15th International Workshop on the Physics of Excited Nucleons

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NSTAR 2026

Experimental Study of the S = +1 Baryon System at J-PARC

KNU
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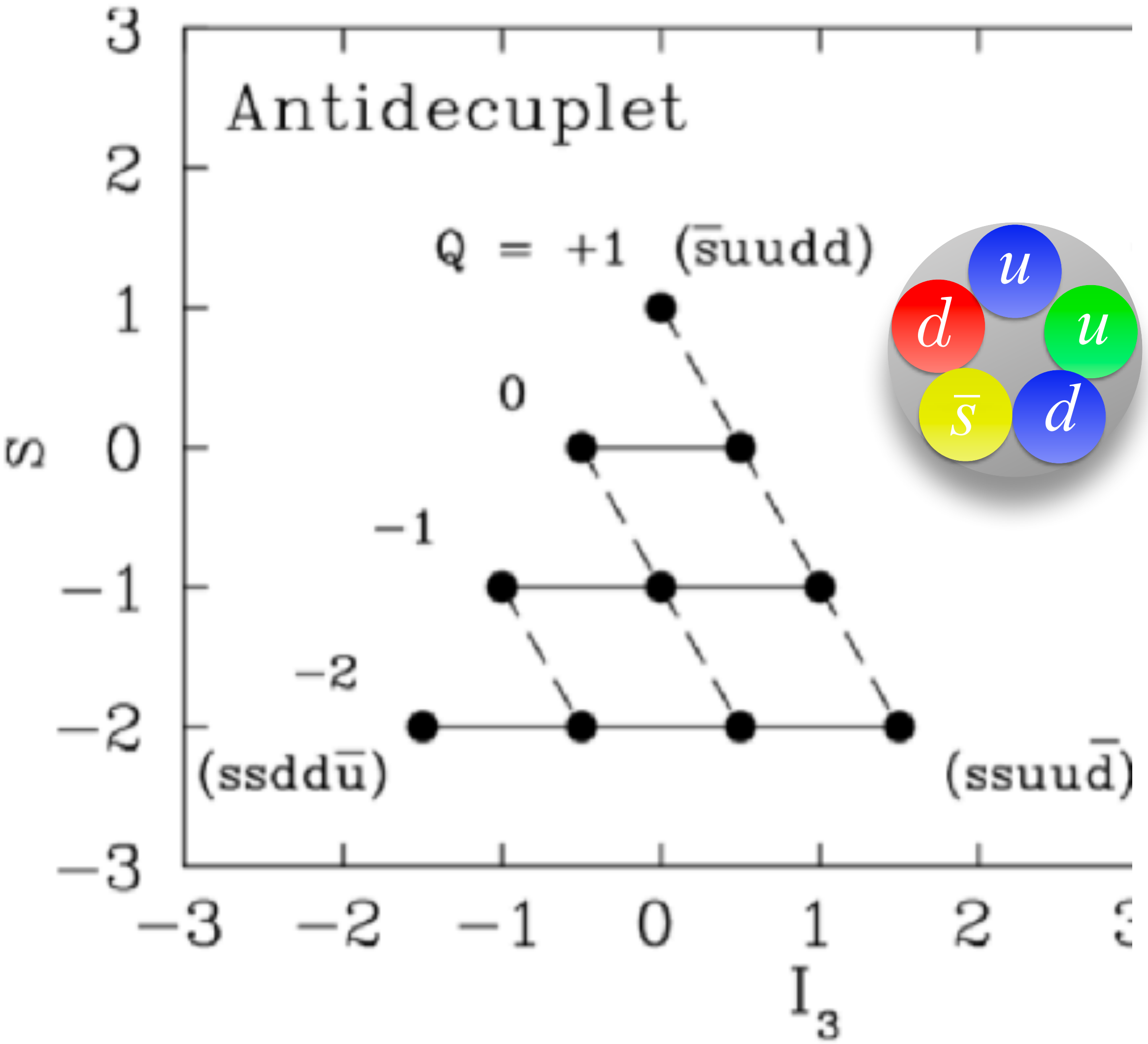
The S=+1 Baryon System

A possible exotic baryon multiplet



$\Theta^+(uudd\bar{s})$: a proposed S=+1 baryon

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

- An S=+1 baryon cannot be formed from three quarks
  → any s-channel baryon resonance with S = +1 must be exotic
- Unlike $\bar{K}N$, low-energy KN is free from conventional Λ* and Σ* resonances
  → a relatively clean system for studying exotic hadron dynamics

➔ The Θ+ is one possible manifestation of the broader S=+1 dynamics.

Θ⁺ Search History Summary

Photoproduction

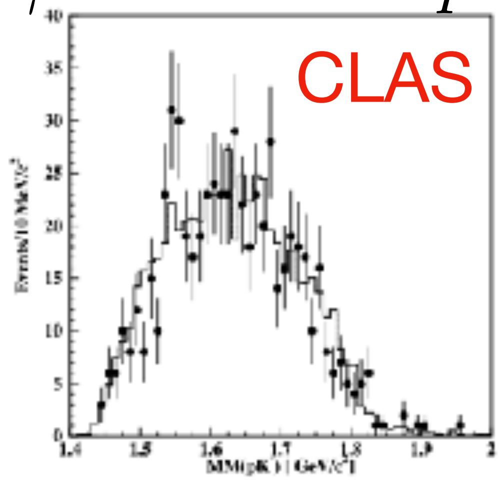
$\gamma d \to K^+ n K^- p$

$\gamma p \to K^0{}_S K^+ n$

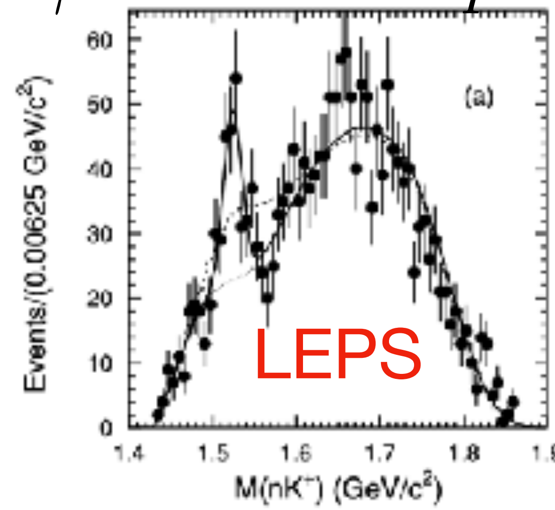
$\gamma p \to K^0{}_S K^0{}_L p$

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

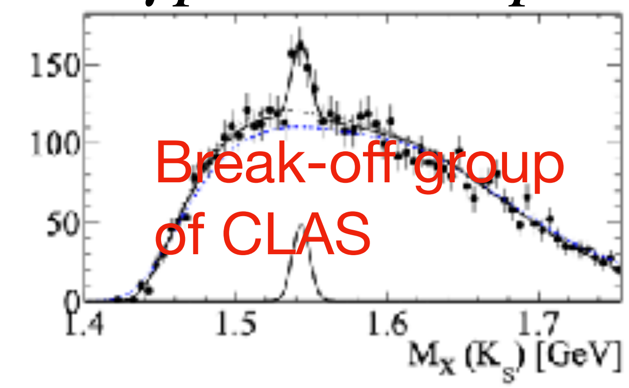
$\gamma d \to K^+ K^- pn$



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



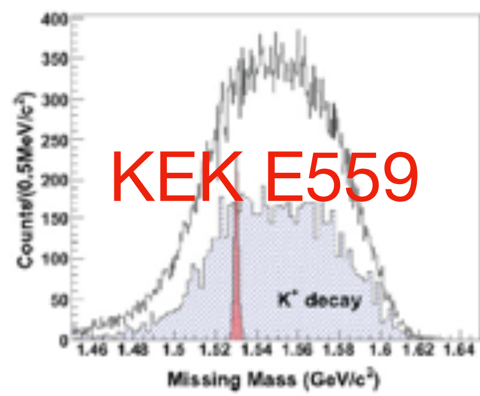
$\gamma p \to \bar{K}^0 K^0 p$



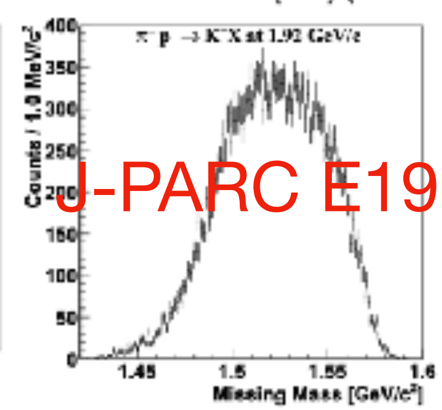
Hadronic production

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

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



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

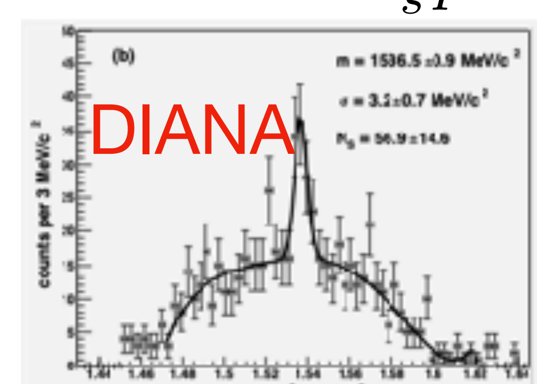


$\pi^- p \to \Theta^+ K^-$

Direct formation on nuclei

$K^+ n$(in nuclei) → Θ^+ → $K^0 p$

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



huge background
K^- angle acceptance

VS.

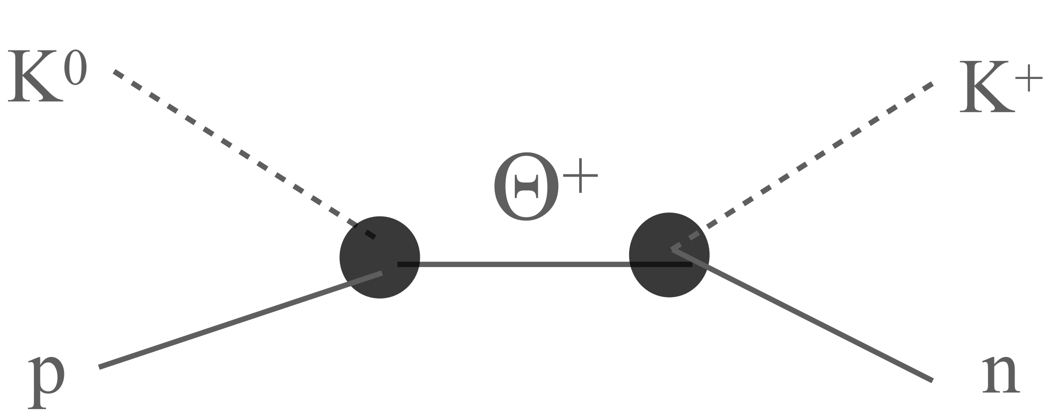
with a kinematic cut

- Direct KN formation offers a complementary test with a different reaction mechanism.

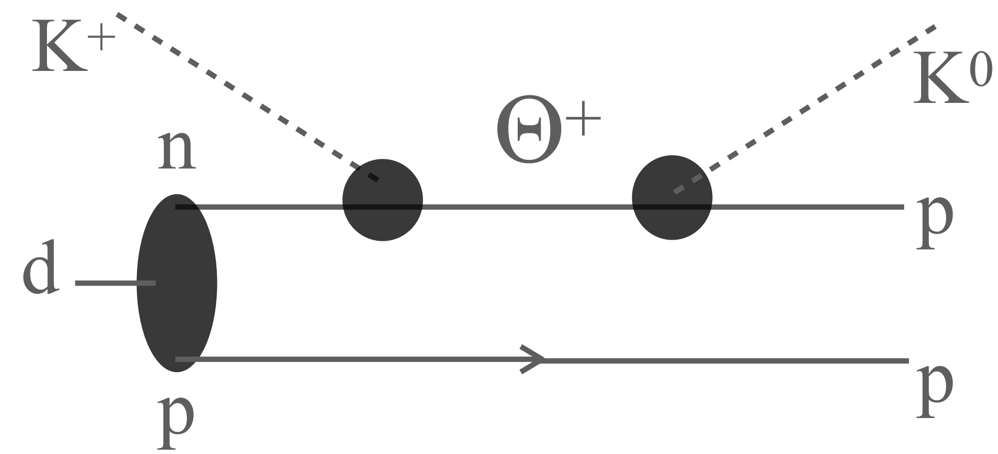
Direct Formation in the S = +1 KN System

- The Θ^+, if it exists, couples to K^+n and K^0p channels.

1. K^0p reaction with K_L beam



2. K^+n reaction with LD_2 target



- The Θ^+ lies 110 MeV above KN threshold & 25 MeV below KNπ threshold.
  → pion production is strongly limited near the Θ^+ production threshold.

- Two complementary approaches:

  K_Lp reaction at **JLab** and K^+d reaction at **J-PARC**

KLF at JLab: Complementary S=+1 Spectroscopy

Proposal for JLab PAC48

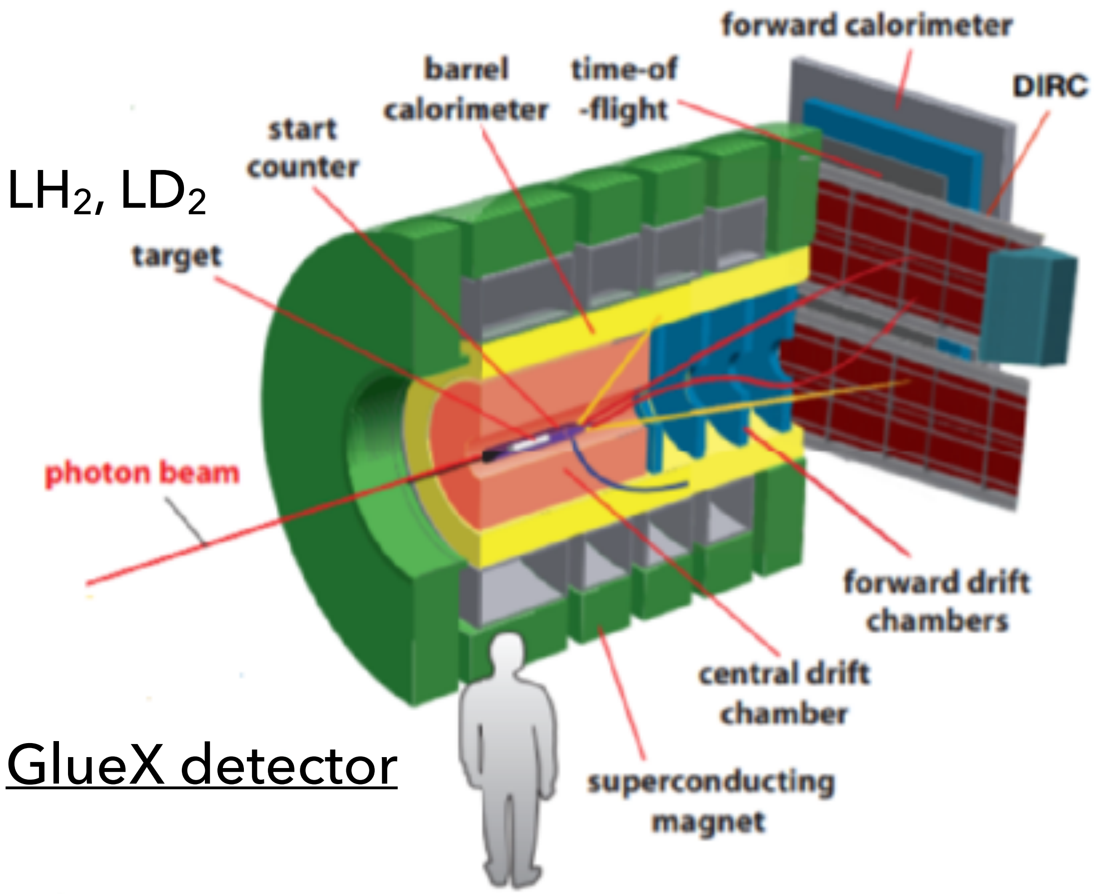
- K-Long Facility (KLF)

Secondary K_L beam planned at Hall D

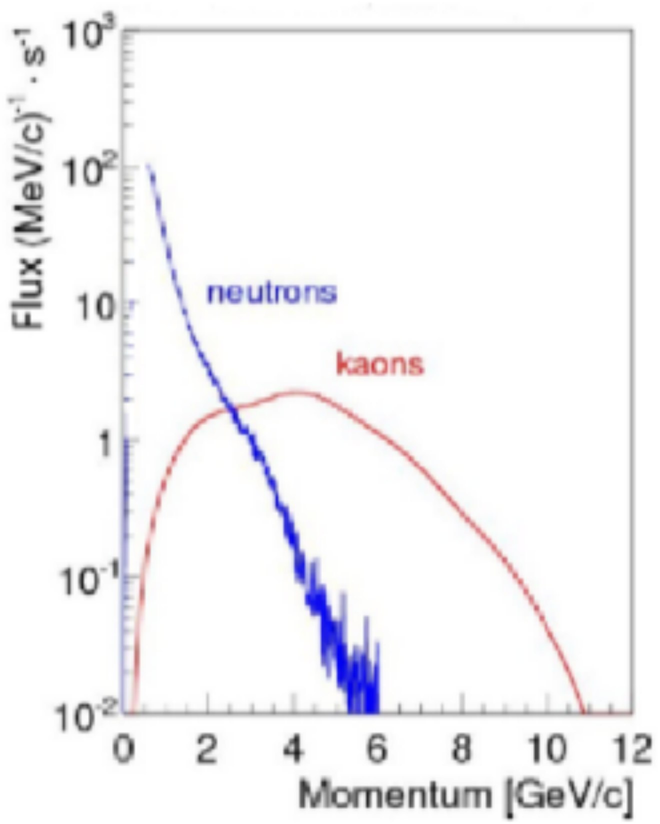
Produced from a 12 GeV e- beam

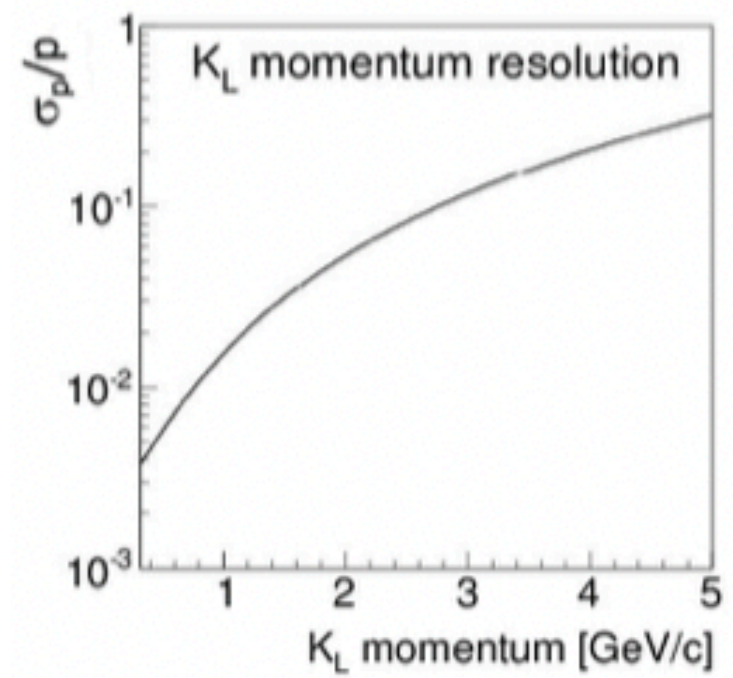
10^4 K_L/s (K_L from ϕ-meson decay)

LH$_2$, LD$_2$

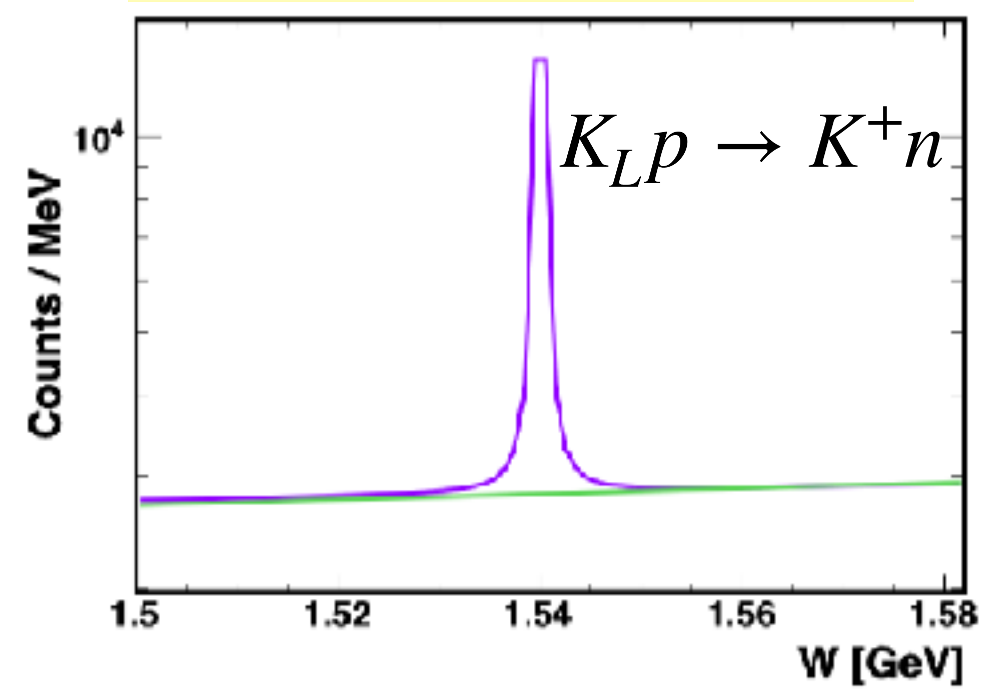


GlueX detector



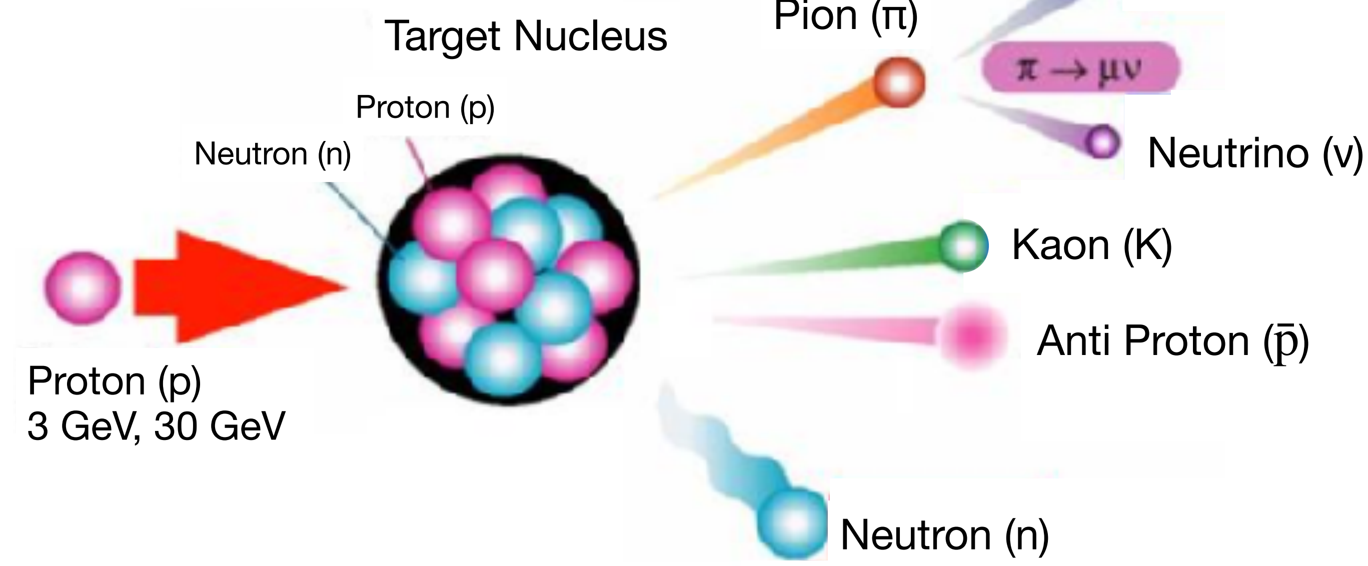


Modern Physics Letters A 39:14 (2024)



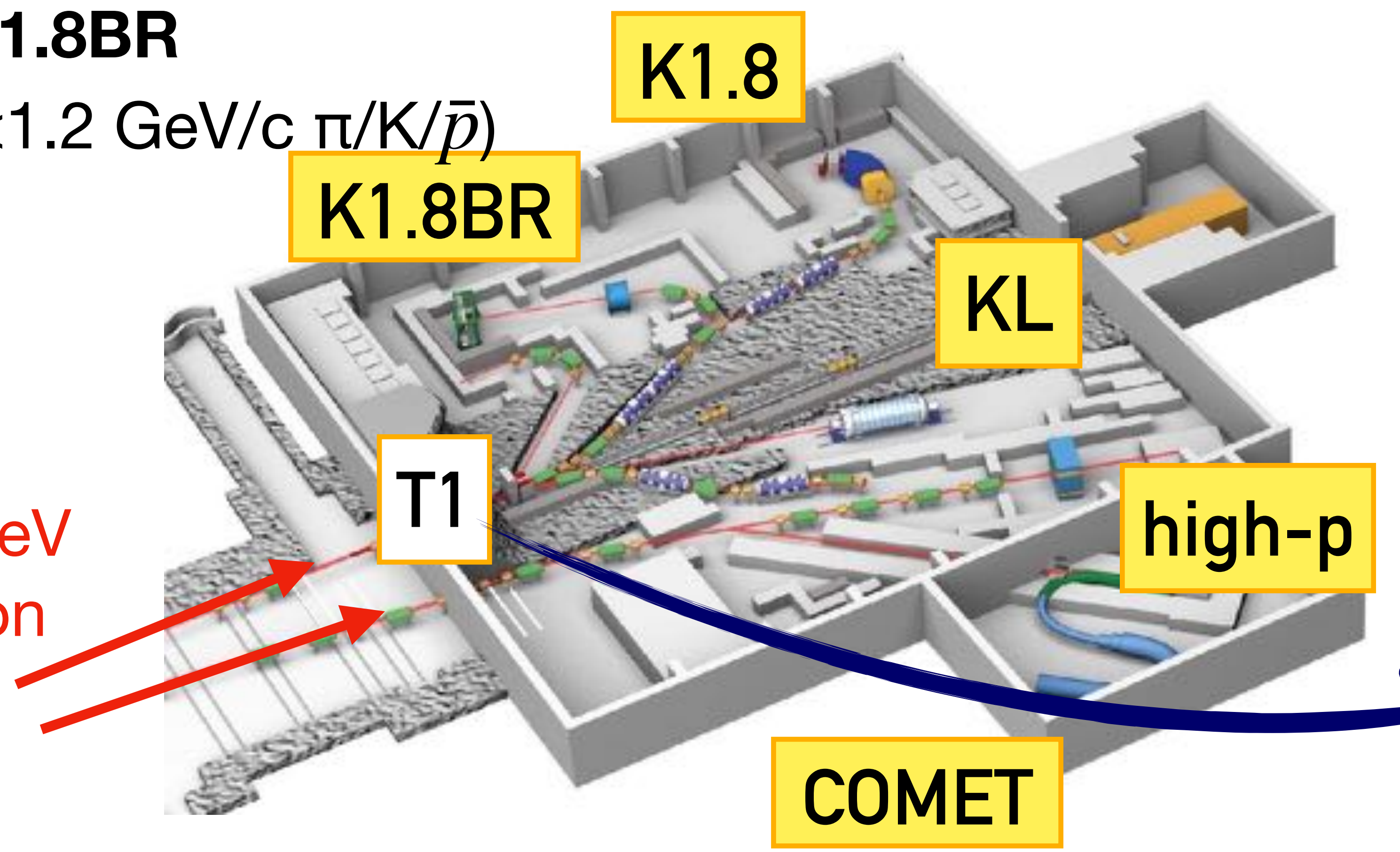
J-PARC Hadron Experimental Facility (HEF)

Spallation reactions

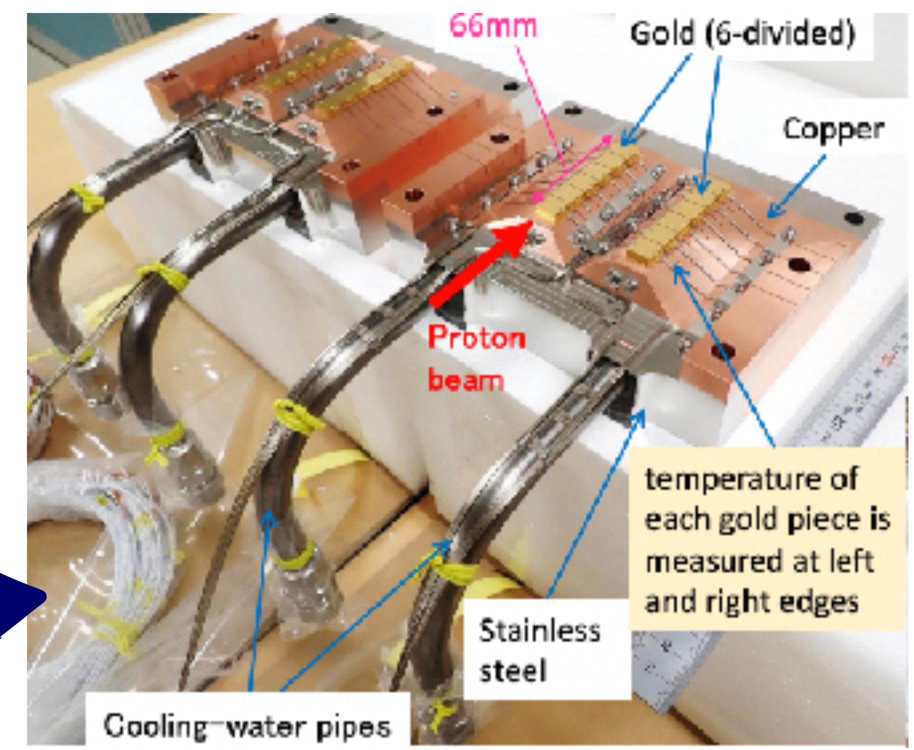


K1.8
(<2.0 GeV/c $\pi/K/\bar{p}$)

K1.8BR
(<1.2 GeV/c $\pi/K/\bar{p}$)

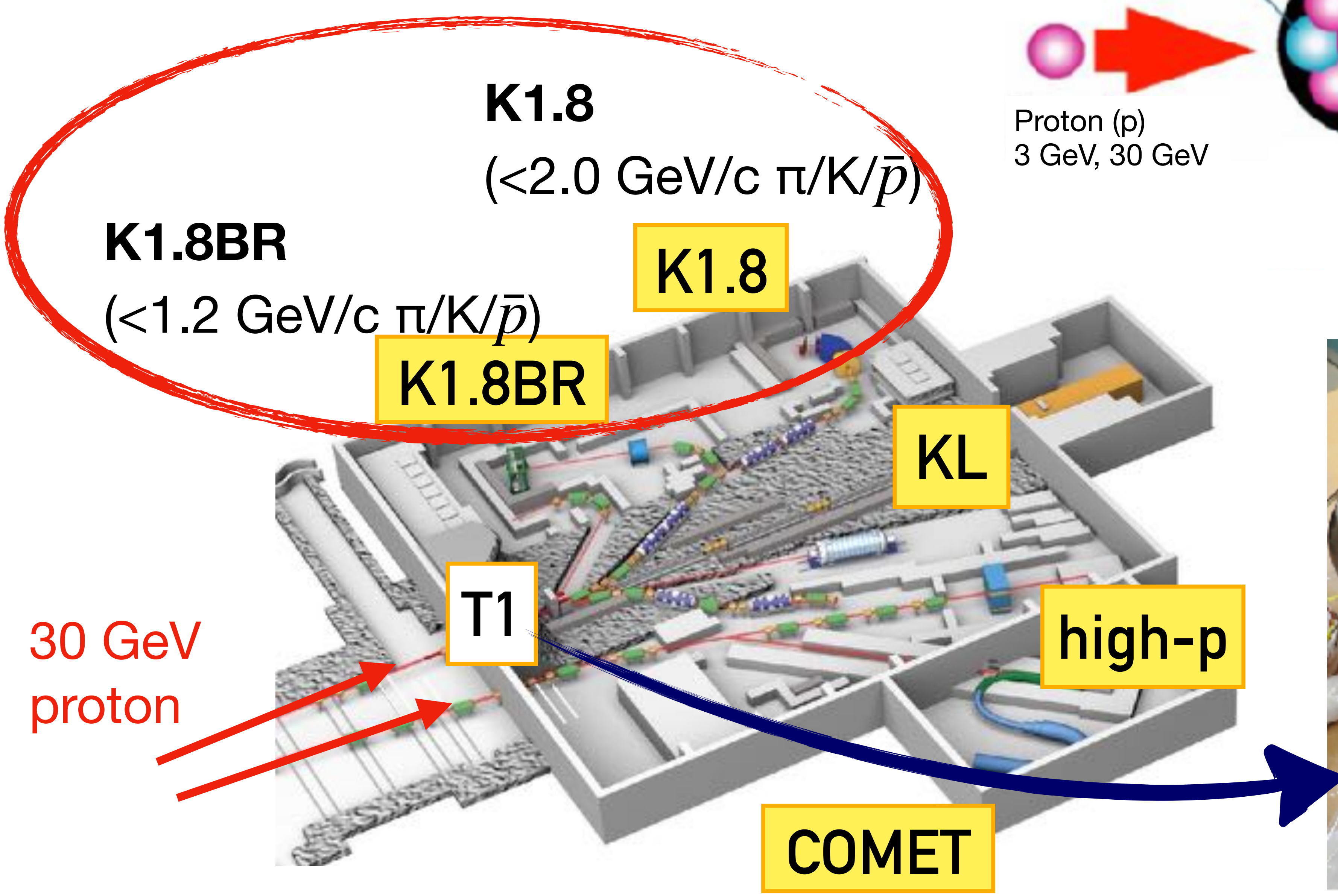


30 GeV
proton

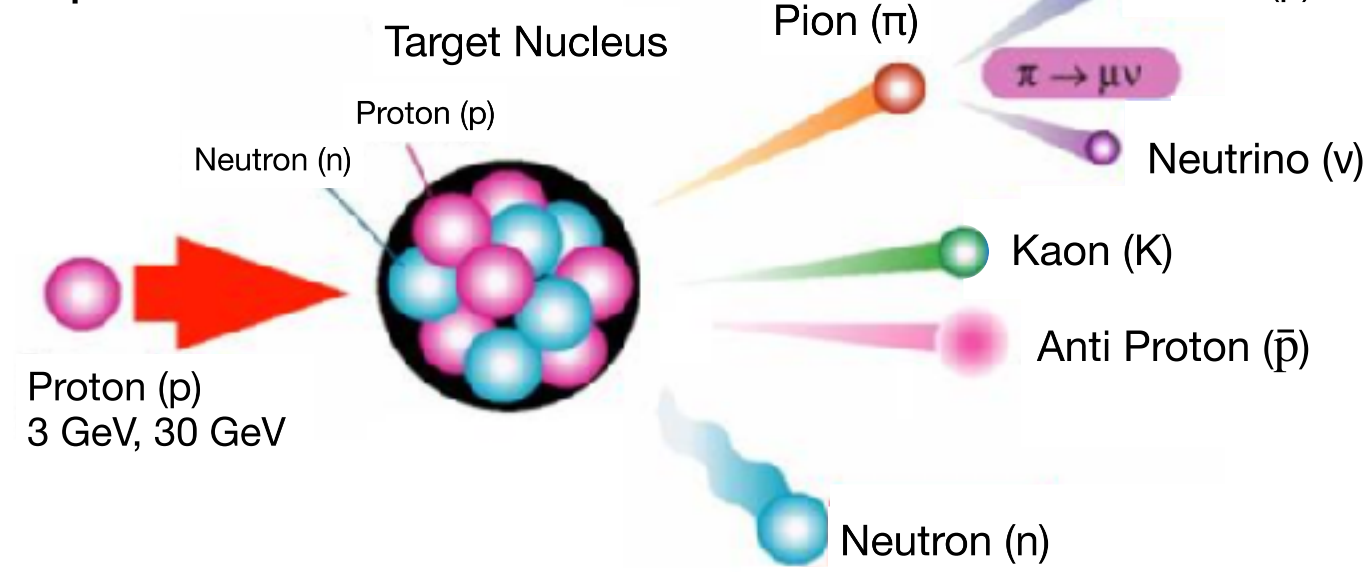


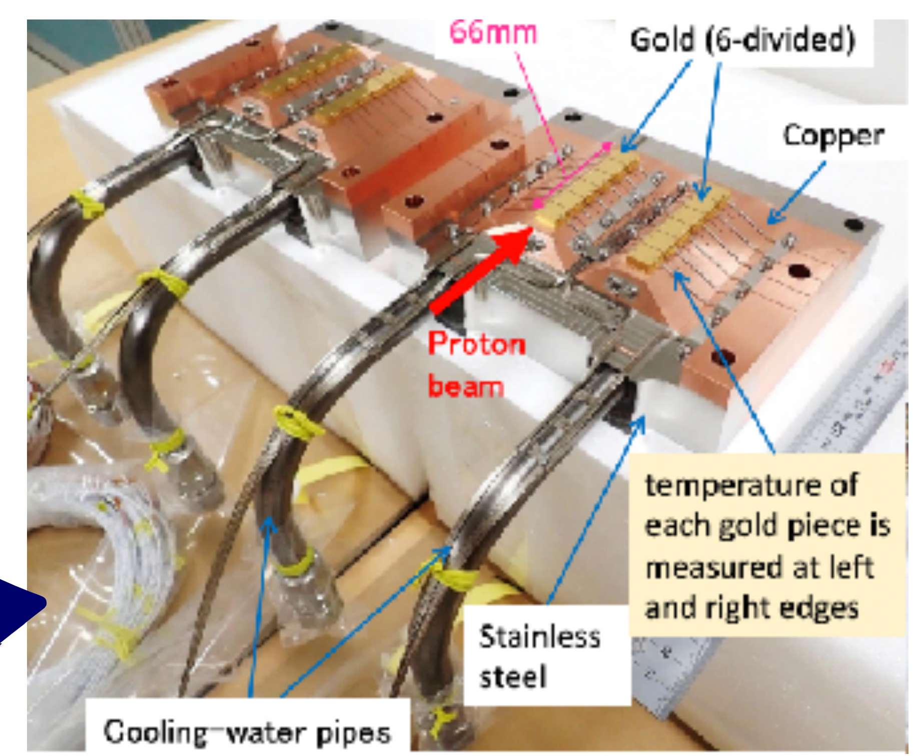
T1 Gold Target

J-PARC Hadron Experimental Facility (HEF)



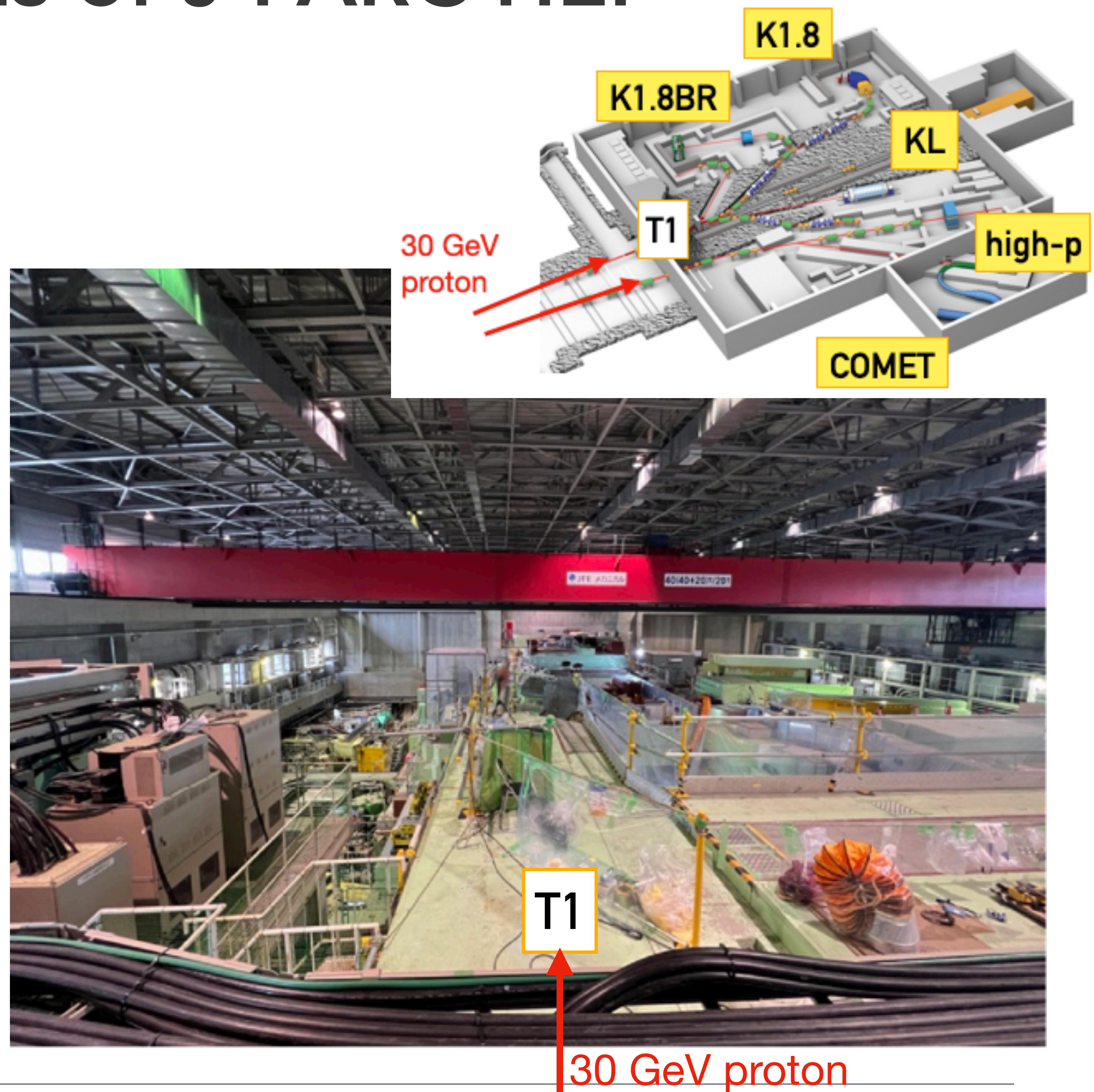
Spallation reactions



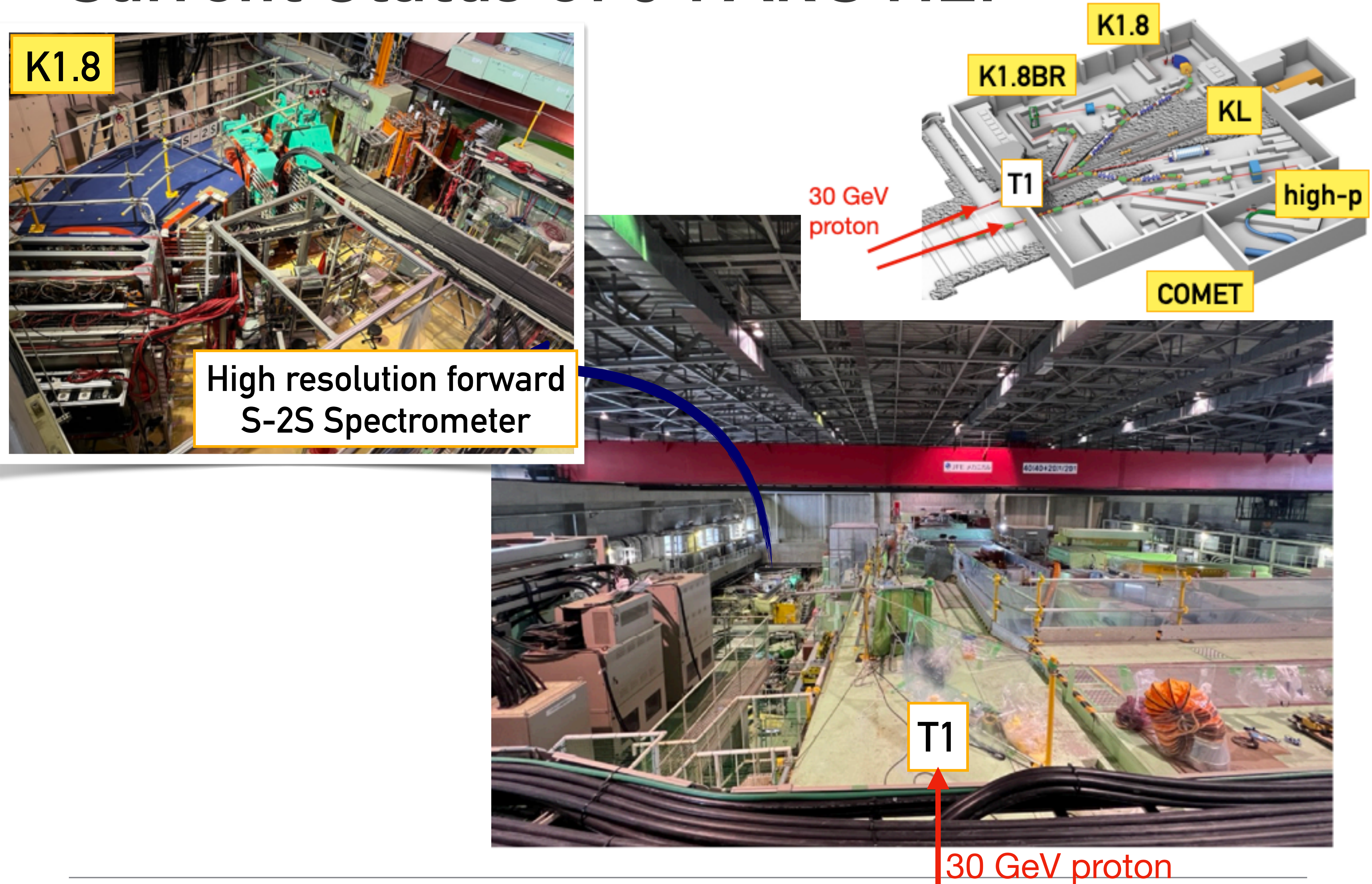


T1 Gold Target

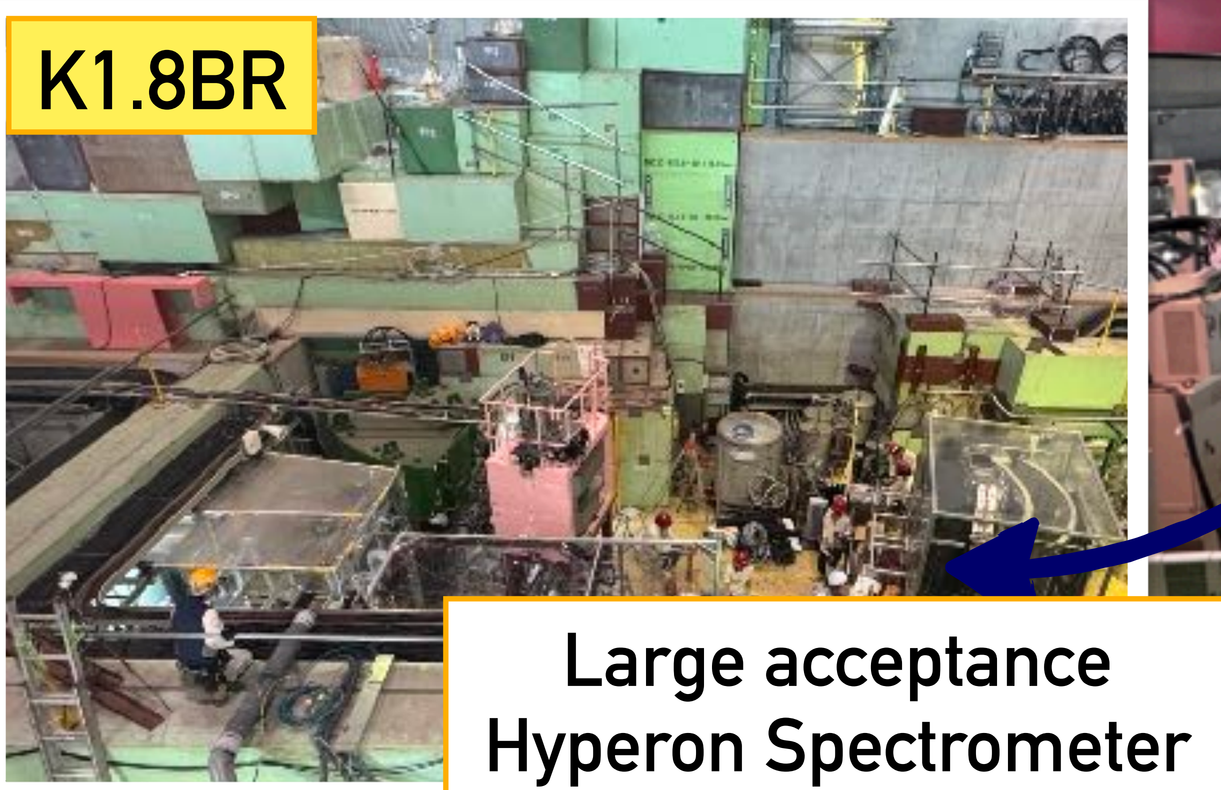
Current Status of J-PARC HEF

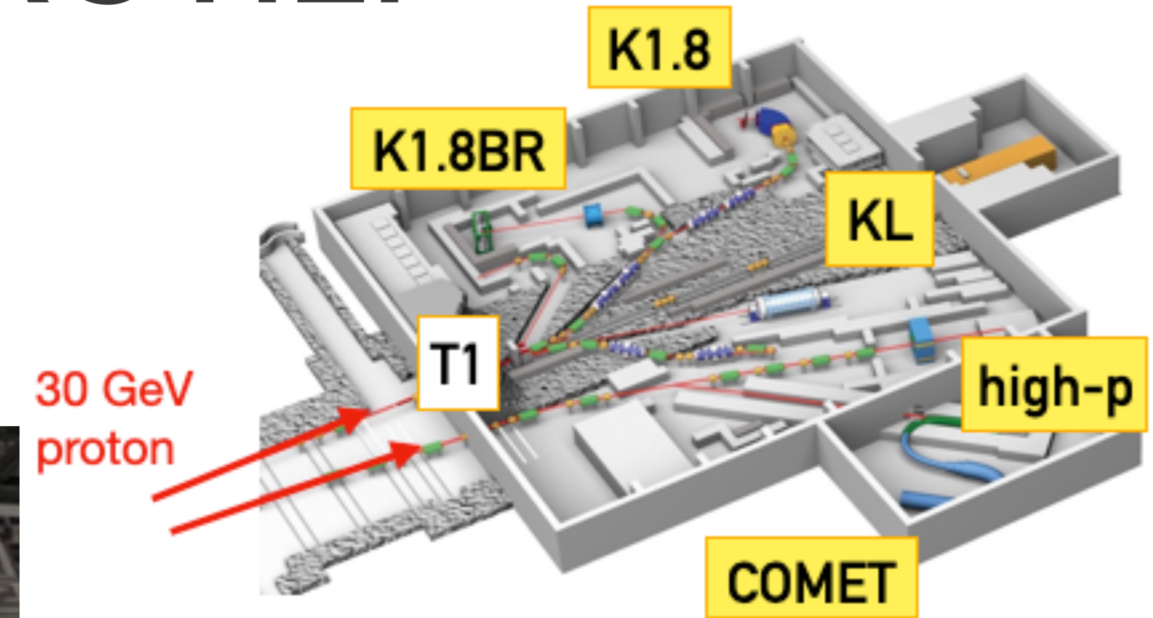


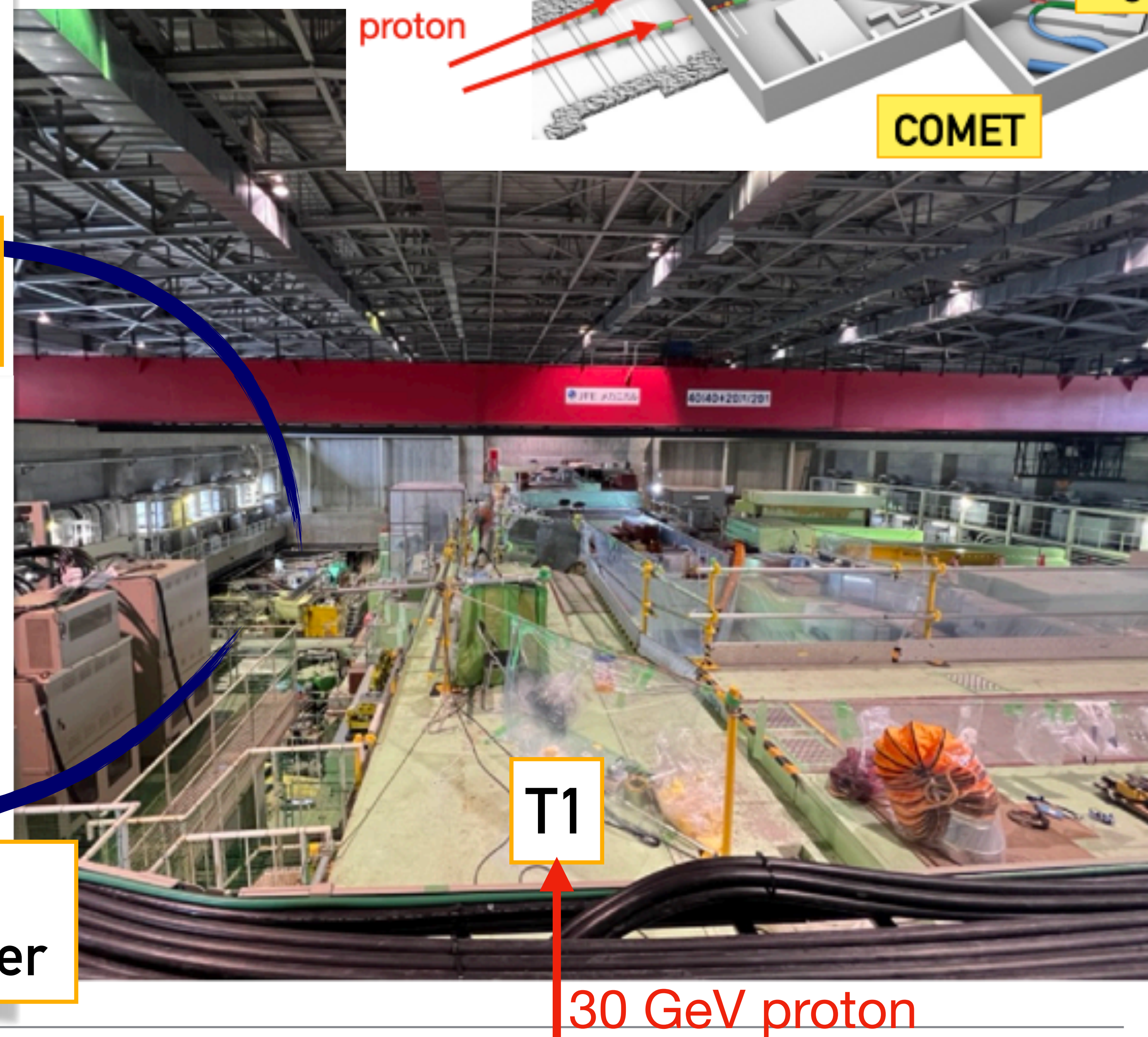
Current Status of J-PARC HEF



Current Status of J-PARC HEF







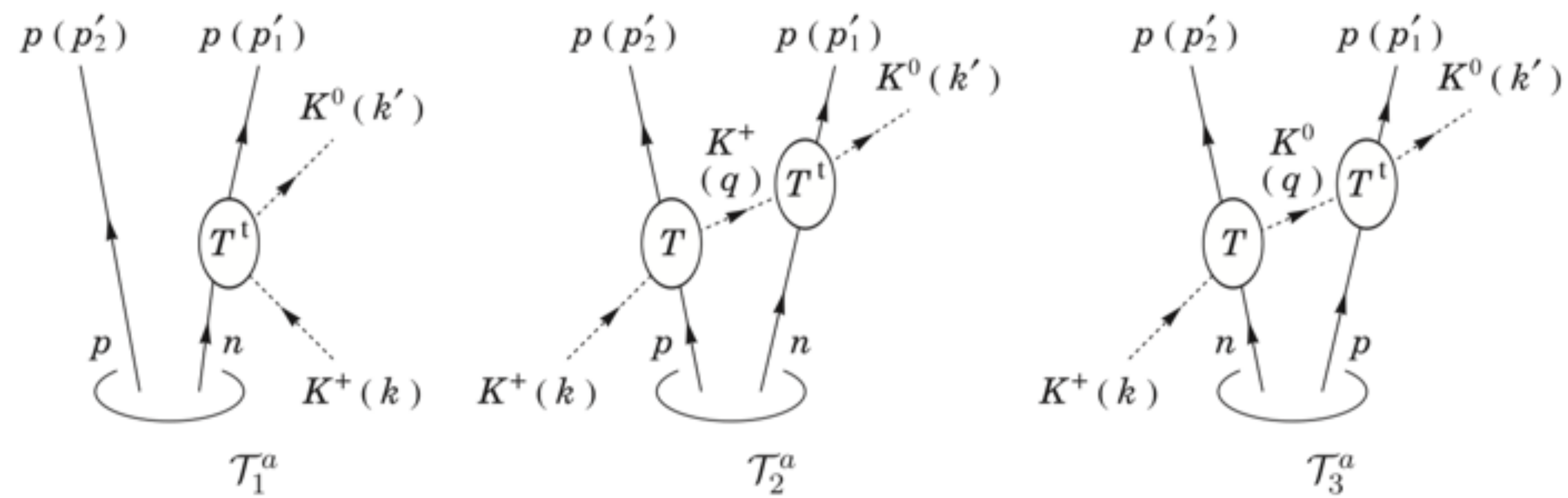
$K^+d \to K^0pp$ for the Θ^+ Production

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

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

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

(a) Impulse process (b) , (c) Two-step processes

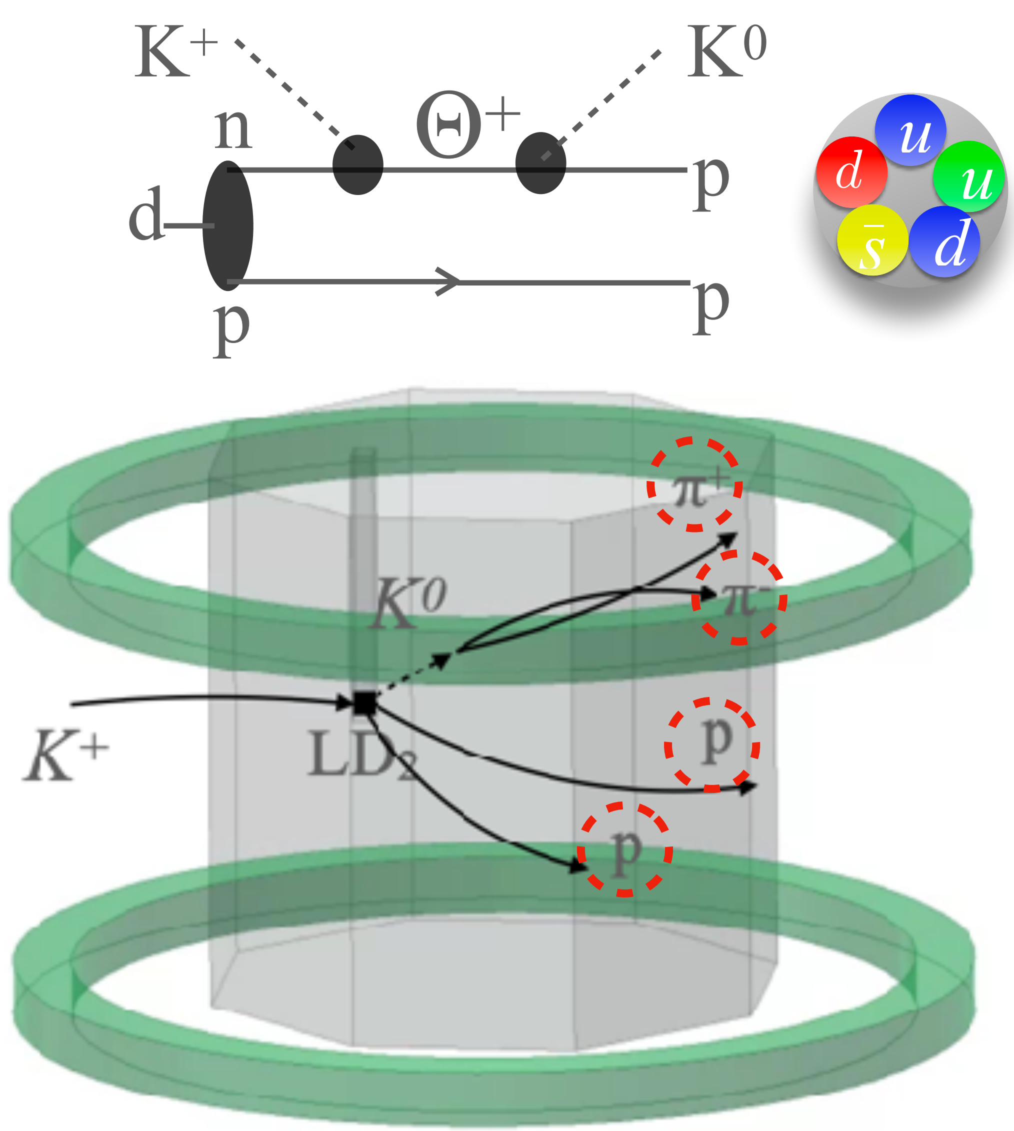


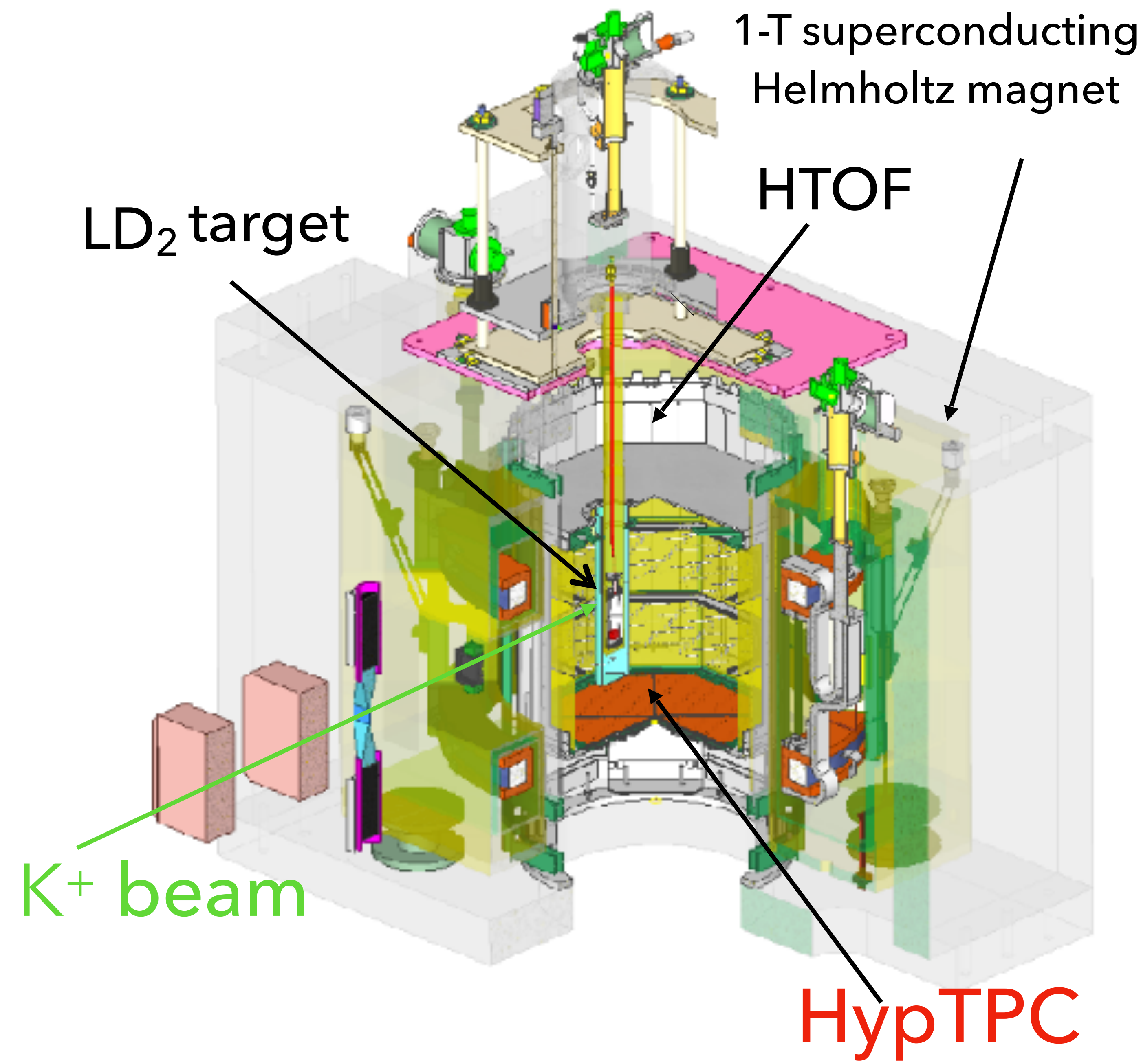
- Predicted Θ^+ production cross section (M_Θ=1524 MeV, Γ_Θ=0.5 MeV)

1. Low momentum at $p_{K+} \approx 0.40$ GeV/c: a few hundred μb ~ 1 mb, impulse scattering process dominates
2. Higher momentum at $p_{K+} \approx 0.85$ GeV/c: drops to the μb level, two-step processes become dominant

1. Low-Momentum Exclusive Measurement

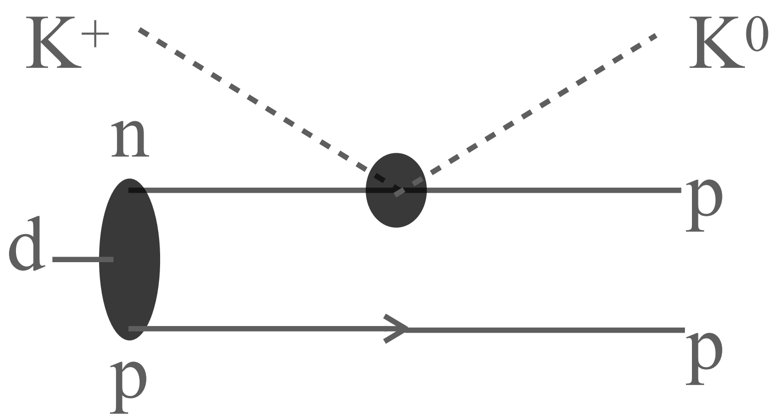
- Goal: to measure the **$K^+d \rightarrow K^0pp$** reaction at **p_{K+}=0.5 GeV/c** at J-PARC K1.8BR beam line using Hyperon Spectrometer.



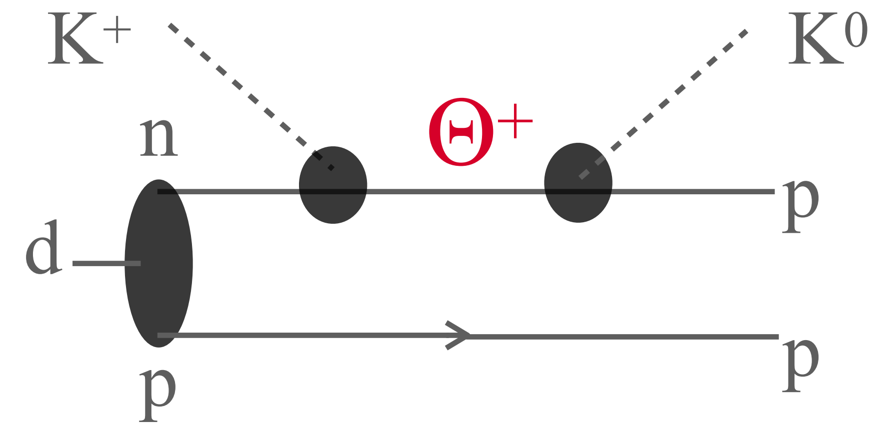


$K^+d \rightarrow K^0pp$ at 0.5 GeV/c Simulation

- Impulse scattering process
  $K^+n \rightarrow K^0p$



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

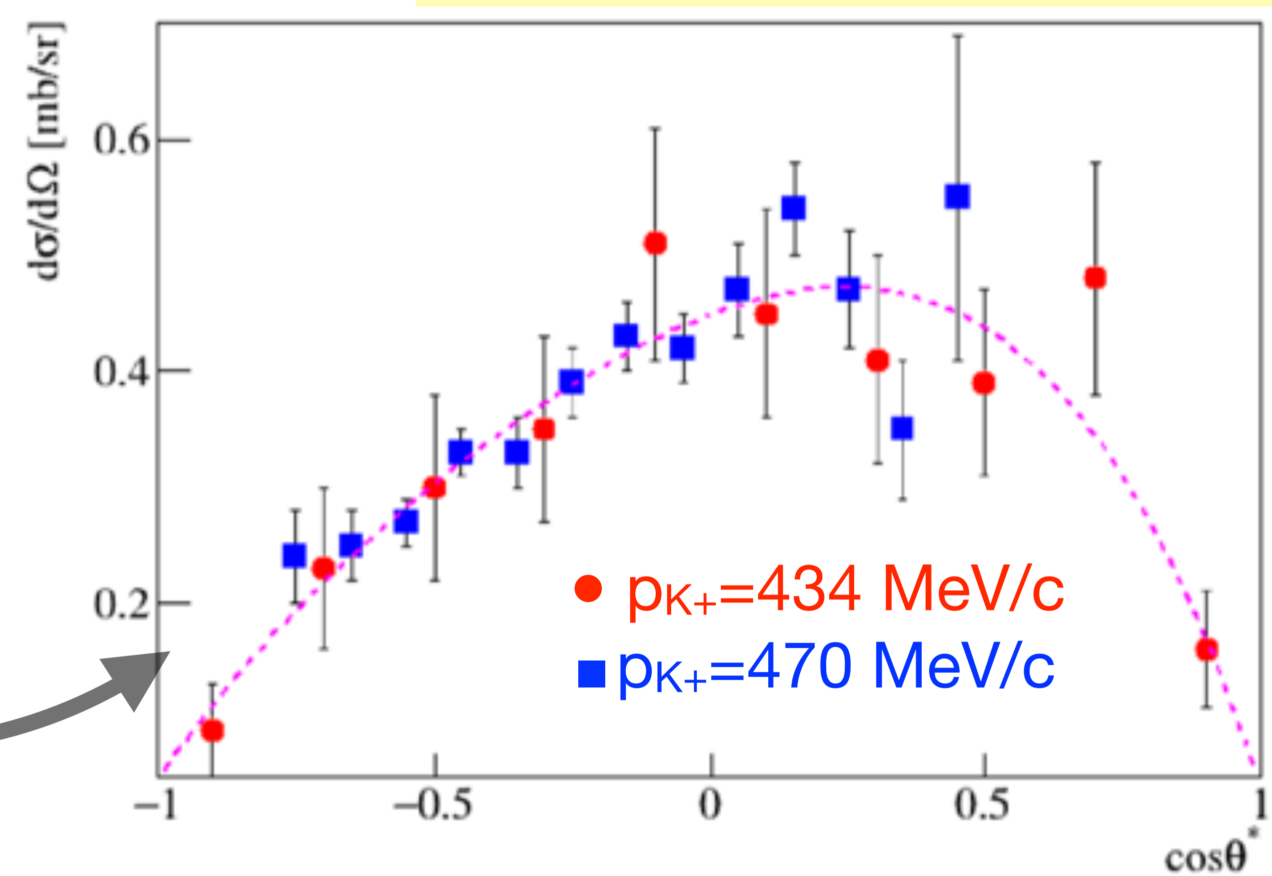
M. Bernheim et al., Nucl. Phys. A 365, 349 (1981).

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

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

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).



Yield Estimation

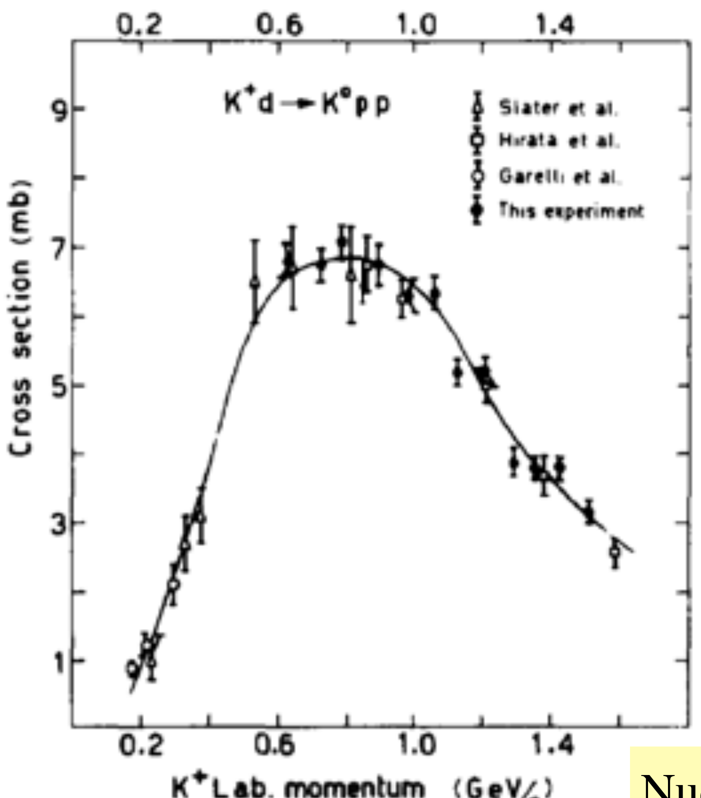
$$N = N_{beam} \times \frac{\rho \times L \times N_A}{A} \times \sigma \times Acc \times Decay$$

K^+ Beam at 0.5 GeV/c (K1.8BR): N_{beam}=2 k/spill

LD_2 Target: ρL=1.03 g/cm^2 (ϕ8 cm), N_A=6.022×10^{23}, A=2

Detector Acceptance (Hyperon Spectrometer): Acc=0.3

$Decay$=0.5 (K^0-K_S conversion) × 0.692 ($K_S \to \pi^+\pi^-$)

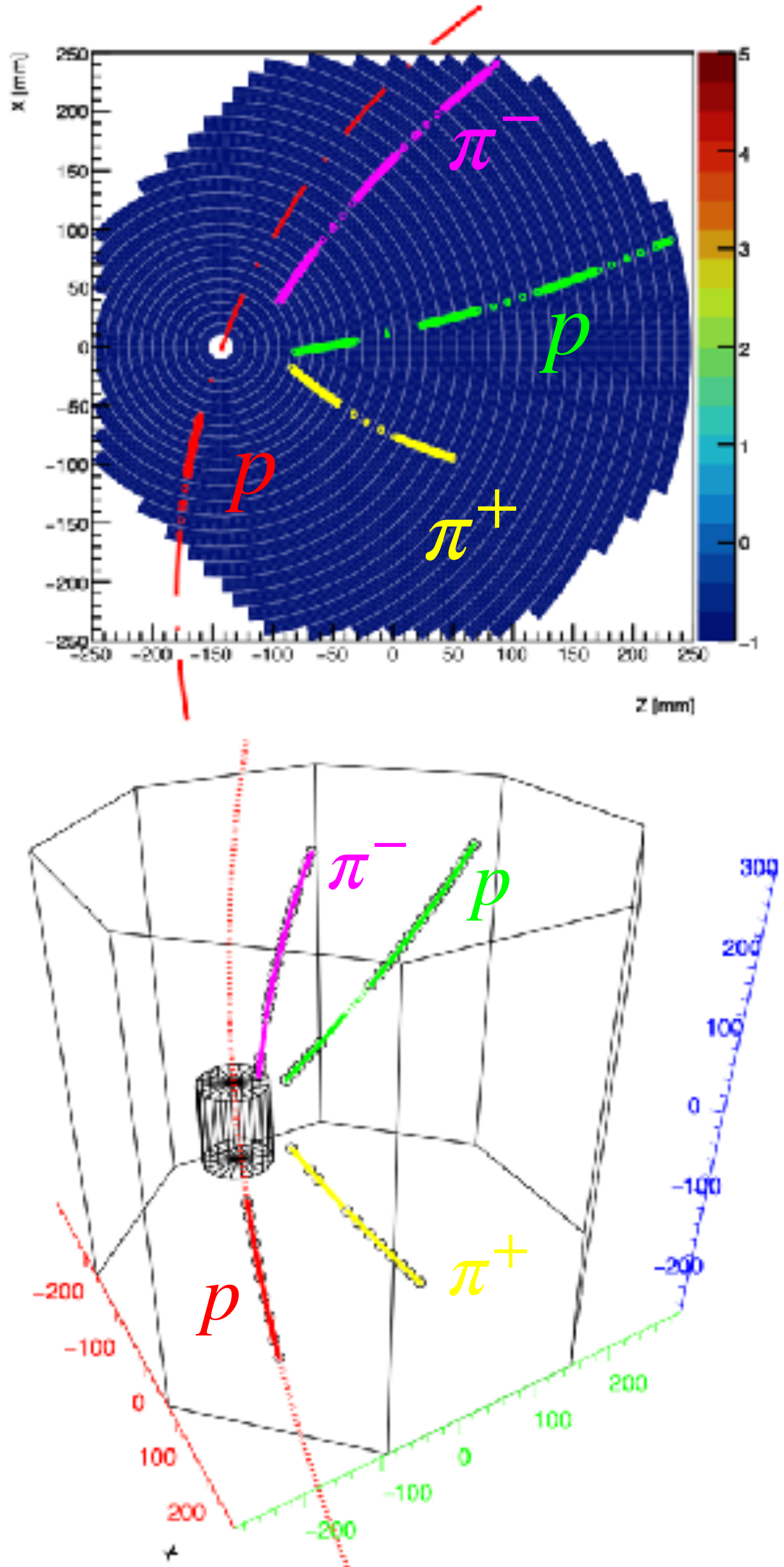


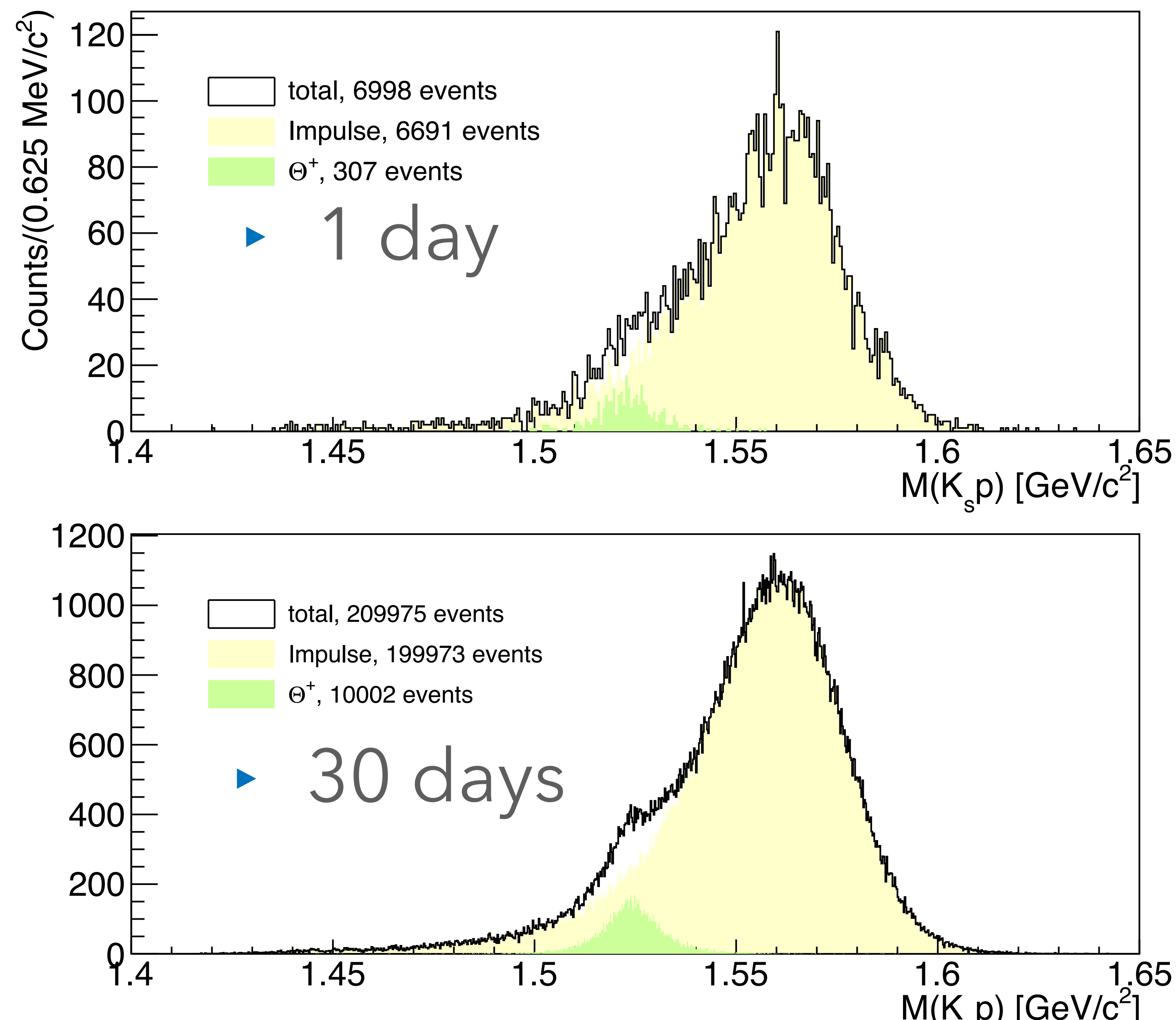
Nucl. Phys. B37 (1972) 577.

	σ	N [/spill]	N [/1 hr]	N [/1 day]
$K^+d \to K^0pp$	5 mb	0.322	273	6.56k
Θ^+	300 μb	0.019	16.4	394

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

Expected Exclusive Spectrum



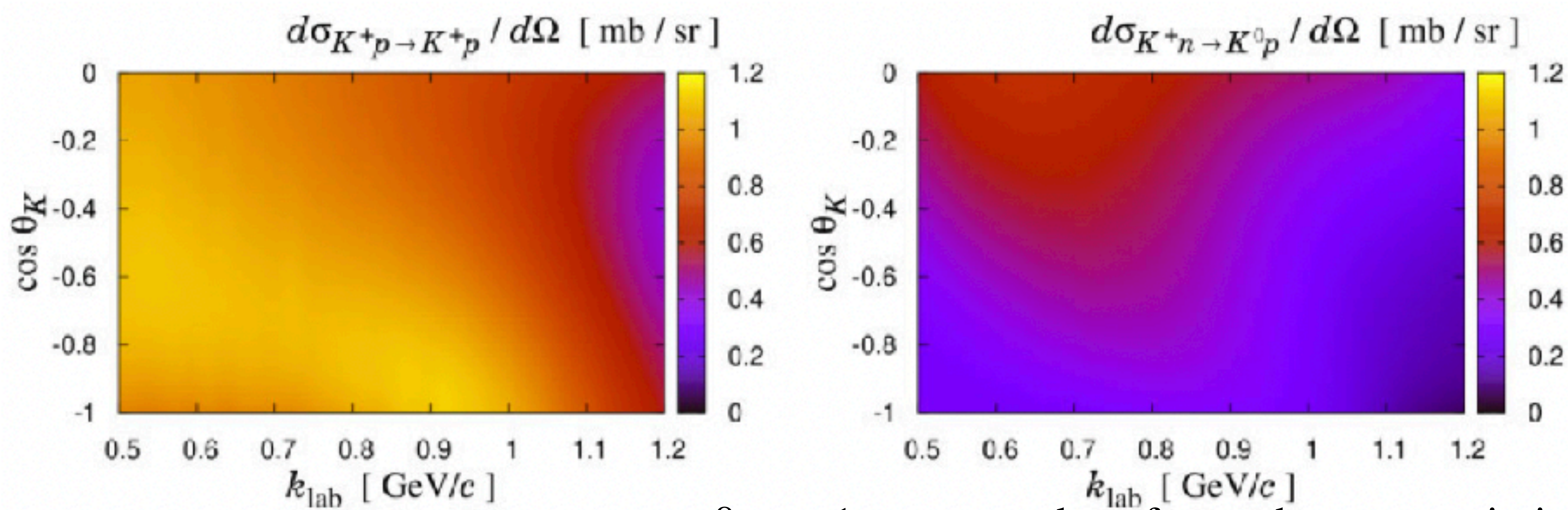


2. Higher-Momentum Inclusive Measurement

- Why 0.9 GeV/c?

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

K^+N differential cross sections calculated from the SAID partial-wave amplitudes

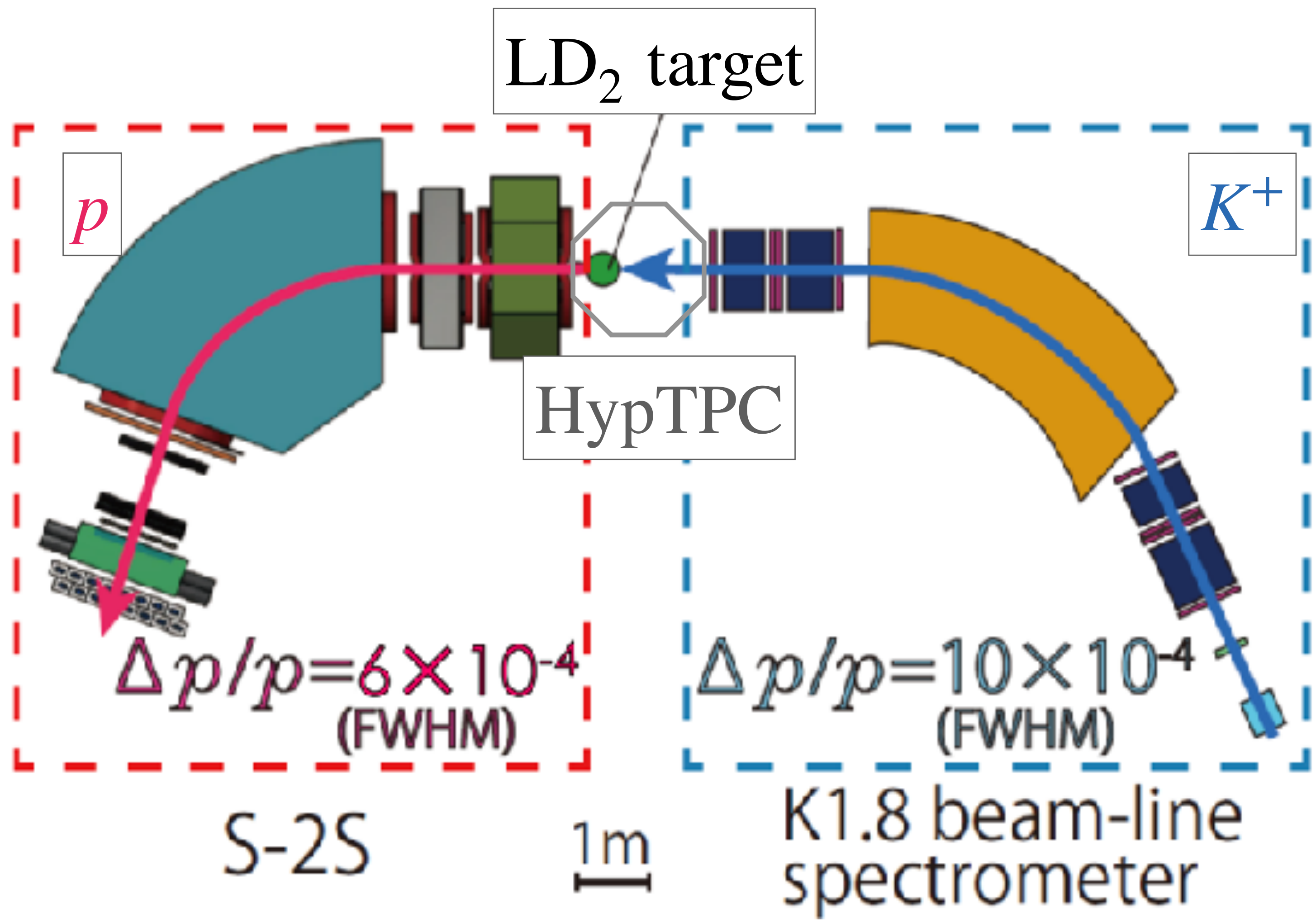


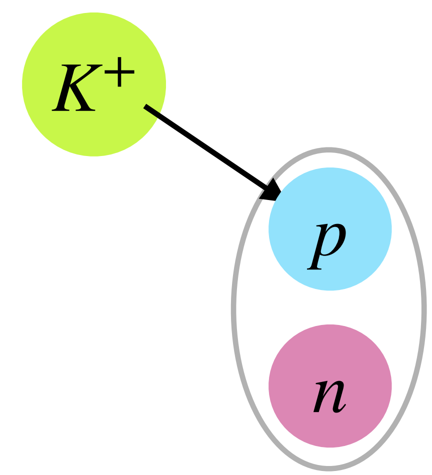
$\cos\theta_K \sim -1$ corresponds to forward-proton emission

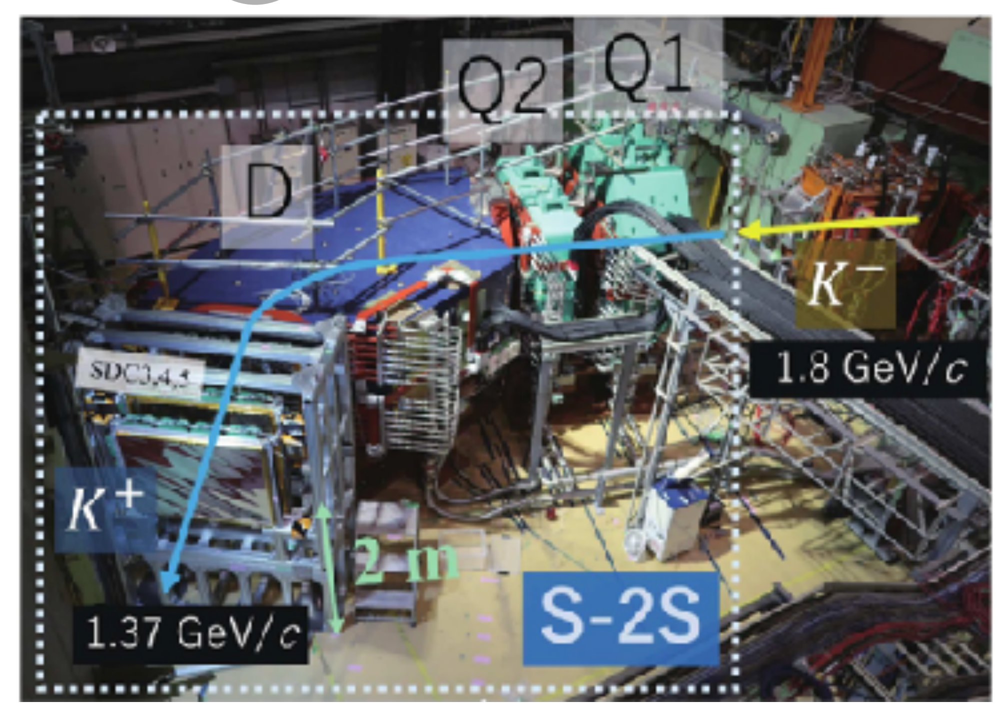
- SAID-based KN amplitudes favor fast forward-proton emission around p_K =0.8–0.9 GeV/c. The fast proton carries away a large fraction of the momentum, leaving a slower intermediate kaon that can interact with the other nucleon to form the Θ^+.

2. Higher-Momentum Inclusive Measurement

- Search for Θ^+ in **d(K⁺,p)** reactions at **0.9 GeV/c** at J-PARC K1.8







- Two-step production mechanism in the deuteron
  - 1. Primary K^+N scattering: $K^+N_1 \rightarrow pK^{+(0)}$
  - 2. The outgoing kaon interacts with the spectator nucleon: $K^{+(0)}N_2 \rightarrow \Theta^+$

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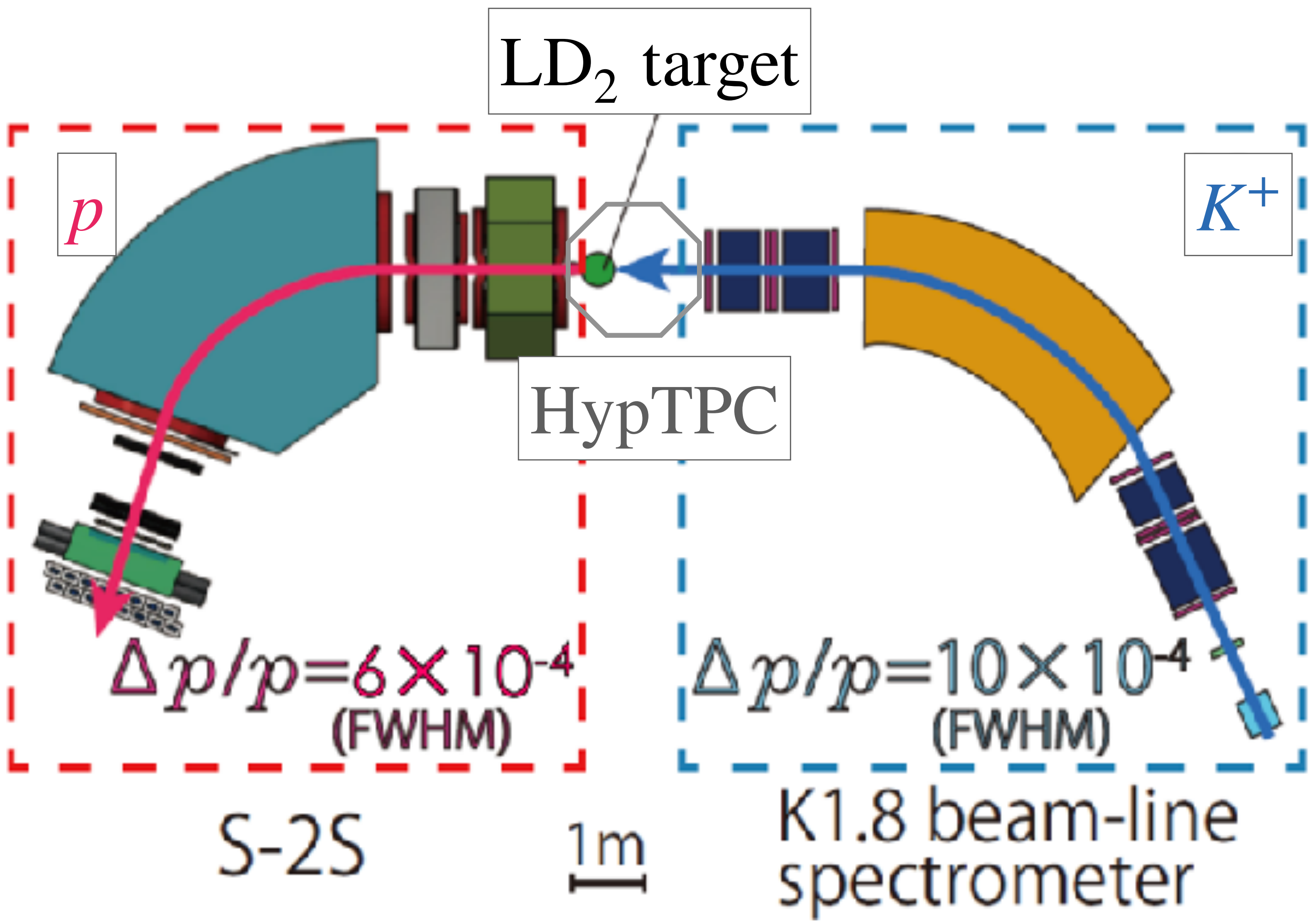

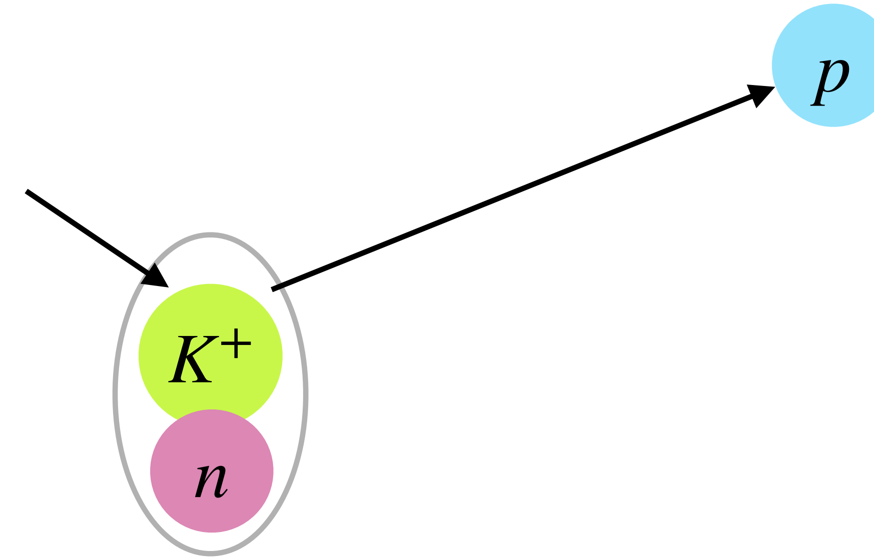

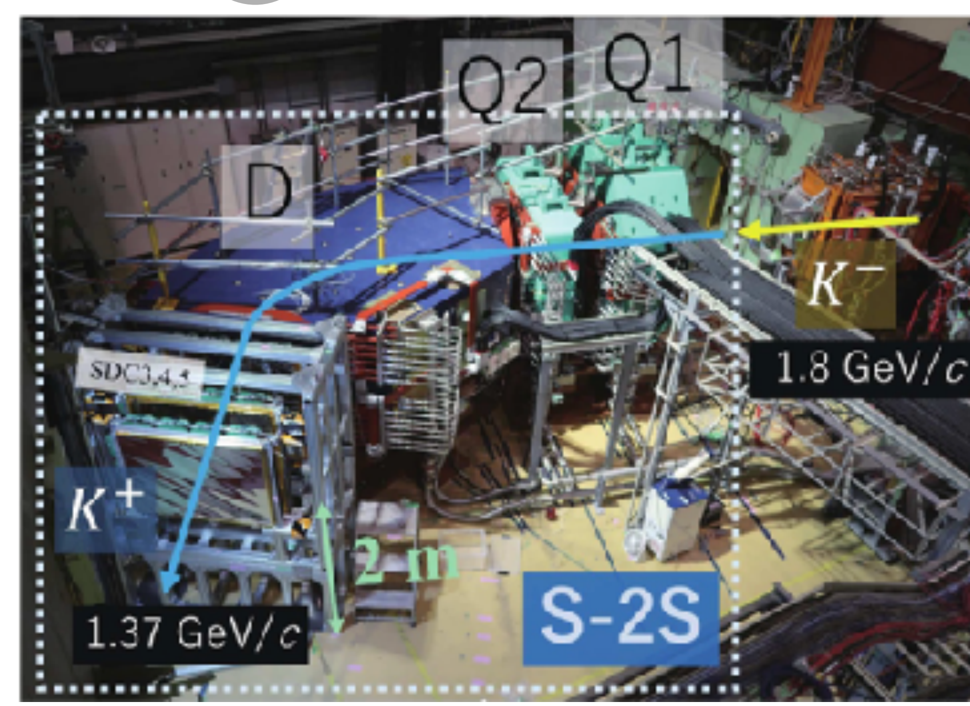

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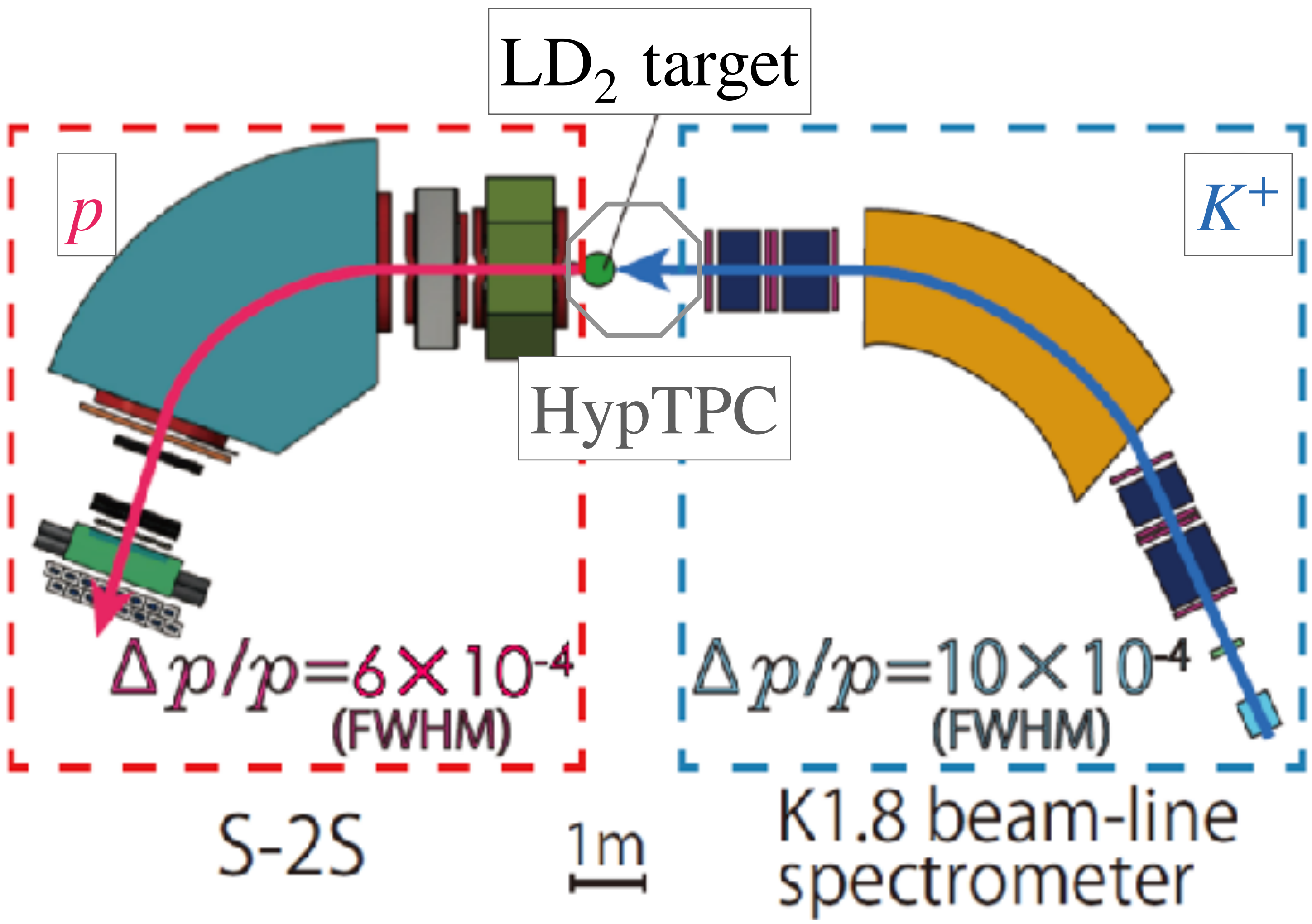

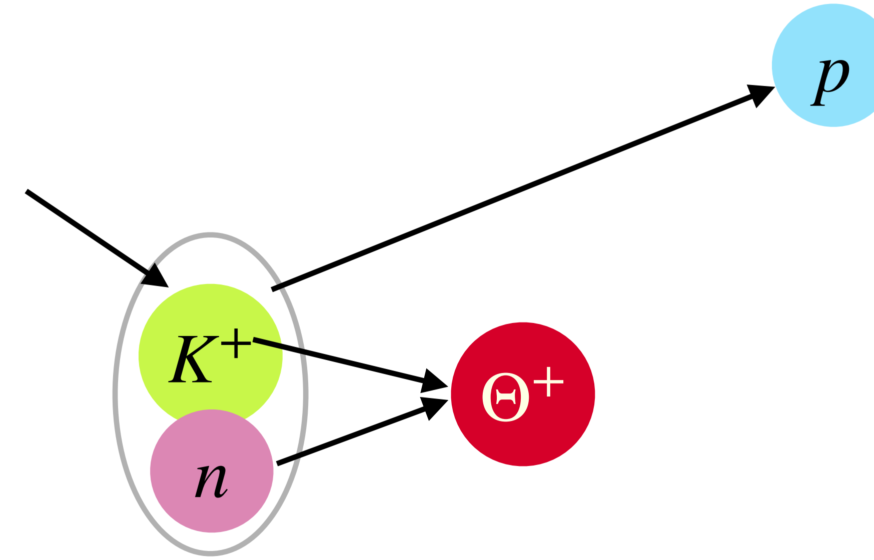

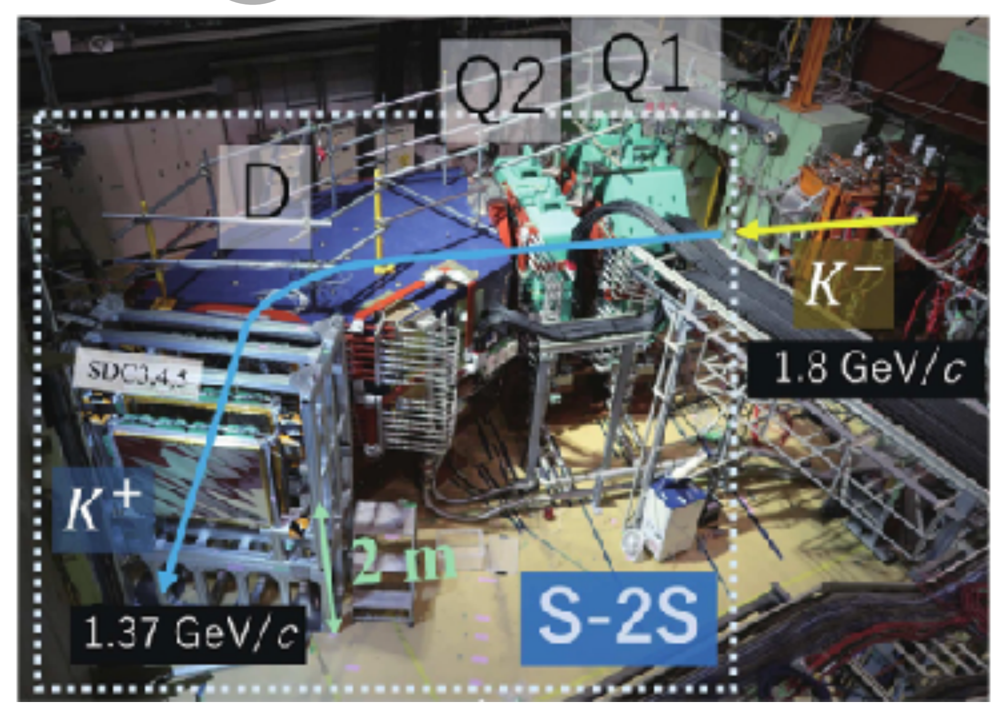

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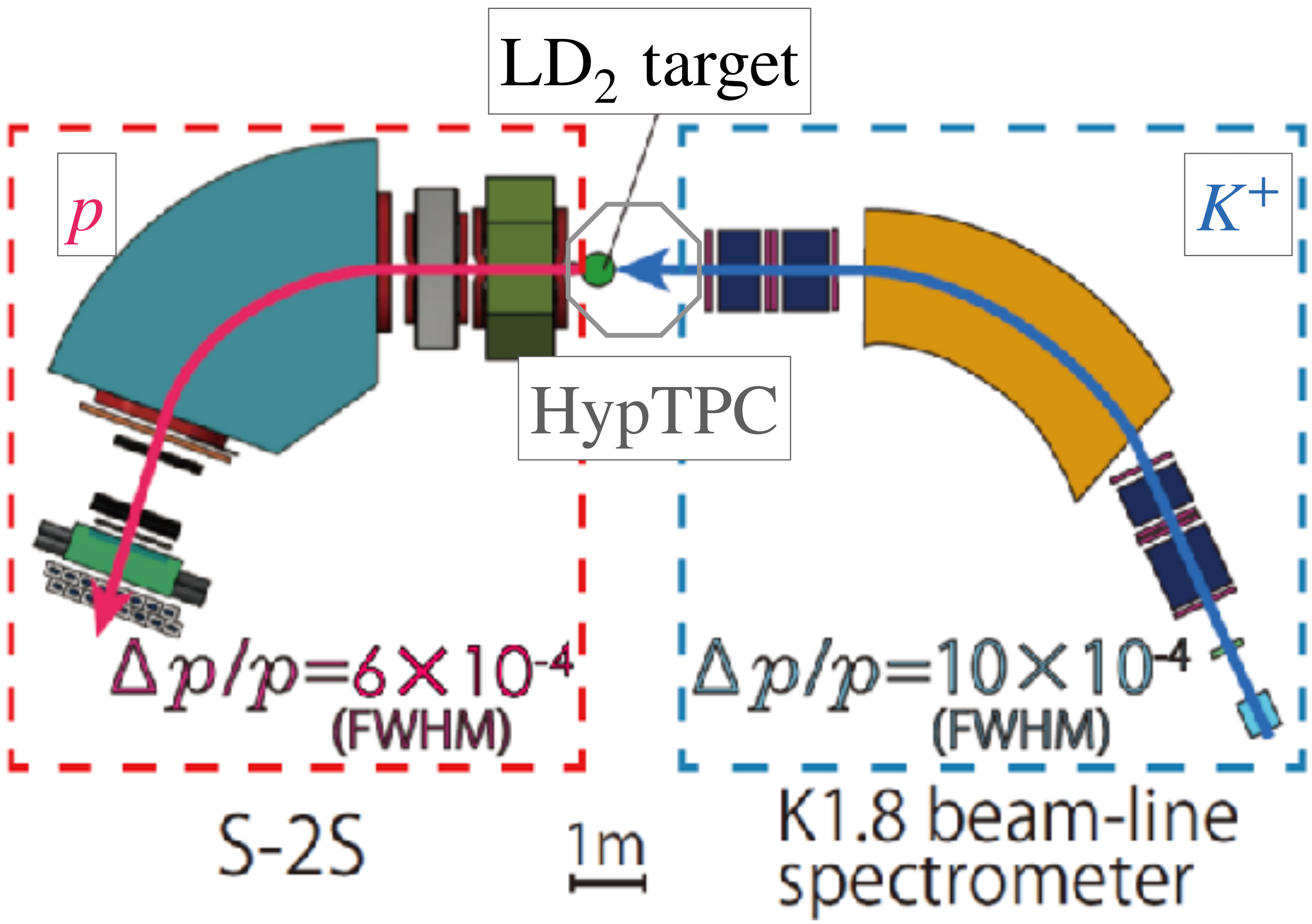

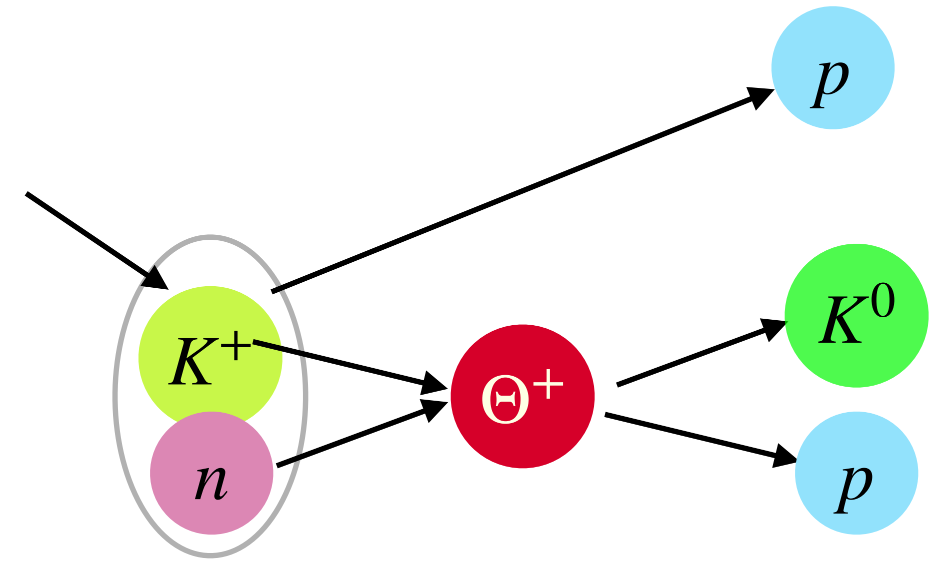

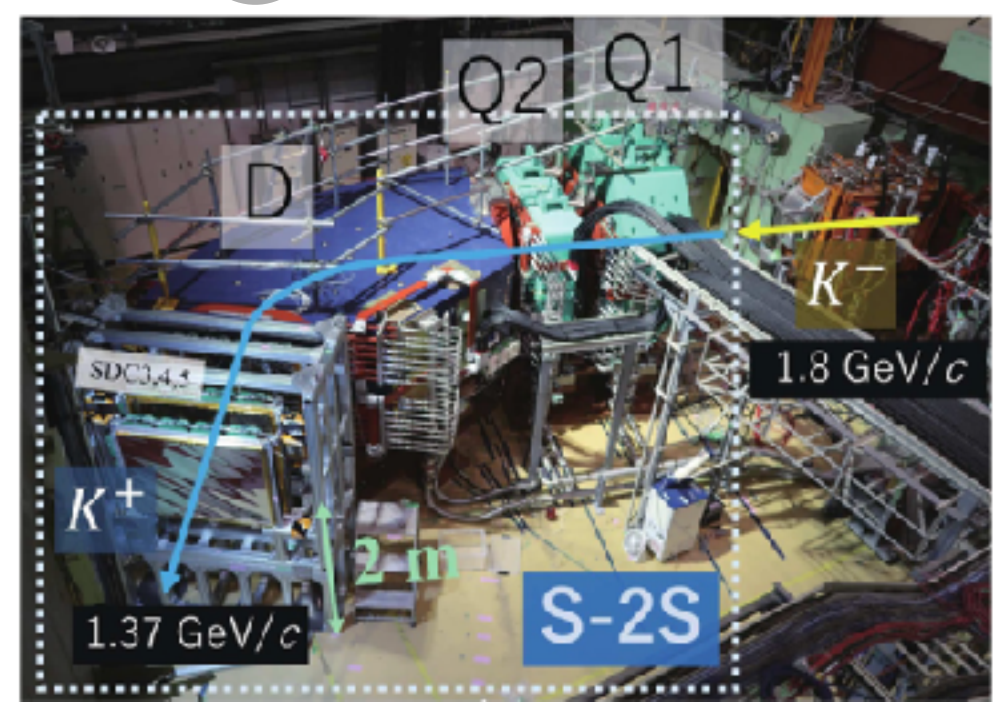

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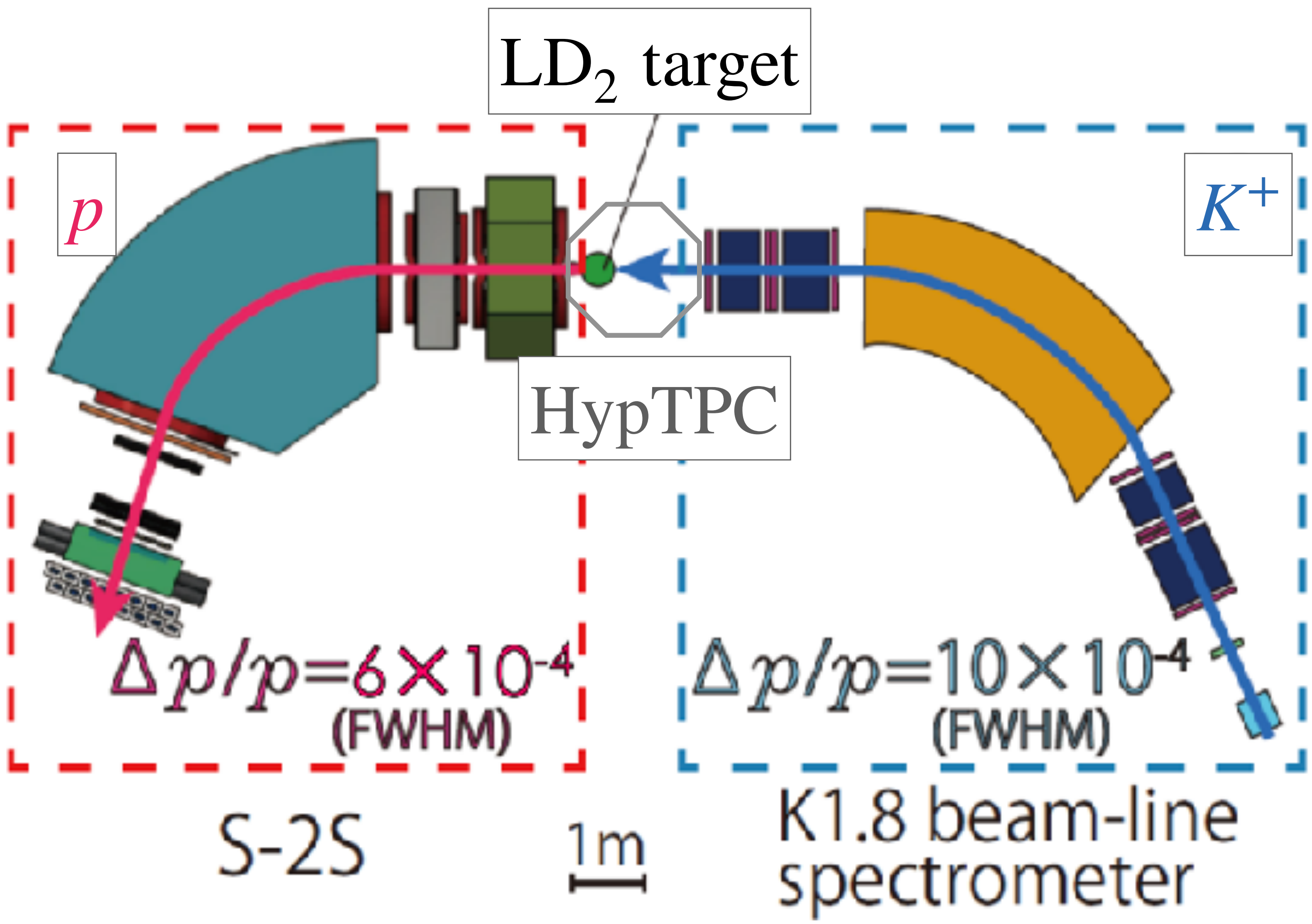
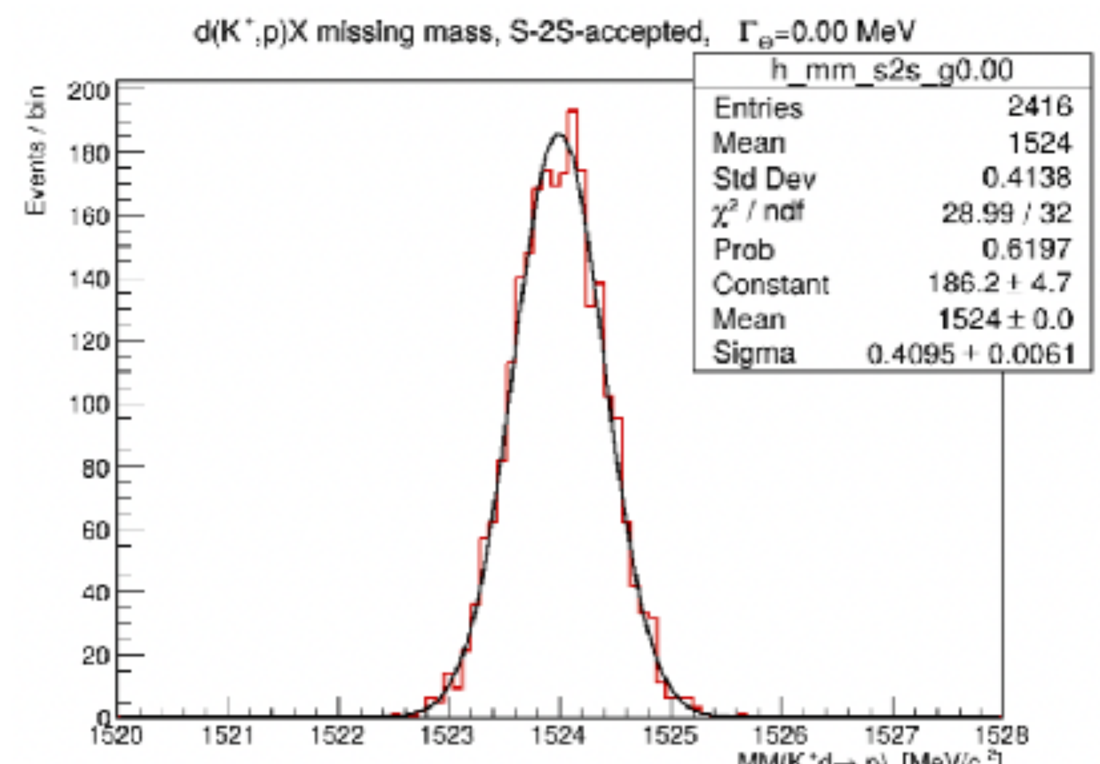
Inclusive Missing-Mass Search

- Search for Θ⁺ in **d(K⁺,p)** reactions at **0.9 GeV/c** at J-PARC K1.8





Spectrometer-only MM resolution:
σ_M~0.4 MeV/c²

- Search for Θ⁺ in d(K⁺,p)X missing mass spectrum
- ➔No need to fully reconstruct a specific Θ⁺ decay mode.

Yield Estimation

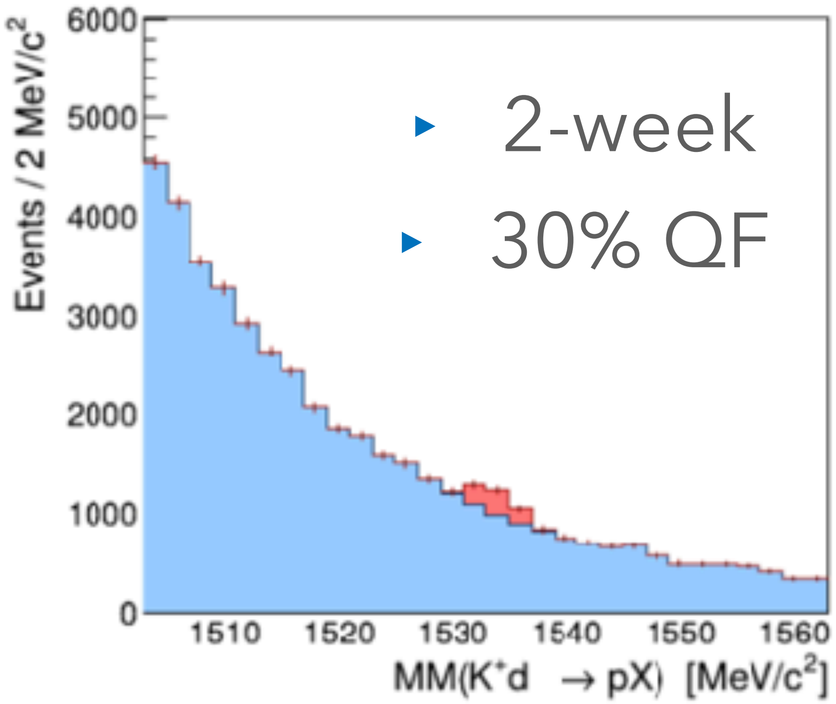
$$N = N_{beam} \times \frac{\rho \times L \times N_A}{A} \times \frac{d\sigma}{d\Omega} \times \Delta\Omega$$

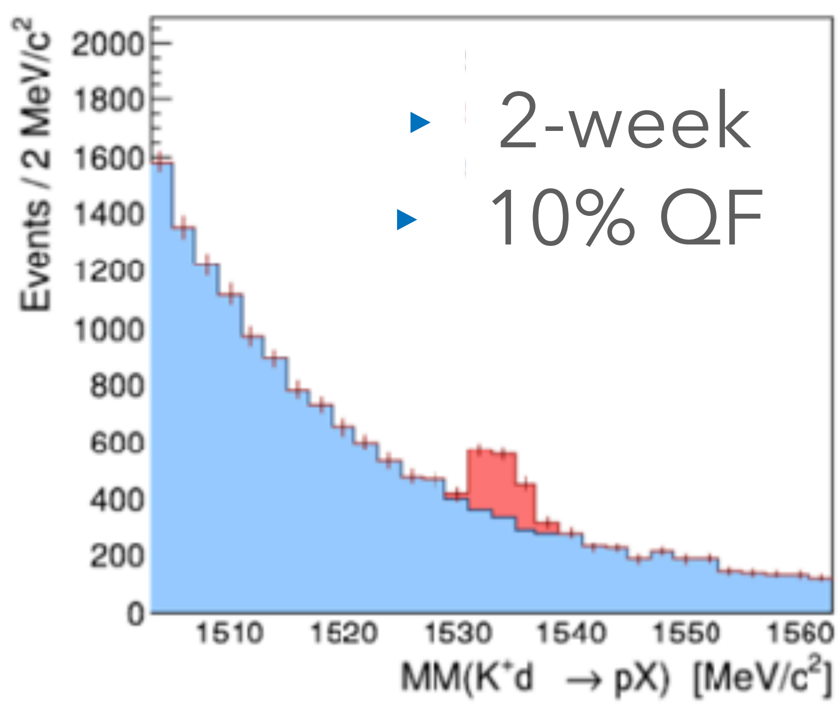
- K^+ intensity at K1.8: 100 k/spill at 100 kW
- Assumed differential cross section: 3 ub/sr

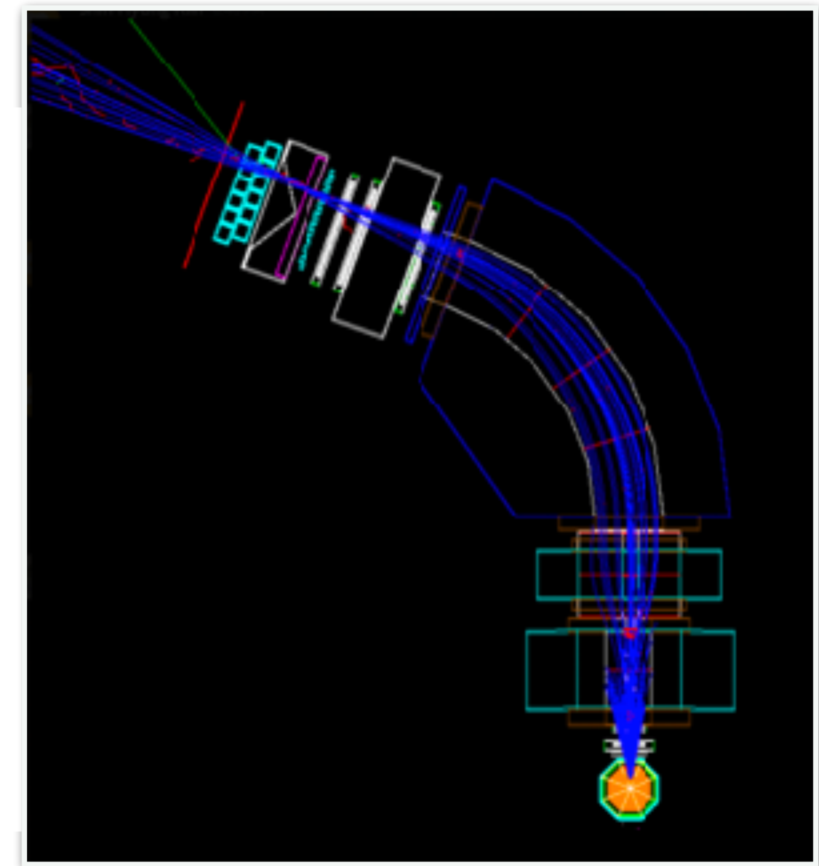
  (BG: $K^+p \to K^+p$: ~ 5 mb/sr, $K^+n \to K^0p$: ~1.5 mb/sr)
- S-2S acceptance: 55 msr
- LD_2 target: 0.55 g/cm^2 (ϕ5.4 cm)

- ~56 events/day (spill cycle: 4.24 s)
- ~780 events for 2 weeks

Expected Inclusive Spectrum







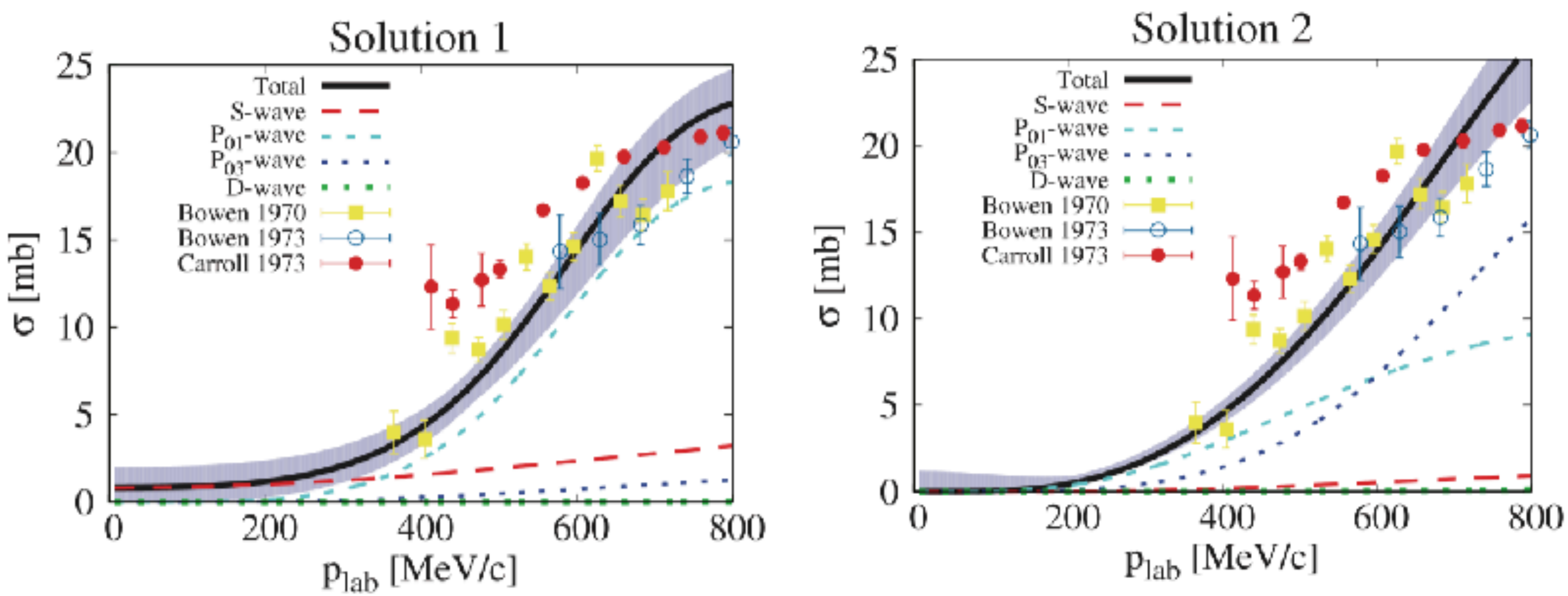
- Suppression of the dominant quasi-free (QF) backgrounds, $K^+p \rightarrow K^+p$ and $K^+n \rightarrow K^0p$, is a key issue for the measurement.
- Information from the surrounding detectors can provide additional QF background rejection.

Beyond the Θ⁺ Search: Low-Energy K⁺N Scattering

- Low-energy KN scattering amplitudes were revisited using a chiral unitary approach

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

- The I=0 total cross sections:



- Existing I = 0 total-cross-section data are limited and have large uncertainties → the I = 0 KN amplitude is still poorly constrained
- New and more precise I = 0 data are strongly needed

Connection to QCD in Nuclear Matter

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

- Recent theoretical studies suggest that

K^+N scattering amplitude ➔ in-medium quark condensate

$$\frac{\langle \bar{u}u + \bar{s}s \rangle^*}{\langle \bar{u}u + \bar{s}s \rangle_0} = \left(1 + \frac{\rho}{M_K^2} \frac{T_{KN}(q=0)}{2M_N} \right)$$

- Current analyses suggest ~10–20% reduction of the condensate at normal nuclear density
➔ indication of partial chiral symmetry restoration

- The I = 1 amplitude is well constrained by K^+p data, while the I = 0 component is still poorly constrained.
➔ New K^+d data can provide important constraints on the I = 0 KN amplitude.

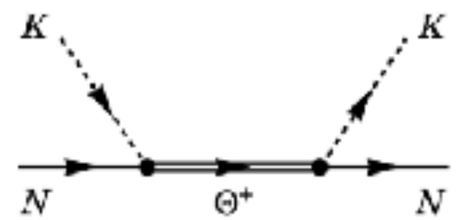
Summary

Θ^+ **Search**

Summary

Θ^+ Search

Photoproduction
Hadronic production
...



KN direct formation

Low-Energy
KN Scattering

Summary

Θ^+ Search

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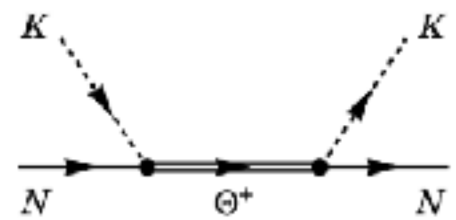
Hadronic production
...



KN direct formation

Non-perturbative QCD test bench

Low-Energy
KN Scattering

KN scattering amplitude

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In-medium
$<\bar{q}q>^*$

Partial chiral symmetry restoration

Summary

Θ^+ Search

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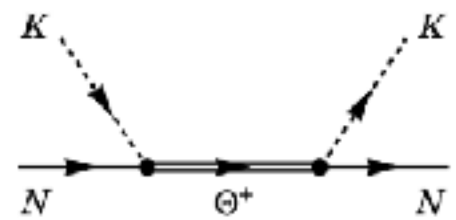
...



KN direct formation

Non-perturbative QCD test bench

Low-Energy KN Scattering

KN scattering amplitude

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In-medium $<\bar{q}q>^*$

Partial chiral symmetry restoration

$I = 1(K^+p)$ well-known

$I = 0$ channel poorly constrained

K^+d (J-PARC)

$K_L p$ (JLab)

Thank you!