Experimental status toward the direct lifetime measurement of Hypertriton using the (K^-, π^0) reaction at J-PARC

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For the J-PARC E73 collaboration

Outline

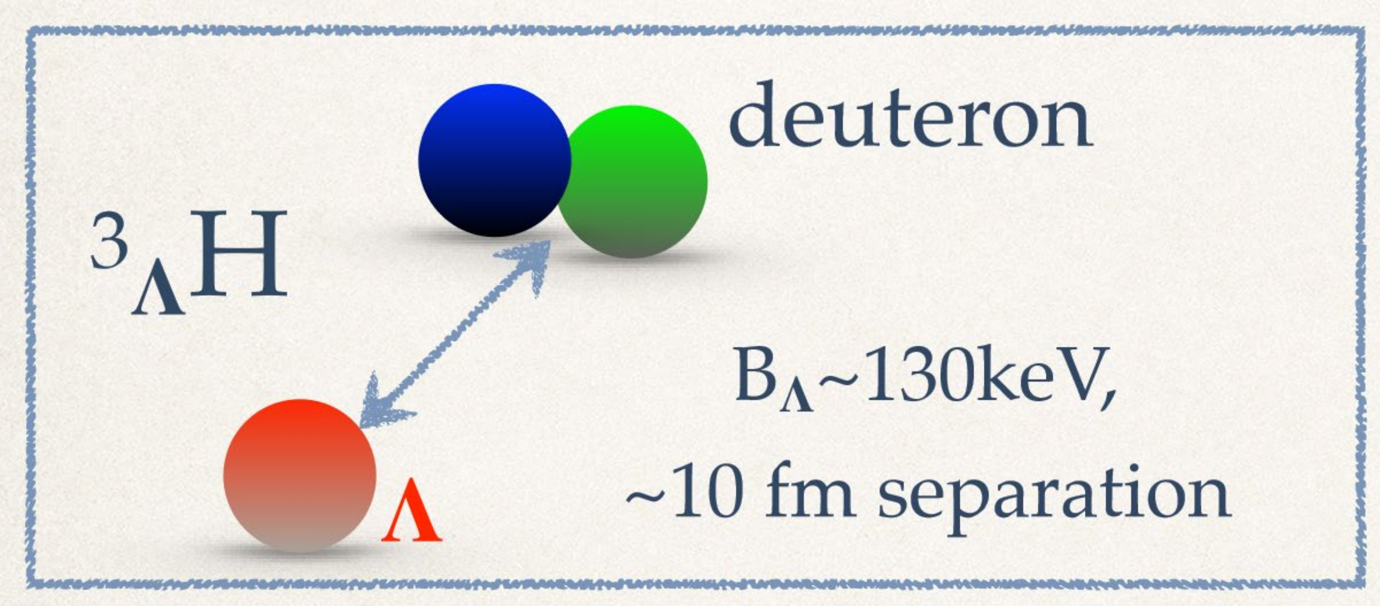
- Introduction
  - Hypertriton lifetime
  - Motivation of J-PARC E73 experiment

- J-PARC E73 experiment
  - Experimental principle
  - Experimental Setup
  - Strategy of direct lifetime measurement
  - timing spectrum of ${}^{4}_{\Lambda}H$ data
  - ${}^{3}_{\Lambda}H$ production result

- Summary

Introduction

- Hypertriton ($^{3}_{\Lambda}H$): Lightest hypernucleus with p, n and Λ
  - ➢Benchmark for hypernuclear physics
  - ➢Small binding energy by emulsion data was generally accepted.
    $B_{\Lambda} = 130 \pm 50$ keV

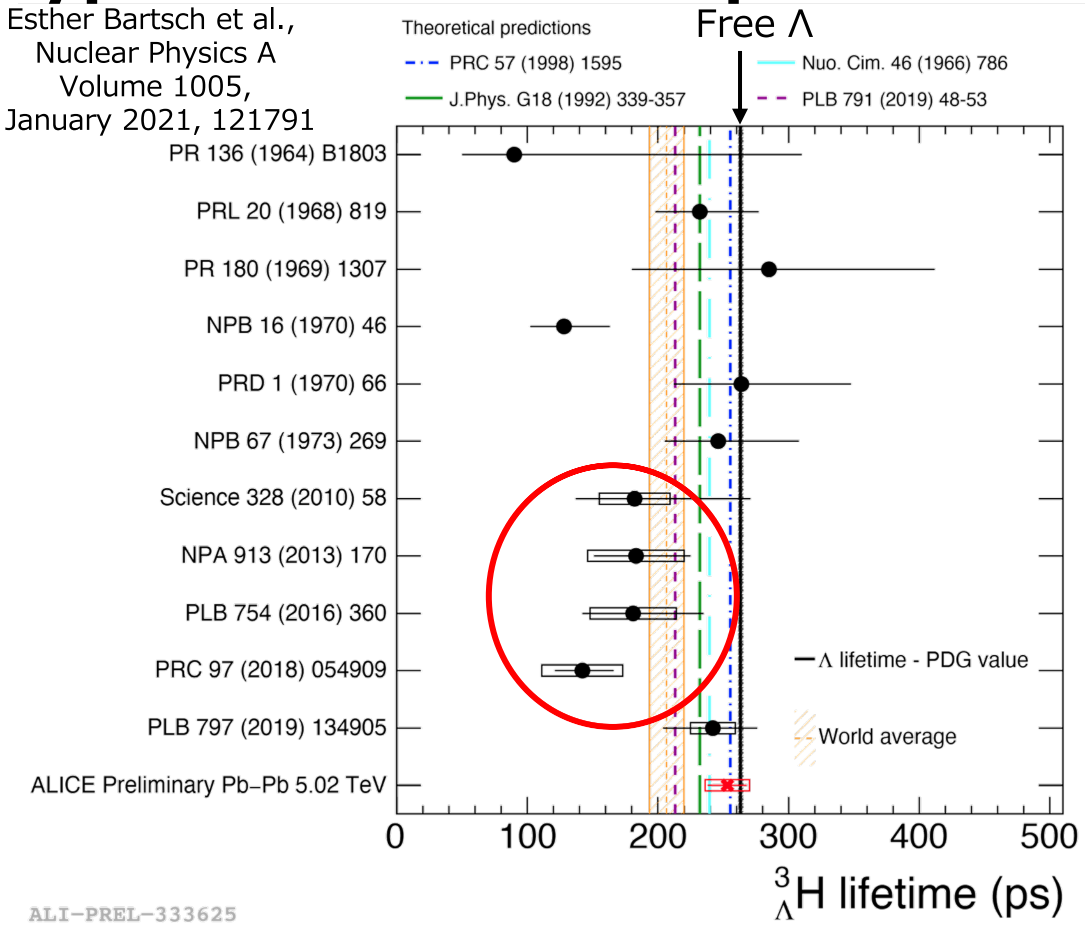


✓Small B_{Λ} → large separation between Λ & d
→ **lifetime τ ~ free Λ (263 ps) is expected**

Introduction

▪ Hypertriton lifetime puzzle

Esther Bartsch et al.,
Nuclear Physics A
Volume 1005,
January 2021, 121791



Exp.	Lifetime
HypHI(2013)	$183^{+42}_{-32} \pm 37$ ps
ALICE(2016)	$181^{+54}_{-39} \pm 33$ ps
STAR(2018)	$142^{+24}_{-21} \pm 29$ ps

✓Still large uncertainty
Signal counts are small
Bad S/N

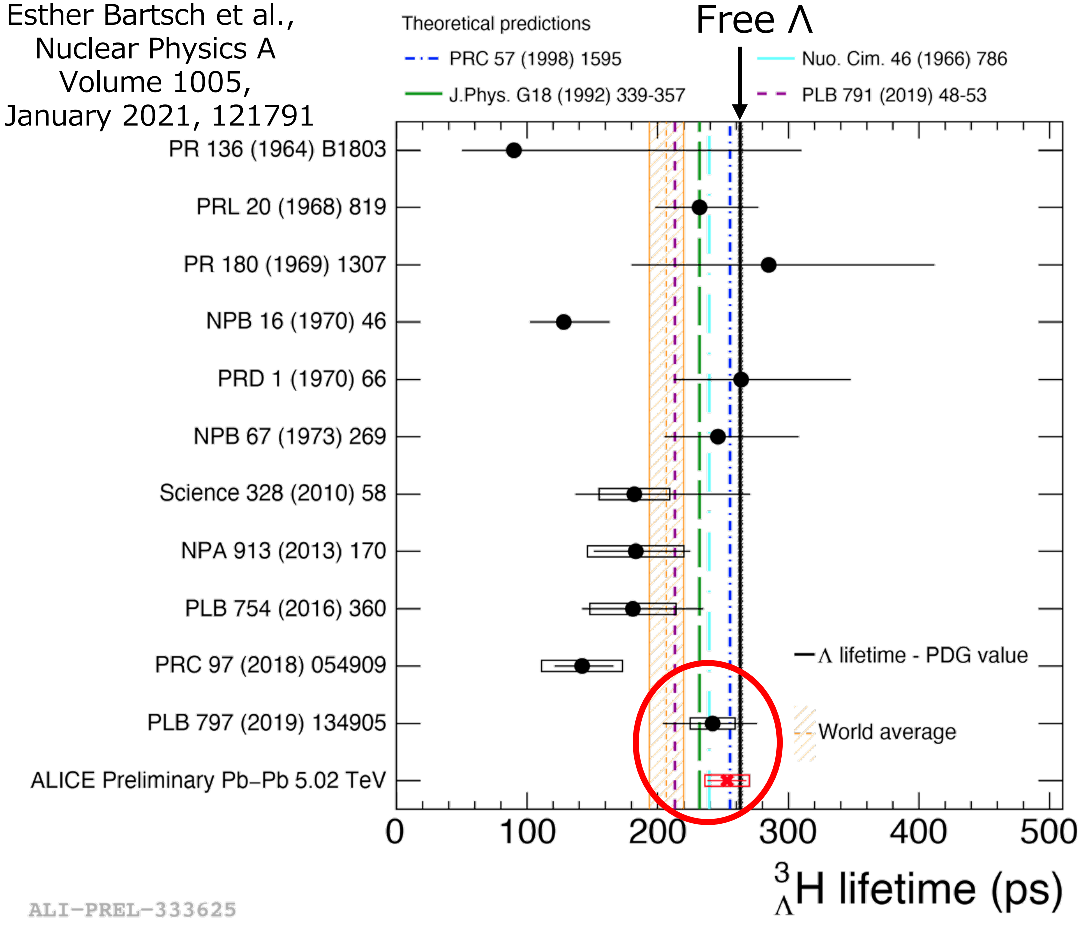
➢**Short lifetimes** from heavy-ion based experiments in 2010's

✓B_Λ=130 KeV, lifetime close to free Λ ⇔ heavy ion result: short lifetime

Introduction

▪ Hypertriton lifetime puzzle

Esther Bartsch et al., Nuclear Physics A Volume 1005, January 2021, 121791



Exp.	Lifetime
ALICE(2019)	$242^{+34}_{-38} \pm 17$ ps
ALICE(2020)	$254 \pm 15 \pm 17$ ps
STAR(2021)	$232 \pm 29.2 \pm 36.7$ ps

✓Better data quality
More Signal
better S/N

⇒Lifetime compatible with free Λ

Is the Hypertriton lifetime puzzle solved ?

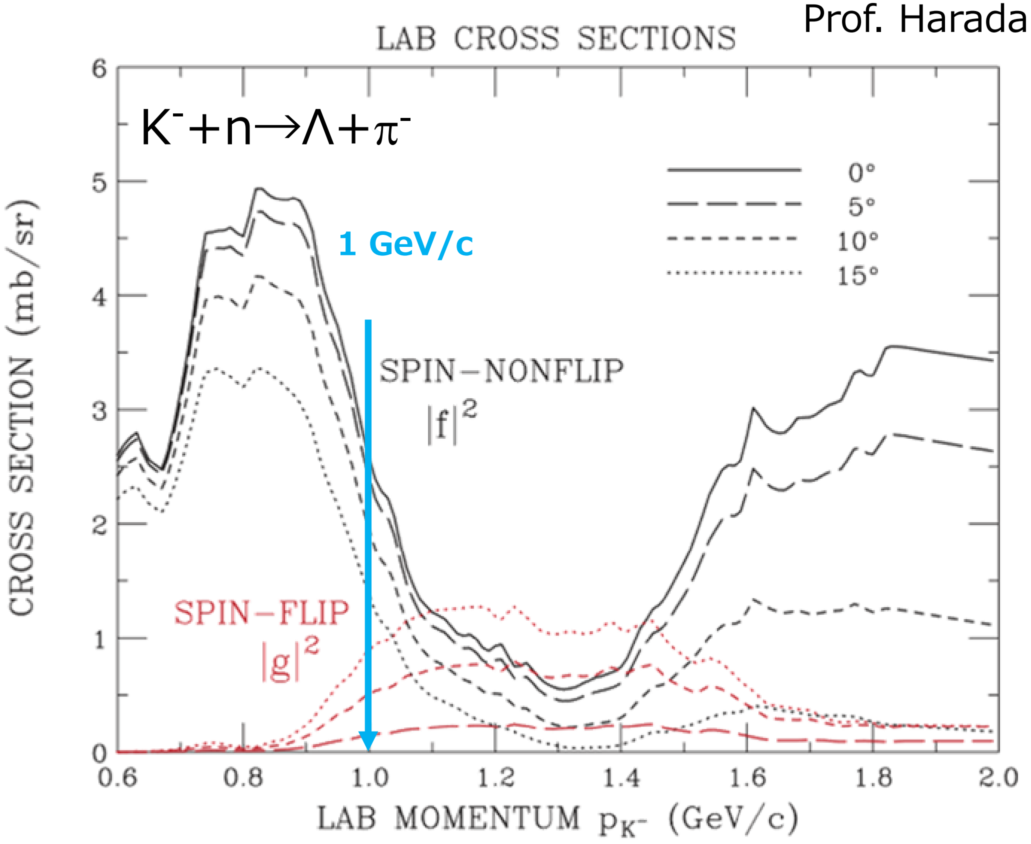
There's something that's not clear(Binding energy, spin)

Toward solving hypertriton lifetime puzzle

- the detail of the $^{3}_{\Lambda}H$ should be clearly understood
  ⇒an independent and complementary approach

Experiment	Heavy ion-based	J-PARC E73
Production method	Heavy ion collision	$^{3}He(K^{-}, \pi^{0})^{3}_{\Lambda}H$
Microscopic process	Thermal model; Coalescence model	**Strangeness exchange**
Quantum number	1/2 and 3/2 mixture?	**spin=1/2 dominant**

calculation by Prof. Harada



➢**provide important data on the hypertriton lifetime puzzle**

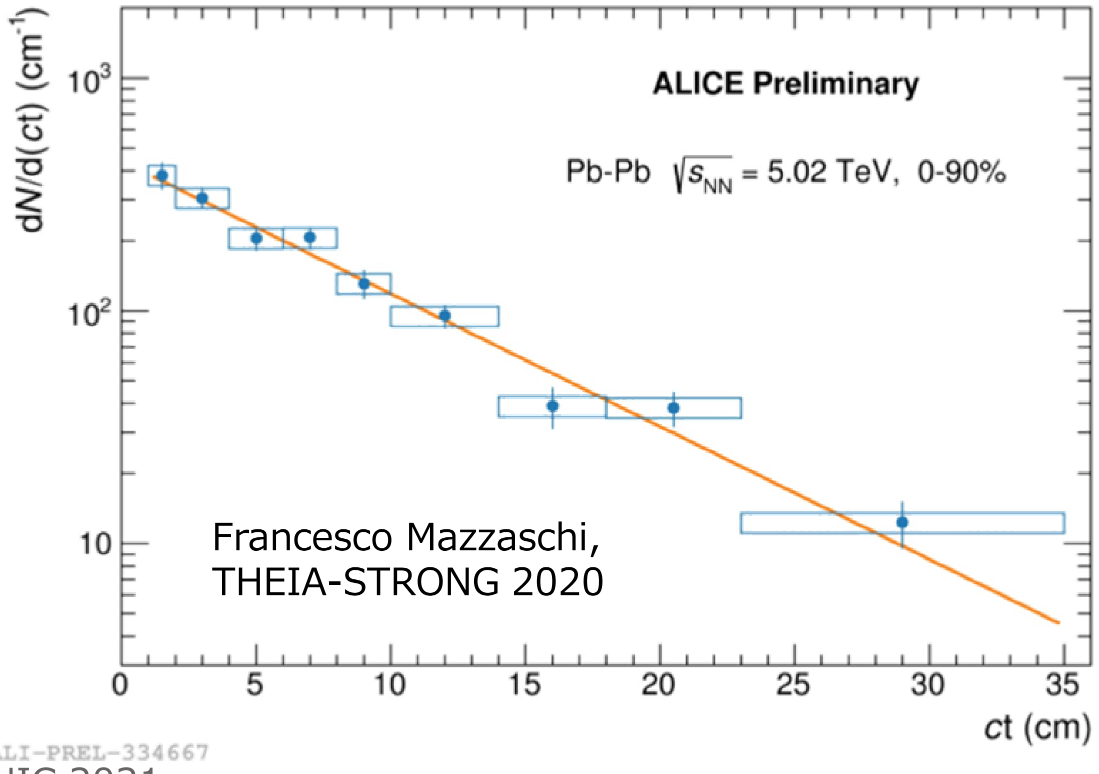
HI exp. vs direct measurement

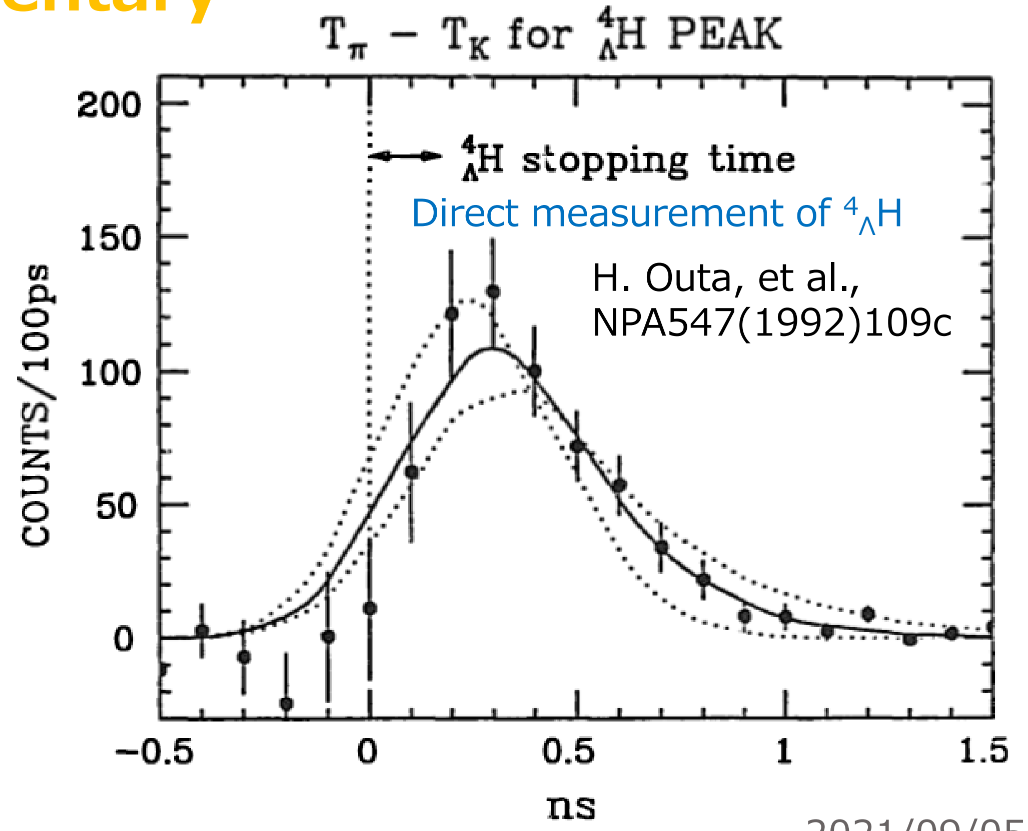
- HI experiments: STAR, ALICE, HypHI
  - reconstructed by Invariant mass
  - Indirect measurement using decay length

- Counter experiment: J-PARC
  - Identified by pion momentum
  - Time of flight

  ⇒**J-PARC E73 experiment**

complementary





Experiments on Hypertriton

- Heavy ion-based experiments
  - STAR
  - ALICE
  - GSI (WASA-FRS experiment)

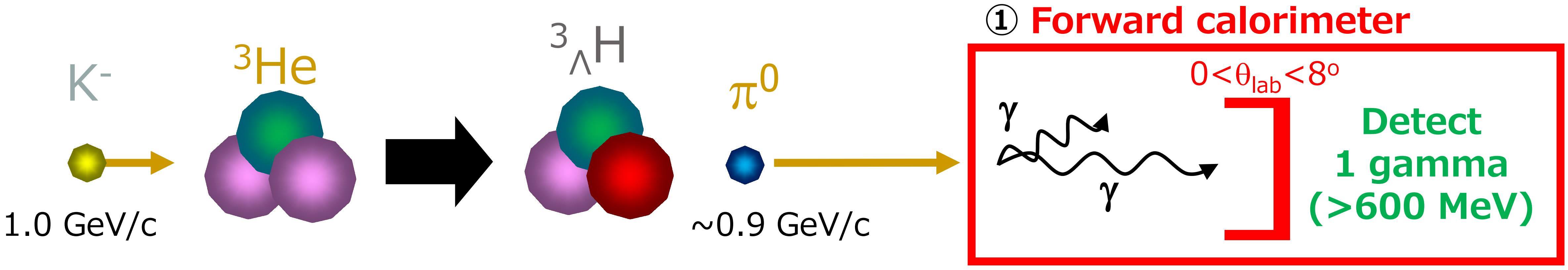
- Counter experiments for lifetime
  - ELPH: (γ, K^+)
  - J-PARC P74: (π^-, K^0)
  - J-PARC E73: (K^-, π^0) ← Our project

- Binding energy measurement
  - MAMI (e, e'K) decay pion spectroscopy
  - JLab (e, e'K)
  - J-PARC E07: Emulsion full scan

J-PARC E73 experiment

J-PARC E73 experiment

- Experimental principle
  - ✓$^{3}He(K^{-}, \pi^{0})^{3}_{\Lambda}H$ reaction



①tag (K^{-}, π^{0}) reaction detect forward high-energy gamma with calorimeter

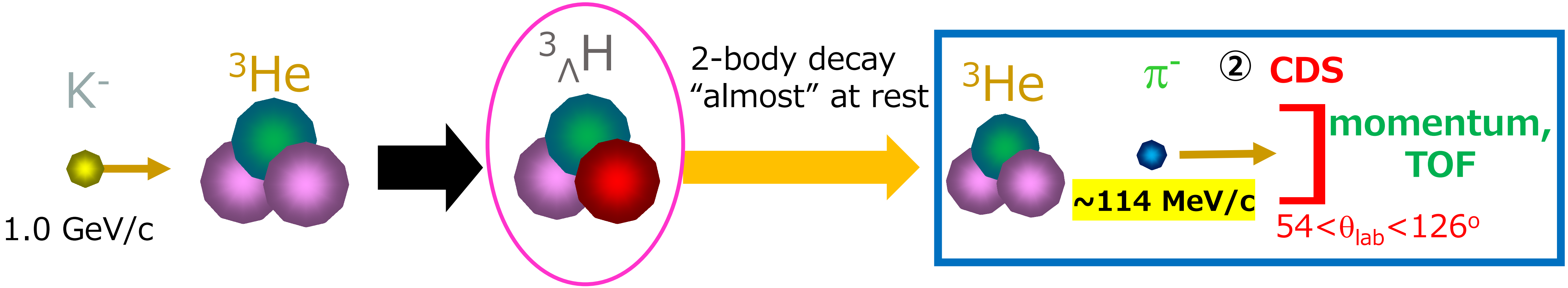
→high momentum pi0

⇒**tag Λ production with low recoil momentum**

Reduce BG due to decay of Λ and Σ, multi pion production

J-PARC E73 experiment

- Experimental principle
  - ✓$^{3}He(K^{-}, \pi^{0})^{3}_{\Lambda}H$ reaction

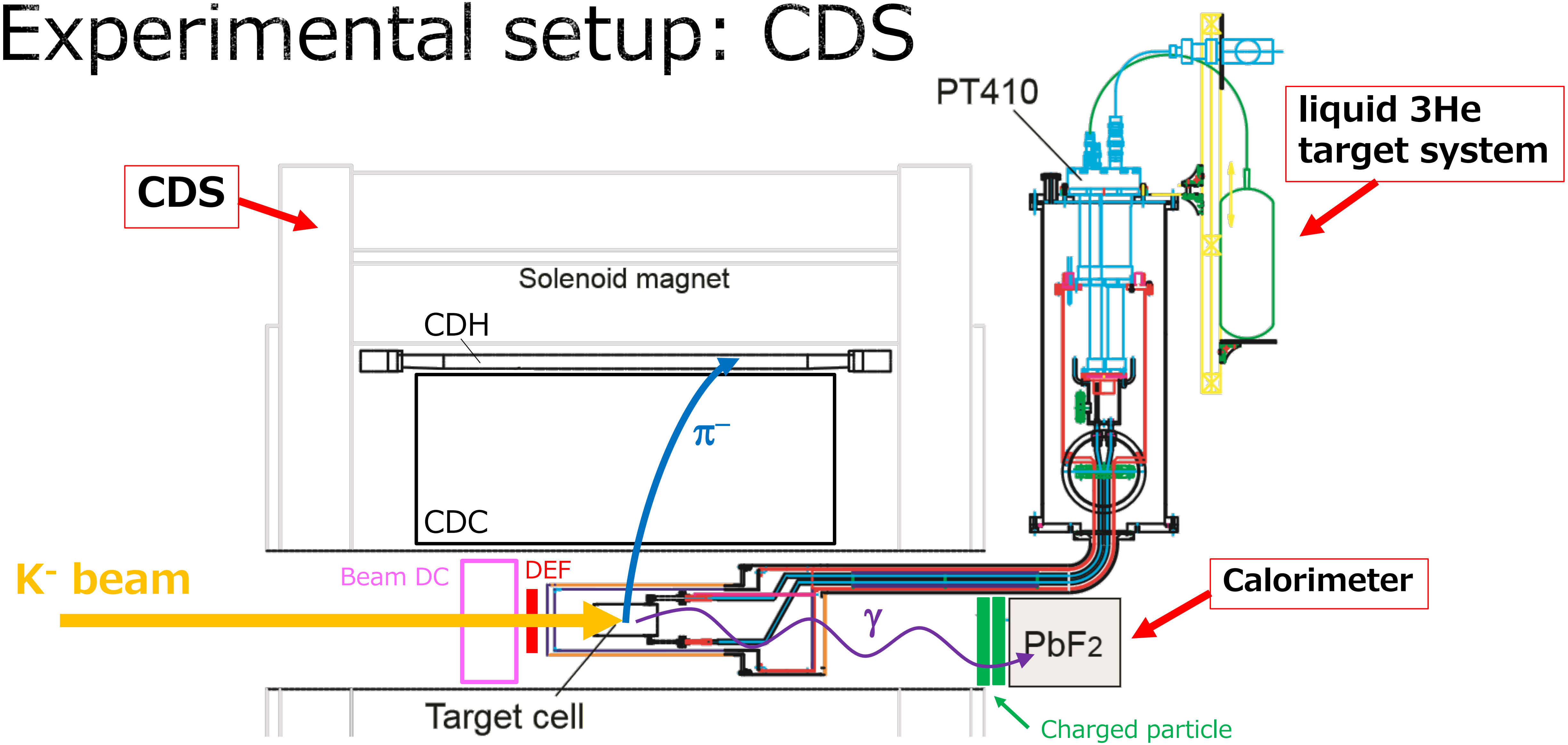


②Measure Momentum and TOF with Cylindrical Detector System (CDS)

select the mono-momentum of π- after 2-body decay

Identify $^{3}_{\Lambda}H$ and derive lifetime from decay time

Experimental setup: CDS

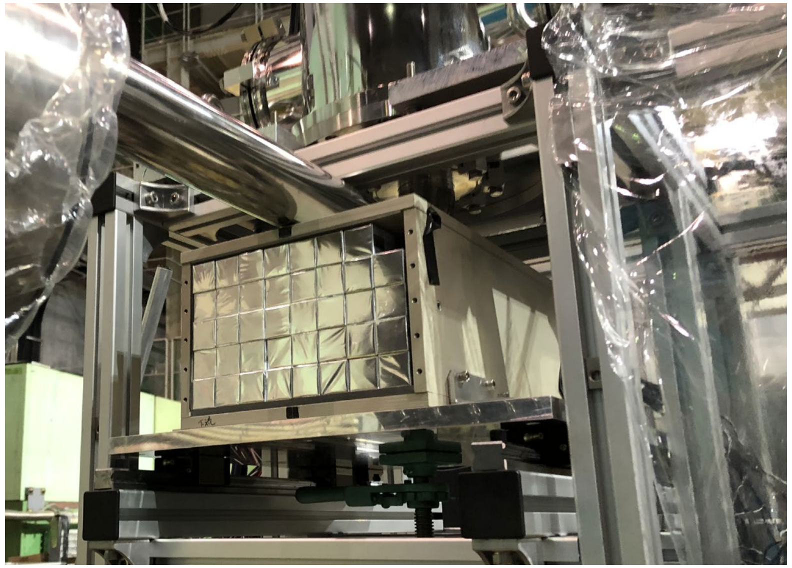


CDS well worked in K1.8BR Beamline

PbF2 new installed

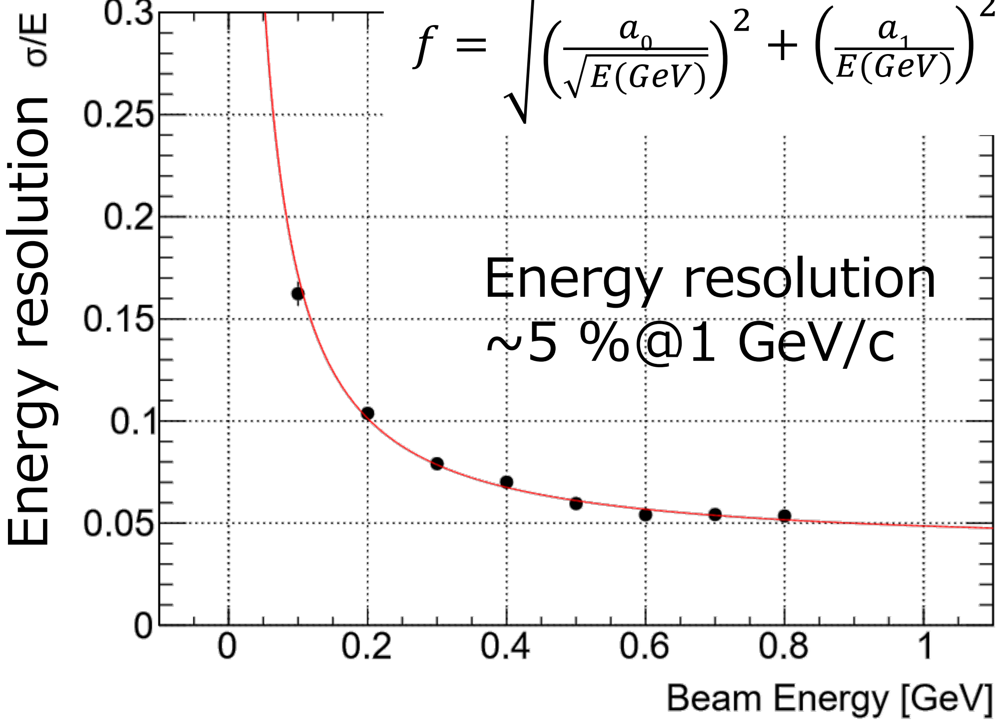
PbF_2 calorimeter performance

- PbF2 calorimeter is installed into the meson beam line to tag fast π^0
- 40 segments used

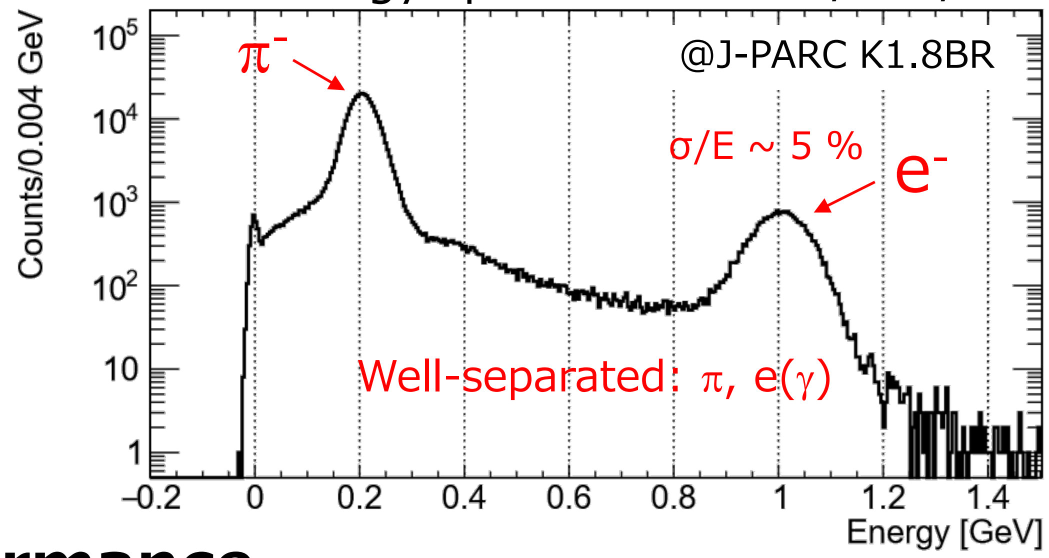


2019.12: Test experiment @ ELPH e⁺ beam

$$f = \sqrt{\left(\frac{a_0}{\sqrt{E(GeV)}}\right)^2 + \left(\frac{a_1}{E(GeV)}\right)^2 + b^2}$$



Energy spectrum@1GeV/c π-/e-



Good enough performance

Idea of (K-, π^0) reaction

- New method
  - Tag the hypernucleus by detecting single gamma ray decaying from π^0
    ⇒**need to establish this method by (K-, π^0) reaction**
  - To effectively populate hypernucleus

Hypernucleus	$^{4}_{\Lambda}H$	$^{3}_{\Lambda}H$
Branching ratio to 2-body decay	50 %	25 %
Relative cross section	R=0.3—0.4	

calculation of cross section by Prof. Harada
T. Harada and Y. Hirabayashi, https://arxiv.org/abs/2106.04256v2

$R = \sigma_{lab}(^{3}_{\Lambda}H)/\sigma_{lab}(^{4}_{\Lambda}H)$

✓expected to be relatively easy to generate and identify $^{4}_{\Lambda}H$
⇒**confirm by experiments using ^{4}He targets**

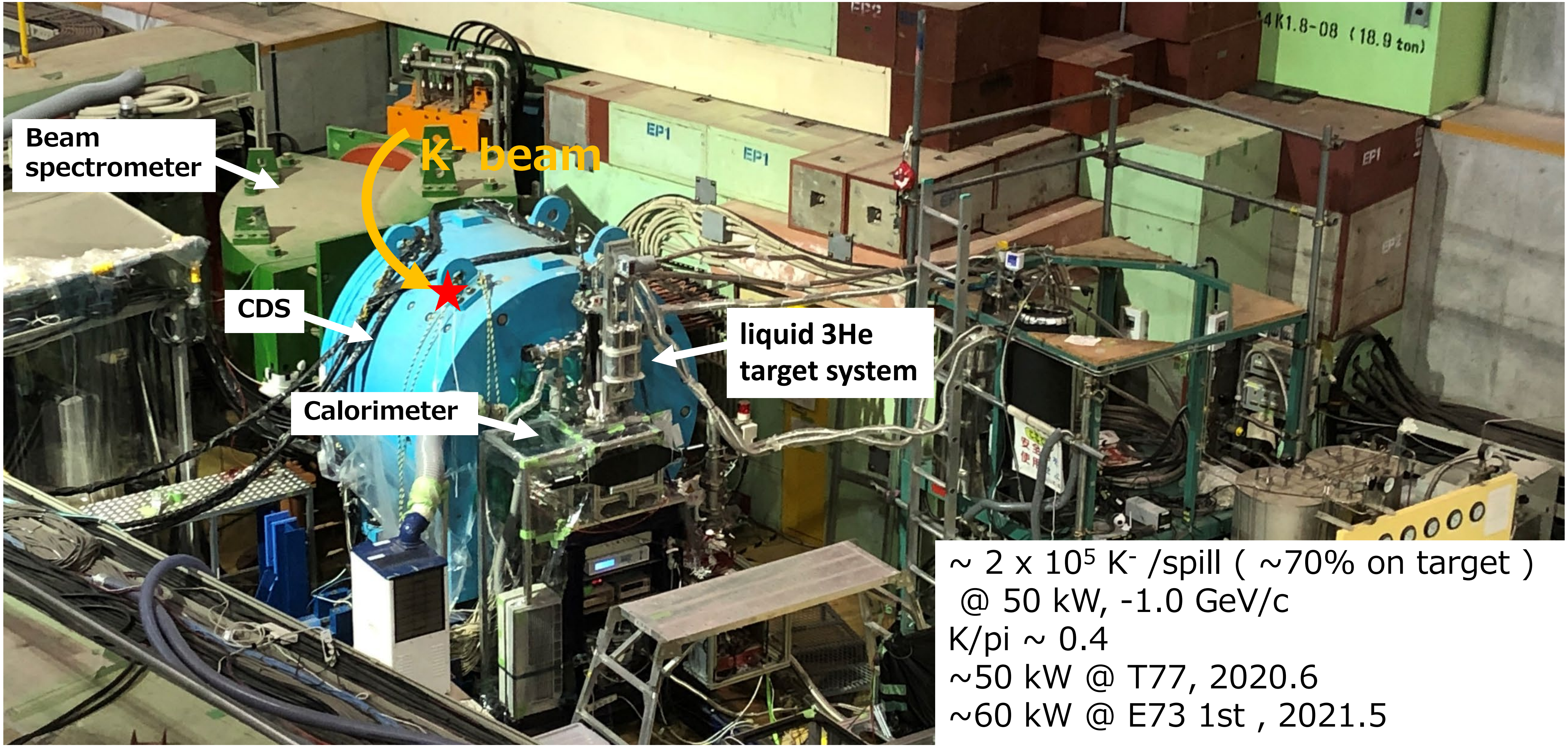
Strategy of J-PARC E73

- Phase-0
  - Feasibility study of the (K-, π^0) reaction on a ^{4}He target
  - Data taking in June 2020

- Phase-1
  - Production cross section study for $^3_\Lambda$H
  - Data taking in May 2021

- Phase-2
  - Direct lifetime measurement for $^3_\Lambda$H
  - planned in FY2022

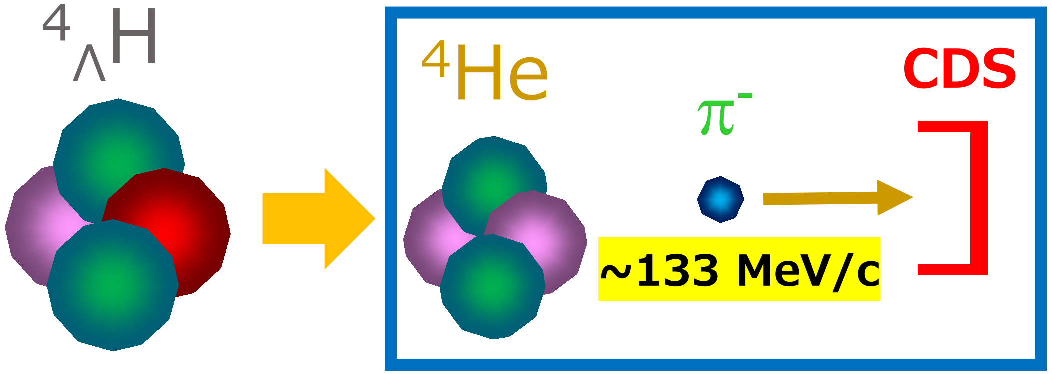
J-PARC K1.8BR Beamline

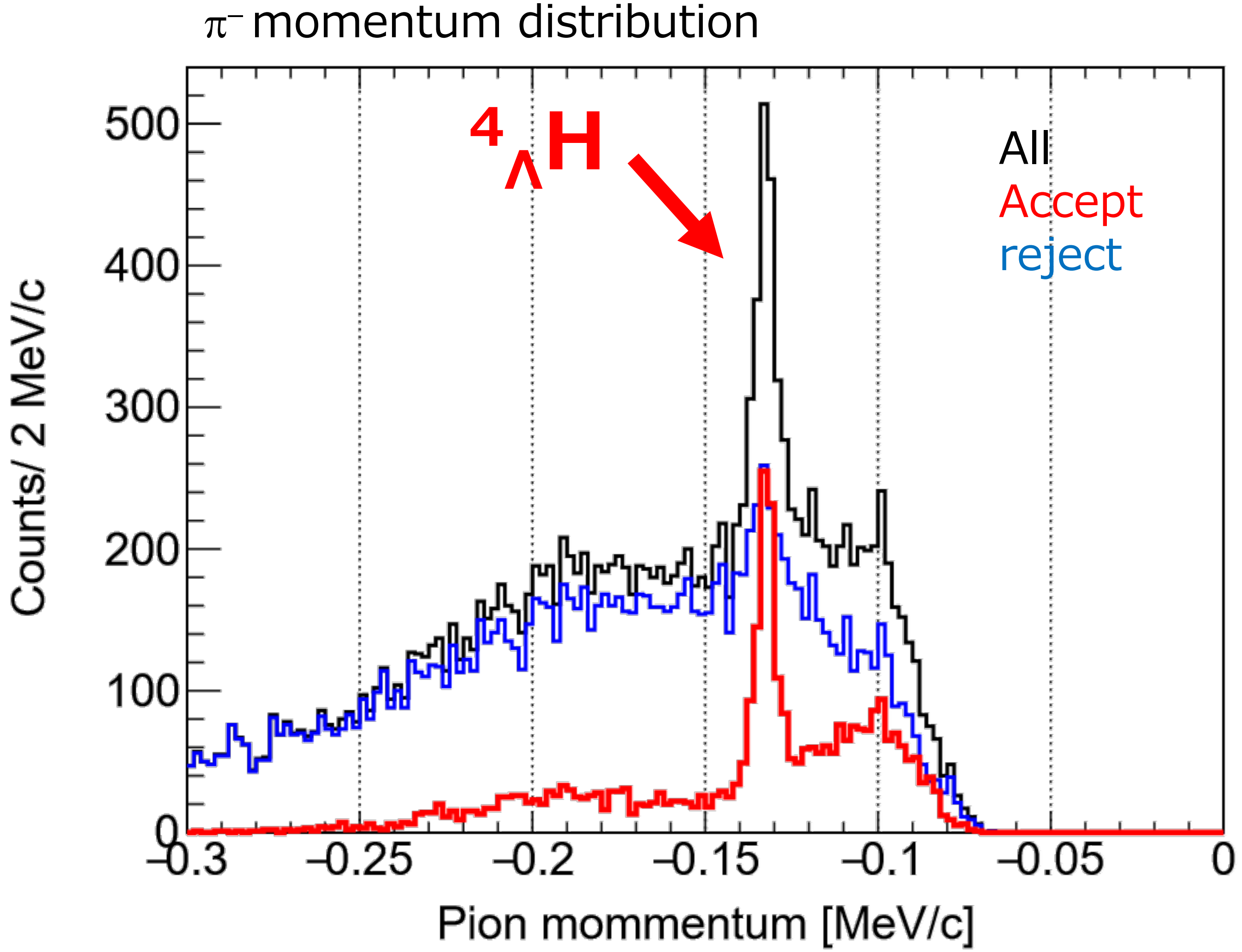


~ 2 x 10^5 K^- /spill (~70% on target)
@ 50 kW, -1.0 GeV/c
K/pi ~ 0.4
~50 kW @ T77, 2020.6
~60 kW @ E73 1st , 2021.5

Phasae-0: Feasibility study

- $^4He(K^-, \pi^0)^4{}_{\Lambda}H$ reaction





- Background reduction by PbF2
  - Selection of high energy γ-rays for $^4{}_{\Lambda}H$ production

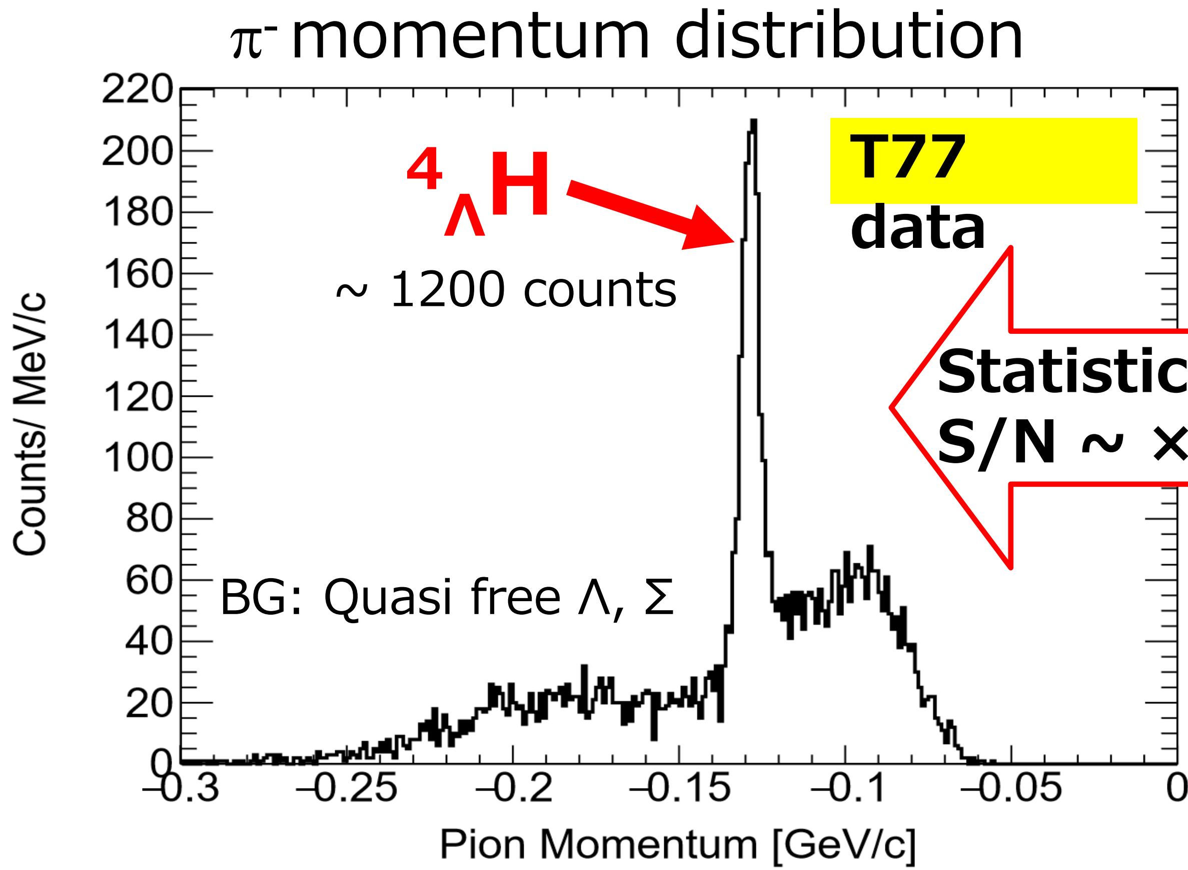
    ⇒Almost no loss of signal

    Improved S/N ratio

    Before cut: 3:2 → **After cut: 4:1**

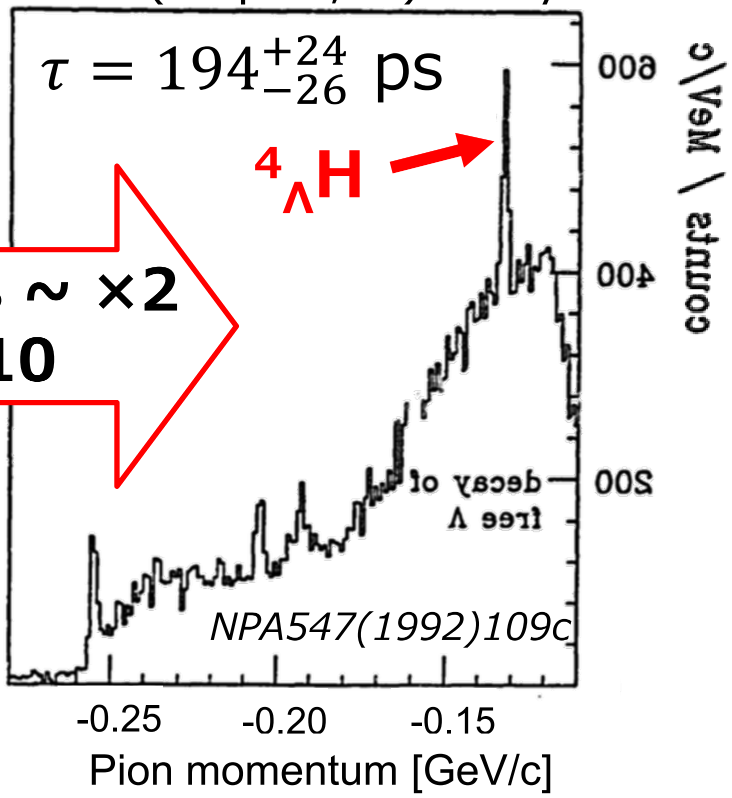
Phasae-0: pi- momentum dis. of $^{4}_{\Lambda}H$

- **Successful Production and Identification of Hypernucleus with new Method**



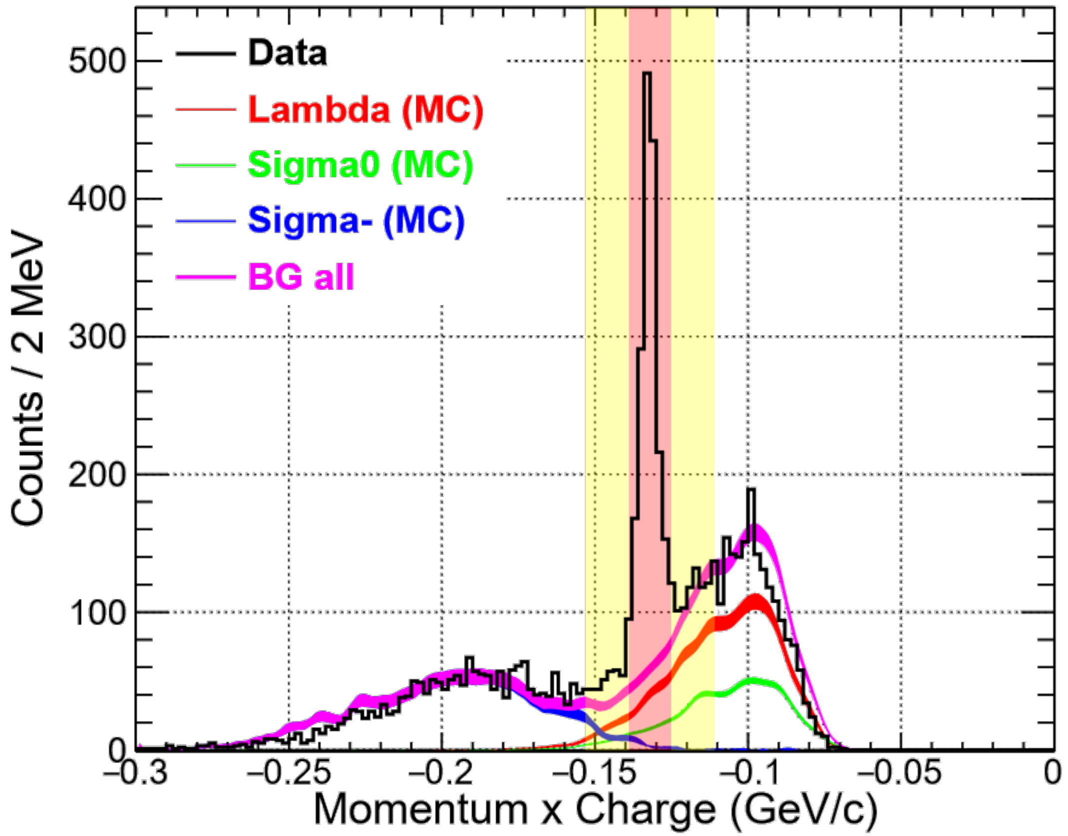
Statistics ~ ×2
S/N ~ ×10

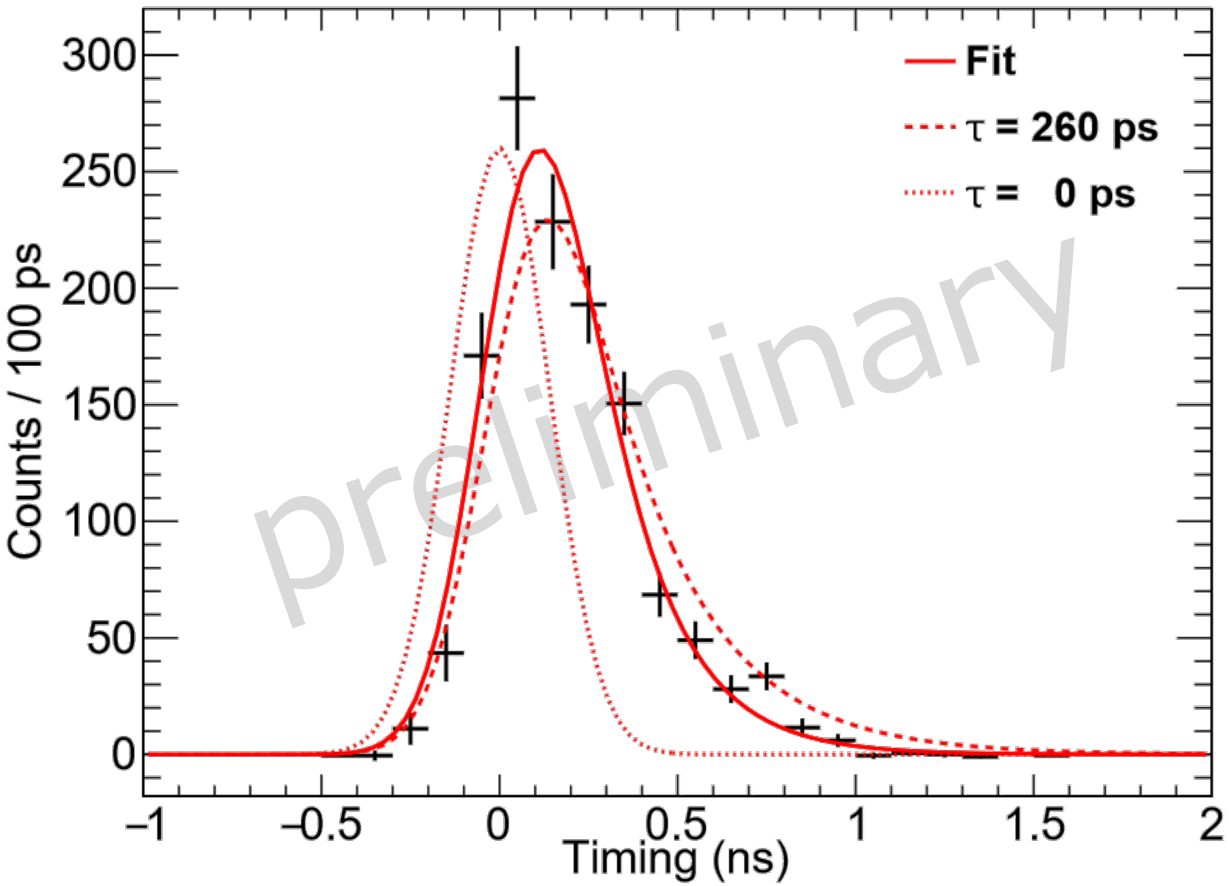
KEK, 1992
$^{4}He(stop\ K^{-}, \pi^{-})$ delayed



Data taking in 3 days beamtime

Phasae-0: timing spectrum of ${}^{4}_{\Lambda}H$ data

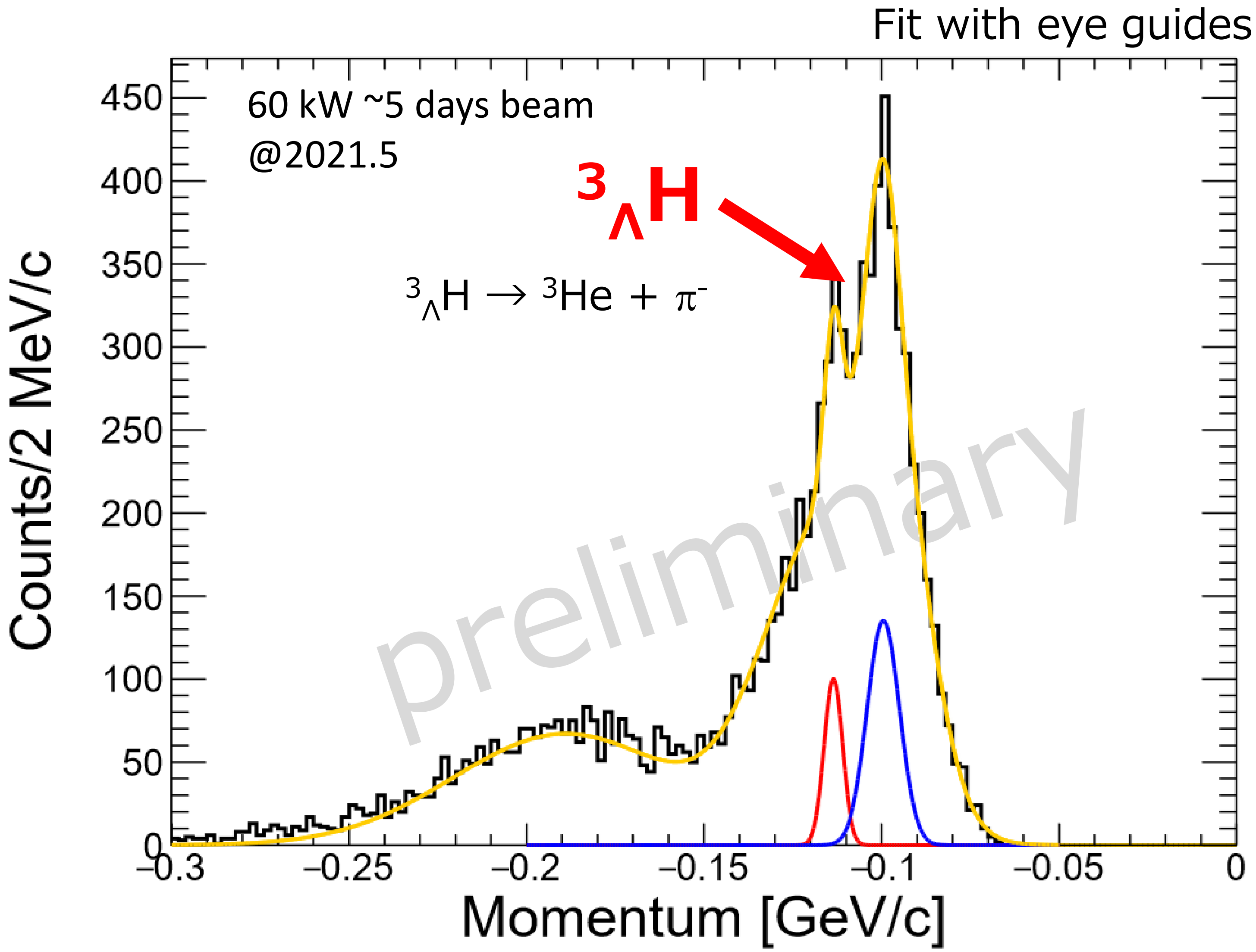




- ${}^{4}_{\Lambda}H$ after sideband subtraction
- Timing response by π^- scattering
- statistical error < 10 ps

will be finalized soon

Phasae-1: pi- momentum dis. of $^{3}_{\Lambda}H$



- ✓Hypertriton events can be seen

  ~ 200 events

  ⇒ **derive the cross section of the hypertriton**

- ✓3-body decay events around ~100 MeV/c

- ✓BG: quasi-free Λ/Σ

Summary

- Hypertriton lifetime Puzzle
  - B_Λ=130 KeV, lifetime close to free Λ $\Leftrightarrow$ heavy ion result: short lifetime
- Direct measurement of $^{3}_{\Lambda}H$ lifetime (J-PARC E73) is planned
  - Different experimental method from heavy ion-based experiment
  - Selectively produce ground state of $^{3}_{\Lambda}H(1/2^{+})$
- Current status of the experiment
  - Phase-0: established a method by (K^{-}, π^{0}) reaction
    $\Rightarrow$ $^{4}_{\Lambda}H$ lifetime
  - Phase-1: confirmed $^{3}_{\Lambda}H$ production
    $\Rightarrow$cross section of $^{3}_{\Lambda}H$
  - Phase-2: $^{3}_{\Lambda}H$ lifetime measurement
    ~ 1 month beam time, $^{3}_{\Lambda}H$ ~1000 events, ~10 % error
    $\rightarrow$ in FY2022

J-PARC E73 collaboration

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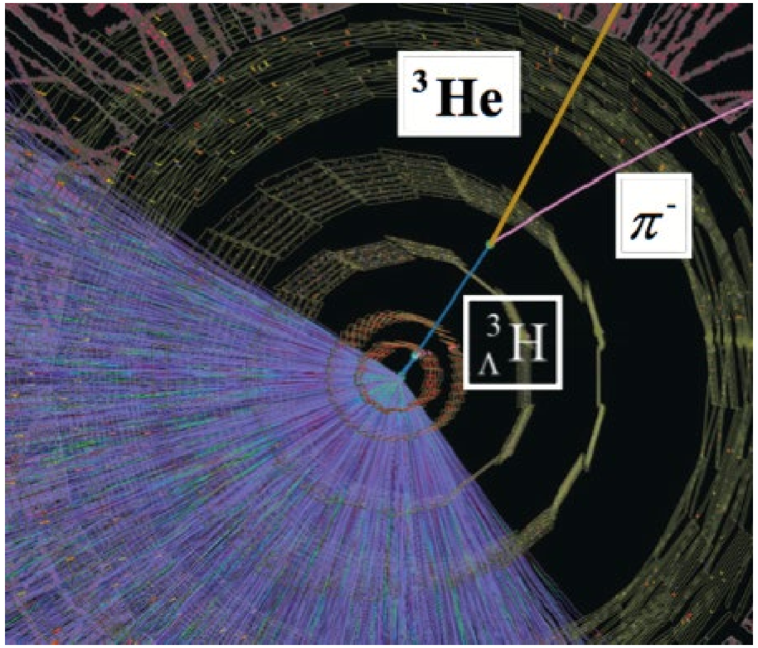
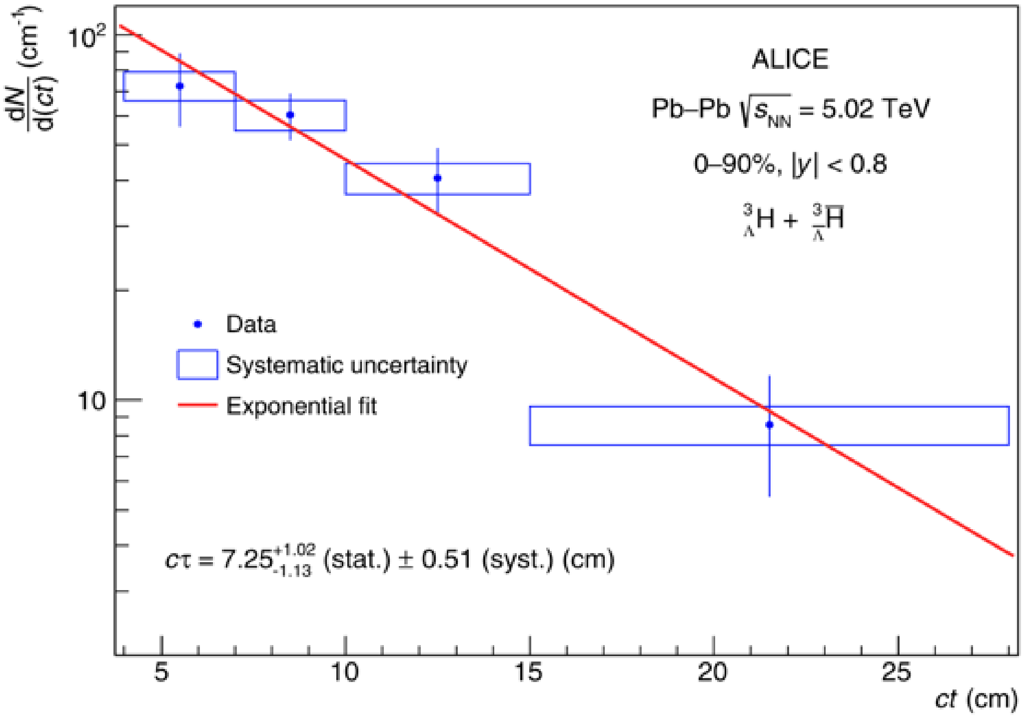
Backup

Introduction: heavy ion results

ALICE as an example for
the experimental approach.



$$\tau = 240^{+40}_{-31}(\text{stat.}) \pm 18(\text{syst.})$$

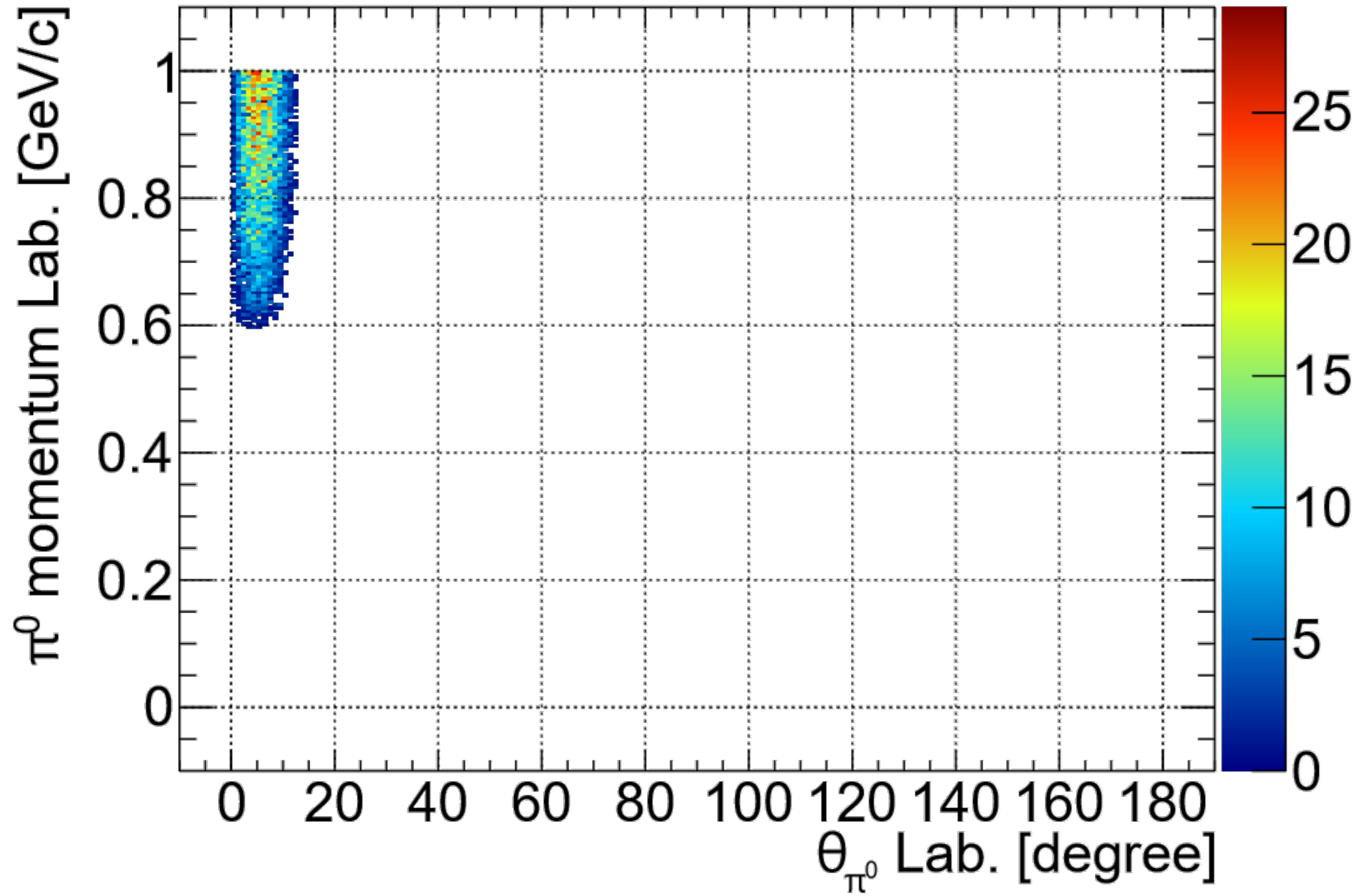


Depends on tracking results for
decay length and momentum as
t = L/βγc

ALICE collaboration, PLB, 797 (2019) 134905

Tagging single γ-ray

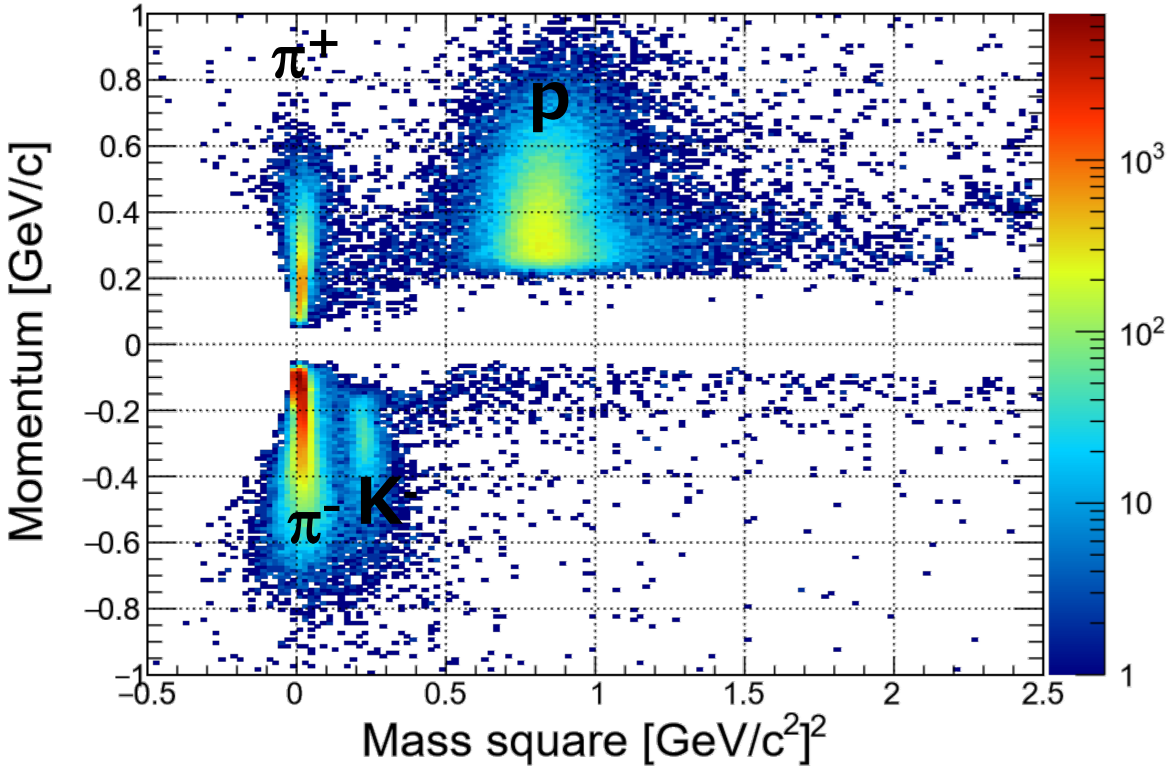
- Simulation: π^0 uniformly 0~1 GeV/c, 0~180 deg
  - Forward calorimeter energy select >0.6 GeV gamma



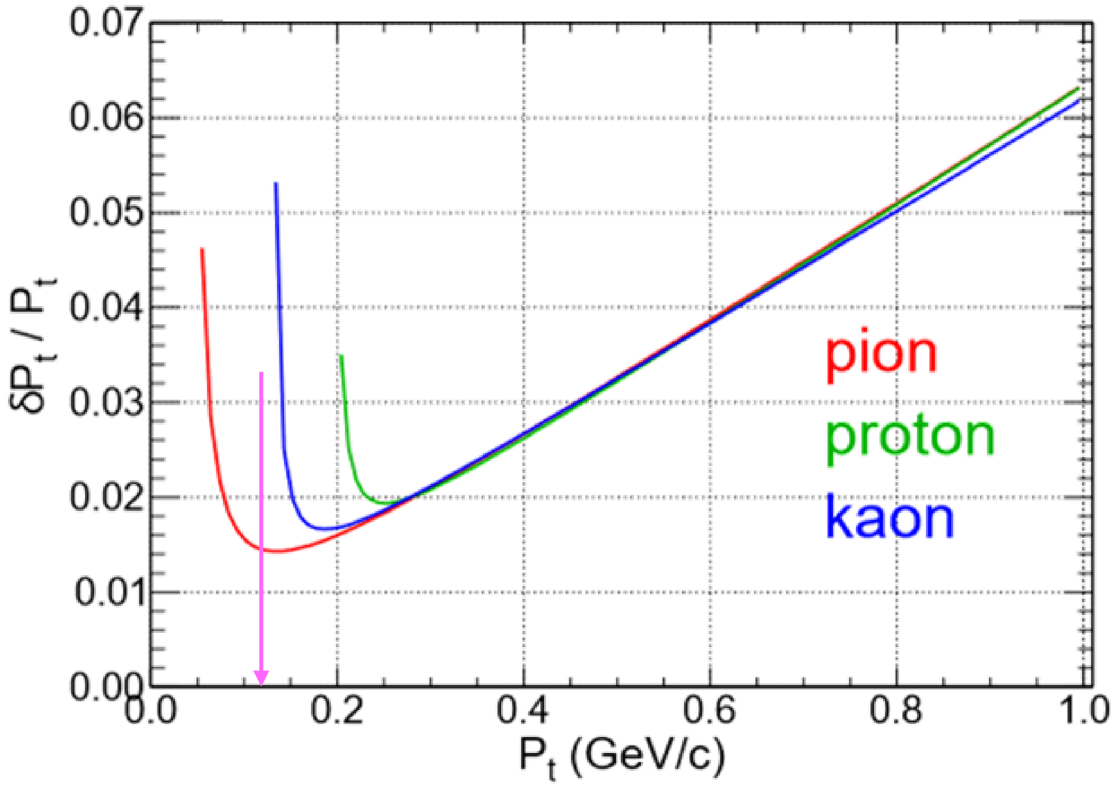
✓forward high-energy π^0 can be selected by detecting 1 gamma

CDS performance

Particle ID



Momentum resolution



✓Well working

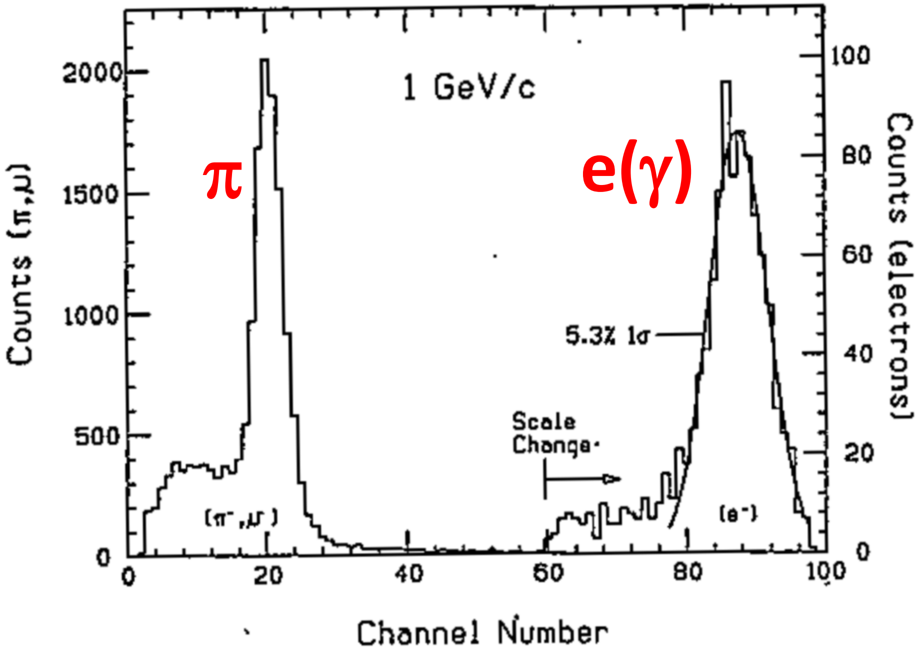
PbF_2 calorimeter

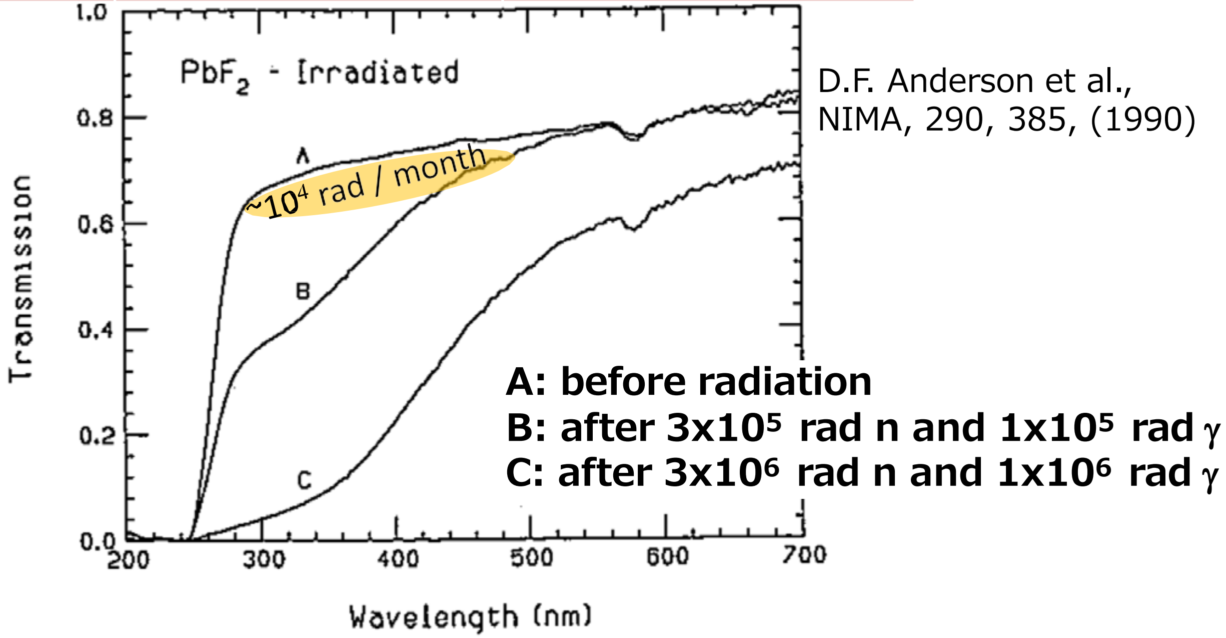
Experiment used PbF2: MAMI A4

EPJA: Hadrons and Nuclei volume 18, p.159–161(2003)

- Basic information

Radiation length	Moliere radius	Density	Refractive index	Energy resolution
0.93 cm	2.22 cm	7.77 g/cm^3	1.82	5 %/√E(GeV)





D.F. Anderson et al., NIMA, 290, 385, (1990)

- Calorimeter with Cherenkov light
  - ✓Fast response
  - ✓Identification of hadrons and e, γ
- High radiation resistance