

Neutron-insensitive gamma-ray detector with aerogel for rare neutral-kaon decay experiment

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on behalf of the KOTO collaboration



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$K_L \rightarrow \pi^0 \bar{v}v$ decay and KOTO experiment



- ◆ matter-antimatter asymmetry in our universe
 - ◆ A new source of CP violation is necessary.

◆ $K_L \rightarrow \pi^0 \bar{v}v$

◆ CP violating rare decay ($\text{Br}_{\text{SM}} = 2.4 \times 10^{-11}$)

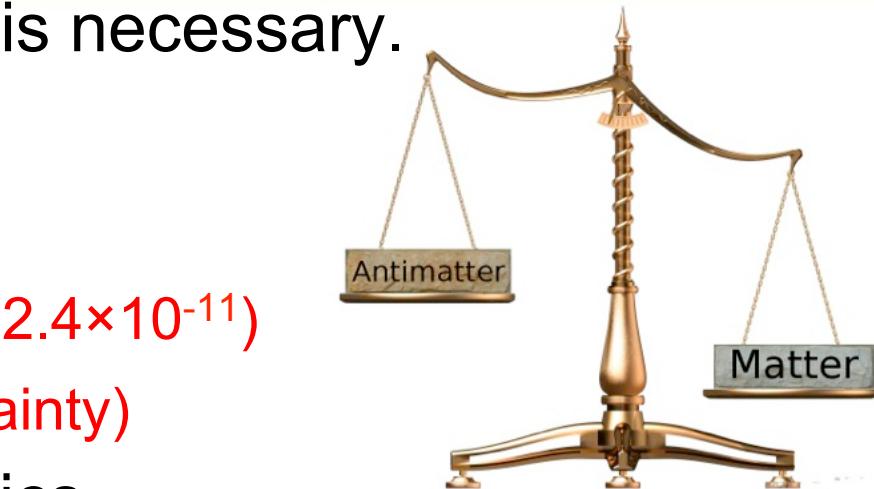
◆ theoretically clean ($\sim 2\%$ uncertainty)

→ excellent probe for BSM physics

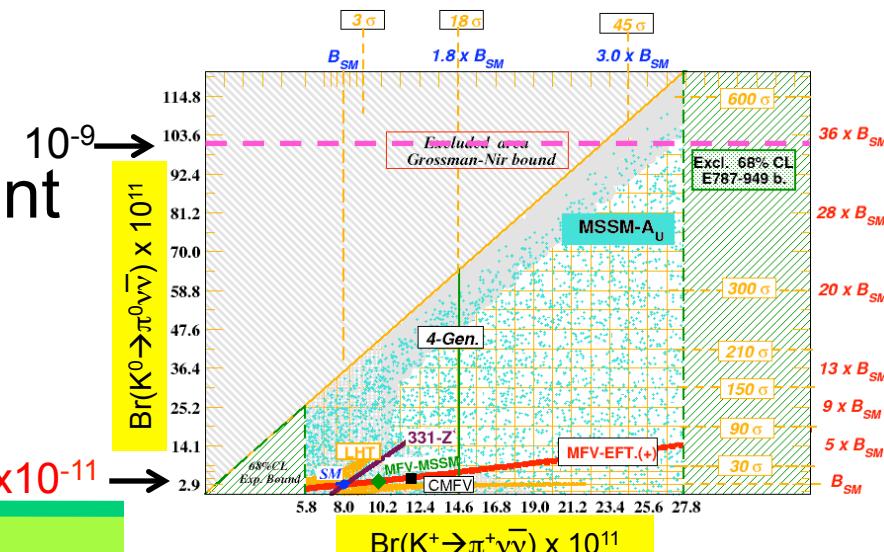
◆ current upper limit :

$< 2.6 \times 10^{-8}$ (90% C.L.)

→ The J-PARC KOTO experiment aims the first detection of signal events.

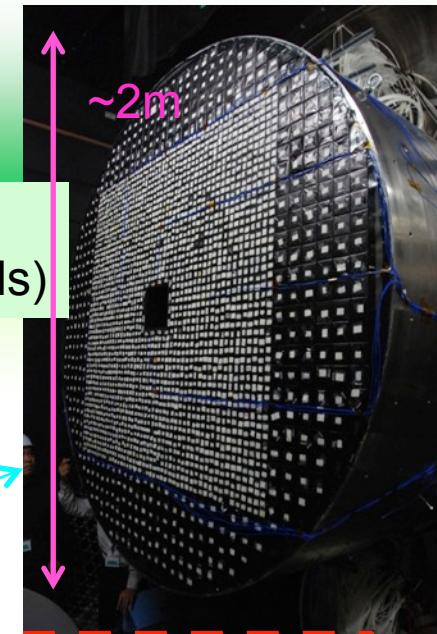


http://www.fnal.gov/pub/today/archive/archive_2013/today13-10-31.html



$K_L \rightarrow \pi^0 \nu \bar{\nu}$: signal detection

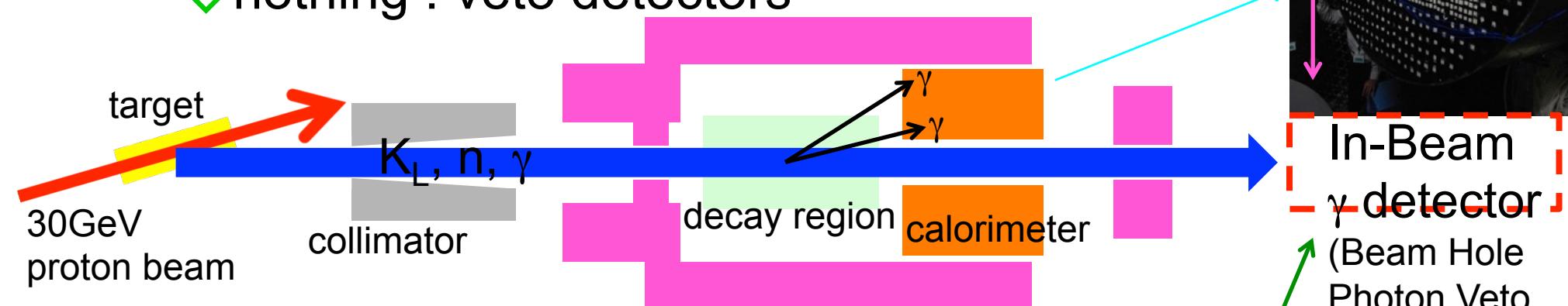
main calorimeter
(~3000 CsI crystals)



◆ signal : $2\gamma + \text{nothing}$

◆ 2γ : undoped CsI calorimeter

◆ nothing : veto detectors



◆ To achieve high sensitivity...

◆ intense K_L beam

◆ but the flux of neutrons also increases...

◆ complete background rejection

◆ a γ detector IN the neutral beam is required

→ The in-beam detector should be sensitive to γ ,
but also insensitive to neutrons

requirement for the in-beam γ detector



◇ BG reduction

◇ $K_L \rightarrow 2\pi^0$ decay (4 γ in final states)

◇ 2 γ hit CsI

◇ 1 γ hits barrel detector

(low energy and hard to detect)

◇ remaining γ escape forward

to be detected by in-beam detector

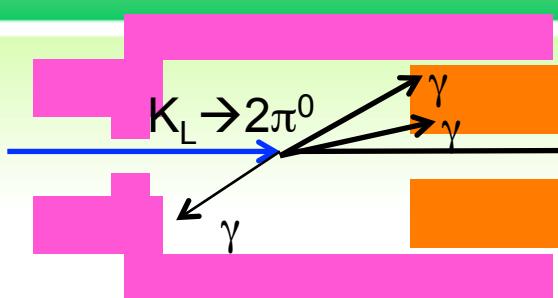
$\rightarrow 10^{-3}$ inefficiency is needed for

$E_\gamma > 1\text{GeV}$

◇ rate tolerance

◇ 0.5GHz neutrons and low energy γ

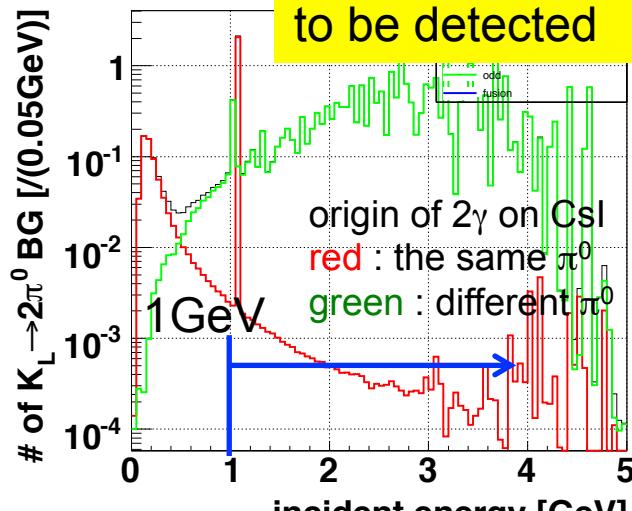
\rightarrow single counting rate / signal loss
should be kept to the tolerable level



J-PARC KOTO experiment

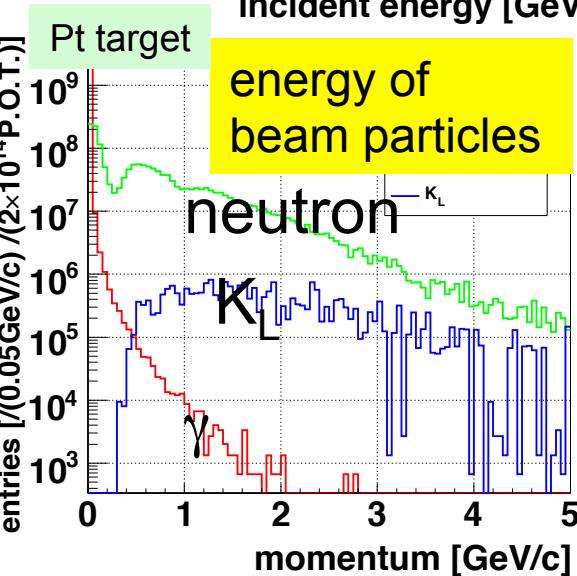
BHPV (in-beam γ detector)

γ energy
to be detected



Pt target
energy of beam particles

neutron

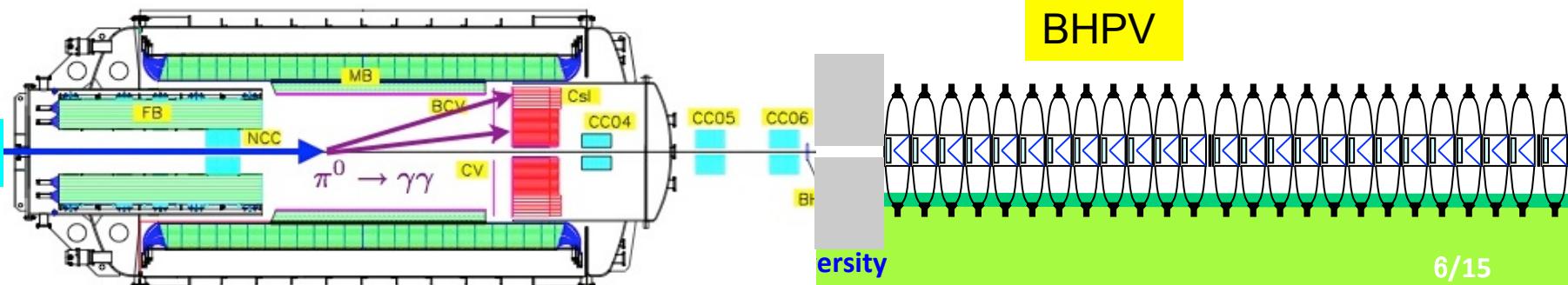
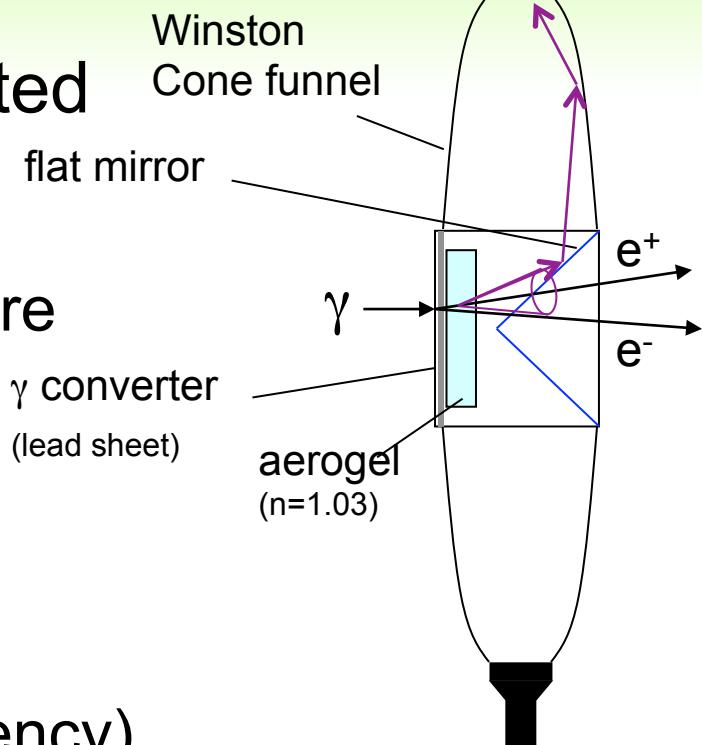


Beam Hole Photon Veto (BHPV)



5inch PMT
DPMC KOTO experiment

- ◆ lead and aerogel γ detector
- ◆ Cerenkov lights in aerogel are detected
 - ◆ γ incidence : converted to e^\pm
→ enough Cerenkov lights
 - ◆ neutron incidence : protons or pions are mainly produced
→ little Cerenkov lights
→ excellent blindness to neutrons
- ◆ 25 dual-readout modules
 - ◆ enough radiation lengths ($9X_0$ is needed to achieve 10^{-3} inefficiency)
 - ◆ require 3-successive-module coincidence for γ detection
→ further separation of neutron and rejection of low energy γ

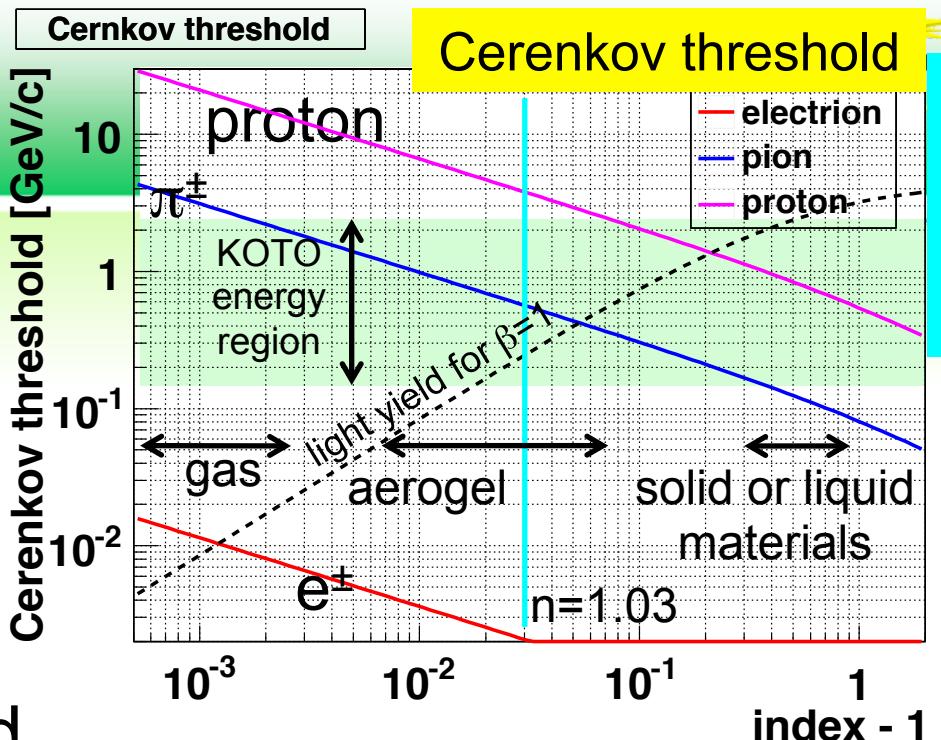


detector components

◆ aerogel

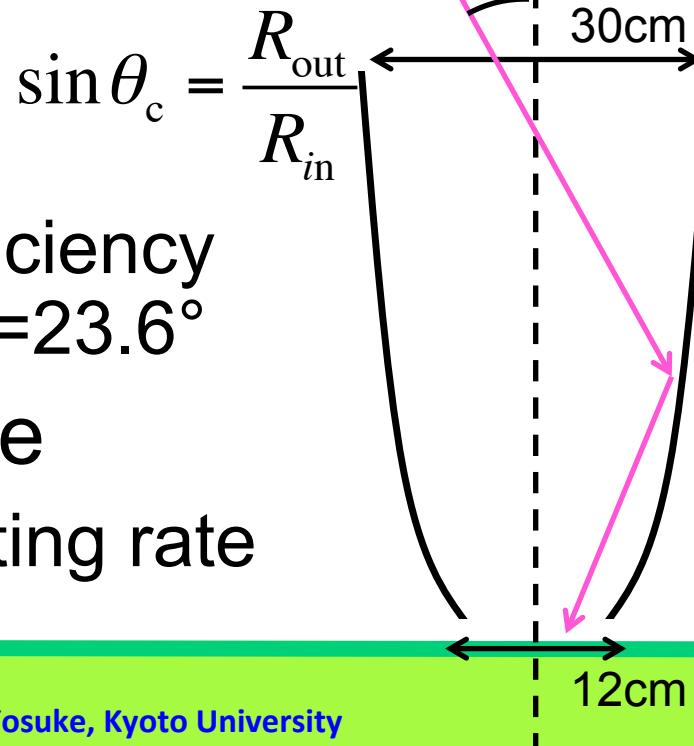


◆ index = 1.03 is suitable to get high efficiency for e^\pm (or γ) while keeping detection of π^\pm and protons (or n) suppressed



◆ Winston Cone

◆ off-axis parabola
◆ 100% collection efficiency for photons w/ $0 < \theta_c = 23.6^\circ$



◆ dual readout module

◆ reduce single counting rate
◆ better uniformity

Cerenkov angle for $n=1.03 : 13.9^\circ$

MC simulation

- ◆ EM shower and Cerenkov lights generation by Geant4

- ◆ Cerenkov ray tracing with a custom-made code

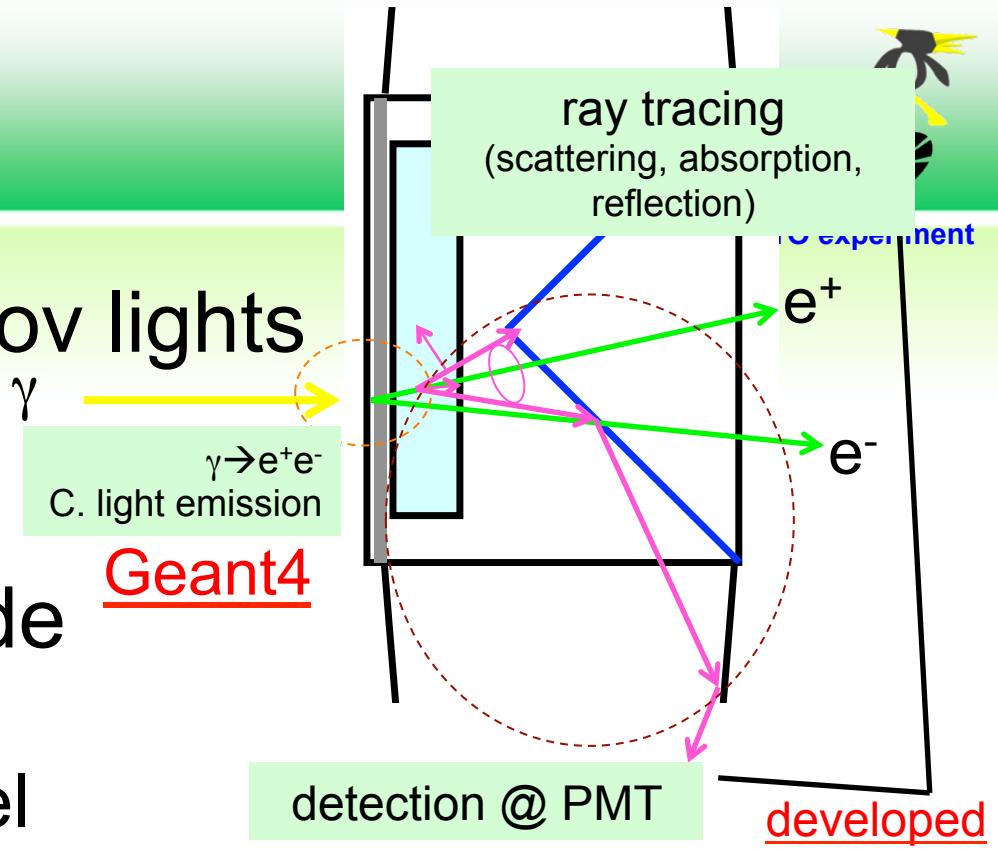
- ◆ Rayleigh scattering and absorption in aerogel

- ◆ $A^* \exp(-C/\lambda^4)$ probability

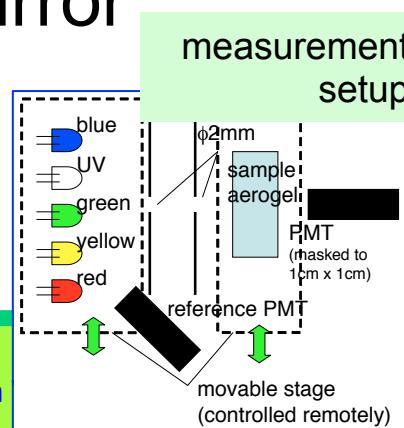
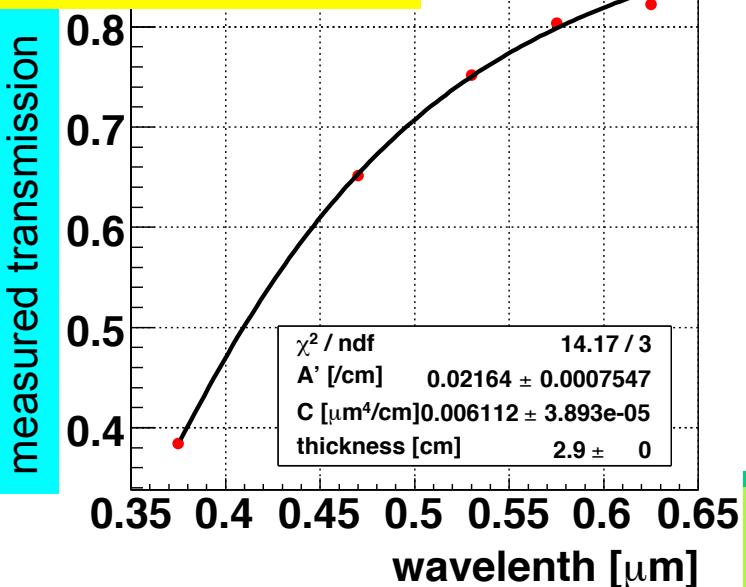
- ◆ parameters are derived from measurement with LED

- ◆ reflection by flat mirror and Winston Cone

- ◆ Q.E. of PMT



aerogel transmission measurement



response to e^+ beam

prototype detector

- ◆ position dependence is measured with 600MeV/c e^+ beam and compared with MC

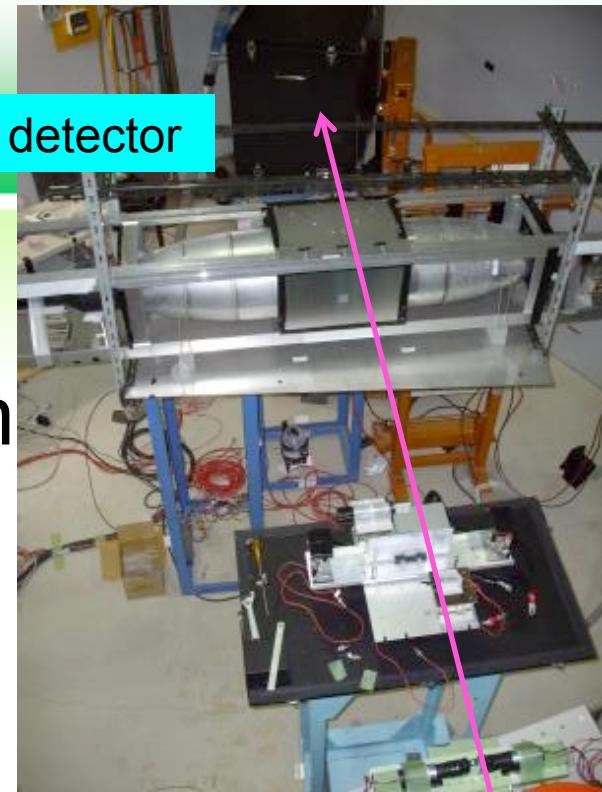
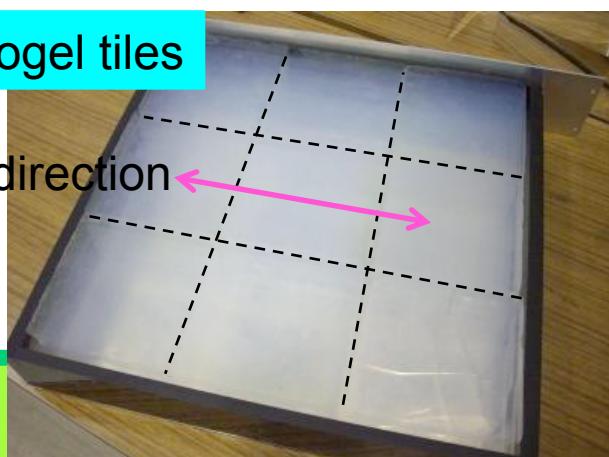
- ◆ result

- ◆ position dependence of light yield is well reproduced by MC

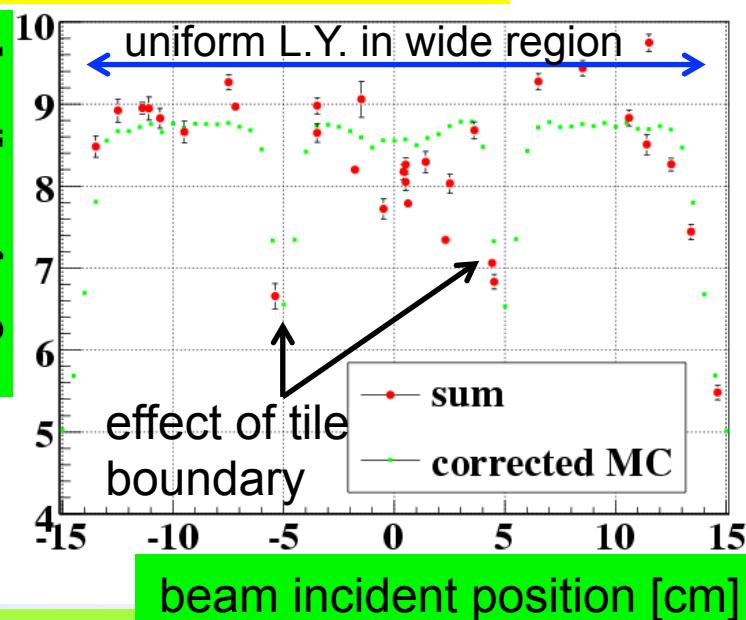
- ◆ disagreement in absolute light yield ($\sim 55\%$ of MC)

3×3 aerogel tiles

scan direction



result of horizontal scan



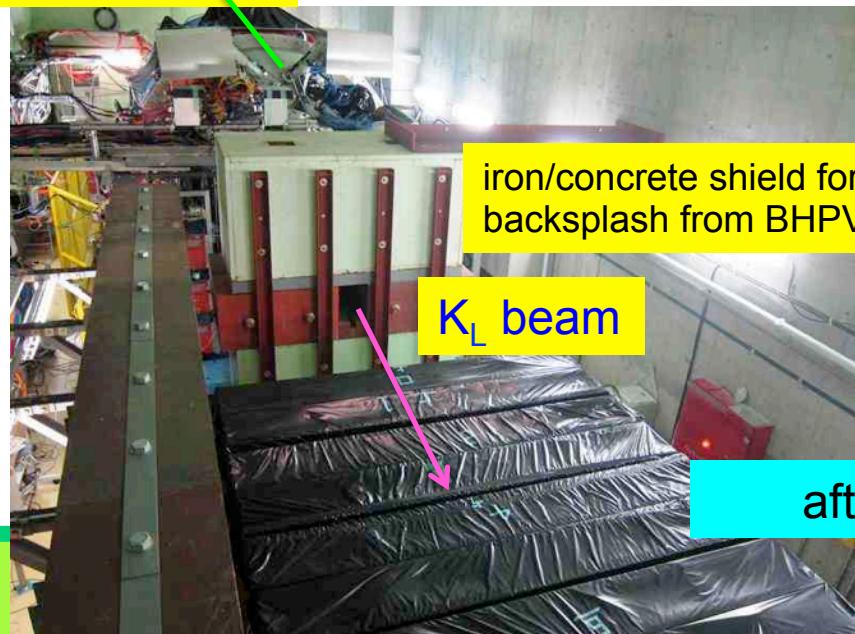
installation for KOTO physics run



- ◆ 12 out of 25 modules in design were installed to the KOTO experimental area for run May2013

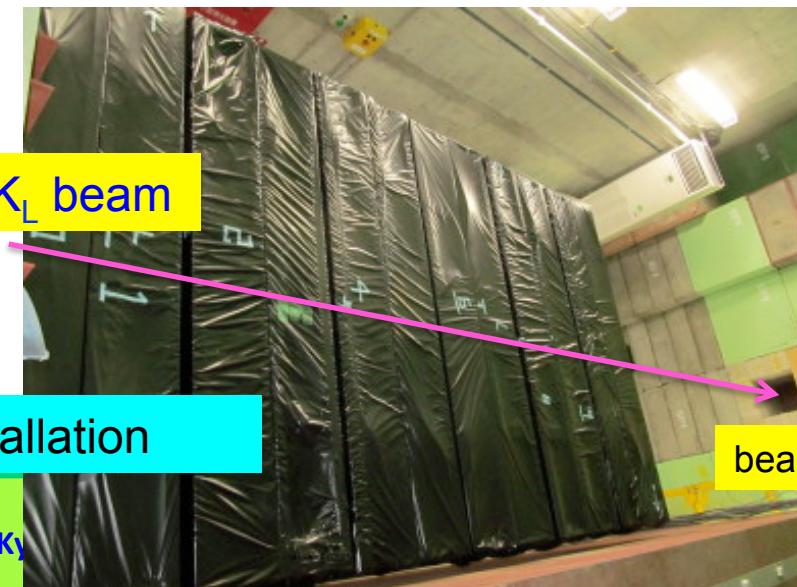
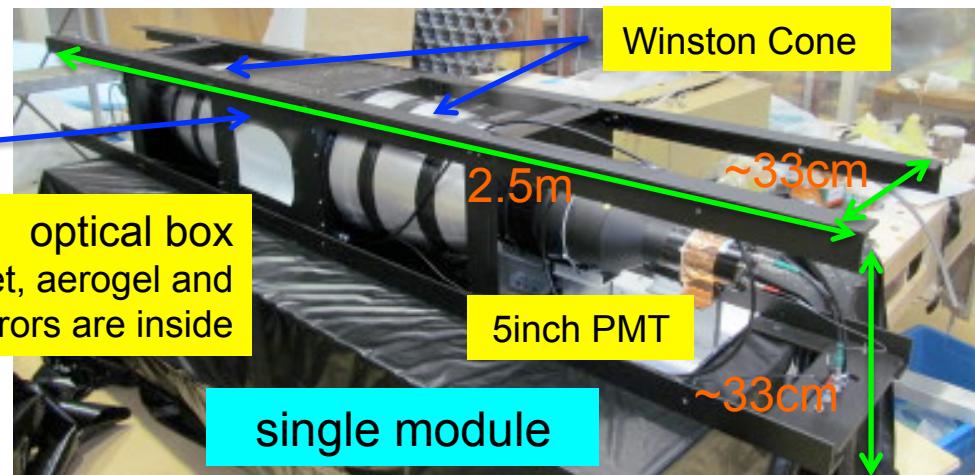


upstream section



after installation

Yosuke, Ky



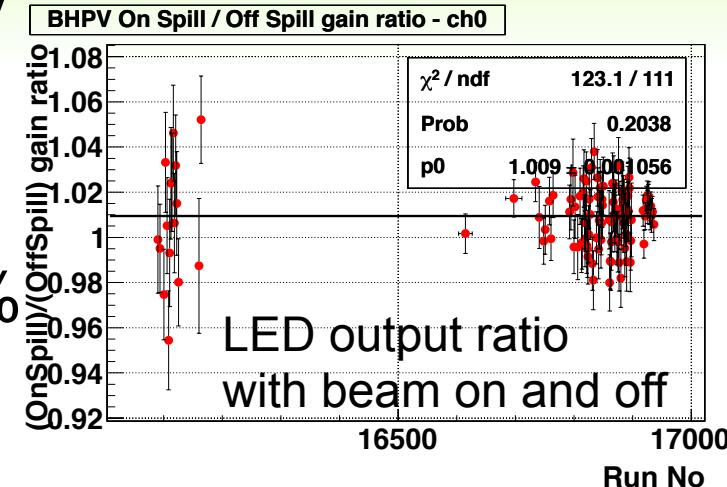
performance during beam operation



J-PARC KOTO experiment

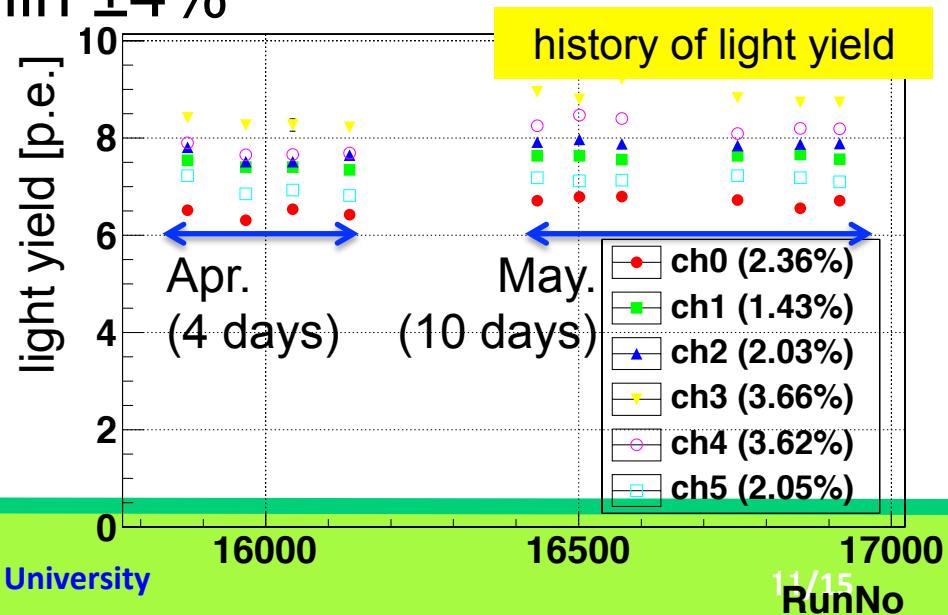
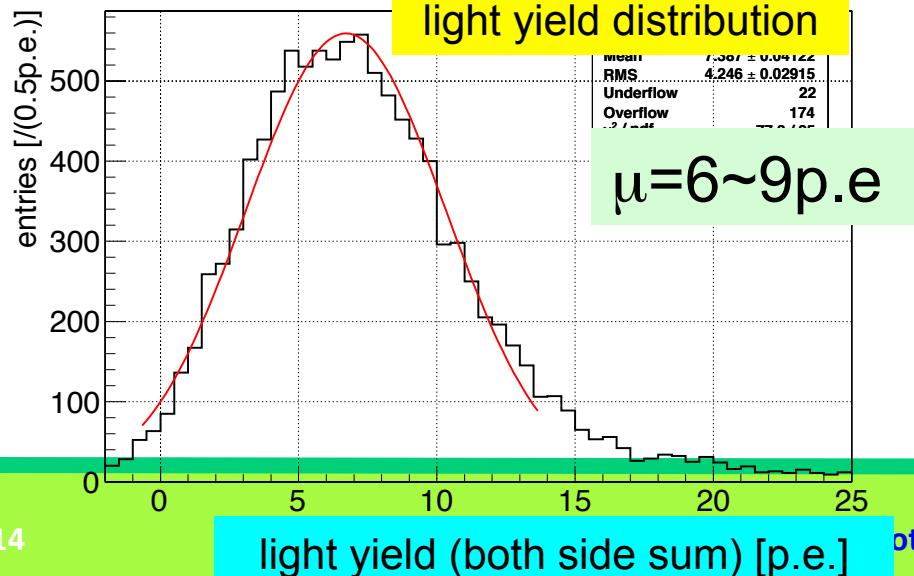
◆ calibration and PMT gain stability

- ◆ checked w/ LED
- ◆ stable within $\pm 5\%$
- ◆ beam loading effect is less than 5%



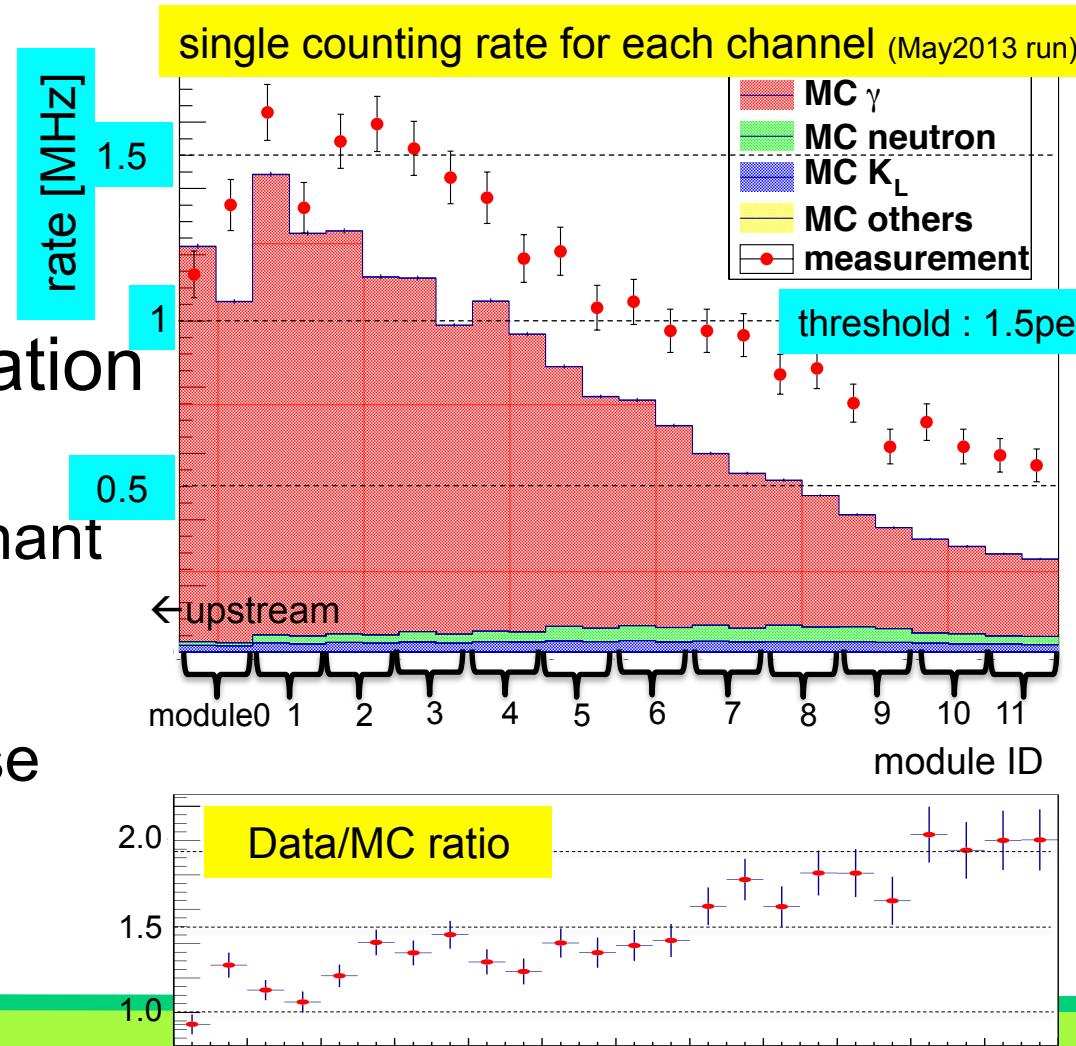
◆ light yield of aerogel

- ◆ tagging the charged particle with hits in other modules
- ◆ as expected and stable within $\pm 4\%$



counting rate

- ◆ Single counting rate is measured by random trigger data and compared with MC simulation.
- ◆ Measured rate is under 2MHz
 - ◆ tolerable level
 - ◆ Agrees to MC expectation within factor 2.
 - ◆ γ contribution is dominant in MC
 - ◆ uncertainty in energy spectrum and response in hadron interaction

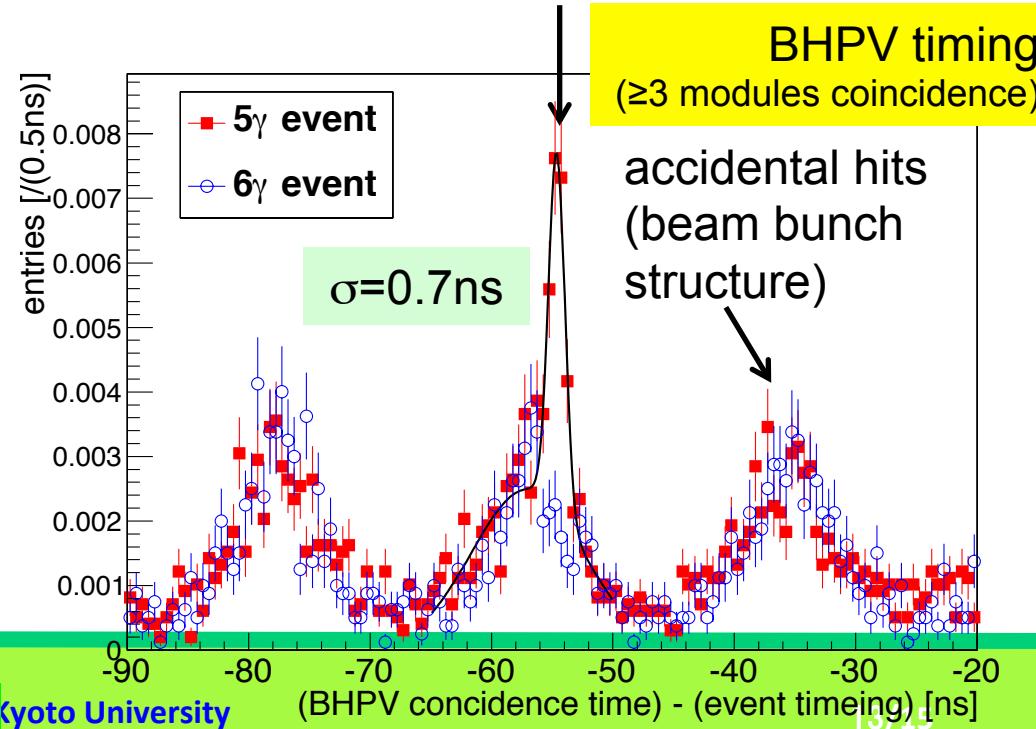
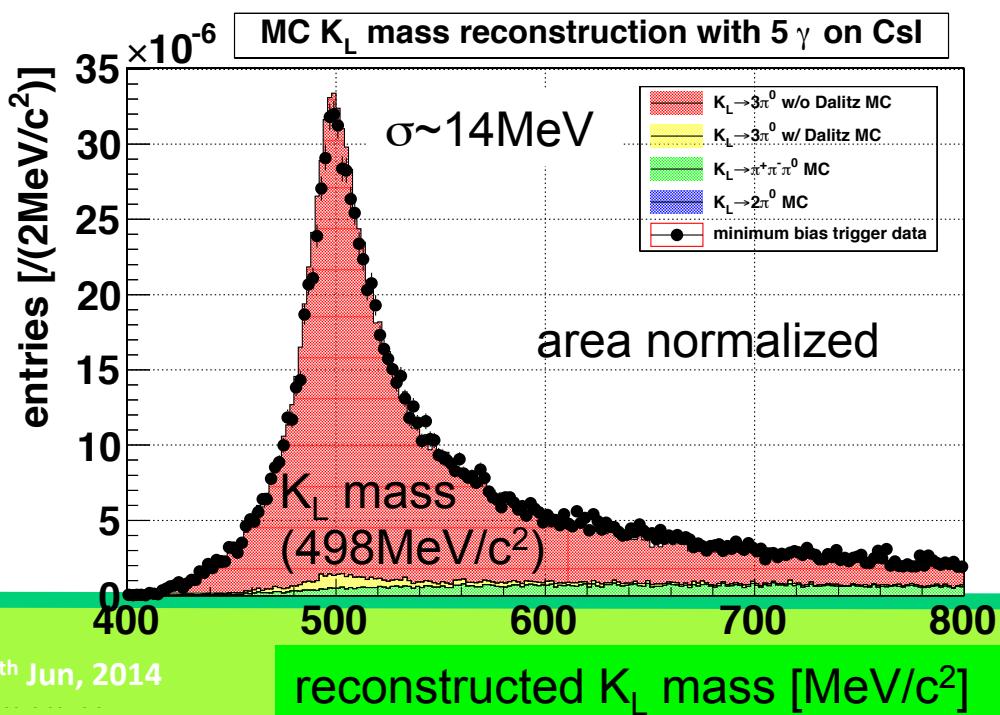
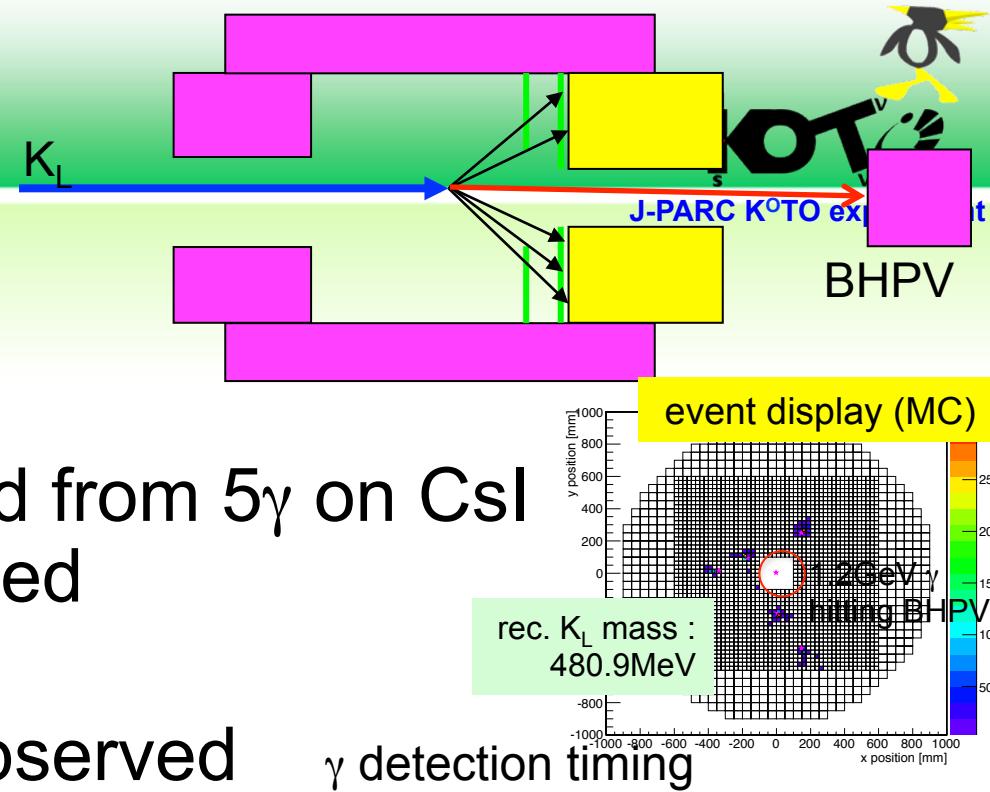


γ detection

◆ $K_L \rightarrow 3\pi^0 \rightarrow 5\gamma$ on CsI
 (Br ~ 20%) + 1 γ to BHPV

◆ K_L mass is reconstructed from 5 γ on CsI
 → K_L events can be tagged

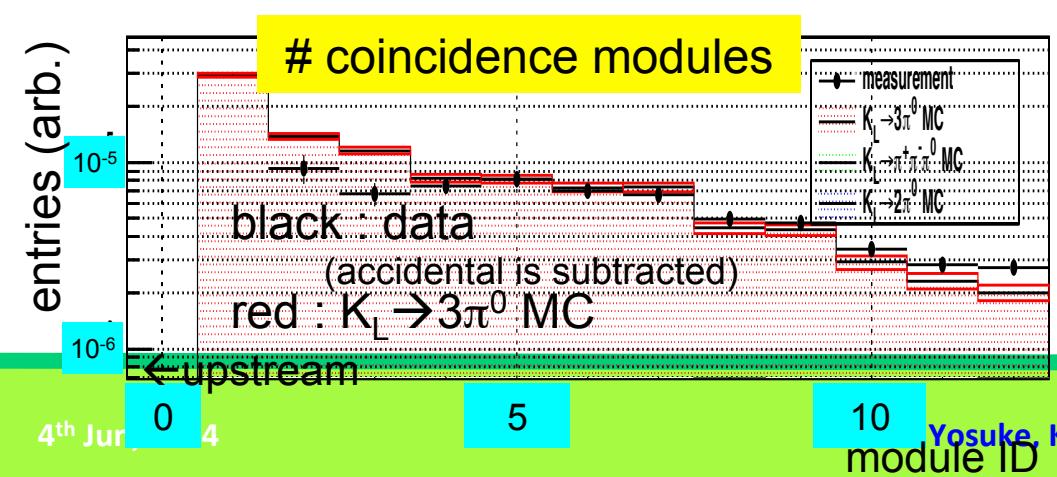
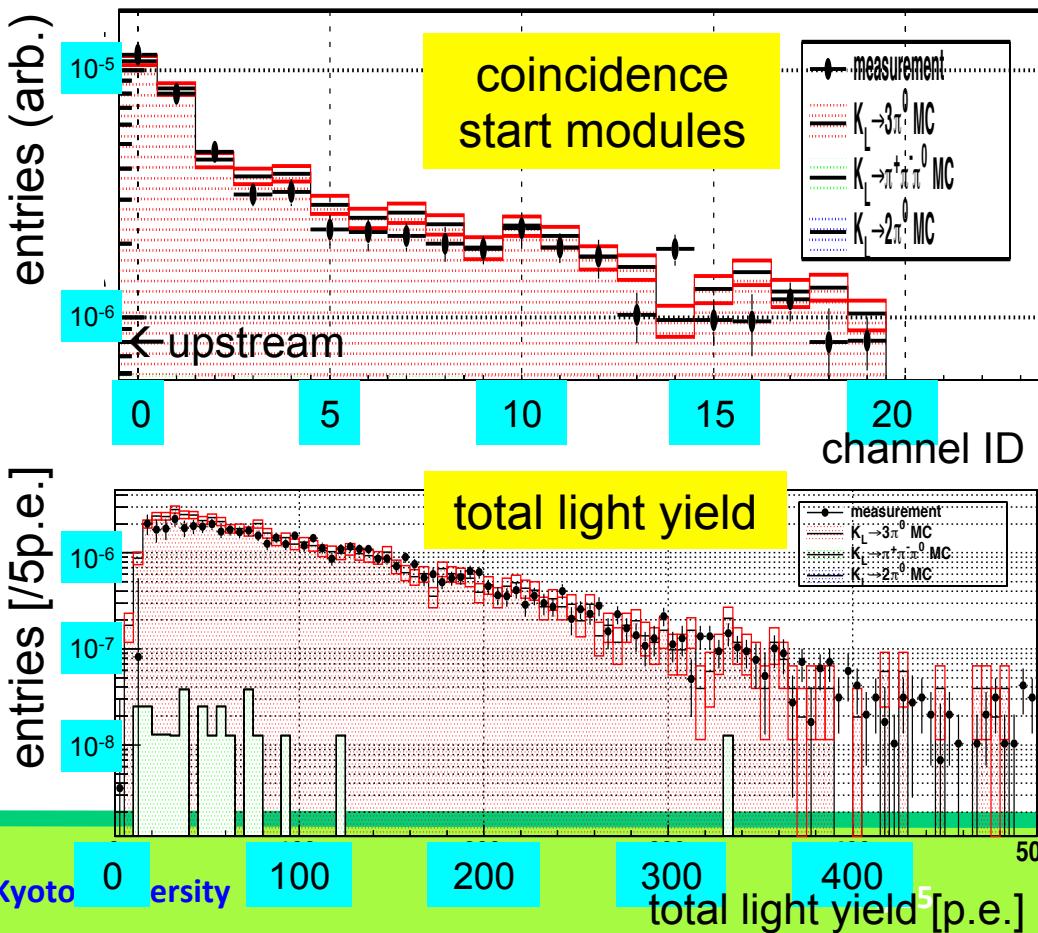
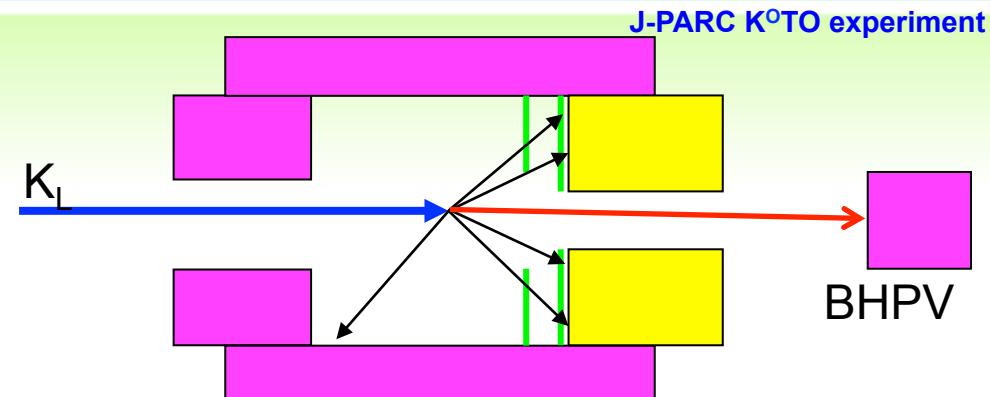
◆ timing of BHPV
 → clear timing peak is observed



response for K_L decay events



- ◆ require 4 γ on CsI
 - ◆ effect of accidental hits are estimated by 6 γ on events and subtracted
- ◆ MC well reproduce measurement data



Yosuke, Kyoto
4th Jun. 2018

summary

- ◆ γ detector which is highly insensitive to neutrons is necessary to search for $K_L \rightarrow \pi^0 \bar{\nu} \nu$ decay.
- ◆ Lead-aerogel sandwich detector is proposed and developed.
- ◆ Response to charged particles well agrees to MC simulation.
- ◆ The detector is partially installed to the KOTO first physics run, and excellent performance is achieved.
- ◆ Preparation for KOTO final sensitivity is also in progress.

backup slides

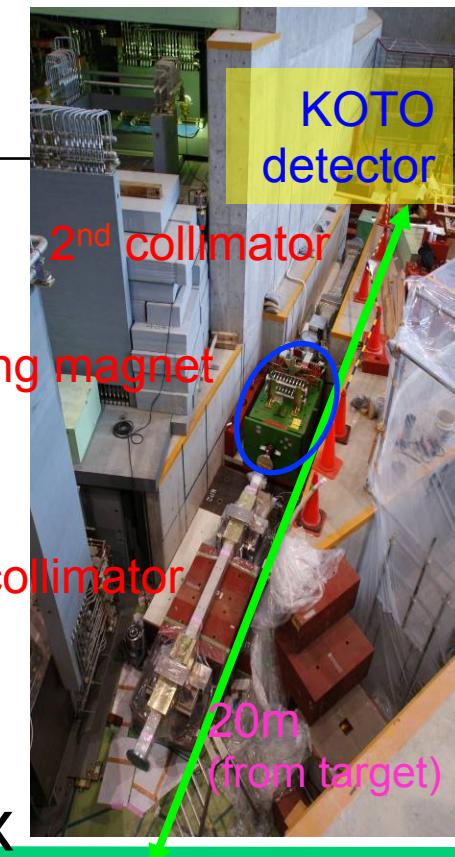
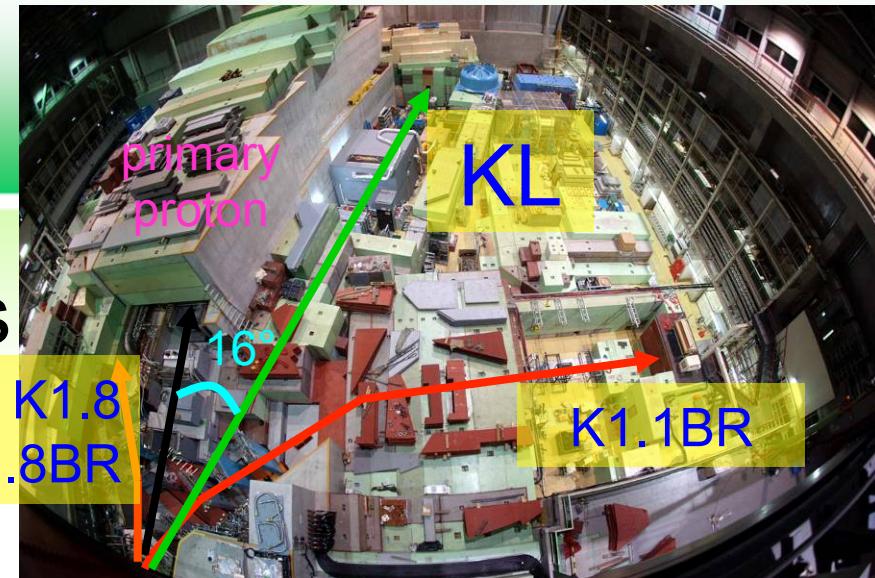
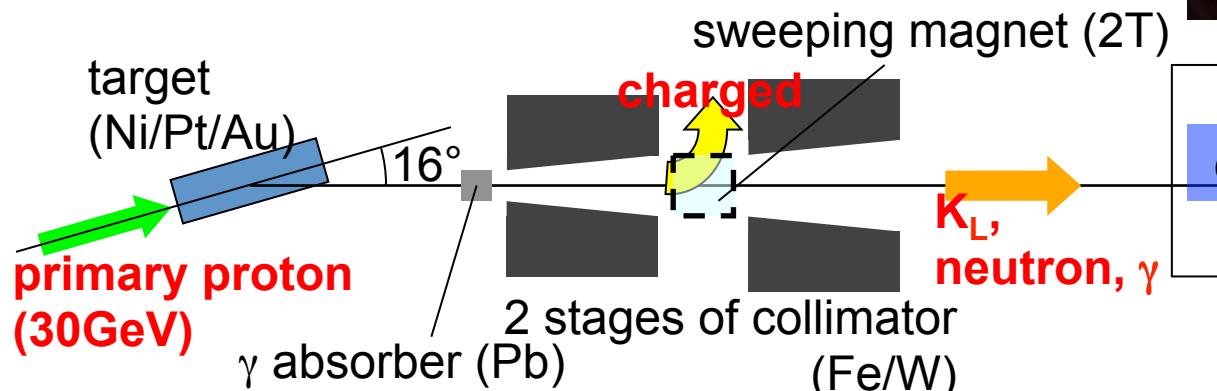
$$K_L^0 \rightarrow \pi^0 \bar{v}v$$

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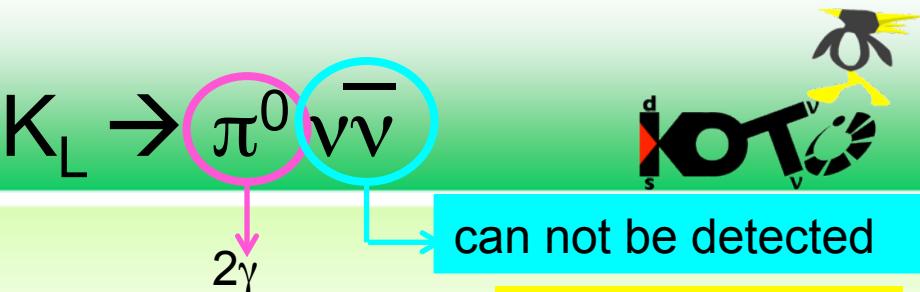
beamline

- ◆ secondary neutral particles are collimated to make narrow beam



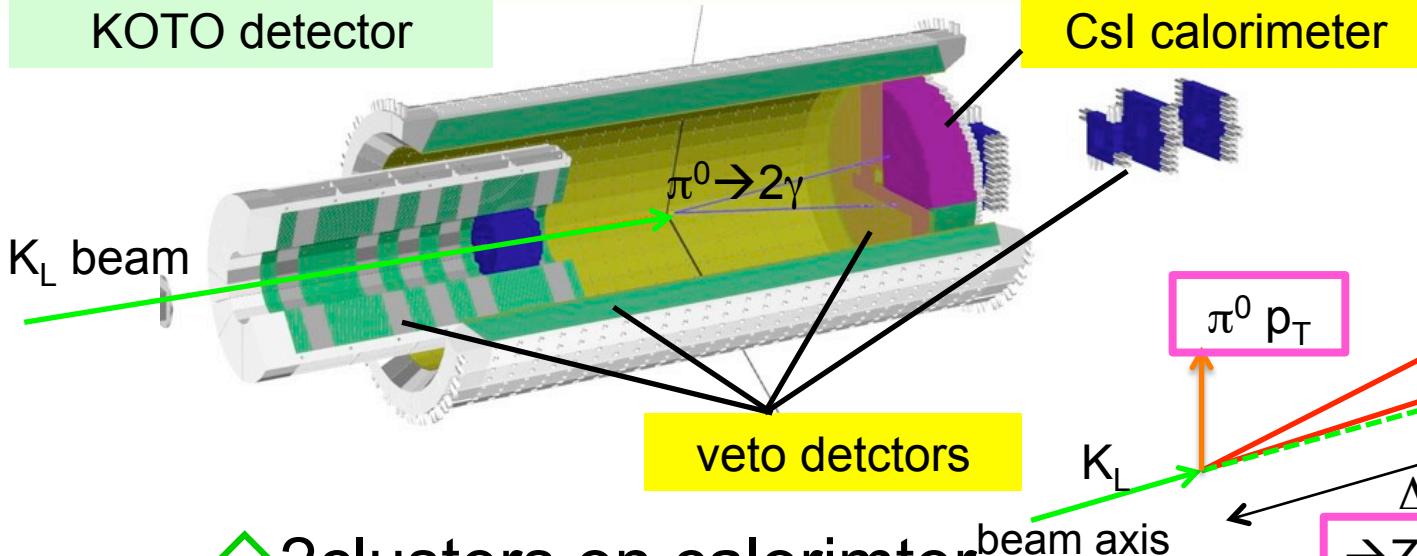
- ◆ magnet : sweep out charged particles
- ◆ γ absorber : reduce γ rate
- ◆ long beam line (~20m) exclude short-lifetime-particles (K_S , Λ ...)
- ◆ narrow beam (~8 μ str) : limit decay vertex

signal reconstruction



◆ signal : “ 2γ and nothing”

KOTO detector



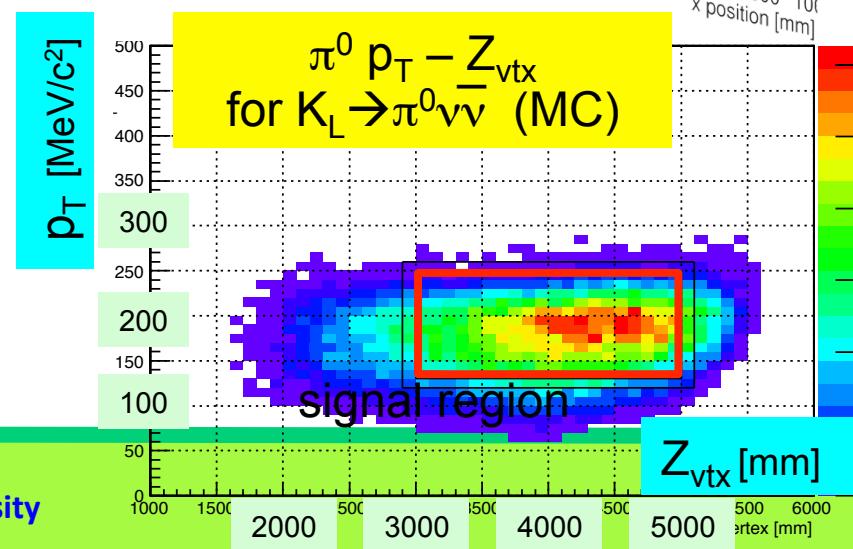
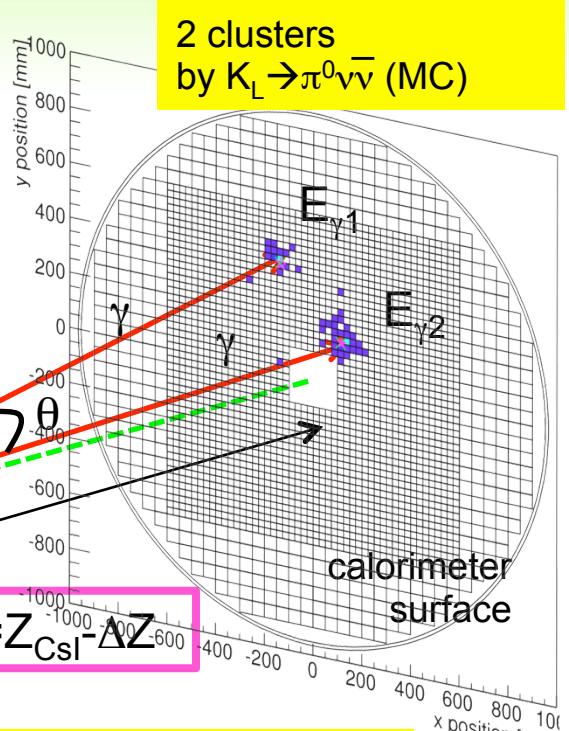
◆ 2clusters on calorimter

◆ π^0 reconstruction assuming its mass

$$M_{\pi^0} = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta)$$

→ apply kinematic selection

◆ no activity in all veto detectors



Winston Cone



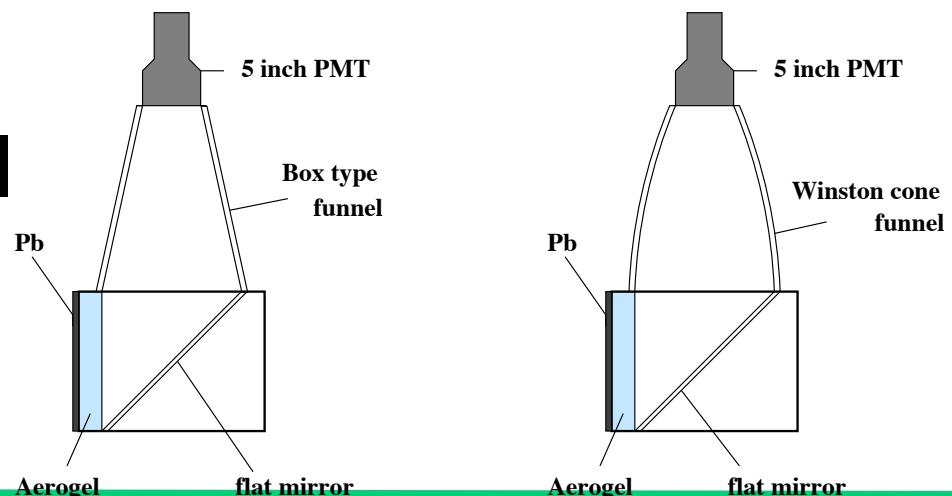
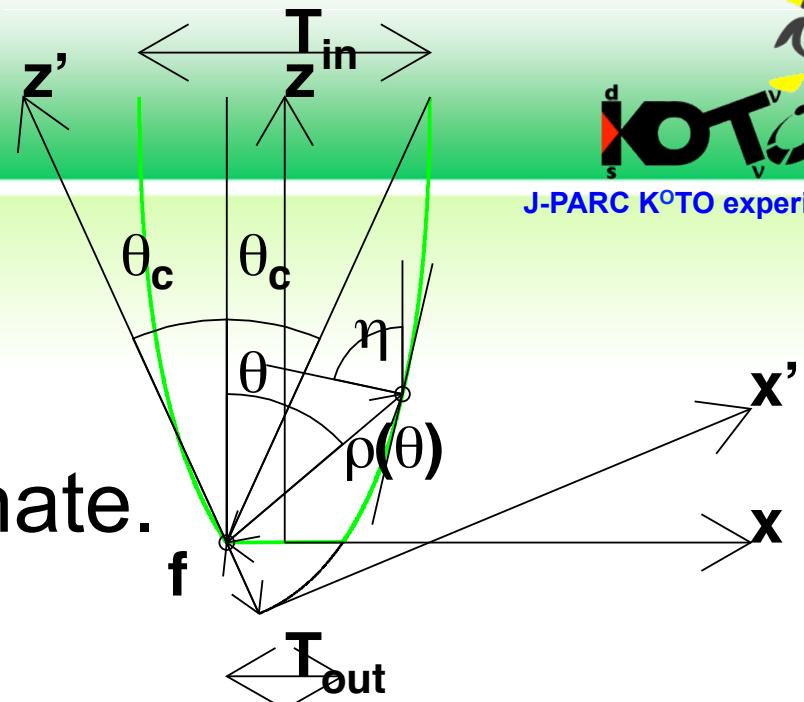
- ◆ rotate parabola in $x'z'$ coordinate ($x'^2=4fz'$) around z -axis in xz coordinate.

$$\sin \theta_c = \frac{T_{\text{out}}}{T_{\text{in}}}$$

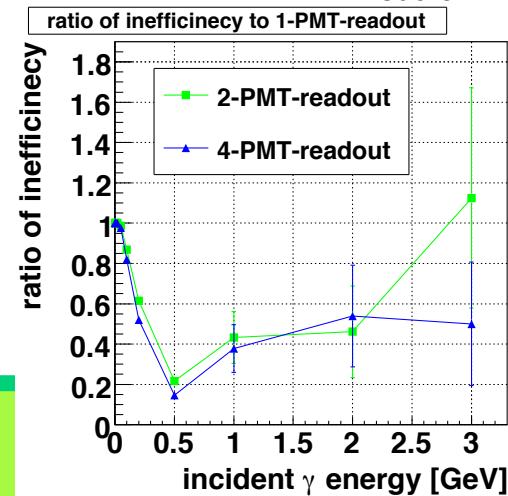
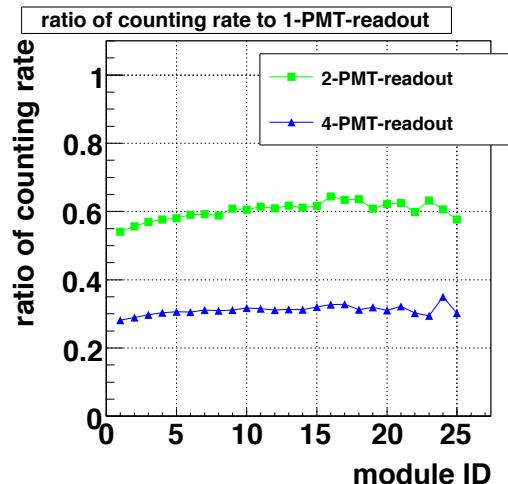
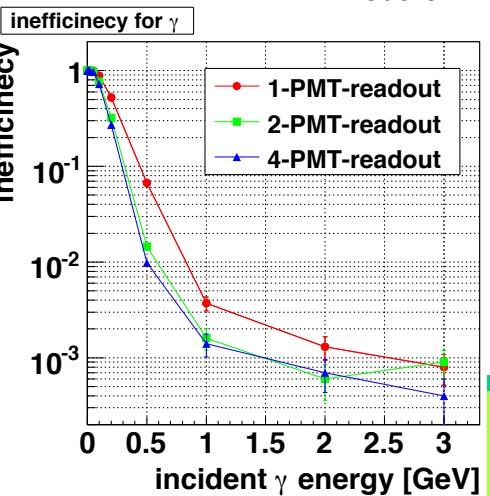
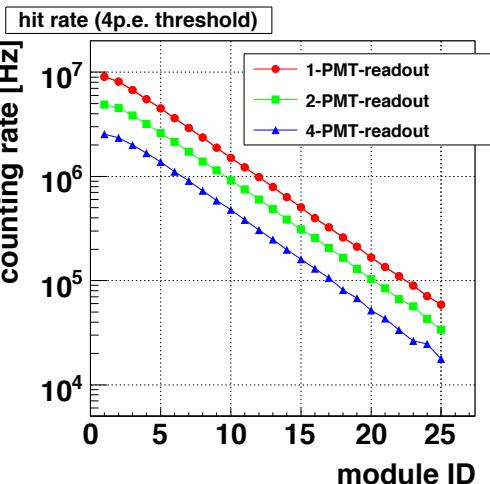
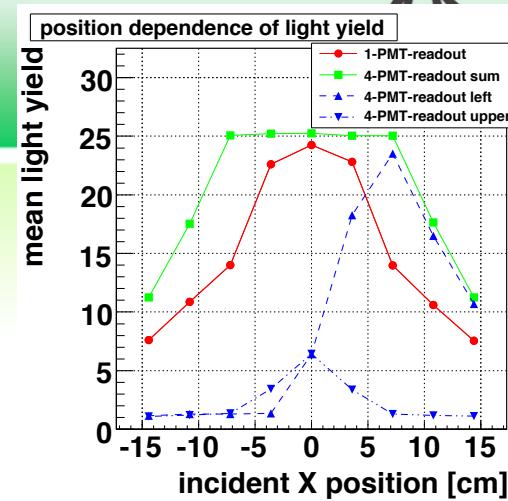
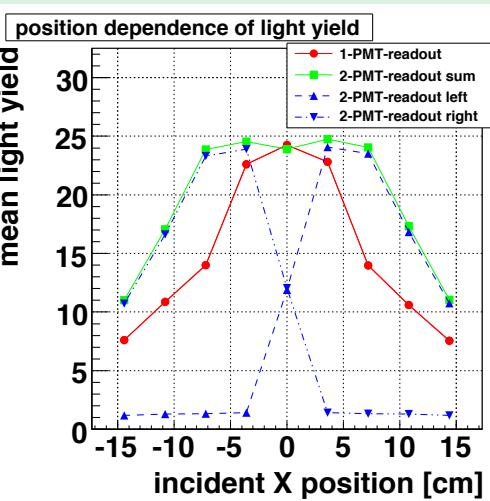
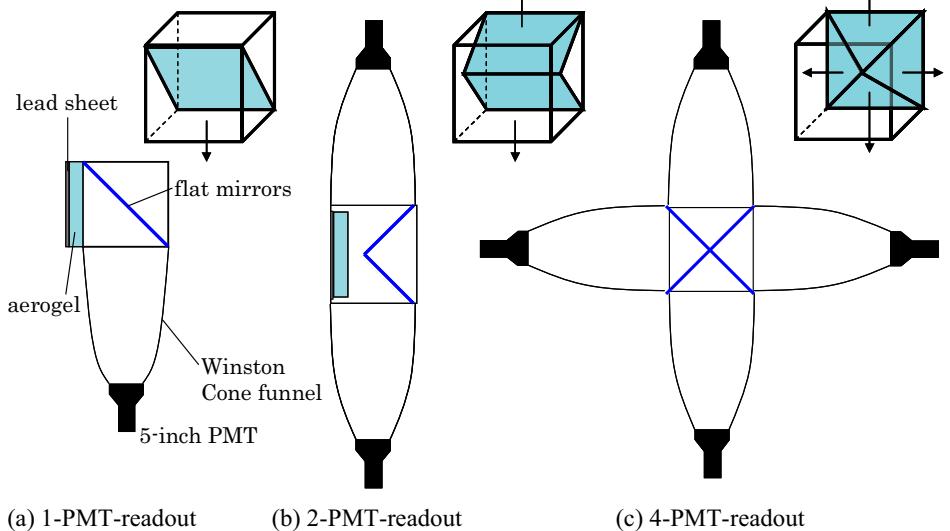
$$L = \frac{(T_{\text{out}} + T_{\text{in}})}{2 \tan \theta_c}$$

$$f = \frac{T_{\text{out}}}{2} (1 + \sin \theta_c)$$

- ◆ 30% larger light yield compared with a funnel by flat mirrors



multi-PMT readout



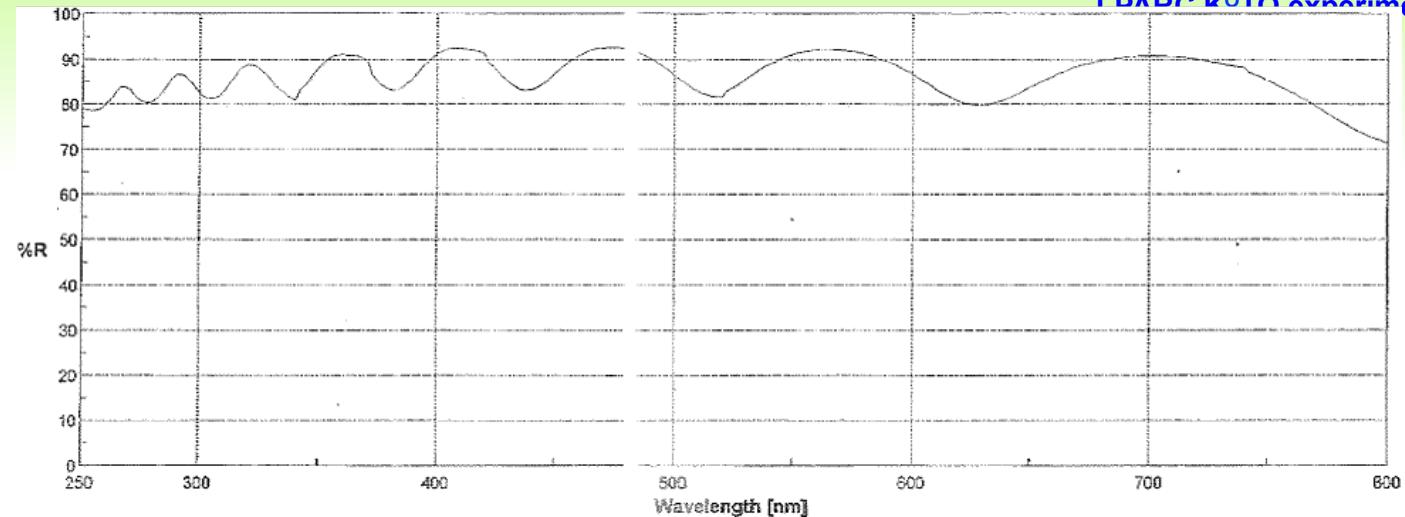
MC input



LPCB KOTO experiment

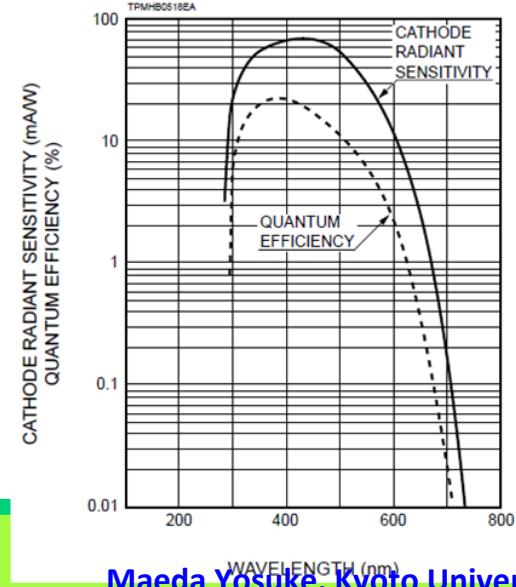
◆ flat mirror

◆ 85%

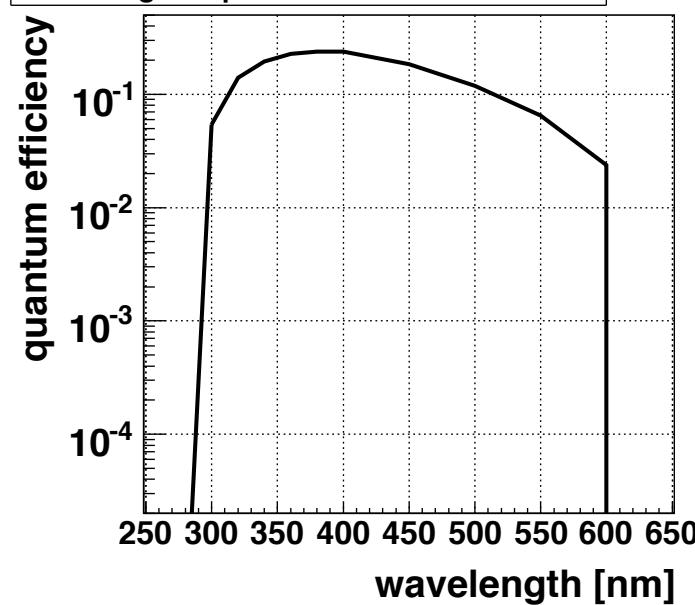


◆ PMT QE

◆ catalog value

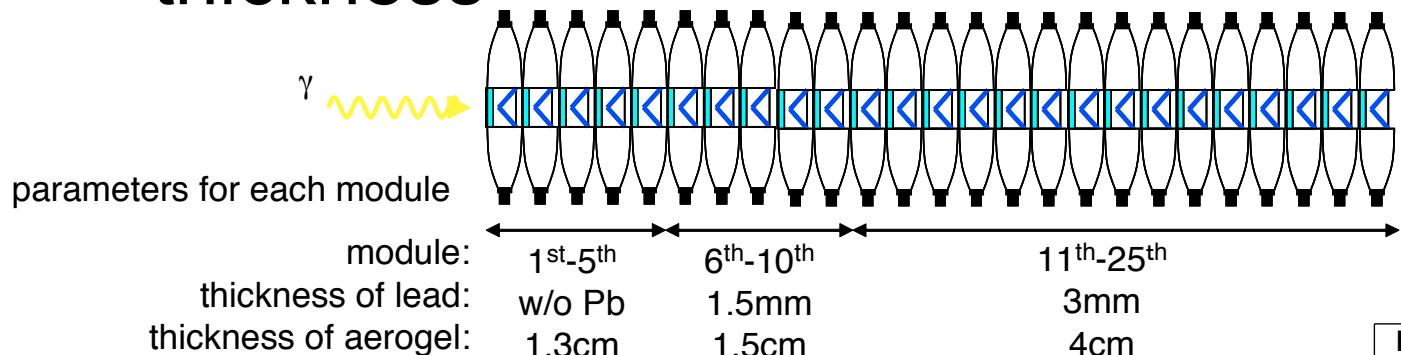


wavelength dependence of Q.E. for R1250

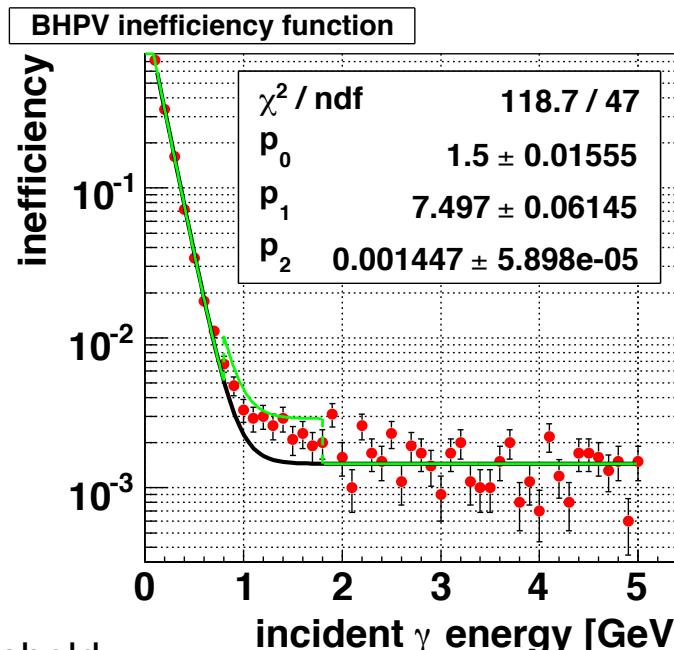
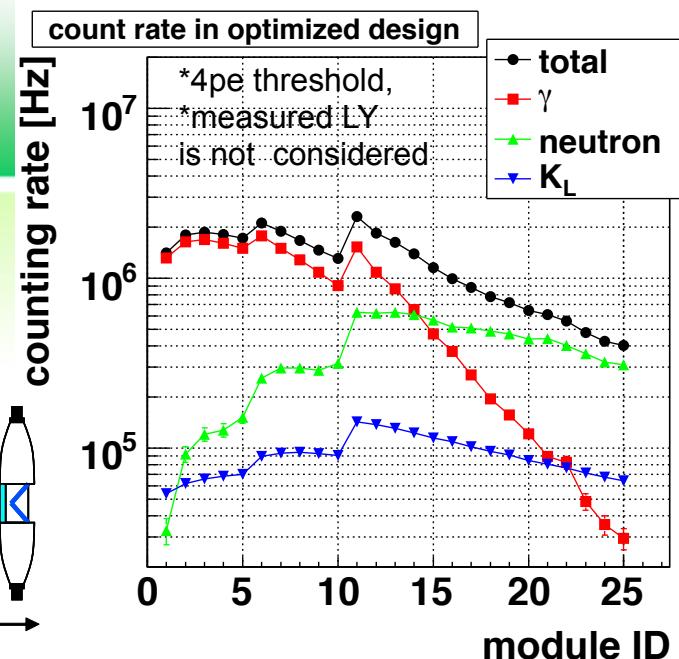


expected performance

- ◆ optimize aerogel and lead sheet thickness

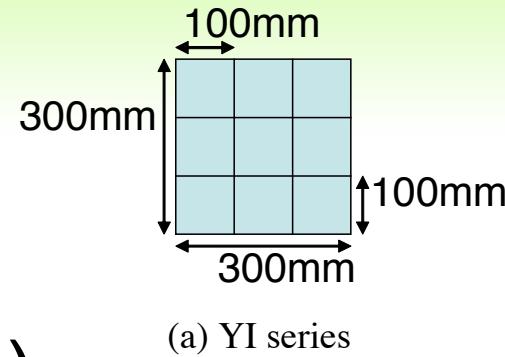


- ◆ thinner aerogel and lead sheet in the upstream part
- ◆ keep total radiation lengths
- ◆ rate $\lesssim 2\text{MHz}$
- ◆ inefficiency (MC)
 - ◆ around 10^{-3} inefficiency is achieved for $E_\gamma > 1\text{GeV}$

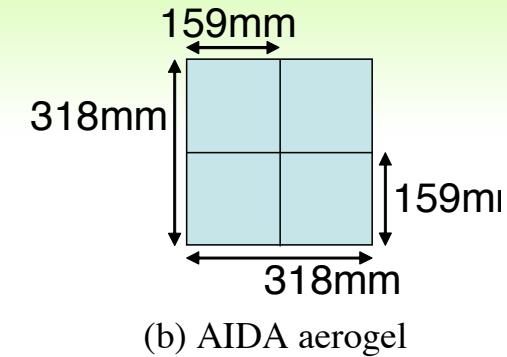


*2pe threshold,
*measured LY is considered

◆ Matsushita aerogel
 (YI series)
 and AIDA aerogel
 (made in Chiba Univ.)

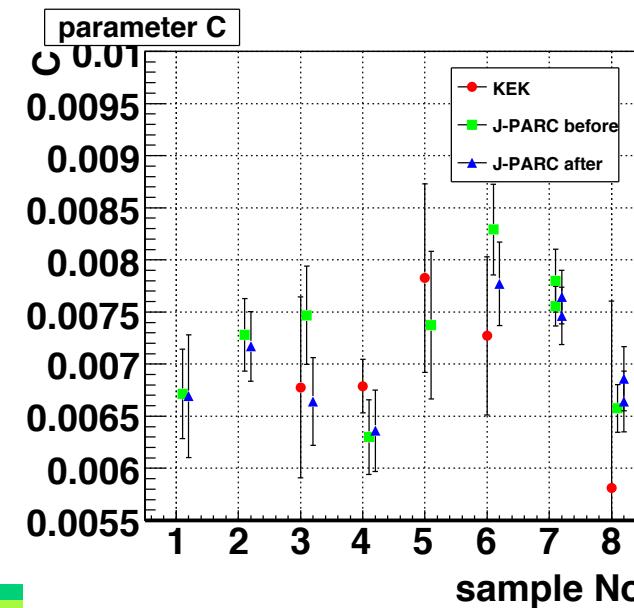
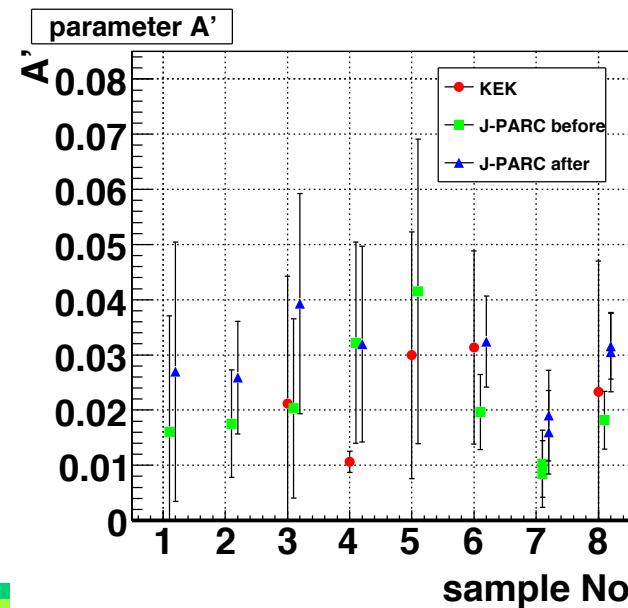


(a) YI series

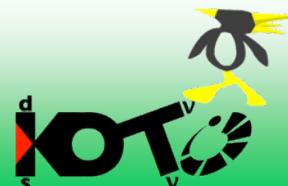


(b) AIDA aerogel

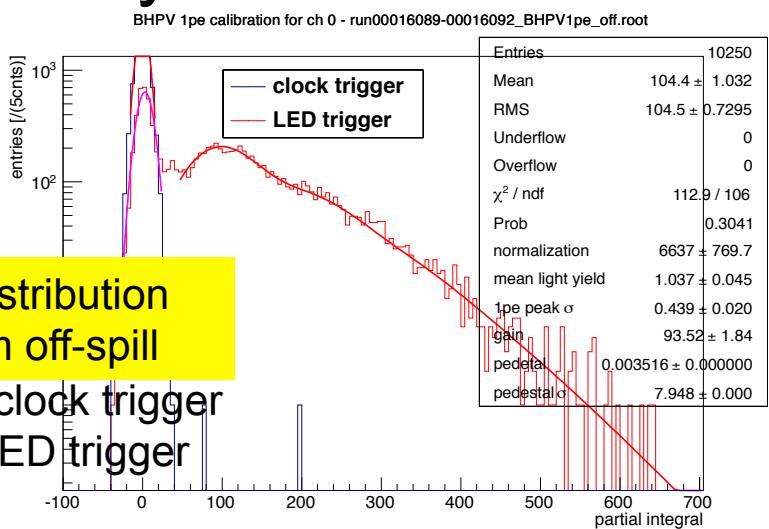
◆ transmission measurement for many samples



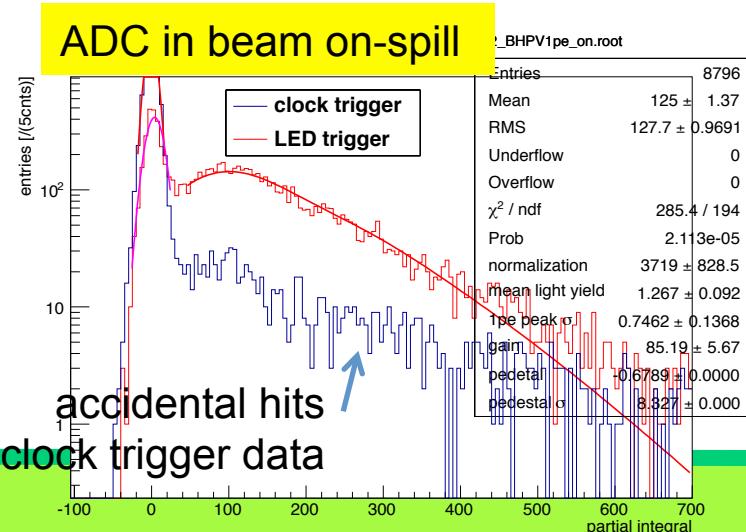
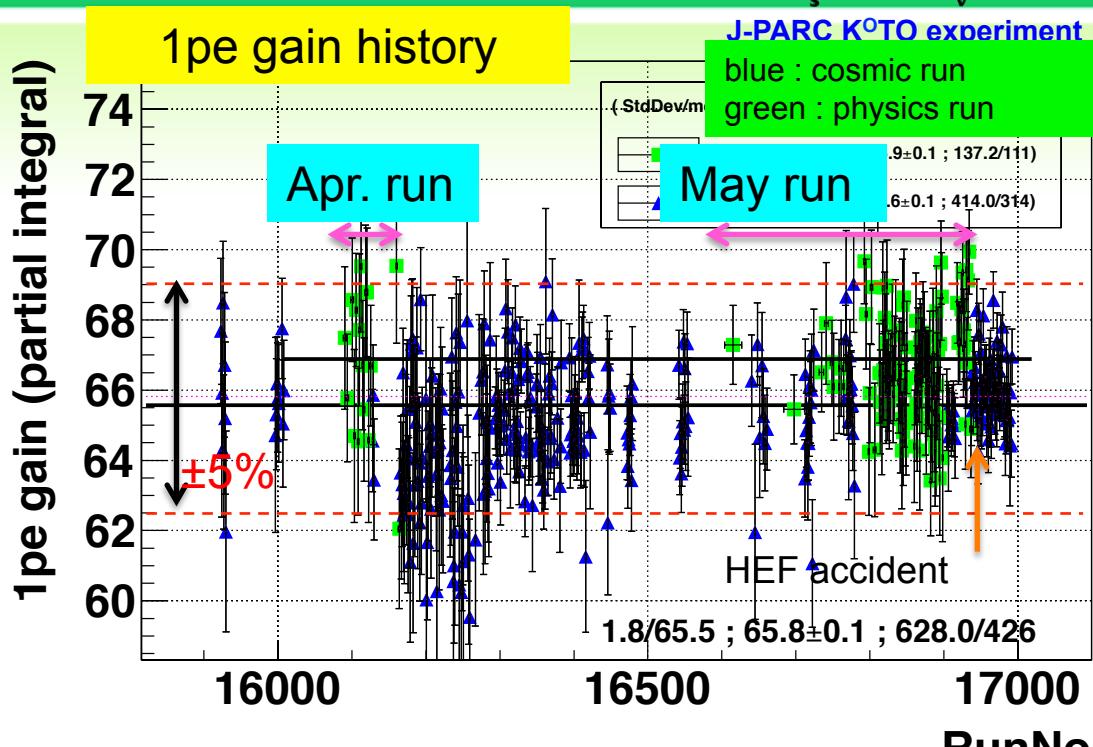
gain stability with LED



- ◆ PMT gain calibration
 - ◆ 1pe peak measured by LED

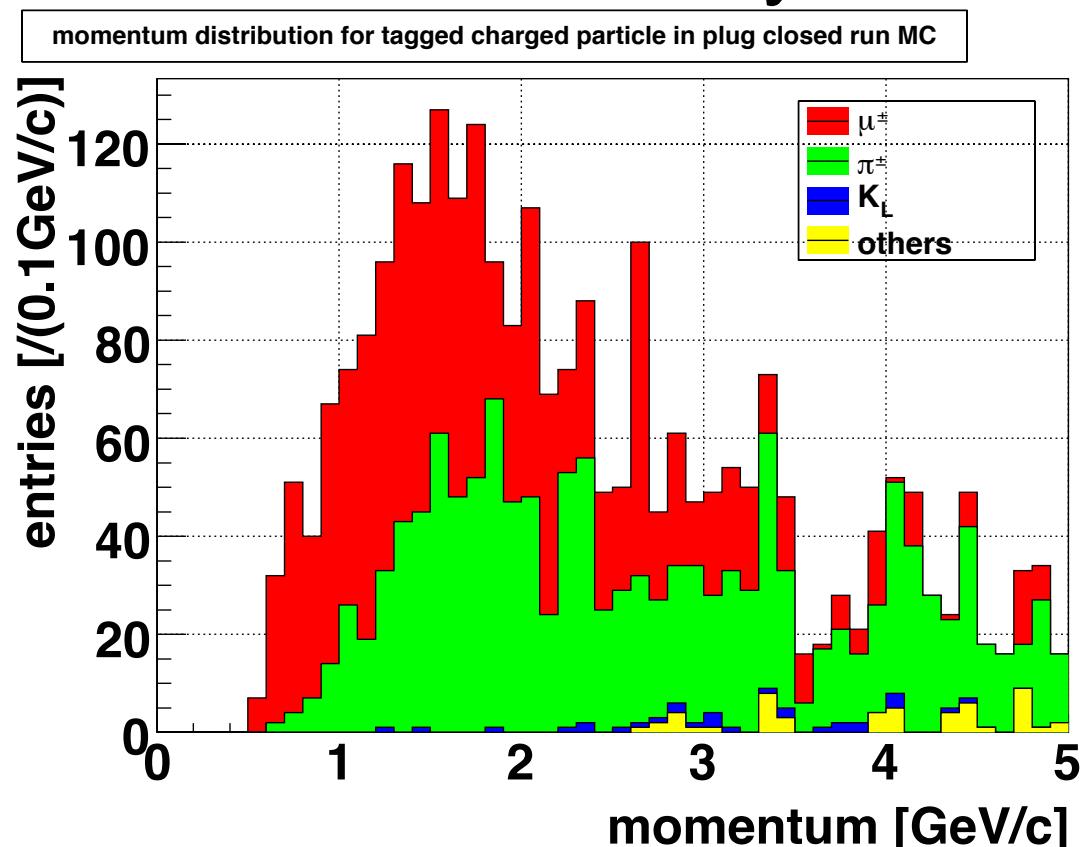


◆ stable within 5%



calibration run

- ◆ close upstream beam plug to reduce the counting rate of detectors
- ◆ charged particle momentum distribution by MC
 - ◆ tagged by hits in all BHPV modules and trigger scintillator located in the down-stream of BHPV
 - ◆ slightly different condition in MC



pulse analysis

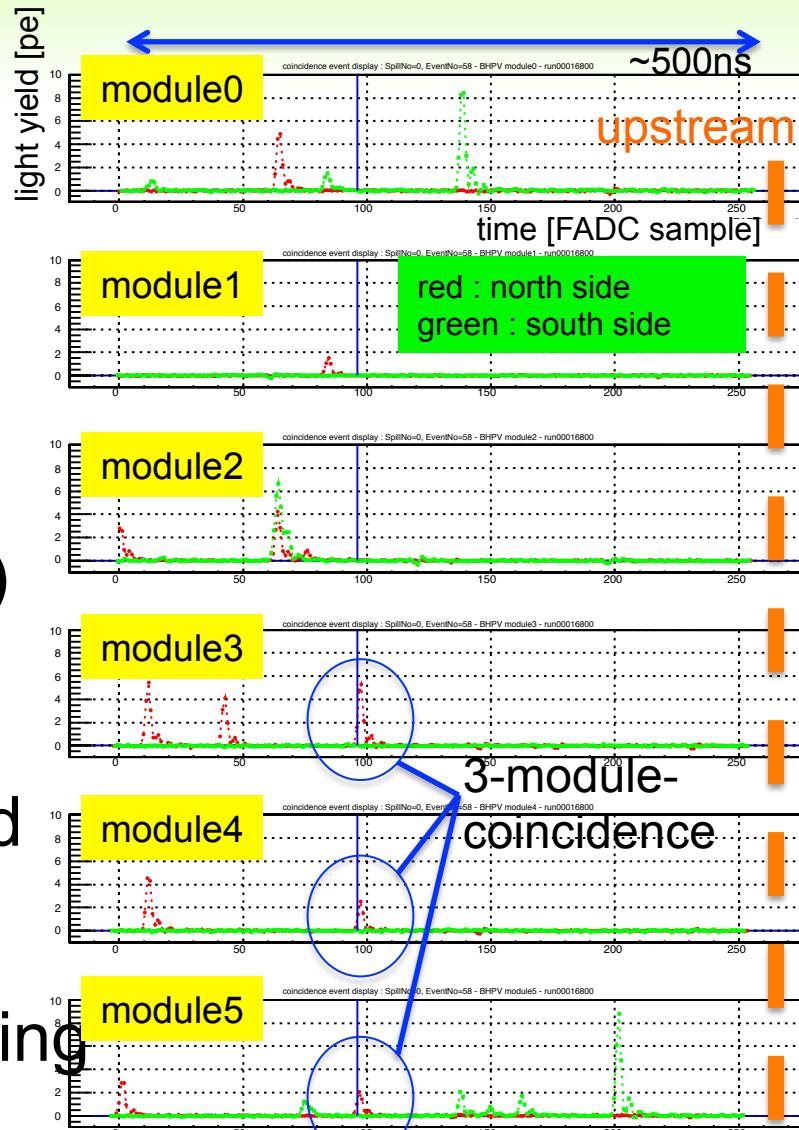


- ◆ High rate detector
→ 500MHz FADC readout
(cf. 125MHz w/ shaper
for most detectors)

- ◆ pulse analysis
 - ◆ multi pulse is considered
 - ◆ find multi pulses in an event
and information(energy & timing)
for all pulses are stored

- ◆ coincidence among modules
 - ◆ Timing of each pulse is corrected
by t0 (timing offset) and TOF.
 - ◆ find pulses whose corrected
timing agrees to that of neighboring
modules within $\pm 10\text{ns}$

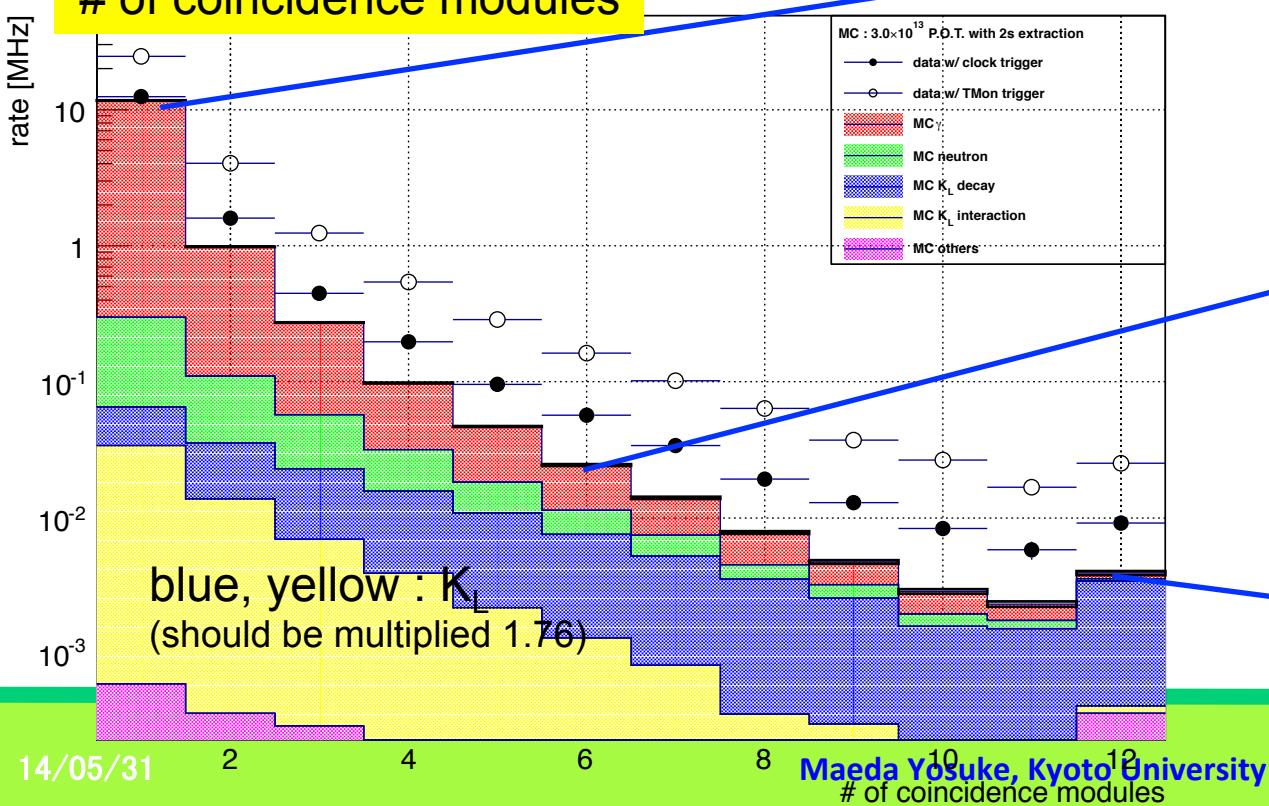
example of waveform for an event



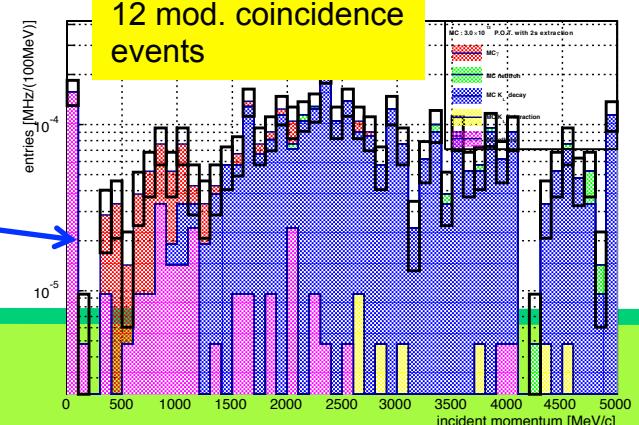
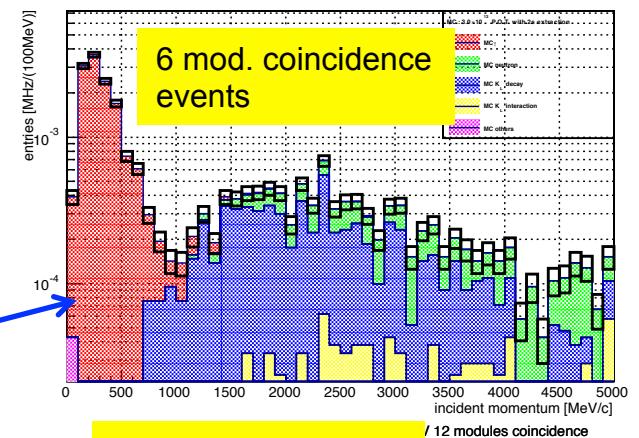
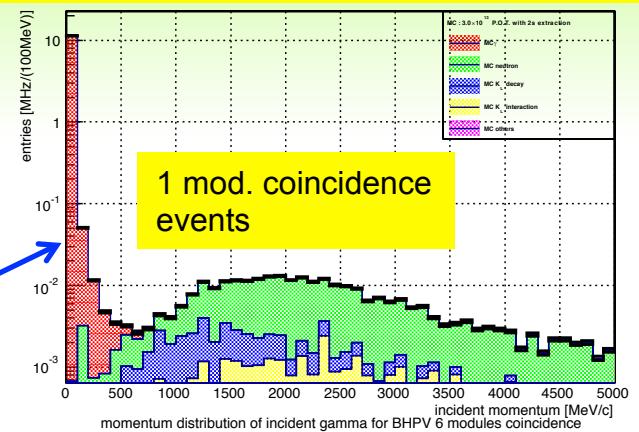
of coincidence modules



◆ sensitive to incident γ energy

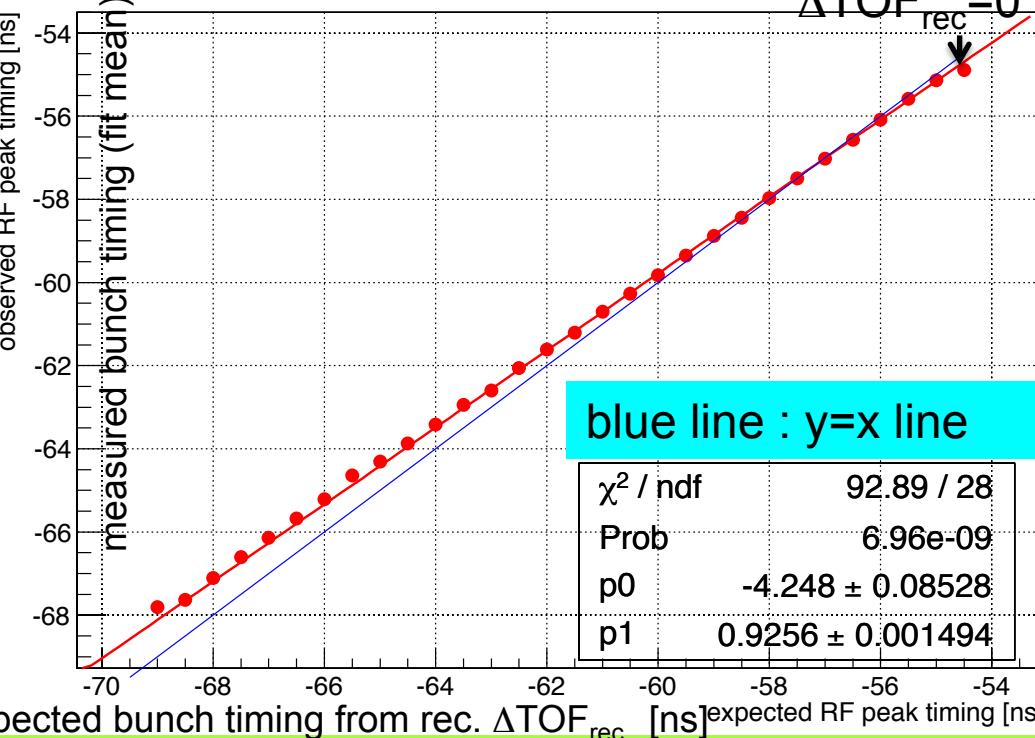
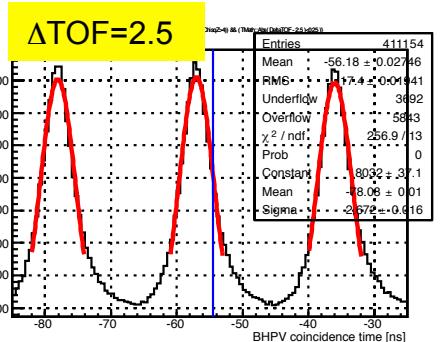
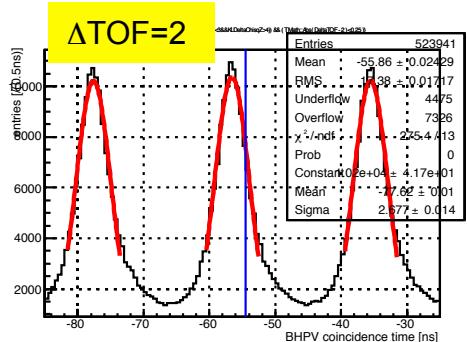
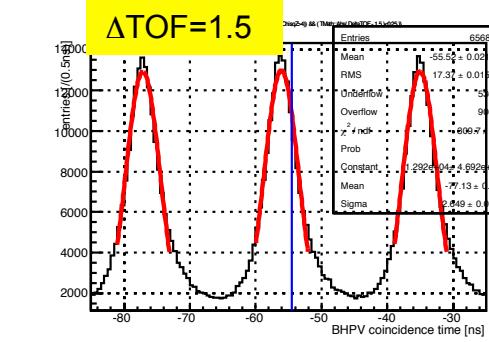
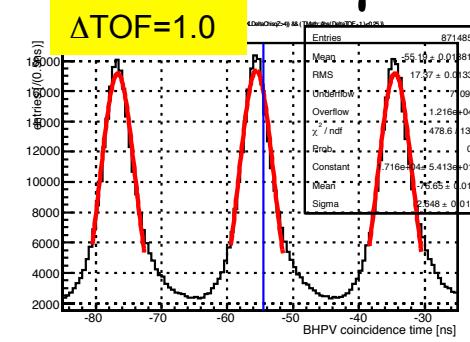
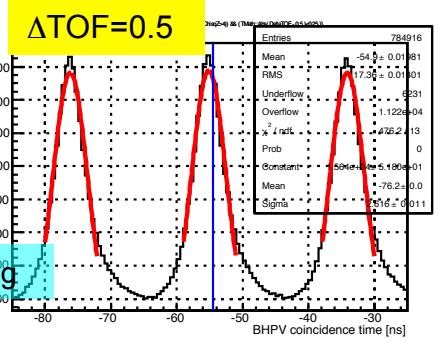
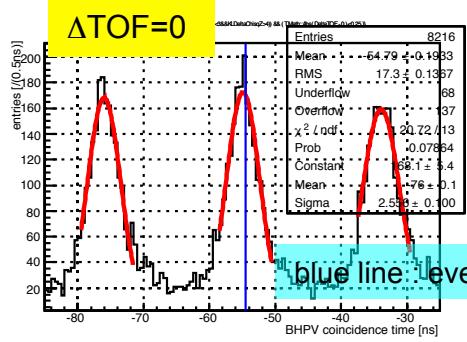


incident momentum distribution



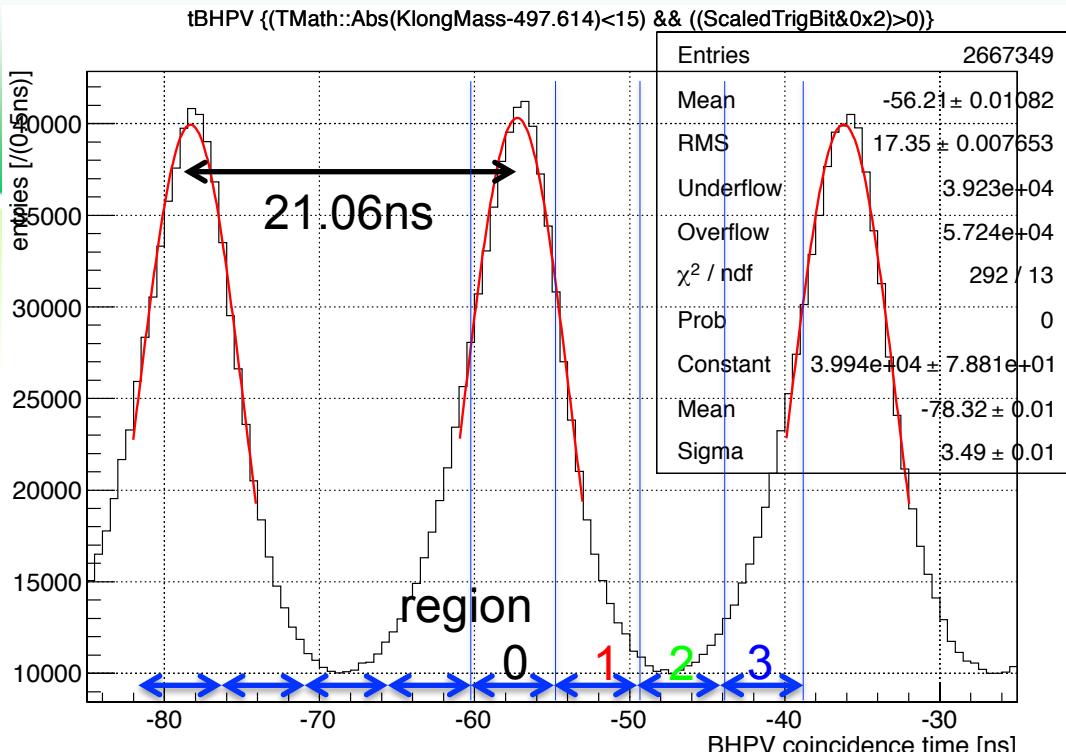
study of beam bunch structure

◆ bunch timing to event timing for various ΔTOF reconstructed in 6γ events

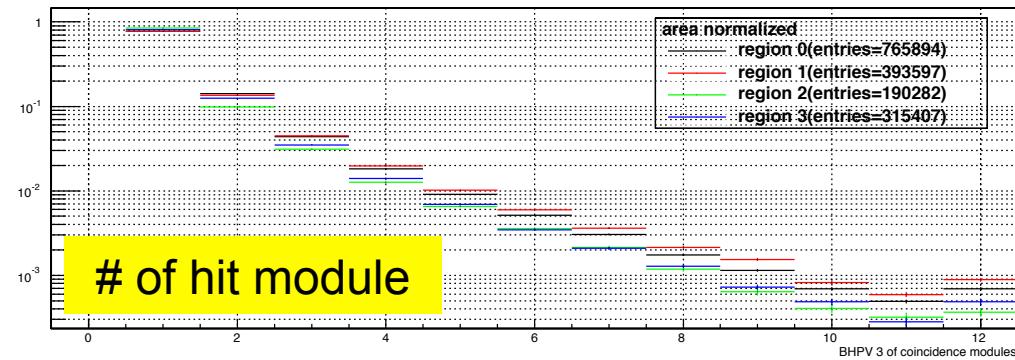


spectrum check (i)

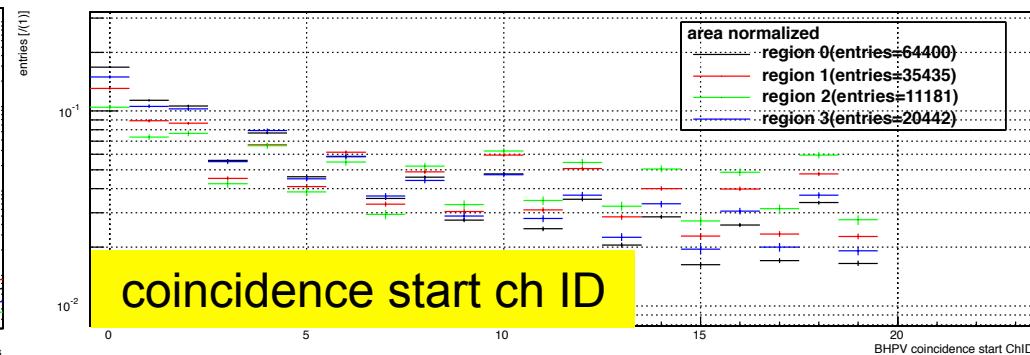
◆ spectrum difference
for each phase of
bunch structure



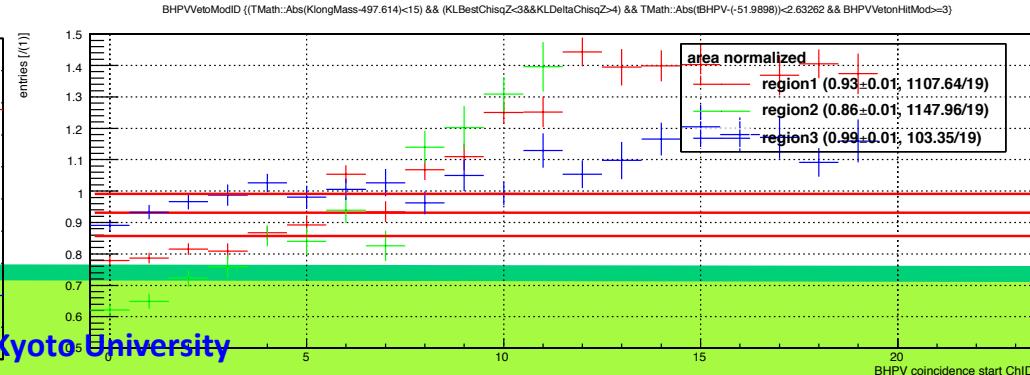
BHPVVetoHitMod { $(TMath::Abs(KlongMass-497.614)<15) \&\& (KLBestChisqZ<3 \&\& KLDeltaChisqZ>4) \&\& TMath::Abs(tBHPV(-57.255))<2.63262$ }



BHPVVetoHitMod { $(TMath::Abs(KlongMass-497.614)<15) \&\& (KLBestChisqZ<3 \&\& KLDeltaChisqZ>4) \&\& TMath::Abs(tBHPV(-57.255))<2.63262$ }

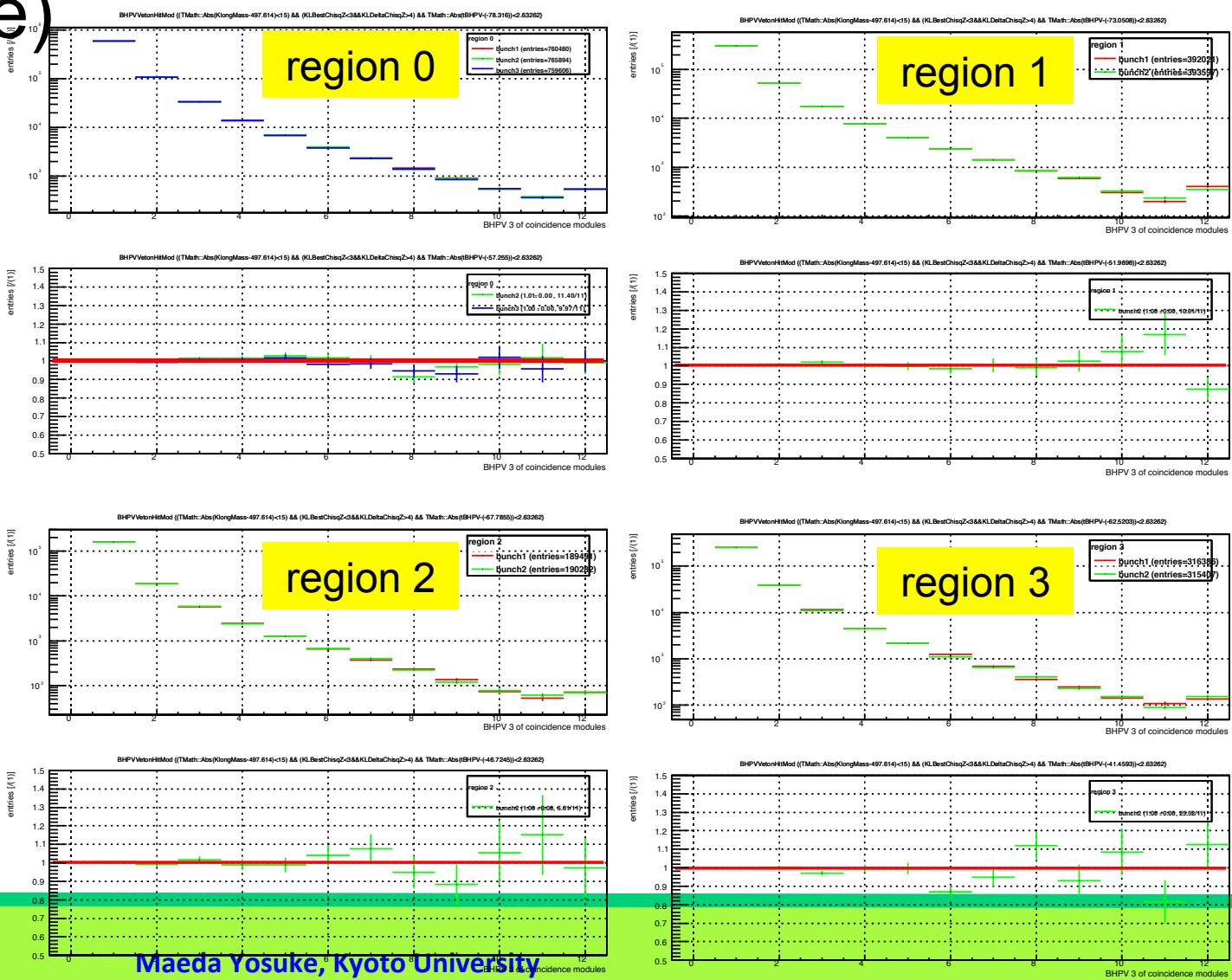


BHPVVetoHitMod { $(TMath::Abs(KlongMass-497.614)<15) \&\& (KLBestChisqZ<3 \&\& KLDeltaChisqZ>4) \&\& TMath::Abs(tBHPV(-51.9898))<2.63262$ }



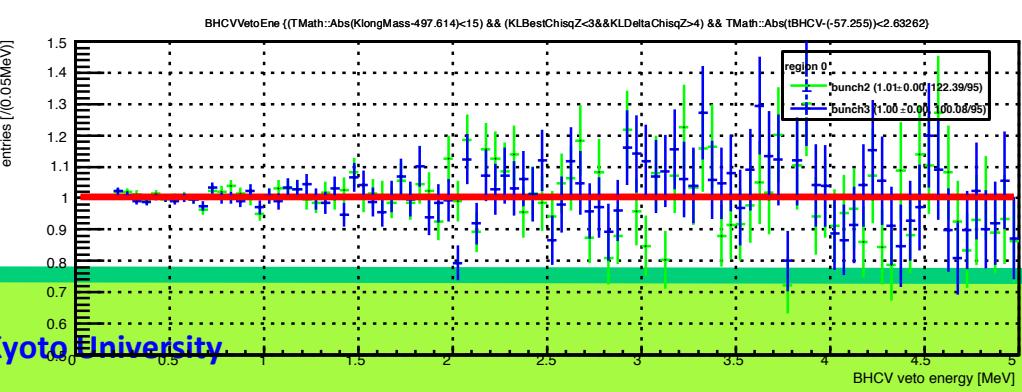
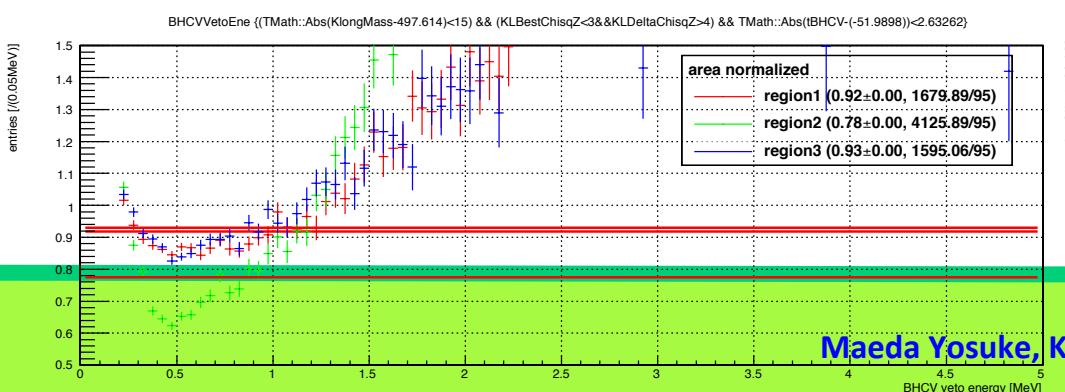
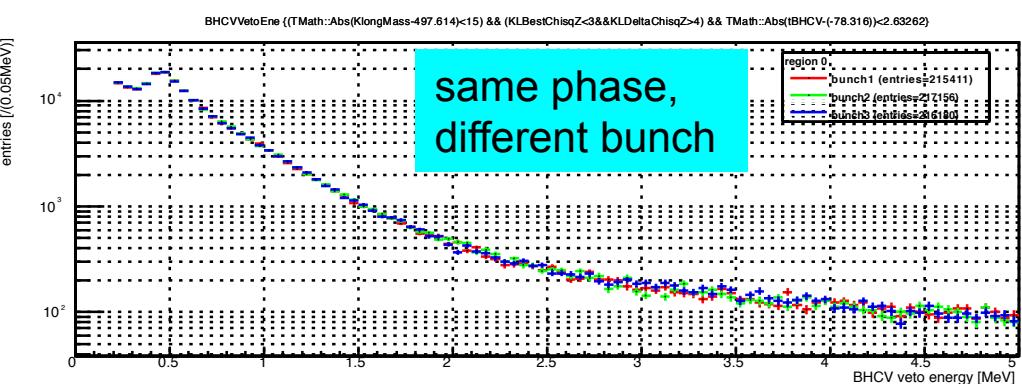
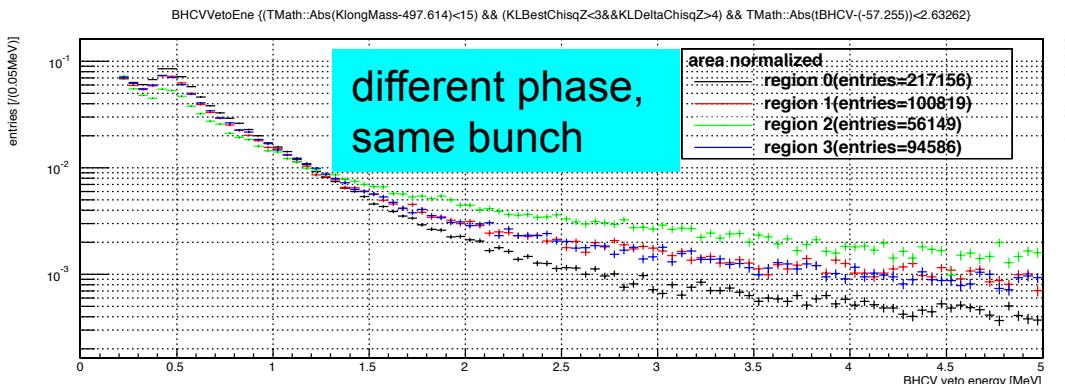
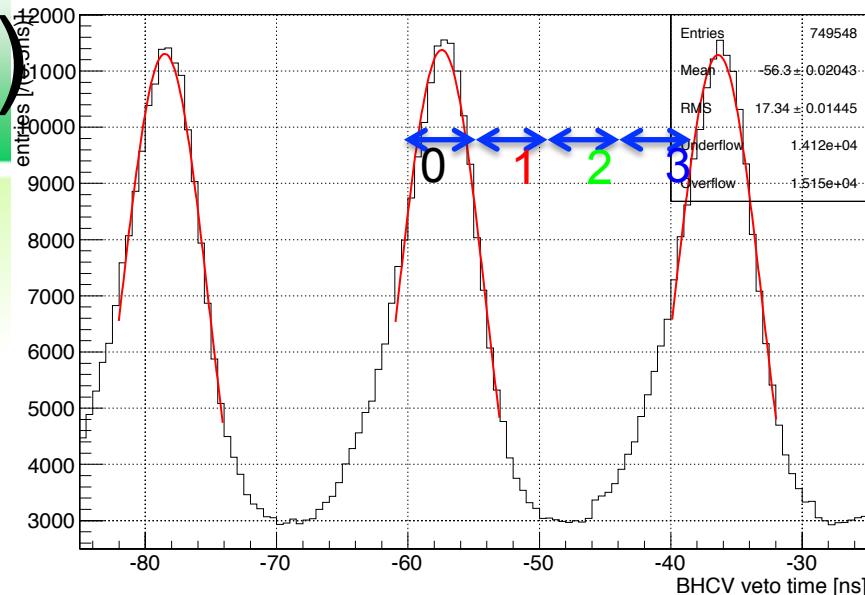
spectrum check (ii)

◆ no bunch by bunch difference
(same phase)



spectrum check (BHCV)

◇ similar study for in-beam plastic scintillator detector (Beam Hole Charged Veto)



γ energy hitting BHPV in 4γ sample

- ◇ require 4 cluster on CsI calorimeter

- ◇ cuts

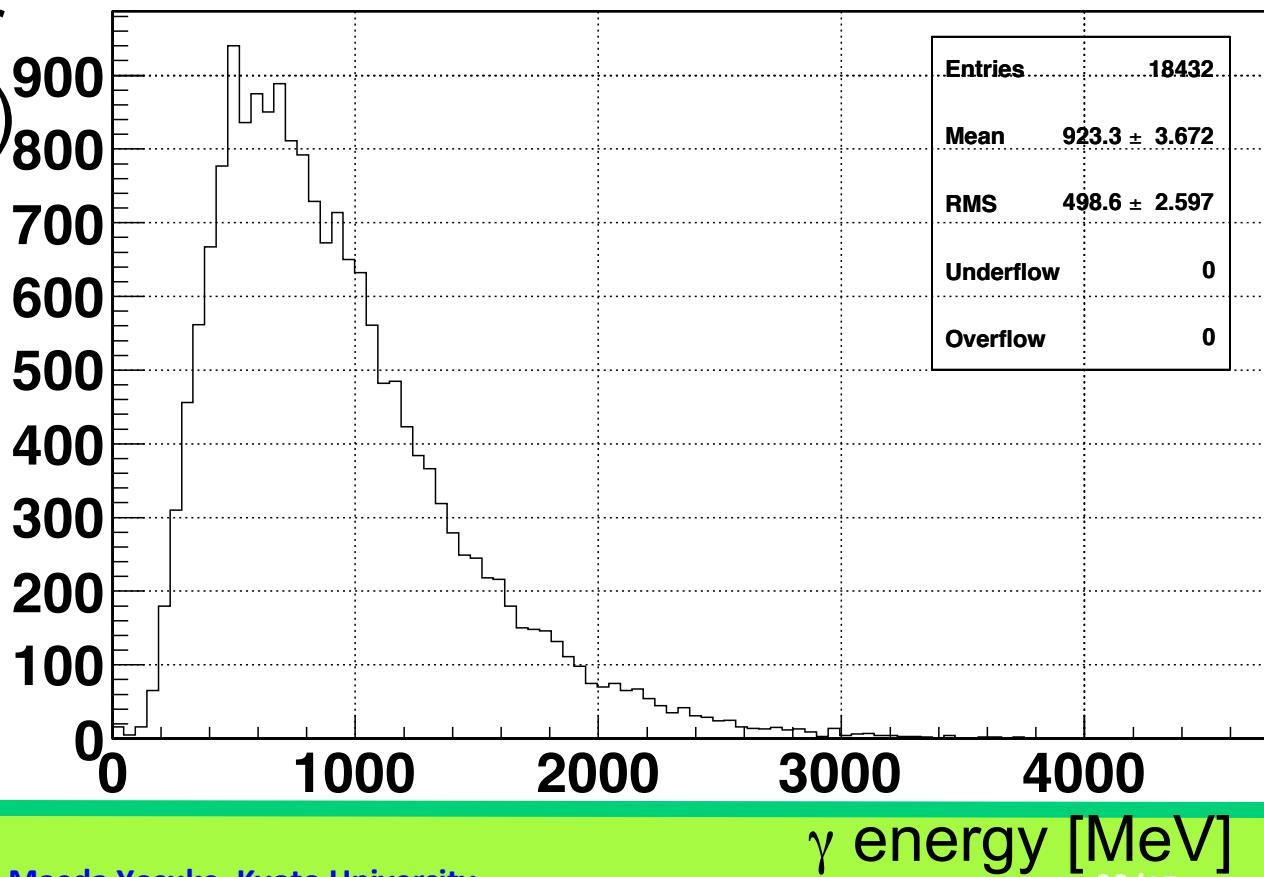
- ◇ total energy > 650 MeV

- ◇ no extra cluster

- ($|\Delta t_{\text{ex.clus.}}| > 10 \text{ ns}$)

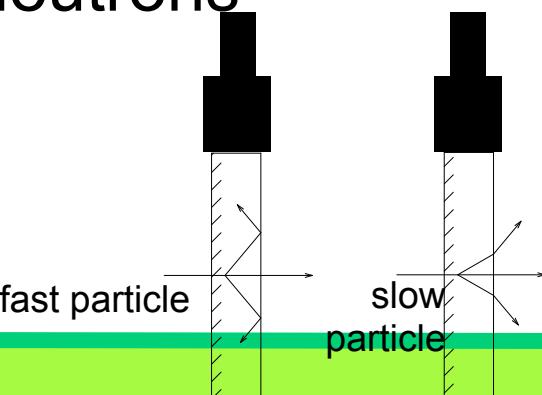
- ◇ CV veto

- (0.2 MeV)



future prospects

- ◆ new aerogel production for full module installation
 - ◆ More aerogel is needed, but we run short of one used in the past experiment (AIDA.)
 - ◆ planning to produce new one.
- ◆ guard counter
 - ◆ cover wider range for further BG suppression
 - ◆ acrylic-lead detector
 - ◆ also insensitive to neutrons thanks to Cerenkov and total reflection threshold



Maeda Yosuke, Kyoto University

