Result of J-PARC E73 initial run on observation of weak decay of hypertriton and ${}^{4}_{\Lambda}H$ lifetime

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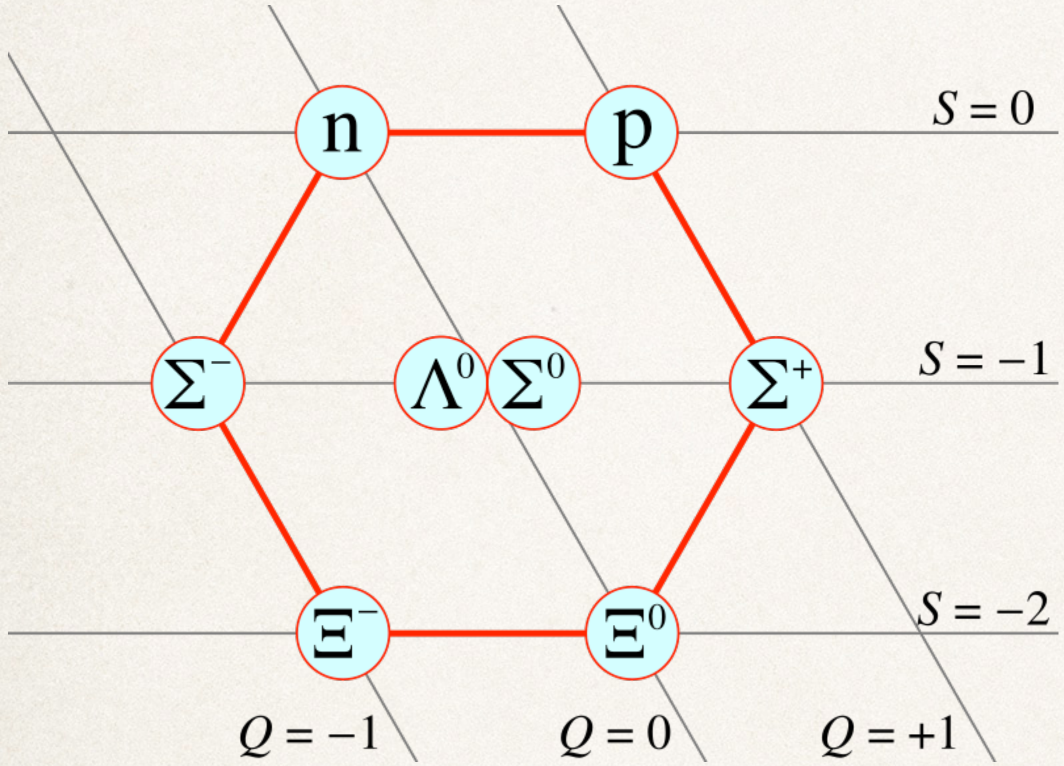
2022/02/02

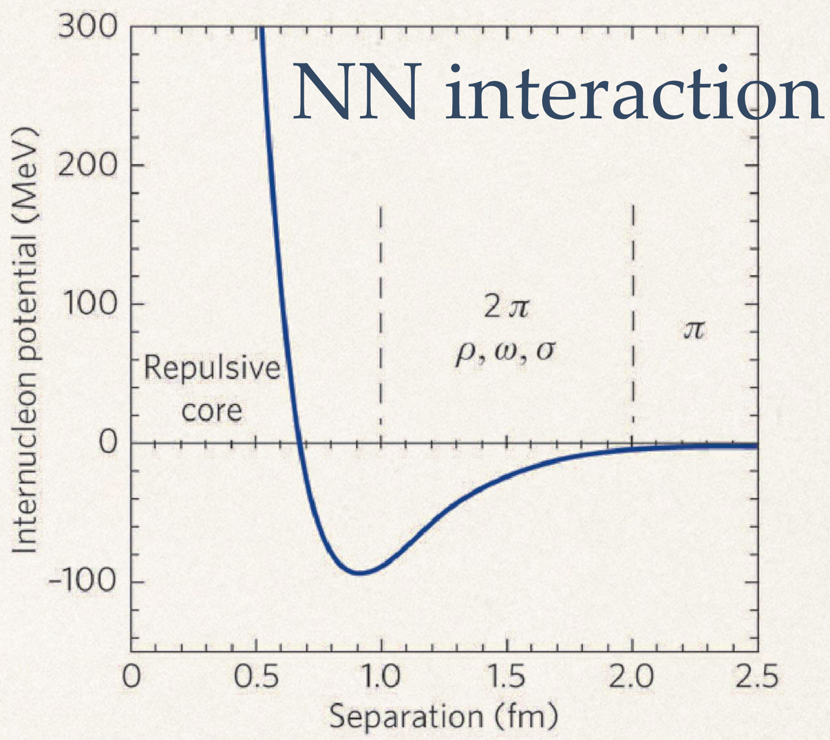
Outline

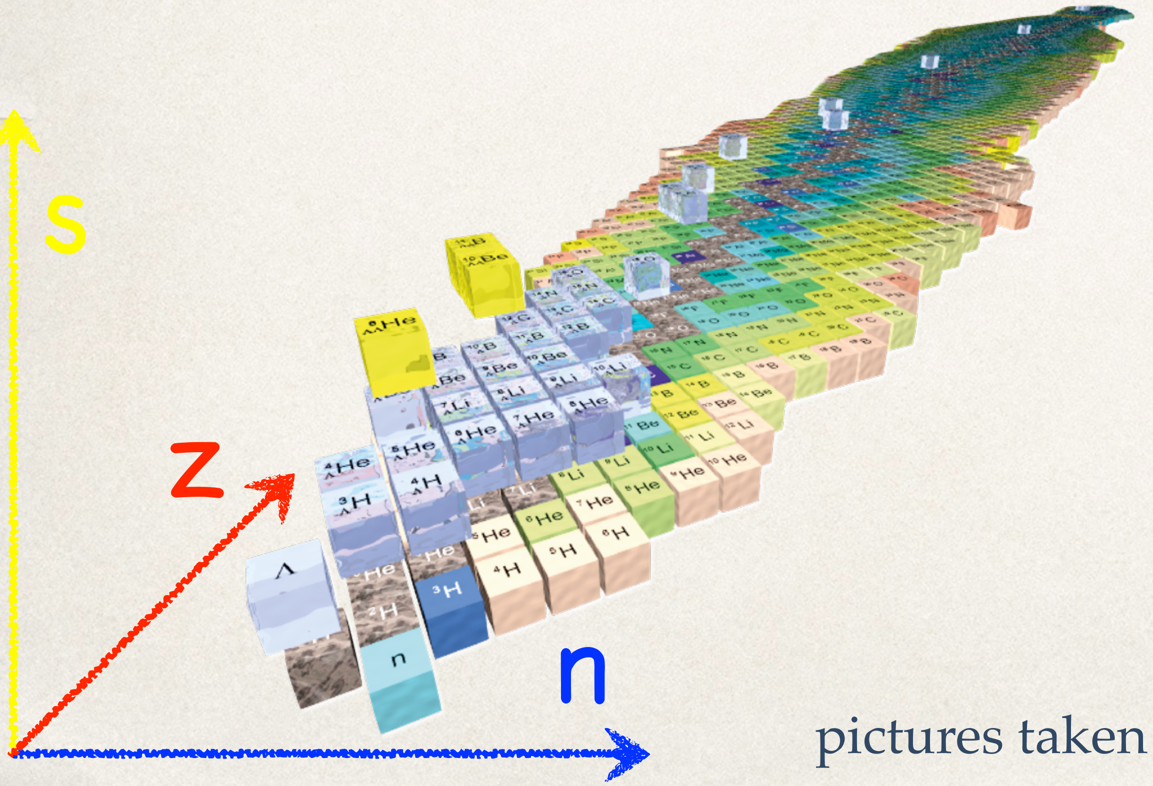
- Introduction & motivation
- J-PARC E73:
  - Experimental method
  - Current status
- Summary

Introduction & motivation

Nucleon vs Hyperon



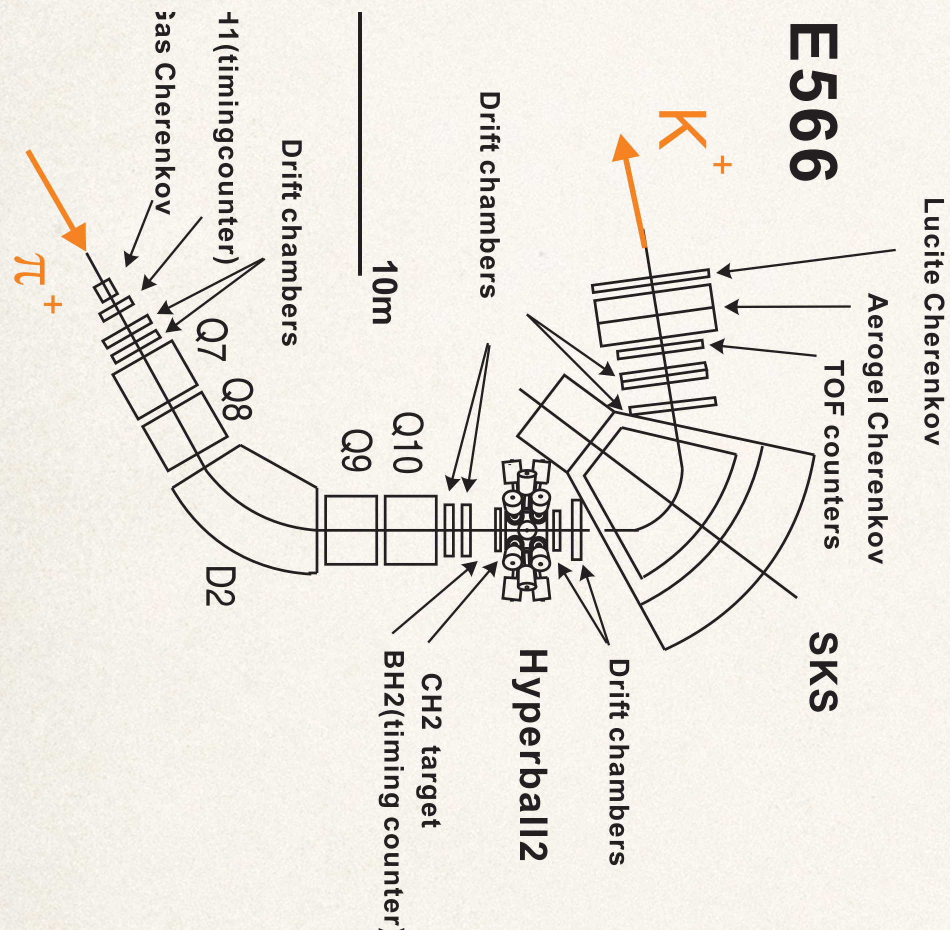


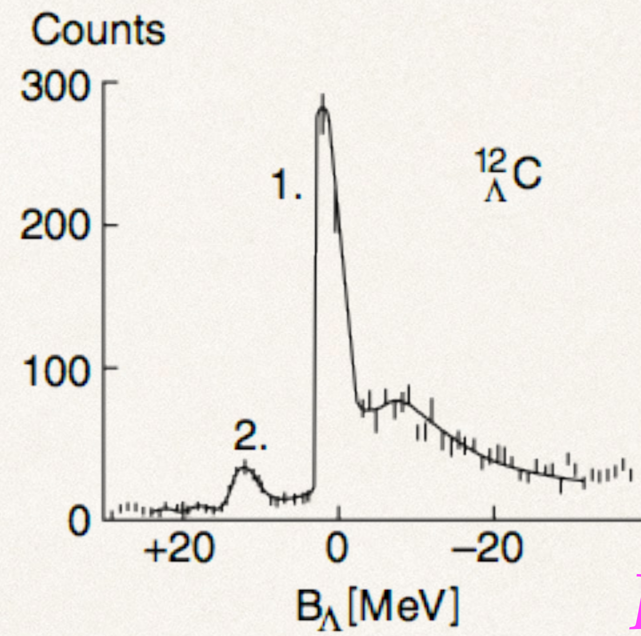


1. First step for a unified baryon-baryon interaction
2. Expanding our view from the Earth to neutron star
3. Probing nuclear structure

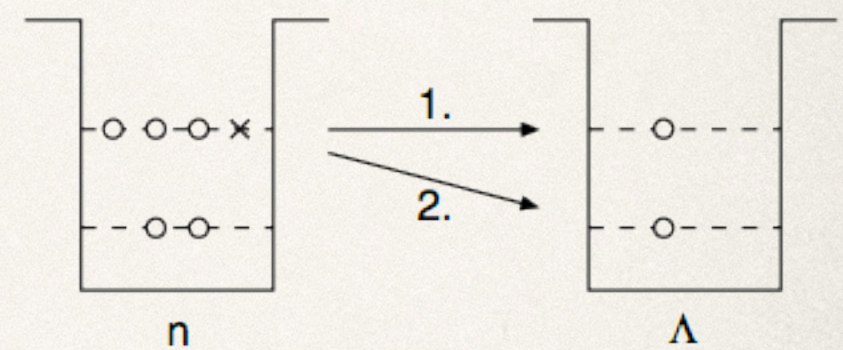
pictures taken from Hyp06 poster and Nature

Probing nuclear structure

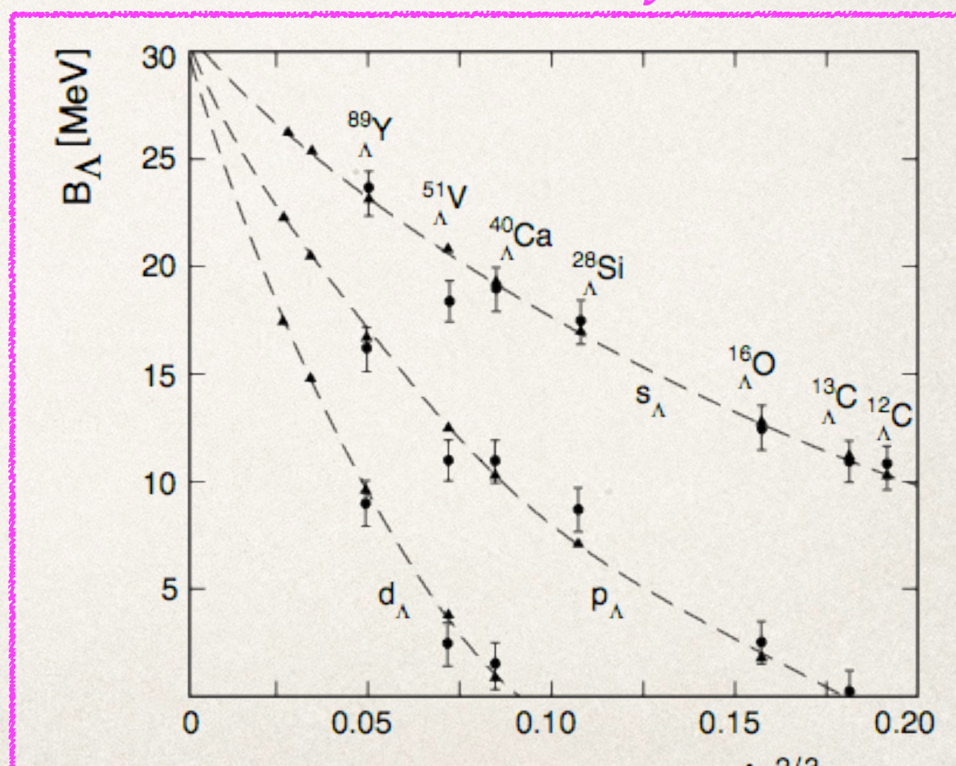




$^{12}C(K^-, \pi^-)^{12}{}_\Lambda C$ reaction



First direct evidence for nuclear mean field



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

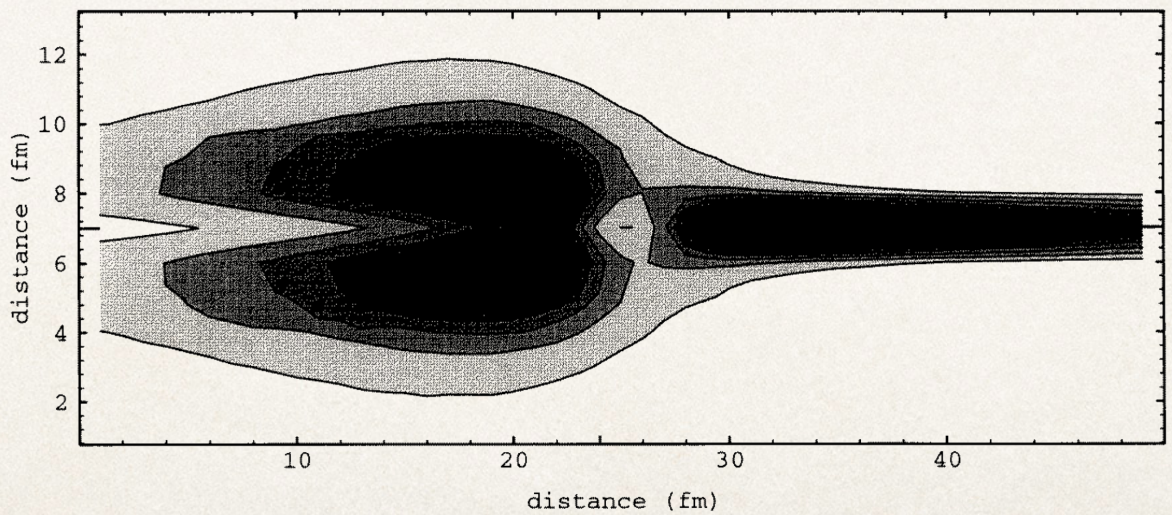
beam tracking

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

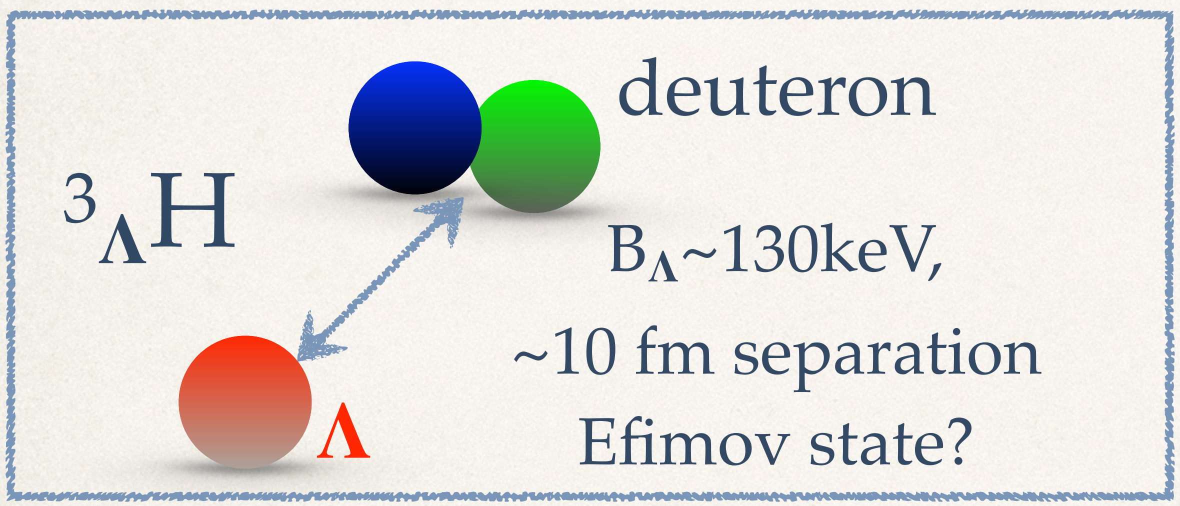


DOI: 10.1088/0954-3899/23/4/002

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

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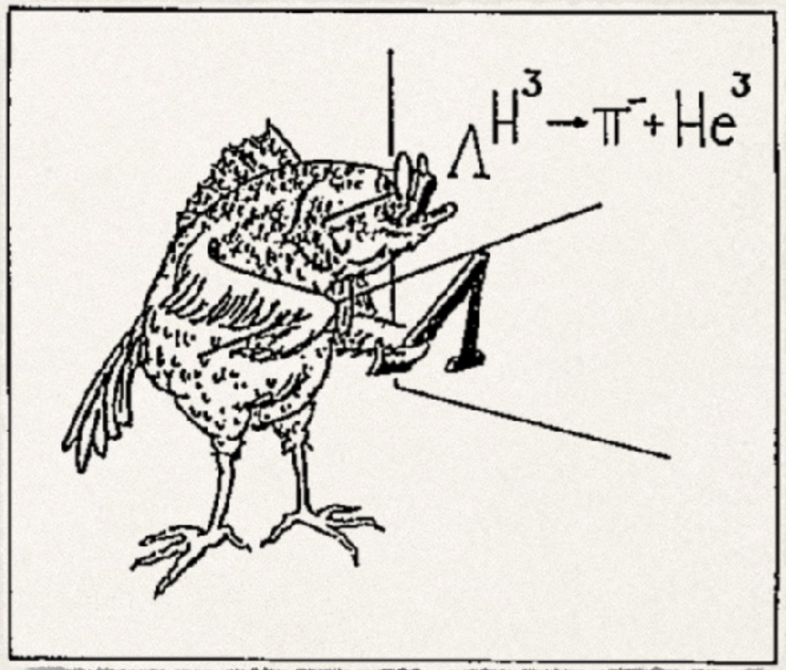
Up to a few years ago, we believe: $\tau \approx 263$ ps ($B_{\Lambda} = 130 \pm 50$ keV); However, heavy ion experiments suggest $\tau \approx 180$ ps…

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$29(syst.) 221$\pm$15(stat.)$\pm$19(syst.)	2018 [2] 2021 [6]
ALICE	Pb collider	181^{+54}_{-39}(stat.)$\pm$33(syst.) 242^{+34}_{-38}(stat.)$\pm$17(syst.)	2016 [3] 2019 [5]

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

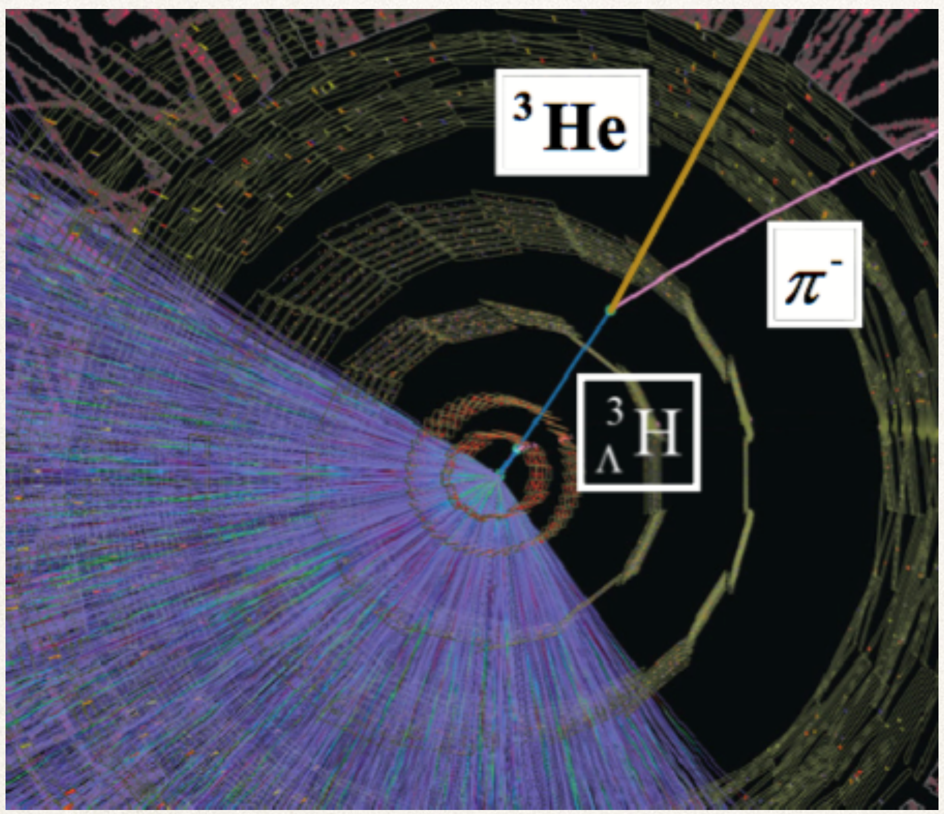


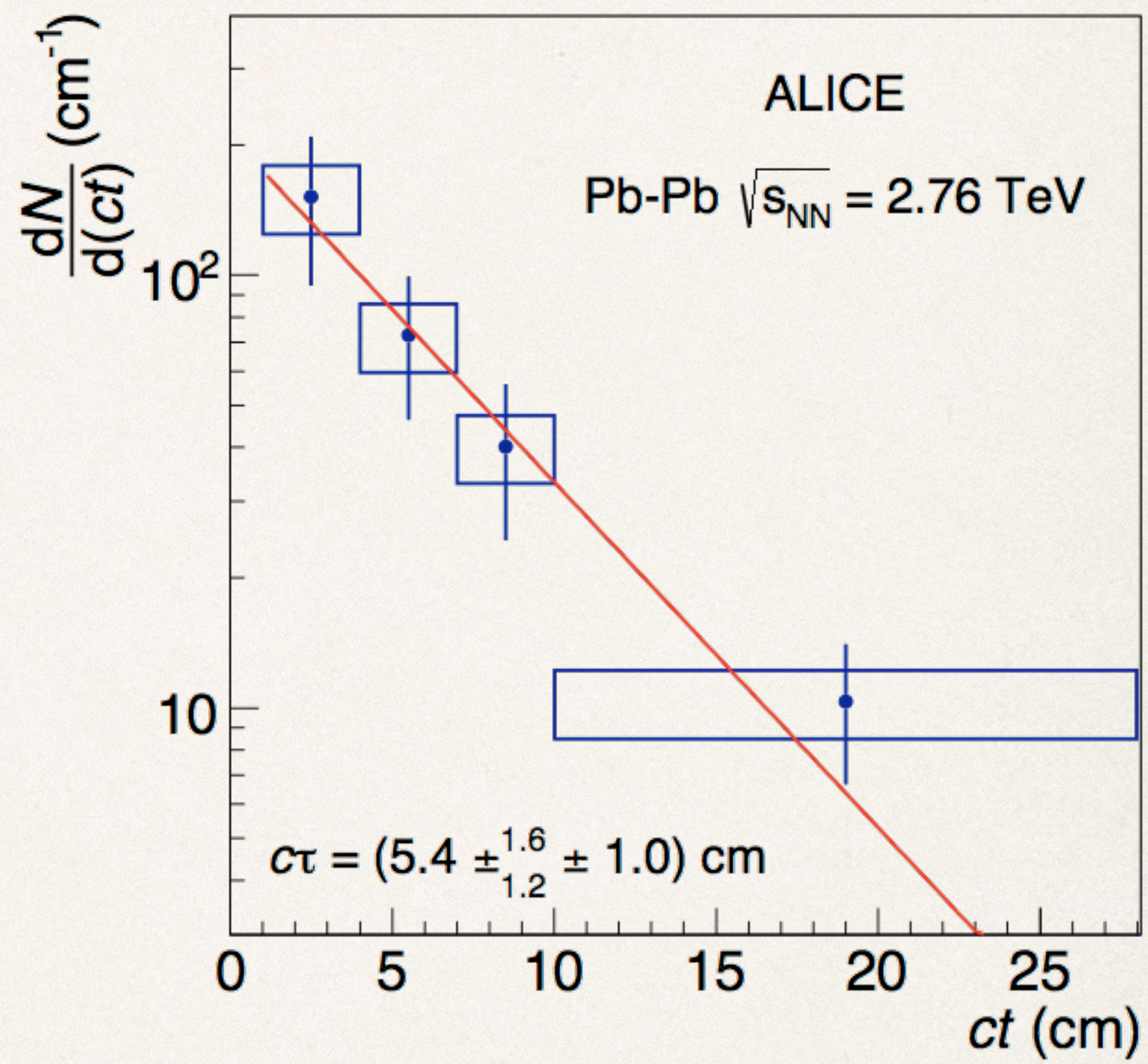
Neither fish nor fowl?

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

Heavy ion experiments: *indirect measurement*

ALICE as an example for the experimental approach.



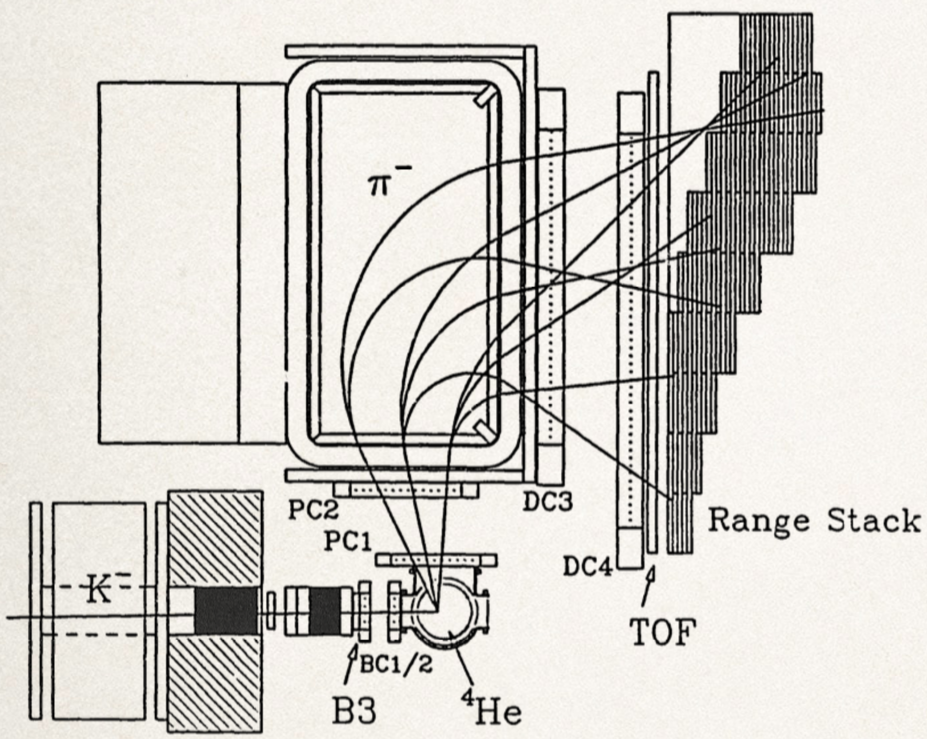


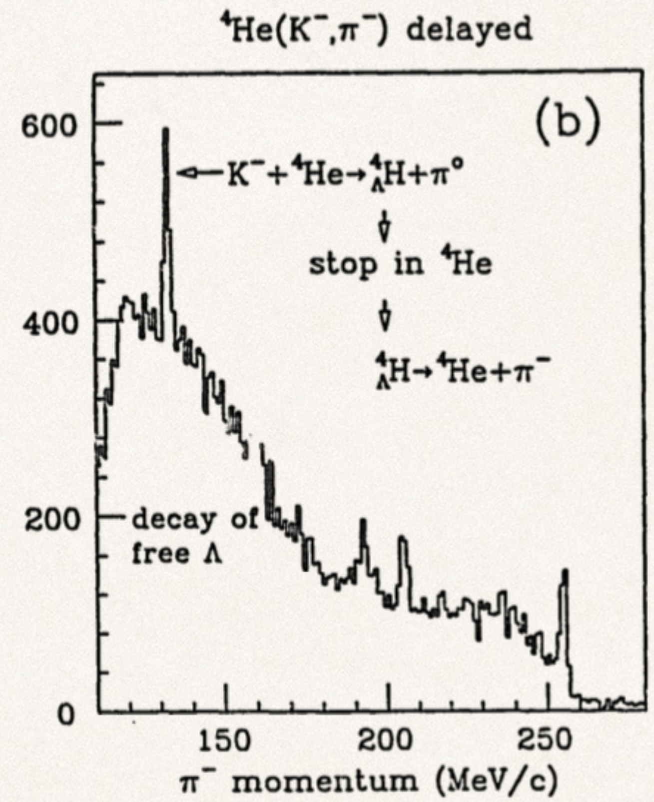
$$c\tau = \left(5.4^{+1.6}_{-1.2}(stat.) \pm 1.00(syst.)\right) cm$$
$$\tau = \left(181^{+54}_{-39}(stat.) \pm 33(syst.)\right) ps$$

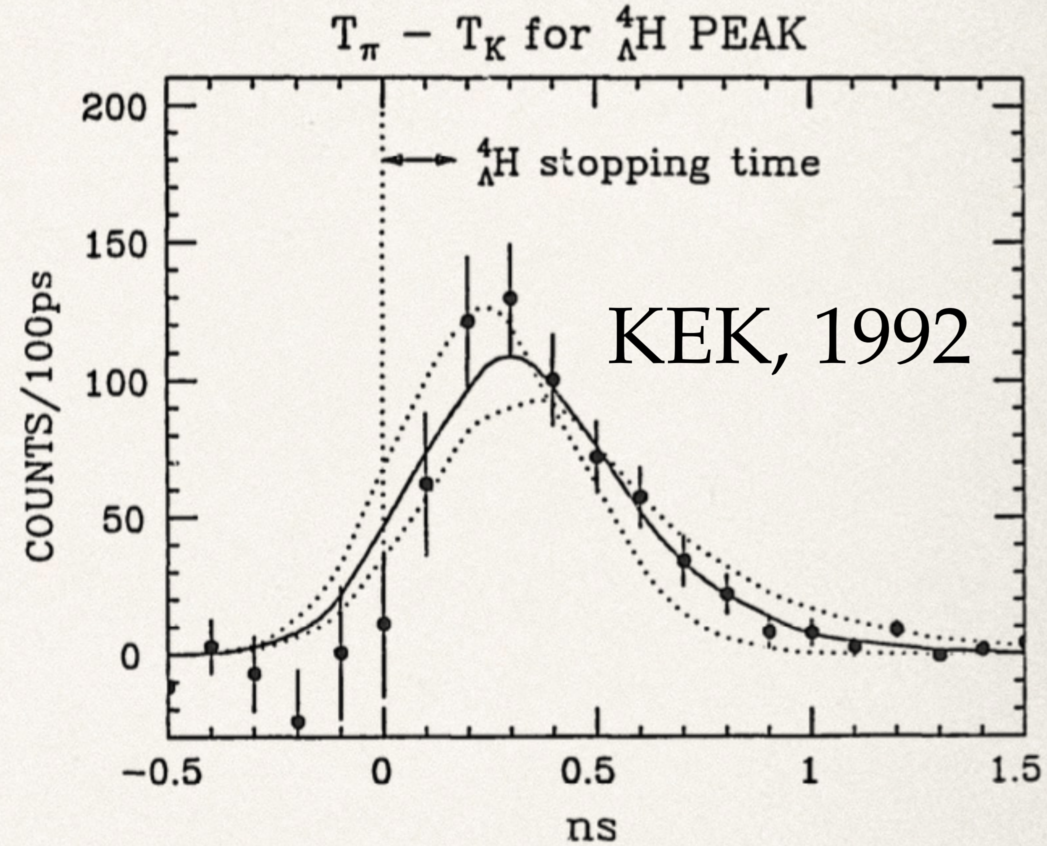
Depends on tracking results for decay length and momentum as

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

Another choice: *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

J-PARC E73 experimental method

Methods for *direct lifetime measurement*

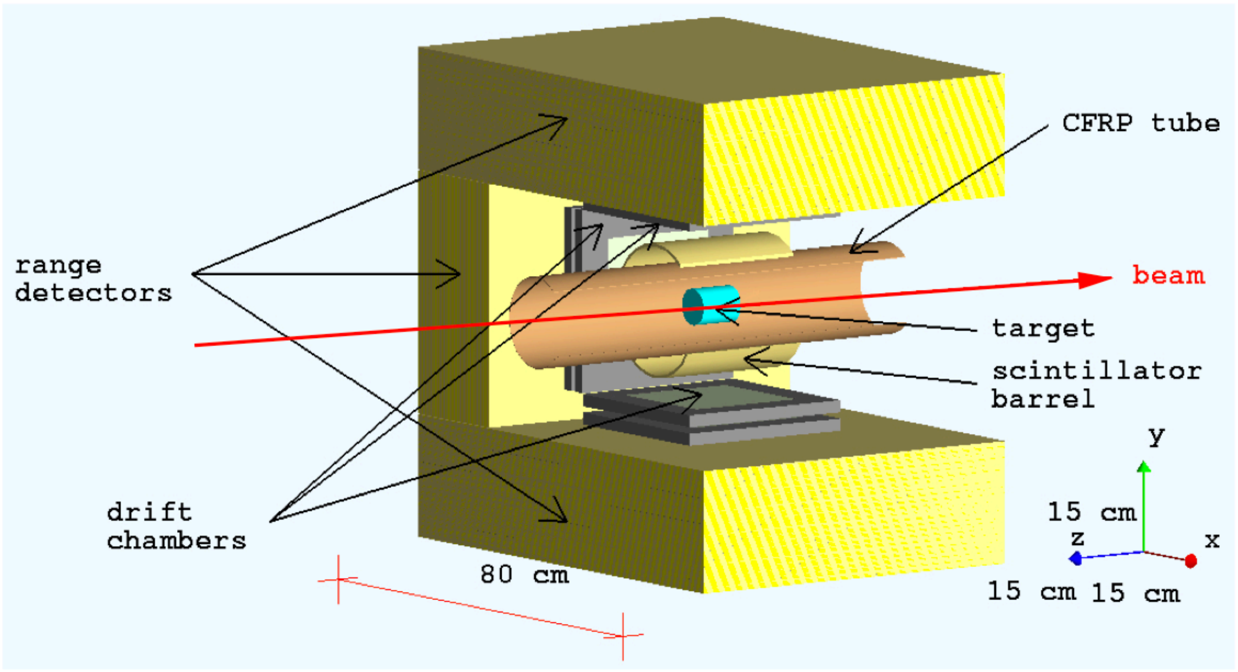
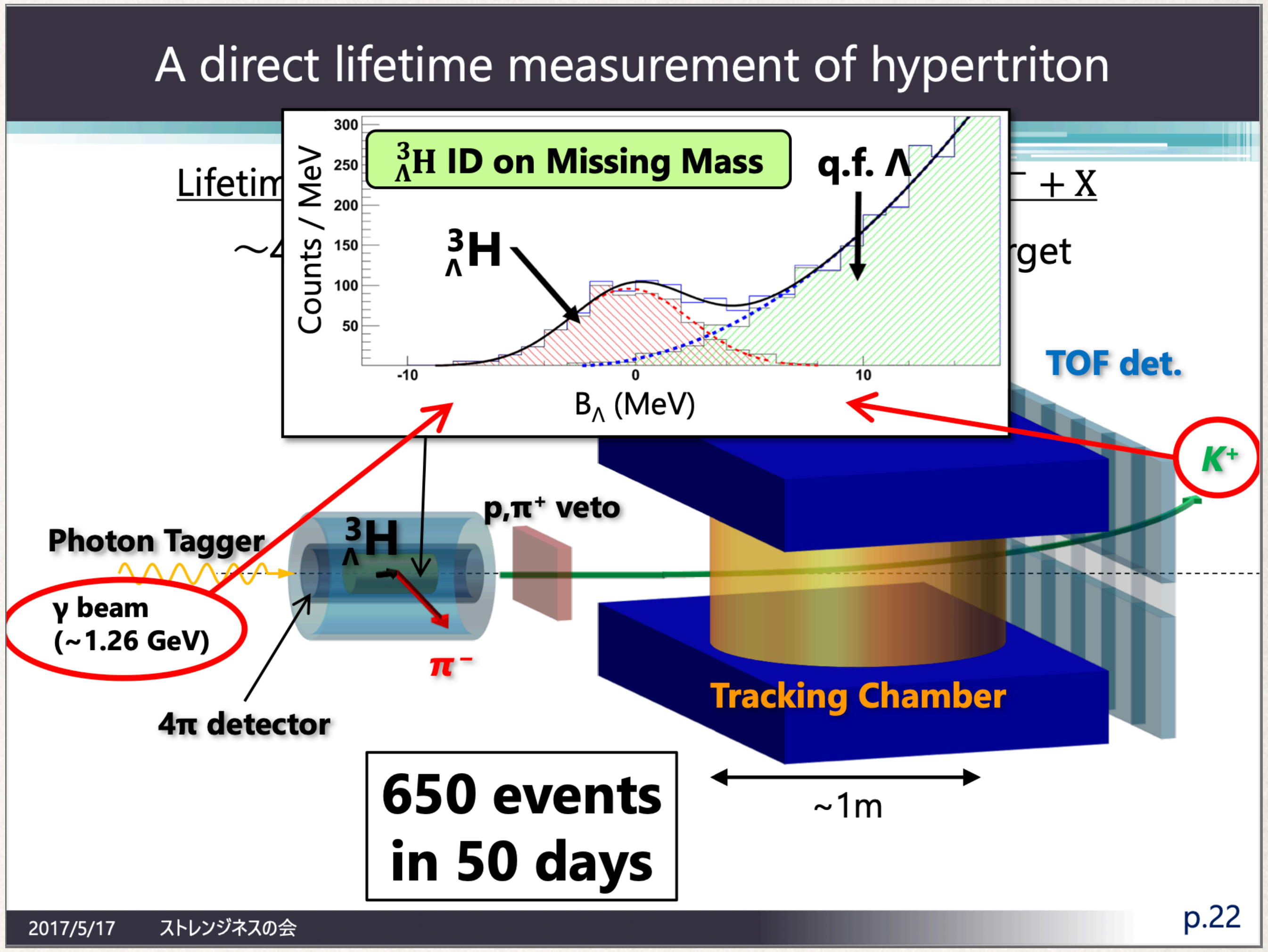


Figure 7: Pictorial view of the proposed *target-range hodoscope region* experimental set-up, as it is currently implemented in the GEANT4 simulation program. One of the quadrant of the apparatus has been removed to permit to see the interior details.



- pi- + He3 --> K0 + Hypertriton:
  - by A. Feliciello, INFN, Italy
- gamma + He3 --> K+ + Hypertriton:
  - by S. Nagao, Tohoku University

Both ideas are very brilliant!

Slides from J-PARC P74 proposal and Dr. Nagao's presentation

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

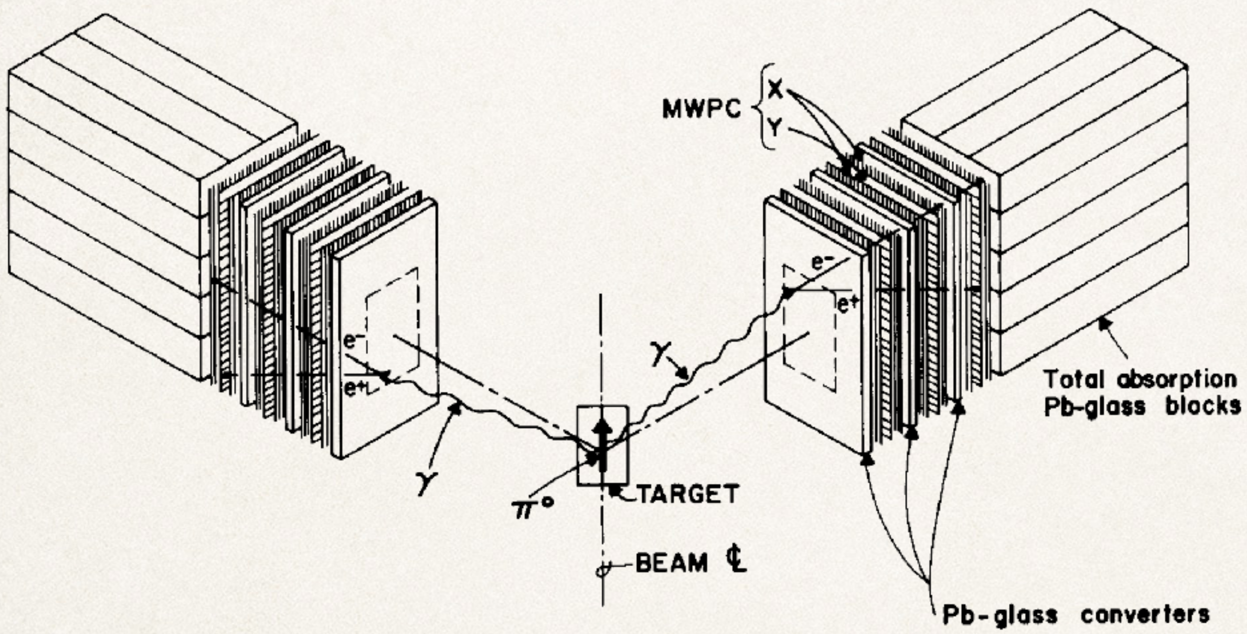


Fig. 1. A schematic diagram of the detector. The orientation of the two arms with respect to each other and to the scattering target is indicated. Also indicated is the convention for the x and y coordinates.

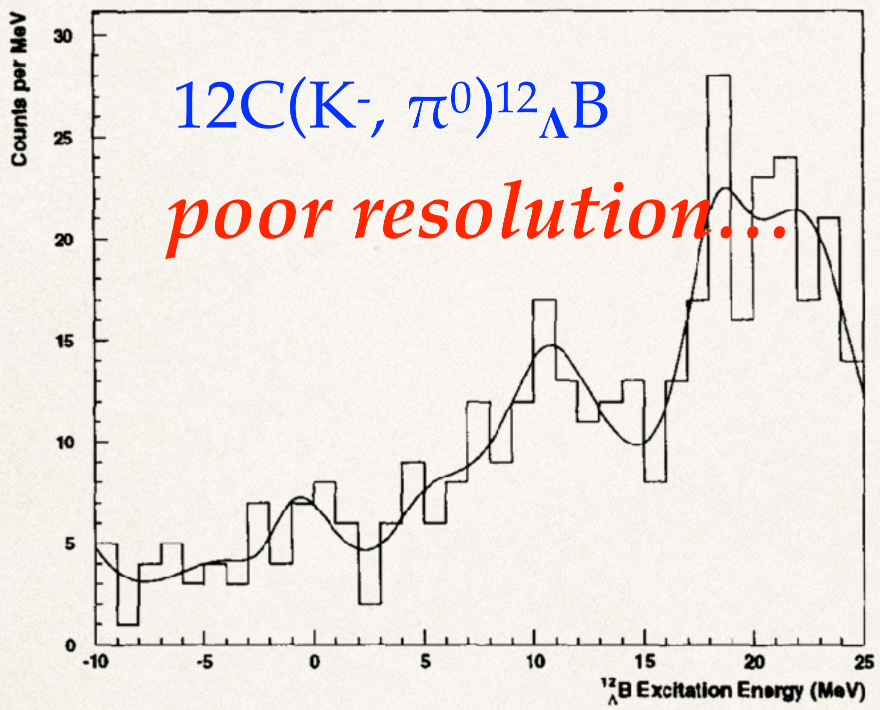
Working principle:

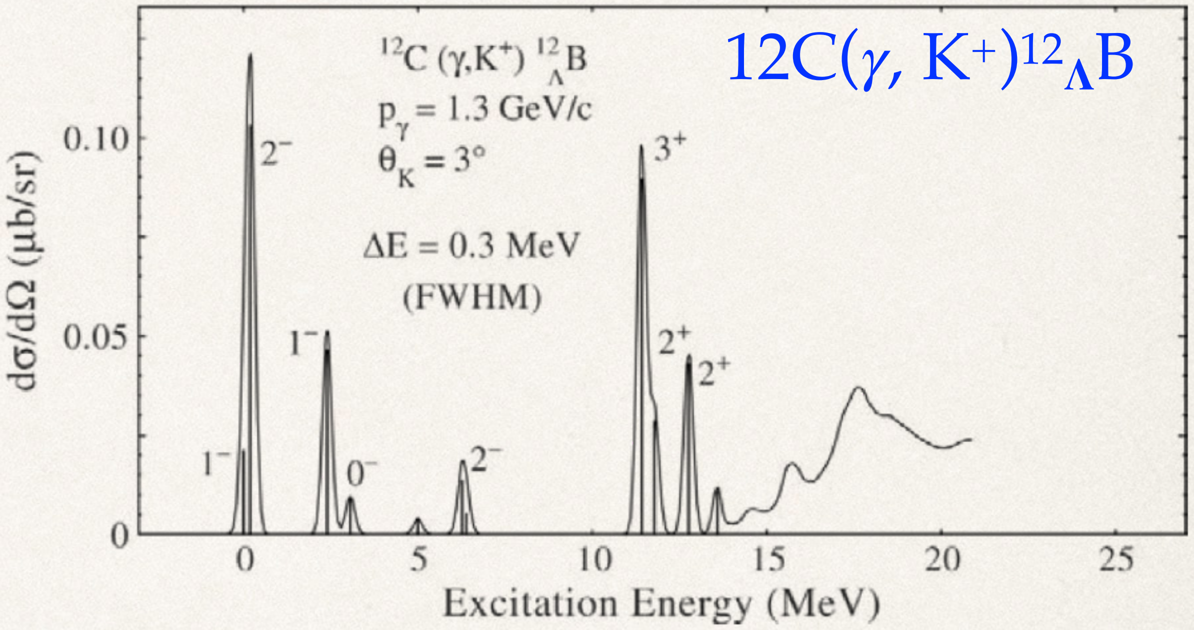
- γ converter
- Tracking chamber
- Calorimeter
- γ opening angle ⊕ energy

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

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

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



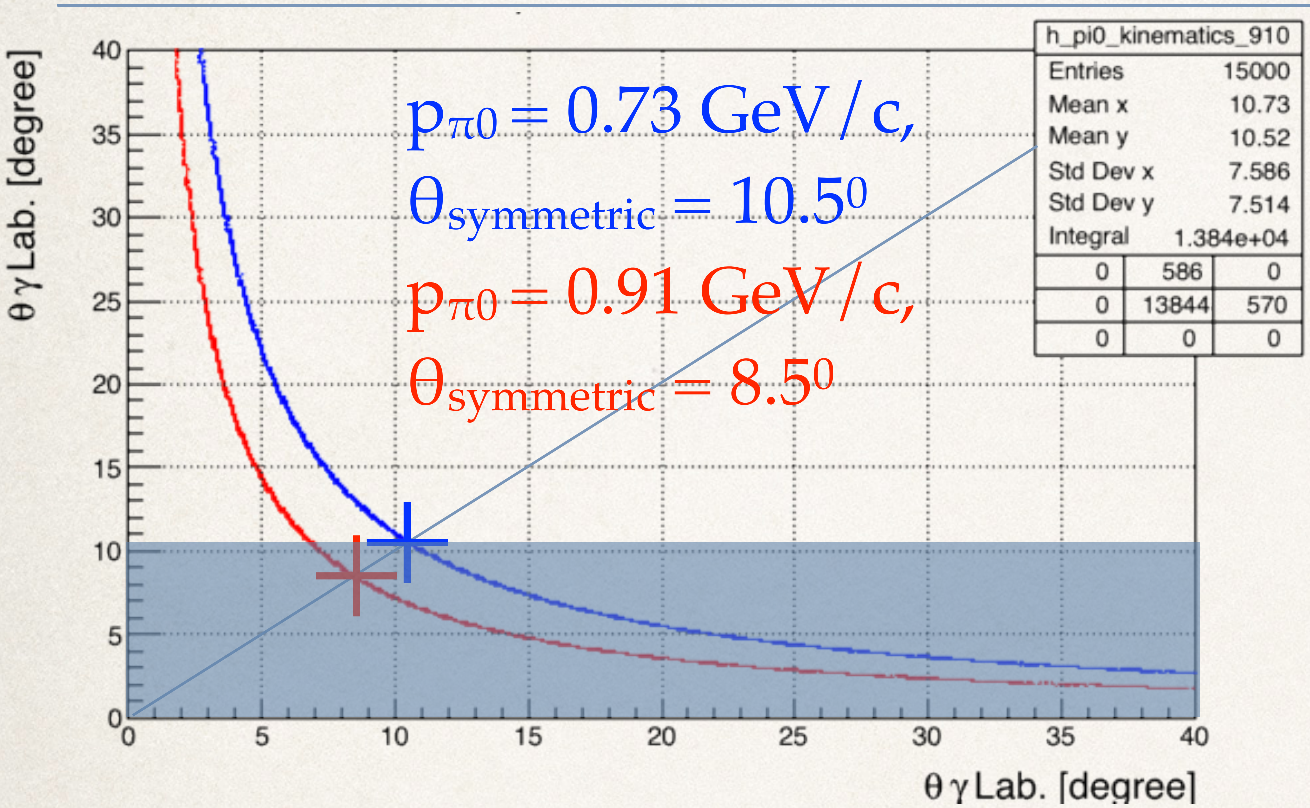


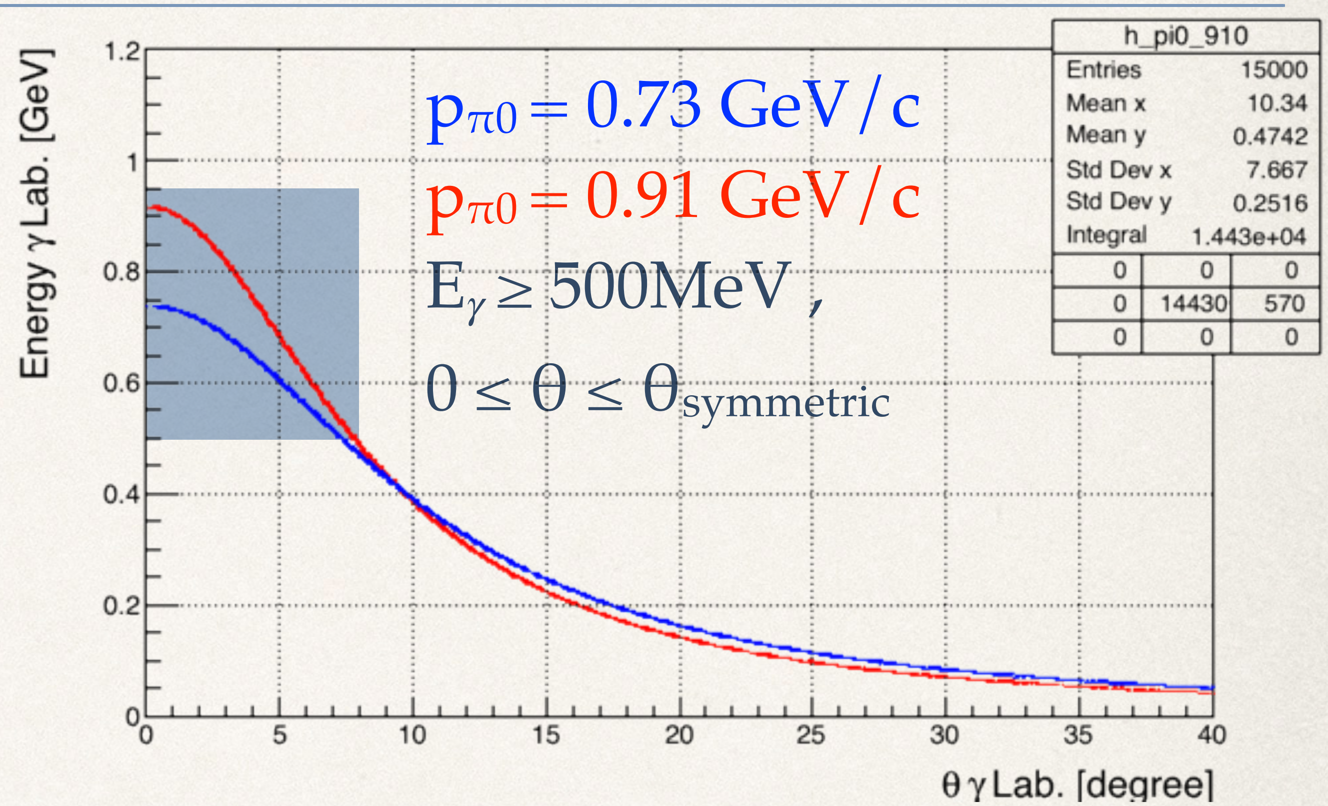
Neutral Meson Spectrometer

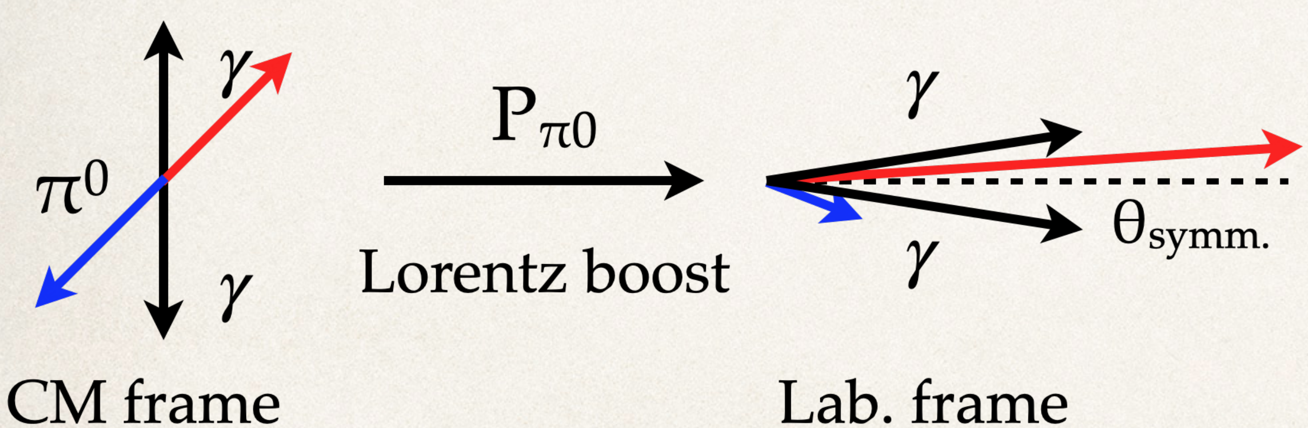
- Constructed at Los Alamos and shipped to BNL
- MM resolution ***~3MeV*** (design value ***~1MeV***)
- Bad resolution compare to (γ, K^+) channel

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

Revisit π^0 decay kinematics







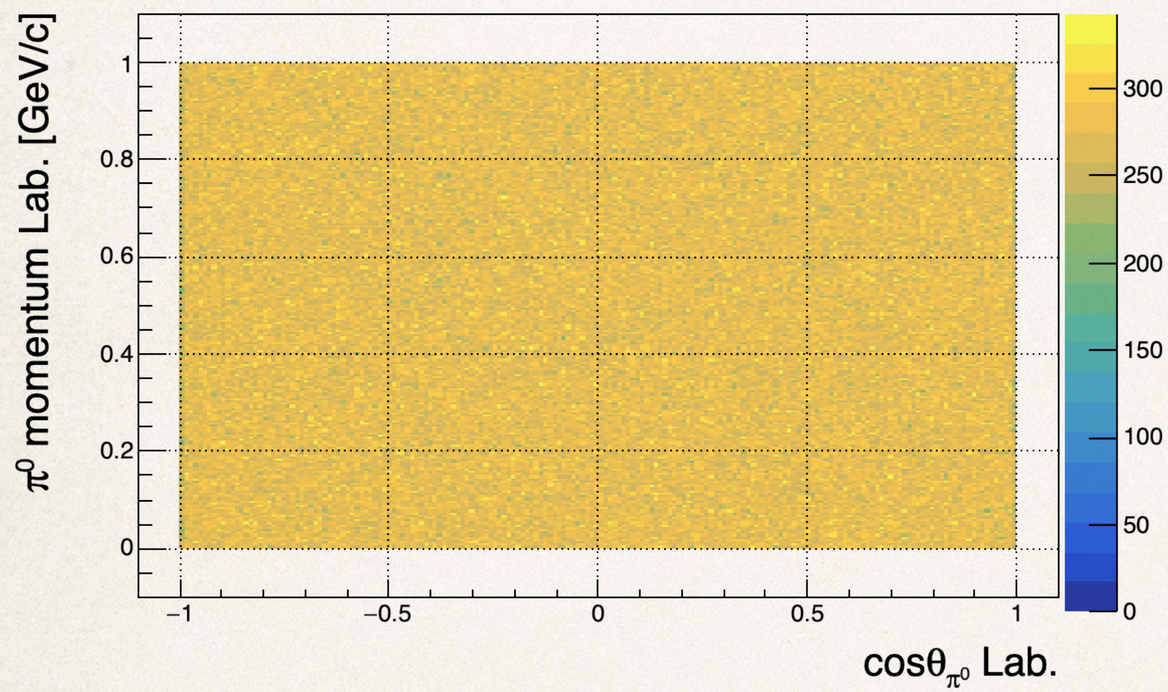
- 0.73~0.91GeV/c π^0 boosts γ forwardly;
- By covering $0 \sim \theta_{symmetric}$, tag the γ with higher energy ($E_\gamma \geq 500$MeV)

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

Do we *really* need missing mass?

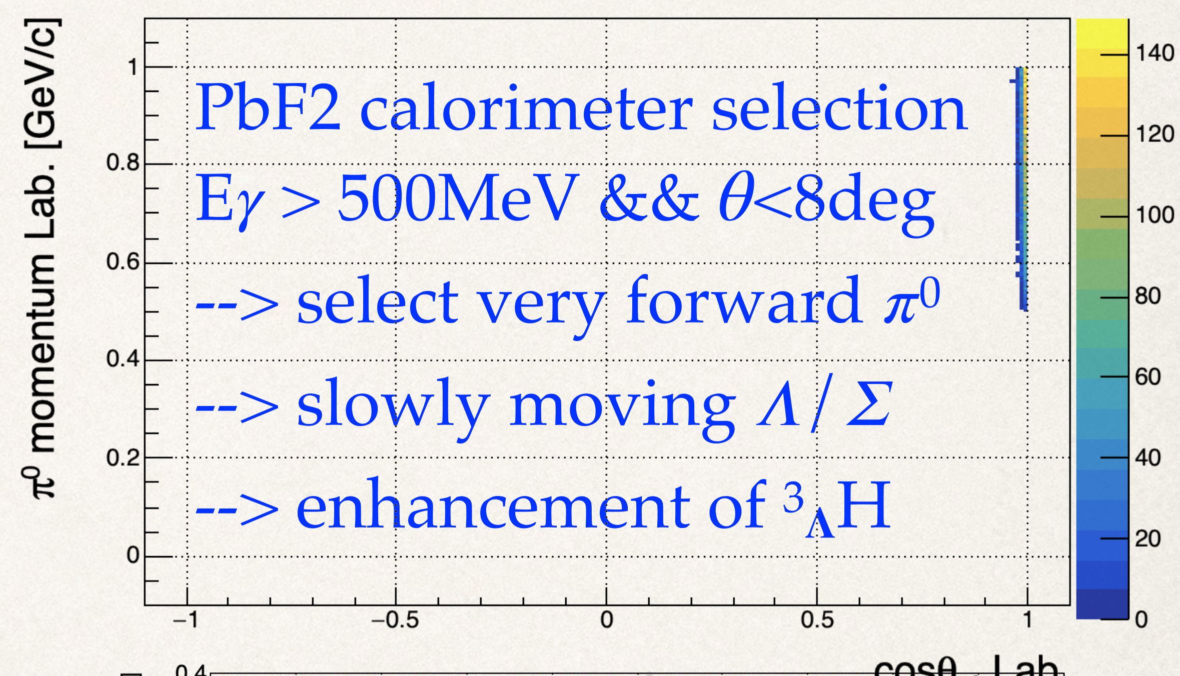
Input

π^0: 0~1GeV/c; 0~180deg

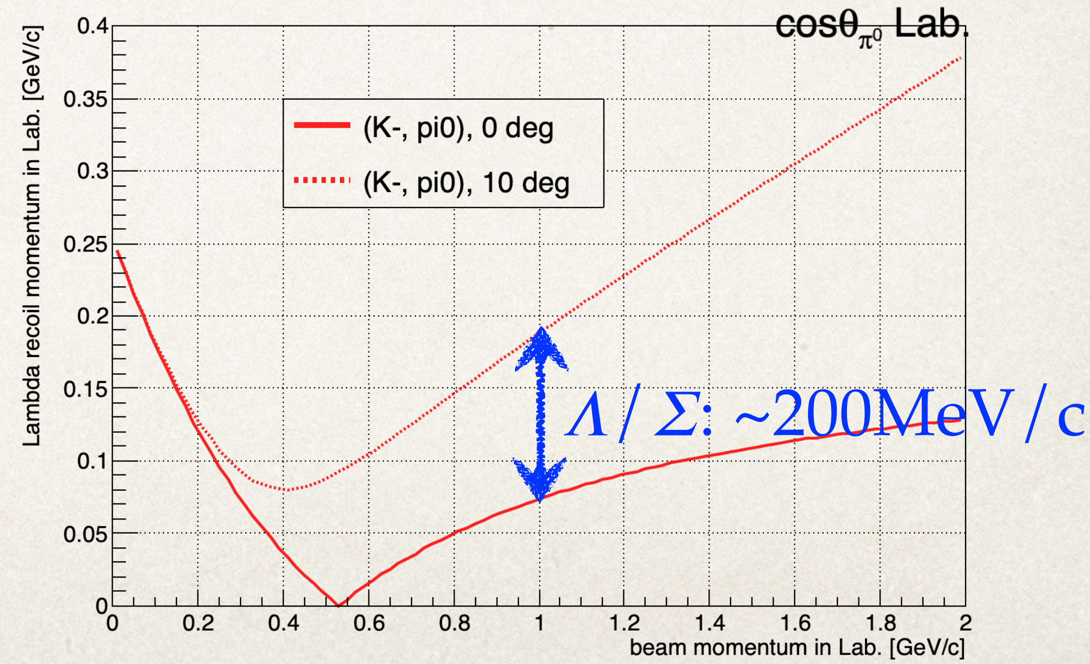


W/ PbF2 calorimeter cut

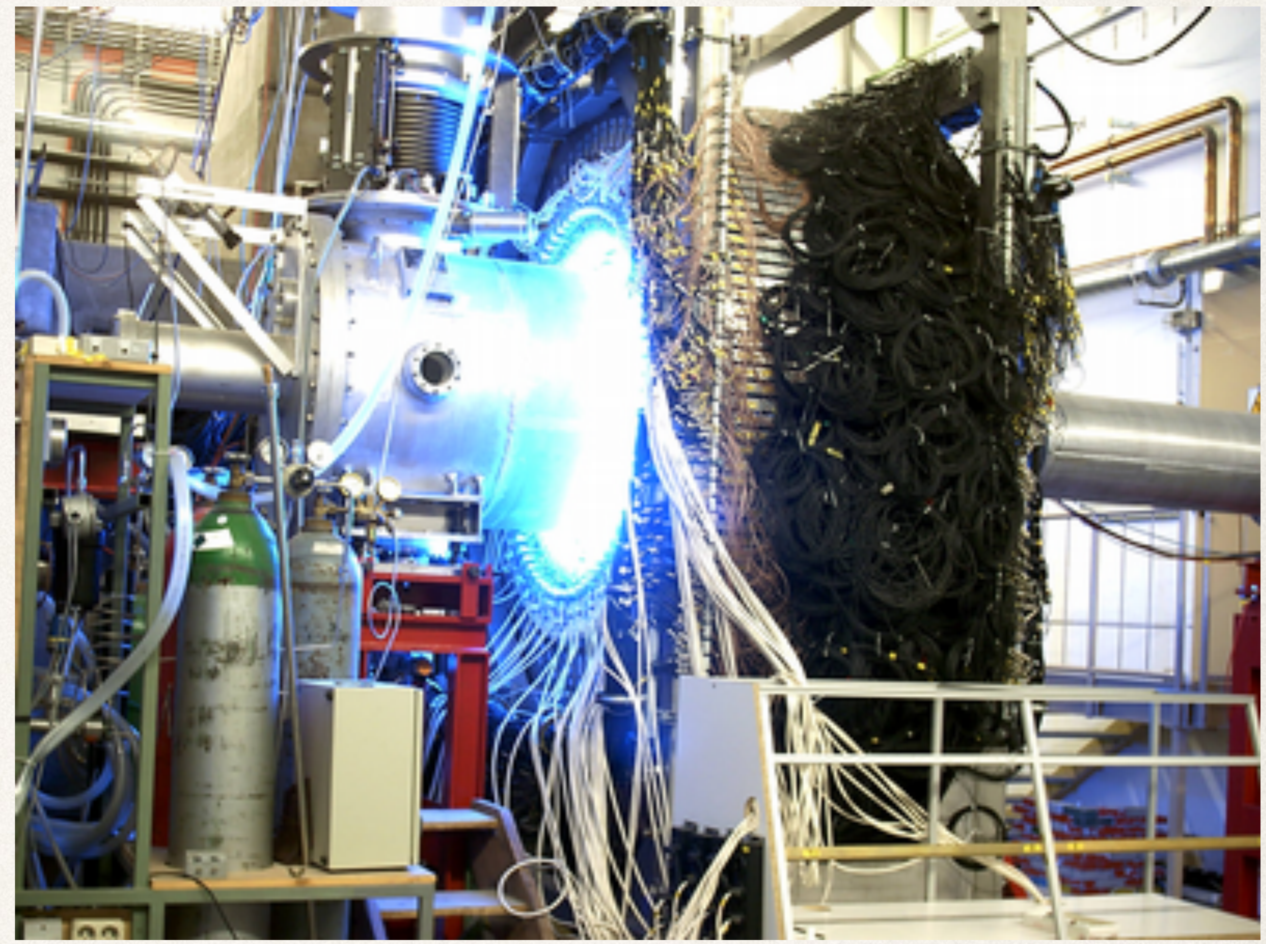
π^0: 0.8~1GeV/c; 0~10deg



^{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.

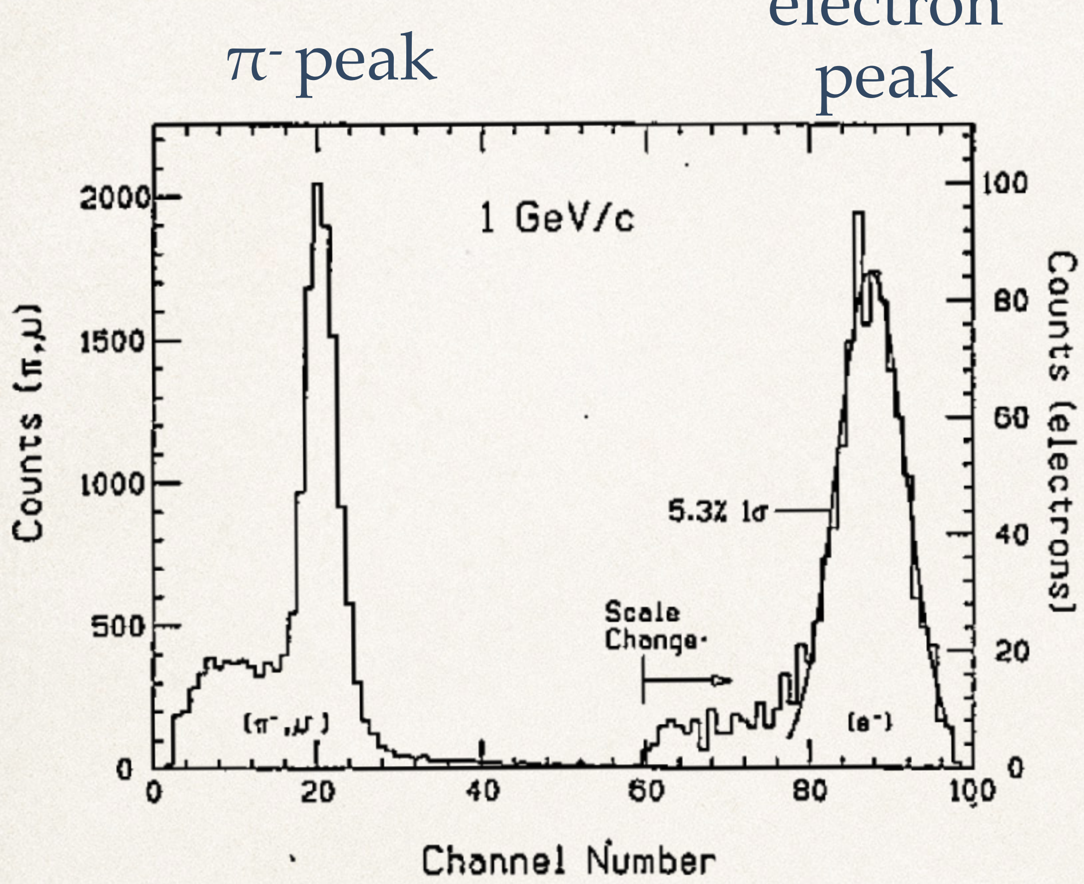


Can we construct a fast calorimeter?

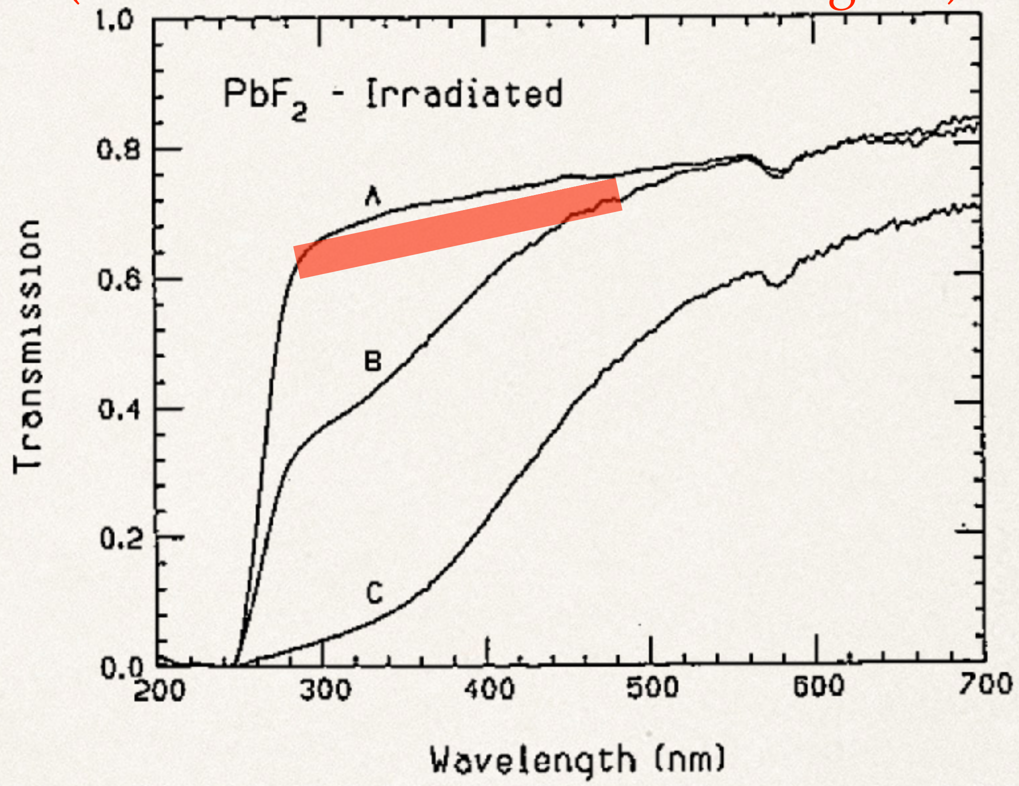


- π^0 tagger needs to be ***located along beam line***
  - ***Nobody has ever put a calorimeter IN the intensive beam***
- Main stream: slow inorganic scintillator of μs signal tail
- Inspired by MAMI A-4 spectrometer
  - postdoc with Prof. Frank Maas, 2009~2011

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



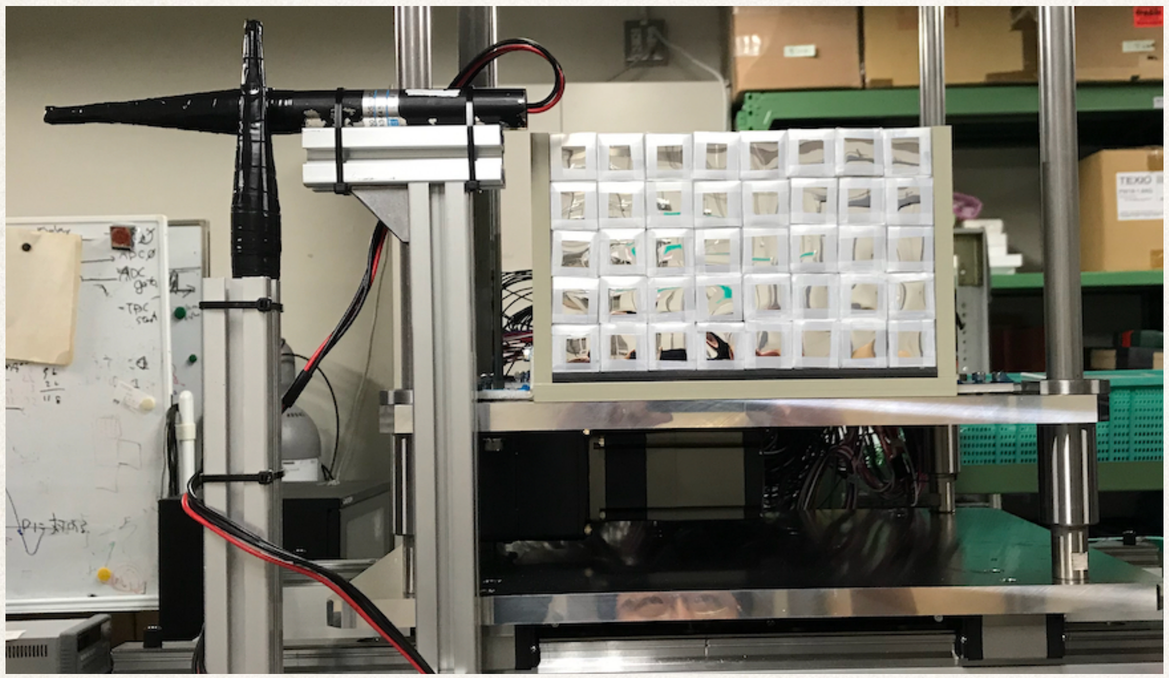
expected performance after one month beam time
(10 times more resistive than Pb glass)

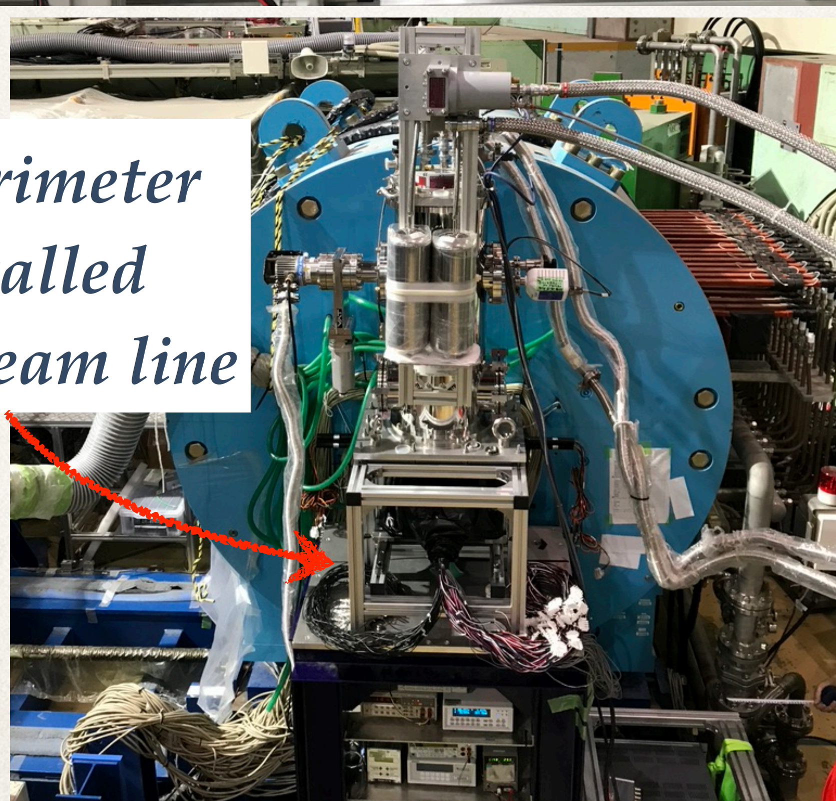


Crystal	Radiation length	Moliere radius	Density	Cost	Resolution	Signal length
PbF_2	0.93 cm	2.22 cm	7.77 g/cm^3	12 USD/cc	5%	2ns

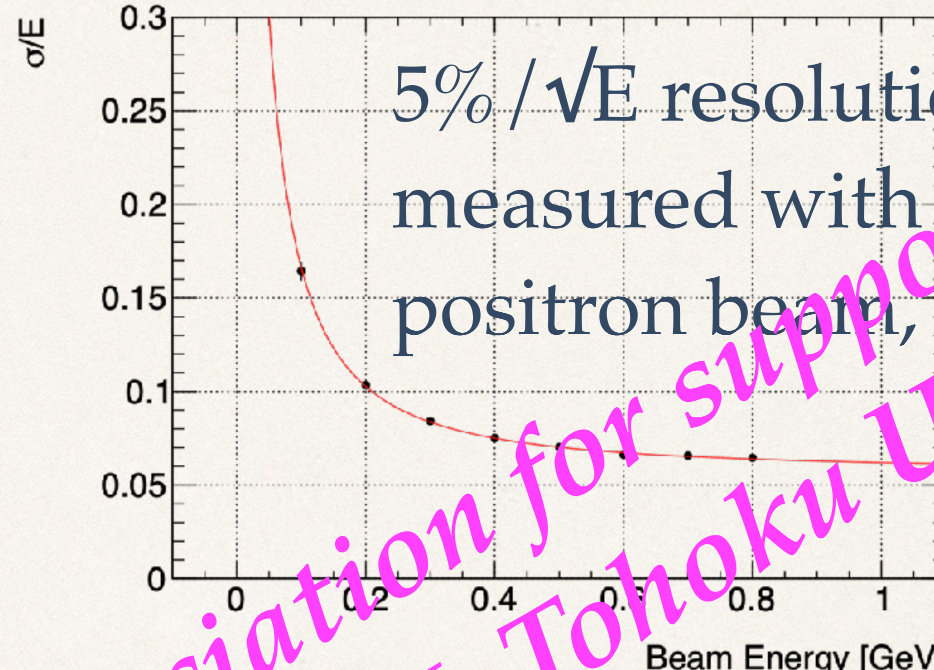
D.F. Anderson, ***et al.***, Nucl. Inst. Meth. A290 (1990) 385
P. Achenbach, ***et al.***, Nucl. Inst. Meth. A416 (1998) 357

PbF2 calorimeter performance @ELPH

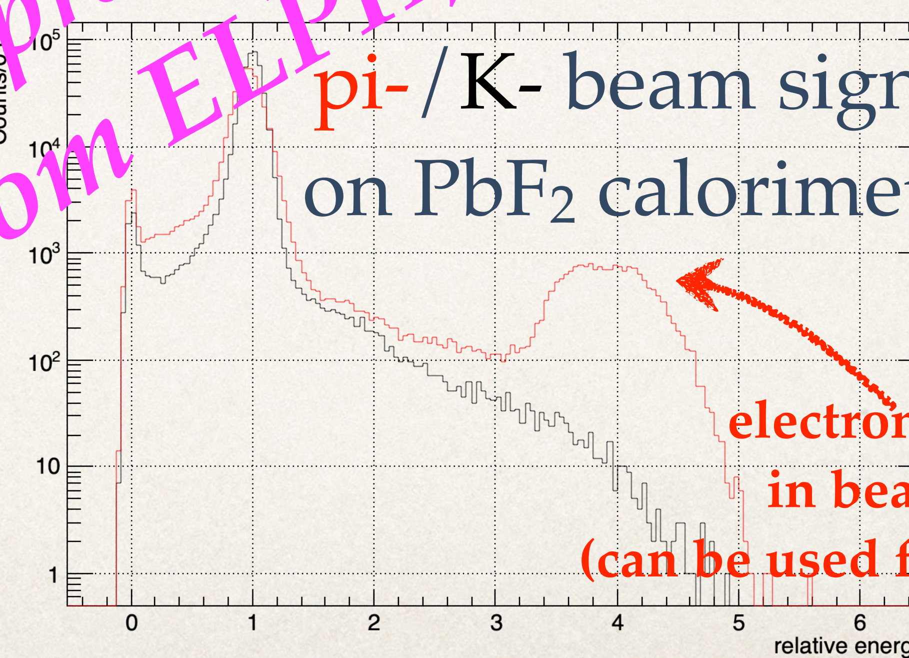




PbF2 calorimeter was installed ***INTO*** *the beam line*



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



pi- / K- beam signal on PbF_2 calorimeter

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

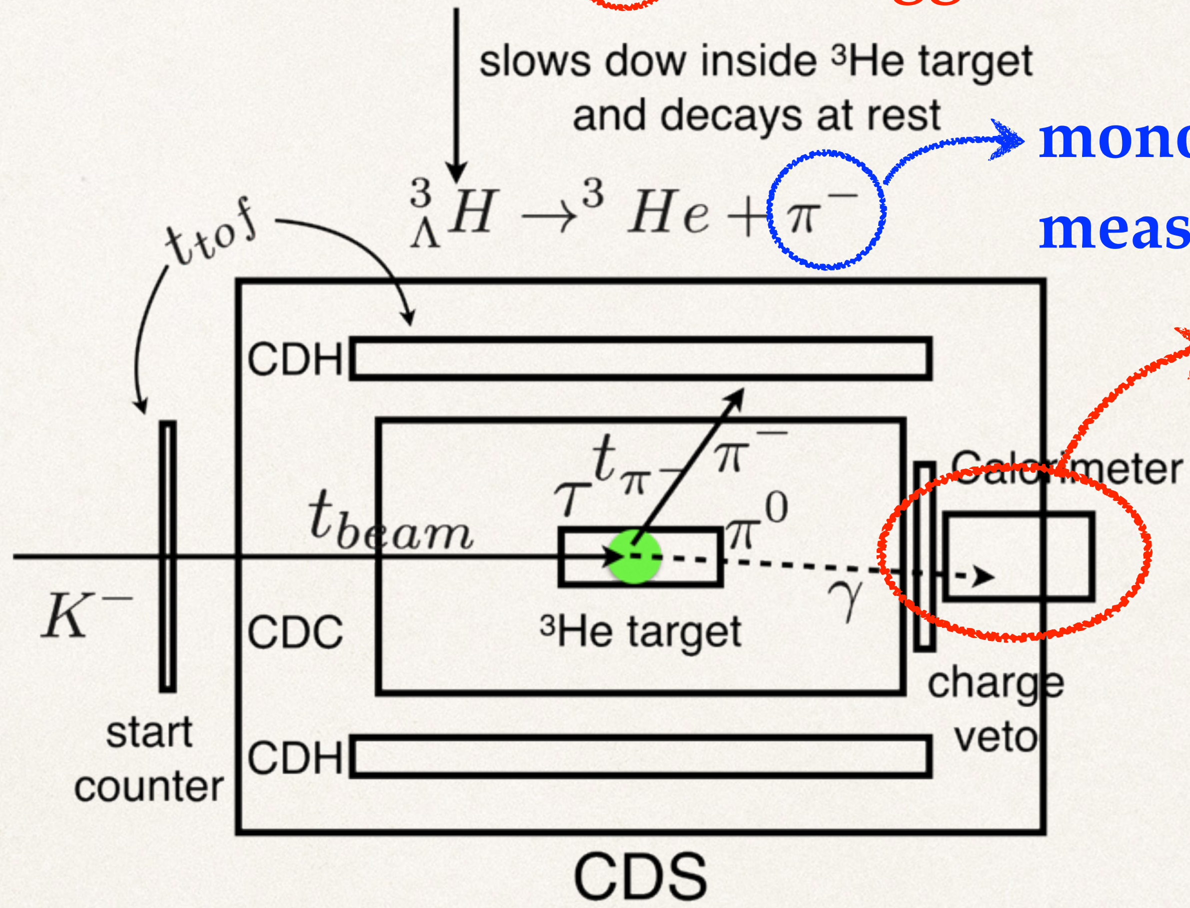
Appreciation for support from ELPH, Tohoku Univ.

E73 Experimental setup

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

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: $\sigma/\sqrt{N} \sim 30ps$

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	Waiting for approval; beam time in 2023?

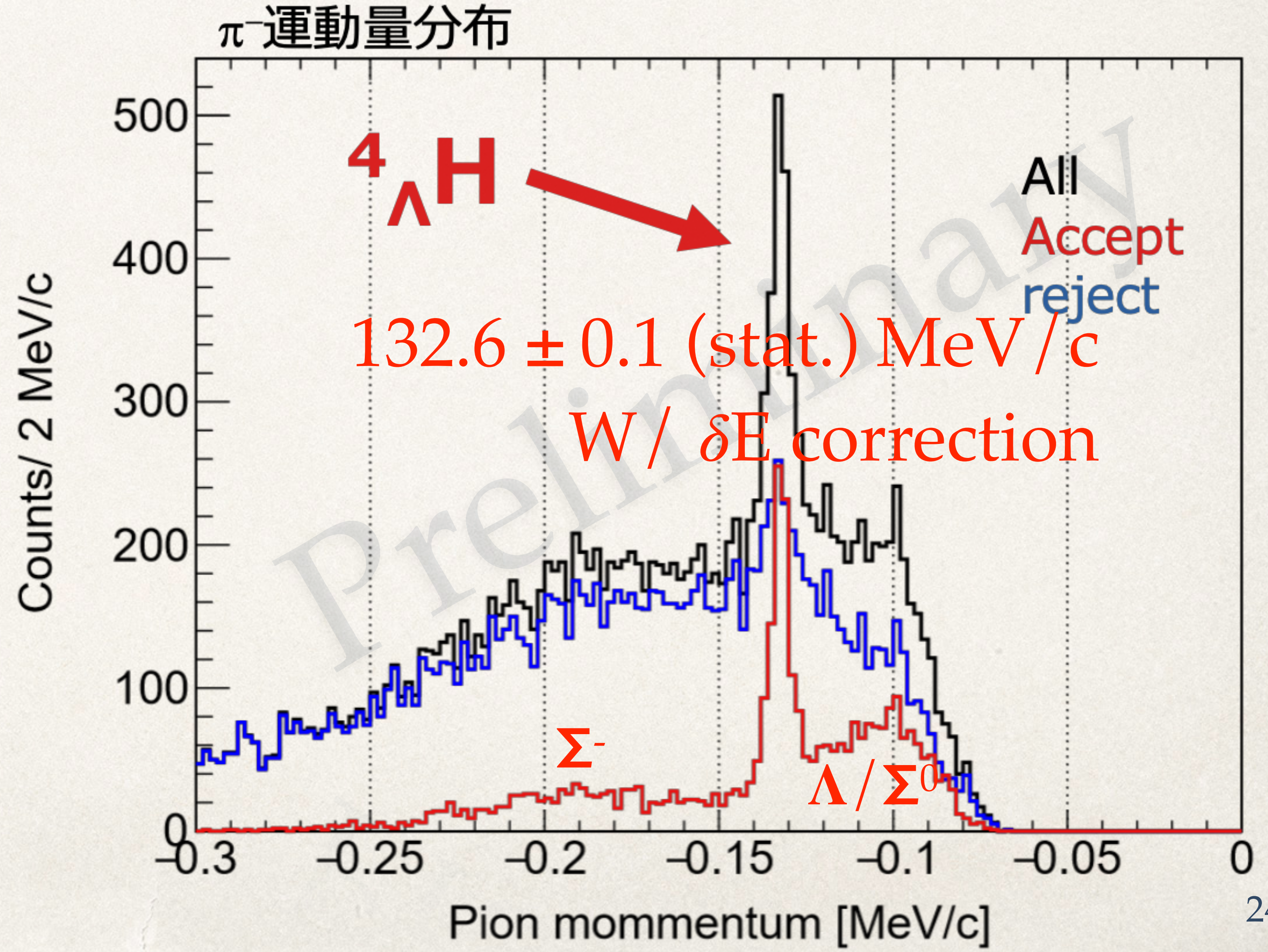
Stage-0: feasibility study for E73

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

slows down inside ⁴He target and decays at rest

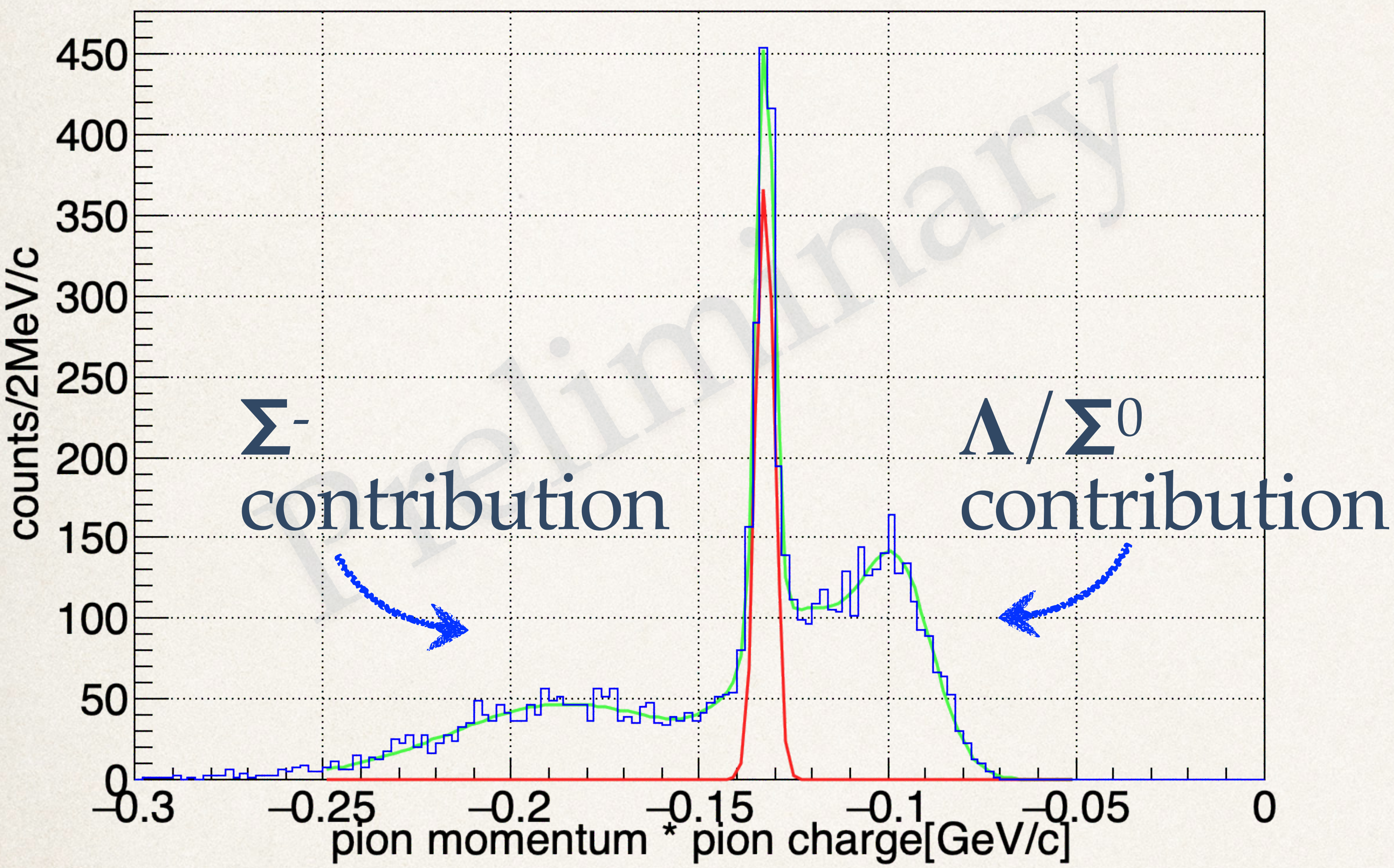
$${}^4_\Lambda H \rightarrow {}^4He + \pi^- \; 132.9 \text{ MeV/c}$$

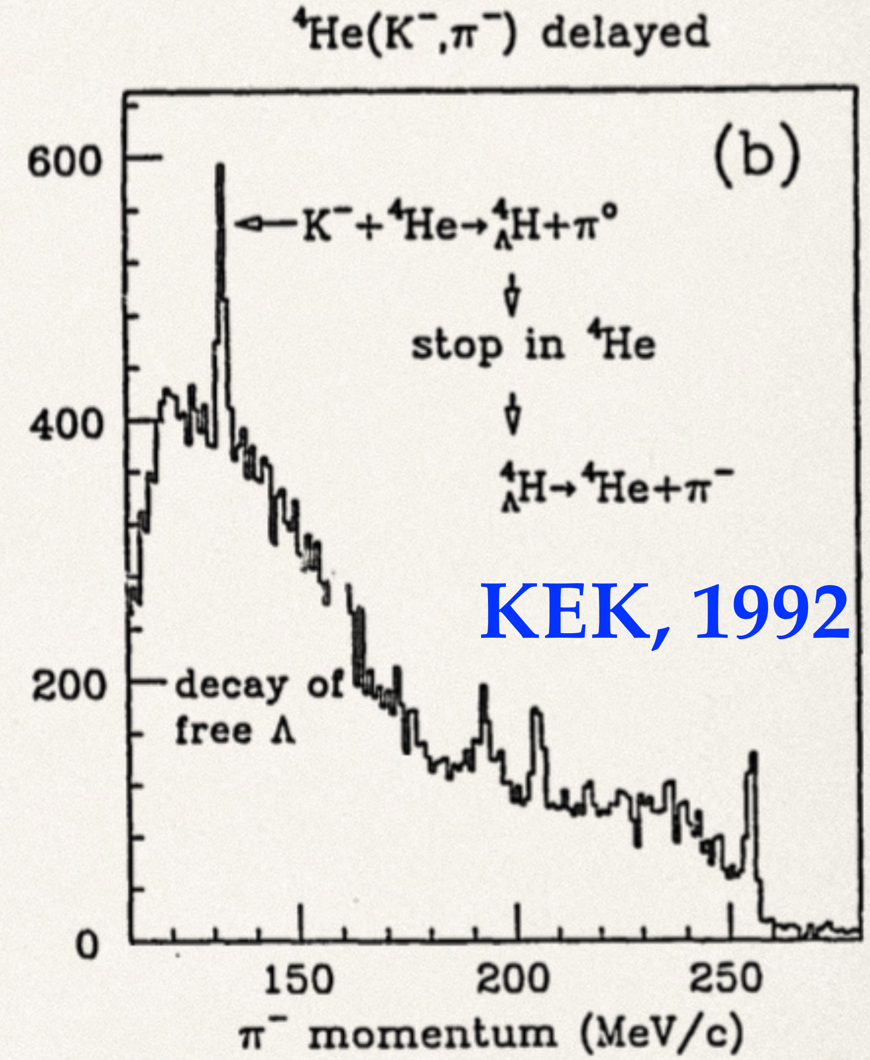
- T77 refreshes world record for $^4{}_\Lambda$H statistics by twice (***1.2k events***);
- New method improves S/N by ~ 10 times;
- ***All these happen within 3days of beam time!***



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

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

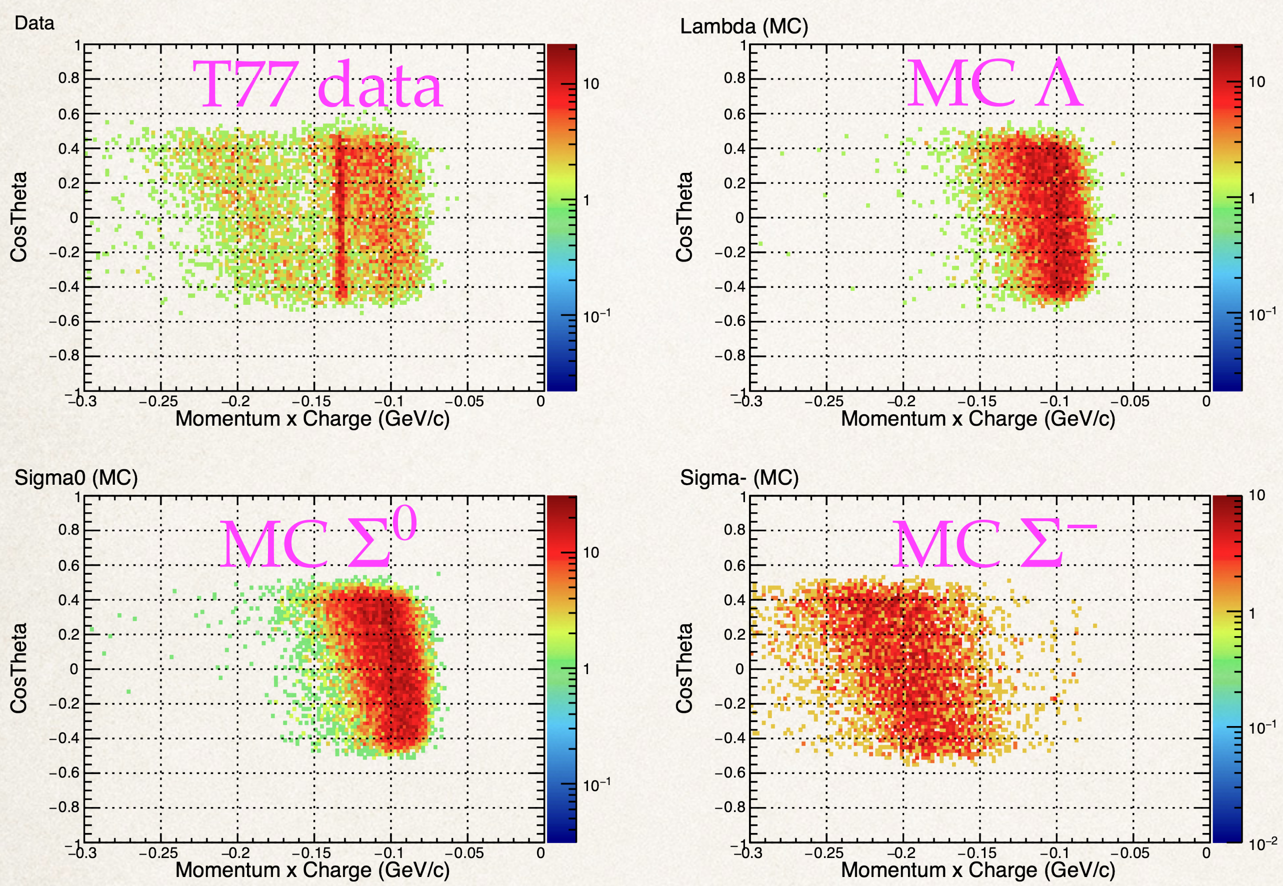




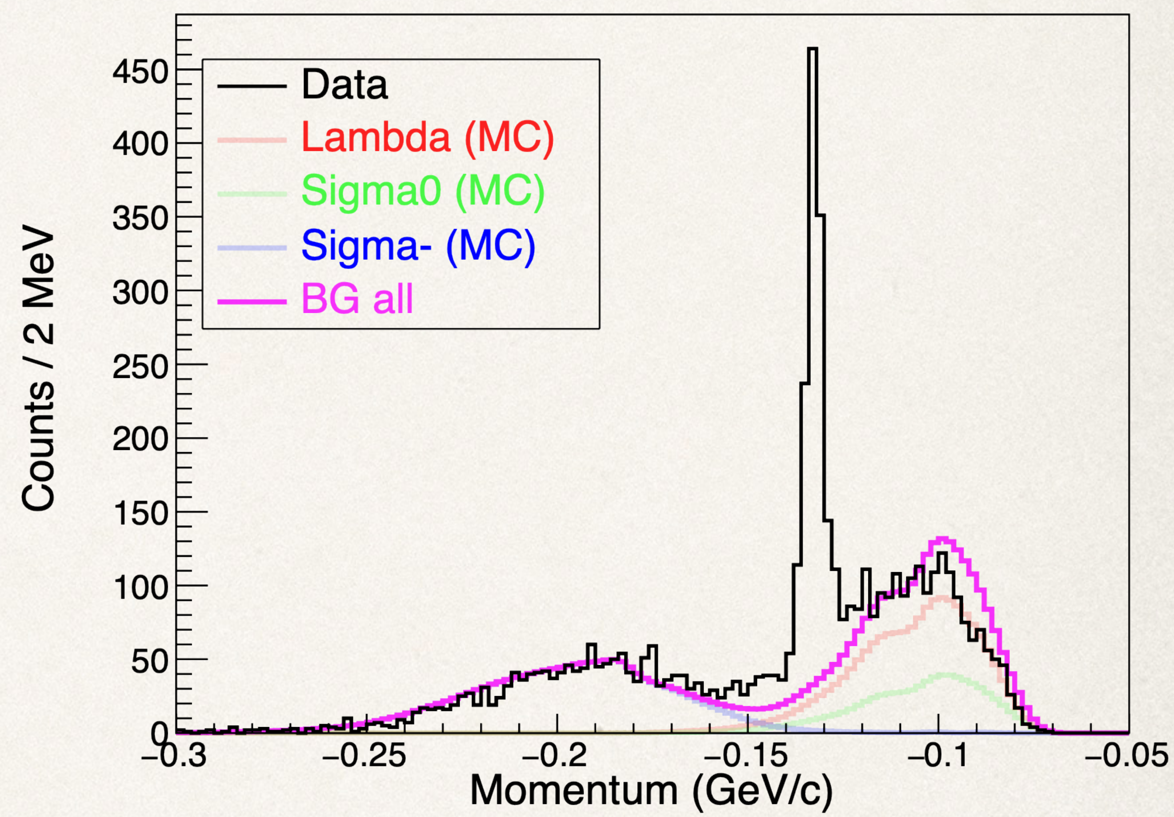
- T77 refreshes world record for $^{4}_{\Lambda}$H statistics by twice;
- New method improves S/N by ~ 10 times;
- *All these happen within 3days of beam time!*

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;

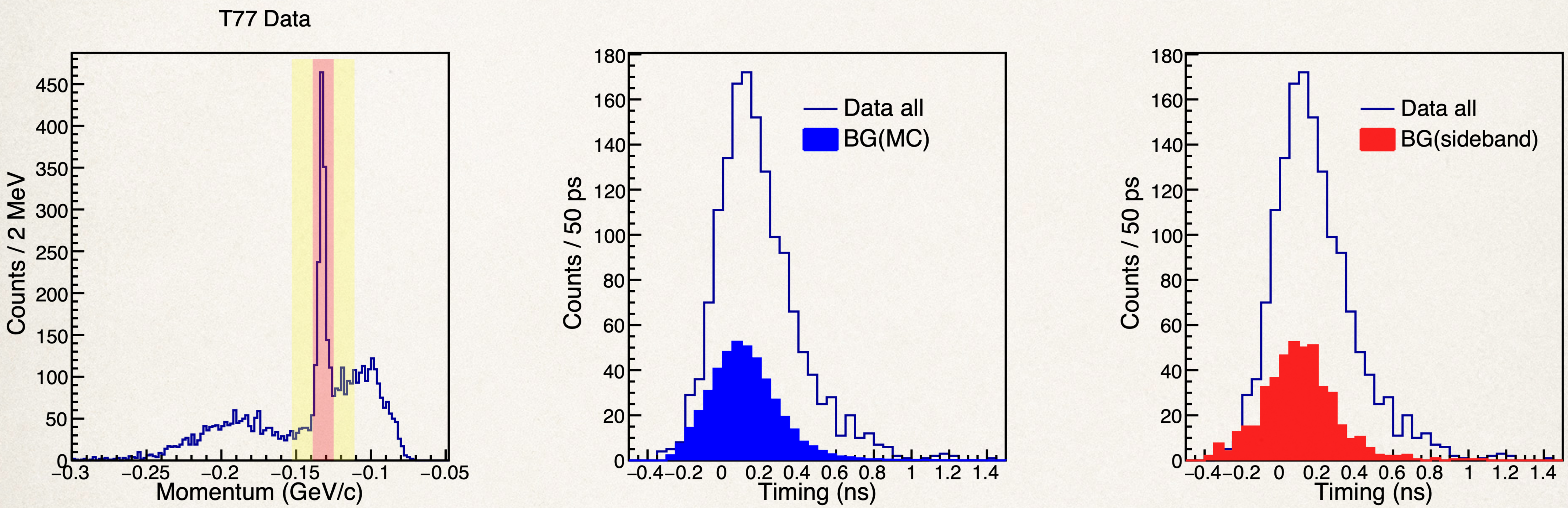
$N(K^-, \pi^0)$Y elementary reaction with published data +

convoluted with Argonne AV18+UX Fermi motion

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

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

Good agreement between MC and data.



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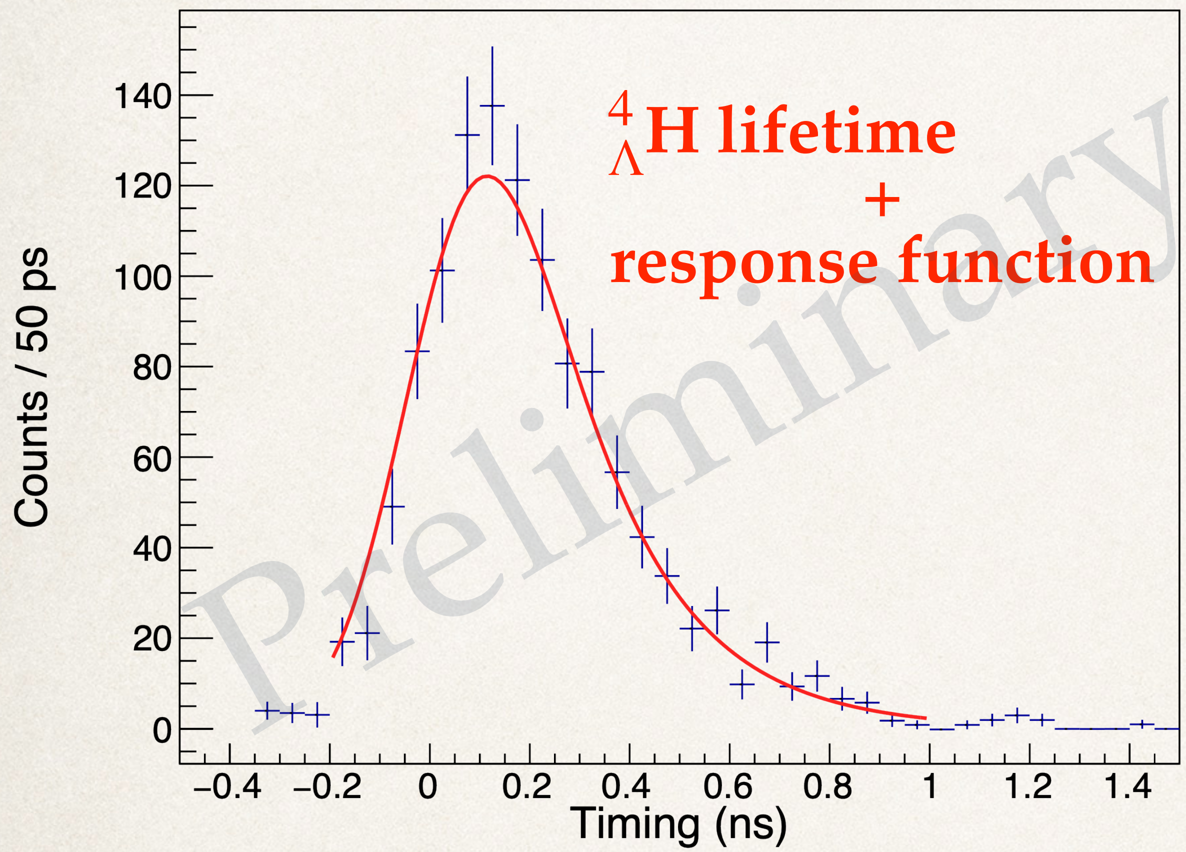
R.B. Wiringa et al, Phys. Rev. C **89**, 024305

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

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

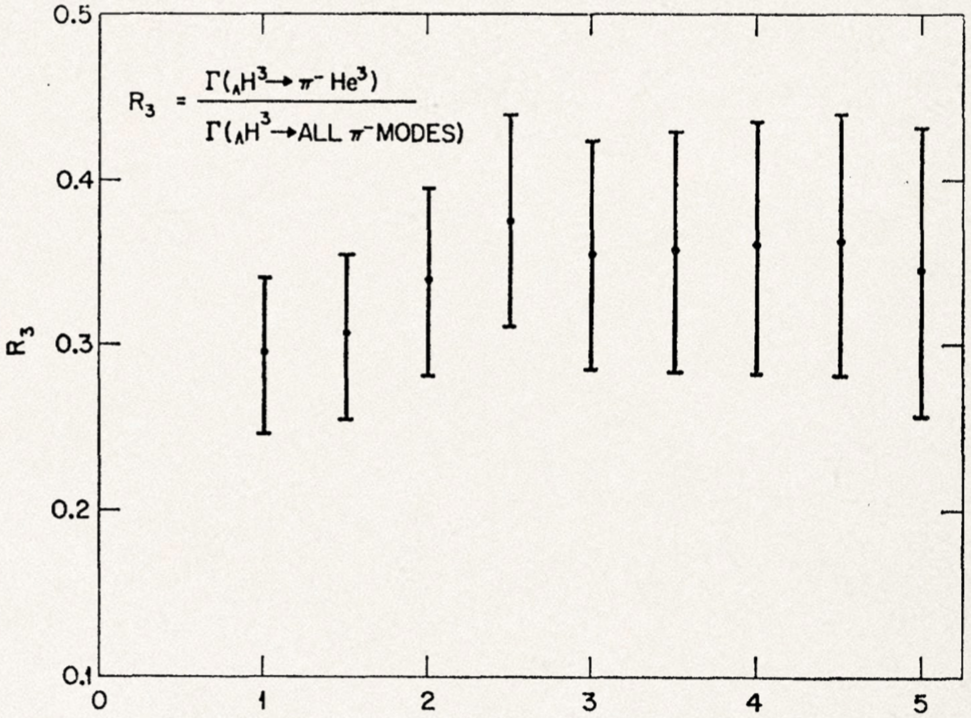
@ STAR, Au-Au collision

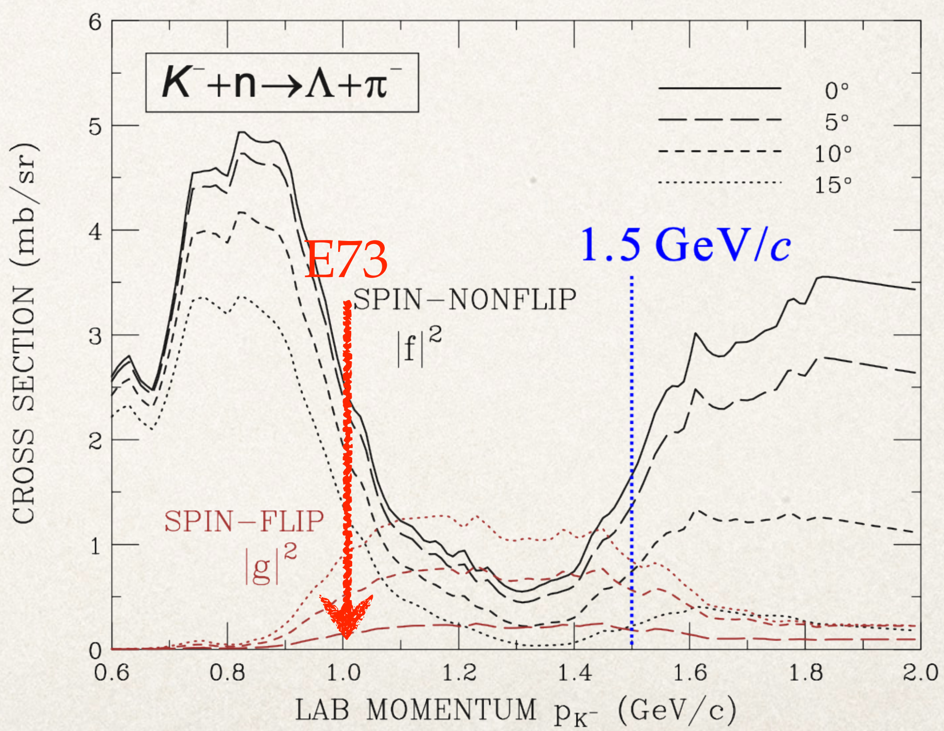
arXiv:2110.09513

Our result is amongst the most precise data;
Finalizing the data analysis and preparing for publication.

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

- Hypertriton isospin:
  - ${}^{4}He$: T=0 & ${}^{3}He$: T=1/2
  - ${}^{3}He(K^{-}, \pi^{0}){}^{3}_{\Lambda}H$ --> ${}^{3}_{\Lambda}H$: 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

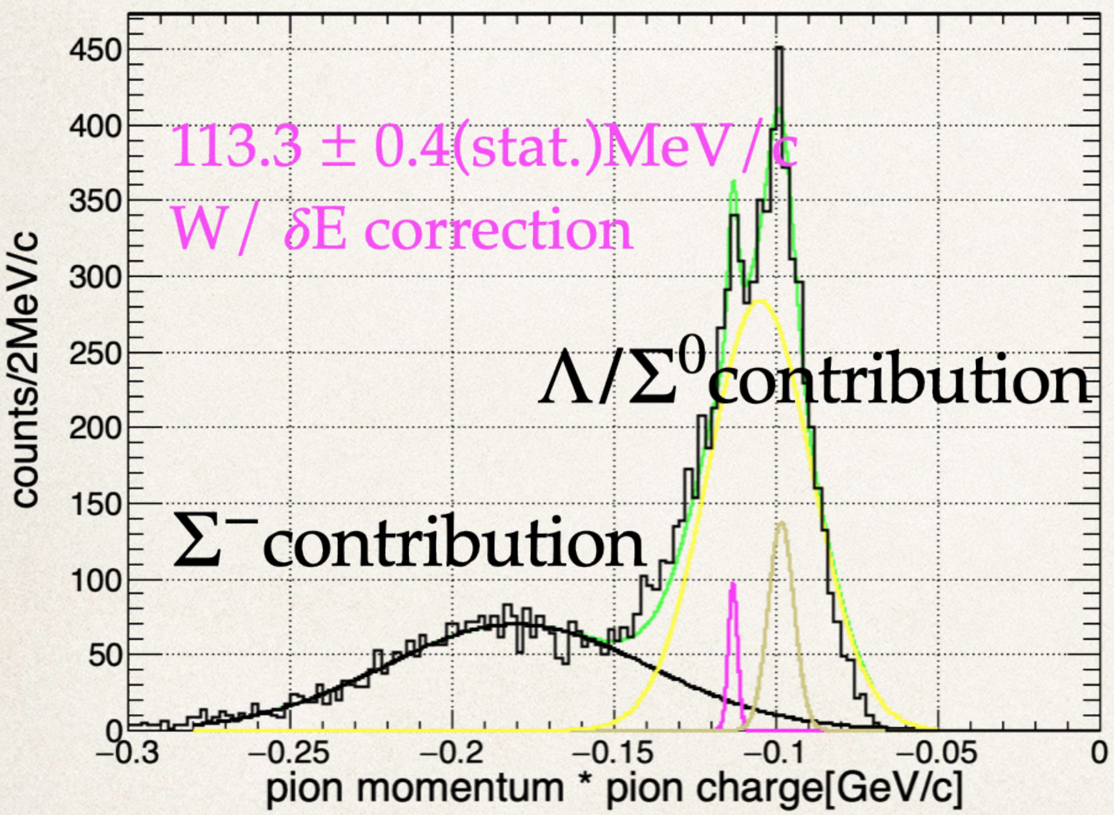
Stage-1: cross section & spin of ${}^{3}_{\Lambda}\mathrm{H}$

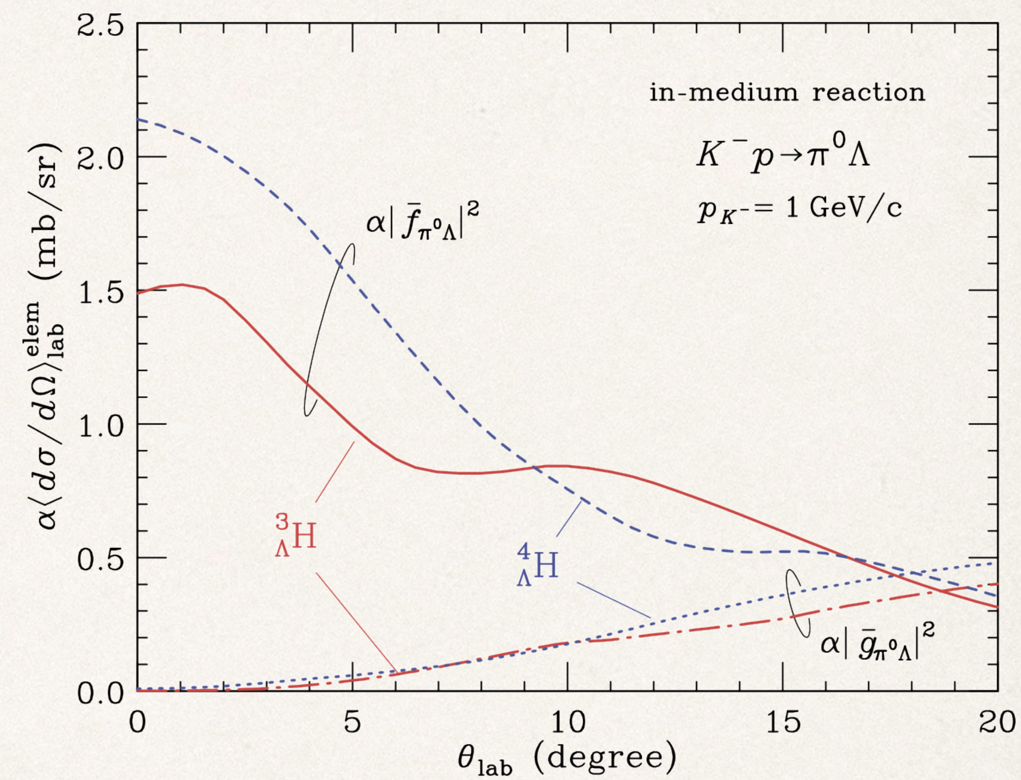
$$\mathrm{K}^- + {}^3\mathrm{He} \to {}^3_\Lambda\mathrm{H} + \pi^0$$

↓ slows down and decays at rest

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

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





- 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 (?)
- Special thanks for Prof. Dr. Josef Pochodzalla and Prof. Dr. Patrick Achenbach, who serves at J-PARC PAC committee, for the discussion and questions.

E73/T77 collaborator list

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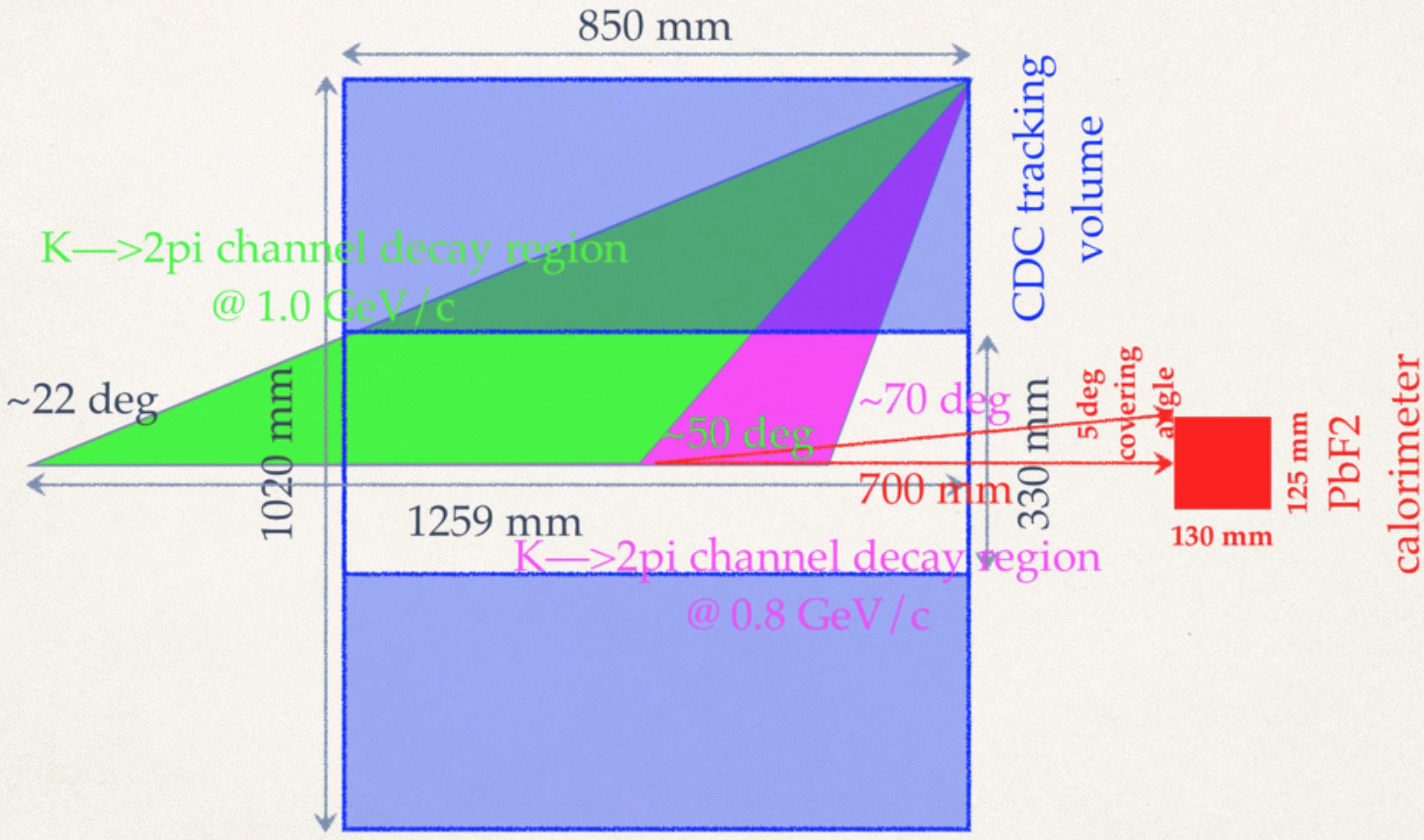
- Backup

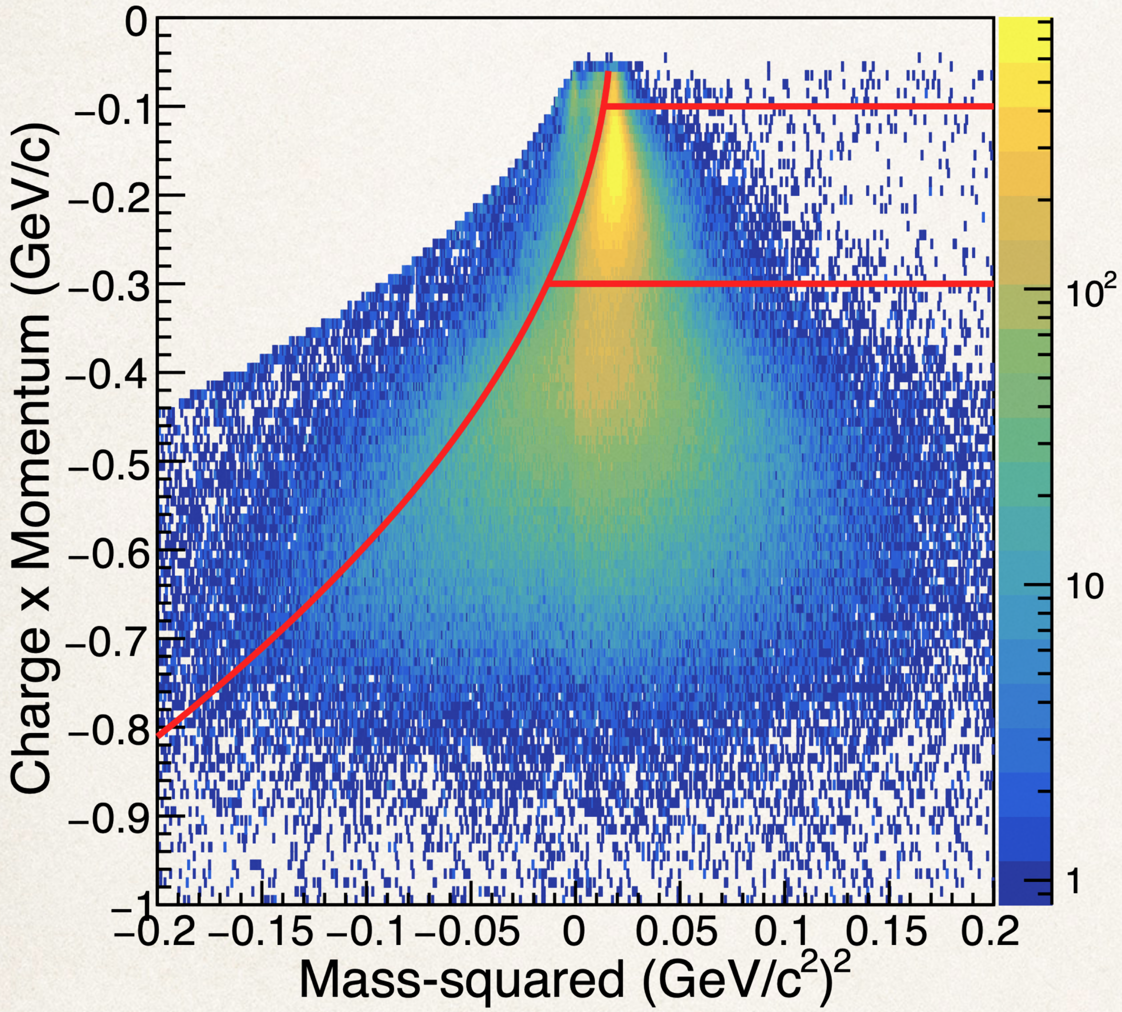
CDC acceptance vs Kaon in-flight decay



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

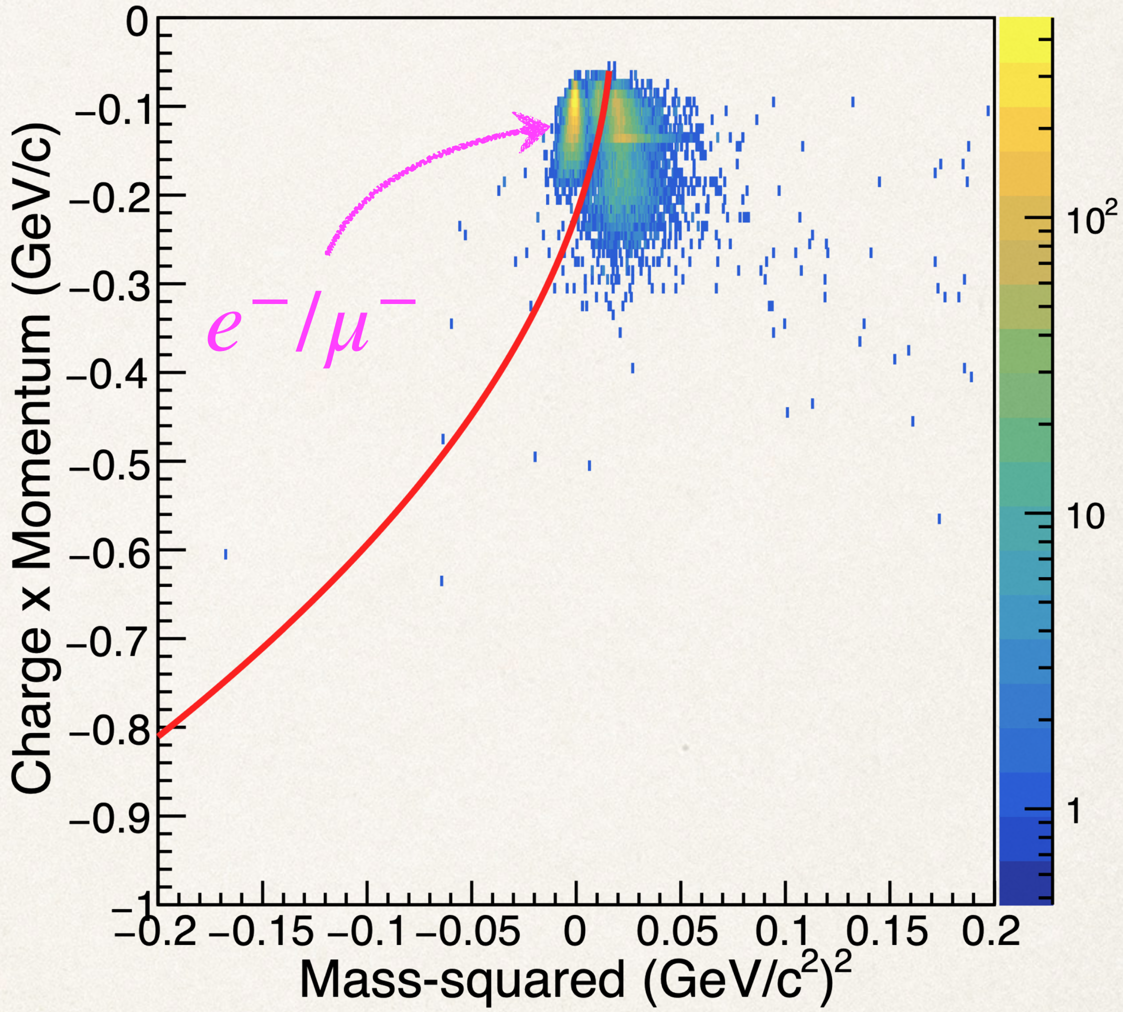
Detector performance: tracking and PID

Calibration and slewing correction events



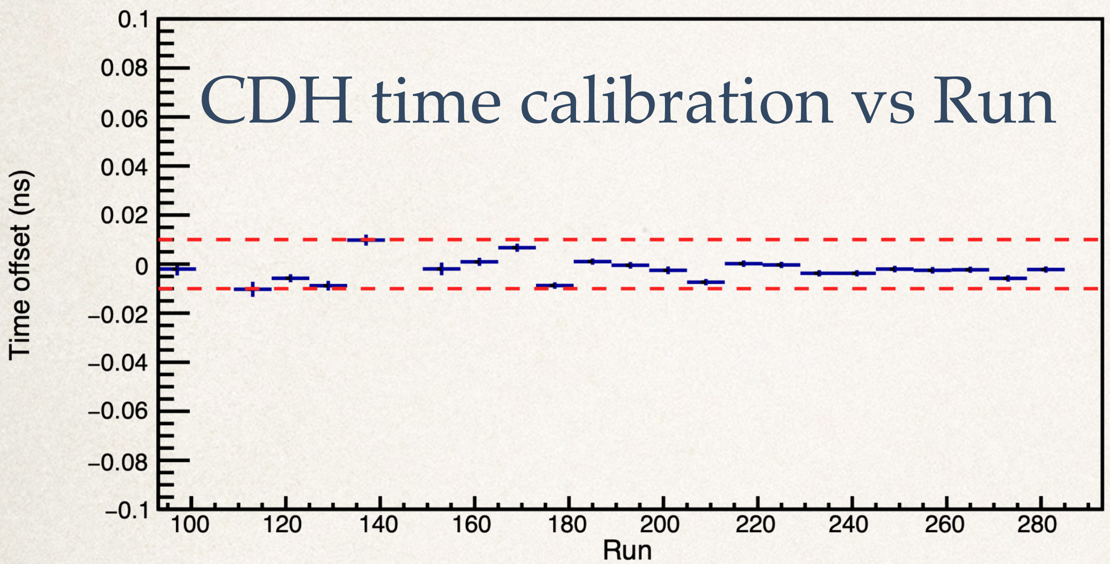
(K^-, π^-)
W/O requesting calorimeter dE

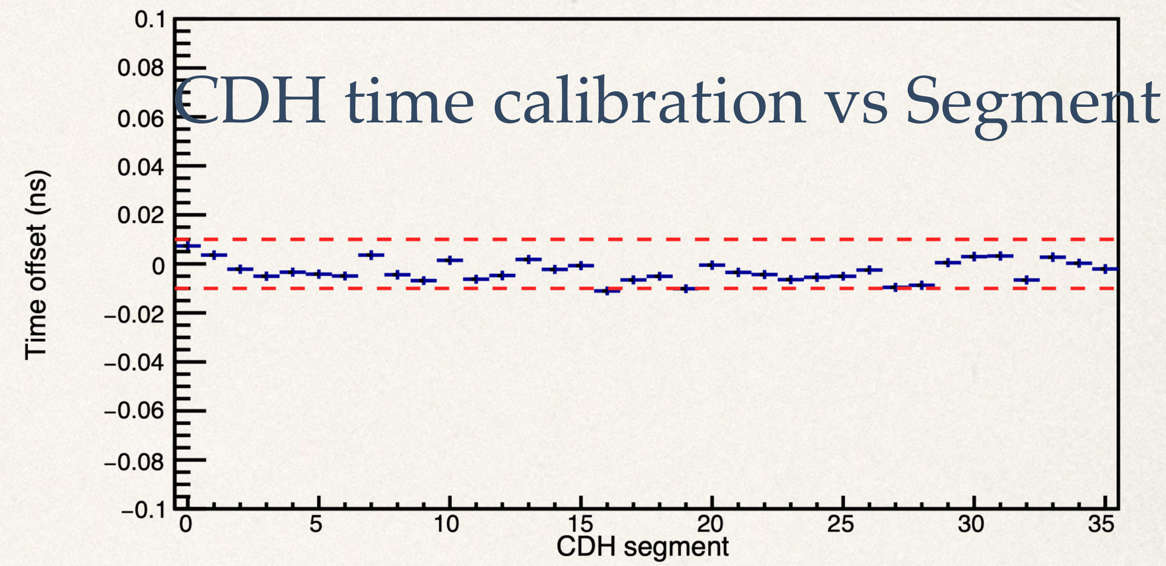
Interested physics events

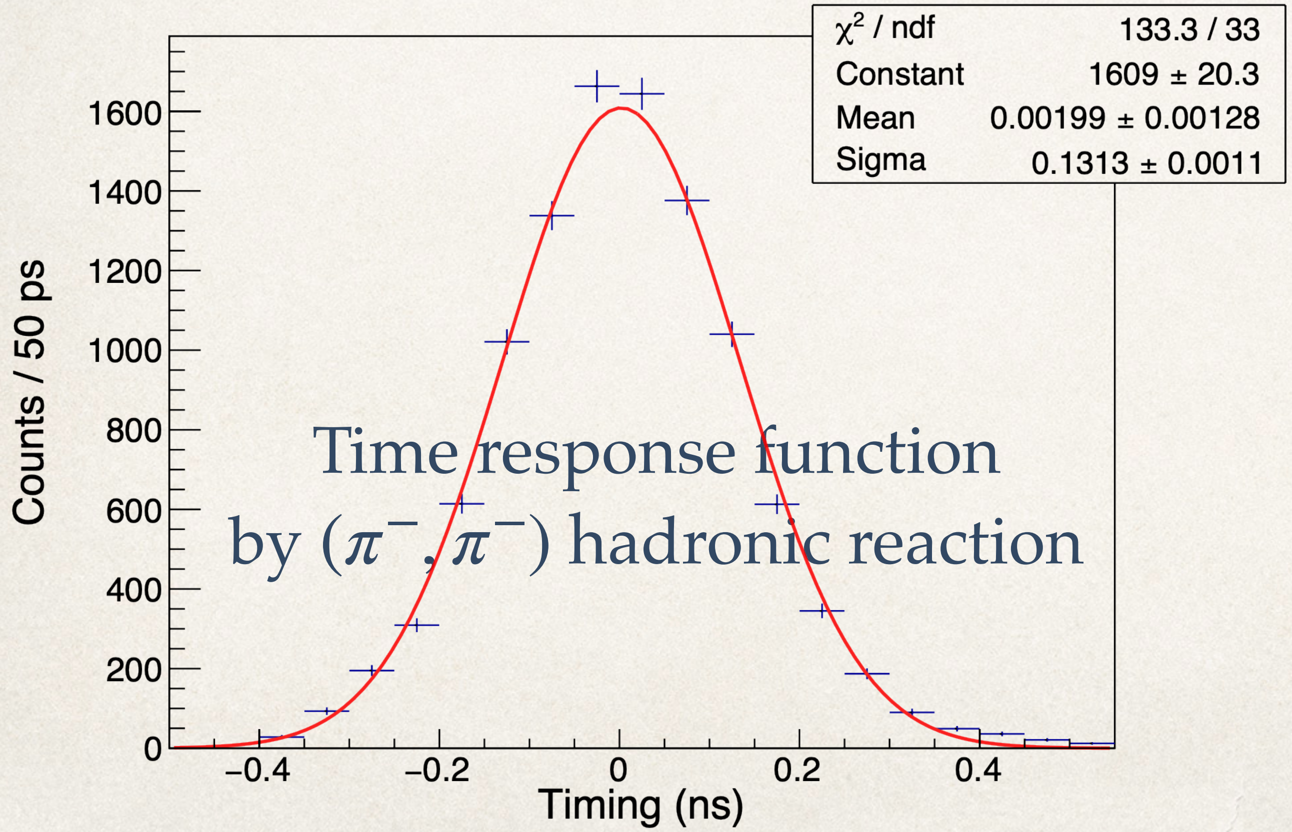


(K^-, π^-)
W/ requesting calorimeter dE > 500 MeV

Uncertainty of time calibration:



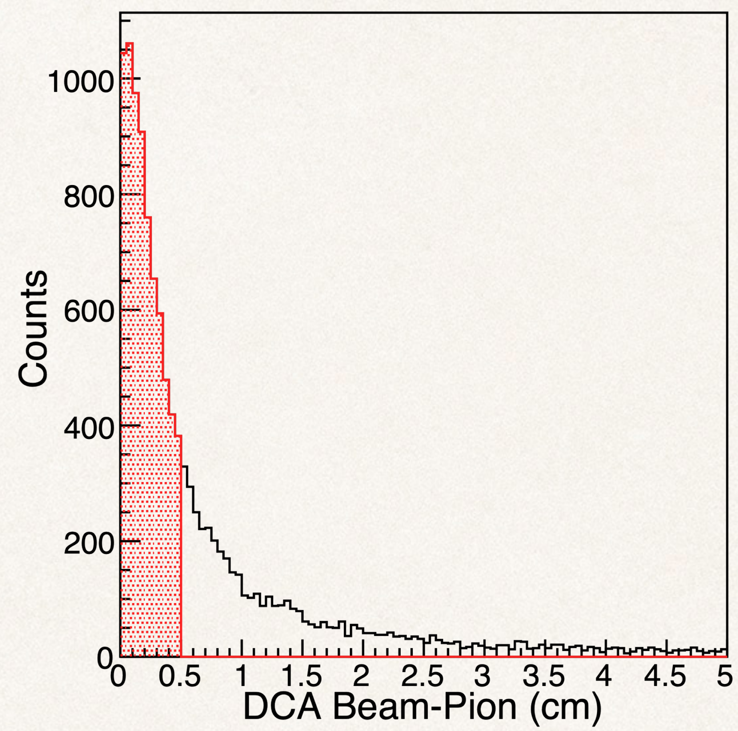


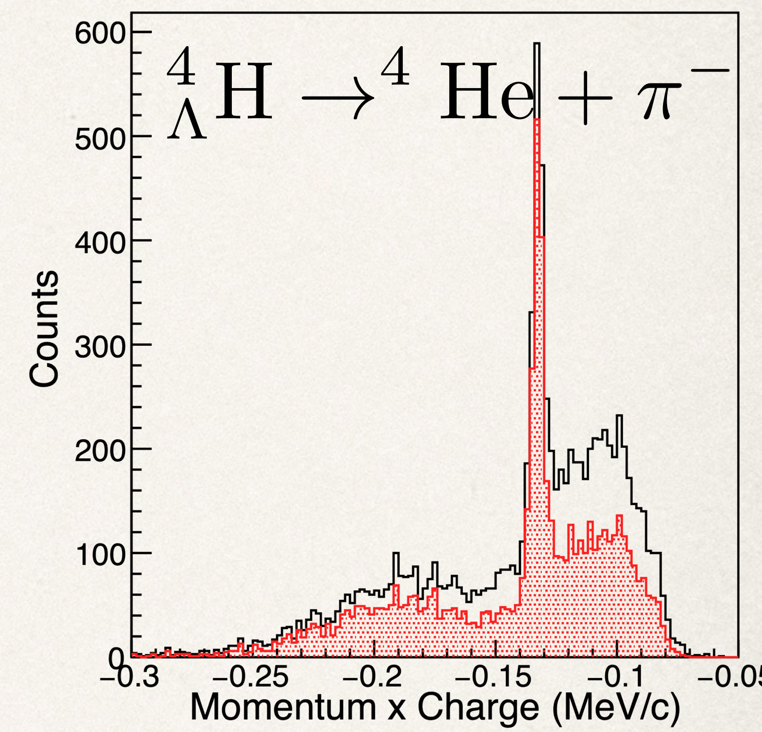


- CDH time calibration performed run-by-run & segment-by-segment;
- Calibration precision < 10ps;
- (π^-, π^-) hadronic events used to obtain time response function;
- Time resolution: $\sigma_t \sim 130$ ps

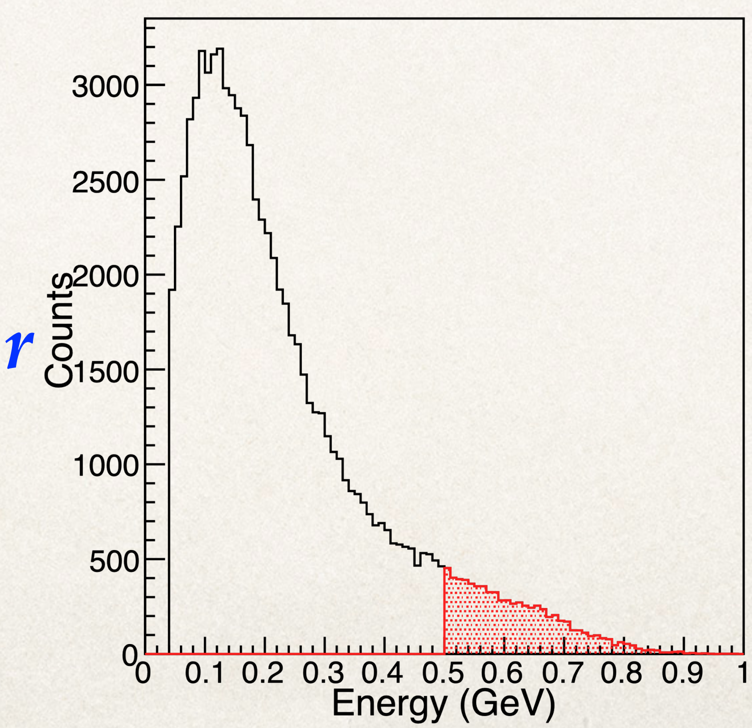
Event selection: DCA & calorimeter cut

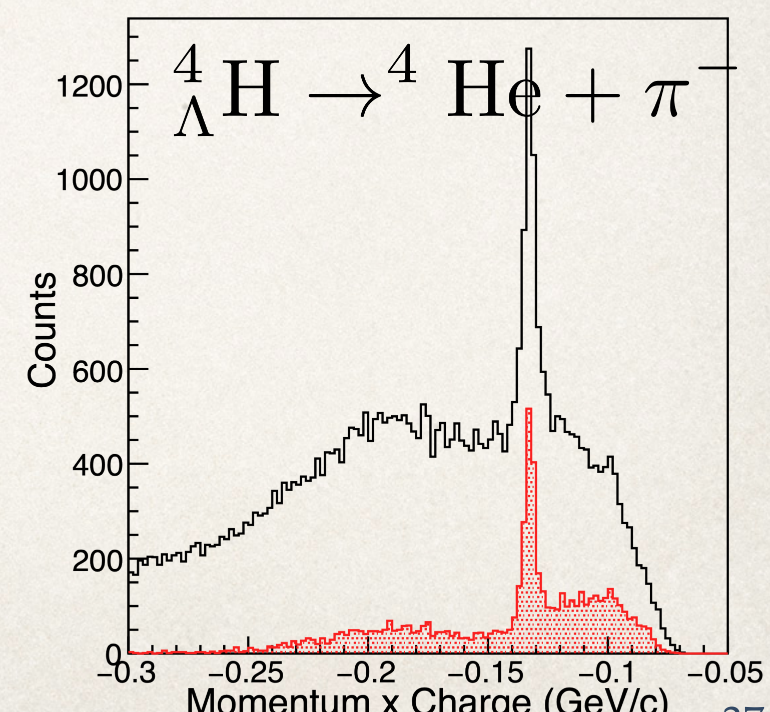
DCA < 5mm
used for event selection





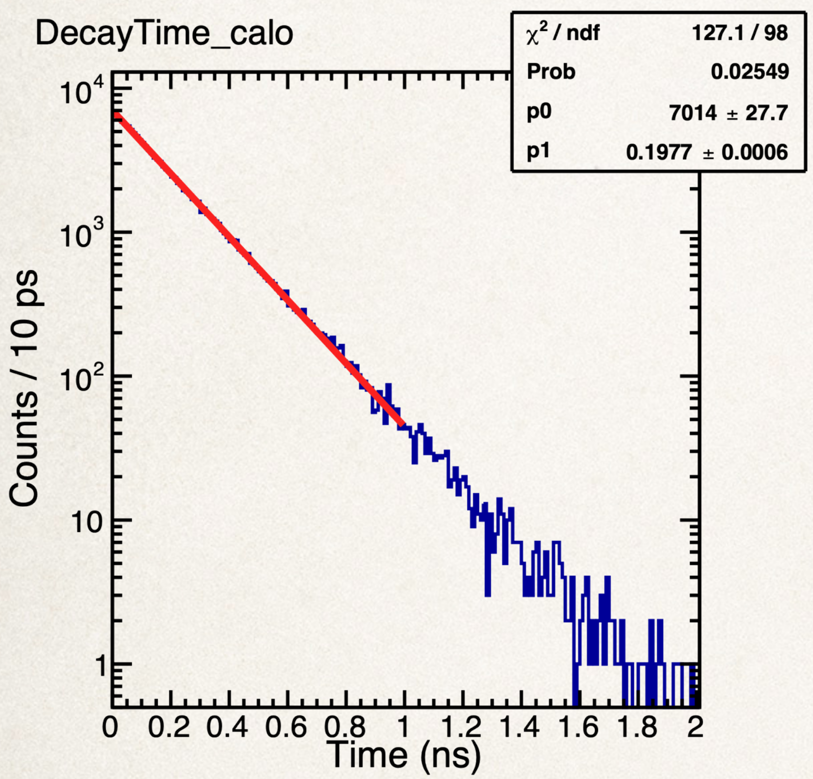
Selecting $^4_\Lambda$H events by using
calorimeter dE > 500MeV
--> our innovative method for selecting hypernucleus by tagging high energy gamma



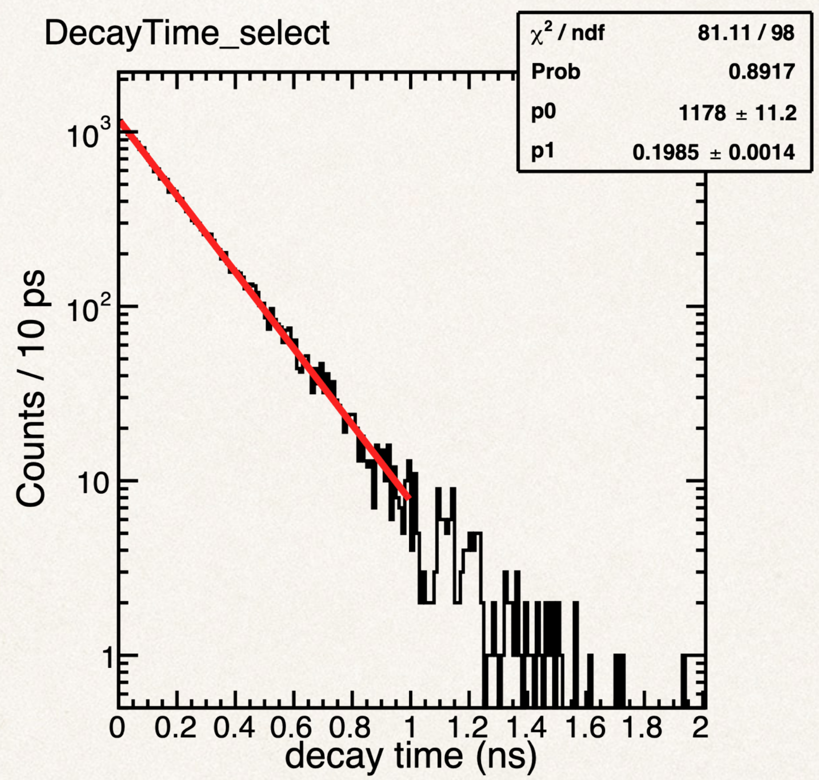


Intrinsic bias of T77(E73) approach

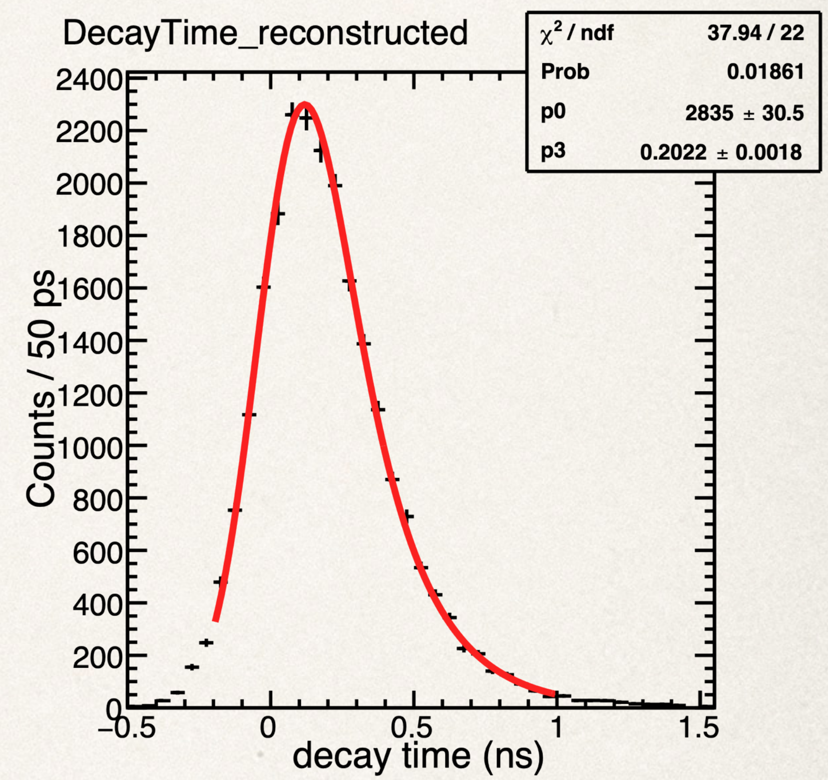
MC input: $\tau = 197.7$ ps



MC true W/ cuts: $\tau = 198.5$ ps



Analyzer output: $\tau = 202.2$ ps

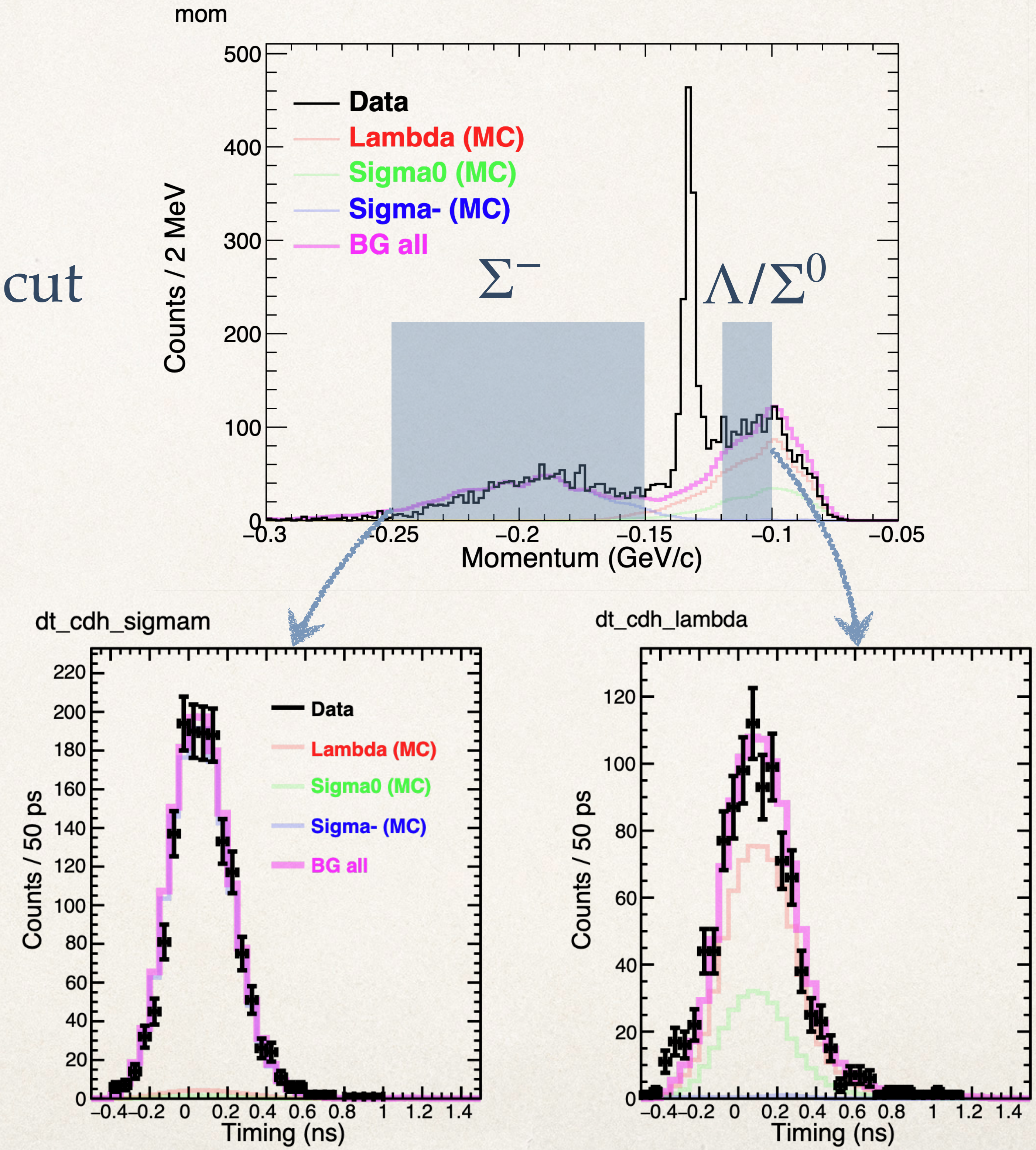


- ${}^{4}_{\Lambda}H$ differential cross section from Prof. T. Harada;
- Assuming reaction vertex is the same as the decay vertex;
    - Vertex determined by connecting K^- and π^- track;
    - A systematic bias studied with MC data

T. Harada, Y. Hirabayashi, Nucl. Phys. A, 1015, 122301 (2021)

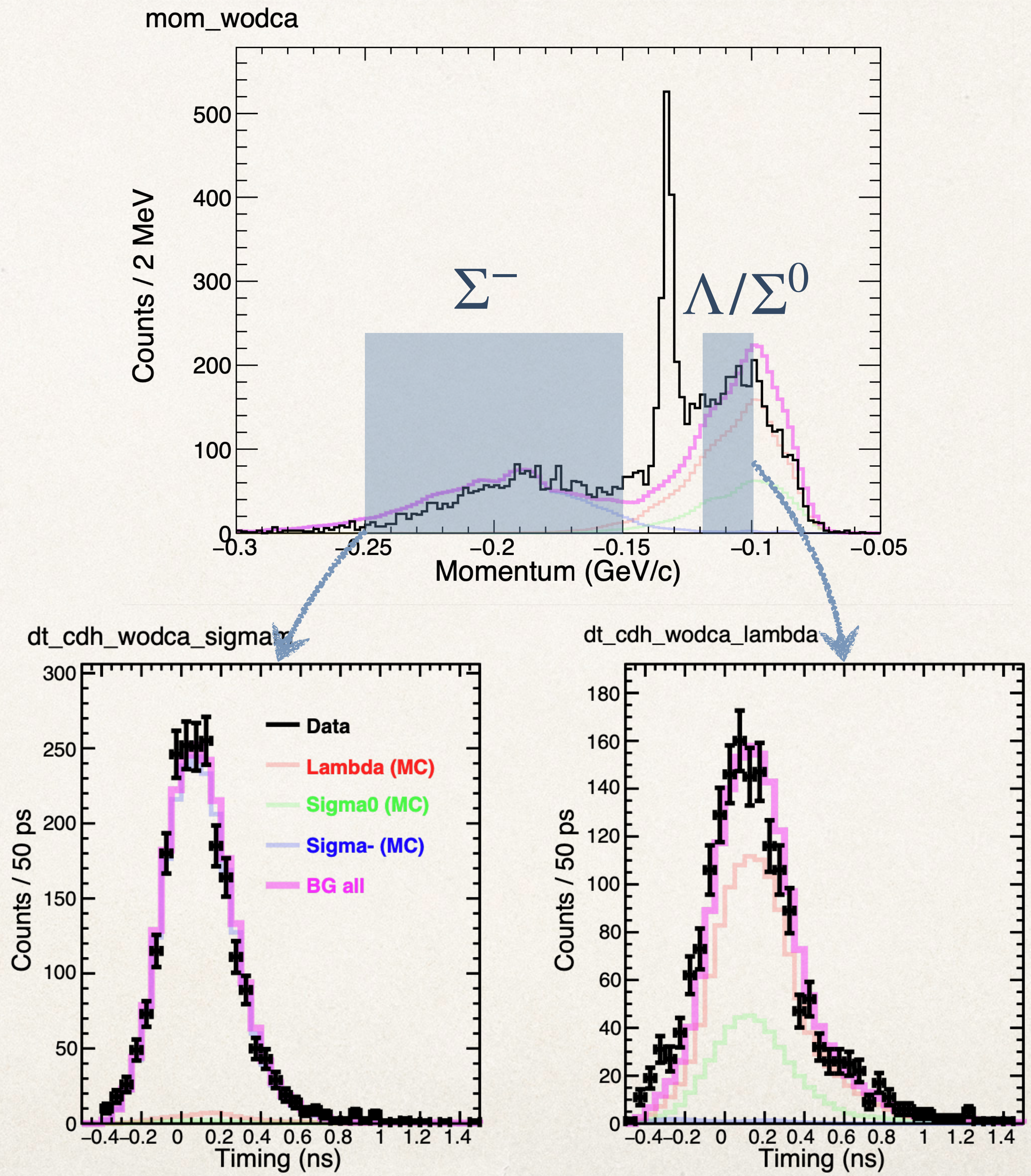
quasi-free hyperon decay time spectrum

W/ DCA<5mm cut

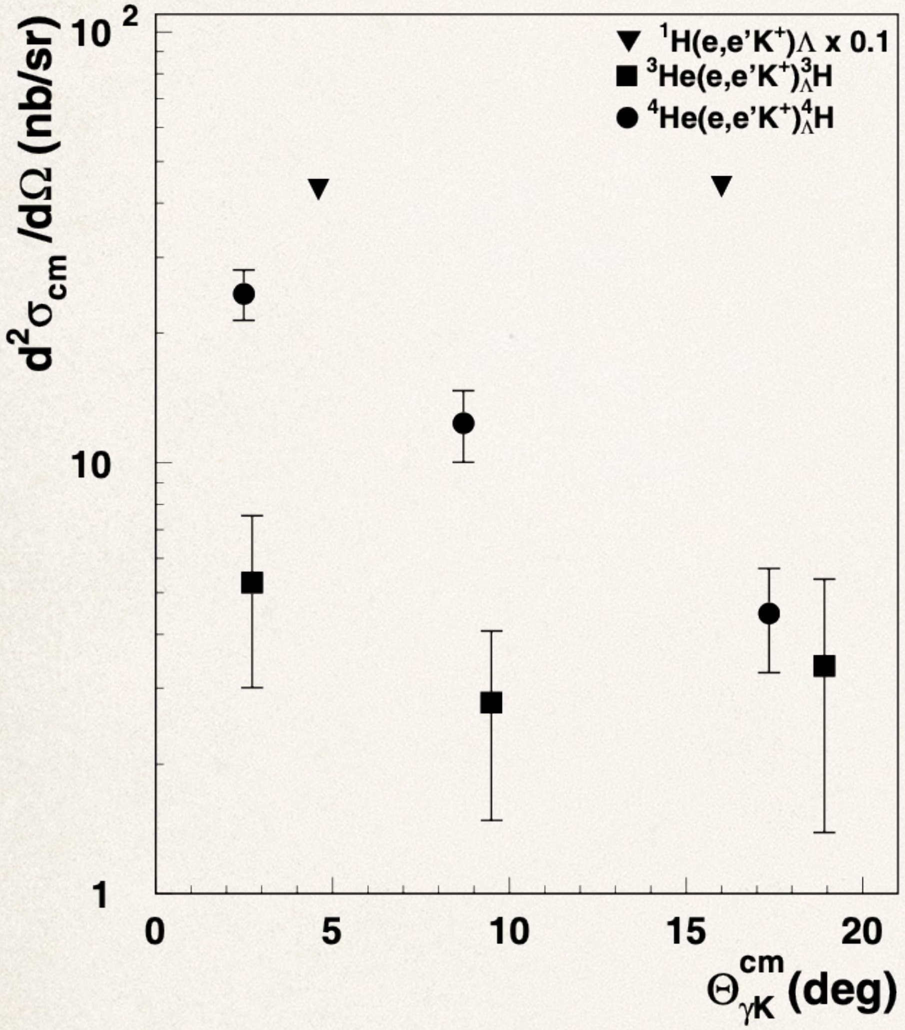


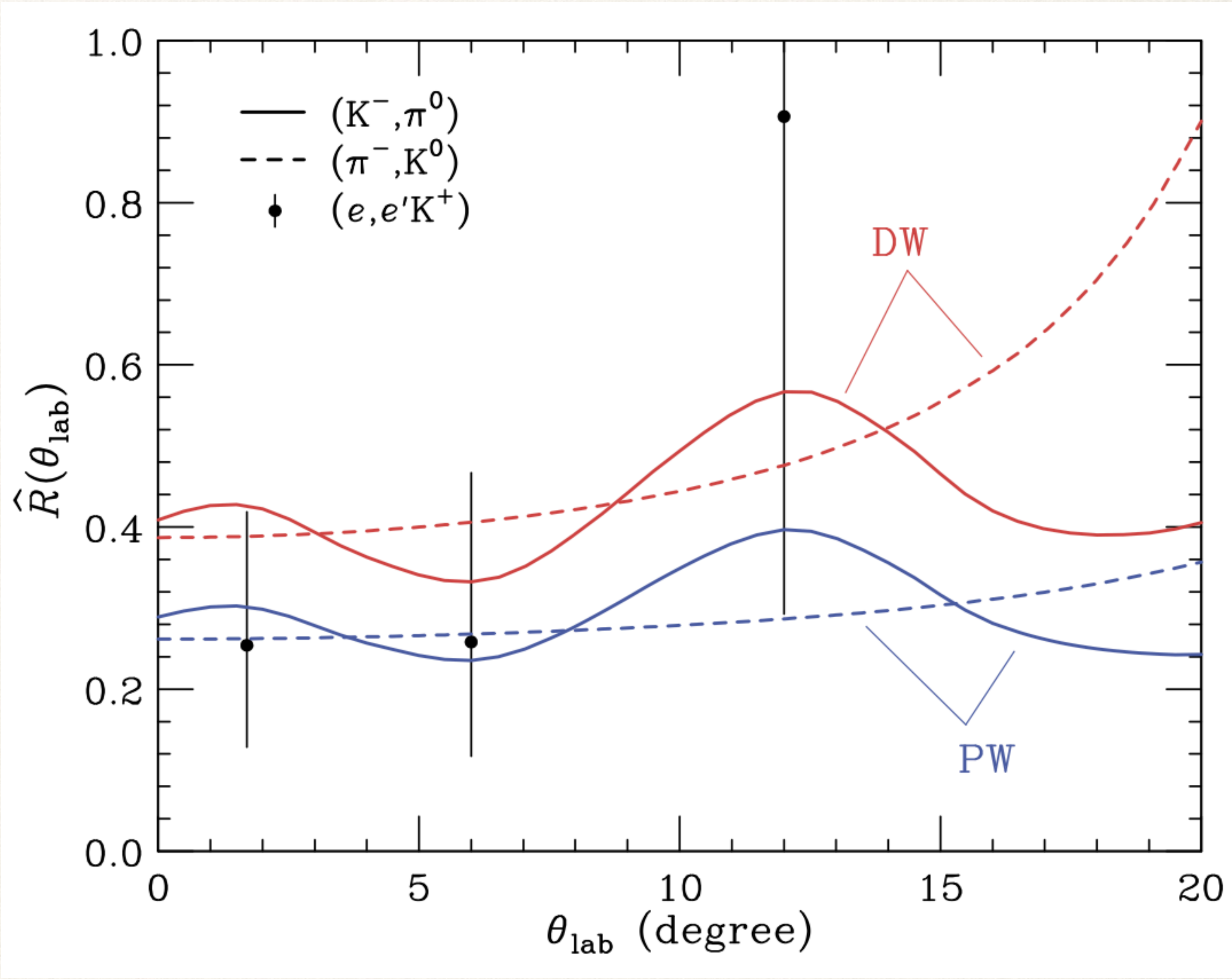
quasi-free hyperon decay time spectrum

W/O DCA cut



Production method vs hypertriton spin





(e, e′K+) reaction @ J-Lab

$^3{}_\Lambda$H/$^4{}_\Lambda$H ~ 0.26 ± 0.10 in average

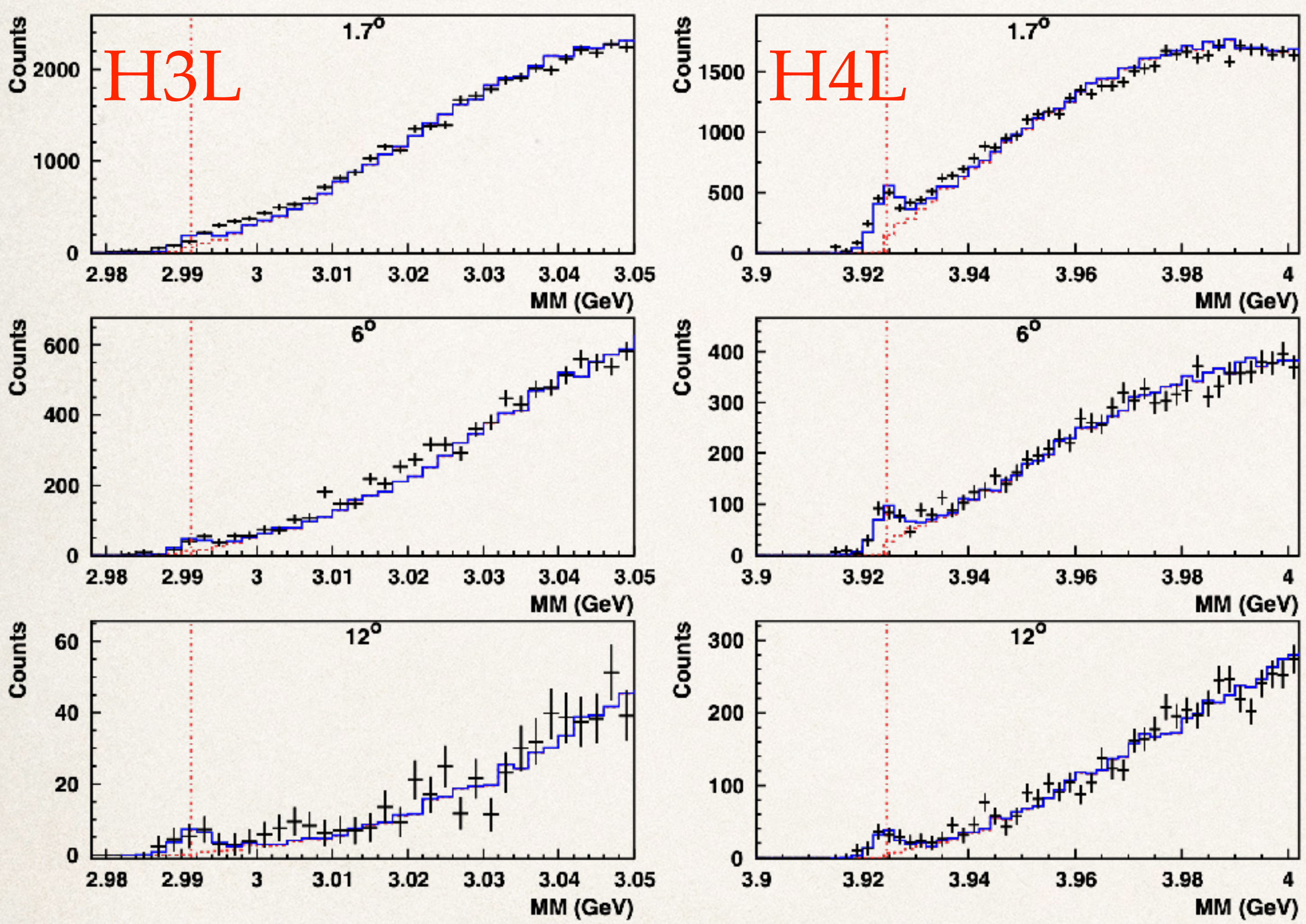
1.7 deg: 0.25 vs 12 deg: 0.90:

Difficult to interpret, something new?

DOI: 10.1103/PhysRevLett.93.242501; 10.1103/PhysRevD.1.66

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