Towards solving the hypertriton lifetime puzzle with *direct lifetime measurement*: current status of J-PARC E73 experiment

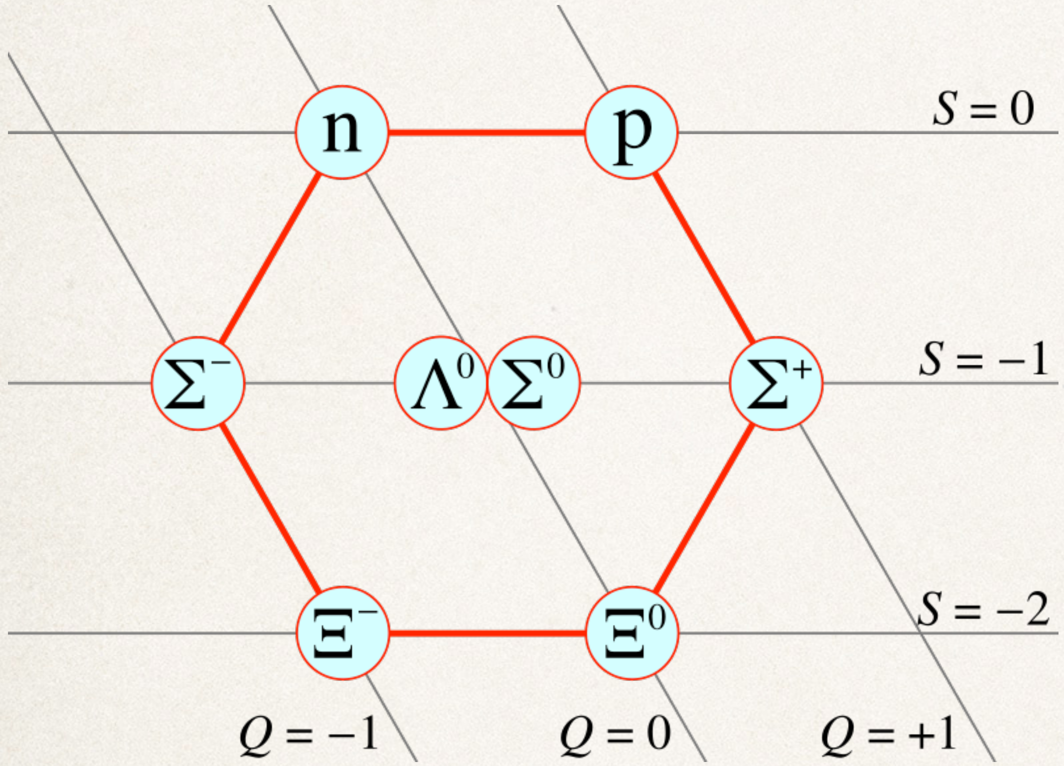
y.ma@riken.jp

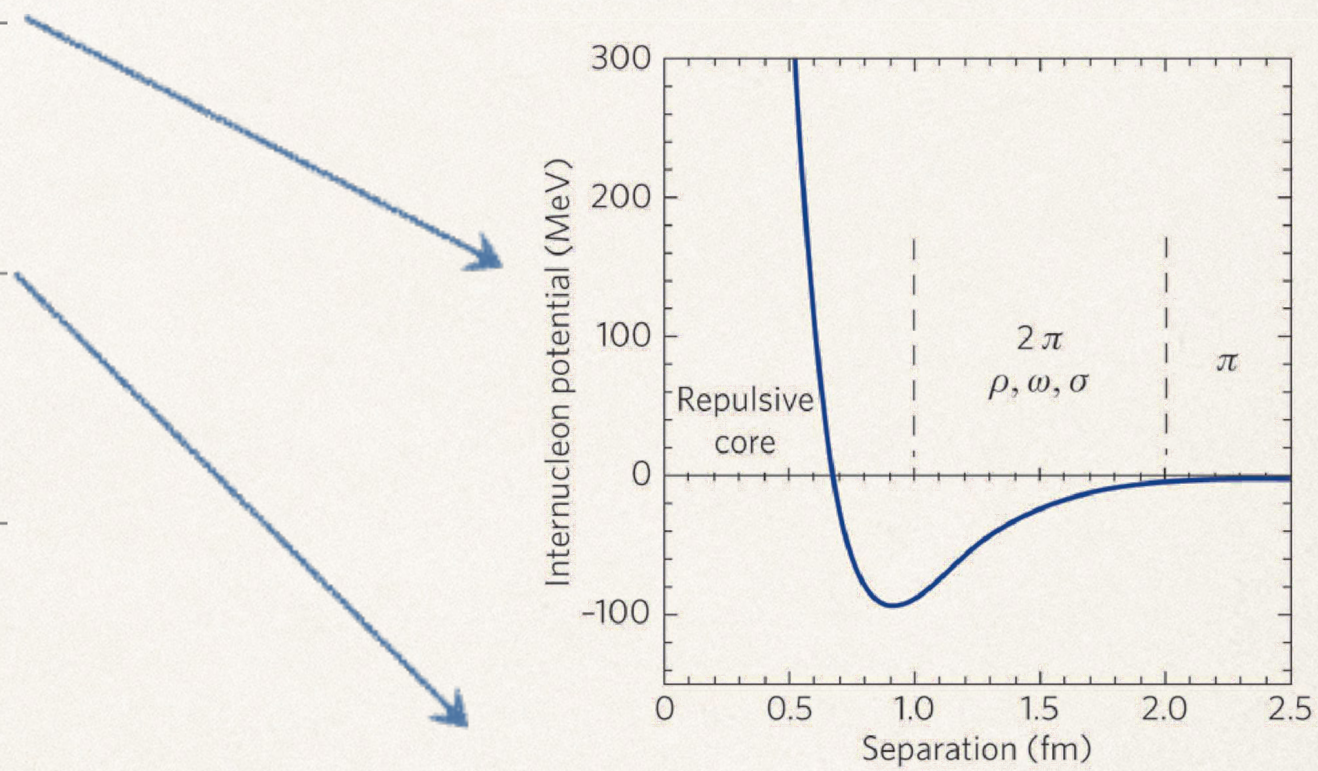
2021/03/05

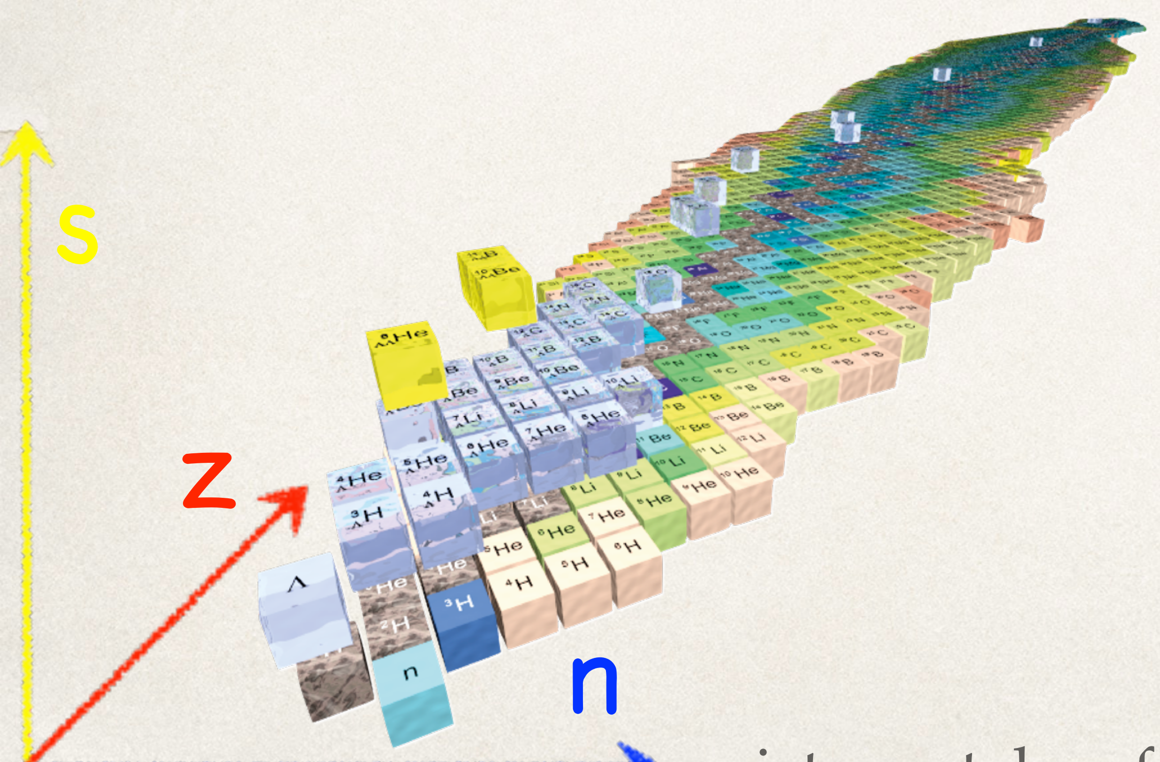
Outline

- 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

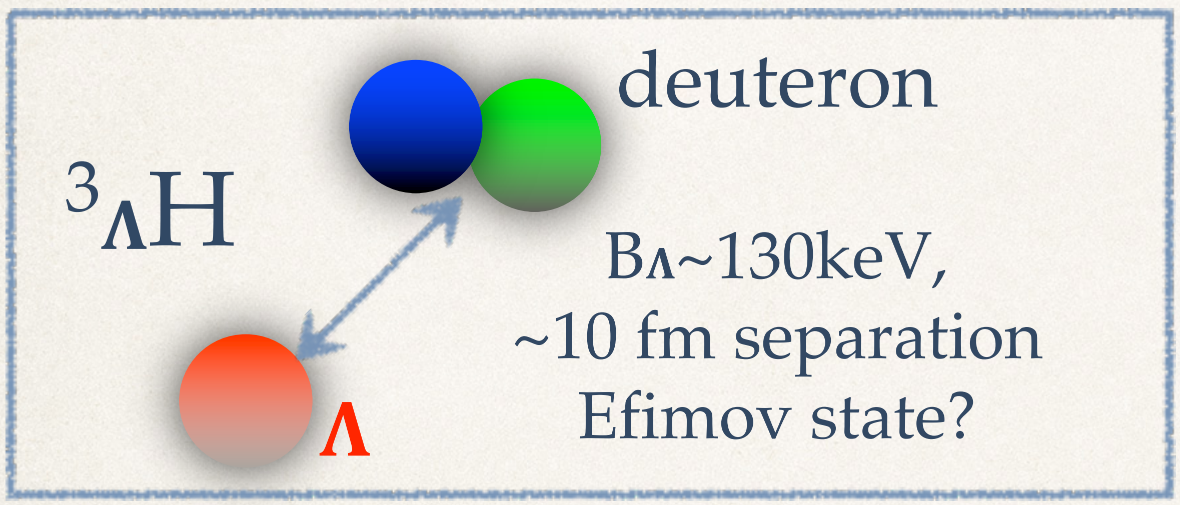
pictures taken from Hyp06 poster and Nature

Quiz: which one is "*bigger*"?

- Hypertriton($^{3}_{\Lambda}H$: **Λ**+n+p) vs Pb208 (82p + 126n)
  - Which one is bigger?? (a good homework for your student)
  - Hint: a harmonic oscillator toy model, or, r ~ sqrt($\hbar^2/4uB_\Lambda$)
- Hypertriton: **Λ**(T=0) + d(T=0) @ ~130keV binding energy --> ~10fm; Pb208: ~7fm
- Answer: Hypertriton is *"bigger"* than Pb208

Introduction: motivation

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 mod

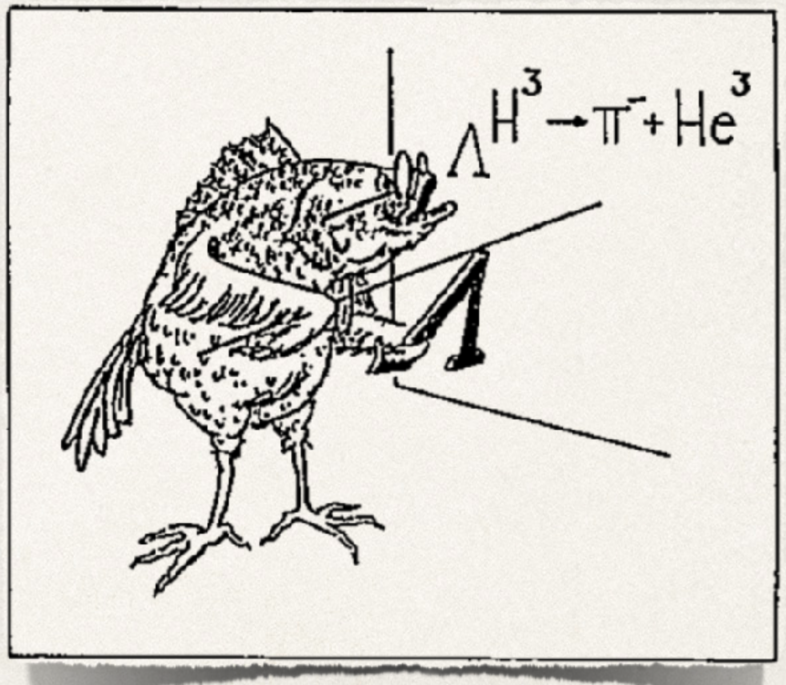
Introduction: motivation

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
ALICE	Pb collider	240^{+40}_{-31}(stat.)±18(syst.)	2019
STAR	Au collider	142^{+24}_{-21}(stat.)±29(syst.)	2018
HypHI	fixed target	183^{+42}_{-32}(stat.)±37(syst.)	2013

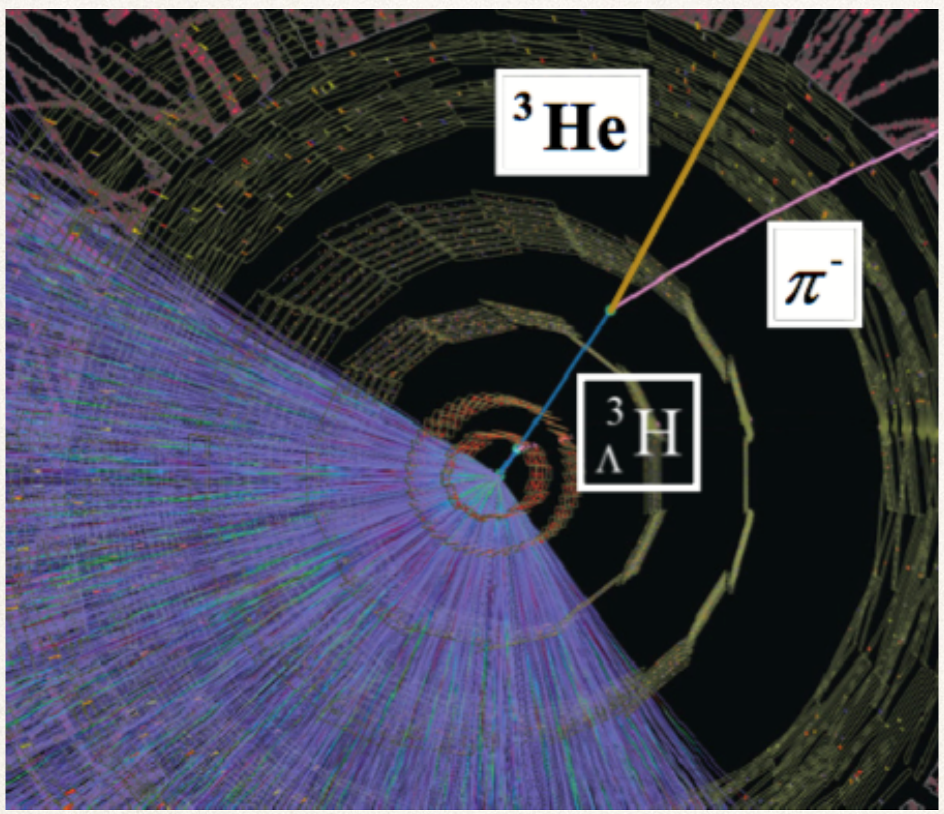


Neither fish nor fowl?

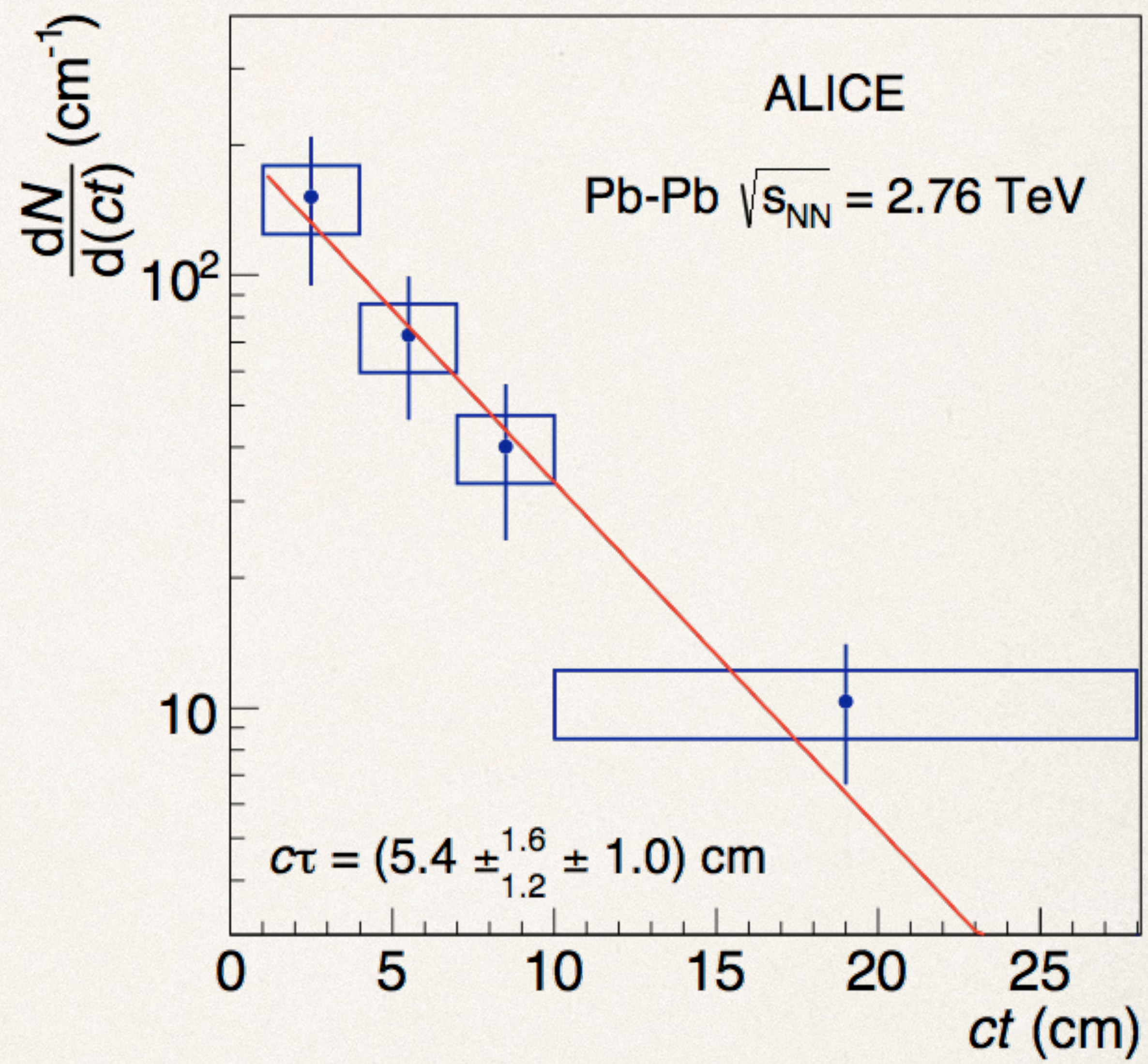
Picture taken from MM. Block et al. Proc. Int. Conf. Hyperfragments, 1963

Heavy ion experiments: *indirect measurement*

ALICE as an example for the experimental approach.



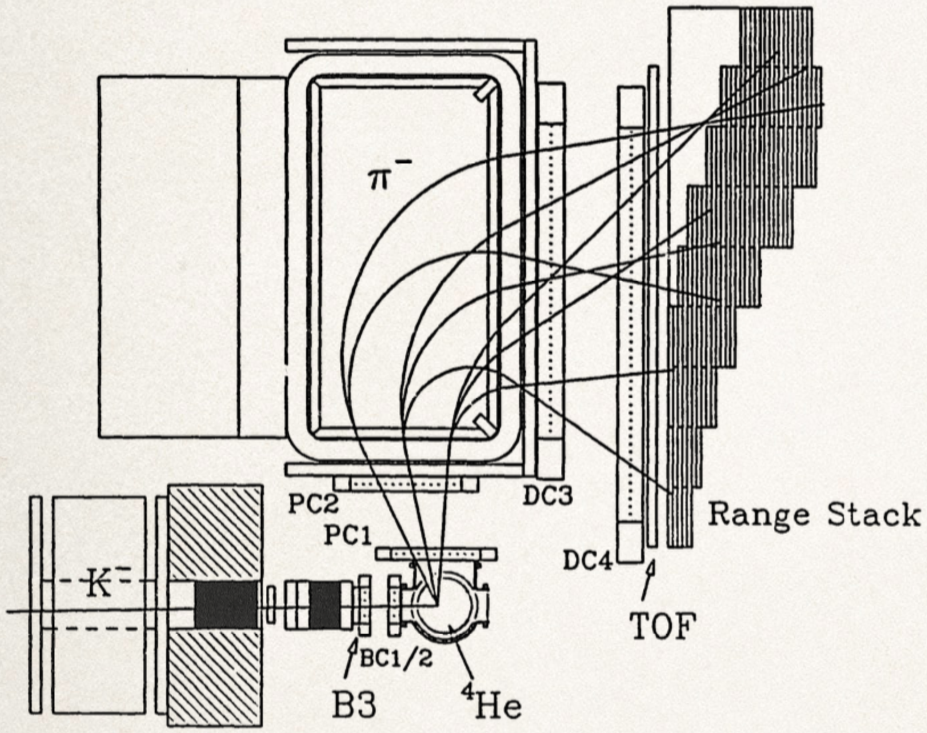
$$c\tau = \left(5.4^{+1.6}_{-1.2}(stat.) \pm 1.00(syst.)\right) cm$$
$$\tau = \left(181^{+54}_{-39}(stat.) \pm 33(syst.)\right) ps$$

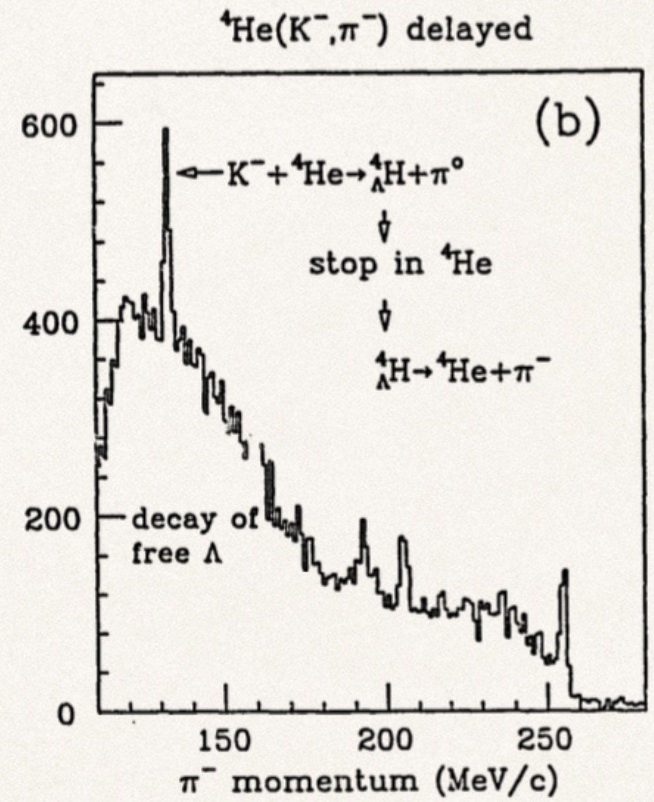


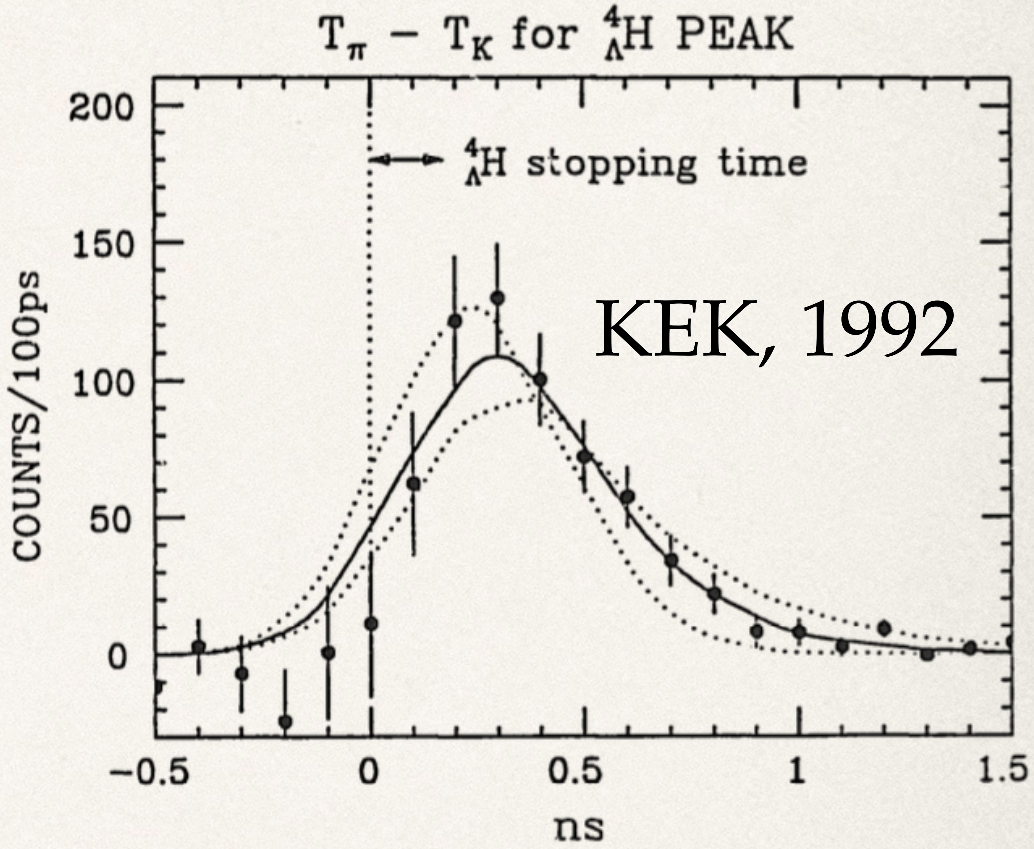
Depends on tracking results for decay length and momentum as

$$t = L/\beta\gamma c$$

Counter experiment: *direct measurement*







Example: stopped K- experiment at KEK:

1. tagging pi0 with NaI
2. measuring π- momentum with 300ps delay
3. subtract background from neighboring pi- bins
4. fit lifetime with convoluted distribution

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

Methods for *direct lifetime measurement*

- pi- + He3 --> K0 + Hypertriton:
  - proposed by A. Feliciello, INFN, Torino, Italy
- gamma + He3 --> K^+ + Hypertriton:
  - proposed by S. Nagao, Tohoku University
- K- + He3 --> pi0 + Hypertriton: by J-PARC E73 collaboration --> how to detect pi0 --> 2 gamma almost immediately?

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

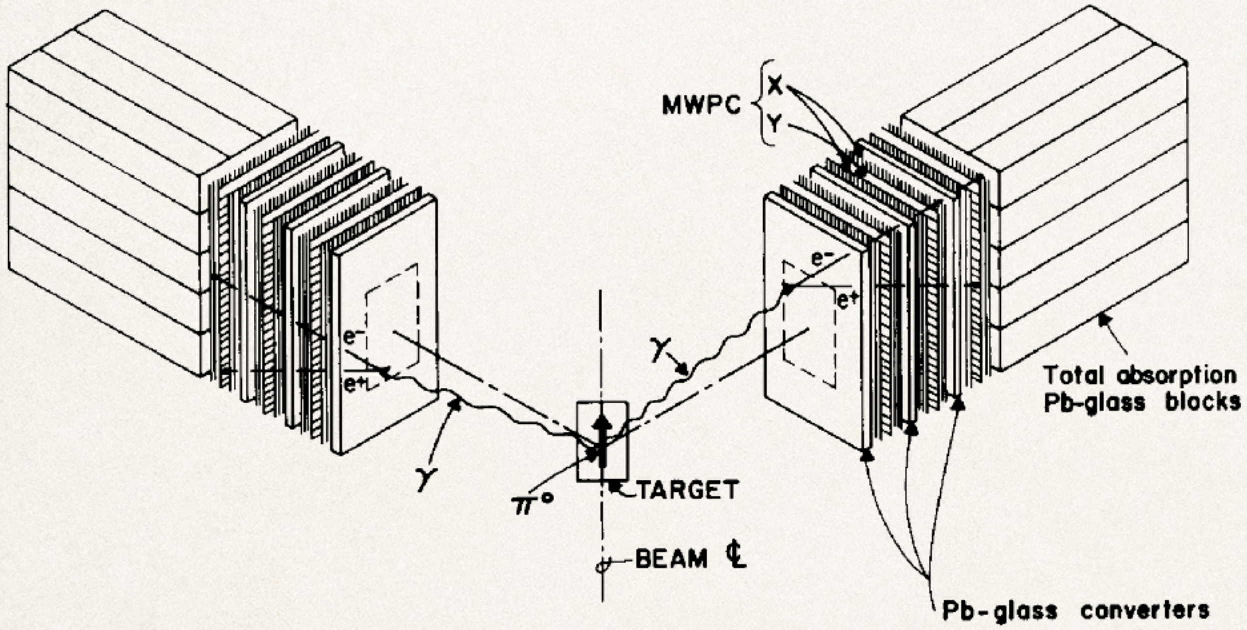


Fig. 1. A schematic diagram of the detector. The orientation of the two arms with respect to each other and to the scattering target is indicated. Also indicated is the convention for the x and y coordinates.

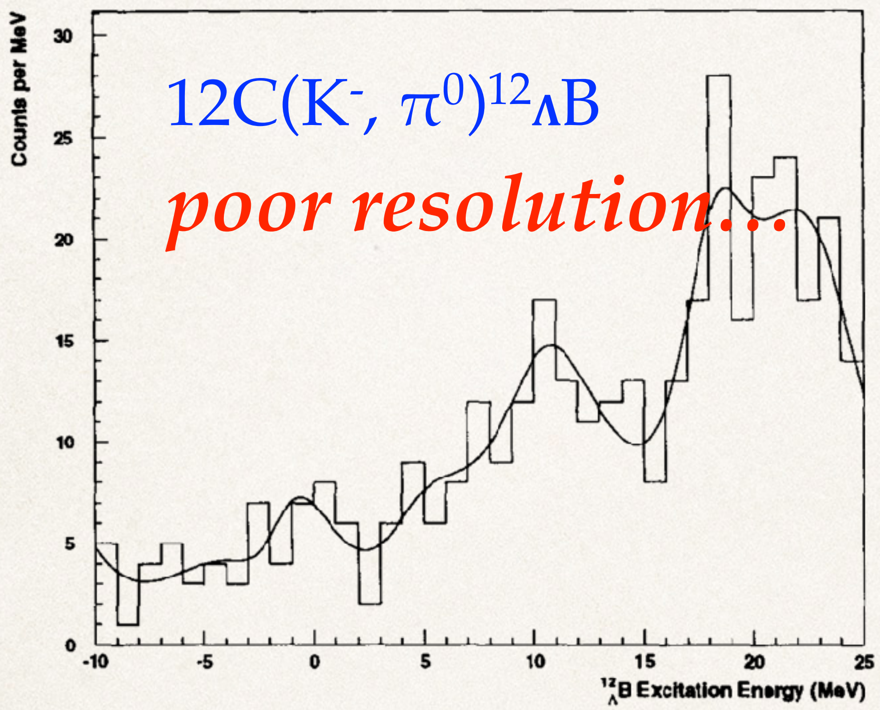
Working principle:

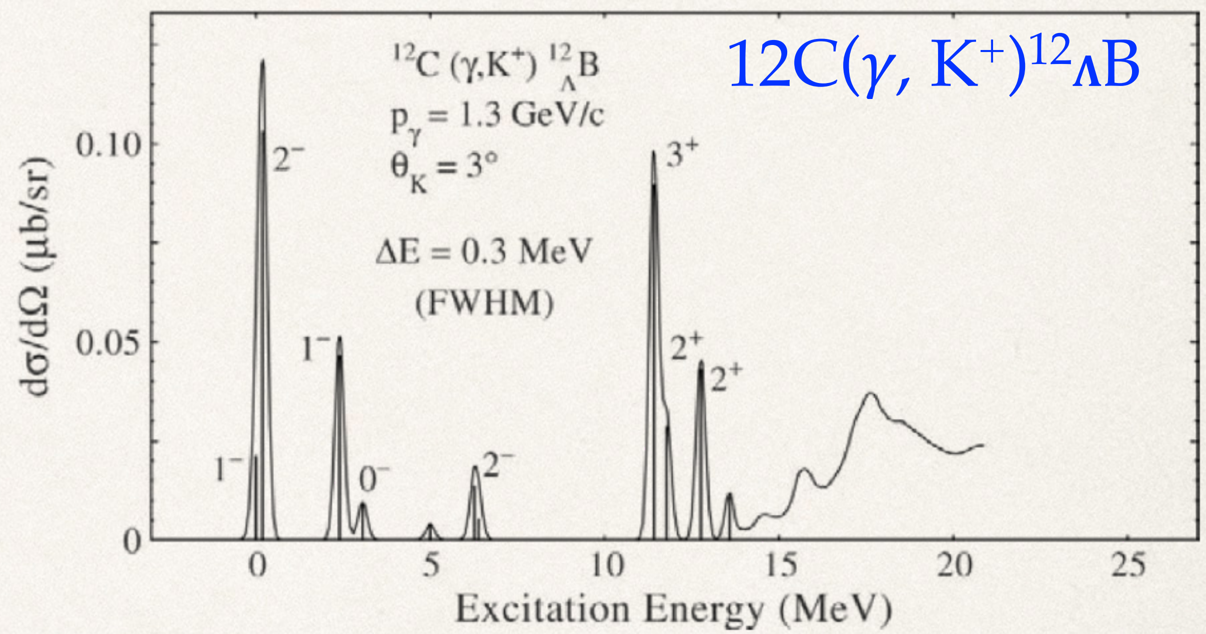
- γ converter
- Tracking chamber
- Calorimeter
- γ opening angle $\oplus$ energy

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

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

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



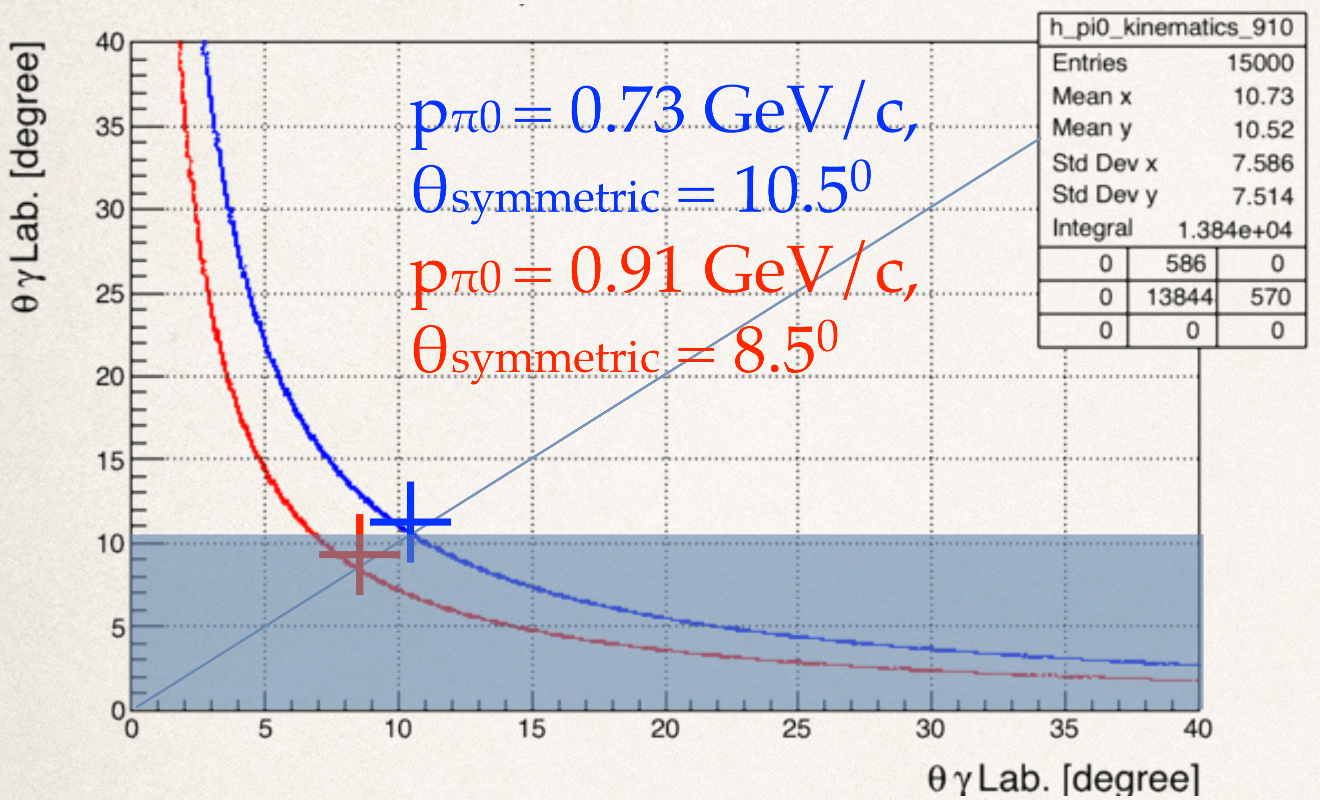


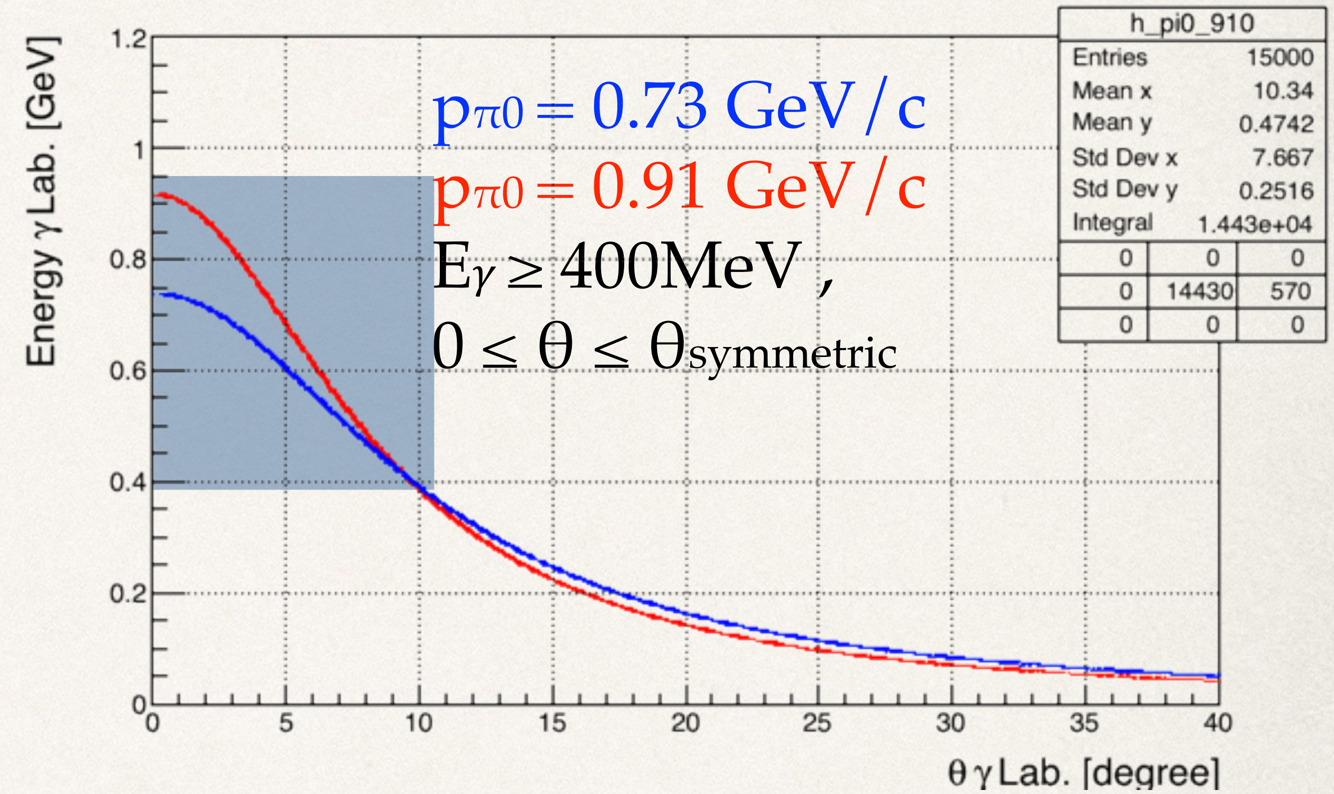
Neutral Meson Spectrometer

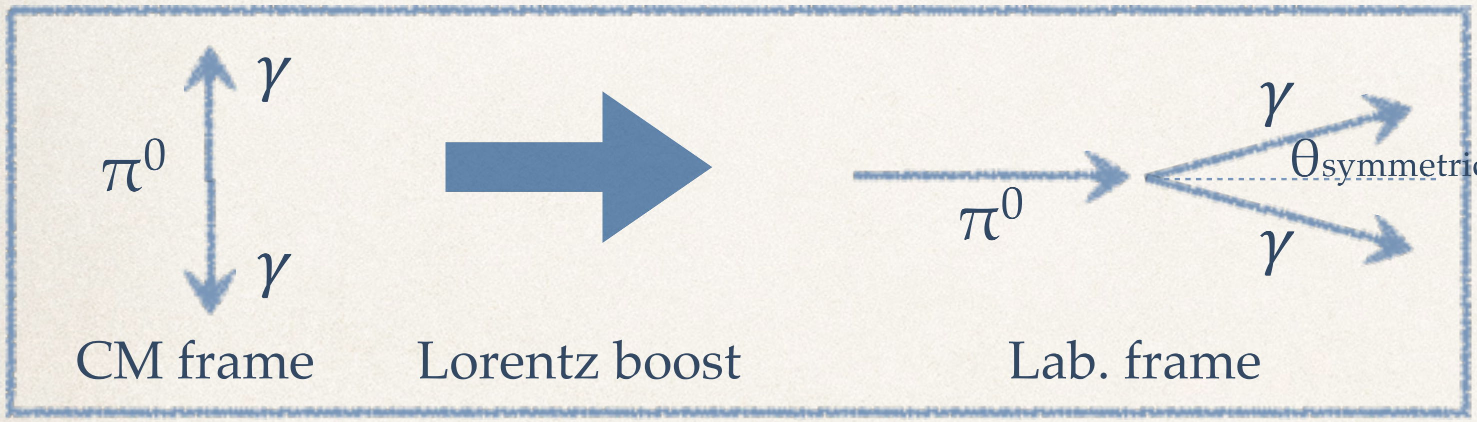
- Constructed at Los Alamos and shipped to BNL
- MM resolution ***~3MeV*** (design value ***~1MeV***)
- Bad resolution compare to (γ, K^+) channel

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

Revisit π^0 decay kinematics





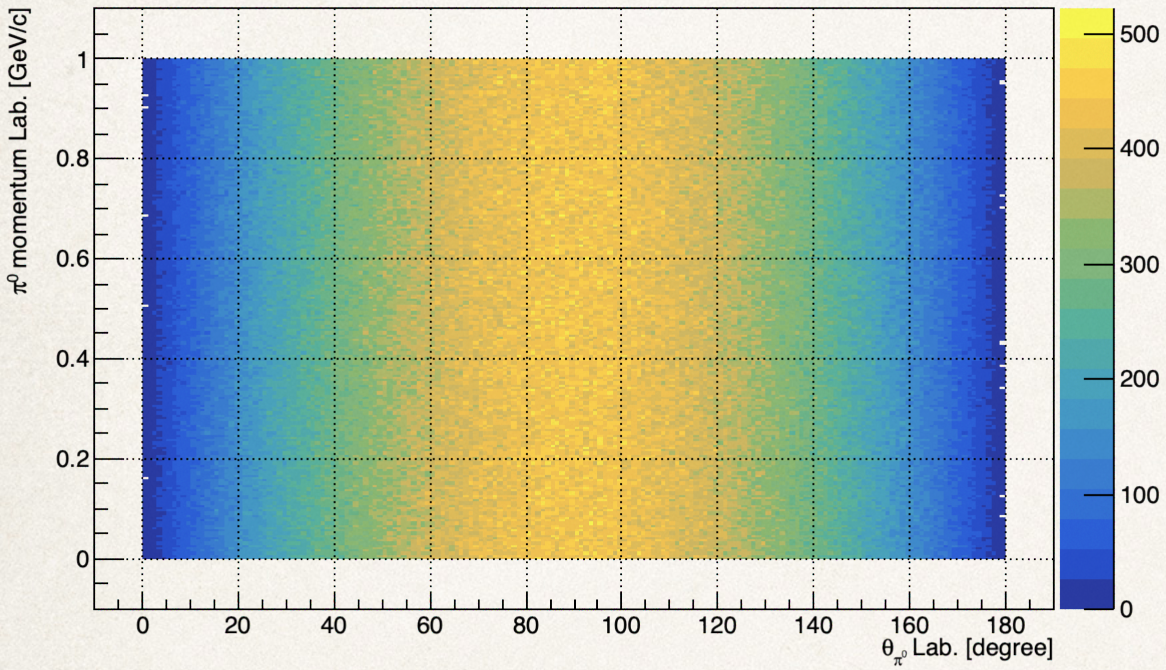


- 0.73~0.91GeV/c π^0 boosts γ forwardly;
- By covering 0~$\theta_{symmetric}$, tag the γ with higher energy ($E_\gamma \geq$ 400MeV)

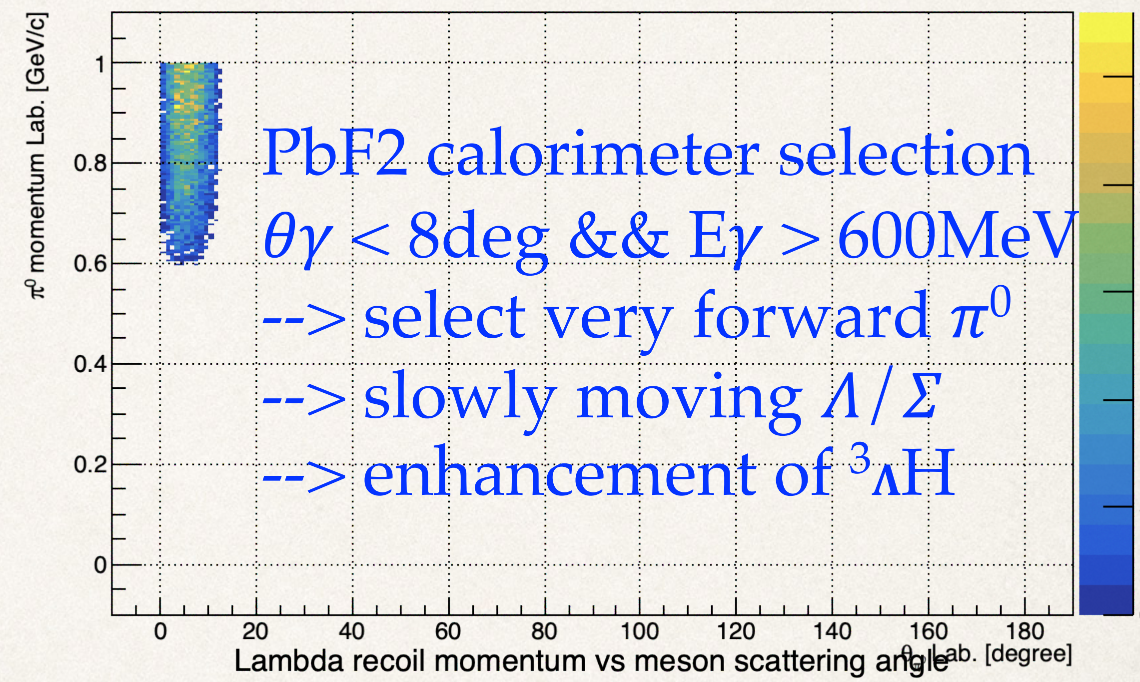
- π^0 tagger needs to be ***located along beam line***
- ***Fast response, radiation hardness***

How does E73 work by tagging single γ-ray?

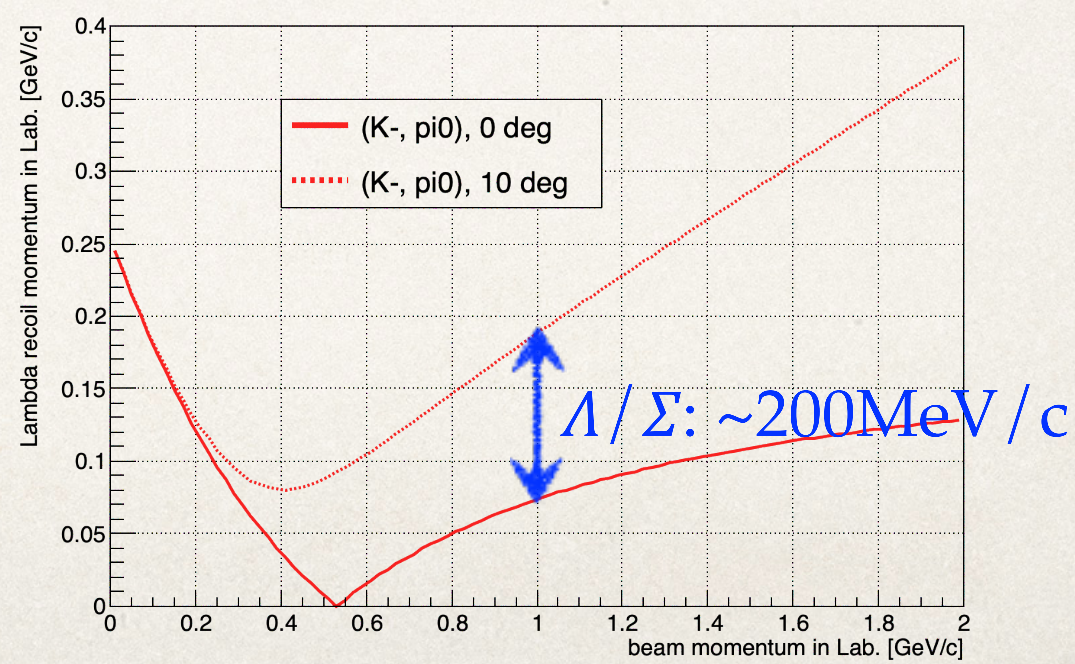
Input
π^0: 0~1GeV/c; 0~180deg



W/ PbF2 calorimeter cut
π^0: 0.8~1GeV/c; 0~10deg



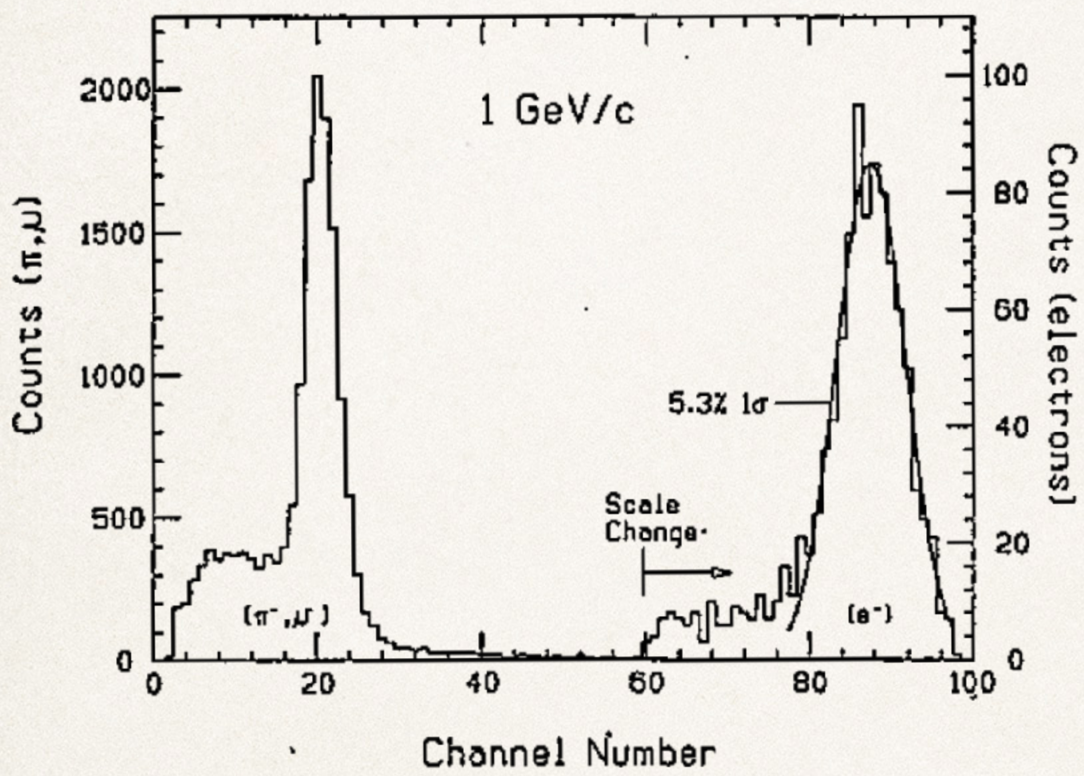
^{3}He(K-, pi0)$^3{}_\Lambda$H strangeness exchange reaction is known for its spin non-flip feature --> helps to pin down the $^3{}_\Lambda$H Q.N.



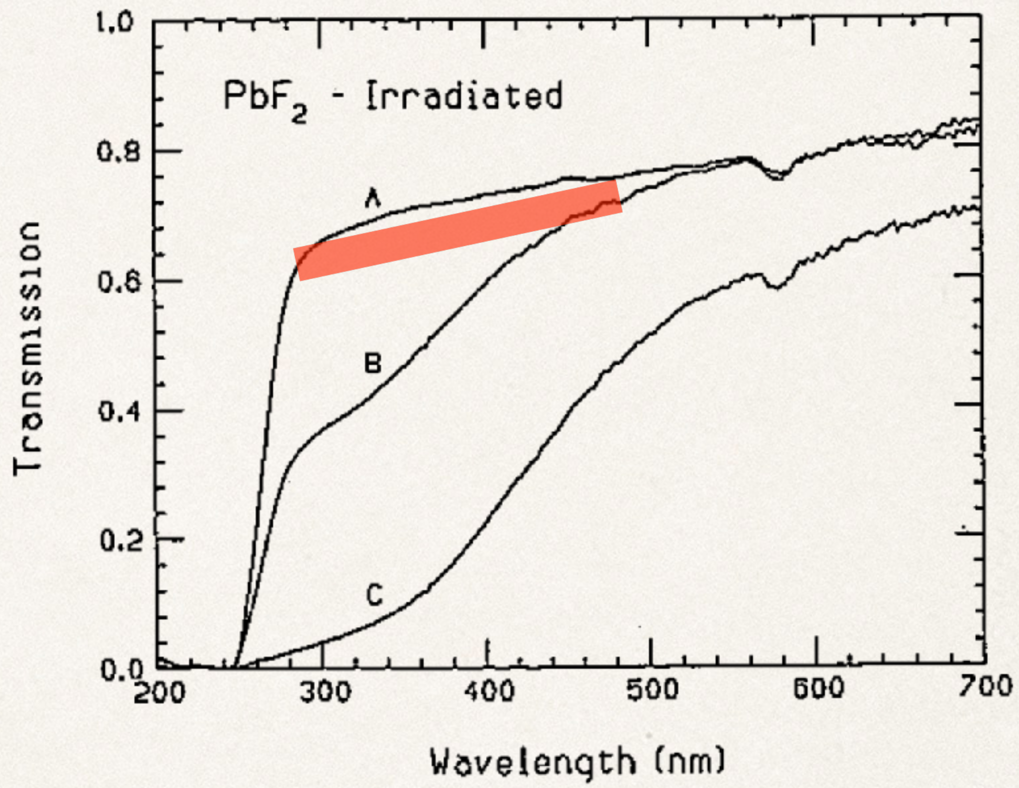
Experimental setup: π^o tagger (PbF_2)

π^- peak

electron peak



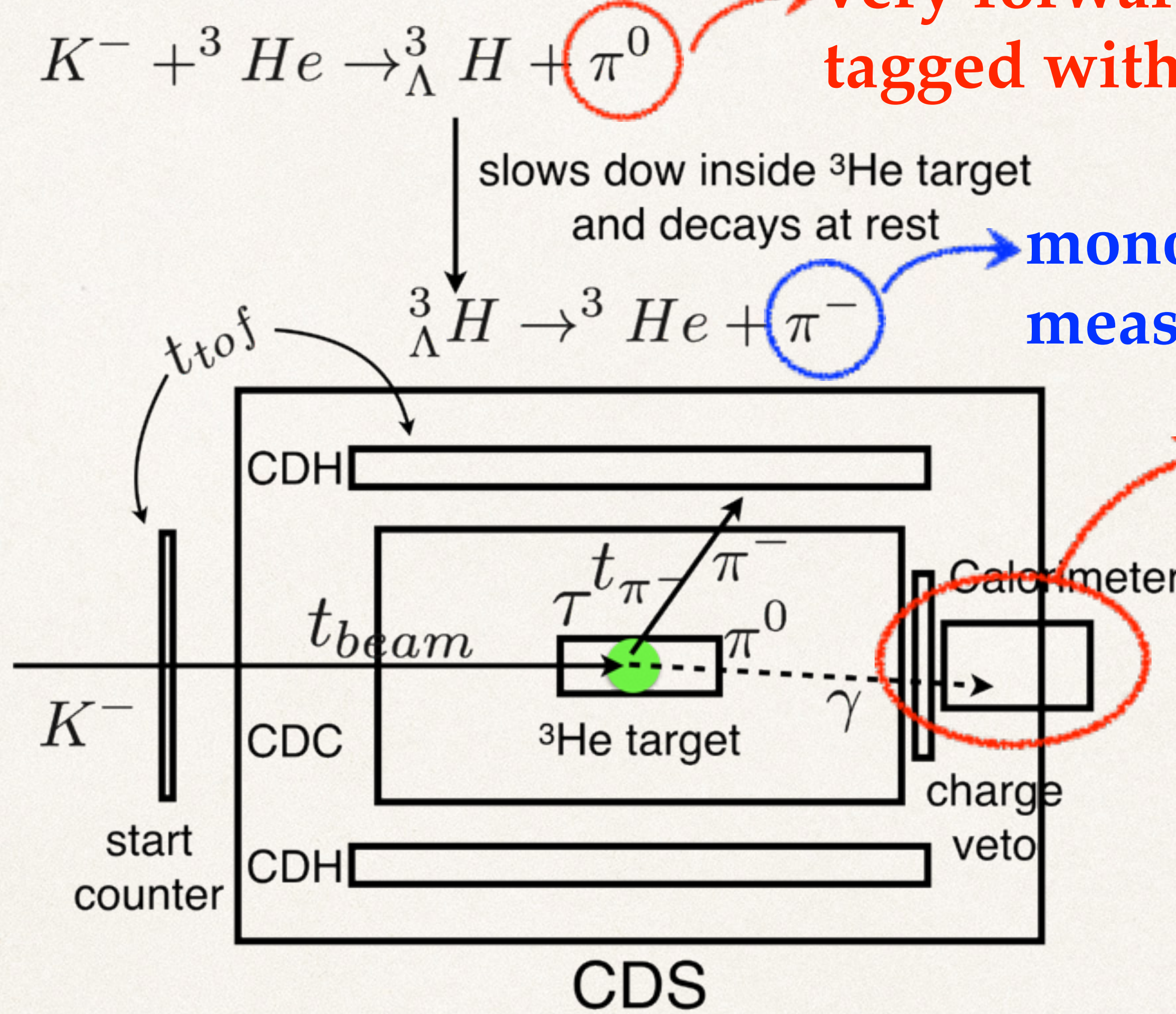
expected performance after one month beam time
(10 times more resistive than Pb glass)



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

E73 Experimental setup



very forward $\pi 0$ projectile; tagged with decayed high energy γ

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

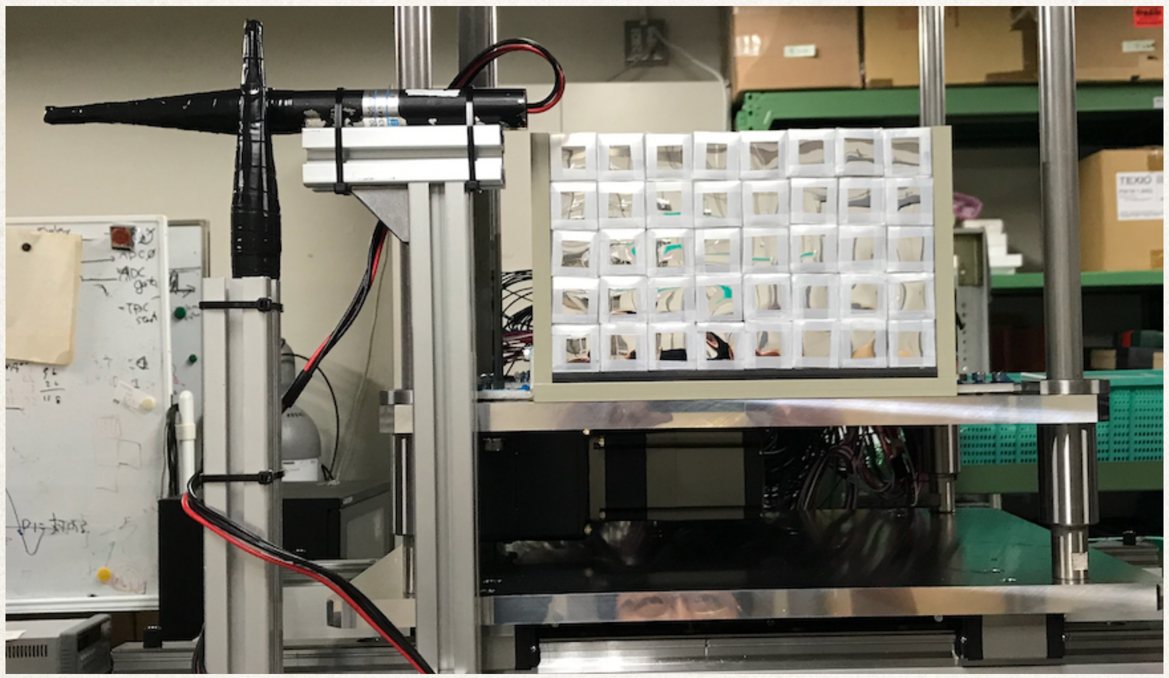
5x8 PbF2 Cherenkov Calo
R&D has been completed

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

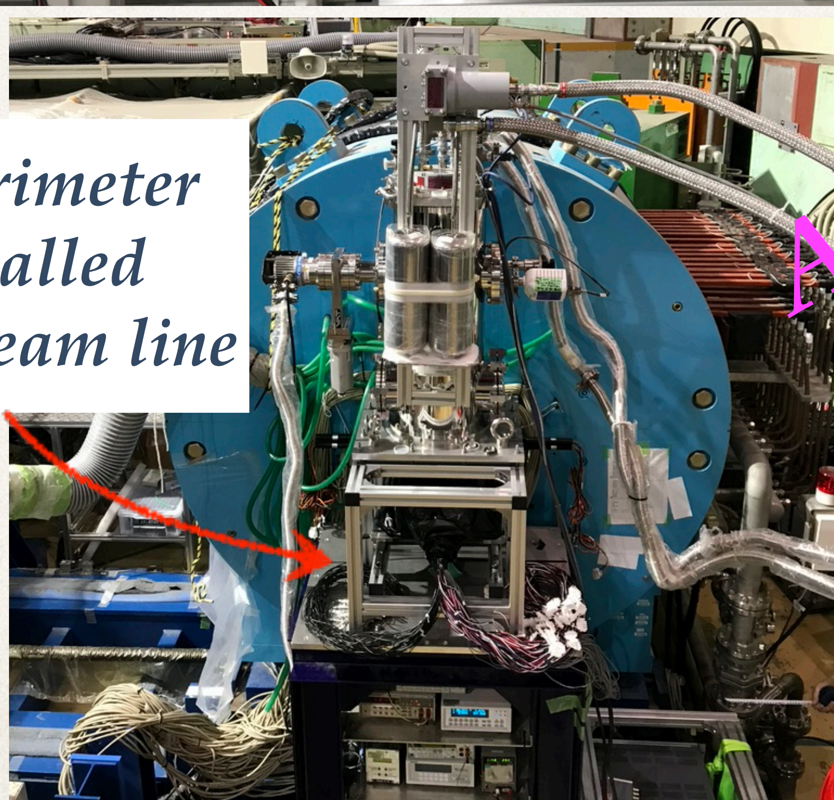
The idea of ***direct measurement***: $T_{CDH}-T_0=t_{beam}+t_{\pi^-}+\tau$;

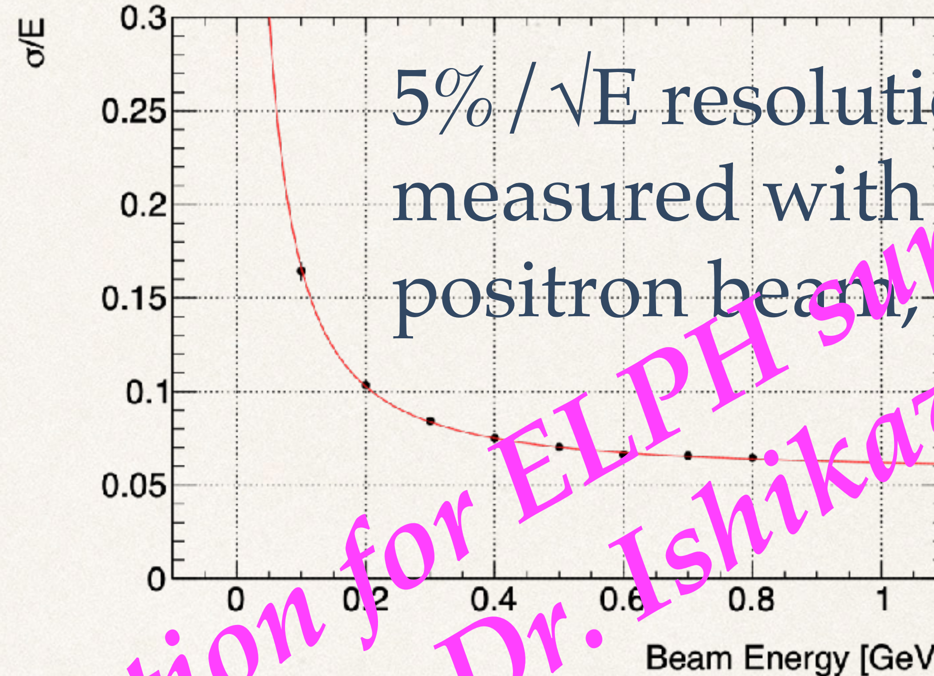
1. A complementary measurement for Heavy Ion results
2. Achievable precision: $\sigma/\sqrt{N}$ ~ 30ps

PbF_2 calorimeter performance @ELPH

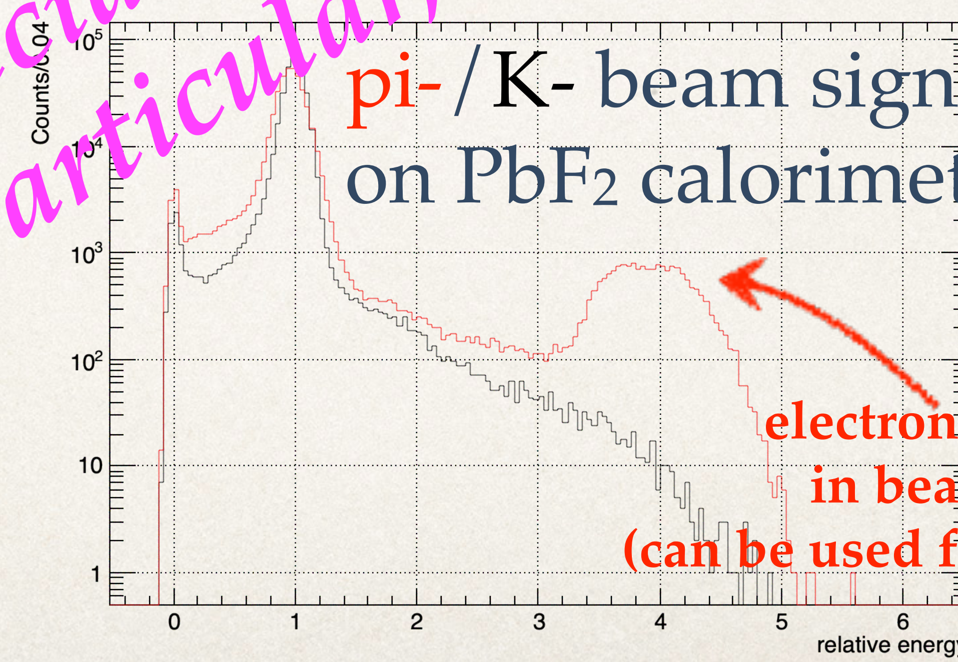


PbF2 calorimeter
was installed
INTO the beam line





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)

Appreciation for ELPH support!
In particular, Dr. Ishikawa san

Current status of J-PARC E73

Staging:	Stage-0	Stage-1	Stage-2
Task:	Background study with $^{4}He(K^{-}, \pi^{0})^{4}_{\Lambda}H$	First measurement for $^{3}He(K^{-}, \pi^{0})^{3}_{\Lambda}H$ 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:	Cleared by T77 experiment	Fully ready for beam time from now on	Depends on Stage-1 results

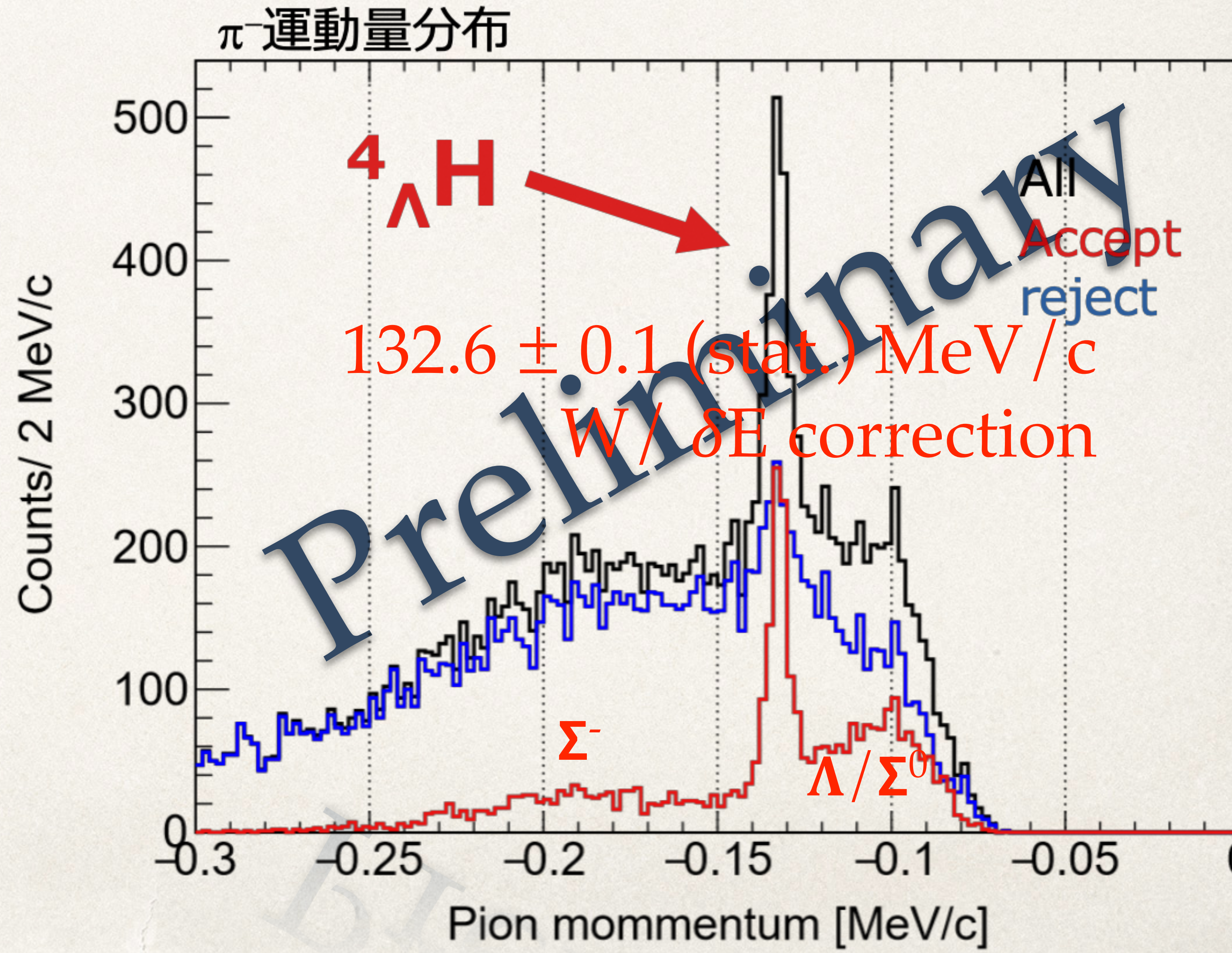
Stage-0: feasibility study for E73

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

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

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

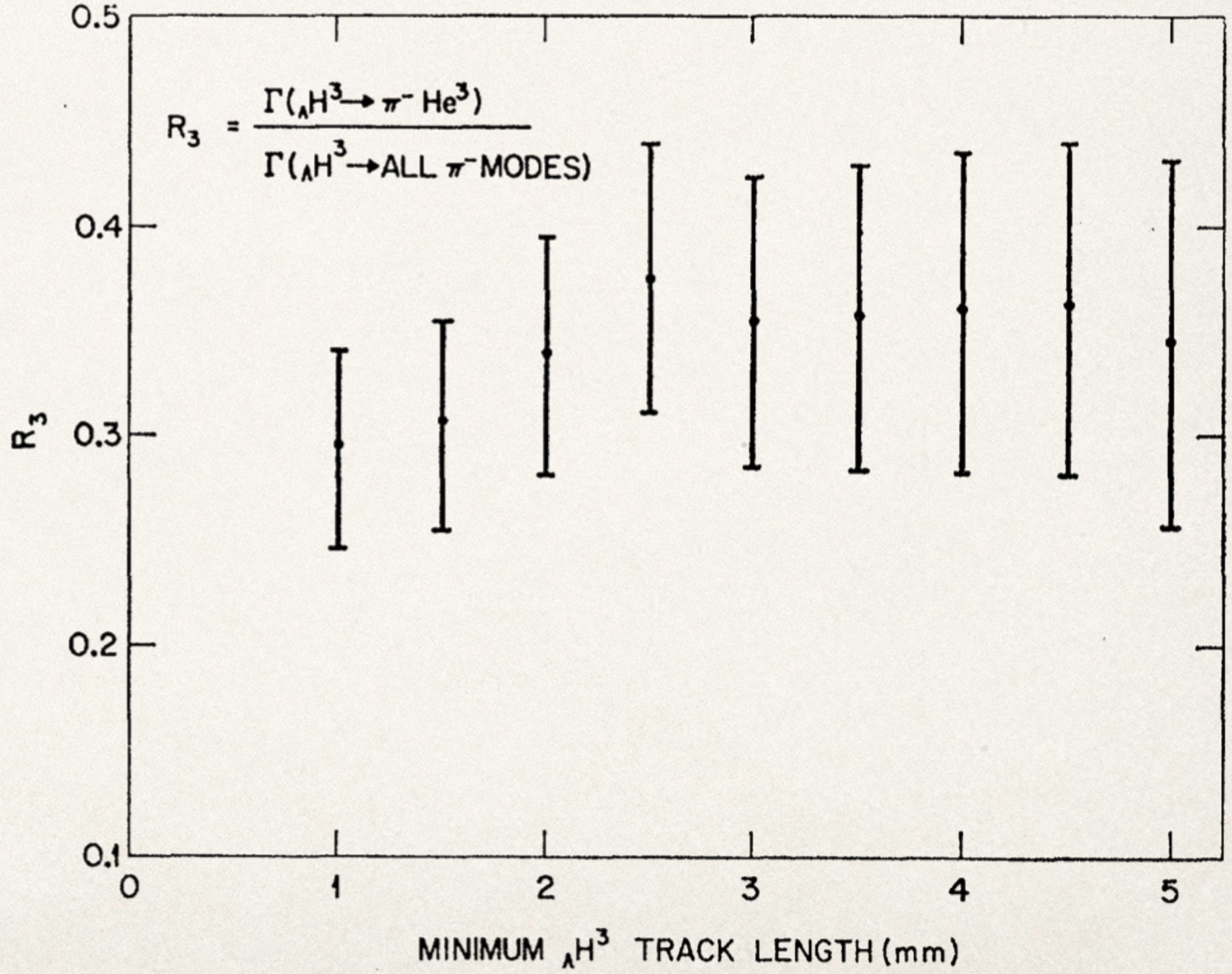
- T77 refreshes world record for $^4{}_\Lambda$H statistics by twice (***1.2k events***);
- New method improves S/N by ~ 10 times;
- ***All these happen within 3days of beam time!***



Stage-1: cross section & spin of Hypertriton

- Hypertriton isospin:
  - He4: T=0 & He3: T=1/2
  - He3(K-, pi0)H3L --> H3L: T=0

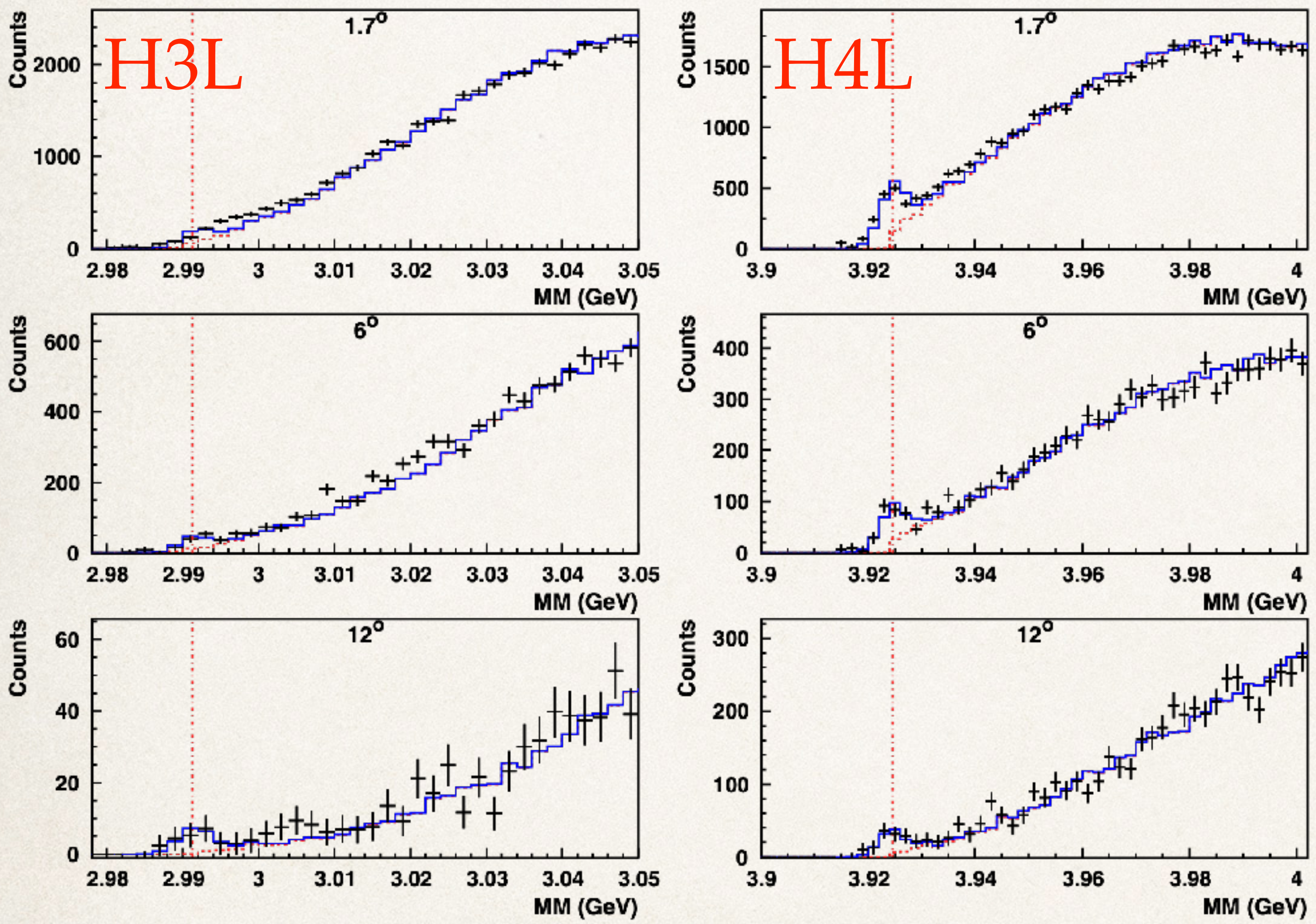
- Hypertriton ground state spin is determined by two-body/three-body ratio.
- No direct determination so far...
- E73 experiment will shed light on this issue.



https://doi.org/10.1103/PhysRevD.1.66

Stage-1: cross section & spin of Hypertriton

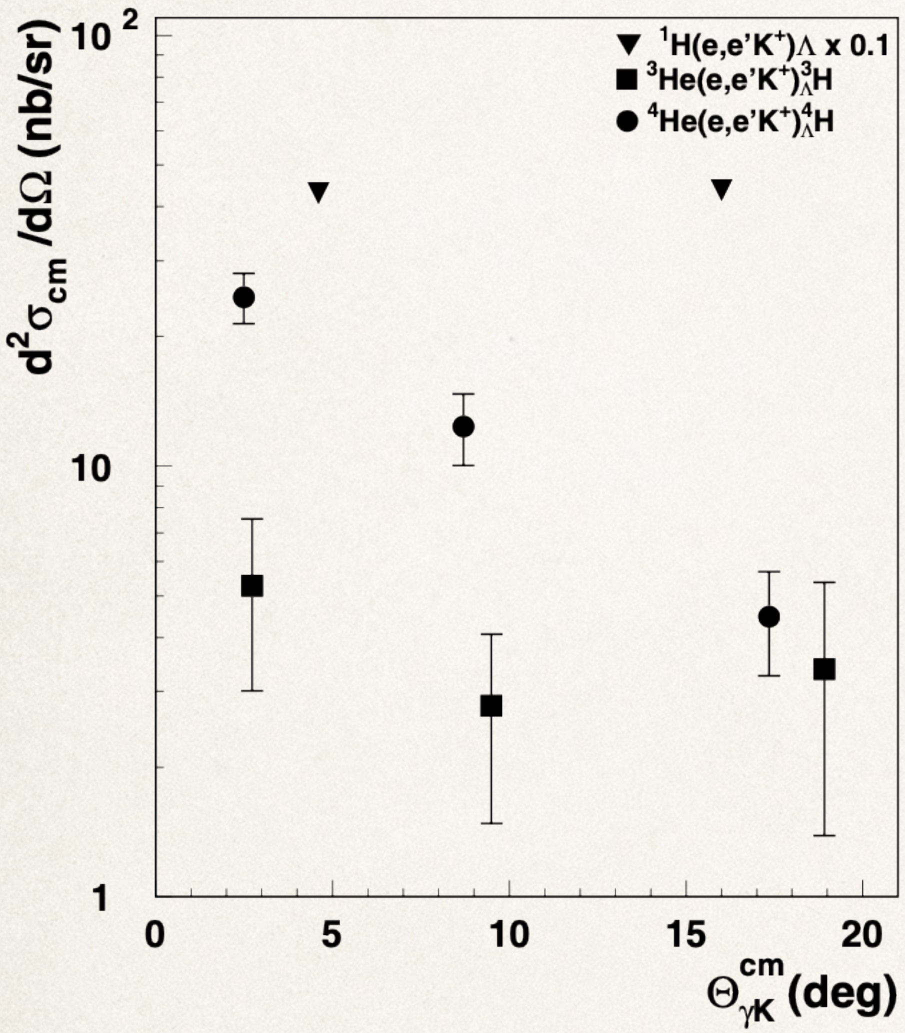
(e, e′K+) reaction @ J-Lab

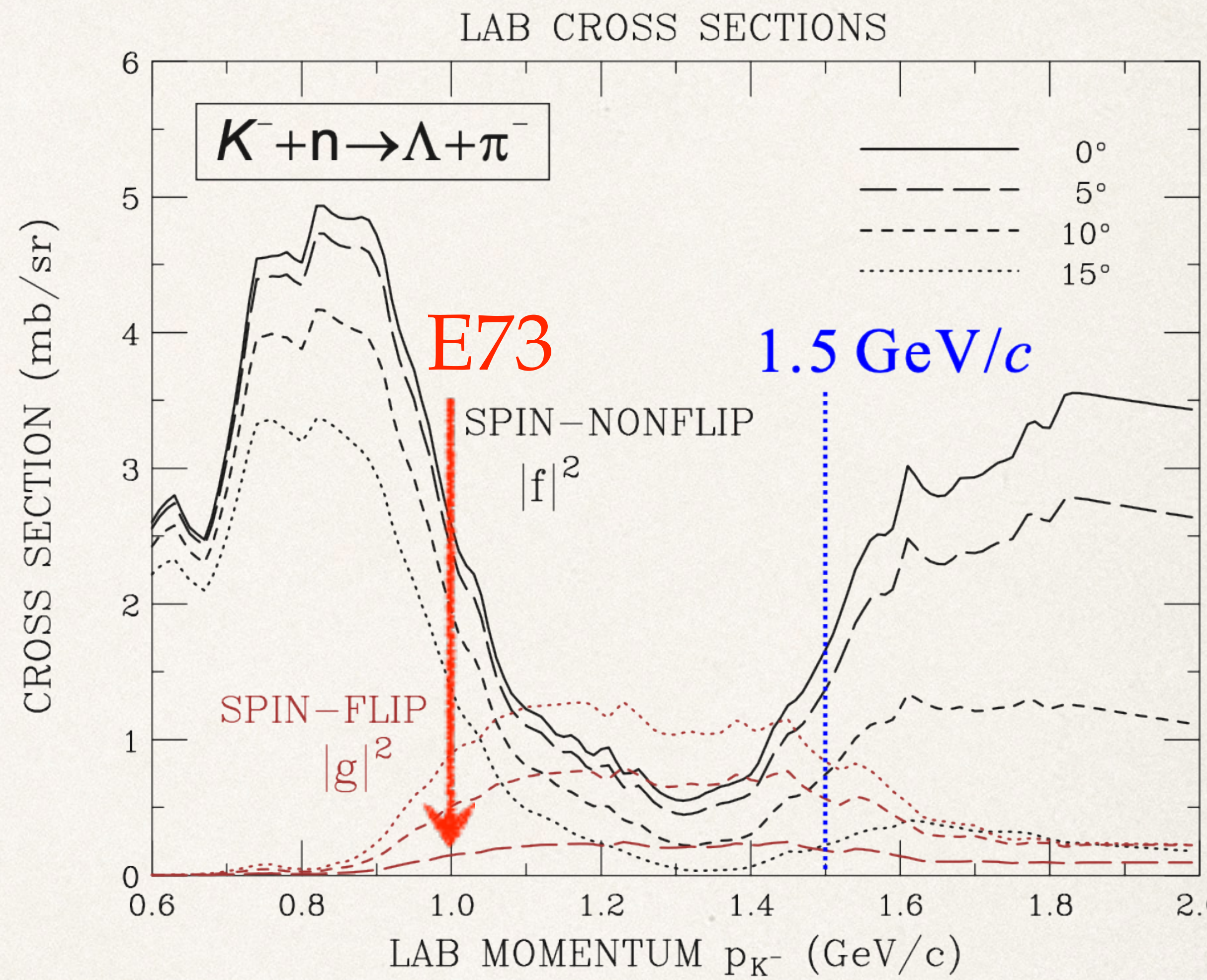


- $^{4}_{\Lambda}$H contains both 0+ and 1+ states (spin-flip favored) in J-Lab results;
- $^{3}_{\Lambda}$H is pure 1/2+ or has a virtual 3/2+ state near threshold?
- Can not be distinguished with ~4MeV resolution

DOI: 10.1103/PhysRevLett.93.242501

Stage-1: cross section & spin of Hypertriton





(e, e′K+) reaction @ J-Lab
$^3{}_\Lambda H / ^4{}_\Lambda H$ ~ 0.26 ± 0.10 in average
1.7 deg: 0.25 vs 12 deg: 0.90:
Difficult to interpret, something new?

- (K, pi) reaction is well-known as spin non-flip feature
- Prof. T. Harada's calculation: $^3{}_\Lambda H / ^4{}_\Lambda H$ ~ 1/3 for ground state

DOI: 10.1103/PhysRevLett.93.242501; Dr. T. O. Yamamoto's PhD thesis

Summary

- We have established a new method to investigate the isospin mirror Hypernuclei by gamma-ray tagging

- E73 experiment has been approved as stage-1 and ready for data taking from now on

  - First counter experiment to determine the Hypertriton ground state spin & cross section --> hint for the 3/2+ state by combining J-Lab results

- Lifetime measurement is planned around ~2022

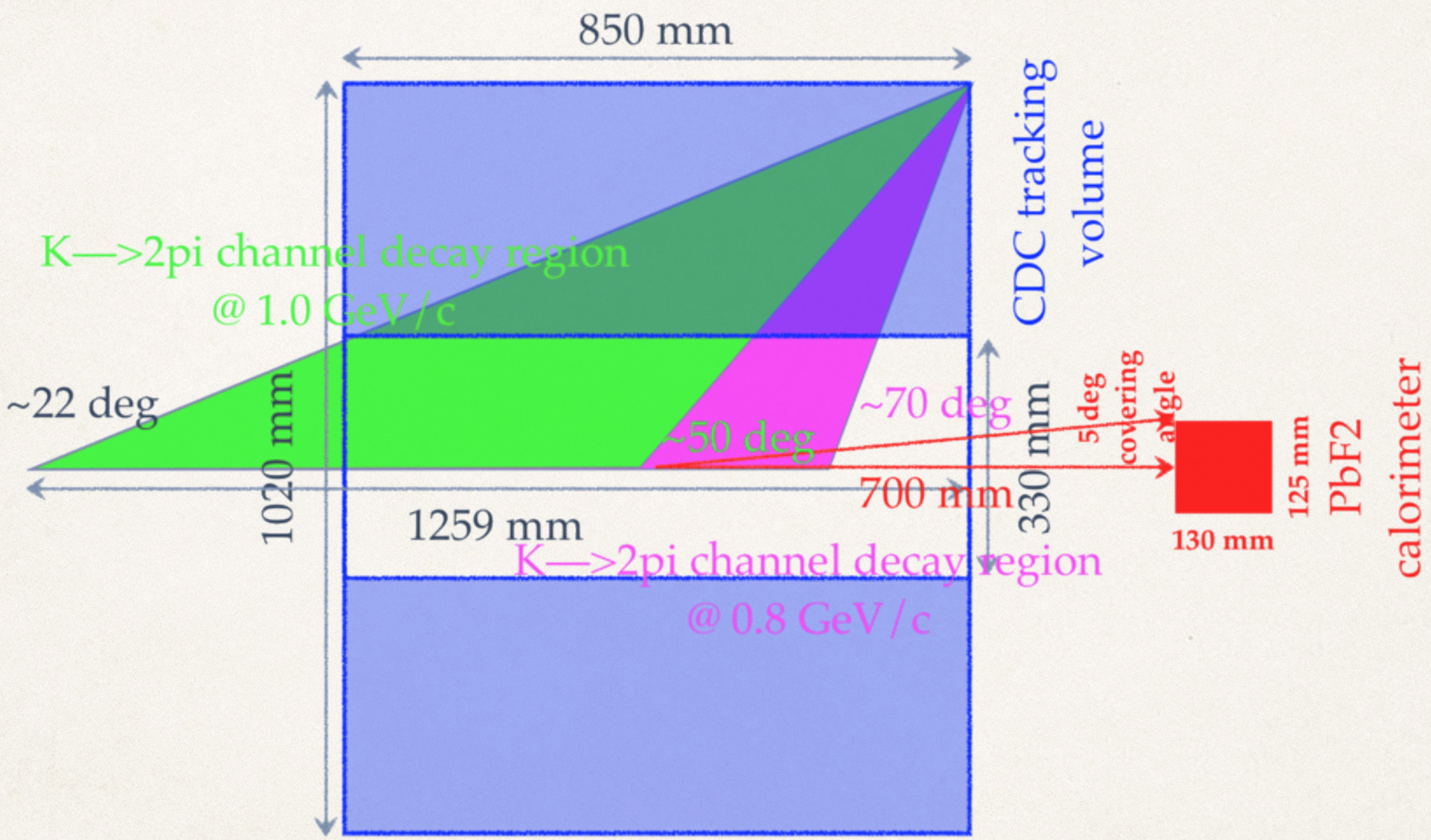
P73/T77 collaborator list

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

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

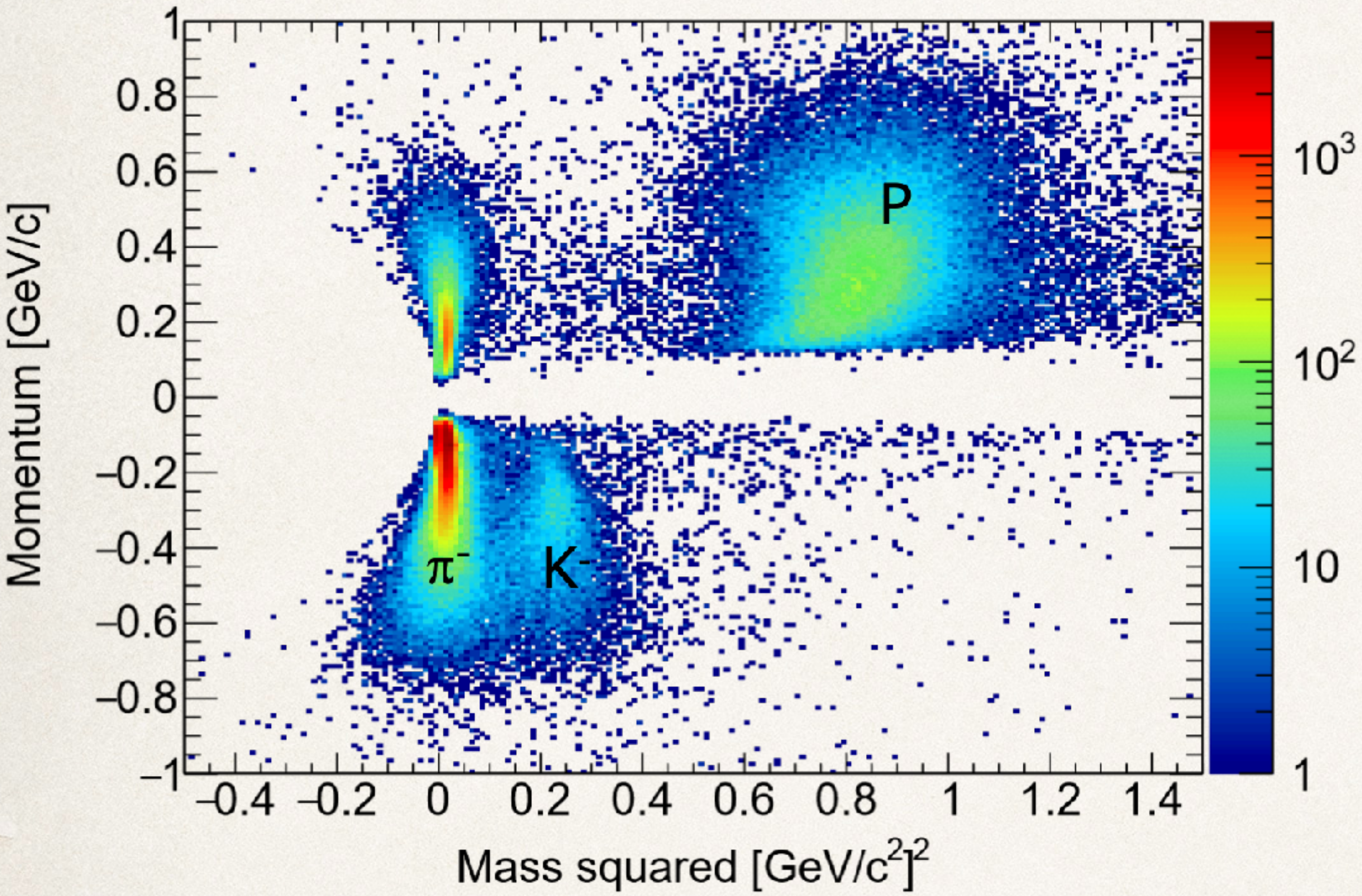
- Backup

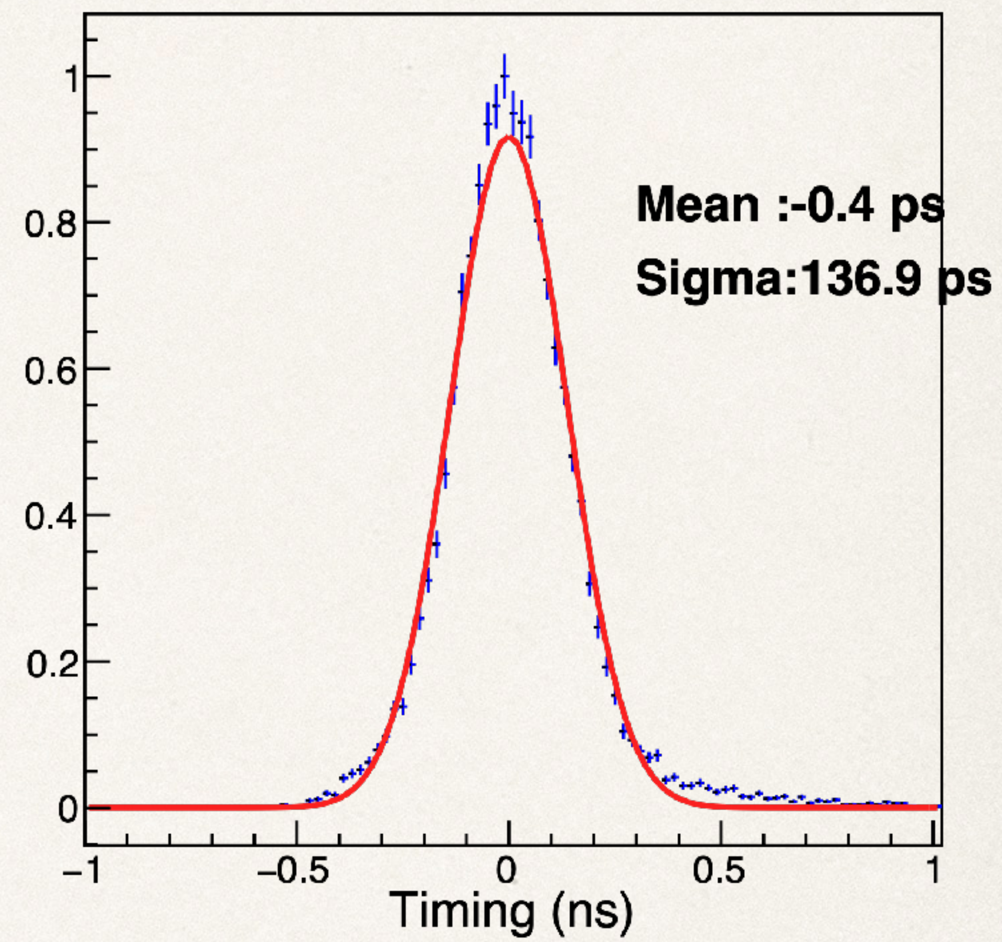
CDC acceptance vs Kaon decay background



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

E73 CDS tracking performance

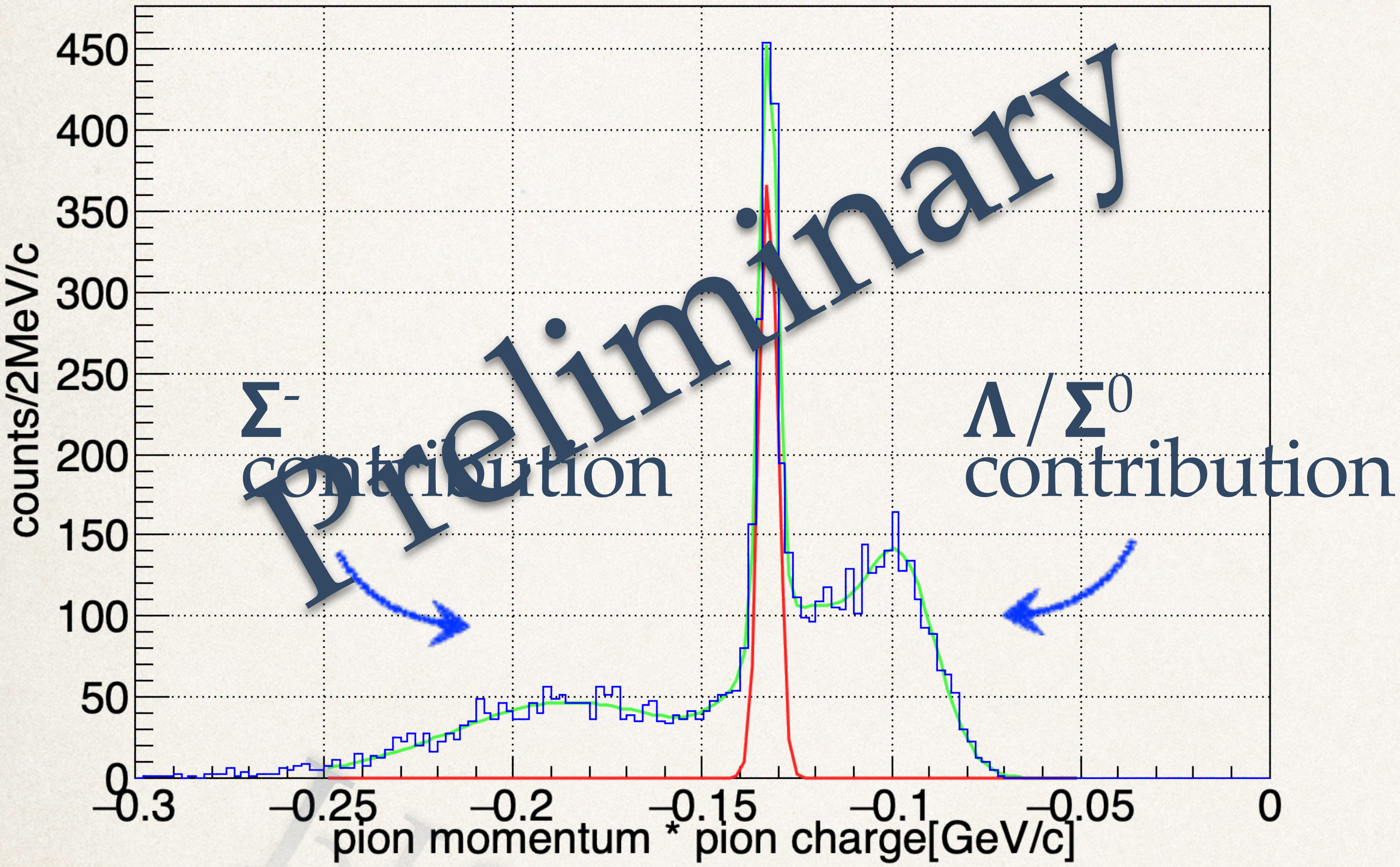


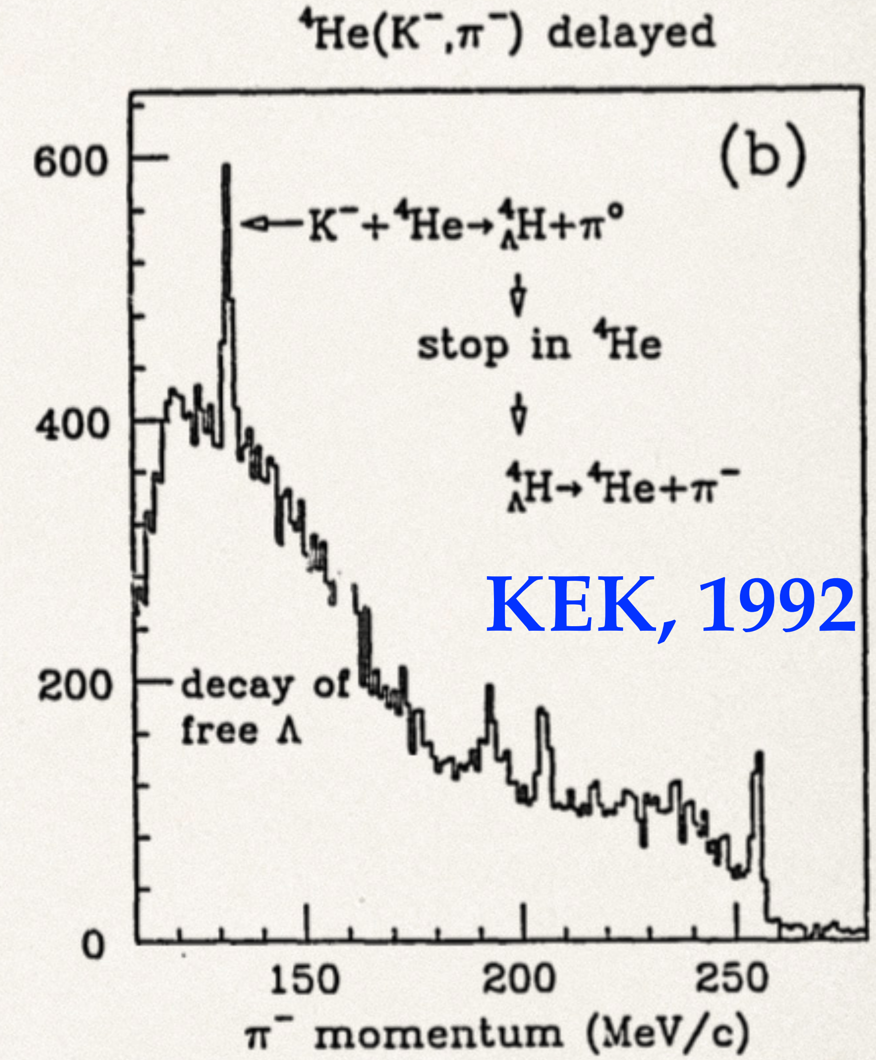


- CDS tracking system works well;
- ~2% momentum resolution for ~100MeV/c pi- signals;
- TOF resolution ~137ps from prompt pi- scattered event

T77 results: pi- spectrum from $^4{}_{\Lambda}H$

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





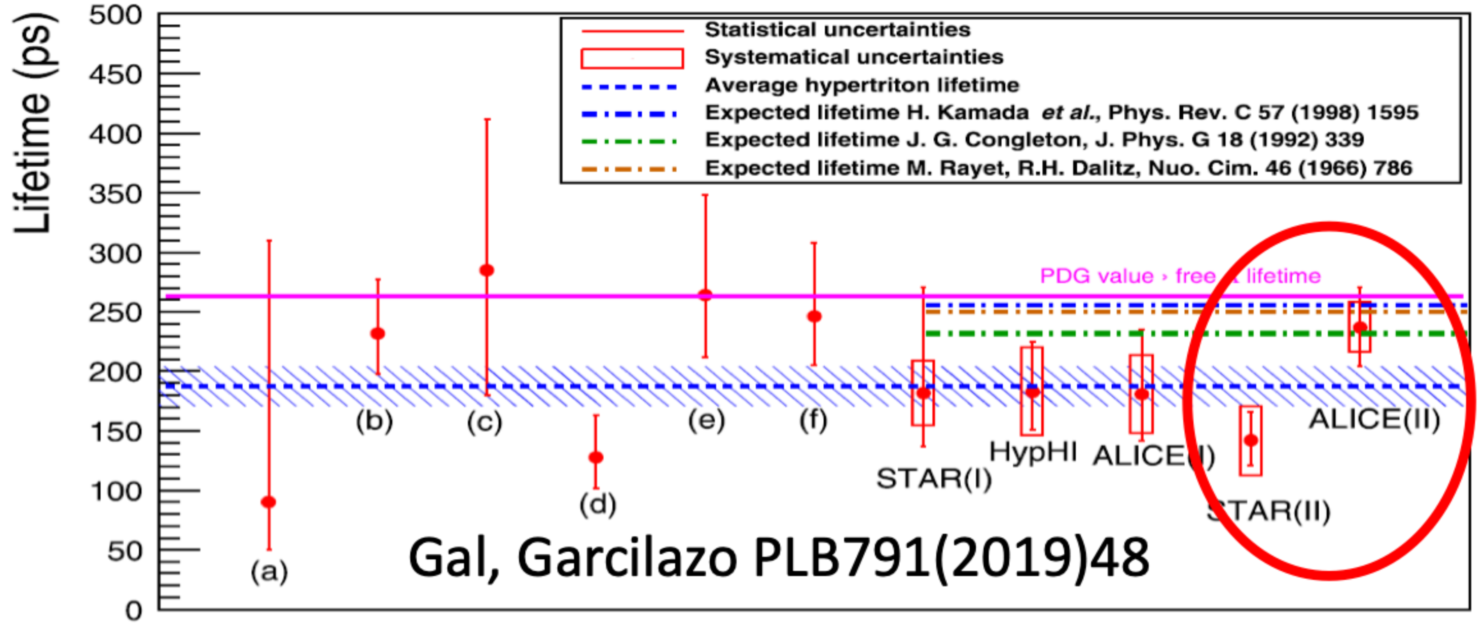
- T77 refreshes world record for $^4{}_{\Lambda}H$ statistics by twice;
- New method improves S/N by ~ 10 times;
- *All these happen within 3days of beam time!*

Physics Motivation

- Recent heavy-ion experiments reported different lifetime of **hyper-triton, $^{3}_{\Lambda}H$**:

STAR (2018)	ALICE (2018)	free Λ
$142^{+24}_{-21} \pm 29$ ps	$237^{+33}_{-36} \pm 17$ ps	263 ± 2 ps

- $\tau(^{3}_{\Lambda}H) \sim \tau(\text{free } \Lambda)$ is naively expected, because $^{3}_{\Lambda}H$ is known to be very loosely bound system (~0.13MeV)

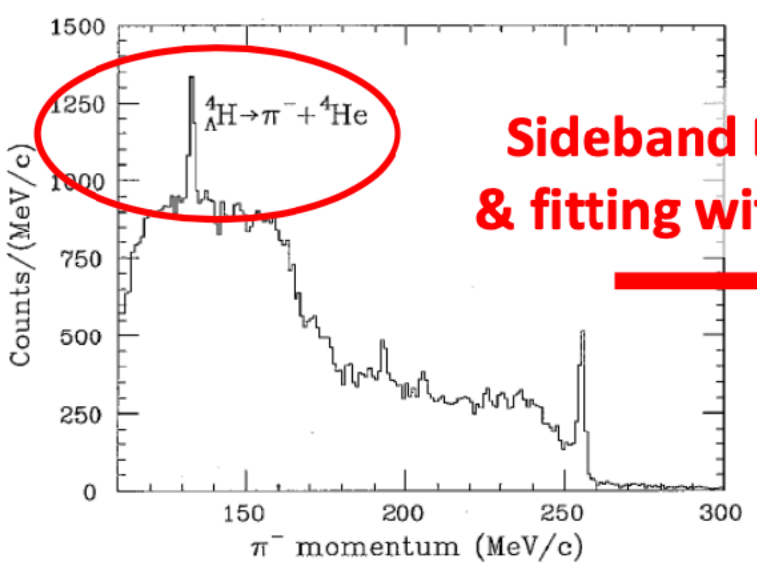


→ need to clarify the situation using different experimental technique

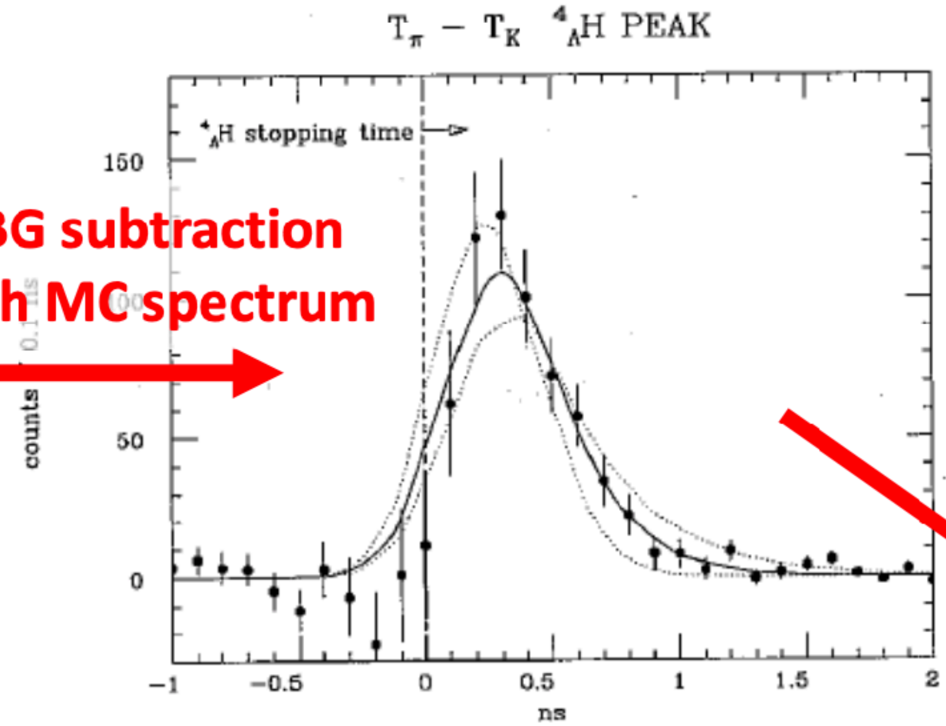
3

$^{4}_{\Lambda}$H Lifetime @ KEK

- ^{4}He(stopped K^{-}, π^{-})$^{4}_{\Lambda}$H reaction
- The lifetime was obtained from a fitting with a simulated spectrum

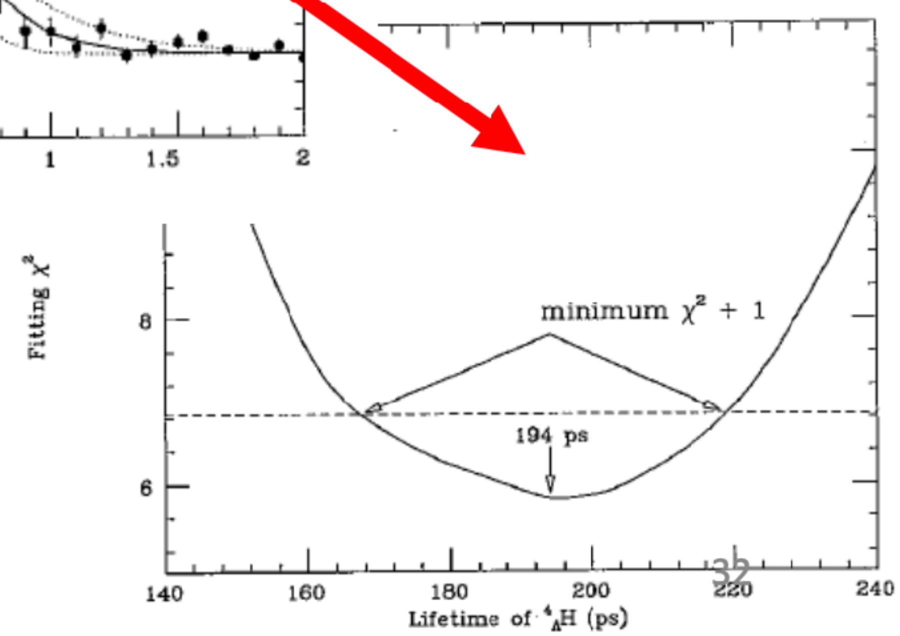


Sideband BG subtraction & fitting with MC spectrum



H. Outa, D-thesis

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



For cross-check, we will apply the same procedure to the $^{3}_{\Lambda}$H analysis.