Development of an aerogel Cherenkov counter for the LEPS2 experiment at SPring-8

Research Center for Electron Photon Science (ELPH)

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physics motivation

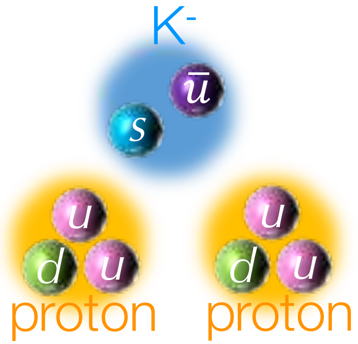
$\bar{K}N$ interaction

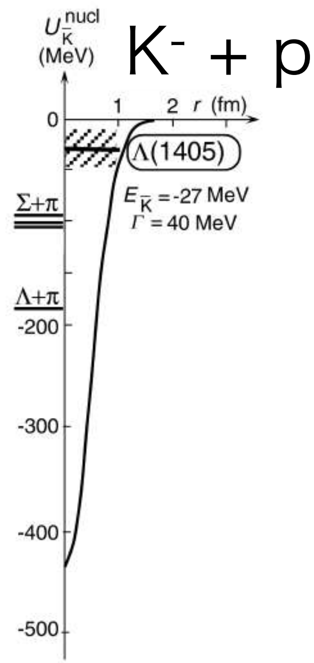
It is known that $\bar{K}N$ interaction is attractive from Kaonic-hydrogen X-ray data and $\bar{K}N$ scattering data.

Y.Akaishi and T.Yamazaki assumed that $\Lambda(1405)$ is $\bar{K}N$ bound state and calculated $\bar{K}N$ potential.

- $\bar{K}N$ interaction is strong attractive (I=0).
- **Kaonic nucleus** exist.

The simplest kaonic nuleus : **K^-pp bound state.**





Y. Akaishi and T. Yamazaki, Phys. Rev. C 65, 044005 (2002)

physics motivation

J-PARC E27

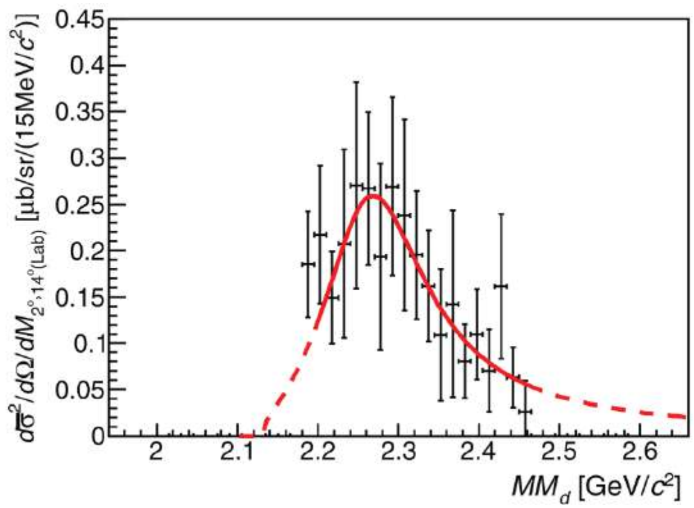
$\pi^+ d \rightarrow K^+ X$ … K^* exchange

missing mass spectrum

+ identify final state ($\Sigma^0 p$)

Binding energy : $95^{+18}_{-17}(stat)^{+20}_{-21}(syst)\,\mathrm{MeV}$

width : $162^{+87}_{-45}(stat)^{+66}_{-78}(syst)\,\mathrm{MeV}$



Y. Ichikawa *et al.*, Prog. Theor. Exp. Phys (2015) 021D01

J-PARC E15

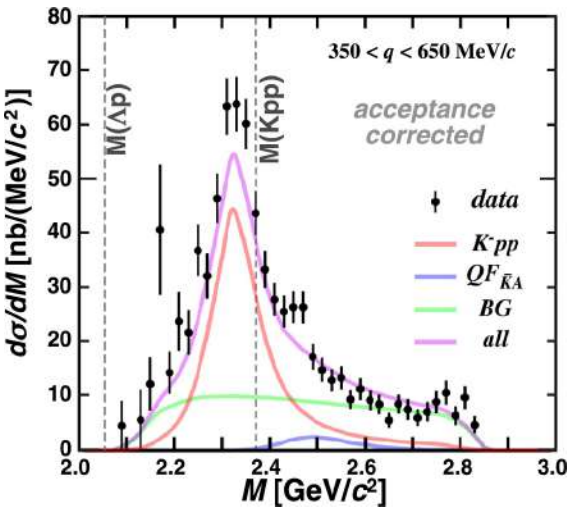
$K^- \, ^3\mathrm{He} \rightarrow n\, X$

missing mass spectrum

+ invariant mass spectrum (Λp)

Binding energy : $47^{+3}_{-3}(stat)^{+3}_{-6}(syst)\,\mathrm{MeV}$

width : $115^{+7}_{-7}(stat)^{+10}_{-20}(syst)\,\mathrm{MeV}$



S. Ajimura *et al.*, Phys. Lett. B 789, 620-625 (2019).

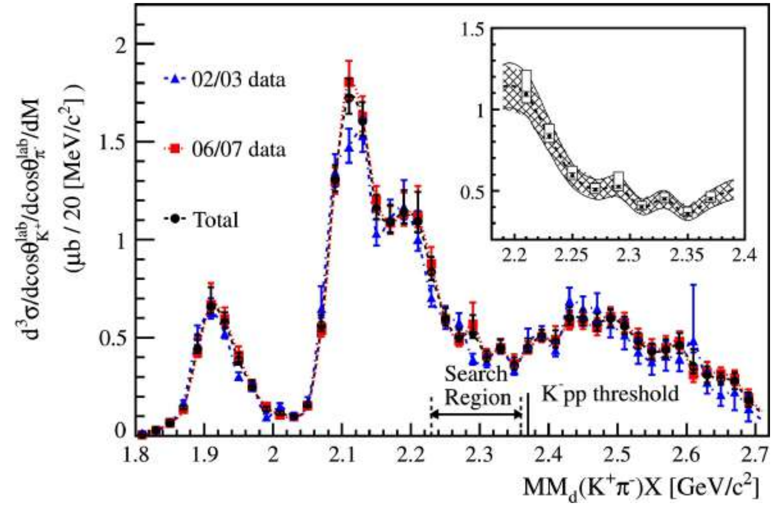
physics motivation

SPring-8/LEPS

$\boldsymbol{\gamma d \to K^+ \pi^- X}$ **…** $K,\ K^*$ exchange

missing mass spectrum

… peak structure was NOT observed.

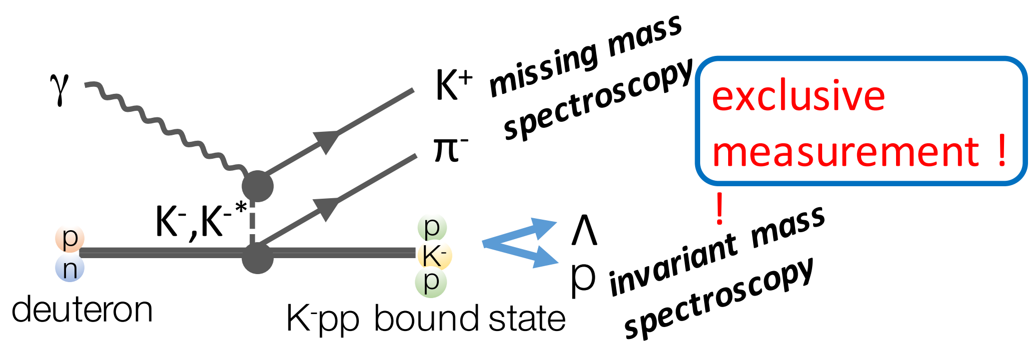


A. O. Tokiyasu *et al.*, Phys. Lett. B 728 616-621 (2014).

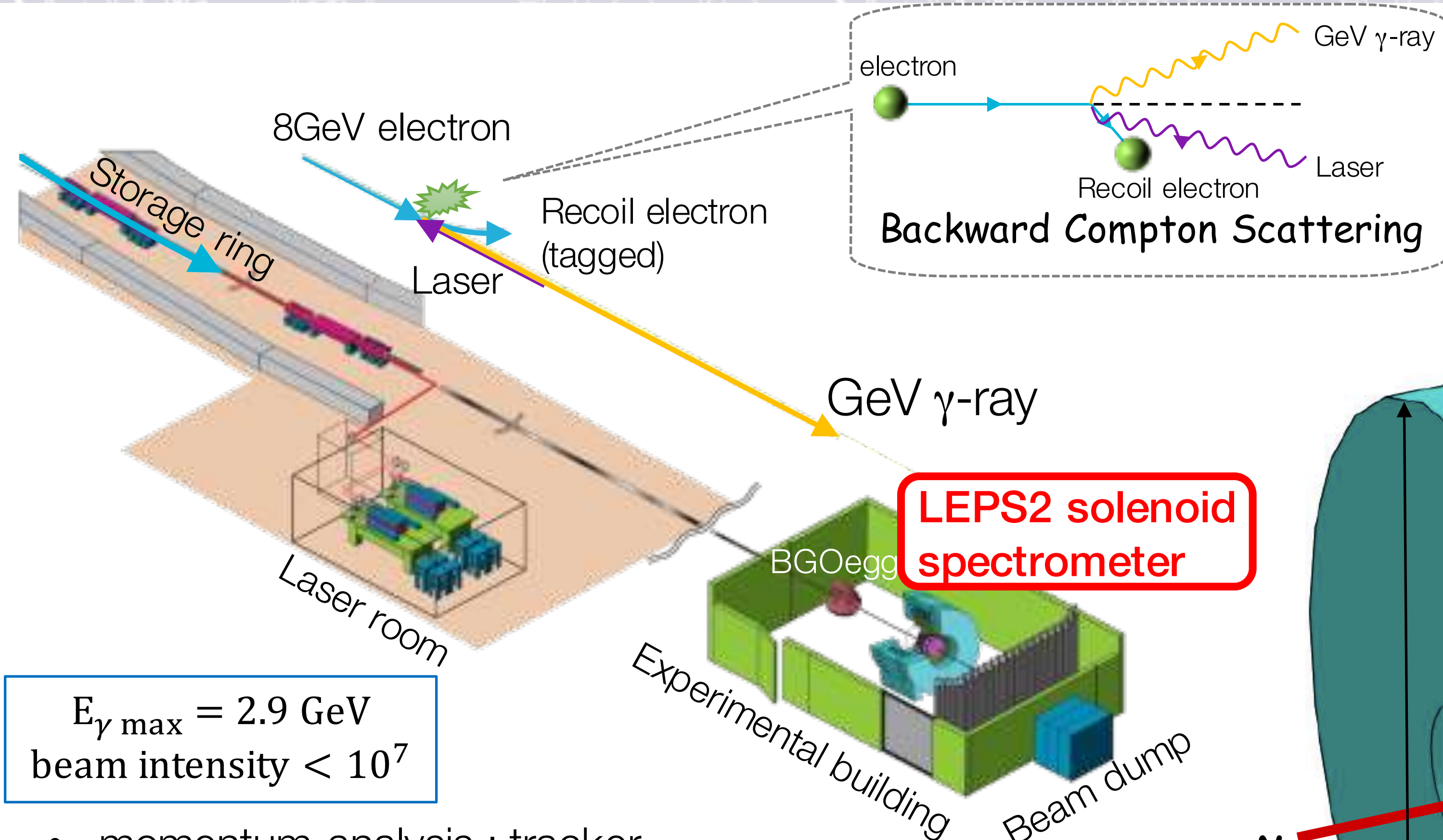
SPring-8/LEPS2

take data 10 times more than LEPS

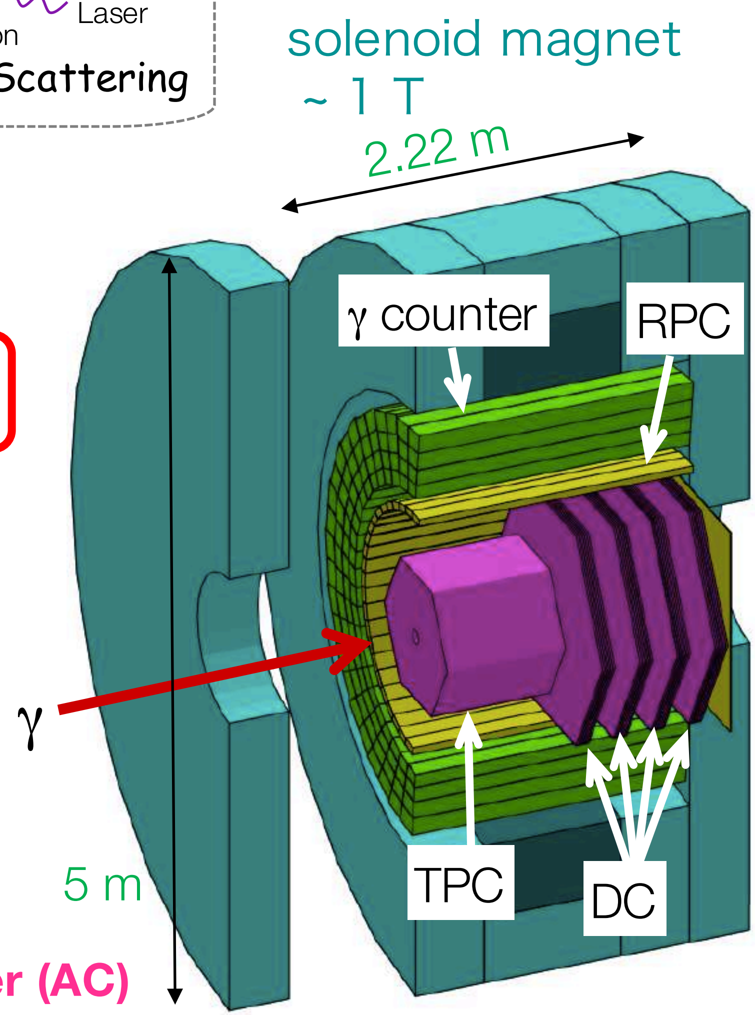
missing mass spectrum + invariant mass spectrum



LEPS2 experiment



$E_{\gamma\ max} = 2.9$ GeV
beam intensity $< 10^7$



- momentum analysis : tracker
  (Time Projection Chamber, Drift Chamber)
- Time of Flight : Resistive Plate Chamber
- velocity (faster than threshold) : **Aerogel Cherenkov counter (AC)**

Aerogel Cherenkov counter

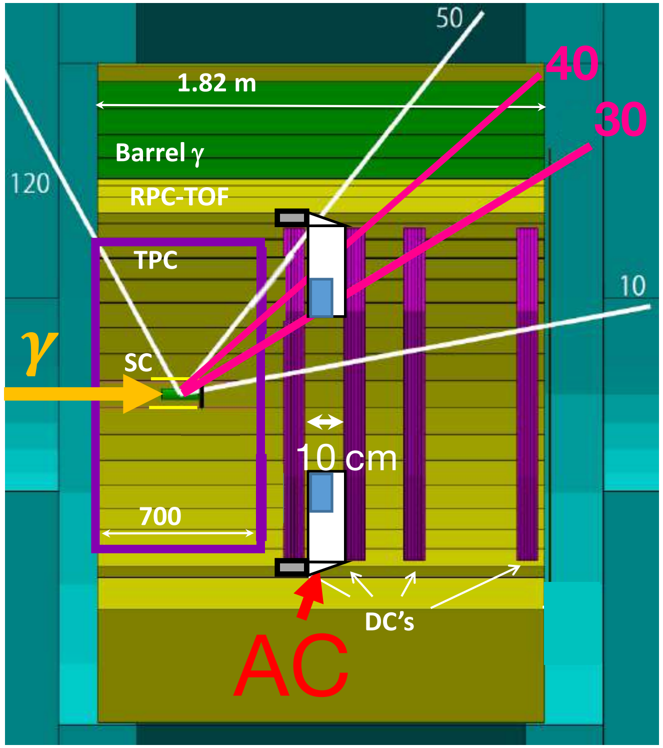
Purpose : separate π and K in the momentum region 1 – 2 GeV/*c*

We use aerogels which refractive index = **1.03**.

Requirement

- π detection efficiency > 95%
- acceptance region : 30° – 40°
- install in the small gap (10 cm)
- work in the magnetic field
- minimize the material budget

LEPS2 spectrometer



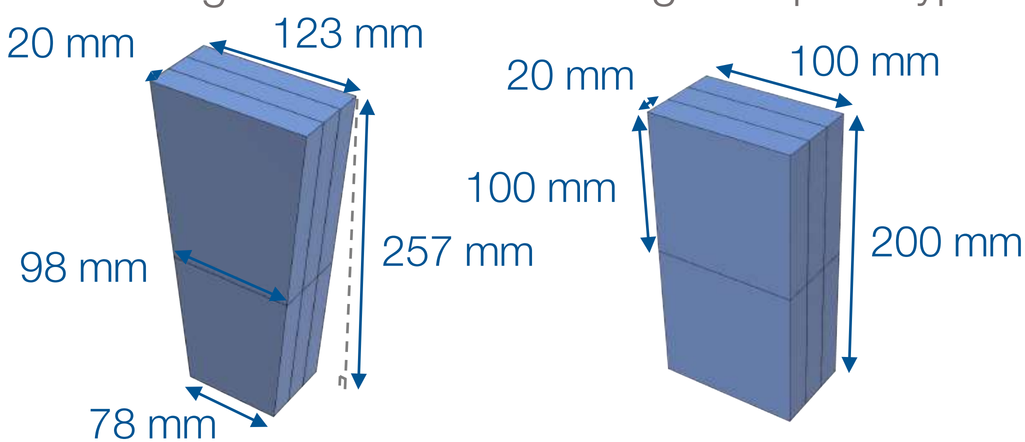
Shape of AC

Shape of aerogels

for AC : trapezoid

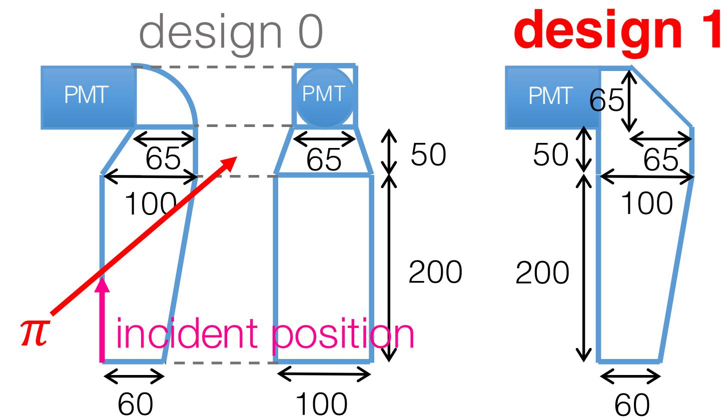
accurate size & cutting method were not decided.

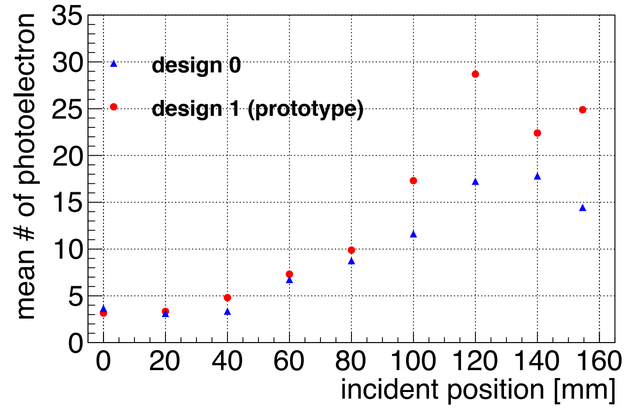
for prototype : rectangle



Shape of box

optimize shape of box using an optical simulation code, Guide-7.

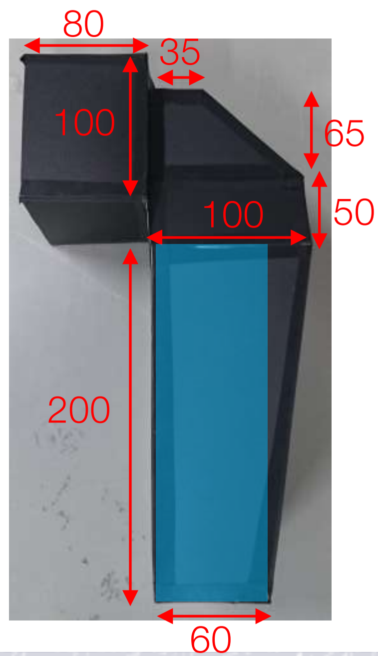


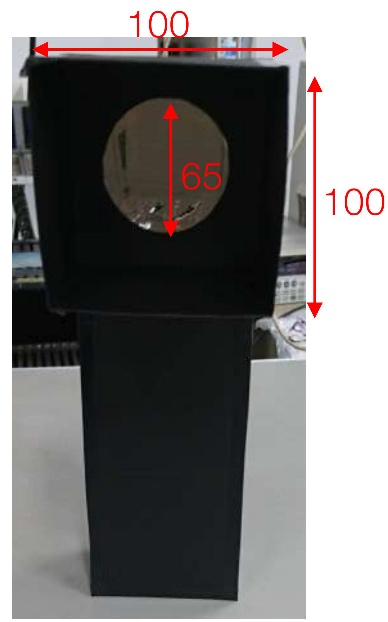


Components of prototype

components

- aerogel (n = 1.03, $10\times10\times2$ cm, 6 pieces)
- box : polypropylene sheet
- inner reflector (Enhanced Specular Reflector, ESR)
- 3-inch fine-mesh PMT (hamamatsu R5543)





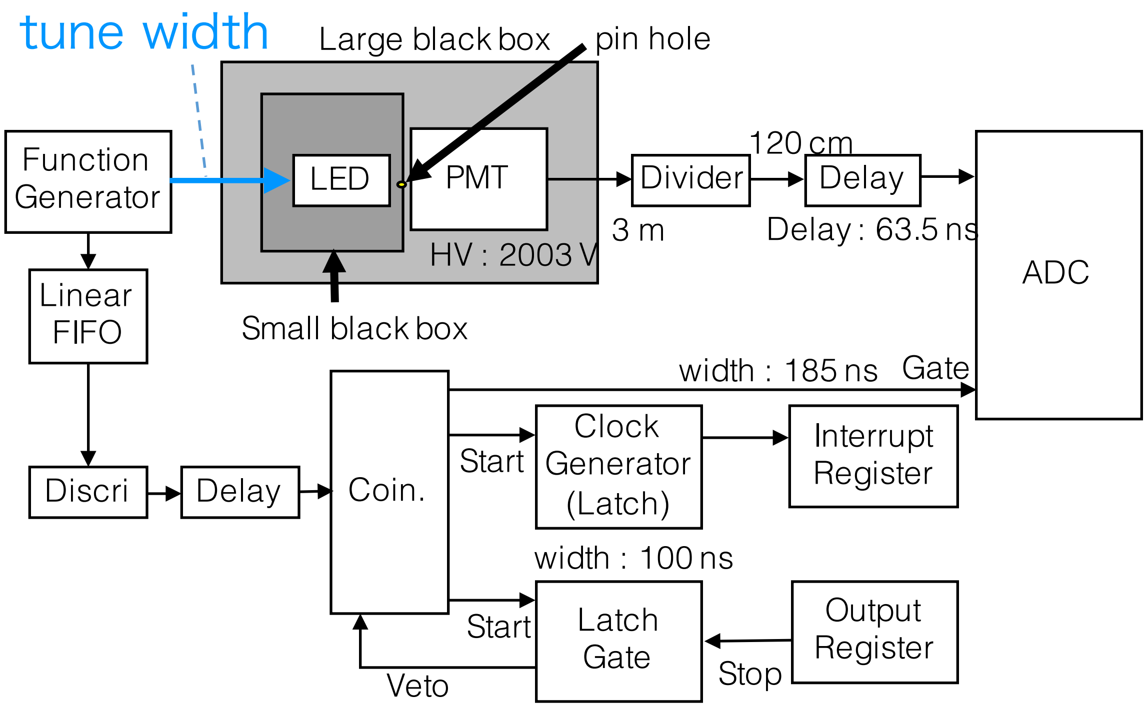
fine-mesh PMT

Single photo-electron signal

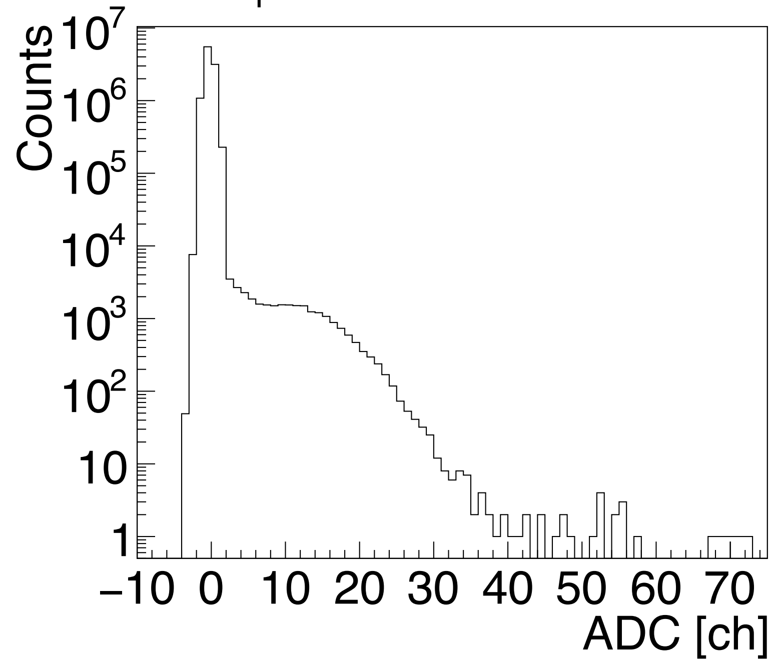
number of photo-electron (N_{pe}) follows a poisson distribution.

When pedestal events account for 95%,

2 photo-electron events become about 0.2%.



Charge distribution
which pedestal is more than 95%



calibration

- How to make multi photo-electron signal

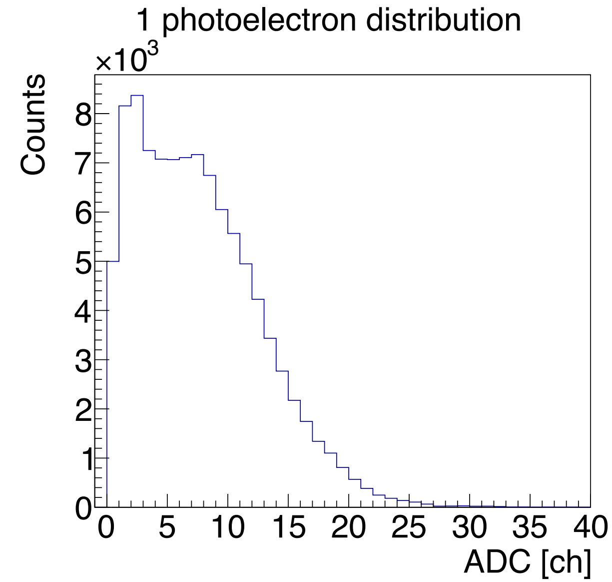
  Photo-electrons generate following a poisson distribution which mean is μ.

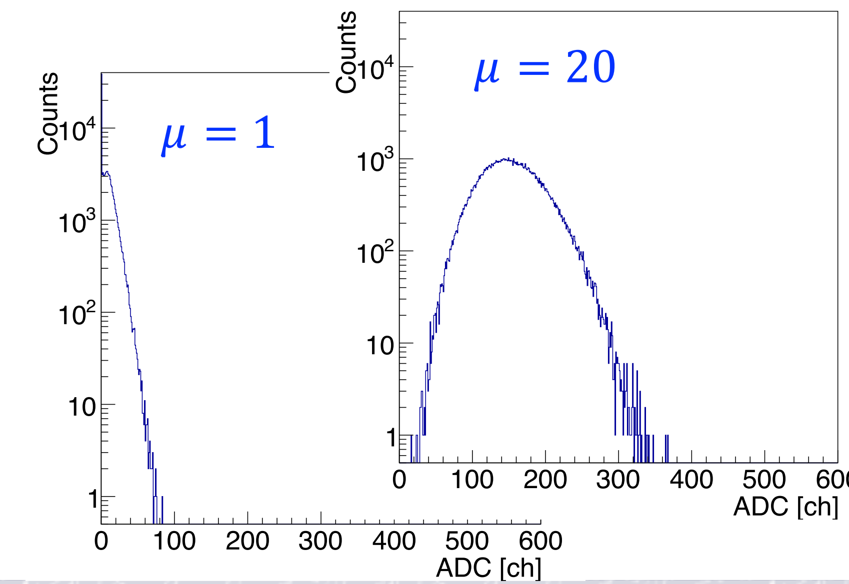
  ADC value of each photo-electron signal follows the 1 photo-electron distribution.

- How to estimate mean of N_{pe} of a charge distribution of performance test

  χ^2 test for comparing a charge distribution of performance test and multi photo signals

  μ = mean of N_{pe} when χ^2 is minimum.





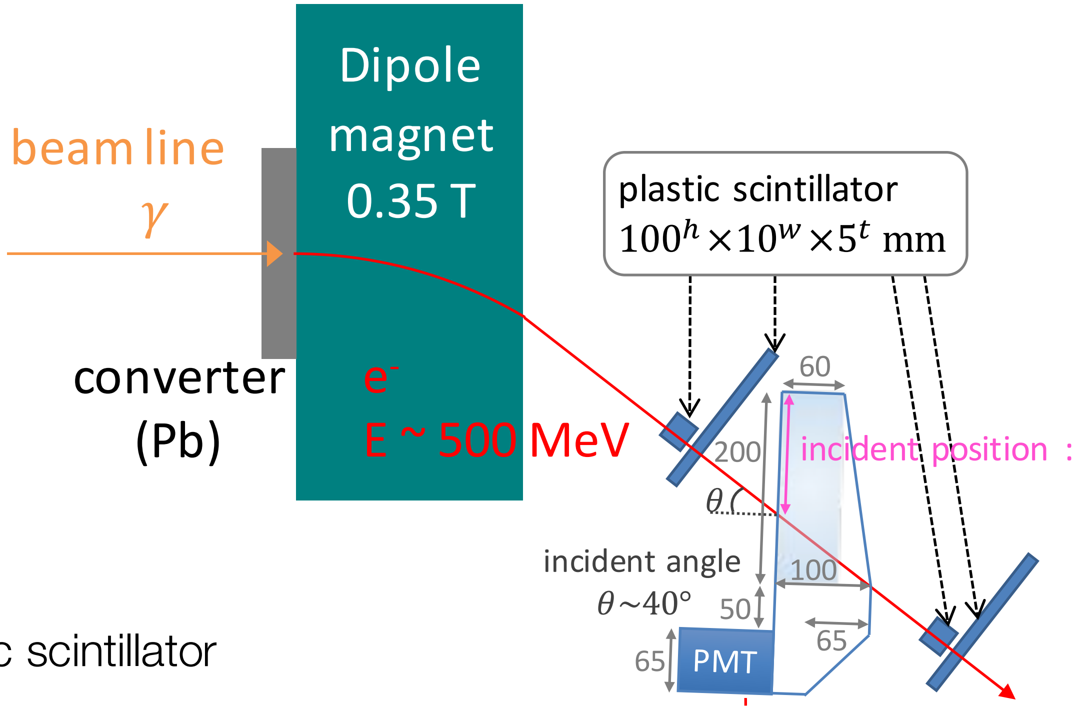
performance test : electron beam test

performed 2018/07/17 – 19 @LEPS

Purpose

to check a light output of $\beta\sim1$ particle

- mean N_{pe}
- π detection efficiency
- K mis-identification probability
- position dependence



Conditions

- trigger signal : coincidence of 4 plastic scintillator
- trigger rate ~ 50 Hz
- incident position : 0, 60, 120 mm
- with / without aerogel in the prototype

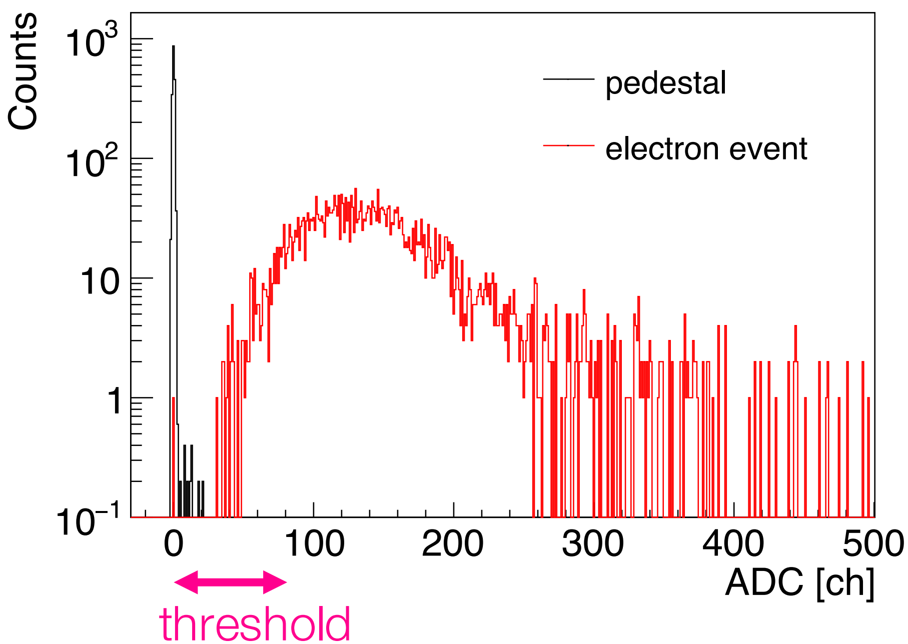
π detection efficiency

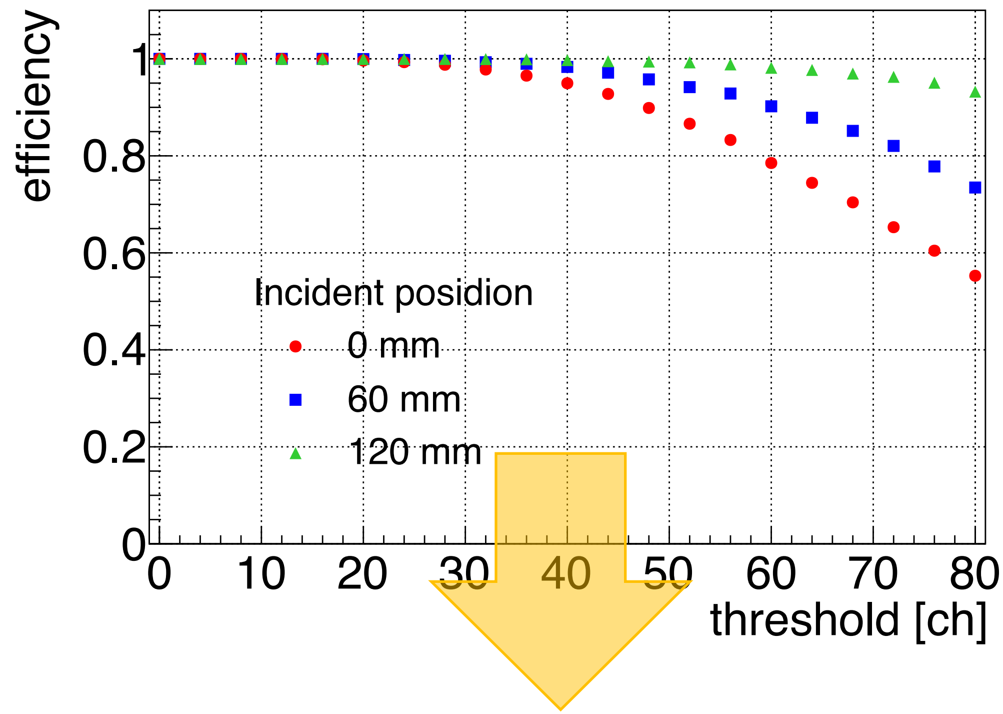
Charge distribution (with aerogel)

estimate $\boldsymbol{\pi}$ detection efficiency

$$\text{efficiency} = \frac{\text{Counts (ADC > threshold)}}{\text{Counts (Trigger)}}$$

Charge distribution
(with aerogel)





Required $\boldsymbol{\pi}$ detection efficiency > 95%

threshold < 36 ch

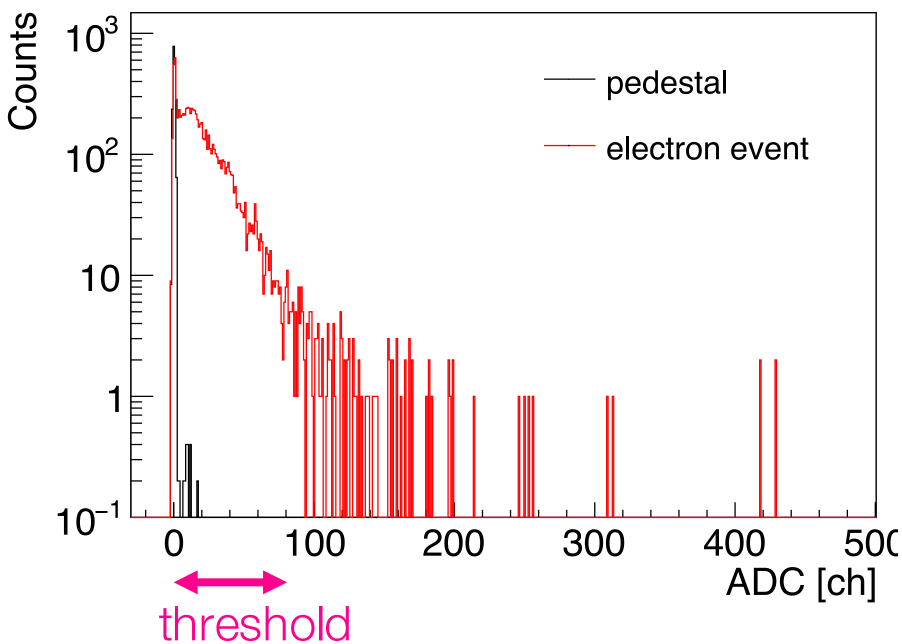
K mis-identification probability

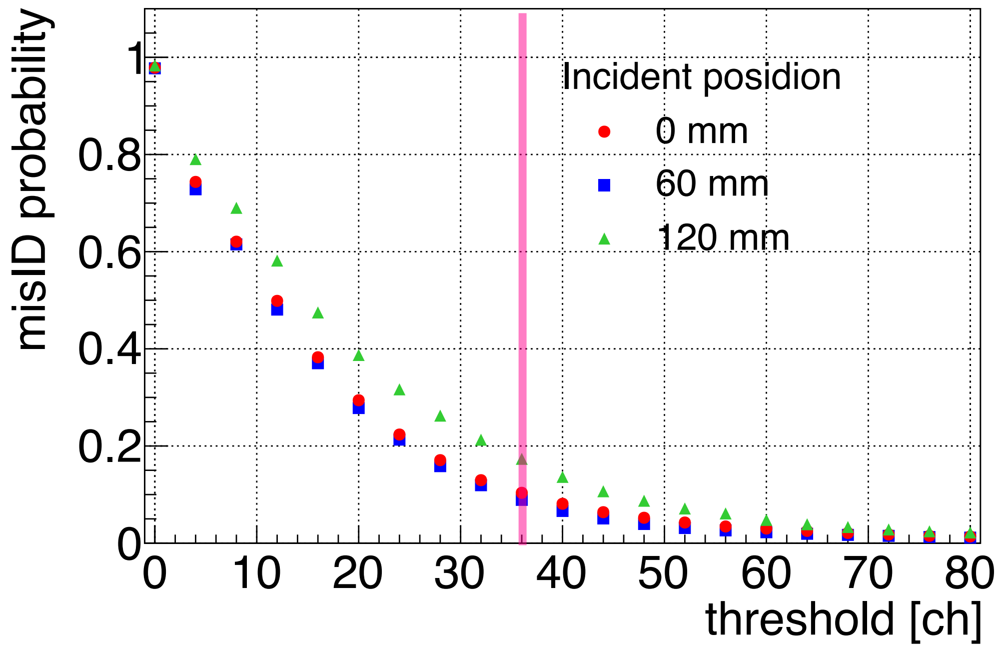
Charge distribution (without aerogel)

K mis-identification probability

$$\text{misID} = \frac{\text{Counts (ADC} > \text{threshold)}}{\text{Counts (Trigger)}}$$

Charge distribution
(without aerogel)





Required π detection efficiency > 95%

threshold < 36 ch

When threshold is 36 ch

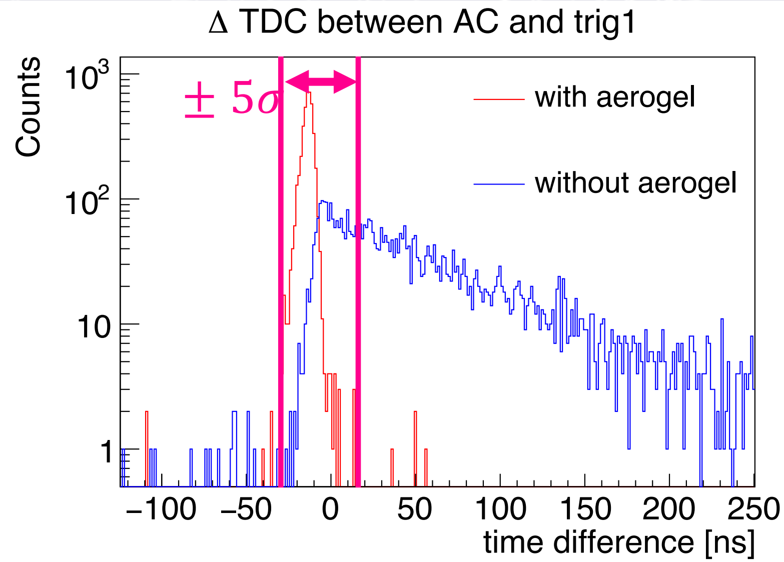
K misID probability < ~17%

Suppression of K mis-identification probability

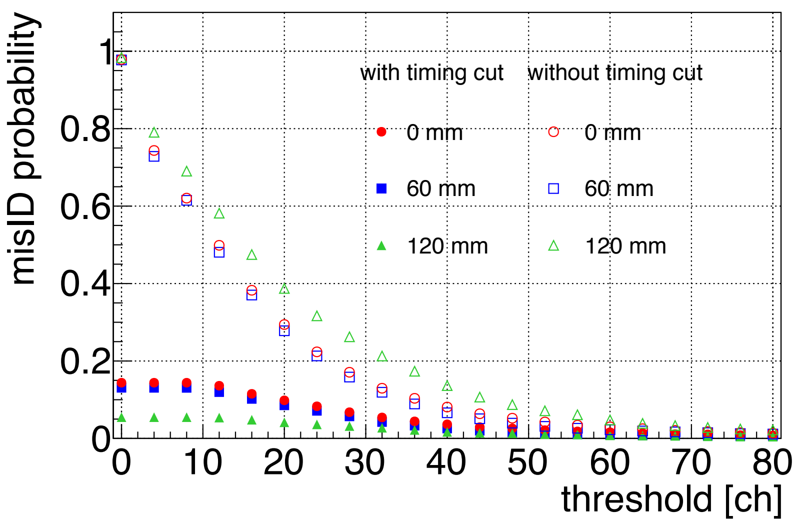
Event selection using time information

Scintillation light is emitted slower than Cherenkov light.

limit ΔTDC [ns] between AC and trigger scintillator



Charge distribution



ADC [ch]

π detection efficiency > 95%

K misID probability < 11%

→ Event selection using time information is useful to suppress K misID probability

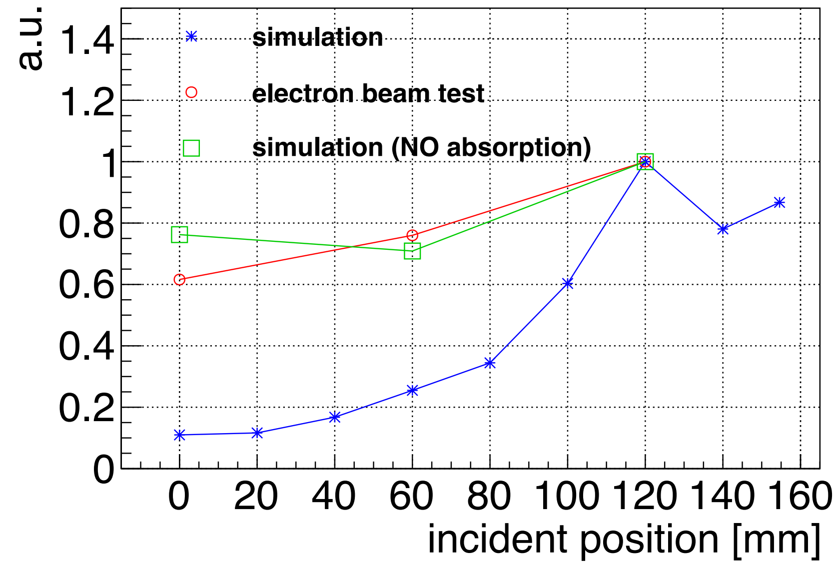
ADC [ch]

Compare test results and simulation

mean N_{pe} of Cherenkov light from aerogels

= mean N_{pe} (with aerogel) – mean N_{pe} (without aerogel)

Compare ratio $\frac{\text{mean } N_{pe}}{\text{mean } N_{pe} \text{ (incident position=120 mm)}}$



- Simulation concerning absorption of light by aerogel

  Position dependence is larger than test results.

- Simulation neglecting absorption of light by aerogel

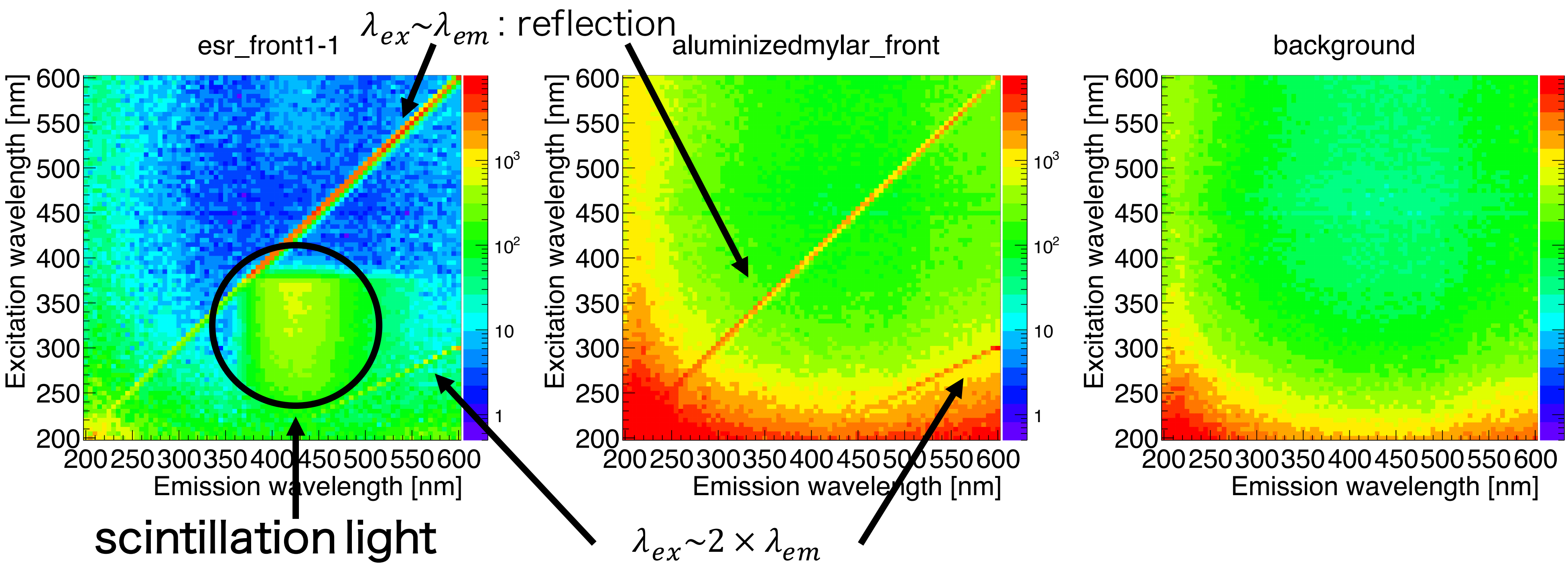
  The tendency of position dependence is almost same to test results.

→ In a aerogel, light is scattered than absorbed.

Study of scintillation light from reflector

measure an intensity of emission light from a sample when induce exicitation light

Using HITACHI spectro-fluorophotometer F-4500.

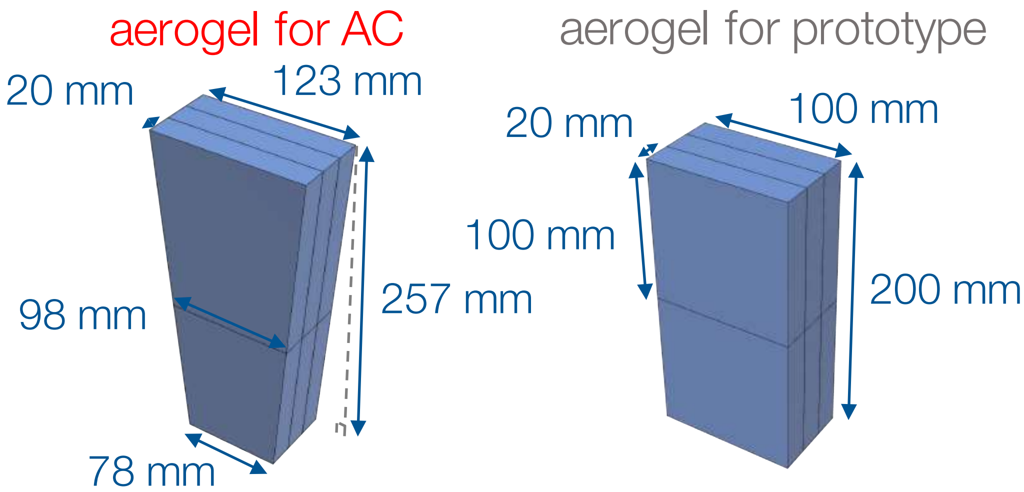


Scintillation light which wavelength is about 400 – 500 nm is emitted from ESR.

From aluminizedmylar, scintillation light is not emitted.

future plan

- Optimize shape of AC box using simulation neglecting light absorption by aerogal.



- Construct AC using ESR and aluminizedmylar.

  reflectivity of ESR : ~ 98% , reflectivity of aluminizedmylar : ~ 92%

  … Scintillation light will be suppressed by using aluminizedmylar.

  Cherenkov light will also become small.

  perform beam test and decide to use which reflector

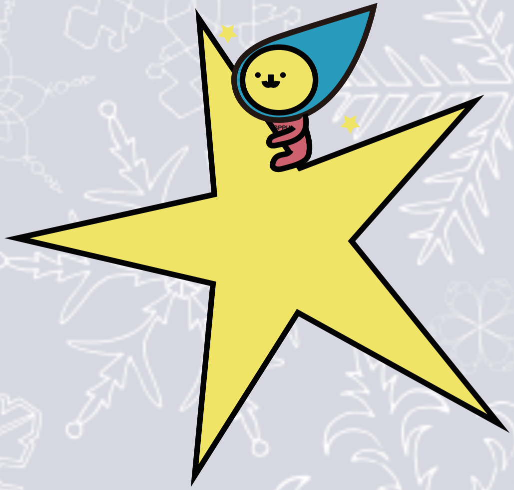
- Mass production, take physics data in 2020.

summary

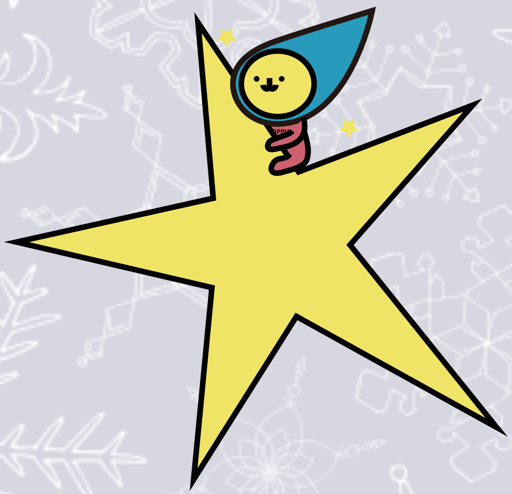
- We will plan to do K$^-$pp bound state search experiment using $\gamma d \rightarrow K^{+}\pi^{-}X$.
- We developed the aerogel Cherenkov counter for π/K separation in the momentum region 1 – 2 GeV/c.
- We performed electron beam test and study scintillation light from reflector.
  - When π detection efficiency > 95% (threshold 36 ch), K misID probability is ~ 17%

    Event selection using time information suppresses K misID probability to ~ 11%.
  - Scintillation light which wave length is 400 – 500 nm is emitted from ESR.

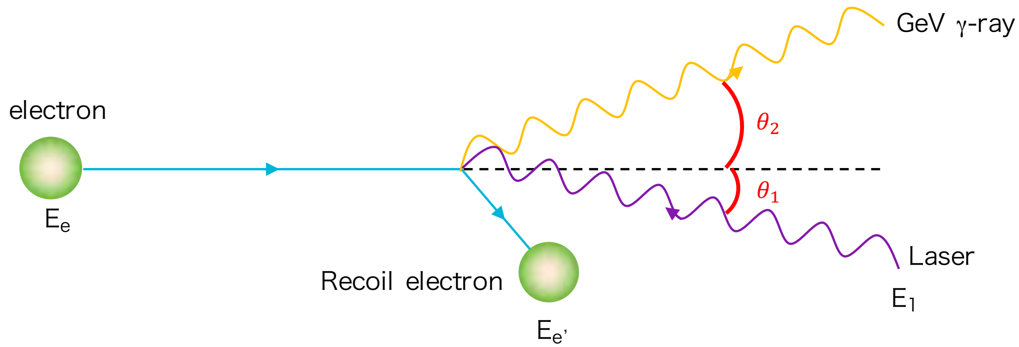
    Scintillation light will be suppressed by using aluminizedmylar.
- As a next step, we will optimize shape of AC box using simulation neglecting light absorption by aerogel. Then decide to use which reflector (ESR or aluminizedmylar).



appendix



γ ray generated by backward Compton scattering



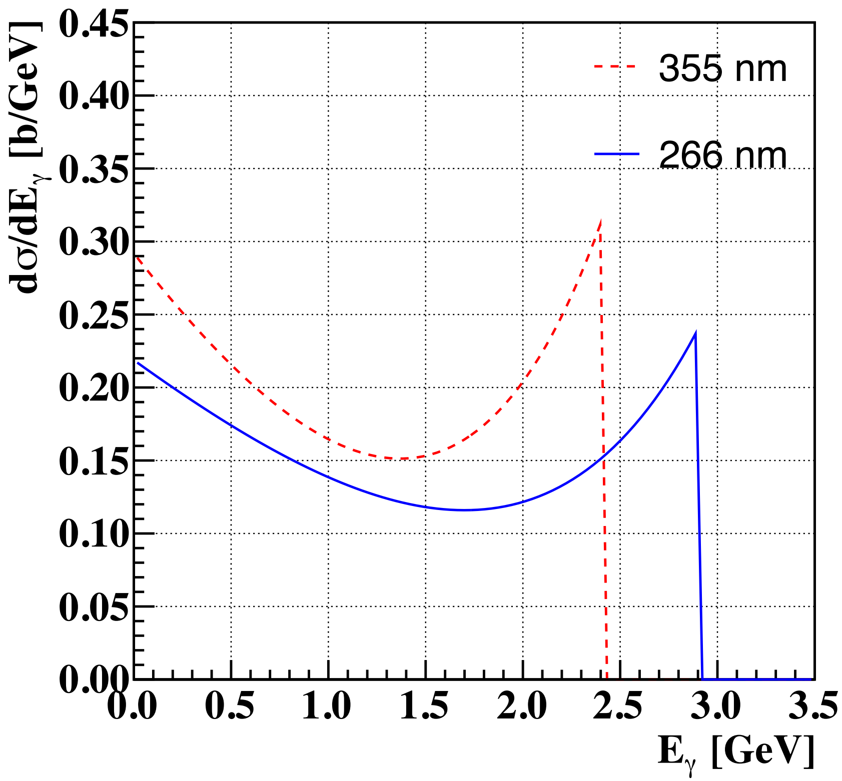
$$E_\gamma = E_1 \frac{1-\beta\cos\theta_1}{(1-\beta\cos\theta_2)+\dfrac{E_1}{E_e}(1-\cos(\theta_2-\theta_1))}$$

When use a laser which wave length is 266 nm,

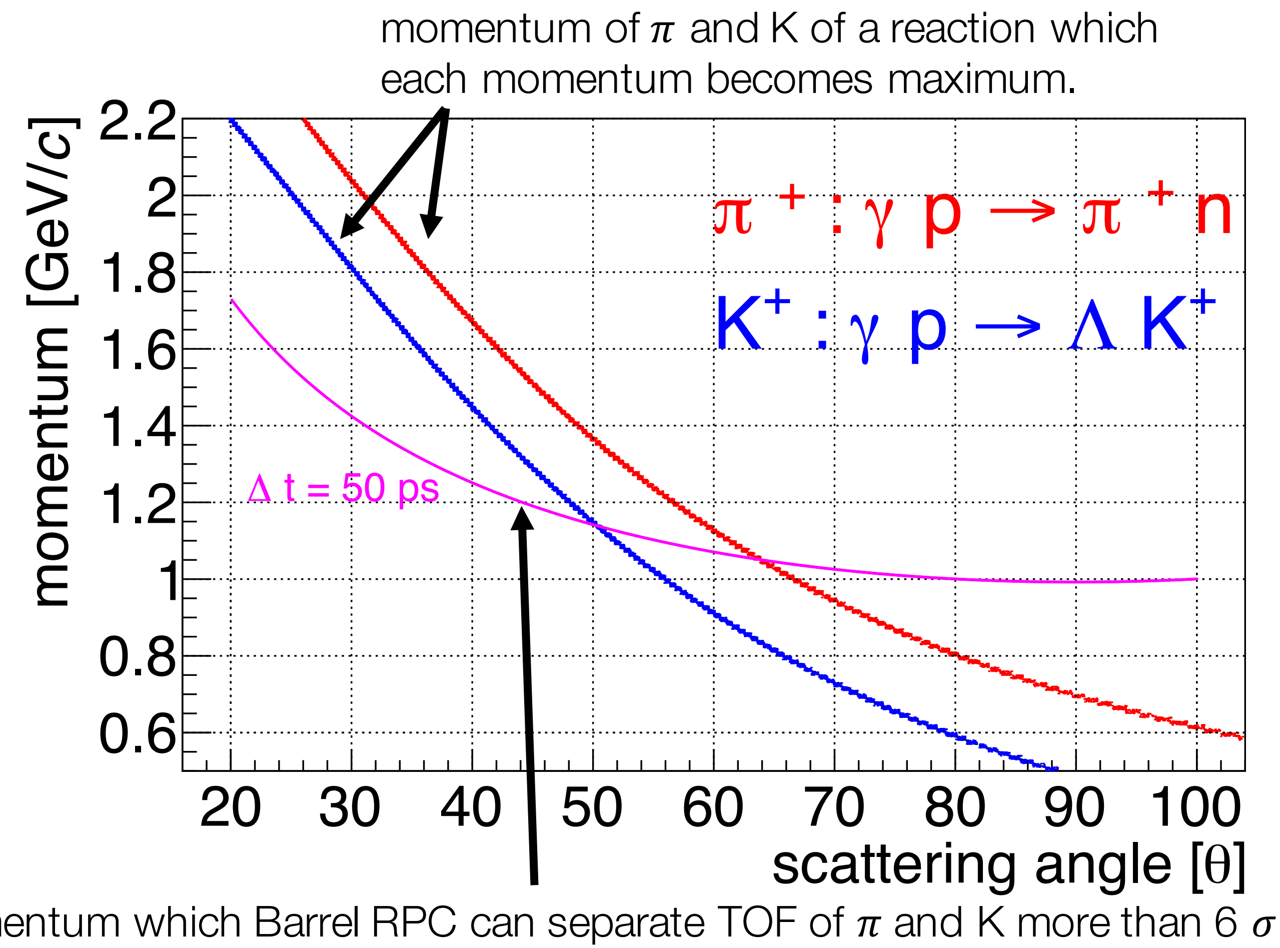
$E_{\gamma\ max} \sim 2.9$ GeV.

When use a laser which wave length is 355 nm,

$E_{\gamma\ max} \sim 2.4$ GeV.



PID using TOF



→ Barrel RPC can not separate π and K scattered less than 50°.

→ < 30° : Forward RPC, 30° – 40° : AC2, 40° - 50° : AC1

ratio of π and K events scattering 30° – 40°

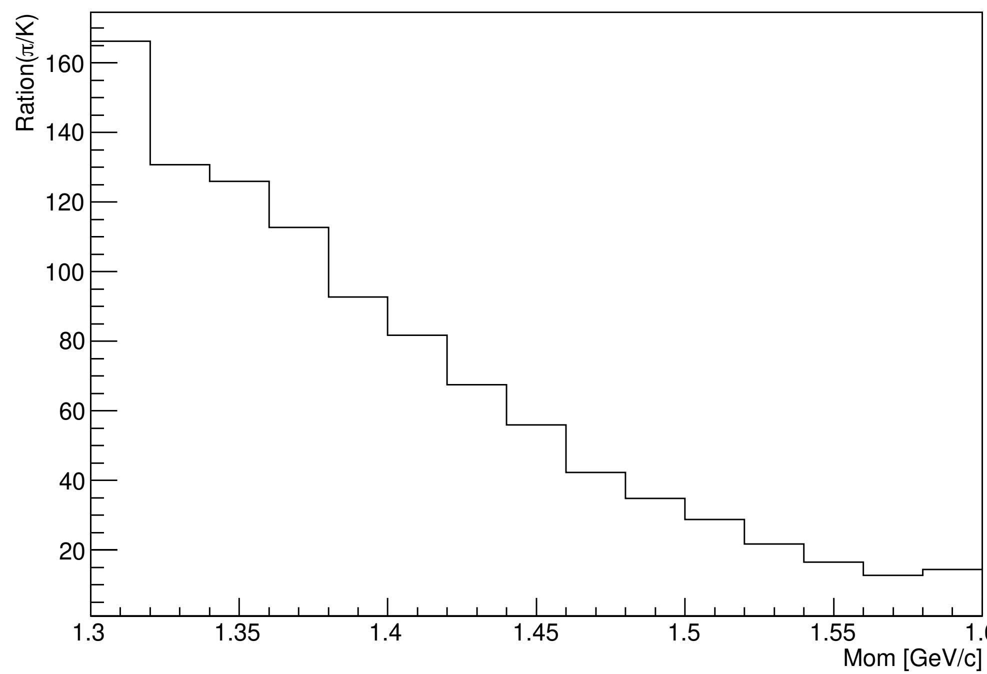
calculate ratio of π and K events scattering 30° – 40° using SAID.

http://gwdac.phys.gwu.edu/

caluculated reactions ($E_\gamma = 2.5$ GeV)

$$\gamma\, p \quad\rightarrow\quad \pi\, n$$
$$\gamma\, p \quad\rightarrow\quad \pi\,\pi\, N$$
$$\gamma\, p \quad\rightarrow\quad \pi\,\pi\,\pi\, N$$
$$\gamma\, p \quad\rightarrow\quad \Lambda\, K^+$$
$$\gamma\, p \quad\rightarrow\quad \Sigma^0\, K^+$$

caluculated π/K ratio

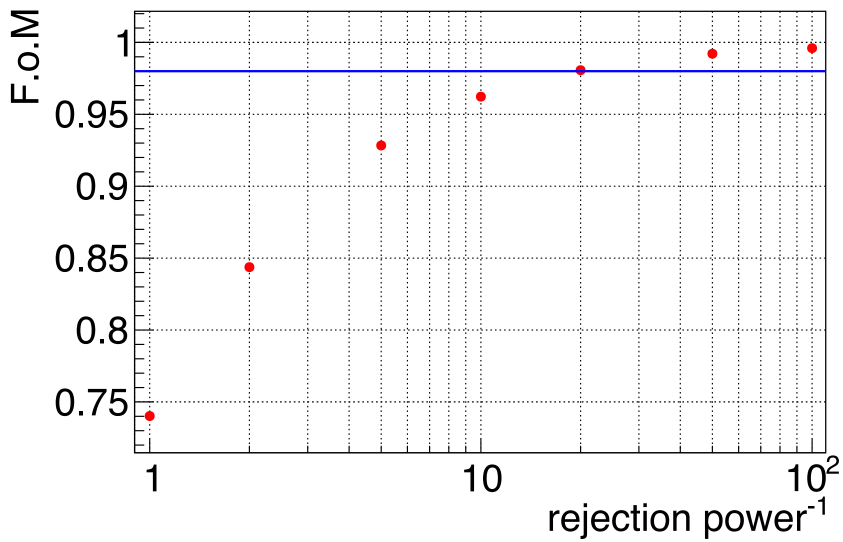


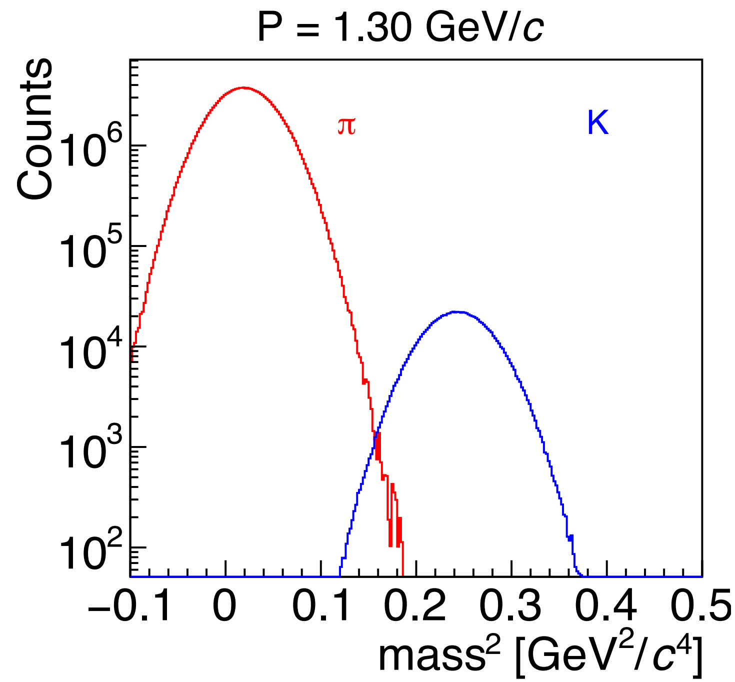
Requirement for AC

$f_{purity}(p) = \frac{N_K(p)}{N_\pi(p)+N_K(p)}$: purity of K scattering 30° - 40°

$N_\pi(p)$, $N_K(p)$: number of π or K scattering 30° - 40° which mass² value is within $\pm 2.5\sigma$ from a mean of gaussian fitted K mass² distribution.

$F.o.M = \{\prod_n f_{purity}(p_n)\}^{-1/n}$: mean of purity





Rejection power > 5%
= π detection efficiency > 95%

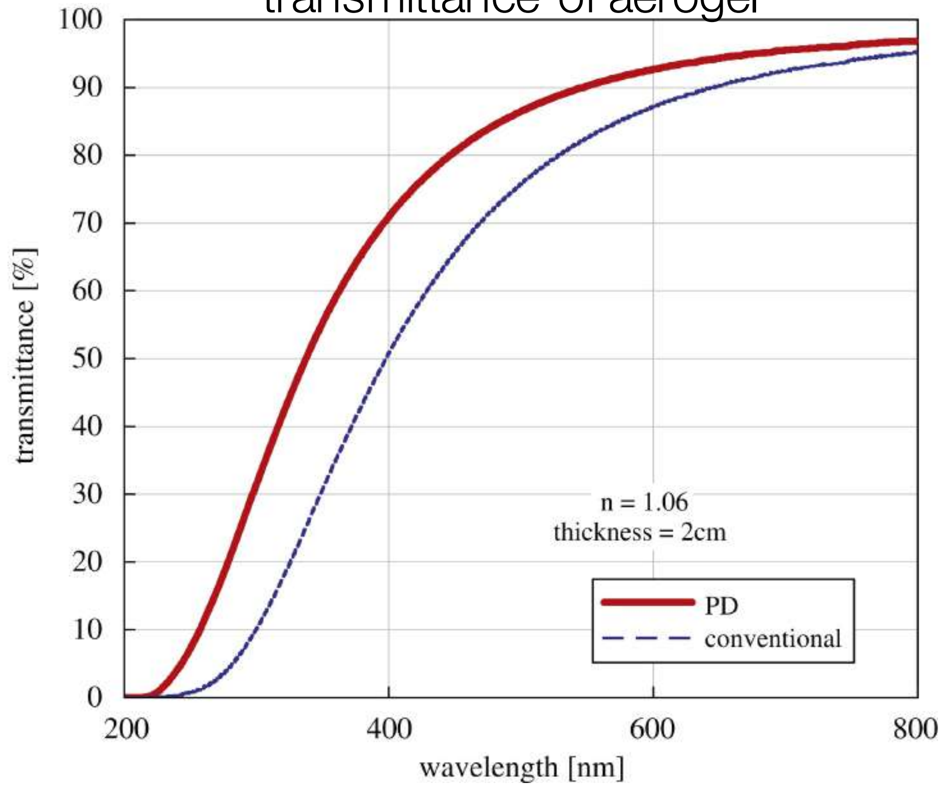
Simulation condition

Simulation code : Guide-7

Condition

- incident particle : π
- momentum : 2.0 GeV/c
- reflectivity of reflector : 98%
- PMT response range : 200 – 650 nm
- PMT quantum efficiency : 20%

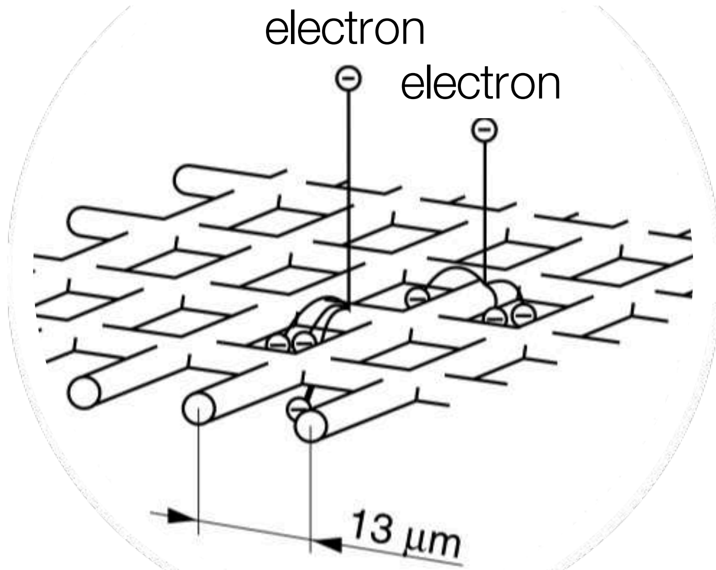
transmittance of aerogel



I. Adachi *et al.*, Nucl. Instrum. Methods. A, 639 222-224 (2011)

fine-mesh PMT

mesh dynodes are placed with a narrow gap



- to efficientry multiply photoelectron in the magnetic field
- Single photo-electron signal is NOT a gaussian.
- The relation of ADC and mean of number of photo-electron (N_{pe}) is not linear.

performance test : proton beam test

performed 2018/10/17 – 18 @CYRIC

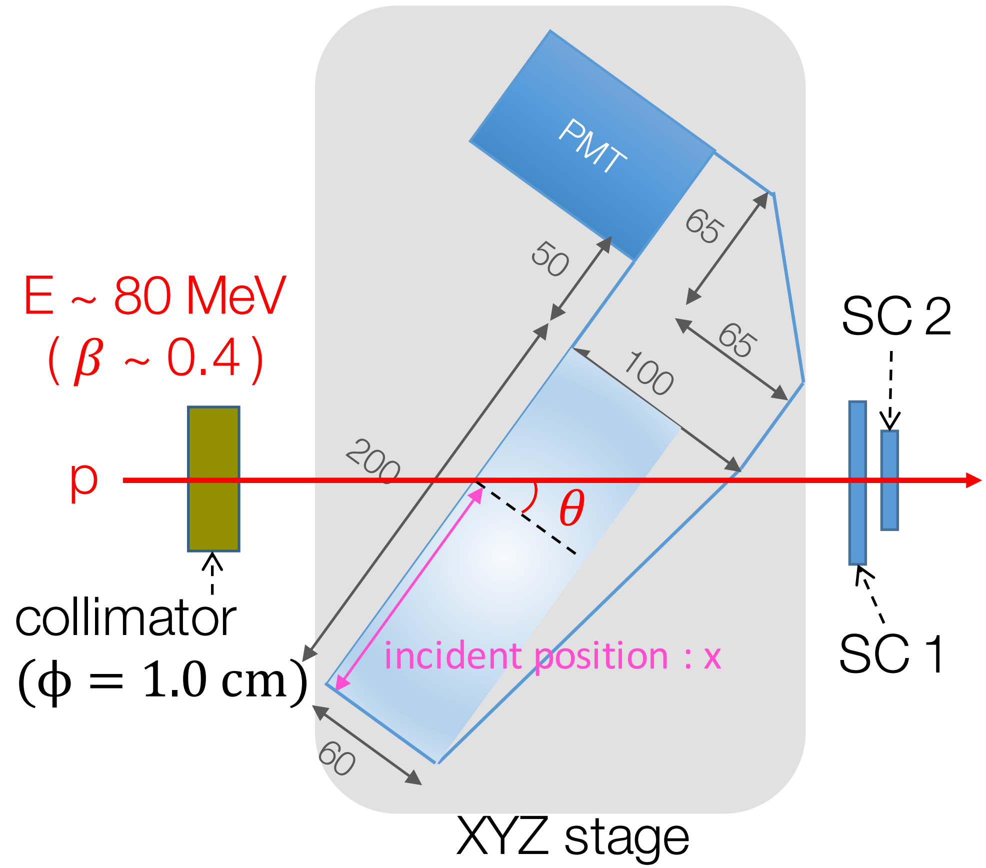
Purpose

to check a light output of $\beta < \beta_{th}$ particle

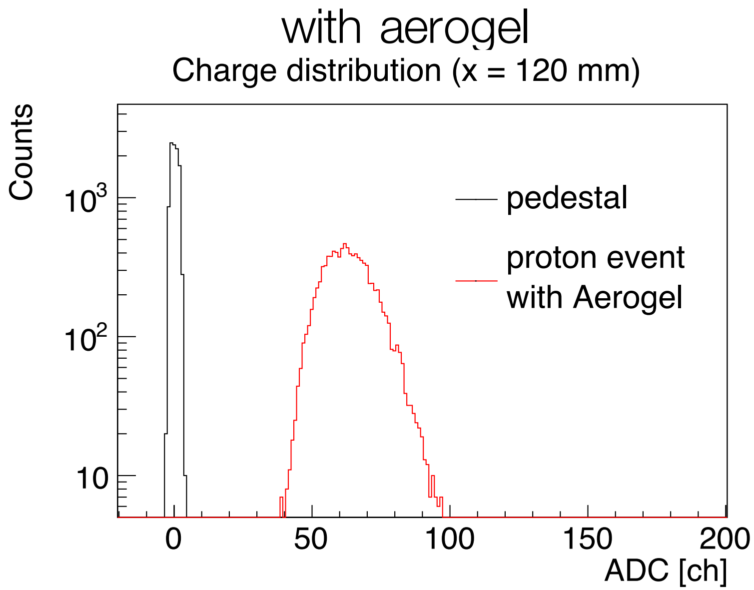
- compare light output with and without aerogel
- position dependence

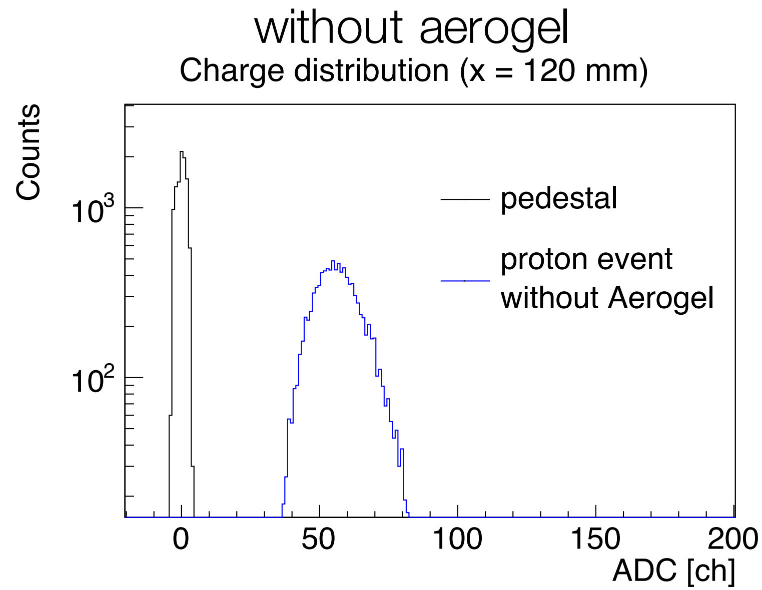
Conditions

- trigger signal : coincidence of 2 plastic scintillator
- trigger rate ~ 50 Hz
- incident position : 0, 60, 120 mm
- with / without aerogel in the prototype



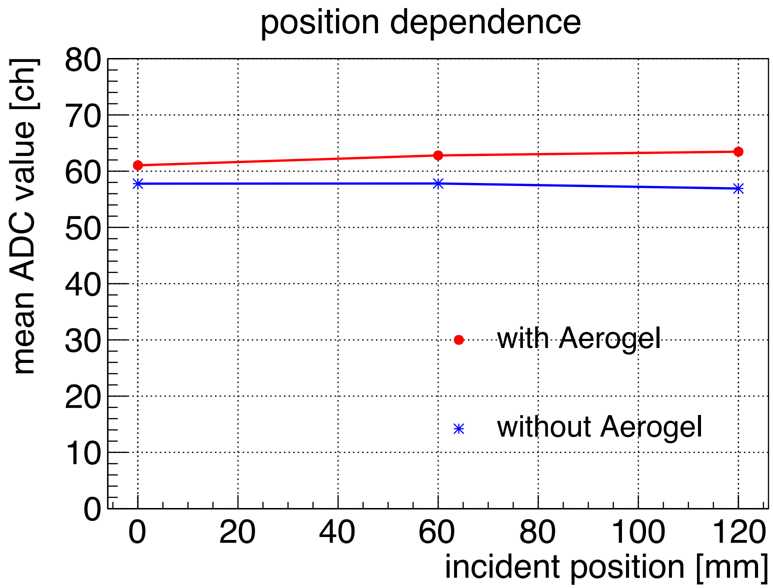
light output with and without aerogel



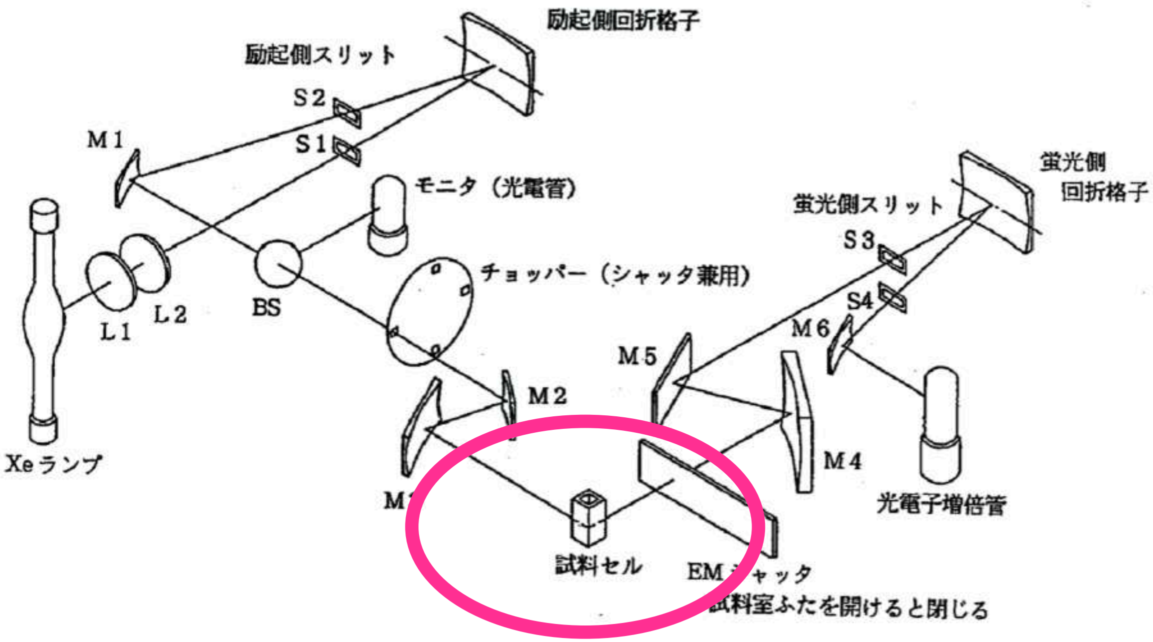


- Difference of light output between with and without aerogel is small.
- Position dependence is small.

→ Is scintillation light emitted from reflector ?



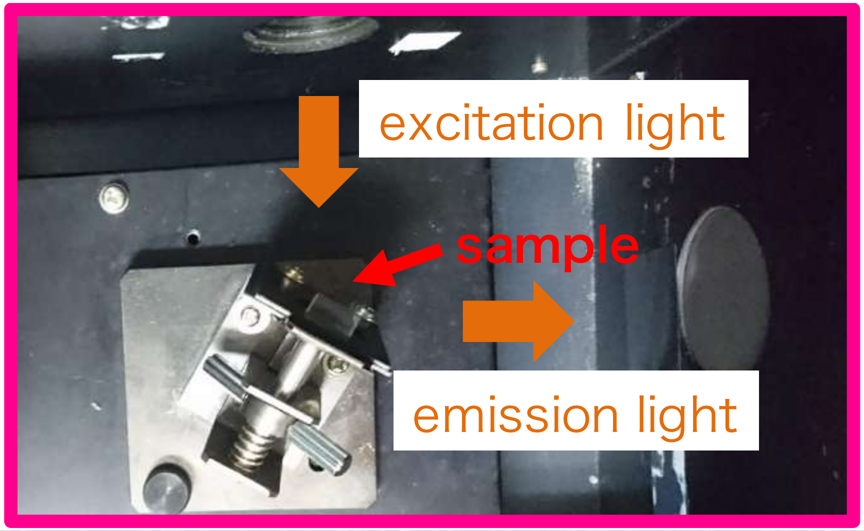
Study of scintillation light from reflector



2018/11/18 @KEK

HITACHI spectro-fluorophotometer

F-4500



Condition

- excitation wavelength : 200 – 600 nm (Δ 5 nm)
- emission wavelength : 200 – 600 nm (Δ 5 nm)

Cherenkov light from air

calculate ratio of Cherenkov N_{pe} from aerogel and air

refractive index of air = 1.0002

→ $\beta_{th} = 0.9998$ ($\beta_{electron} > \beta_{th}$, $\beta_{proton} < \beta_{th}$)

$$\frac{d^2 N_{pe}}{dLd\lambda} = \frac{2\pi\alpha z^2}{\lambda}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

flight pass L : ~ 7 cm (aerogel), ~ 8 – 12.5 cm (air)

integrate from 200 – 650 nm (PMT response range)

→ $N_{pe}(aerogel) : 614,\ N_{pe}(air) : 4.8 - 7.7$

→ N_{pe} (air)/N_{pe} (aerogel) < about 1%

Cherenkov light by δ-electron

kinetic energy distribution of δ-electron

$$\frac{d^2N}{dTdx} = \frac{1}{2}Kz^2\frac{Z}{A}\frac{1}{\beta^2}\frac{F(T)}{T^2}$$

$$F(T) = (1 - \beta^2 T/T_{max})$$

maximum kinetic energy of δ-electron

(T_{max})

$$T_{max} = \frac{2m_e c^2\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

integrate $\frac{d^2N}{dTdx}$ from Cherenkov kinetic energy threshold T_{th} to T_{max}

→ mean of number of generated δ-electron

number of generated δ-electron follows a poisson distribution.

→ probability of number of generated δ-electron becomes more than 1 = δ-electron generating probability (P_δ)

incident particle	β	T_{max} [MeV]	P_δ
electron	~ 1	35.6	0.04
proton	~ 0.4	< T_{th}	-

→ effect of δ-electron is less than 4%

light source

light source when electron beam test and proton beam test

incident particle	with or without aerogel	light source
electron ($\beta \sim 1$)	with aerogel	Cherenkov light from aerogel
		Cherenkov light from air
		Cherenkov light by δ-electron
		Scintillation light from reflector
	without aerogel	Cherenkov light from air
		Scintillation light from reflector
proton ($\beta \sim 0.4$)	with aerogel	Cherenkov light by δ-electron
		Scintillation light from reflector
	without aerogel	Scintillation light from reflector

response by 1.5 GeV/c π and K

Cherenkov light : $\frac{d^2 N_{pe}}{dLd\lambda} = \frac{2\pi\alpha z^2}{\lambda}\left(1 - \frac{1}{\beta^2 n^2}\right)$

Scintillation light ∝ $\frac{1}{\beta^2}$

incident particle	β	$N_{cherenkov}$	$N_{scintillation}$	N_{all}
electron (80 MeV)	~ 1.0	16.5	3.0	19.5
π (1.5GeV/c)	0.996	14.2	3.0	17.2
K (1.5 GeV/c)	0.950	-	3.3	3.3

scale the charge distribution of electron beam test

- When threshold is 32 ch, $\boldsymbol{\pi}$ detection efficiency : 95%, K misID probability : 25%

Event selection using time information …

- When threshold is 20 ch, $\boldsymbol{\pi}$ detection efficiency : 95%, K misID probability : 11%