Hypertriton lifetime puzzle and our solution

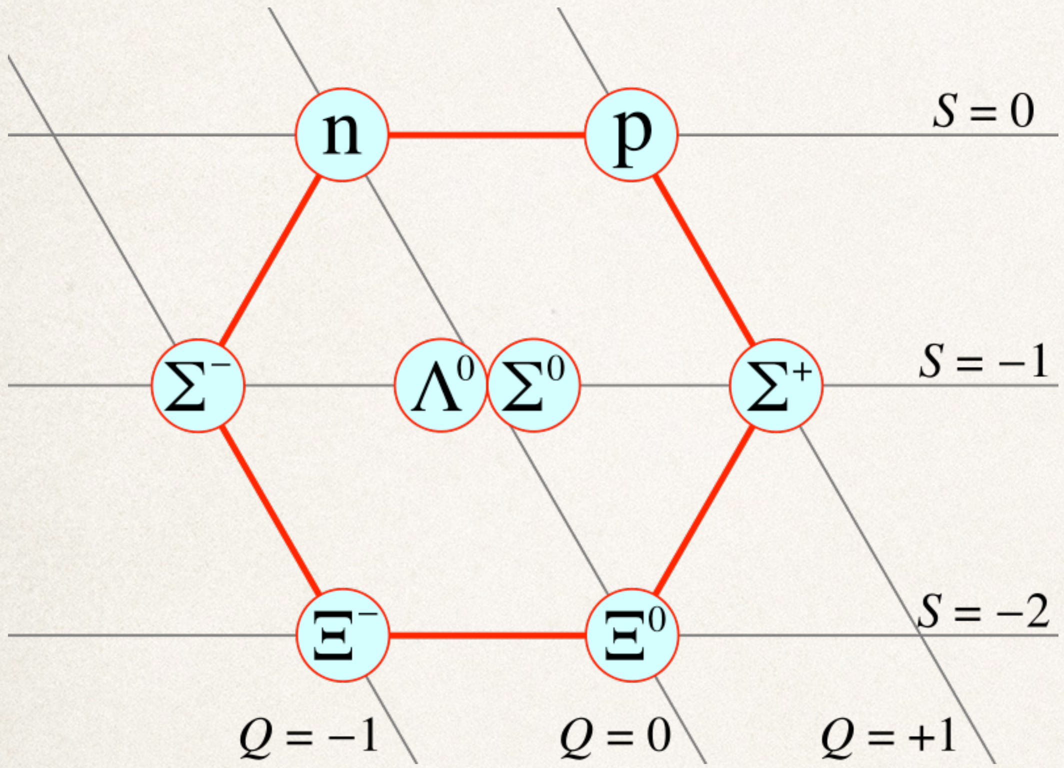
y.ma@riken.jp

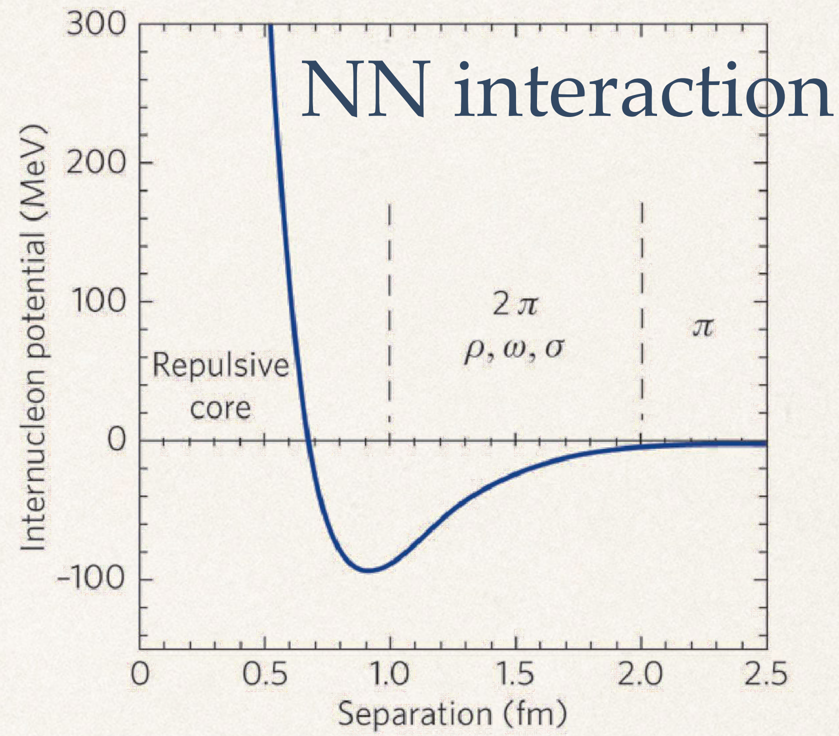
2024/03/05

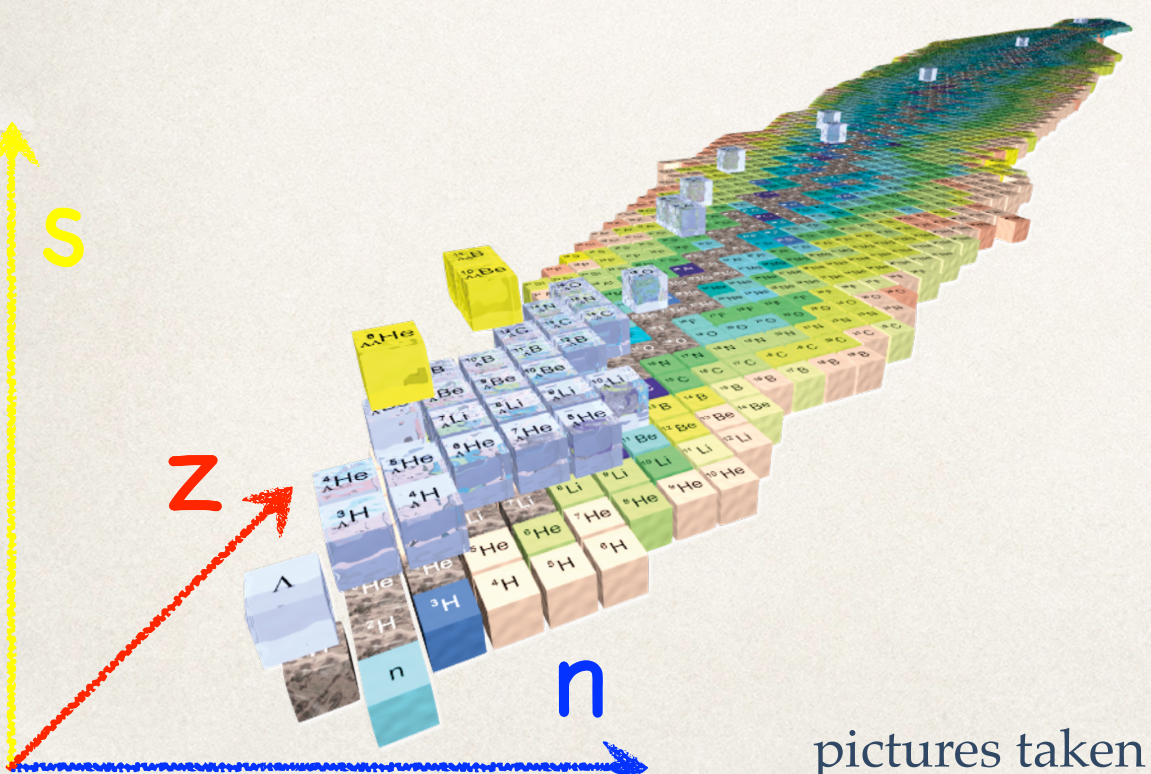
Outline

- Introduction & motivation
- J-PARC E73:
  - Experimental method
  - Current status
- Summary

Nucleon vs Hyperon



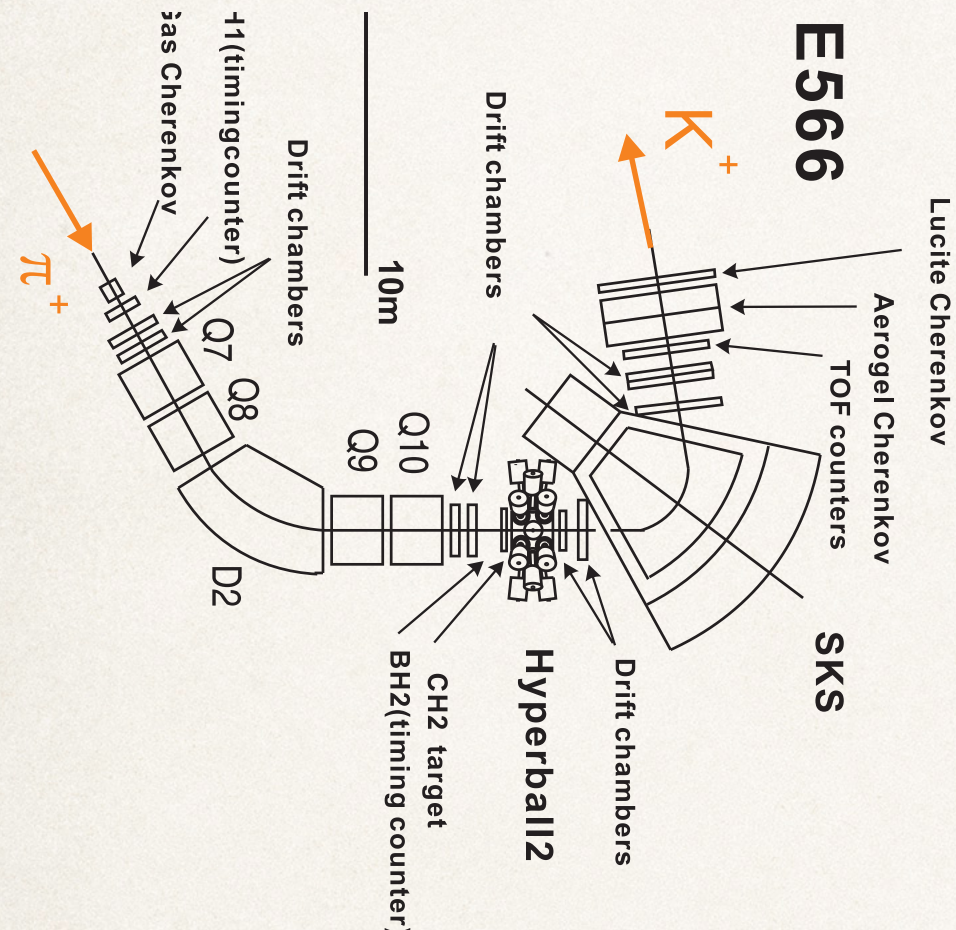


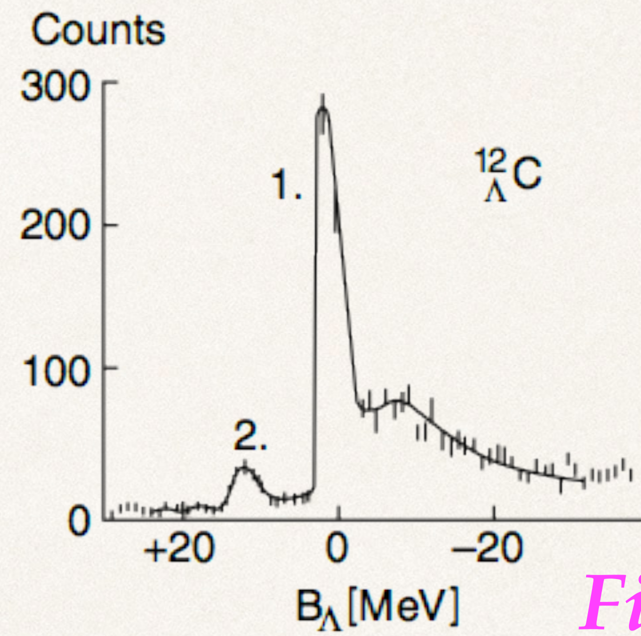


1. First step for a unified baryon-baryon interaction
2. Expanding our view from the Earth to neutron star
3. Probing nuclear structure

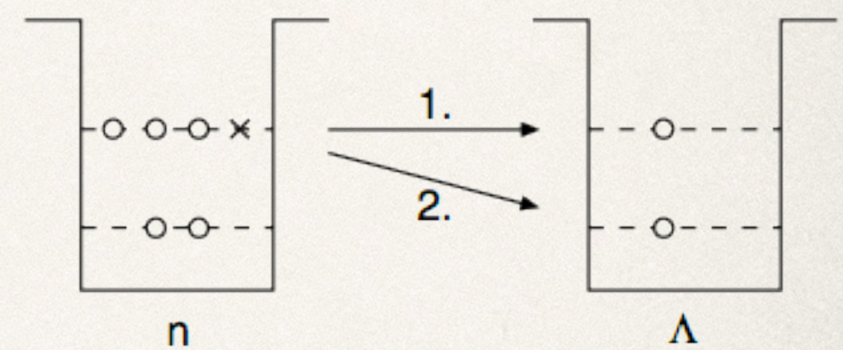
pictures taken from Hyp06 poster and Nature

Probing nuclear structure

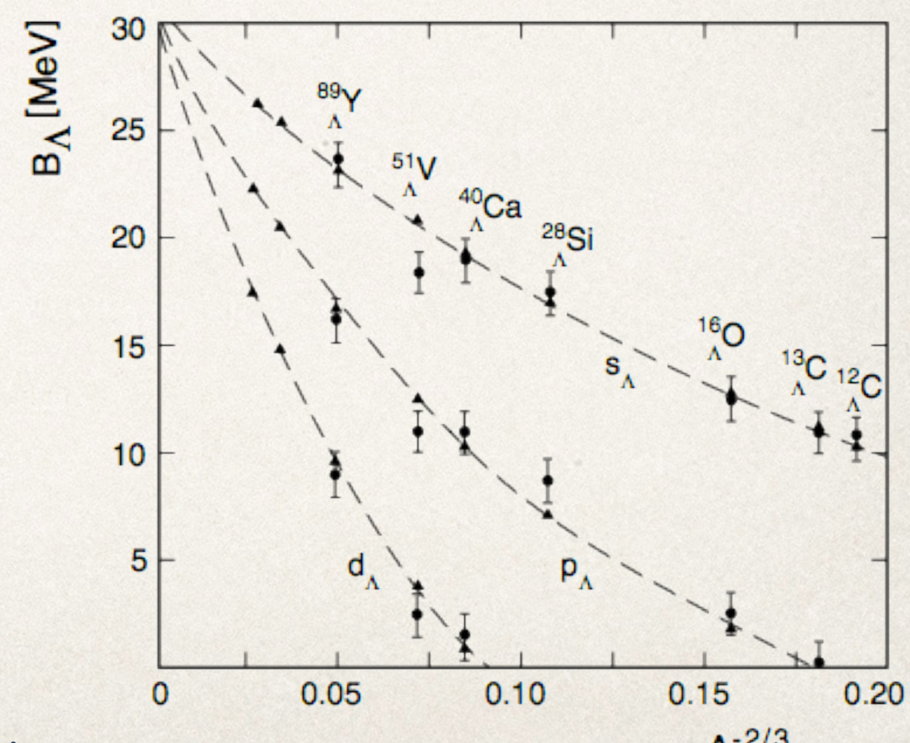




$^{12}C(K^-, \pi^-)^{12}{}_{\Lambda}C$ reaction



First direct evidence for nuclear mean field



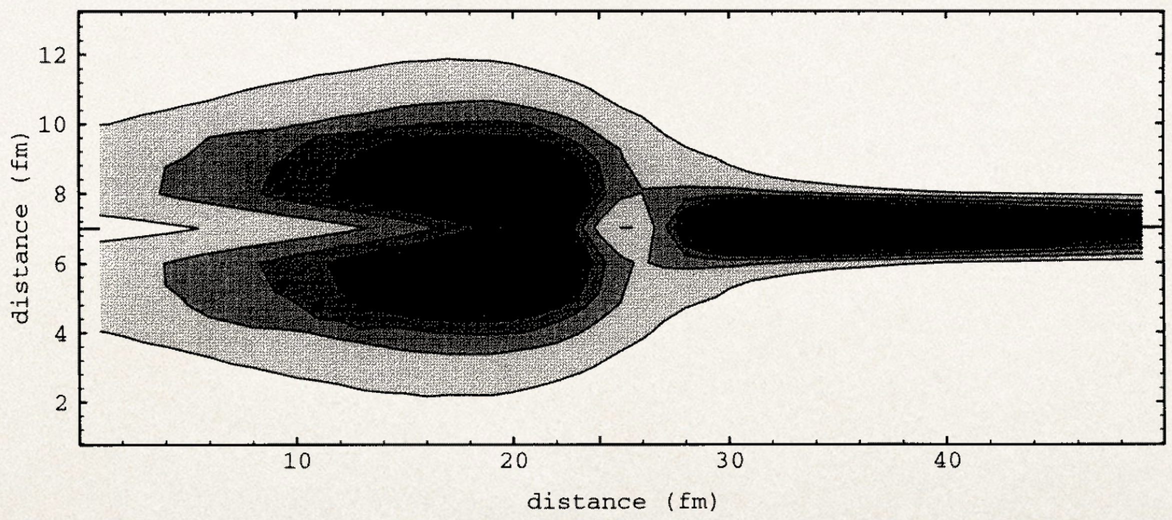
$$M_{HY} = \sqrt{(E_K + M_A - E_\pi)^2 - (p_K^2 + p_\pi^2 - 2p_K p_\pi cos\theta_{K\pi})}$$

beam tracking   scattered particle tracking

B. Povh *et al.*, Particle and Nuclei

Quiz: $^{3}_{\Lambda}H$ vs ^{208}Pb which one is "*bigger*"?

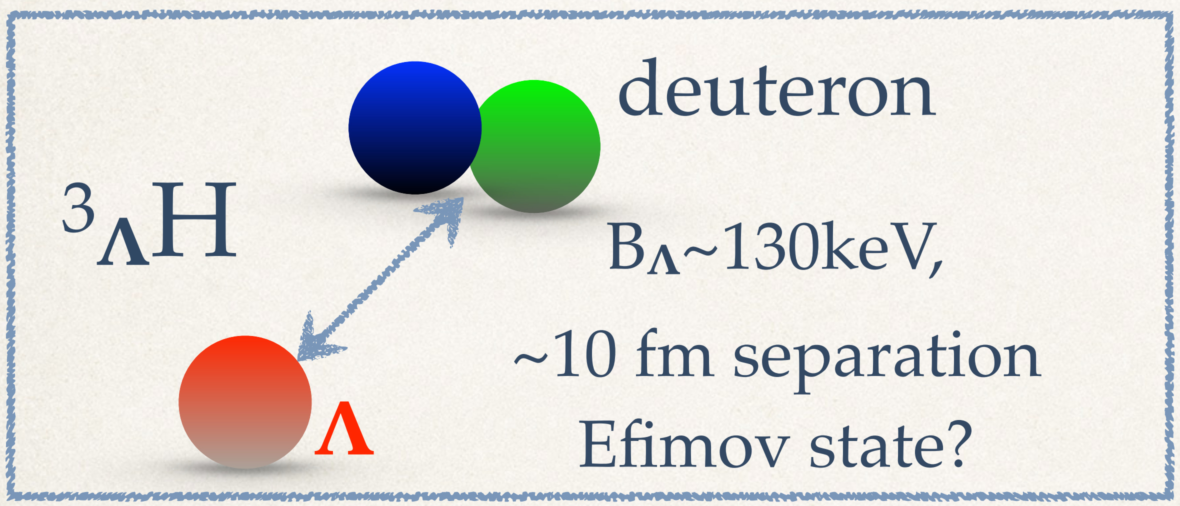
- A good homework for your students
- Hint: a harmonic oscillator toy model, or, r ~ sqrt($\hbar^2/4uB_\Lambda$)
- Hypertriton: **Λ**(T=0) + d(T=0) @ ~130keV
- Answer: Hypertriton ~10fm is *"bigger"* than ^{208}Pb ~7fm assuming liquid drop model



DOI: 10.1088/0954-3899/23/4/002

Motivation for J-PARC E73 experiment

As the lightest hypernucleus, ${}^{3}_{\Lambda}H$ should tell us some important fact of YN interactions just as deuteron for nuclear physics.



Up to a few years ago, we believe:
$\tau \approx 263$ ps ($B_\Lambda = 130 \pm 50$ keV).

${}^{3}_{\Lambda}H \longrightarrow {}^{3}He + \pi^-$ decay probability:
kinematics× | transition matrix $|^2$
~ phase space×wave function overlap

a small term
(separation of ~10fm)

A well separated wave function between **Λ** and deuteron implies small modification of ${}^{3}_{\Lambda}H$ lifetime from deuteron and, thus, its lifetime should be presumably determined by free **Λ** decay.

Motivation for J-PARC E73 experiment

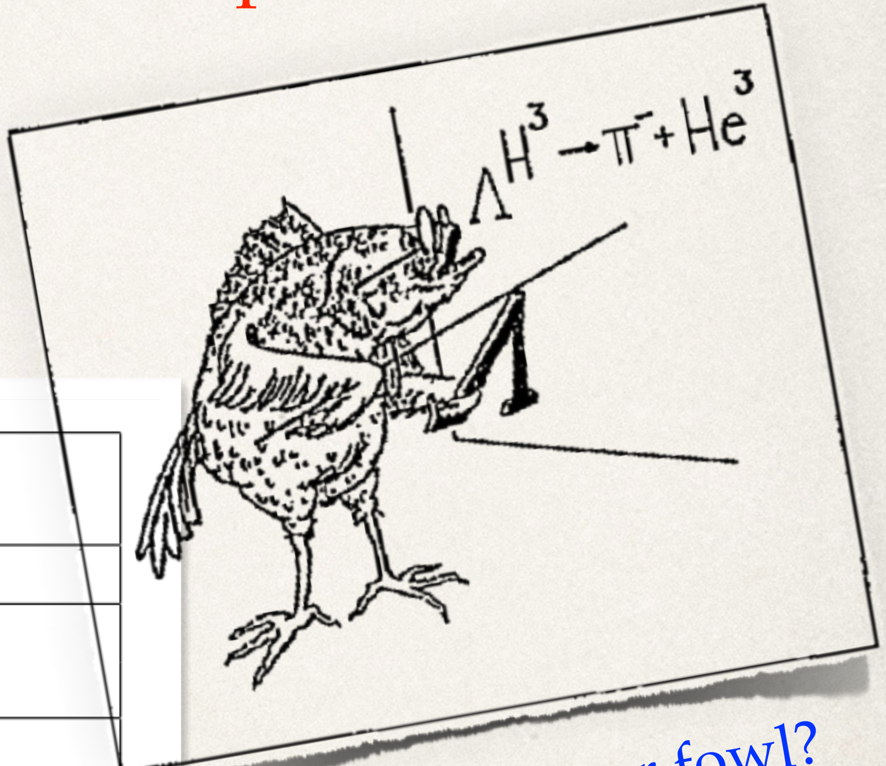
As the lightest hypernucleus, $^{3}_{\Lambda}H$ should tell us some important fact of YN interactions just as deuteron for nuclear physics.

Up to a few years ago, we believe: $\tau \approx 263$ ps ($B_\Lambda = 130 \pm 50$ keV); However, heavy ion experiments suggest $\tau \approx 180$ ps…

Hypertriton lifetime puzzle challenges the very foundation of our knowledge for hypernucleus.

Collaboration	Experimental method	$^{3}_{\Lambda}$H lifetime [ps]	Release date
HypHI	fixed target	183^{+42}_{-32}(stat.)$\pm$37(syst.)	2013 [4]
STAR	Au collider	142^{+24}_{-21}(stat.)$\pm$29(syst.)	2018 [2]
		221$\pm$15(stat.)$\pm$19(syst.)	2021 [6]
ALICE	Pb collider	181^{+54}_{-39}(stat.)$\pm$33(syst.)	2016 [3]
		253$\pm$11(stat.)$\pm$6(syst.)	2023 [5]

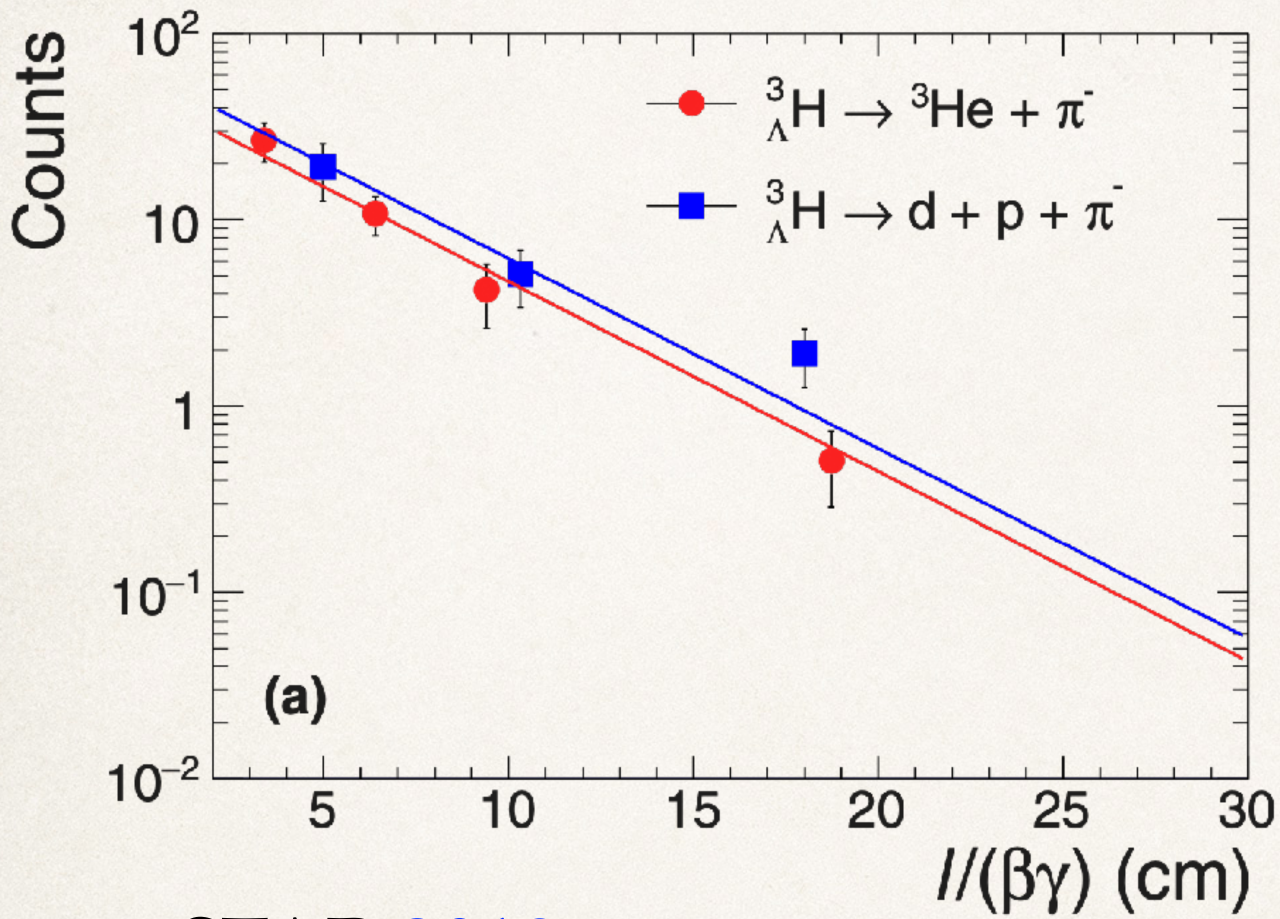
TABLE I. Summary of recent measurements on $^{3}_{\Lambda}$H lifetime.

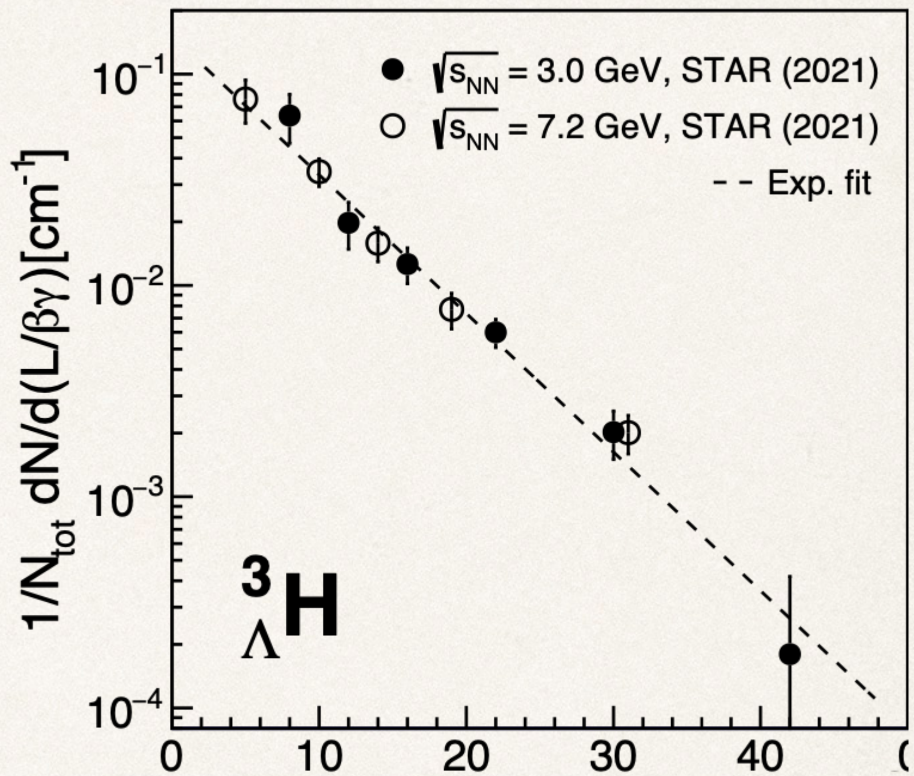


Neither fish nor fowl?

Picture taken from MM. Block et al. Proc. Int. Conf. Hyperfragments, 1963

Introduction: hypertriton lifetime puzzle





(doi.org/10.1103/PhysRevLett.128.202301)

STAR 2018:

$\tau \sim 142^{+24}_{-21} \pm 29$ ps

(doi.org/10.1103/PhysRevC.97.054909)

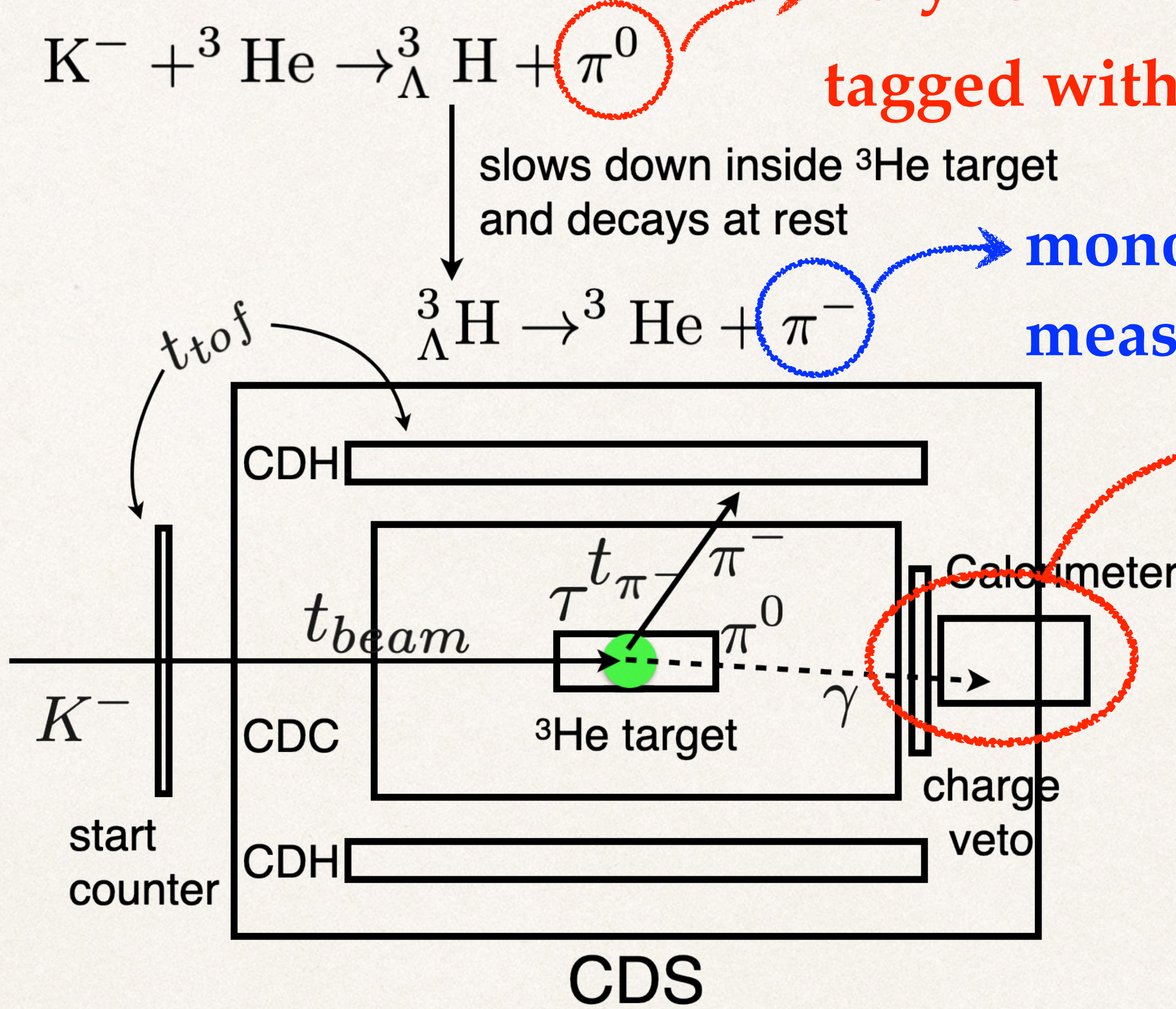
STAR 2022:

$\tau = 221 \pm 15 \pm 19$ ps

(doi.org/10.1051/epjconf/202227108002)

What happened? What shall we do?

E73 experimental: direct lifetime measurement



very forward $\pi 0$ projectile;

tagged with decayed high energy γ

mono-energetic, ~114MeV/c;

measured with CDS

Cherenkov Calorimeter

Fully ready

${}^3_\Lambda H$ decay time can be derived by TOF and CDS tracking

The idea of ***direct measurement***: $T_{CDH}-T_0=t_{beam}+t_{\pi-}+\tau$;

1. A complementary measurement for Heavy Ion results
2. Achievable precision: $\sigma/\sqrt{N} < 20ps$
3. *Direct lifetime measurement with fixed J=1/2 state*

$^{3}He(K^{-},\pi^{0})^{3}_{\Lambda}H$ vs heavy ion production

Experiment	J-PARC E73	BNL STAR
Production method	$^{3}He(K^{-}, \pi^{0})^{3}_{\Lambda}H$	Au+Au
Microscopic process	Strangeness exchange	Thermal model; Coalescence model
PID	pi- momentum	Invariant mass;
Quantum number	spin=1/2 dominant	1/2 and 3/2 mixture?
Lifetime derivation	Time of flight	Decay length

Once upon a time… an ambitious project for Neutral Meson Spectroscopy

(K^-, π^0) vs (K^-, π^-):

- Motivation: isospin mirror hypernucleus on T=0 target
- Method: measure π^0/π^- momentum

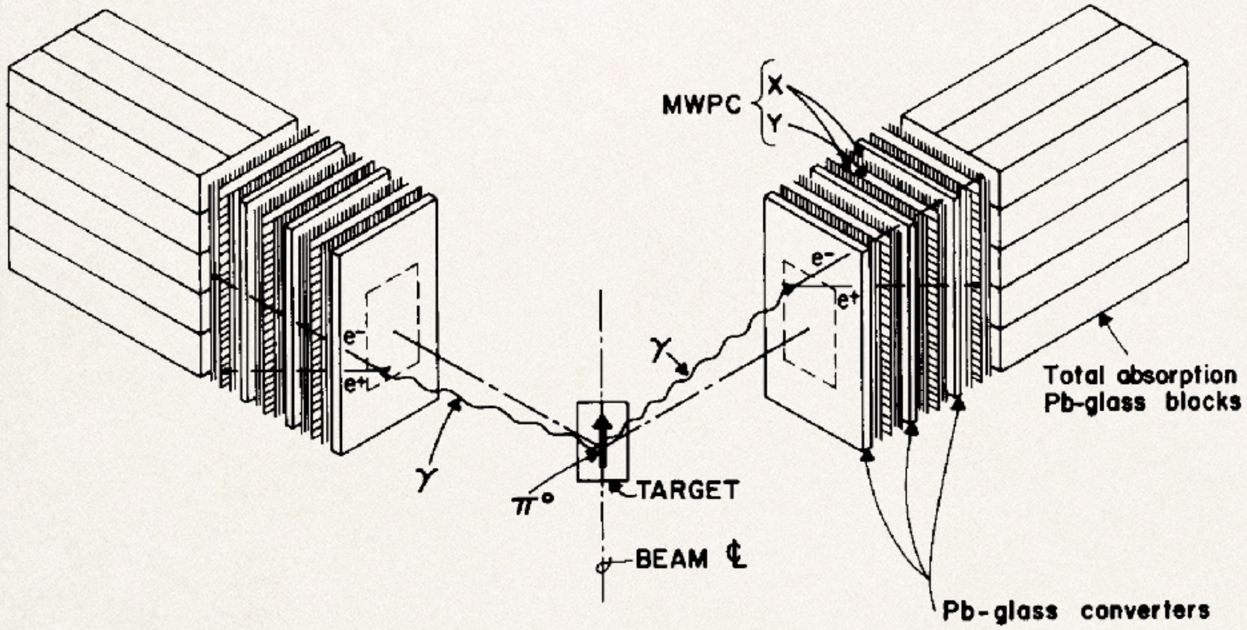


Fig. 1. A schematic diagram of the detector. The orientation of the two arms with respect to each other and to the scattering target is indicated. Also indicated is the convention for the x and y coordinates.

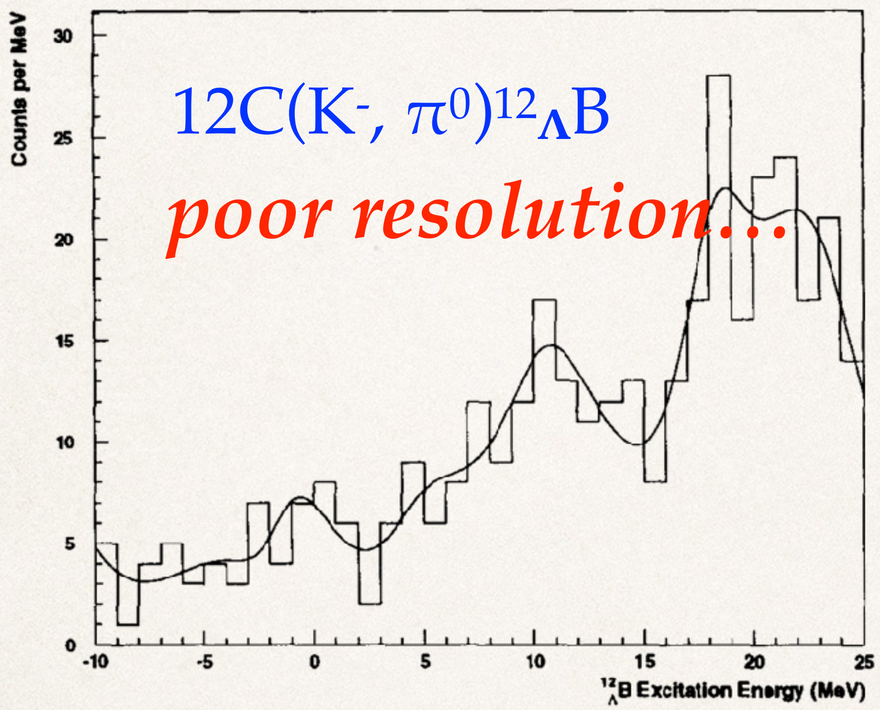
Working principle:

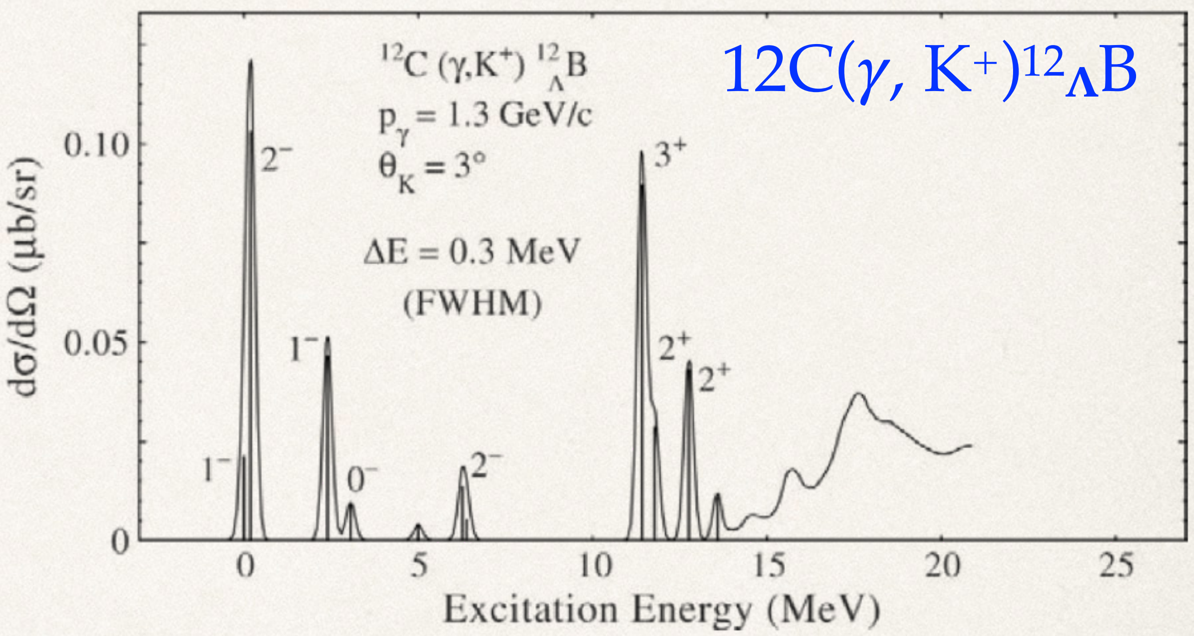
- γ converter
- Tracking chamber
- Calorimeter
- γ opening angle $\oplus$ energy

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

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

Once upon a time…
an ambitious project for Neutral Meson Spectroscopy



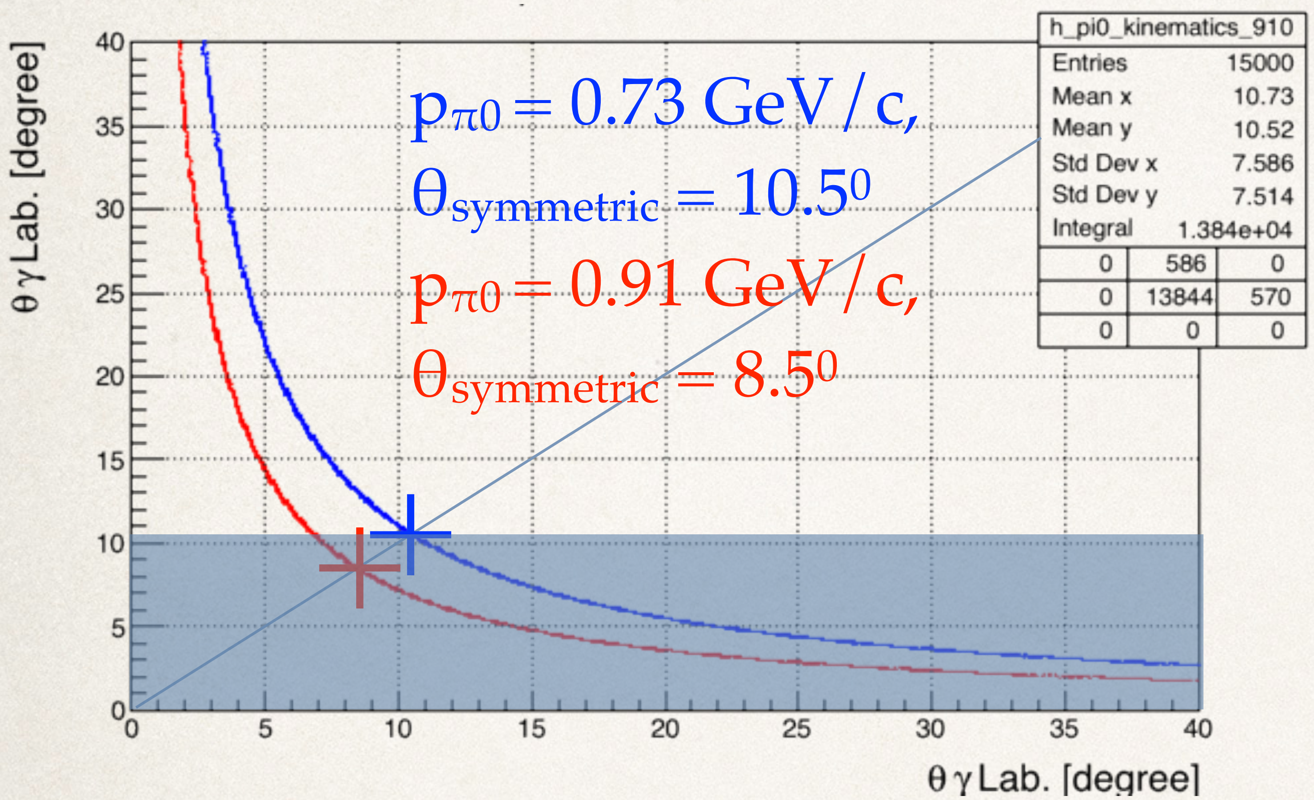


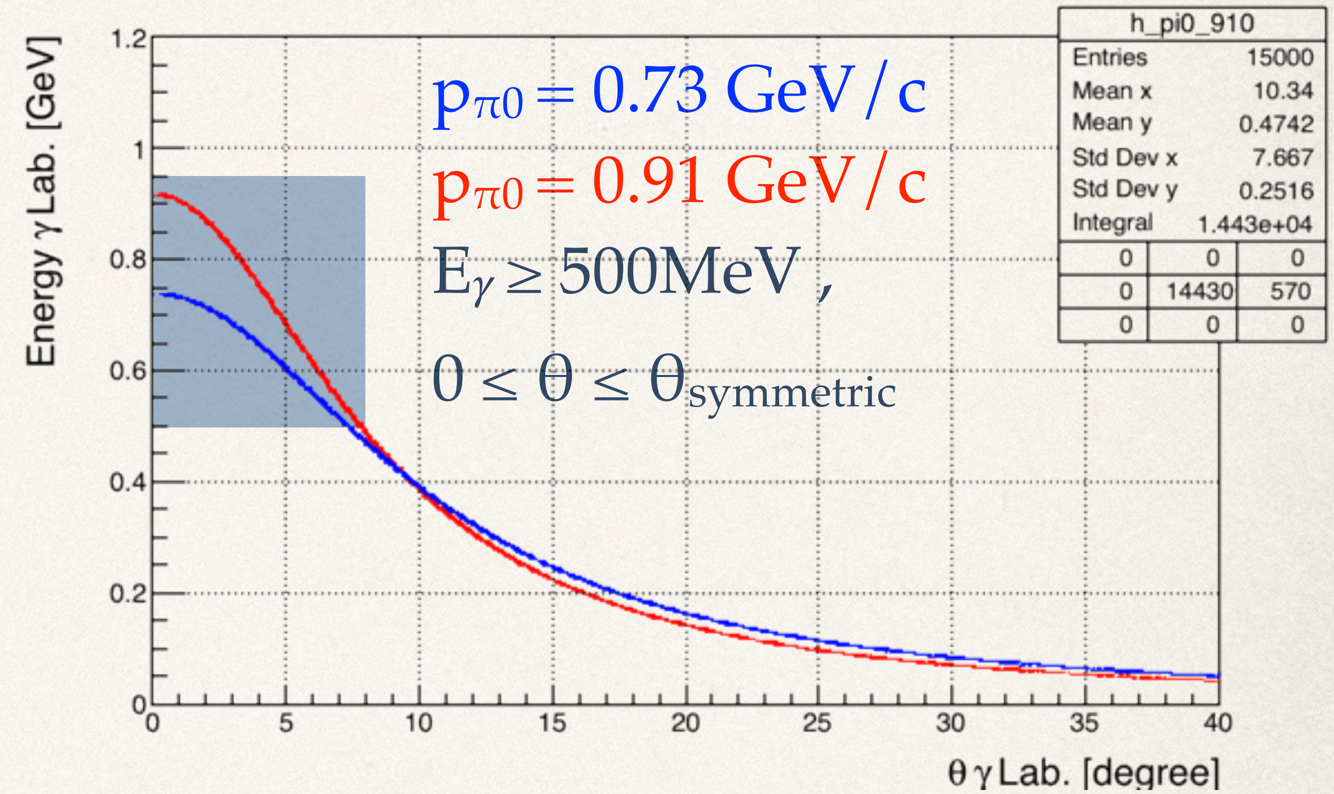
Neutral Meson Spectrometer

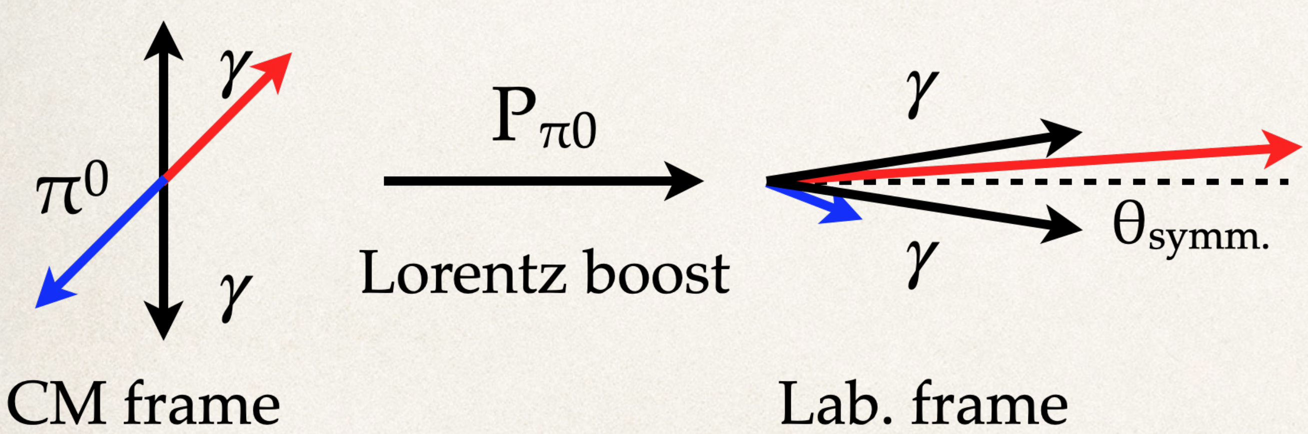
- Constructed at Los Alamos and shipped to BNL
- MM resolution ***~3MeV*** (design value ***~1MeV***)
- Bad resolution compare to (γ, K+) channel

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

Revisit π^0 decay kinematics







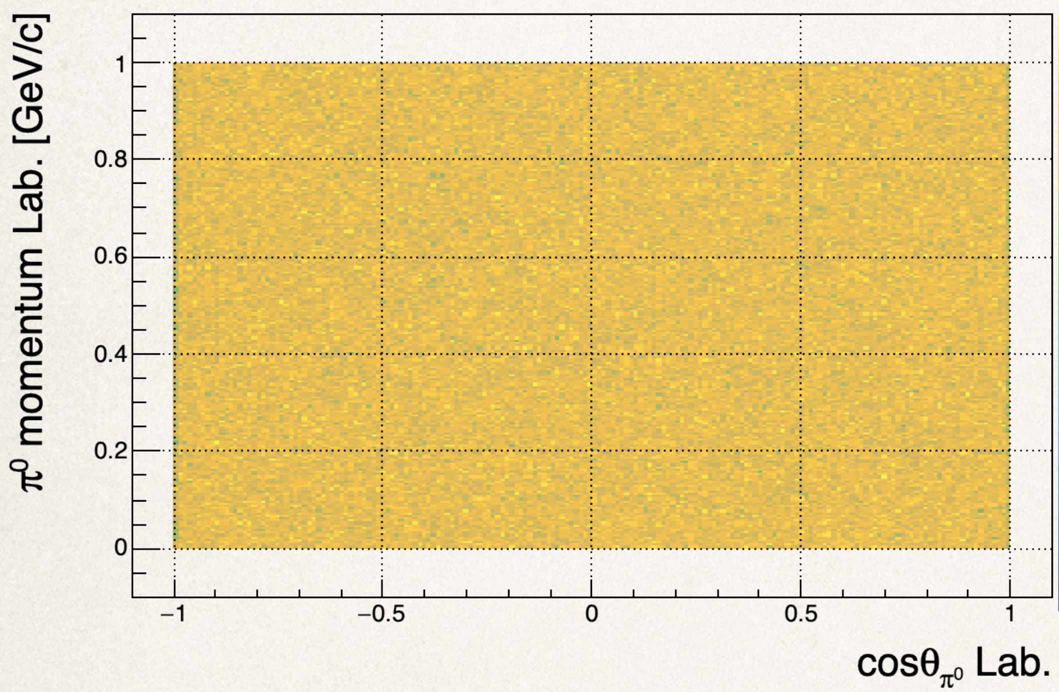
- 0.73~0.91GeV/c π^0 boosts γ forwardly;
- By covering $0 \sim \theta_{symmetric}$, tag the γ with higher energy ($E_\gamma \geq 500$MeV)

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

Do we *really* need missing mass?

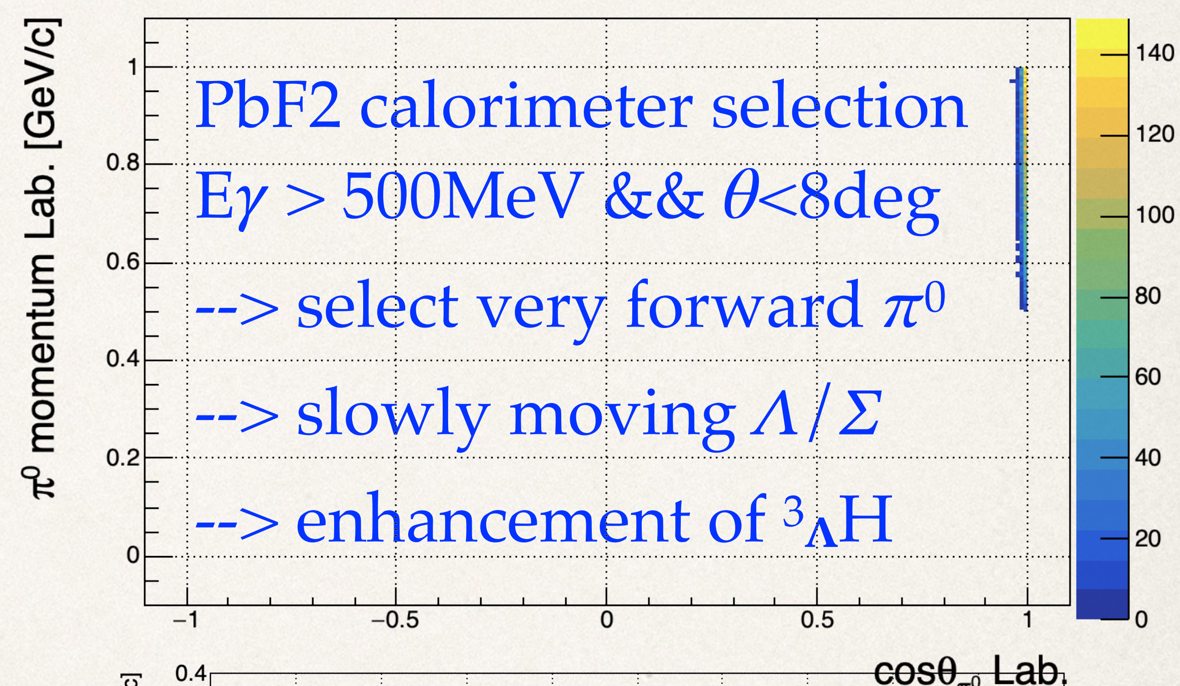
Input

π^0: 0~1GeV/c; 0~180deg

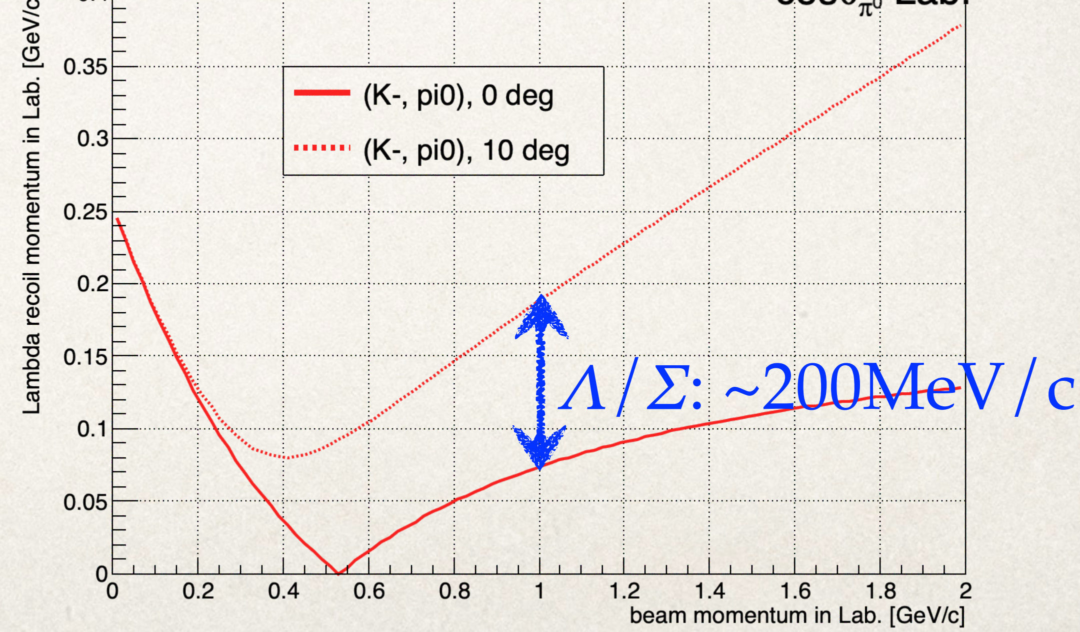


W/ PbF2 calorimeter cut

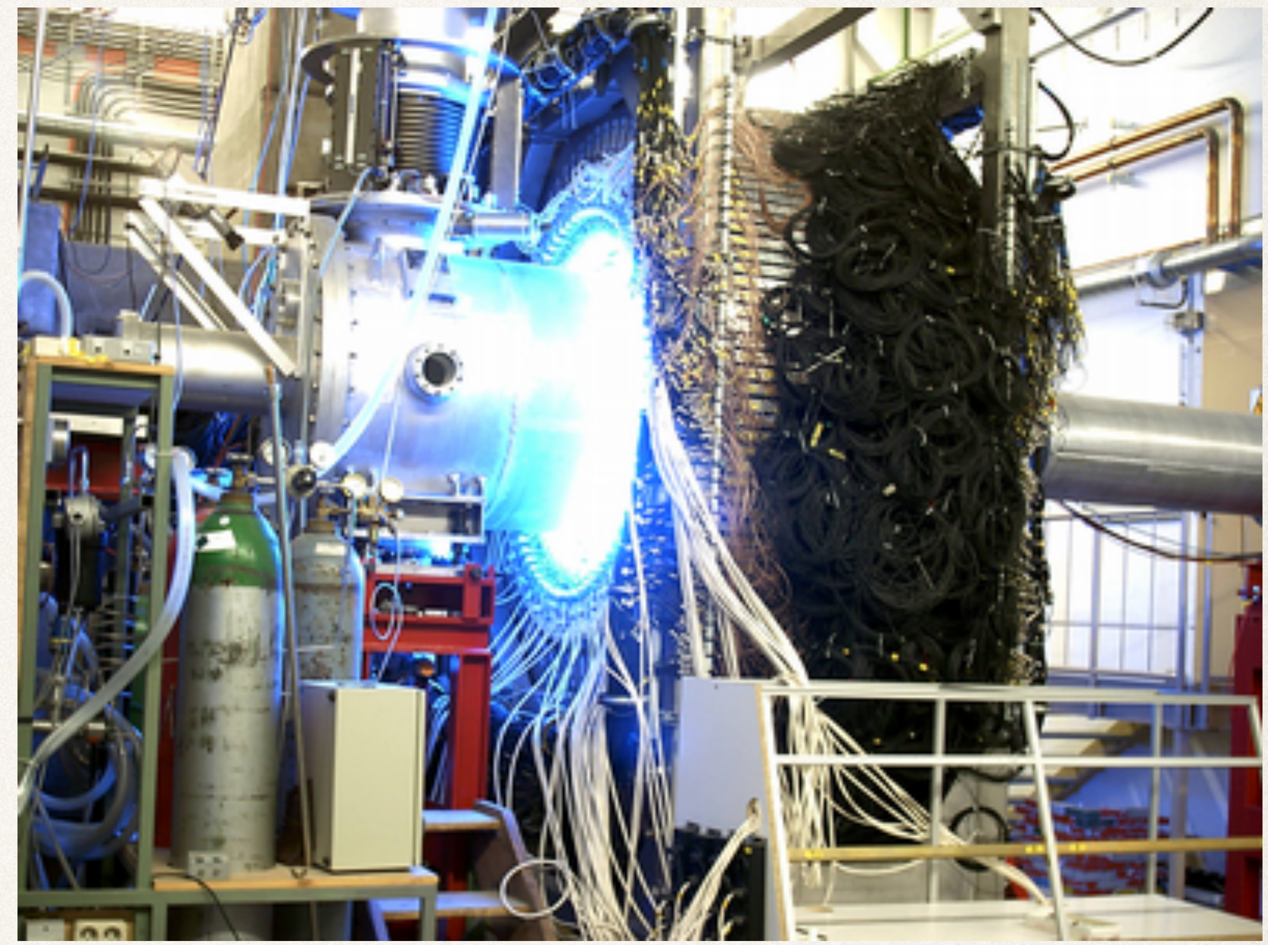
π^0: 0.8~1GeV/c; 0~10deg



^{3}He(K-, pi0)$^3{}_\Lambda$H strangeness exchange reaction is known for its spin non-flip feature --> helps to pin down the $^3{}_\Lambda$H Q.N.



Can we construct a fast calorimeter?

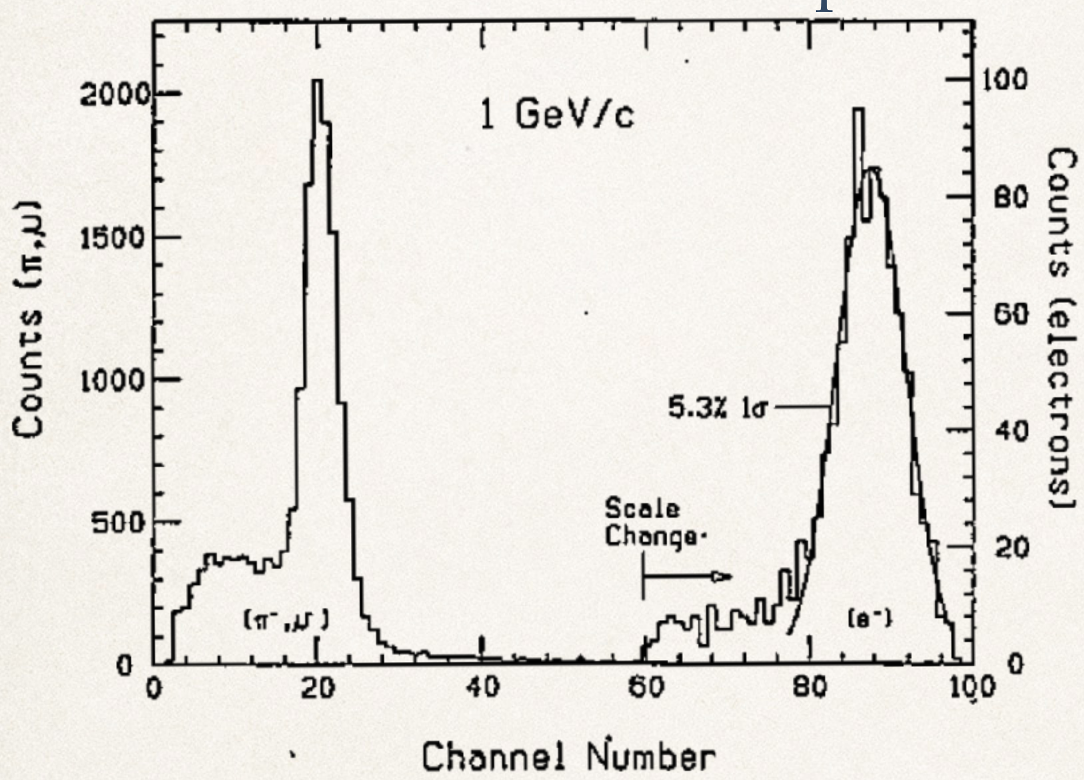


- π^0 tagger needs to be ***located along beam line***
  - ***Nobody has ever put a calorimeter IN the intensive beam***
- Main stream: slow inorganic scintillator of μs signal tail
- Inspired by MAMI A-4 spectrometer
  - postdoc with Prof. Frank Maas, 2009~2011

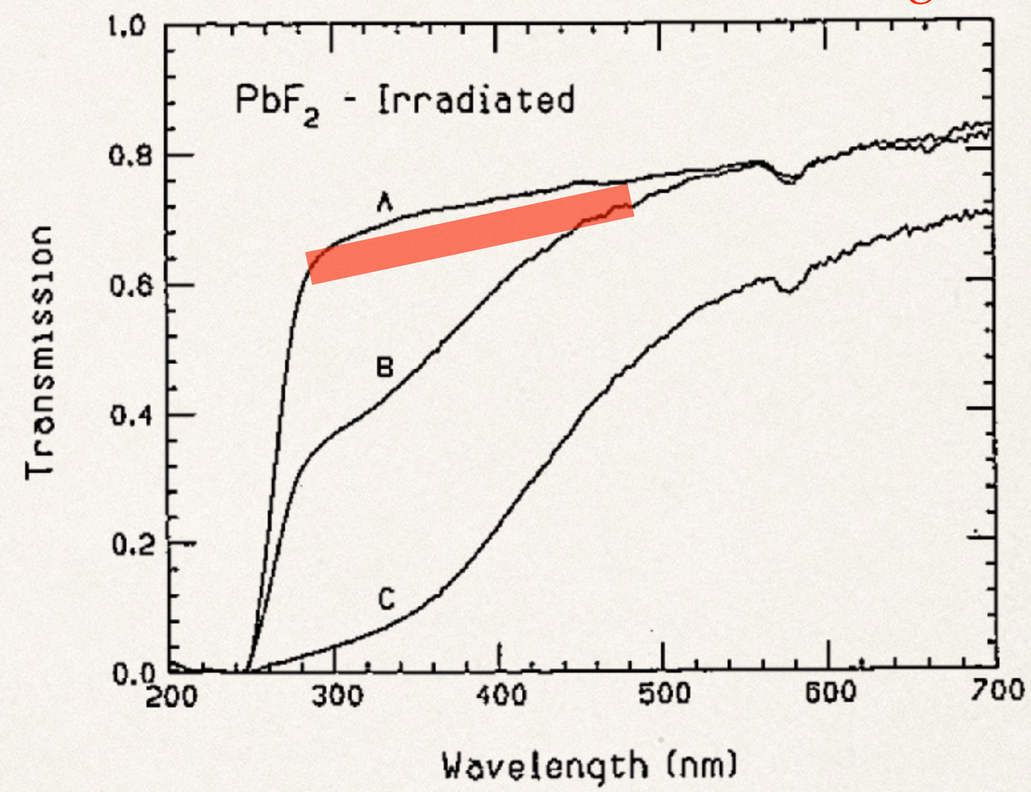
PbF2 calorimeter as π^0 tagger (inspired by A4)

π^- peak

electron peak



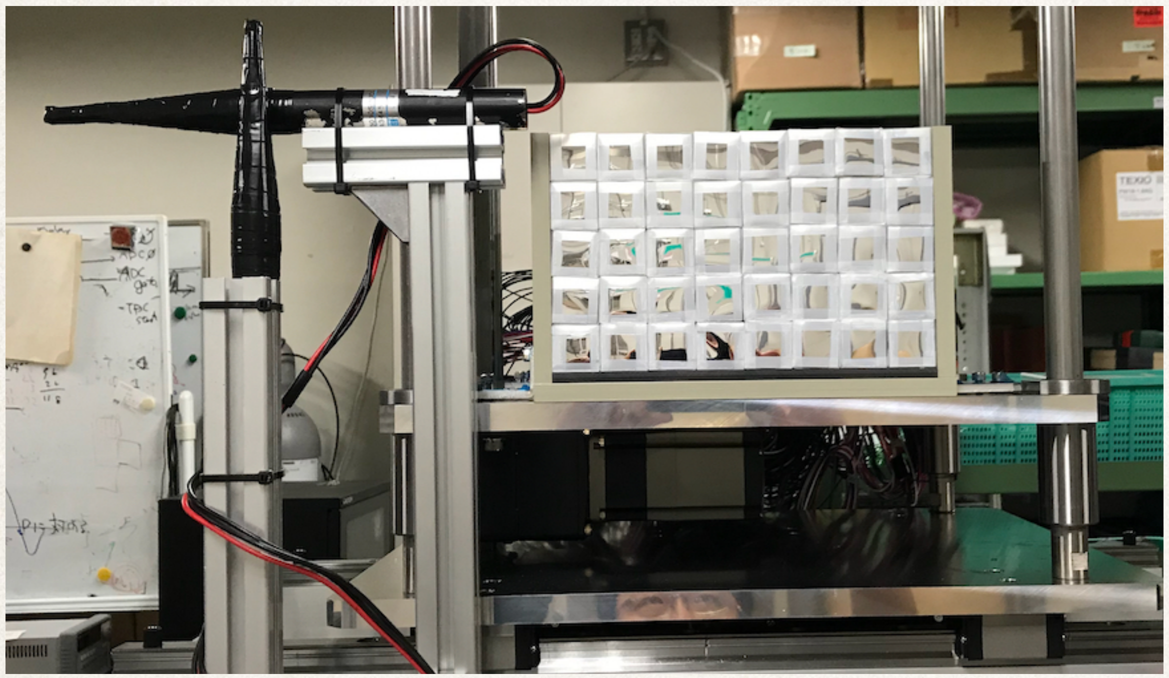
expected performance after one month beam time
(10 times more resistive than Pb glass)

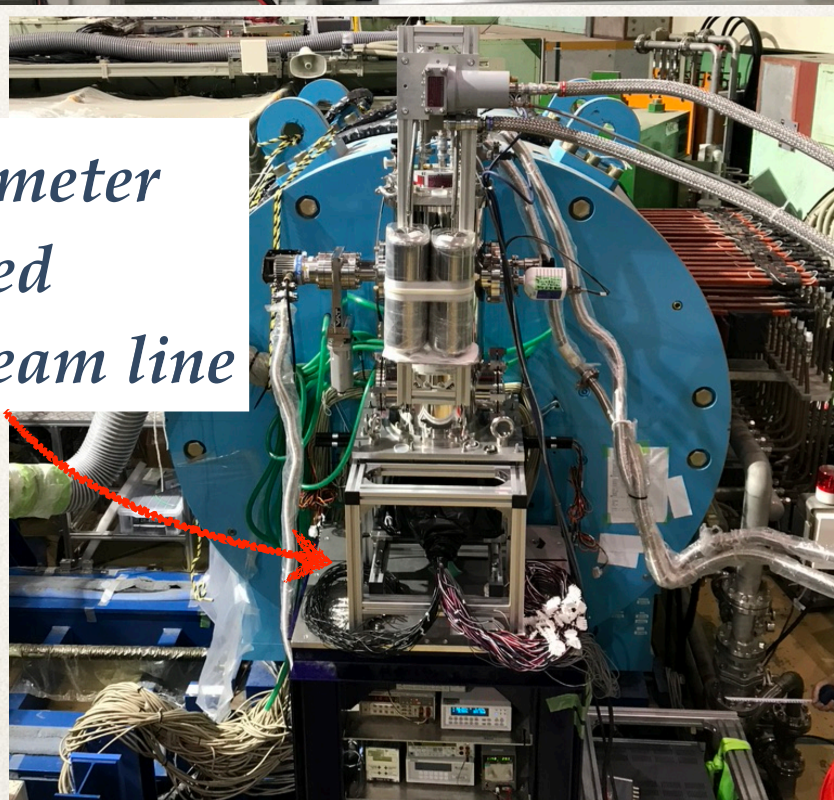


Crystal	Radiation length	Moliere radius	Density	Cost	Resolution	Signal length
PbF_2	0.93 cm	2.22 cm	7.77 g/cm^3	12 USD/cc	5%	2ns

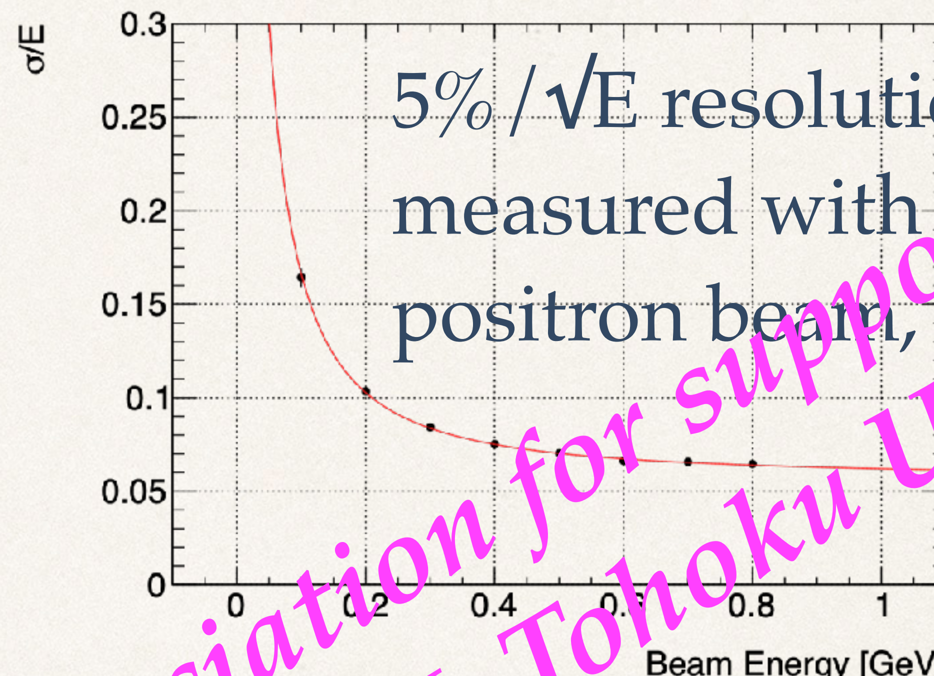
D.F. Anderson, ***et al.***, Nucl. Inst. Meth. A290 (1990) 385
P. Achenbach, ***et al.***, Nucl. Inst. Meth. A416 (1998) 357

PbF2 calorimeter performance @ELPH



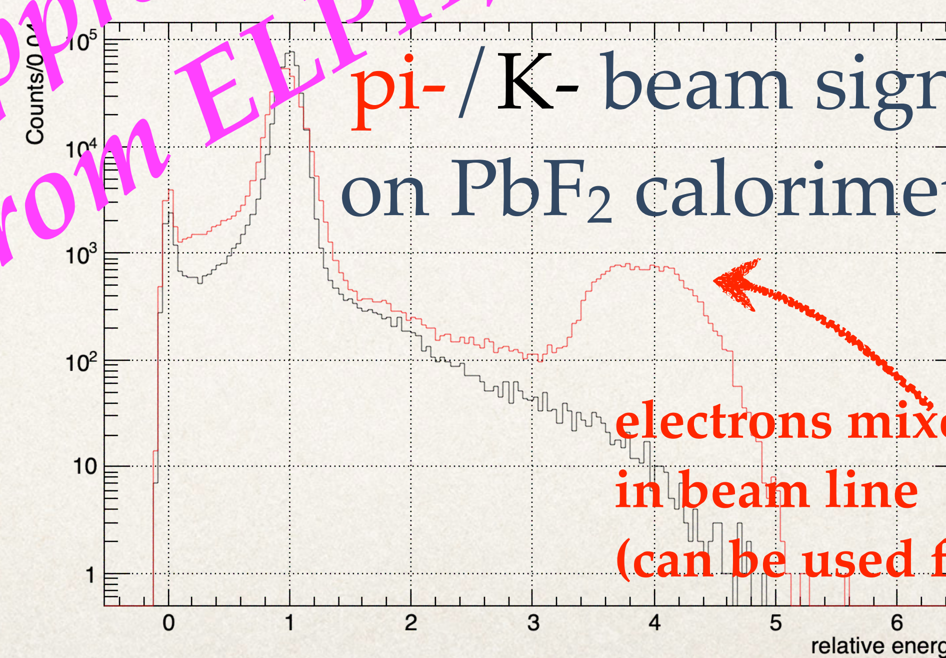


PbF2 calorimeter
was installed
INTO the beam line



5% / √E resolution
measured with
positron beam, 2019

Appreciation for support
from ELPH, Tohoku Univ.



pi- / K- beam signal
on PbF_2 calorimeter

electrons mixed
in beam line
(can be used for calibration)

J-PARC E73 staging & status

Staging:	Pilot (June, 2020)	Stage-1 (May, 2021)	Stage-2
Task:	Background study with $^{4}He(K-,pi0)^{4}{}_{\Lambda}H$	First measurement for $^{3}He(K-, pi0)^{3}{}_{\Lambda}H$ reaction	Direct lifetime measurement for $^{3}{}_{\Lambda}H$
Output:	Established a new method as: (K-,pi0) + decay spectrum	Production cross section study for $^{3}{}_{\Lambda}H$ @ 1GeV/c	Pin down Hypertriton lifetime puzzle
Status:	$^{4}{}_{\Lambda}H$ lifetime paper published by PLB	Successfully observed $^{3}{}_{\Lambda}H$ from mesonic weak decay	Request for beam time allocation (80kWx25days)

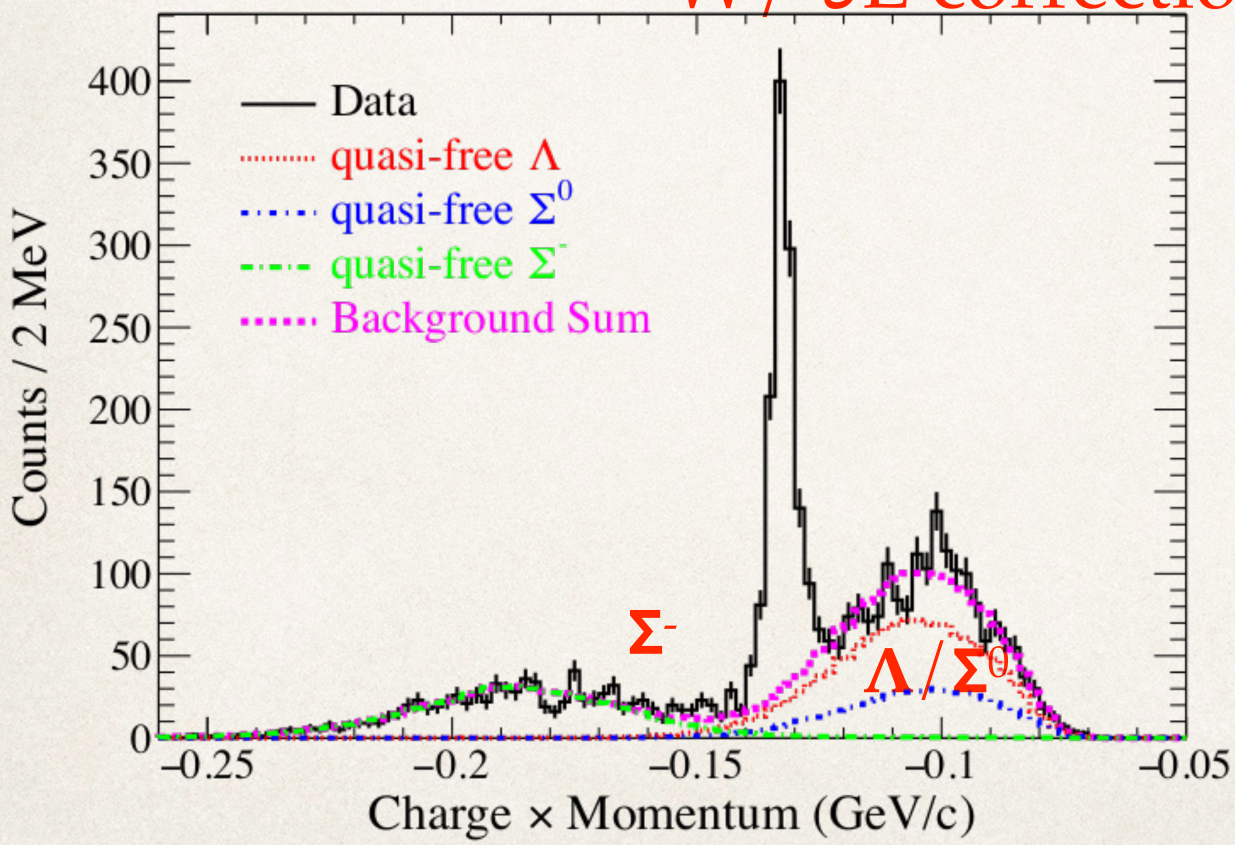
Pilot run results: ${}^4_\Lambda$H lifetime

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

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

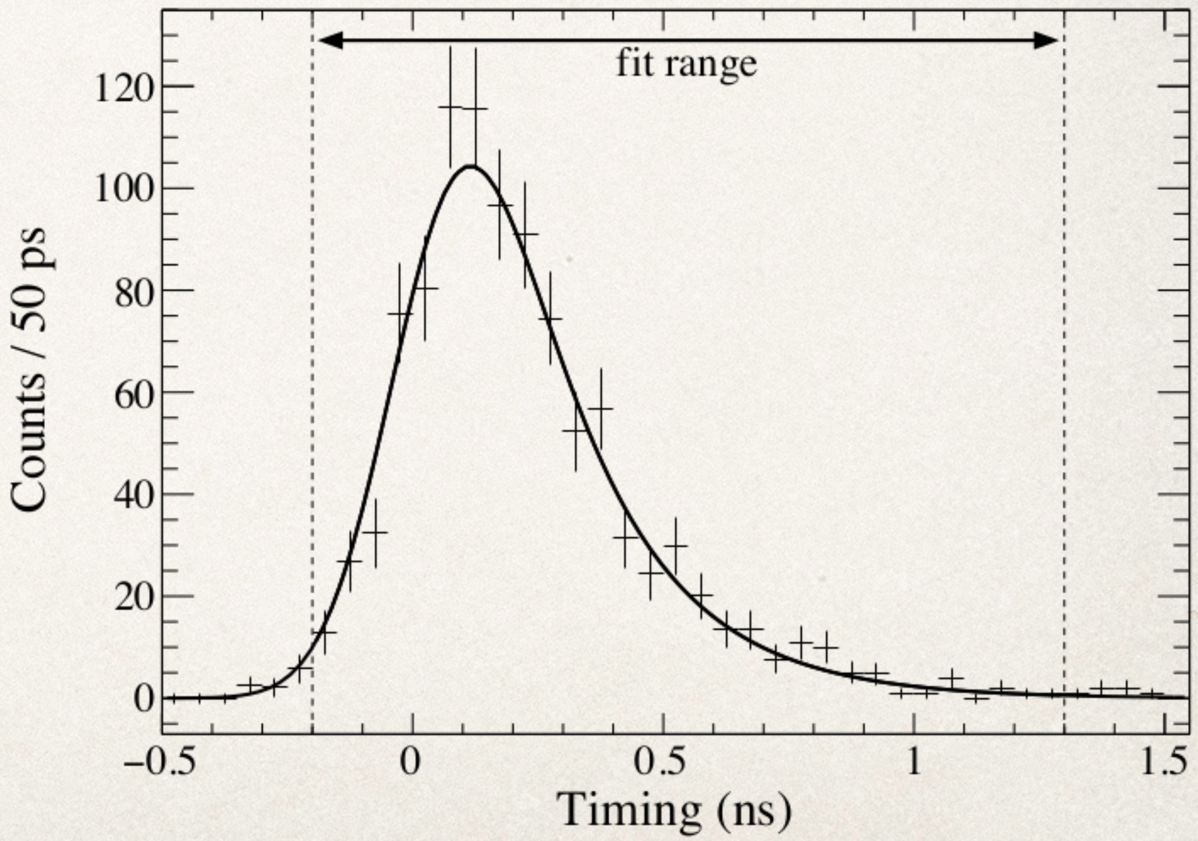
$${}^4_\Lambda\text{H} \rightarrow {}^4\text{He} + \pi^- \quad 132.9\ \text{MeV}/c$$

132.6 ± 0.1 (stat.) MeV/c
W/ δE correction



218 ± 6(stat.) ± 13(sys.) ps
@ STAR, Au-Au collision
(doi.org/10.1103/PhysRevLett.128.202301)

206 ± 8(stat.) ± 12(syst.) ps
Physics Letters B 845, 138128 (2023)
analyzed by T. Hashimoto



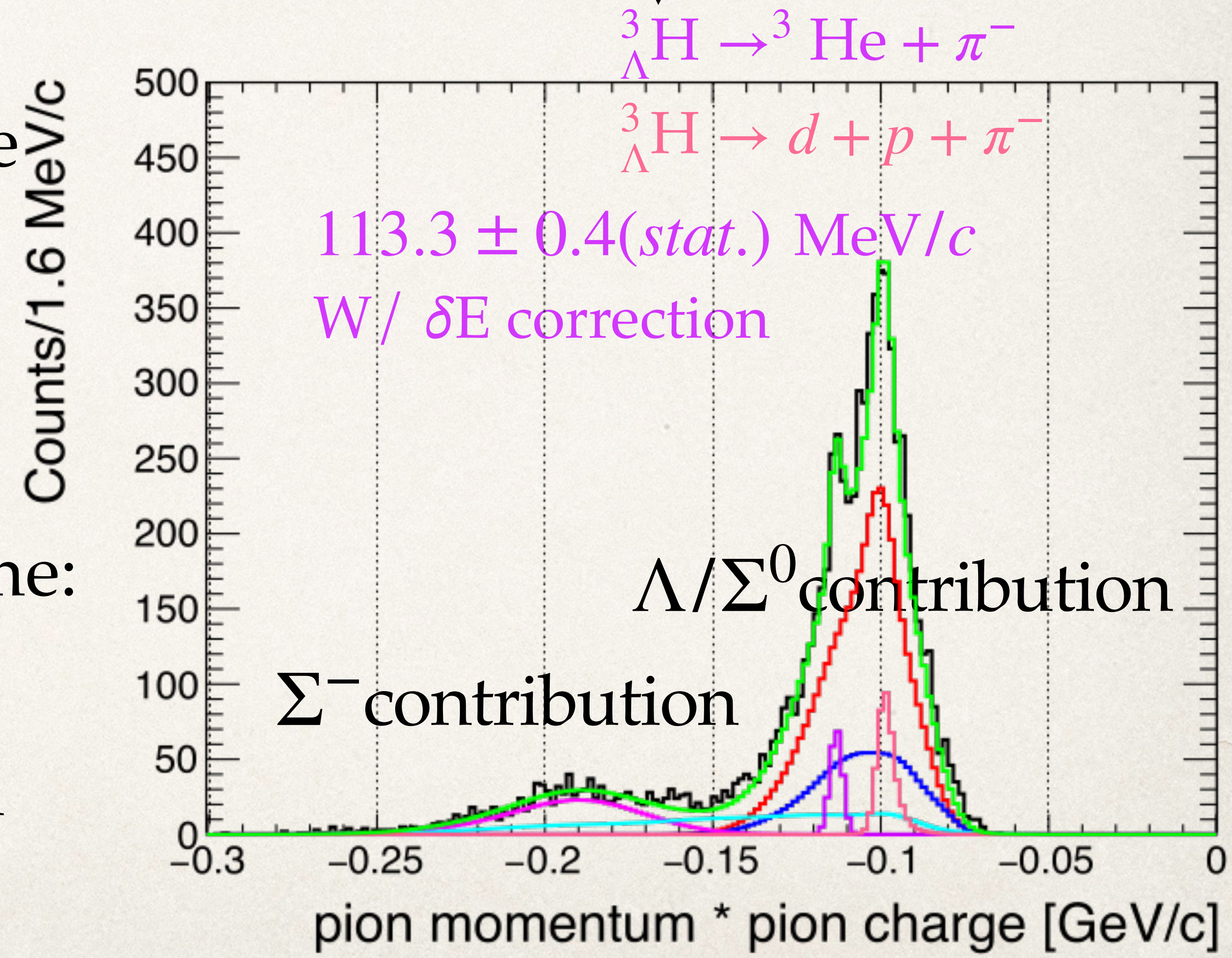
Stage-1 results: ${}^{3}_{\Lambda}\mathrm{H}$ cross section

- First measurement for ^{3}He(K-, pi0)$^{3}{}_{\Lambda}$H reaction cross section; ***direct determination of $^{3}{}_{\Lambda}$H ground state spin;***
- Ready for E73 Stage-2 beam time with 25days @ 80kW beam time for ~1k 2-body decay events scaled with Phase-1 data
- Expected precision for ${}^{3}_{\Lambda}\mathrm{H}$ lifetime:
  - statistical error ~20 ps;
  - systematic error ~20 ps based on the ${}^{4}_{\Lambda}\mathrm{H}$ result

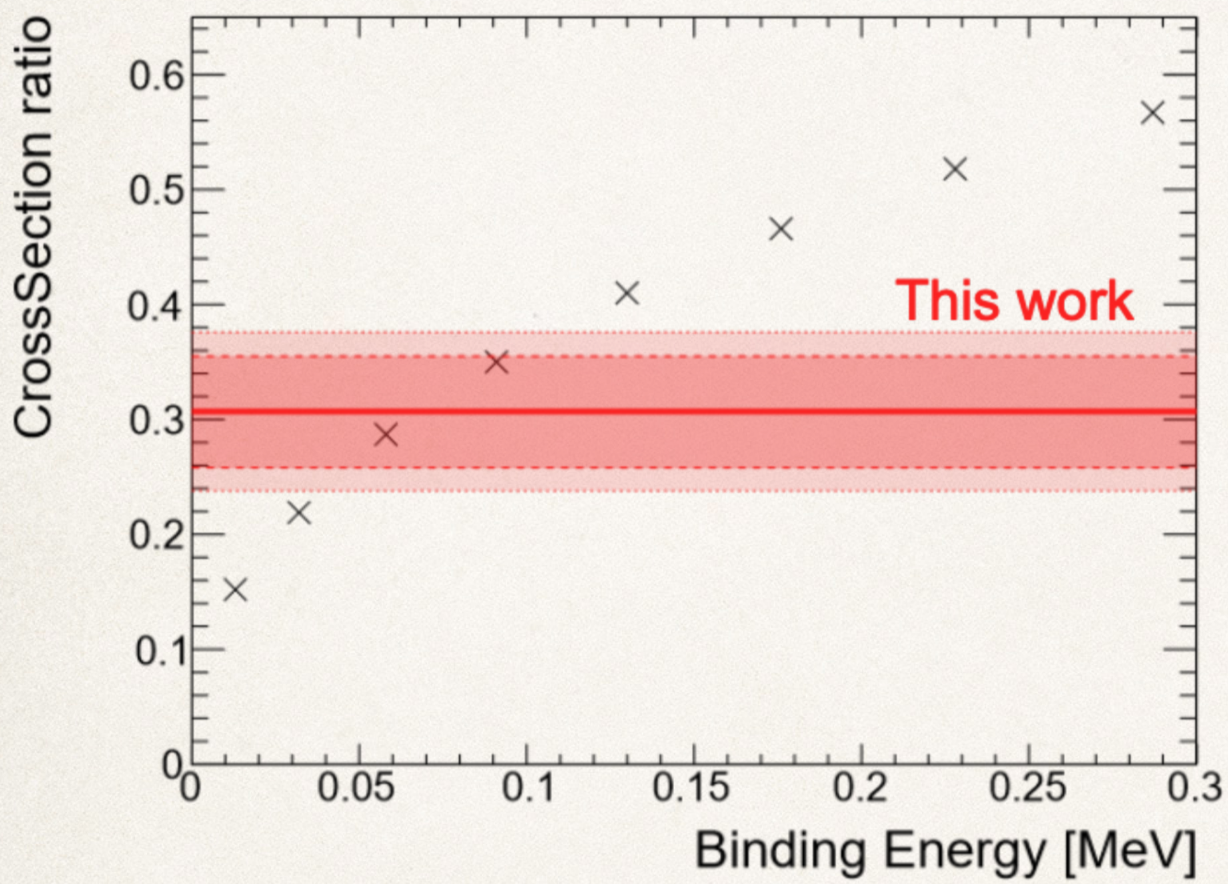
273kW*Day executed in May, 2021

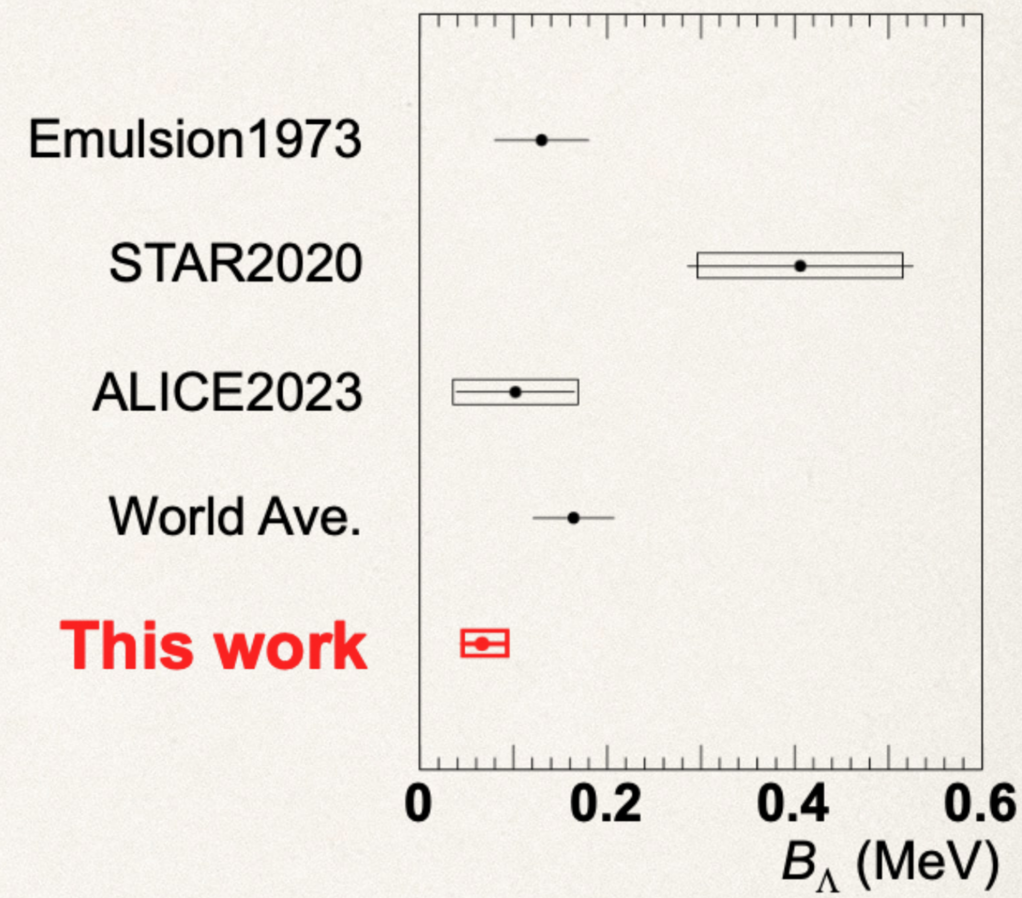
$$\mathrm{K}^{-} + {}^{3}\mathrm{He} \rightarrow {}^{3}_{\Lambda}\mathrm{H} + \pi^{0}$$

slows down and decays at rest



Dr. T. Akaishi's new approach for ${}^{3}_{\Lambda}\mathrm{H}$ B_{Λ}





Dr. T. Akaishi successfully derived B_{Λ} with impressive precision by measuring $\sigma_{{}^{3}_{\Lambda}\mathrm{H}}/\sigma_{{}^{4}_{\Lambda}\mathrm{H}}$ obtained from E73 pilot run and Stage-1 data utilizing the fact that the production cross section is sensitive to B_{Λ} as supported by Prof. Harada

PhD thesis submitted to Osaka University
10.1016/j.nuclphysa.2021.122301

Summary

- E73 aims to shed light on the Hypertriton lifetime puzzle
    - We established a new method to investigate the isospin mirror hypernuclei by gamma-ray tagging
    - E73 is ready for final data taking NEXT MONTH
- 岩崎さん、おめでとうございます！
- Thank you for your patience!

E73/T77 collaborator list

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]

[1]Osaka University, Toyonaka, 560-0043, Japan
[2]RIKEN, Wako, 351-0198, Japan
[3]High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
[4]Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
[5]Institute of Modern Physics, Gansu 730000, China
[6]School of Nuclear Science and Technology, Lanzhou University, Gansu 730000, China
[7]Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy
[8]Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Magurele, Romania
[9]CENTRO FERMI - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, 00184 Rome, Italy
[10]Tohoku University, 982-0826, Sendai, Japan

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