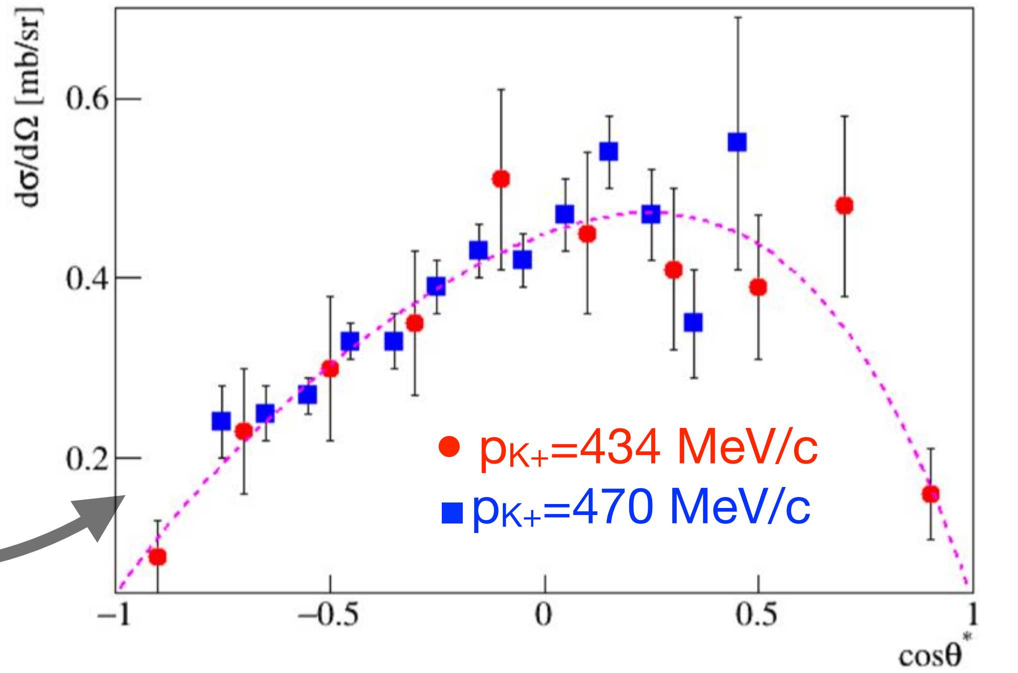
M. Bernheim et al., Nucl. Phys. A 365, 349 (1981).

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

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

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

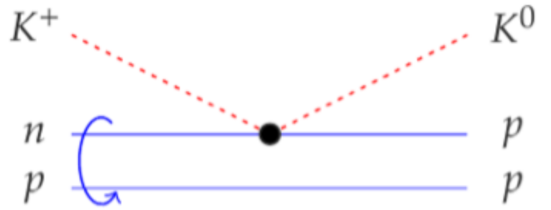
J.K. Ahn and S.H. Kim, JKPS 82, 579 (2023).



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

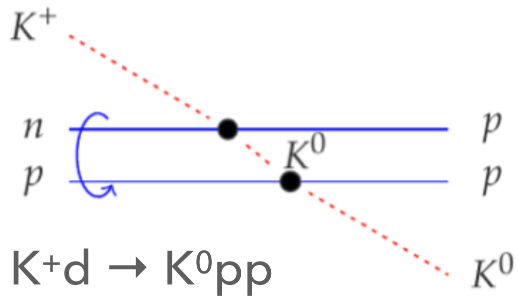
- Impulse scattering process

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

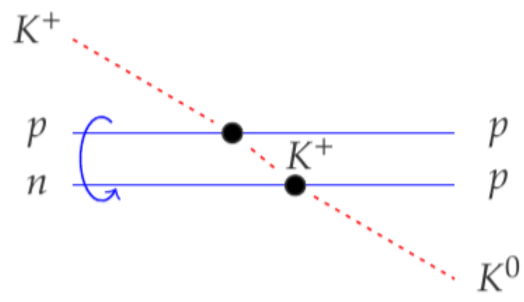


- Two-step processes

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



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



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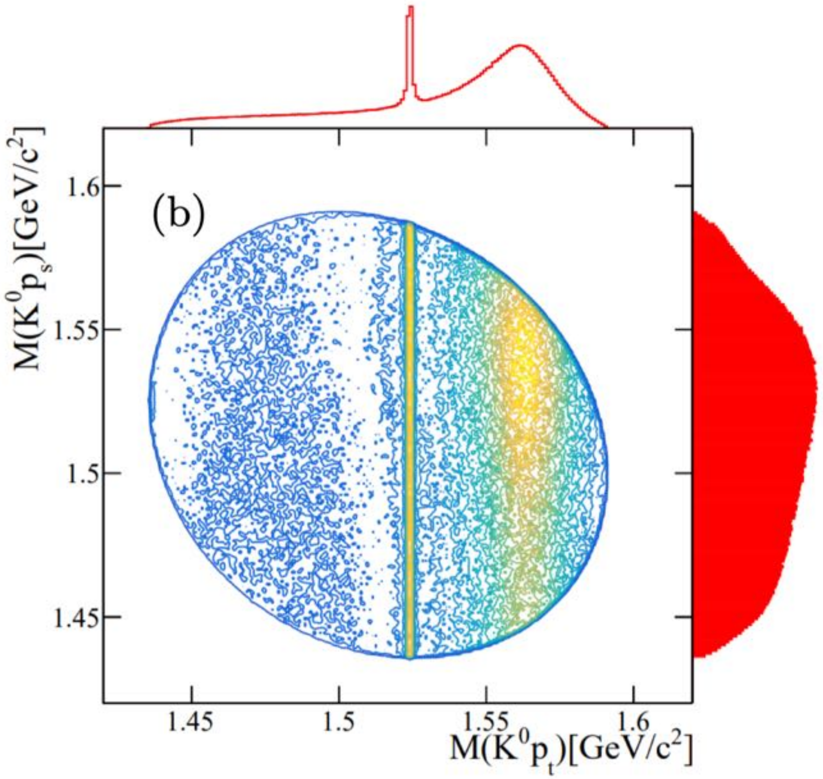
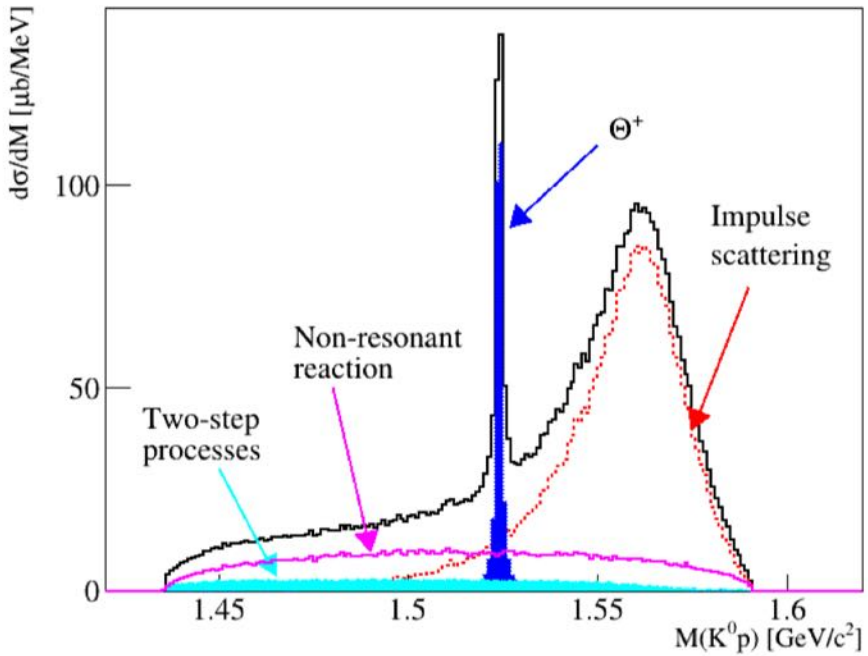
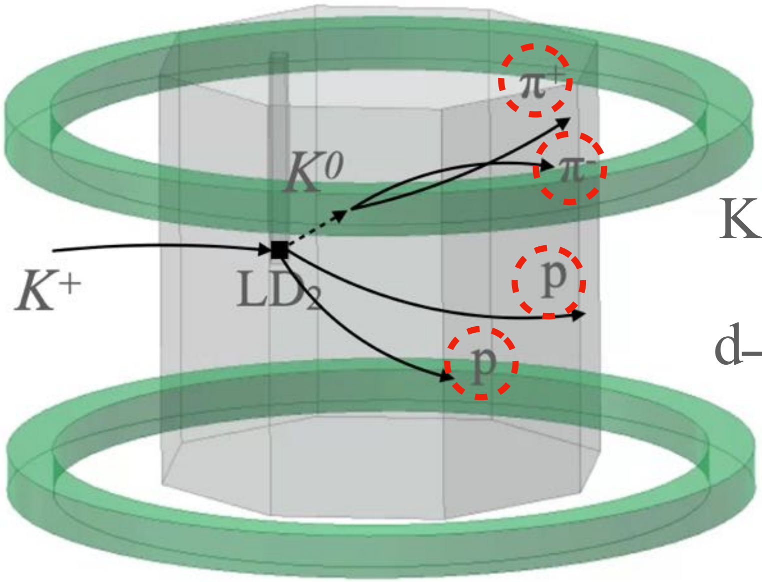


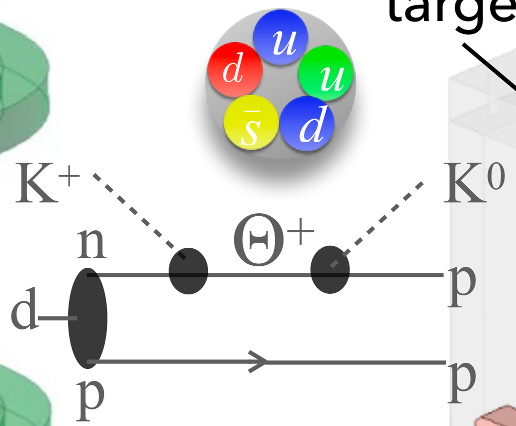


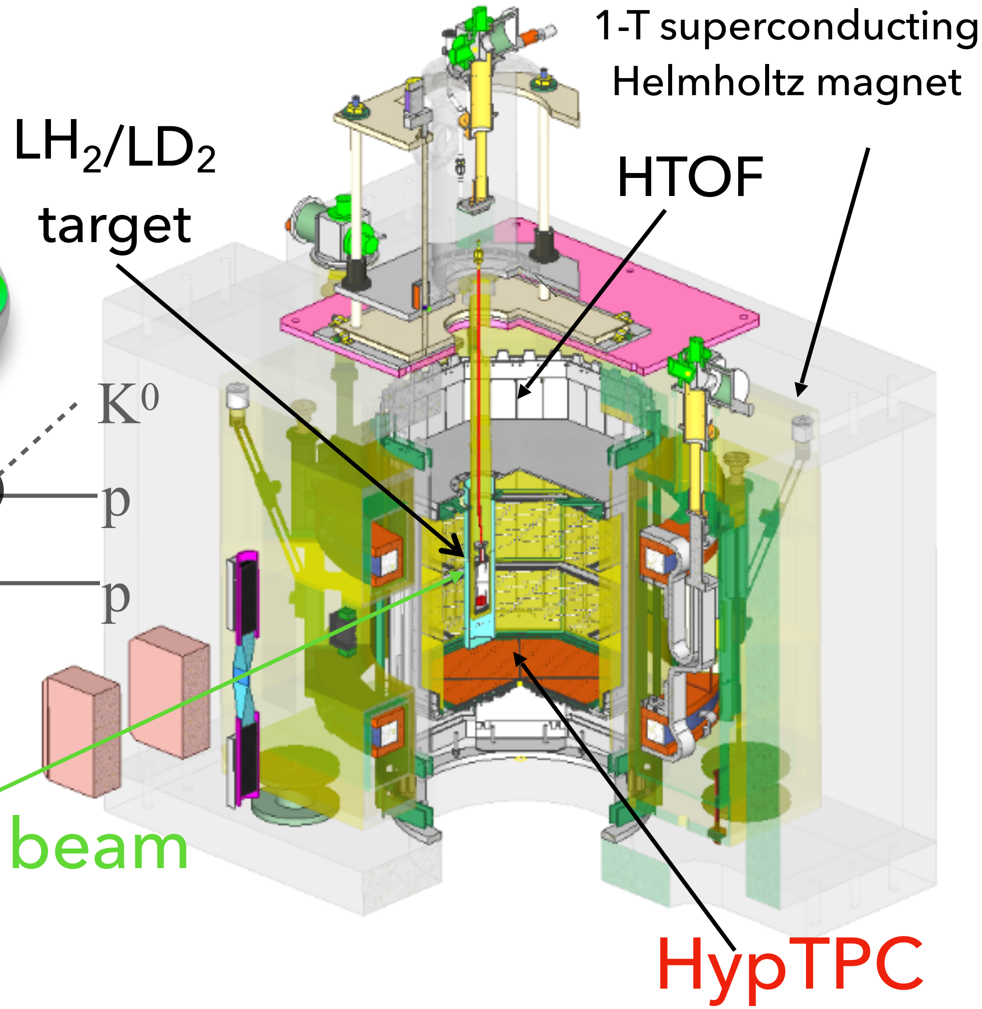
J.K. Ahn and S.H. Kim, JKPS 82, 579 (2023).

New Proposal at J-PARC

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

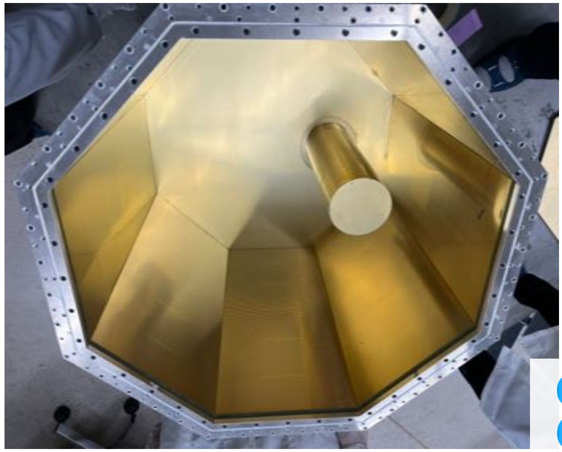


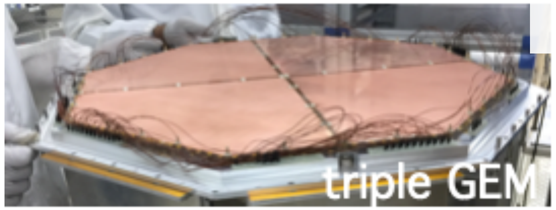


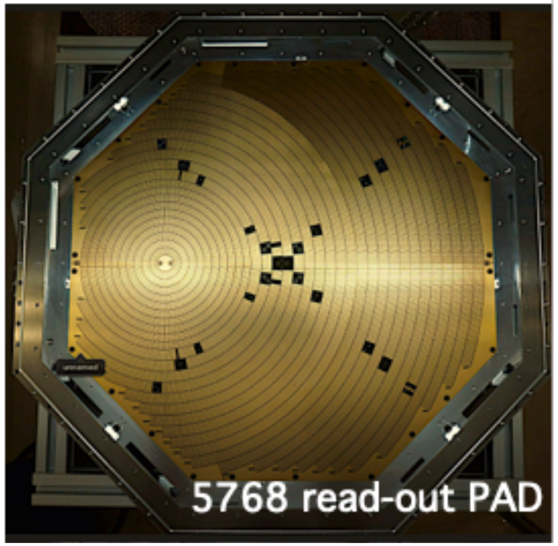


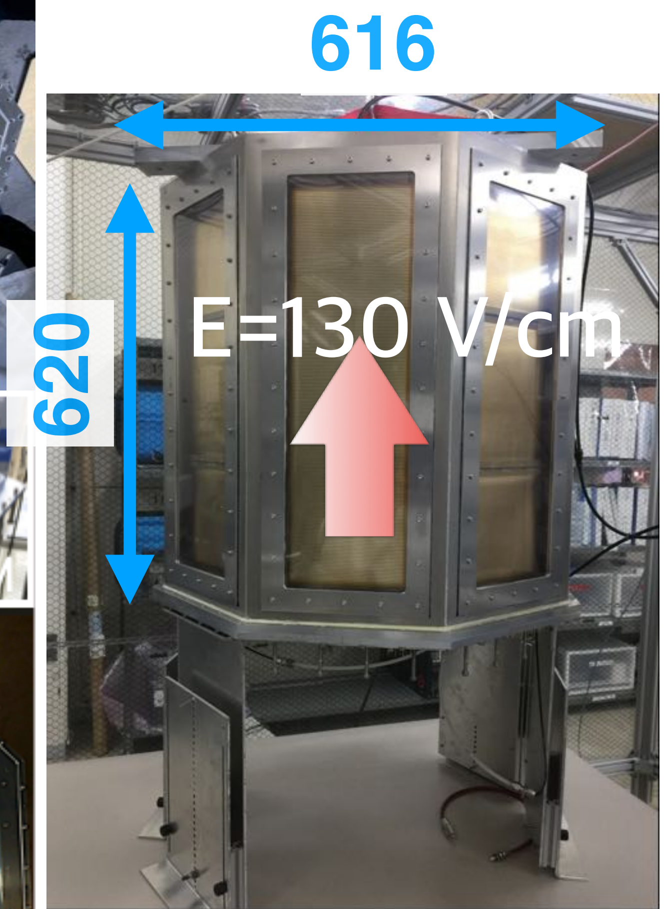
- No significant background

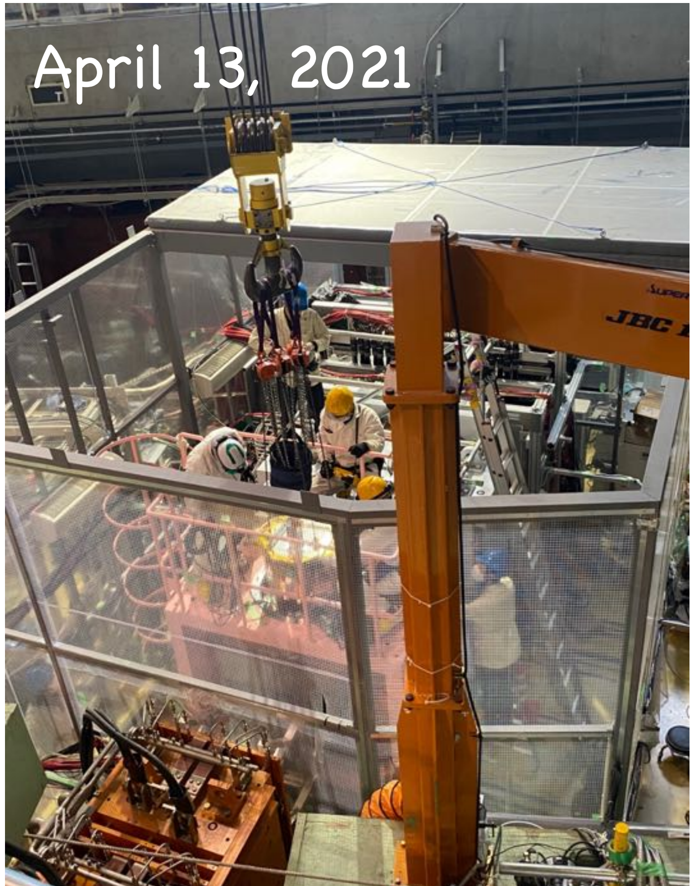
Hyperon Spectrometer

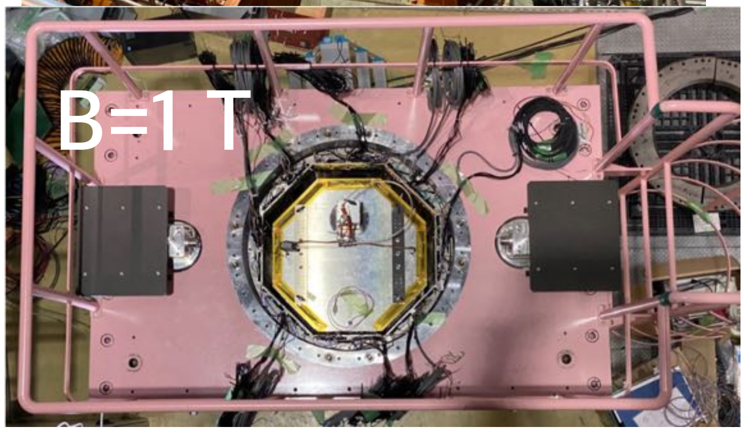








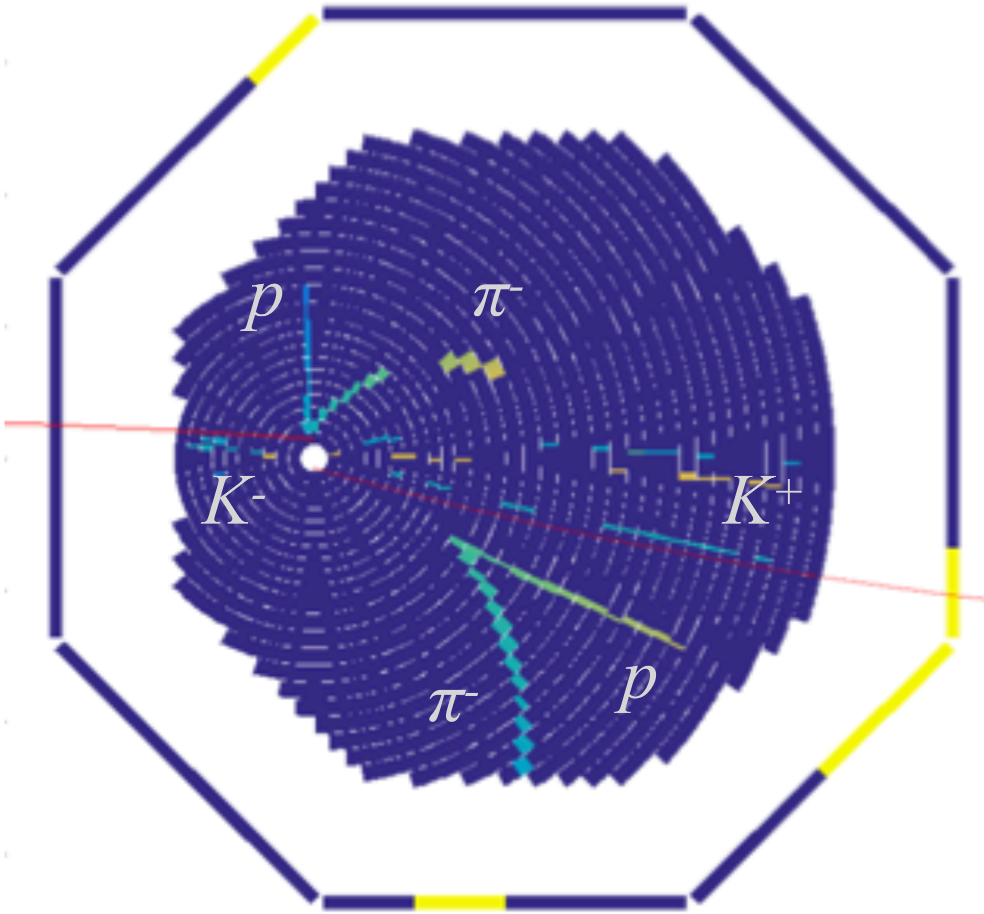




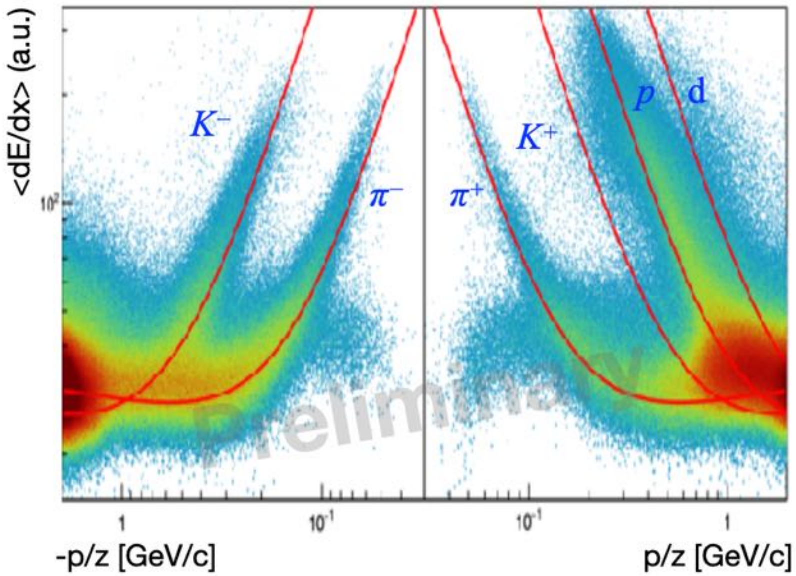
- *HypTPC* Δx ~ 300 μm, Δp ~ 1-3 %

PID by Hyperon Spectrometer

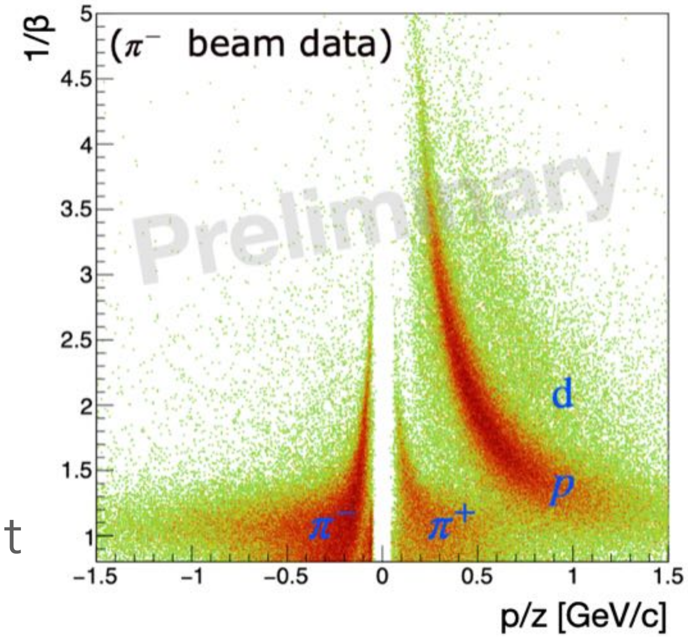
- J-PARC E42



- HypTPC dE/dx



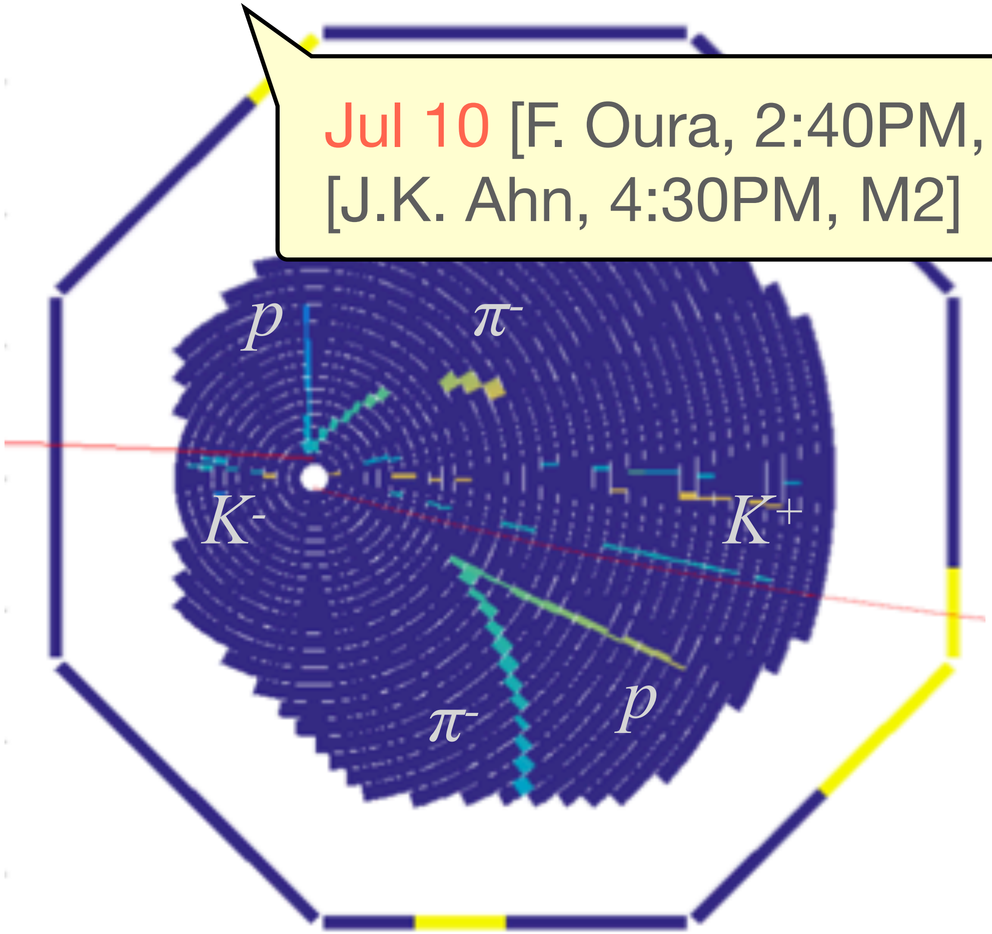
- HTOF Time-of-Flight



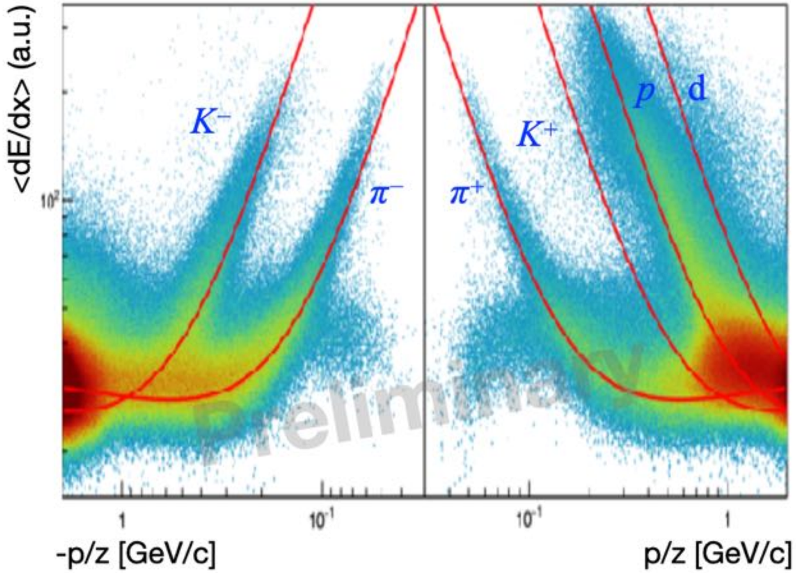
PID by Hyperon Spectrometer

- J-PARC E42

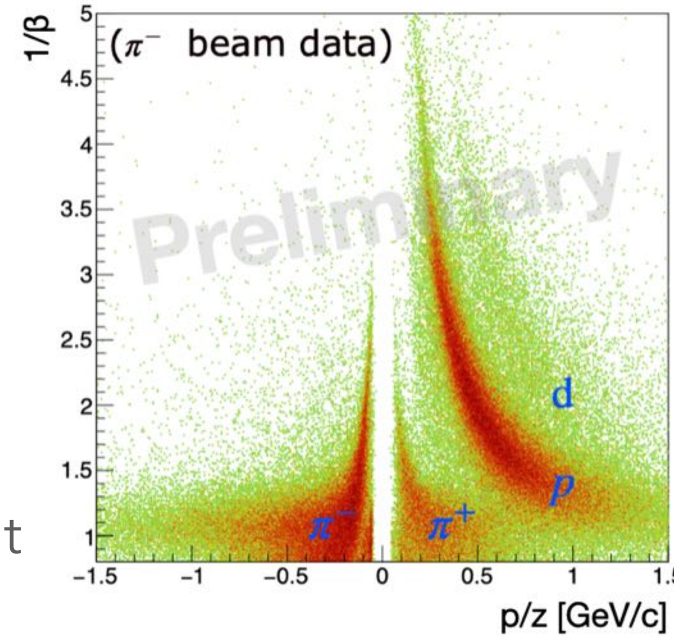
Jul 10 [F. Oura, 2:40PM, M5], [J.K. Ahn, 4:30PM, M2]



- HypTPC dE/dx

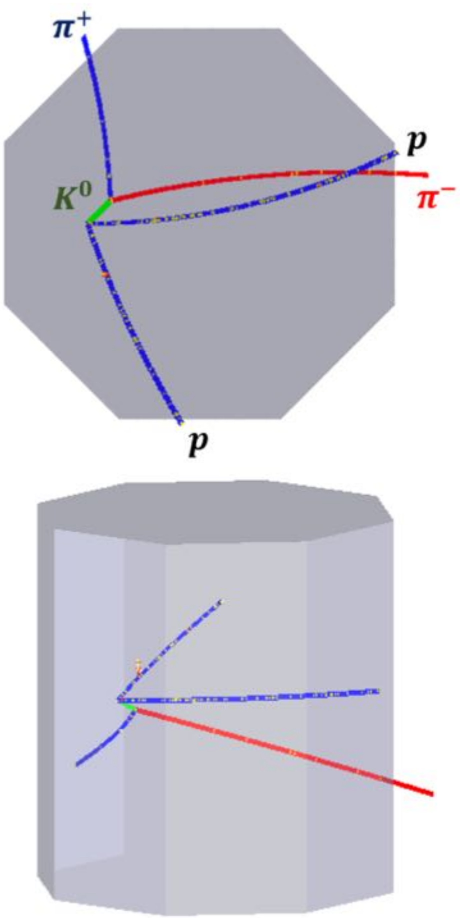


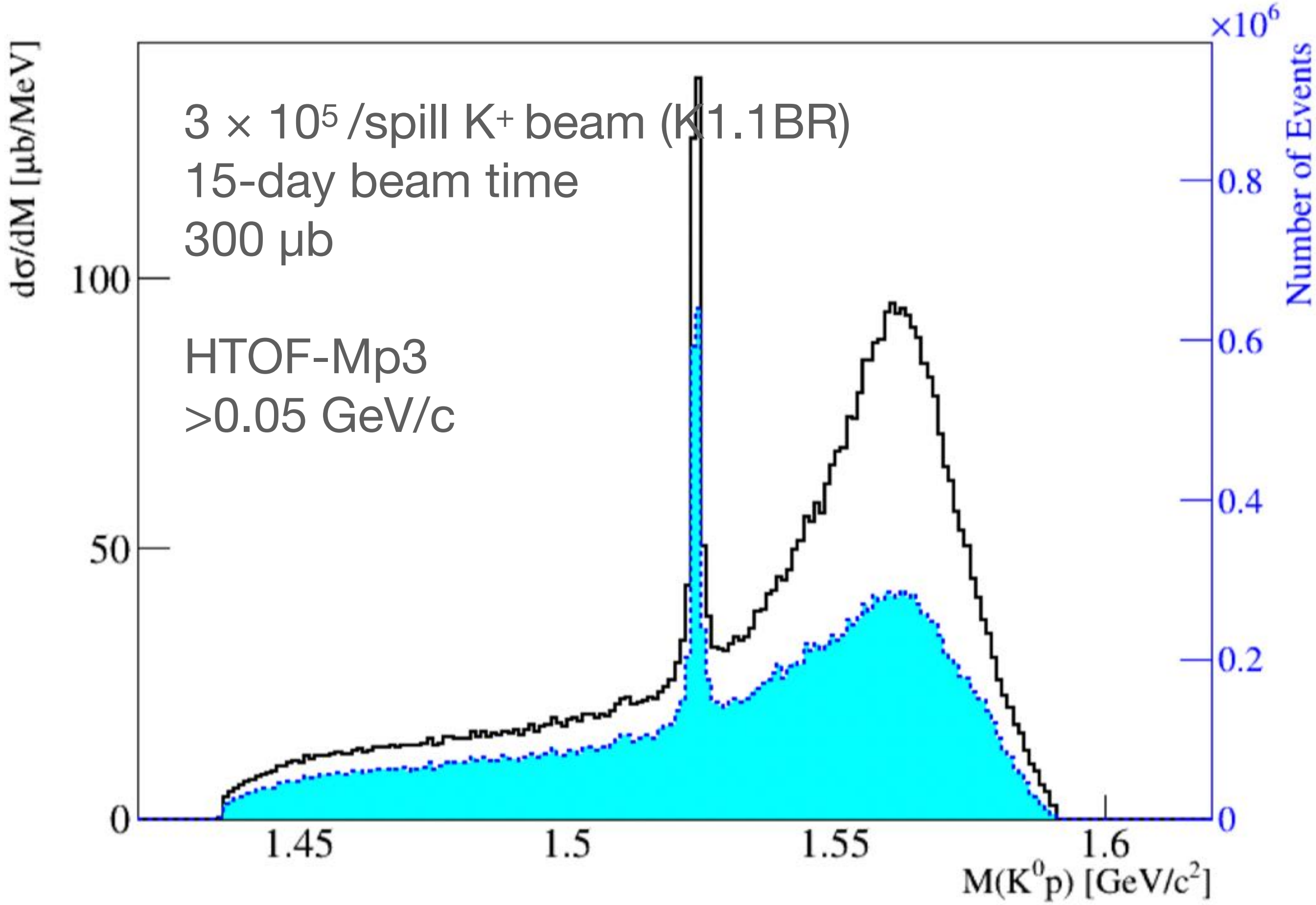
- HTOF Time-of-Flight



Expected results

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





- 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.

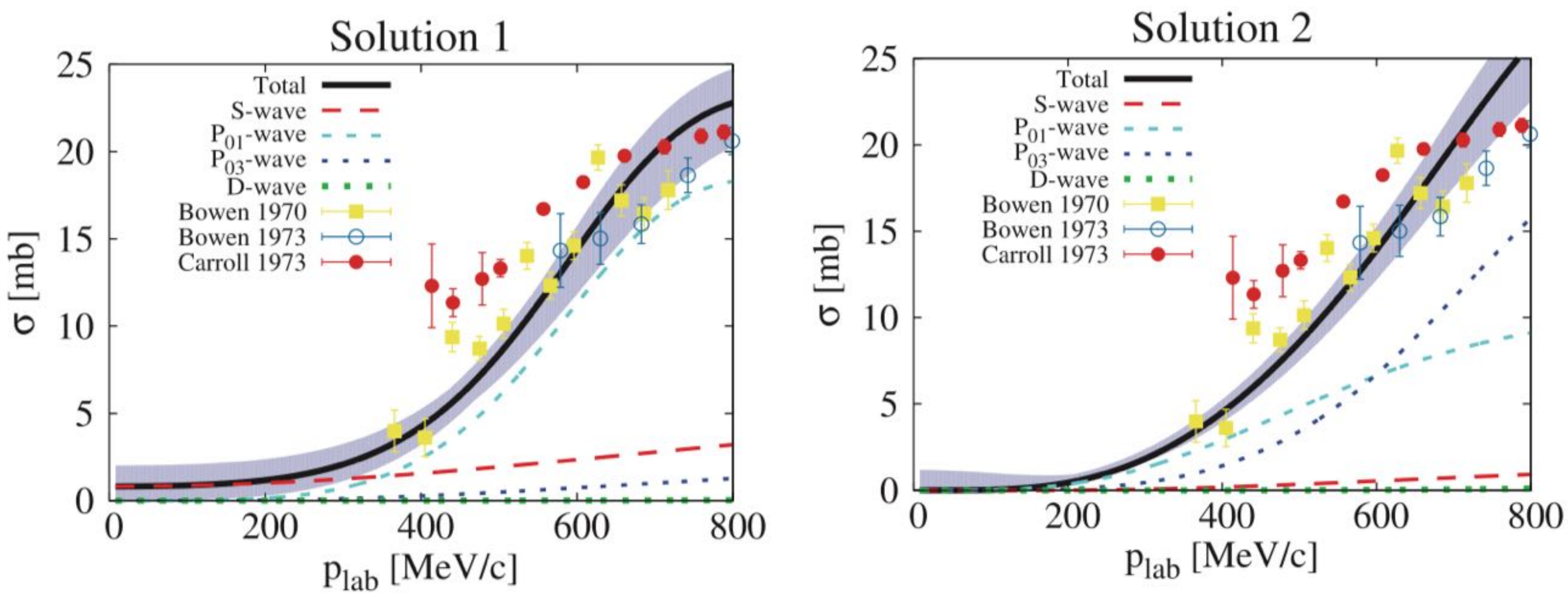
Recent Calculation of K^+N Scattering

- 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

- The I=0 total cross sections

Y. Iizawa, D. Jido, and S. Hübsch, Prog. Theor. Exp. Phys. 2024, 053D01



- 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).

Recent Calculation of K⁺N Scattering

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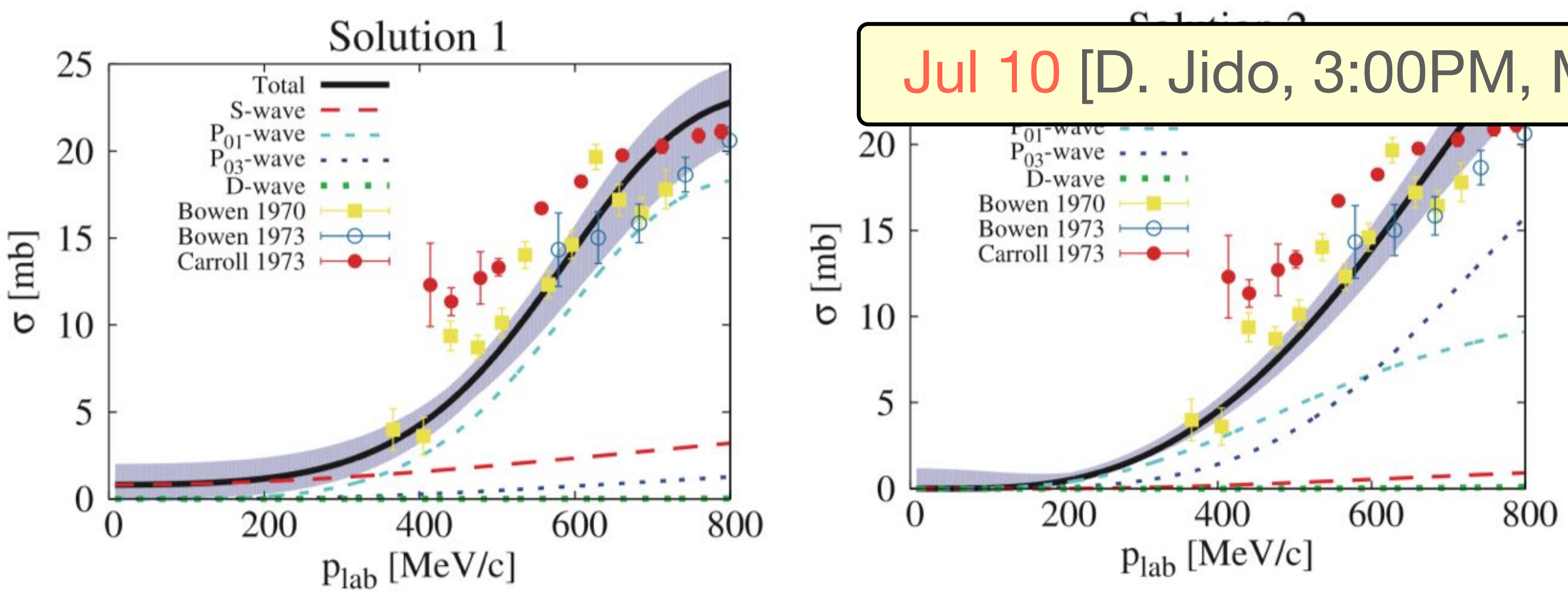
K. Aoki and D. Jido, Prog. Theor. Exp. Phys. 2019, 013D01

- The I=0 total cross sections

Y. Iizawa, D. Jido, and S. Hübsch, Prog. Theor. Exp. Phys. 2024, 053D01

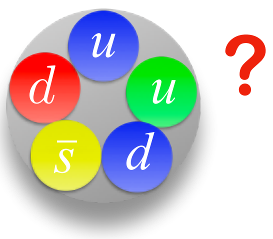
Jul 10 [D. Jido, 3:00PM, M5]

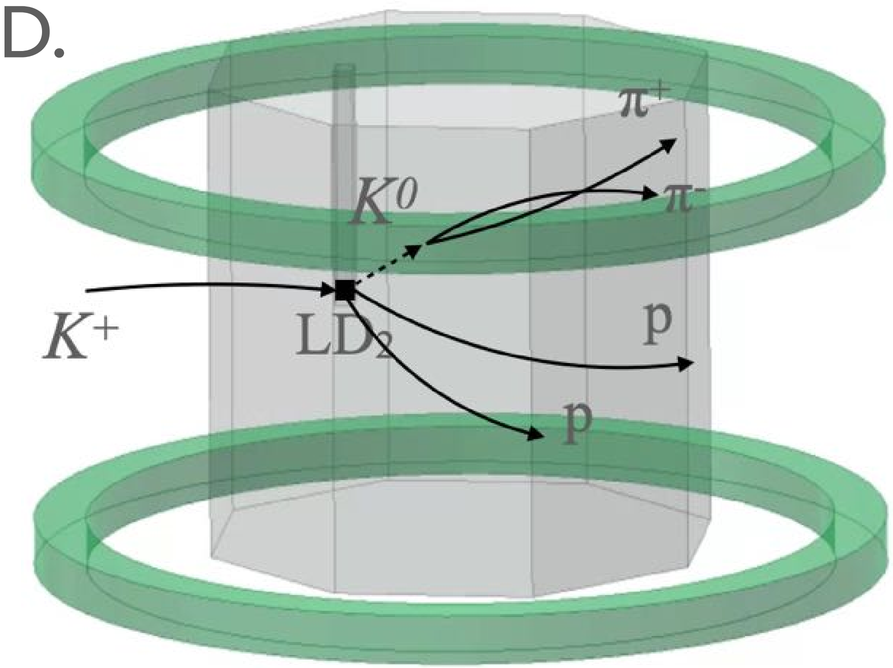


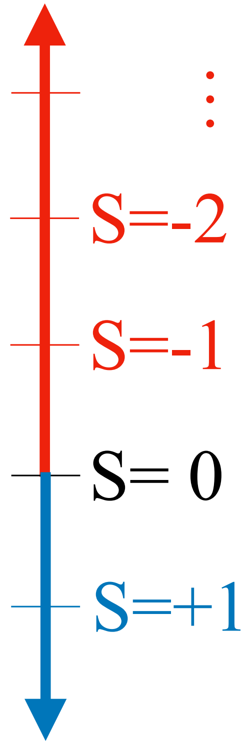
- Solution 1 supports a dominant P_{01} (1/2⁺, M=1617, Γ=305) amplitude, whereas Solution 2 predicts a large contribution from P_{03} (3/2⁺, M=1678, Γ=403).

Summary

- We propose a direct formation of Θ^+ in $K^+d \to K^0pp$ 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!