${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ mesonic weak decay lifetime measurement with ${}^{3,4}He(K^{-}, \pi^{0}){}^{3,4}_{\Lambda}H$ Reaction

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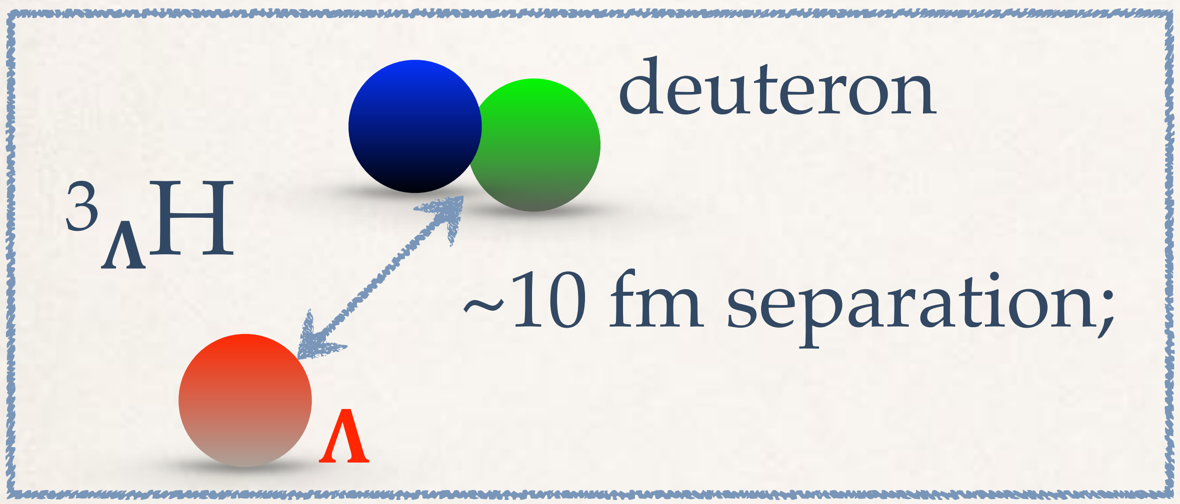
Outline

- Introduction
- Experimental setup & Expected performance
- Proposal timeline
- Summary

Introduction: motivation

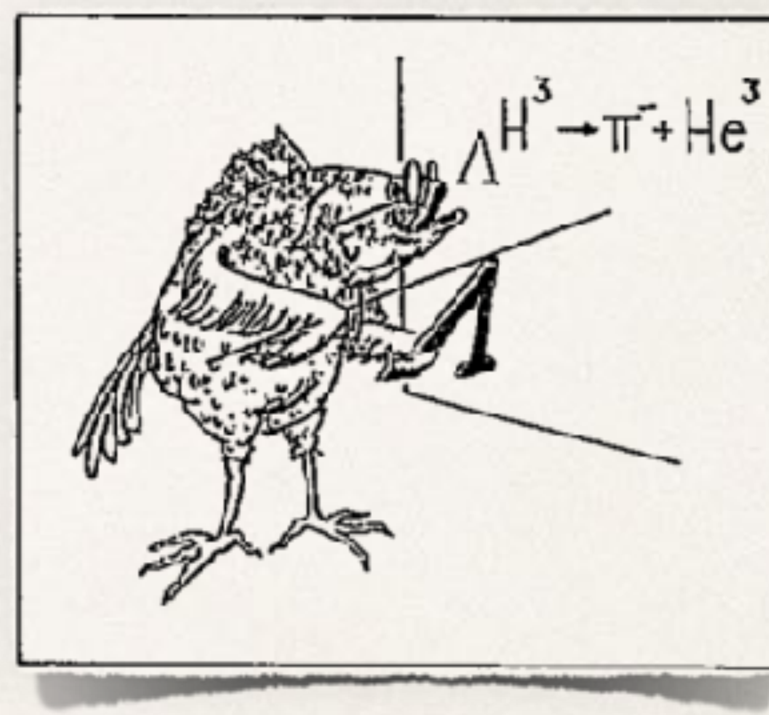
As the lightest hypernucleus, $^3{}_\Lambda H$ should tell us some important fact of YN interactions just as deuteron for nuclear physics.



Collaboration	Experimental method	$^3_\Lambda H$ lifetime [ps]	Release date
STAR	Au collider	142^{+24}_{-21}(stat.)±29(syst.)	2018
ALICE	Pb collider	181^{+54}_{-39}(stat.)±33(syst.)	2016
HypHI	fixed target	183^{+42}_{-32}(stat.)±37(syst.)	2013

Table 1: Summary of recent measurements on $^3_\Lambda H$ lifetime.

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…

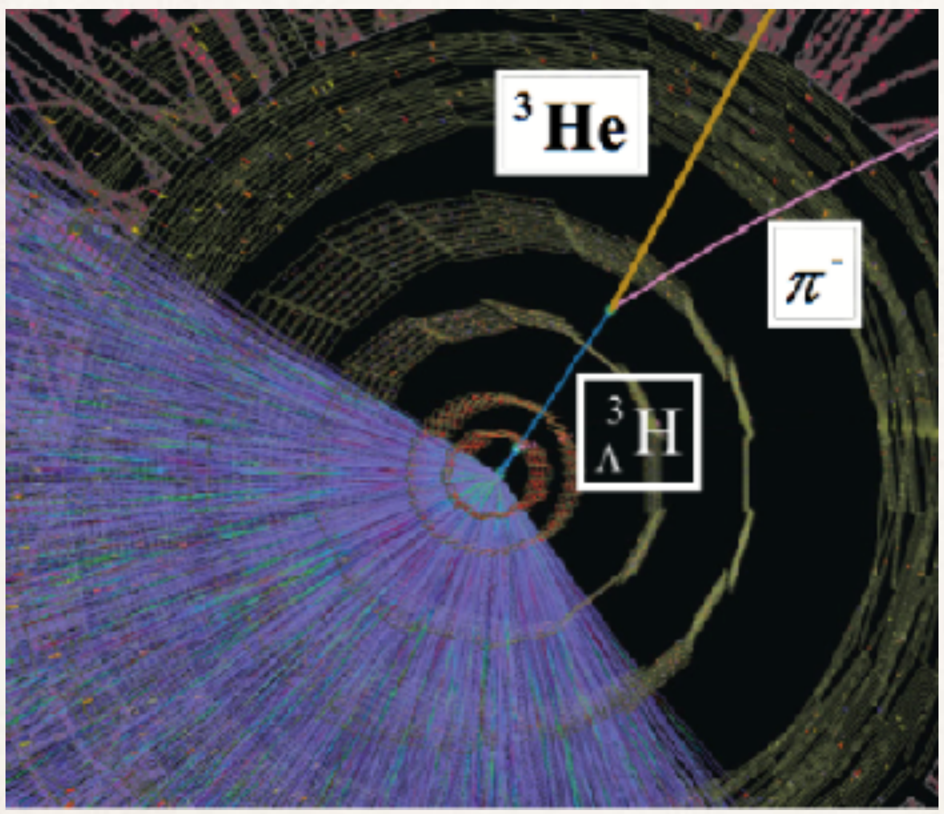


Neither fish nor fowl?

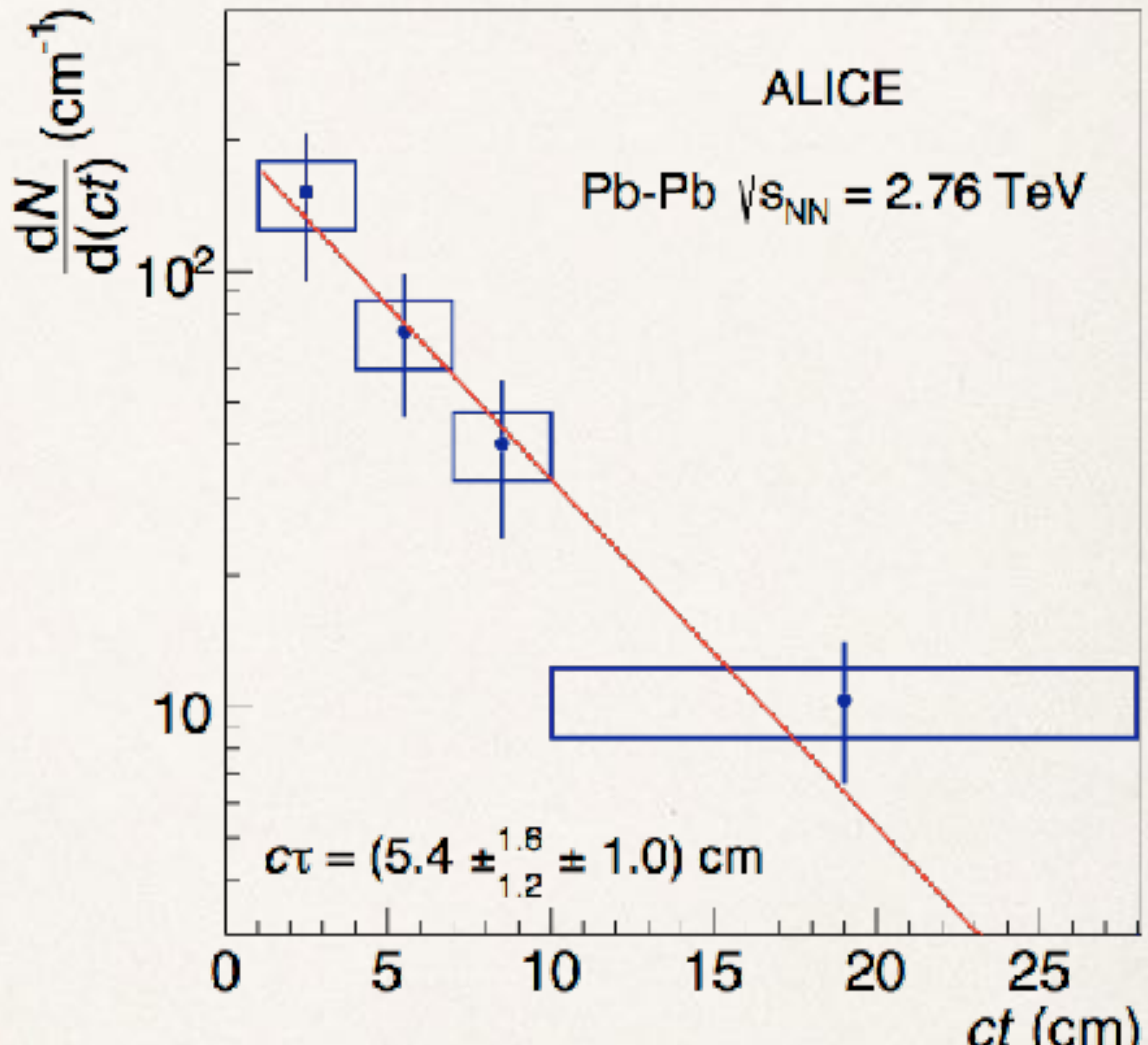
Picture taken from MM. Block et al. Proc. Int. Conf. Hyperfragments, 1963

Introduction: heavy ion results

ALICE as an example for
the experimental approach.

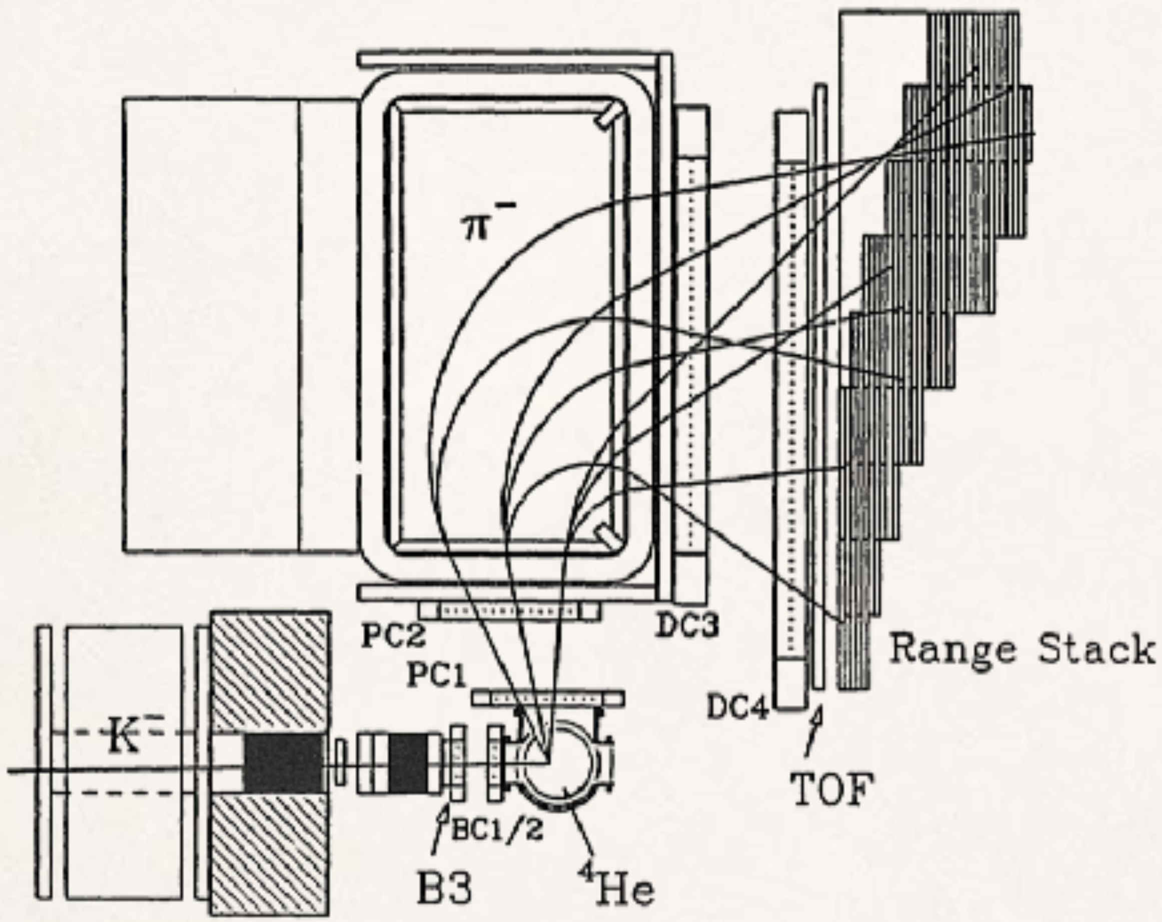


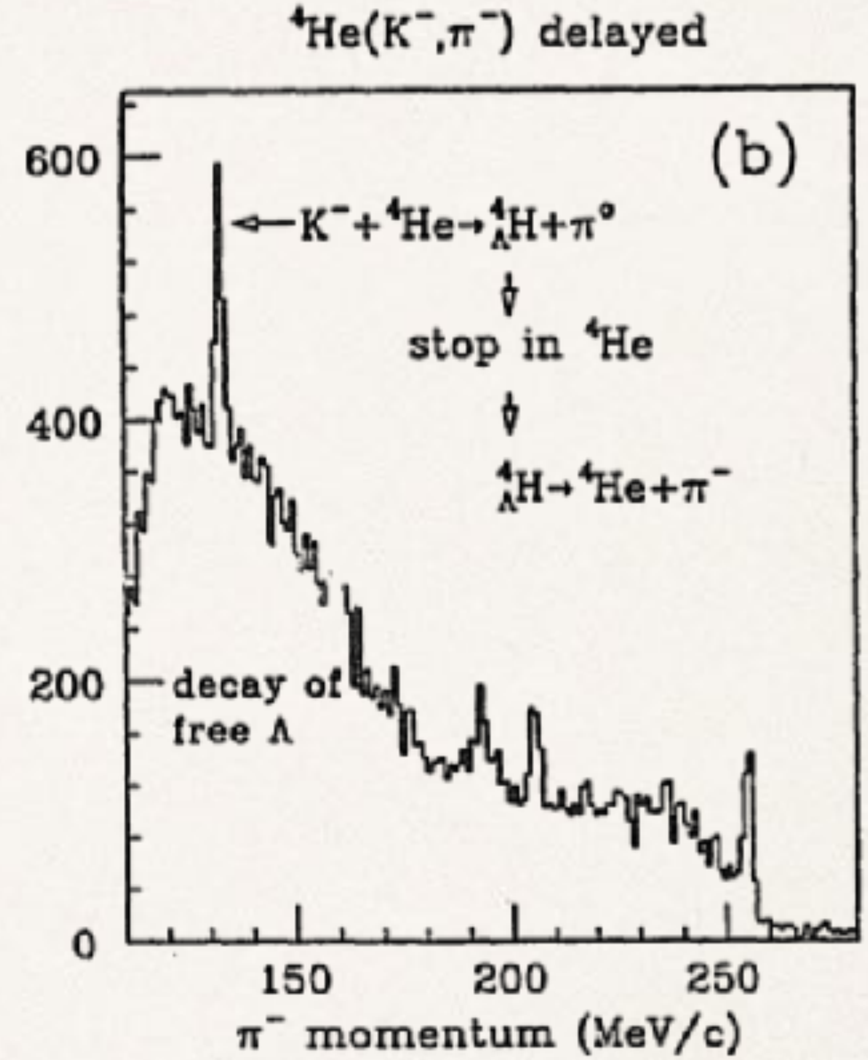
$$c\tau = \left(5.4^{+1.6}_{-1.2}(stat.) \pm 1.00(syst.)\right) cm$$
$$\tau = \left(181^{+54}_{-39}(stat.) \pm 33(syst.)\right) ps$$



Depends on tracking results for decay length and momentum as $t = L/\beta\gamma c$

Introduction: stopped K- example



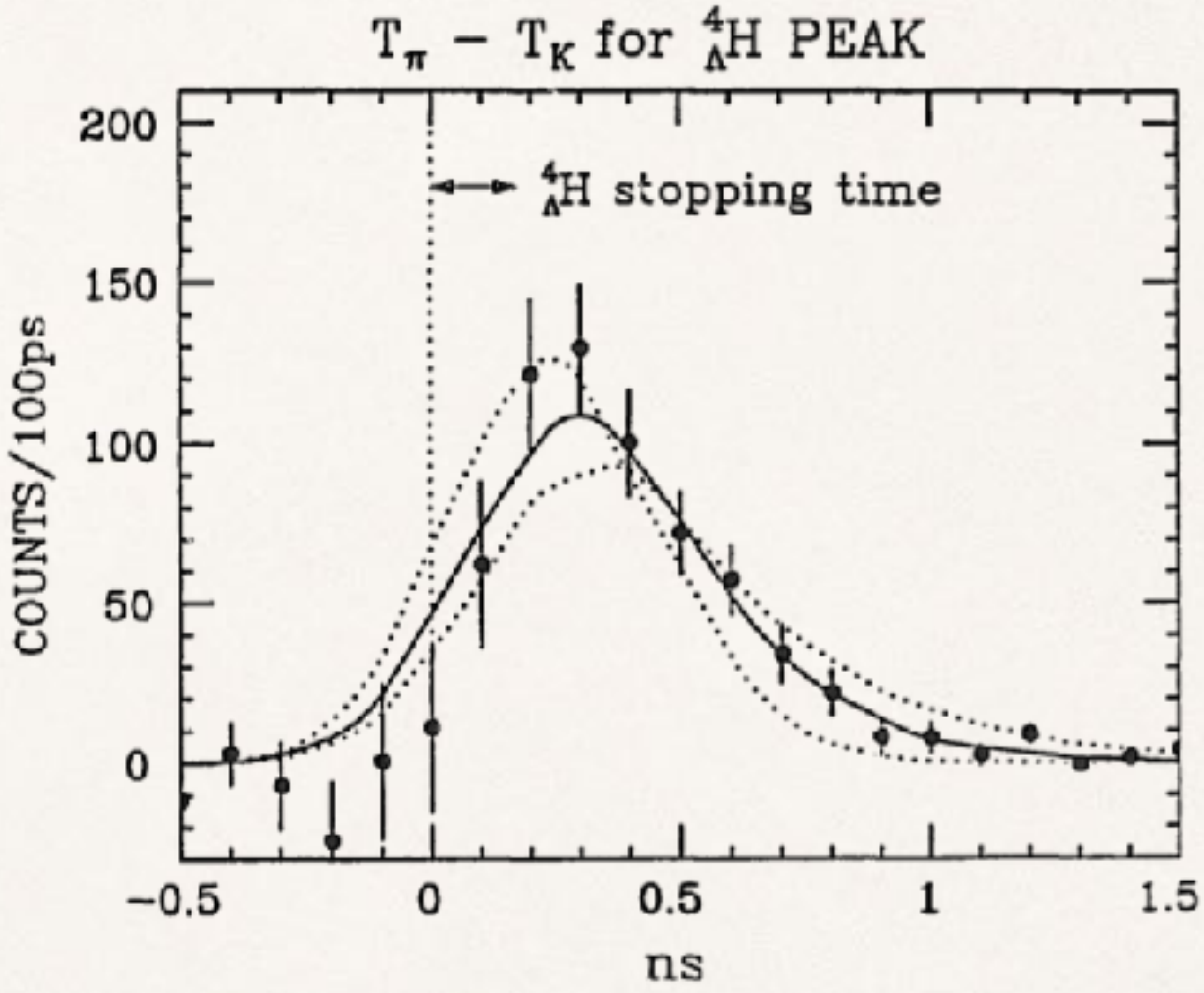


Example: stopped K- experiment at KEK:

1. tagging pi0 with NaI
2. measuring π- momentum with 300ps delay

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

Introduction: stopped K- example



Example: stopped K- experiment at KEK:

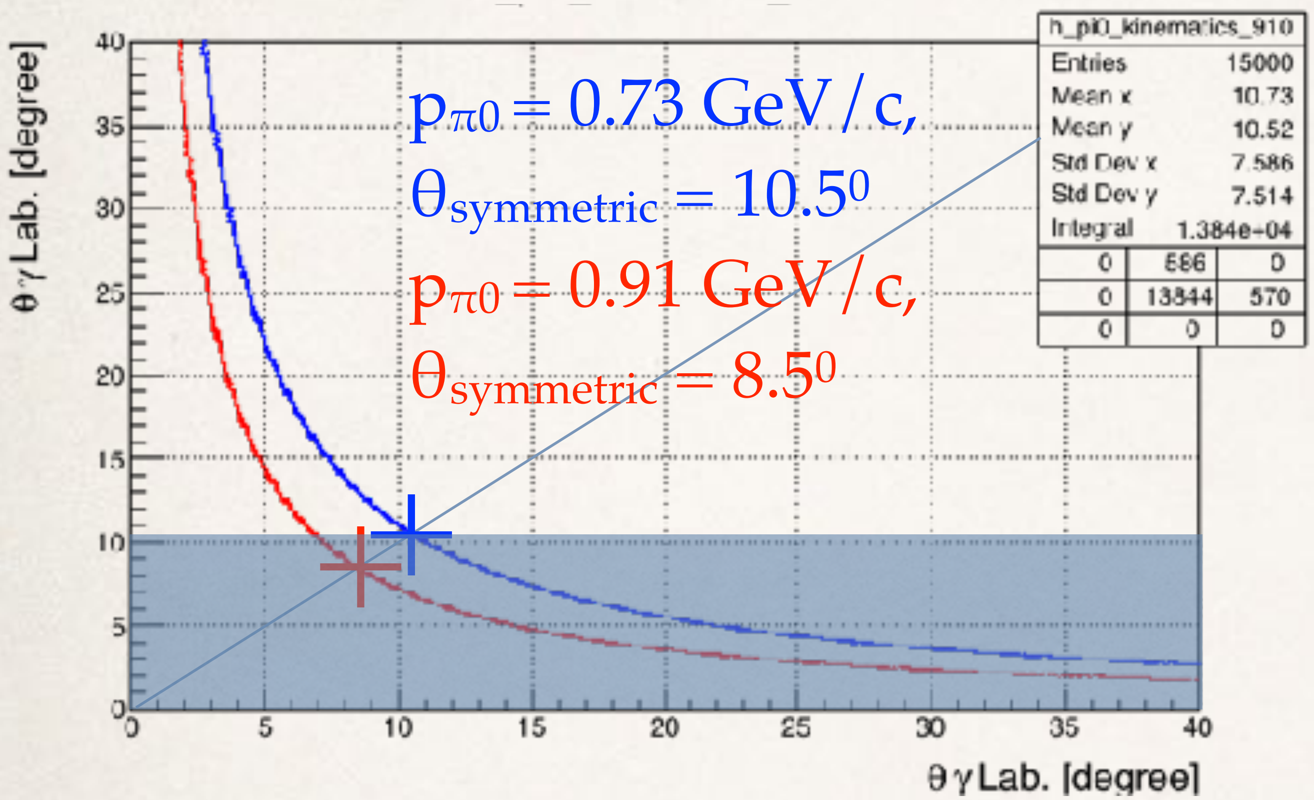
1. subtract background from neighboring pi- bins
2. fit lifetime with convoluted distribution

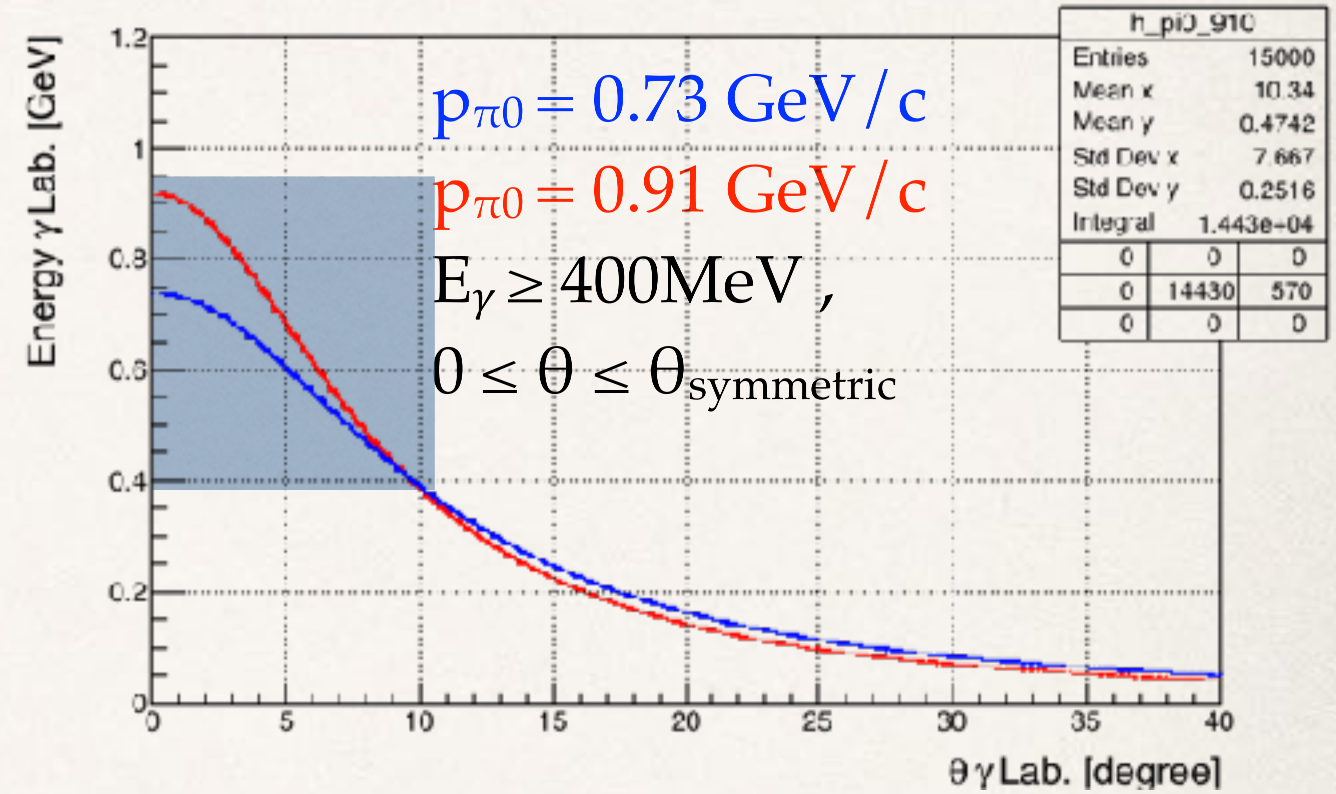
H. Outa, *et al.*, Nucl. Phys. A 547, (1992), 109c-114c

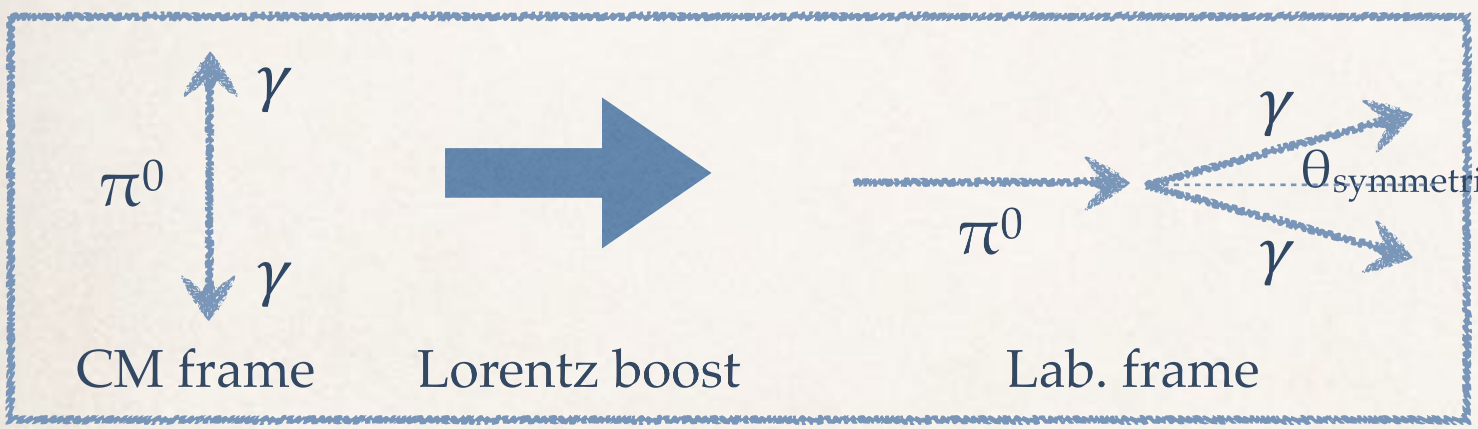
Experimental setup: in-flight reaction

- We propose an in-flight reaction with similar final products: $^{3,4}He(K^-, \pi^0)^{3,4}{}_{\Lambda}H$ at 1GeV/c
- *Pros*
  - *better event selectivity in very forward angle*
- *Cons*
  - *very hard to measure π^0 kinematics*
  - *π^0 —>2 γ projectile overlap with meson beam direction*
- Tagging fast π^0 in very forward angle to select events with a proton converted into Lambda; precisely measure mono-energetic π^- decayed from $^{3,4}{}_{\Lambda}H$ as signal to derive $^{3,4}{}_{\Lambda}H$ lifetime

Experimental setup: π^0 kinematics







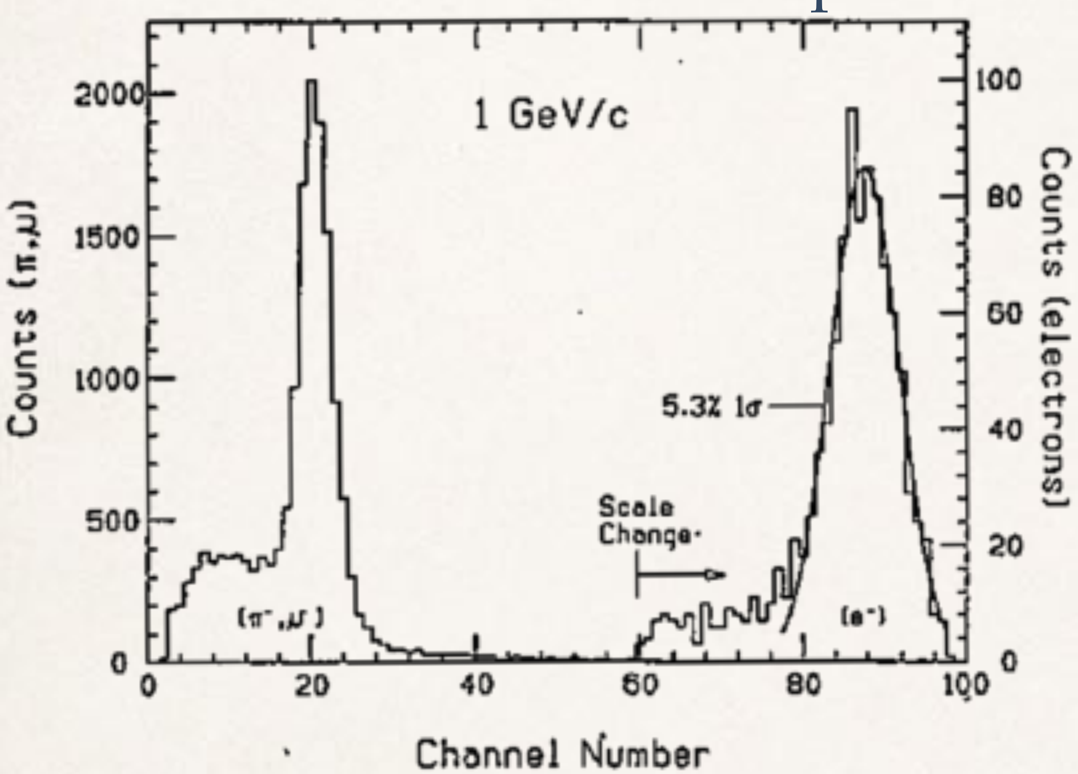
- 0.73~0.91GeV/c π^0 boosts γ forwardly;
- By covering 0~$\theta_{symmetric}$, tag the γ with higher energy ($E_\gamma \geq$ 400MeV)

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

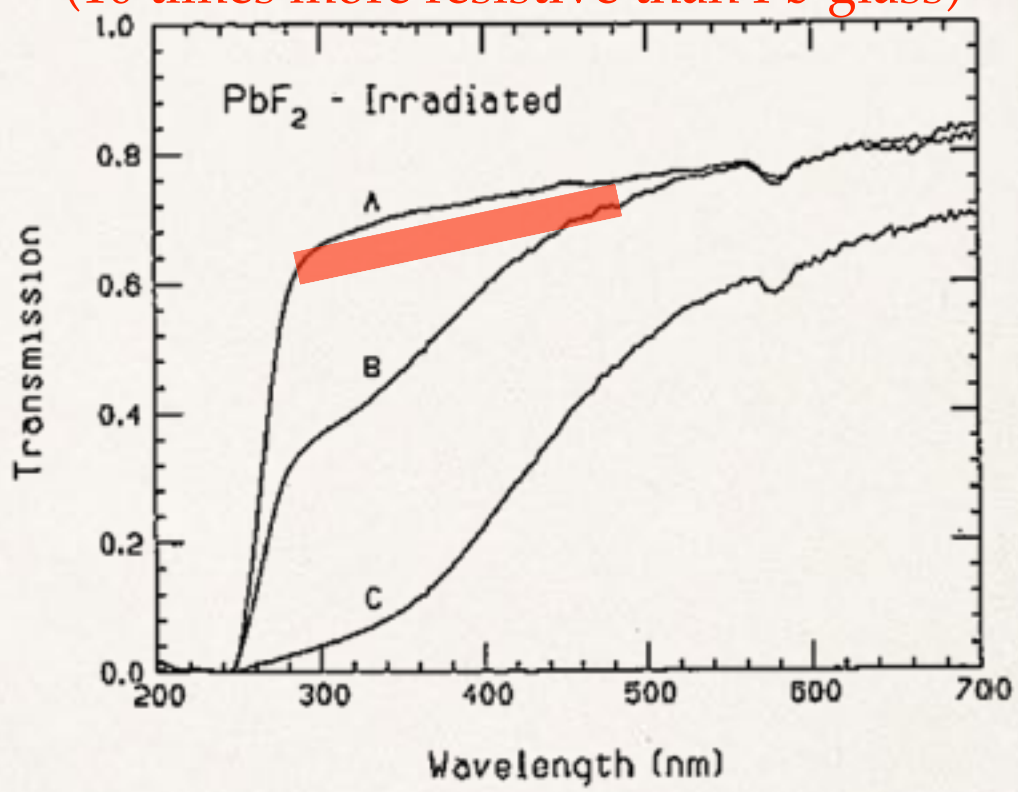
Experimental setup: π^0 tagger (PbF_2)

π^- peak

electron peak



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

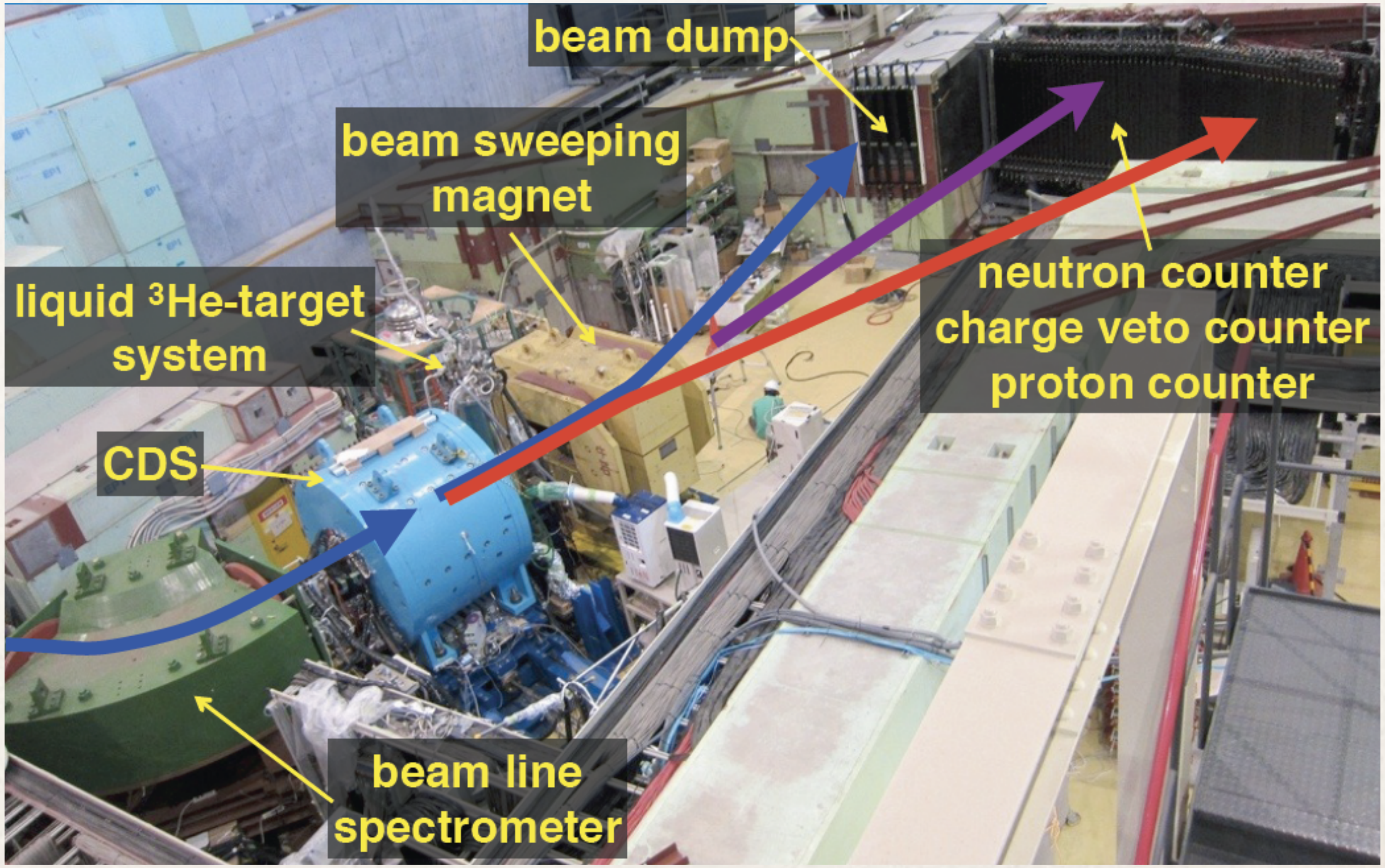


Crystal	Radiation length	Moliere radius	Density	Cost	Resolution	Signal length
PbF_2	0.93 cm	2.22 cm	7.77 g/cm³	12 USD/cc	5%	2ns

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

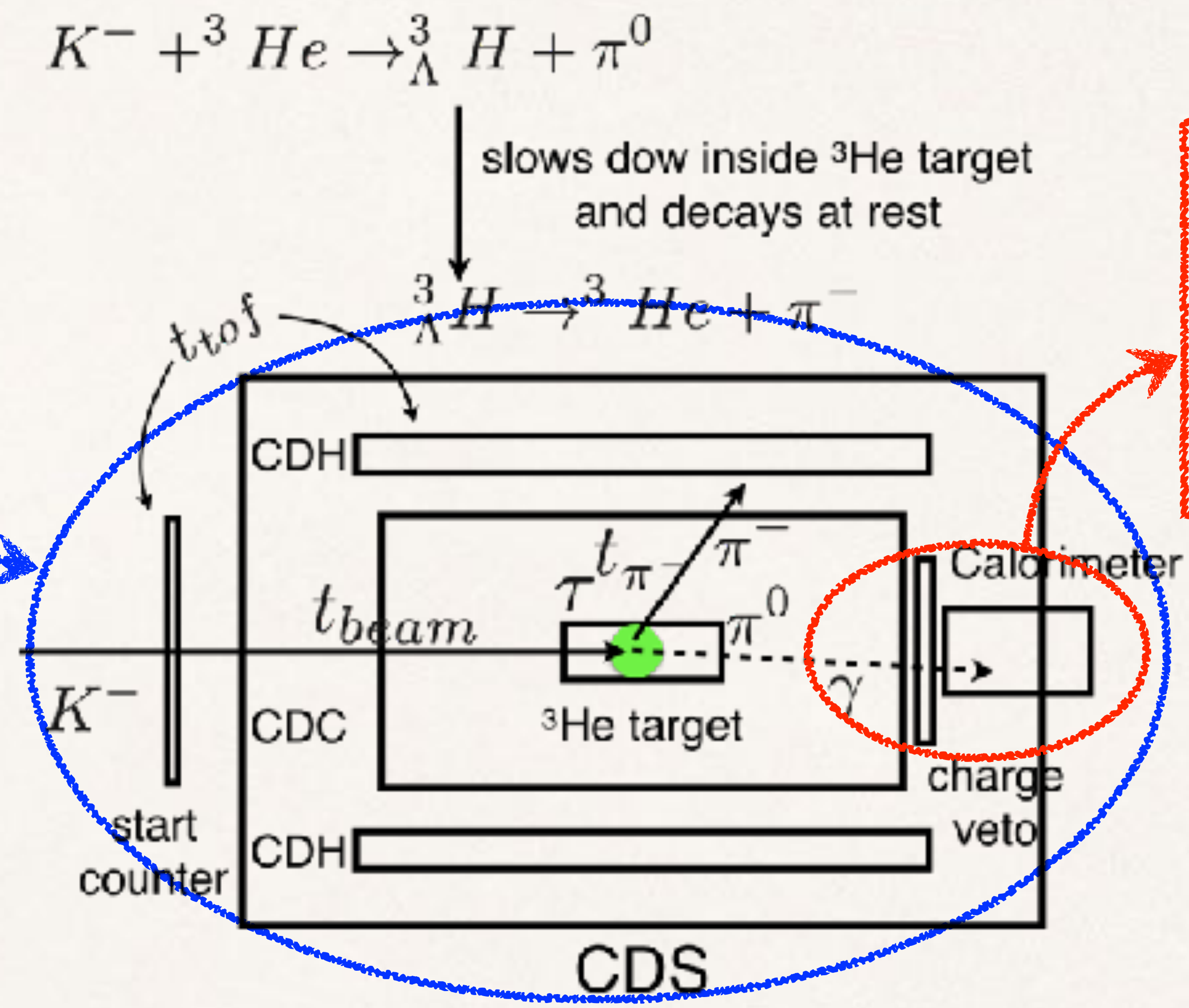
Experimental setup: detector concept

The main apparatus to measure decayed pi- momentum
is a solenoid spectrometer,
Cylindrical Spectrometer System (CDS).
Successfully employed for E15 and E17 at K18BR of Hadron Hall.



Experimental setup: detector concept

Ready at K1.8BR;
Successfully used for
E15 & E31 experiments

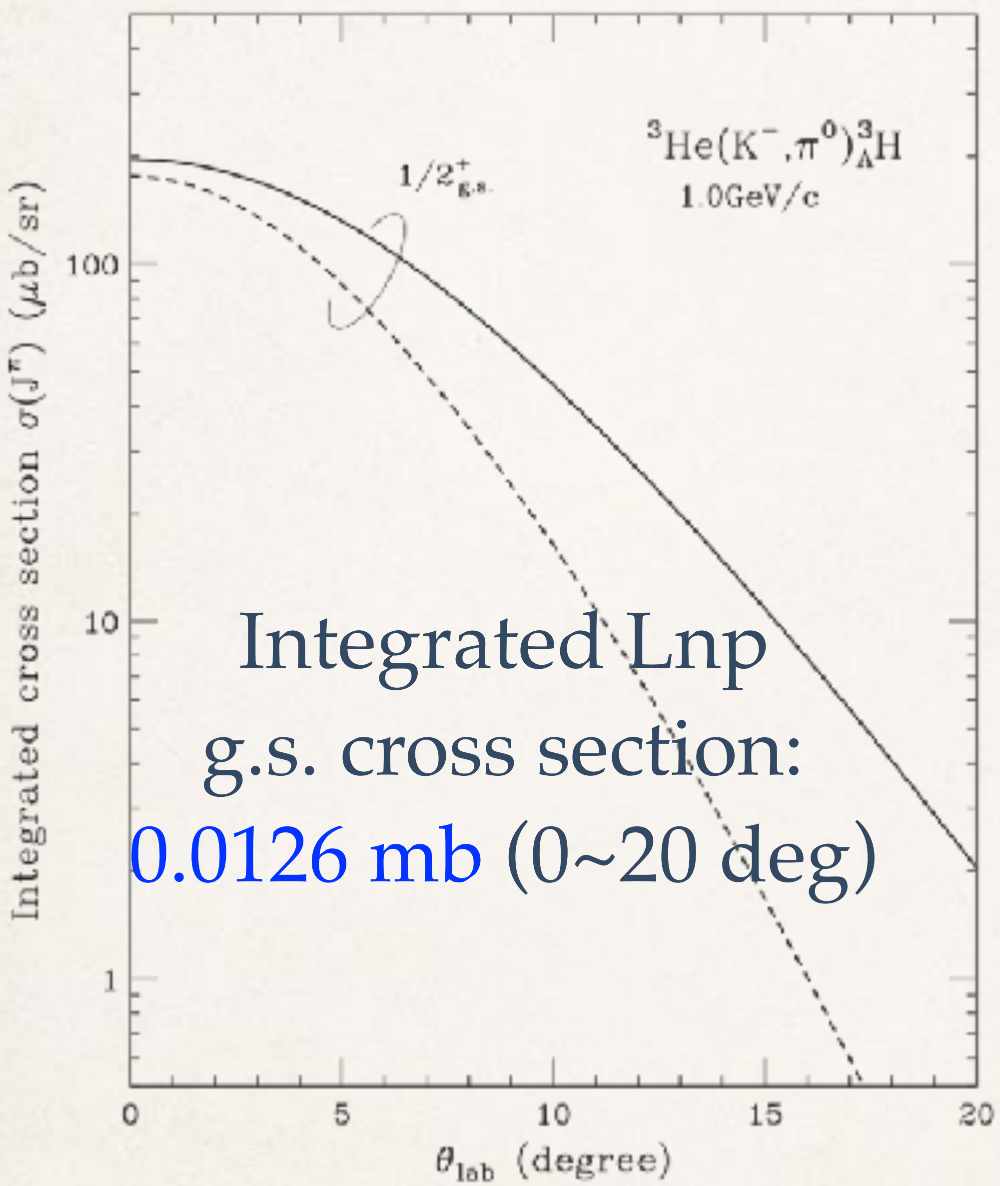


5x5 pieces of
2.5×2.5×14 cm^3
PbF2 Cherenkov Calo
R&D is on going…

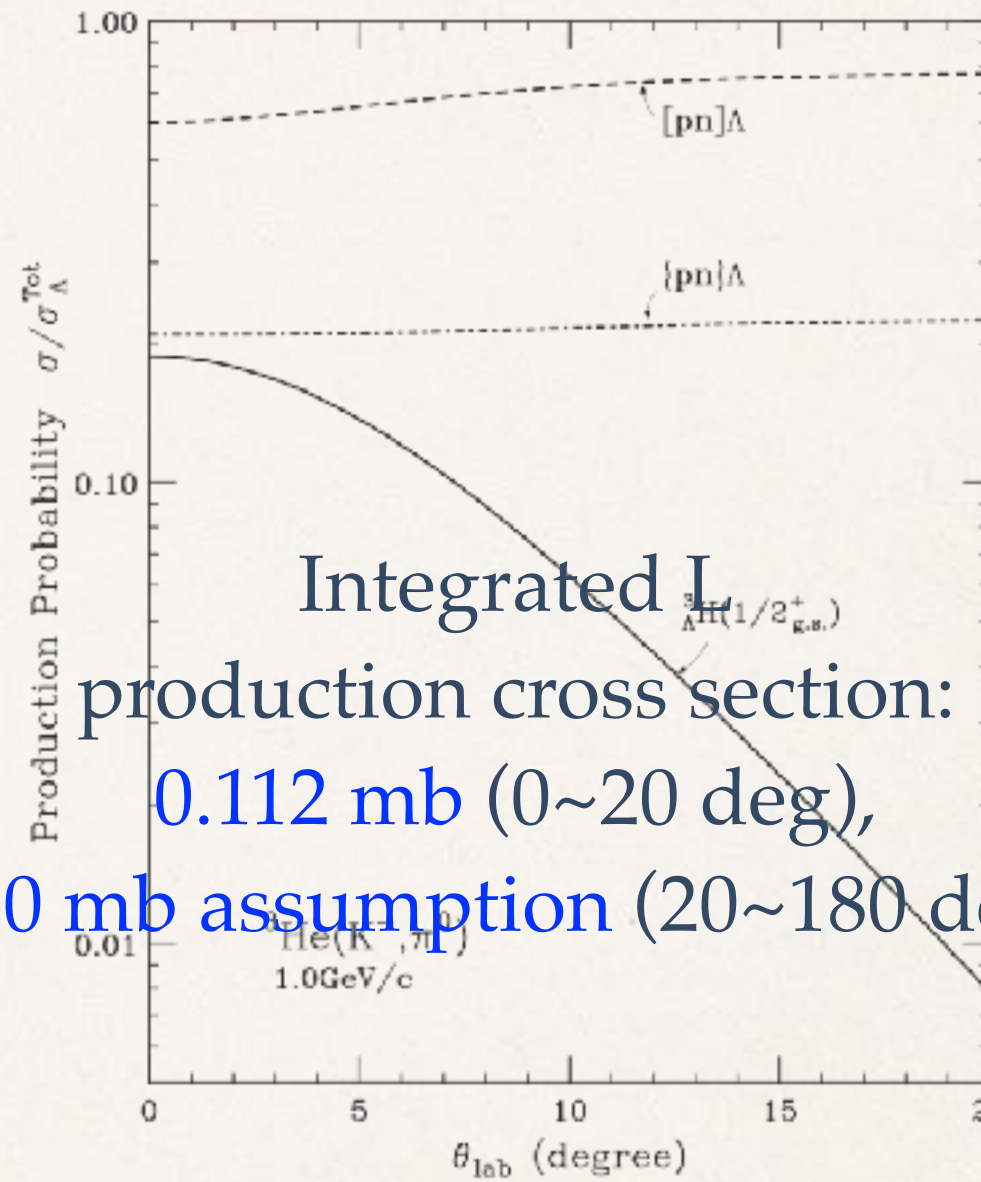
The idea of *direct measurement*: $T_{CDH}-T_0=t_{beam}+t_{\pi^-}+\tau$;

1. Uniform efficiency in time domain.
2. Time resolution convoluted with lifetime:
   $f(t) = \int e^{-t/\tau} * gauss(t-u)du$
3. Achievable precision: $\sigma/\sqrt{N}$ ~ 40ps

Performance estimation: $^{3}_{\Lambda}H$ cross section



Integrated Lnp
g.s. cross section:
0.0126 mb (0~20 deg)

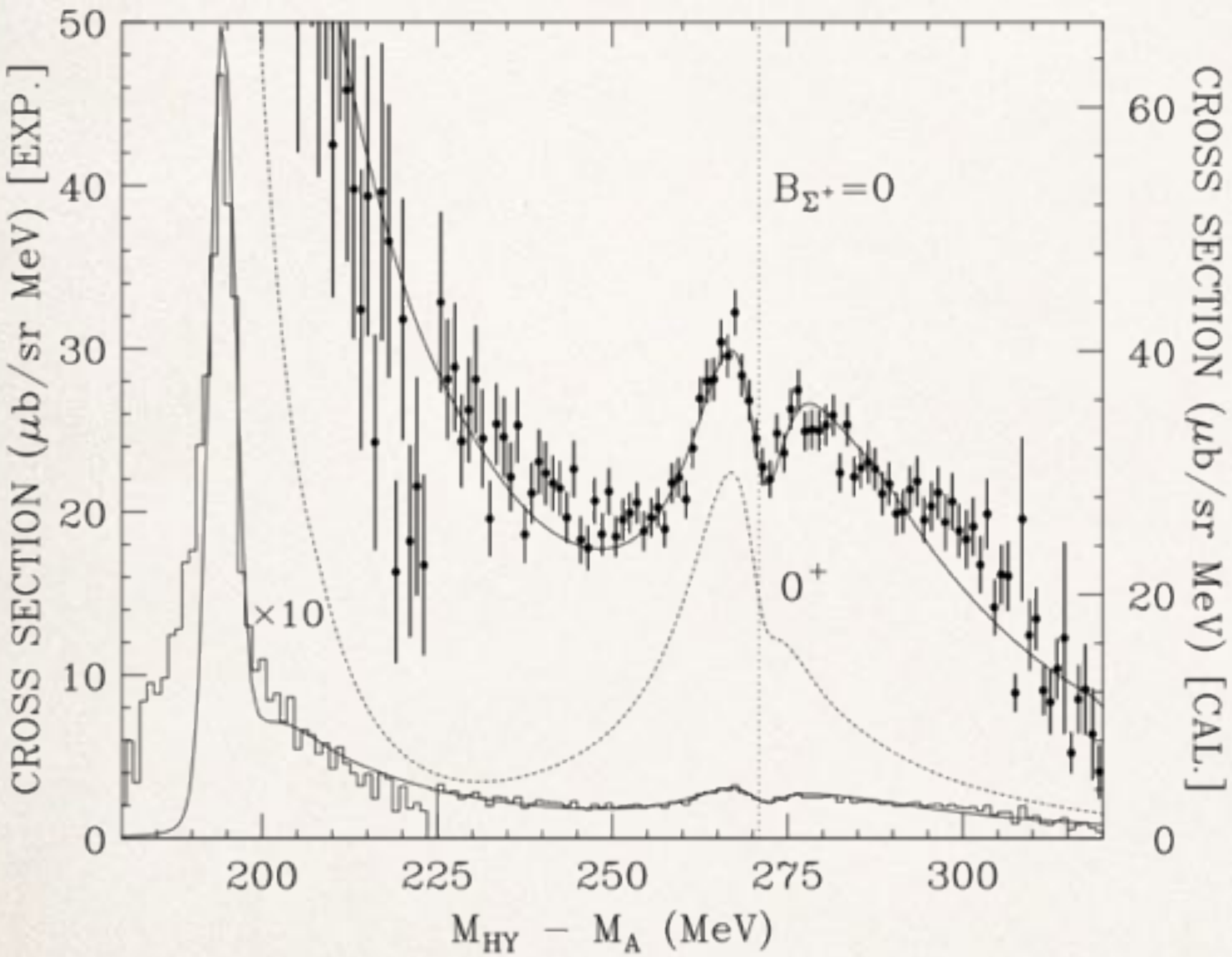


Integrated L
production cross section:
0.112 mb (0~20 deg),
3.0 mb assumption (20~180 deg)

$^{3}He(K^{-}, \pi^{0})^{3}_{\Lambda}H$ cross section calculated by Prof. Harada

Private communication with Prof. T. Harada

Performance estimation: $^{4}{}_{\Lambda}H$ cross section



No direct calculation available for $^{4}He(K^{-}, \pi^{0})^{4}{}_{\Lambda}H$ reaction at 1GeV/c

1, for $^{4}He(K^{-}, \pi^{-})^{4}{}_{\Lambda}He$ reaction, σ~3.5mb/sr at 0.6GeV/c, 4deg

2, taking into account iso-spin coupling factor of 1/2

3, considering recoiling momentum and $n(K^{-}, \pi^{-})\Lambda$ elementary cross section between 0.6 and 1.0 GeV/c K- beam

$^{4}{}_{\Lambda}H$ cross section *estimated* to be ~3 times of $^{3}{}_{\Lambda}H$

T. Harada, Phys. Rev. Lett., 81, 5287, (1998)

Performance estimation: yield estimation

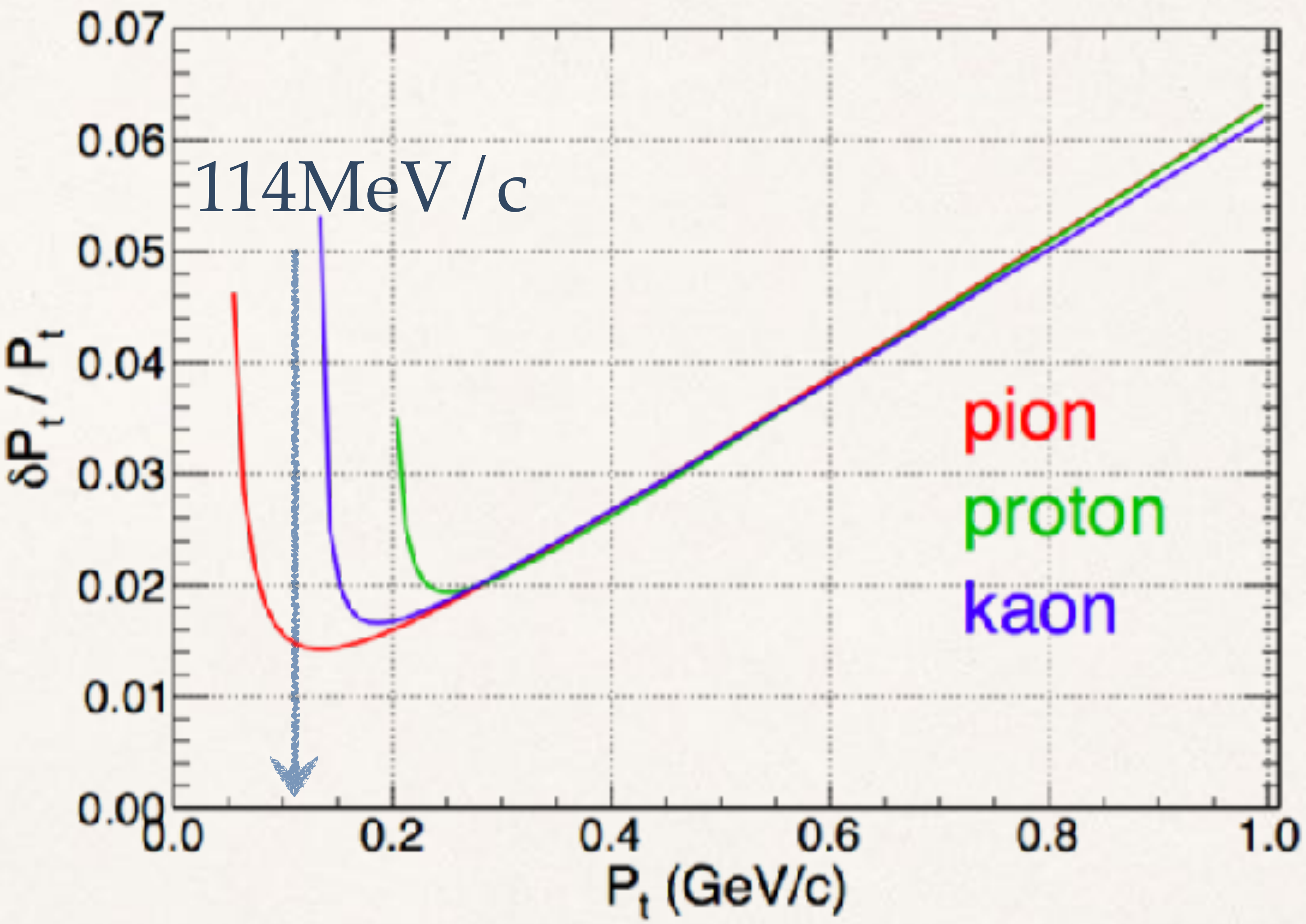
Target: liquid 3He, 10cm	1.6×10^{23}/cm^2
K- intensity @ 1GeV/c	2×10^5/5.2s
σ of $^3{}_\Lambda$H g.s.	0.0126 mb
Total yield	1.8×10^5/4 weeks
Beam acep. & DAQ eff.	50%
$^3{}_\Lambda H \rightarrow {}^3He+\pi^-$ b.r.	25%
π- & π0 acceptance	6%
$^3{}_\Lambda$H signal yield	***~1000 events/4 weeks***

$^4{}_\Lambda$H signal yield (same target cell):

~3(cross section)×2(π^- branching ratio)×$^3{}_\Lambda$H signal yield

==> ***~1000 events/1 week***

Performance estimation: pi- resolution



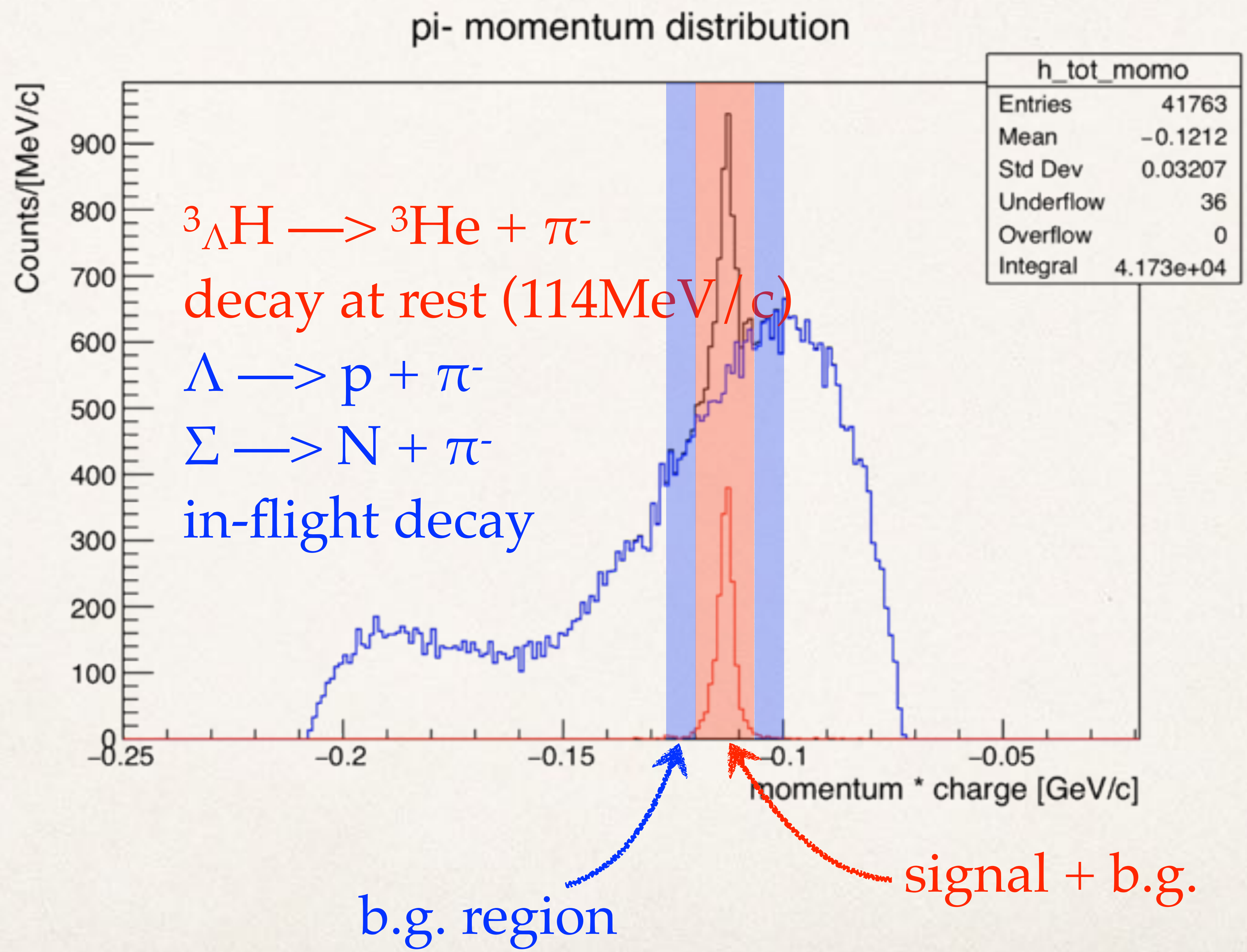
According to GEANT4 simulation,
~2% momentum resolution is achieved for total π^- momentum (pt + pl) after energy loss correction.

T. Hashimoto PhD thesis, University of Tokyo, 2013

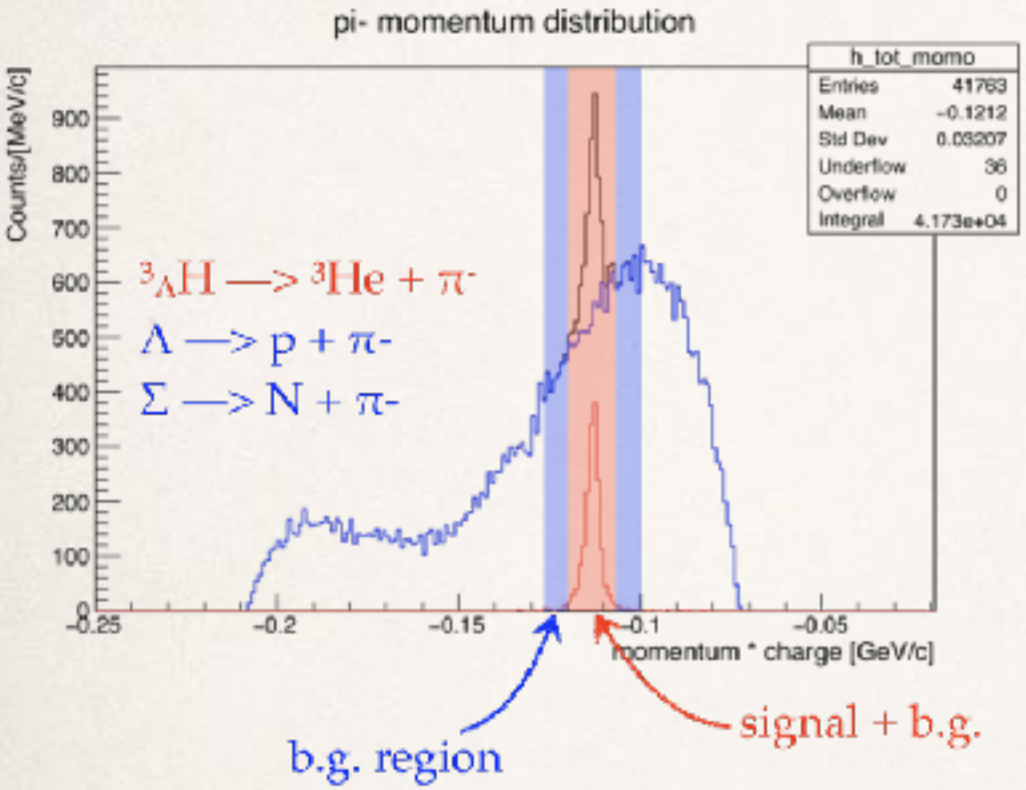
Performance estimation: simulation

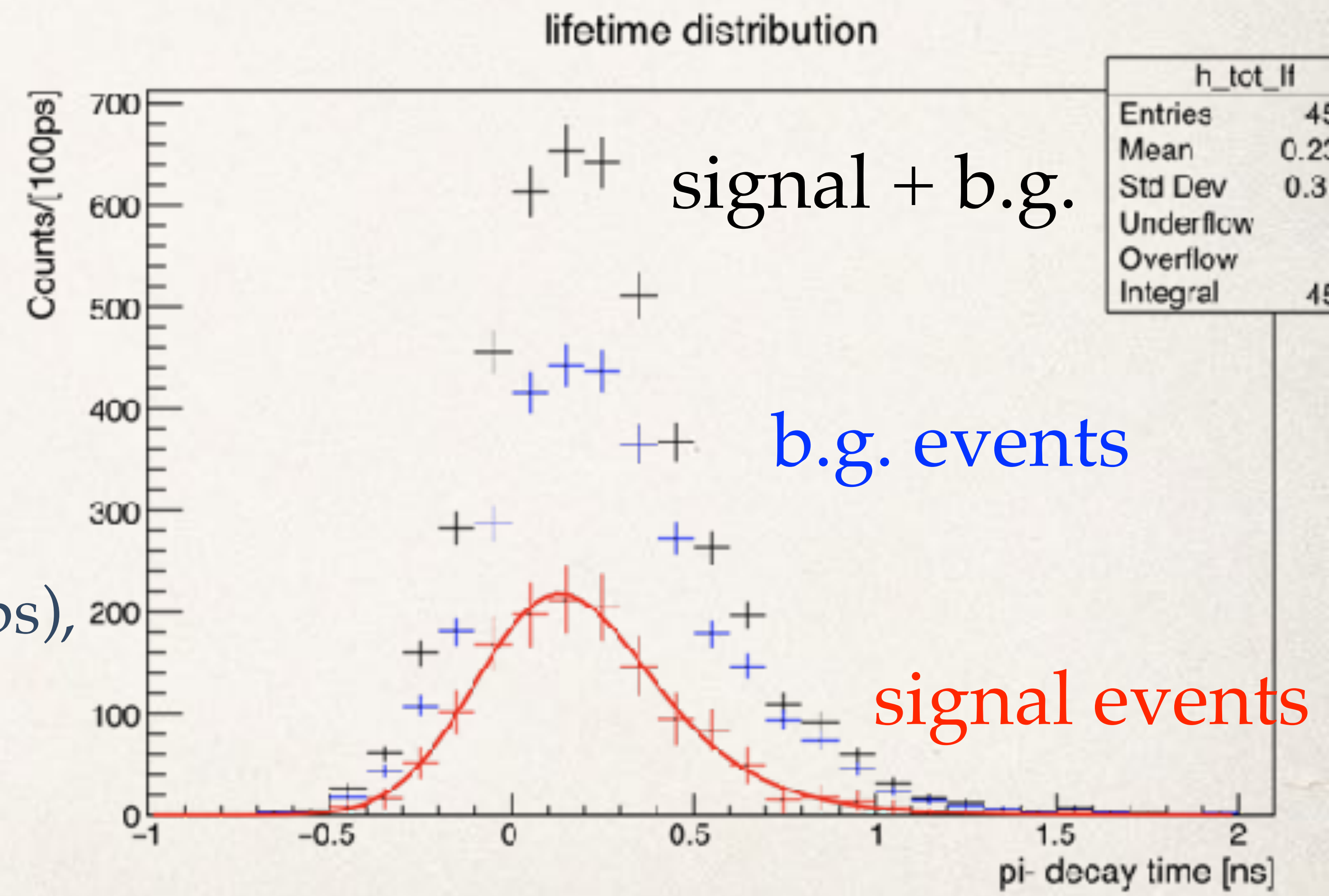
- Most serious π^- background comes from Λ and Σ in-flight decay;
- We bombard liquid ^3He with K- beam with GEANT4 built in cross section;
  - The target density is scaled by a factor of 10 to achieve reasonable amount of luminosity;
  - On a 40-core server, we accumulated 10 hours equivalent luminosity with 1 week computing time.
  - To have a "safety factor", simulated background was scaled by a factor of 2
- After optimization, we fix PbF2 calo at z = 70 cm

Performance estimation: simulation



Performance estimation: simulation





Lifetime from *direct measurement*:

$\tau = T_{CDH} - T_0 - t_{beam} - t_{\pi-}$,

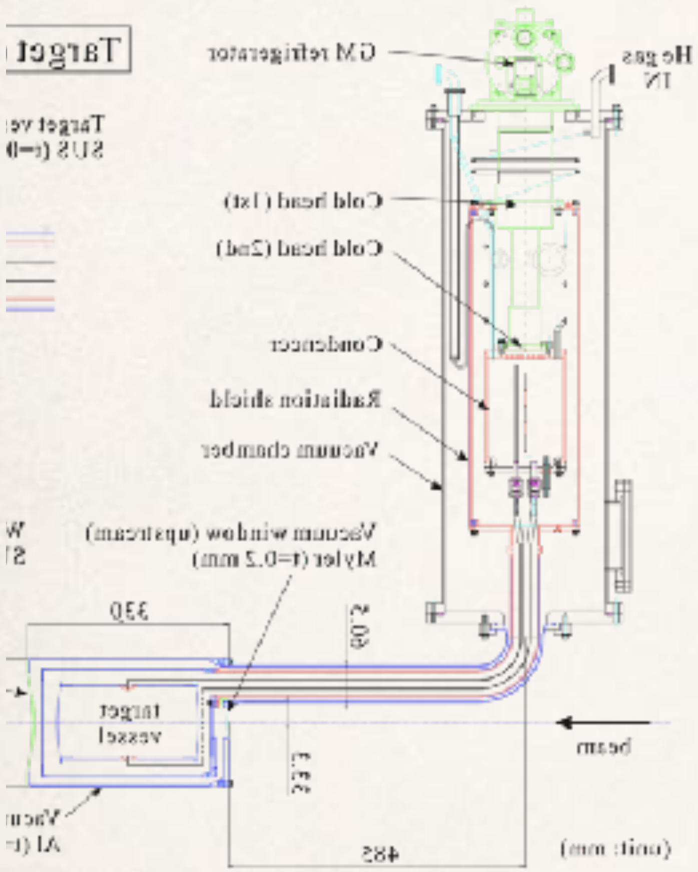
T_{CDH} and T_0 are obtained from TOF (σ~150ps),

t_{beam} and $t_{\pi-}$ can be derived from tracking;

fitting results: σ~40ps

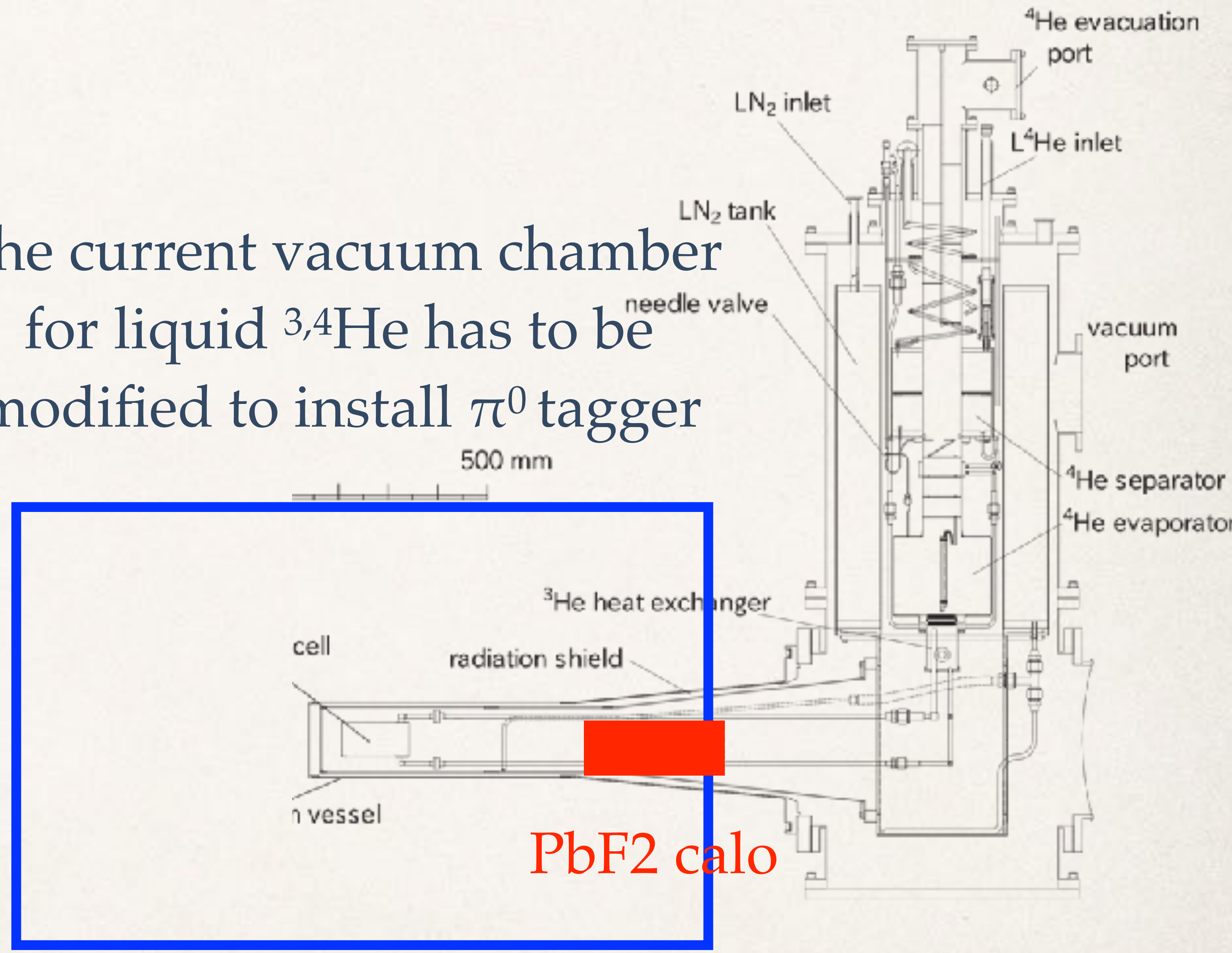
comparable error bar with heavy ion experiment results

Proposal timeline: target modification



Liquid ^{4}He target system for E13 experiment

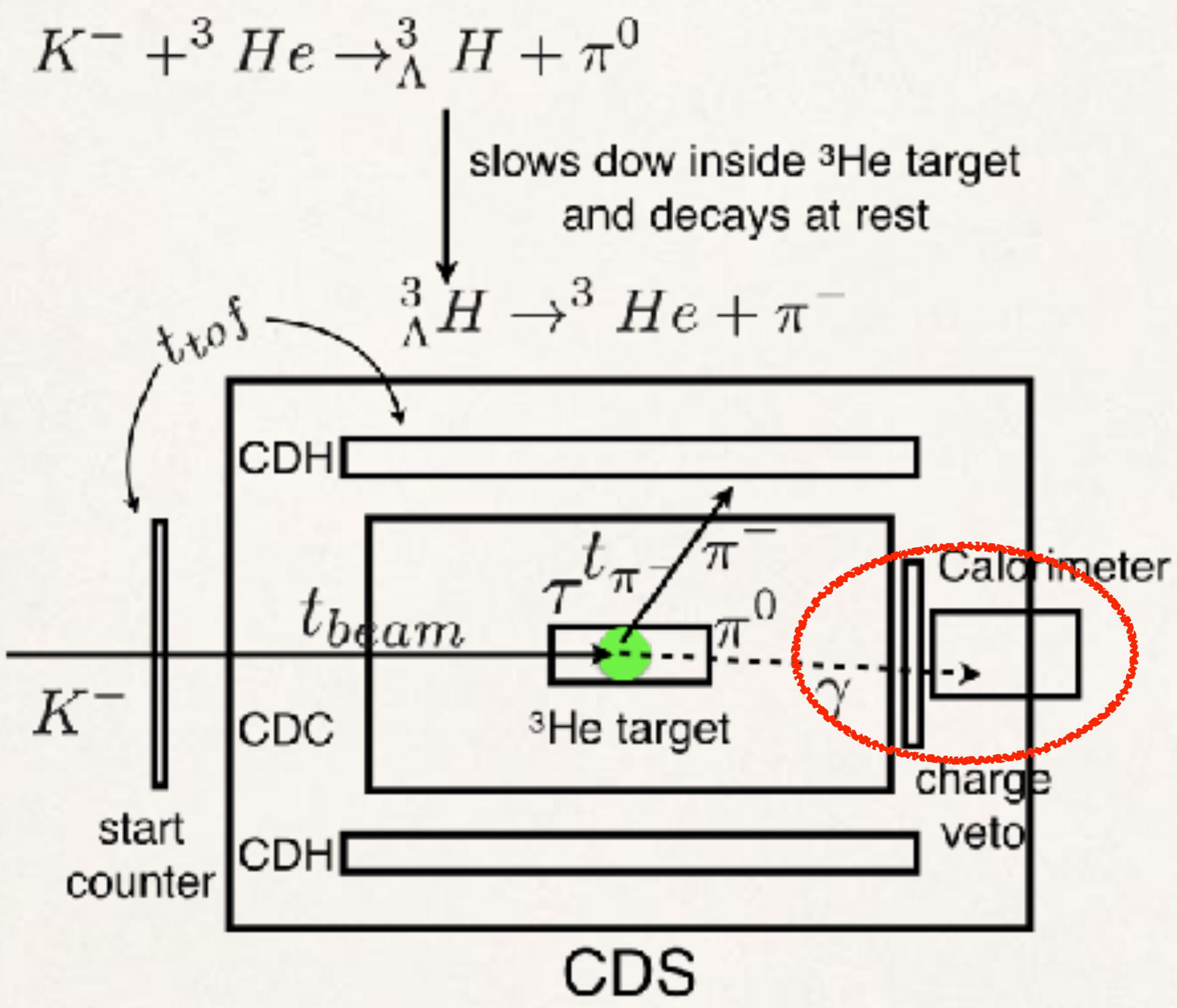
The current vacuum chamber for liquid ^{3,4}He has to be modified to install π^0 tagger

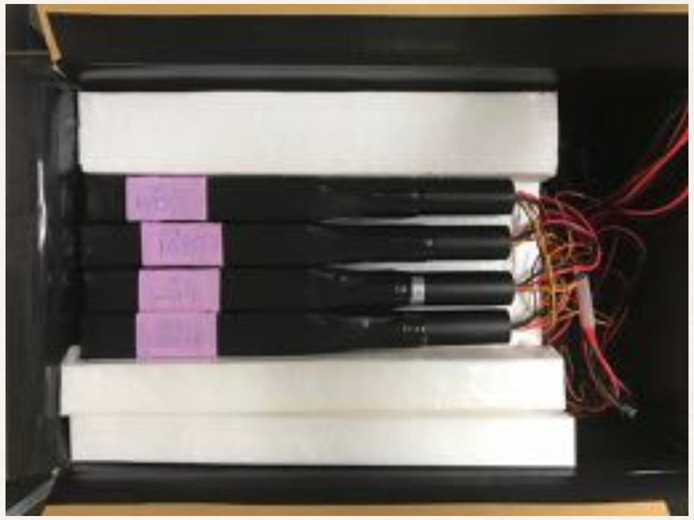


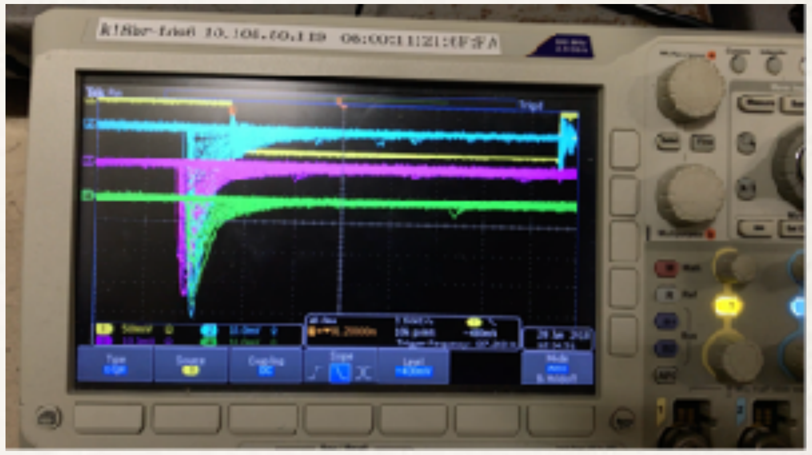
CDS

T. O. Yamamoto PhD thesis, Tohoku University, 2016
T. Yamaga PhD thesis, Osaka University, 2018

Proposal timeline: detector R&D







1. Clean Cherenkov signal has been observed at J-PARC during E62 beam time
2. Veto counter + PbF2 calorimeter will be installed in strong fringing field of CDS (0.75T in CDS center)
3. Material effect on CDS due to PbF2 crystal

Summary

- A new method to measure Hypertriton lifetime is proposed to J-PARC 30GeV Synchrotron
- Reasonable resolution with minimum investment can be achieved based on full simulation
- Technical details will be fixed within 2019 and ready to run, hopefully…

backup

GEANT4 *model?* for K-+He3

Code	Name	Mass	Charge	Life Time	Anti-Particle
		[GeV/c2]		[ns]	
0	GenericIon	9.382723e-01	1.000000e+00	-1.000000e+00	
1000020030	He3	2.808391e+00	2.000000e+00	-1.000000e+00	anti_He3
1000020040	alpha	3.727379e+00	2.000000e+00	-1.000000e+00	anti_alpha
1000010020	deuteron	1.875613e+00	1.000000e+00	-1.000000e+00	anti_deuteron
1000010030	triton	2.808921e+00	1.000000e+00	3.885235e+17	anti_triton

GEANT4 handling for multi-nucleon events seems strange:
only energy is conserved;
NO recoiling momentum from these events…

Vetoed during simulation

PbF2 effects on CDS flux

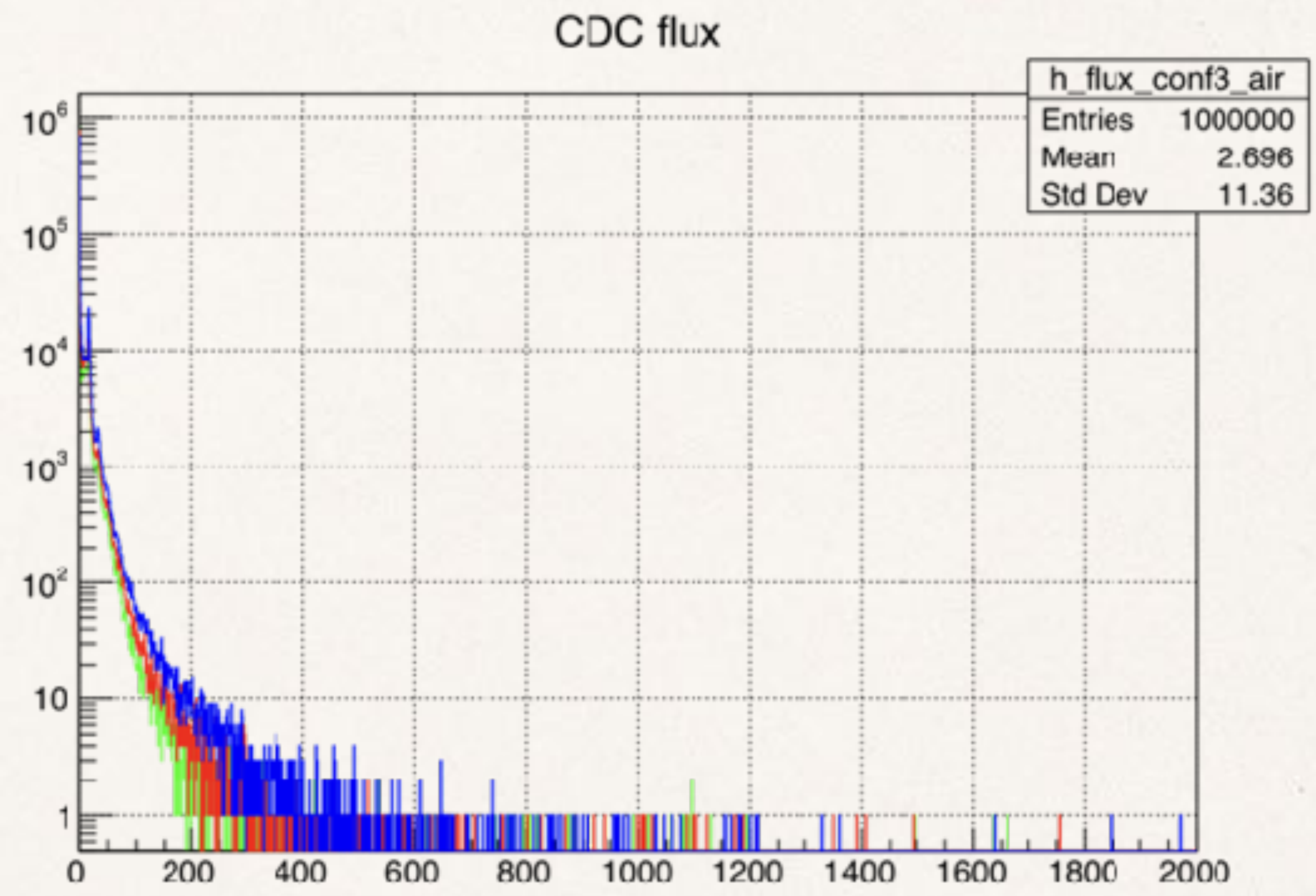
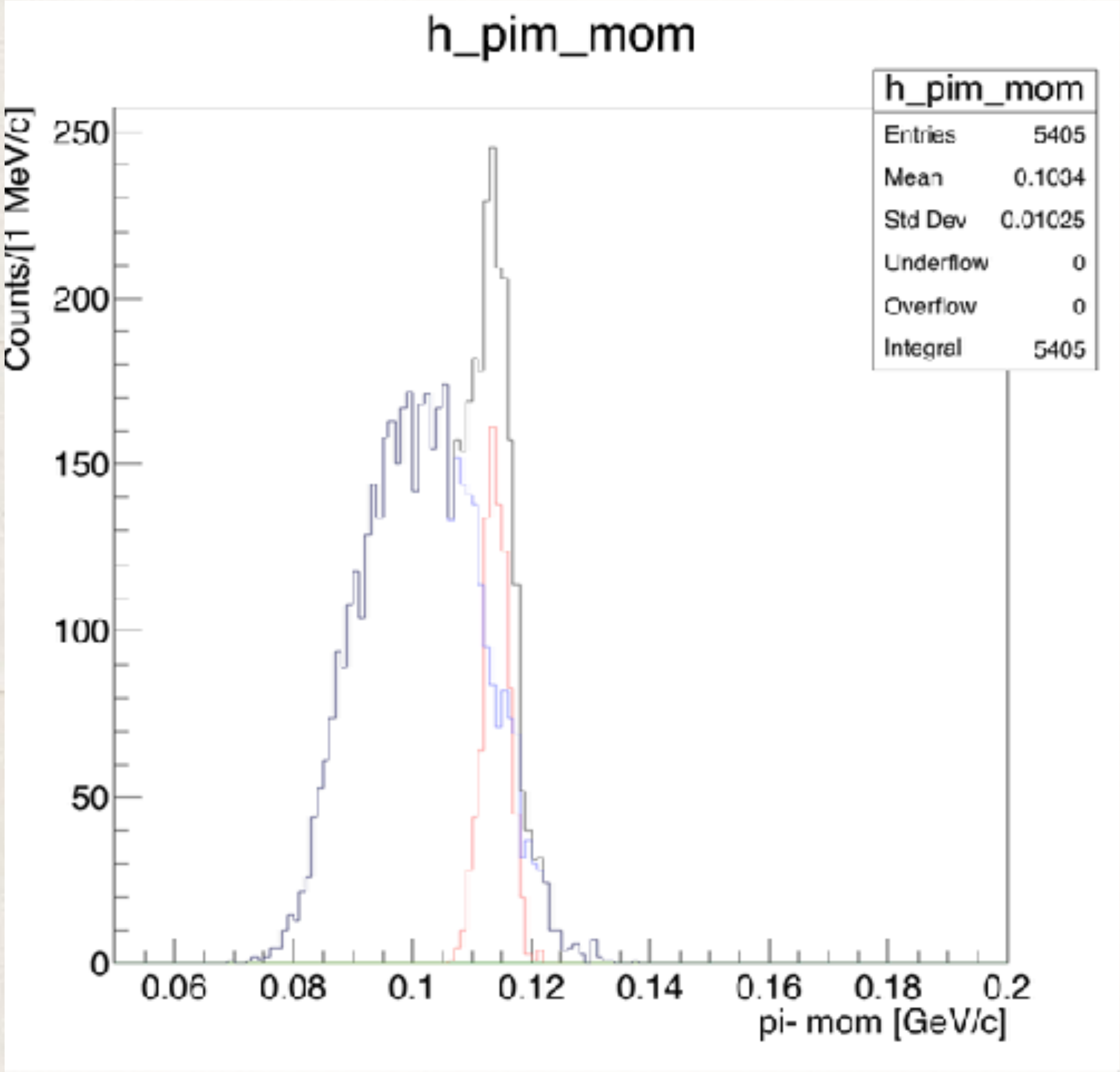
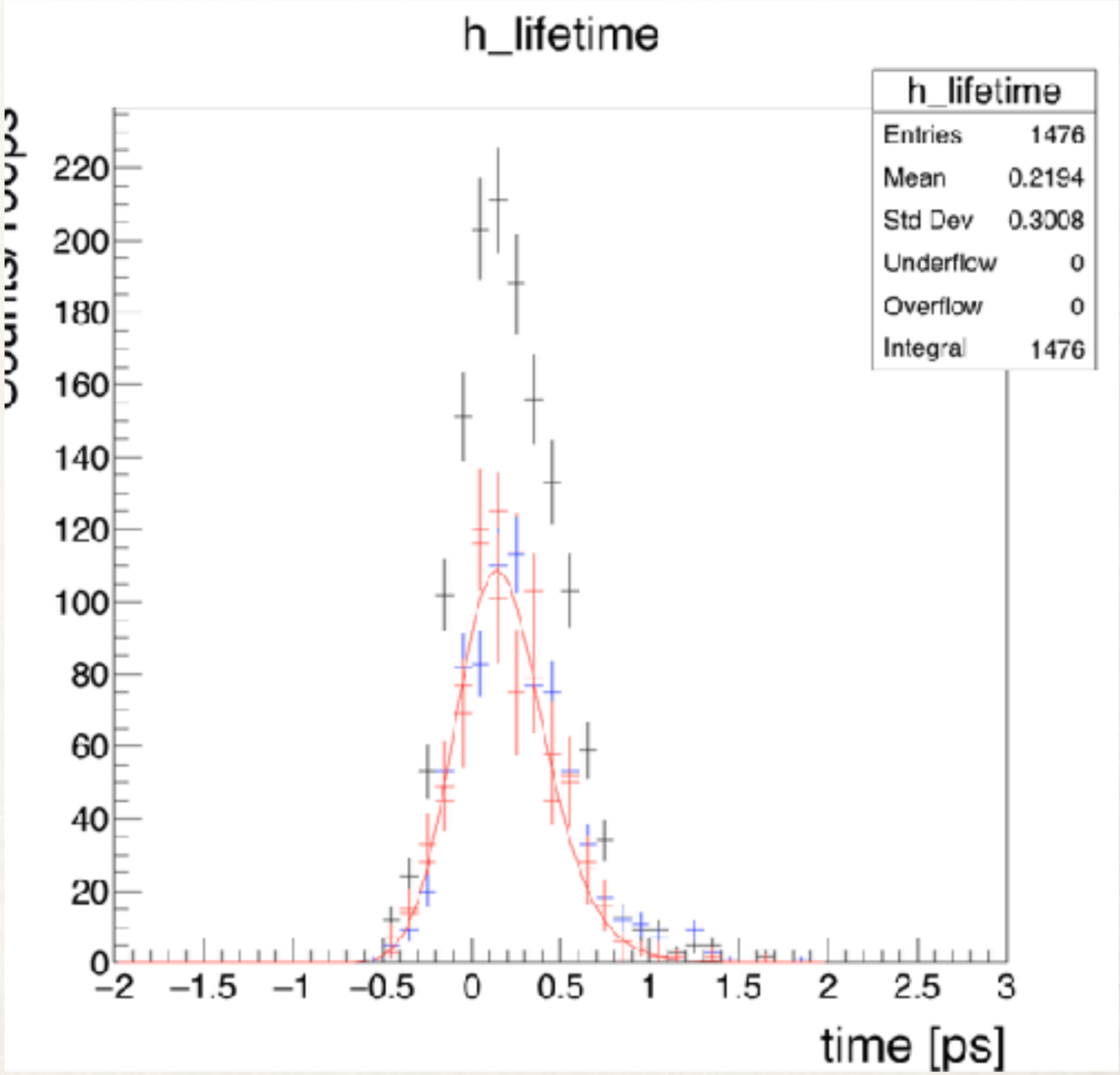


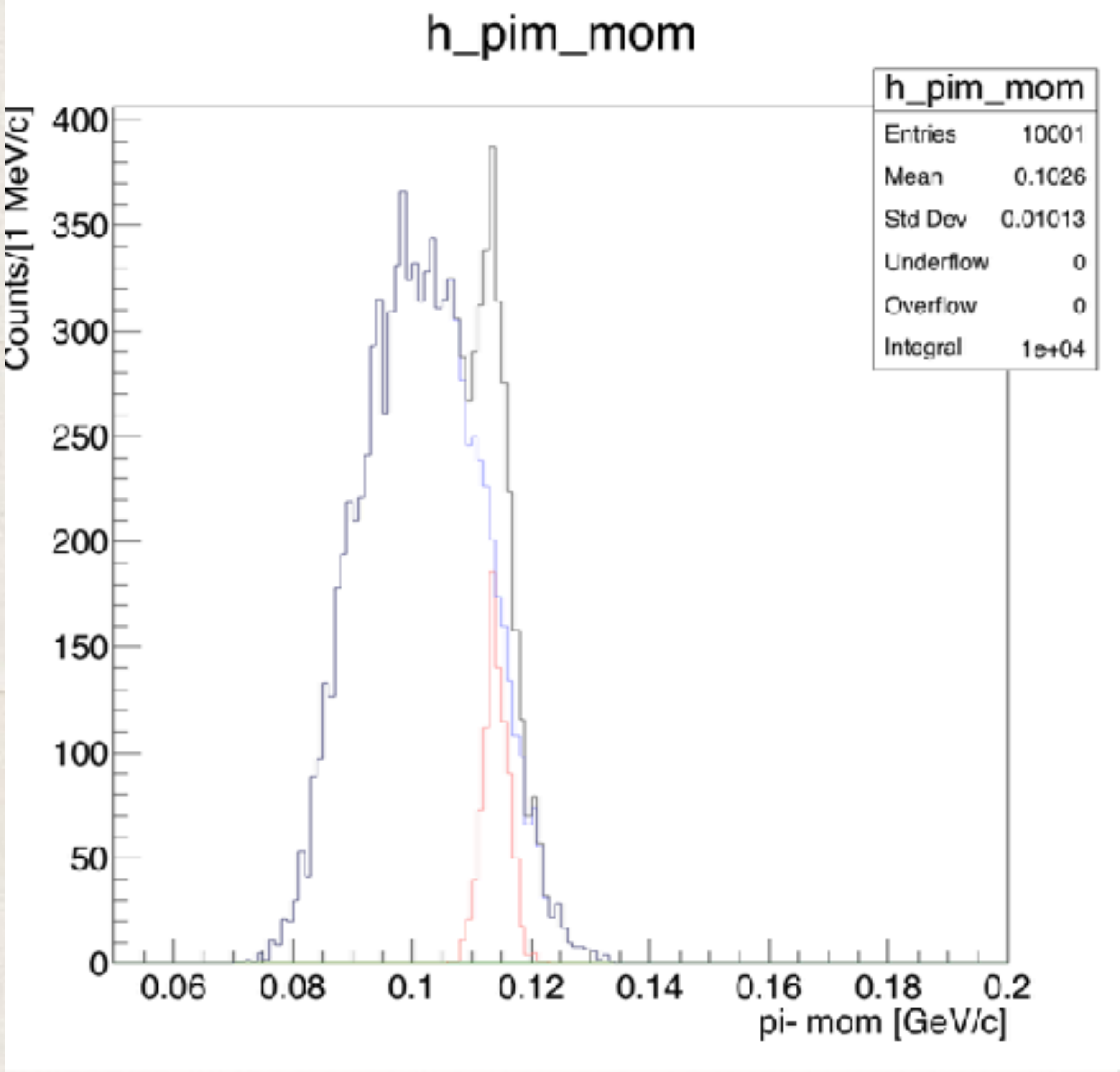
Figure 14: CDC hits flux distribution per event with different detector setup: W/O PbF_2 calorimeter (green), PbF_2 calorimeter located at 70 cm downstream of target center (red), PbF_2 calorimeter located at 30 cm of target center (blue).

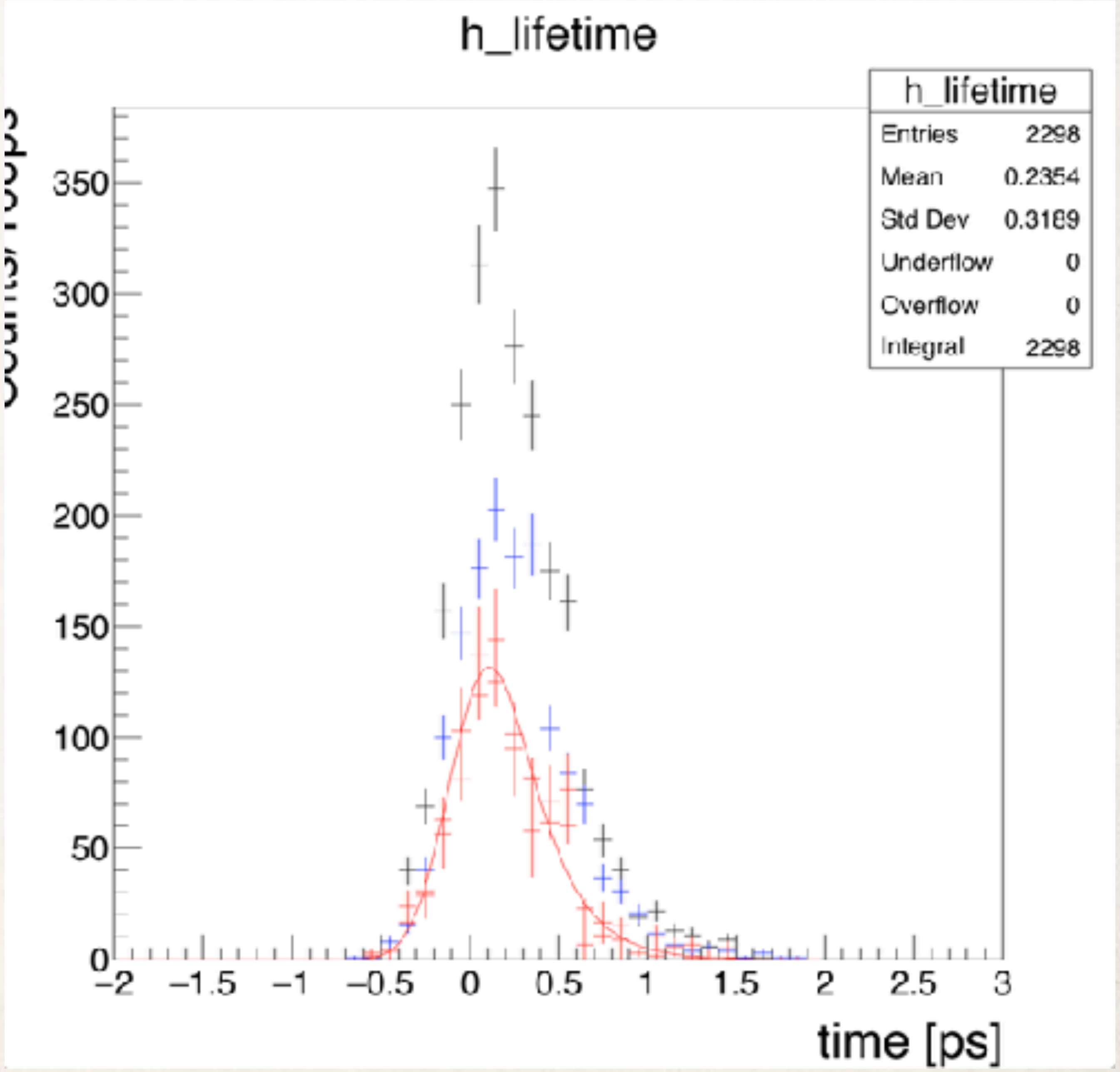
Phase space + Harada calc. b.g. x 1





Phase space + Harada calc. b.g. x 2



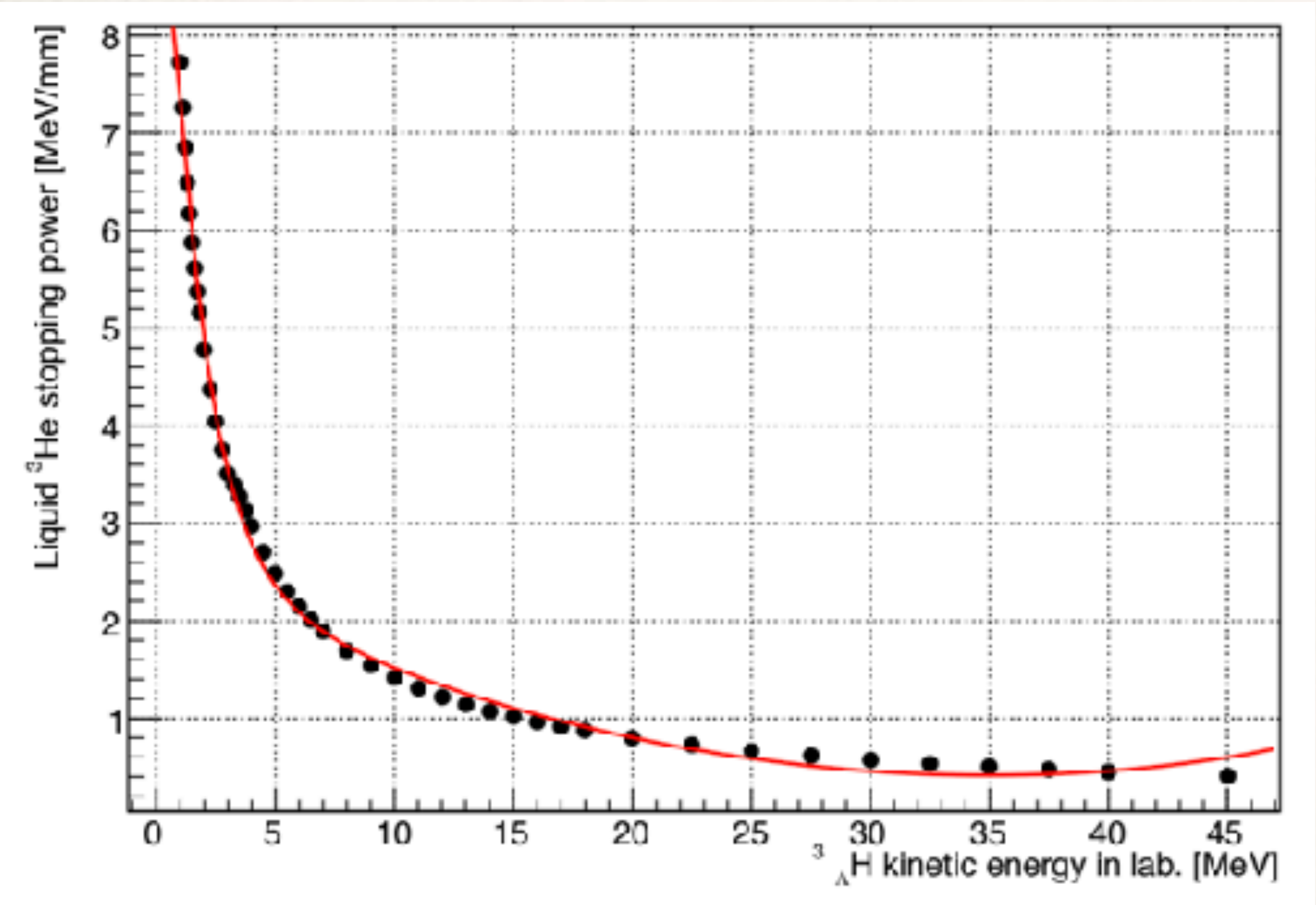


Part I: Performance estimation

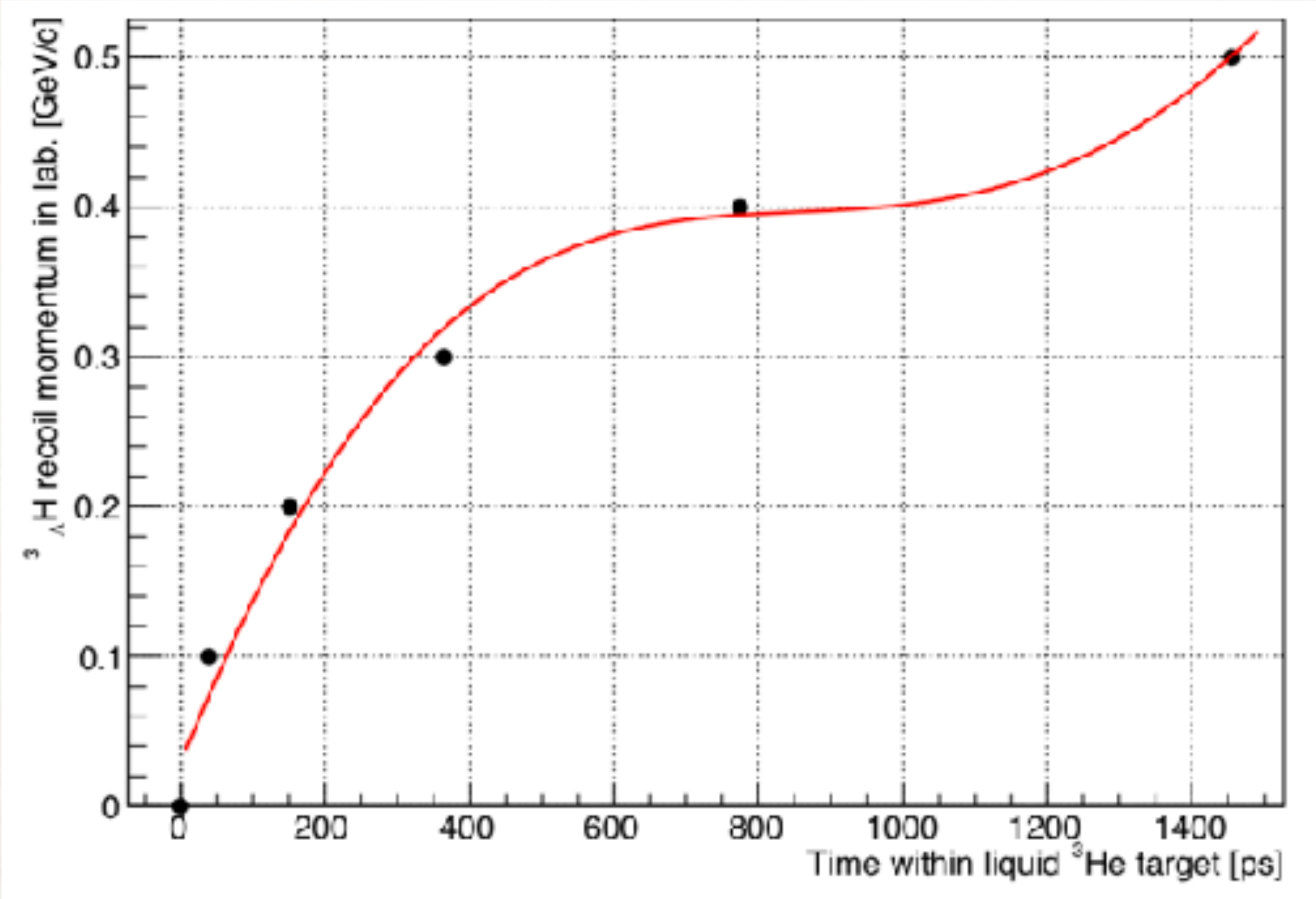
out of pi0⊕pi- acceptance

Reaction(decay) and final states	Charged particle timing structure	Branching ratio	σ [mb/Sr] for p_{K^-}=0.9GeV/c and θ_{π^0}=0
$K^-\,{}^3He \rightarrow \pi^0\,{}^3_\Lambda H \rightarrow \pi^0\,\pi^-\,{}^3He \rightarrow 2\gamma\,\pi^-\,{}^3He$	delayed π^-	?%	?%
$K^-\,{}^3He \rightarrow \pi^0\,{}^3_\Lambda H \rightarrow \pi^0\,p\,n\,n_s \rightarrow 2\gamma\,p\,n\,n$	delayed p	?%	?%
$K^- \rightarrow \pi^0\mu^-\bar{\nu}_\mu \rightarrow 2\gamma\mu^-\bar{\nu}_\mu$	prompt μ^-	3.32%	Not included
$K^- \rightarrow \pi^0\pi^- \rightarrow 2\gamma\pi^-$	prompt π^-	20.92%	
$K^- \rightarrow \pi^0\pi^0\pi^- \rightarrow 4\gamma\pi^-$	prompt π^-	1.76%	
$K^-\,p \rightarrow \pi^0\,\Lambda \rightarrow \pi^0\,\pi^0\,n \rightarrow 4\gamma\,n$	N. A.	35.8%	4.5
$K^-\,p \rightarrow \pi^0\,\Lambda \rightarrow \pi^0\,\pi^-\,p \rightarrow 2\gamma\,\pi^-\,p$	delayed π^-, p	63.9%	
$K^-\,p \rightarrow \pi^0\,\Sigma^0 \rightarrow \pi^0\,\gamma\,\Lambda \rightarrow \pi^0\,\gamma\,\pi^0\,n \rightarrow 5\gamma\,n$	N. A.	35.8%	0.36 (scaled)
$K^-\,p \rightarrow \pi^0\,\Sigma^0 \rightarrow \pi^0\,\gamma\,\Lambda \rightarrow \pi^0\,\gamma\,\pi^-\,p \rightarrow 3\gamma\,\pi^-\,p$	delayed π^-, p	63.9%	
$K^-\,p \rightarrow \pi^-\,\Sigma^+ \rightarrow \pi^-\,\pi^0\,p \rightarrow 2\gamma\,\pi^-\,p$	prompt π^-, delayed p	51.57%	0.9
$K^-\,p \rightarrow \pi^-\,\Sigma^+ \rightarrow \pi^-\,\pi^+\,n$	N. A.	48.31%	
$K^-\,p \rightarrow \pi^+\,\Sigma^- \rightarrow \pi^+\,\pi^-\,n$	N. A.	100%	Not included
$K^-\,n \rightarrow \pi^-\,\Lambda \rightarrow \pi^-\,\pi^0\,n \rightarrow 2\gamma\,\pi^-\,n$	prompt π^-	35.8%	Not included
$K^-\,n \rightarrow \pi^-\,\Lambda \rightarrow \pi^-\,\pi^-\,p \rightarrow 2\pi^-\,p$	N. A.	63.9%	
$K^-\,n \rightarrow \pi^-\,\Sigma^0 \rightarrow \pi^-\,\gamma\,\Lambda \rightarrow \pi^-\,\gamma\,\pi^0\,n \rightarrow 3\gamma\,\pi^-\,n$	prompt π^-	35.8%	Not included
$K^-\,n \rightarrow \pi^-\,\Sigma^0 \rightarrow \pi^-\,\gamma\,\Lambda \rightarrow \pi^-\,\gamma\,\pi^-\,p \rightarrow \gamma\,2\pi^-\,p$	N. A.	63.9%	
$K^-\,n \rightarrow \pi^0\,\Sigma^- \rightarrow \pi^0\,\pi^-\,n \rightarrow 2\gamma\,\pi^-\,n$	delayed π^-	100%	0.9 (scaled)

Table 4: Survey for $K^- + {}^3He \rightarrow$ forward π^0 + delayed π^-.



Lnp stops after 200ps within 1mm; the recoiling effects on lifetime and pi- momentum is negligible.



In this work, we revisit the free hyperon decay and confirm the dominance of the pole contributions via the baryon internal conversion process. Then, we show that there exists a strong cancellation between two pole terms which makes the lifetime of the free Λ to be "fine-tuned" to its present small value. In the case of the hadronic decays of light hypernuclei such as ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H, we find that these two pole terms will be affected differently by the spectator nucleons. As a consequence, the fine-tuned cancellation in the free Λ decays is broken and the transition amplitude is enhanced. It leads to a shortening of the lifetimes of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H in their pionic weak decays.

https://arxiv.org/pdf/1604.04208.pdf