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Feasibility study for measurement of beta-decay rates of Λ hypernuclei

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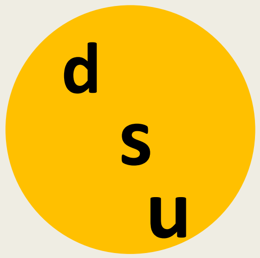
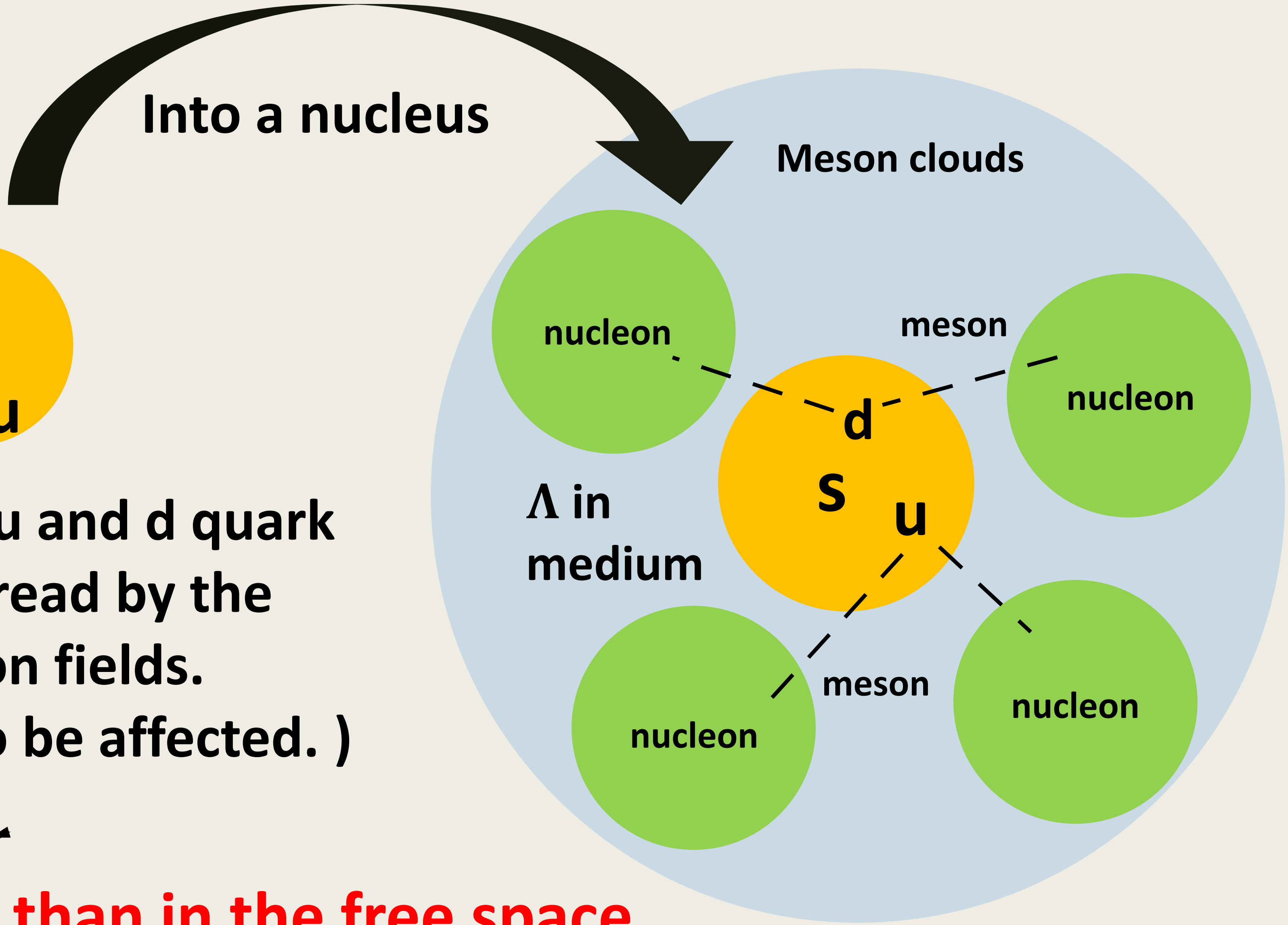
Introduction -- baryon modification

Possible change of Λ's structure in nuclear matter

In the free space

free Λ



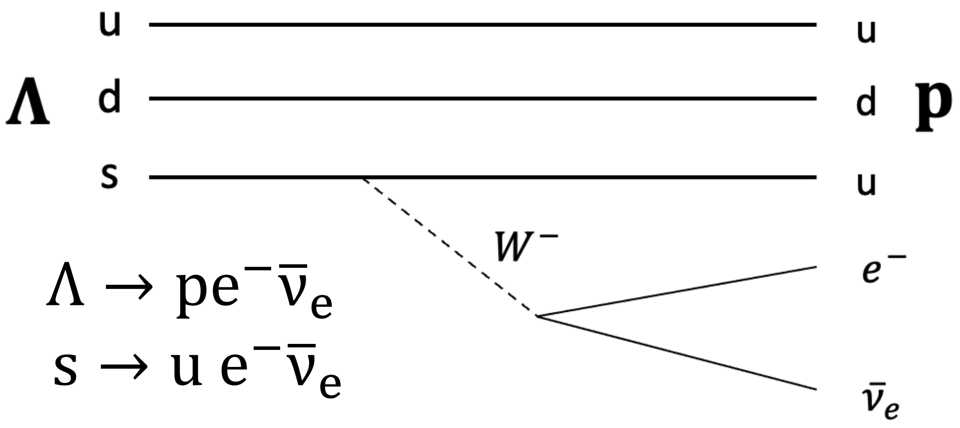


It is conjectured that u and d quark wavefunctions are spread by the interaction with meson fields.
(s is not considered to be affected.)

Λ may **spread more than in the free space.**

Modification of Λ's beta decay rate

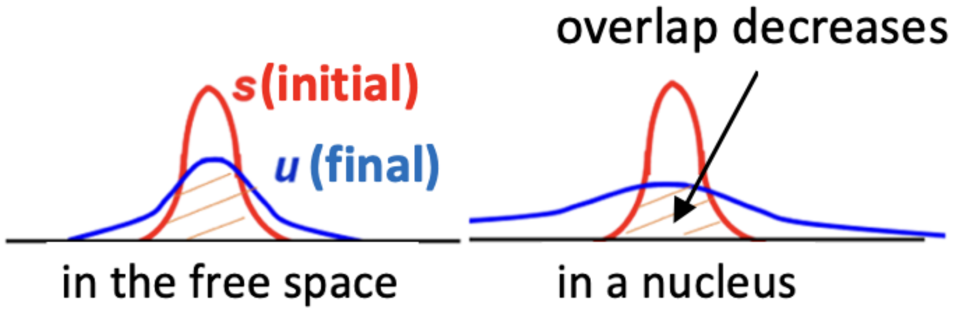
Λ's beta decay



$\Lambda \rightarrow p e^- \bar{\nu}_e$

$s \rightarrow u\, e^- \bar{\nu}_e$

$$\Gamma_\beta \propto \left| < \psi_s \middle| \hat{H}_\beta \middle| \psi_u > \right|^2$$



Overlap of s (initial) and u(final) may decrease

→ **reduce beta decay rate Γ_β**

According to QMC model's calculation [1],

Γ_β of Λ decreases by 20% (Max).

But in a nucleus

- nuclear many-body effects
- hadronic effects

cause reduction of the beta decay rate $\Delta\Gamma_\beta$.

In heavy nuclei → $\Delta\Gamma_\beta \sim 20 - 50\%$

By using light nuclei $^4\mathrm{He}$,

$\Delta\Gamma_\beta \sim$ 5% (small) < 20% (baryon modification)

Measure the beta decay rate of $^5_\Lambda\mathrm{He}$

[1] P. A. M. Guichon, A.W. Thomas, Phys. Lett. B773 (2017) 332.

Measurement of Λ's beta decay rate in a nucleus

Goal: Measure the beta decay rate Γ_β ($^5_\Lambda\mathrm{He}$) within 4.5 % accuracy (statistical)

$$\Gamma_\beta = \frac{\mathbf{BR_{beta}}}{\boldsymbol{\tau}}$$ → Measure the lifetime τ (2%) and the branching ratio BR_β(4%)

Difficulties: Huge background from Λ's main decay modes

Branching ratio of Λ's decay mode in $^5_\Lambda\mathrm{He}$

Decay mode of Λ	$\Lambda \to p\pi^-$	$\Lambda \to n\pi^0$	$\Lambda p \to np$	$\Lambda n \to nn$	$\Lambda \to pe^-\bar{\nu}_e$
BR	0.4	0.2	0.28	0.12	0.00048

Background ($\Lambda \to p\pi^-$, $\Lambda \to n\pi^0$, $\Lambda p \to np$, $\Lambda n \to nn$)

Signal (Beta decay) ($\Lambda \to pe^-\bar{\nu}_e$)

0.00048 = 0.6* (Estimate of Pauli effect) × 0.0008 (Free Λ)

BR(Background) ≫ BR(Signal)

* Calculation of Pauli effect on Λ's beta decay in $^5_\Lambda\mathrm{He}$ has not been carried out.

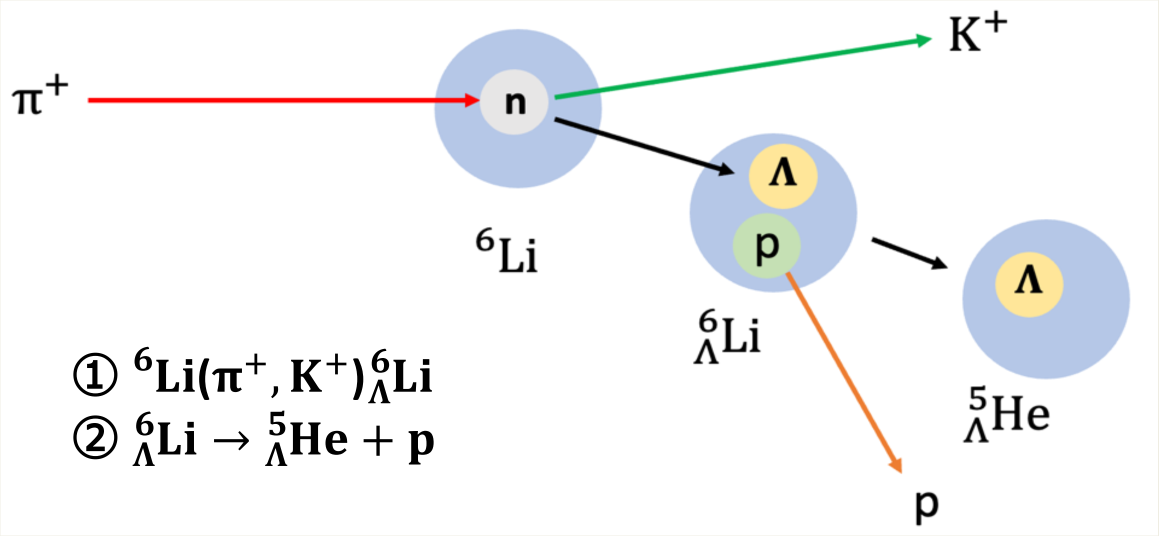
Requirement:

Background contamination < Statistical error of beta decay yield 4%

➡ **Design detectors and develop background reduction methods**

Experimental idea of beta decay rate measurement of ${}^{5}_{\Lambda}\mathrm{He}$

Production of $^{5}_{\Lambda}\mathrm{He}$



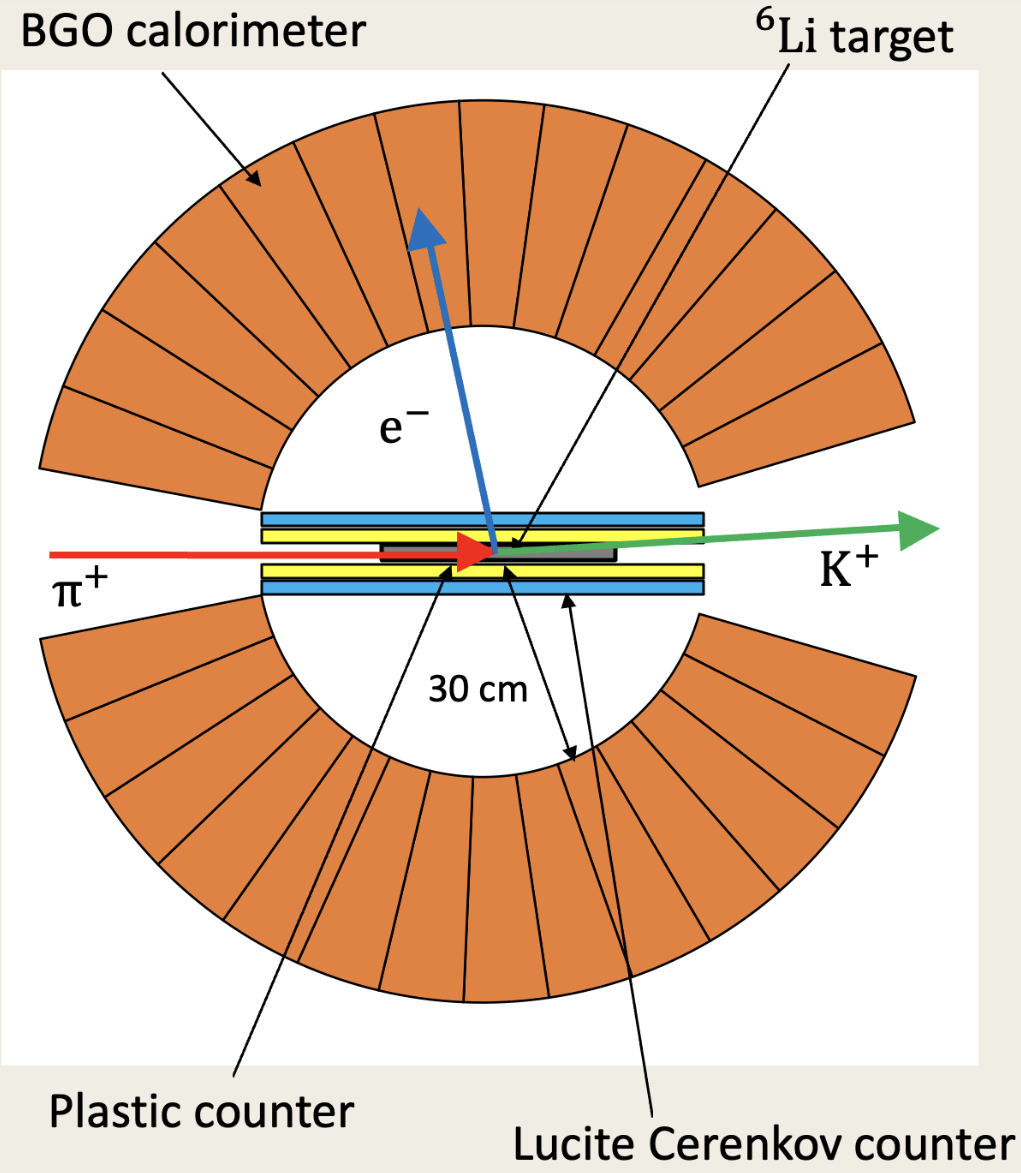
Apparatus around the target

- **Plastic counter:** Identify $e^{\pm}$/ γ, n
- **Lucite Cerenkov counter:**

Identify $e^{\pm}$ ($\beta \sim 1$) / π^-($\beta \sim 0.6$) , p ($\beta < 0.4$)

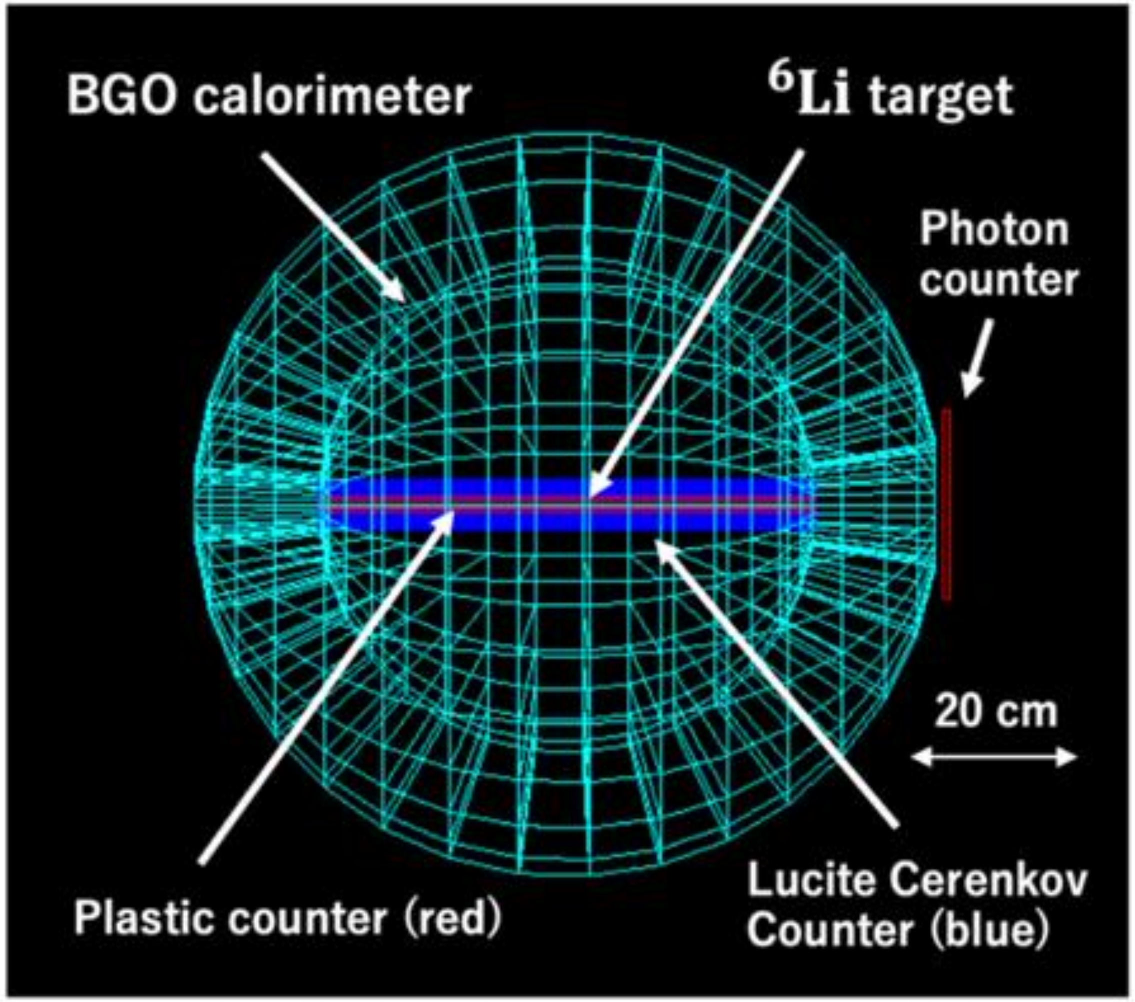
- **BGO scintillator calorimeter:**
  - Measure electron energy (0 – 163 MeV)
  - Analyze the number of clusters

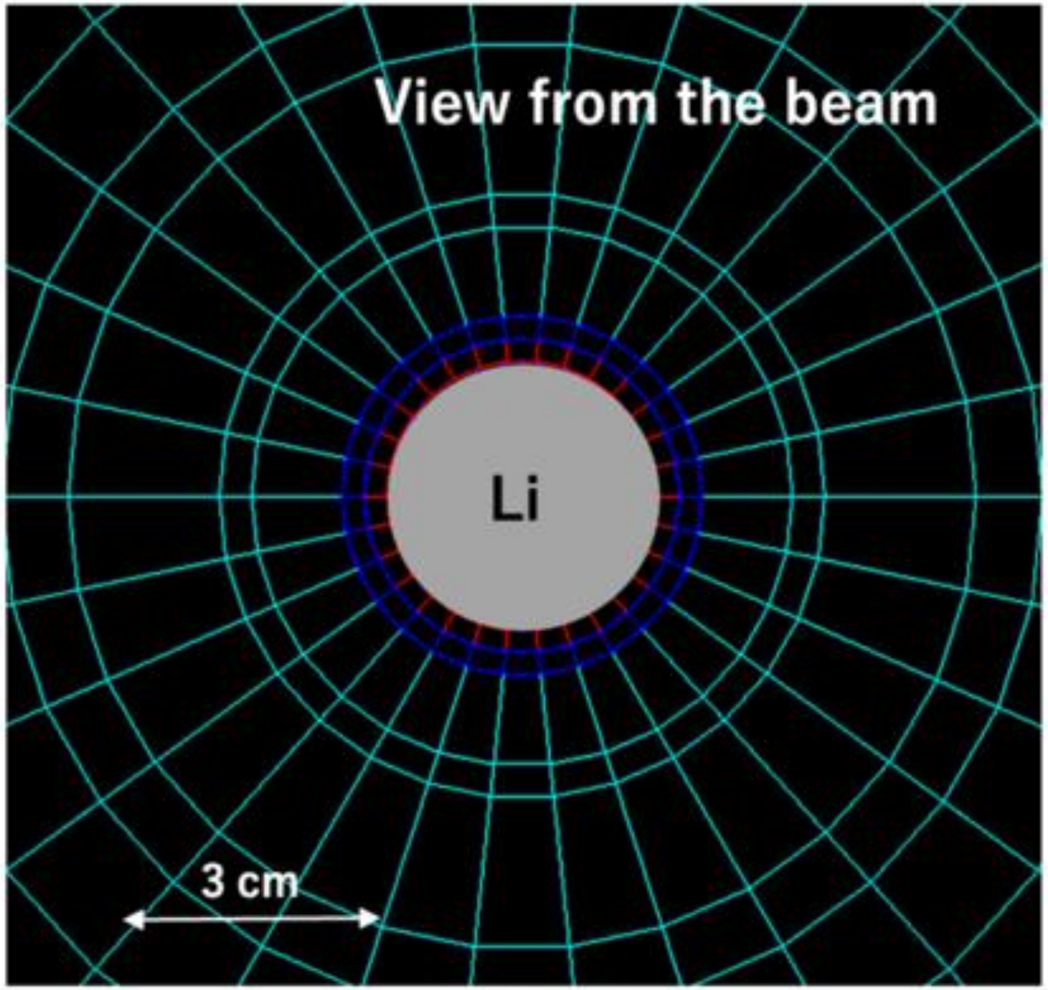
Overview of detectors



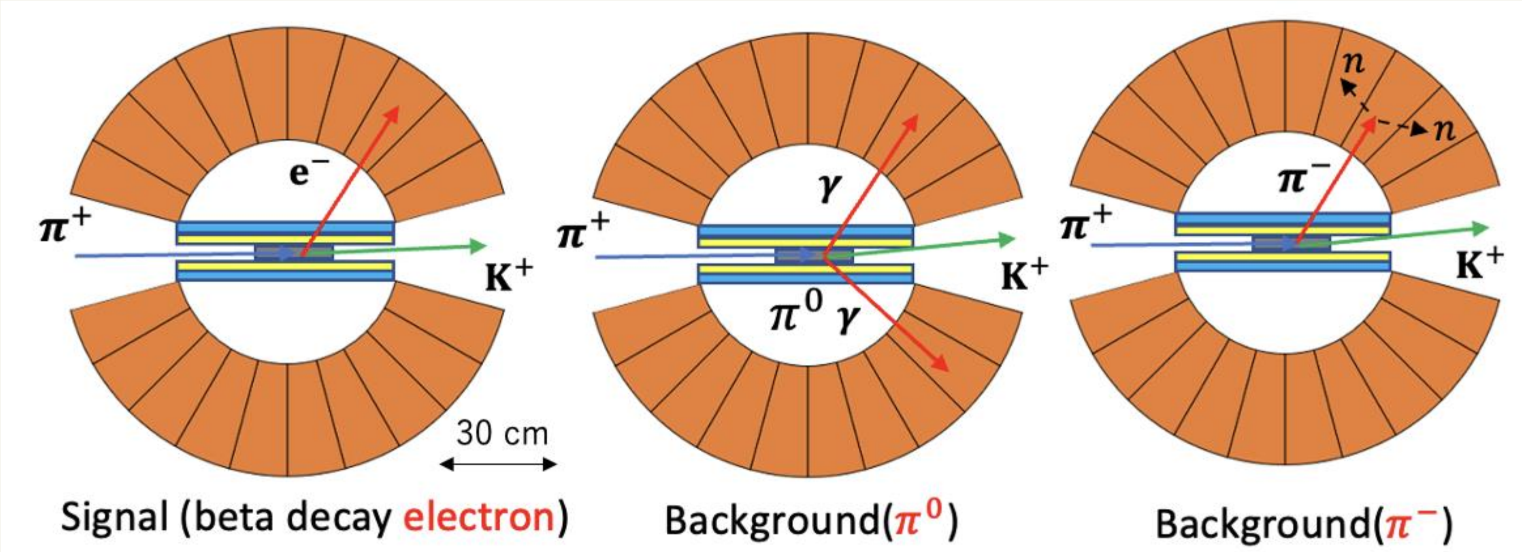
Simulation study for background reduction

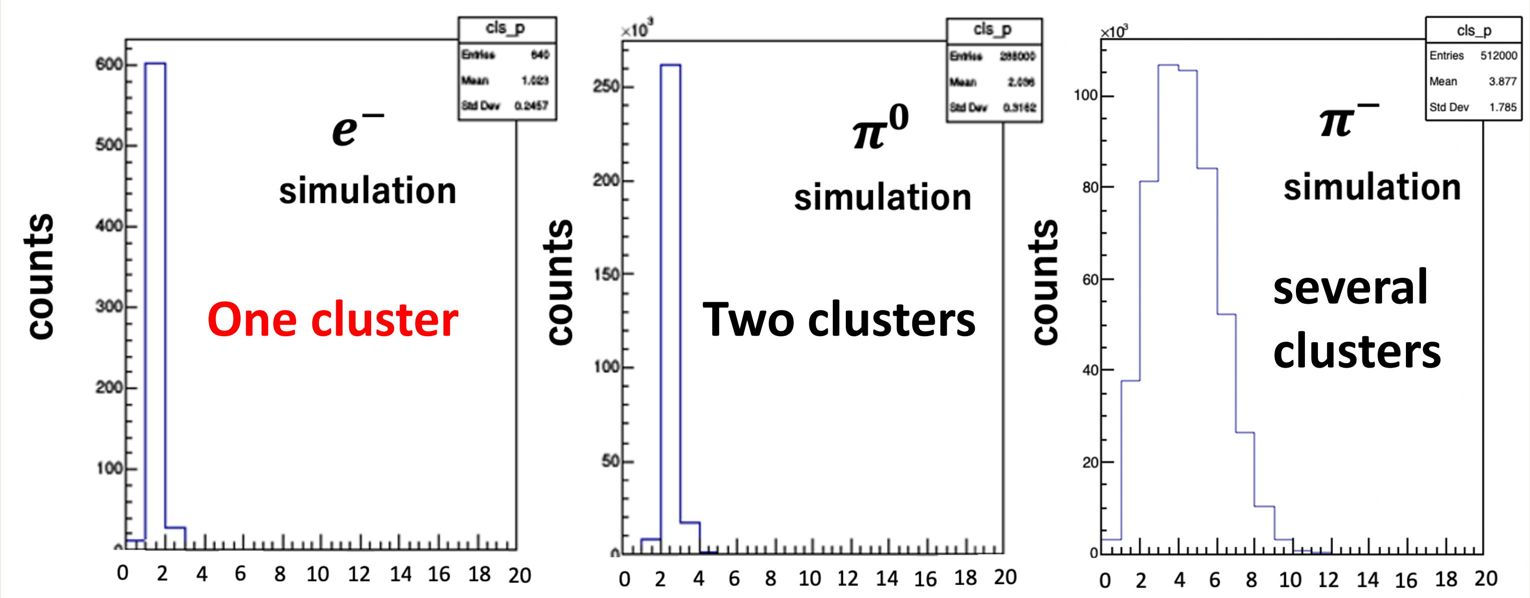
GEANT4 geometry





BGO and Lucite Cerenkov analysis





The number of clusters in BGO

BGO

By selecting **one cluster** events as the beta decay electron

97% of π^0, 92.8% of π^- events are rejected.

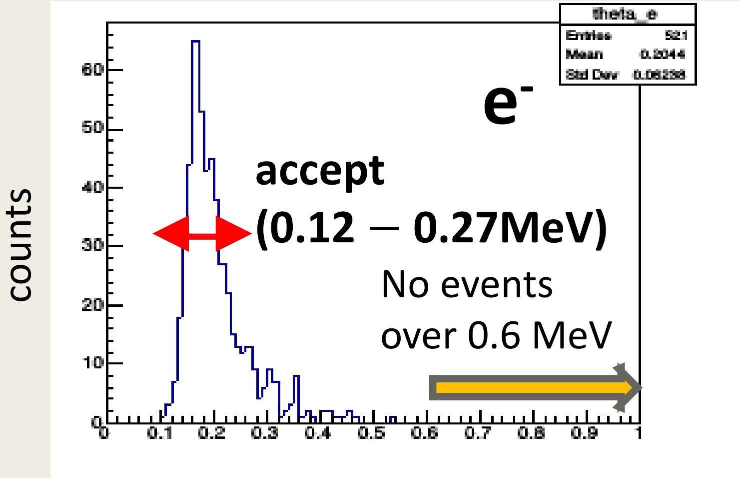
Lucite Cerenkov

By selecting **a hit** as the beta decay electron

90% of π^- and 95.5% of π^0 are rejected.

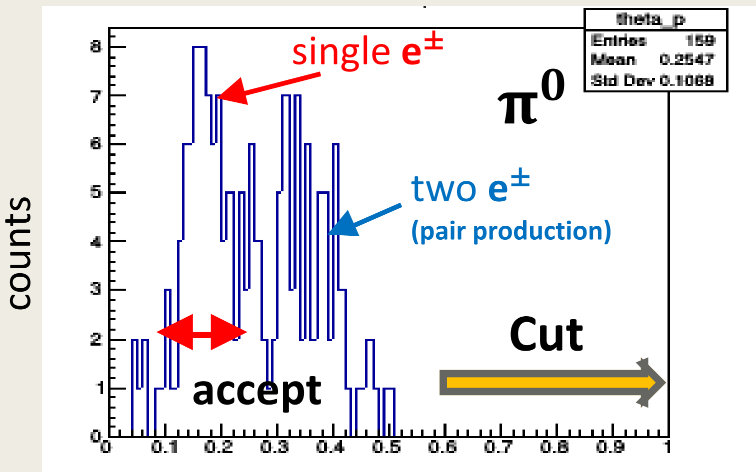
Energy loss in plastic counter

Energy deposit in the plastic counter $\Delta E/\Delta x$ (MeV) (normalized for the path length)



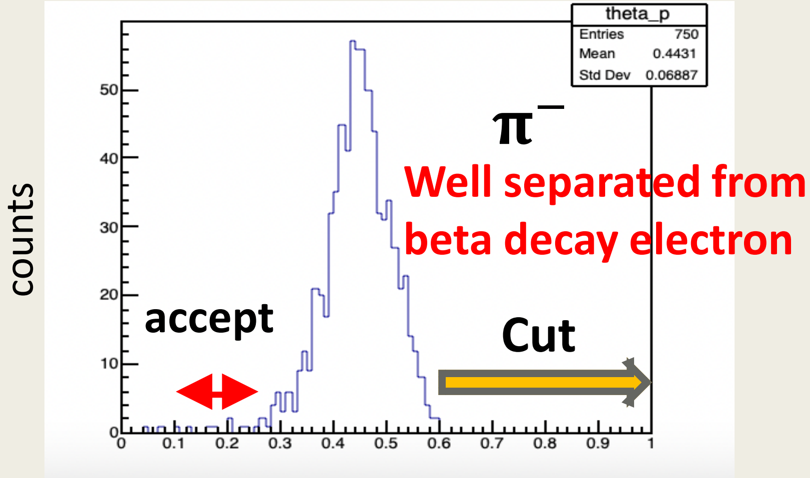
MIP peak at 0.2 MeV

Single $\beta \sim 1 \quad e^{-}$



Peaks at 0.2 & 0.4 MeV

Single or two $\beta \sim 1 \ e^{\pm}$
from $\gamma(\pi^0 \to \gamma\gamma)$



Peak at 0.5 MeV

Single $\beta \sim 0.6 \ \pi^{-}$

By selecting **$\Delta E/\Delta x$ = 0.12 - 0.27 MeV** as the beta decay electron,

88% of π^0, 99.9% of π^- are rejected.

Feasibility of Λ's beta decay experiment

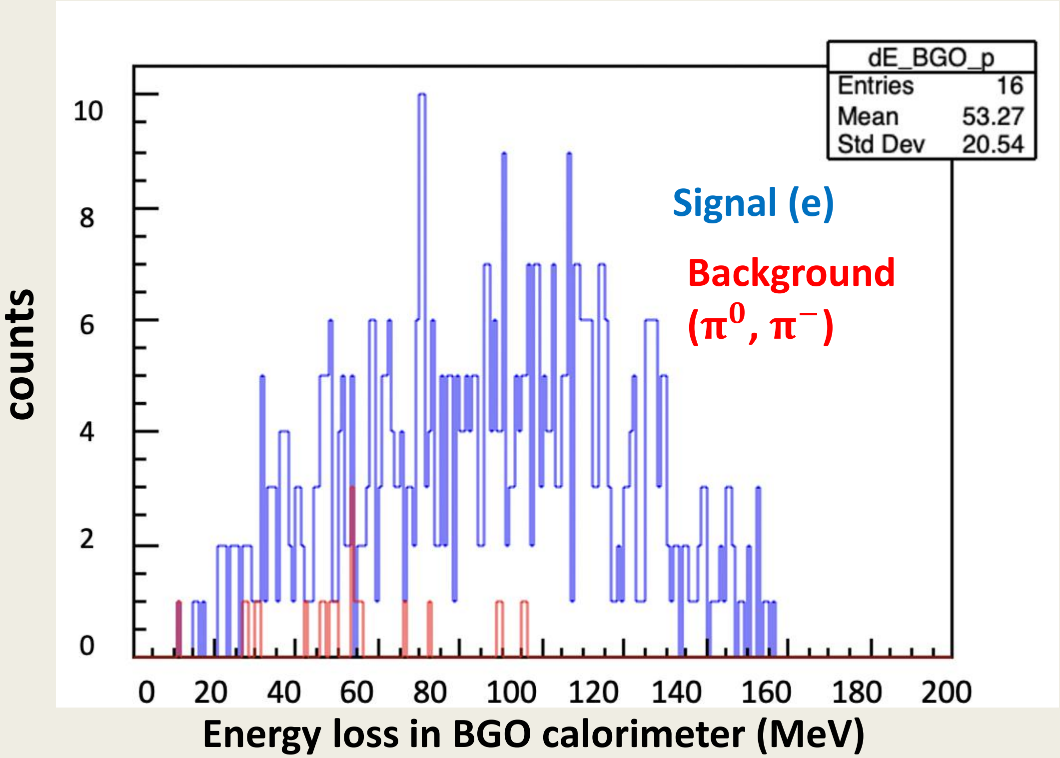
Background suppression of π^0 and π^-

SIG = 0.00048

	BR	BGO	Lucite	Plastic	Other analysis	BG	BG/SIG
π^0	0.2	×0.03	×0.10	×0.10	×0.24	= 0.000014	0.036
π^-	0.4	×0.07	×0.045	×0.001	×1.0	= 0.0000013	0.0026

3.6%+0.26% ~ 4%

Simulated energy spectrum of the beta decay electron



Contamination of Background/Beta decay ~ 4%

Systematic error from background < statistical error of 4%

→ Beta decay measurement is found to be feasible!

Summary & Prospects

- We want to study the modification of baryon properties in a nucleus by measuring Λ's beta decay rate.
- We studied background from $\Lambda' s$ decay modes.

Via analysis of BGO cluster, plastic counter energy loss and lucite Cerenkov counter hit,

BR(background)/BR(beta decay) rate is reduced down to 4%.

Systematic error of BR(background) < statistical error (4%)

➡ **We found that the experiment is feasible.**

- We will make more realistic simulation considering the energy resolution of BGO, plastic counter.
- We will prepare a proposal to J-PARC PAC.

Request to theorists

- We want to measure $\Gamma_{\Lambda\ \mathrm{beta}}$ (medium) reduction (20% at max) by baryon modification
- Other effects are as follows.

1. Pauli blocking of a proton in the beta decay
2. Meson exchange current and nuclear many body effects

To clearly detect the baryon modification effects, we need

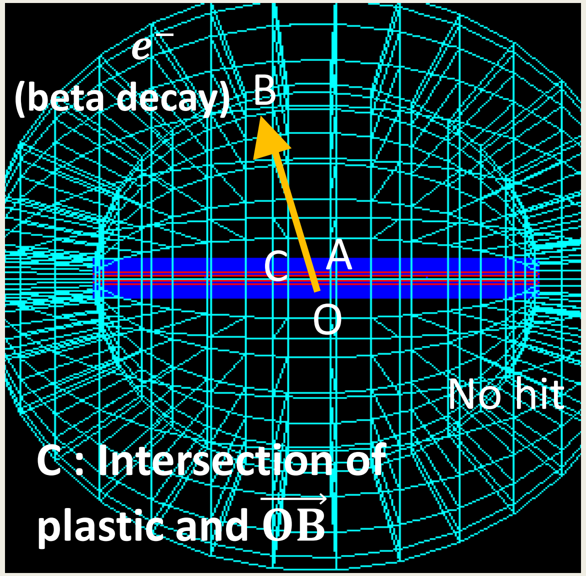
Precise calculations of 1 + 2 effects within 3%.

Thank you for paying attention to this presentation !

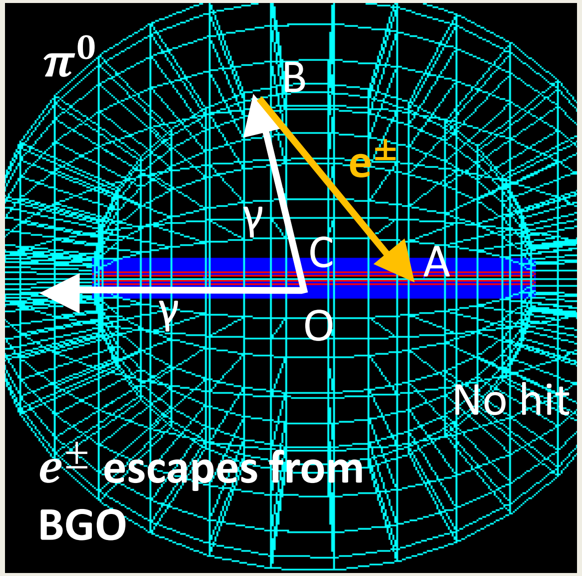
Back up

Other analysis

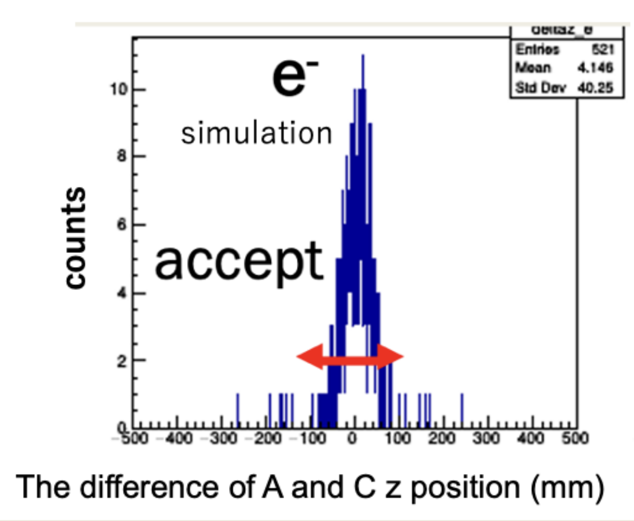
Correlation of hit positions

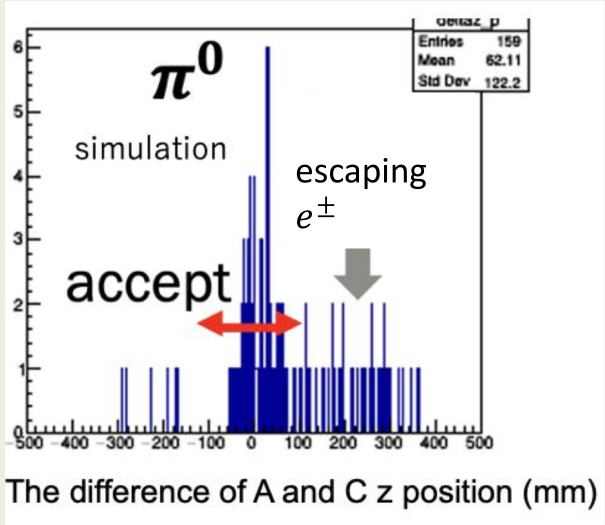


$\Delta z = z(A) - z(C) \sim 0$



$\Delta z = z(A) - z(C) > 0$





Remaining π^0

- One photon escapes from BGO holes
- The other photon enters BGO

Escaping $e^\pm$ from BGO hits plastic counter

Leak event: **Δz widely distributes.**

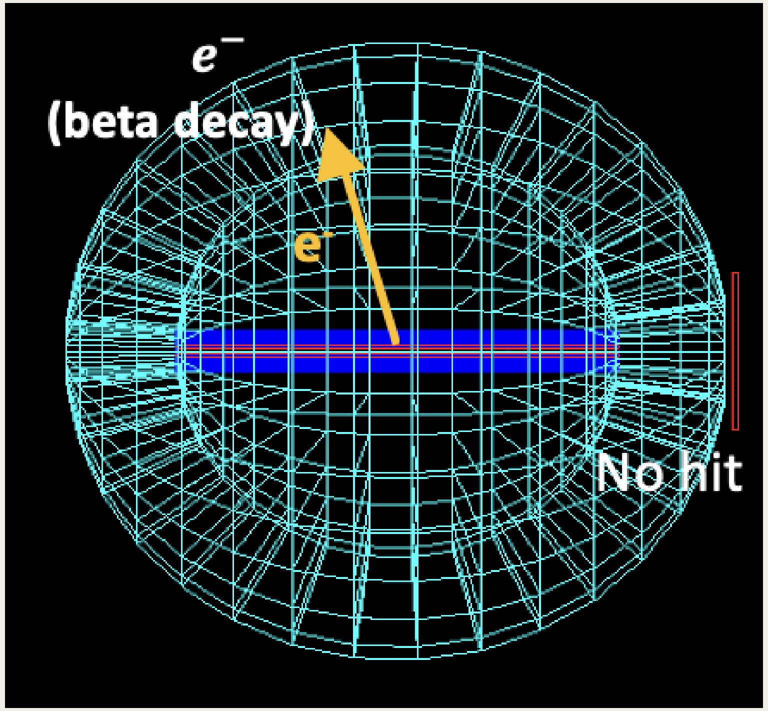
Beta decay event: **$\Delta z \sim 0$**

By accepting

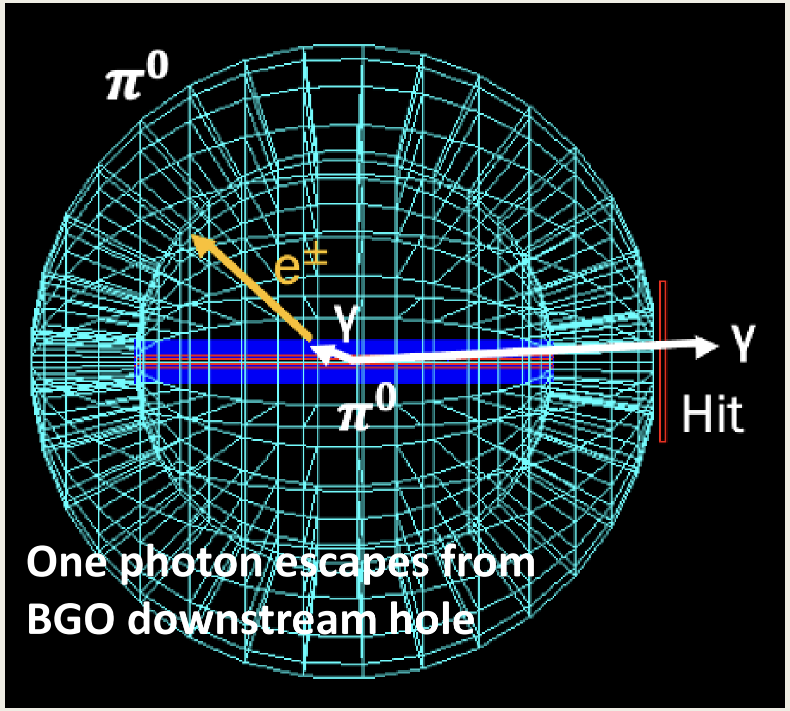
$$-90\text{ mm} < \Delta z < 90\text{ mm}$$

20% of π^0 are rejected.

Leak photon event in π^0 decay



Beta decay electron



Misidentified π^0

Can not be rejected by BGO cluster, Lucite Cerenkov hit and energy loss in plastic counter.

By installing photon veto counter at the exit of BGO downstream hole

70% of remaining π^0 events are rejected.

- Actually, photon veto counter will be installed around the SKS magnet.

Modification of baryon properties in a nucleus

$g_V = 1$
$g_A = -1$ ⇒ $g_A^{\Lambda} = -0.718$ (experiental)

quark level — hadron level (Λ)

In general, the beta decay rate, Γ_{beta}, is written in

$$\Gamma_{beta} \propto g_V^2 M_F^2 + g_A^2 M_{GT}^2 ,$$

$$\Gamma_{beta} \propto g_V^2 + 3g_A^2 .$$

When Λ's beta decay in a nucleus occurs only via Gamov-Teller transition as

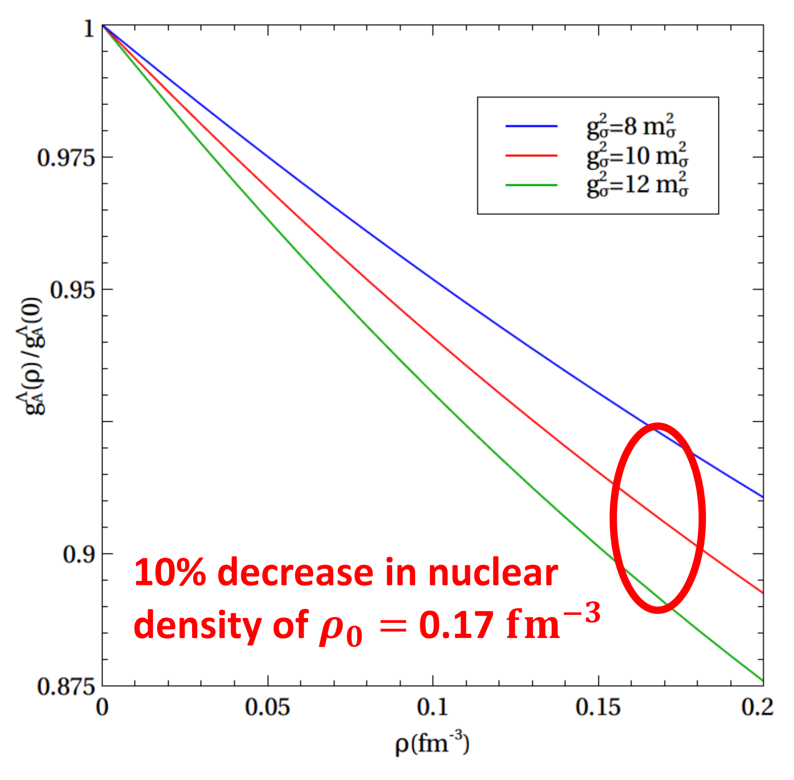
$$\Gamma_{beta} \propto 3g_A^2 ,$$

the beta decay rate decreases by about 20%. When Λ' s beta decay in a 0^+ nucleus occurs in combinations of Fermi and Gamov-Teller transition,

$$\Gamma_{beta} \propto g_V^2 + 3g_A^2 ,$$

the beta decay rate decreases by about 12%.

g_A^{Λ} as a function of nuclear density by QMC model [1]



Quenching of G-T beta decay rate in nuclei

GT beta decay quenching — Matrix element

Reaction	$\log f_A t$	$M(GT)$ (exp)	$M(GT)$ th(free)	$\frac{M(GT)_{exp}}{M(GT)_{th(free)}}$
$^1n(\beta^-)^1H$	3.024(1)	3.100(7)	3.096	1.00
$^3H(\beta^-)^3He$	3.058(1)	2.929(5)	3.096	0.946
$^6He(\beta^-)^6Li$	2.910(1)	2.748(4)	3.031	0.907
$^7Be(EC)^7Li$	3.300(1)	2.882(4)	3.187	0.904
$^{11}C(\beta^+)^{11}B$	3.598(2)	1.480(9)	2.084	0.710
$^{13}N(\beta^+)^{13}C$	3.671(2)	0.788(8)	0.891	0.884

Light nuclei
(reduce by ～ 5%)

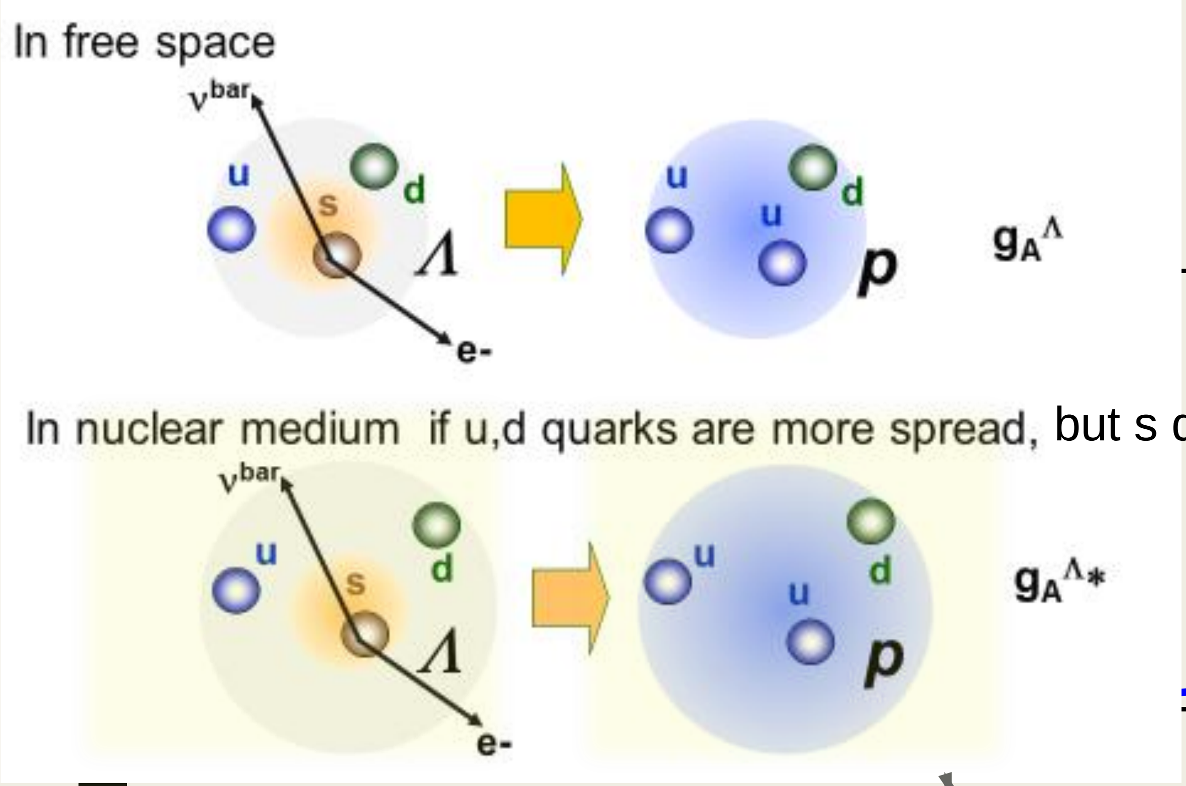
- Nuclear many-body effects and hadronic effect also reduce M_{GT}.
  Except for light (A<4) nuclei, M_{GT} quenching effect is 10 — 30 % or more.
- M_{GT} decreases → beta decay rate $\Gamma_\beta \propto g_A^{\Lambda^2} M_{GT}^2$ decreases.
- By using lighter nuclei such as ^3He, M_{GT} quenching effect is expected to be ～ 5% and beta decay rate decreases by 10 % (< baryon modification effect 20% (max)).

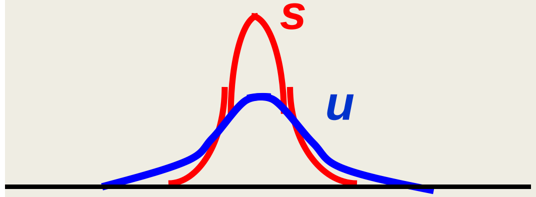
$^5_\Lambda He$ is suitable for measuring baryon modification effect (Other effect -> small)

We will measure the change of $^5_\Lambda He$ beta decay rate, and clearly measure the effect from baryon modification.

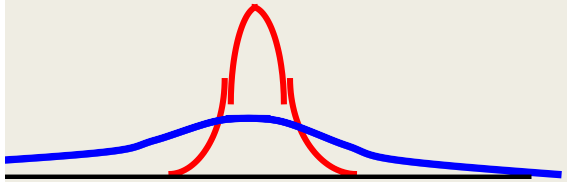
Modification of g_A^{Λ} due to baryon "swelling" in medium

$\Lambda \to p\, e^- \nu^{bar}$ Sensitive to overlap of u and s quark w.f.

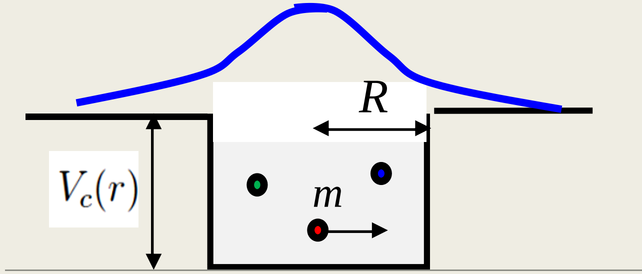




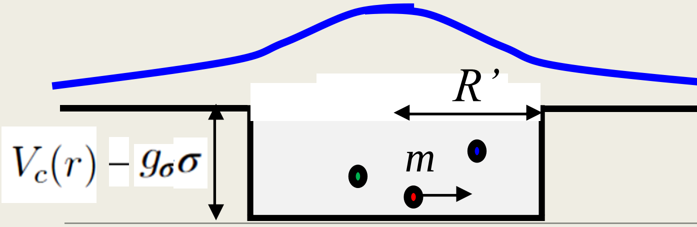
but s quark is not spread, then



Bag model picture



$$[i\gamma \cdot \partial - m_q - V_c(r)]\psi_q(r) = 0$$



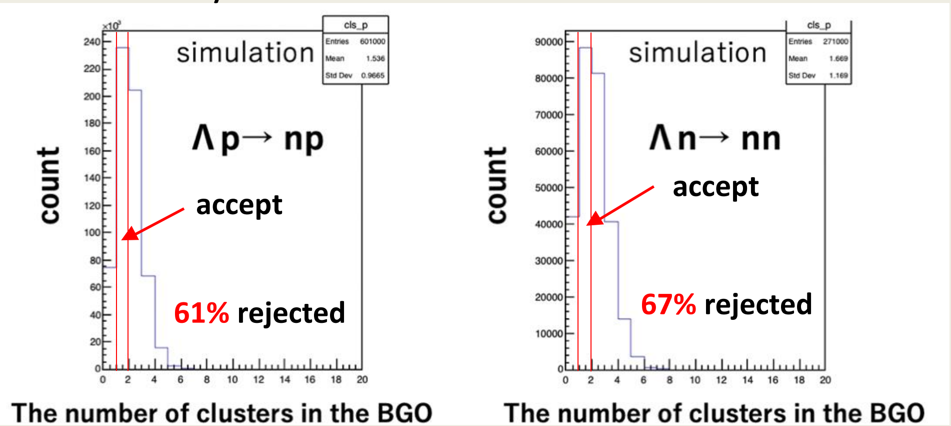
Less overlap between s and u quarks ⇒ *Reduction of beta decay rate in medium*

$$[i\gamma \cdot \partial - \underbrace{(m_q - g_\sigma \sigma)}_{m^*} - V_c(r)]\psi_q(r) = 0$$

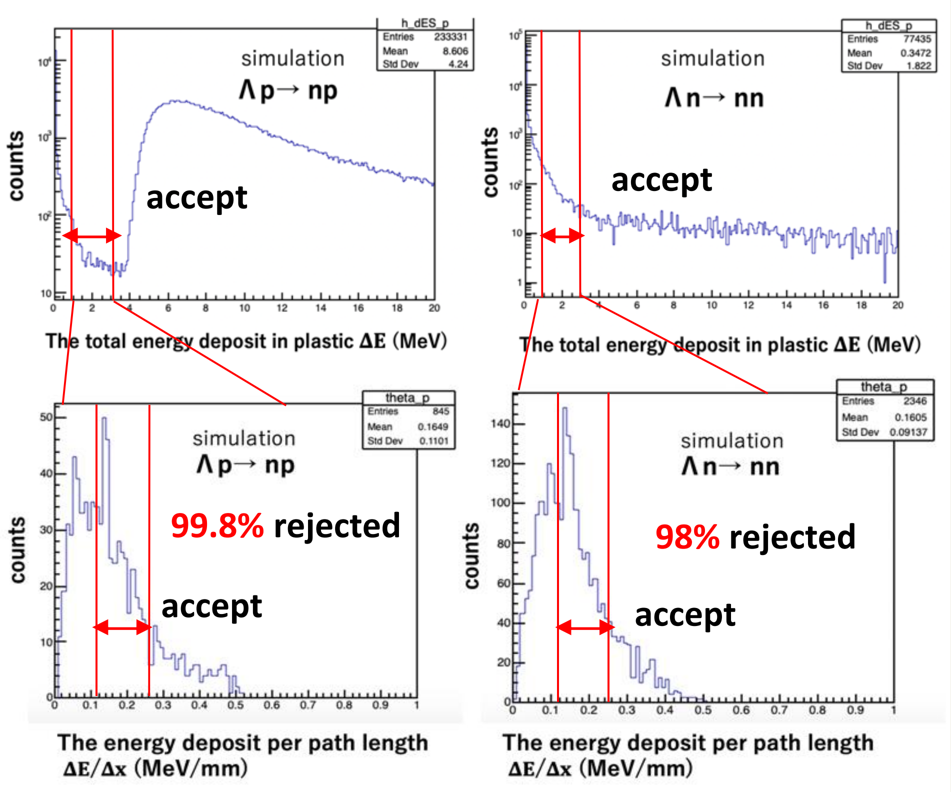
Study of background from nonmesonic weak decay ($\Lambda p \rightarrow np$ and $\Lambda n \rightarrow nn$)

Reduction of nonmesonic weak decay

Cluster analysis



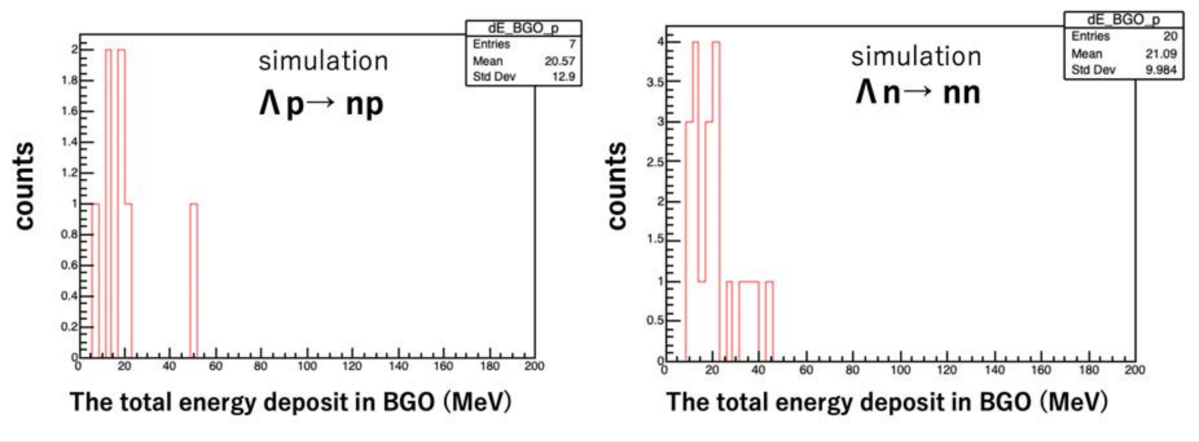
Energy loss analysis in plastic counter



Furthermore, **99.5% of $\Lambda p \rightarrow np$ 99.7% of $\Lambda n \rightarrow nn$** are rejected by lucite Cerenkov counter.

By all the analysis to reduce background

Energy spectra of $\Lambda p \rightarrow np$ and $\Lambda n \rightarrow nn$

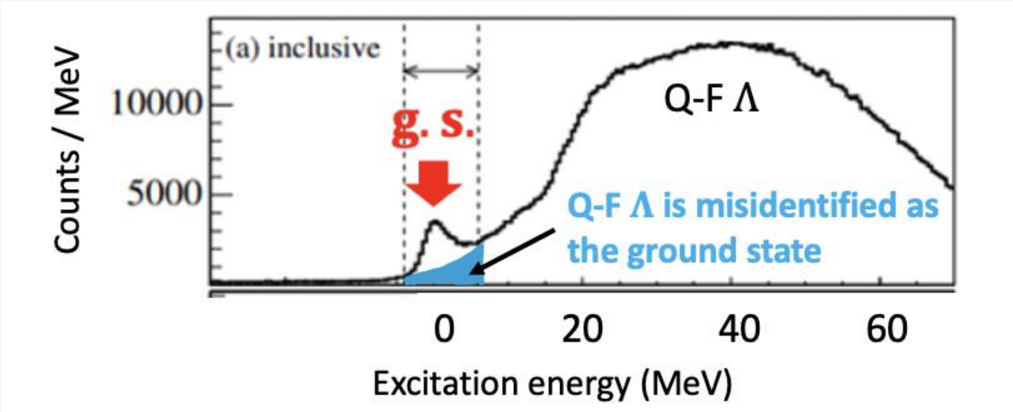


BR(NMWD)/BR(Beta decay) rate (%) $\sim$ 6%

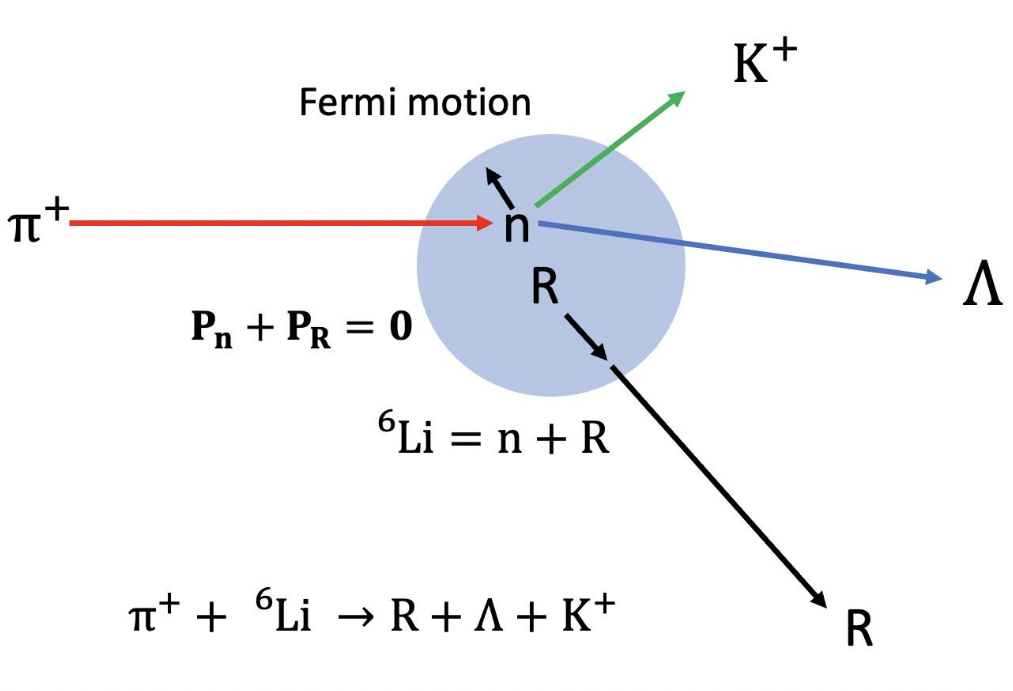
Systematic error of BR(background) can be reduced down to **6% $\times$ 0.3 = 1.8 %** by subtracting background within 30% accuracy.

Simulation study for background from Quasi-free Λ

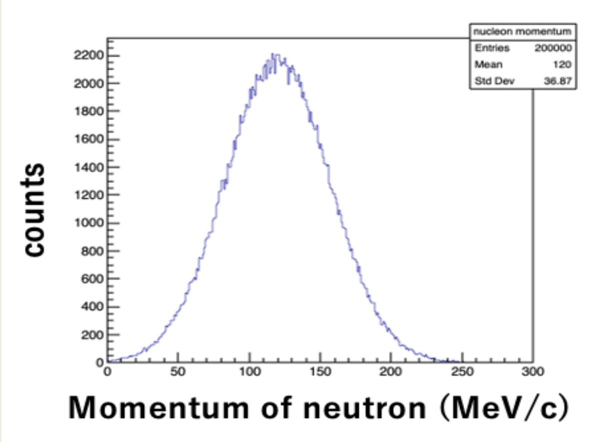
Quasi-free Λ



Quasi –free Λ production



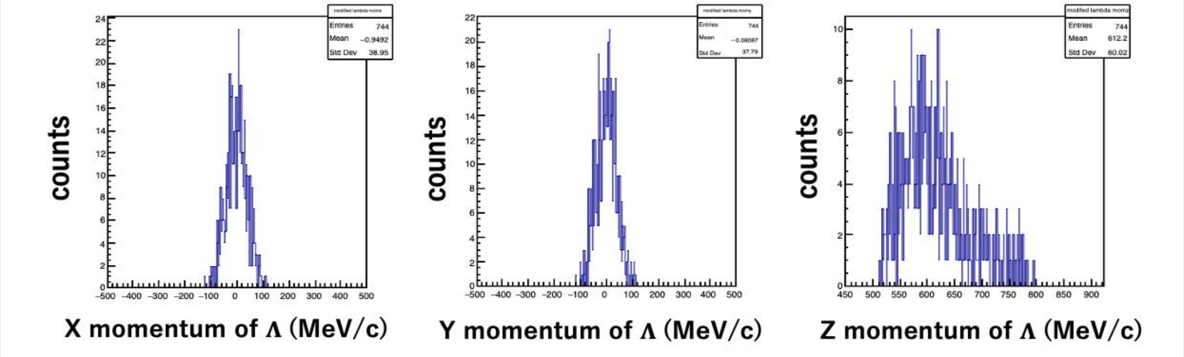
The momentum distribution of the neutron in ^{12}C measured by $^{12}C\ (e, e'p)$ reaction [1]



Since the energy of $^{6}\mathrm{Li}$ should be $\mathrm{E}(^{6}\mathrm{Li}) = \mathrm{M}(^{6}\mathrm{Li})$, we modified the mass of neutron as

$$\mathrm{M}_\mathrm{n}^* = \sqrt{\mathrm{M}_\mathrm{C}^2 + \mathrm{M}_\mathrm{R}^2 - 2\mathrm{M}_\mathrm{C}\sqrt{\mathrm{M}_\mathrm{R}^2 + \mathbf{p}_\mathbf{R}^2}} \leq \mathrm{M}_\mathrm{n}$$

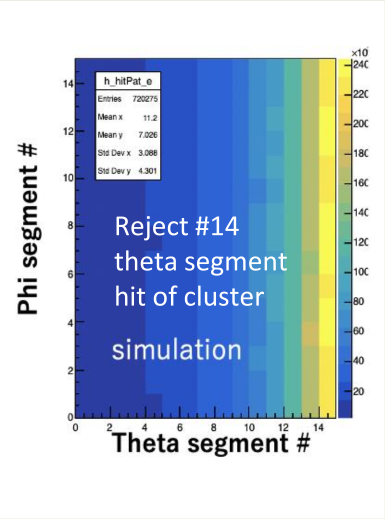
Momentum of Quasi-free Λ



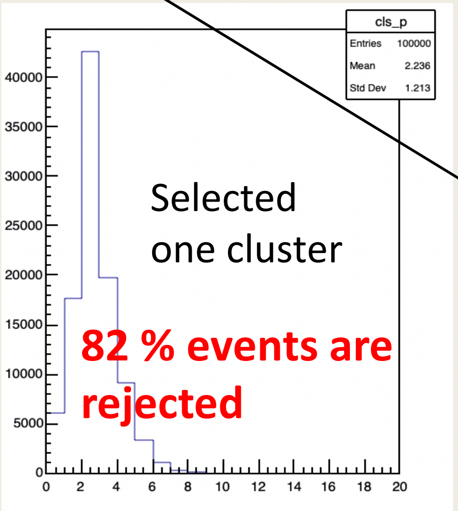
[1] J. Mougey et al., Nucl. Phys. A262, 461 (1976).

Simulation study

BGO counter



Hit pattern



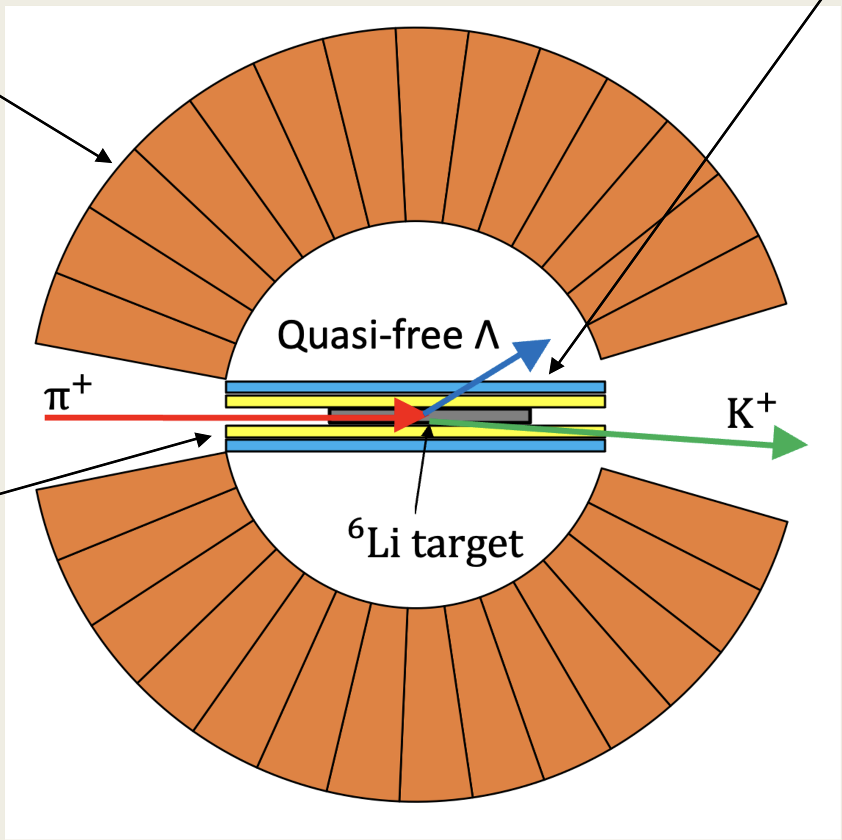
Number of clusters

Lucite Cerenkov counter

57% events are rejected

Bad rejection due to fast π^- from Q-F Λ

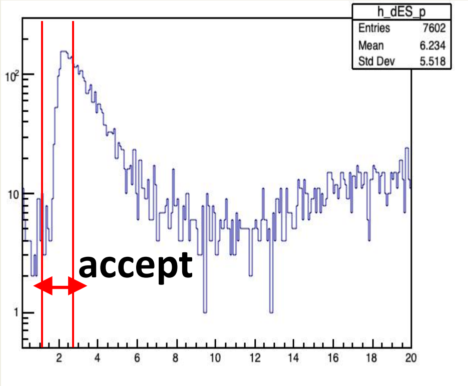
Production of Q-F Λ



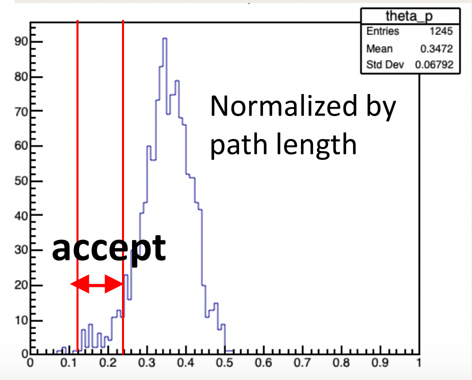
Via all the reduction methods,

$$\frac{N_{\text{QF weak decay}}}{N_{\text{QF beta decay}}} \sim 3\%$$

Plastic counter



Total energy loss (MeV)



Energy loss (MeV/mm)

98.1% events are rejected