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

Apply for stage-1 approval

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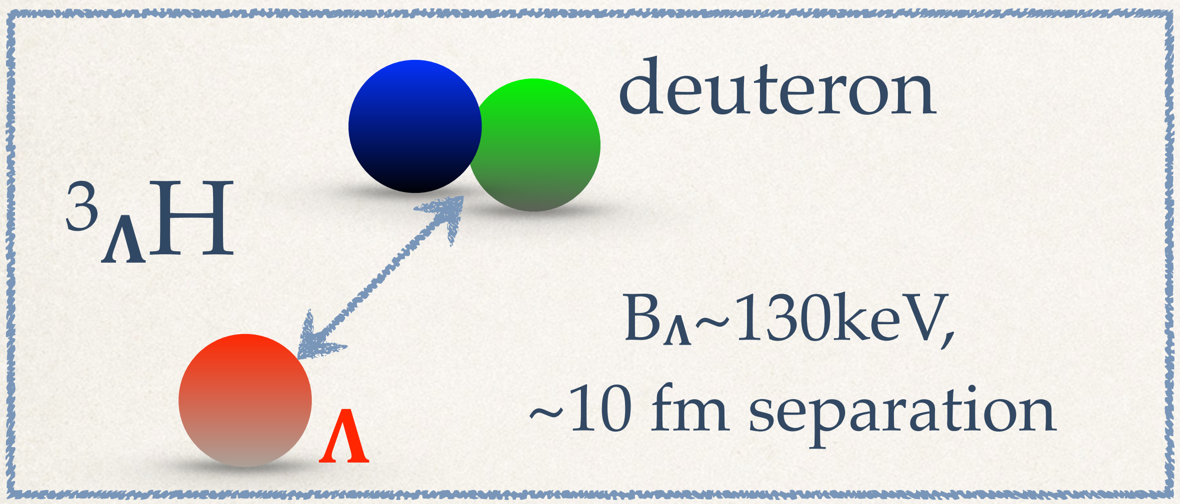
2019/01/17

Outline

- Introduction
- Experimental setup
- Simulation results
- Current status
- 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.



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

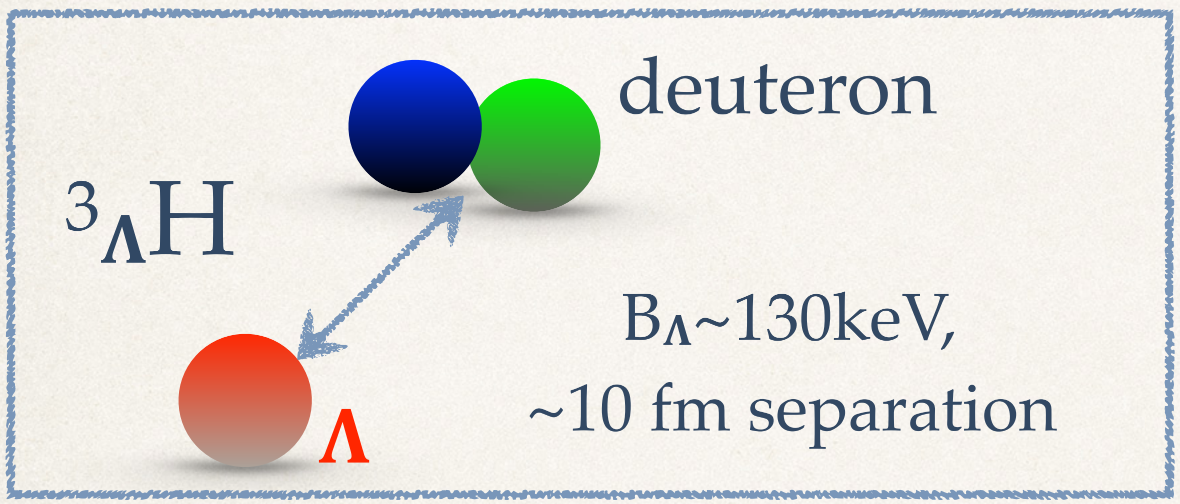
decay probability:
kinematics× | transition matrix |^2
~ phase space×wave function overlap

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.

Introduction: motivation

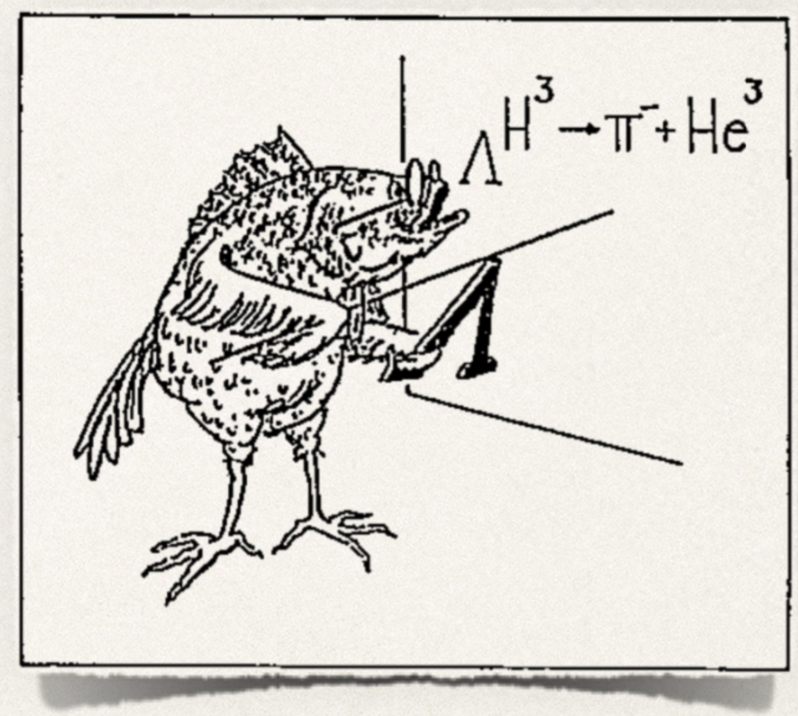
As the lightest hypernucleus, $^3_\Lambda H$ should tell us some important fact of YN interactions just as deuteron for nuclear physics.



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…

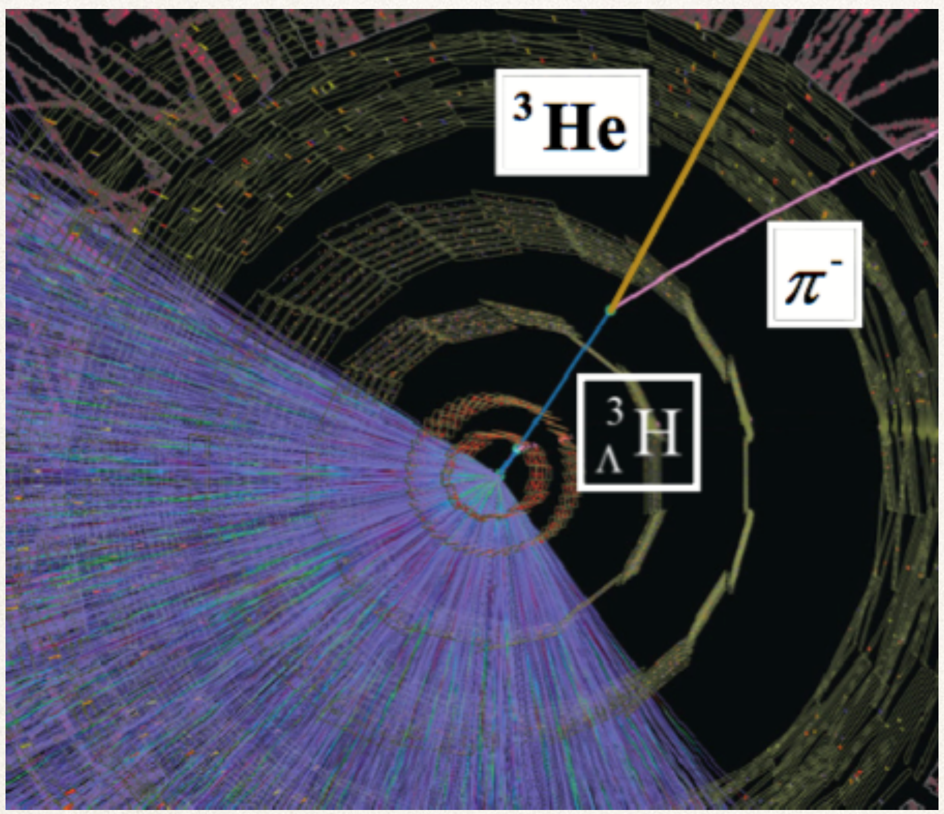


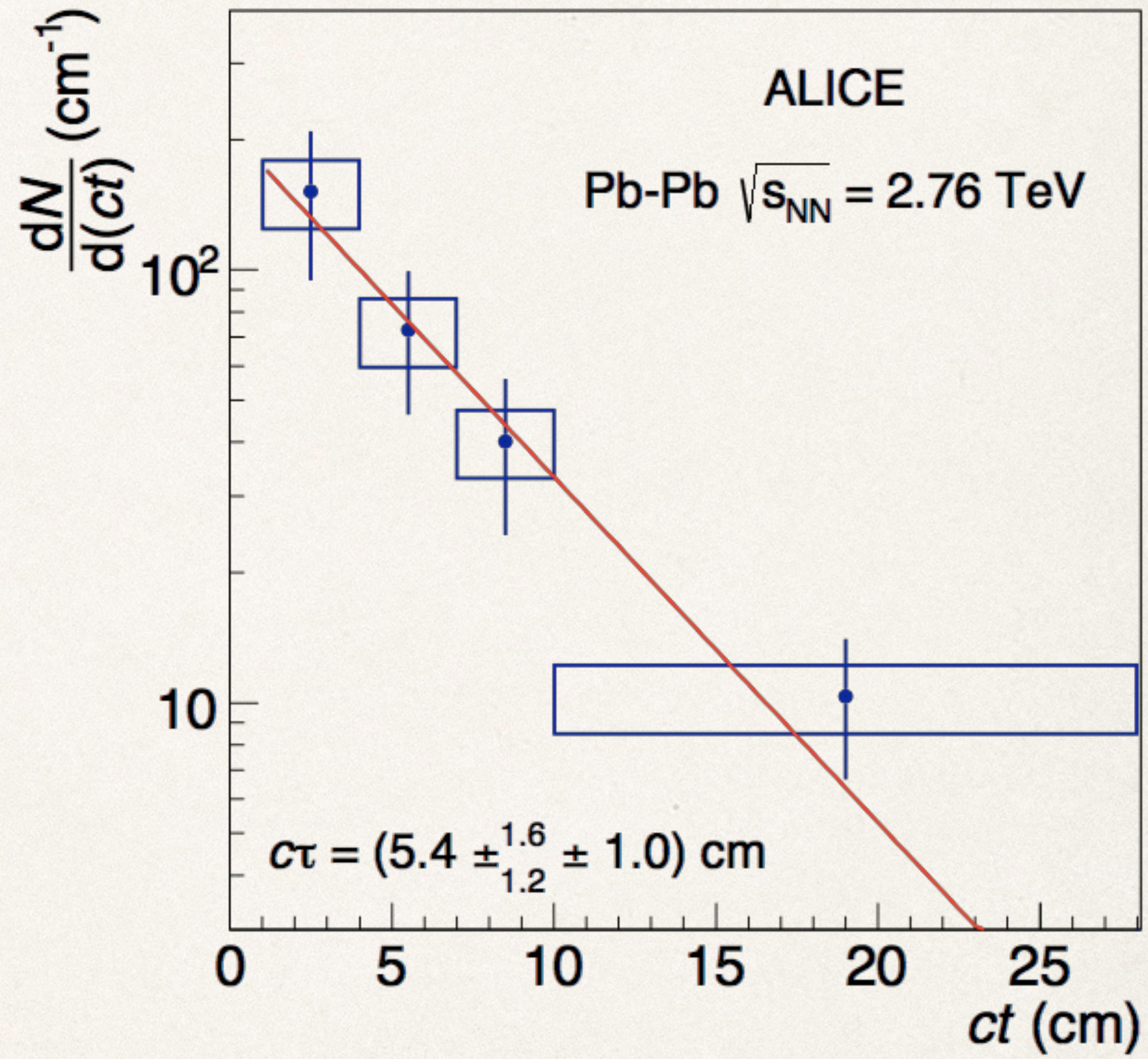
Neither fish nor fowl?

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

Introduction: heavy ion results

ALICE as an example for the experimental approach.





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

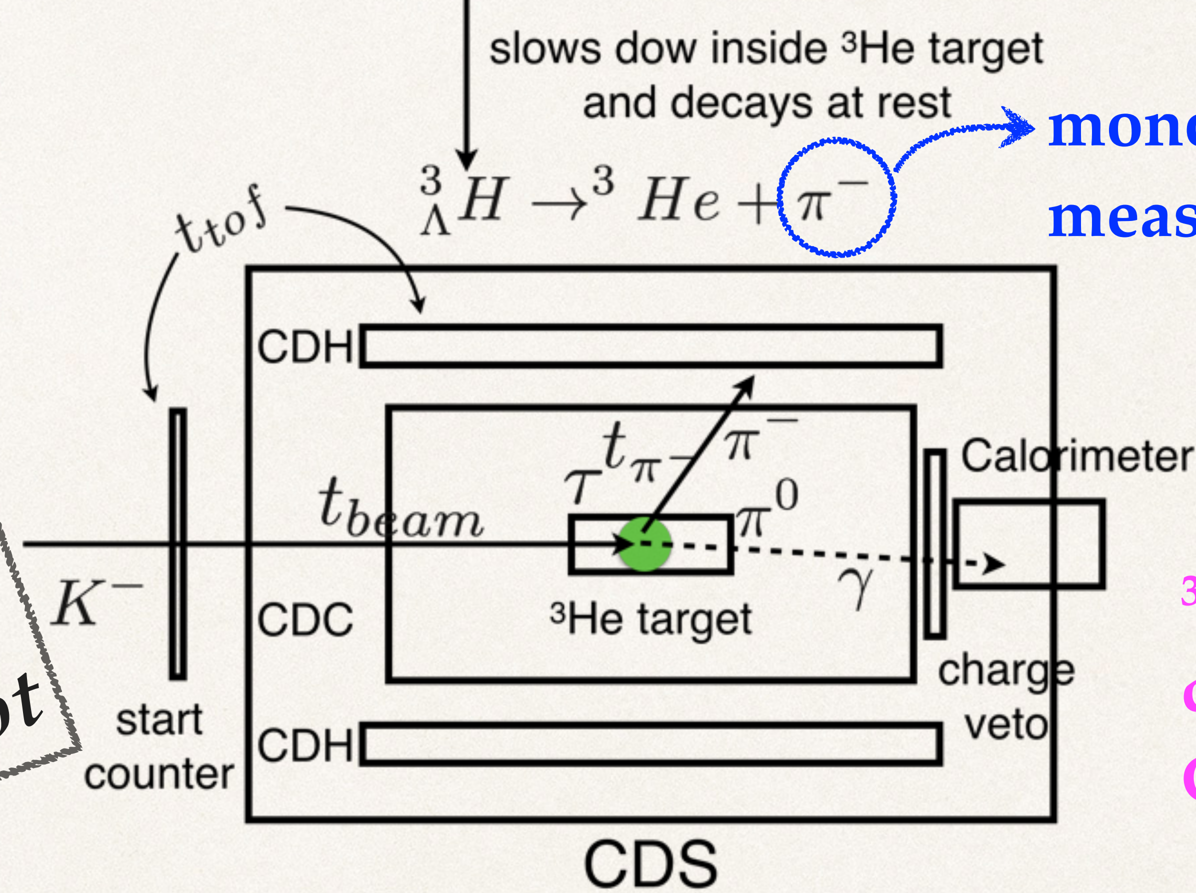
$$\tau = \left(181^{+54}_{-39}(stat.) \pm 33(syst.)\right) ps$$

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

Proposed experimental setup:

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

very forward π0 projectile;
tagged with decayed high energy γ



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

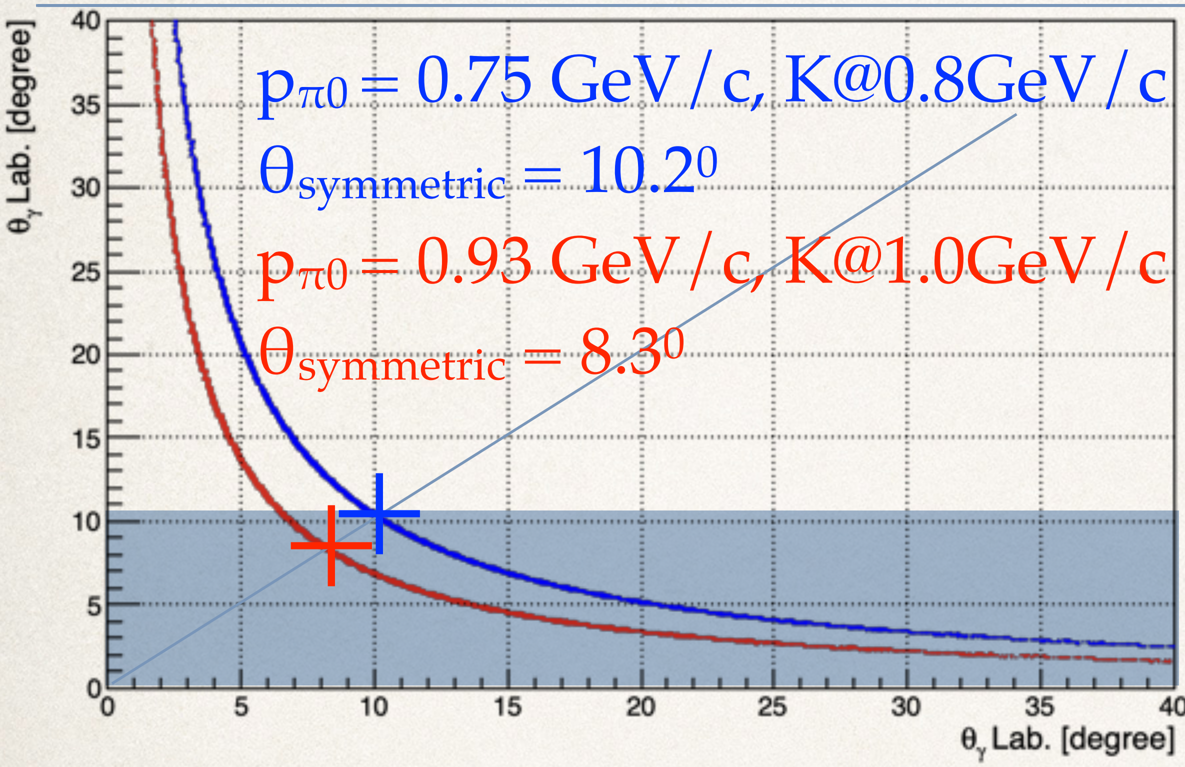
$^3{}_\Lambda$H decay time can be derived by TOF and CDS tracking

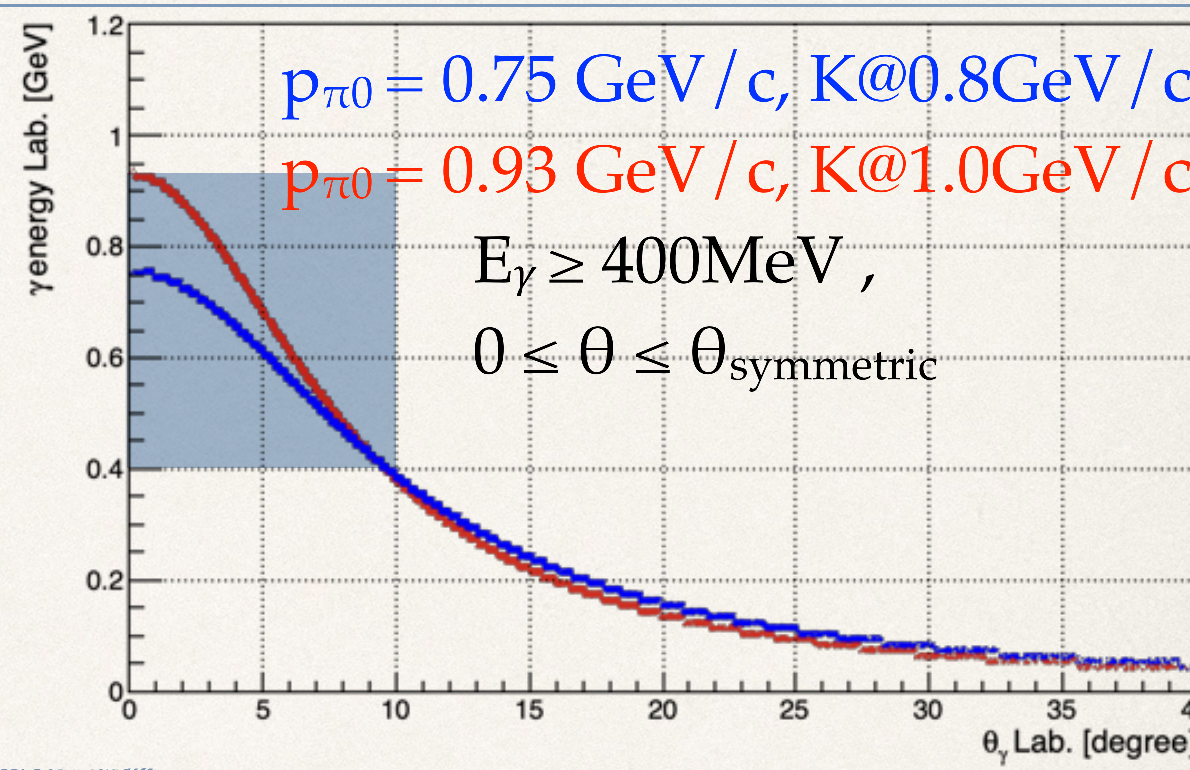
Not to answer *why* but to answer *yes or not*

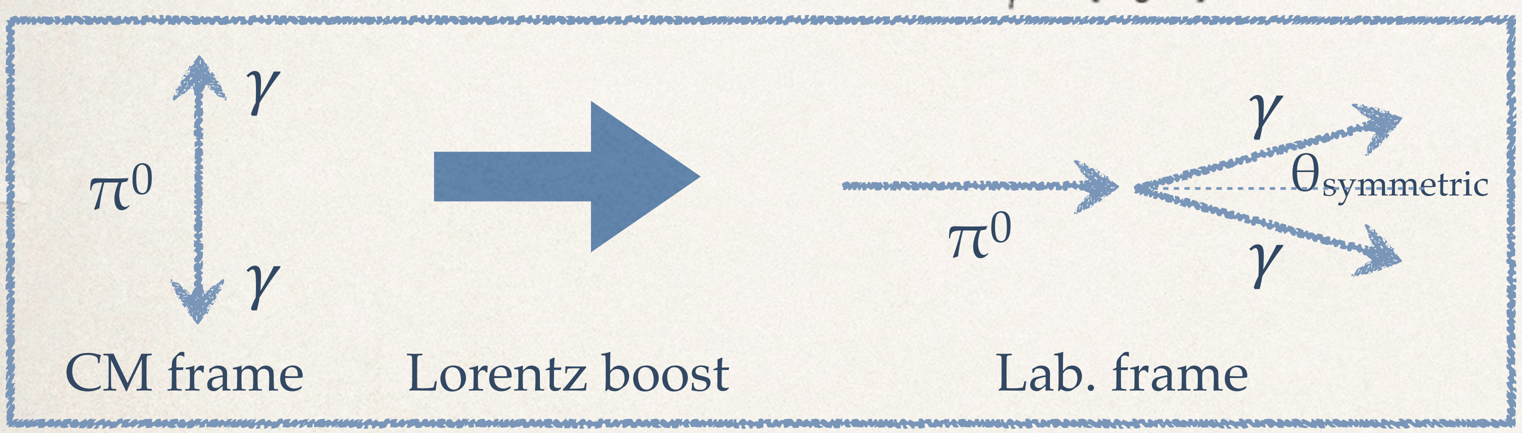
The idea of ***direct measurement***: $T_{CDH}-T_0=t_{beam}+t_{\pi^-}+\tau$;

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

Experimental setup: π^0 kinematics







- 0.75~0.93GeV/c π^0 boosts γ forwardly;
- By covering 0~$\theta_{symmetric}$, we can tag the γ with higher energy ($E_\gamma \geq 400$MeV) with large acceptance

- Effective selection of $^{3,4}{}_\Lambda H/\Lambda$ events by tagging forward γ (E>600MeV)
- π^0 tagger needs to be located along beam line, fast response, radiation hardness --> Cherenkov detector with PbF2 crystal
- 15X0 to ensure the efficiency and reasonable energy resolution

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→^{3}He+π- 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***

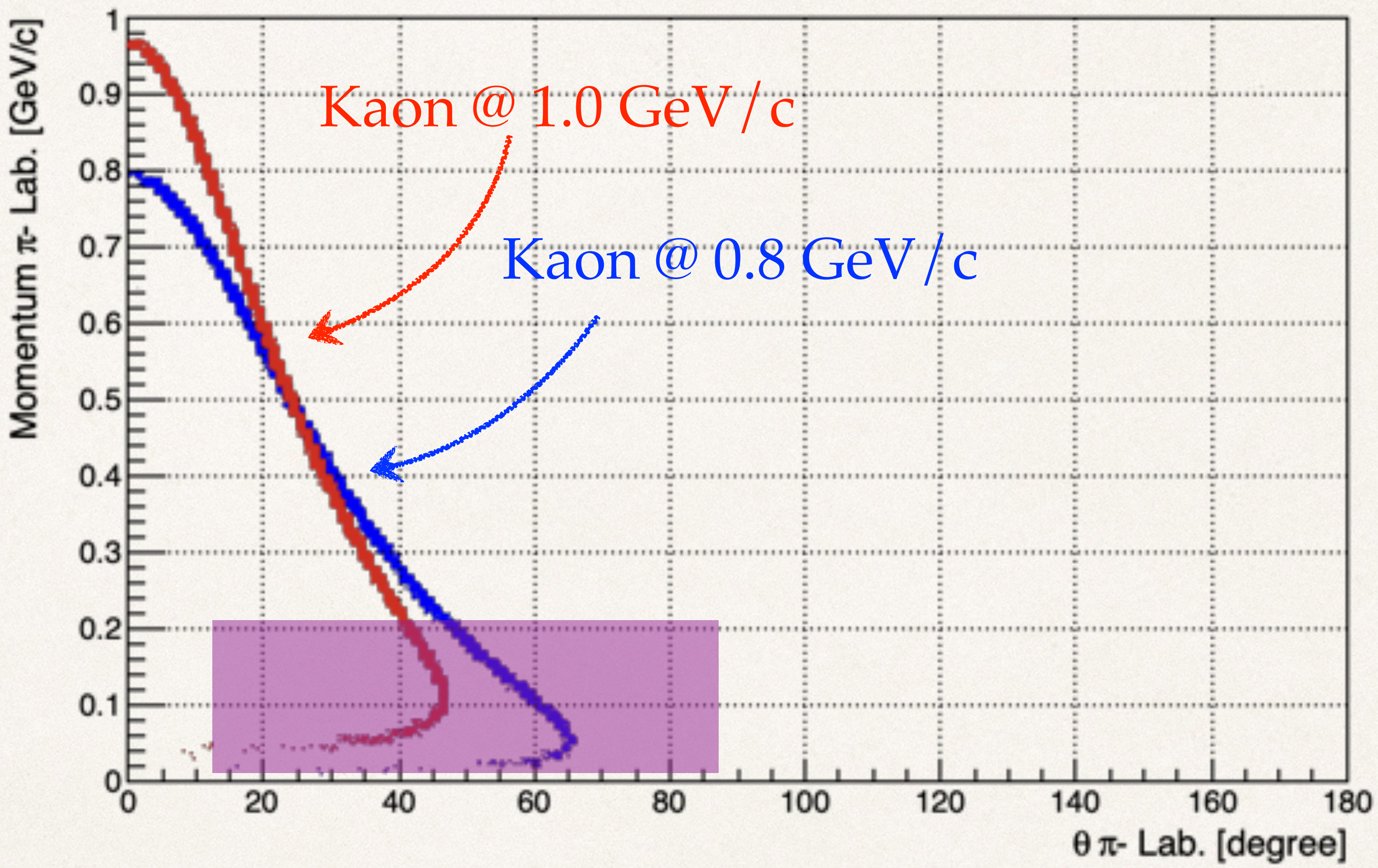
PAC comments from July 2018

In order to proceed to Stage-1 status recommendation, the PAC encourages the P73 collaboration to submit an updated proposal with detailed descriptions of the experiment, including improved Monte Carlo calculations and more details on the setup and analysis method. The beam momentum and the setup (in particular, the position and the size of the target cell and the PbF_2 calorimeter) should be carefully optimized so that the best accuracy is obtained. While the statistical uncertainty of this new lifetime measurement seems to be very competitive, P73 should explain how possible systematic uncertainties can be controlled and to what level they may eventually be eliminated. It should also provide more information on possible background, which may, for example, be caused by K^- decays traversing the detection system.

We have revised our proposal by including

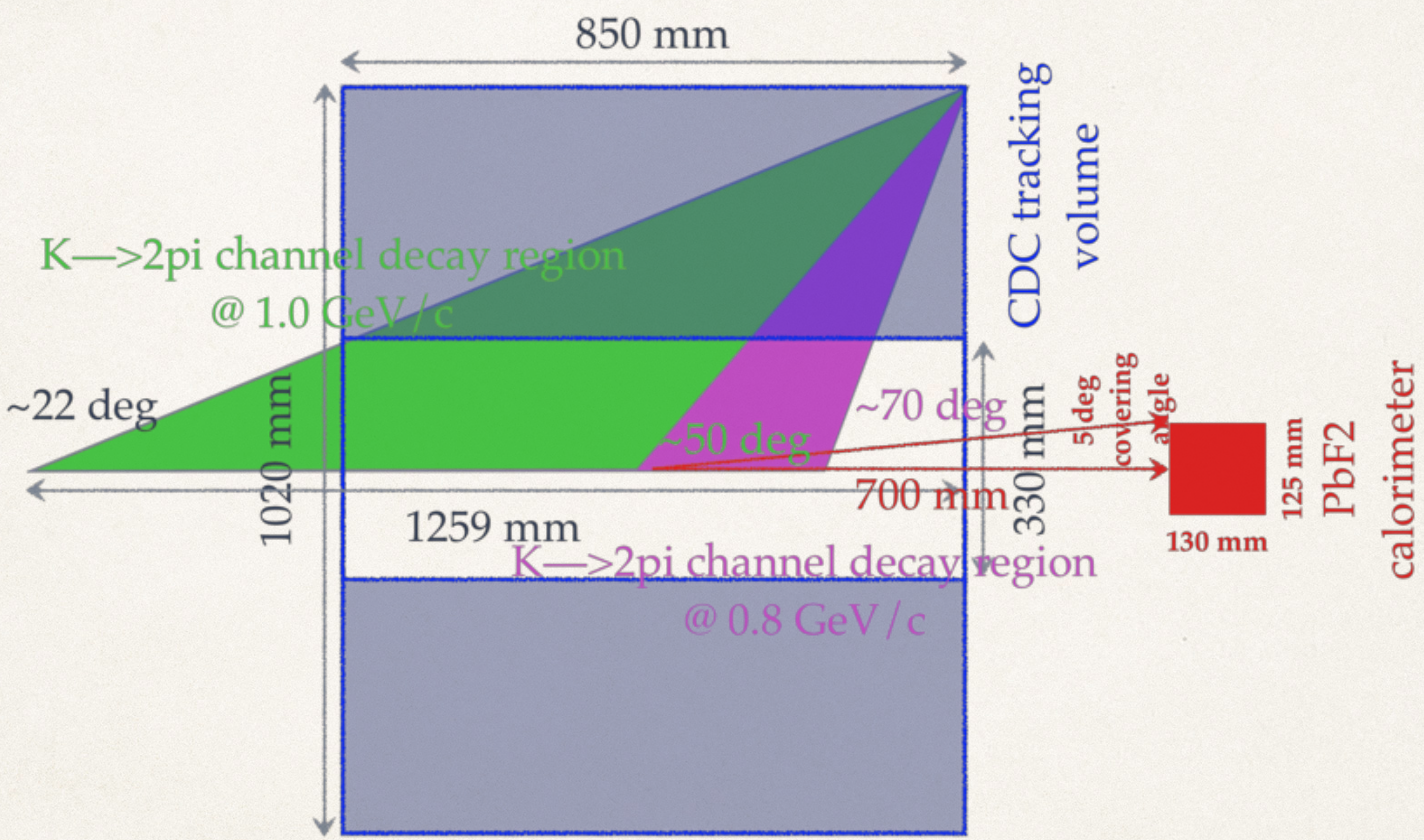
- Kaon in-flight decay background
- Reaction induced background
- Setup optimization
- Statistical and systematic error estimation

Background events from Kaon in-flight decay



For setup like SKS dipole magnet spectrometer, there are severe BG from K- inflight decay.
But in our case, a conjunction measurement of both pi- and pi0, the kaon decay backgrounds can be suppressed by using the pi- decay angle and decay vertex.

CDC acceptance vs Kaon decay background

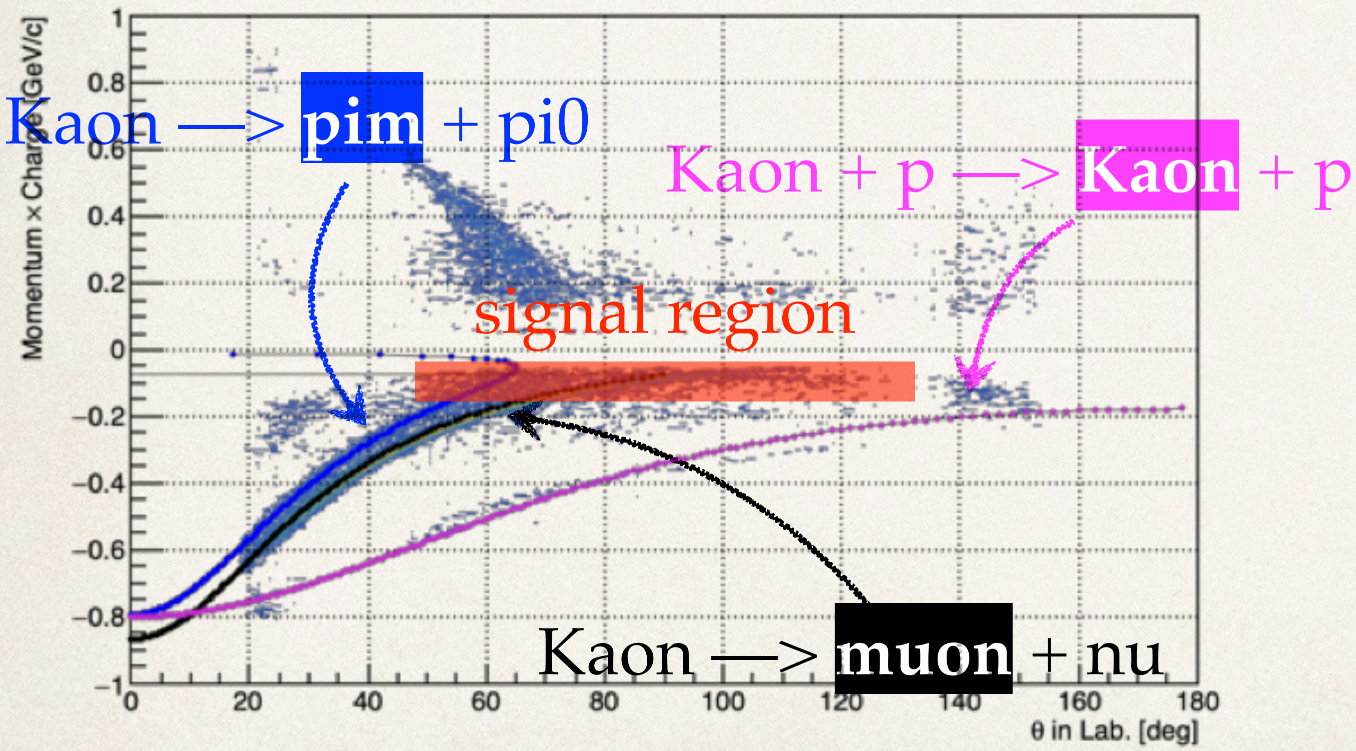


Most of the 1.0 GeV/c K- beam in-flight decay background is out of the acceptance of CDS spectrometer.

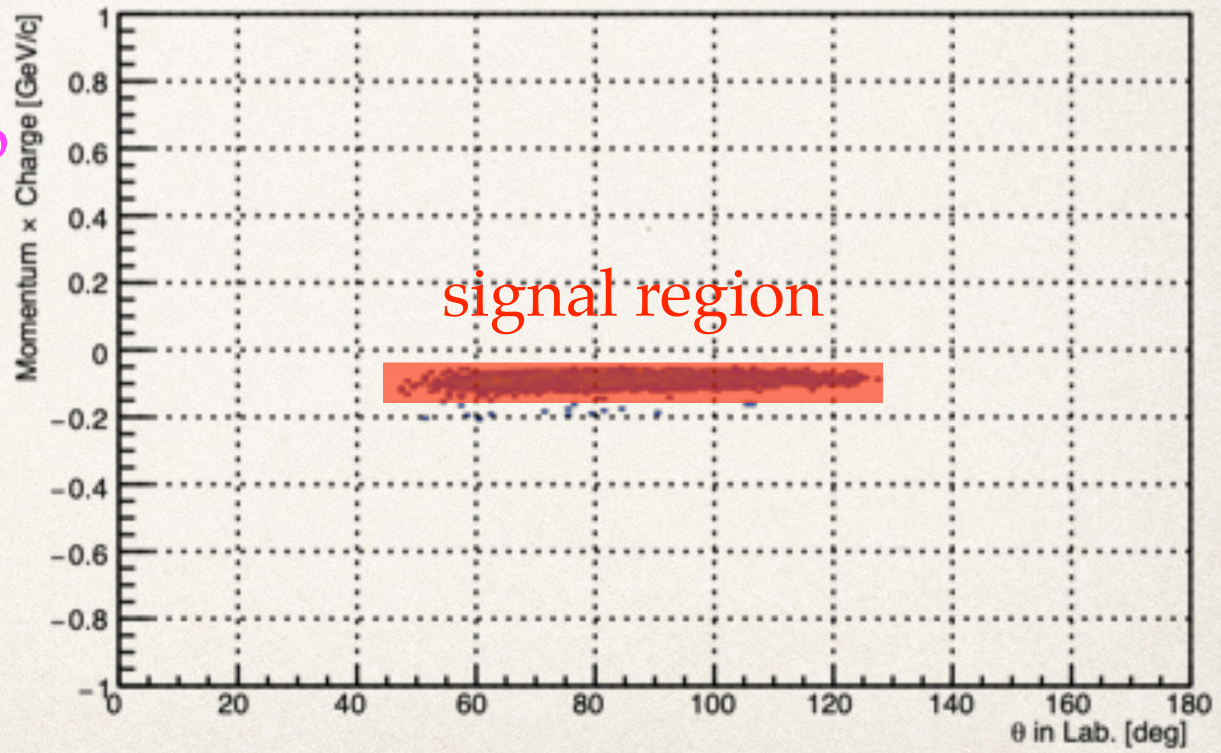
Event selection conditions

- dE veto counter <= 0.2 MeV && PbF2 calorimeter >= 600 MeV
- IH == 1 && CDS charged track == 1
- CDS tracking mass >= 0 && <= 0.3 GeV / c^2
- DCA <= 5mm && fiducial cut

From Monte Carlo information, only hyperon and hypernucleus events survived the event selection --> effective trigger and analysis method

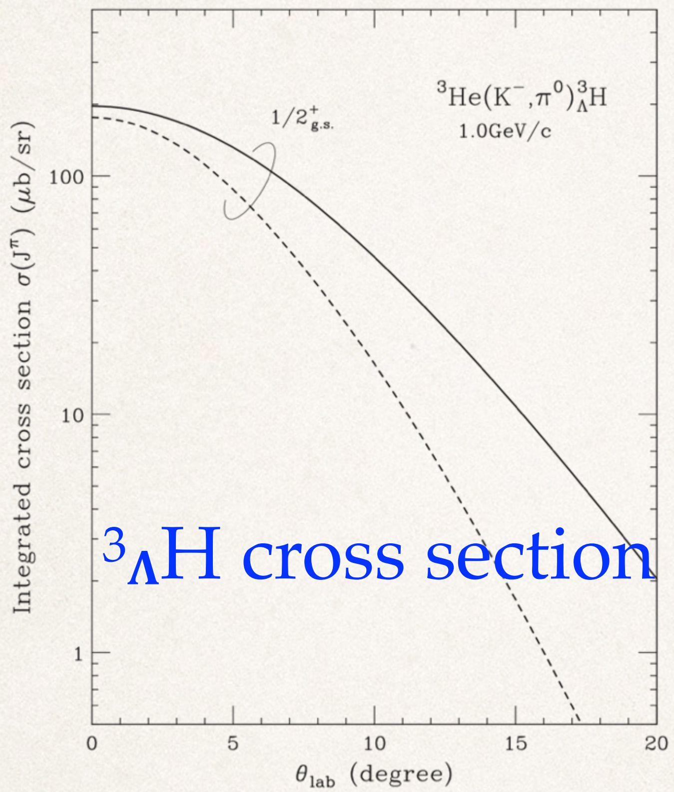


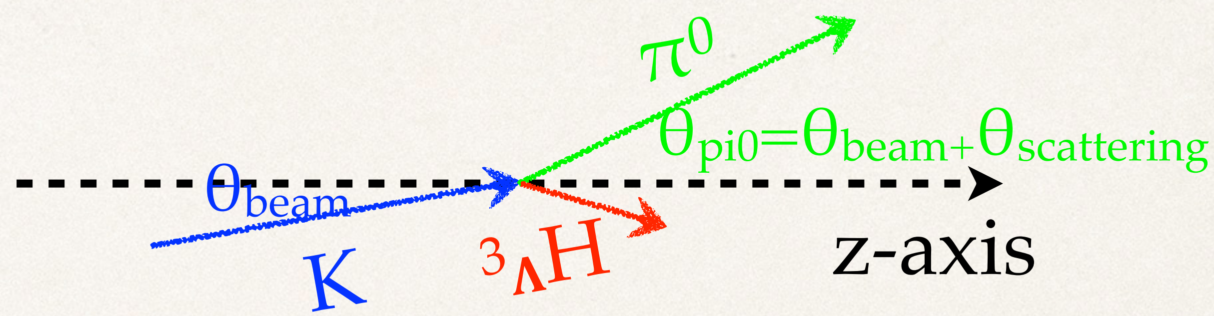
Before event selection

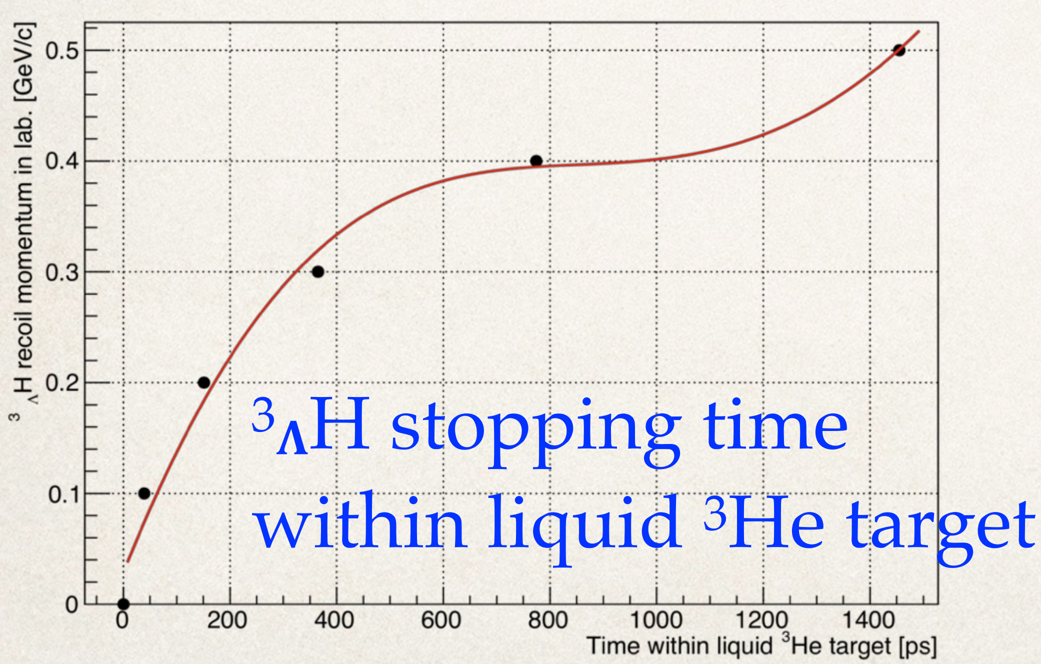


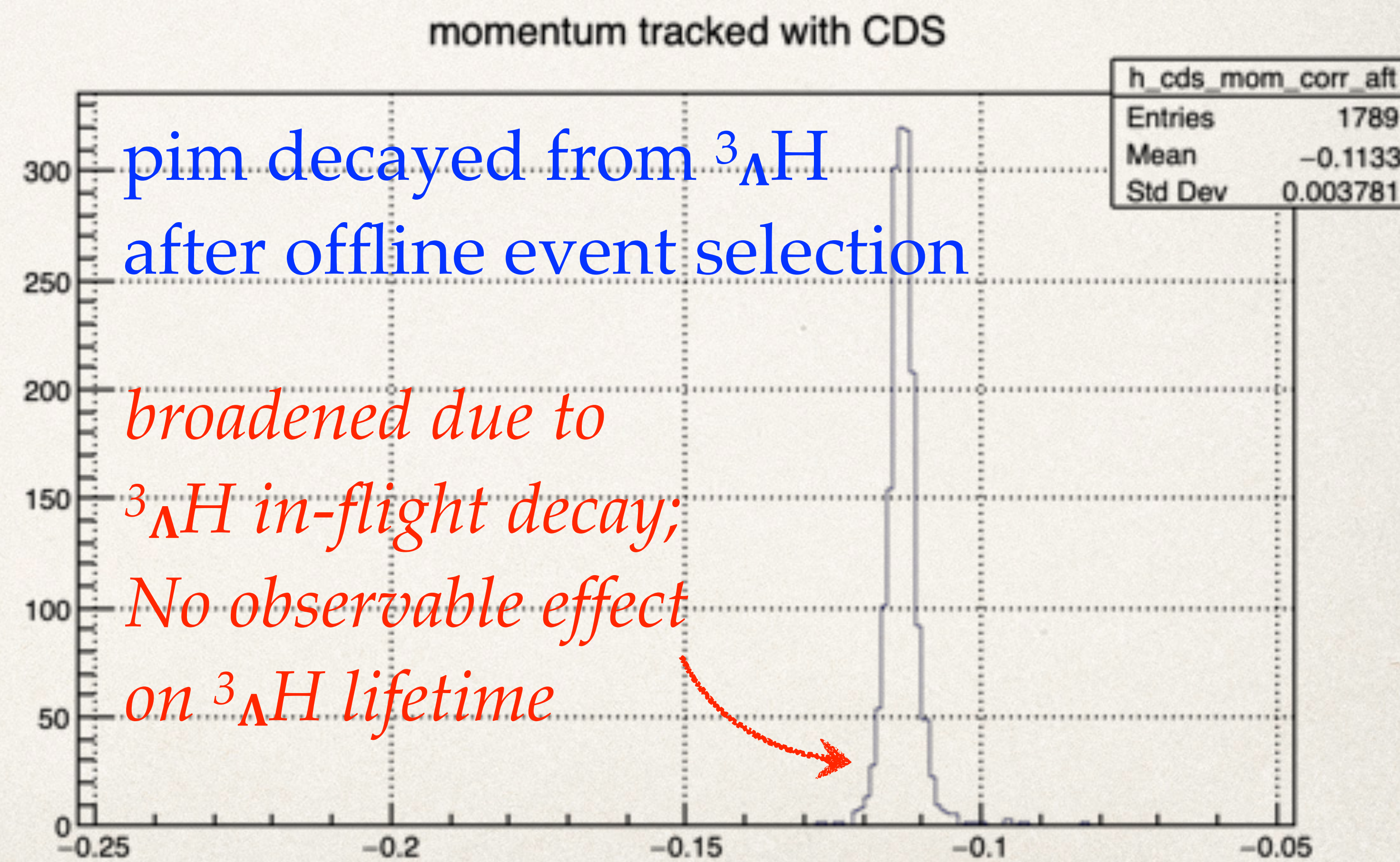
After event selection

Signal events simulation









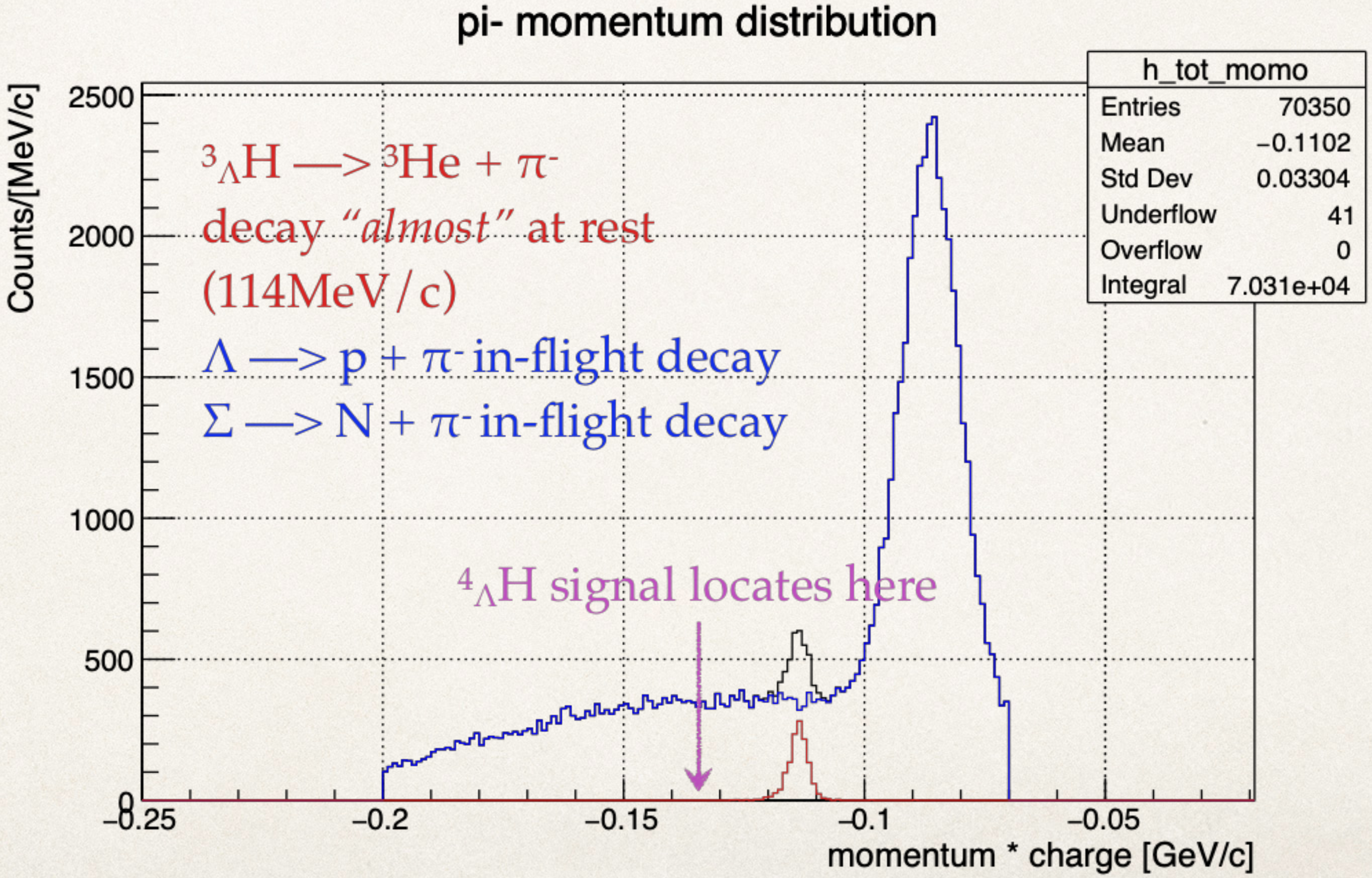
Private communication with Prof. T. Harada

Background from Kaon+N reactions

- To study background events, we bombard liquid ^{3}He/H with K- beam at 1GeV/c and utilize 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 of computing time;
- liquid ^{3}He vs liquid Hydrogen target for comparison

Background evaluation with ^{3}He target

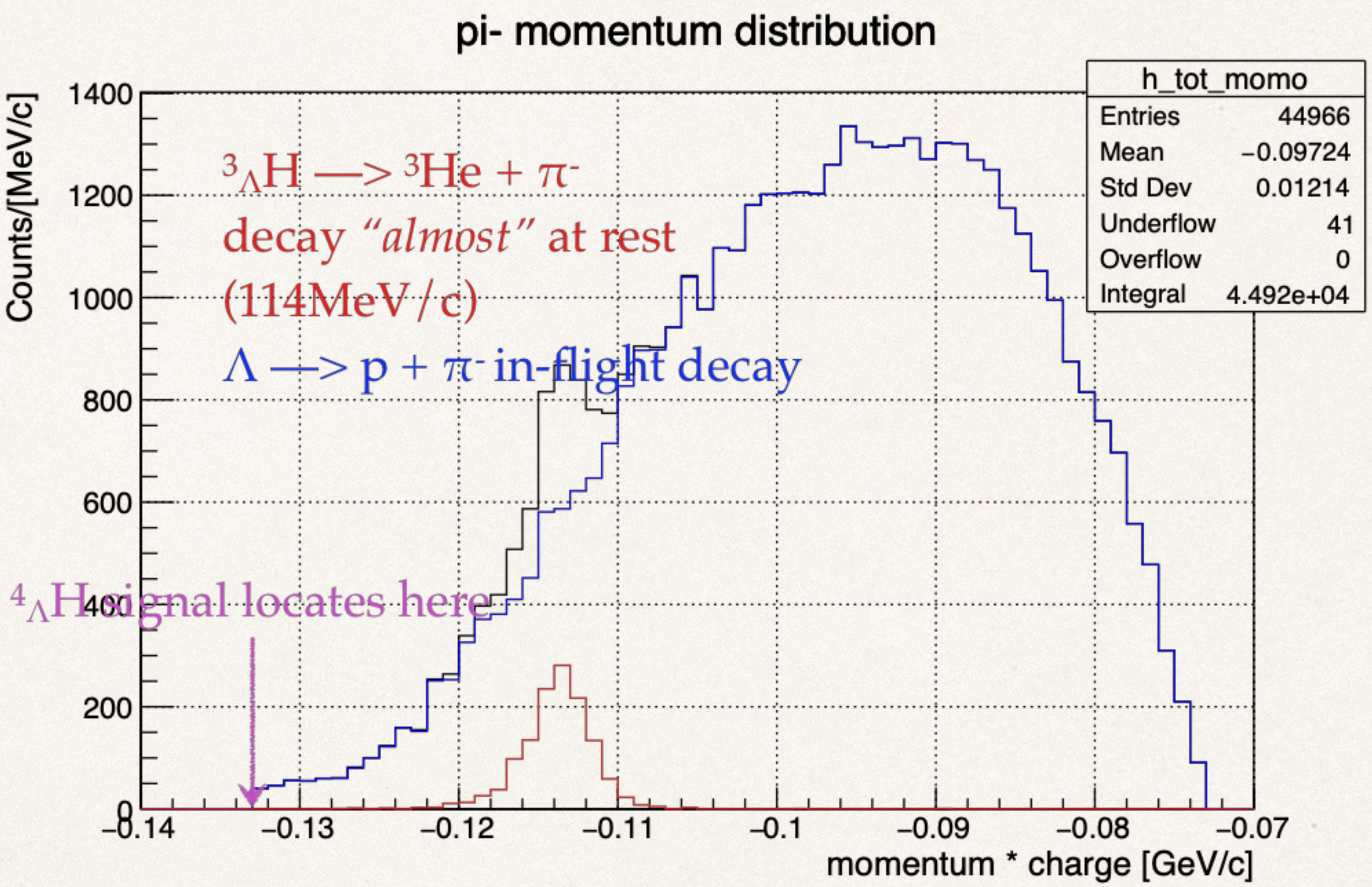
- Geant4 built-in cross section for heavy-ion involved events seems unreliable; For instance, there are two *unphysical* peaks at 0.10058 GeV/c or 0.0880731GeV/c for pi- momentum spectrum



Background evaluation with Hydrogen target

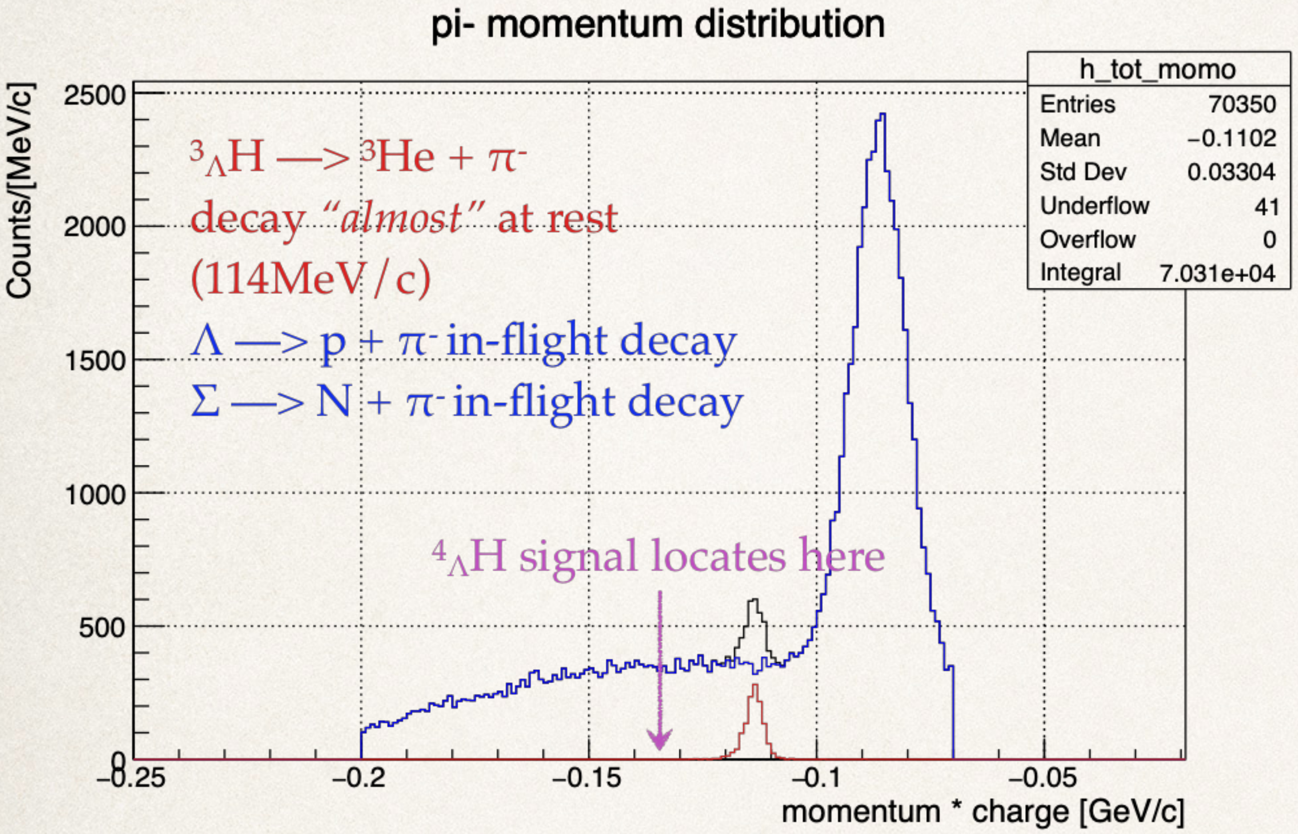
- To cross check the reliability of simulation, change target to 0.831g/cm^3 liquid Hydrogen and perform the same data analysis (normal He3 density is 0.0831g/cm^3)
- The equivalent luminosity can be scaled as followings
  - shadowing effect: cross section ~ $A^{2/3}$ ==> effective "surface" of He3 is ~ 2/3 of nucleon number ==> # of proton = 10 times # of nucleon in experiment = 15 times # of He3 cross section in experiment
  - isospin effect
    - Kp —> pi0Lambda —> pi0pi-p: ~3
    - Kn —> pi0Sigma- —> pi0pi-n: ~1
  - ==> weight of He3 = 3+3+1 = 7, weight of three proton = 3xx = 9; scale of 9/7
- Effective luminosity of proton target is 15 x 9/7 ~ 20 of experimental He3 target
  - Simulation for one hour of 0.831g/cm^3 Hydrogen was scaled by a factor of 33 to account for 4 weeks beam time

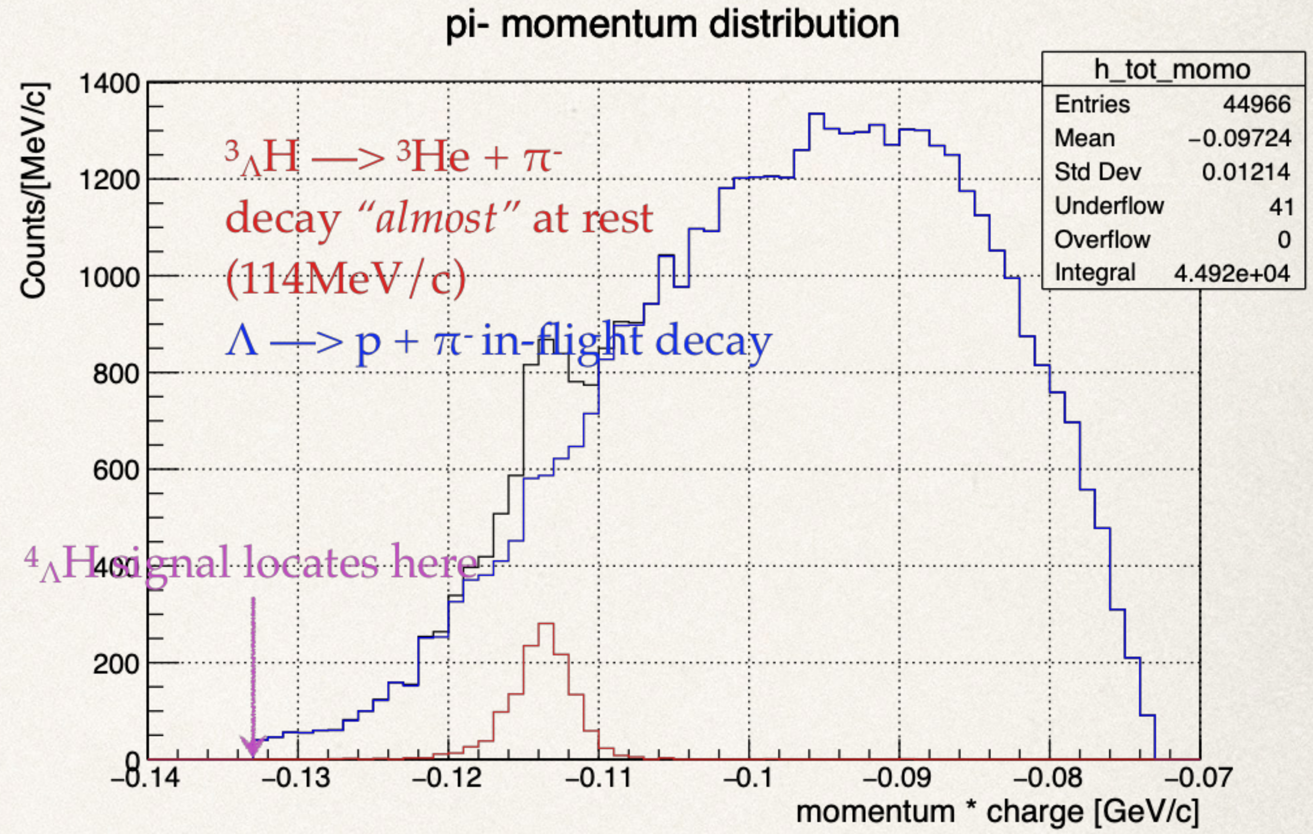
Background evaluation with Hydrogen target



- The background events will be more spread to the left side due to the contribution of pi- decayed from Sigma-
- According to Monte Carlo, almost ~100% background comes from recoiling **Λ**, no contribution from prompt hadronic reactions --> very effective trigger due to kinematic constrains

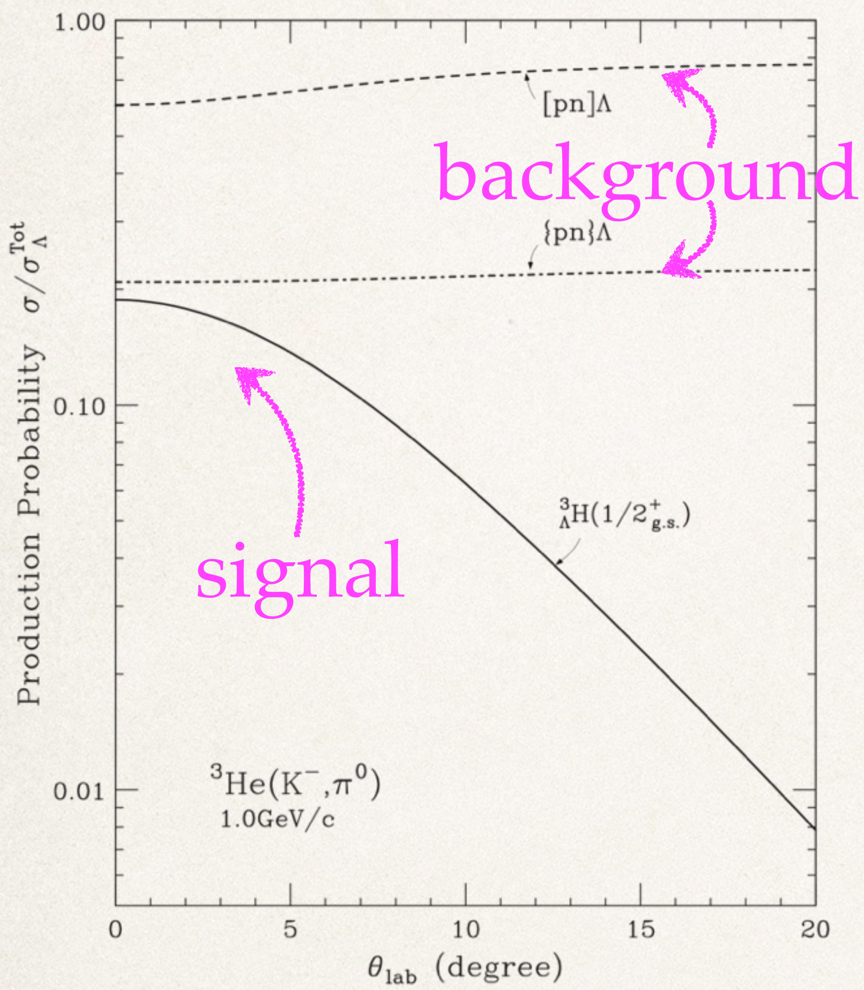
Summary for background evaluation

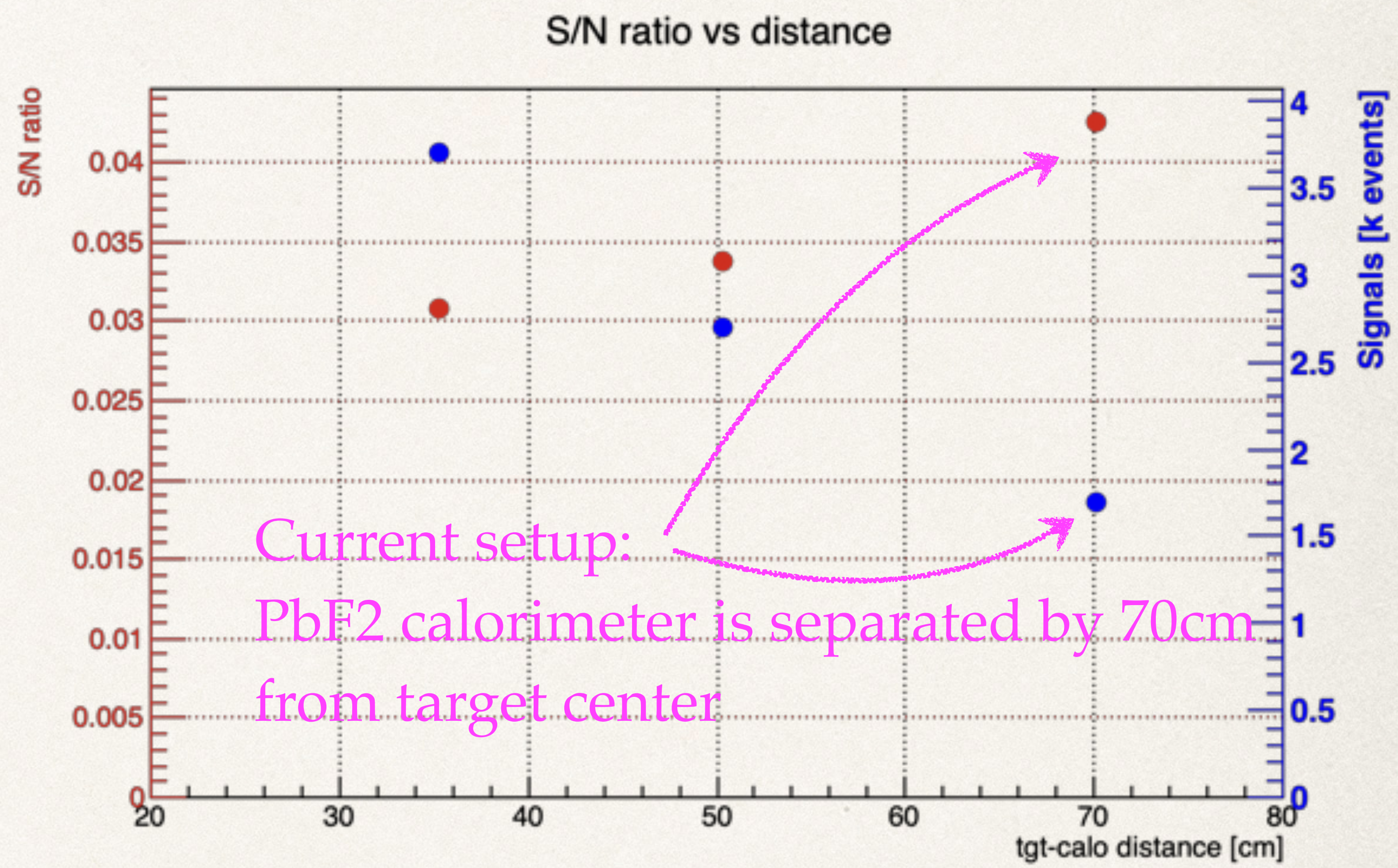




- True background shape may be somewhere in between these two cases ***(an open question)***
- Even for the high background case(Hydrogen), we still can identify the signal region
- $^{4}{}_{\Lambda}H$ signal locates ~130MeV/c, which will have better S/N ratio for both cases: ***one week beam time(50kW) with ^{4}He target*** can tell us the feasibility

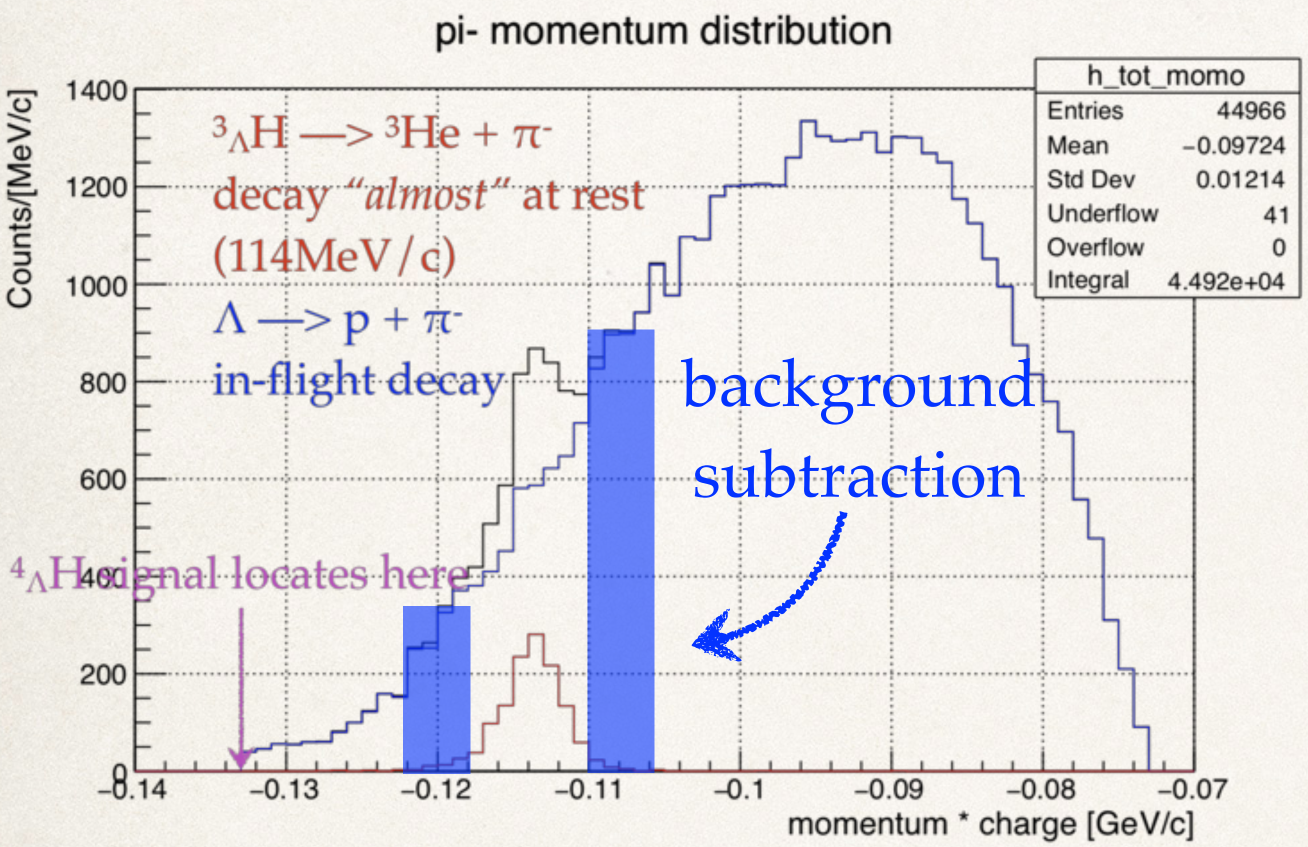
Setup optimization

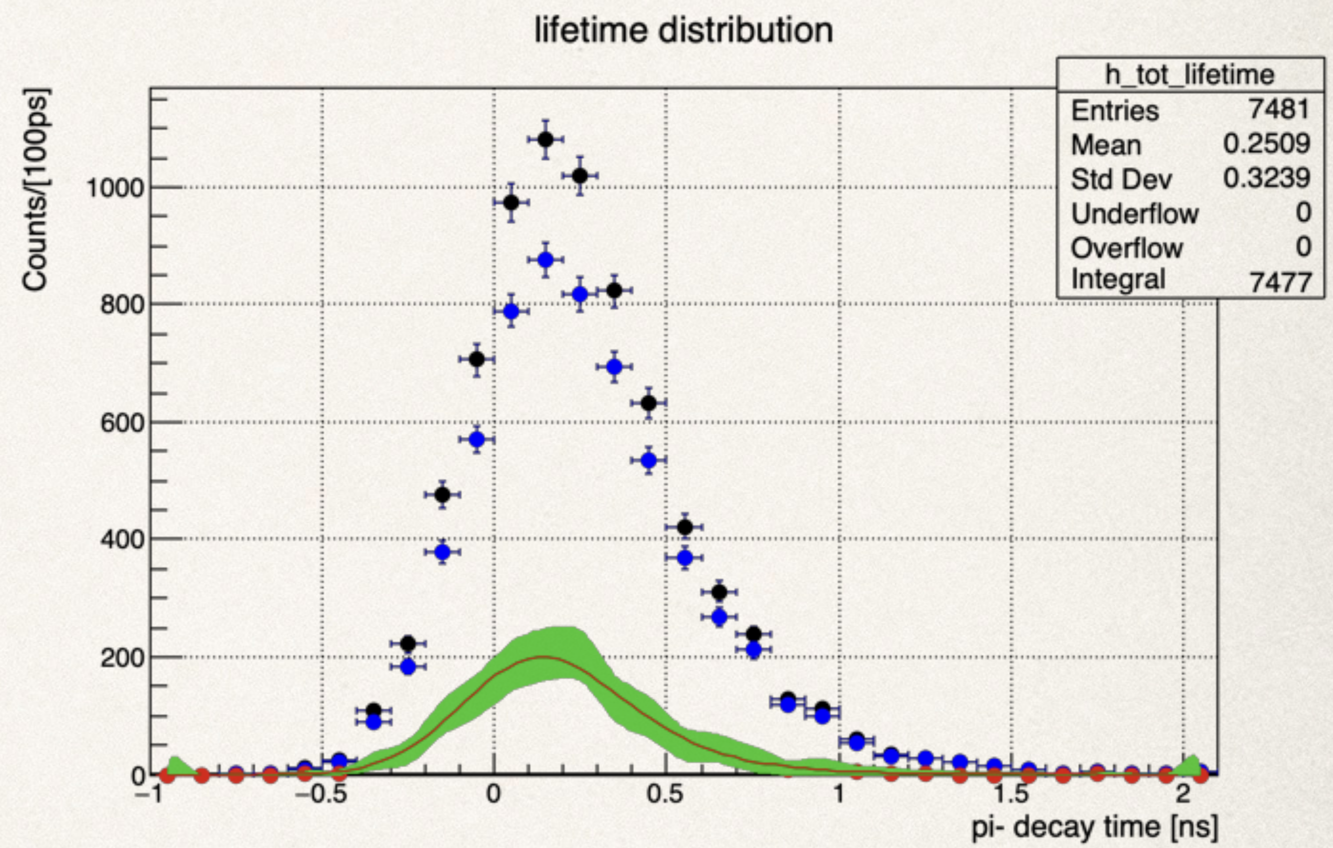




- A balance between S/N and statistical error
- Leave PbF2 calorimeter away from CDS spectrometer to avoid contamination and magnetic field effect on PMT

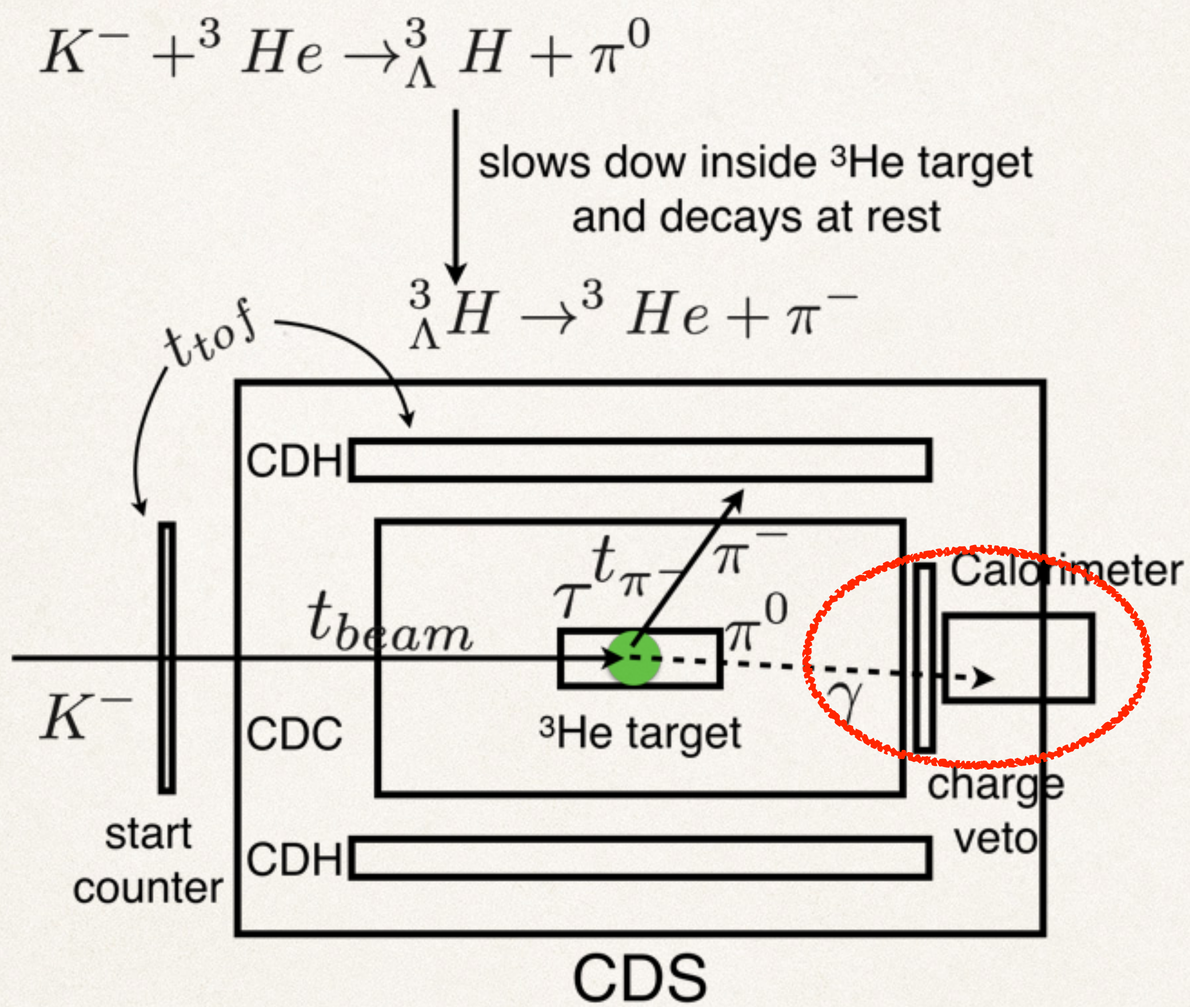
Estimate $^{3}_{\Lambda}H$ lifetime resolution

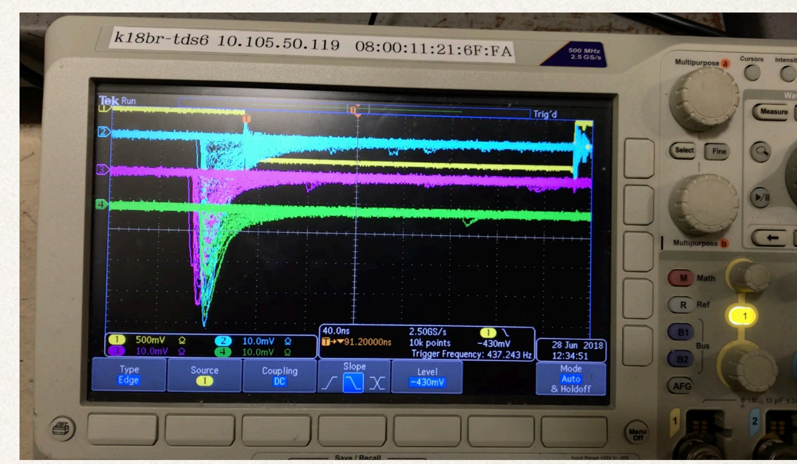




- A stand alone lifetime generator based on simulated background shape: --> statistical error ±25ps
- Systematic error is evaluated by assuming the time zero alignment has ~20ps accuracy --> systematic error ±20ps

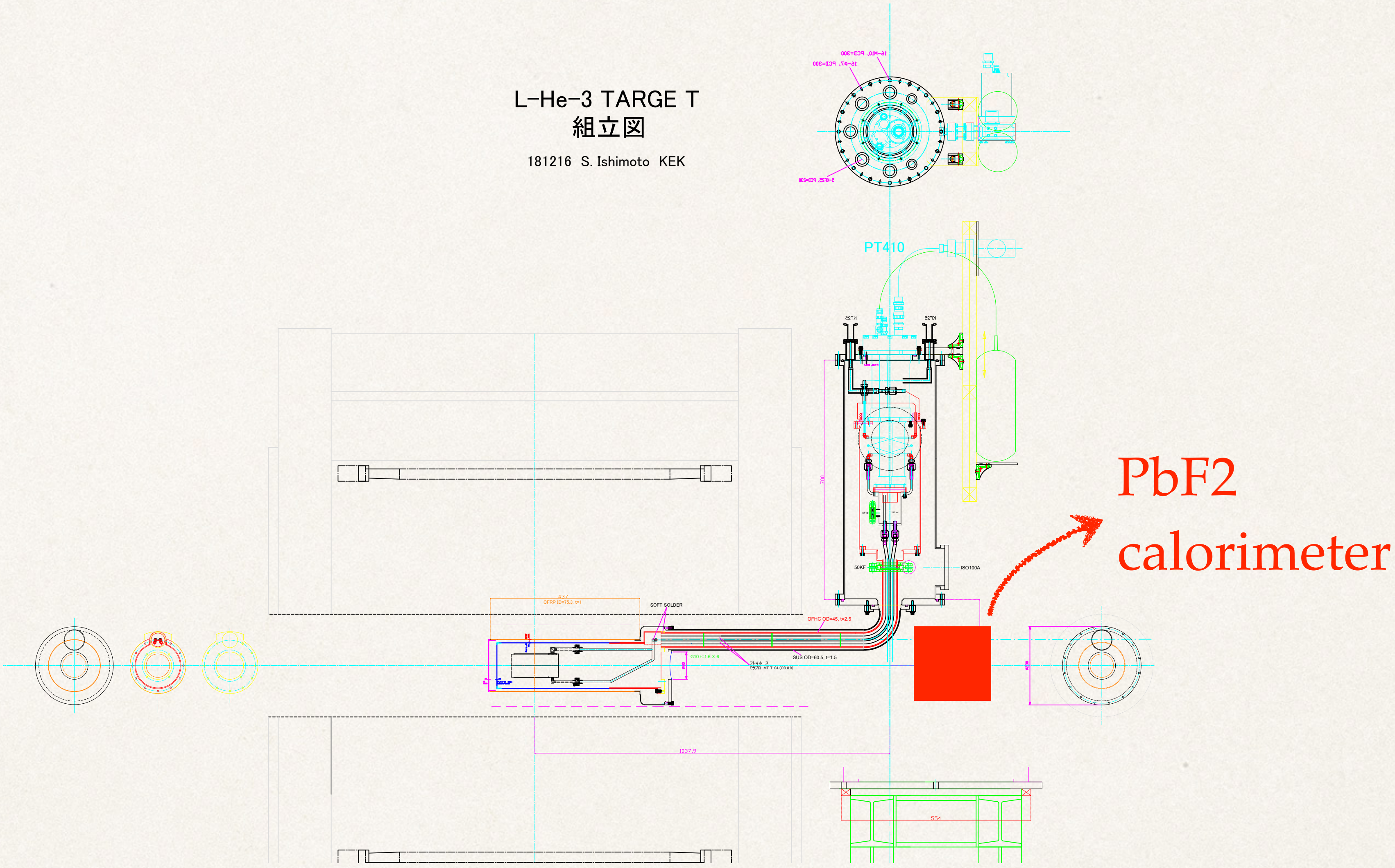
Current status: PbF2 calorimeter





1. Clean Cherenkov signal has been observed at J-PARC
2. All 40 pieces of PbF2 crystals have been delivered in last December (2018)
3. Signal calibration will be performed this year (2019)

Current status: liquid ^{3,4}He target



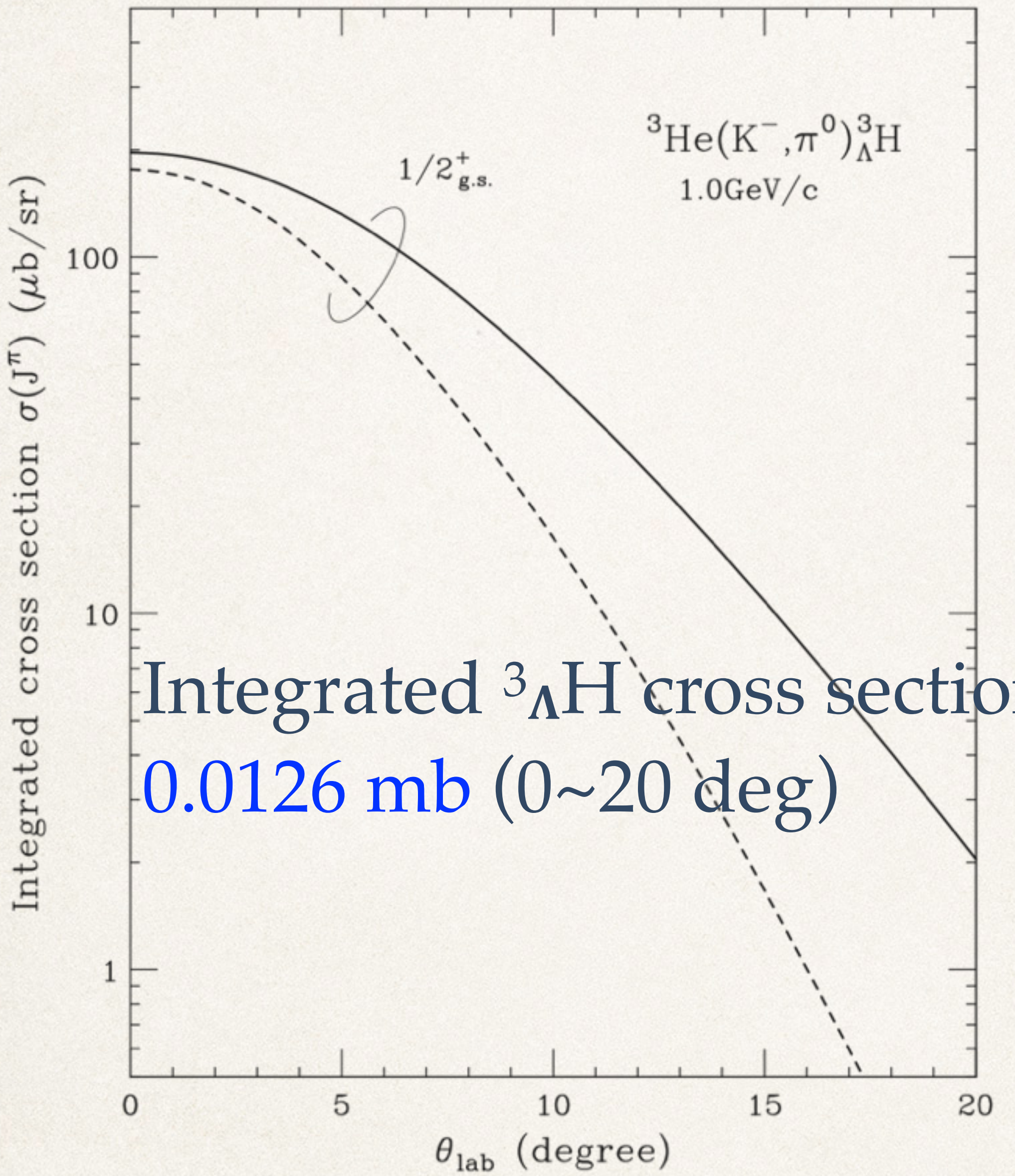
- Designed by Dr. Ishimoto and Dr. T. Hashimoto
- Liquefaction of ^{3,4}He has been confirmed a few weeks ago
- Ready to run by the beginning of 2020

Summary

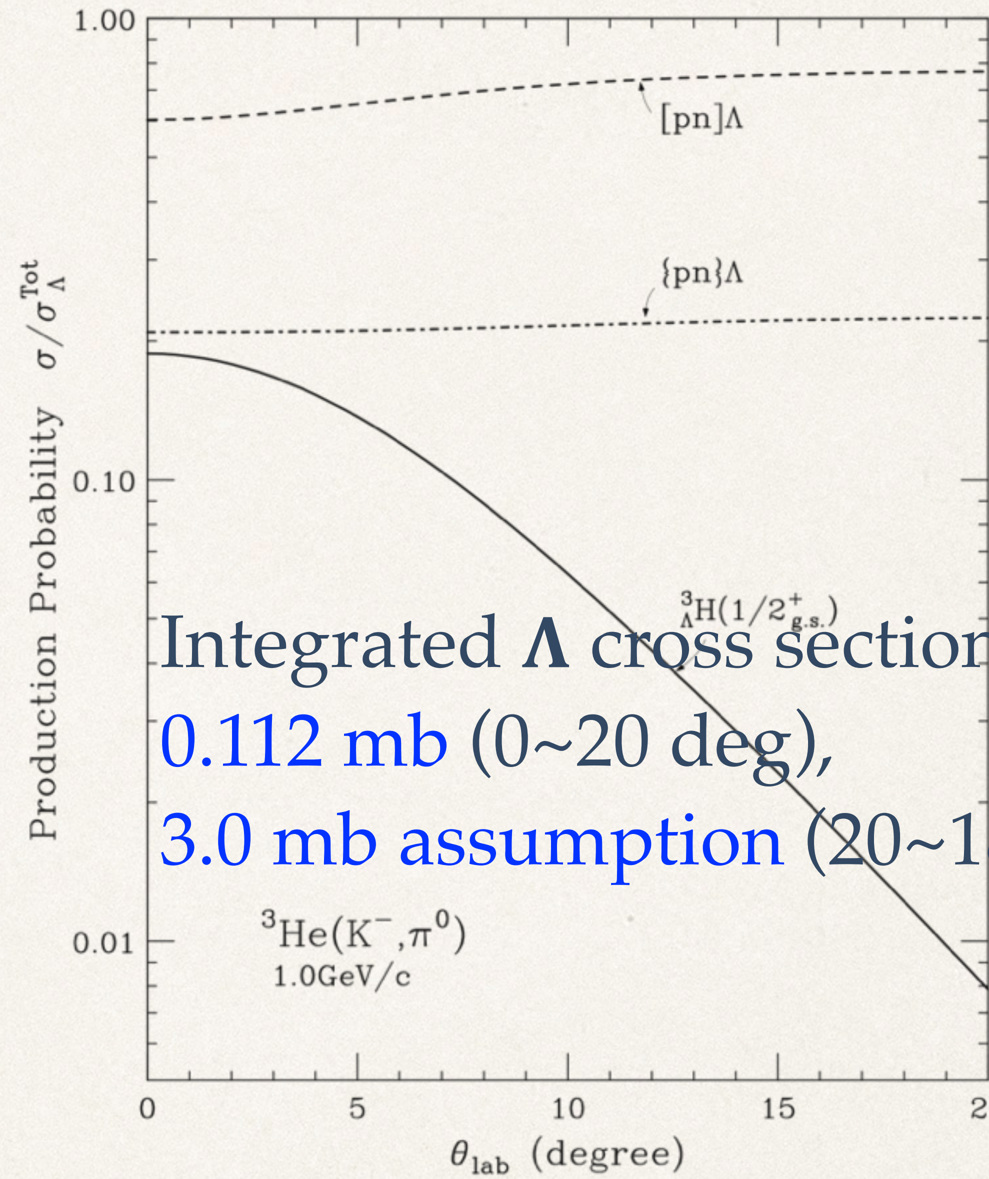
- A new method to measure Hypertriton lifetime is proposed to J-PARC 30GeV Synchrotron for stage-1 approval
- Reasonable resolution with minimum investment can be achieved based on full simulation
- Technical details will be fixed within 2019 and ready to run in the beginning of 2020

backup

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



Integrated $^{3}{}_{\Lambda}$H cross section:
0.0126 mb (0~20 deg)

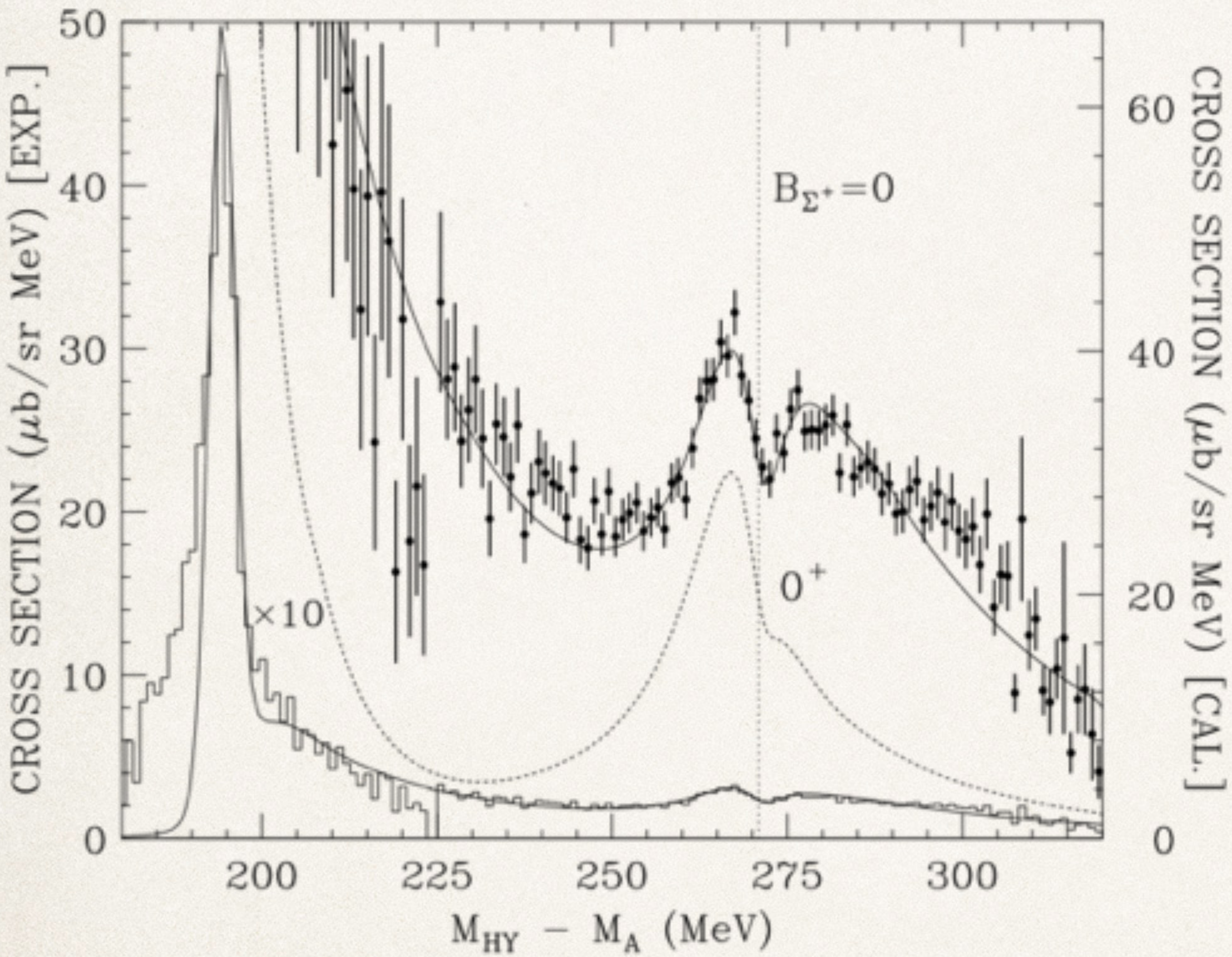


Integrated **Λ** cross section:
0.112 mb (0~20 deg),
3.0 mb assumption (20~180 deg)

^{3}He(K^{-}, π^{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 isospin 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)

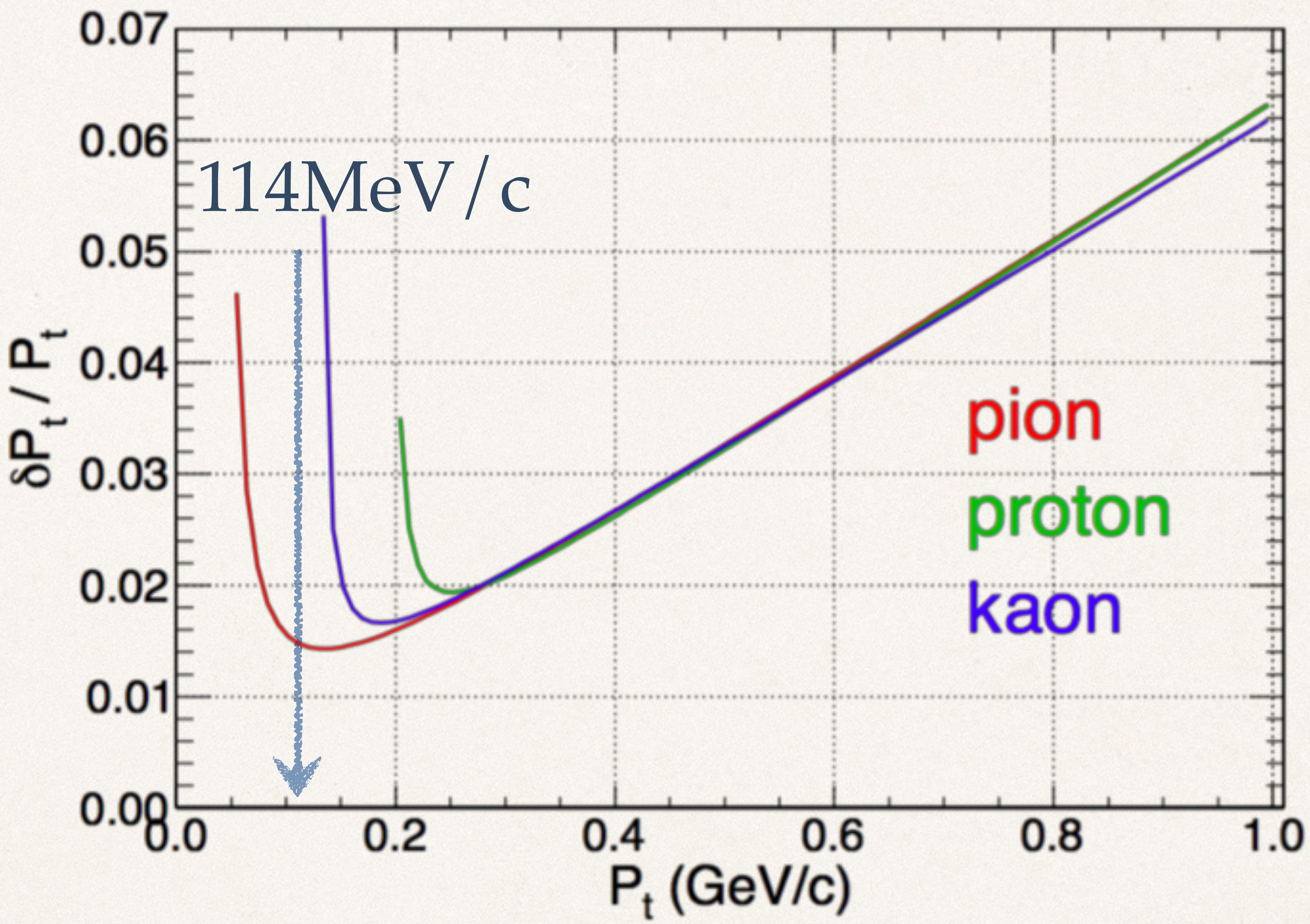
Part I: Performance estimation

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
$K^-\ {}^3He \to \pi^0\ {}^3_\Lambda H \to$	$\pi^0\ \pi^-\ {}^3He \to 2\gamma\ \pi^-\ {}^3He$	delayed π^-	?%	?%
	π^0 p n $n_s \to 2\gamma$ p n n	delayed p	?%	?%
$K^- \to$	$\pi^0\mu^-\bar{\nu}_\mu \to 2\gamma\mu^-\bar{\nu}_\mu$	prompt μ^-	3.32%	Not included
	$\pi^0\pi^- \to 2\gamma\pi^-$	prompt π^-	20.92%	
	$\pi^0\pi^0\pi^- \to 4\gamma\pi^-$	prompt π^-	1.76%	
K^- p $\to \pi^0\ \Lambda \to$	$\pi^0\ \pi^0$ n $\to 4\gamma$ n	N. A.	35.8%	4.5
	$\pi^0\ \pi^-$ p $\to 2\gamma\ \pi^-$ p	delayed π^-, p	63.9%	
K^- p $\to \pi^0\ \Sigma^0 \to \pi^0\ \gamma\ \Lambda \to$	$\pi^0\ \gamma\ \pi^0$ n $\to 5\gamma$ n	N. A.	35.8%	0.36 (scaled)
	$\pi^0\ \gamma\ \pi^-$ p $\to 3\gamma\ \pi^-$ p	delayed π^-, p	63.9%	
K^- p $\to \pi^-\ \Sigma^+ \to$	$\pi^-\ \pi^0$ p $\to 2\gamma\ \pi^-$ p	prompt π^-, delayed p	51.57%	0.9
	$\pi^-\ \pi^+$ n	N. A.	48.31%	
K^- p $\to \pi^+\ \Sigma^- \to \pi^+\ \pi^-$ n		N. A.	100%	Not included
K^- n $\to \pi^-\ \Lambda \to$	$\pi^-\ \pi^0$ n $\to 2\gamma\ \pi^-$ n	prompt π^-	35.8%	Not included
	$\pi^-\ \pi^-$ p $\to 2\pi^-$ p	N. A.	63.9%	
K^- n $\to \pi^-\ \Sigma^0 \to \pi^-\ \gamma\ \Lambda \to$	$\pi^-\ \gamma\ \pi^0$ n $\to 3\gamma\ \pi^-$ n	prompt π^-	35.8%	Not included
	$\pi^-\ \gamma\ \pi^-$ p $\to \gamma\ 2\pi^-$ p	N. A.	63.9%	
K^- n $\to \pi^0\ \Sigma^- \to \pi^0\ \pi^-$ n $\to 2\gamma\ \pi^-$ n		delayed π^-	100%	0.9 (scaled)

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

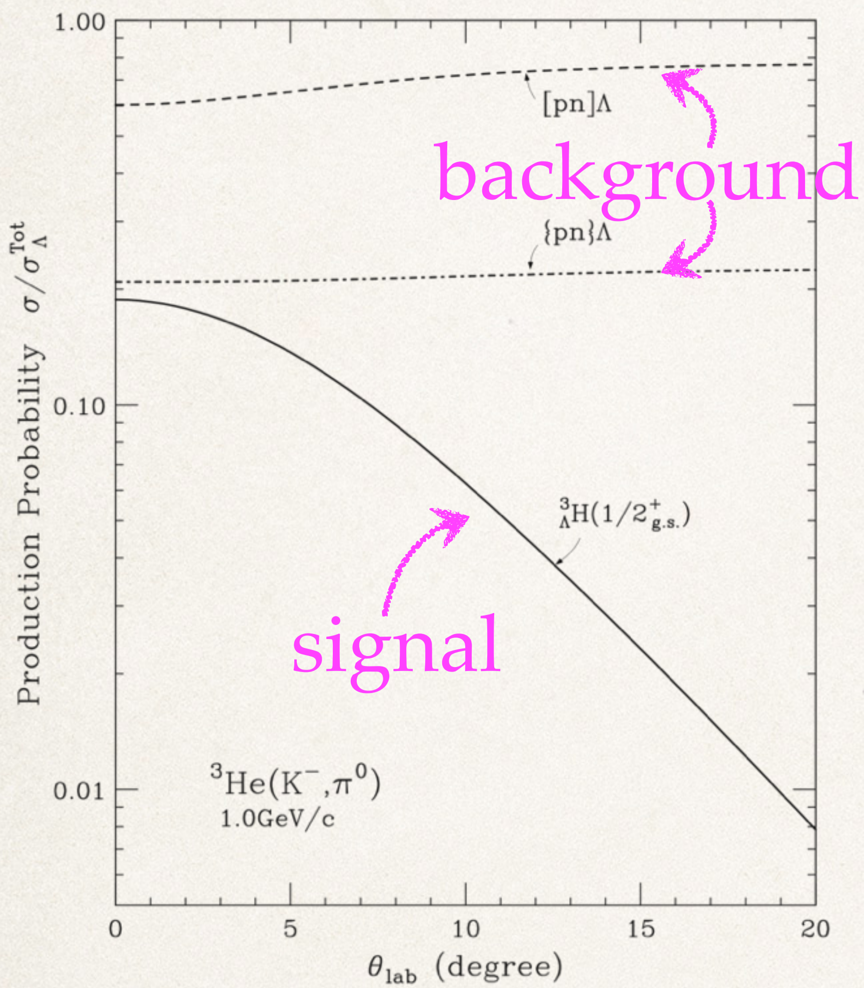
Performance estimation: pi- resolution

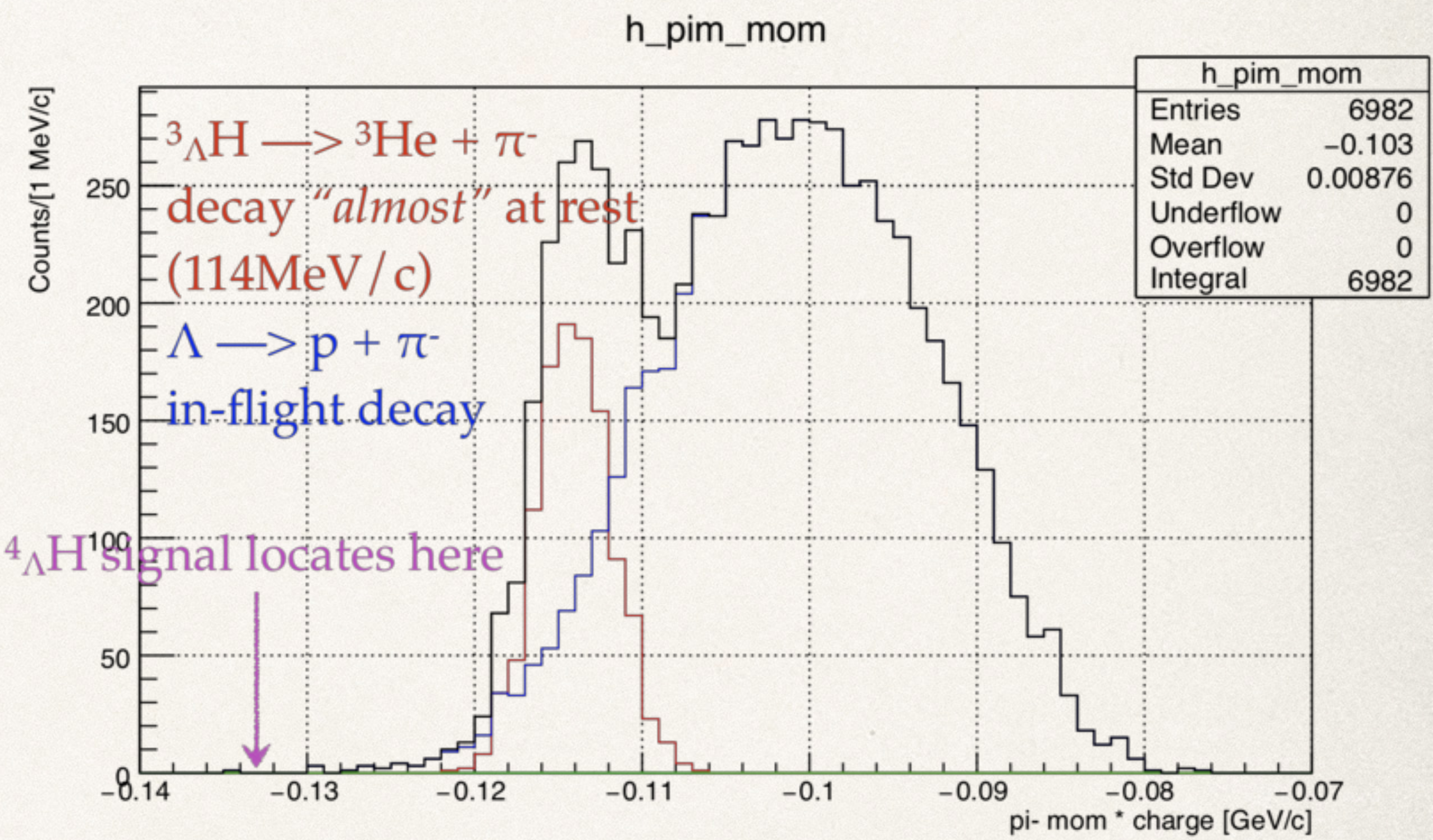


According to GEANT4 simulation,
~2% momentum resolution is achieved for total π^- momentum (pt + pl) after energy loss correction.

T. Hashimoto PhD thesis, University of Tokyo, 2013

Background events from theoretical calculation





The background events estimated with theoretical calculation;
Lnp signal events ~1k, Lambda b.g. scaled proportionally