Current status of hypertriton lifetime measurement with J-PARC E73 experiment

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Outline

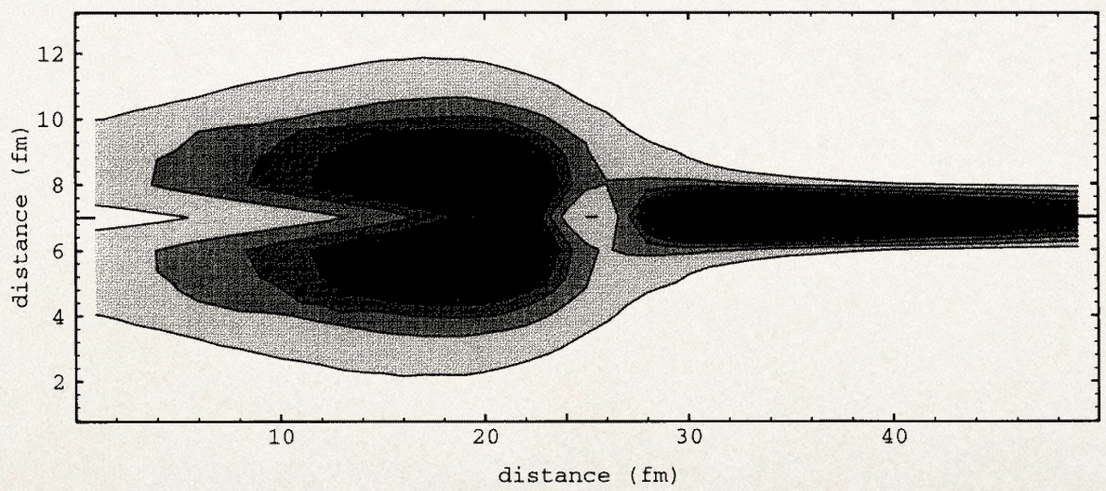
- Introduction & motivation
- J-PARC E73:
  - Experimental method
  - Current status
- Summary

Introduction & motivation

Quiz: ${}^{3}_{\Lambda}\mathrm{H}$ vs ${}^{208}\mathrm{Pb}$ 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 ${}^{208}\mathrm{Pb}$ ~7fm

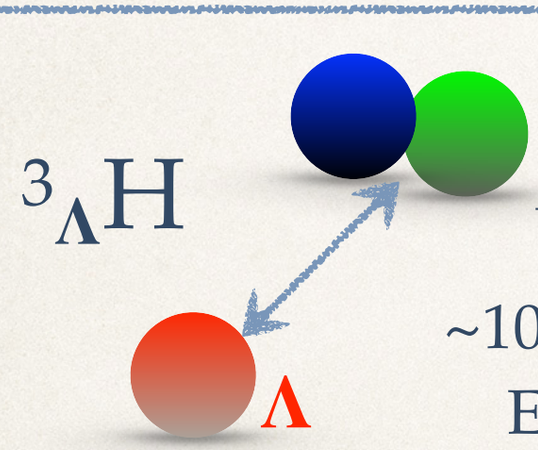
assuming liquid drop model



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).

$^{3}_{\Lambda}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \pi^-$ 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

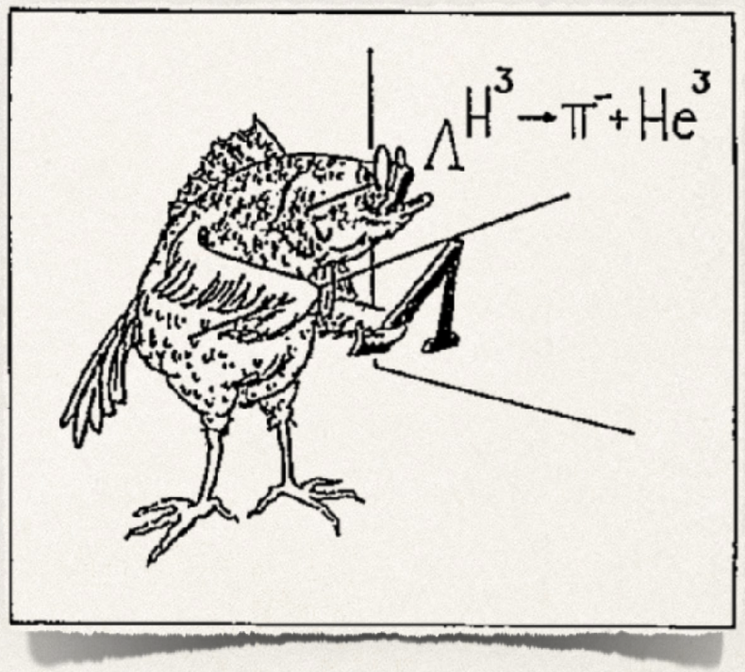
As the lightest hypernucleus,
$^{3}_{\Lambda}$H should tell us some
important fact of YN interactions
just as deuteron for nuclear physics.

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
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$33(syst.)	2016 [3]
		242^{+34}_{-38}(stat.)$\pm$17(syst.)	2019 [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

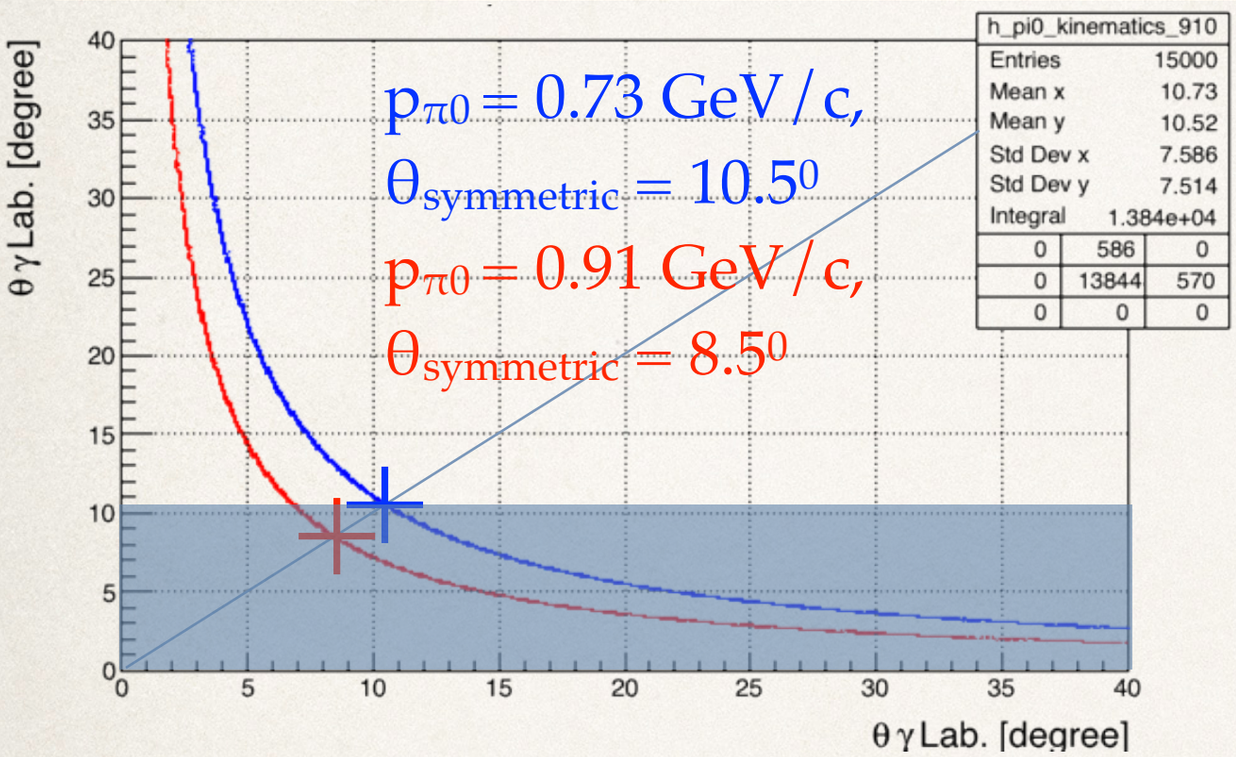
J-PARC E73 experimental method

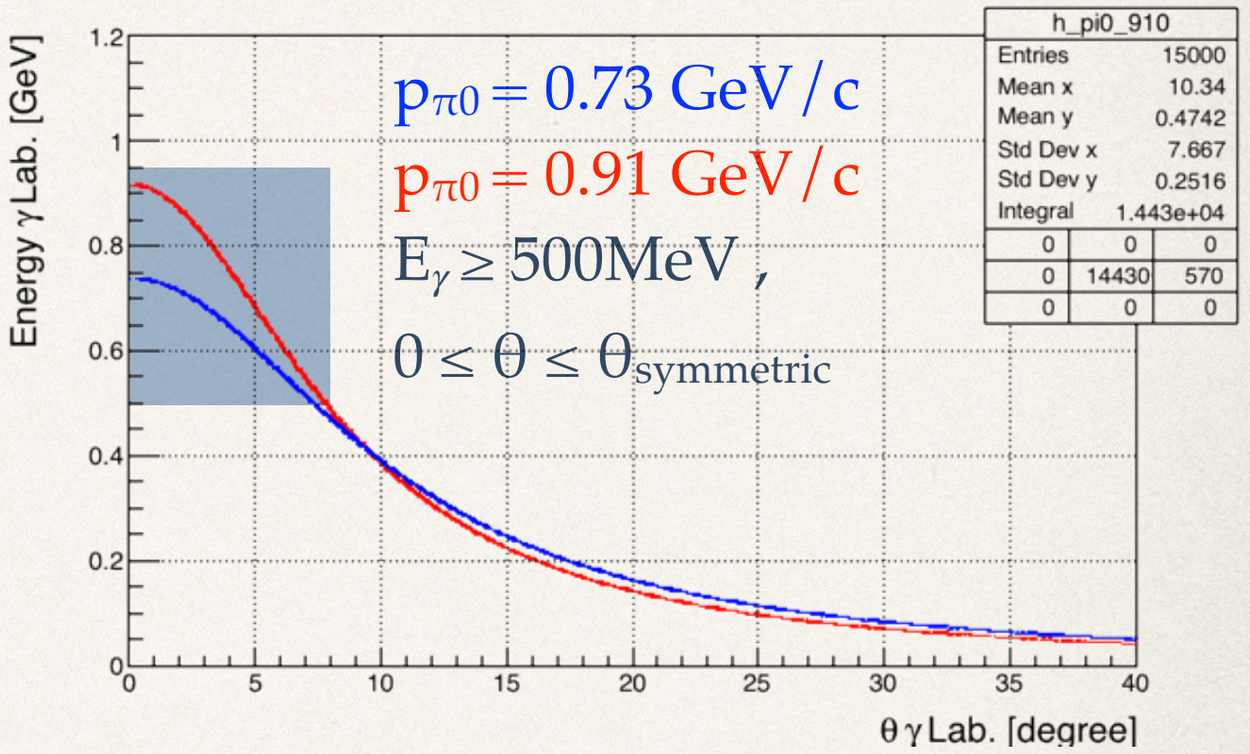
Methods for *J-PARC E73*

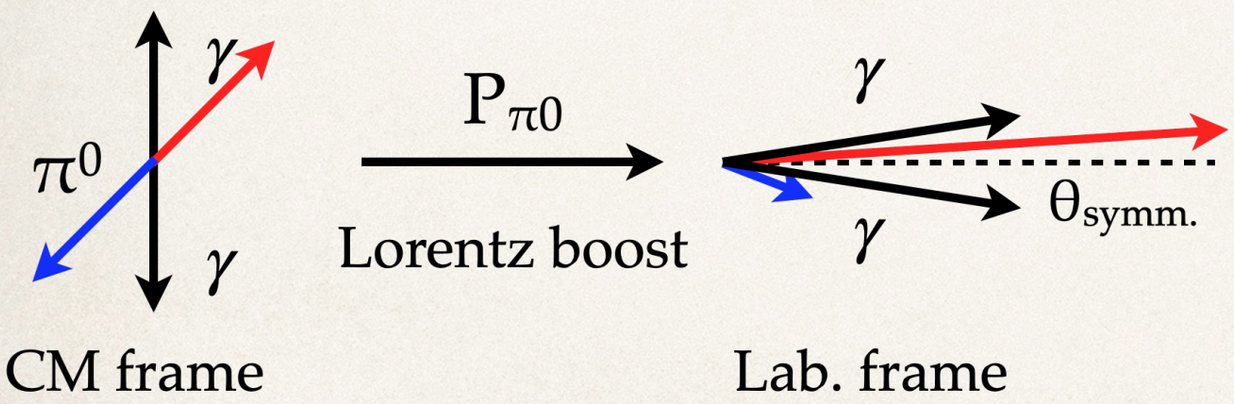
- K- + He3 --> pi0 + Hypertriton
  - how to detect pi0 --> decays into 2 gammas almost immediately?

Experiment	J-PARC E73	BNL STAR
Production method	^{3}He(K-, pi0)$^{3}_{\Lambda}$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

Revisit π^0 decay kinematics







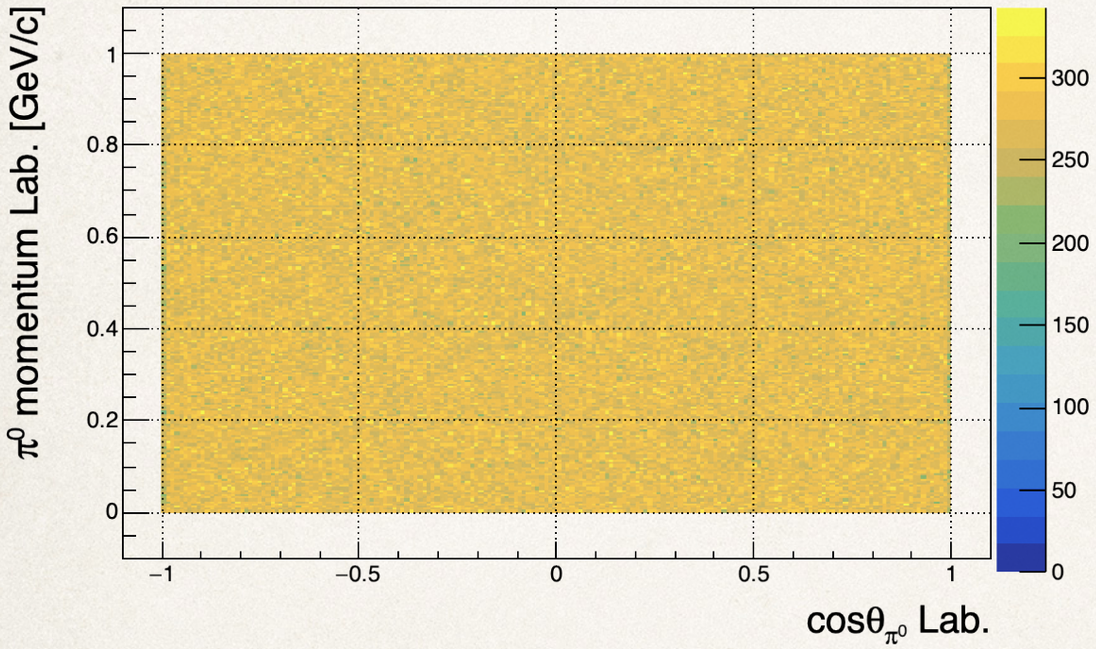
- 0.73~0.91GeV/c π^0 boosts γ forwardly;
- By covering $0 \sim \theta_{symmetric}$, tag the γ with higher energy ($E_\gamma \geq 500$MeV)

- γ-ray tagger needs to be ***located along beam line***
- ***Fast response, radiation hardness***

Do we *really* need missing mass?

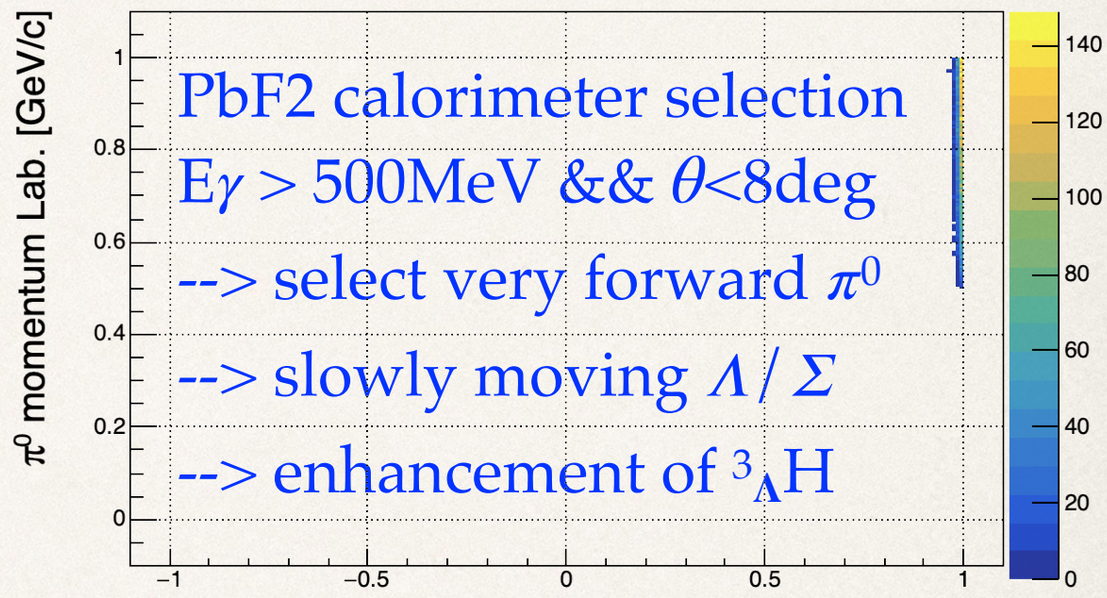
Input

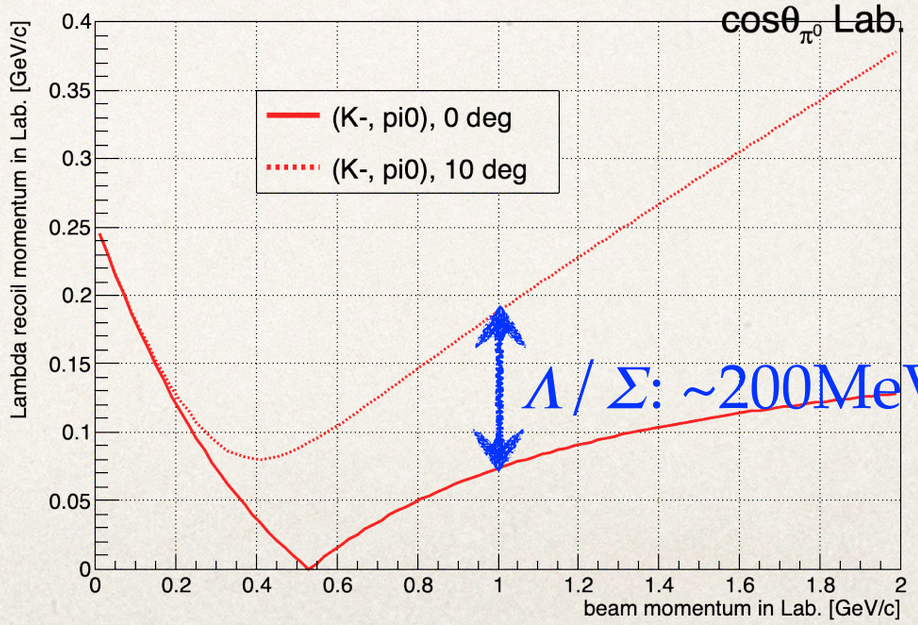
π^0: 0~1GeV/c; 0~180deg



W/ PbF2 calorimeter cut

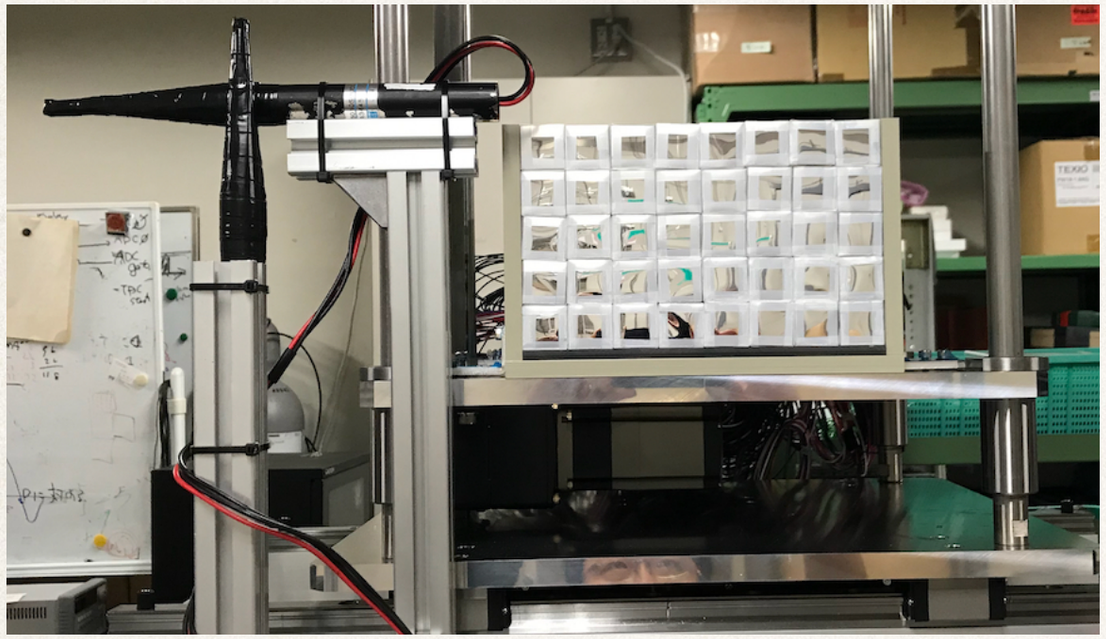
π^0: 0.8~1GeV/c; 0~10deg

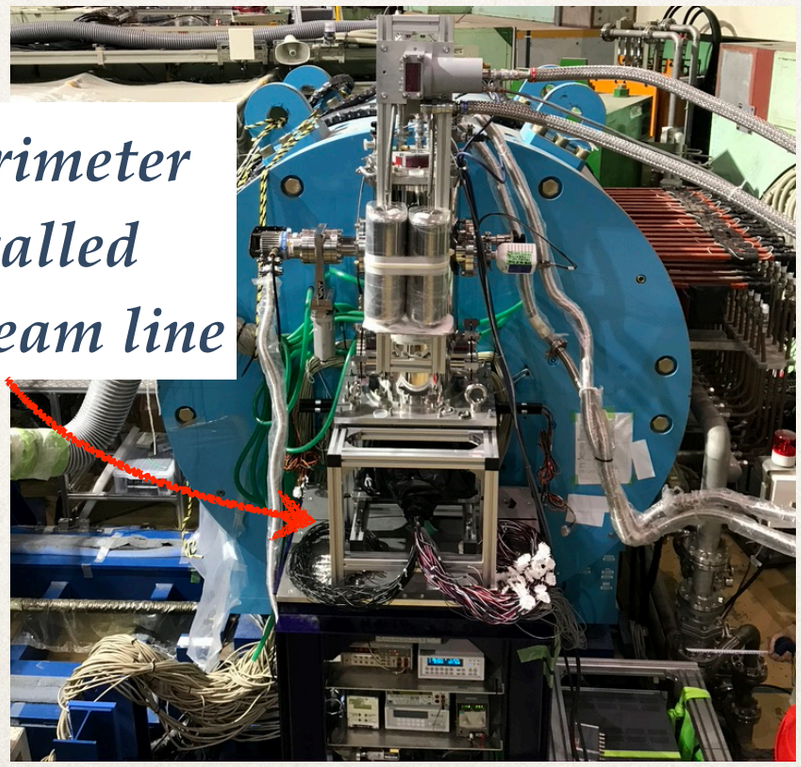




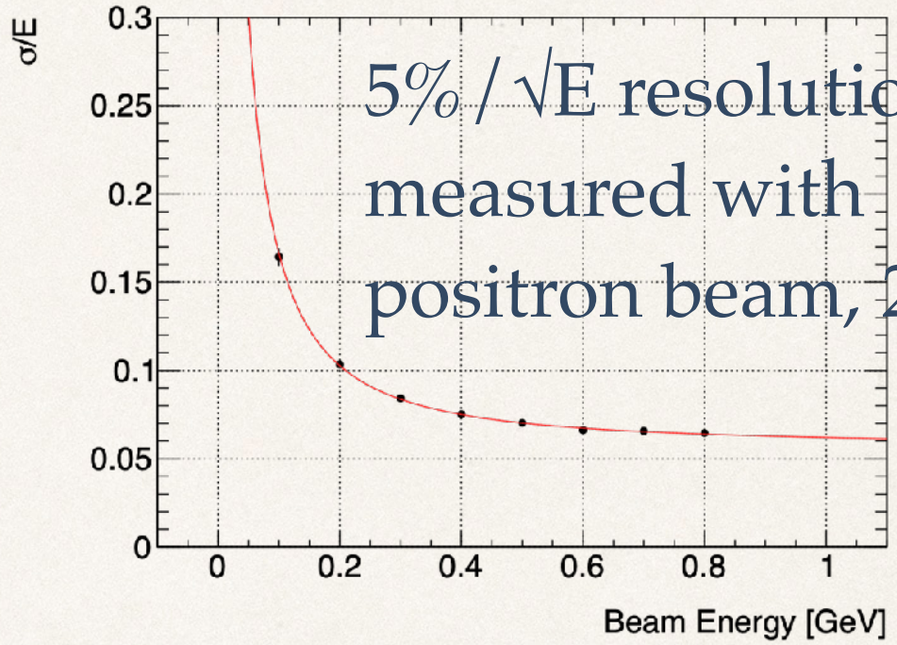
- γ-ray tagger needs to be
  located along beam line
- ***Fast response, radiation hardness***

PbF2 calorimeter performance @ELPH

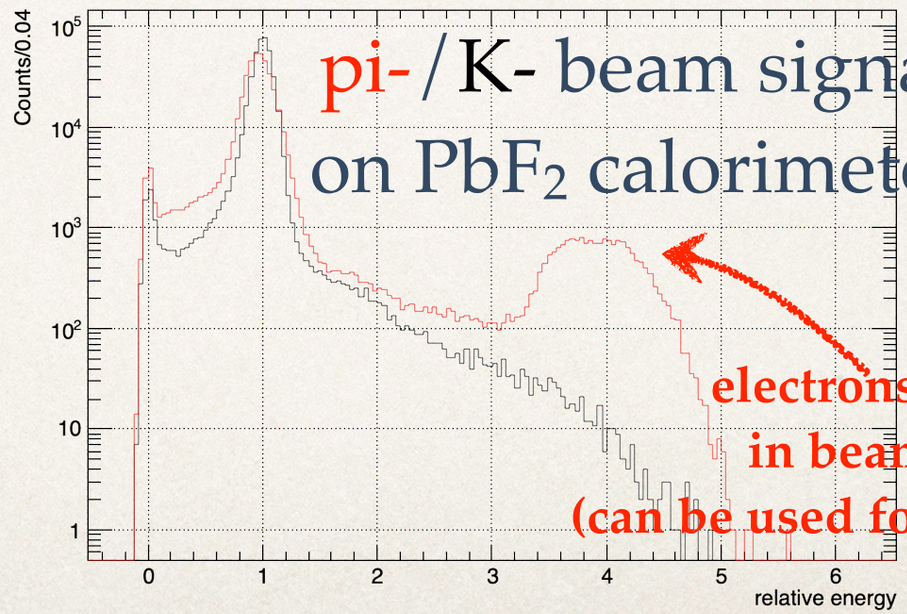




PbF2 calorimeter was installed INTO the beam line



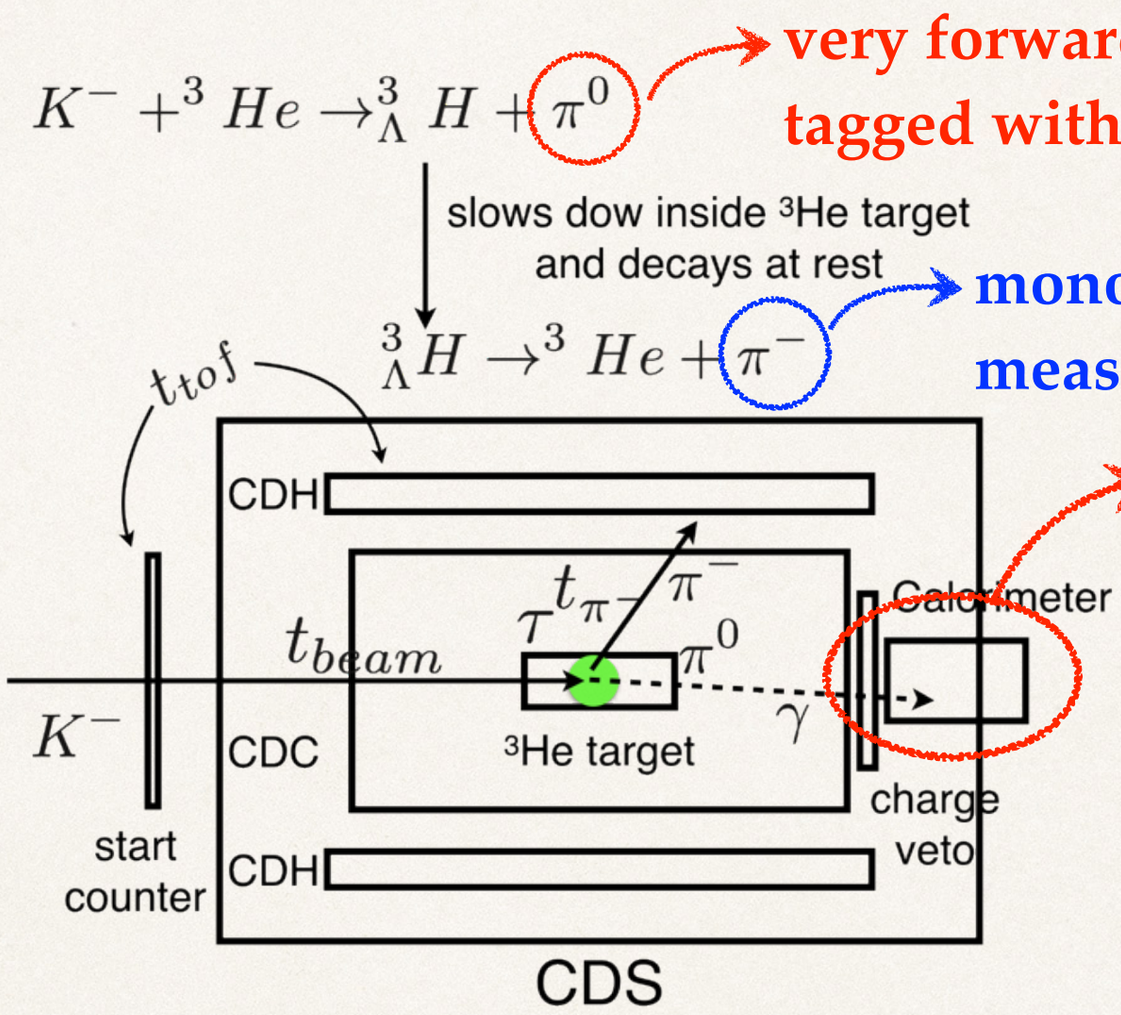
5%/√E resolution measured with positron beam, 2019



pi- / K- beam signal on PbF_2 calorimeter

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

E73 Experimental setup



very forward π0 projectile;
tagged with decayed high energy γ

mono-energetic, ~114MeV/c;
measured with CDS

5x8 PbF2 Cherenkov Calo
R&D has been completed

${}^3_\Lambda$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: $\sigma/\sqrt{N}$ ~ 30ps

J-PARC E73 current status

Current status of J-PARC E73

Staging:	Stage-0	Stage-1	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:	Accomplished in June, 2020	Accomplished in May, 2021	Ready for beam time in early 2023

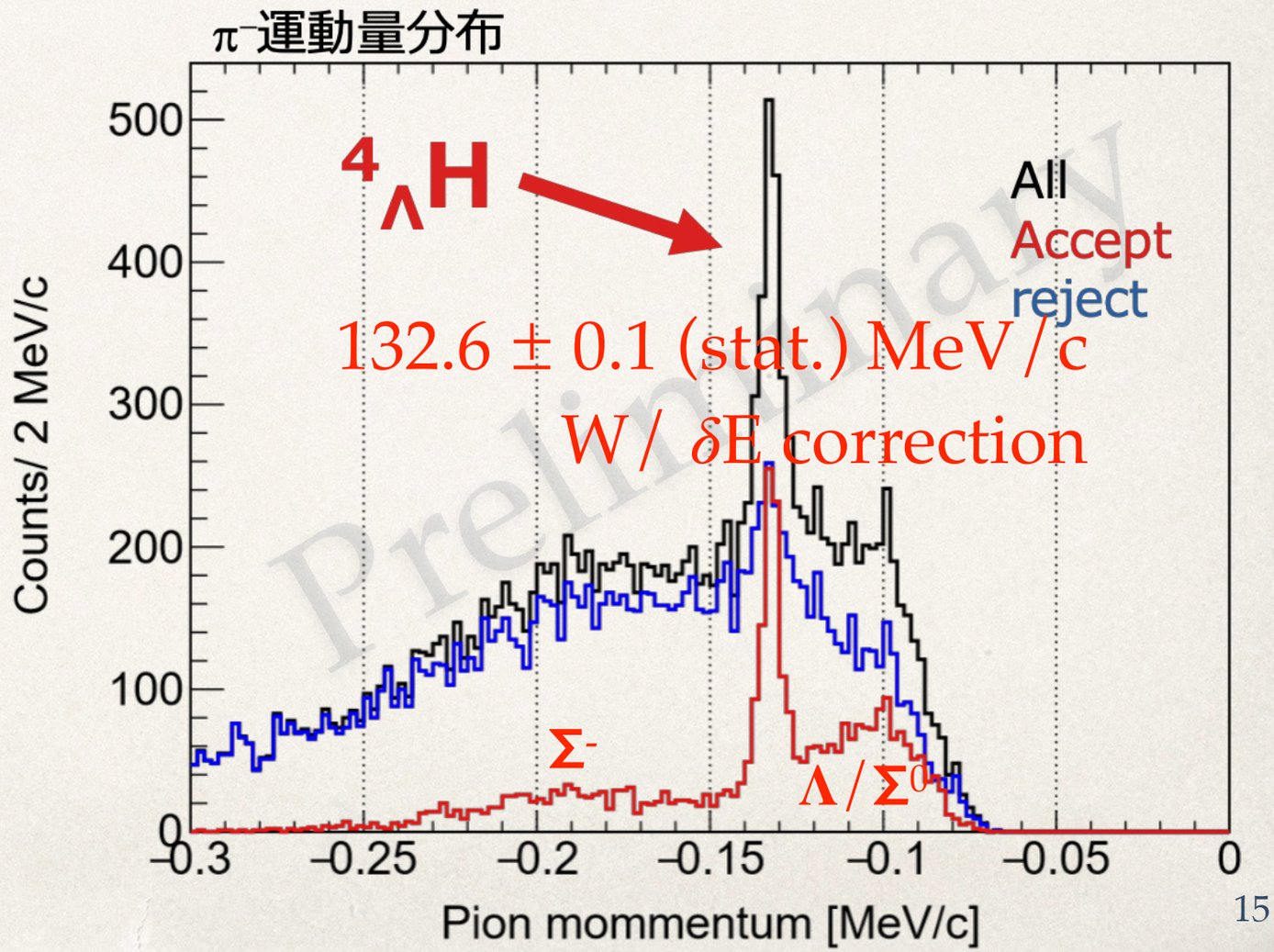
Stage-0: feasibility study for E73

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

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

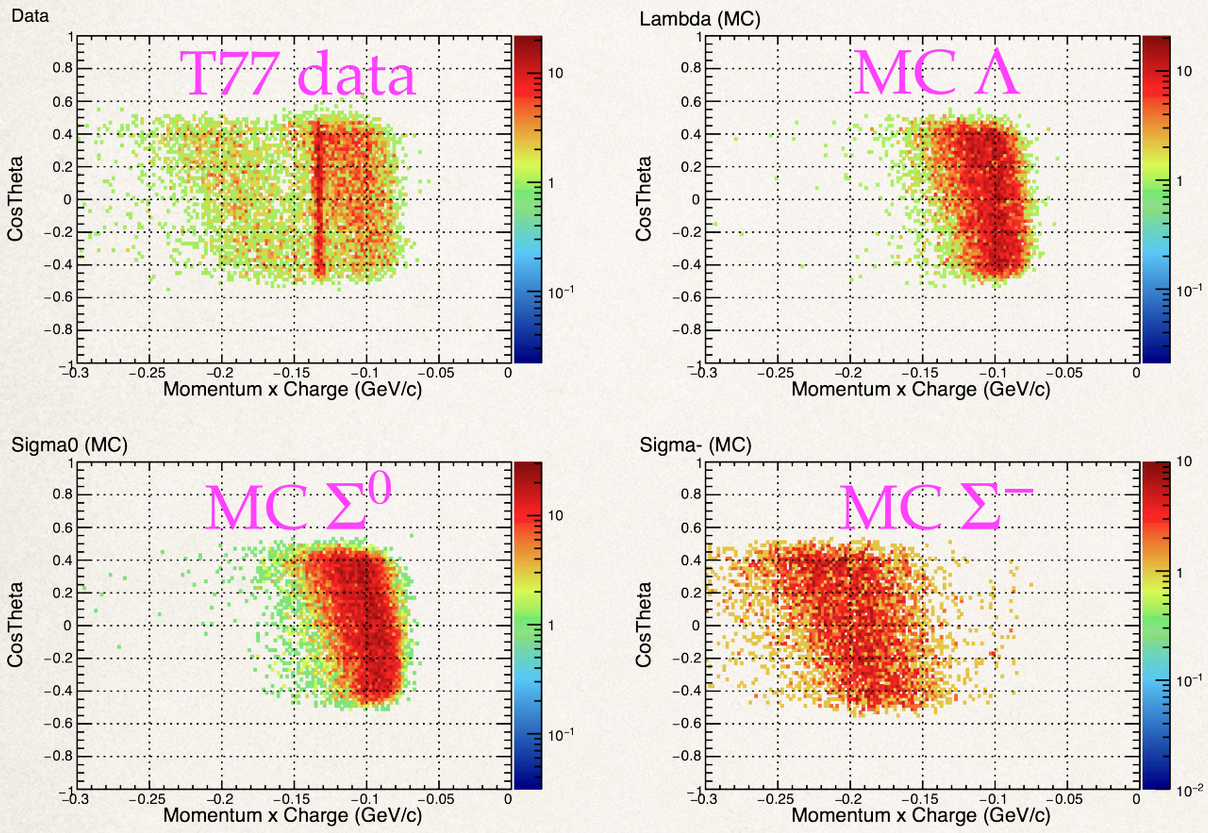
$${}^4_\Lambda H \rightarrow {}^4He + \pi^- \; 132.9\ \mathrm{MeV/c}$$

- T77 refreshes world record for $^4_\Lambda$H statistics by twice (***1.2k events***);
- New method improves S/N by ~ 10 times;
- ***All these happen within 3days of beam time!***

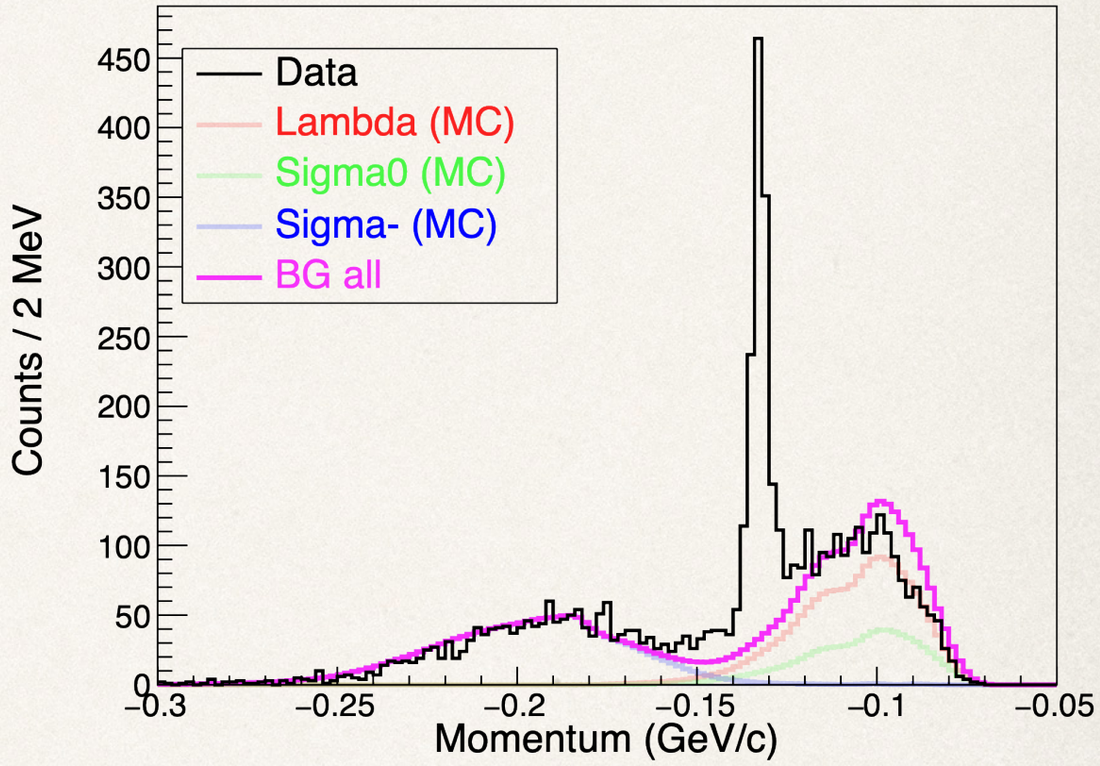


Stage-0: simulation validation

decay π^- momentum vs angle



MC yield tuned to match data



GEANT4 based simulation for quasi-free Λ/Σ in-flight decay;

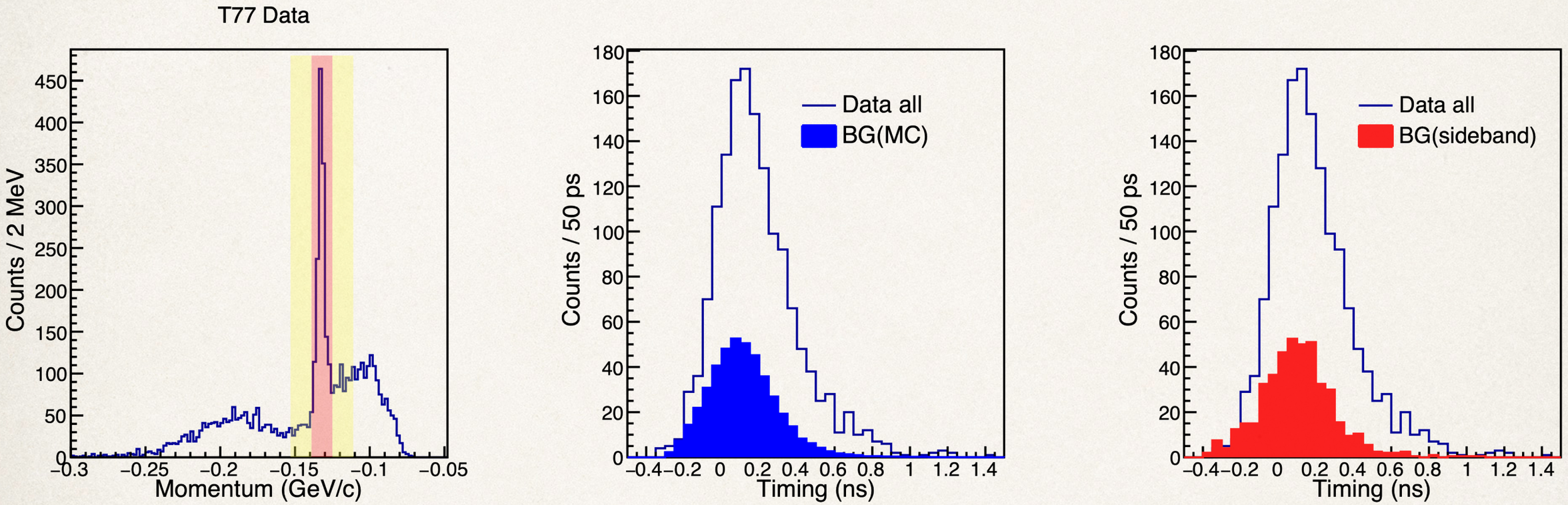
$N(K^-, \pi^0)$Y elementary reaction with published data +

convoluted with Argonne AV18+UX Fermi motion

R.B. Wiringa et al, Phys. Rev. C **89**, 024305

Stage-0: ${}^{4}_{\Lambda}\mathrm{H}$ lifetime analysis

Good agreement between MC and data.



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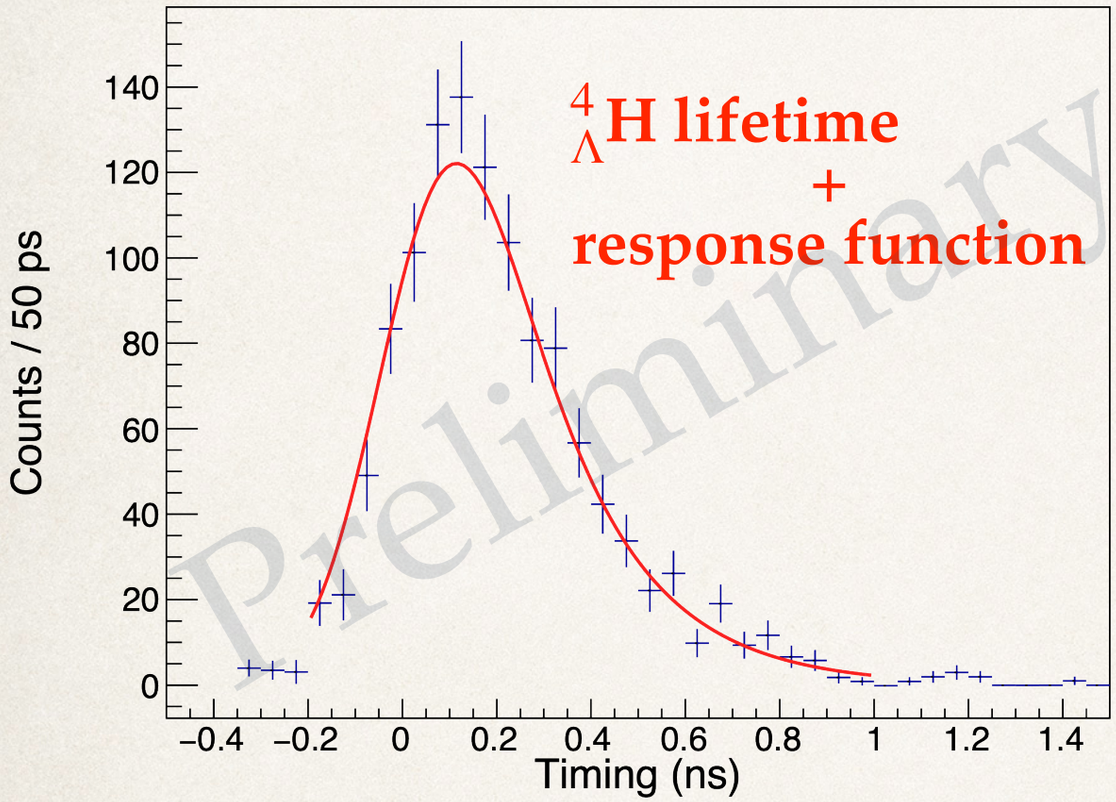
Stage-0: ${}^{4}_{\Lambda}$H lifetime analysis

190 ± 8(stat.)±??(sys.) ps



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

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

218 ± 6(stat.) ± 13(sys.) ps

@ STAR, Au-Au collision

arXiv:2110.09513

Our result is amongst the most precise data;

Finalizing the data analysis and preparing for publication.

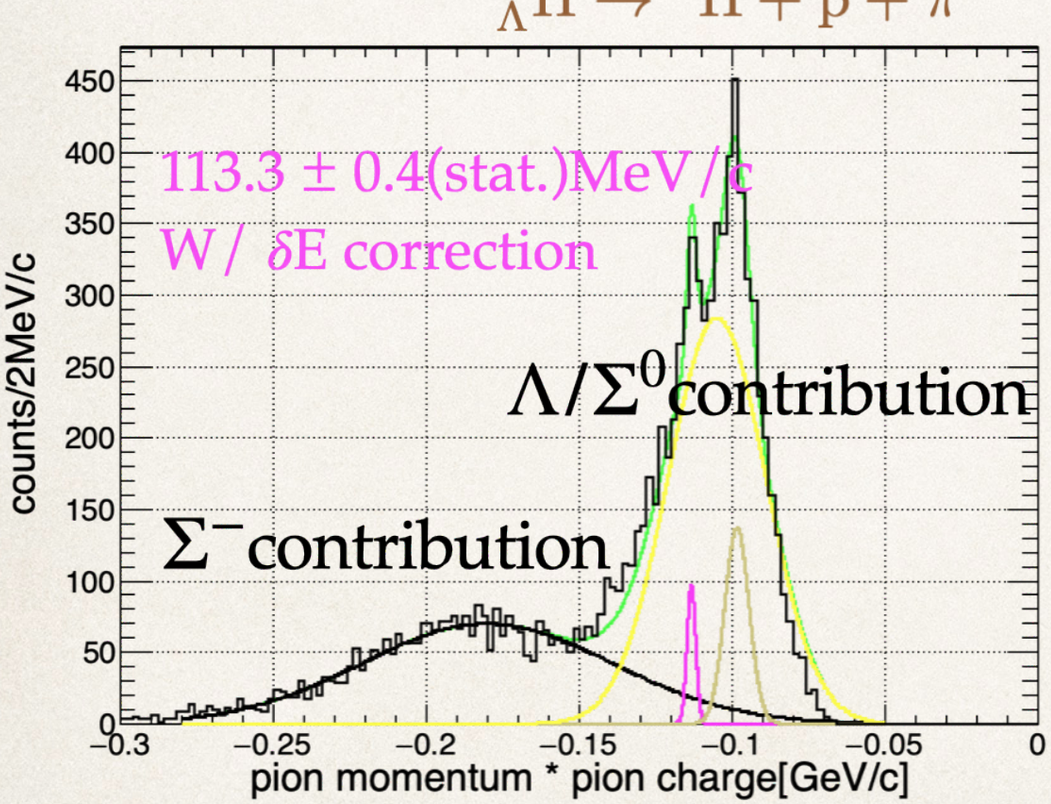
Stage-1: cross section & spin of ${}^{3}_{\Lambda}\mathrm{H}$

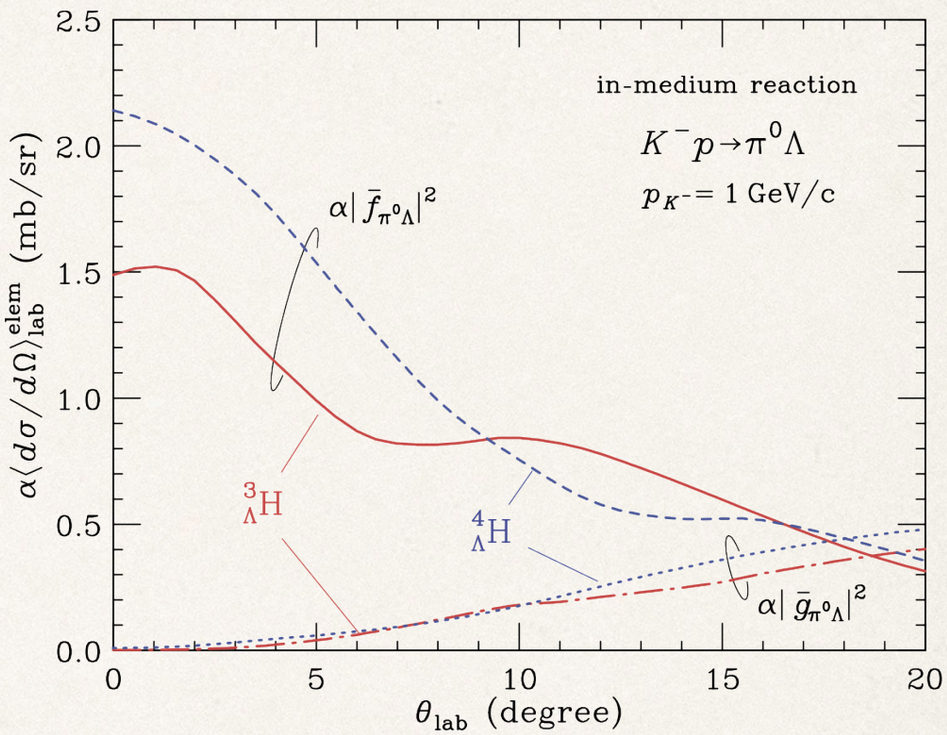
$$\mathrm{K}^- + {}^3\mathrm{He} \rightarrow {}^3_\Lambda\mathrm{H} + \pi^0$$

slows down and decays at rest

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

$${}^3_\Lambda\mathrm{H} \rightarrow {}^2\mathrm{H} + \mathrm{p} + \pi^-$$



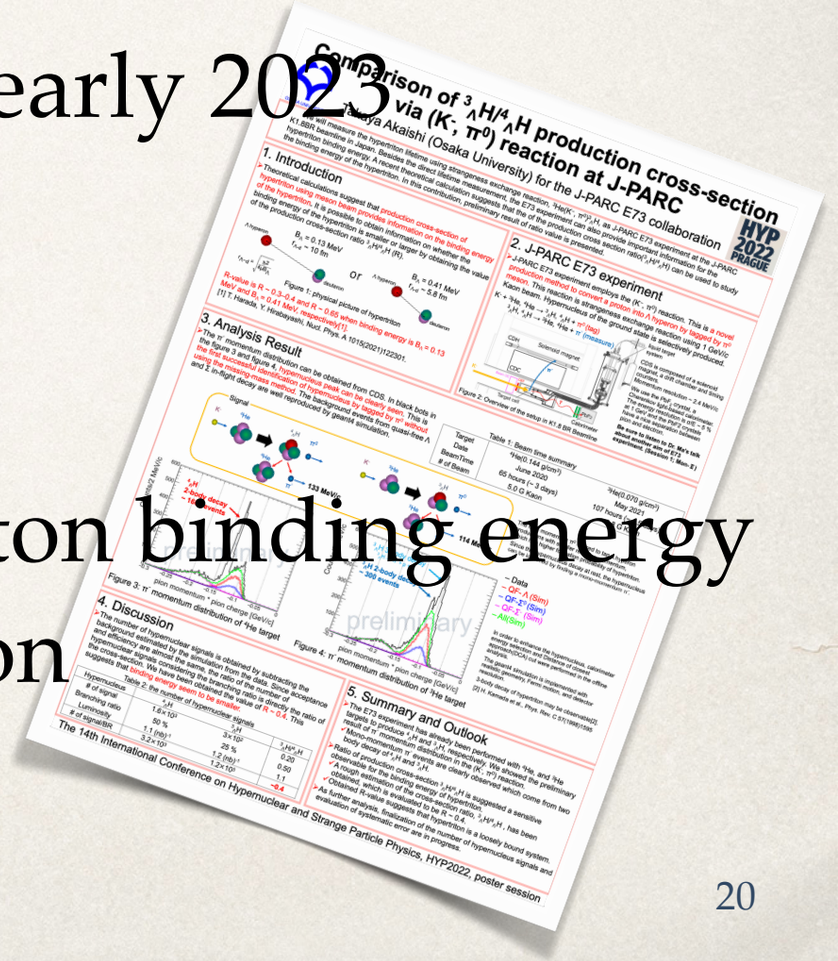


- First direct proof of ${}^3_\Lambda\mathrm{H}$ g.s. spin=1/2
  - ${}^4_\Lambda\mathrm{H}/{}^3_\Lambda\mathrm{H}$ cross section is consistent with Prof. Harada's calculation
- Invitation for theorists: derive ${}^3_\Lambda\mathrm{H}$ binding with 3-body decay mode?

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 in early 2023
- Mr. T. Akaishi's poster tomorrow:
  - His original idea to derive Hypertriton binding energy by comparing H3L/H4L cross section



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]

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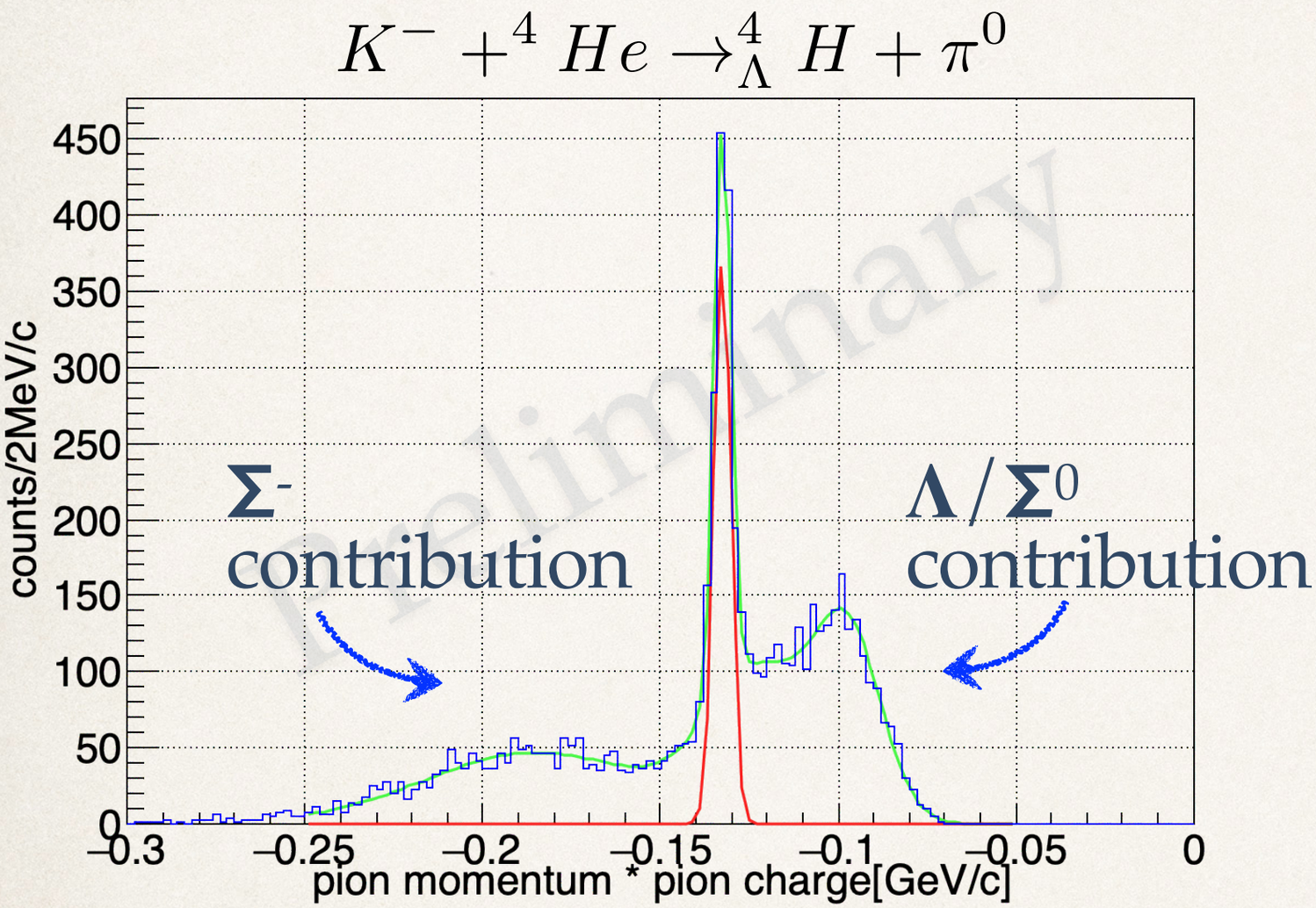
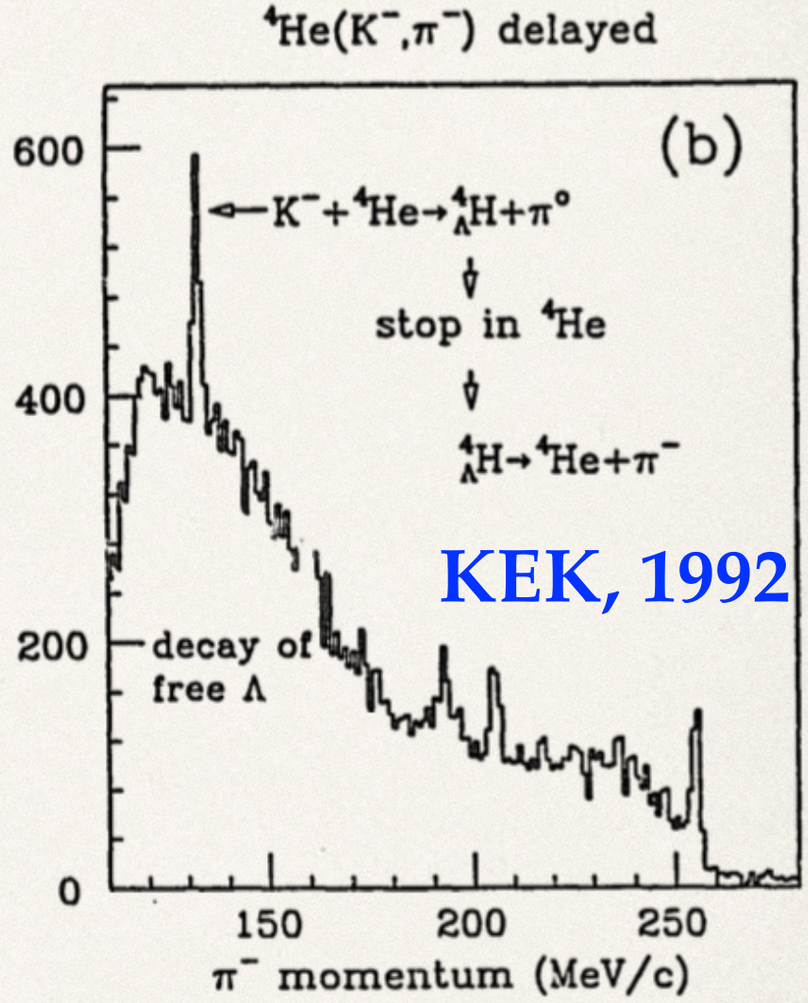
[8]Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Magurele, Romania
[9]CENTRO FERMI - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, 00184 Rome, Italy
[10]Tohoku University, 982-0826, Sendai, Japan

Backup

Stage-0: pi- spectrum from $^4_\Lambda$H

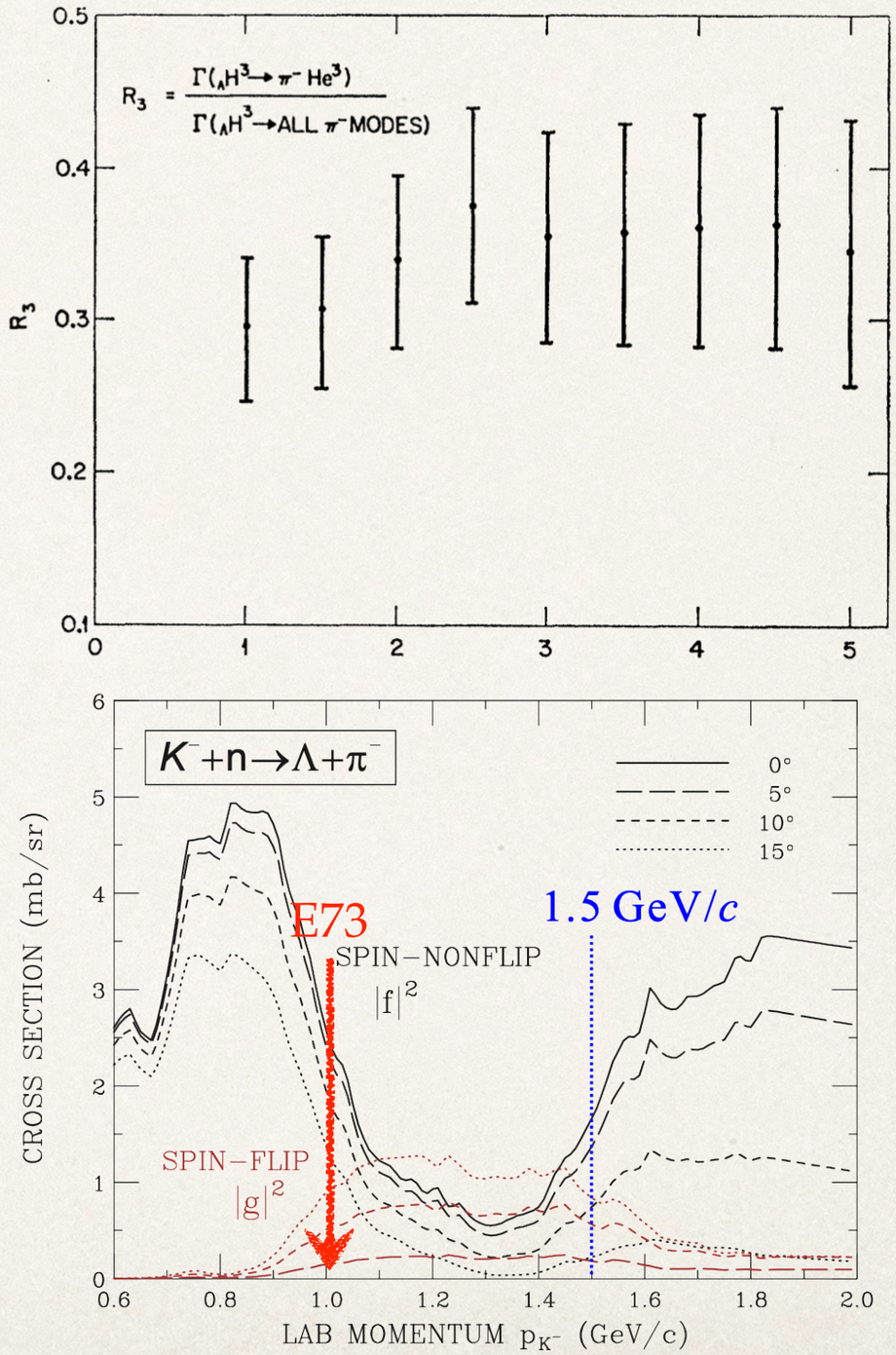




- T77 refreshes world record for $^4_\Lambda$H statistics by twice;
- New method improves S/N by ~ 10 times;
- ***All these happen within 3days of beam time!***

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

- Hypertriton isospin:
  - ${}^{4}\mathrm{He}$: T=0 & ${}^{3}\mathrm{He}$: T=1/2
  - ${}^{3}\mathrm{He}(K^{-}, \pi^{0}){}^{3}_{\Lambda}\mathrm{H}$ --> ${}^{3}_{\Lambda}\mathrm{H}$: T=0
- Hypertriton ground state spin is determined by two-body/ three-body ratio and no direct determination so far...
- E73 stage-1 experiment can contribute on this issue.
  - Thanks to the spin non-flip dominant (K^{-}, π^{0}) reaction



https://doi.org/10.1103/PhysRevD.1.66; Dr. T. O. Yamamoto's PhD thesis