$^{3}_{\Lambda}H/^{4}_{\Lambda}H$ Production cross sectionの比較によるハイパートライトンの束縛エネルギーの研究
(J-PARC E73: ハイパートライトン直接寿命測定)

1

Osaka University
T. Akaishi
For the J-PARC E73 collaboration

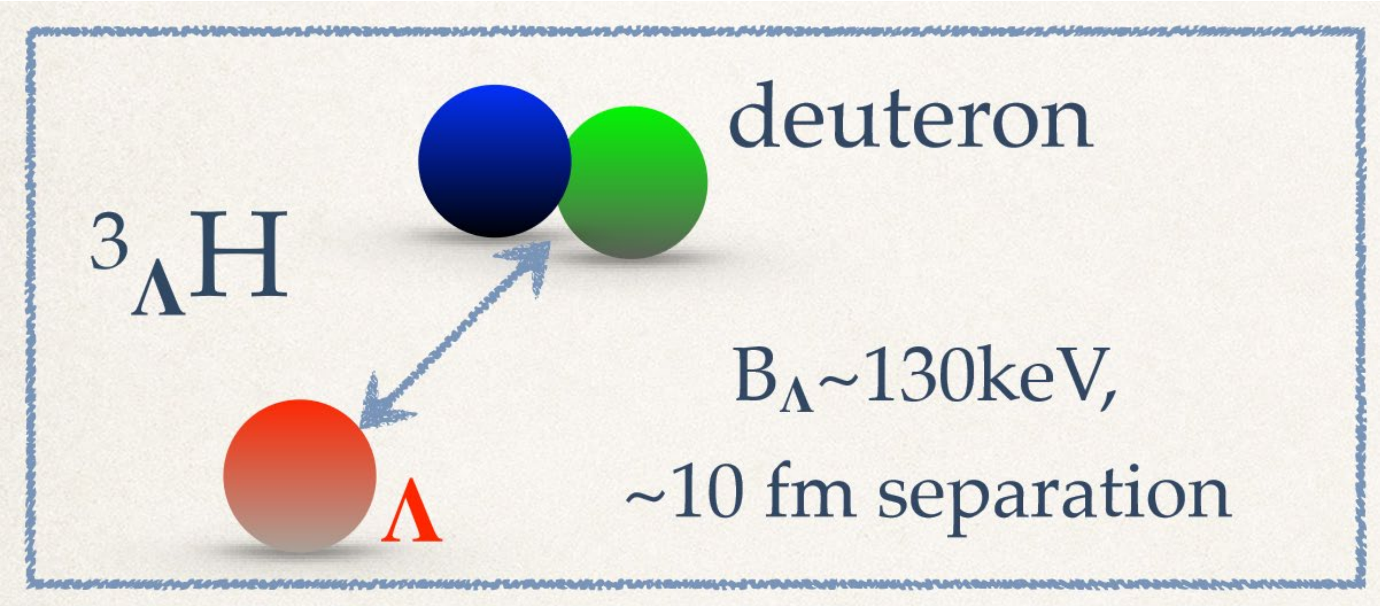
Outline

- Introduction
  - Hypertriton
  - Motivation of J-PARC E73 experiment
  - Information of binding energy from production cross section
- J-PARC E73 experiment
  - Experimental principle
  - Pion momentum distribution of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$
  - Ratio of production cross section
- 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



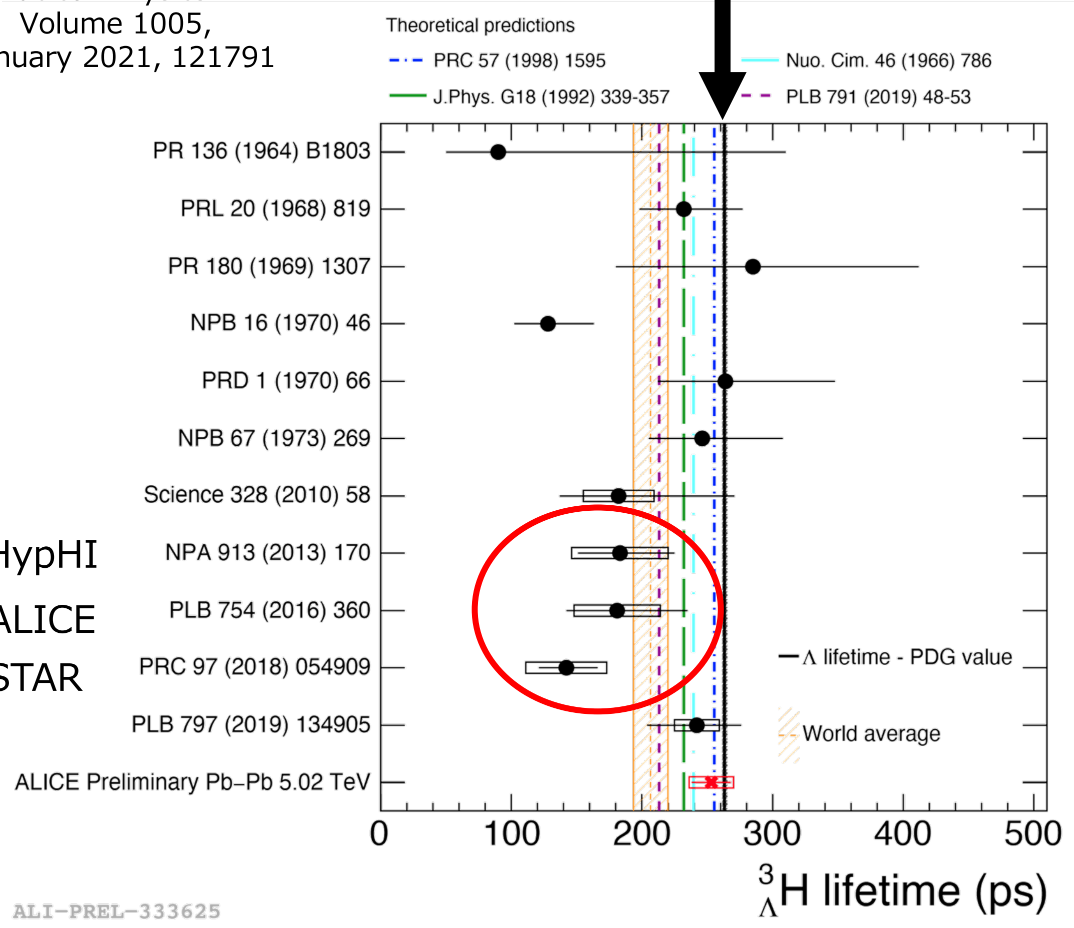
✓Small B_Λ → large separation between Λ & d

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

Hypertriton lifetime

Free Λ

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



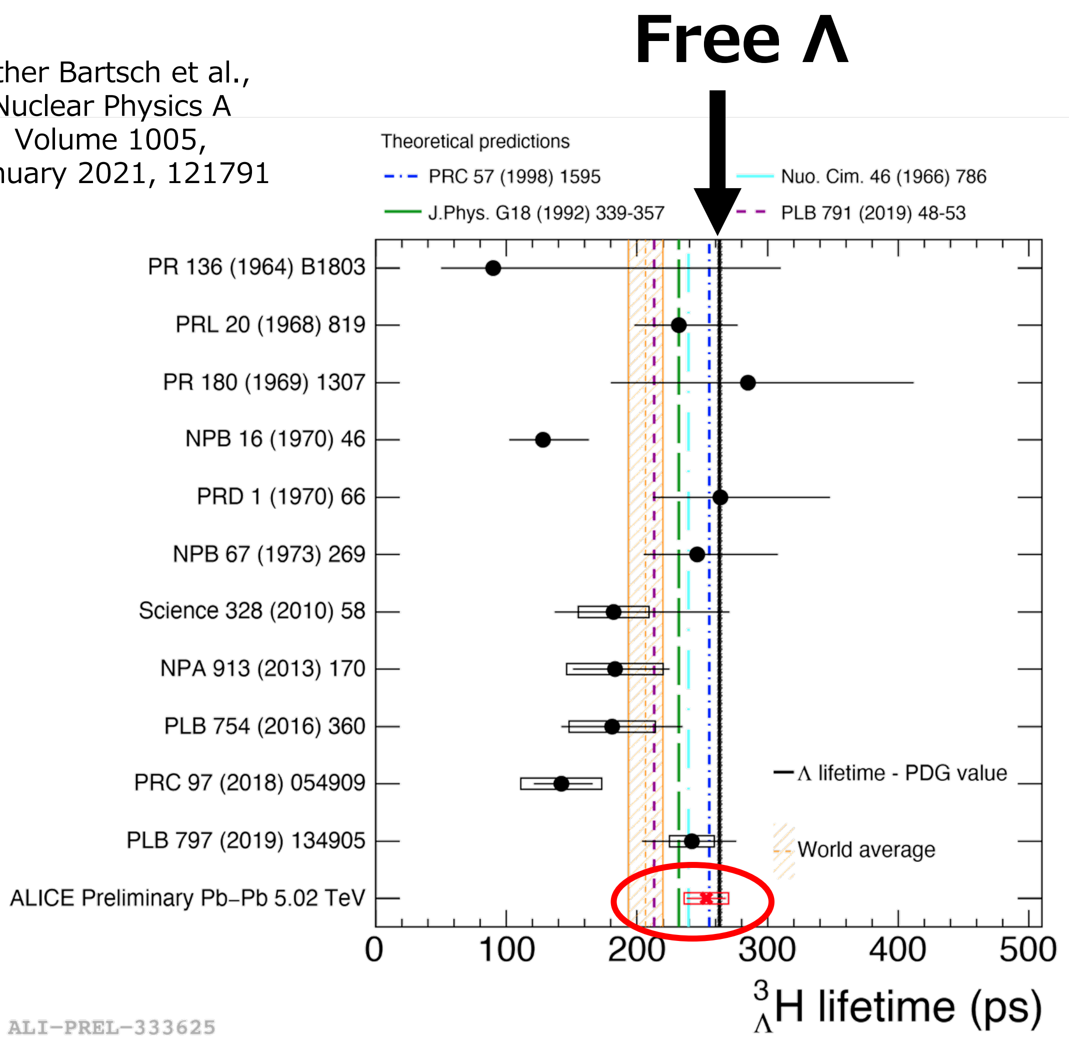
Exp.	Lifetime
HypHI(2013)	$183^{+42}_{-32} \pm 37$ ps
ALICE(2016)	$181^{+54}_{-39} \pm 33$ ps
STAR(2018)	$142^{+24}_{-21} \pm 29$ ps

Free Λ(263 ps)

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

Hypertriton lifetime

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)	$221 \pm 15 \pm 19$ ps

STAR
arXiv:2110.09513

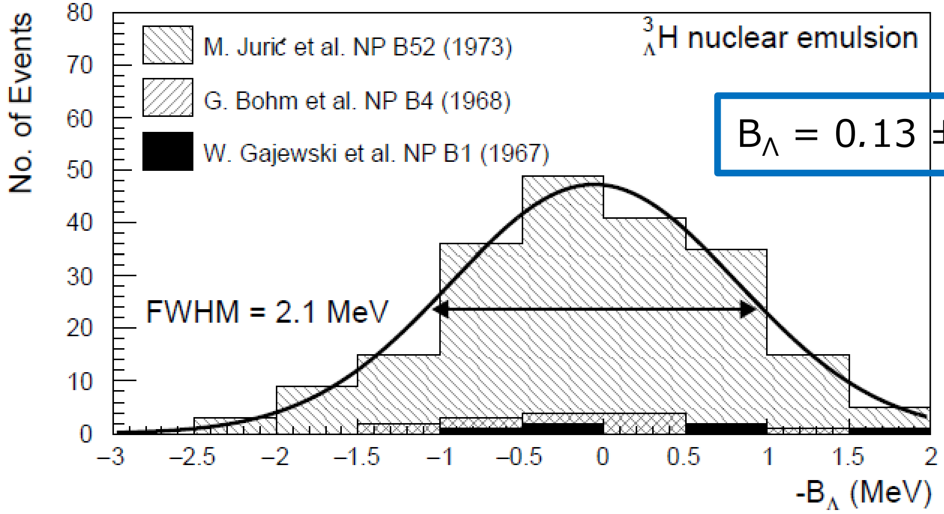
Comparable with Free Λ

- updated result was reported recently

Binding energy

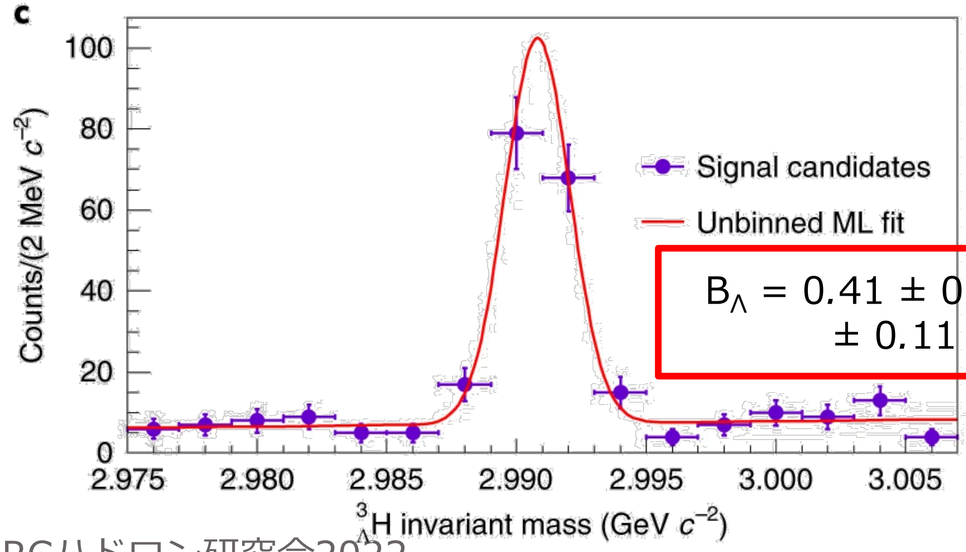
Emulsion measurement

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



B_Λ = 0.13 ± 0.05 MeV

Heavy-ion experiment – STAR in Au-Au collisions

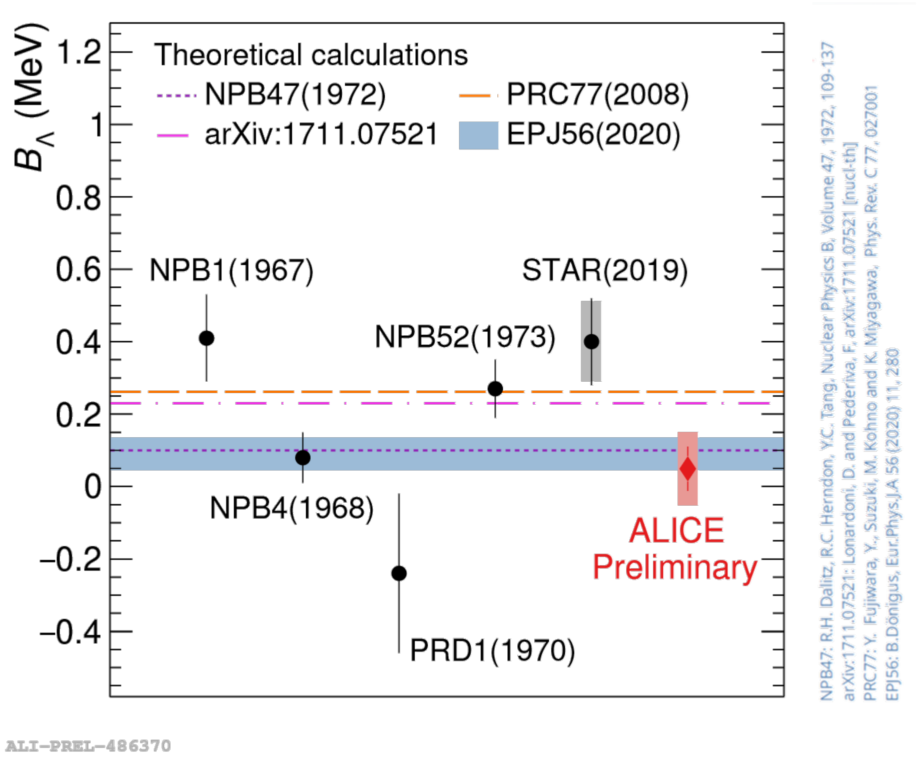


B_Λ = 0.41 ± 0.12 (stat.) ± 0.11 (syst.) MeV

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

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

Michael Hartung, PANIC2021



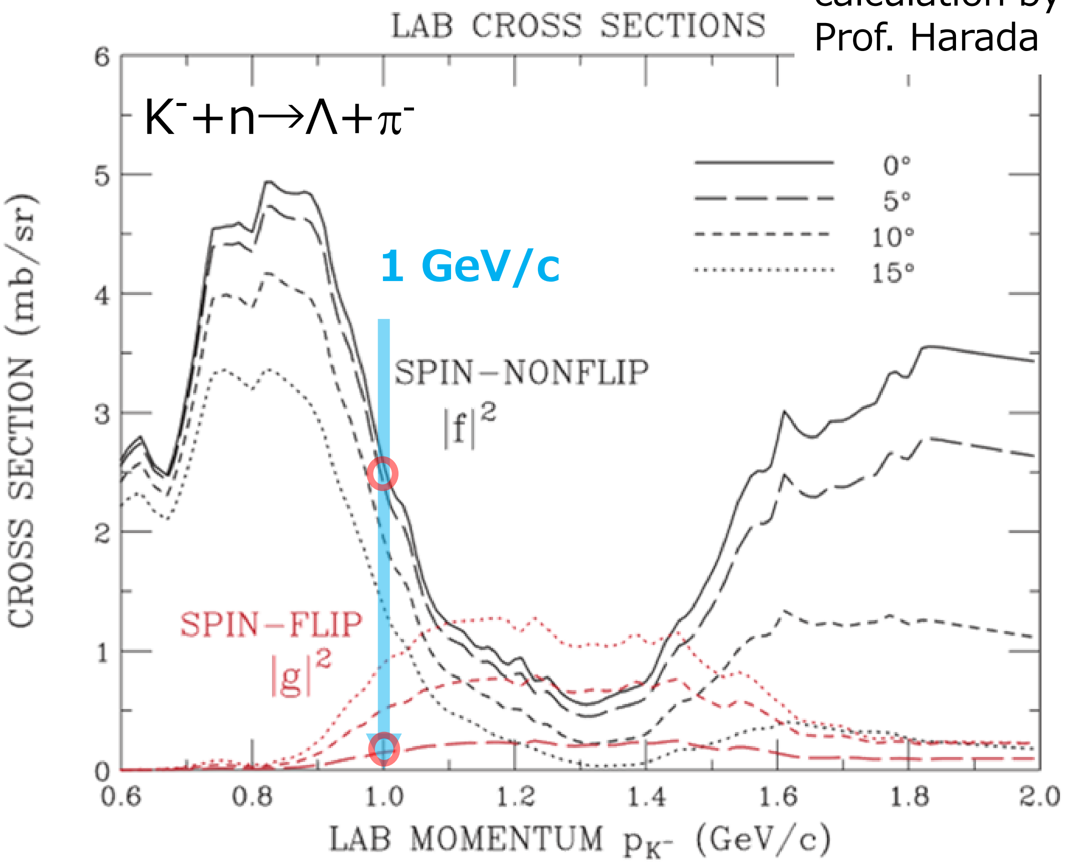
The binding energy is still not determined

Toward solving hypertriton lifetime puzzle

- an independent experimental approach is needed
  ⇒ **Measurement using strangeness exchange reaction (J-PARC E73)**

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



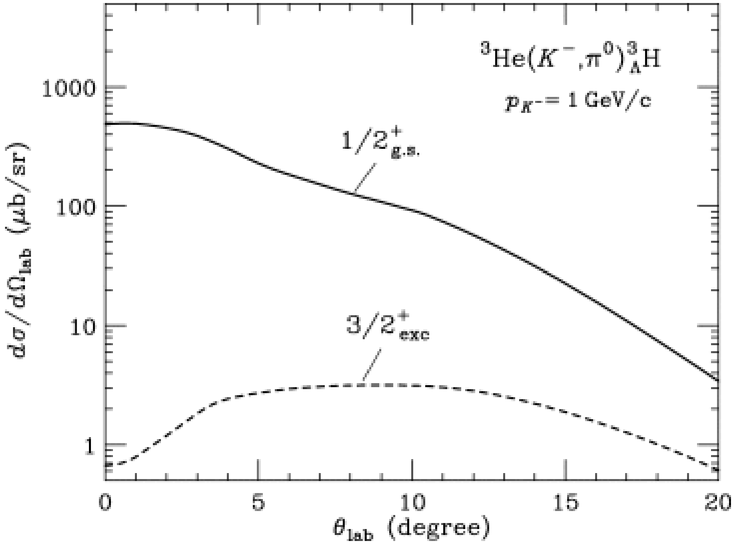
- ➢ produce the ground state of $^3_\Lambda H(1/2^+)$
- ➢ **provide important data on the hypertriton lifetime puzzle**

Ratio of production cross section

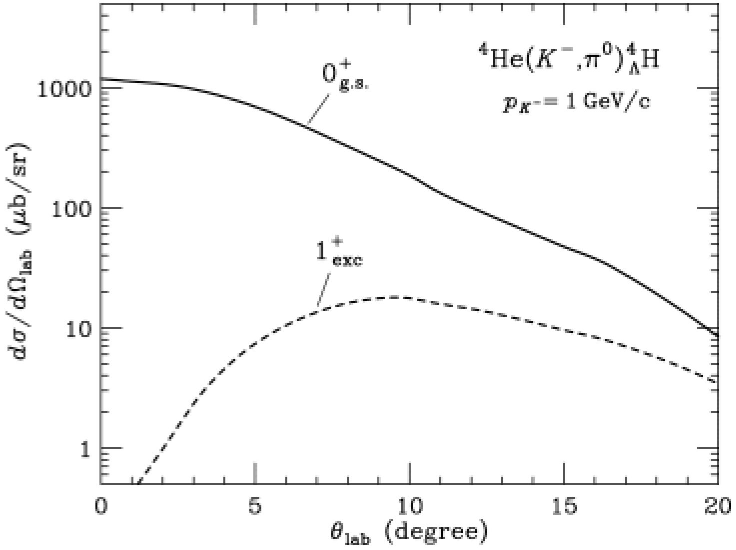
- Theoritical calculaction(DWIA)

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

$^{3}_{\Lambda}H$



$^{4}_{\Lambda}H$



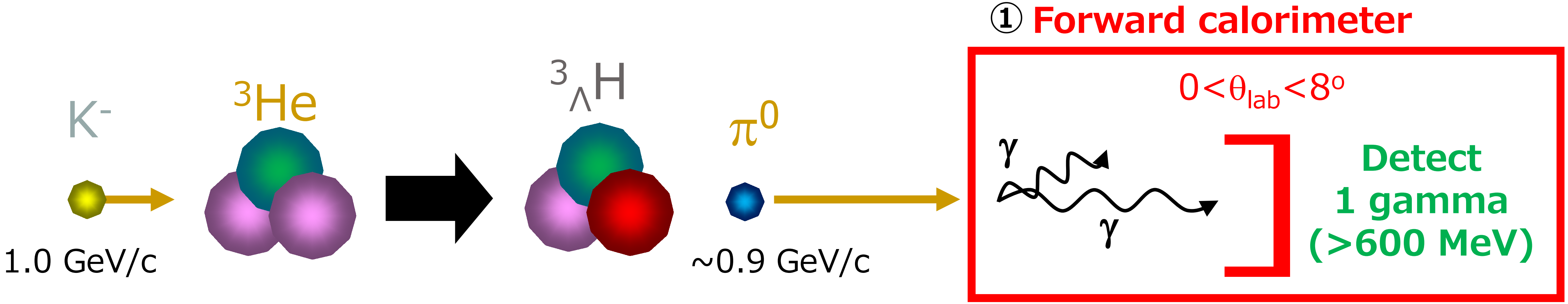
R = $\sigma_{lab}(^{3}_{\Lambda}H)/\sigma_{lab}(^{4}_{\Lambda}H)$
R ~ 0.3—0.4 @ B_{Λ}=0.13 MeV(Emulsion), ~ 0.65 @ B_{Λ}=0.41 MeV(STAR)

→provides a better understanding of the structure of the $^{3}_{\Lambda}H$ bound states

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

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

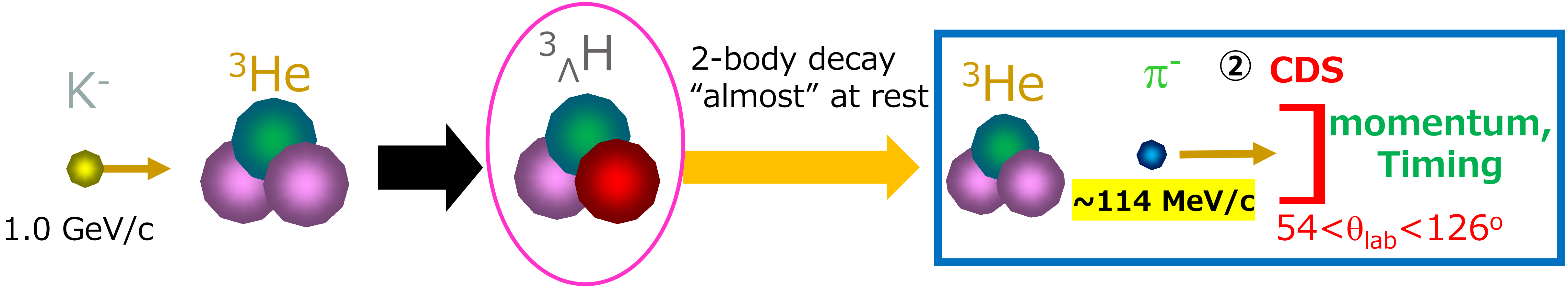
→almost 100% detection efficiency for forward going π^0 ($0< \theta_{lab}^{\pi^0} <10$)

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

Reduce BG from Y decays and multi pion production

J-PARC E73: Experimental principle

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



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

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

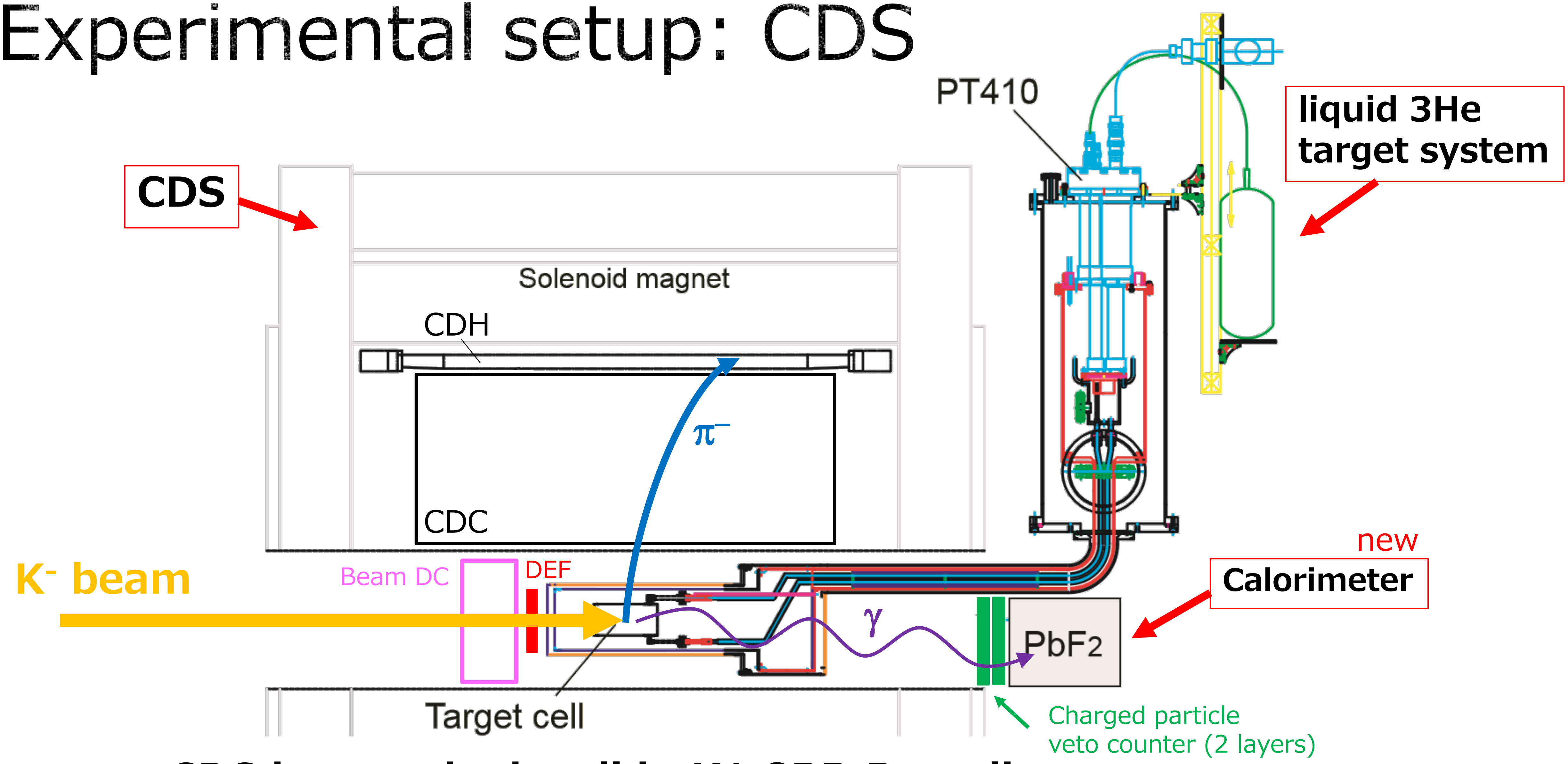
low recoil momentum (~100 MeV/c)

→Hypertriton stops immediately inside the target

⇒2-body decay "almost" at rest

Identify $^3_\Lambda H$ and derive lifetime from decay timing

Experimental setup: CDS



CDS has worked well in K1.8BR Beamline

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

Current status 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 JFY2023 (1 month)

Hypernucleus	$^4_\Lambda$H	$^3_\Lambda$H
B.R. (2-body)	50 %	25 %
Relative σ	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

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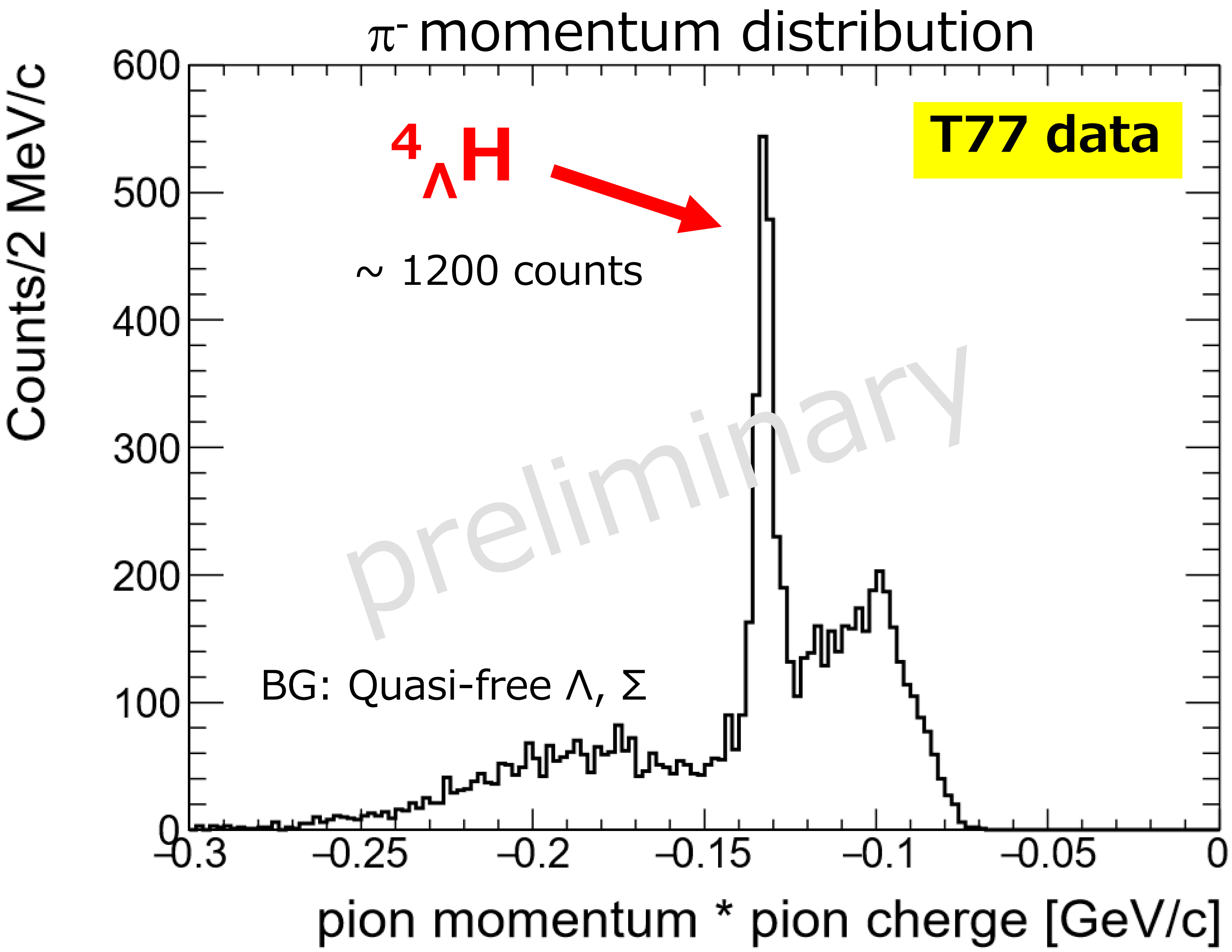
calculation of cross section by Prof. Harada

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

We have $^3_\Lambda$H and $^4_\Lambda$H production data

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



- $^{4}_{\Lambda}H$ signal is clearly seen
  ~ 1200 events

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

- Main BG: Quasi-free Λ, Σ

  - $^{4}_{\Lambda}H$ lifetime will be finalized soon

Background at 4He target

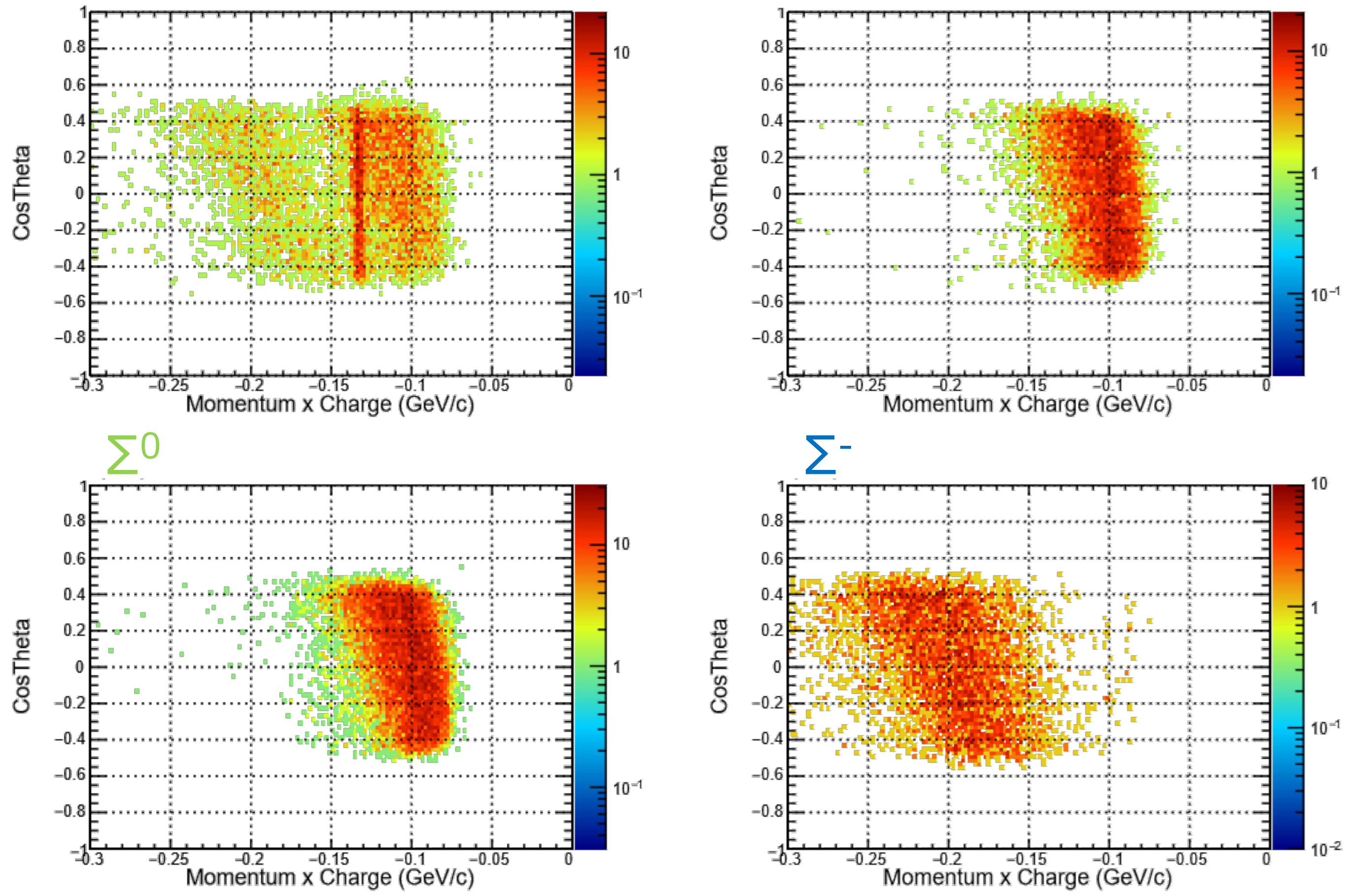
- Monte Carlo simulation

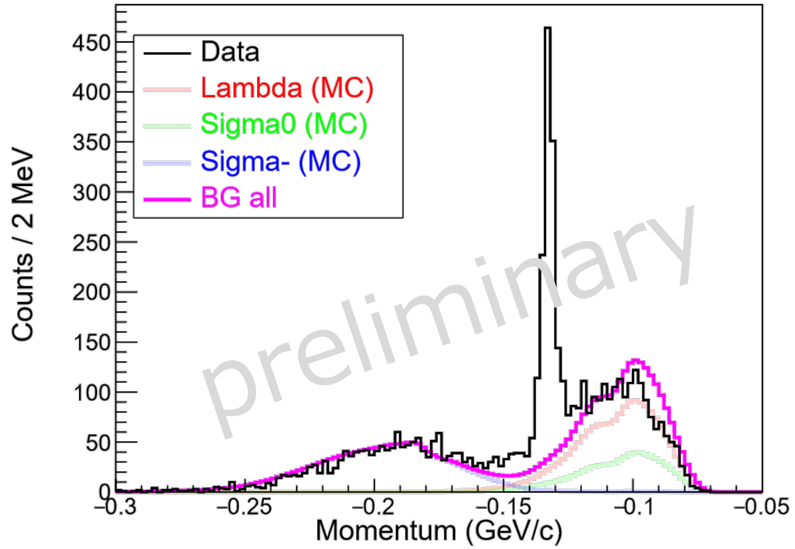
Data

Λ

Σ0

Σ-

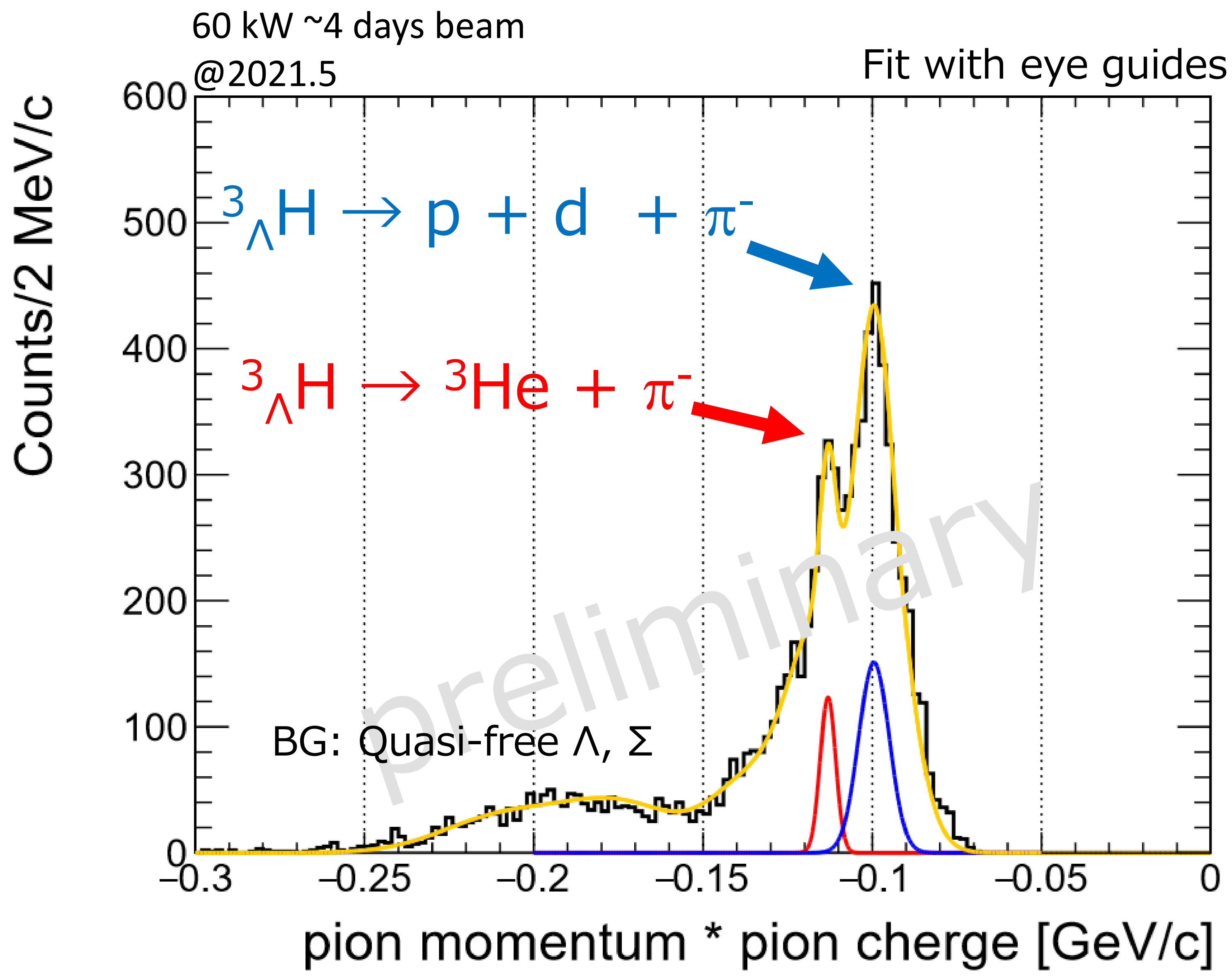




- the N(K−,π0)Y elementary cross section
- w/ the Fermi motion inside 4He nucleus
  R. B. Wiringa et al.,
  Phys. Rev. C 89, 024305, (2014)13

→can reproduce the data well

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



- 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)**

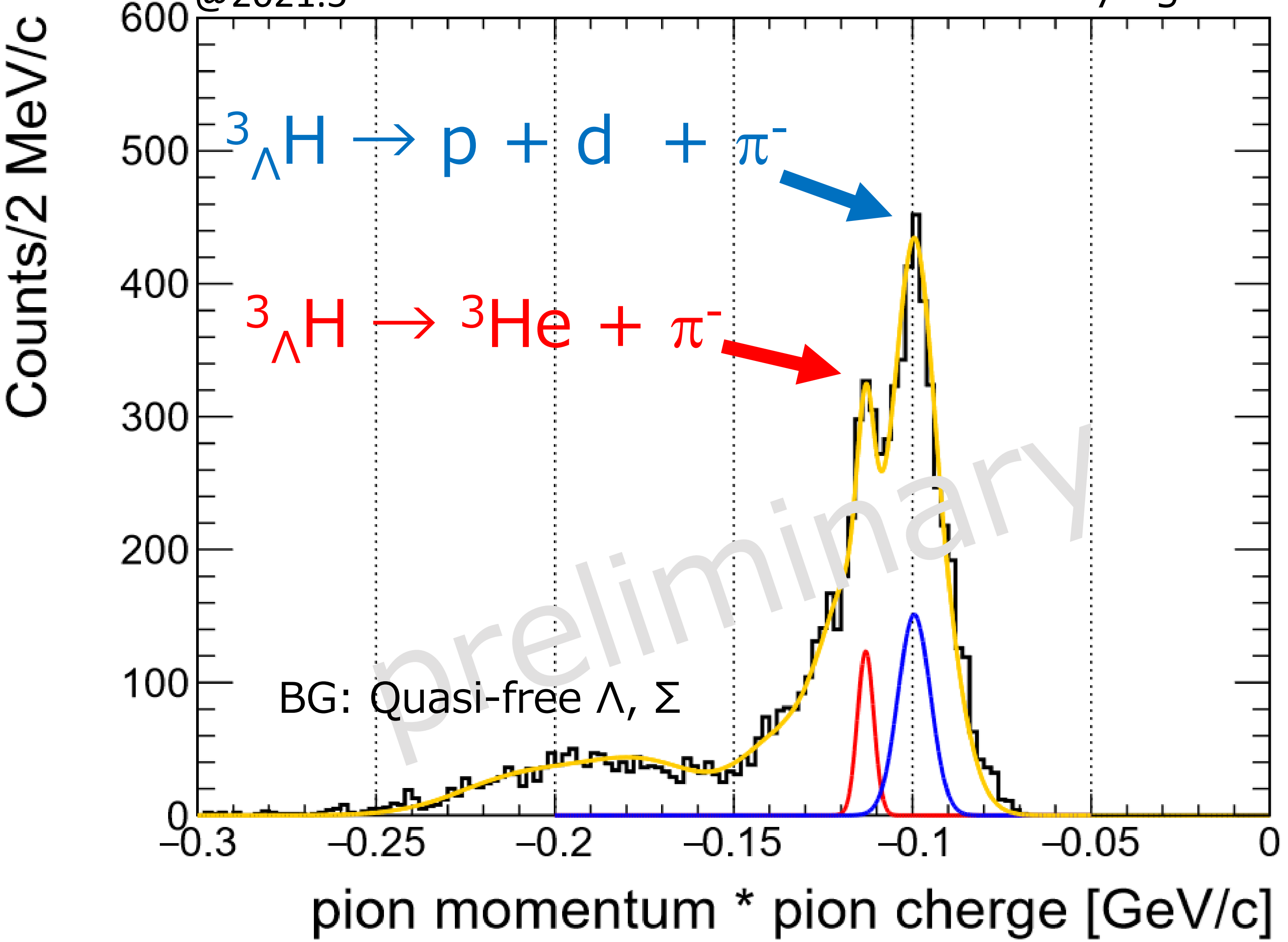
✓**2-body/3-body ratio**

will be derived

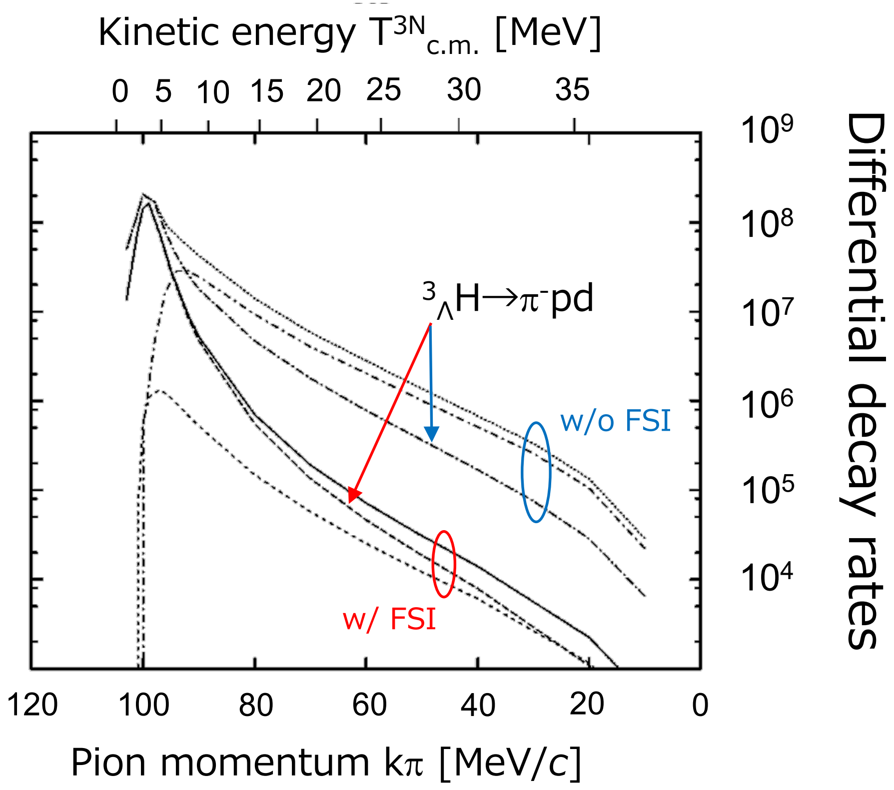
$^{3}_{\Lambda}H$ 3-body decay

60 kW ~4 days beam
@2021.5

Fit with eye guides



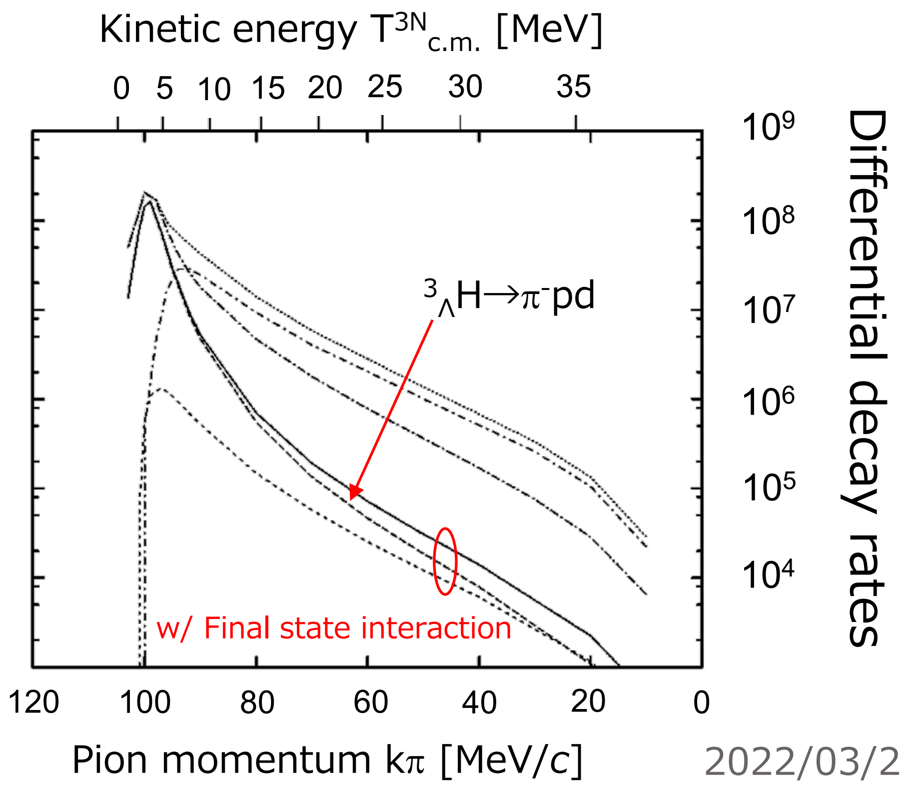
H. Kamada, et al.,
Phys. Rev. C57, 1595 (1998)



$^{3}_{\Lambda}H$ 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



cross section ratio $^{3}_{\Lambda}H$/ $^{4}_{\Lambda}H$

- Rough estimation

	Hypernucleus	$^{4}_{\Lambda}H$	$^{3}_{\Lambda}H$	$^{3}_{\Lambda}H/^{4}_{\Lambda}H$	
Measured	# of Beam	5.04 G Kaon	8.84 G Kaon	1.75	Luminosity → 1 : 1.13 almost same
	# of target	0.145 g/cm^3 /4	0.070 g/cm^3 /3	0.64	
	# of signal	~1200	~200	0.15	
	Relative σ	1	0.3	R=0.3	

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

$R \sim 0.3—0.4$ @ 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

→ **Binding energy does not seem to be large up to 0.41 MeV**

Summary

- J-PARC E73: Direct measurement of $^{3}_{\Lambda}H$ lifetime
  - Different experimental method from heavy ion-based experiment
  - Selectively produce ground state of $^{3}_{\Lambda}H(1/2^{+})$
- Information of binding energy from production cross section
  - R ~ 0.3—0.4 @ B_{Λ}=0.13 MeV(Emulsion), ~ 0.65 @ B_{Λ}=0.41 MeV(STAR) (theoretical calculation)

  - We have $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ production data
    - ✓Ratio rough estimation: R~0.3

    → Binding energy does not seem to be large up to 0.41 MeV

    I will get the details of the value and error as soon as possible.

J-PARC E73 collaboration

T. Akaishi[1], H. Asano[2], X. Chen[5], A. Clozza[7], C. Curceanu[7], R. Del Grande[7], C. Guaraldo[7], C. Han[5], T. Hashimoto[4], M. Iliescu[7], K. Inoue[1], S. Ishimoto[3], K. Itahashi[2], M. Iwasaki[2], Y. Ma[2], M. Miliucci[7], R. Murayama[2], H. Noumi[1], H. Ohnishi[10] S. Okada[2], H. Outa[2], K. Piscicchia[7,9], A. Sakaguchi[1], F. Sakuma[2], M. Sato[3], A. Scordo[7], K. Shirotori[1], D. Sirghi[7,8], F. Sirghi[7,8], S. Suzuki[3] K. Tanida[4], T. Toda[1], M. Tokuda[1], T. Yamaga[2], X. Yuan[5], P. Zhang[5], Y. Zhang[5], H. Zhang[6]

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Backup

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

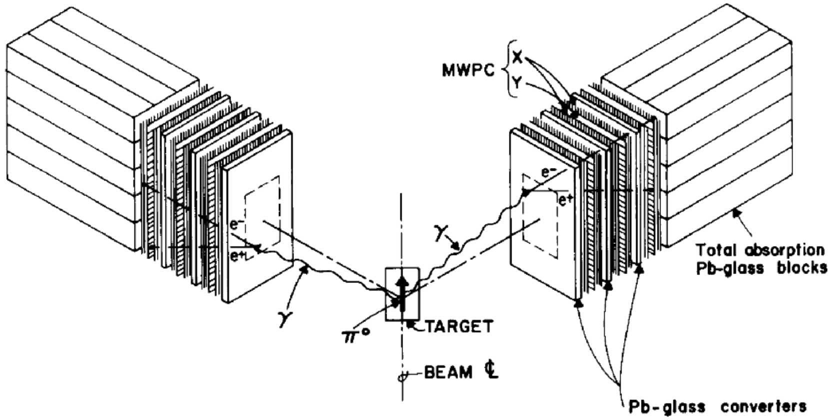
Previous Experiment using (K^-, π^0) reaction

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

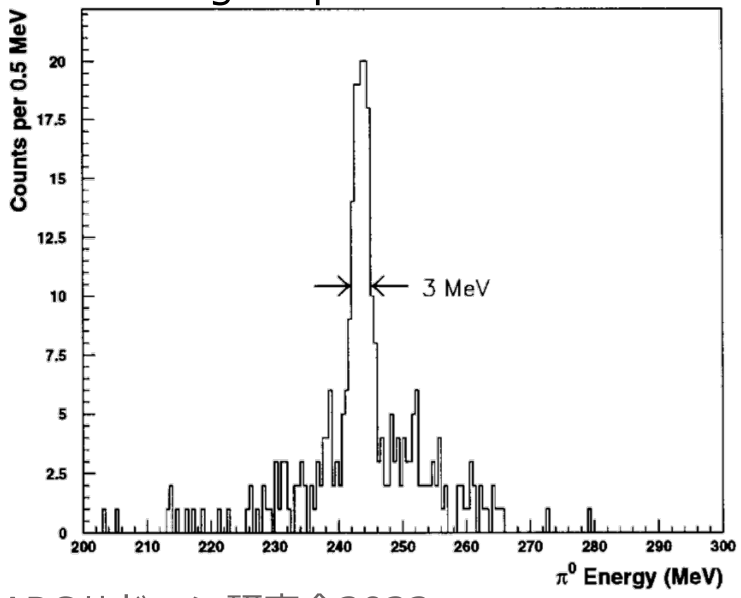
✓ $$E_{\pi^0} = E_1 + E_2 = m_{\pi^0}\sqrt{\frac{2}{(1-\cos\eta)(1-X^2)}},\quad X = \frac{E_1 - E_2}{E_1 + E_2}$$

η: opening angle

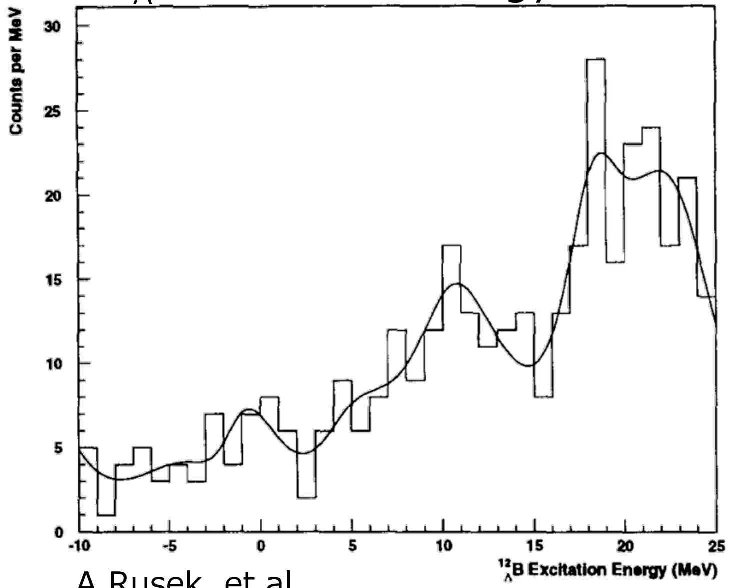
H.W. Baer, et al.,
Nucl. Inst. Meth. 180(1981)445



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

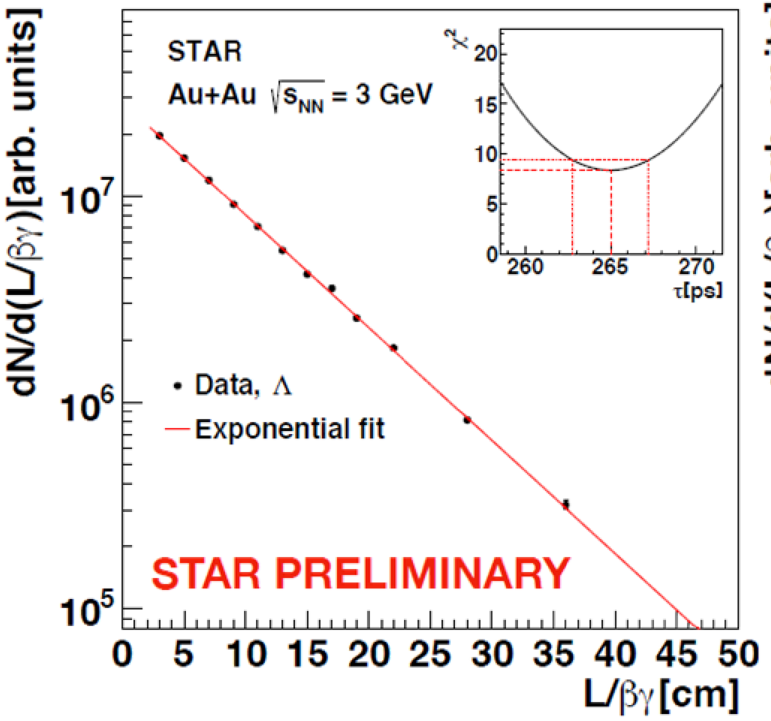
Difficult method

STAR new result

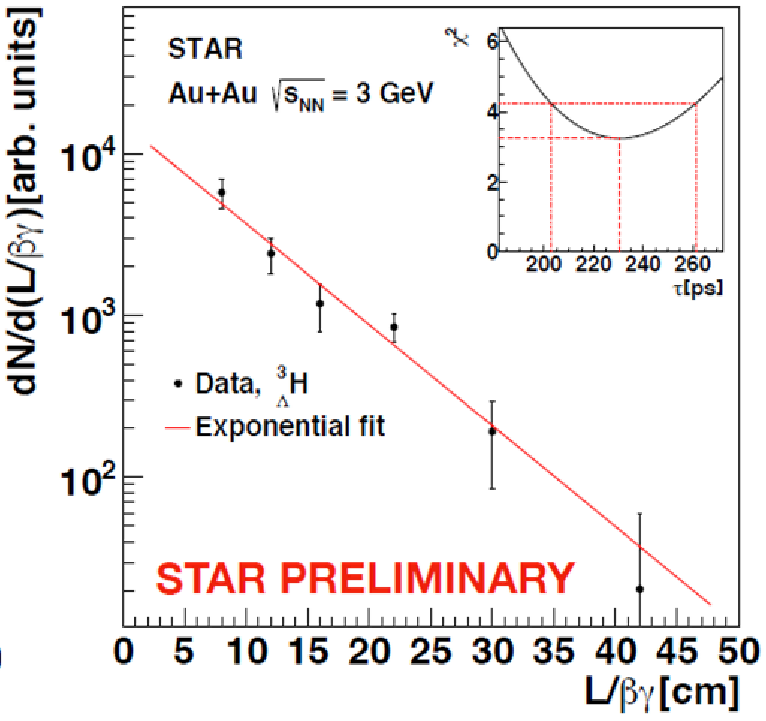
- Fixed target mode $\sqrt{S_{NN}} = 3$ GeV

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

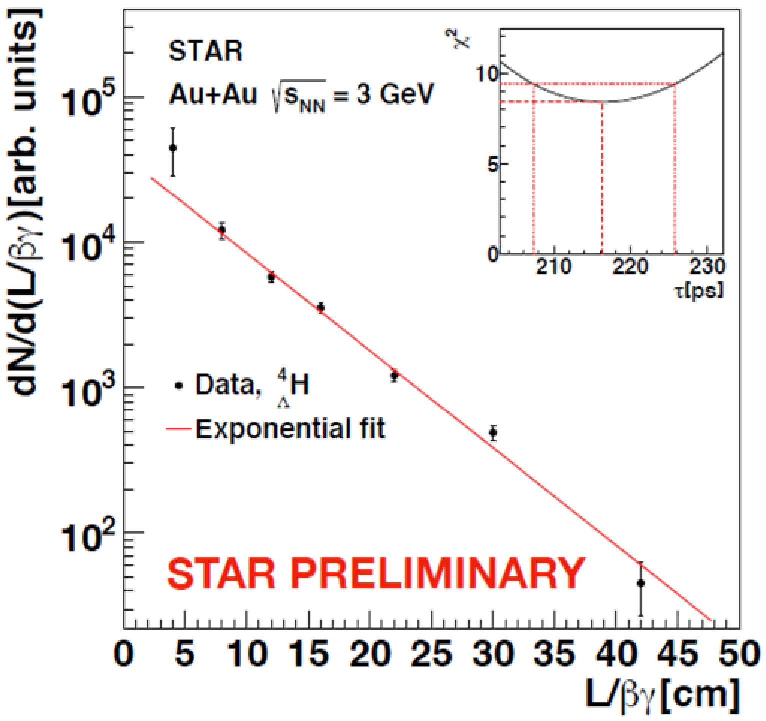
Λ



$^{3}_{\Lambda}H$



$^{4}_{\Lambda}H$



Λ **lifetime** $(265.0 \pm 2.2)[ps]$

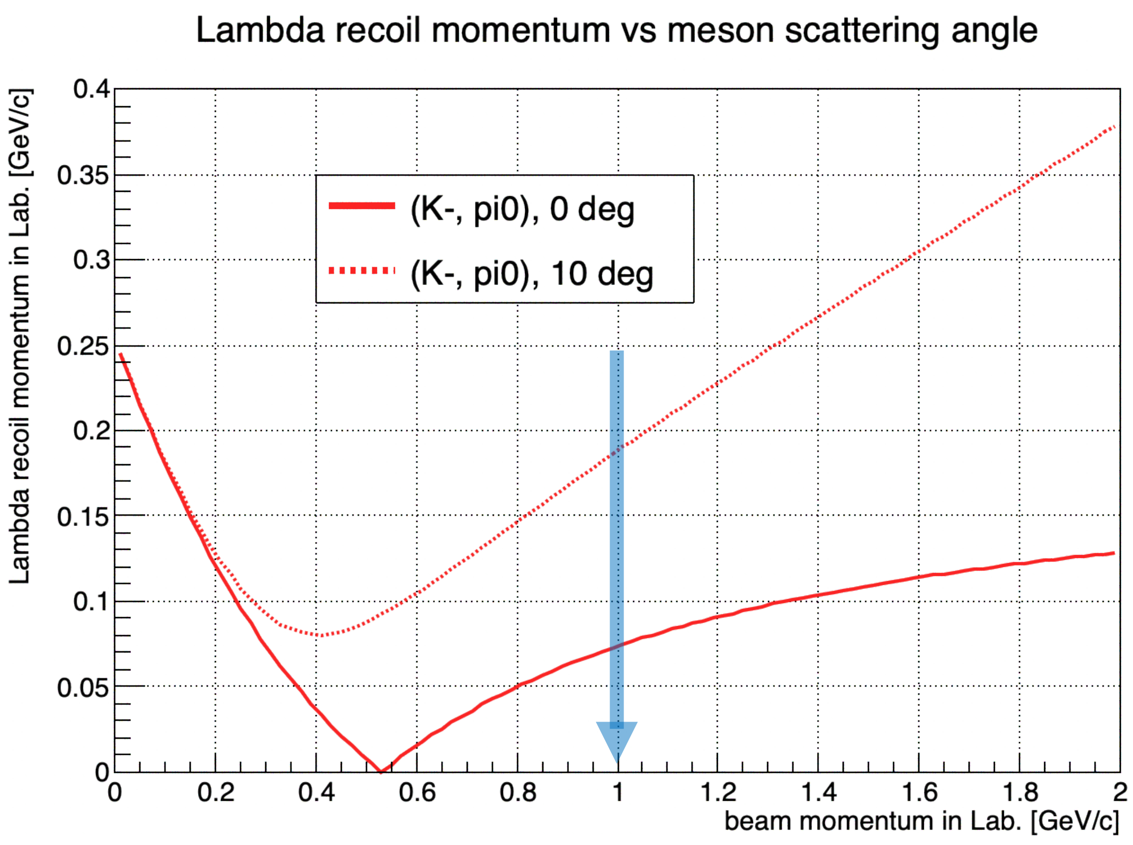
PDG value $(263.1 \pm 2.0)[ps]$

$^{3}_{\Lambda}H : \tau = 232.1 \pm 29.2(stat) \pm 36.7(syst)[ps]$

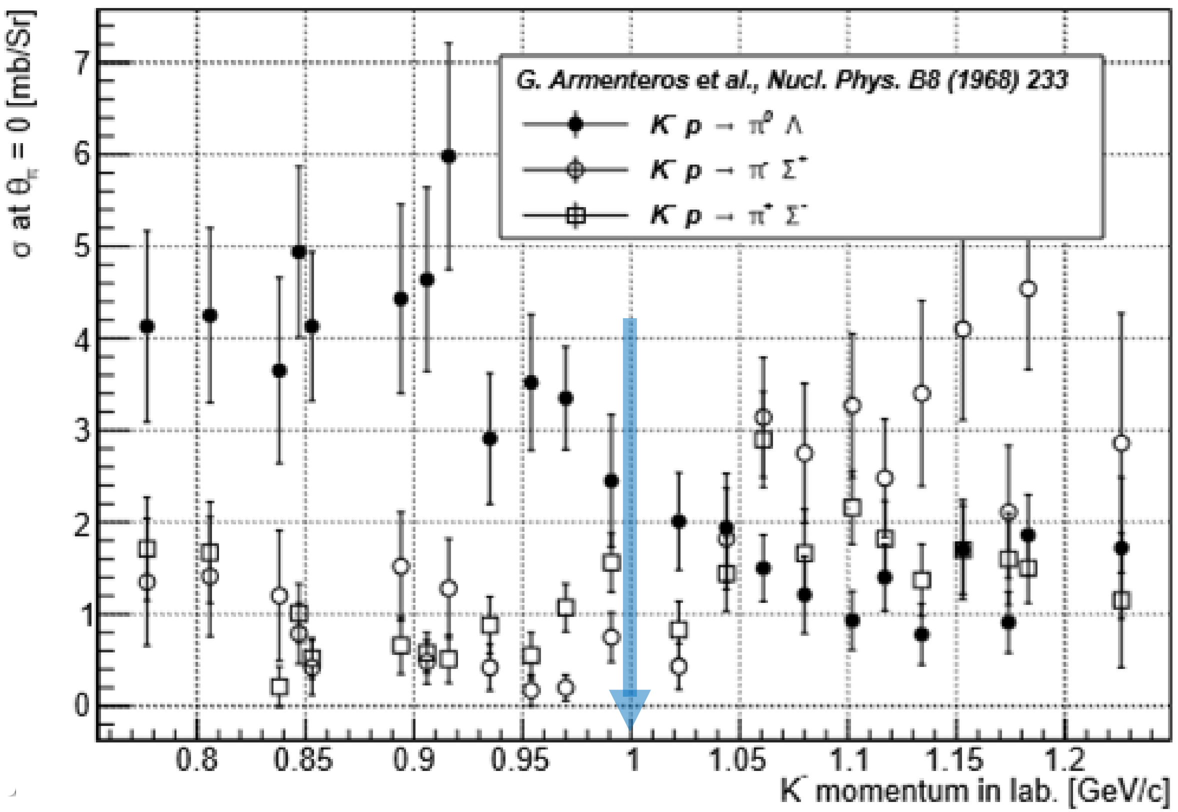
$^{4}_{\Lambda}H : \tau = 218.3 \pm 7.5(stat) \pm 11.8(syst)[ps]$

Experiment concept

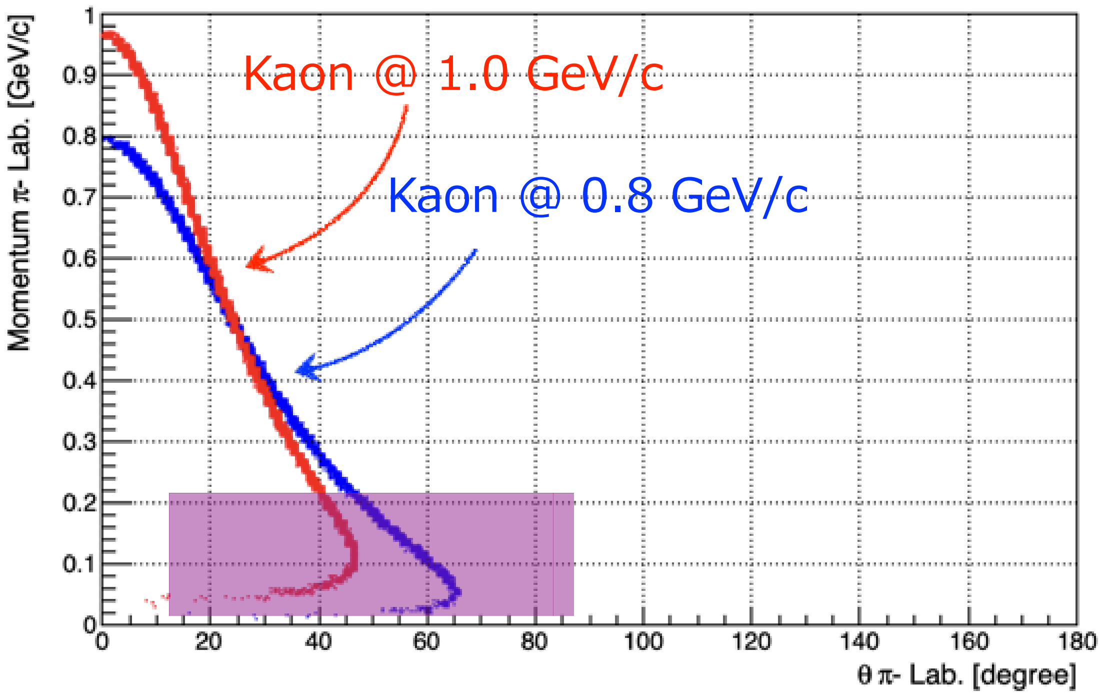
Beam Momentum selection



Elementary cross section

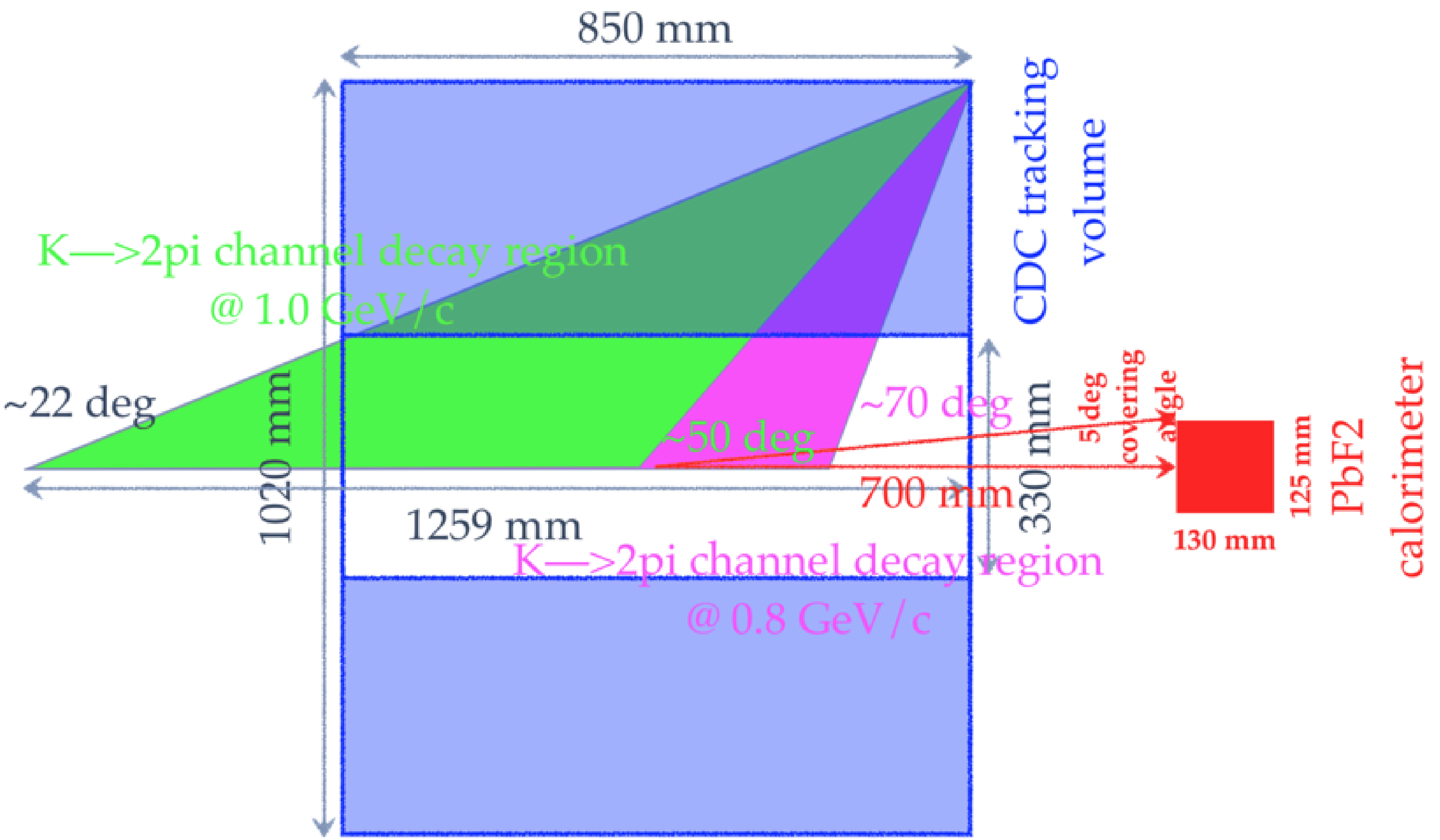


Background events from Kaon in-flight decay



- 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.

Reaction and final states

out of
pi0⊕pi-
acceptance

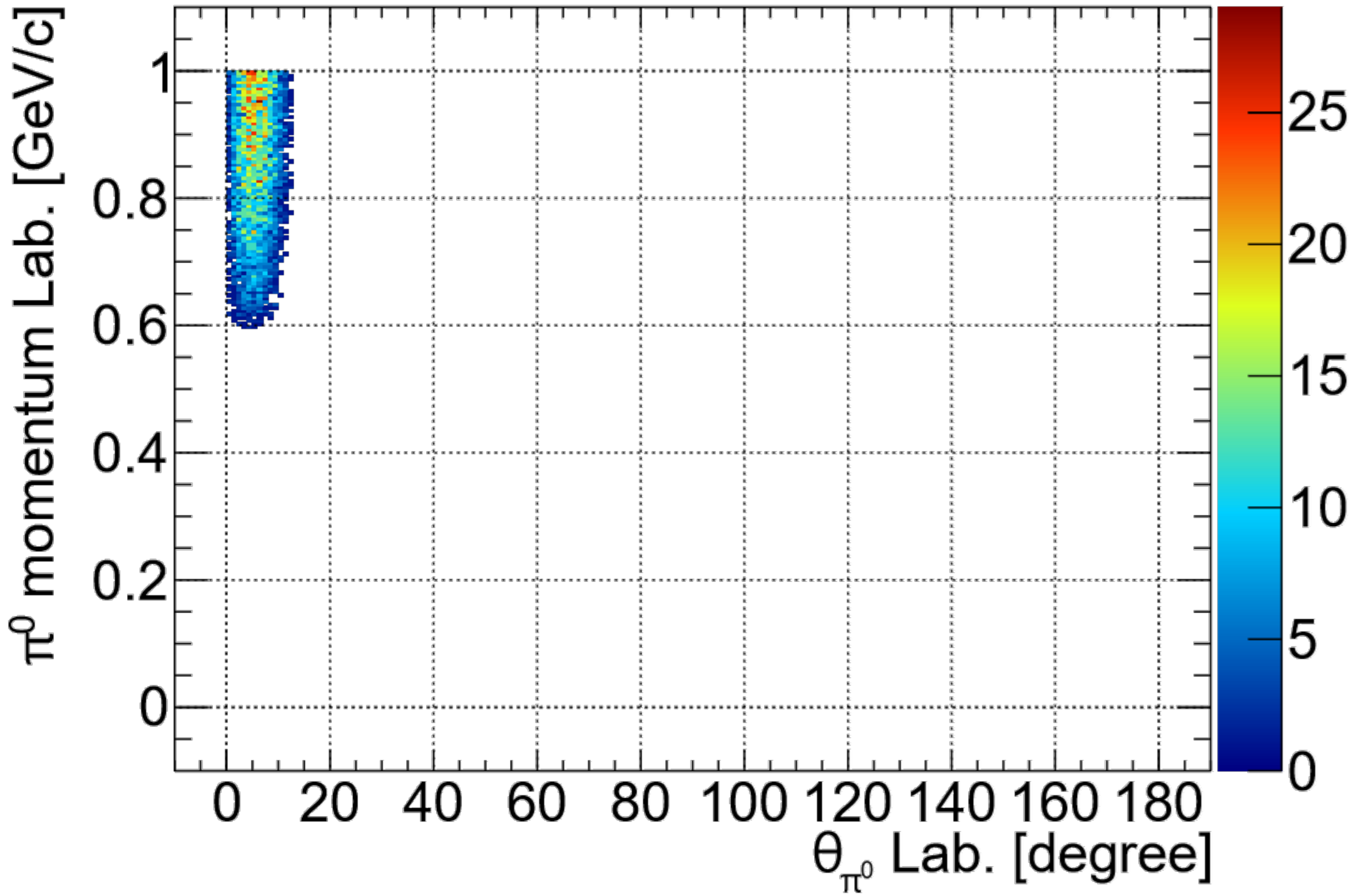
Reaction(decay) and final states	Charged particle timing structure	Branching ratio	σ [mb/Sr] for p_{K^-}=0.9GeV/c and θ_{π^0}=0
$K^- \, ^3He \to \pi^0 \, ^3_\Lambda H \to$ $\pi^0 \pi^- \, ^3He \to 2\gamma \pi^- \, ^3He$	delayed π^-	?%	?%
$K^- \, ^3He \to \pi^0 \, ^3_\Lambda H \to$ $\pi^0 p n n_s \to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

27

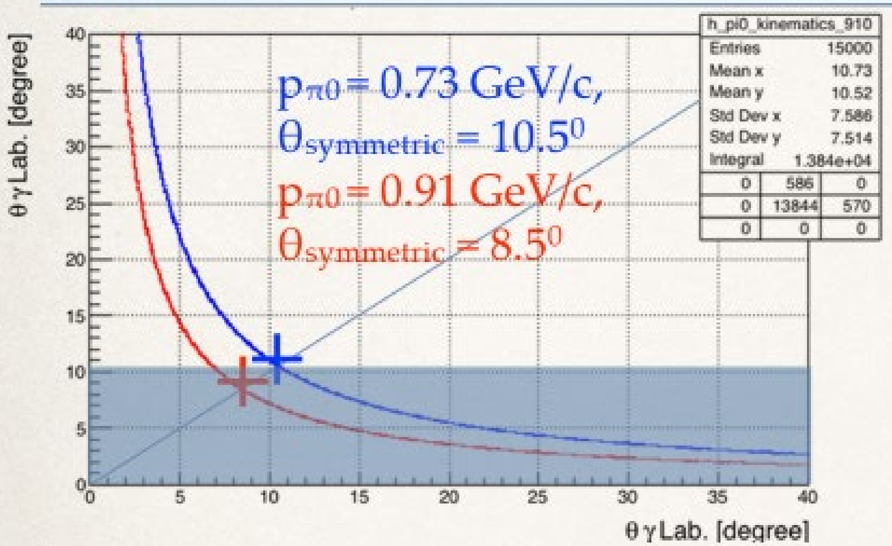
Tagging single γ-ray

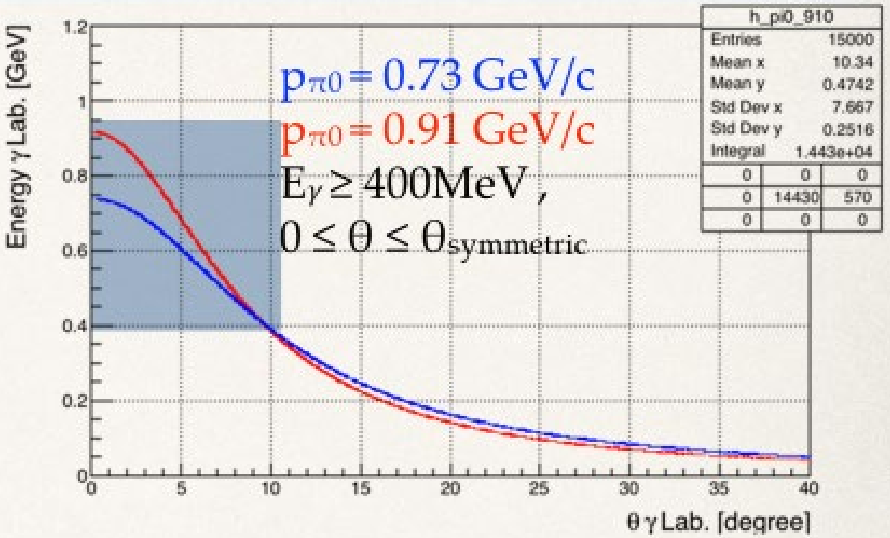
- Simulation: π^0 uniformly 0~1 GeV/c, 0~180 deg
  - Forward calorimeter energy select >0.6 GeV gamma

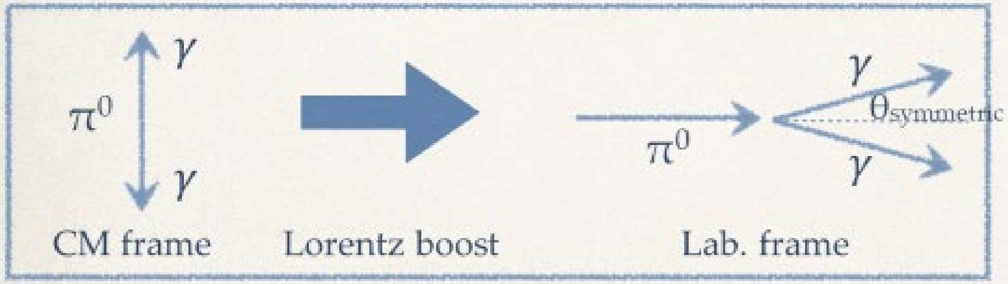


✓forward high-energy π^0 can be selected by detecting 1 gamma

Revisit π^0 decay kinematics





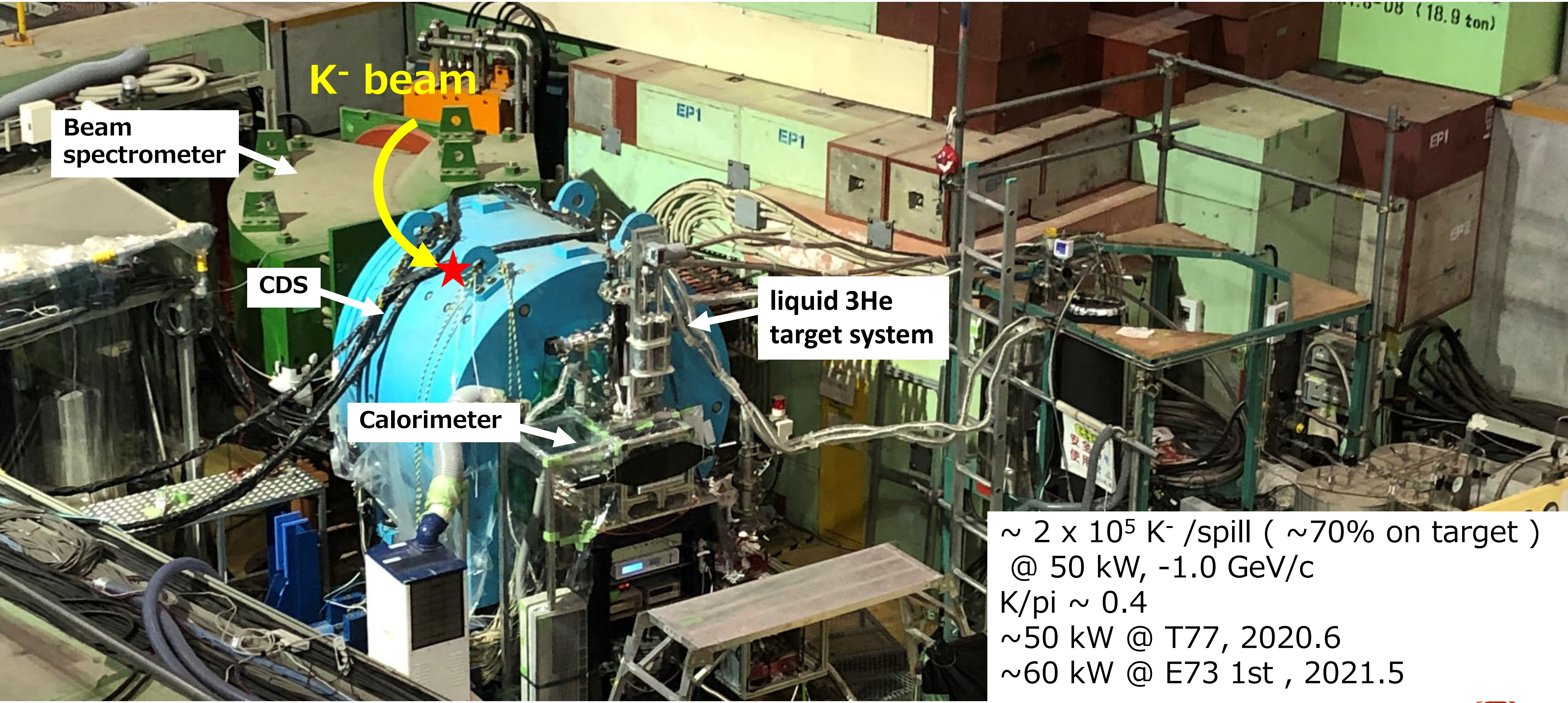


- 0.73~0.91GeV/c π^0 boosts γ forwardly;
- By covering 0~$\theta_{symmetric}$, tag the γ with higher energy ($E_\gamma \geq$ 400MeV)

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

CDS performance

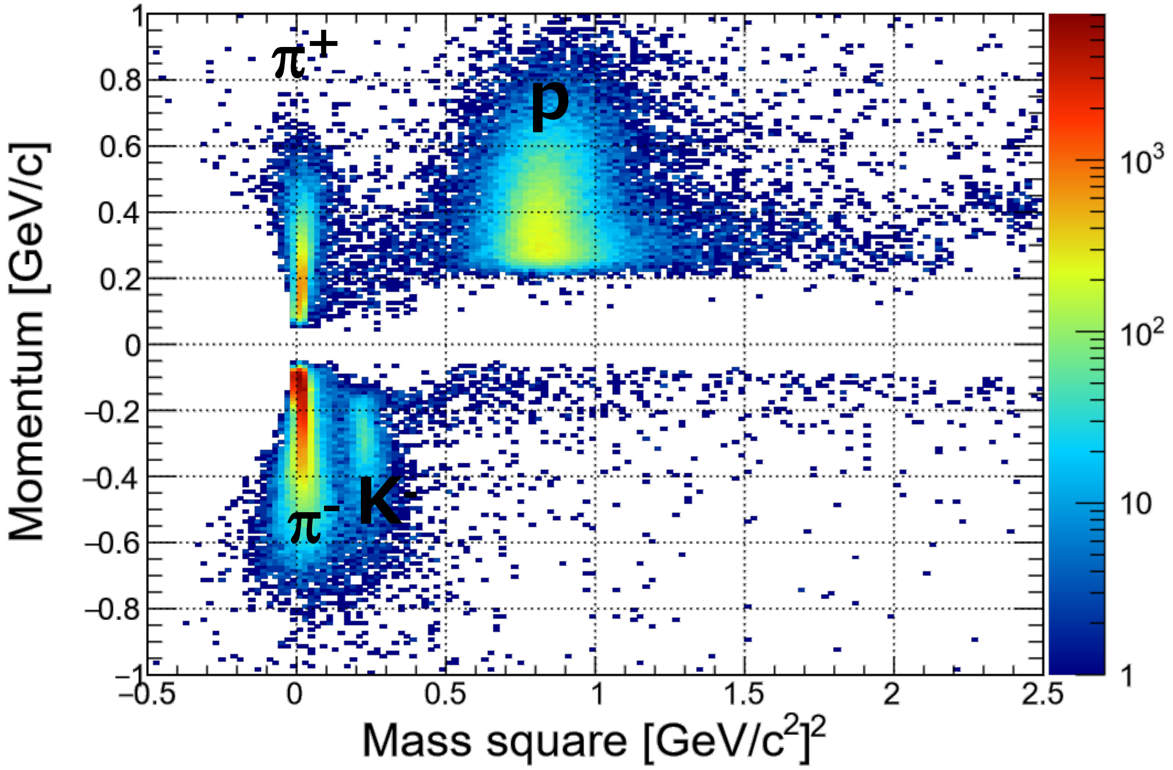
J-PARC K1.8BR Beamline



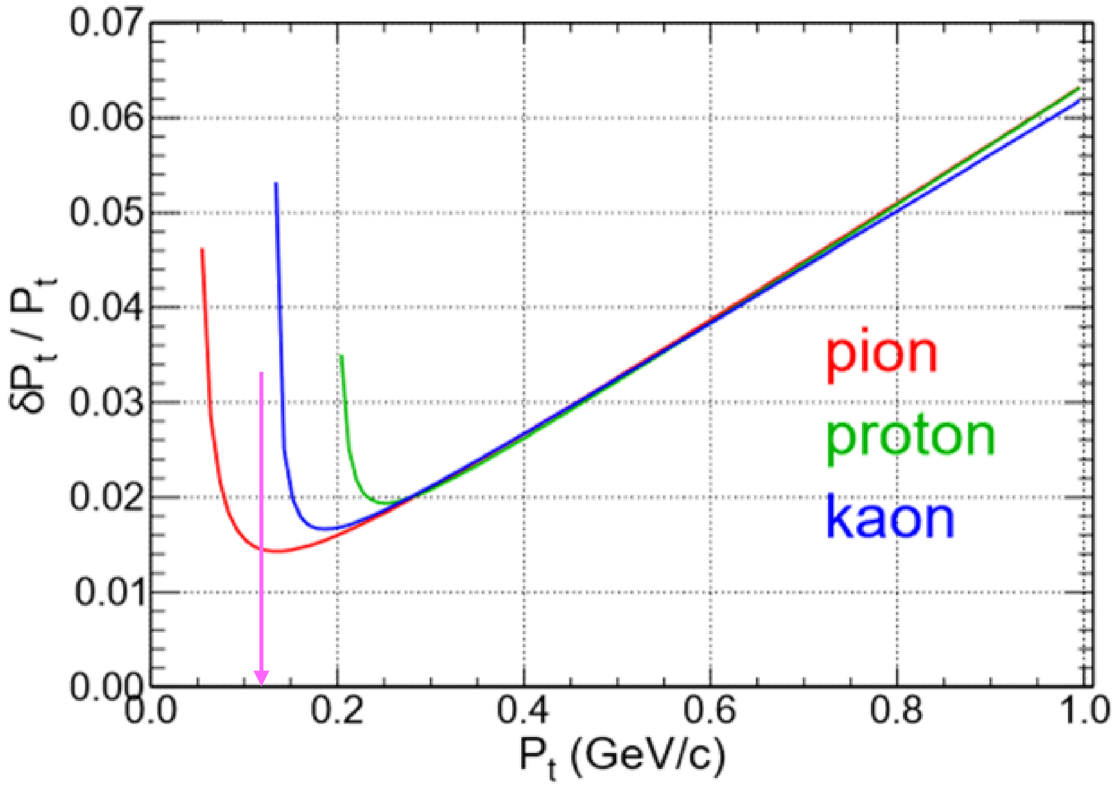
~ 2 x 10^5 K^- /spill (~70% on target)
@ 50 kW, -1.0 GeV/c
K/pi ~ 0.4
~50 kW @ T77, 2020.6
~60 kW @ E73 1st , 2021.5

CDS performance

Particle ID



Momentum resolution



✓Well working

PbF2 calorimeter

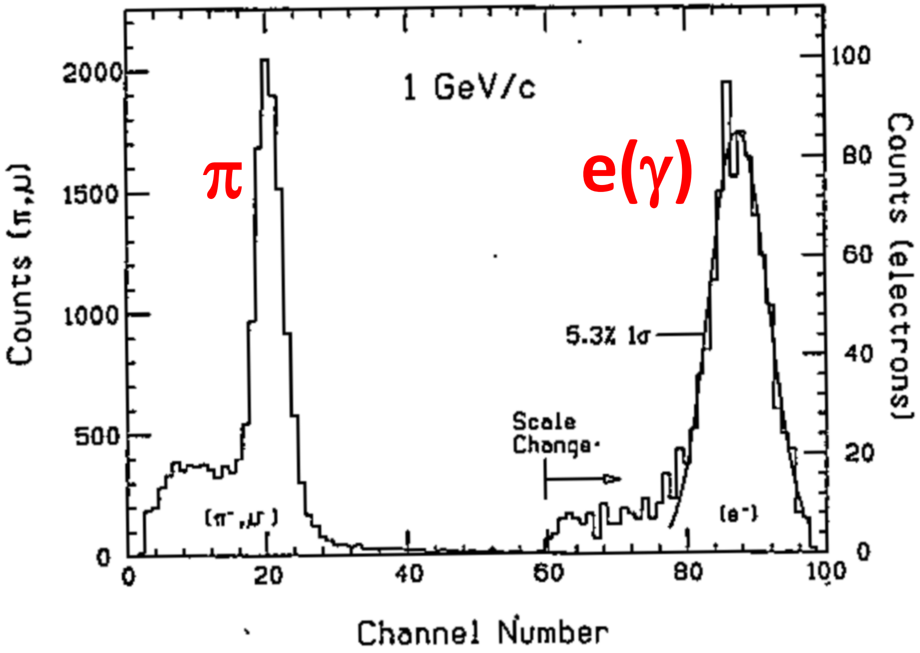
PbF_2 calorimeter

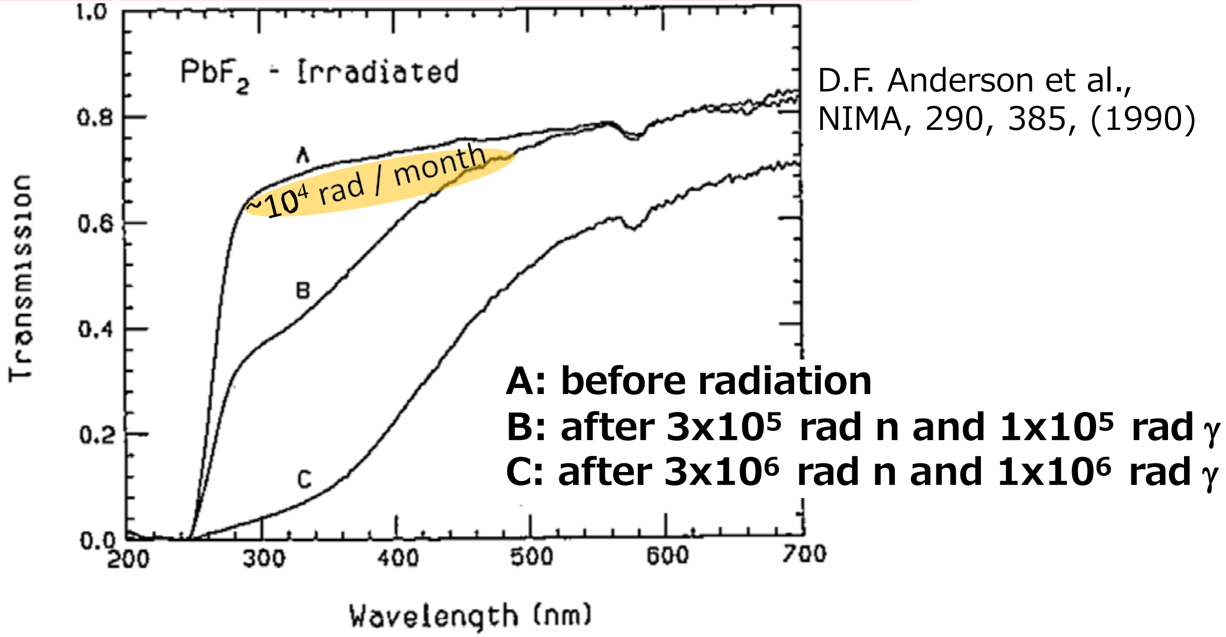
Experiment used PbF2: MAMI A4

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)

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

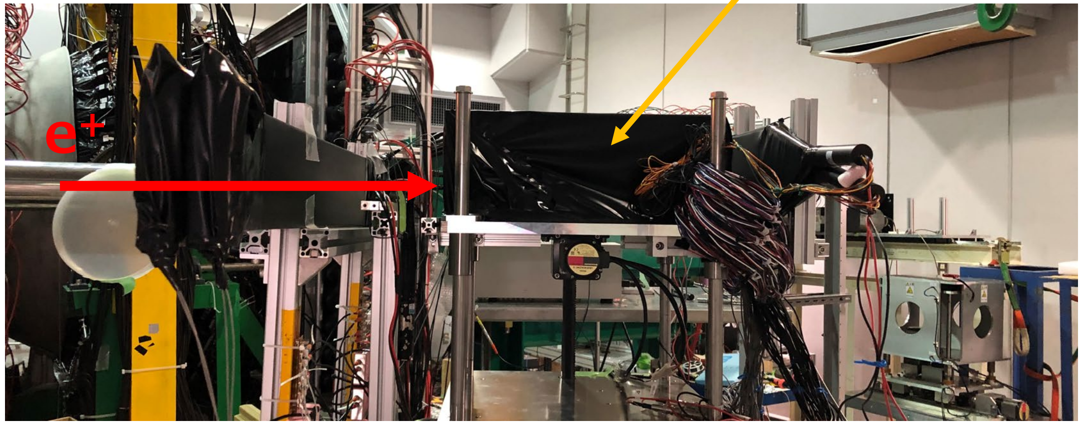
PbF_2 calorimeter operation

- Beam test – two pattern
  - 40 segments used

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

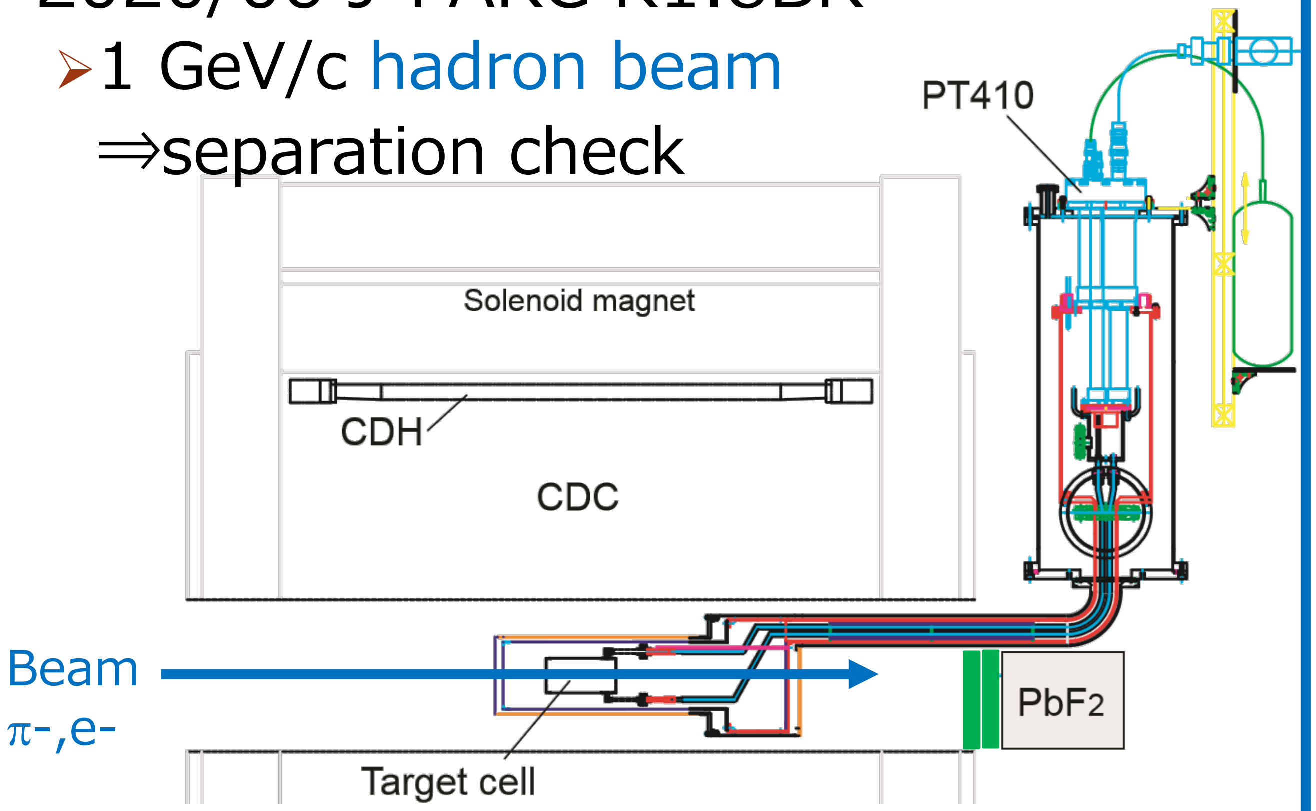
Experimental setup

PbF_2



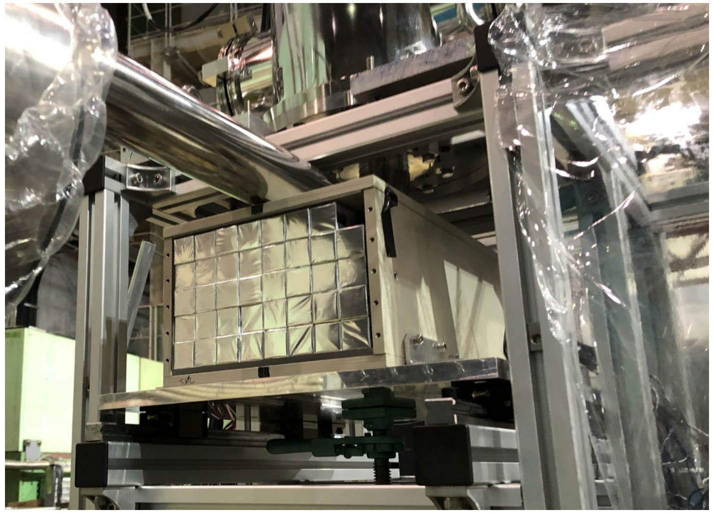
- 2020/06 J-PARC K1.8BR
  - 1 GeV/c hadron beam

  ⇒separation check



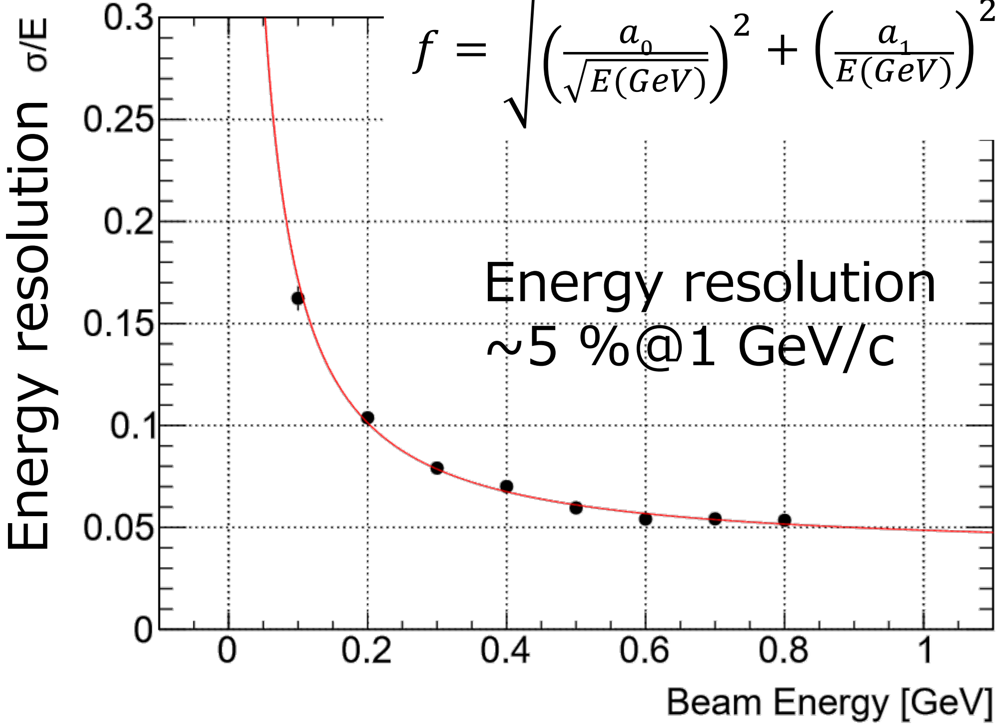
PbF_2 calorimeter performance

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

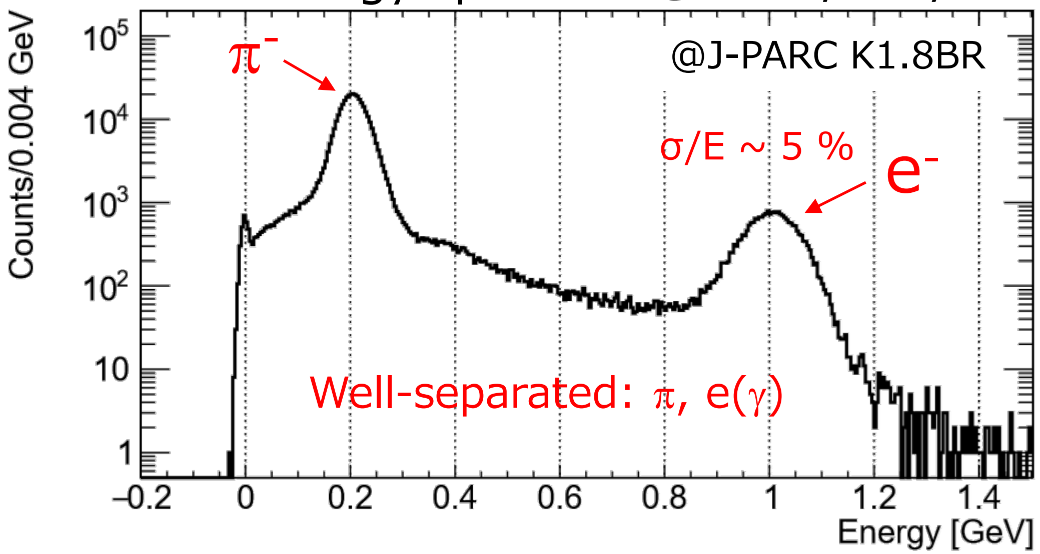


2019.12: Test experiment @ ELPH e^+ beam

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



Energy spectrum@1GeV/c π-/e-

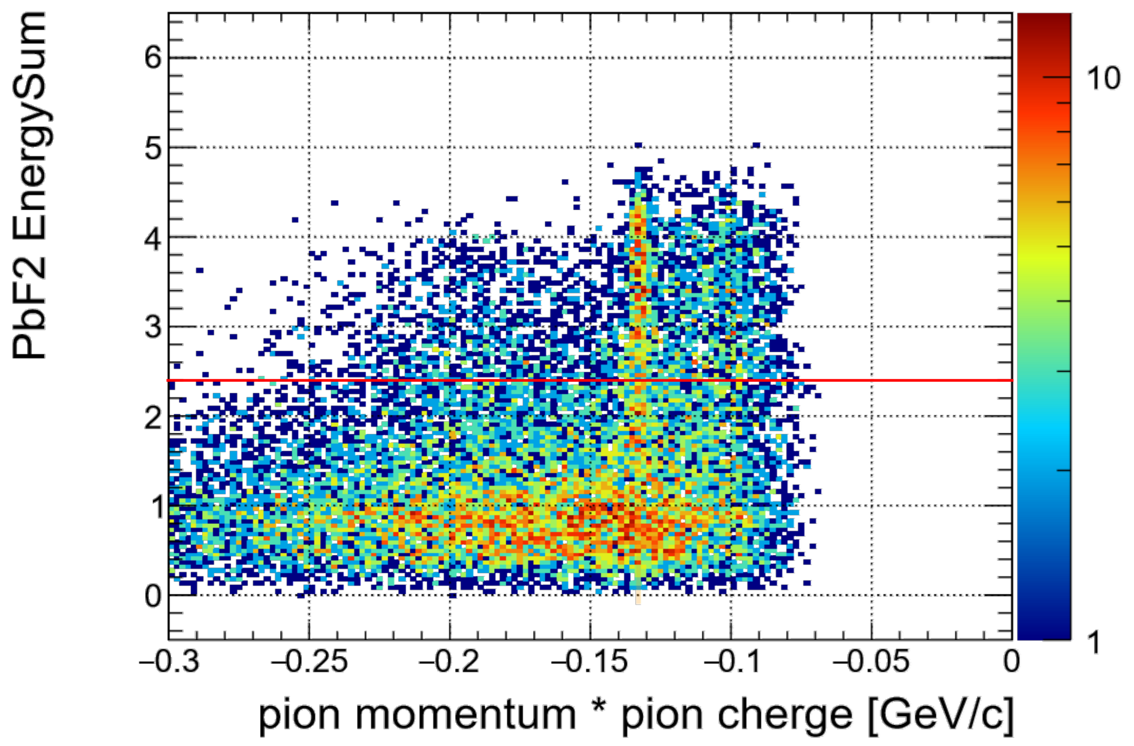


Good performance to distinguish $\pi^-/e^-,\gamma$

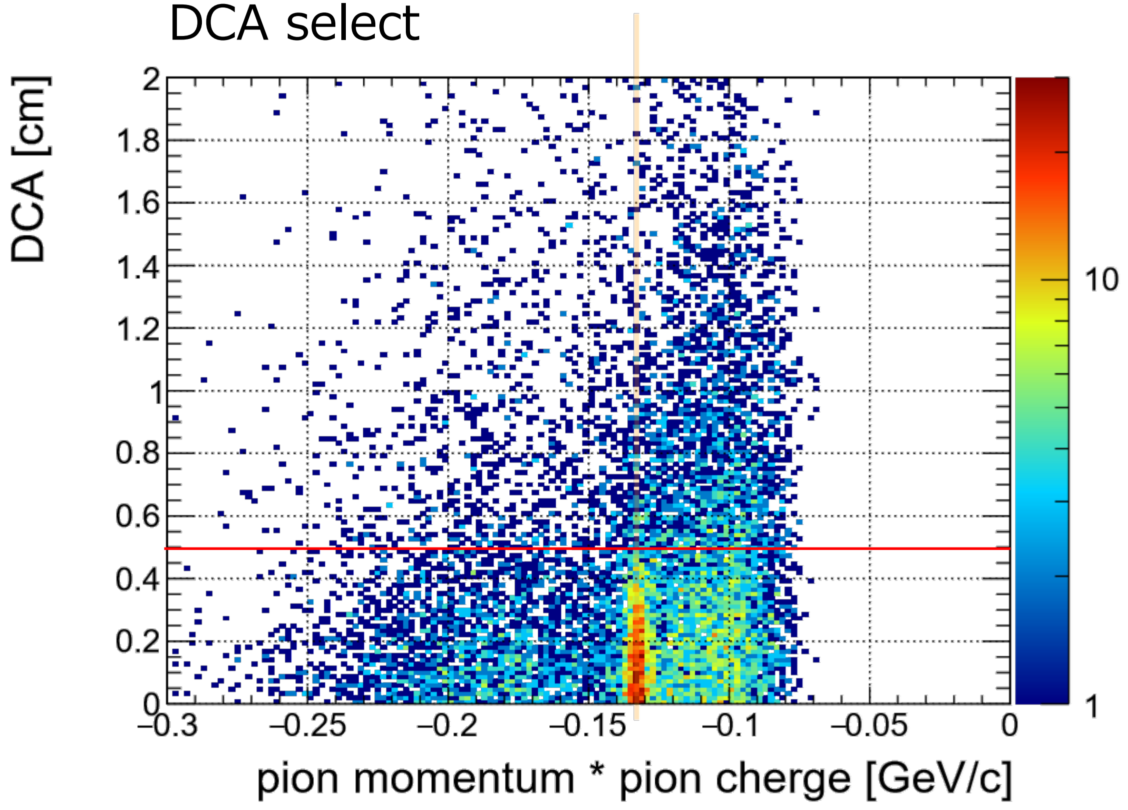
J-PARC T77 experiment
$^{4}_{\Lambda}H$ lifetime

Background subtraction

Calorimeter Energy select

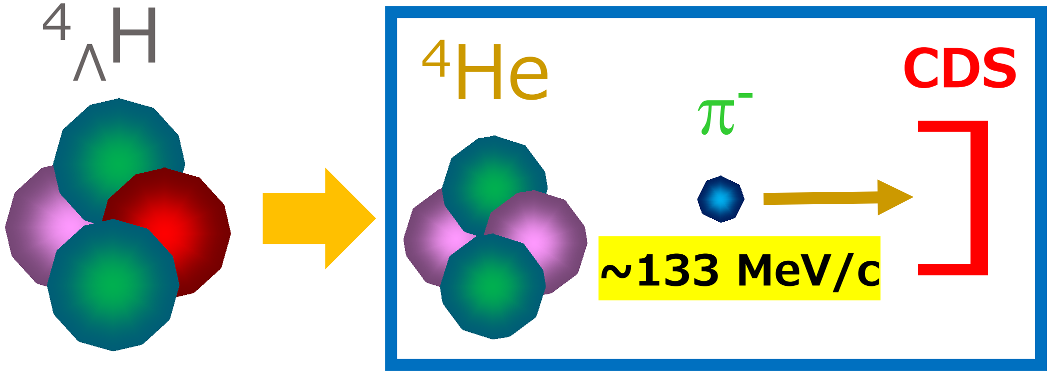


DCA select



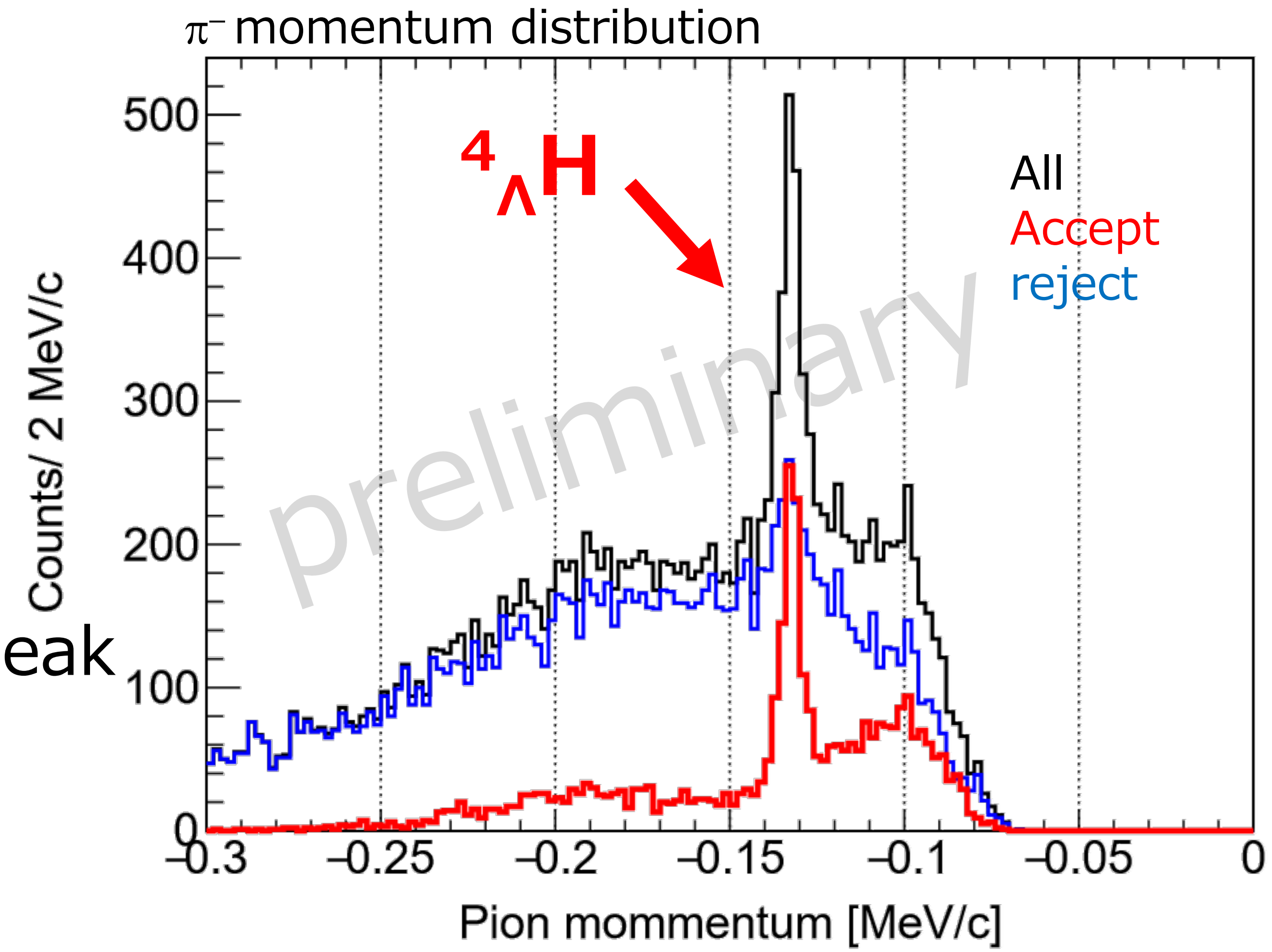
Feasibility study

- ^{4}He(K^{-}, π^{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

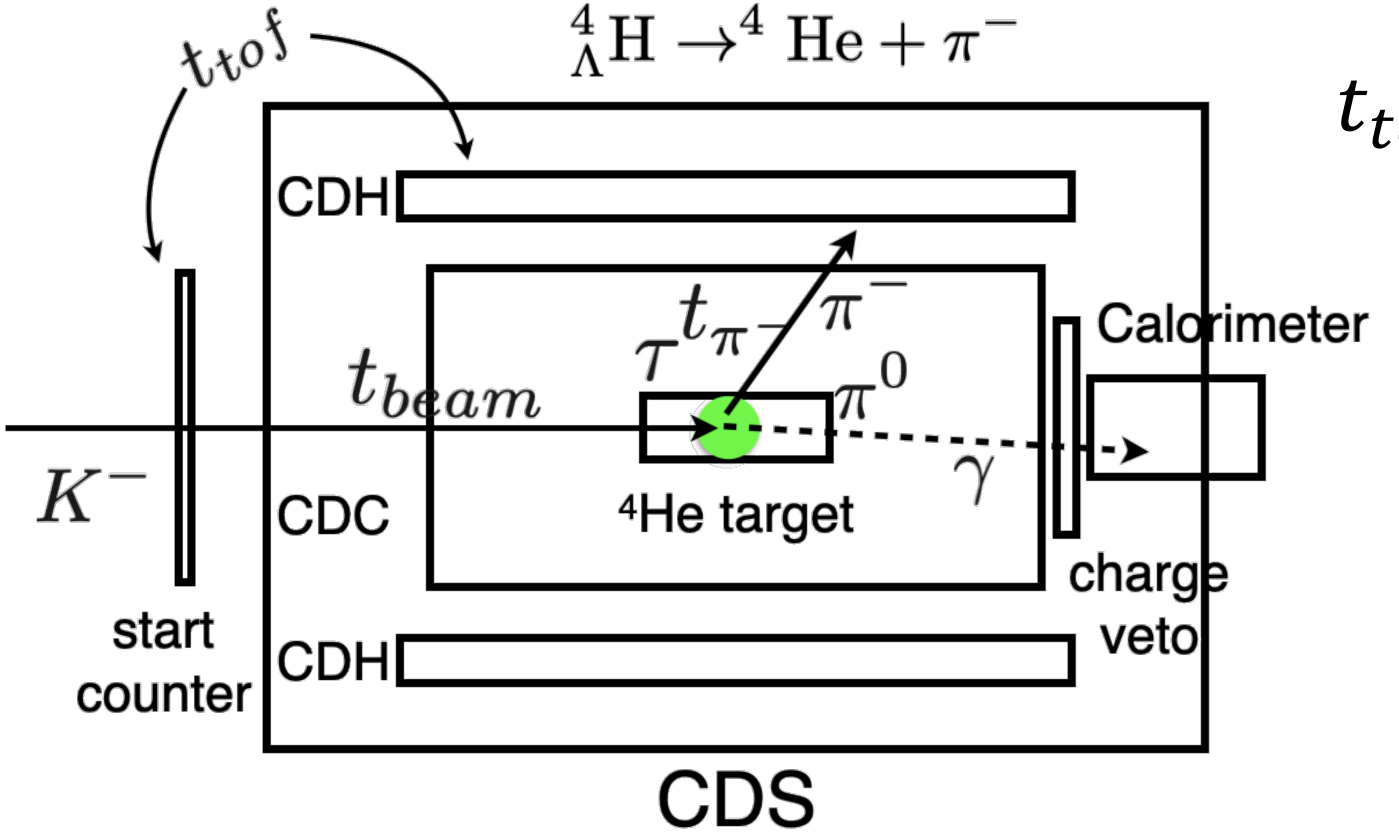


Derive lifetime

$$\mathrm{K}^- + {}^4\mathrm{He} \rightarrow {}^4_\Lambda\mathrm{H} + \pi^0$$

slows down inside ^{4}He target
and decays at rest

$${}^4_\Lambda\mathrm{H} \rightarrow {}^4\mathrm{He} + \pi^-$$

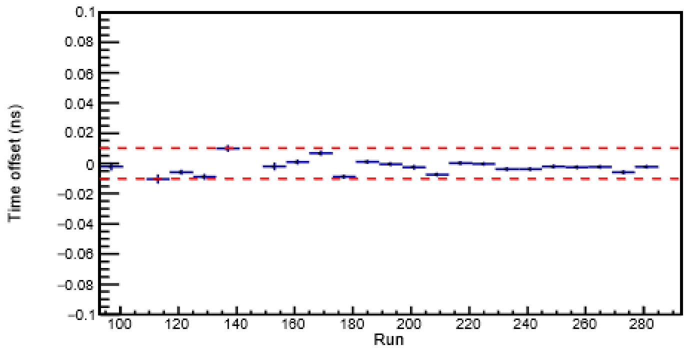


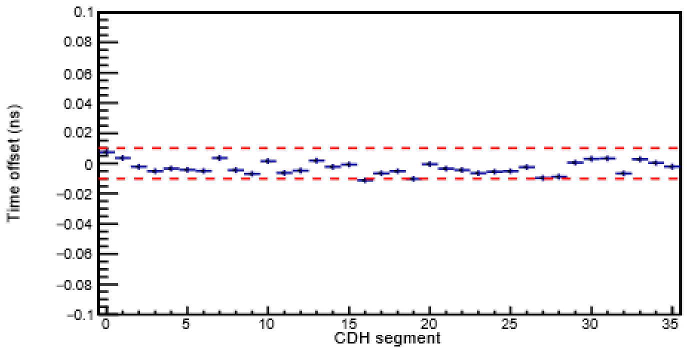
$$t_{tof} = t_{beam} + t_{\pi^-} + \tau$$

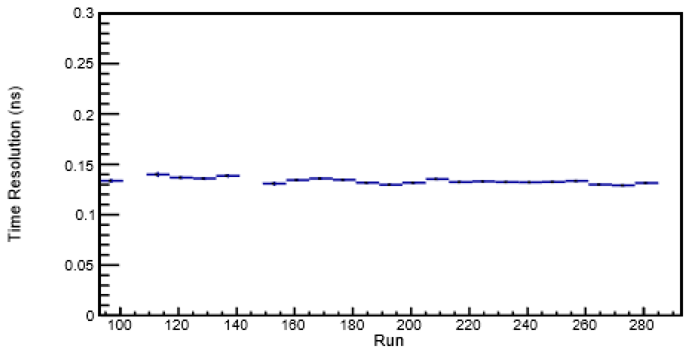
Hypertriton lifetime

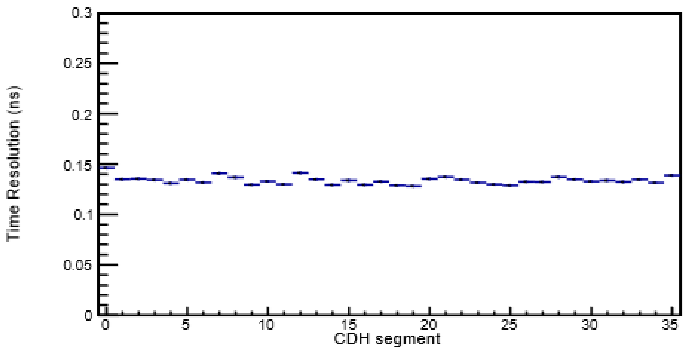
Analysis for timing

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

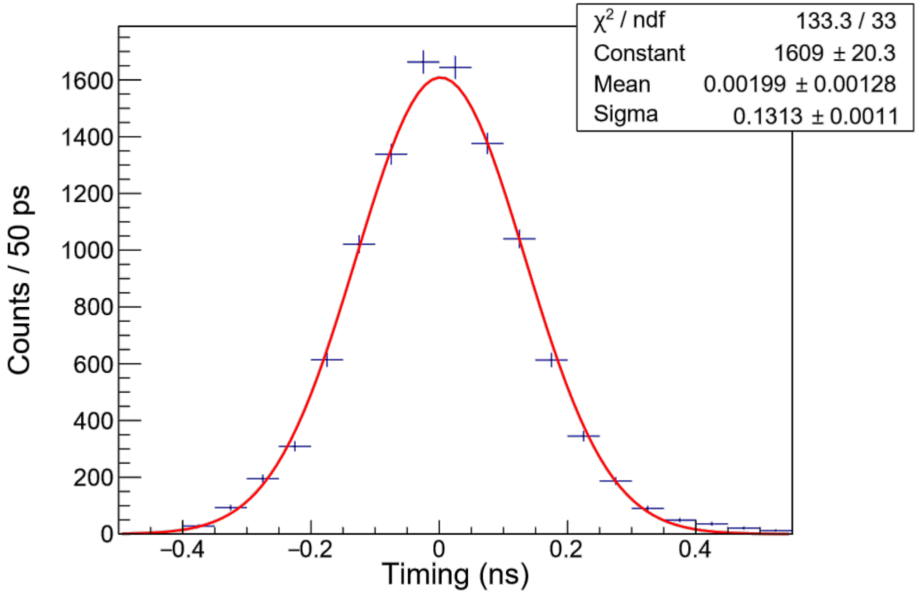






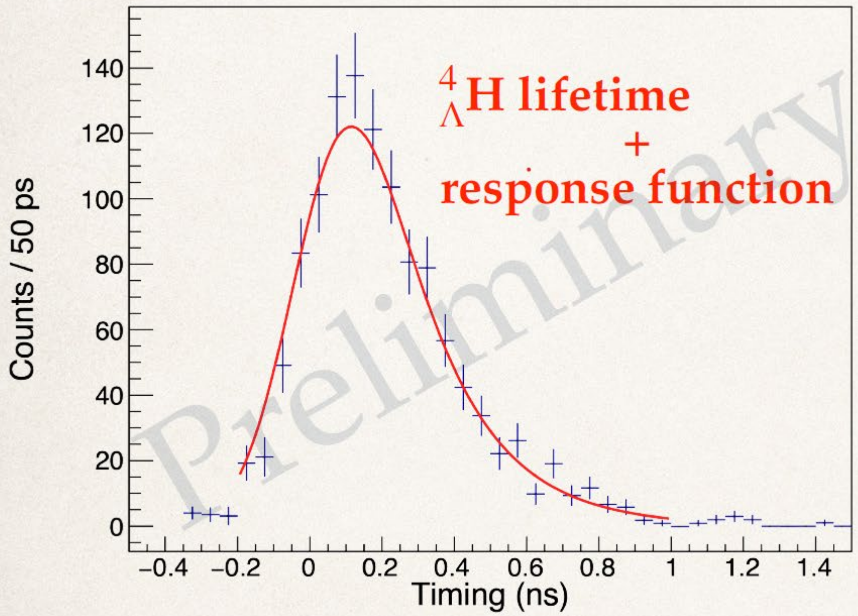


Time response function



${}^{4}_{\Lambda}$H lifetime analysis

$190 \pm 8(\text{stat.}) \pm 17(\text{sys.})$ ps



194^{+24}_{-26} ps @ KEK stop K-

H. Outa, et al., Nucl. Phys. A 547, (1992), 109c-114c

$218 \pm 6(\text{stat.}) \pm 13(\text{sys.})$ ps

@ STAR, Au-Au collision

arXiv:2110.09513

Contribution	Value
Uncertainty of time calibration	±10 ps
Intrinsic bias of T77(E73) approach	-5 ±5 ps
Uncertainty induced by background subtraction	±8 ps
Uncertainty induced by fitting range	±10 ps

will be finalized soon