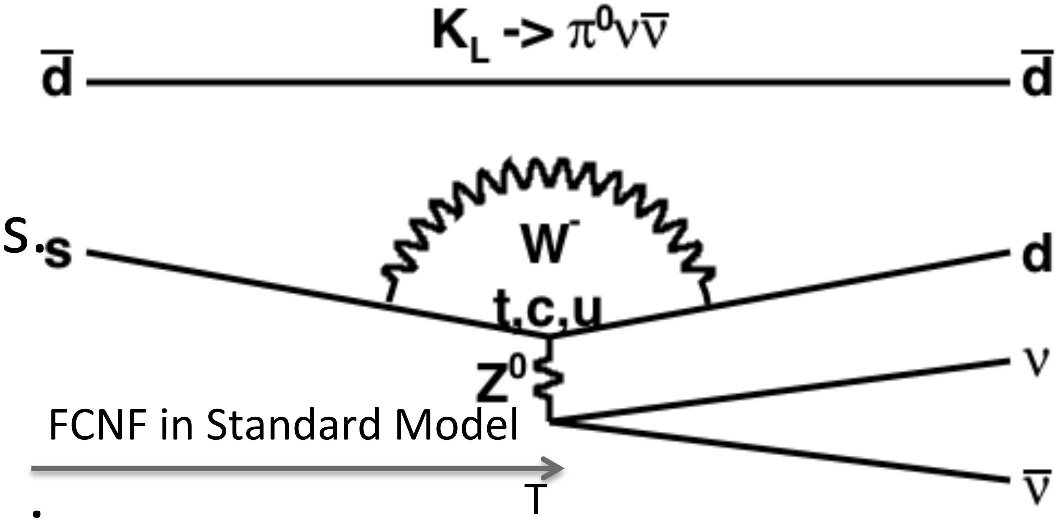
# Performance of a New Pb/ Scintillator Sampling Calorimeter of KOTO experiment

Kim,JunLee
Korea Univ.

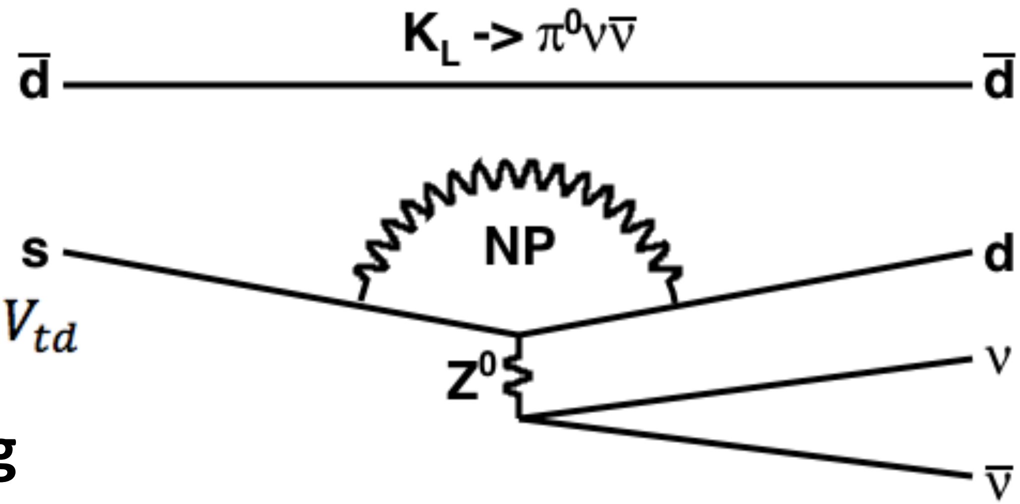
E14 한국 Collaboration 워크샵

# Introduction to KOTO

- FCNC(flavor changing neutral current
  - No direct s -> d process.
  - s -> t, c, u -> d with W boson
  - Explained by CKM matrix
    - s -> d ; $V_{td}^{*}V_{ts}$ (mainly)




New Physics



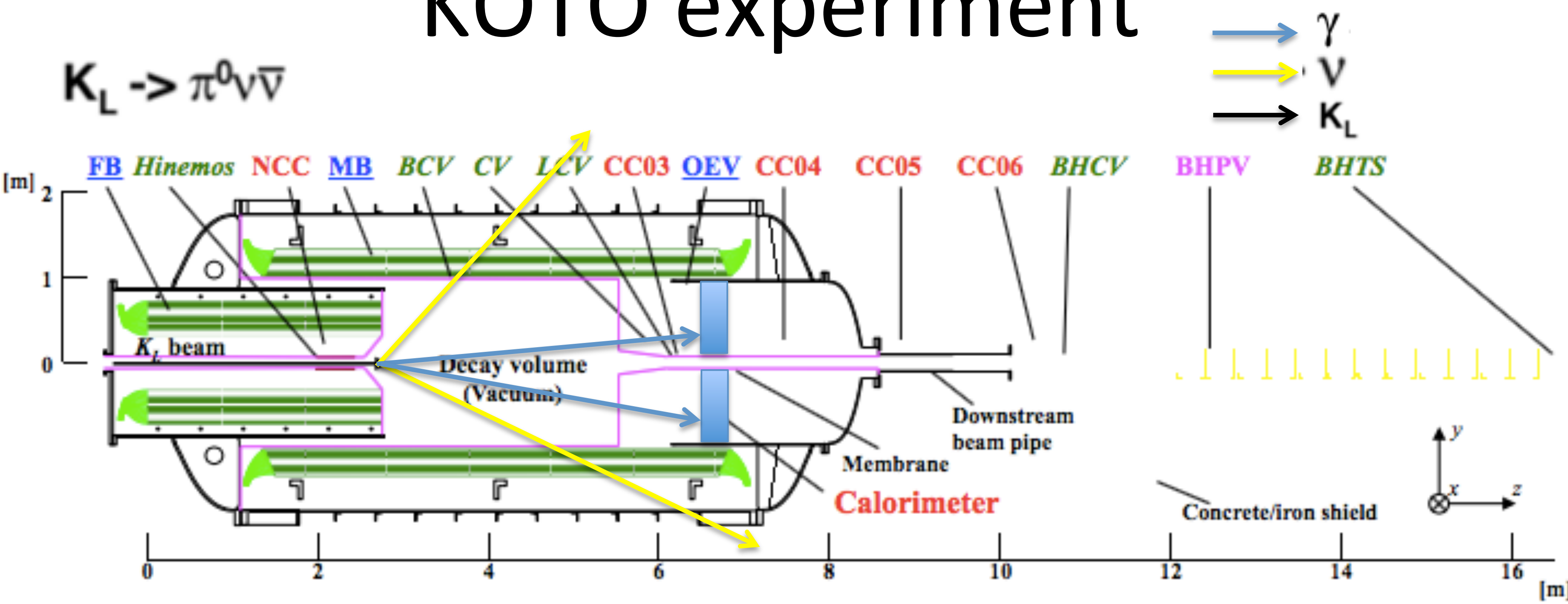

$$K_L = \frac{s\bar{d} + \bar{s}d}{\sqrt{2}}$$

$$(s \to d) + (\bar{s} + \bar{d}) \sim V_{td}^{*}V_{ts} - V_{ts}^{*}V_{td}$$

$$= 2\mathrm{Im}(V_{td}^{*}V_{ts}) \neq 0$$

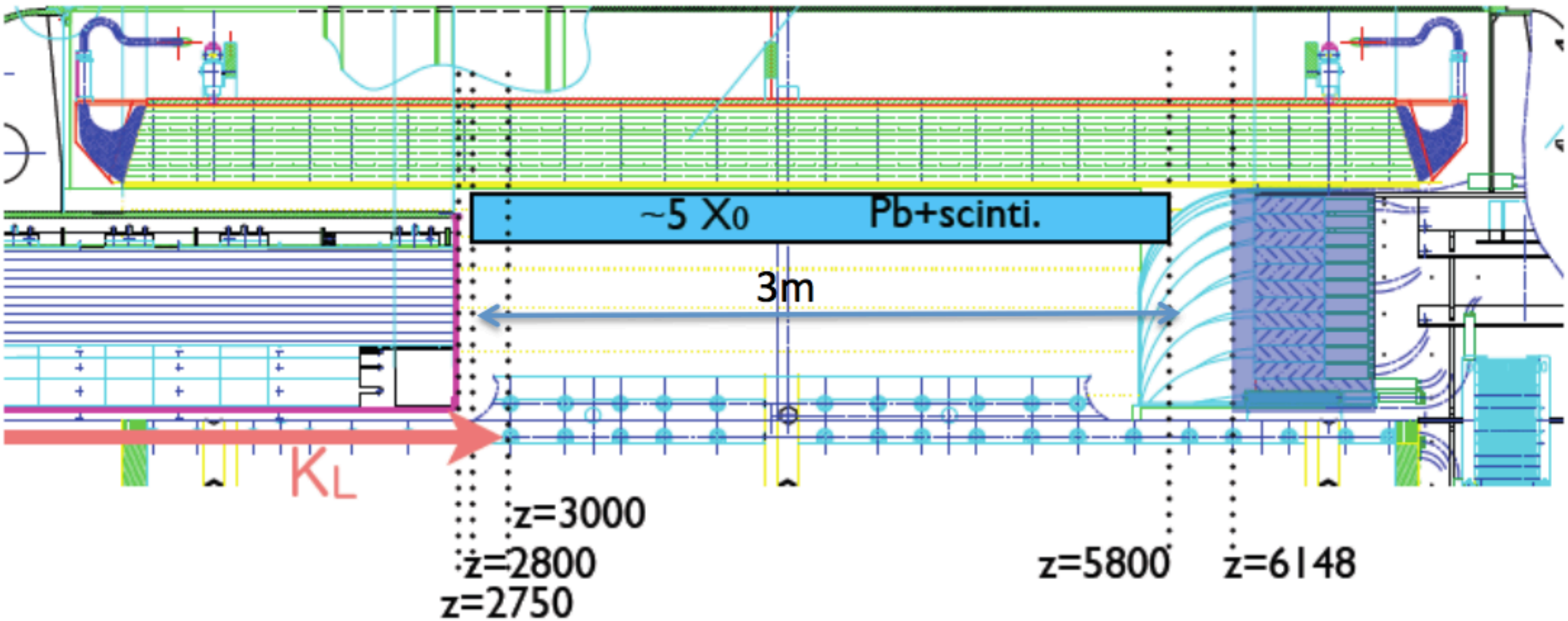
**CP violating**

# KOTO experiment




- 2γ + nothing
  - CsI Calorimeter for 2γ
    - Need for discrimination of signal induced by neutron
  - Hermetic veto detectors for nothing
    - Need for more radiation length of barrel for reducing inefficiency of gamma detection. (IB)

# Motivation of Inner Barrel

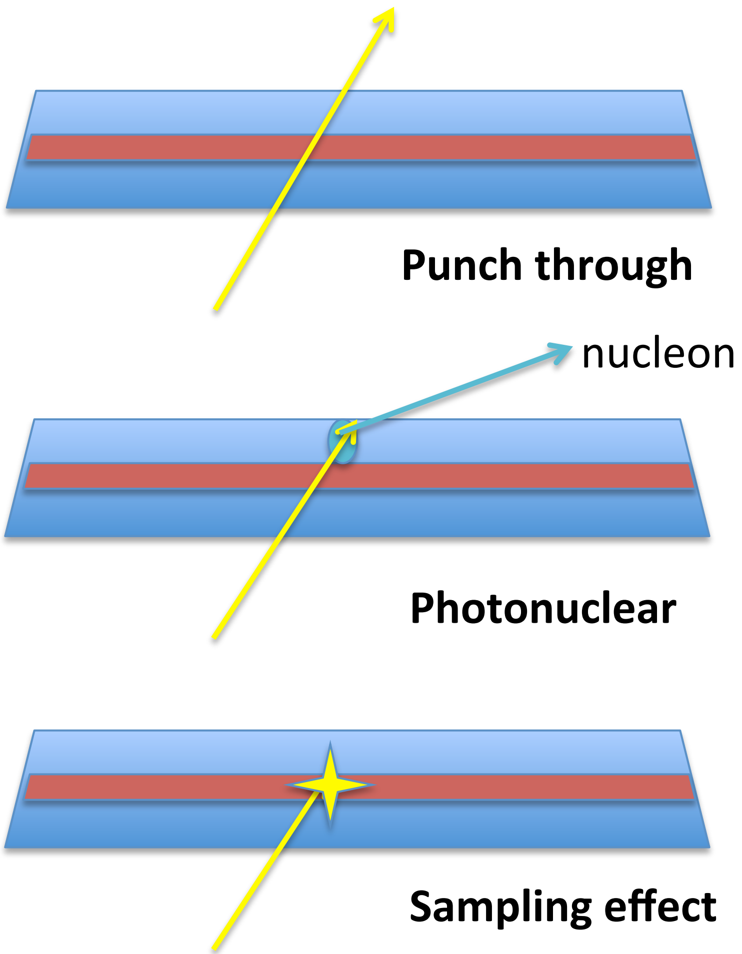



- Inner Barrel = New Pb/Scintillator detector
  - $5X_0$ radiation length
    - Decrease gamma detection inefficiency.
  - Better timing resolution (than MB)
    - Decrease acceptance loss caused by back-splash or veto timing window.

| detector | #events |
|---|---|
| E391 MB | 2.90 |
| **E391 MB + $5X_0$** | **1.39** |
| E391 MB + $10X_0$ | 1.30 |

# Pb/Scintillator sampling calorimeter

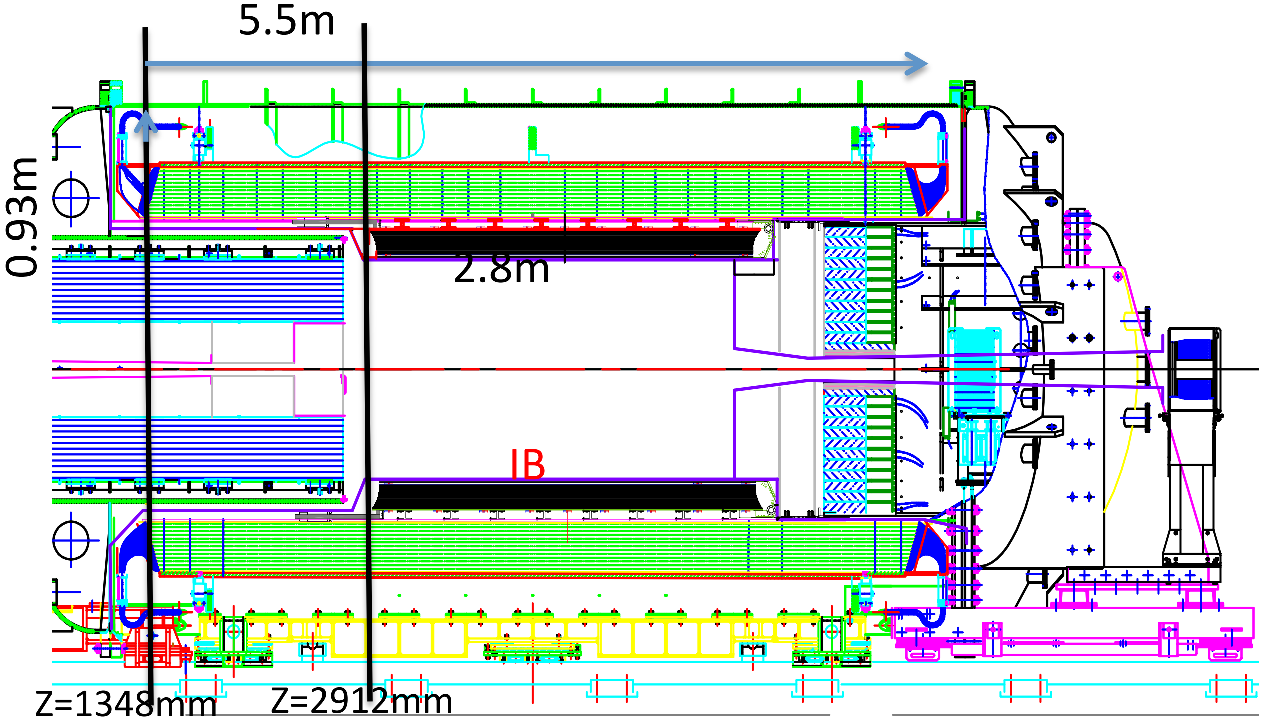
- Alternating structure of Pb and Scintillator
  - Effectively enhance radiation length
    - $1.35X_0$ from Pb (1mm*24)
    - $3.65X_0$ from Scintillator (5mm*25)
  - Scintillator : Readout (light)
    - #lights ~ energy deposit
  - Lead : Absorber
  - Sampling Fraction
    - $SF = E_{Readout}/(E_{Readout} + E_{Absorber})$
    - Full energy deposit estimation
- Inefficiency components
  - Punch through-photon
  - Photonuclear
  - Sampling effect

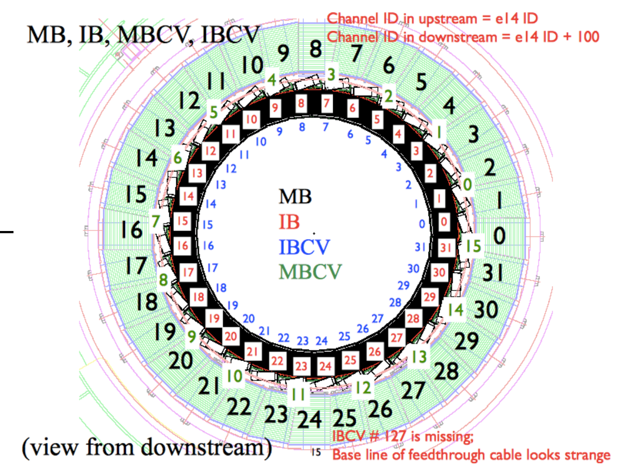


# Inside Scintillator/Fiber

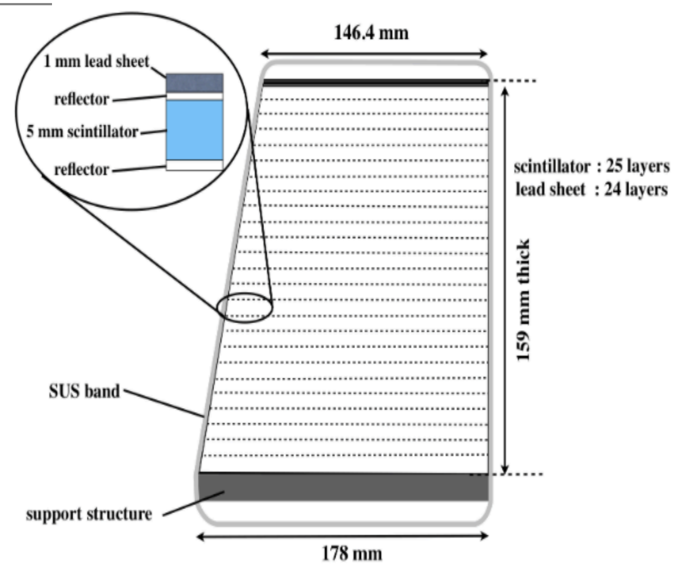
- Charged particles excite electron in atom.
  - Excited electrons emit scintillating light during de-excitation.
  - Sometimes, Charged particles makes electron in atom be free(delta ray).
    - Delta ray(also charged particle) makes many scintillating light again.
      - Landau distribution
  - Totally, $2*10^4$ lights are emitted from 1cm MIP signal
- Fibers(BCF-92) for enhancing attenuation length in matter.
  - KOTO Scintillator(~400mm), Fiber(~5000mm)
  - Fibers absorb light from scintillator and emit light in fiber.
  - ~7% trapping efficiency

# Inner Barrel




- 25-layer Pb/Scintillator.($5X_0$)
- Reflectors btw Pb and Scintillator($TiO_2$, 0.2mm)
- 32modules forming cylinder
- Both end readout with PMT
  - Upstream : R329EGP
  - Downstream : R7724
- Charged Veto(IBCV) inside Inner Barrel
  - One same scintillator only

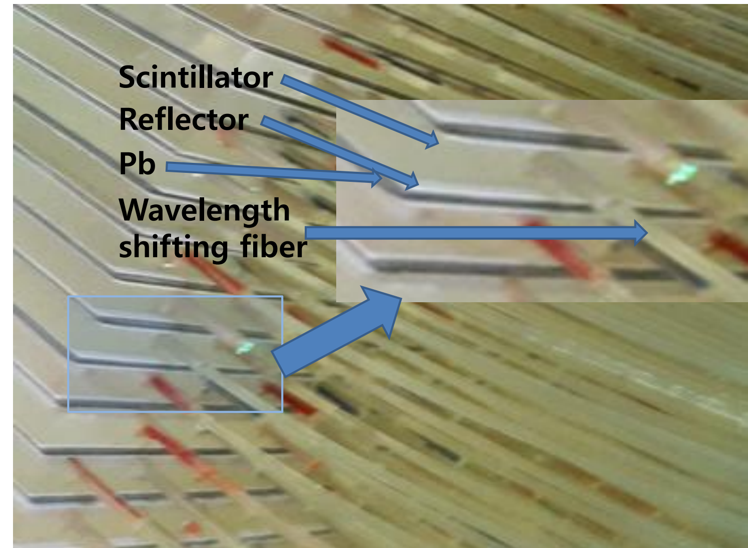


# Production & Installation of IB (1)

- Production
  - Scintillator
    - Make grooves at the surface of scintillator for attaching fibers
    - Make holes for bolts
  - Fiber
    - Put the fibers on grooves in scintillators.
    - Give fibers tension using weights on both end of fibers.
    - Attach fibers on scintillators with optical cement.

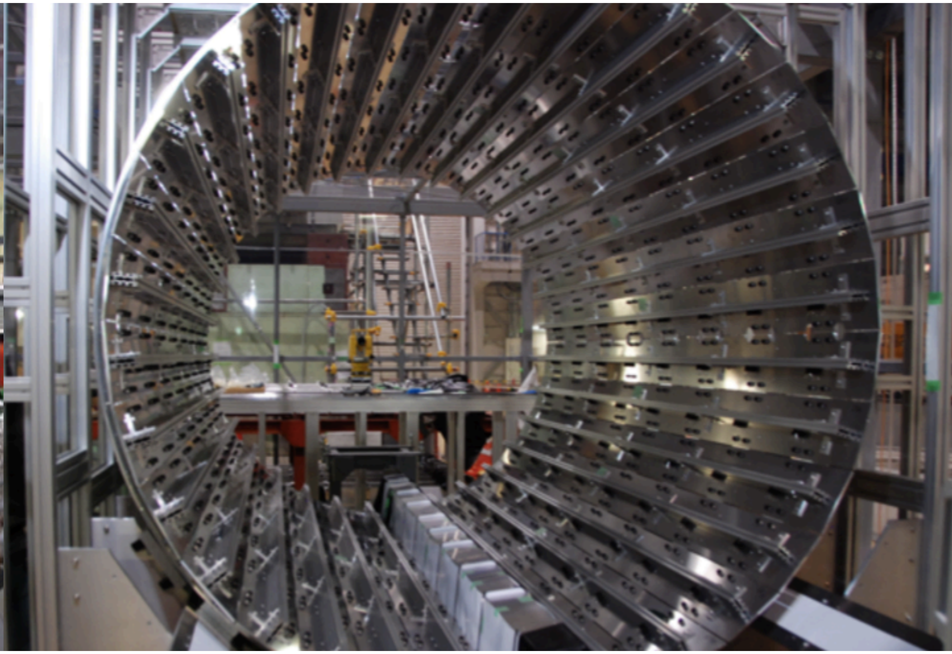
# Production & Installation of IB (2)

- production
  - Scintillator treatment
    - Annealing scintillators with ~600kg/IB pressure
      - Make density of scintillator uniform
    - Evacuation test
  - Pb/Scintillator stacking
    - Stack Pb, Scintillator, reflector in order of Scintillator – Reflector – Pb- Reflector
    - Be careful of breaking fibers, deformation of Lead plate, and mis-stacking
  - Bundling
    - Give stacked IB the pressure for fixing IB tightly with stainless band



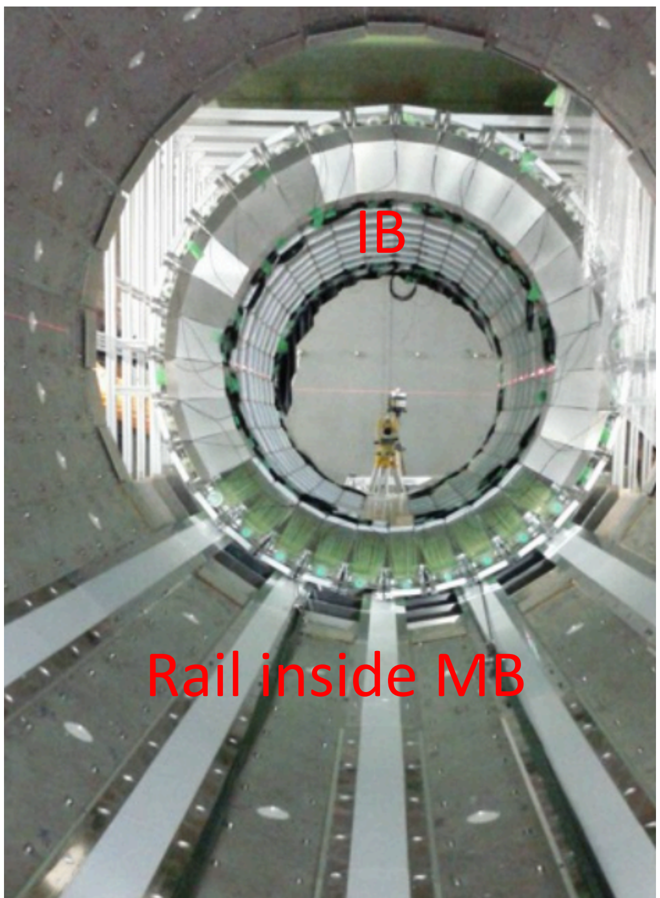

# Production & Installation of IB (3)

- Installation
  - Make cylindrical shape from Inner Barrel using supporter structures.
    - Test with dummy plates

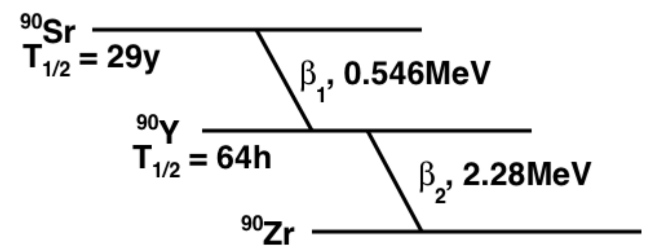
# Production & Installation of IB (4)

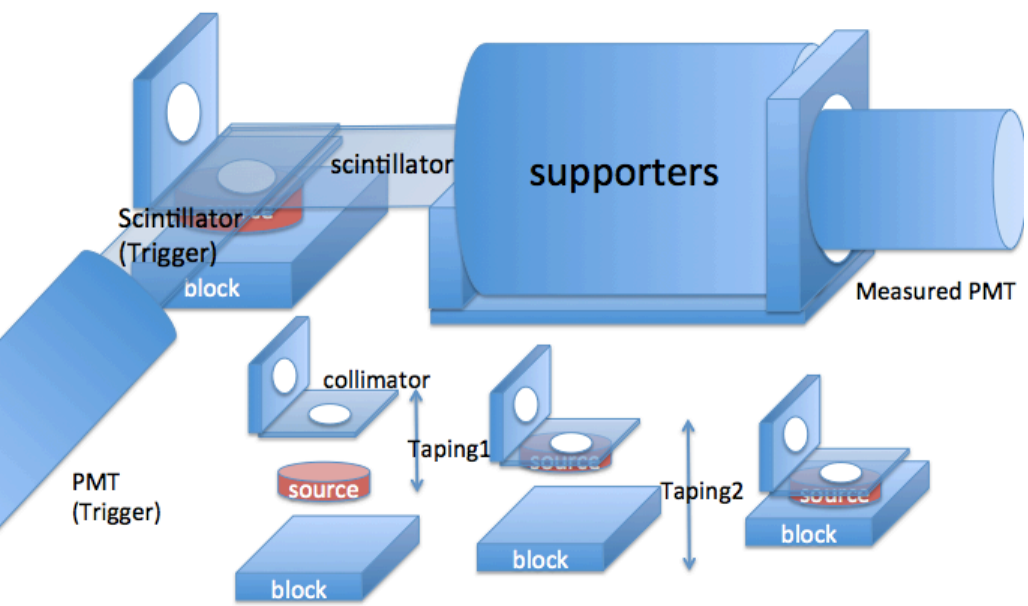
- Installation
  - Make Teflon rail for inserting Inner Barrel into Main Barrel
  - Cabling Barrel detectors
    - HV, Signal, LED

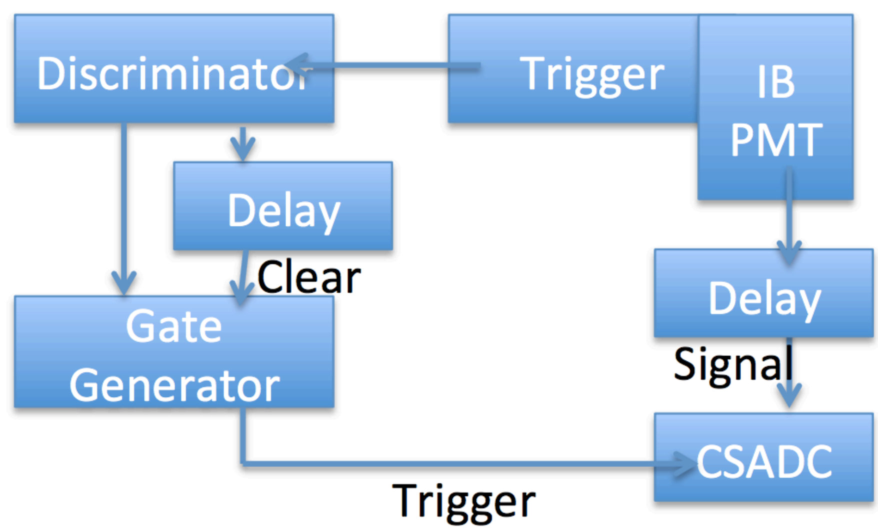



# Gain matching of IB PMT

- IB is one of online-veto detectors
  - ADC is used as online-veto signal
  - Need to arrange HV for making same output from same input module by module
    - Equal treatment for all modules
  - $^{90}$Sr is used for this gain matching

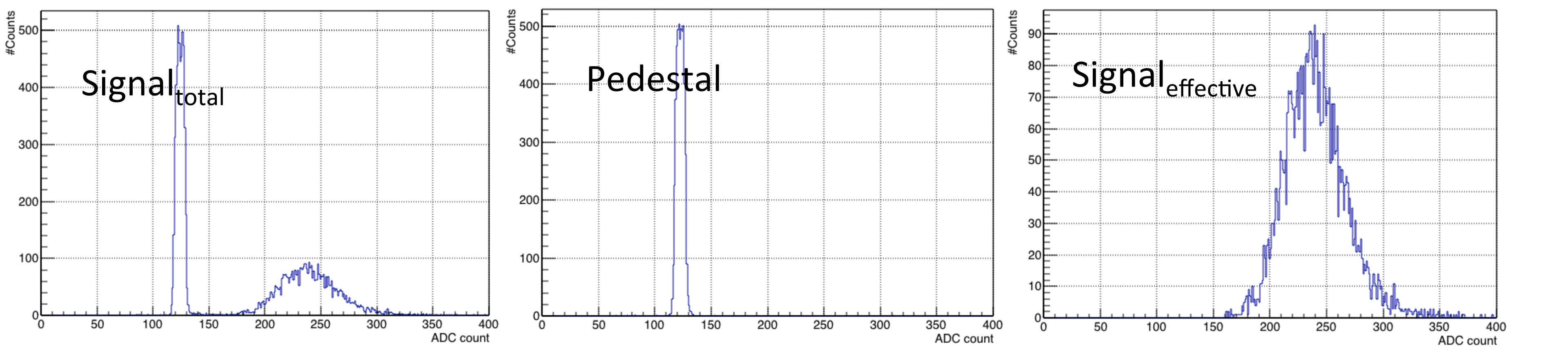


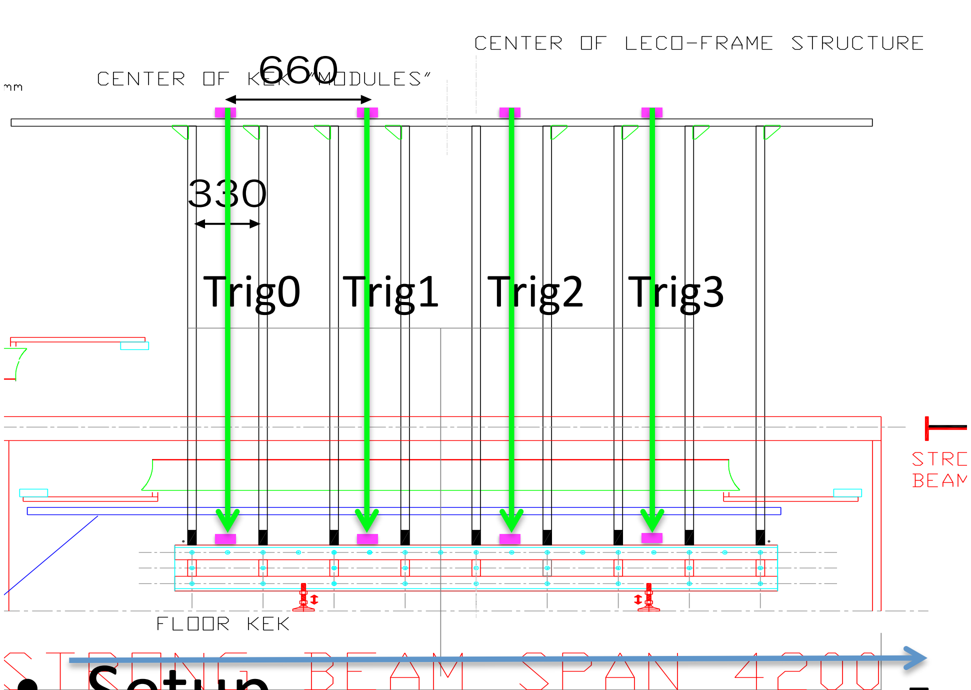



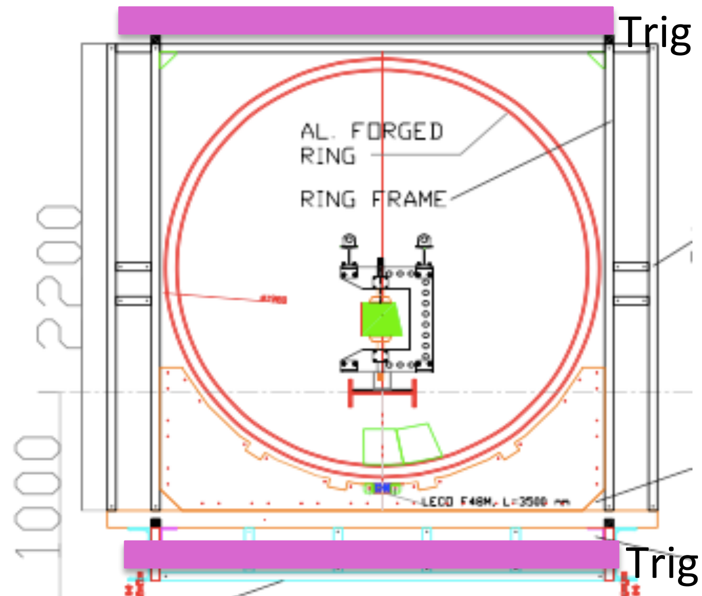
# How to match Gain

- $\text{Signal}_{\text{effective}} = \text{Signal}_{\text{total}} - \text{Pedestal}$
- Relative Gain = $\text{Signal}_{\text{effective}}$ of ith PMT / $\text{Signal}_{\text{effective}}$ of standard PMT
  – In equation $ADC = A(HV)^B$, That constant B for all PMT are same is approximated.
- Measurement of $\text{Signal}_{\text{total}}$ and Pedestal are done.

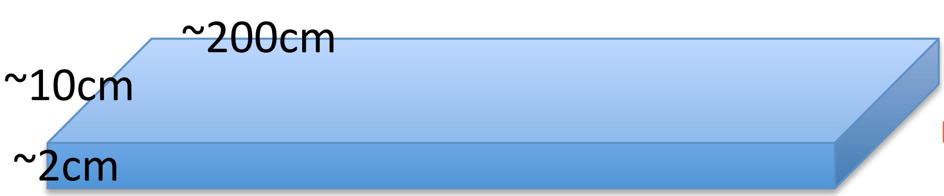


# Cosmic ray test at KEK (16/01/20)

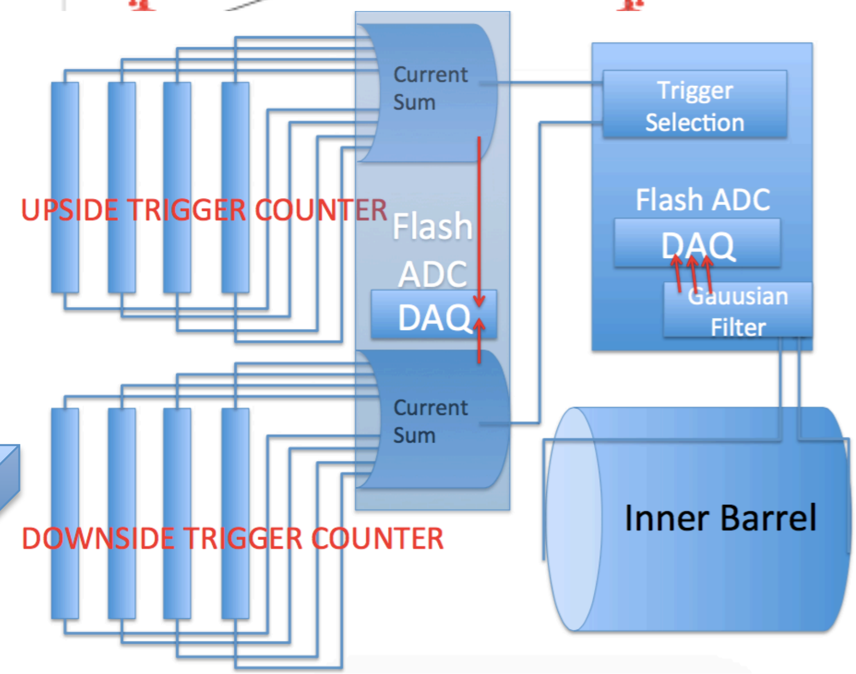


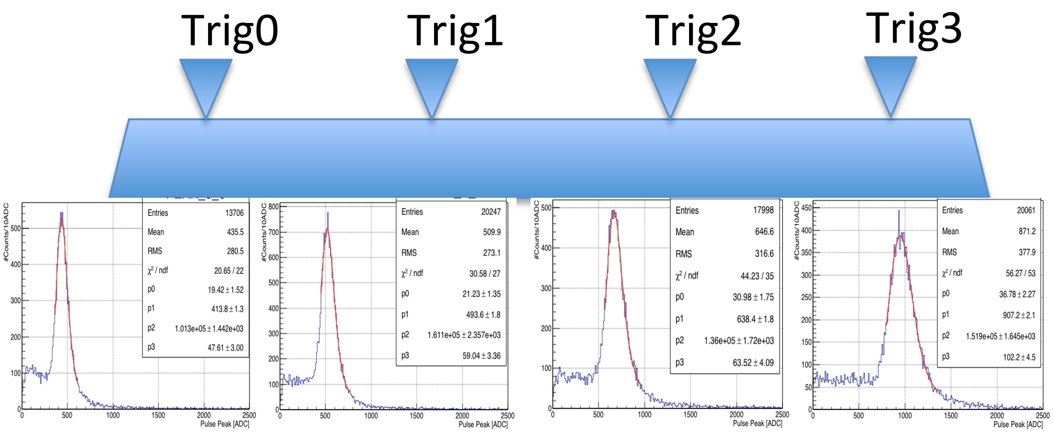

- Setup
  - 8 Scintillator trigger
    - pink squares on figures
  - 125MHz FADC

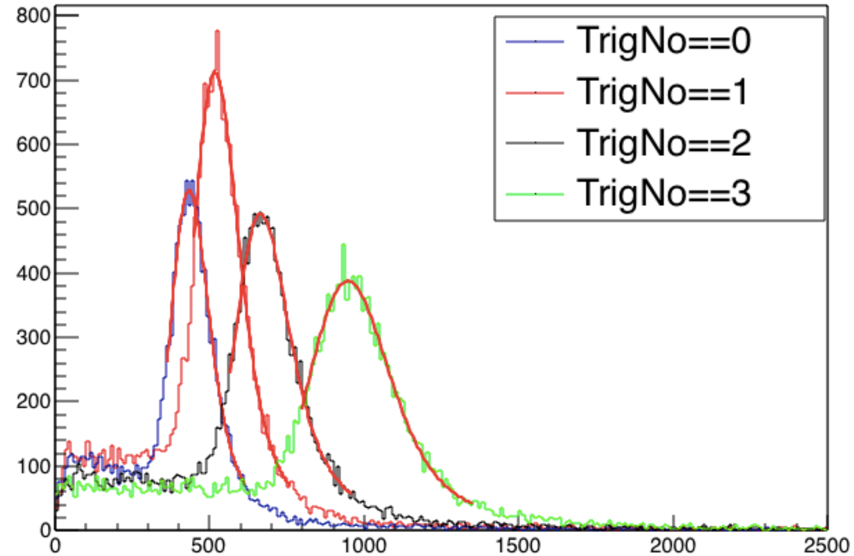



Scintillator trigger

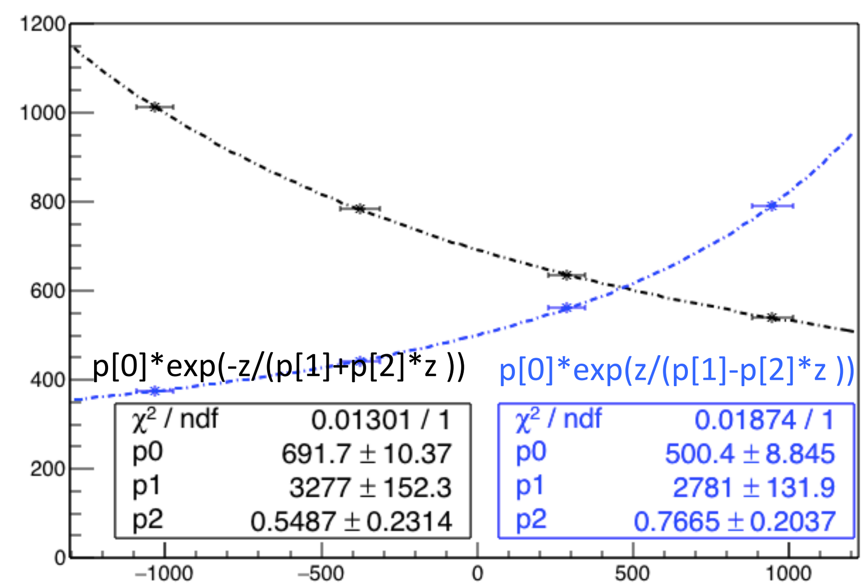


# Result of cosmic ray test at KEK



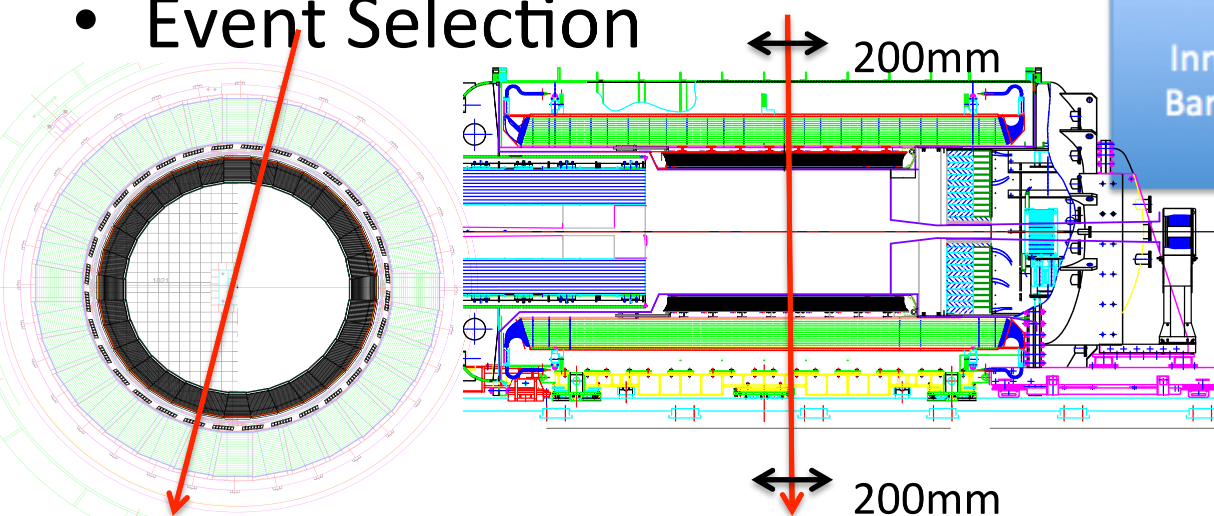



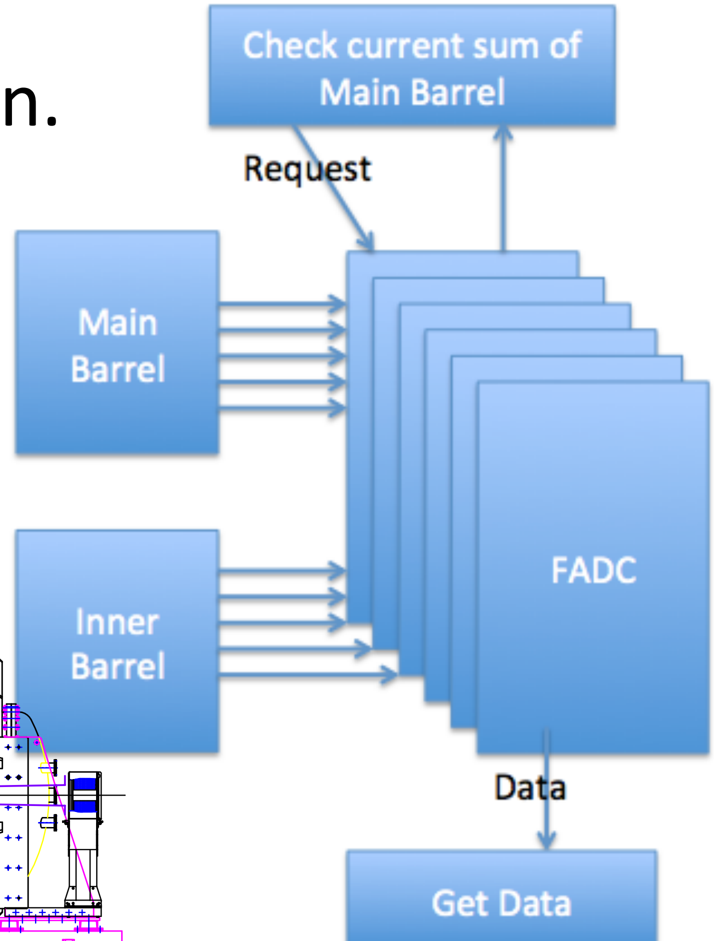

- ADC spectra check
  - Landau distribution
    - Scintillating light + delta ray from cosmic ray
  - Attenuation effect
    - Absorption in matter, scattering at surface
    - Function of wavelength
      - Different QE(λ) for each PMT



# Cosmic ray data analysis at J-PARC

- ~100hours cosmic ray data.
  - 6/8, 6/15, 6/23, 6/29, 7/1
- Cosmic ray data for calibration.
  - Time calibration.
  - Energy calibration.
- Trigger
  - Current Sum of MB
- Event Selection



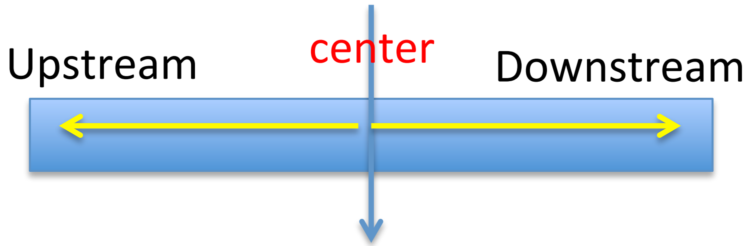



# Calibration of Inner Barrel

- Calibration process
  - Timing Calibration -> Energy Calibration
  - Timing Calibration
    - Hit Position Calibration
    - Hit Timing Calibration
  - Energy Calibration
    - For equal treatment between modules, same output from same input
    - Need to know injection position of cosmic ray to Inner Barrel
      - Timing Calibration need to be done first.

# Timing calibration

## Internal correction in module



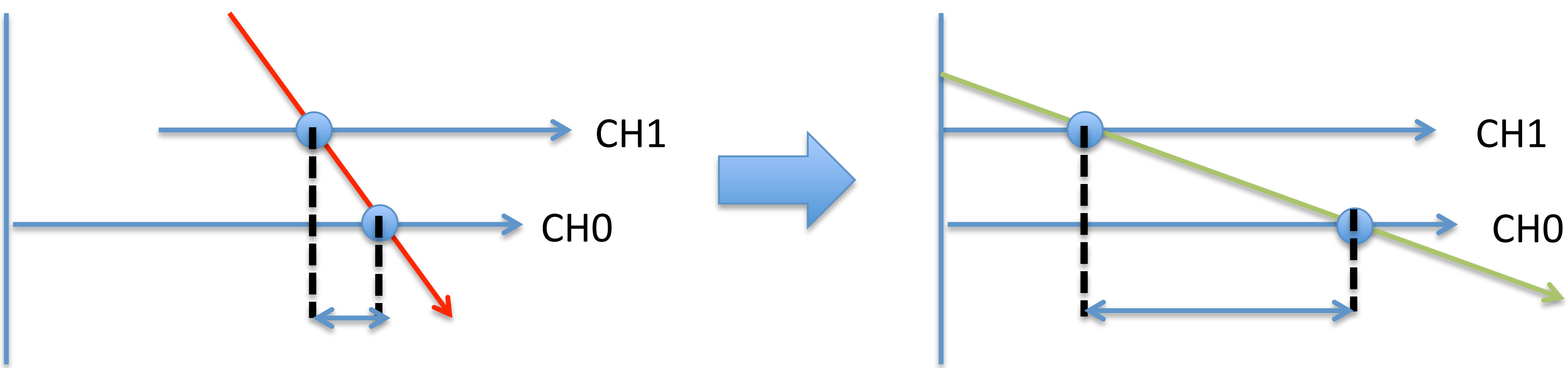

$\text{HitZ} = V_{prop}(\text{Time}_{Up} - \text{Time}_{Down})/2$

$\text{Time}_{Up} = \text{RealTime}_{Up} + \text{offset}_{Up}$

$\text{Time}_{Down} = \text{RealTime}_{Down} + \text{offset}_{Down}$

$\text{HitZ}_{center} = V_{prop}(\text{offset}_{Up} - \text{offset}_{Down})/2$

## Module-module correction



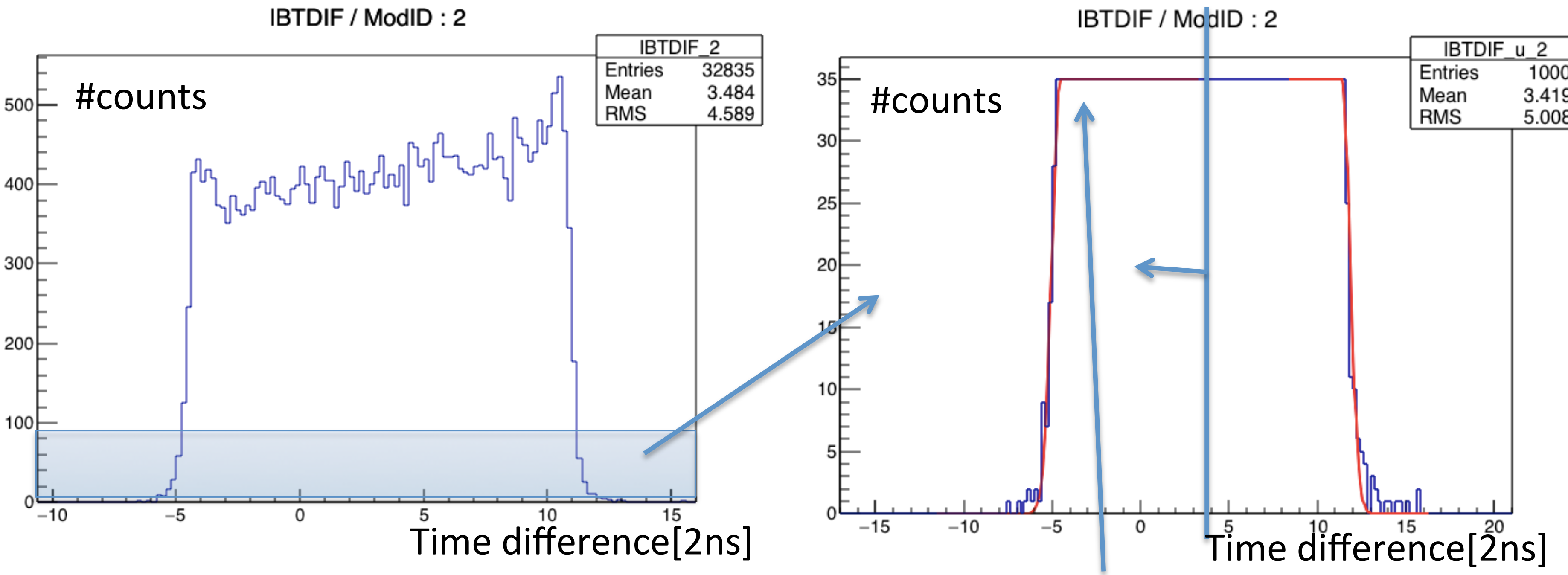

expected situation

$\Delta t = \text{Time}_0 - \text{Time}_1 (\text{ToF})$

measurement situation

$\Delta t + (\text{offset}_0 - \text{offeset}_1)$

# Hit position correction

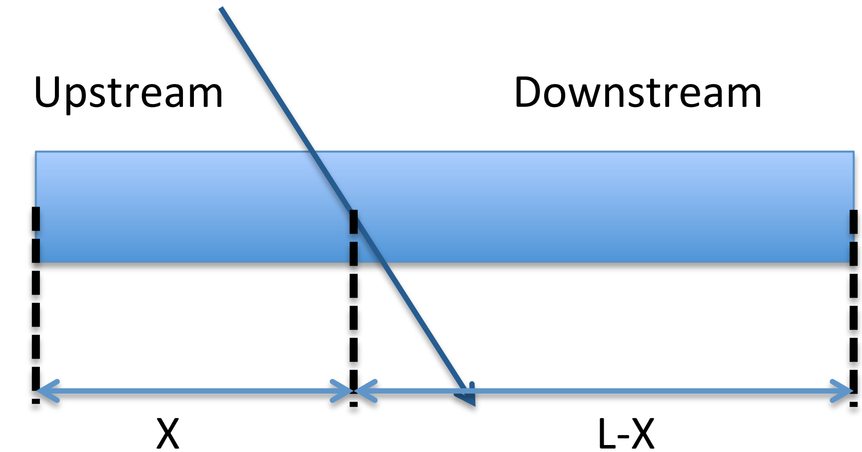



$$P0 \exp\left[0.5\left(\frac{\min(x, P1) - P1}{P2}\right)^2\right]$$

- 1) Cut raw-distribution
- 2) fitting with empirical step function
- 3) Get both-edge positions
- 4) make center as zero. (by subtracting offset)

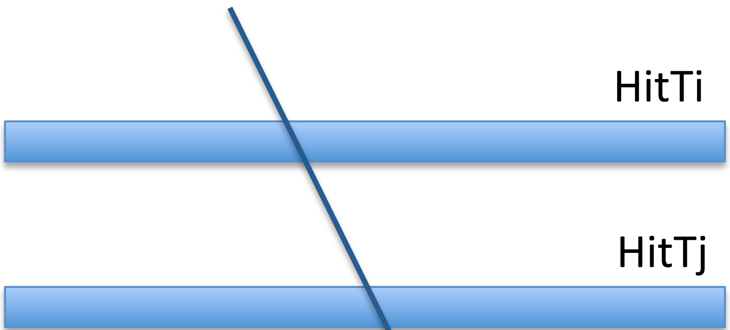
P0 : height
P1 : edge position
P2 : slope of edge

# Hit timing correction



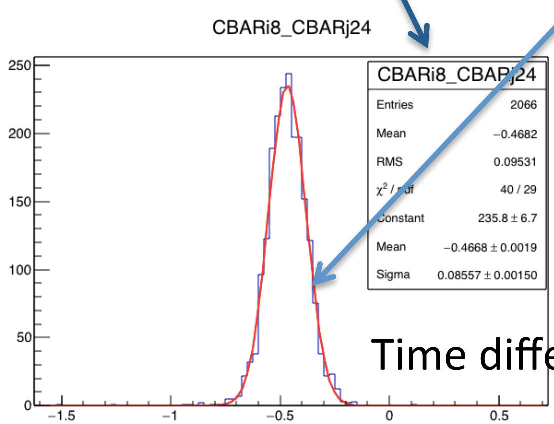

$Time_{Up}$ = HitT + $V_{prop}$X
$Time_{Down}$ = HitT + $V_{prop}$(L-X)

HitT = ($Time_{Up}$+$Time_{Down}$)/2 + const(ignore)



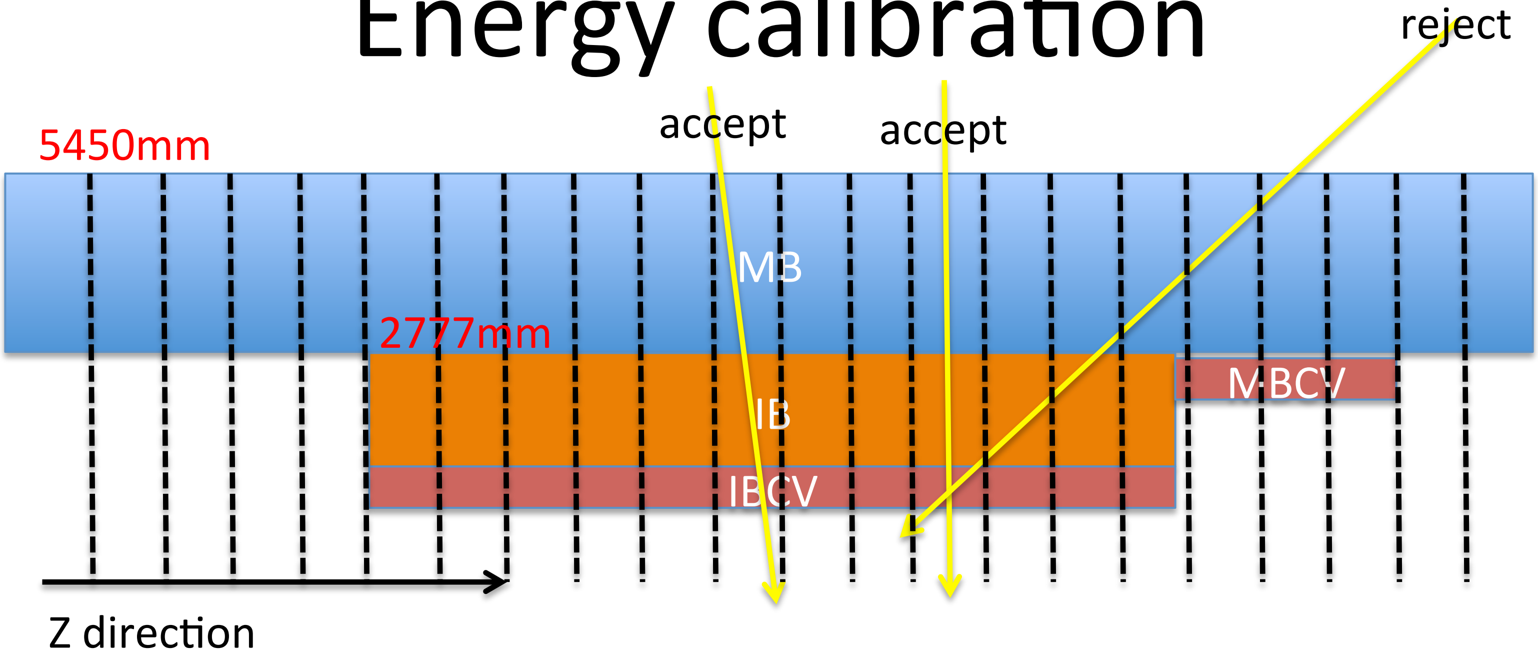

$HitT_i - HitT_j = ToF_{ij} + (offset_i - offset_j)$
$offset_i = (offset_{i\_Up} + offset_{i\_Down})/2$

Measured value : $HitT_i - HitT_j$ with same HitZ



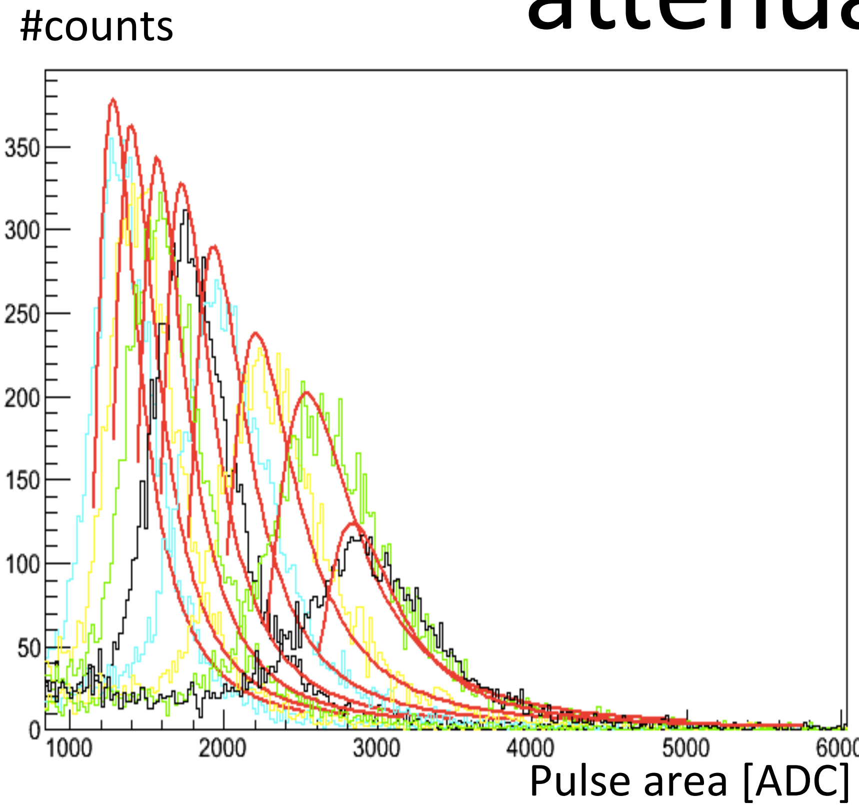

$$\chi^2 = \sum_{i,j\ (i \neq j)} \left(\frac{Mean(HitT_i - HitT_j) - ToF_{ij} + offset_i - offset_j}{Error(HitT_i - HitT_j)}\right)^2$$

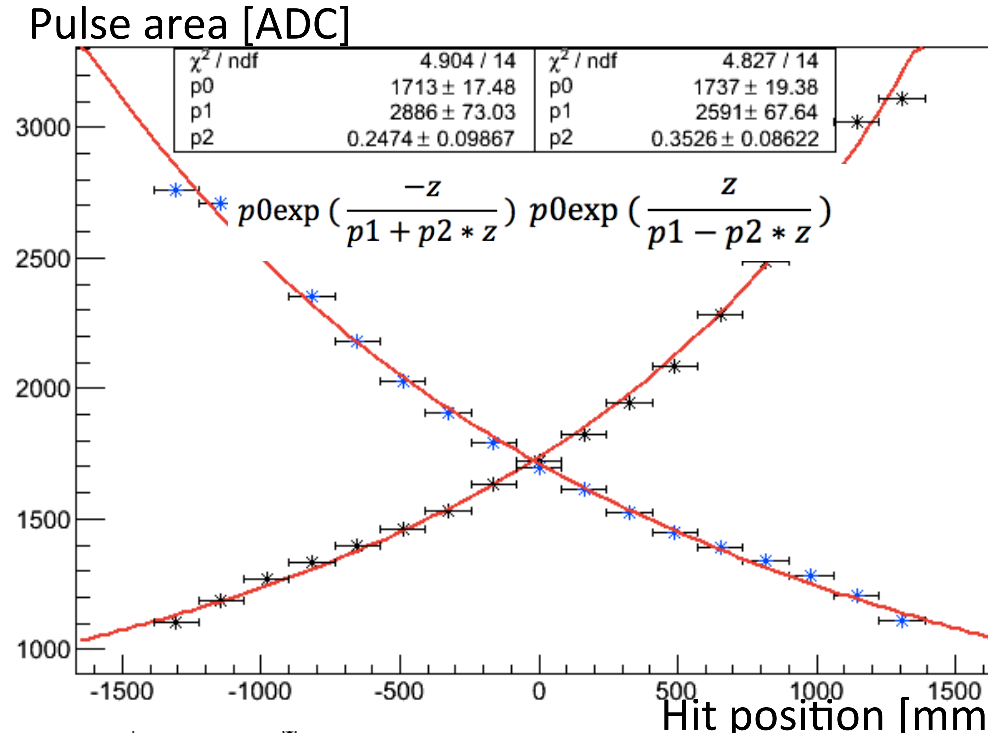
# Energy calibration

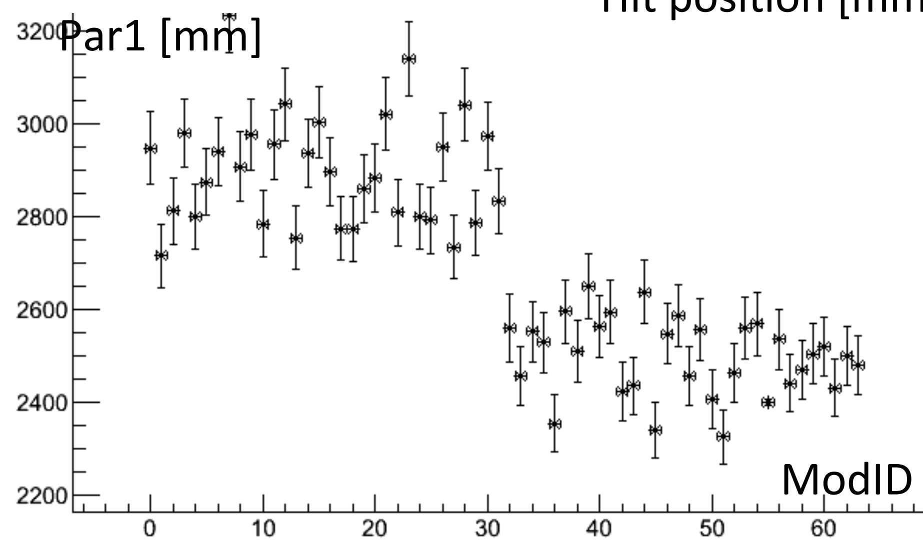



- Separate Main Barrel into 32 parts along Z-direction
  - 16 parts assigned for Inner Barrel
- Track Requirements
  - 1) diagonal module coincidence.
  - 2) Same Hit-Z positions.
- Get ADC distribution for each Hit-Z positions & each modules

# attenuation effect



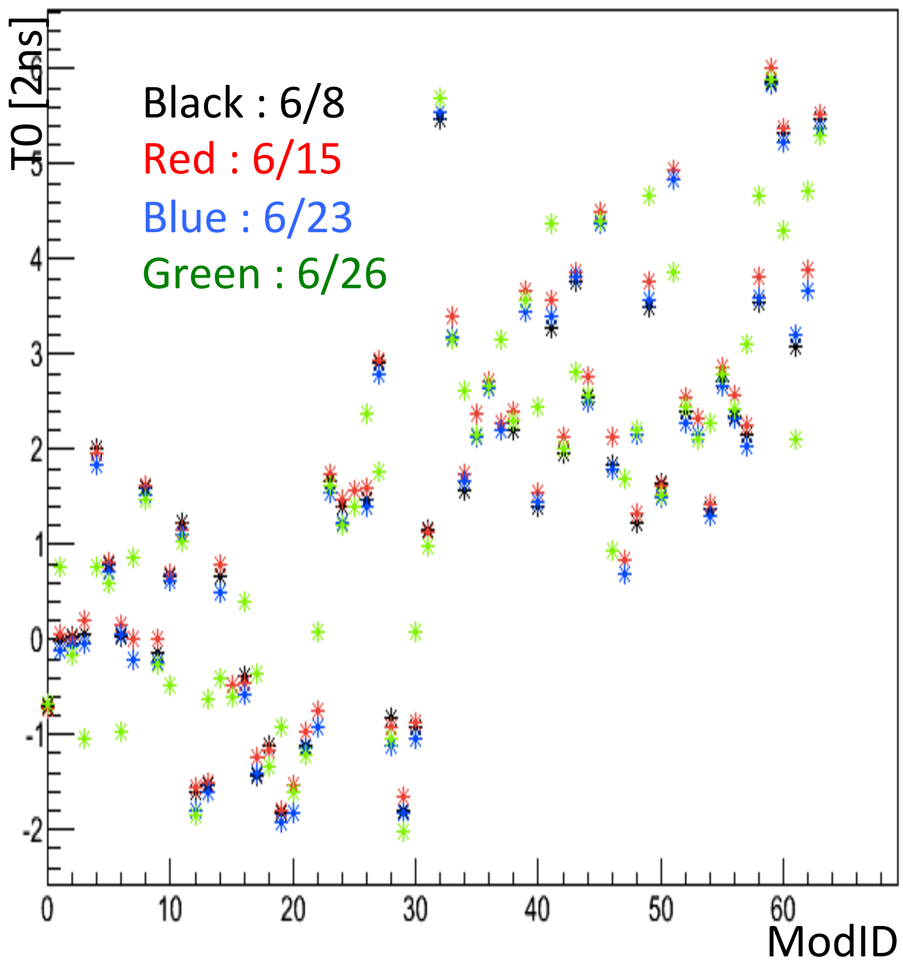



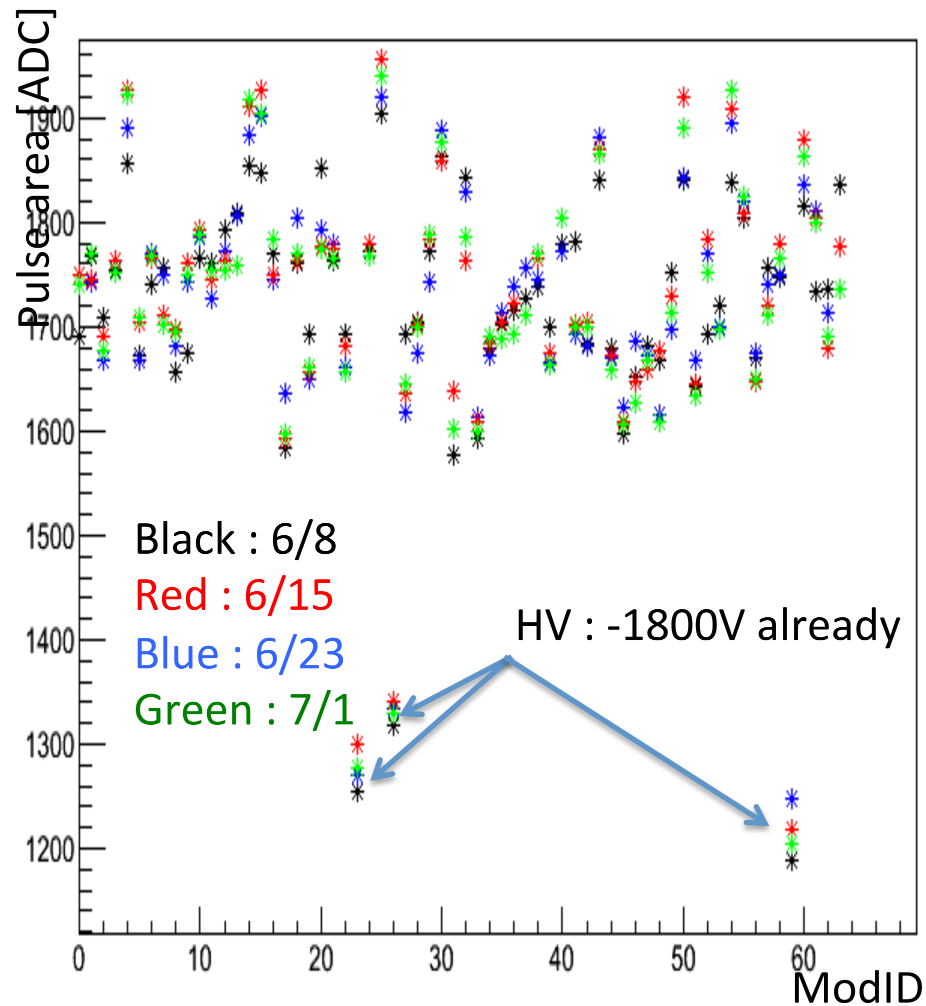

- Fitting MIP peak with landau function for each position
- Attenuation curve fitting with empirical functions

# Status of calibration during Run69

**Time Offset**

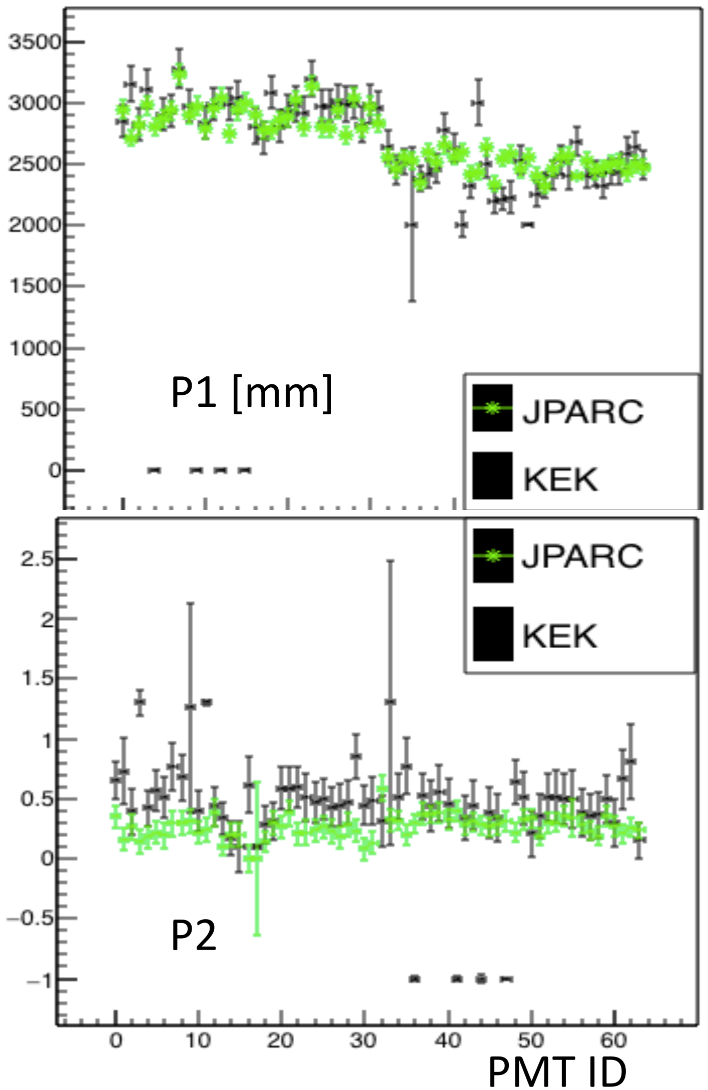



**Pulse Area**

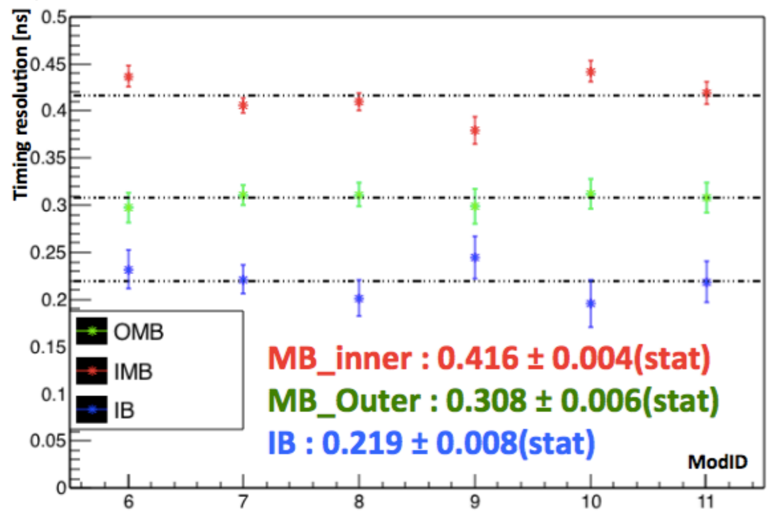


# result of cosmic ray data analysis at J-PARC

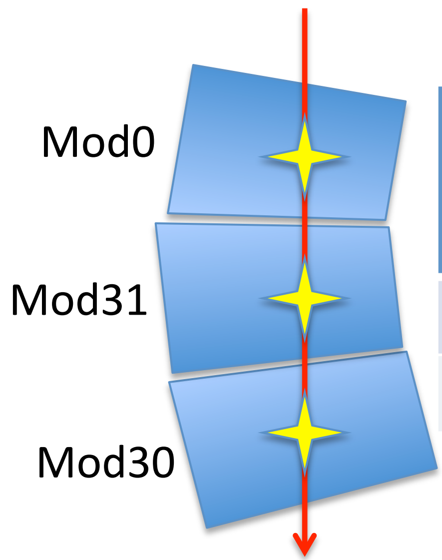
**Attenuation effect**




**Timing resolution from Run69 cosmic ray data**




**Special track selection for FADC effect on Timing Resolution**

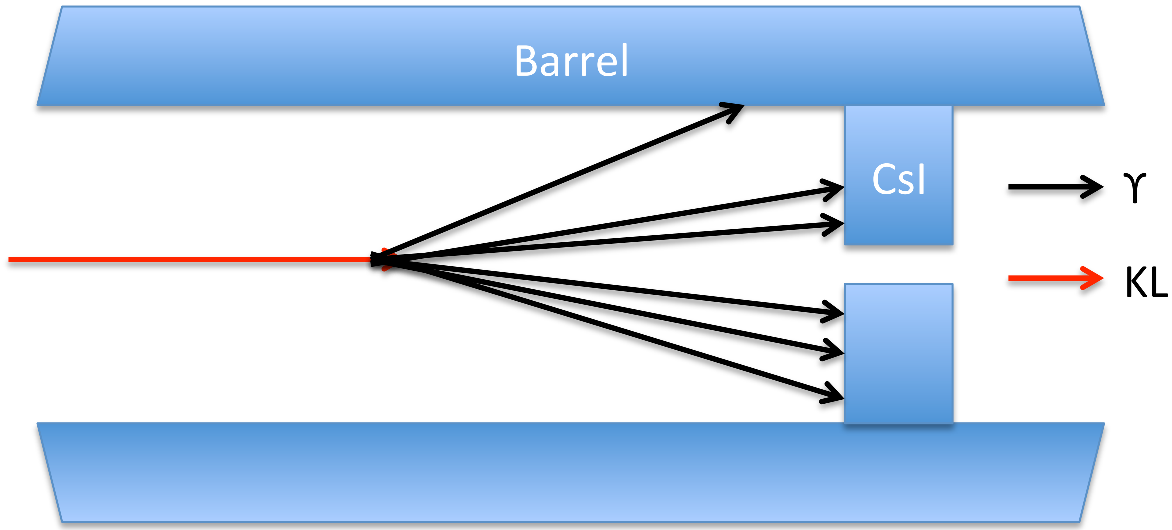



| Situation | Timing Resolution [ns] |
|---|---|
| KEK(125MHz FADC) | 0.28 |
| JPARC(500MHz FADC) | 0.18 |

# Motivation of $K_L \to \pi^0\pi^0\pi^0$ Reconstruction with Barrel

- Reconstruction of $K_L \to \pi^0\pi^0\pi^0$ from 5ϒ on CsI and 1ϒ on Barrel
  - Position of gamma on barrel is obtained from timing difference
    - Better timing resolution of IB will improve KL mass distribution
  - Comparison of KL mass distribution between run62 and run69
  - Dependence on energy deposit in barrel

# Reconstruction (1)




- Calculation of direction of 1 missing ϒ.
  - 5ϒs on CsI
    - $2\pi^0$ vertex from 4ϒs
    - Minimum vertex-chi2
  - 1ϒ on barrel
    - Z position from timing differences between upstream PMT and downstream PMT
    - X, Y position from Module ID.

# Reconstruction (2)

$E_s, P_s$ : Energy and momentum of a 5th ϒ on CsI which is not associated with $2\pi^0$

$E_r, P_r$ : Energy and momentum of a 6th ϒ hitting IB+MB.

$$2(E_s E_r - \vec{P}_s \cdot \vec{P}_r) = m_\pi{}^2$$

$$\vec{P}_s \cdot \vec{P}_r = E_s E_r cos\theta$$

$$E_r = m_\pi{}^2/(2E_s(1 - cos\theta))$$

$$M_{KL}{}^2 = (\sum_{i=1}^{5} E_i + E_r)^2 - (\sum_{i=1}^{5} \vec{P}_i + \vec{P}_r)^2$$

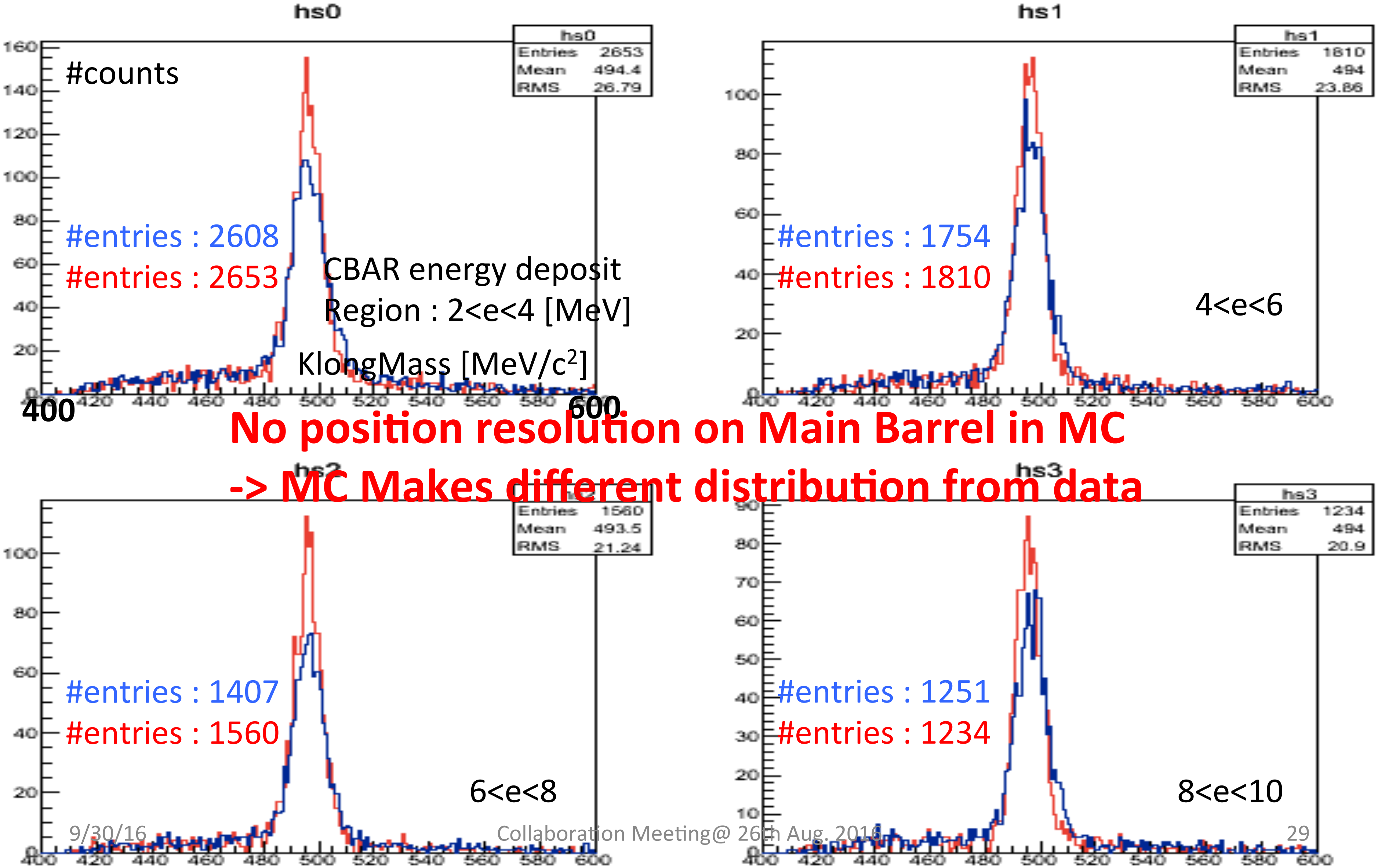
# Data information

- Used Run62(April, 2015) data
  - 27kW beam only.
  - $4.253*10^{15}$ (Proton On Target)
- Used Run69(June, 2016) data
  - Run23713~ : changed FADC delay time(330->327)
  - $7.393*10^{15}$ (Proton On Target)
- Run69/Run62 = 1.74
- MC data
  - KL default decay
  - #KLs = $5*10^{8}$
    - $2,778*10^{15}$(Proton On Target)

# Dependence of mass distribution on MB energy deposit

Red : MC

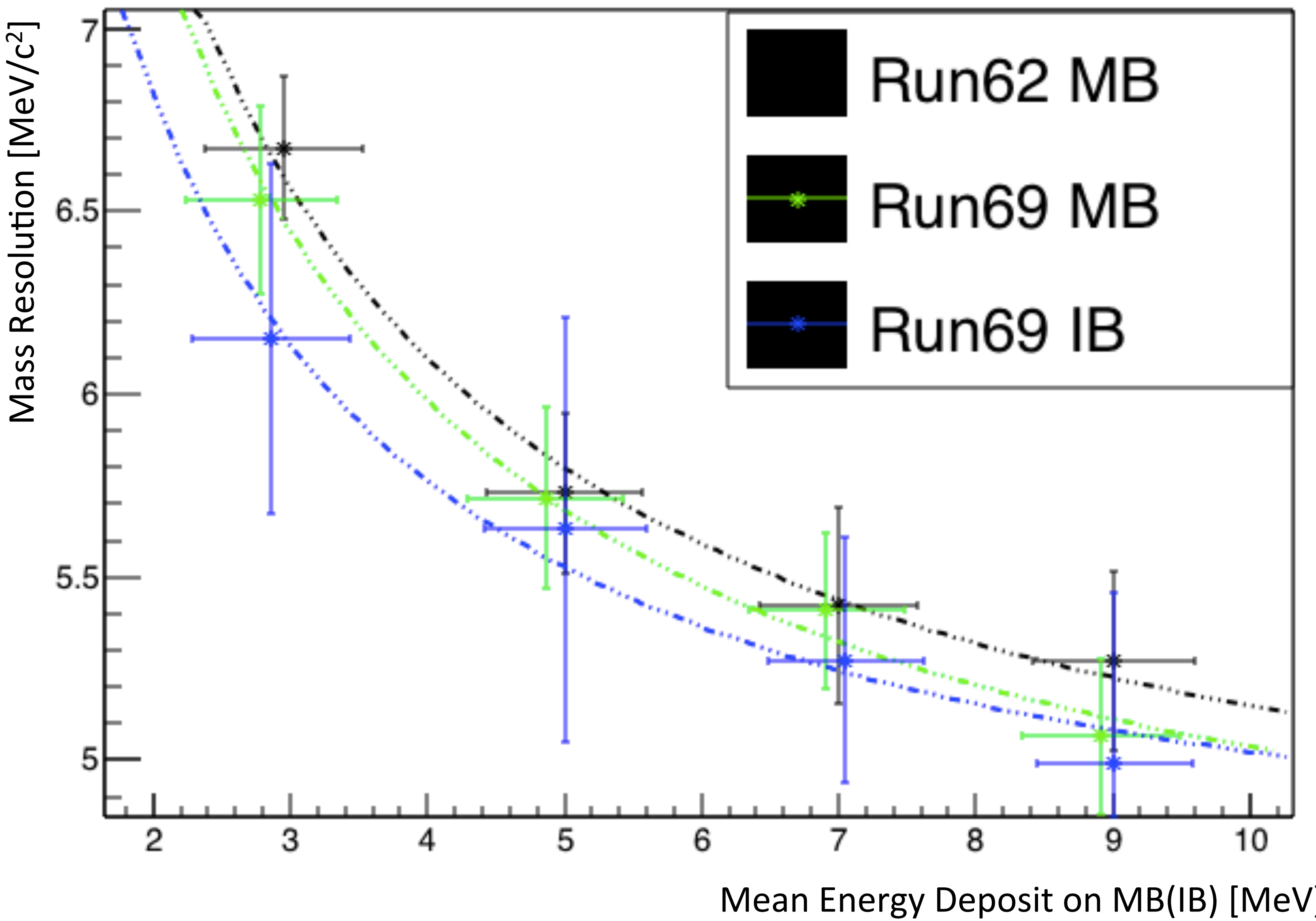
Blue : data




**No position resolution on Main Barrel in MC**

**-> MC Makes different distribution from data**

# Mass resolution



# Summary

- Production and Installation Inner Barrel is done
  - Barrel timing resolution
  - Additional radiation length
- Calibration of Inner Barrel is done
  - ~7% error energy calibration
    - 3 low gain channel -> amplifier in next run
  - Timing calibration
    - Need timing calibration whenever rebooting FADC.
- $\mathbf{K_L} \to \pi^0\pi^0\pi^0$ reconstruction study in the case of 5ϒ on CsI && 1ϒ on barrel is ongoing
  - Mass reconstruction
  - Mass resolution
    - Dependence on MB energy deposit.
  - Things to do
    - Klong Pt cut effect.
    - Other cut parameter
    - $\mathbf{K_L} \to \pi^0\pi^0\pi^0$ physics study

# kaon physics, CKM matrix

**Eigenstates of CP**

$$K_2 = \frac{1}{\sqrt{2}}(K_0 + \overline{K_0})$$

$$K_1 = \frac{1}{\sqrt{2}}(K_0 - \overline{K_0})$$

**CP violating**

$$K_L = \frac{1}{\sqrt{1+\epsilon^2}}(K_2 + \epsilon K_1)$$

$$K_S = \frac{1}{\sqrt{1+\epsilon^2}}(\epsilon K_2 + K_1)$$

Quark transition through weak interacti