K中間子ビームを用いたハイパートライトン寿命測定実験の現状
Current status of hypertriton lifetime measurement using K meson beam

Osaka Univ.
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For the J-PARC E73 collaboration

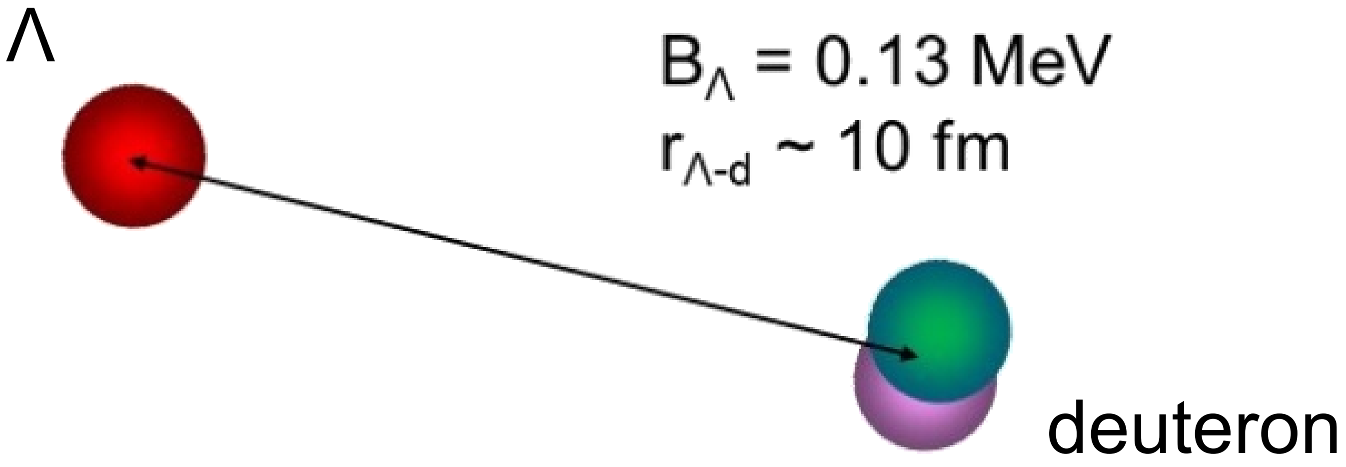
Outline

- Introduction
  - Hypertriton
  - Motivation of J-PARC E73 experiment
- J-PARC E73 experiment
  - Experimental principle
- Current status
  - ${}^{4}_{\Lambda}$H lifetime
  - Production cross section σ(${}^{3}_{\Lambda}$H), σ(${}^{4}_{\Lambda}$H)
  - Outlook for ${}^{3}_{\Lambda}$H lifetime measurement
- 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_Λ = 130 ± 50 keV

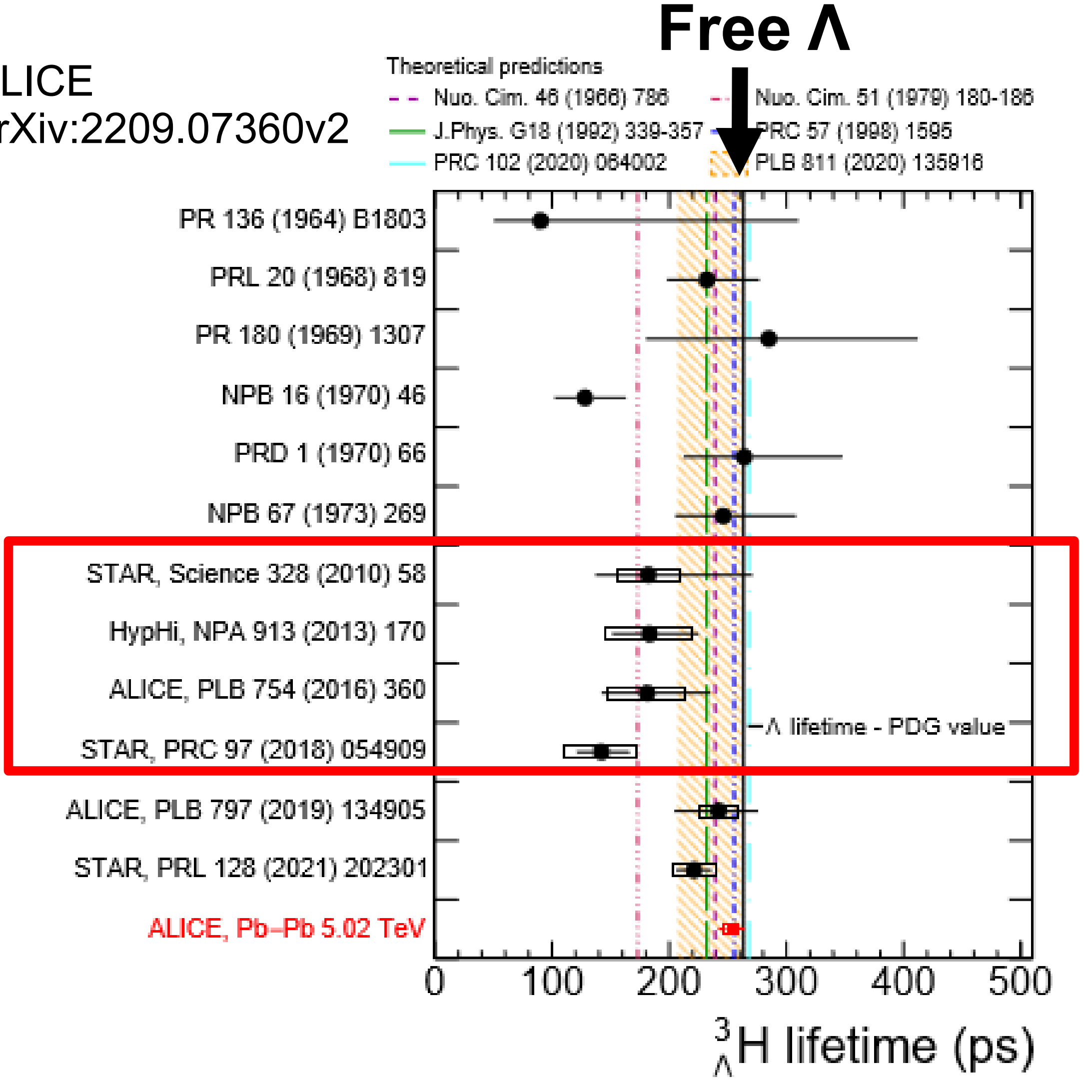


✓Small B_Λ → large separation between Λ & d

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

Hypertriton lifetime

ALICE
arXiv:2209.07360v2



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)

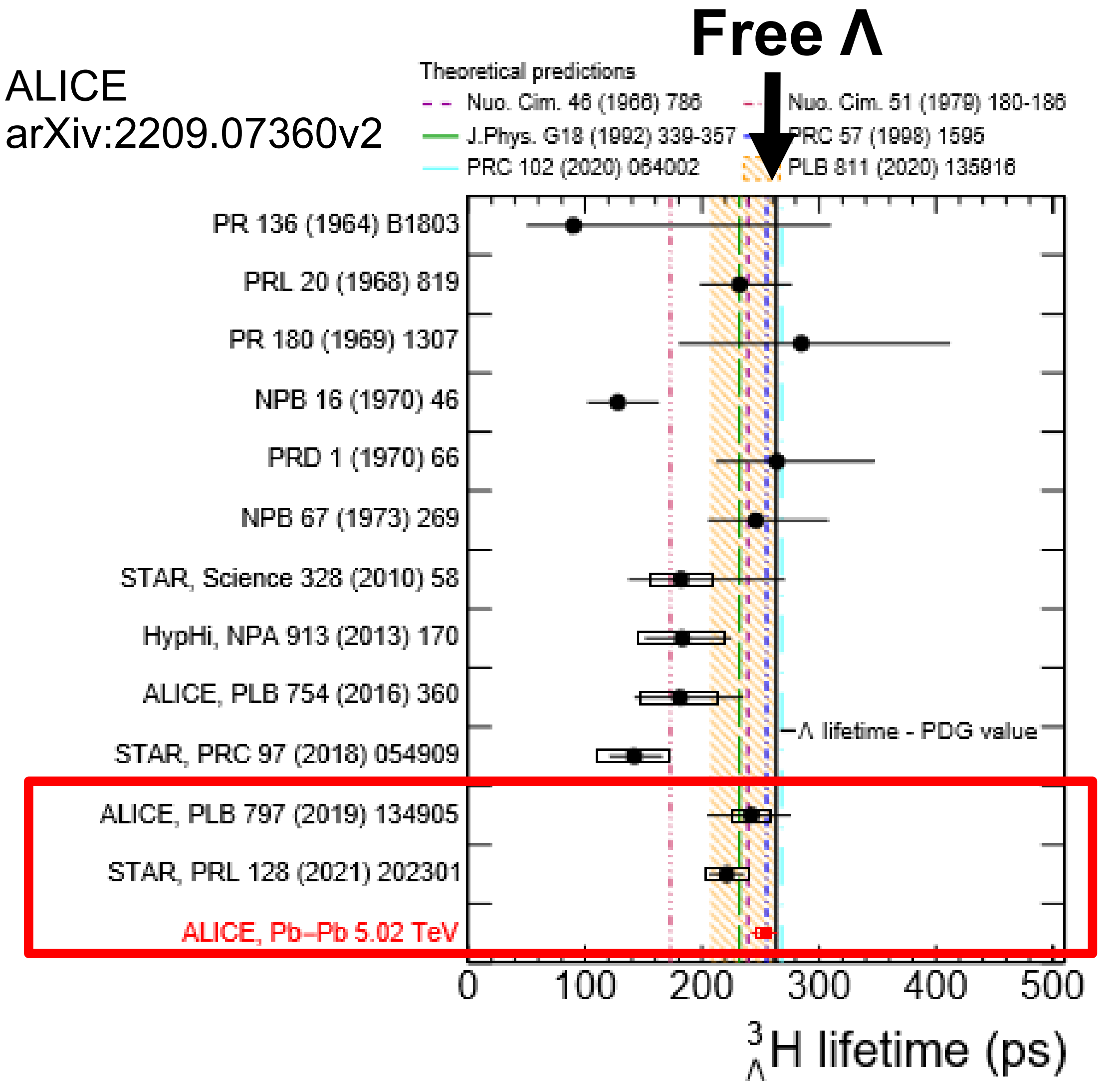
"Hypertriton Lifetime Puzzle"

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

Hypertriton lifetime

ALICE
arXiv:2209.07360v2

Free Λ



- ➢updated result was reported recently

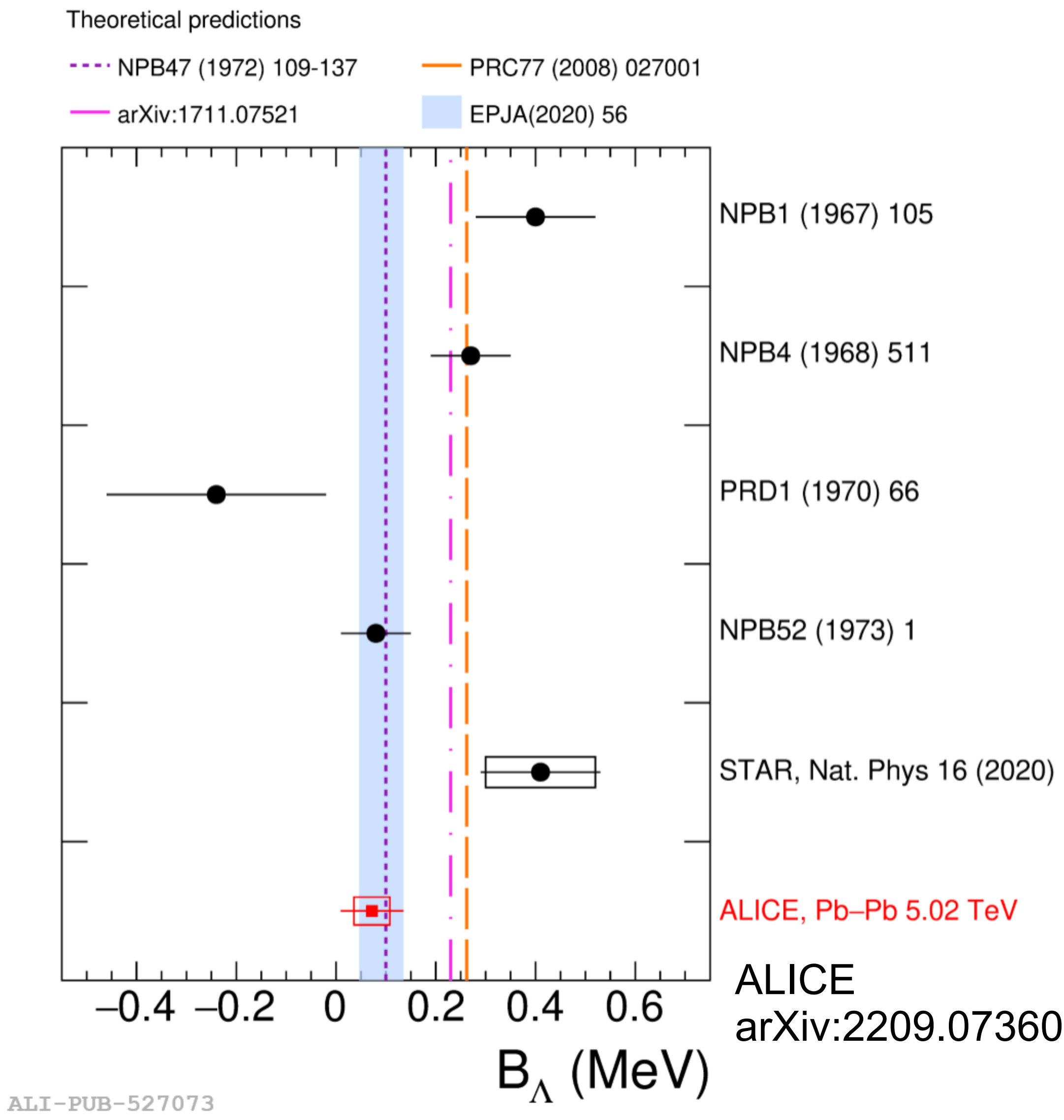
STAR
PRL 128, 202301 (2022)

Exp.	**Lifetime**
STAR(2021)	$221 \pm 15 \pm 19$ ps
ALICE(2022)	$253 \pm 11 \pm 6$ ps

ALICE
arXiv:2209.07360v2

Comparable with Free Λ

Hypertriton Binding energy



ALICE
arXiv:2209.07360v2

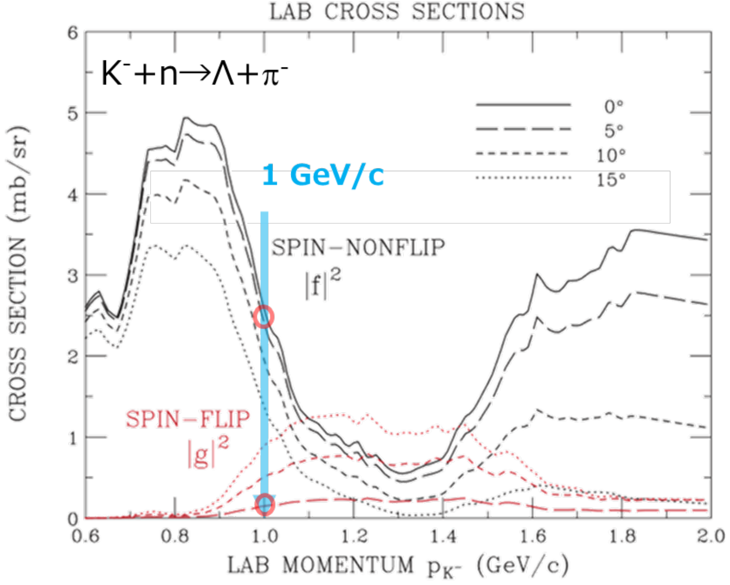
Exp.	Binding energy
Emulsion	0.13 ± 0.05 MeV
STAR(2020)	$0.41 \pm 0.12 \pm 0.11$ MeV
ALICE(2022)	$0.072 \pm 0.063 \pm 0.036$ MeV

The binding energy is still not determined

Need Lifetime and binding energy measurements by a different method
⇒Promoting direct measurement of $^{3}_{\Lambda}$H lifetime at J-PARC

Toward solving hypertriton lifetime puzzle

- J-PARC E73 experiment
  - ➢Hypernucleus production by (K^-, π^0) reaction
    - ✓Strangeness exchange reaction
      - ⇒Selective production of ground-state hypernucleus

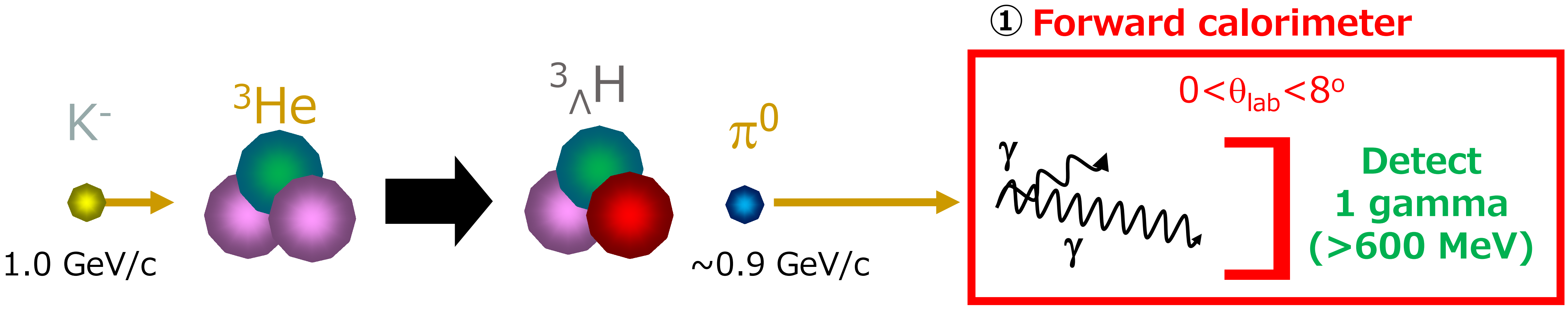


  - ➢$^3_\Lambda$H lifetime direct measurement
    - ✓Time domain
    - ✓Different systematic measurement from heavy-ion collision experiment

  - ➢Information of $^3_\Lambda$H binding energy by production cross section
    - ✓Cross section is sensitive to binding energy
    - ✓$\sigma(^3_\Lambda\mathrm{H})$ = 25.9 μb (E_Λ= 0.13 MeV), 41.0 μb (E_Λ= 0.41 MeV) by theoretical calculation
      - ⇒can be discussed by comparing R=σ(3ΛH)/σ(4ΛH)

J-PARC E73: Experimental principle

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



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

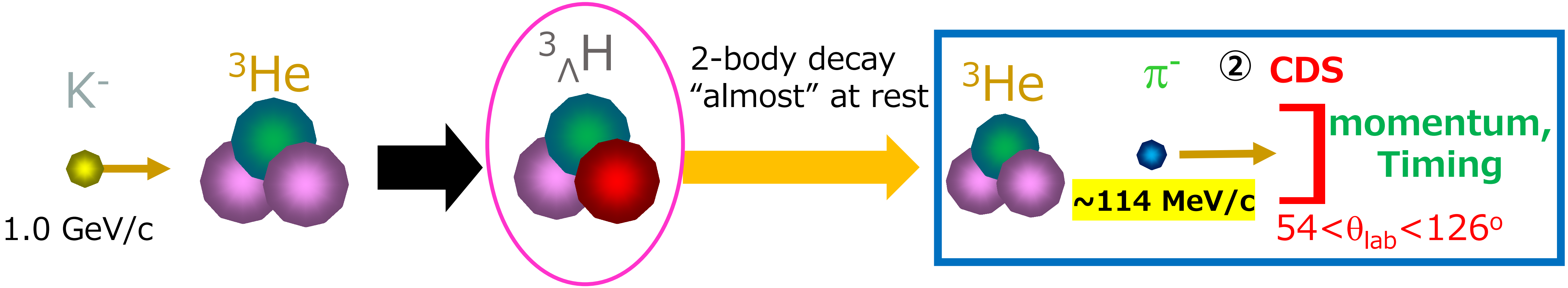
→almost 100% detection efficiency for forward going π^{0} $(0< \theta_{lab}^{\pi^{0}} <10)$

⇒tag Λ production with low recoil momentum

Reduce BG from Y decays and multi pion production

J-PARC E73: Experimental principle

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



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

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

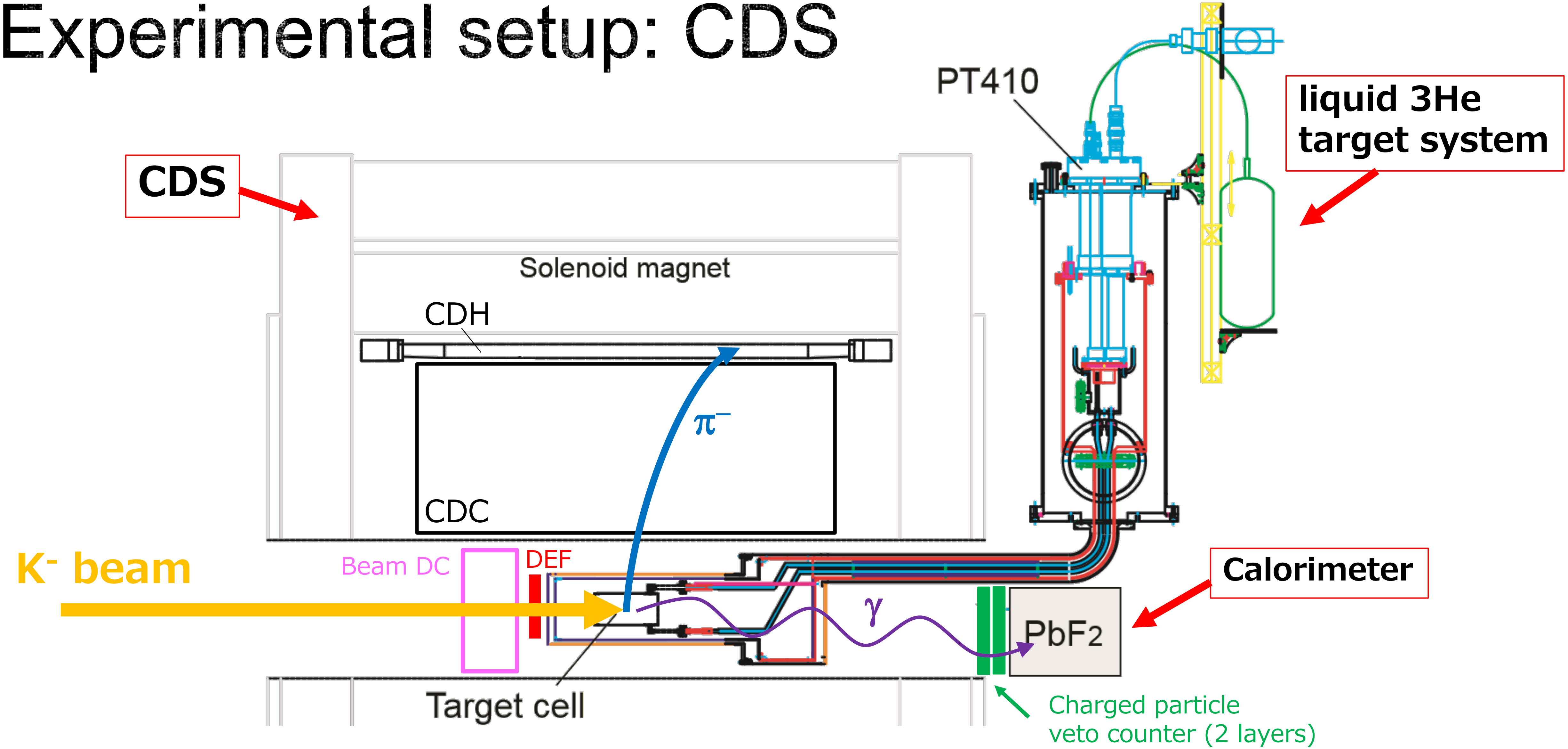
low recoil momentum (~100 MeV/c)

→Hypertriton stops immediately inside the target

⇒2-body decay “almost” at rest

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

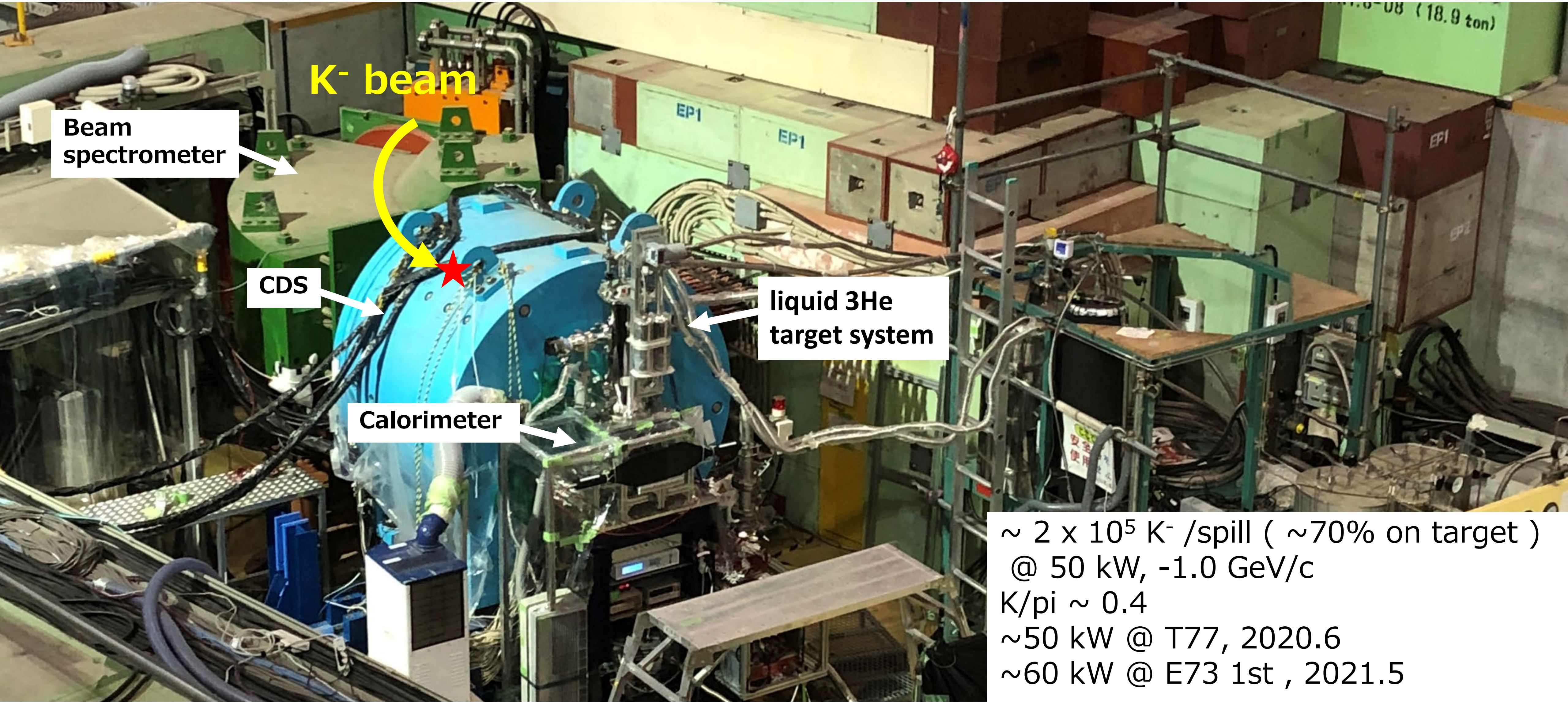
Experimental setup: CDS



CDS has worked well in K1.8BR Beamline

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

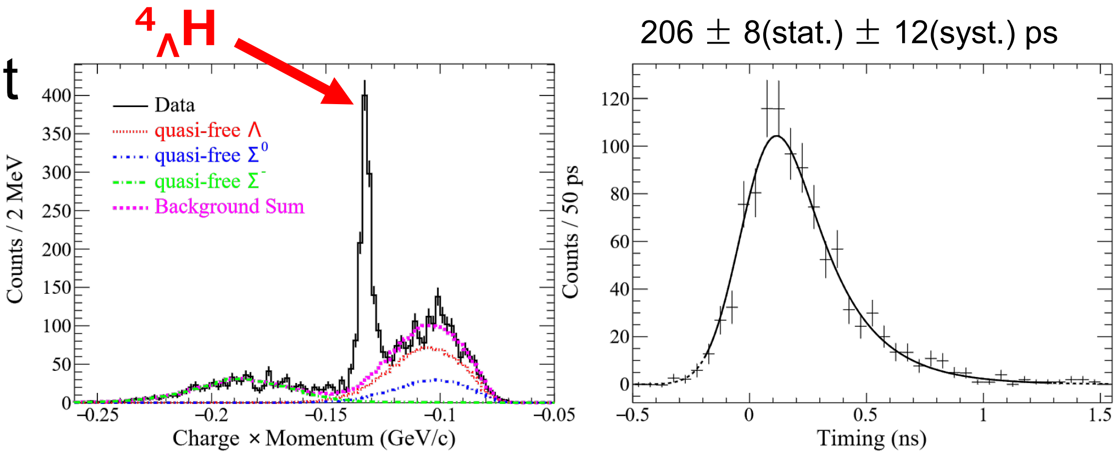
J-PARC K1.8BR Beamline



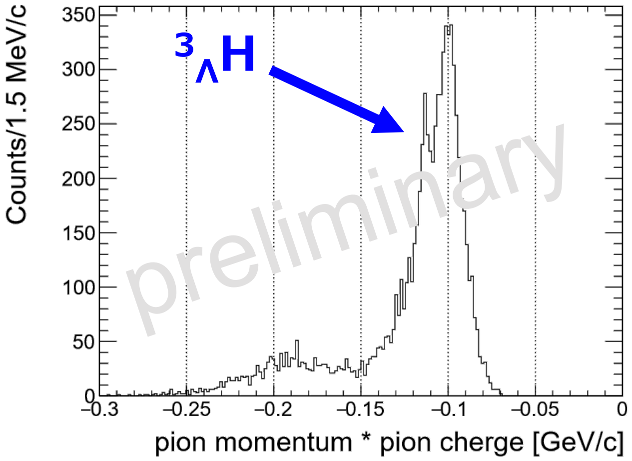
~ 2 x 10^5 K^- /spill (~70% on target)
@ 50 kW, -1.0 GeV/c
K/pi ~ 0.4
~50 kW @ T77, 2020.6
~60 kW @ E73 1st , 2021.5

Current status of J-PARC E73

- Phase-0
  - ➢Feasibility study of (K^-, π^0) reaction @^{4}He target
    - ✓Data taking in June 2020 (3 d)
    - ⇒ Establishment of the method, $^4_\Lambda$H lifetime
    - **now being submitted:**
      https://arxiv.org/abs/2302.07443



- Phase-1
  - ➢measurement of production cross section of $^3_\Lambda$H
    - ✓Data taking in May 2021(4.5 d)
    - ⇒**Confirmation and derivation of production cross section**

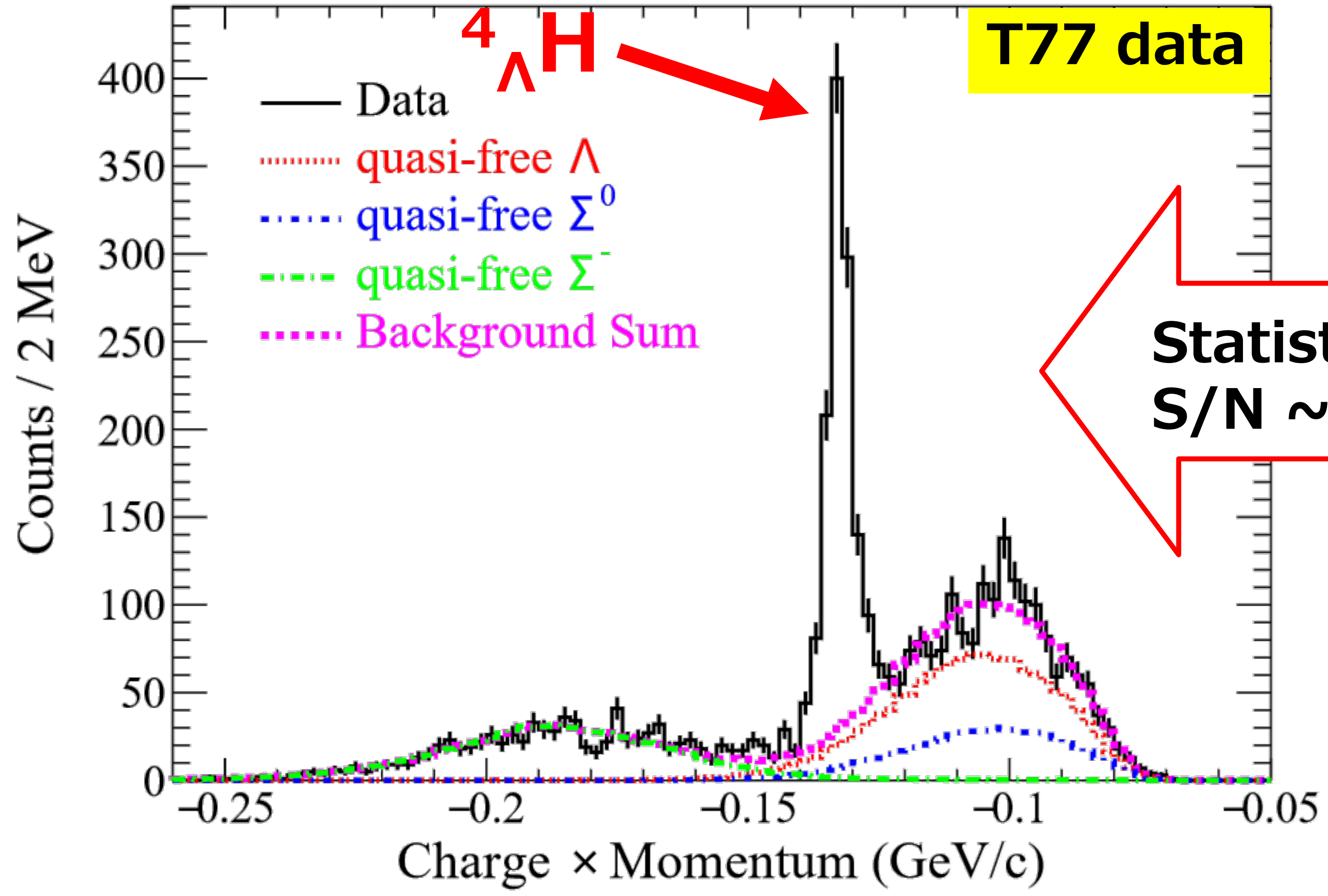


- Phase-2
  - ➢$^3_\Lambda$H lifetime measurement
    - ✓planned in JFY2023 (1 month)
    - ⇒**Upgrade to increase the solid angle of forward γ-ray**

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

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

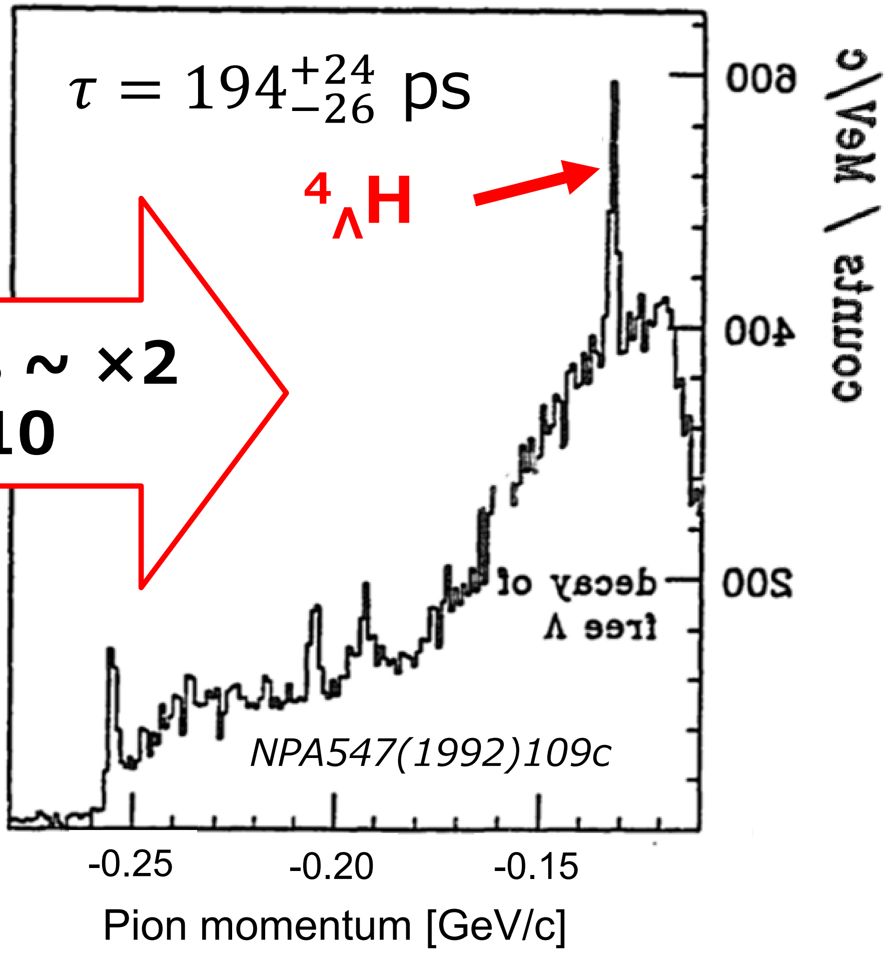
π^- momentum distribution



Statistics ~ ×2
S/N ~ ×10

KEK, 1992

^{4}He(stop K$^-$, π^-) delayed

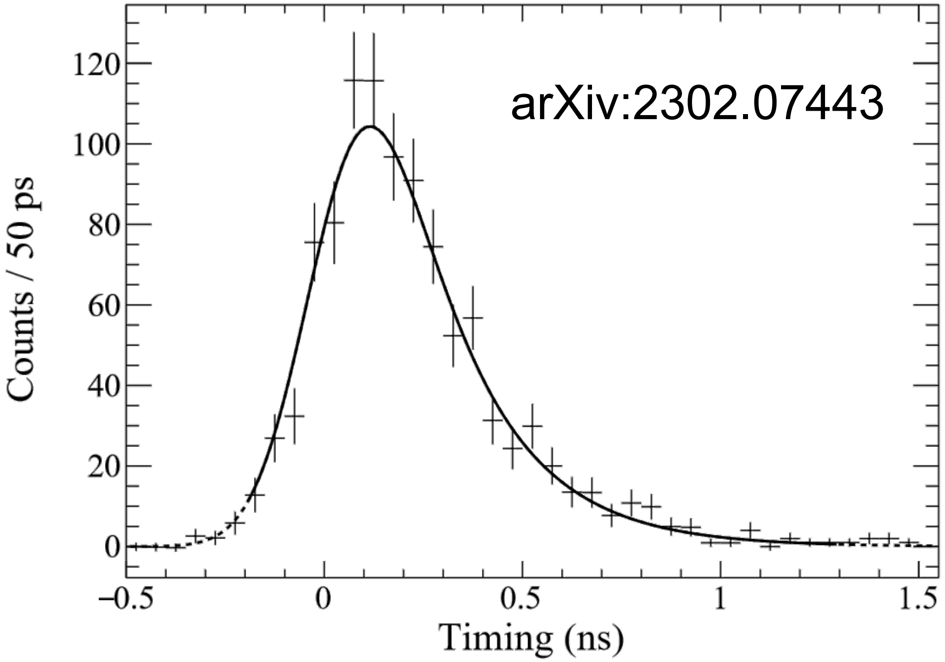


- **Successfully established new method of (K-, pi0) reaction**

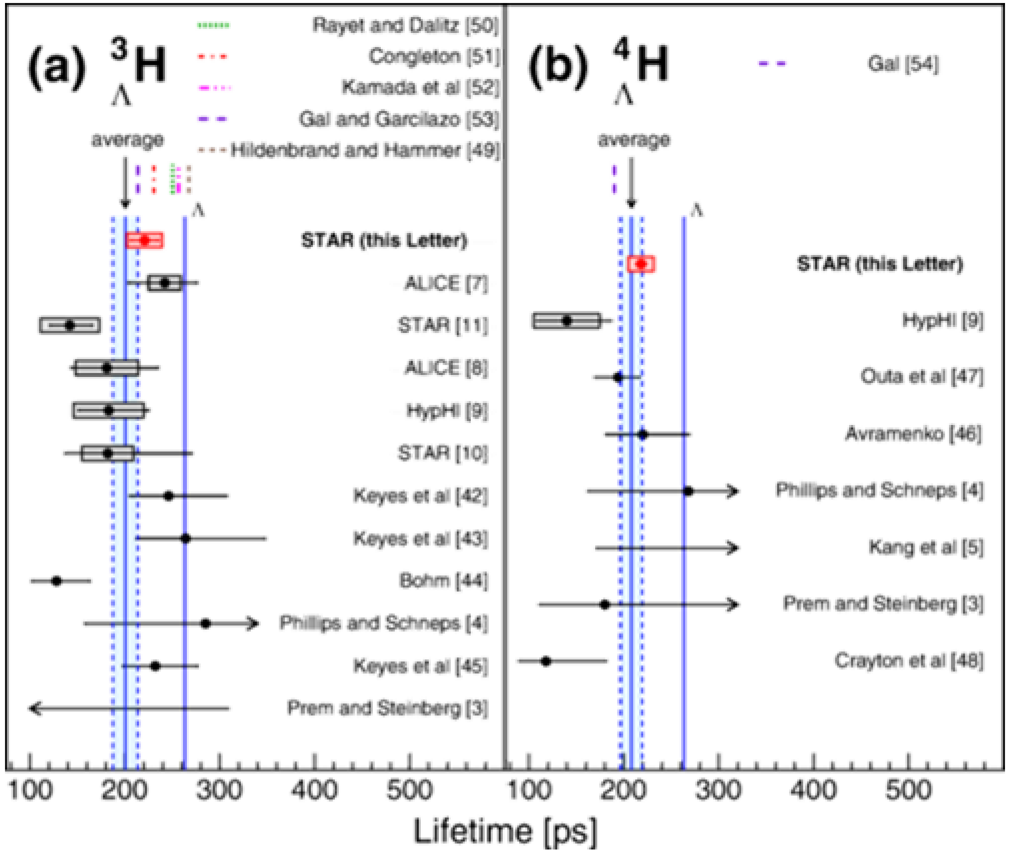
$^{4}_{\Lambda}$H lifetime

STAR
PRL 128, 202301 (2022)

206 ± 8(stat.) ± 12(syst.) ps


arXiv:2302.07443

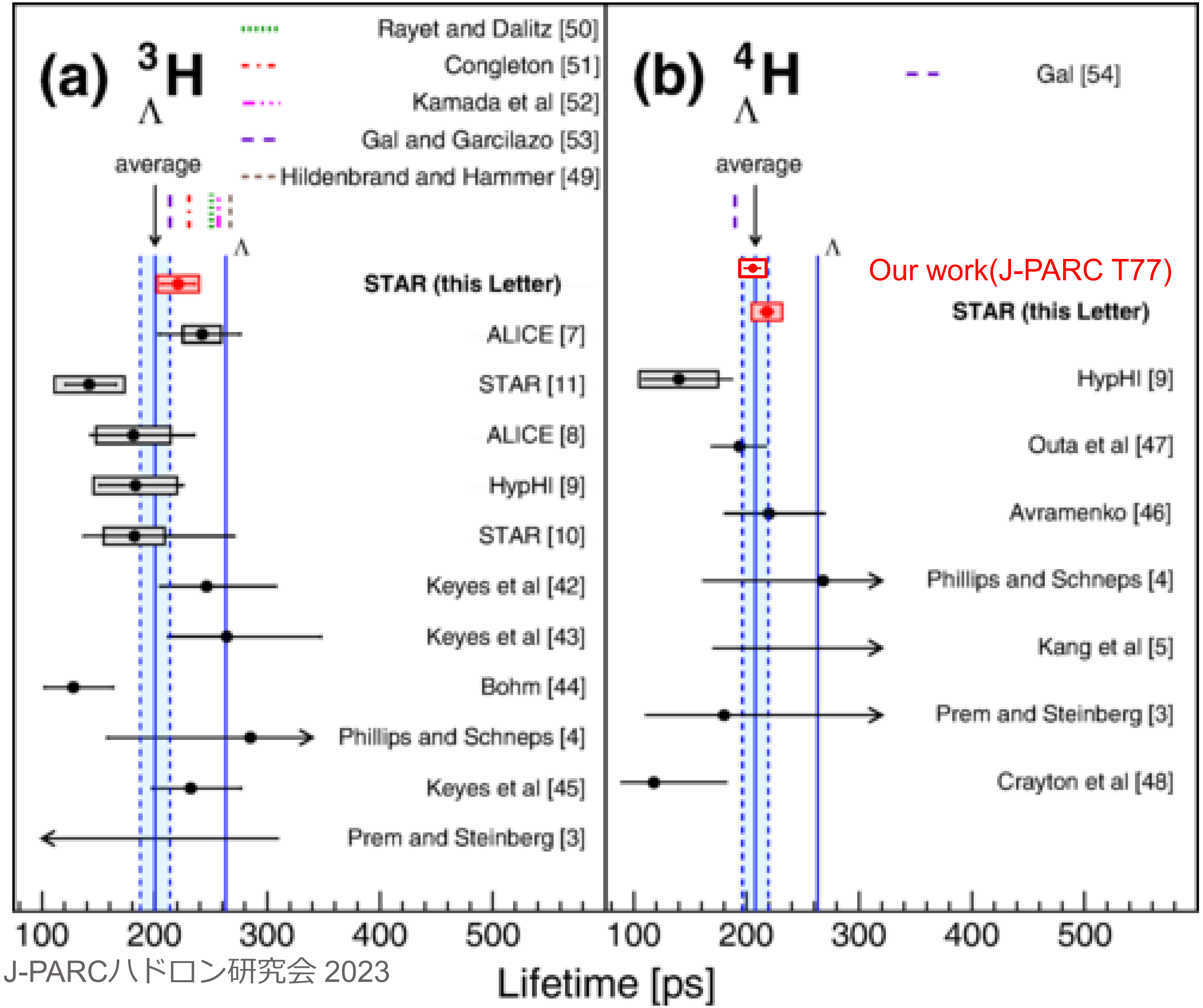
Contribution	Value
Intrinsic bias of J-PARC T77 approach	±2 ps
Uncertainty from γ selection	±4 ps
Uncertainty of time calibration	±7 ps
Uncertainty of background subtraction	±5 ps
Uncertainty in fitting process	±7 ps
Total (quadratic sum)	±12 ps



- 194$^{+24}_{-26}$ ps @KEK stop K-
  - H. Outa, et al., Nucl. Phys. A 547, (1992), 109c-114c
- 218 ± 6(stat.) ± 13(syst.) ps @STAR, Au-Au collision
  - PRL 128, 202301 (2022)

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

STAR
PRL 128, 202301 (2022)



- 206 ± 8(stat.) ± 12(syst.) ps @J-PARC T77
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- 194^{+24}_{-26} ps @KEK stop K-
  - H. Outa, et al., Nucl. Phys. A 547, (1992), 109c-114c

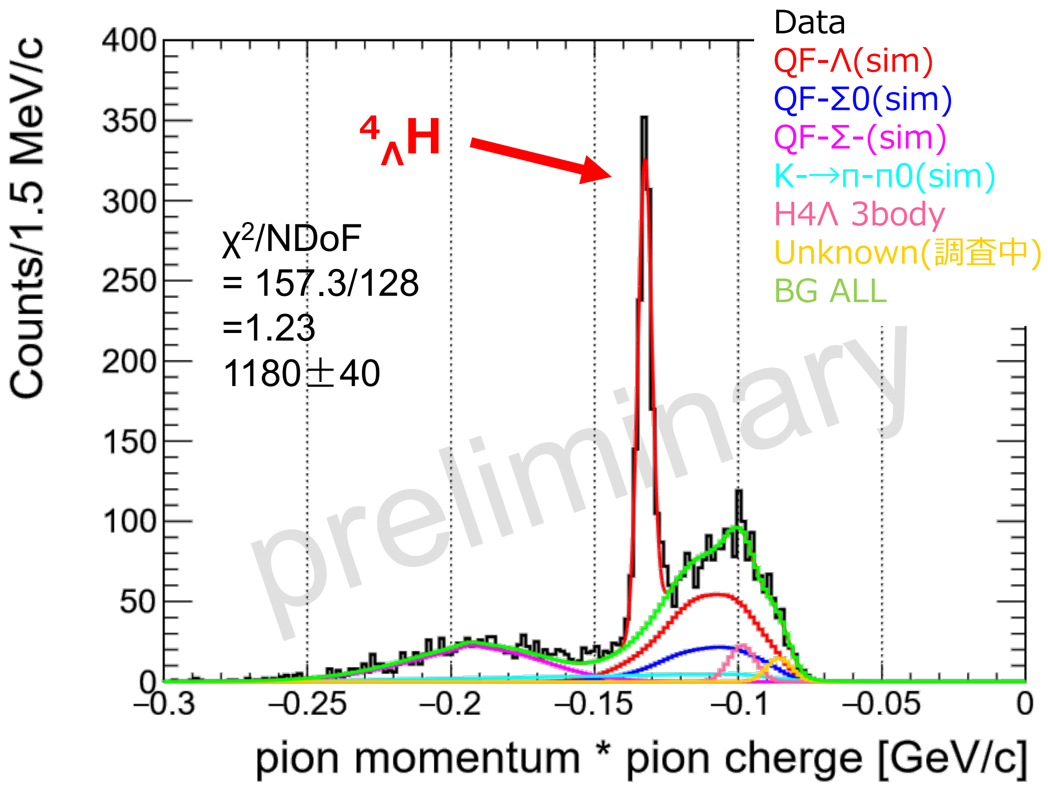
⇒Comparable precision with the latest STAR data

Production cross section of ${}^{4}_{\Lambda}H$ and ${}^{3}_{\Lambda}H$

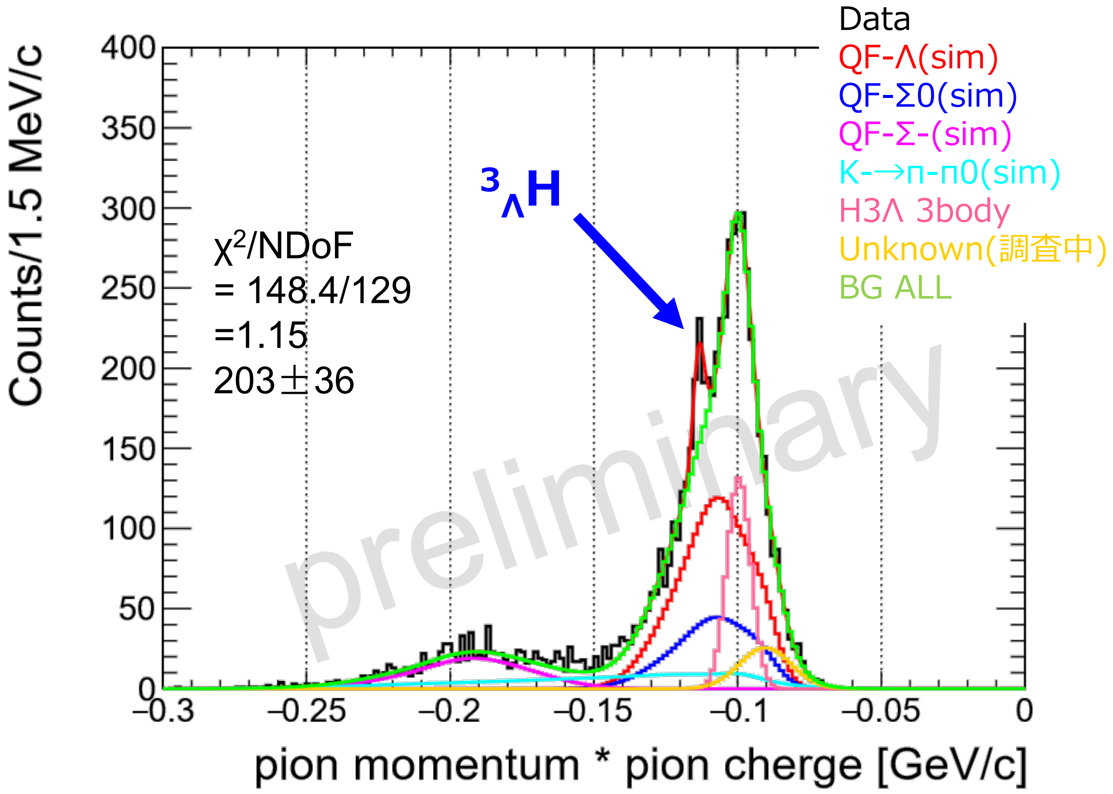
Background estimation

- Reproduction by Geant4 simulation
  - ✓Momentum distribution

Production(^{4}He target)



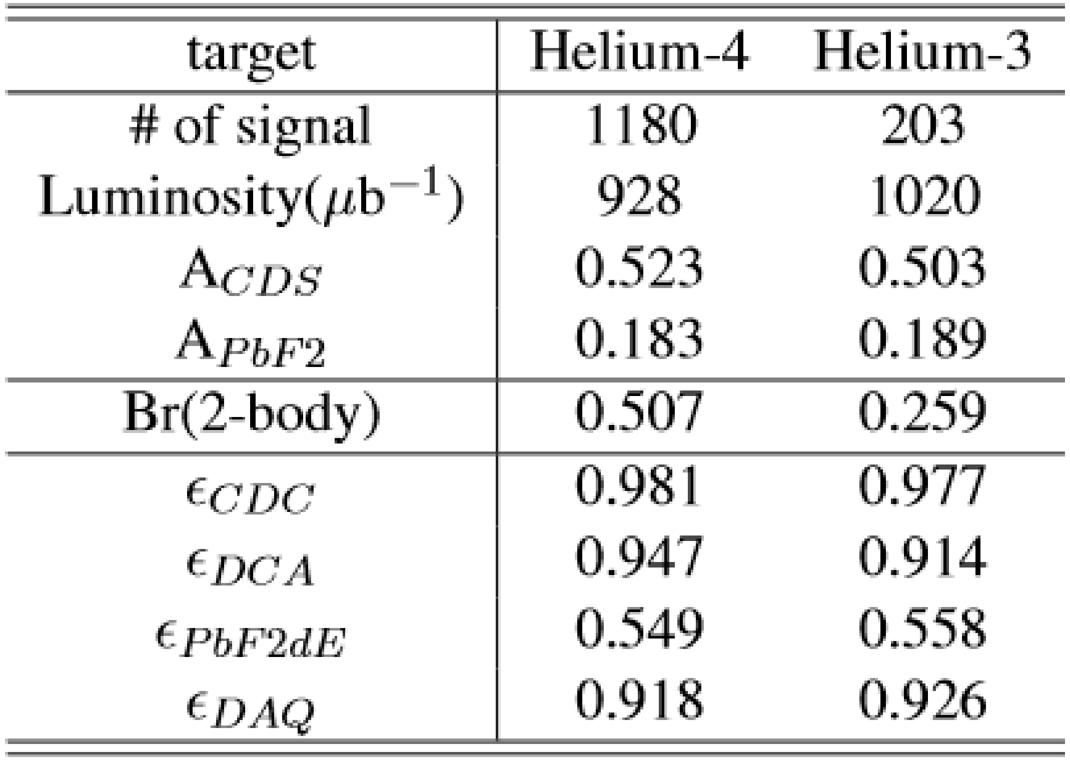
Production(^{3}He target)



  - ✓Observation of 3ΛH 2-body decay peak
  - ✓Discussion of 2-body/3-body ratio

Integrated production cross section

- $$\sigma = \frac{N_{signal}}{Luminosity \times \mathrm{A}_{\mathrm{CDS}} \times \mathrm{A}_{PbF2} \times Br \times \epsilon}$$



target	Helium-4	Helium-3
# of signal	1180	203
Luminosity(μb^{-1})	928	1020
A_{CDS}	0.523	0.503
A_{PbF2}	0.183	0.189
Br(2-body)	0.507	0.259
ϵ_{CDC}	0.981	0.977
ϵ_{DCA}	0.947	0.914
ϵ_{PbF2dE}	0.549	0.558
ϵ_{DAQ}	0.918	0.926

- A_{PbF2}: π^0 acceptance by PbF2

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

- A_{CDS}: π^- acceptance by CDS

- Br: Calculate Branching ratio to 2-body

  Ref: Suplemento de la Revista Mexicana de
  Fısica30308069 (2022) 1–6

π^0 acceptance by PbF2

- Estimate by geant4 simulation

  Input: Angular distribution $\theta^{lab}_{0°\text{-}20°}$ of the reaction

  is assumed by theoretical calculation

  by Prof. Harada (Osaka EC Univ.)

T. Harada and Y. Hirabayashi
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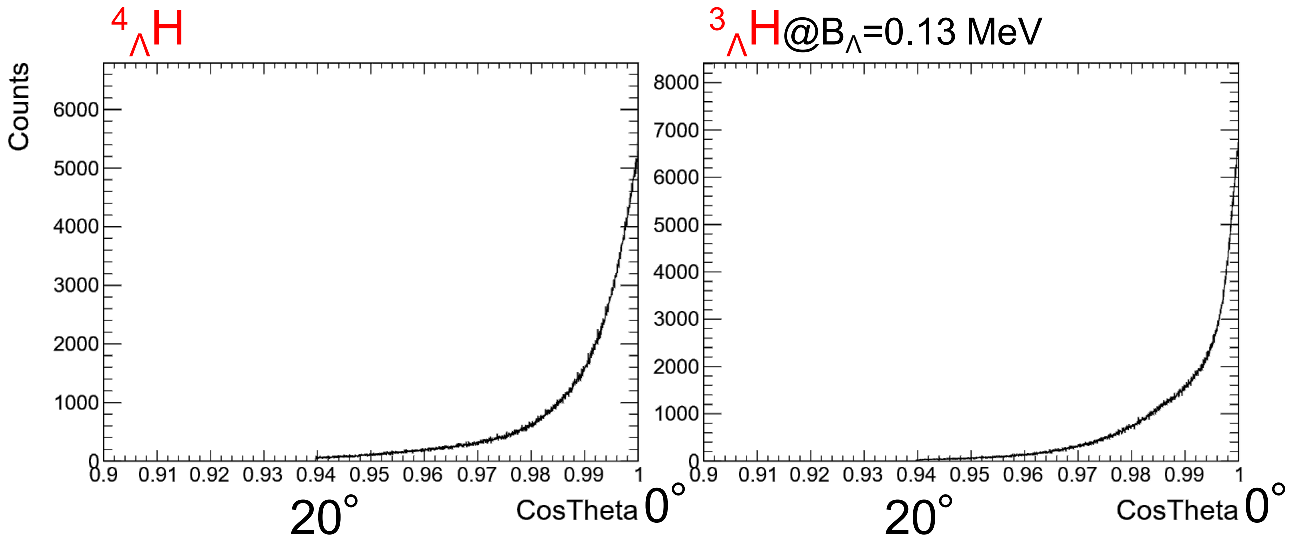
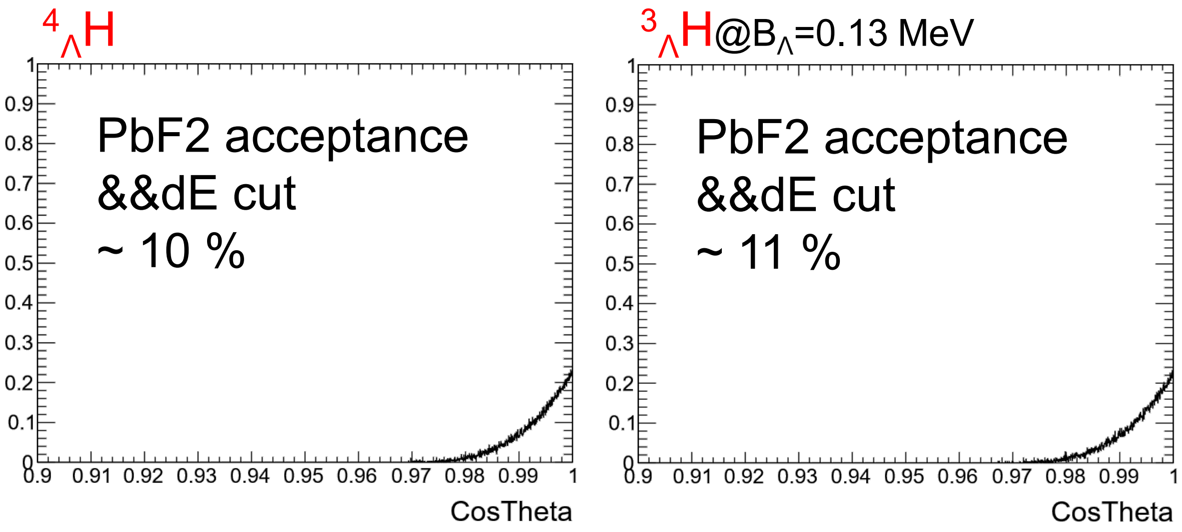
π^0 angular distribution



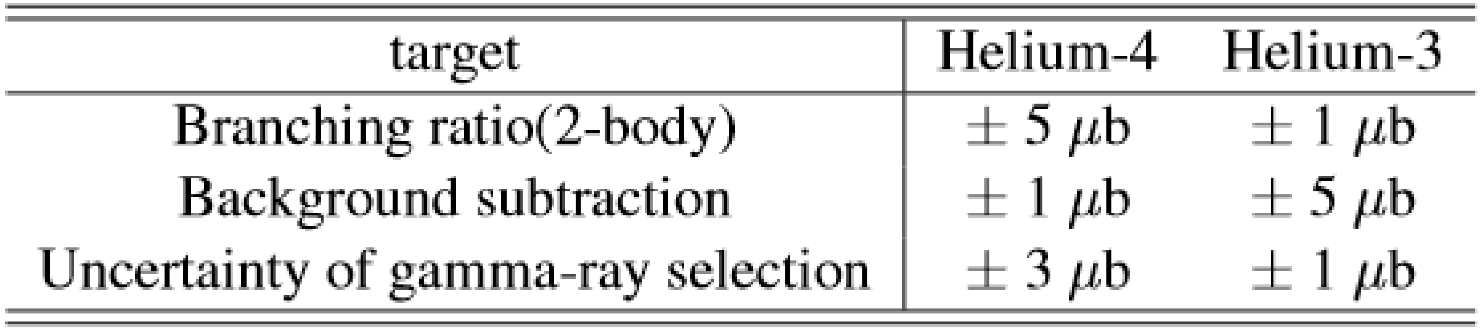
π^0 acceptance



✓Acceptance is almost the same

Result

- $\theta^{lab}_{0^\circ\text{-}20^\circ}$ Integrated cross section(preliminary)
  - $\sigma({}^{4}_{\Lambda}\mathrm{H})$ = **56 ± 2(stat.) ± 6(syst.) μb**
  - $\sigma({}^{3}_{\Lambda}\mathrm{H})$ = **18 ± 3(stat.) ± 5(syst.) μb**
    - ✓Main components of systematic error



target	Helium-4	Helium-3
Branching ratio(2-body)	$\pm 5\ \mu$b	$\pm 1\ \mu$b
Background subtraction	$\pm 1\ \mu$b	$\pm 5\ \mu$b
Uncertainty of gamma-ray selection	$\pm 3\ \mu$b	$\pm 1\ \mu$b

- Ratio of production cross section $\sigma({}^{3}_{\Lambda}\mathrm{H})/\sigma({}^{4}_{\Lambda}\mathrm{H})$
  - **R = 0.31 ± 0.06(stat.) ± 0.09(syst.) (preliminary)**

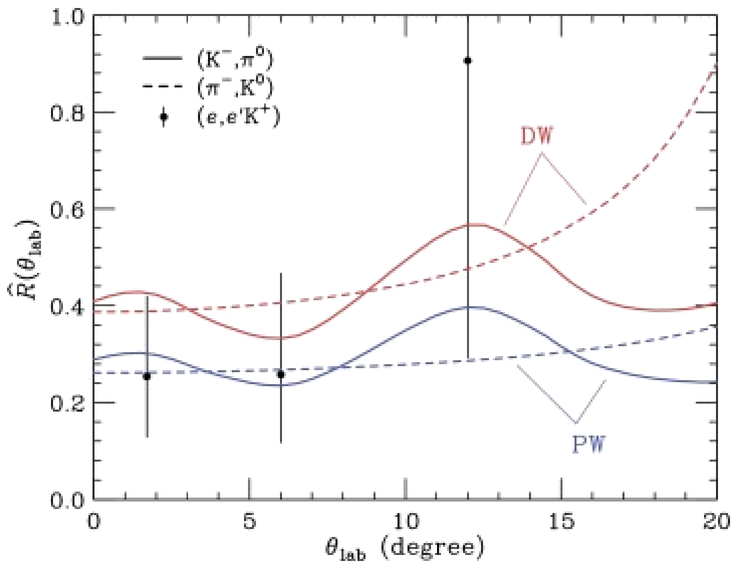
Value will be finalized soon!

Discussion

- Information of the value of the binding energy of $^{3}_{\Lambda}\mathrm{H}$ by the production cross section ratio $R = \sigma(^{3}_{\Lambda}\mathrm{H})/\sigma(^{4}_{\Lambda}\mathrm{H})$

  Emulsion: B_{Λ}=0.13 MeV ⇒ $\sigma(^{3}_{\Lambda}\mathrm{H})/\sigma(^{4}_{\Lambda}\mathrm{H}) \sim 0.3\text{-}0.4$

  heavy ion collision(STAR): B_{Λ}=0.41 MeV ⇒ $\sigma(^{3}_{\Lambda}\mathrm{H})/\sigma(^{4}_{\Lambda}\mathrm{H}) \sim 0.65$



T. Harada and Y. Hirabayashi,
NPA 1015 (2021) 122301

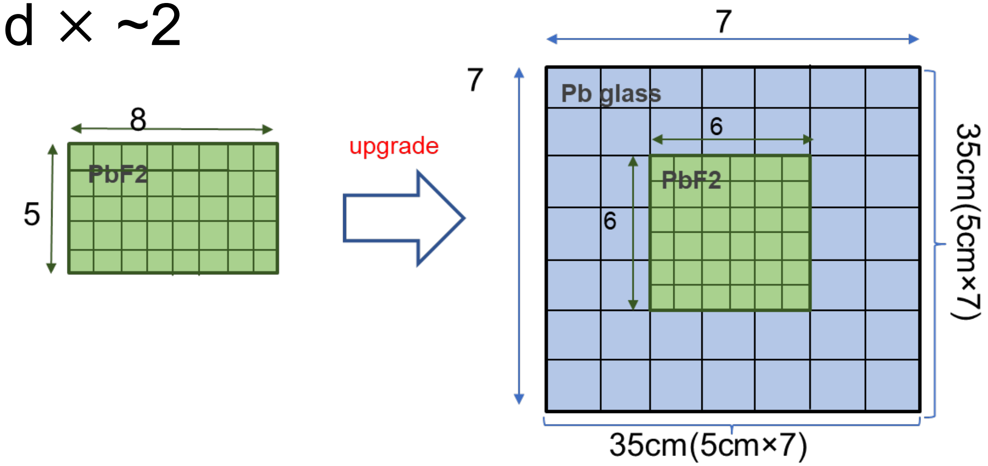
- **Experimental result: R = 0.31 ± 0.06(stat.) ± 0.09(syst.) (preliminary)**

  ⇒ Hypertriton prefer loosely bound system

Outlook for ${}^{3}_{\Lambda}H$ lifetime measurement

Upgrade toward measurement

- Forward calorimeter
  - ➢**increase the solid angle with Pb glass**
    - ✓yield × ~2



	PbF2	Pb glass
Radiation length X0(cm)	0.93	1.7
Moliere radius(cm)	2.22	2.89
Density(g/cm3)	7.77	5.2
Geometry(cm3)	2.5×2.5×14	5×5×26

- Vertex detector(VFT)
  - ➢UU’VV’(45 degrees) spiral 4 layers around the target
    - ✓Improvement of momentum resolution

⇒Lifetime measurement of ${}^{3}_{\Lambda}$H in JFY2023

~20 (stat.), < 20 (syst.) ps

Summary

- Toward Solving the Hypertriton Lifetime Puzzle
  - Lifetime and binding energy must be measured by a method different from heavy-ion collision experiments
- J-PARC E73 experiment
  - Direct Measurement of Hypertriton Lifetime
    - ✓Selective production of the ground state of hypernucleus by the (K^-, π^0) reaction
- Lifetime
  - τ(**$^4_\Lambda$H**) : **206 ±8(stat.) ± 12(syst.) ps** → arXiv:2302.07443
  - τ(**$^3_\Lambda$H**) will be measured in JFY2023: ~20 (stat.), < 20 (syst.) ps
- Integrated production cross section of $^4_\Lambda$H, $^3_\Lambda$H
  - **σ($^4_\Lambda$H) = 56 ± 2(stat.) ± 6(syst.) μb**
  - **σ($^3_\Lambda$H) = 18 ± 3(stat.) ± 5(syst.) μb**

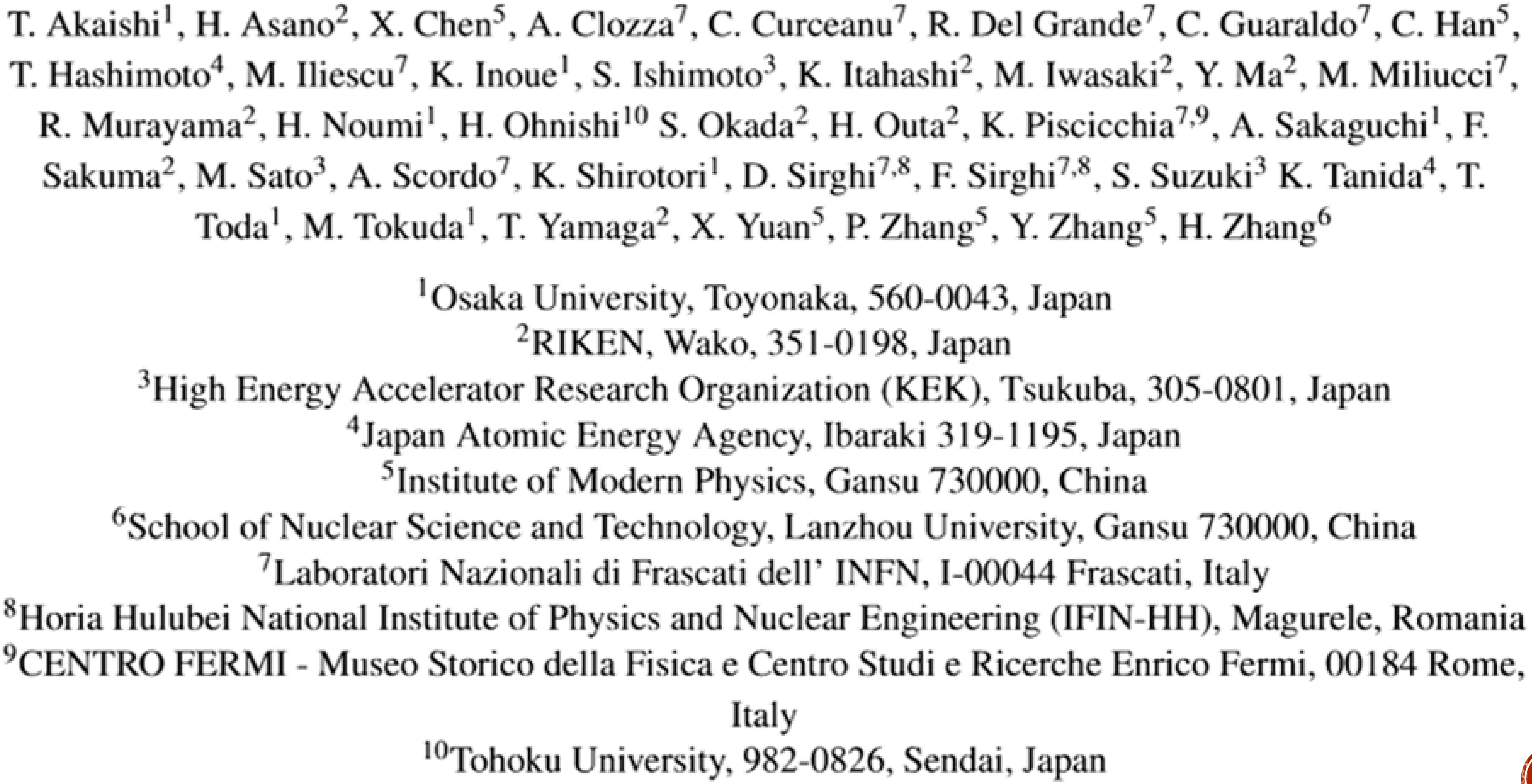
(preliminary)

- Information of the value of the binding energy of $^3_\Lambda$H
  - **R = 0.31 ± 0.06(stat.) ± 0.09(syst.)   (preliminary)**

⇒ Hypertriton prefer loosely bound system

Theoretical calc.
R ~ 0.3-0.4 (B_Λ=0.13 MeV)
R ~ 0.65 (B_Λ=0.41 MeV)

J-PARC E73 collaboration



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