K中間子ビームを用いたハイパートライトンの寿命測定の現状

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Osaka University
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For the J-PARC E73 collaboration

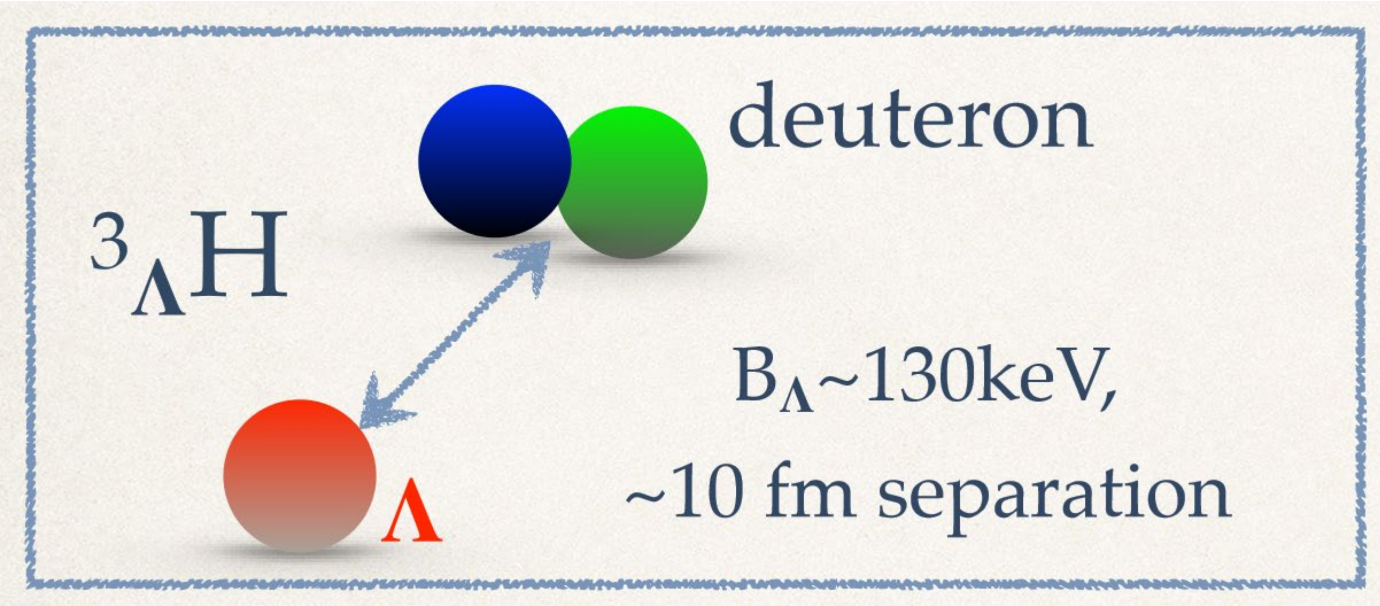
Outline

- Introduction
  - Hypertriton lifetime
  - Motivation of J-PARC E73 experiment
- J-PARC E73 experiment
  - Experimental principle
  - Result of $^{4}_{\Lambda}H$ data
  - $^{3}_{\Lambda}H$ production result with pilot run
- Summary

Introduction

- Hypertriton ($^3_\Lambda$H): Lightest hypernucleus with p, n and Λ
  - Benchmark for hypernuclear physics
  - Small binding energy by emulsion data has been generally accepted.

    $B_\Lambda = 130 \pm 50$ keV

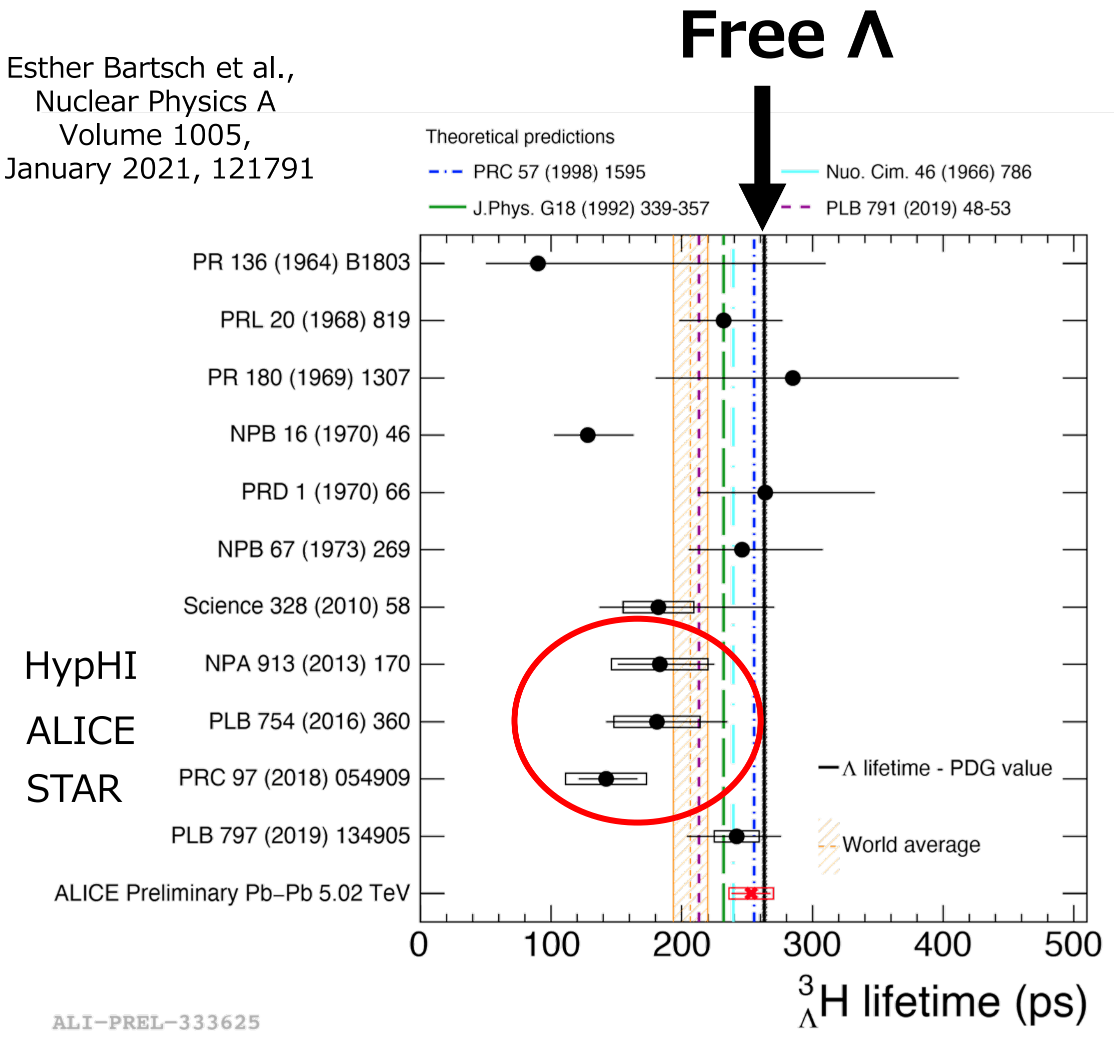


✓Small B_Λ → large separation between Λ & d

→ **lifetime τ ~ free Λ is naively expected**

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

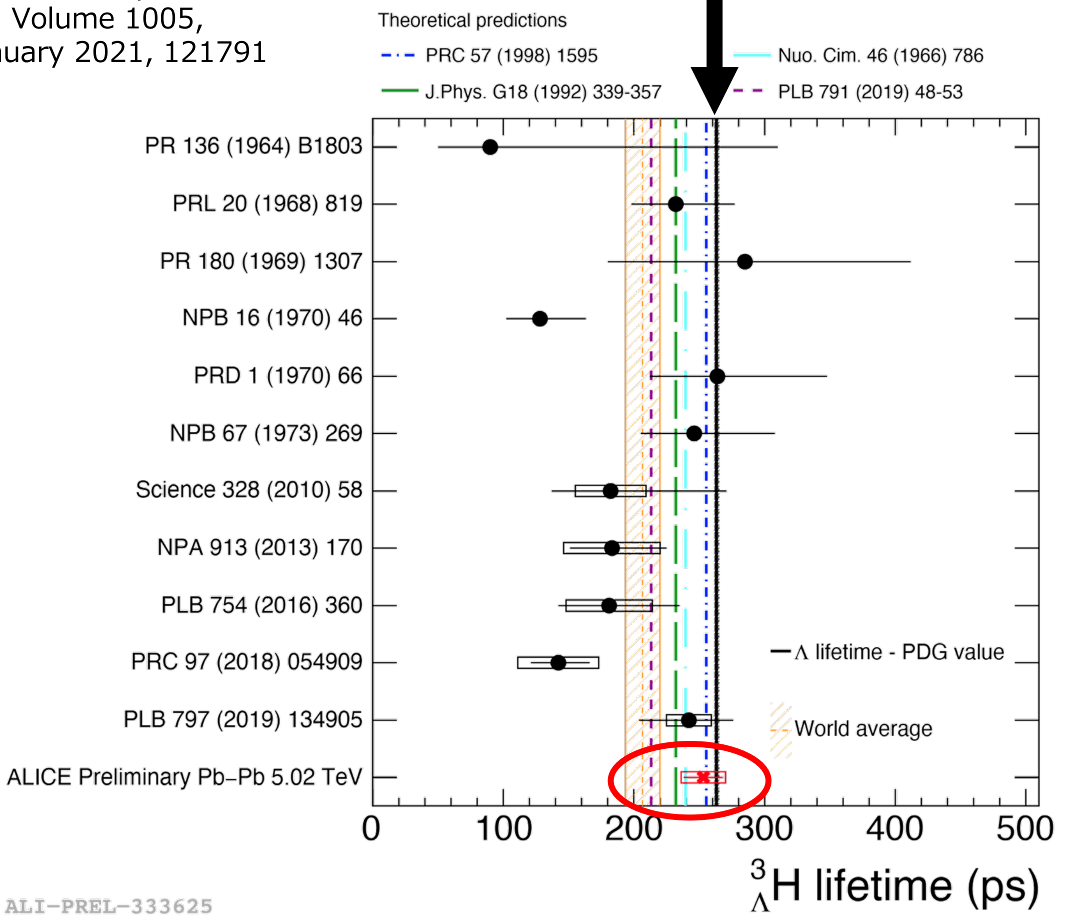
Free Λ(263 ps)

- **Short lifetimes** from heavy ion experiments in 2010’s

Hypertriton lifetime puzzle

Free Λ

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



Francesco Mazzaschi
THEIA-STRONG 2020
ALICE Preliminary result

Exp.	Lifetime
ALICE(2020)	$254 \pm 15 \pm 17$ ps
STAR(2021)	$232 \pm 29.2 \pm 36.7$ ps

Yue-Hang Leung
REIMEI-THEIA web seminar
STAR Preliminary result

Comparable with Free Λ

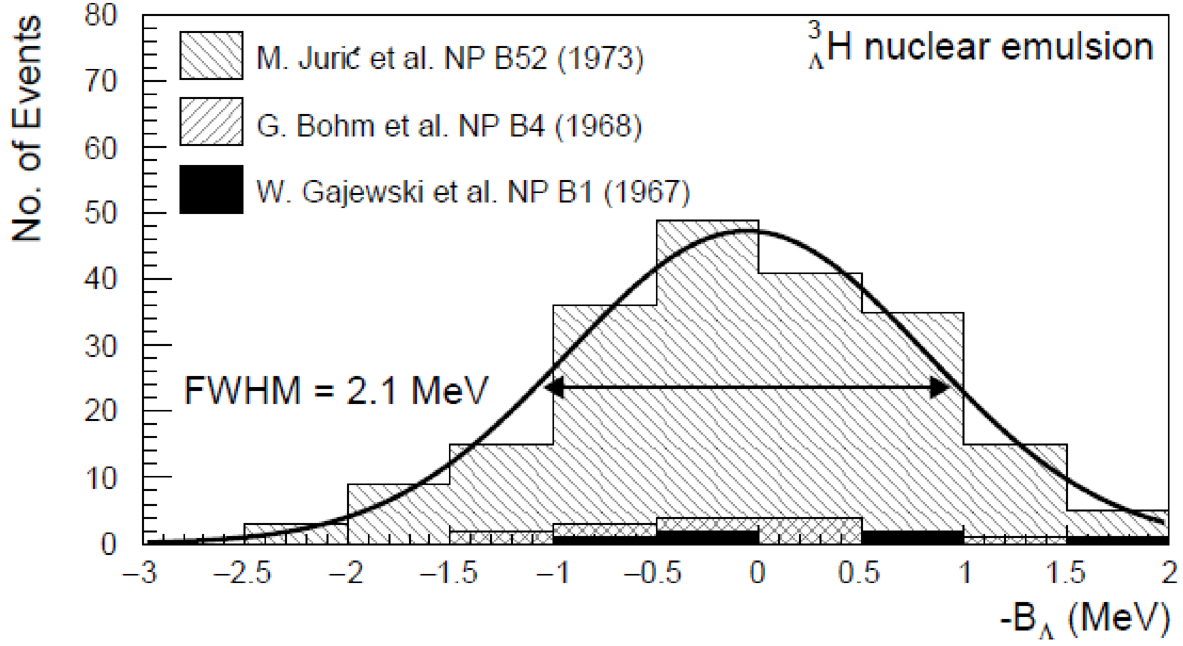
the Hypertriton lifetime puzzle is still not solved

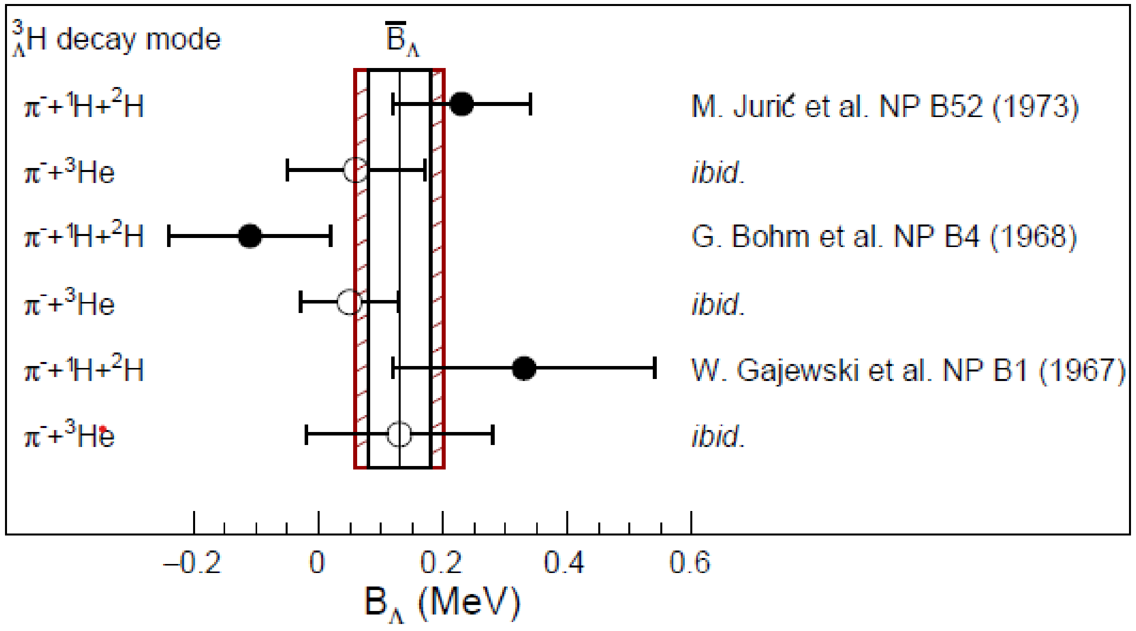
⇒ **spin mixture of 1/2 and 3/2 should be avoided**

Binding energy

- Emulsion measurement

P. Achenbach, *et al, PoS(Hadron2017)*207

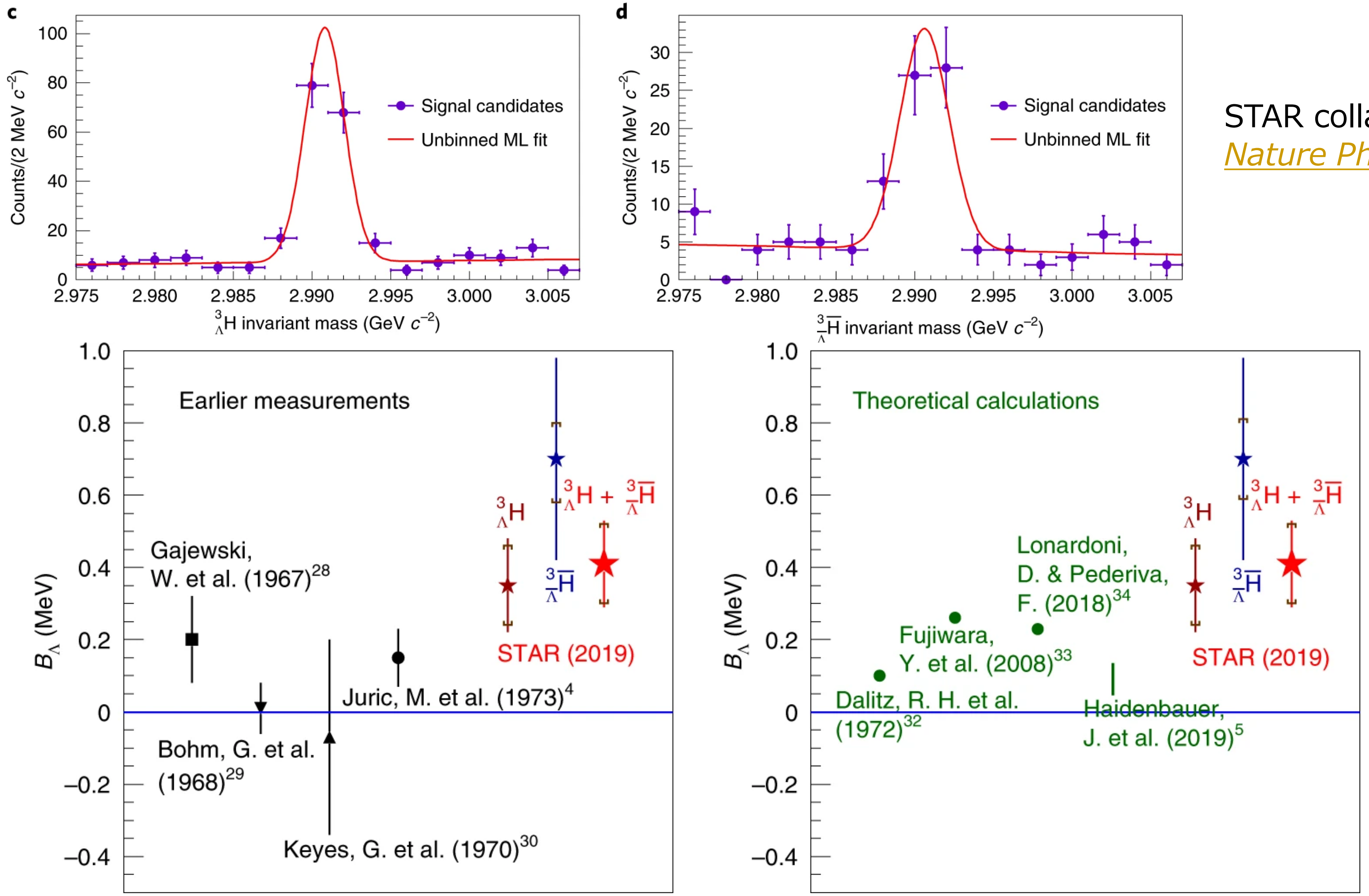




$B_{\Lambda} = 0.13 \pm 0.05$ MeV

Binding energy

- Heavy-ion experiment - STAR

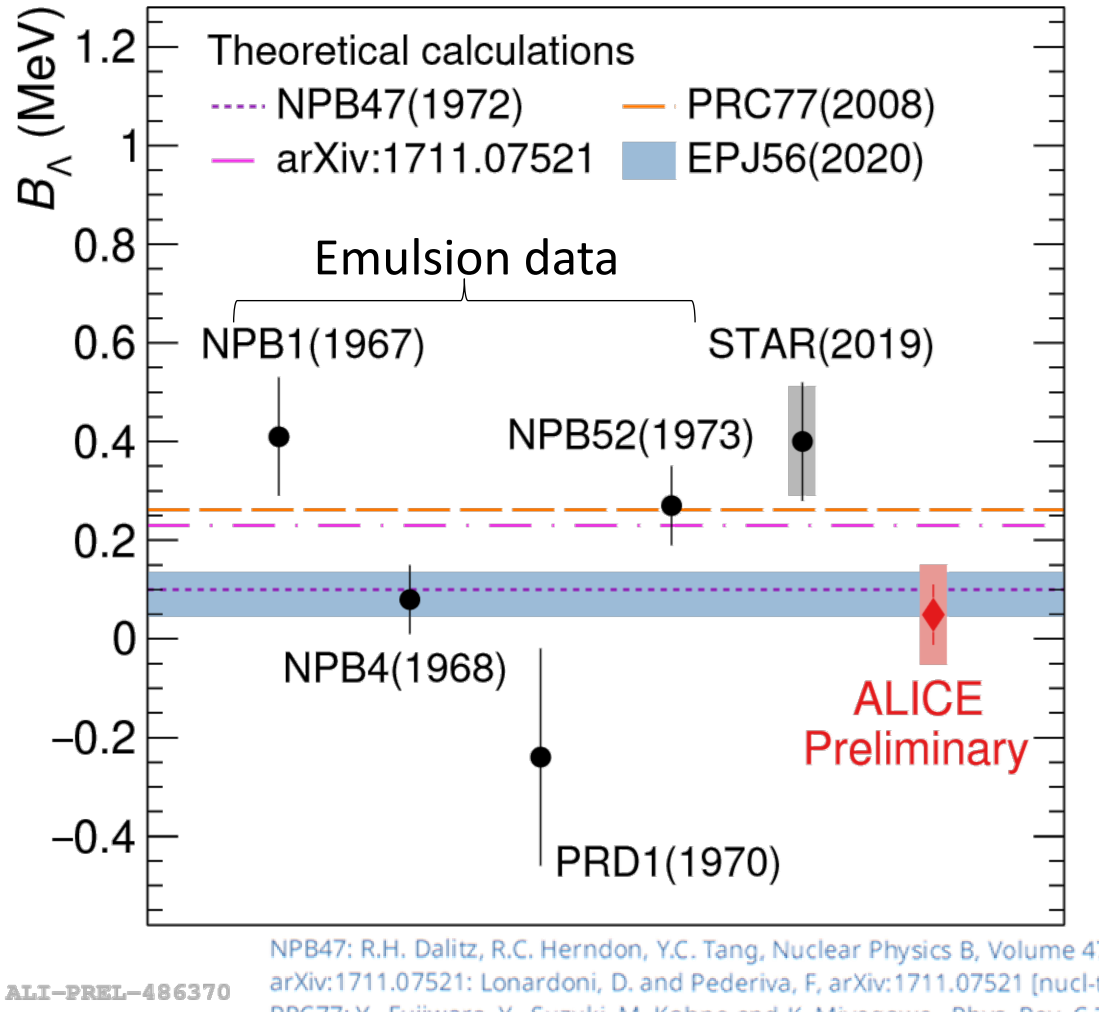


STAR collaboration
Nature Physics **volume 16**, pages409–412 (2020)

$$B_{\Lambda} = 0.41 \pm 0.12\ (\mathrm{stat.}) \pm 0.11\ (\mathrm{syst.})\ \mathrm{MeV}$$

Binding energy

- Heavy-ion experiment – ALICE in 2018 Pb-Pb collisions



NPB47: R.H. Dalitz, R.C. Herndon, Y.C. Tang, Nuclear Physics B, Volume 47, 1972, 109-137
arXiv:1711.07521: Lonardoni, D. and Pederiva, F, arXiv:1711.07521 [nucl-th]
PRC77: Y. Fujiwara, Y., Suzuki, M. Kohno and K. Miyagawa, Phys. Rev. C 77, 027001
EPJ56: B.Dönigus, Eur.Phys.J.A 56 (2020) 11, 280

From ALICE public Preliminary figure
https://alice-figure.web.cern.ch/node/19569

ALICE collaboration hypertriton binding energy new result

suggest the loosely bound system of Hypertriton

Need more

Experiments on Hypertriton

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

- Counter experiments for lifetime
  - ELPH, Tohoku-U, Japan: (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

Hypertriton still motivates activates studies

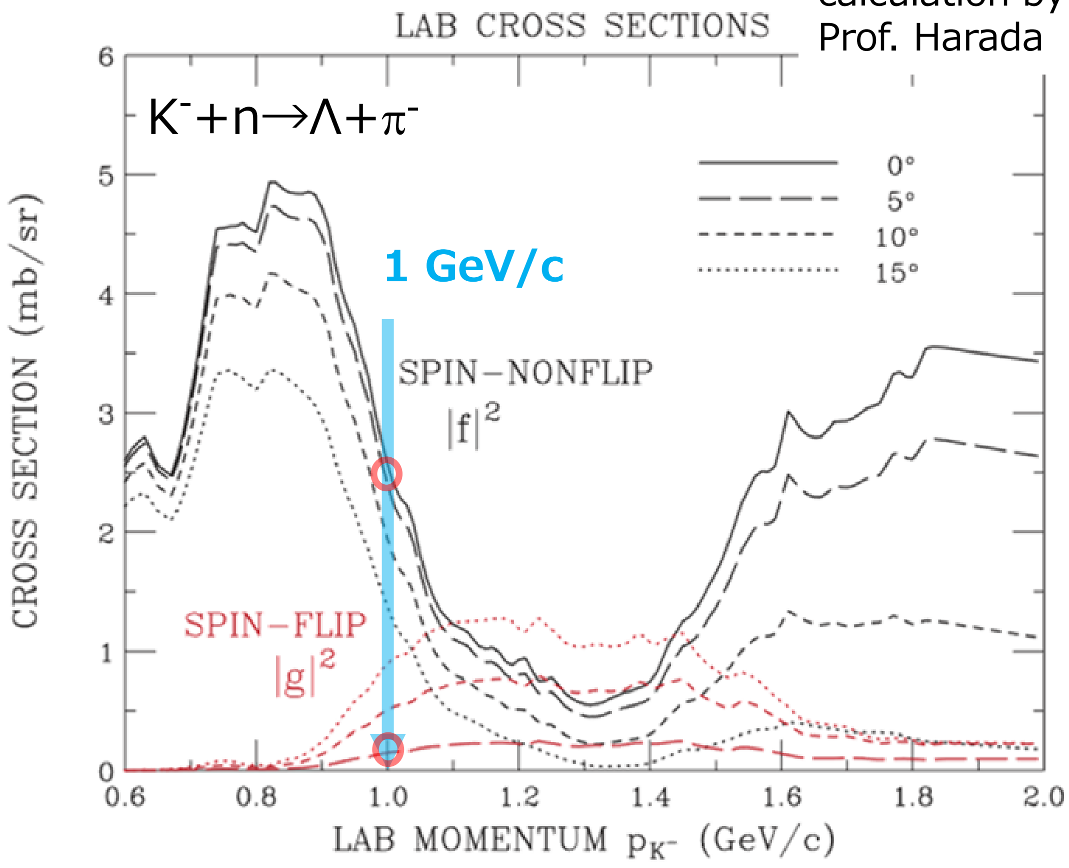
Toward solving hypertriton lifetime puzzle

Toward solving hypertriton lifetime puzzle

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

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

calculation by Prof. Harada



➢produce the ground state of $^3_\Lambda H(1/2^+)$

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

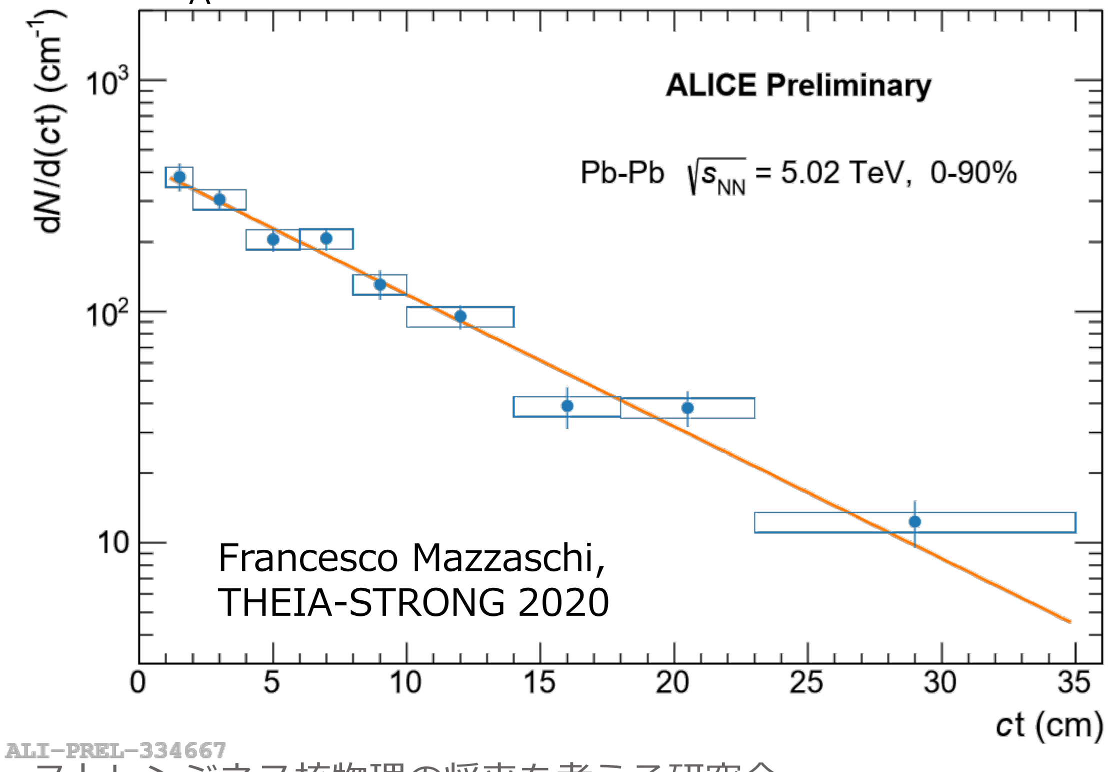
HI exp. vs direct measurement

- Heavy ion experiments
  - ➢ reconstructed by invariant mass
  - ➢ Indirect measurement using decay length

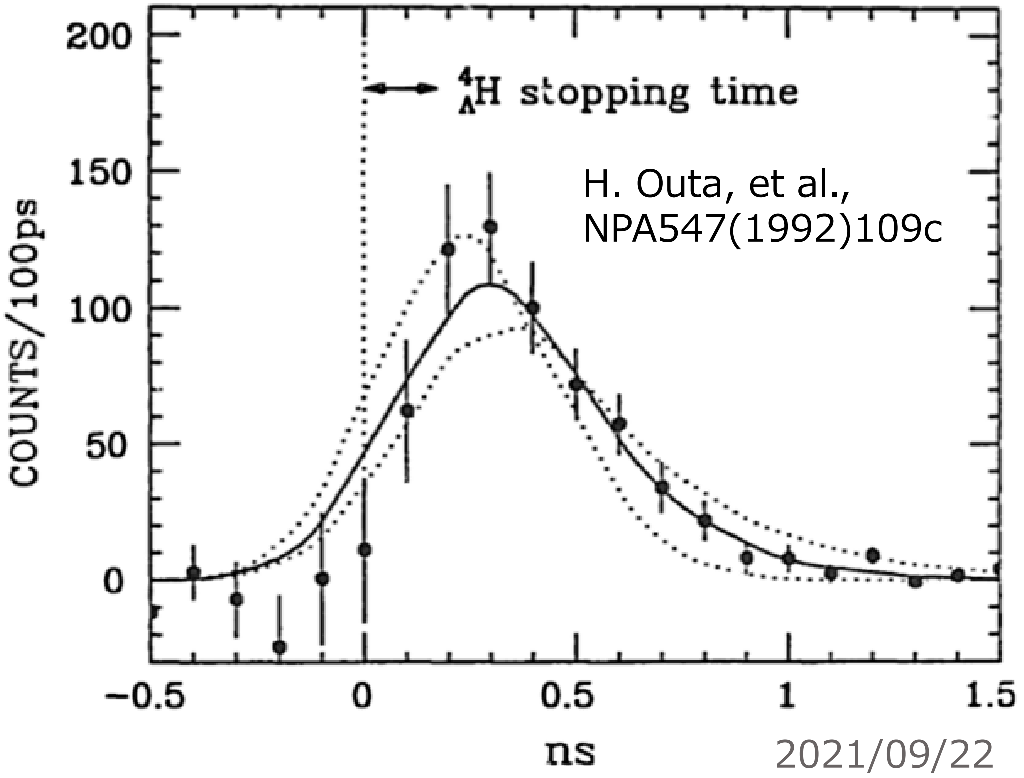
- Counter experiment
  - ➢ Direct timing measurement using Decay pion

complementary

$^{3}{}_{\Lambda}$H lifetime@ALICE



^{4}He(stop K^{-}, π^{-})$^{4}{}_{\Lambda}$H @KEK



HI exp. vs direct measurement

- Heavy ion experiments
  - reconstructed by invariant mass
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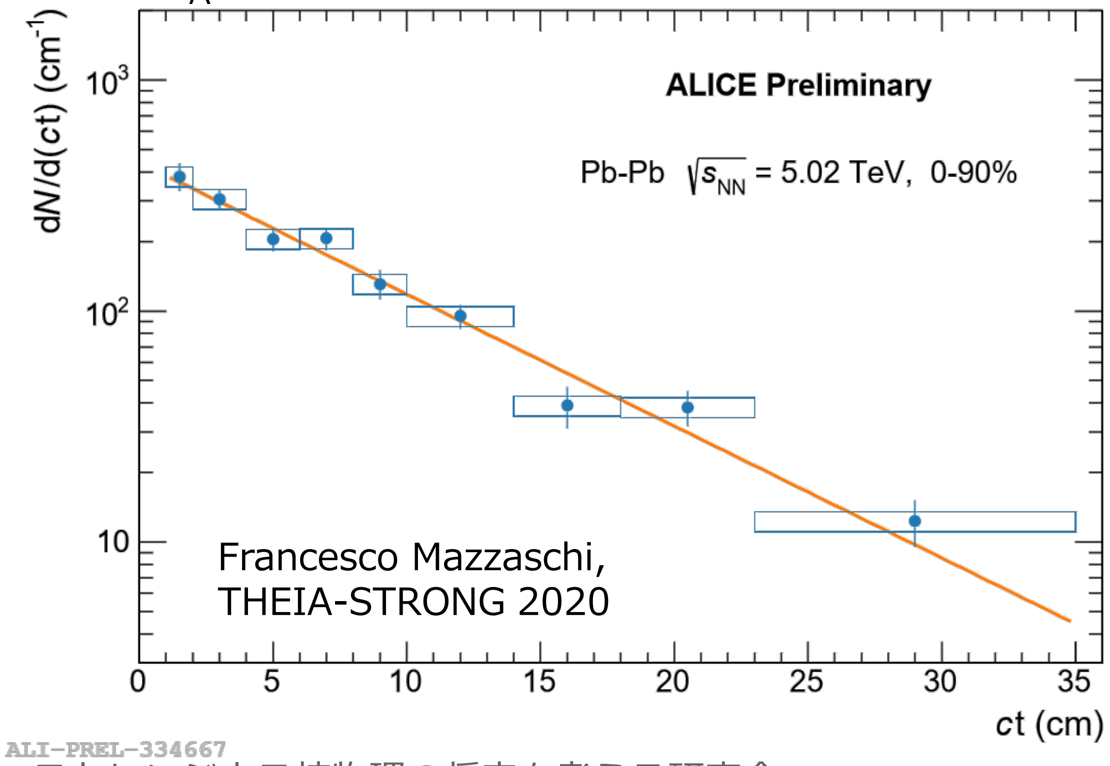
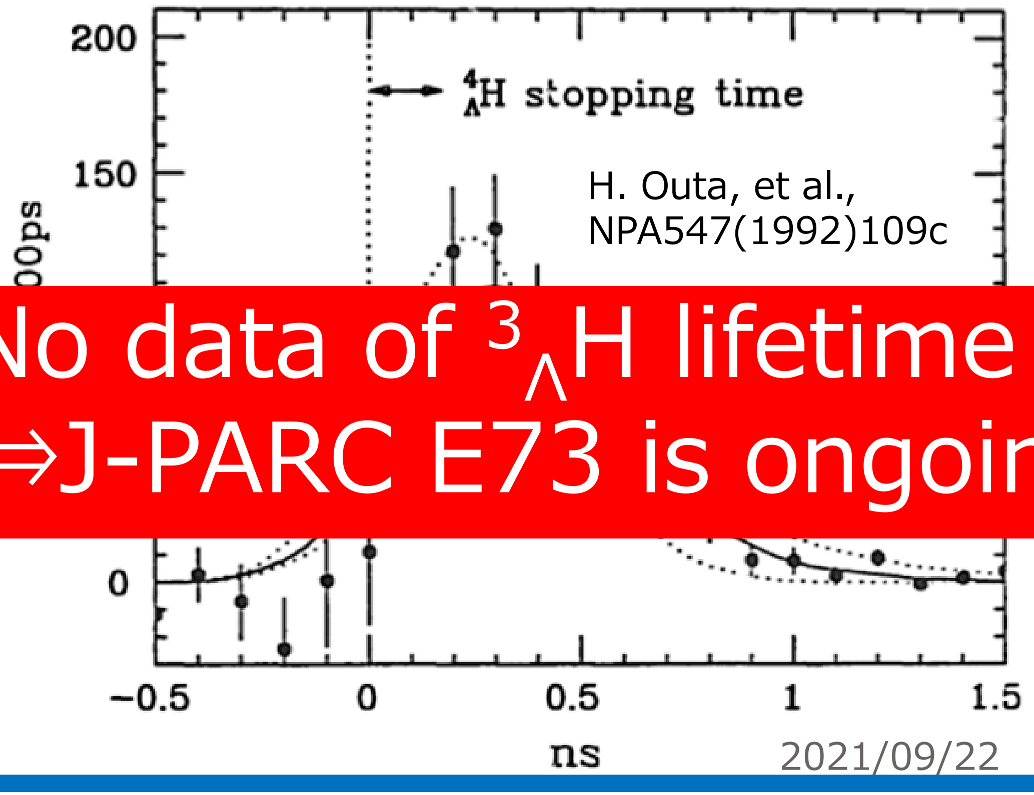
complementary

- Counter experiment
  - Direct timing measurement using Decay pion

$^{3}_{\Lambda}H$ lifetime@ALICE



$^{4}He(stop\ K^{-}, \pi^{-})^{4}_{\Lambda}H$ @KEK



No data of $^{3}_{\Lambda}H$ lifetime
⇒J-PARC E73 is ongoing

J-PARC E73 experiment with (K^-,π^0) reaction

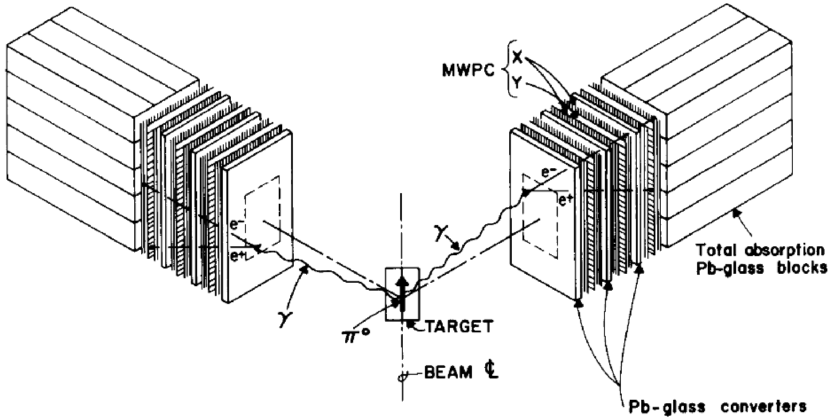
Previous Experiment using (K^-, π^0) reaction

- Neutral Meson Spectroscopy @BNL (1997)
  - Reaction: $^{12}C(\text{stop } K^-, \pi^0)^{12}{}_{\Lambda}B$
  - Measured π^0 energy

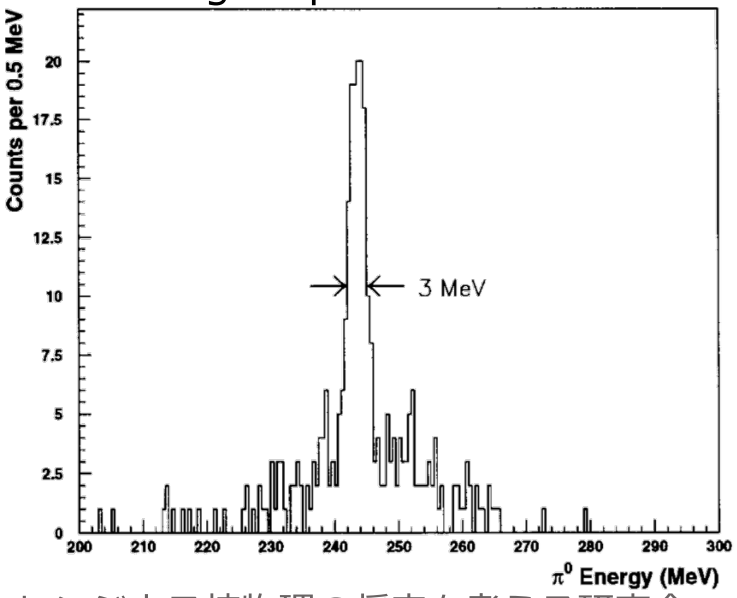
✓ $$E_{\pi^0} = E_1 + E_2 = m_{\pi^0}\sqrt{\frac{2}{(1-\cos\eta)(1-X^2)}},\ X = \frac{E_1 - E_2}{E_1 + E_2}$$

η: opening angle

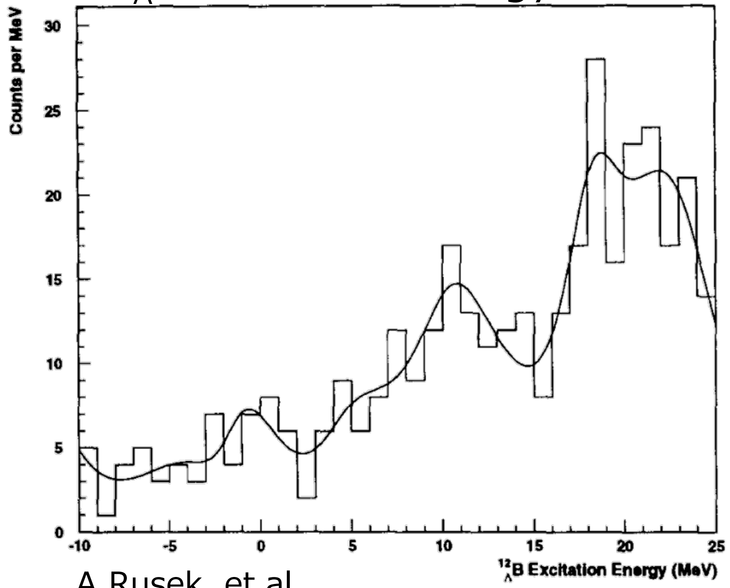
H.W. Baer, et al.,
Nucl. Inst. Meth. 180(1981)445



Energy resolution
using stop $K^+ \rightarrow \pi^+ + \pi^0$



$^{12}C(\text{stop } K^-, \pi^0)$ reaction
$^{12}{}_{\Lambda}B$ excitation energy

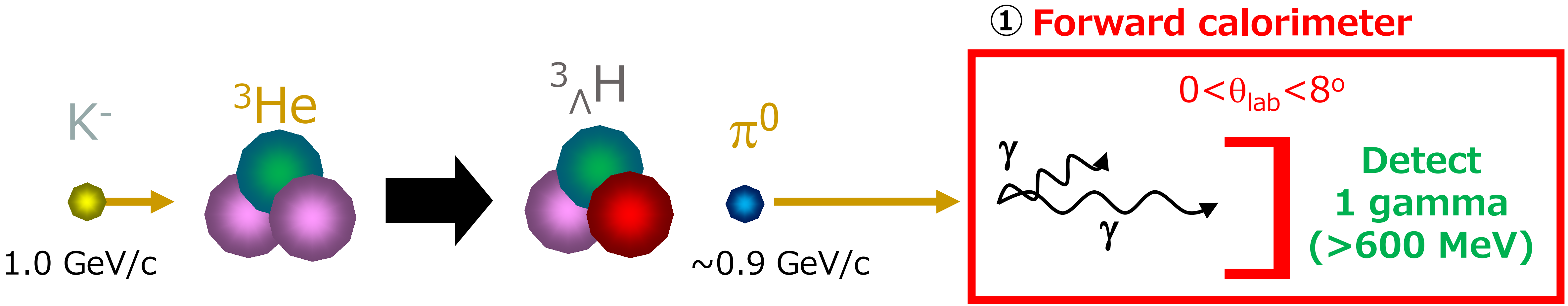


A.Rusek, et al.,
Nucl. Phys. A 639(1998)111c

Bad resolution

J-PARC E73: Experimental principle

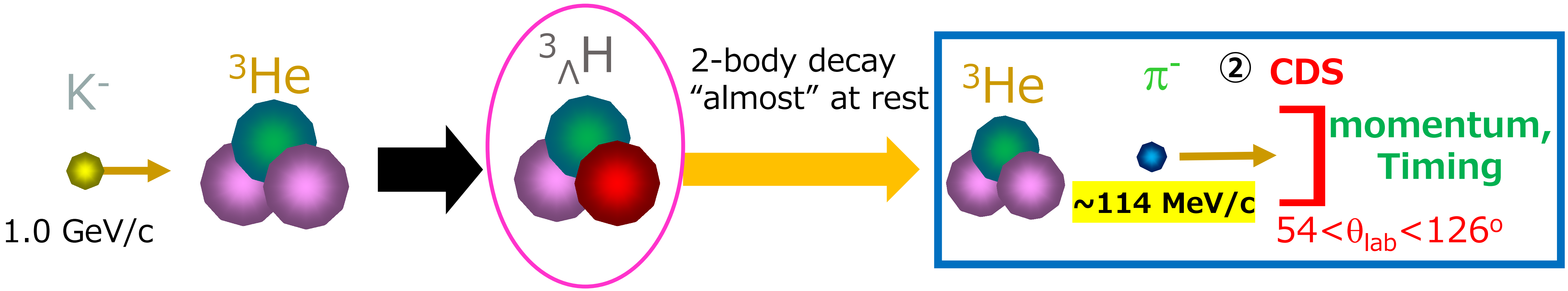
✓ $^3He(K^-, \pi^0)^3_\Lambda H$ reaction



①tag (K^-, π^0) reaction by detecting
forward single high-energy gamma with calorimeter
→almost 100% detection efficiency for forward going π^0 $(0< \theta_{lab}^{\pi^0} <10)$
⇒tag Λ production with low recoil momentum
Reduce BG from Y decays and multi pion production

J-PARC E73 experiment

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



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

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

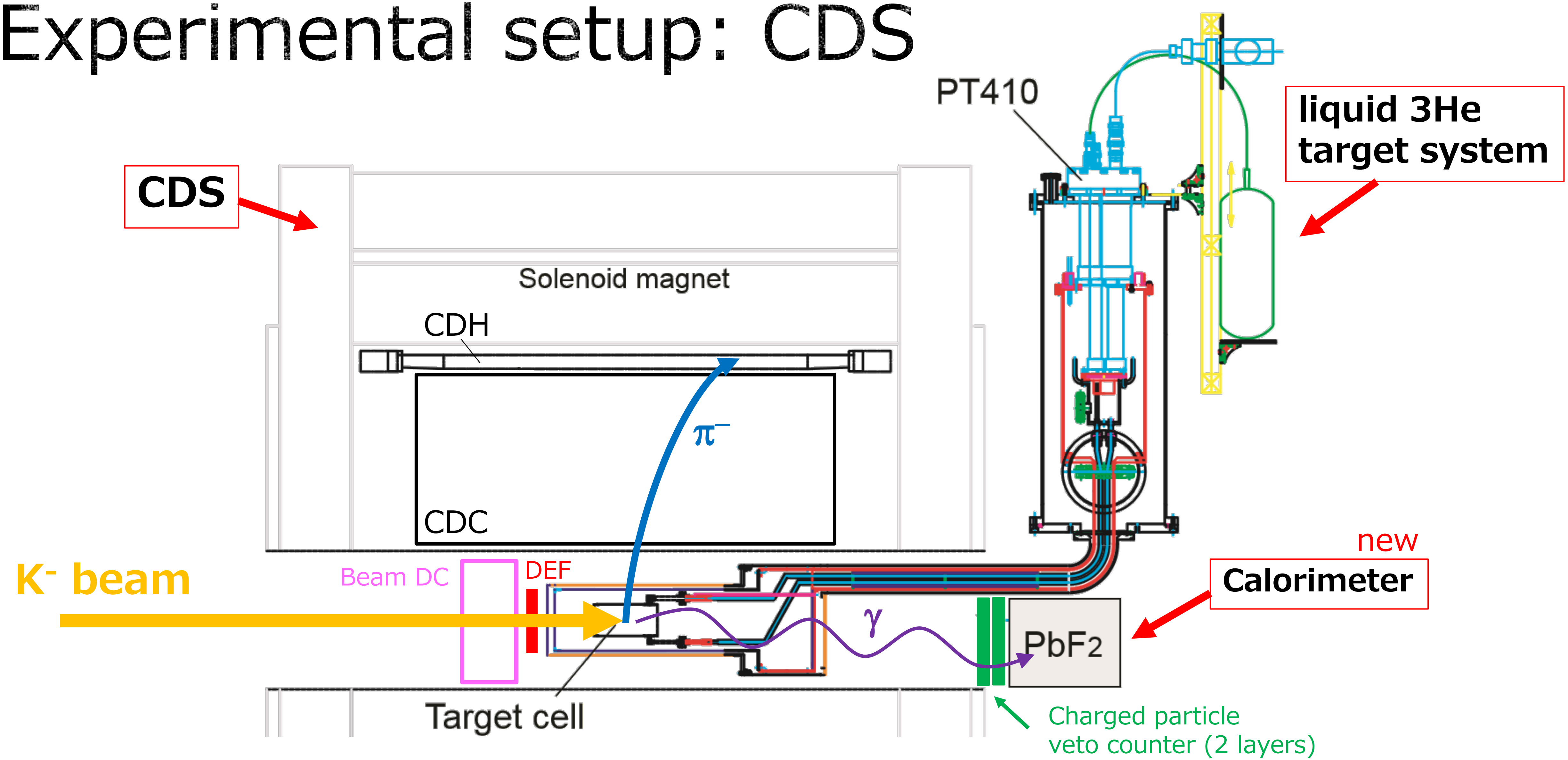
low recoil momentum (~100 MeV/c)

→Hypertriton stops immediately inside the target

⇒2-body decay "almost" at rest

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

Experimental setup: CDS



CDS has worked well in K1.8BR Beamline

Using E15(K^-pp)/E31(Λ1405)/E57(K^-d atom)

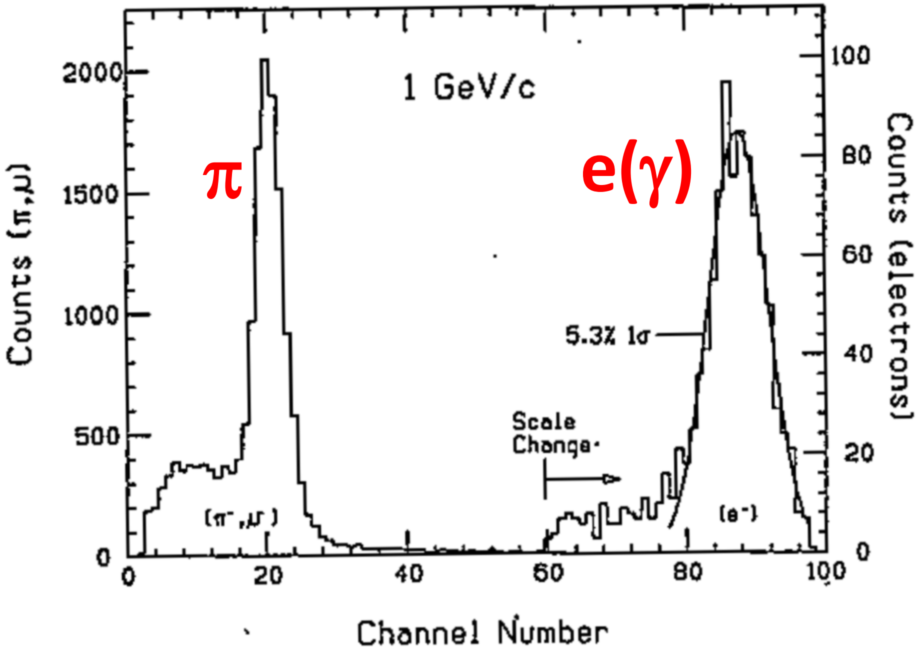
PbF_2 calorimeter

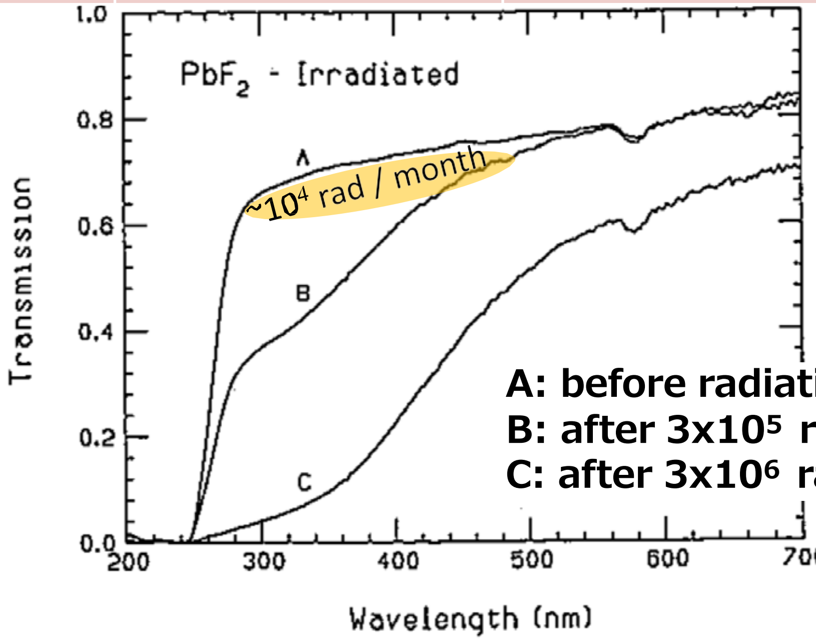
Experiment used PbF2: MAMI A4

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/cm³	1.82	5 %/√E(GeV)





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

A: before radiation
B: after 3x10⁵ rad n and 1x10⁵ rad γ
C: after 3x10⁶ rad n and 1x10⁶ rad γ

➢ Calorimeter with Cherenkov light
  - ✓ Fast response
  - ✓ Identification of hadrons and e, γ

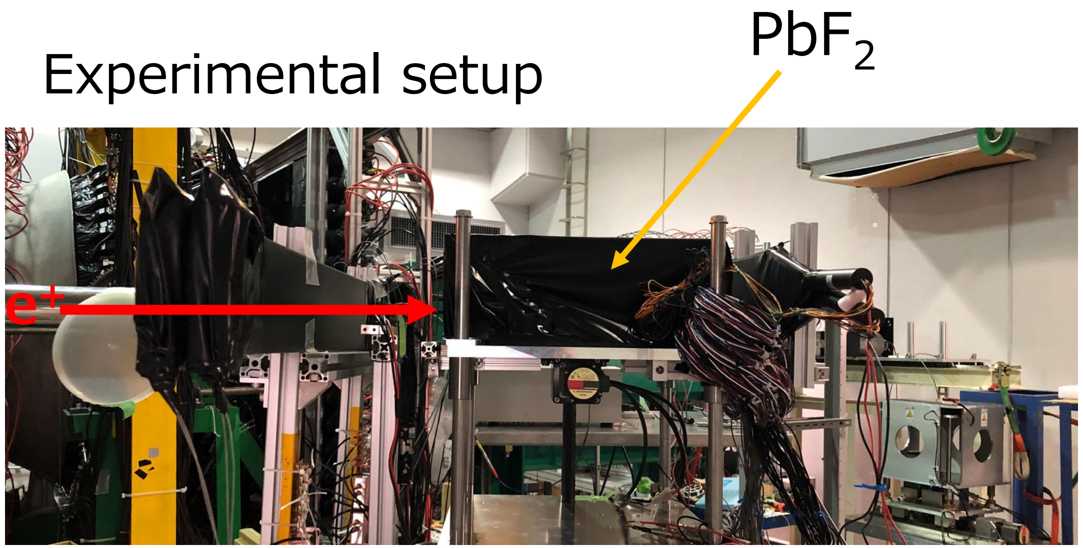
➢ High radiation resistance

PbF_2 calorimeter operation test

- Two experiment for operation

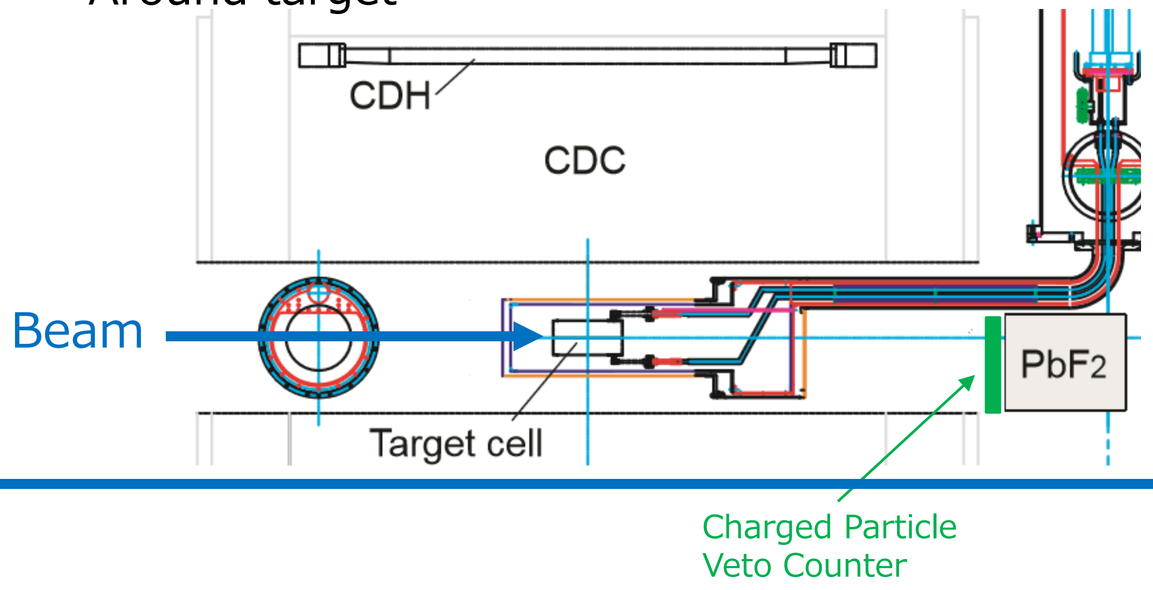
- 2019/12 ELPH
  - ➢100—800 MeV/c **e^+ beam**
    - ✓Basic performance test

Experimental setup



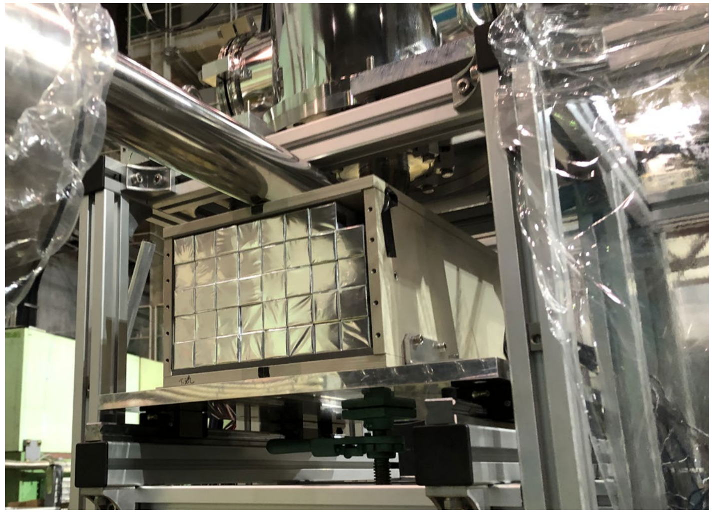
- 2020/06 J-PARC K1.8BR
  - ➢1GeV/c hadron beam
  - ⇒Feasibility study(physics run)
    - performed with He-4 target

Around target



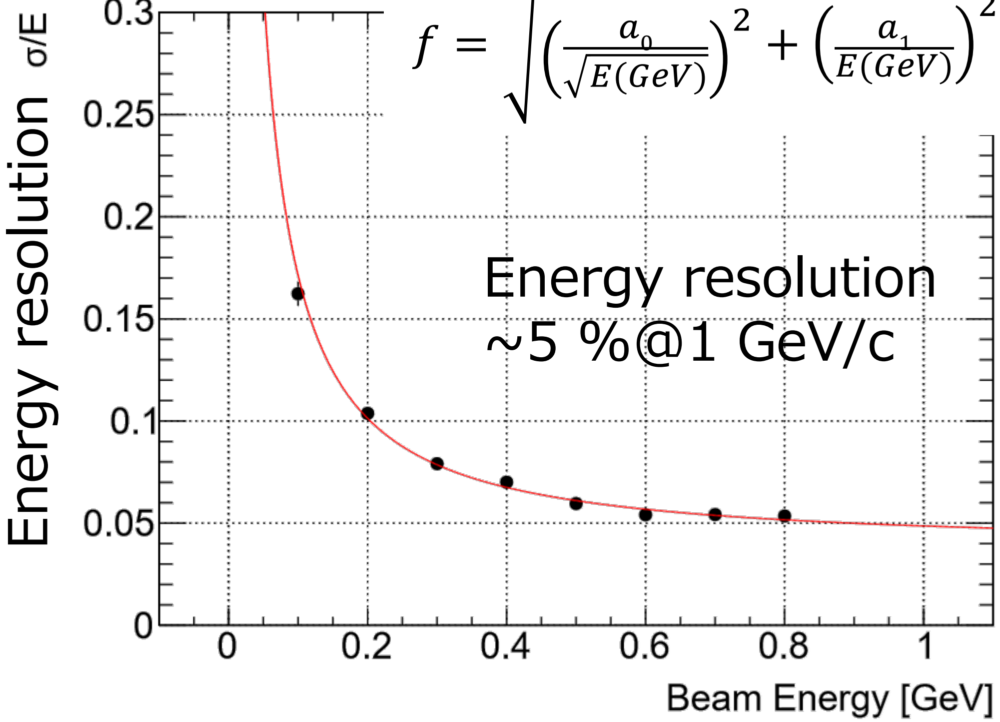
PbF_2 calorimeter performance

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

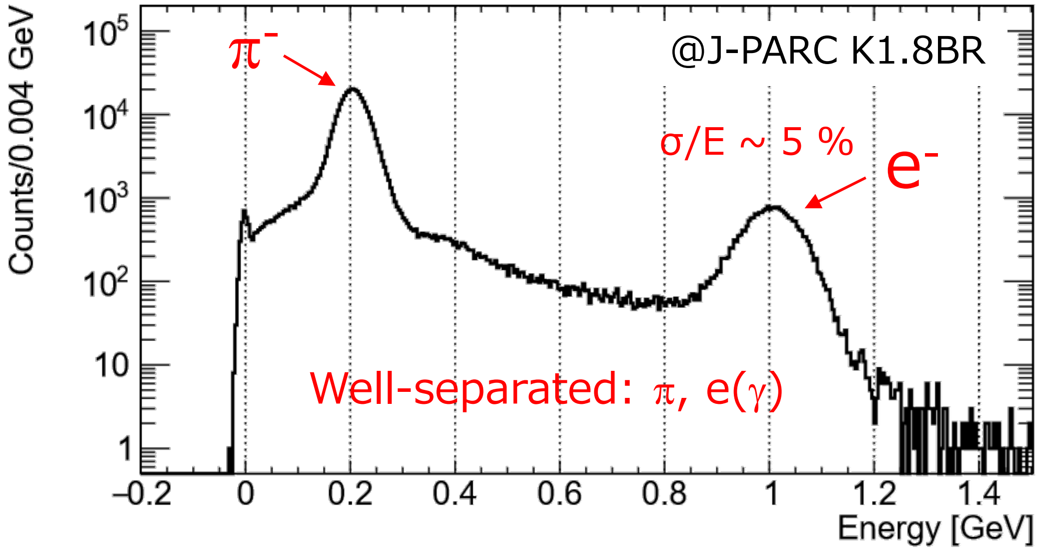


2019.12: Test experiment @ ELPH e^+ beam

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



Energy spectrum@1GeV/c π-/e-



Good performance to distinguish $\pi^-/e^-,\gamma$

Strategy of J-PARC E73

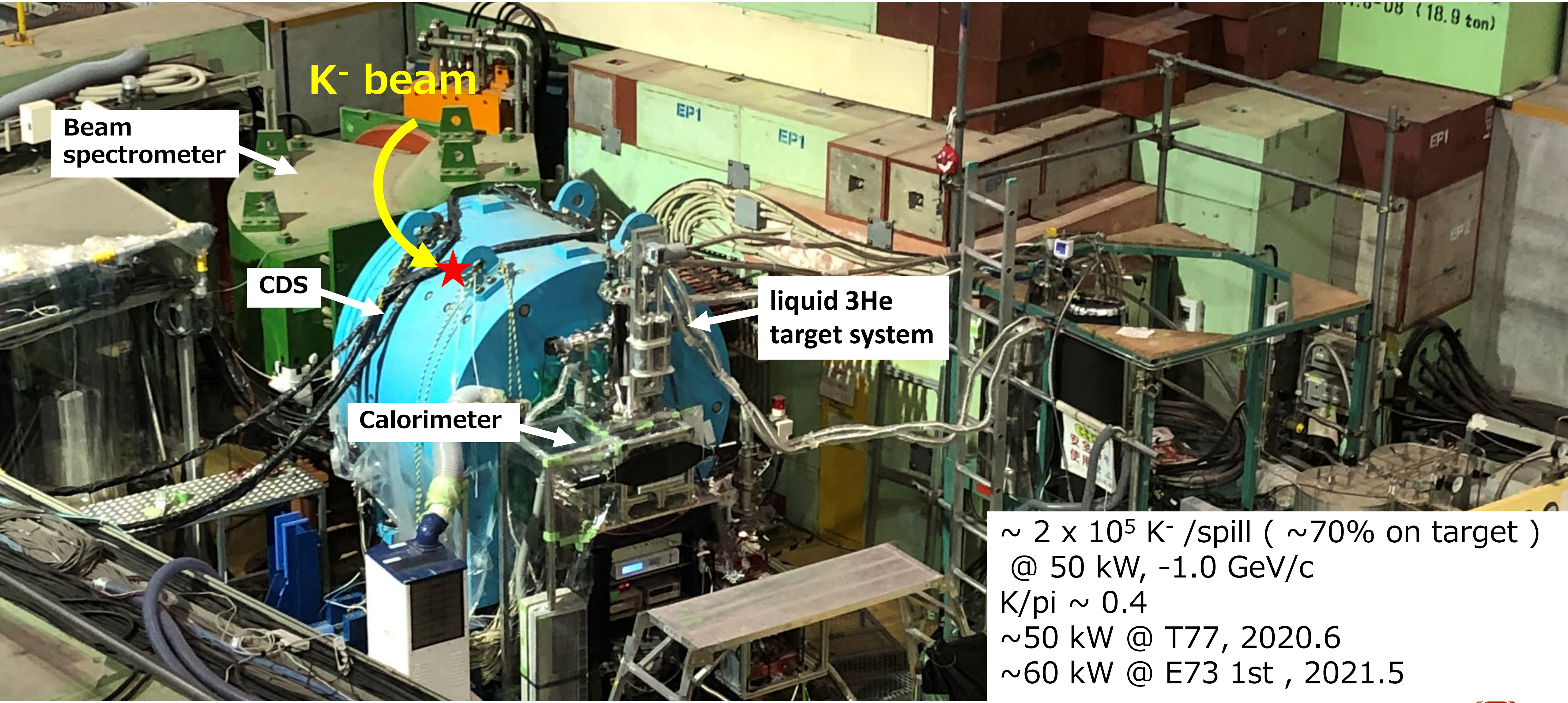
- Phase-0
  - Feasibility study of new method with the (K-, π^0) reaction using ^{4}He target
    ⇒expected to be relatively easy to generate and identify $^4_\Lambda$H
  - Data taking in June 2020 (3 d)
- Phase-1
  - Production cross section study for $^3_\Lambda$H
  - Data taking in May 2021(4 d)
- Phase-2
  - Direct lifetime measurement for $^3_\Lambda$H
  - planned in JFY2022 (1 month)

Hypernucleus	$^4_\Lambda$H	$^3_\Lambda$H
Branching ratio to 2-body decay	50 %	25 %
Relative cross section	1	0.3—0.4
Relative yield	1	0.15—0.2

calculation of cross section by Prof. Harada

T. Harada and Y. Hirabayashi
Nuclear Physics A 1015 (2021) 122301

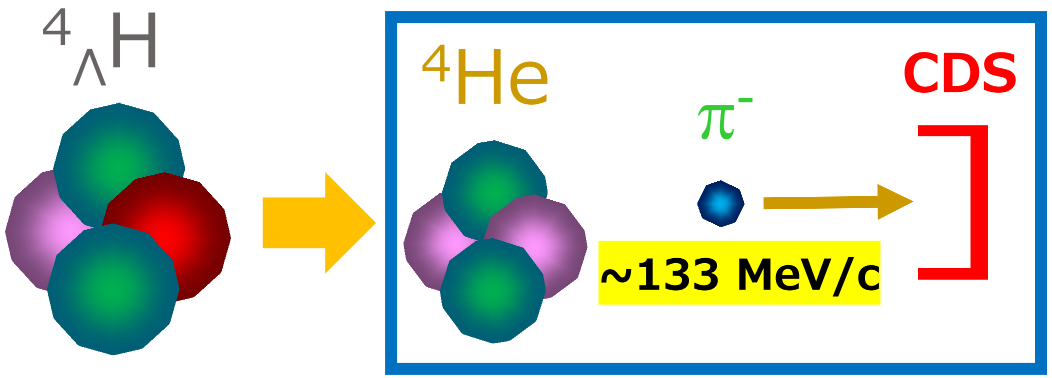
J-PARC K1.8BR Beamline



~ 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

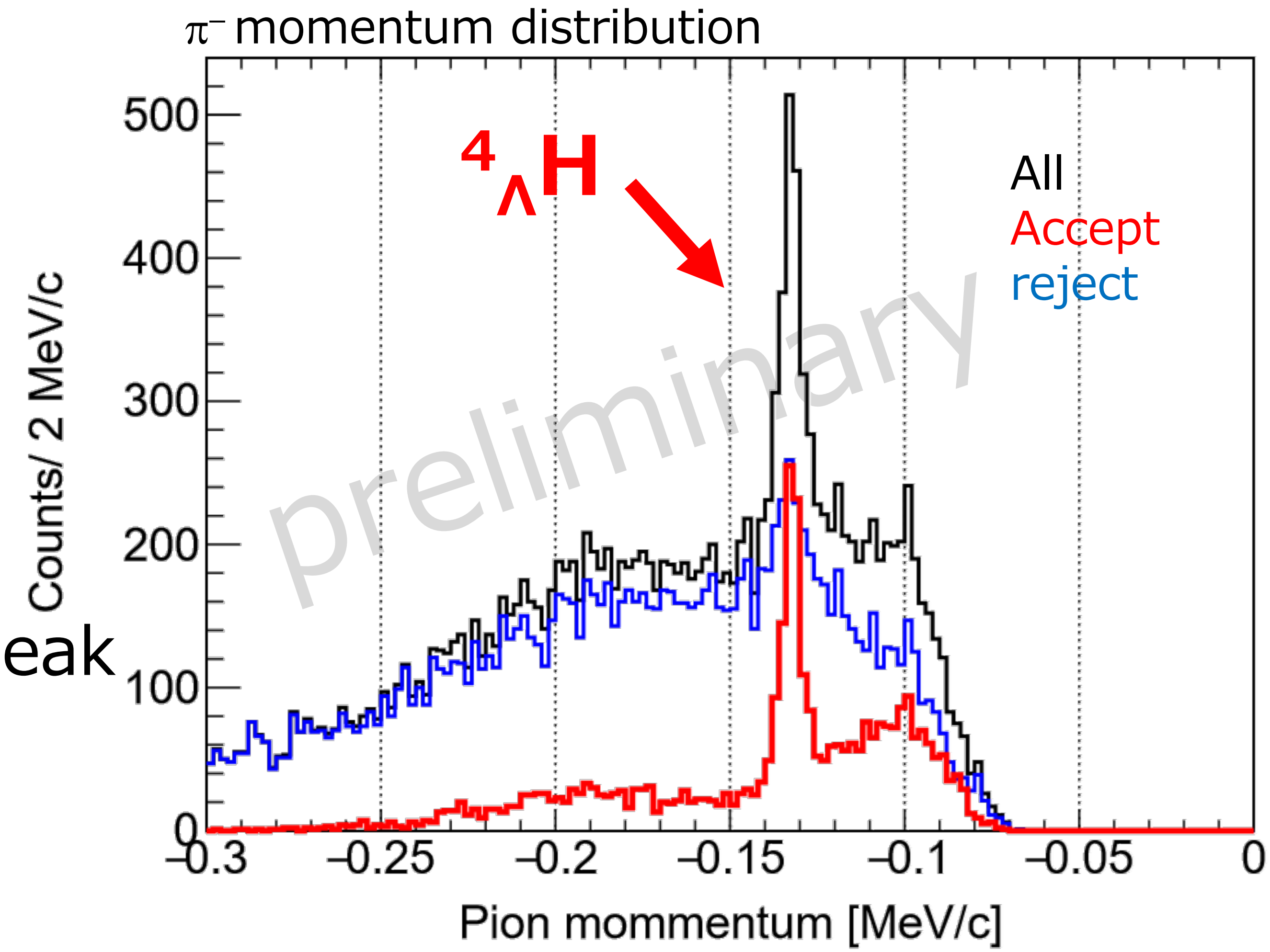
Phasae-0: Feasibility study

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



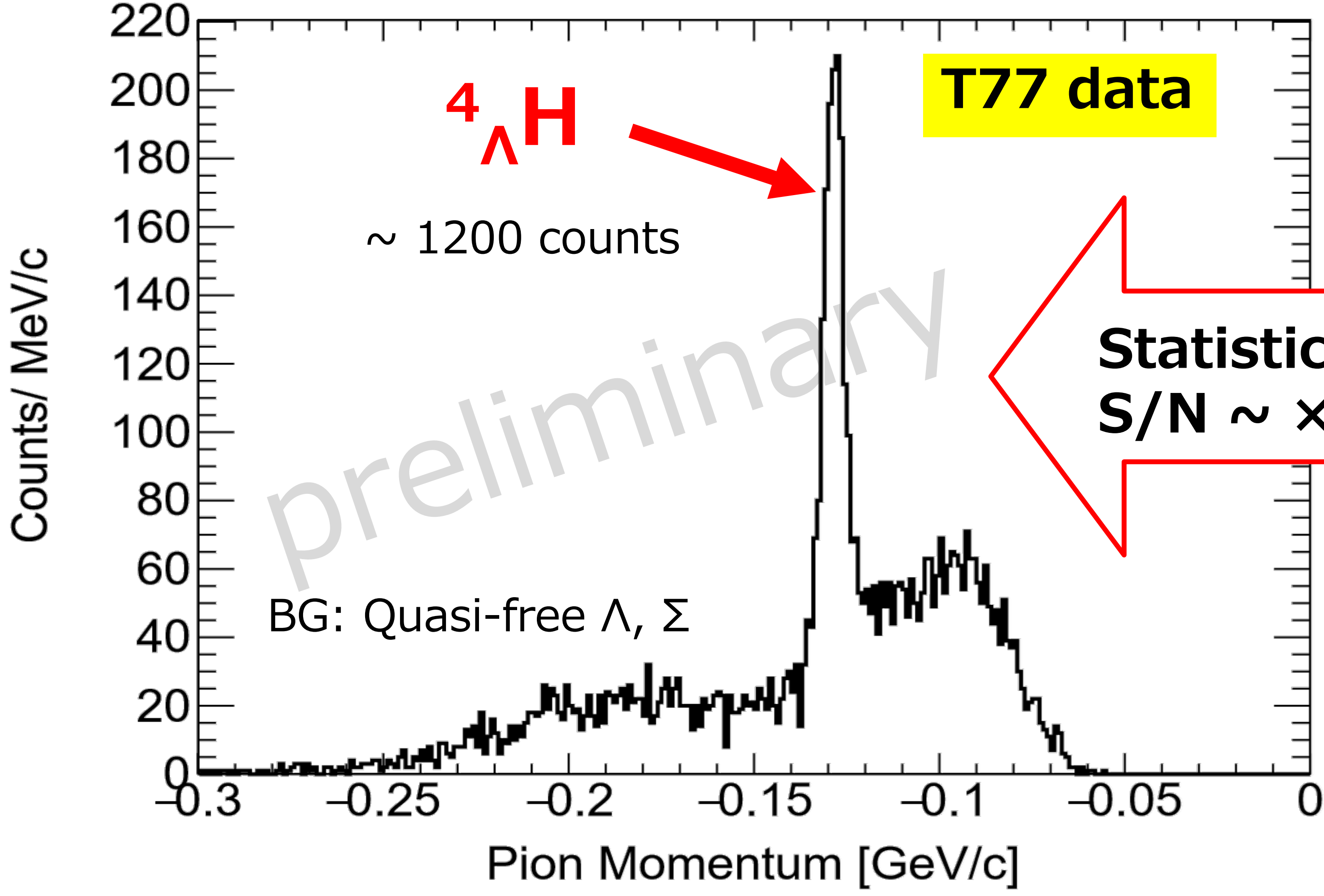
- select 1 gamma ray ⇒ the $^{4}{}_{\Lambda}H$ peak can be seen like the black line
- Background reduction by PbF2
  - ➢Selection of high energy γ-rays for $^{4}{}_{\Lambda}H$ production

    ⇒Improved S/N ratio(3/2 → **4/1**) Red line



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

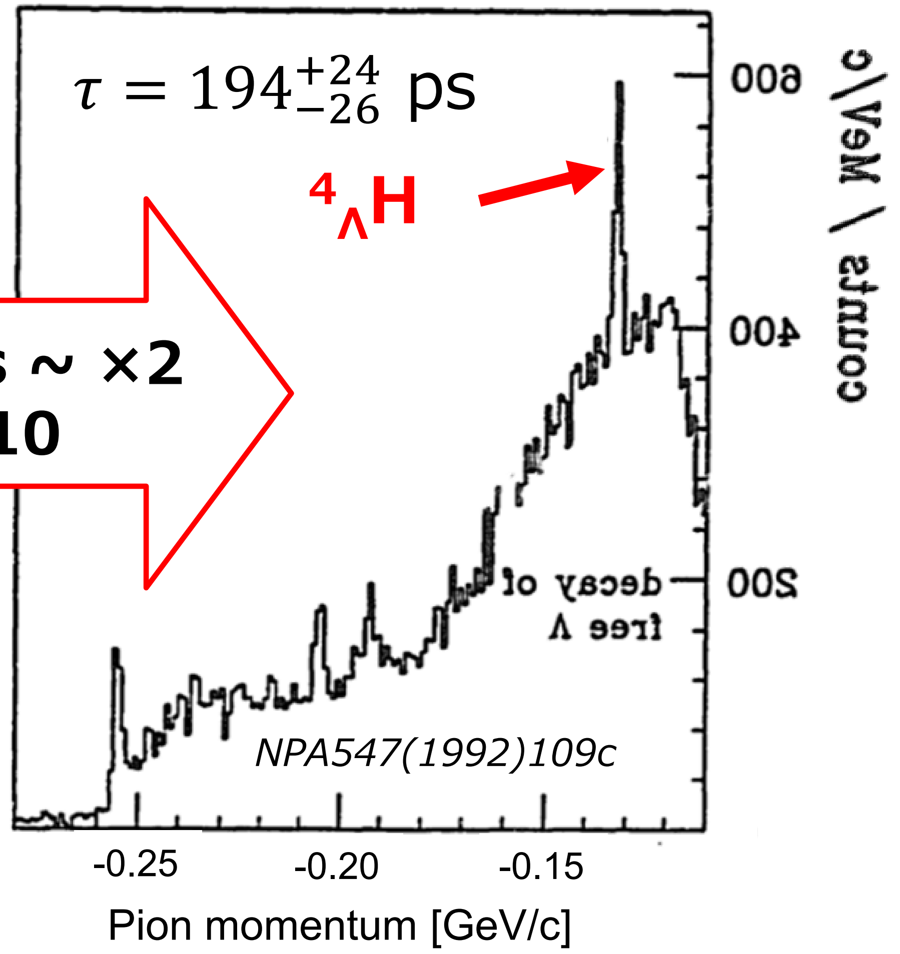
π^- momentum distribution



Statistics ~ ×2
S/N ~ ×10

KEK, 1992

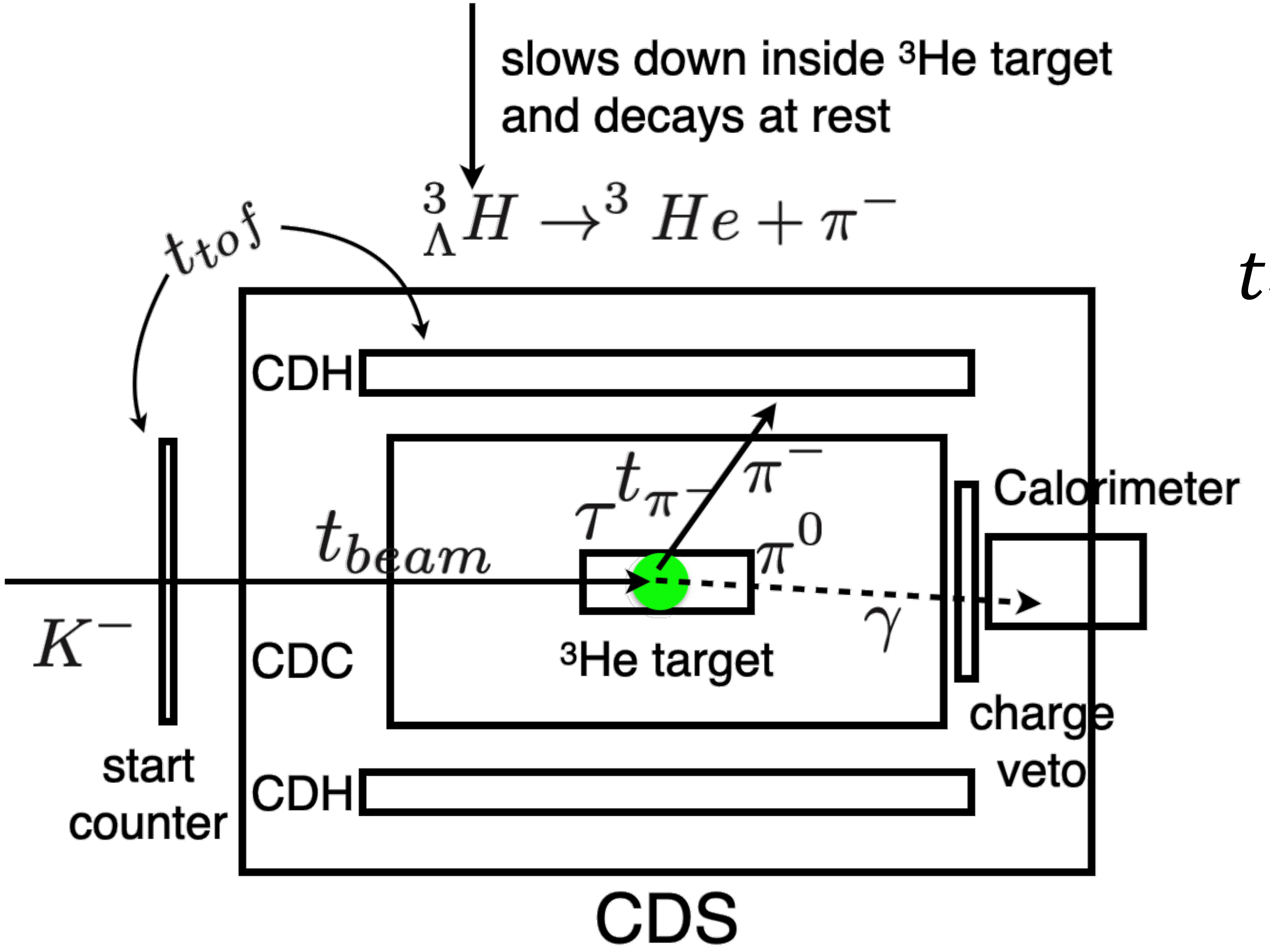
^4He(stop K^-, π^-) delayed



- **Successfully established new method of (K-, pi0) reaction**

Derive lifetime

$$K^- +^3 He \rightarrow^3_\Lambda H + \pi^0$$

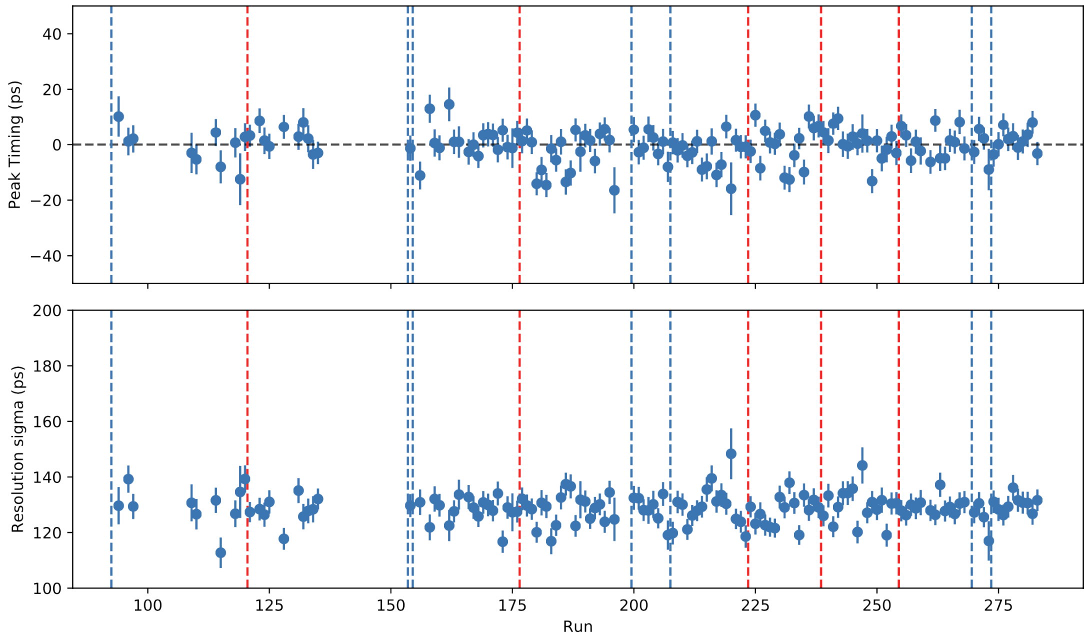


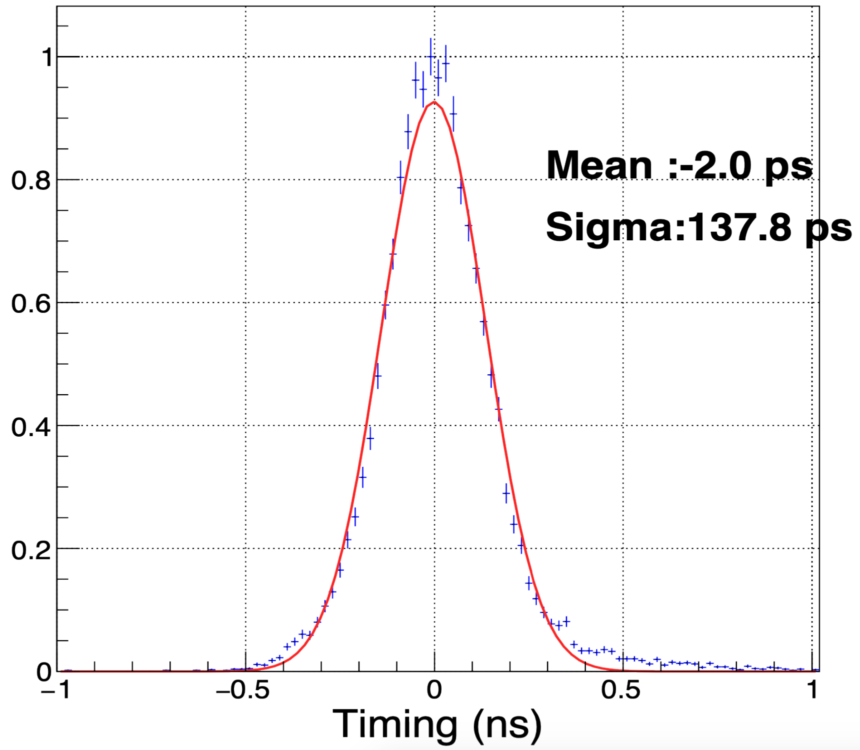
$$t_{tof} = t_{beam} + t_{\pi^-} + \tau$$

Hypertriton lifetime

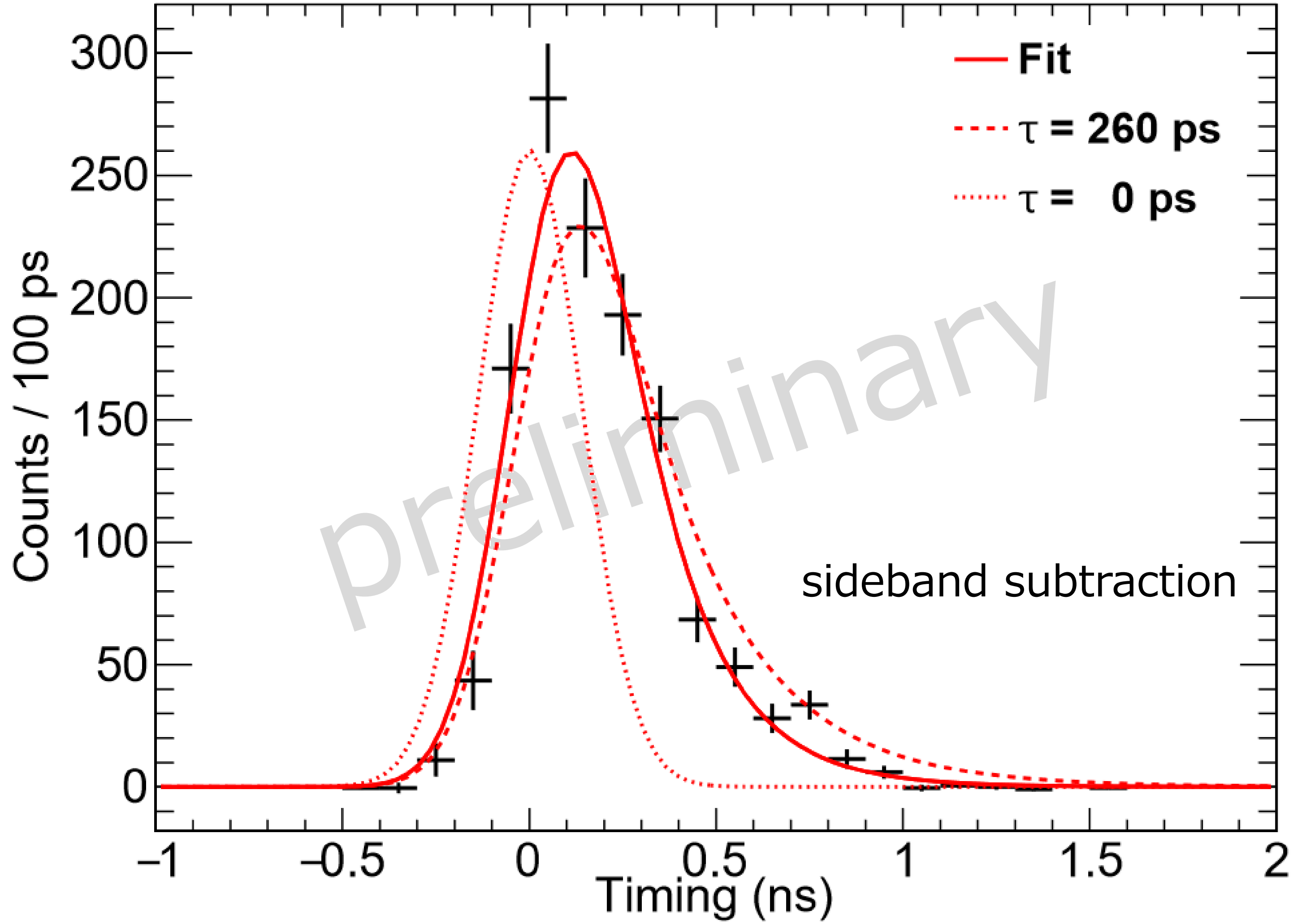
Analysis for timing

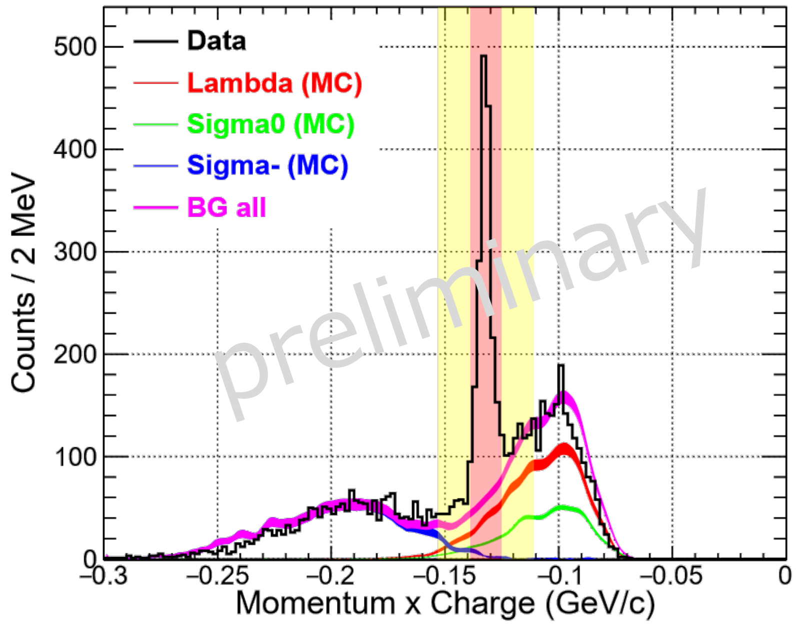
- Calibration with $\pi^{-}N \rightarrow \pi^{-}N$ scattering $(t_{beam} + t_{\pi^-})$
  - ➤ TOF(T0-CDH)
    - ✓Select beam pion and scattering pion
    - ✓Adjusted Time offset





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



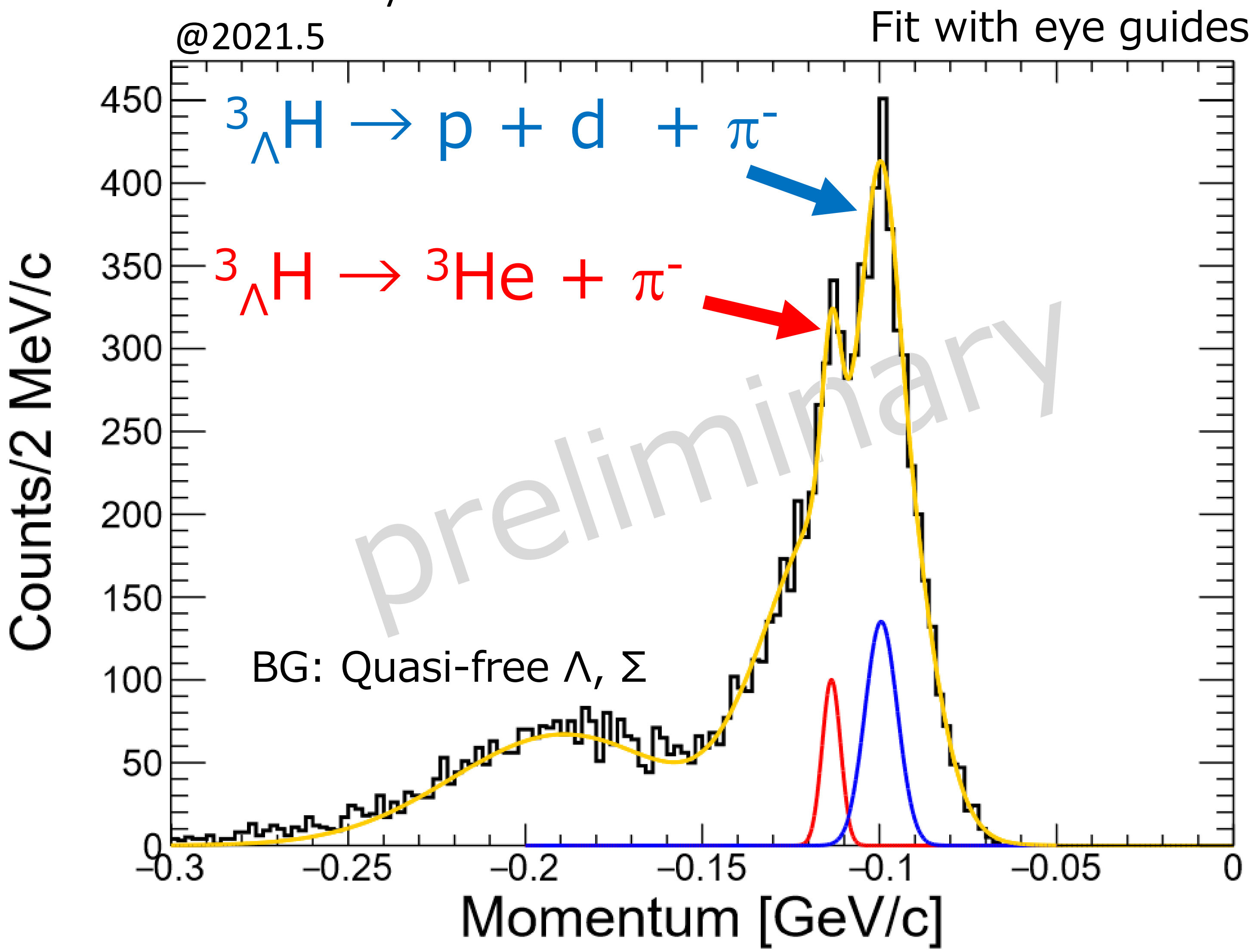


- Timing response evaluated by $\pi^{-}N \rightarrow \pi^{-}N$ scattering
- statistical error < 10 ps

will be finalized soon

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

60 kW ~4 days beam
@2021.5



- Hypertriton events can be seen
  ~ 200 events(2 body)
- 3-body decay events can also be seen around ~100 MeV/c

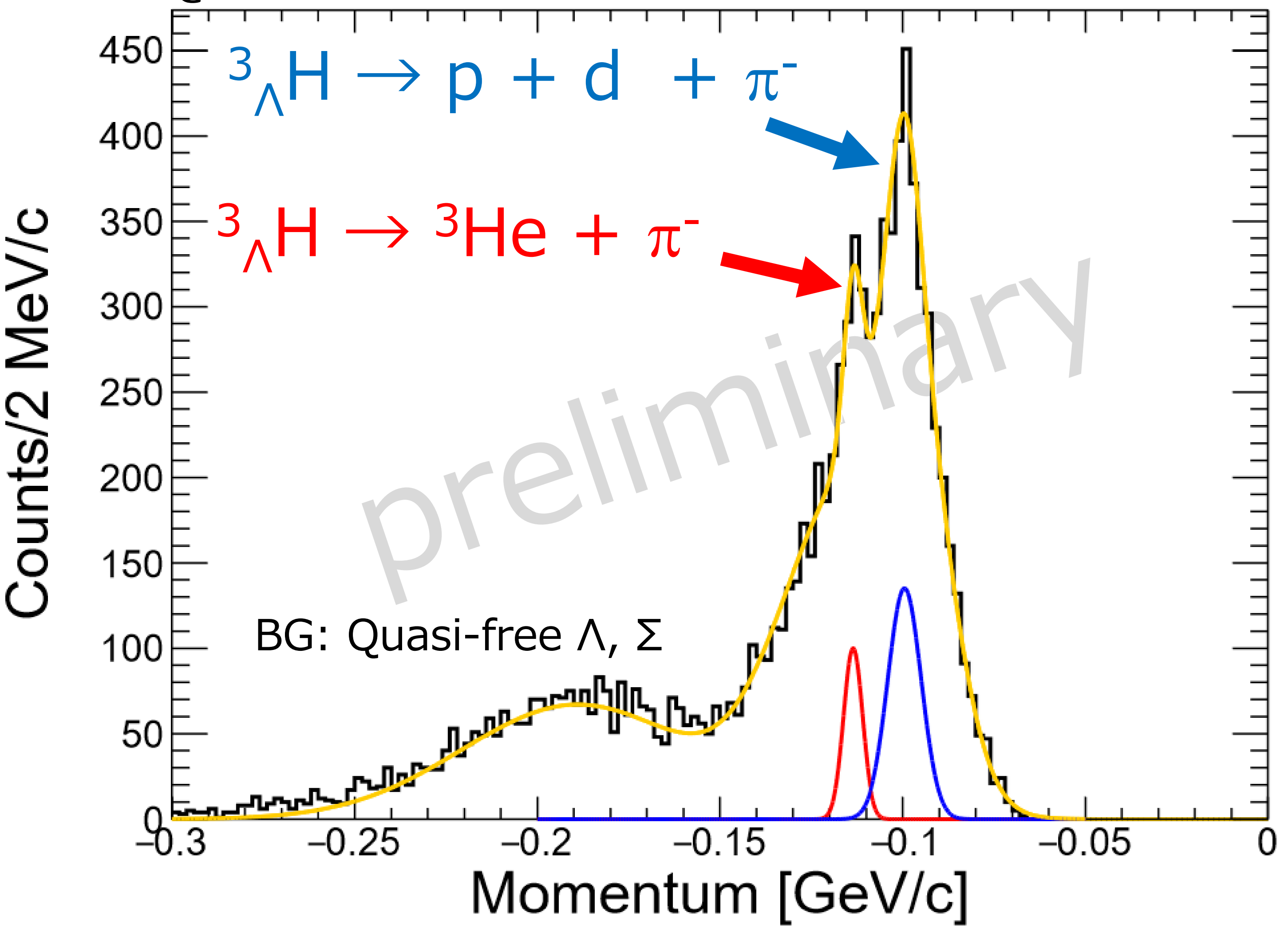
✓**cross section(B.R.×σ)**
✓**2-body/3-body ratio will be derived**

not enough to derive lifetime
⇒ need more statistics

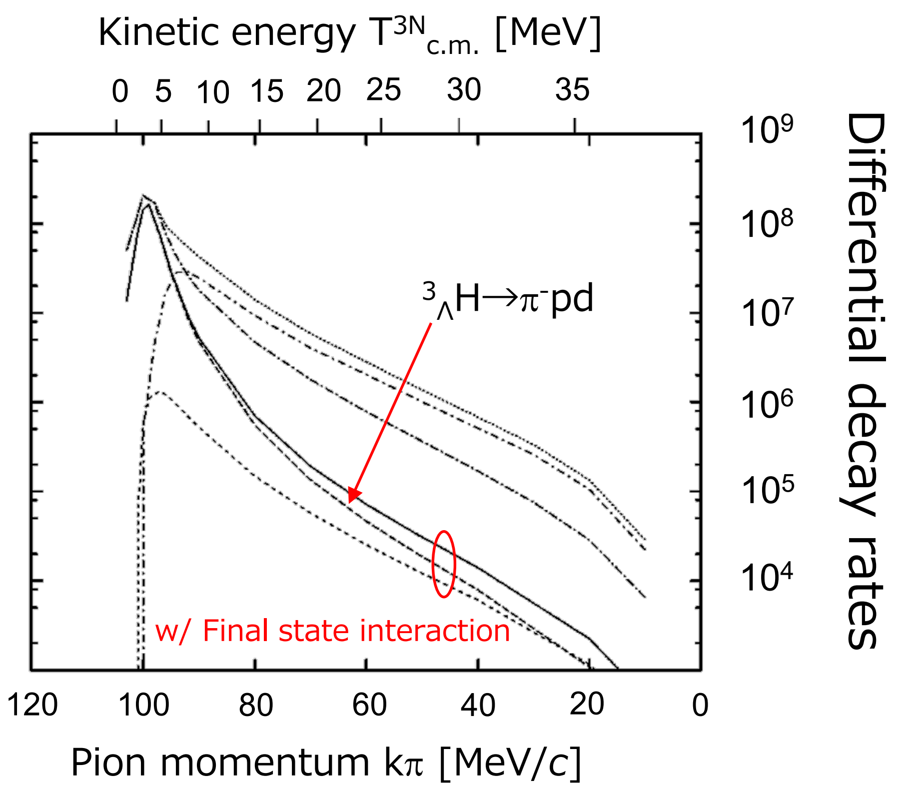
Phase-1: $^{3}_{\Lambda}H$ 3-body decay

60 kW ~4 days beam
@2021.5

Fit with eye guides



H. Kamada, et al.,
Phys. Rev. C57, 1595 (1998)



Phase-1: cross section ratio $^{3}_{\Lambda}H / ^{4}_{\Lambda}H$

- Rough estimation

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

	Hypernucleus	$^{4}_{\Lambda}H$	$^{3}_{\Lambda}H$	
Expected	**Relative cross section**	R = 0.3—0.4		
	Branching ratio to 2-body decay	50 %	25 %	
	Relative yield	1	0.15—0.2	
Measured	**Luminosity**	6.05 G Kaon × 0.145 g/cm^3 /4	11.32 G Kaon × 0.070 g/cm^3 /3	→ 1 : 1.2 almost same
	# of signal	~1200(1)	~200(0.167)	
	Relative cross section	R ~ 0.334		

R ~ 0.3—0.4 @ B_{Λ}=0.13 MeV(Emulsion), ~ 0.65 @ B_{Λ}=0.41 MeV(STAR)

T. Harada and Y. Hirabayashi,
Nuclear Physics A 1015 (2021) 122301

Summary

- J-PARC E73: Direct measurement of $^{3}_{\Lambda}H$ lifetime
  - 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
    ⇒ $^{4}_{\Lambda}H$ lifetime
  - Phase-1: confirmed $^{3}_{\Lambda}H$ production
    ⇒cross section of $^{3}_{\Lambda}H$
  - Phase-2: $^{3}_{\Lambda}H$ lifetime measurement
    ~ 1 month beam time, $^{3}_{\Lambda}H$ ~1000 events, ~10 % error
    → in JFY2022

J-PARC E73 collaboration

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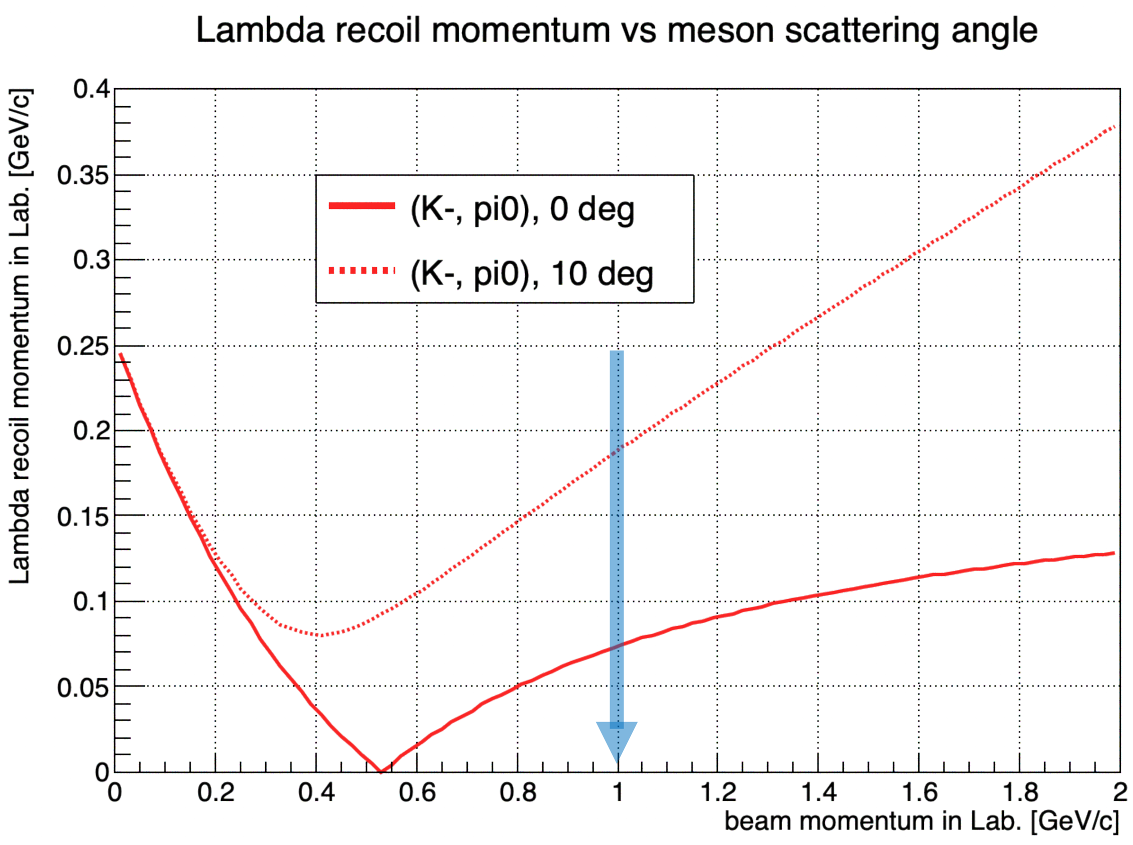
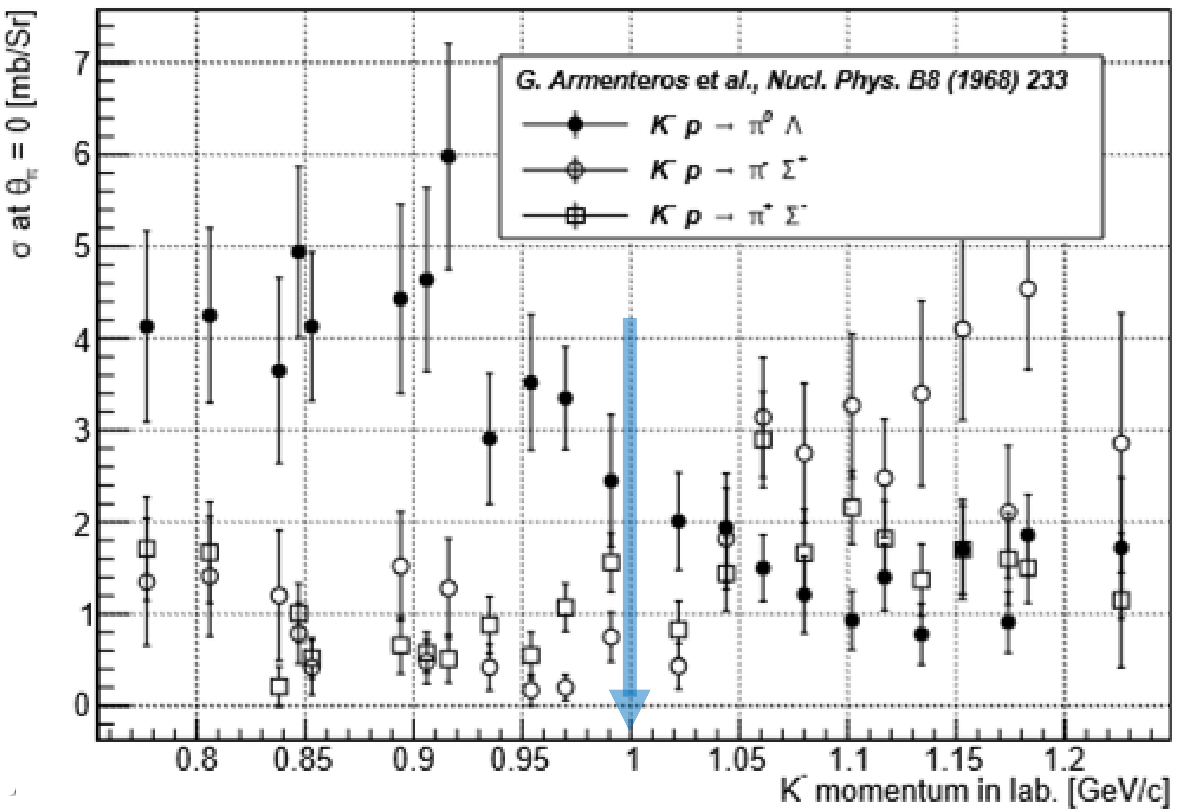
Backup

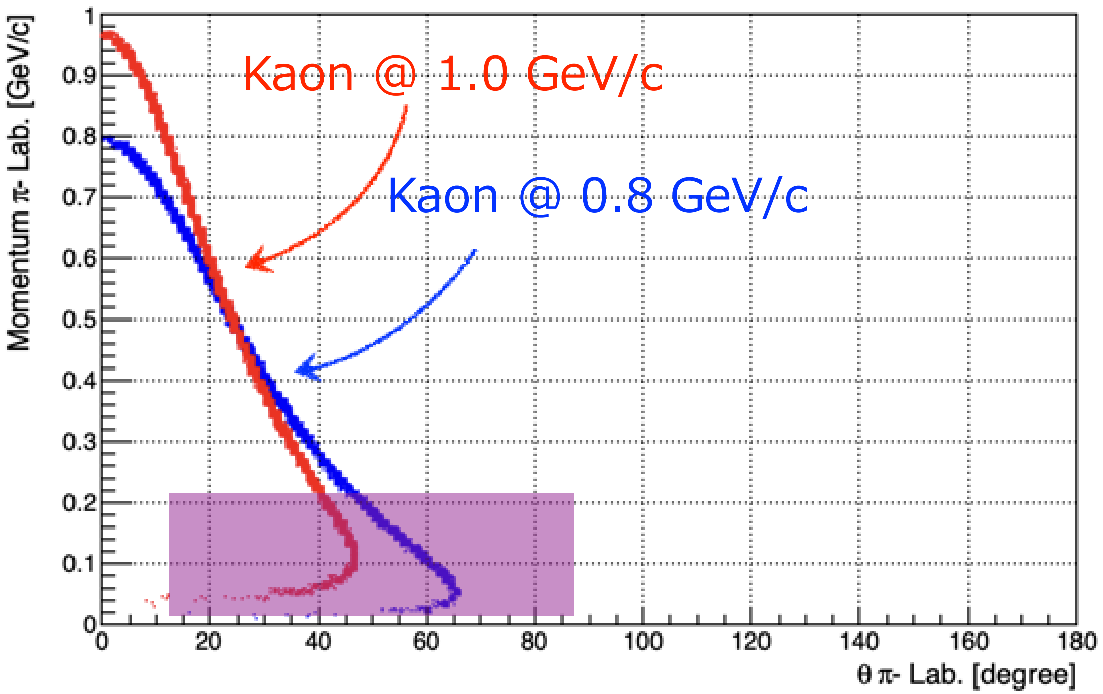
Beam Momentum selection



Elementary cross section

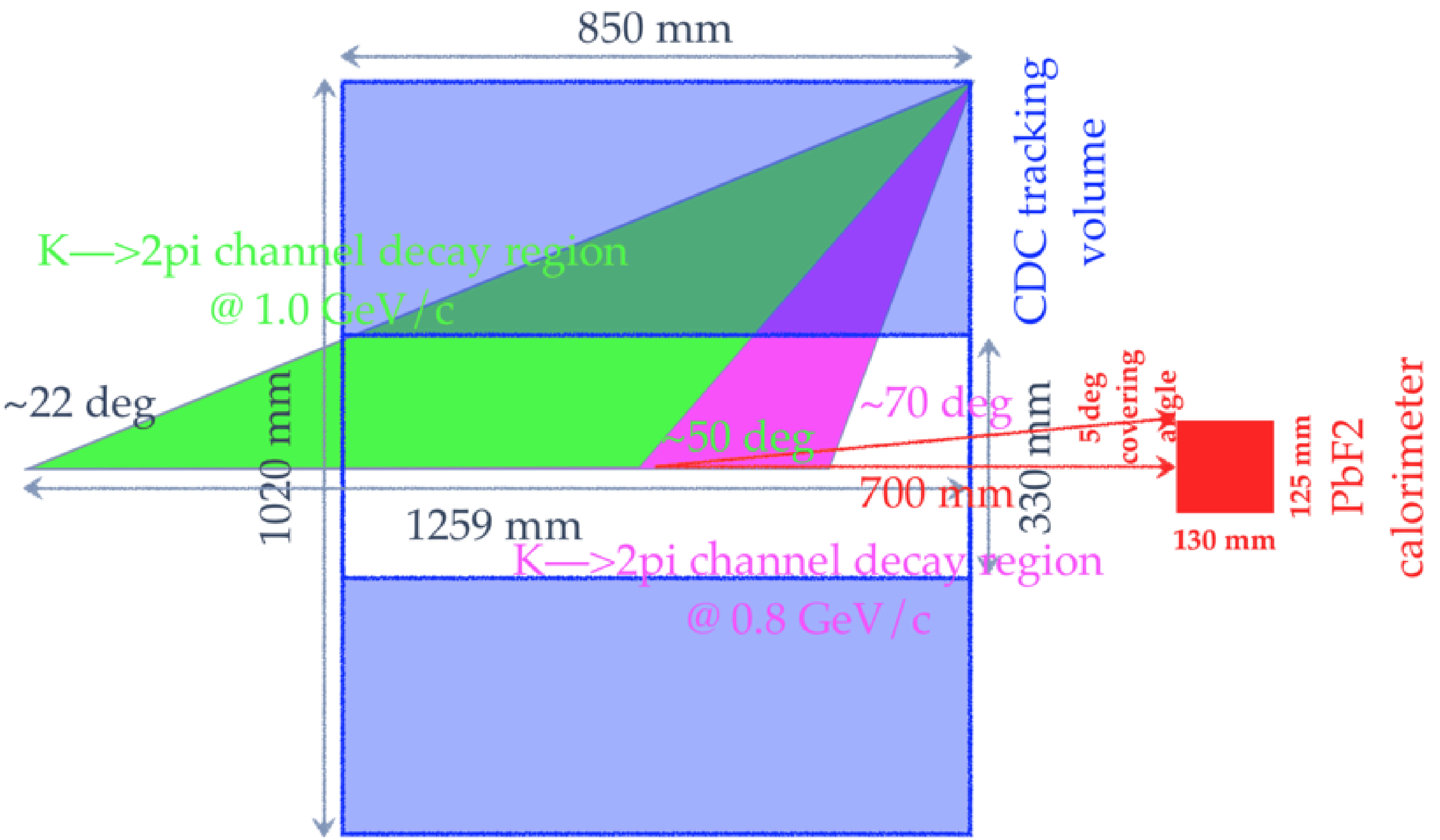


Background events from Kaon in-flight decay



- For setup like SKS dipole magnet spectrometer, there are severe BG from K- inflight decay.
- But in our case, a conjunction measurement of both pi- and pi0, the kaon decay backgrounds can be suppressed by using the pi- decay angle and decay vertex.

CDC acceptance vs Kaon decay background



- Most of the 1.0 GeV/c K- beam in-flight decay background is out of the acceptance of CDS spectrometer.

out of pi0⊕pi- acceptance

Reaction(decay) and final states	Charged particle timing structure	Branching ratio	σ [mb/Sr] for p_{K^-}=0.9GeV/c and θ_{π^0}=0
$K^-\ {}^3He \to \pi^0\ {}^3_\Lambda H \to$ $\pi^0\pi^-\ {}^3He \to 2\gamma\pi^-\ {}^3He$	delayed π^-	?%	?%
$\pi^0\ p\ n\ n_s \to 2\gamma\ p\ n\ n$	delayed p	?%	?%
$K^- \to$ $\pi^0\mu^-\bar{\nu}_\mu \to 2\gamma\mu^-\bar{\nu}_\mu$	prompt μ^-	3.32%	Not included
$\pi^0\pi^- \to 2\gamma\pi^-$	prompt π^-	20.92%	
$\pi^0\pi^0\pi^- \to 4\gamma\pi^-$	prompt π^-	1.76%	
$K^-\ p \to \pi^0\ \Lambda \to$ $\pi^0\ \pi^0\ n \to 4\gamma\ n$	N. A.	35.8%	4.5
$\pi^0\ \pi^-\ p \to 2\gamma\ \pi^-\ p$	delayed π^-, p	63.9%	
$K^-\ p \to \pi^0\ \Sigma^0 \to \pi^0\ \gamma\ \Lambda \to$ $\pi^0\ \gamma\ \pi^0\ n \to 5\gamma\ n$	N. A.	35.8%	0.36 (scaled)
$\pi^0\ \gamma\ \pi^-\ p \to 3\gamma\ \pi^-\ p$	delayed π^-, p	63.9%	
$K^-\ p \to \pi^-\ \Sigma^+ \to$ $\pi^-\ \pi^0\ p \to 2\gamma\ \pi^-\ p$	prompt π^-, delayed p	51.57%	0.9
$\pi^-\ \pi^+\ n$	N. A.	48.31%	
$K^-\ p \to \pi^+\ \Sigma^- \to \pi^+\ \pi^-\ n$	N. A.	100%	Not included
$K^-\ n \to \pi^-\ \Lambda \to$ $\pi^-\ \pi^0\ n \to 2\gamma\ \pi^-\ n$	prompt π^-	35.8%	Not included
$\pi^-\ \pi^-\ p \to 2\pi^-\ p$	N. A.	63.9%	
$K^-\ n \to \pi^-\ \Sigma^0 \to \pi^-\ \gamma\ \Lambda \to$ $\pi^-\ \gamma\ \pi^0\ n \to 3\gamma\ \pi^-\ n$	prompt π^-	35.8%	Not included
$\pi^-\ \gamma\ \pi^-\ p \to \gamma\ 2\pi^-\ p$	N. A.	63.9%	
$K^-\ n \to \pi^0\ \Sigma^- \to \pi^0\ \pi^-\ n \to 2\gamma\ \pi^-\ n$	delayed π^-	100%	0.9 (scaled)

Table 4: Survey for $K^- + {}^3He \to$ forward π^0 + delayed π^-.

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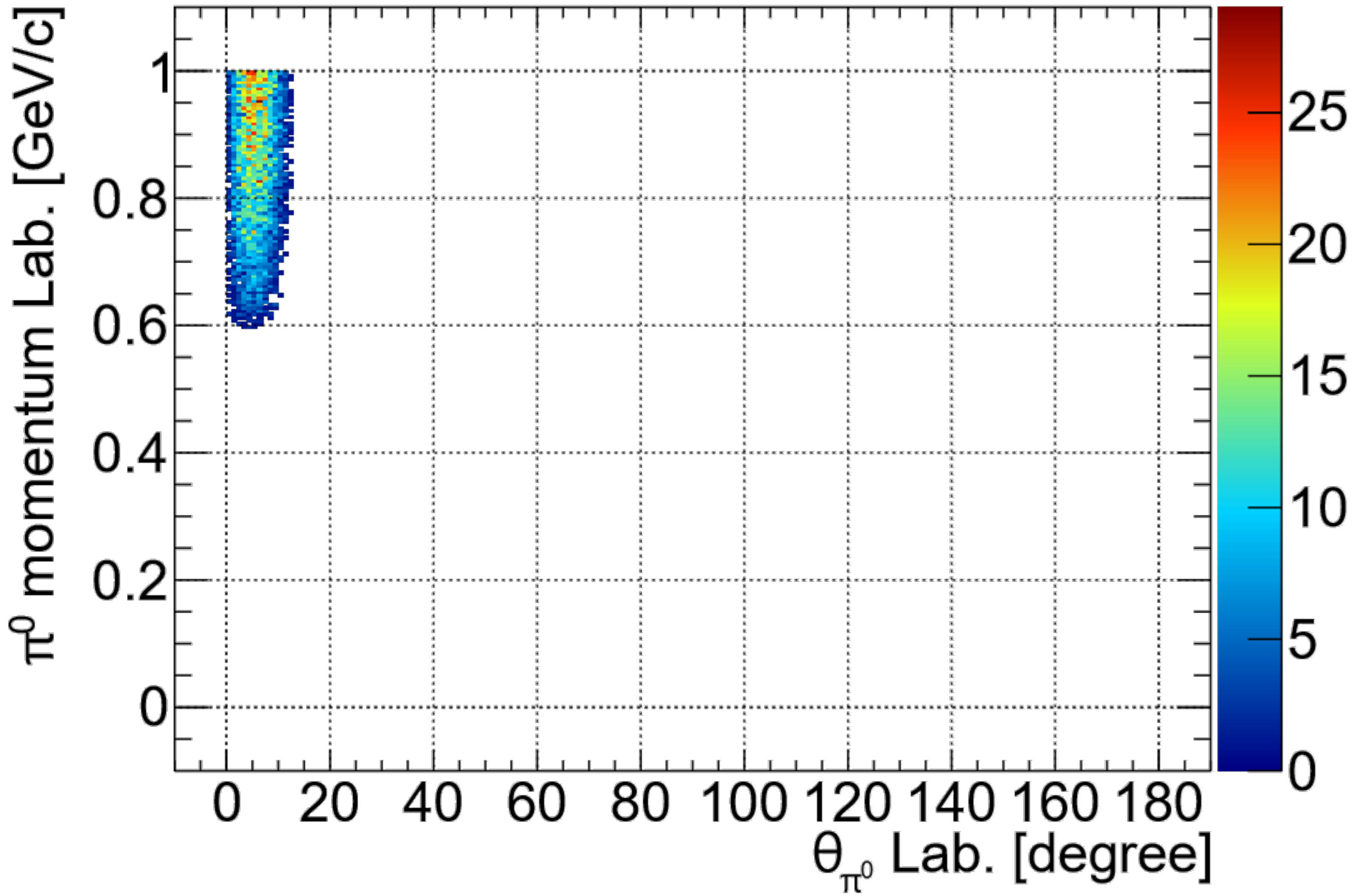
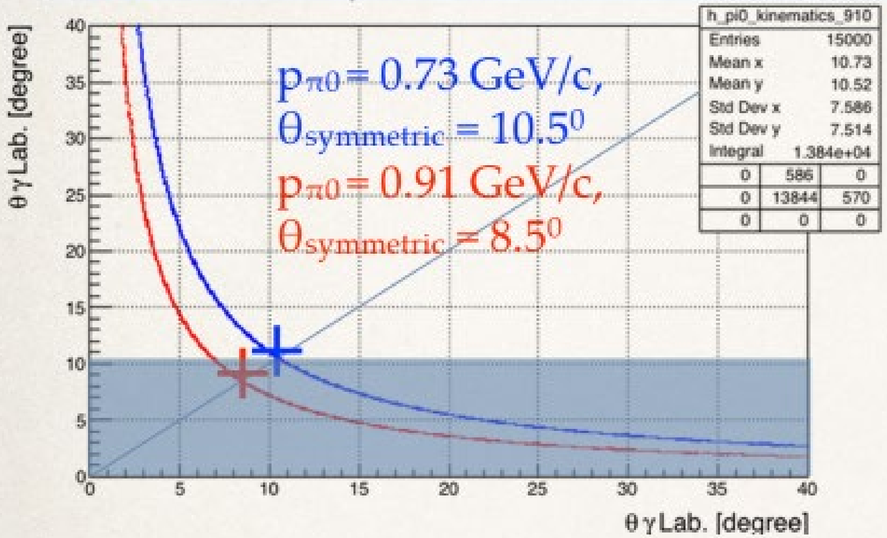
Tagging single γ-ray

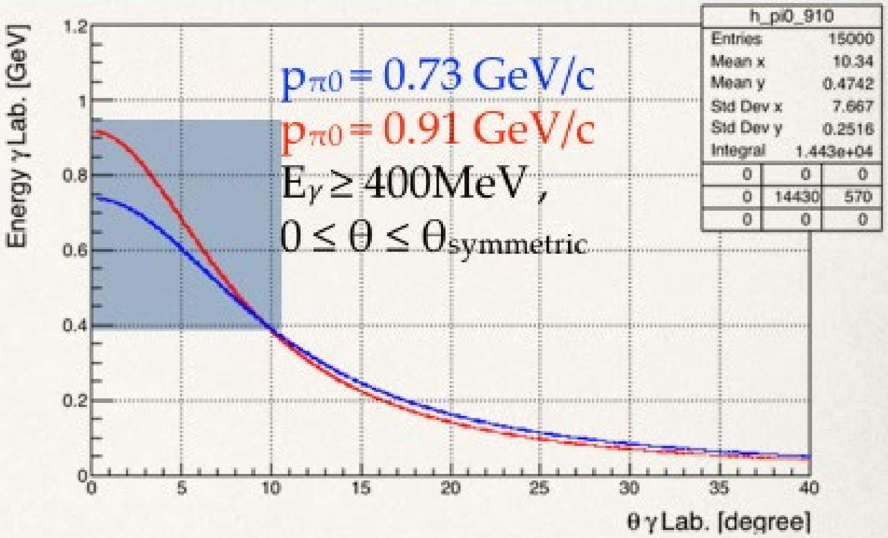
- Simulation: π^0 uniformly 0~1 GeV/c, 0~180 deg
  - Forward calorimeter energy select >0.6 GeV gamma

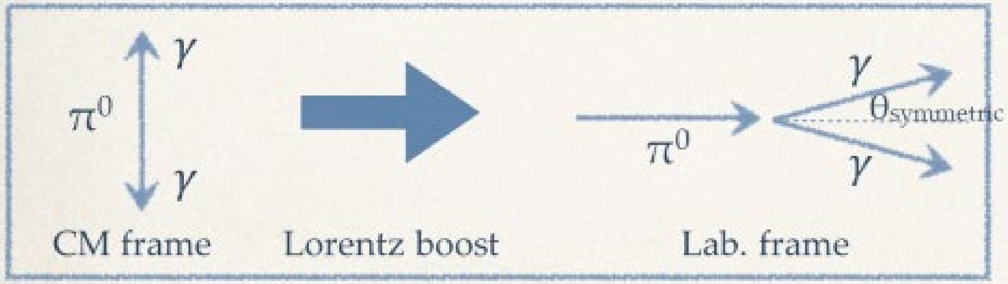


✓forward high-energy π^0 can be selected by detecting 1 gamma

Revisit π^0 decay kinematics





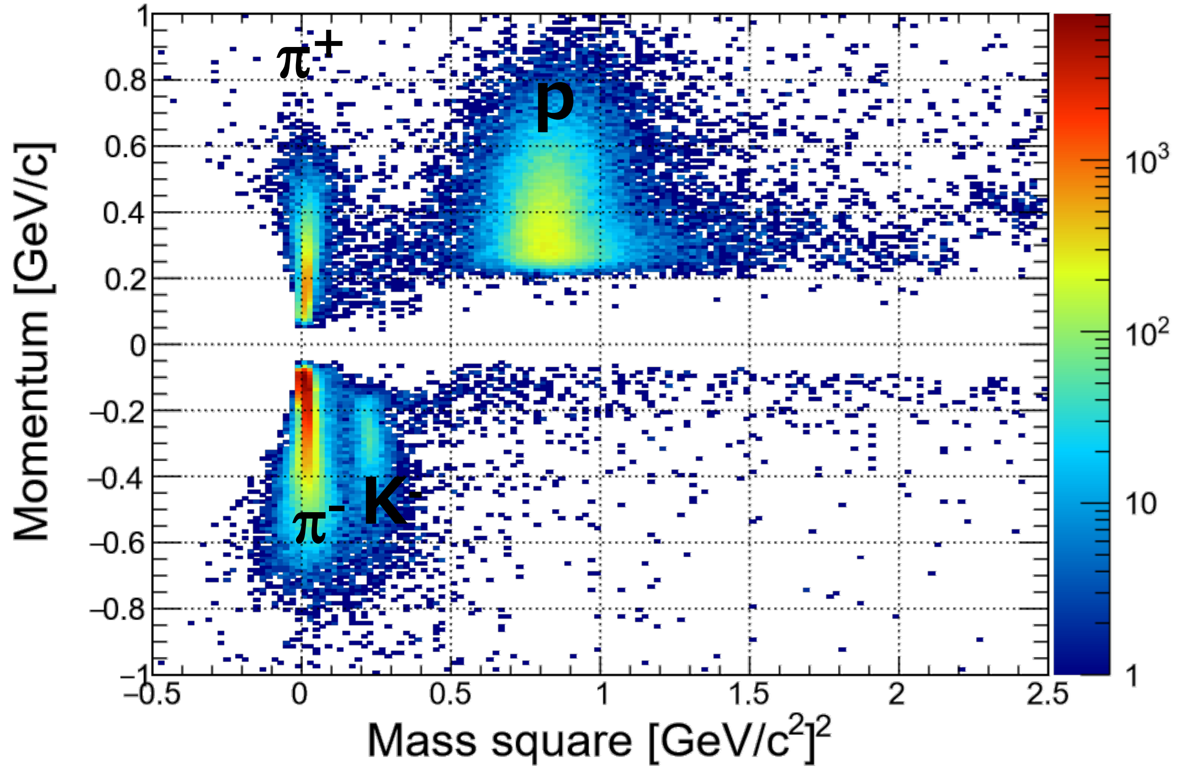


- 0.73~0.91GeV/c π^0 boosts γ forwardly;
- By covering 0~$\theta_{symmetric}$, tag the γ with higher energy ($E_\gamma \geq 400$MeV)

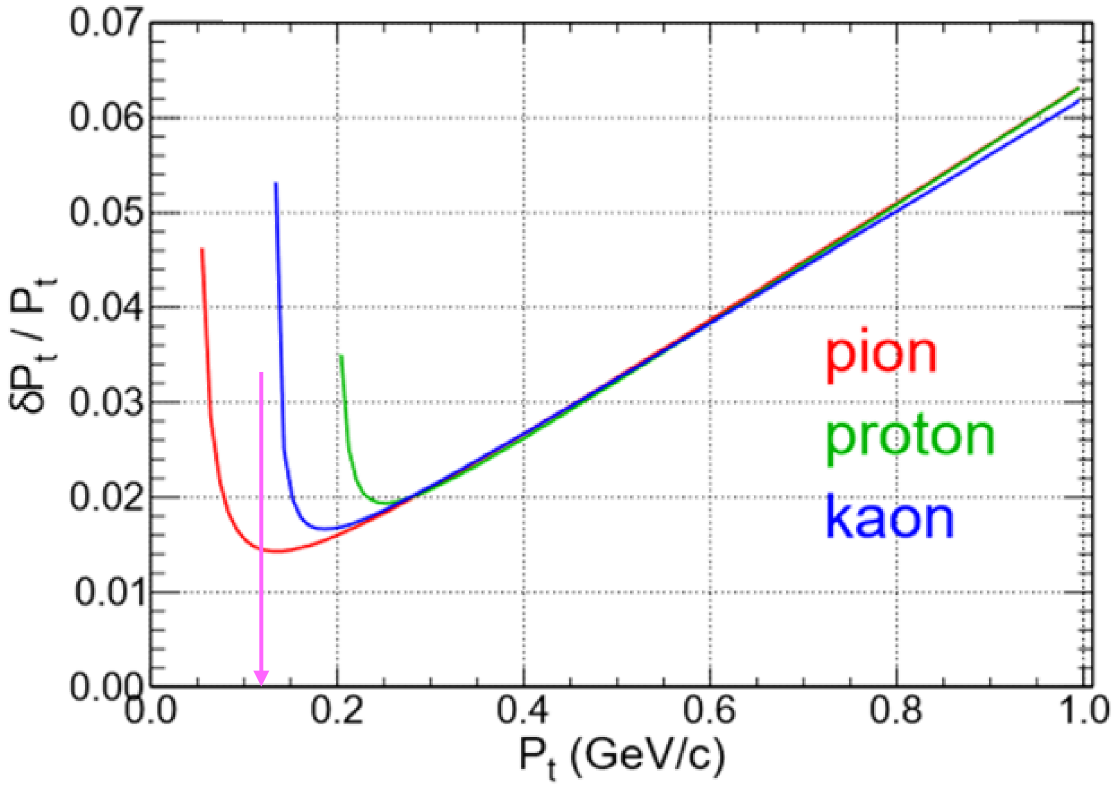
- π^0 tagger needs to be ***located along beam line***
- ***Fast response, radiation hardness***

CDS performance

Particle ID



Momentum resolution



✓Well working

Phase-1: $^{3}_{\Lambda}H$ 3-body decay

- Why be seen peak structure of 3-body decay
  - Qualitative
    - ✓$^{3}_{\Lambda}H$ 3-body decay
    - ✓large separation between Λ & d → fermi motion of Λ is small
    - ✓Small effect to pion momentum
  - Theorical
    - ✓H. Kamada, et al.,
      Phys. Rev. C57, 1595 (1998)

need to be careful
when estimating the # of events