Thin scintillation counter with a new readout method for KOTO

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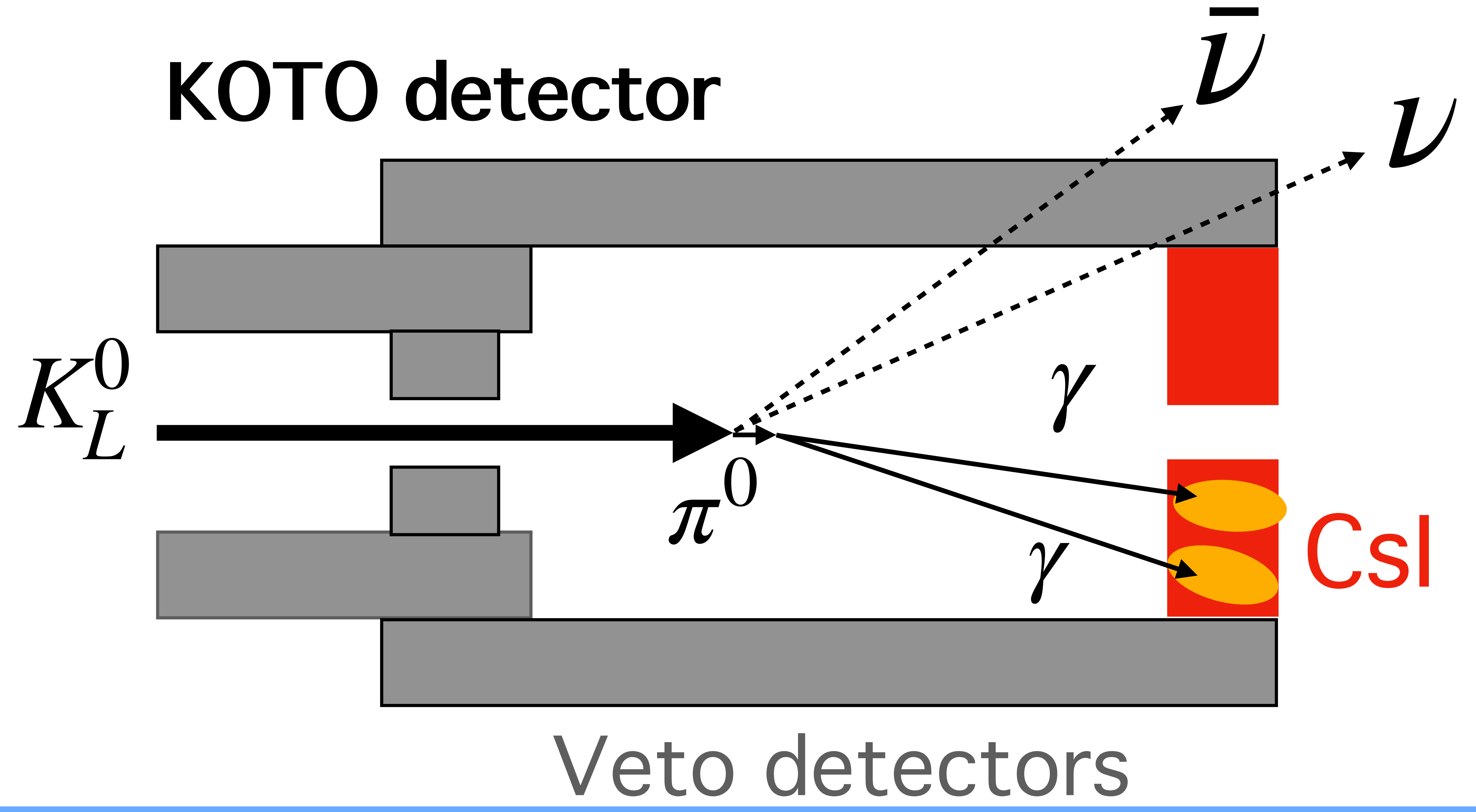
J-PARC KOTO Experiment

Search for the rare $K_L \to \pi^0 \nu \bar{\nu}$ decay

- Direct $\not{CP}$ process
- Rare decay $(BR_{SM} = 3 \times 10^{-11})$
- Small theoretical uncertainty (~2%)

→ Good probe for new physics search

KOTO detector



Signature of this decay

$(\pi^0 \to)\, 2\gamma$ → CsI calorimeter

+

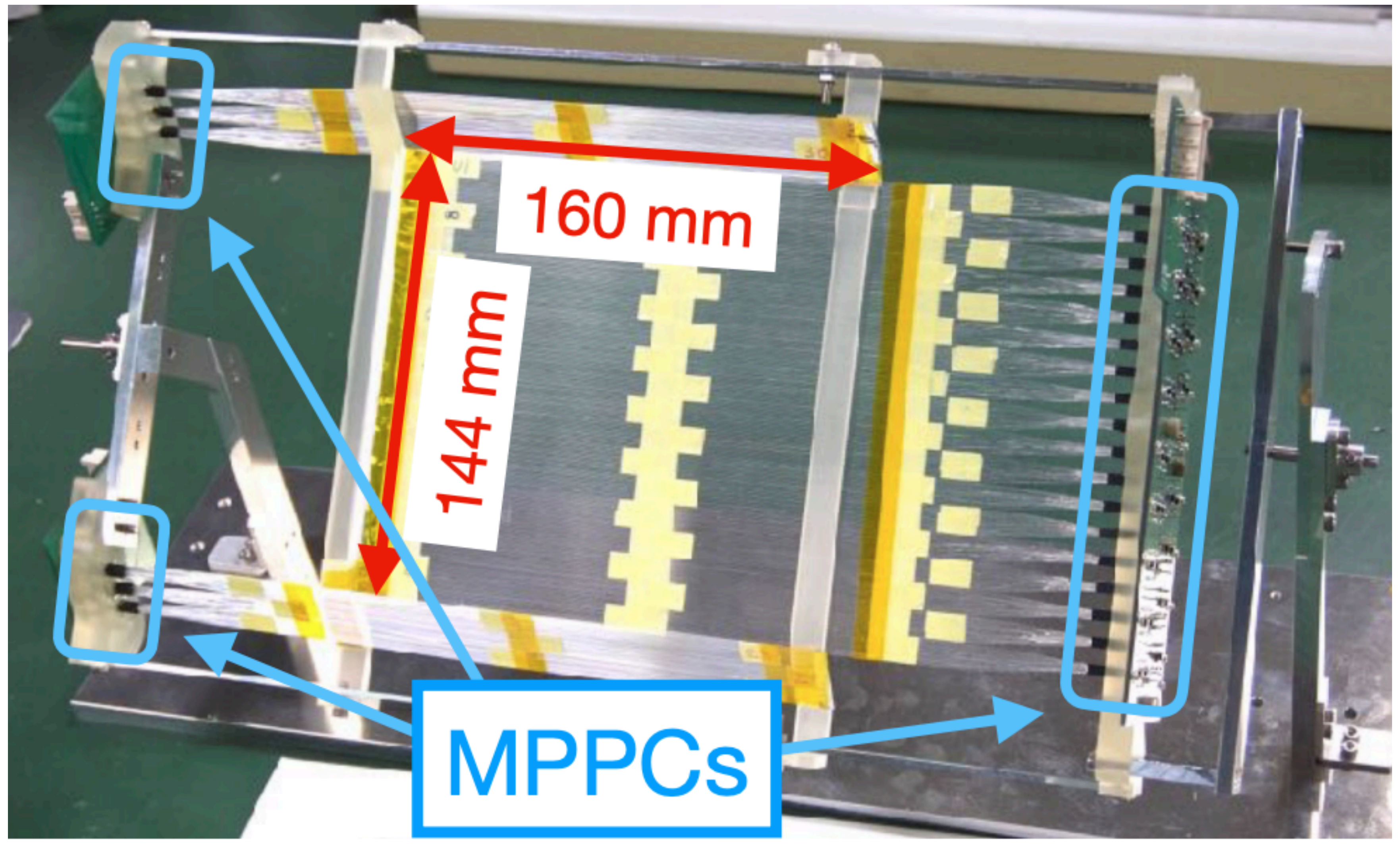
Nothing → Veto detectors

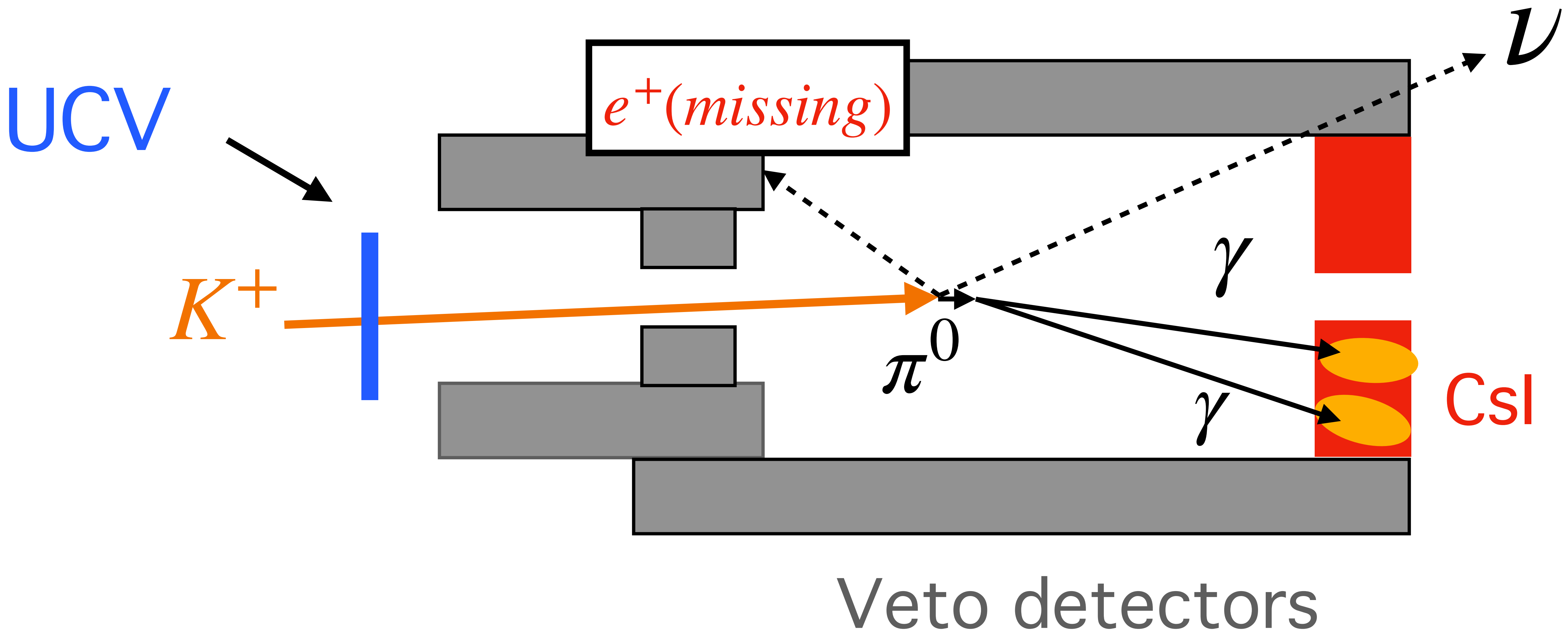
Charged K background

K^+ **decay** : Largest background in 2016-2018

⇒Installed a charged particle detector (**U**pstream **C**harged **V**eto) **in the beam** in 2020

Current UCV





Main contribution : $K^+ \to \pi^0 e^+ \nu$

Key feature

- **Low mass** detector → a plane of **0.5-mm** thick scintillation fibers
- Inefficiency ~ **8%** → × ~**1/10** K^+ **background reduction**

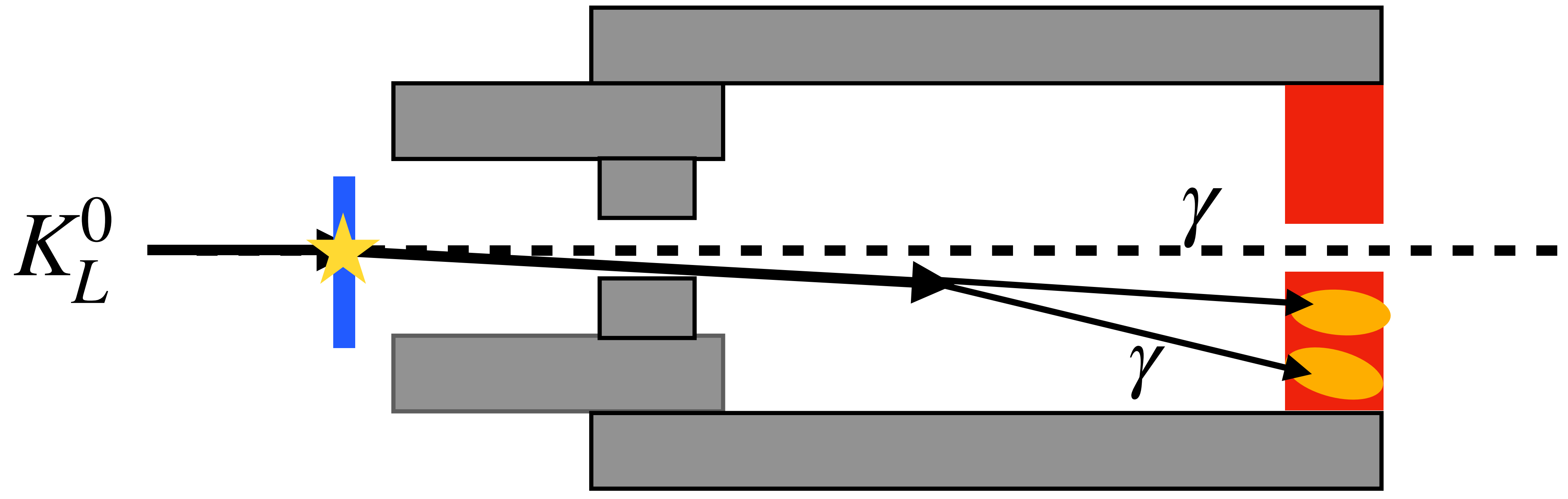
Problem on current UCV

- Installing 0.5-mm-thick scintillator in the neutral beam

⇒ **Increased other backgrounds**

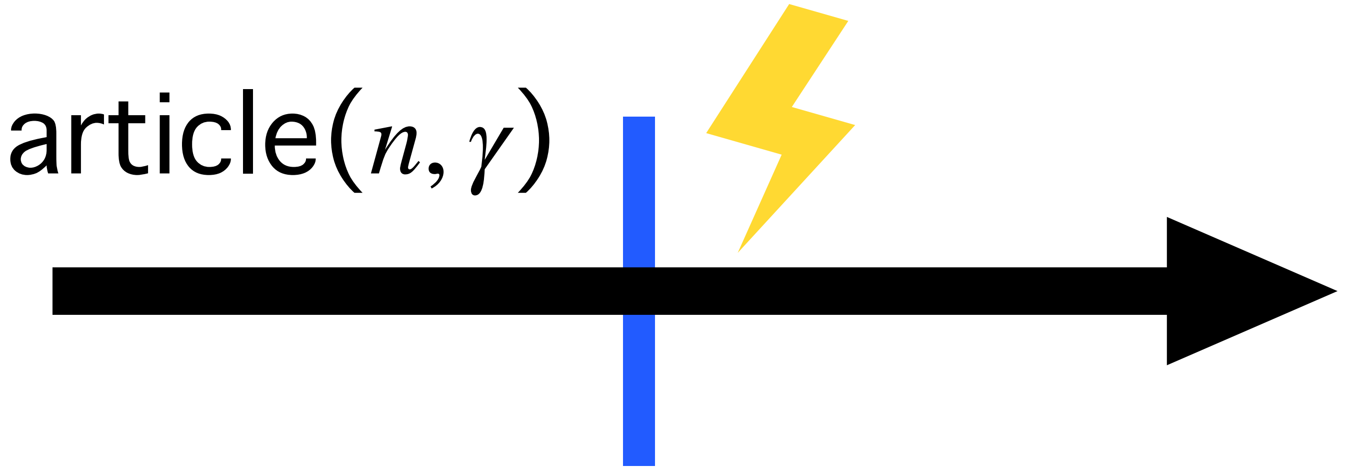
- Due to scattering of neutral particle

Ex) scattered $K_L \to 2\gamma$



⇒ **Increased the loss of signal**

- Due to ① high counting rate of UCV itself
  ② scattered neutral particle
  hitting other veto detector



- ×1/10 K^+ BG reduction ⇒ **Need further reduction in the near future**

Developing a new version of UCV

Film UCV

Thinner + more sensitive detector

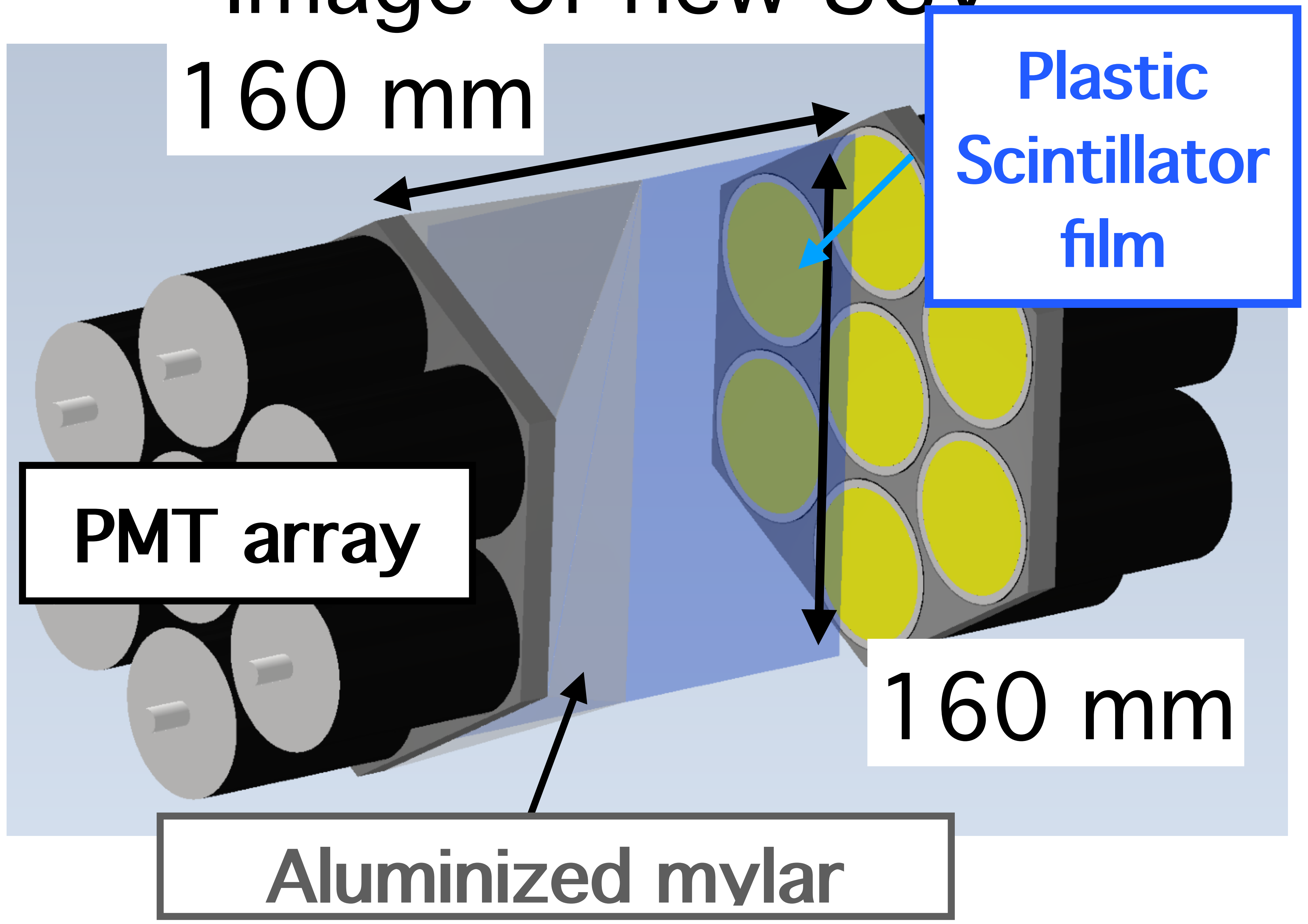
Q : How do we achieve it?

A : Use 0.2-mm-thick plastic scintillator film

+

12-μm-thick Aluminized mylar

Image of new UCV



Total thickness : 0.5 mm ⇒ ~ 0.2 mm

Inefficiency : 8% ⇒ 1%

K^+BG rejection : ~1/10 ⇒1/100

Light collection method

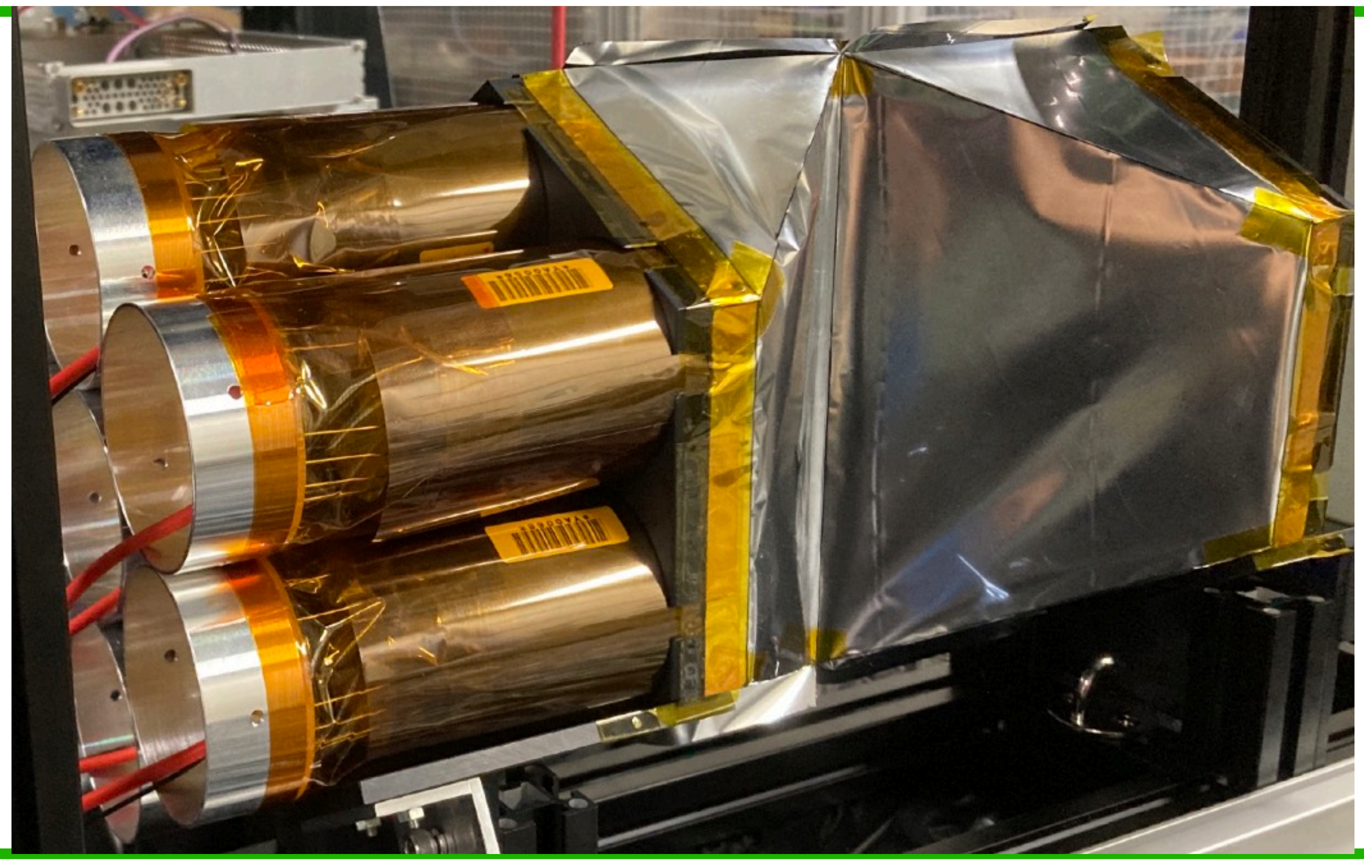
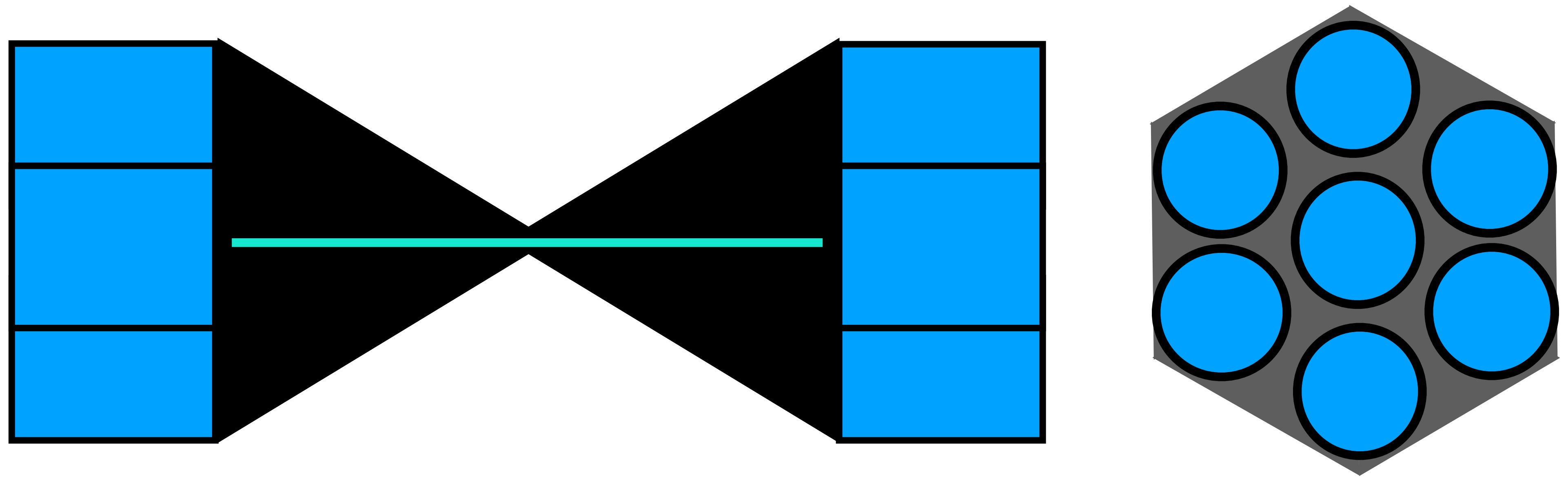
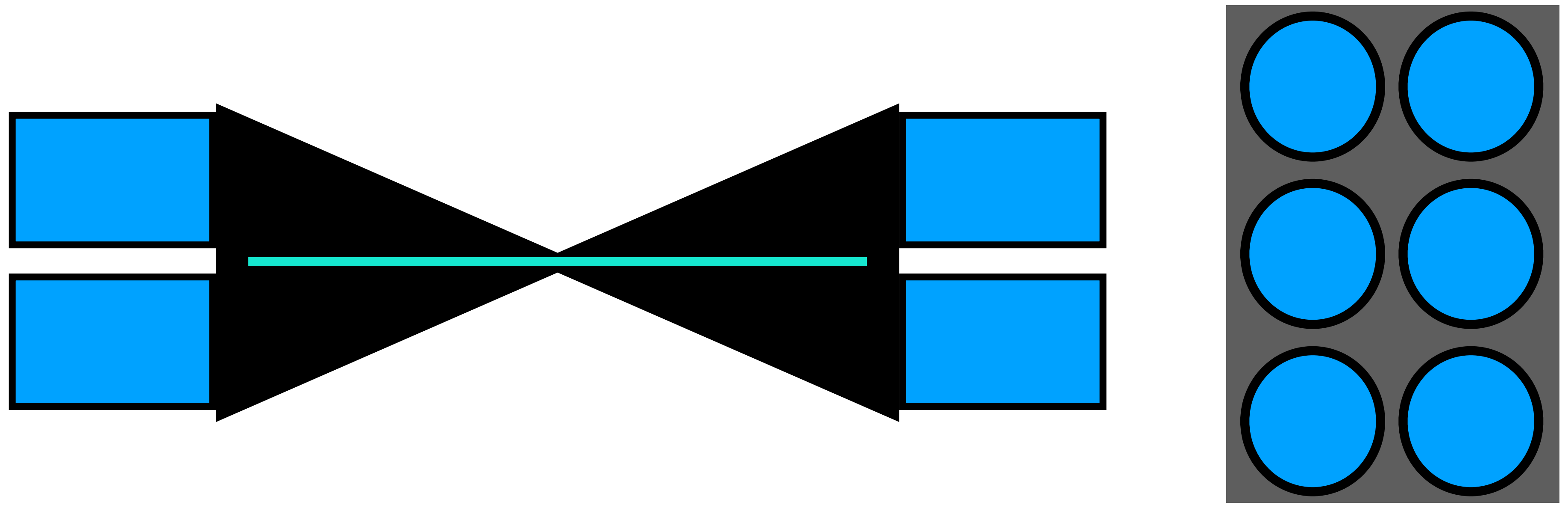
Q : How do we get enough light yield?

A : Use the scintillation light escaping from its surface

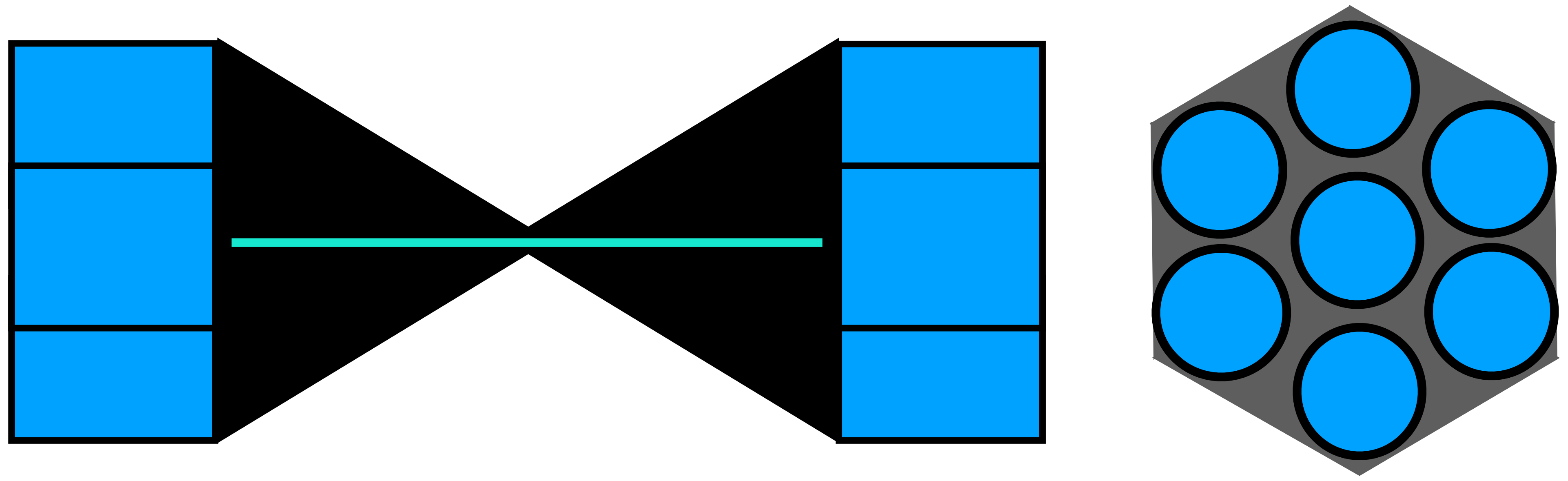
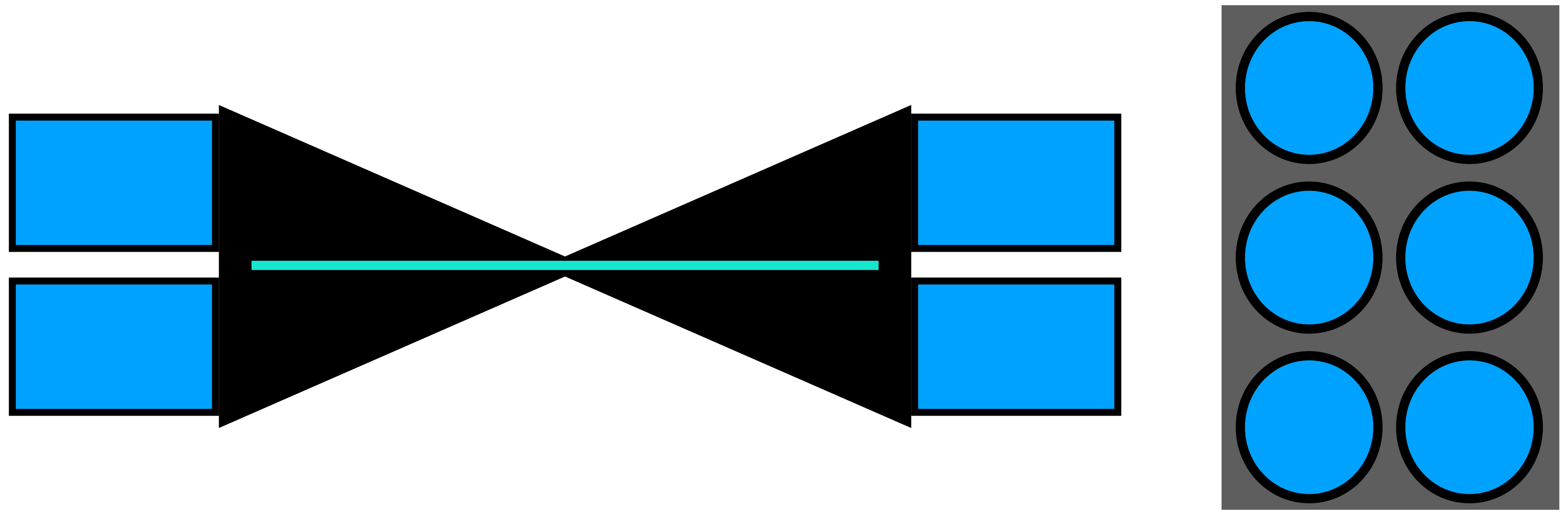
- **Reflect** and **collect light with** Al mylar

Optical design

- There were two optical designs

	1. Hexagonal type	2. Rectangular type
Picture		
Shape		
# of PMT	7 PMTs per side	6 PMTs per side

Result of ray tracing simulation

	1. Hexagonal type	2. Rectangular type
Shape		
Light yield Ratio	1.26 (14.6 p.e.)	1 (11.6 p.e.)
Threshold (ineff 1%)	6 p.e.	4 p.e.

How about the actual performance ?

➡ Evaluated the performance with an electron beam

Performance test with electron beam

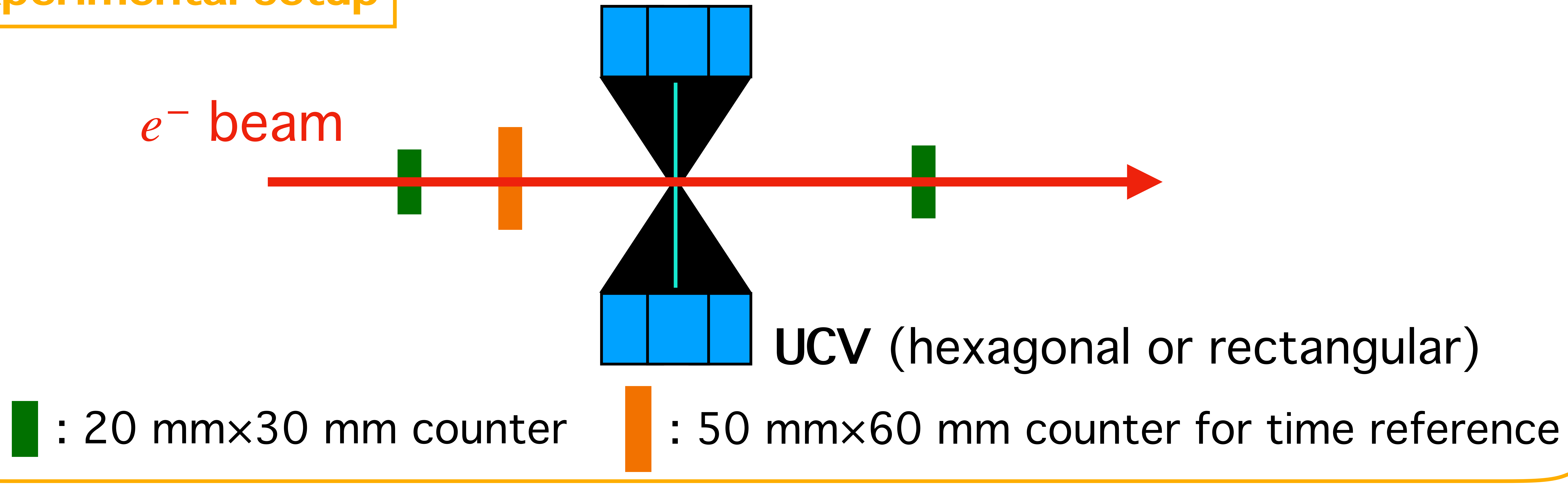
Objective

① light yield, inefficiency

② comparison between hexagonal and rectangular types

③ timing resolution

Experimental setup



Evaluation of light yield

- Determined the peak height in each channel in a 100 ns time window

Peak height = Maximum - Pedestal

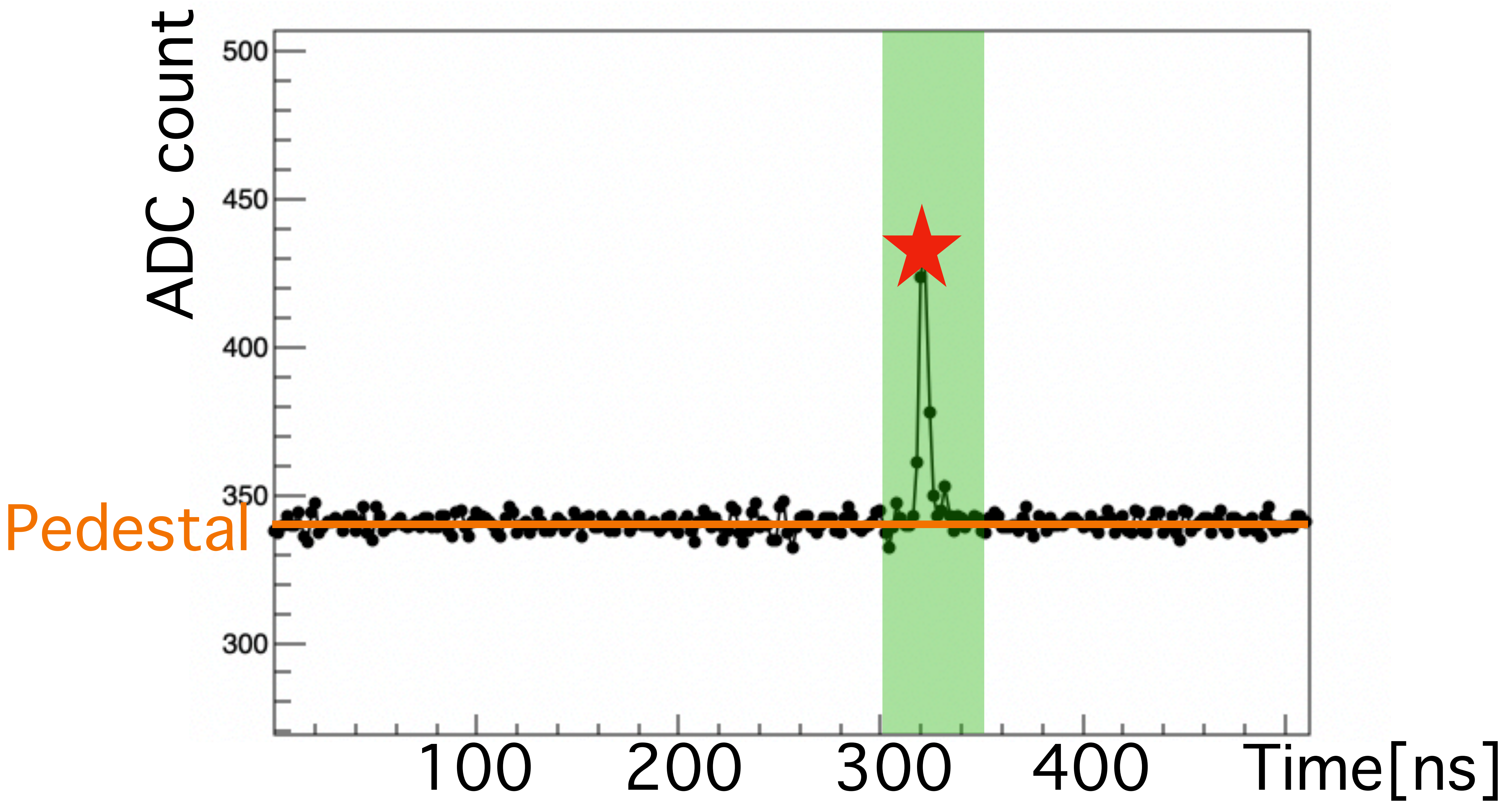
↓

- **Convert Peak height to # of p.e.** with 1p.e. calibration data

↓

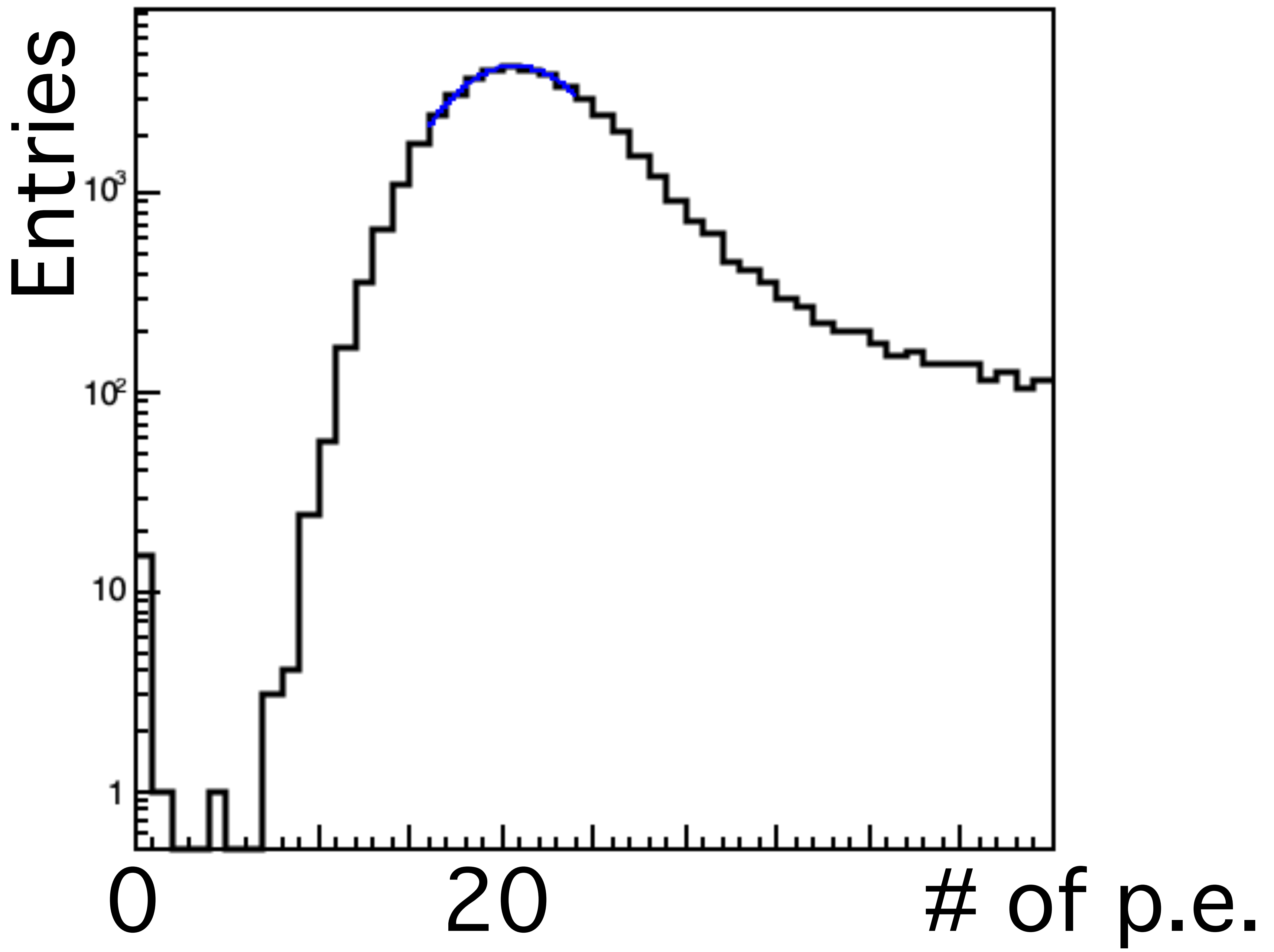
- Calculate **total light yield of UCV**

Example of waveform of a channel

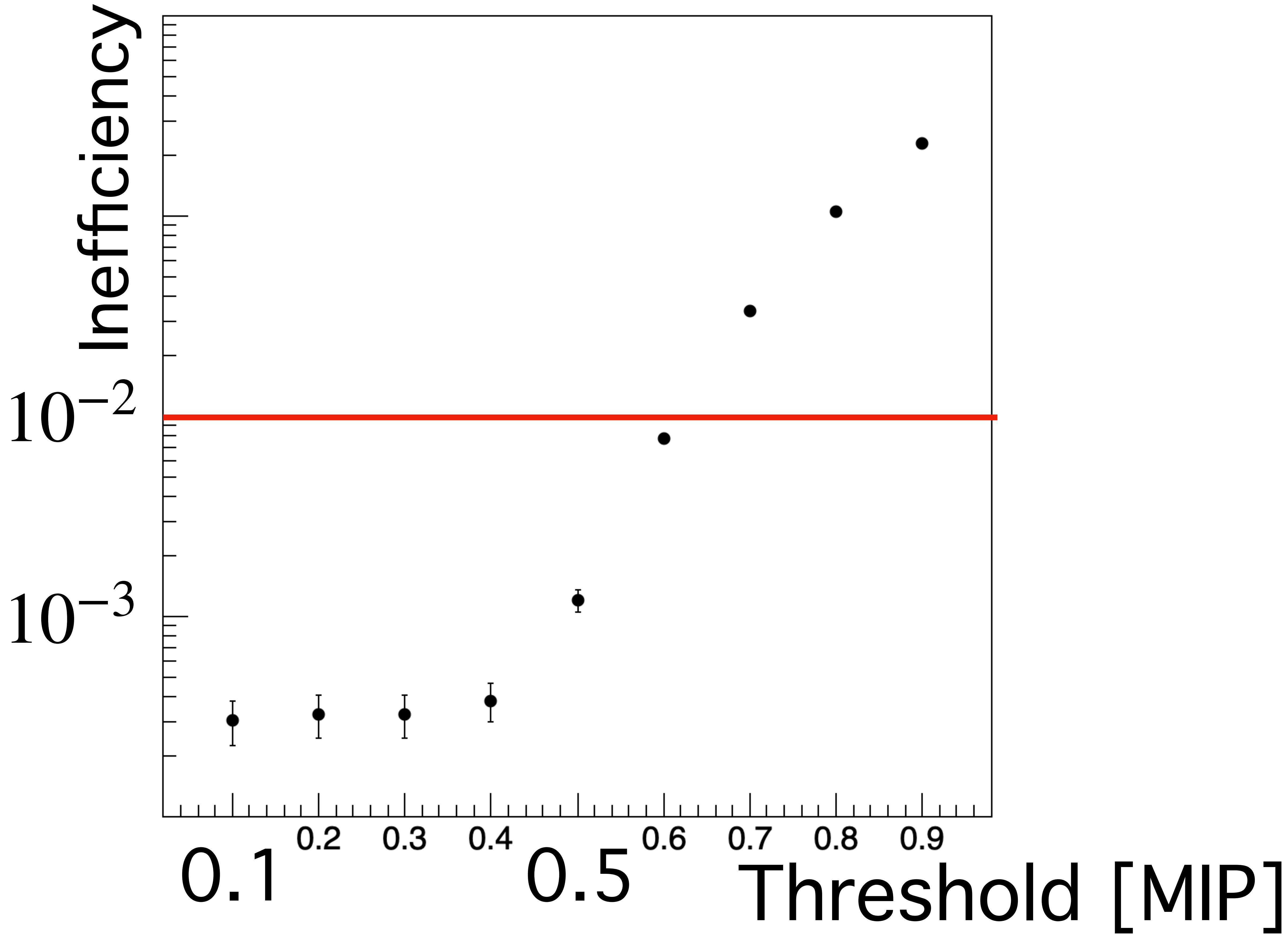


Light yield and inefficiency : hexagonal type

of p.e. distribution



Inefficiency

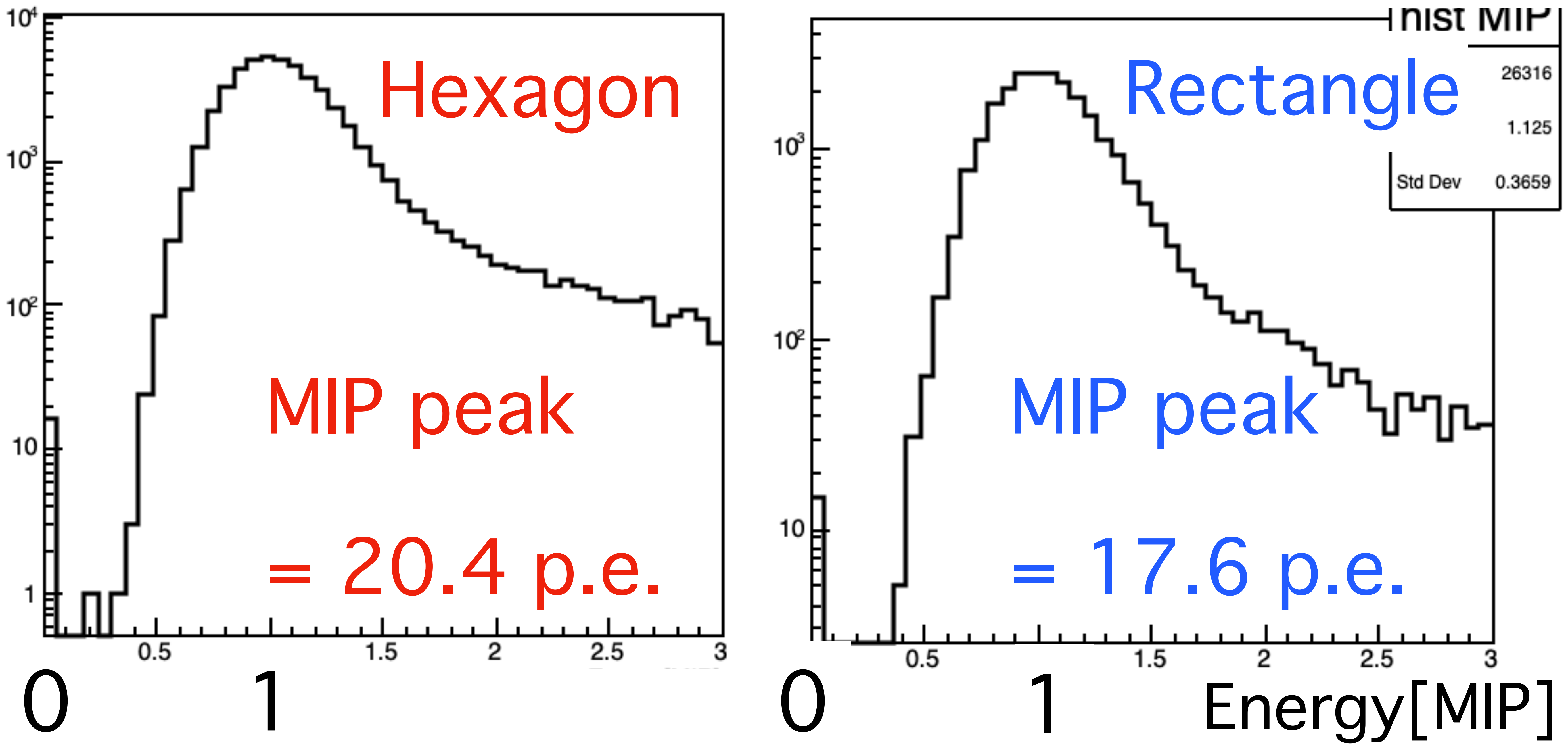


Light yield : ~ **20 p.e./MIP**
Inefficiency : **<1% inefficiency with threshold < 0.6 MIP**

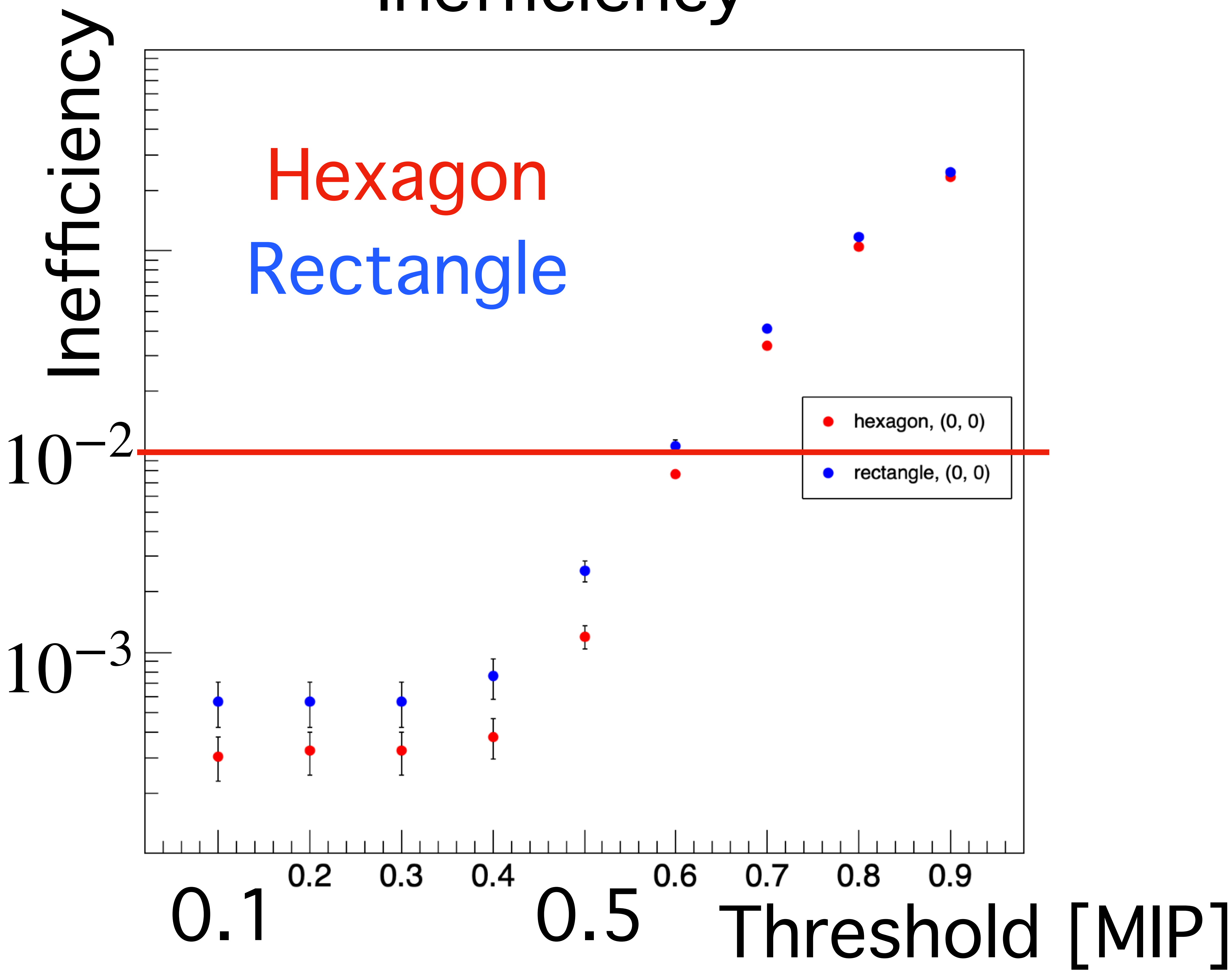
➡ **Sufficient Performance**

Hexagonal vs rectangular types

Energy distribution



Inefficiency



Hexagon has 16% higher light yield and
<1% inefficiency at higher threshold

➡ Decided to use Hexagonal type

- Discrepancy between data and simulation is under study

Evaluation of timing resolution

- Calculated Constant Fraction Timing(CFTime) $T[j]$ for each channel

↓

- Calculated the UCV timing (T_{UCV})

Definition : Average weighted by light yield

$$T_{UCV} = \frac{\Sigma T[j] \cdot N_{p.e.}[j]}{\Sigma N_{p.e.}[j]}$$

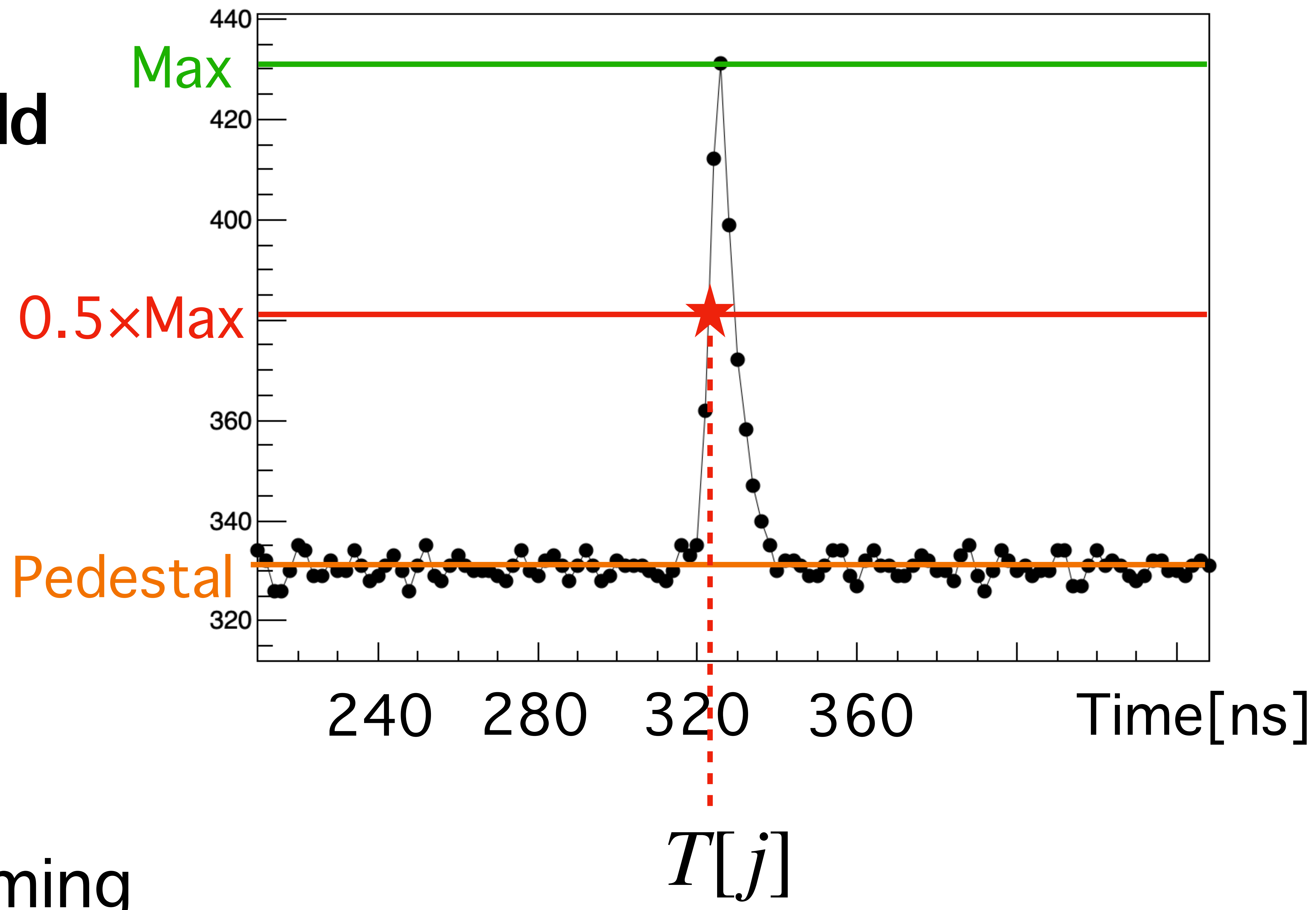
$T[j]$: timing of channel j

$N_{p.e.}[j]$: light yield of channel j

↓

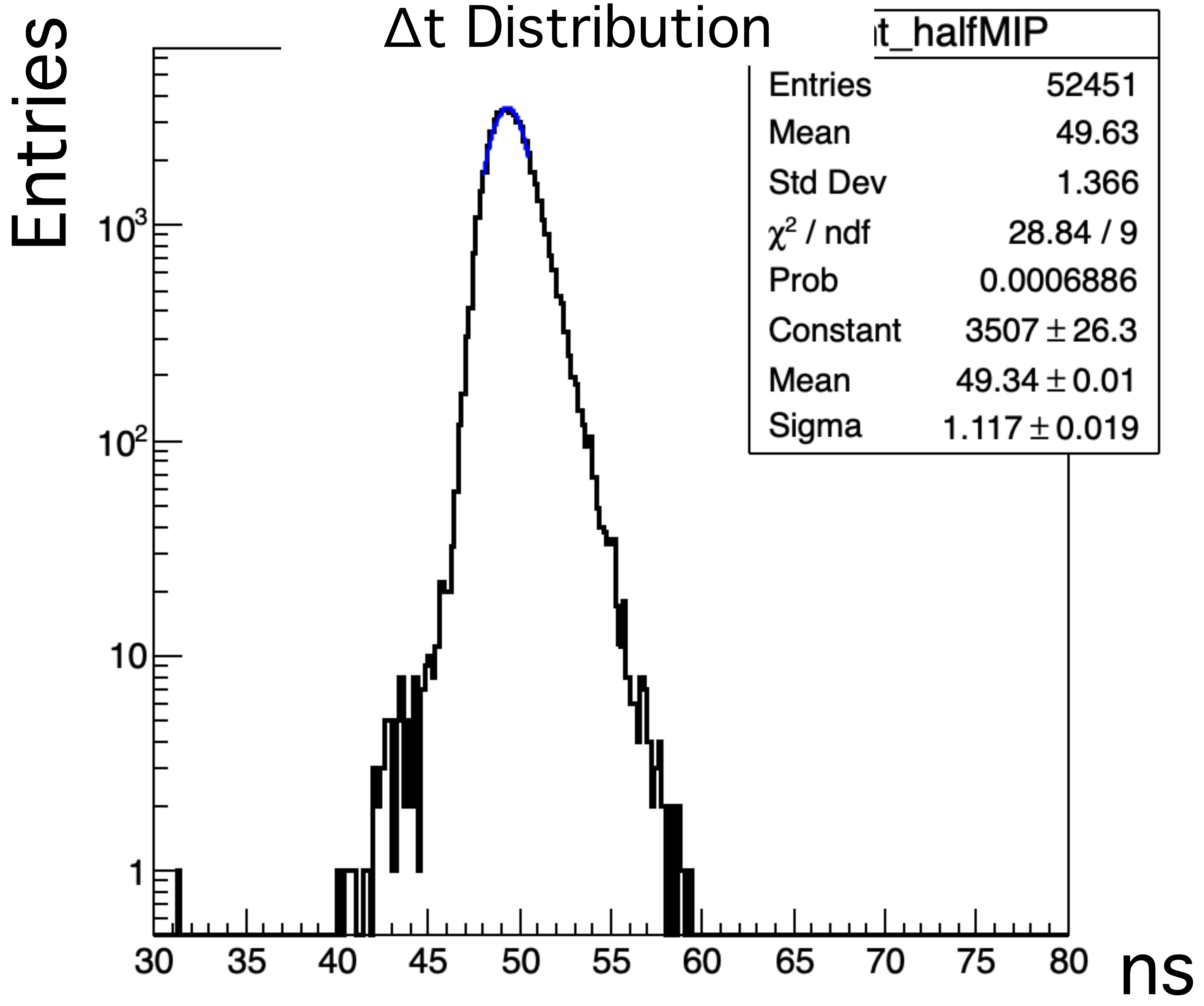
- Timing $\Delta t = T_{UCV}$ - reference counter Timing

Example of waveform of channel j



Result : Timing Resolution

- Selected events with light yield ≧ 0.5 MIP



Timing Resolution σ ~1.1 ns

Conclusion and Prospect

Conclusion

- Upgrading charged particle detector (UCV) : Film UCV

  0.2-mm-thick plastic scintillator + 12-μm-thick Al mylar

- Performance test with e^- beam

  ➡ **Light yield : ~ 20 p.e. /MIP (at hexagonal type)**

  Inefficiency : Achieved < 1% inefficiency at < 0.6 MIP threshold

  Timing resolution : σ ~ 1.1 ns

Prospect

- Will Install this detector in the KOTO beam line in next year

Backup

Design of new UCV

- Size : 160 × 160 mm^2

  ⇒ **Large enough to cover the beam**

- Structure of optical box (Al mylar)

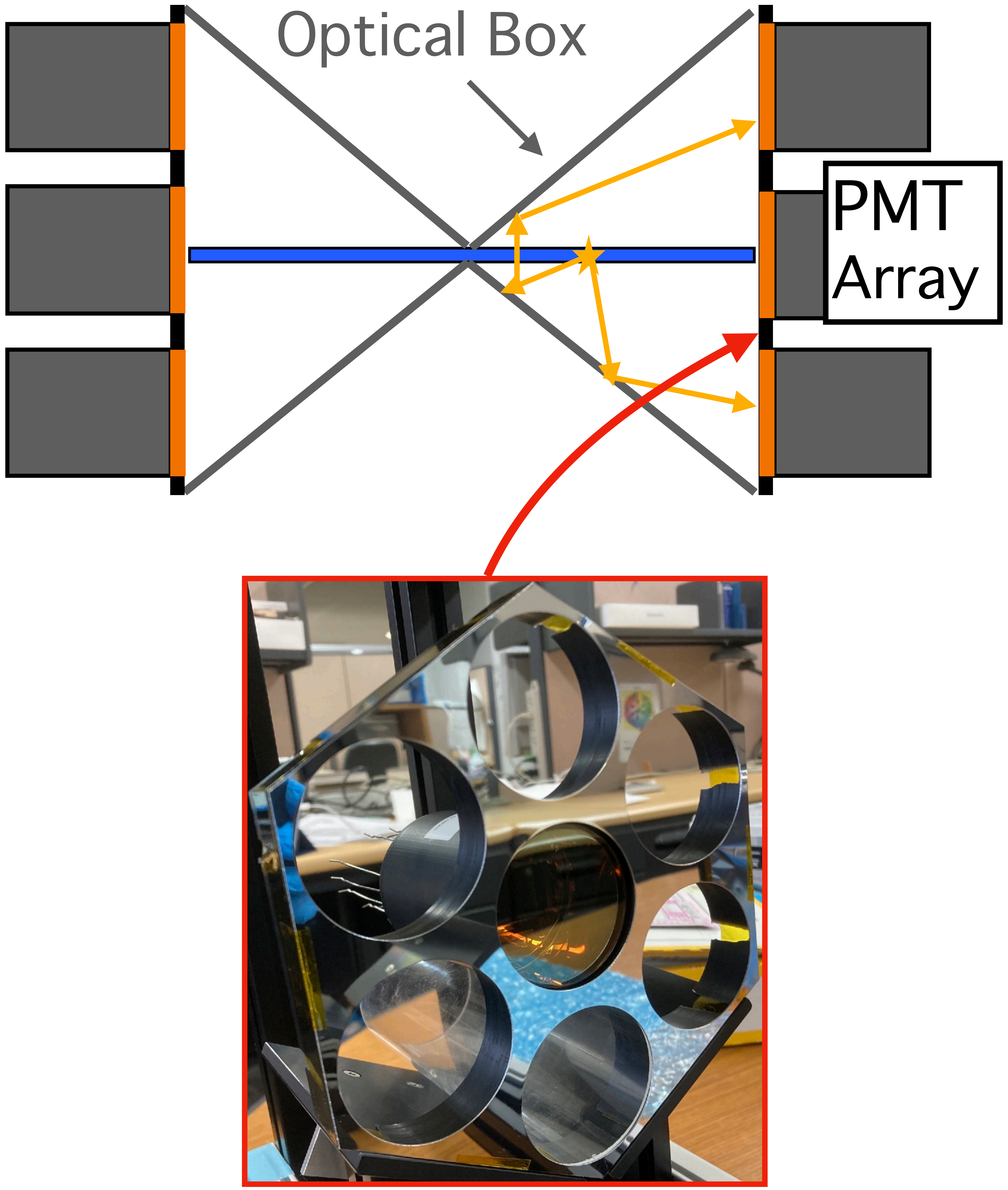
  ⇒**Collect photons with a few reflections**

- Readout by several PMTs

  ⇒**Get large area of photocathode**

- Mirror around photocathodes

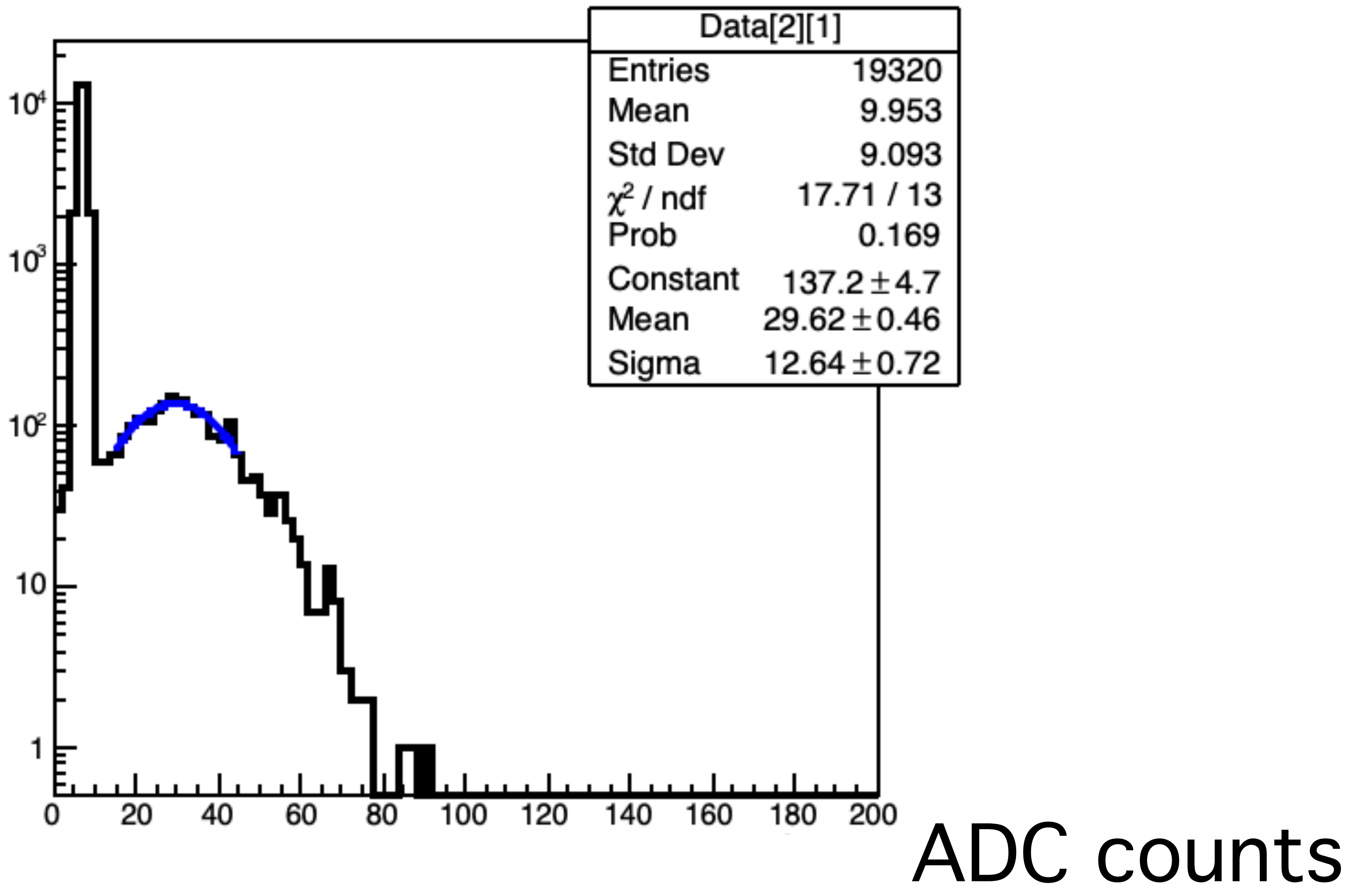
  ⇒**Increase light yield**

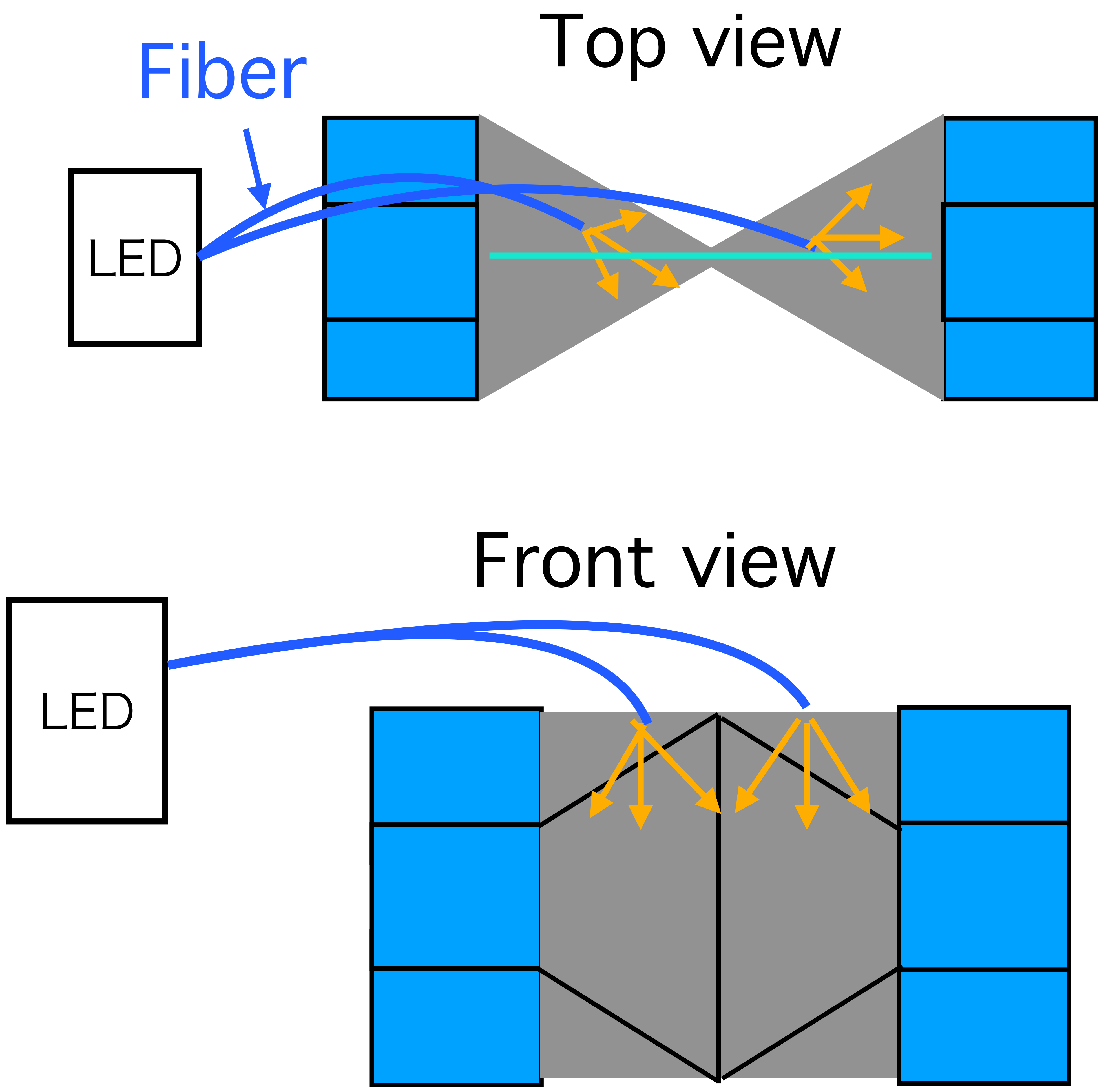


1 p.e. calibration

- Used LED light through fibers

Example of 1p.e. distribution





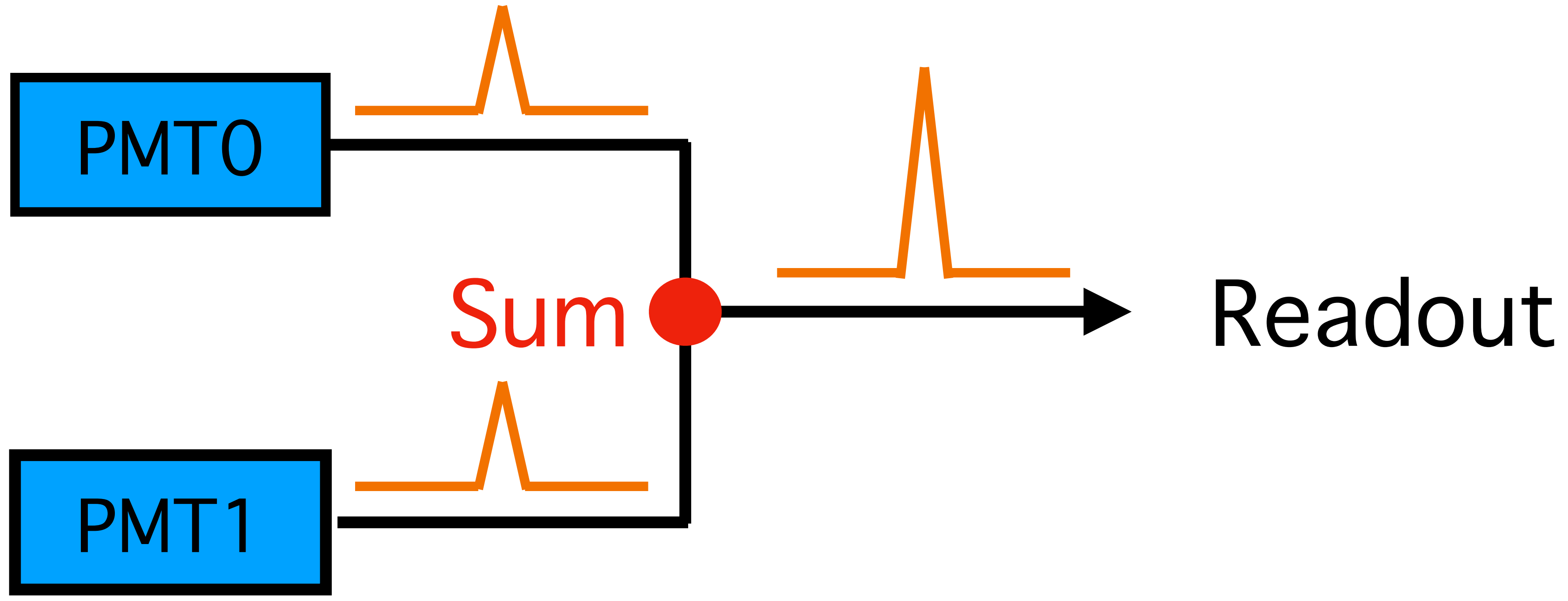
- **Adjusted the gains of PMTs**: 1 p.e. ~ 30 ADC counts

Signal readout

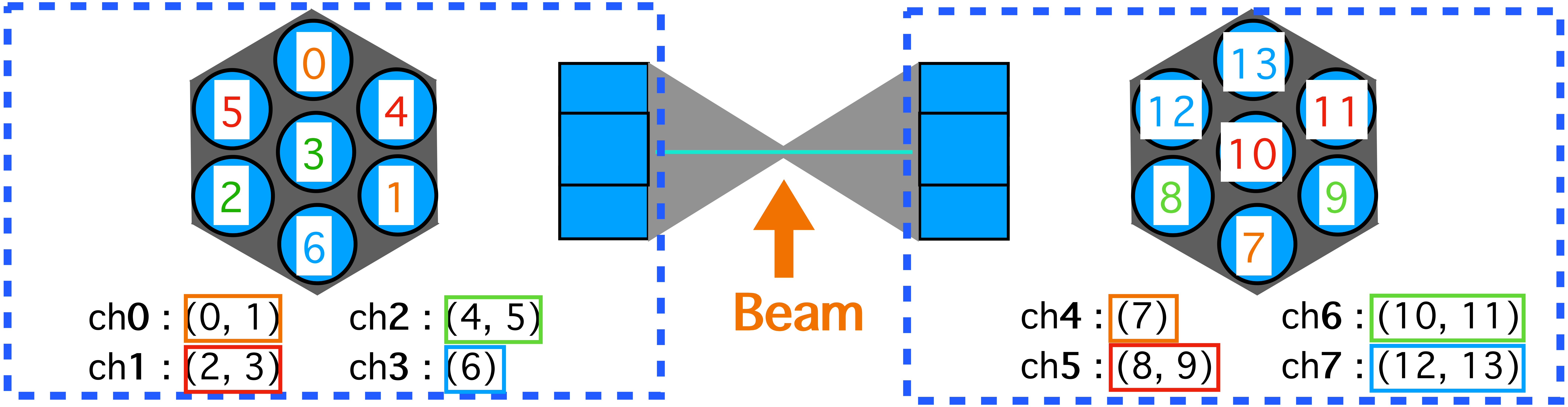
- Total # of PMT channels : **14** for hexagonal type (**12** for rectangle type)
- Used **sum Amplifier** (talk by Kawata)

➡ **Sum 2 signals** on the same side

(Due to the shortage of ADC channel)



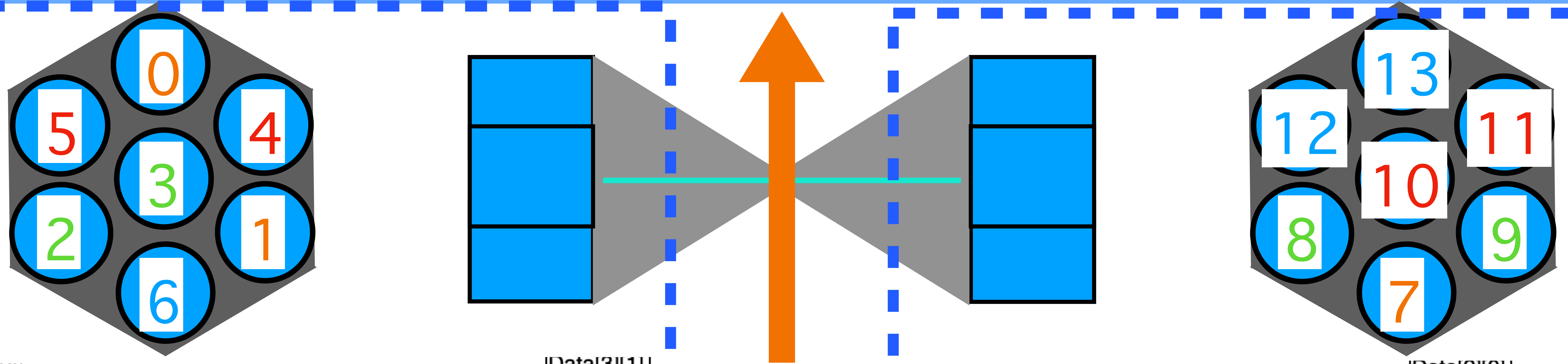
EX) hexagonal type



➡ In Total, **8 ch for hexagonal type** (6ch for rectangle)

of p.e distribution for each ch

ch0 : (0, 1)
ch1 : (2, 3)
ch2 : (4, 5)
ch3 : (6)



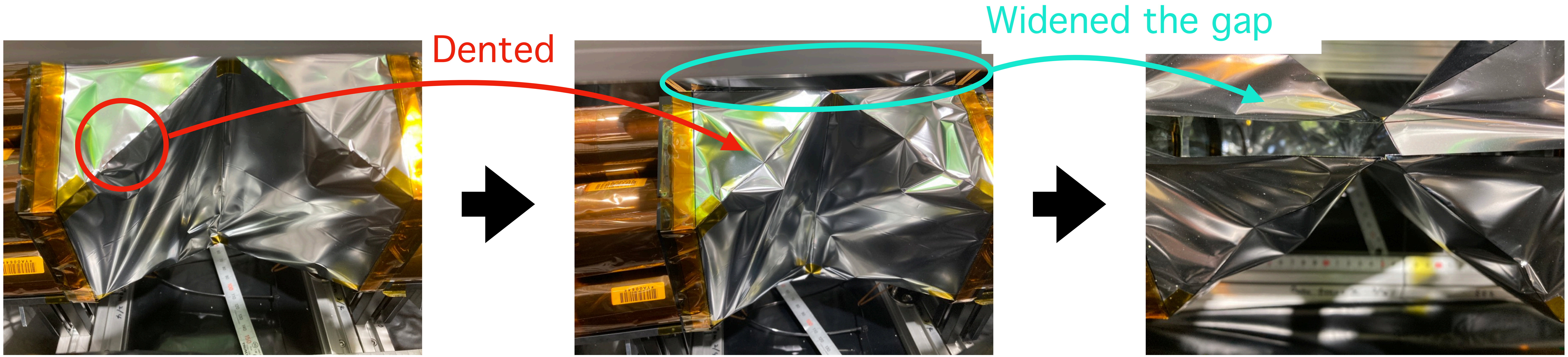
ch4 : (7)
ch5 : (8, 9)
ch6 : (10, 11)
ch7 : (12, 13)

1~4 p.e. contribution was observed for each channel ➡ Calculated total light yield

Deformation of optical box

Light yield is Likely to change due to deformation of shape of optical box

➡ Tried to change the shape of optical box as much as possible

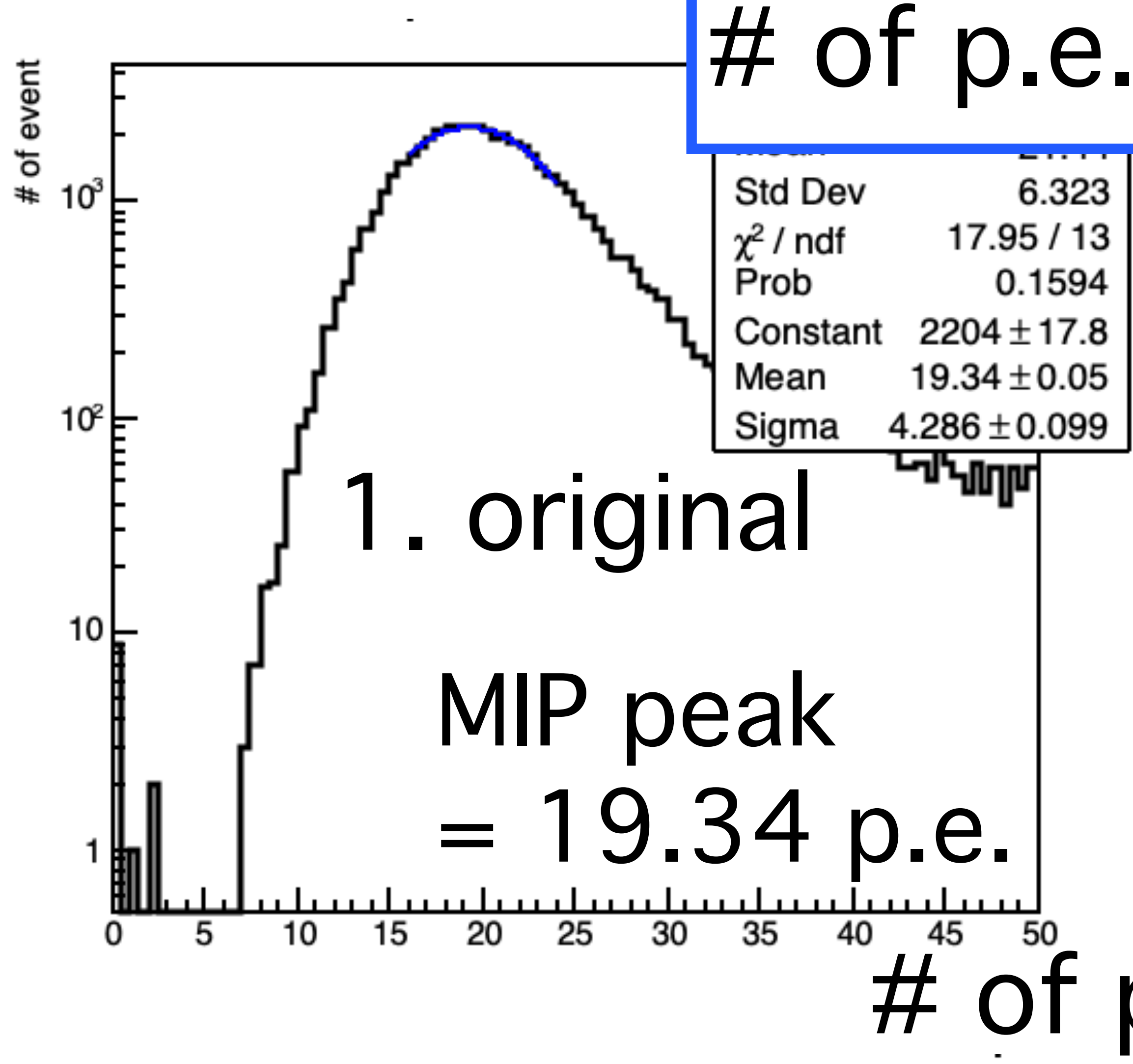


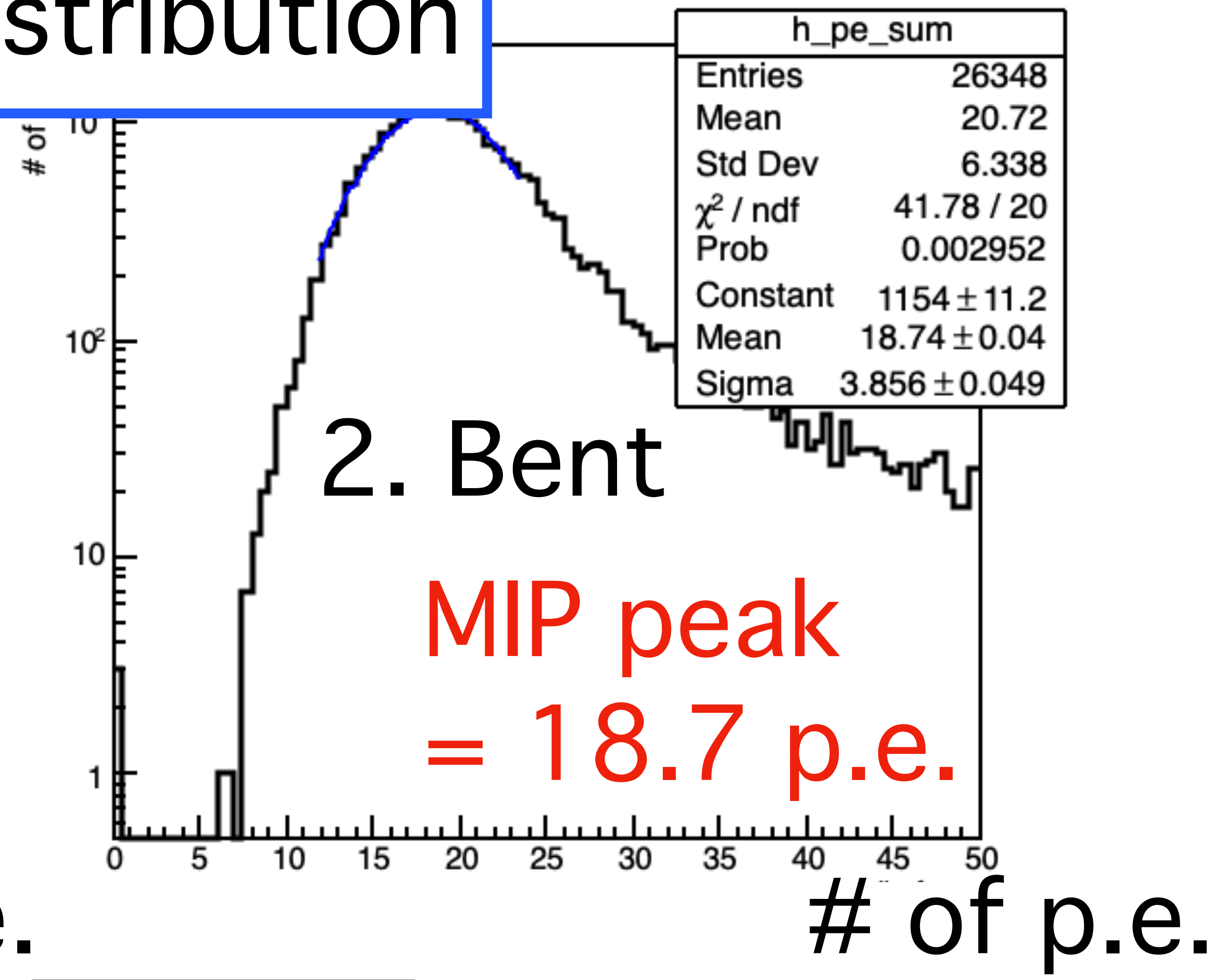
1. Original 2. Dent 3. Dent + gap

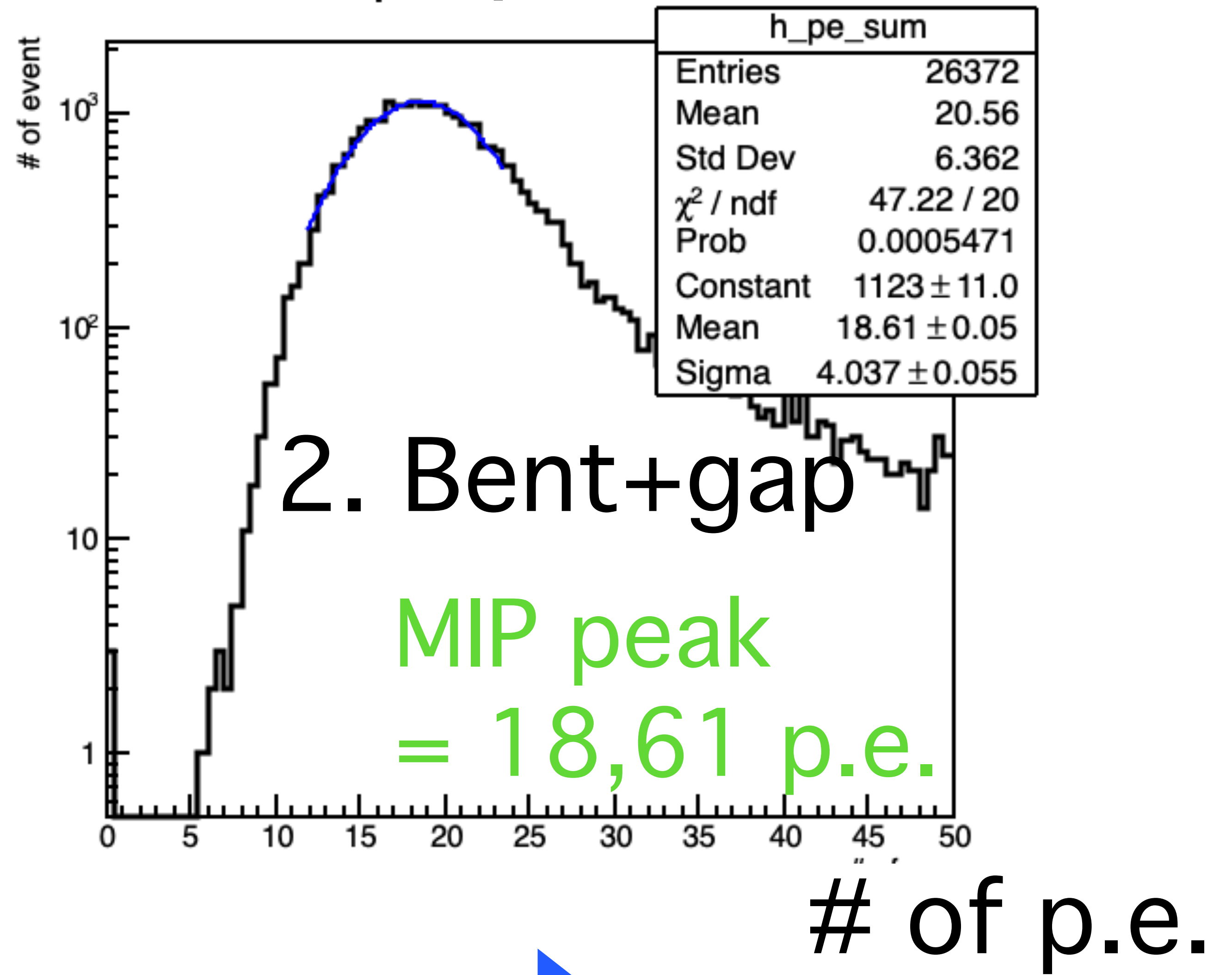
Compared the light yield and inefficiency

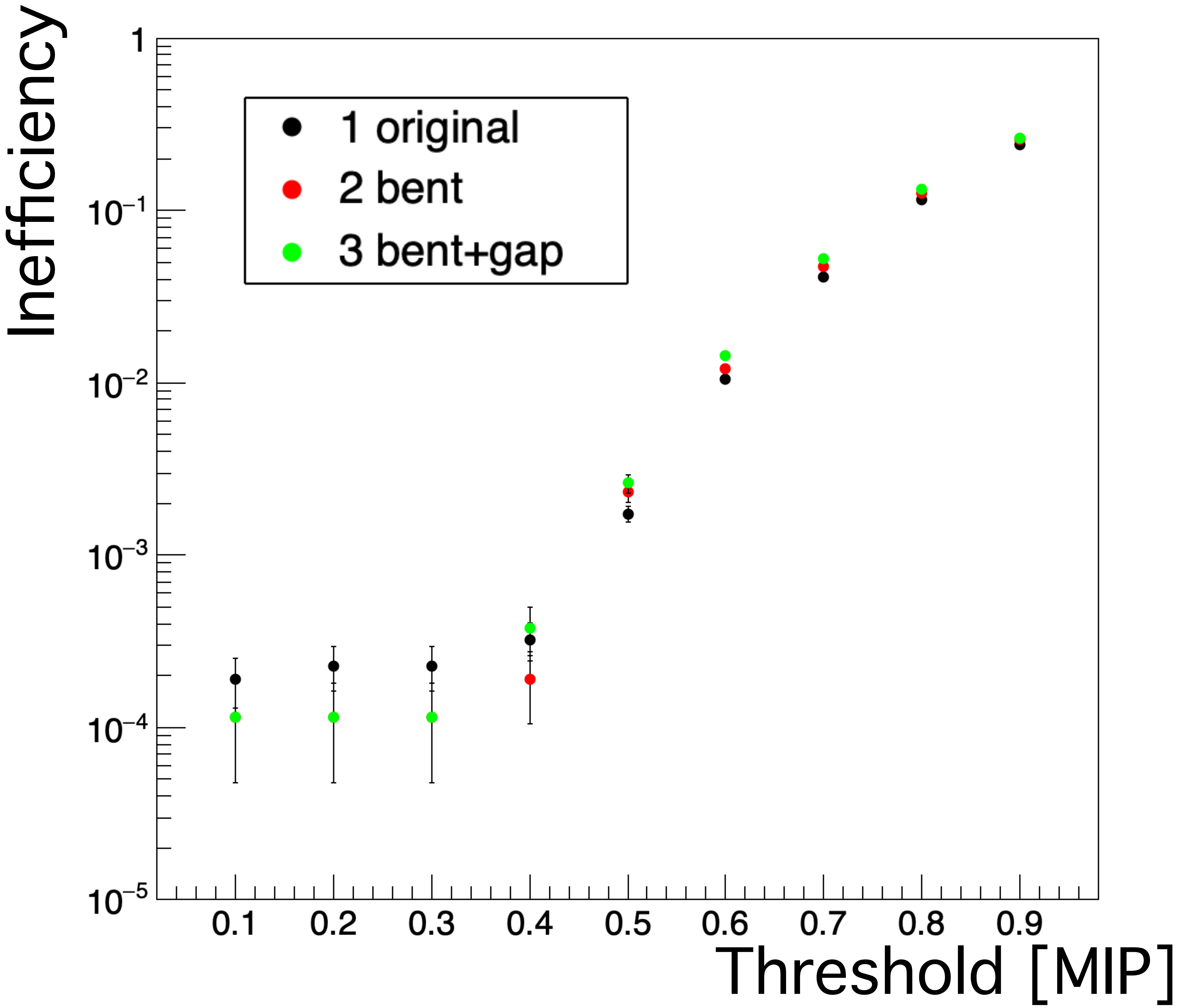
Result

of p.e. distribution





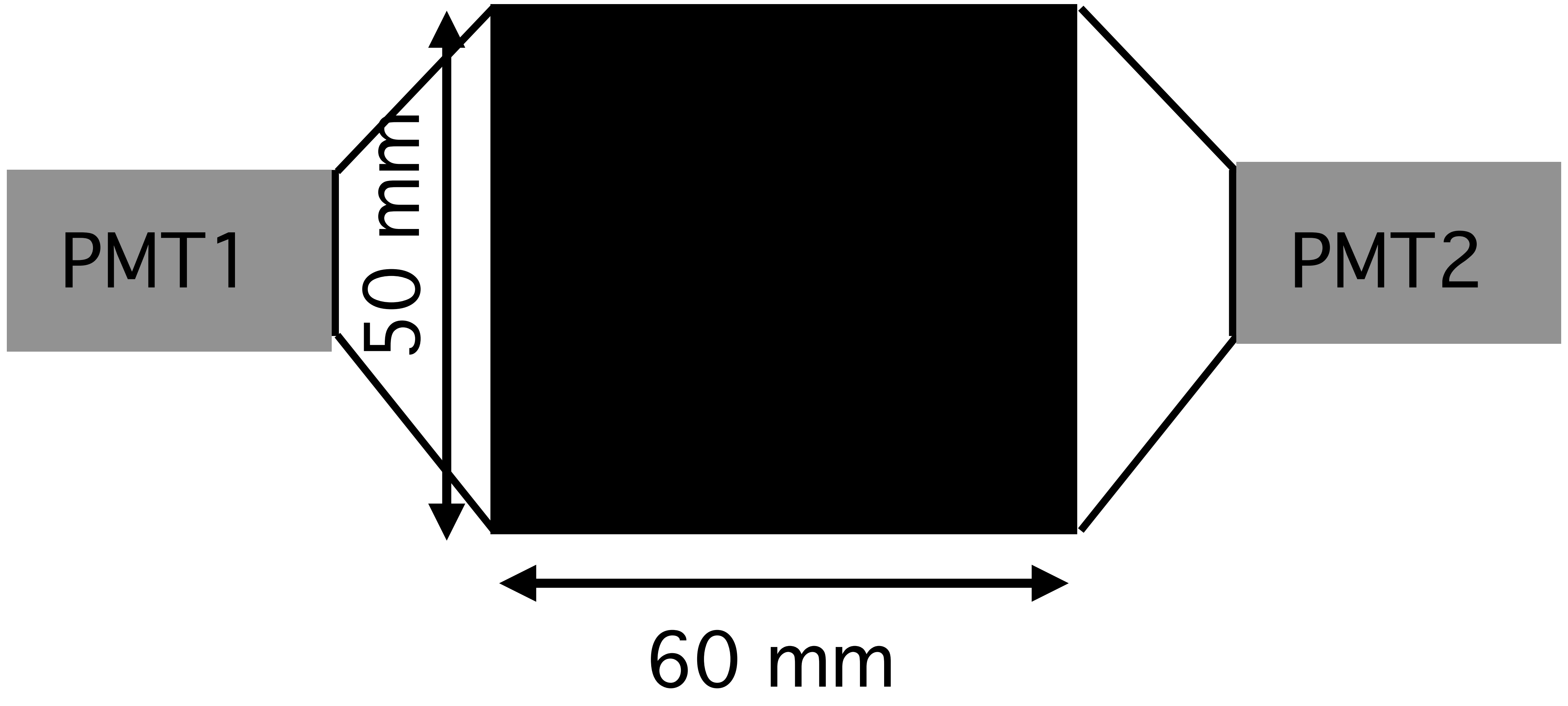


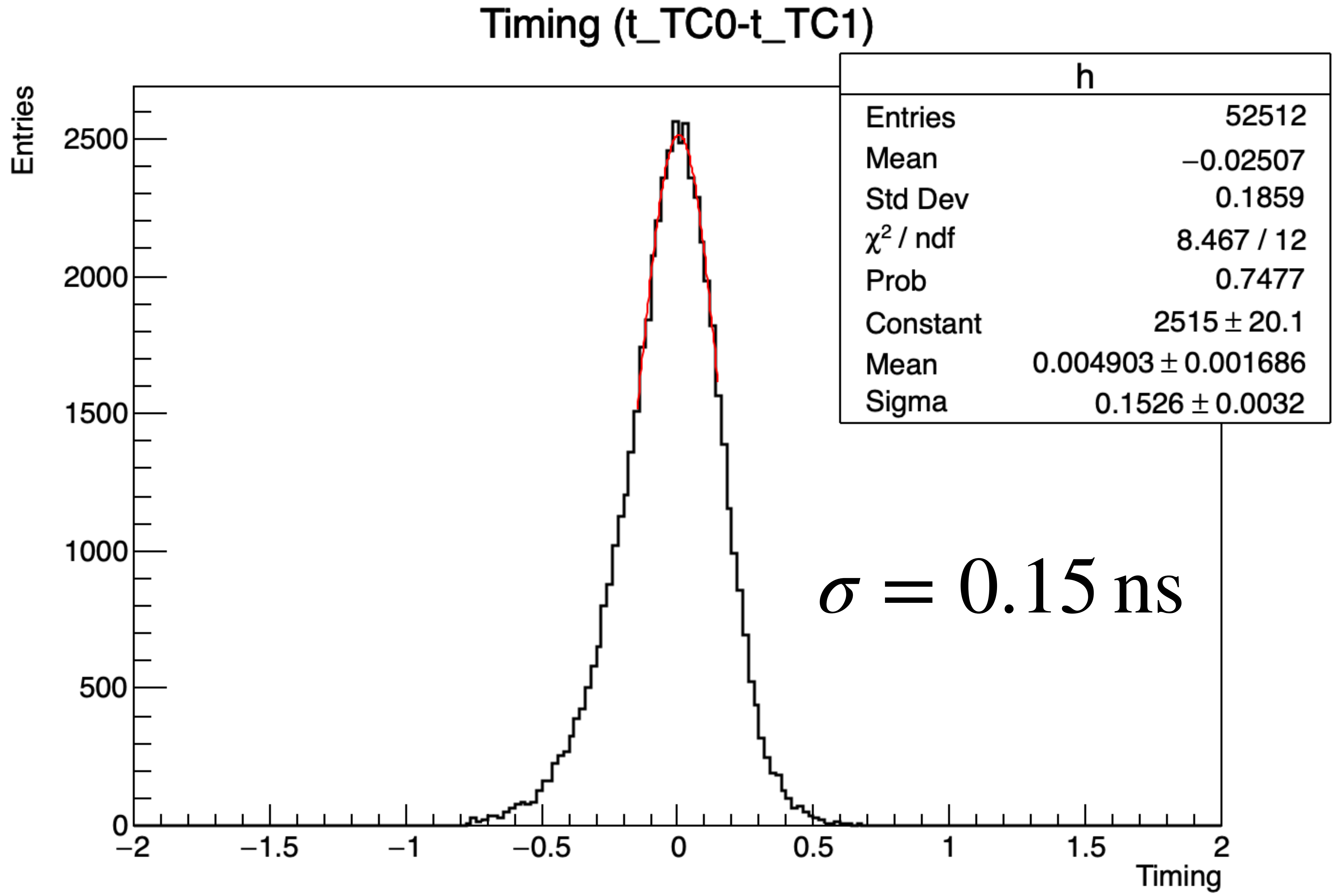


➡ **Effect of the deformation is small**

Correlation between oneside and bothside

Timing resolution of reference center





$\sigma = 0.15\,\mathrm{ns}$

Assuming that the resolutions of 2 channel is same

$$\sigma_1 = \sigma_2 = \sim 0.1\,\mathrm{ns}$$

Contribution of emitted light

- Compare the light yield between w and w/o mask