薄膜プラスチックシンチレータを用いたKOTO実験用荷電粒子検出器の性能評価

小野　啓太 (大阪大学)

第30回ICEPPシンポジウム

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J-PARC KOTO experiment

Search for the rare CP-violating $K_L \to \pi^0 \nu\bar{\nu}$ decay at J-PARC

- Highly suppressed in SM ($BR_{SM} = 3 \times 10^{-11}$)
- Small theoretical uncertainty (~2%)

Sensitive to new physics

- $K_L \to \pi^0 \nu\bar{\nu}$ decay has **NOT** been observed yet

$\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu}) < 2.0 \times 10^{-9}$ (Preliminary)

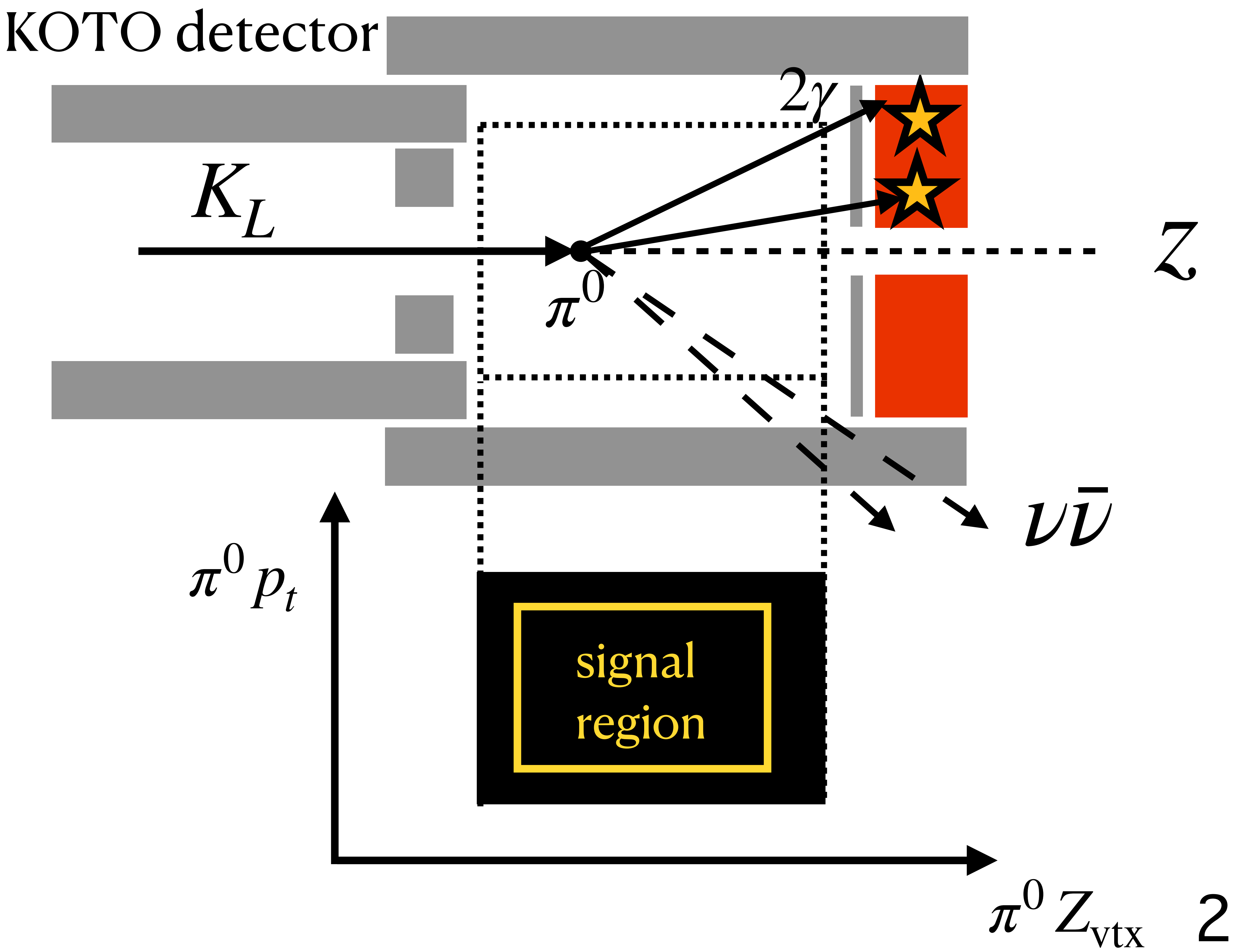
with KOTO 2021 **data**

Signature of this signal

($\pi^0 \to$) 2γ → CsI calorimeter

\+

Nothing → Veto detectors



K^+ background and UCV

Rare decay search = Fighting against backgrounds

$K^\pm$ **decay** : One of main backgrounds in KOTO $F_{K^\pm}/F_{K_L} = 3.2 \times 10^{-5}$

- Source : $K^\pm \to \pi^0 e^\pm \nu$

- Reduce K^+ BG by **detecting** K^+ **with a charged particle detector in the beam from** 2021 (**U**pstream **C**harged **V**eto)

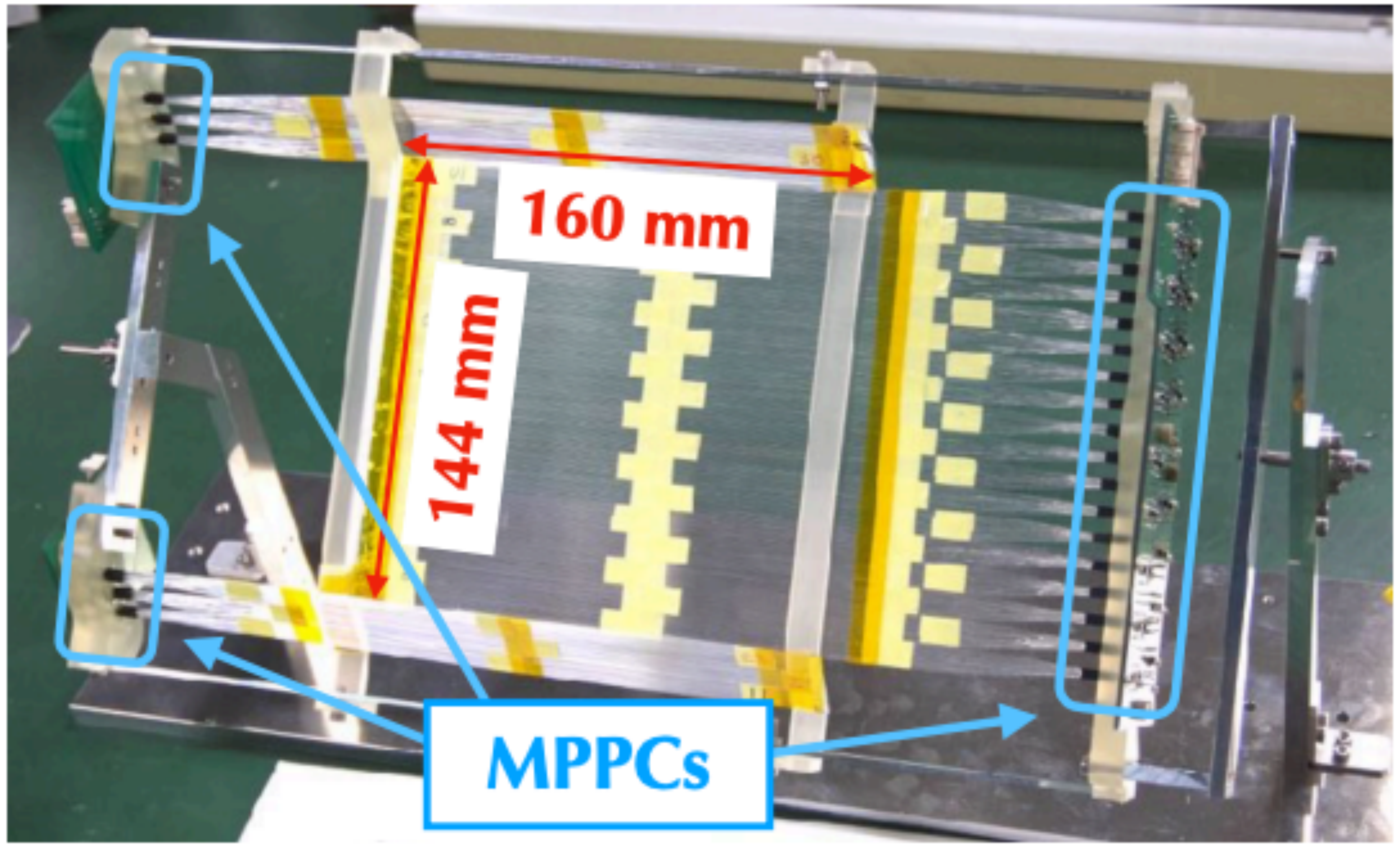
- K^+ BG level(2021 data): #BG(K^+)/#Signal(SM) = 1.1

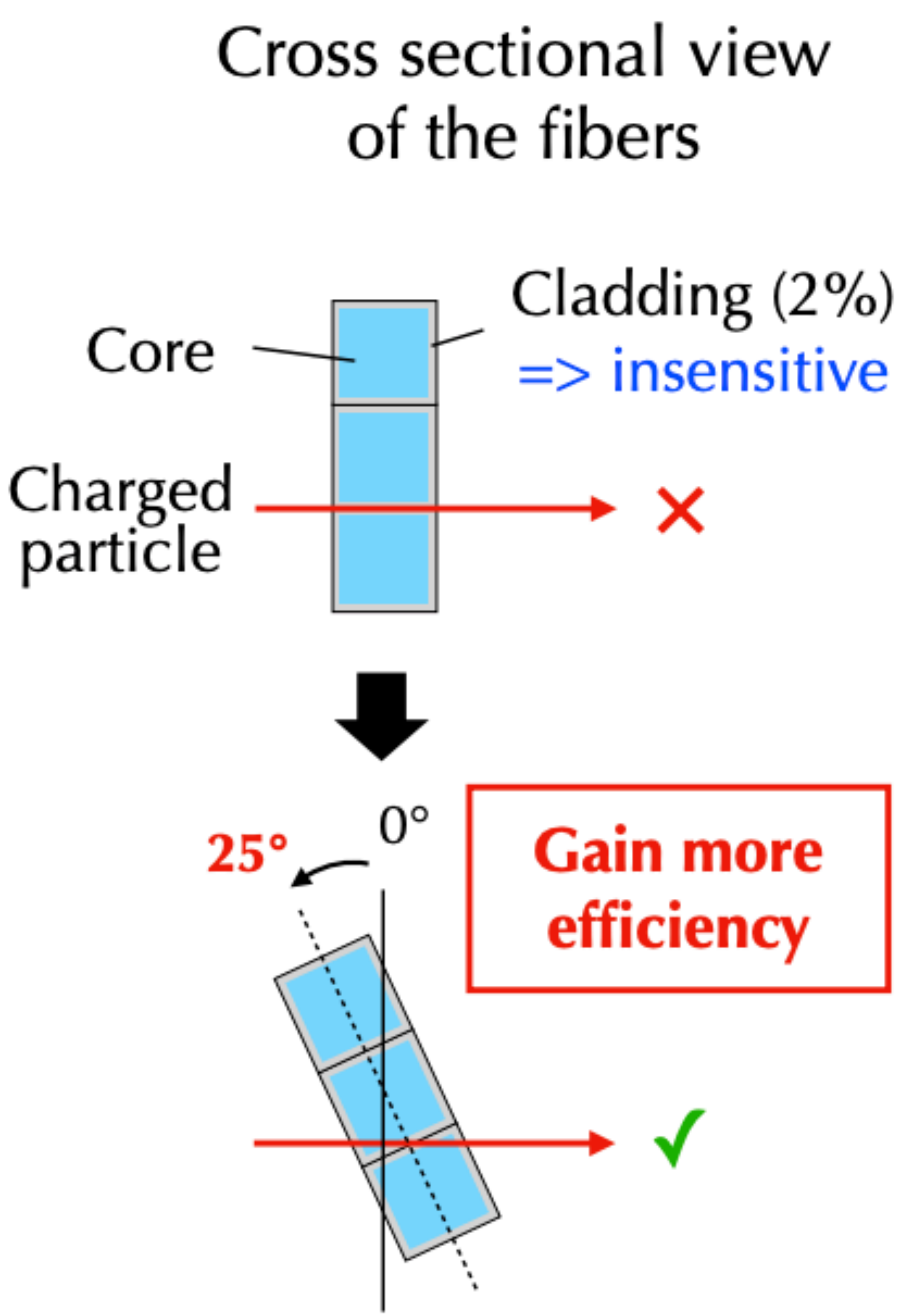
Previous UCV

0.5-mm-thick scintillating fiber
+
Silicon photo-sensors (MPPCs)

- Detector is tilted by 25° to reduce inefficiency

➡ Inefficiency = 7.8×10^{-2}
K+ BG rejection : 1/13





New version of UCV (filmUCV)

Developed the new version of UCV (FilmUCV)

Requirements

- Reduce the probability of interaction of neutral particles in UCV
- Raise the detection efficiency against charged particle

➡ **Thinner** + **More Sensitive** detector

Q : How do we achieve them?

A : Use 0.2**-mm-thick plastic scintillator film**

0.5**-mm thick** ⇒ ~ 0.2**-mm thick**

Goal

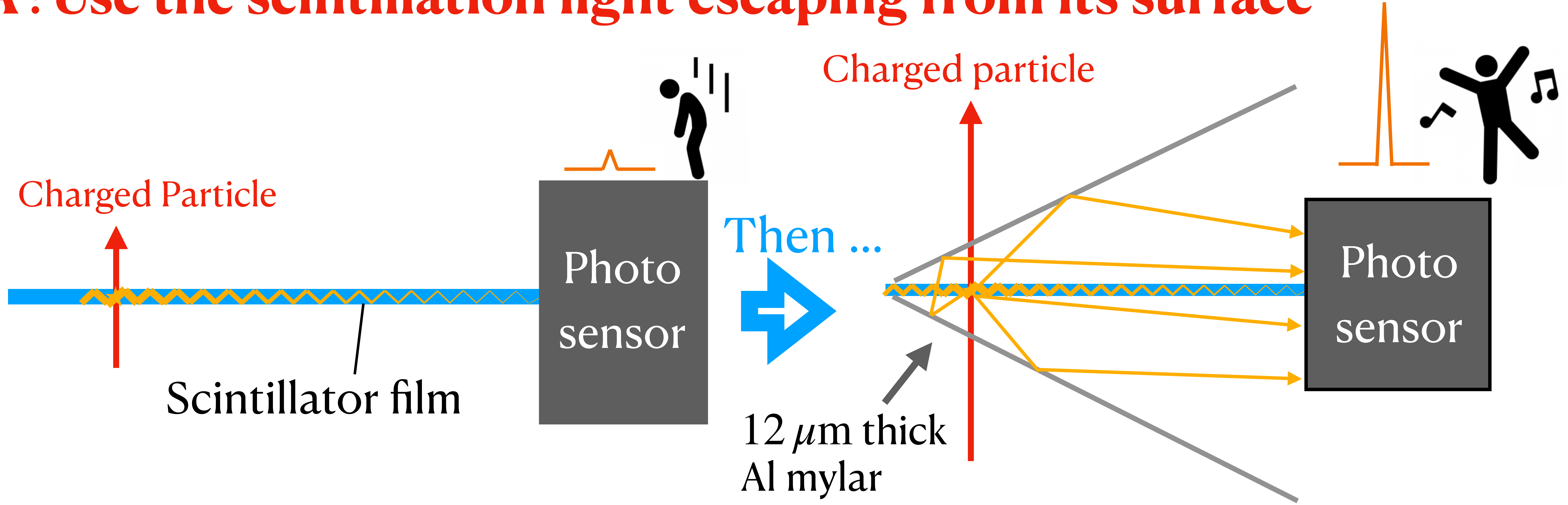
	Previous		Today
Inefficiency :	8%	⇒	1%
K^+**BG rejection :**	~1/13	⇒	1/100

Light collection method

High efficiency -> large light yield

Q : How do we get enough light yield?

A : Use the scintillation light escaping from its surface

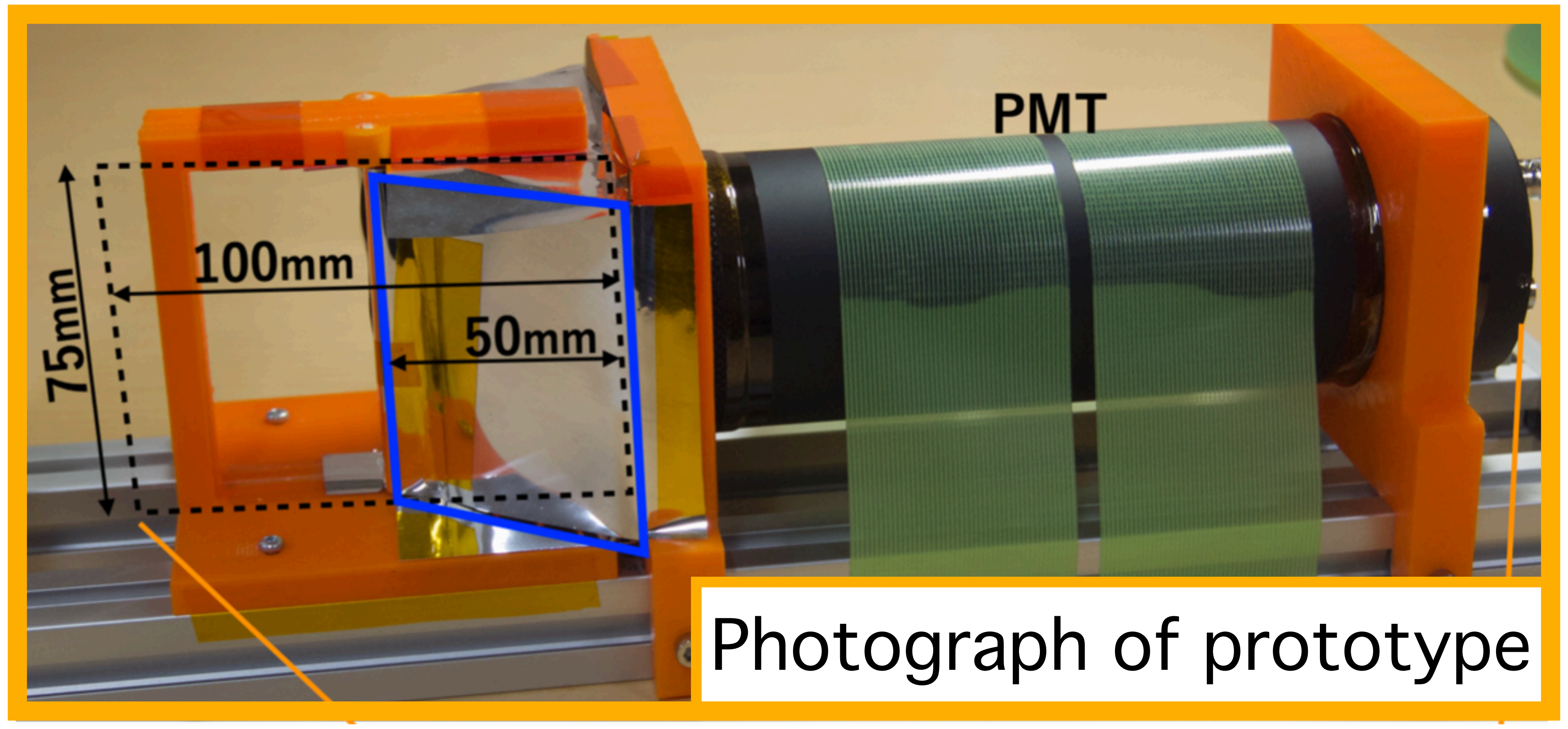


- **Reflect** and **collect light with** 12 μm **thick Al mylar**

Check of yield of the light escaping from the scintillator

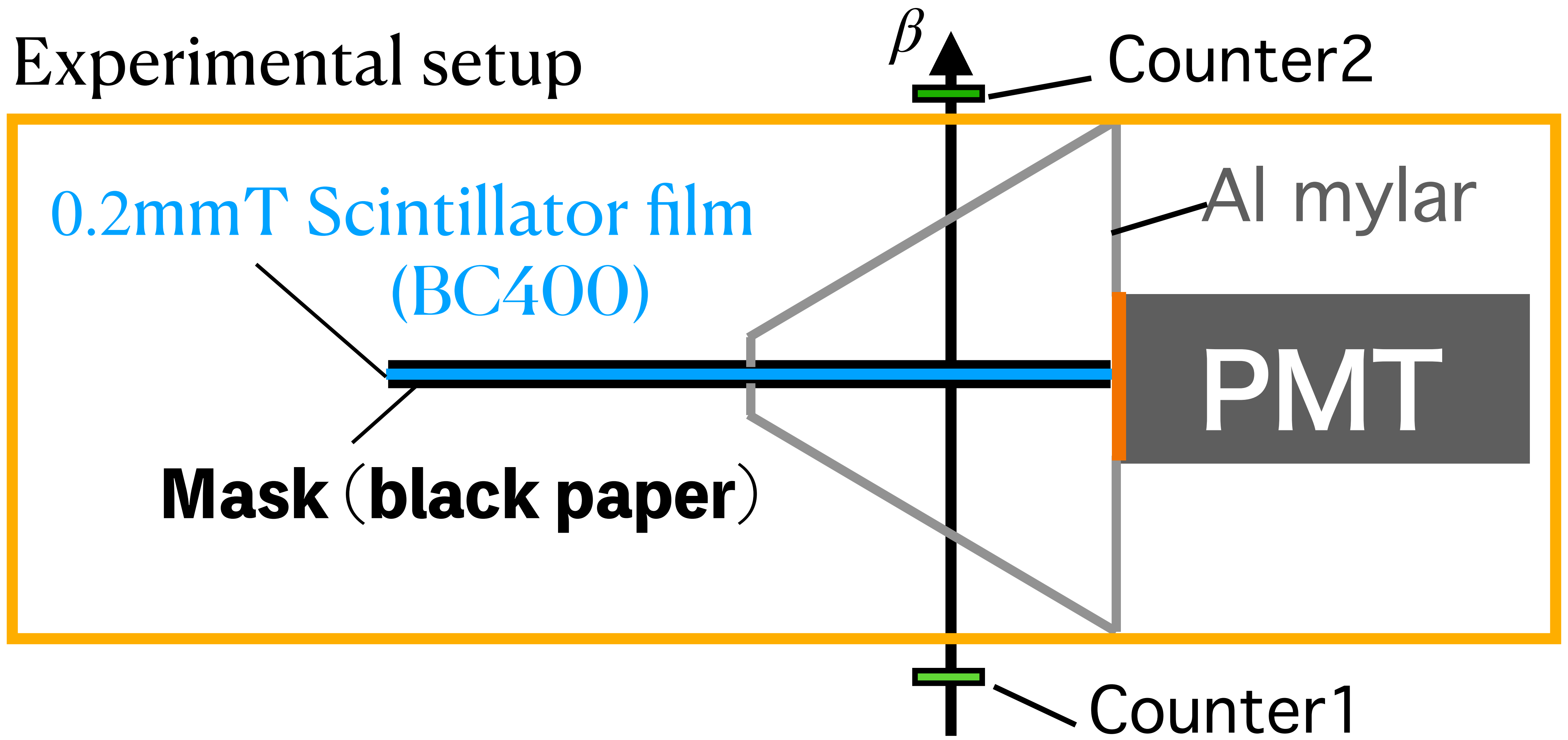
Checked the yield of the light escaping from scintillator film with prototype

- Compared the light yield 1. w/ mask : light yield propagating inside the film
  2. w/o mask : collected light by Al-mylar reflections, in addition

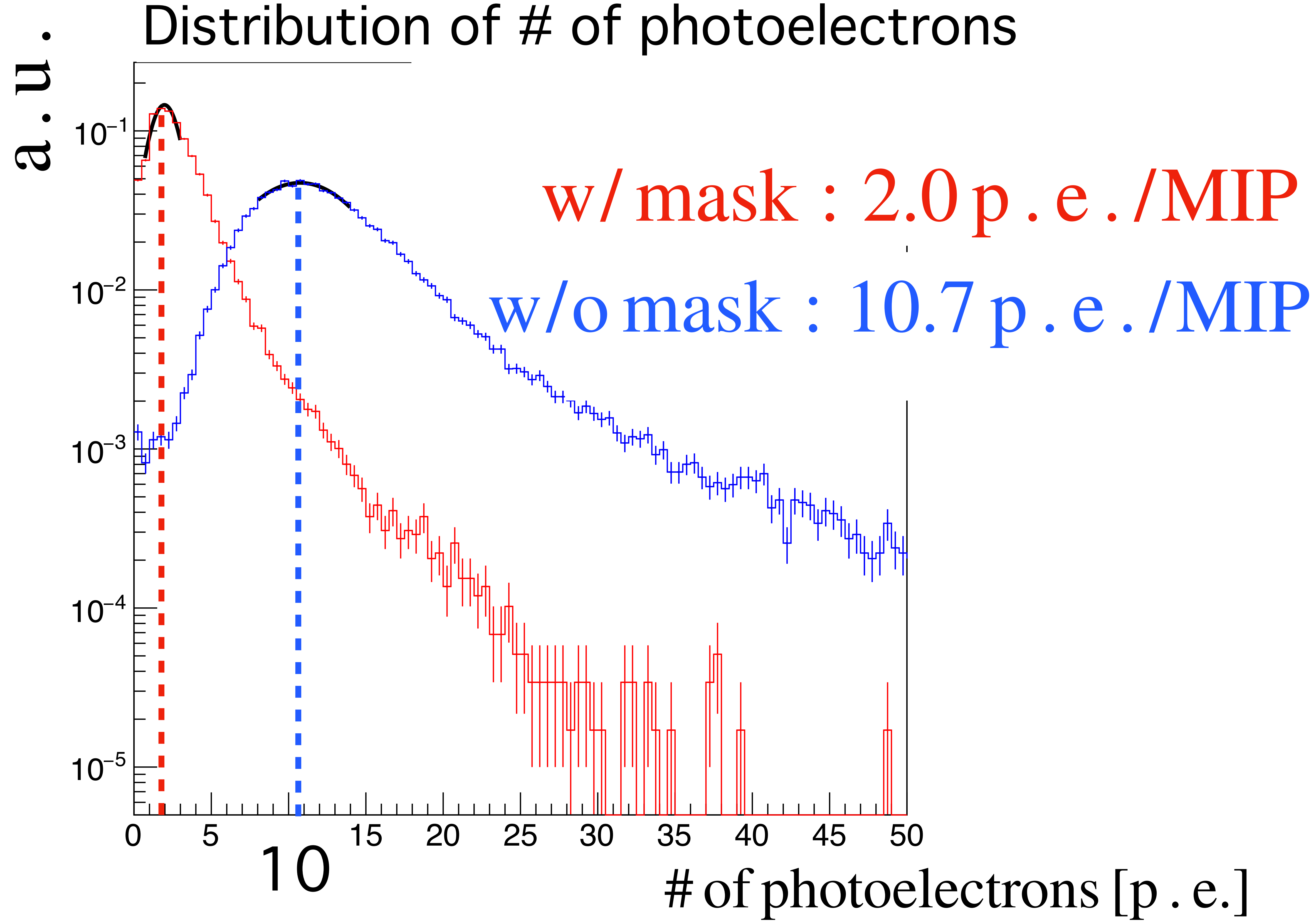


Photograph of prototype

Experimental setup



Distribution of # of photoelectrons



Got ×5.5 light yield

Design of filmUCV

- Size : 160 mm × 160 mm

⇒ **large enough to cover the beam**

- Structure of reflector

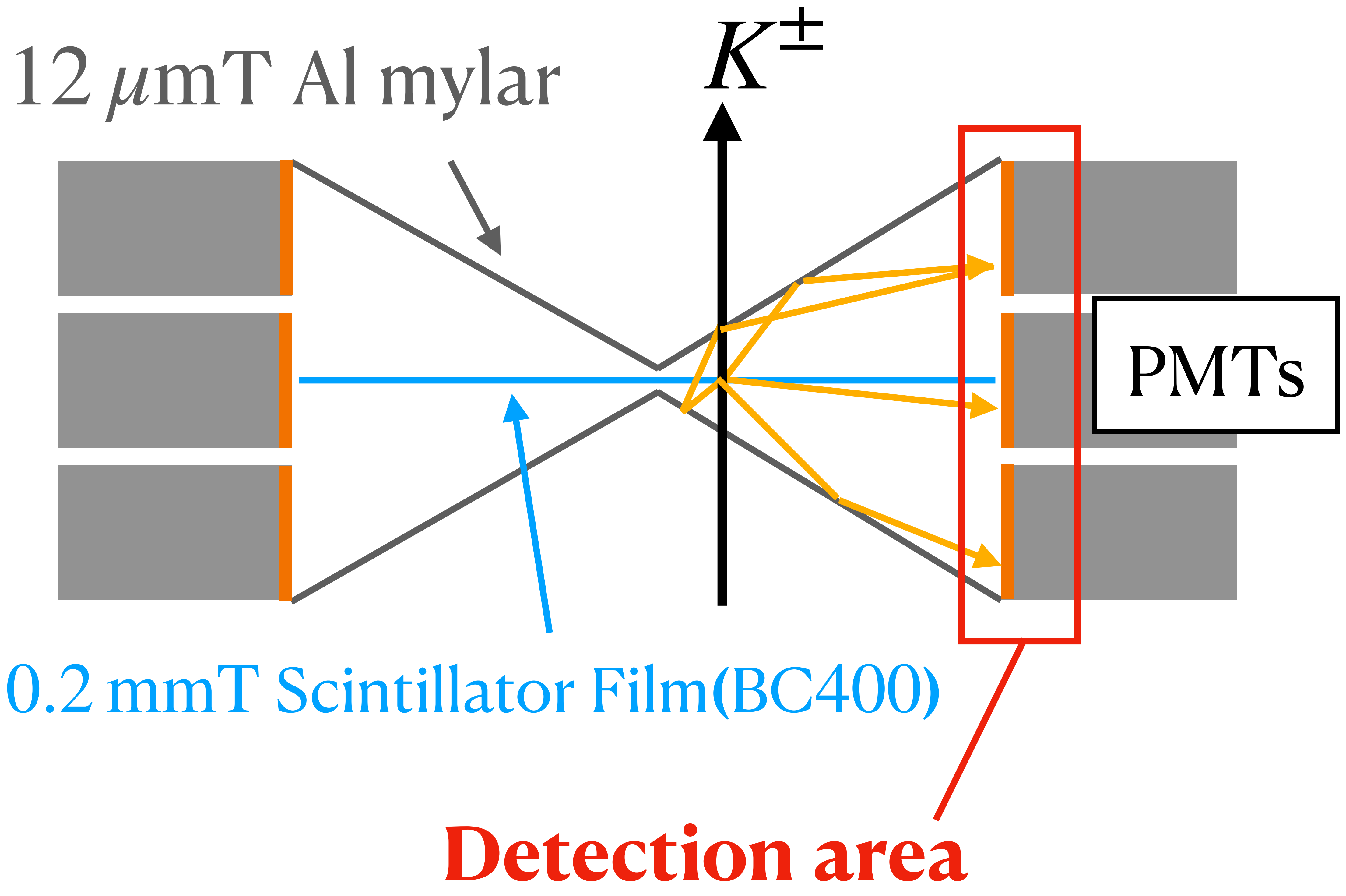
⇒ **Collect photons with a few reflections**

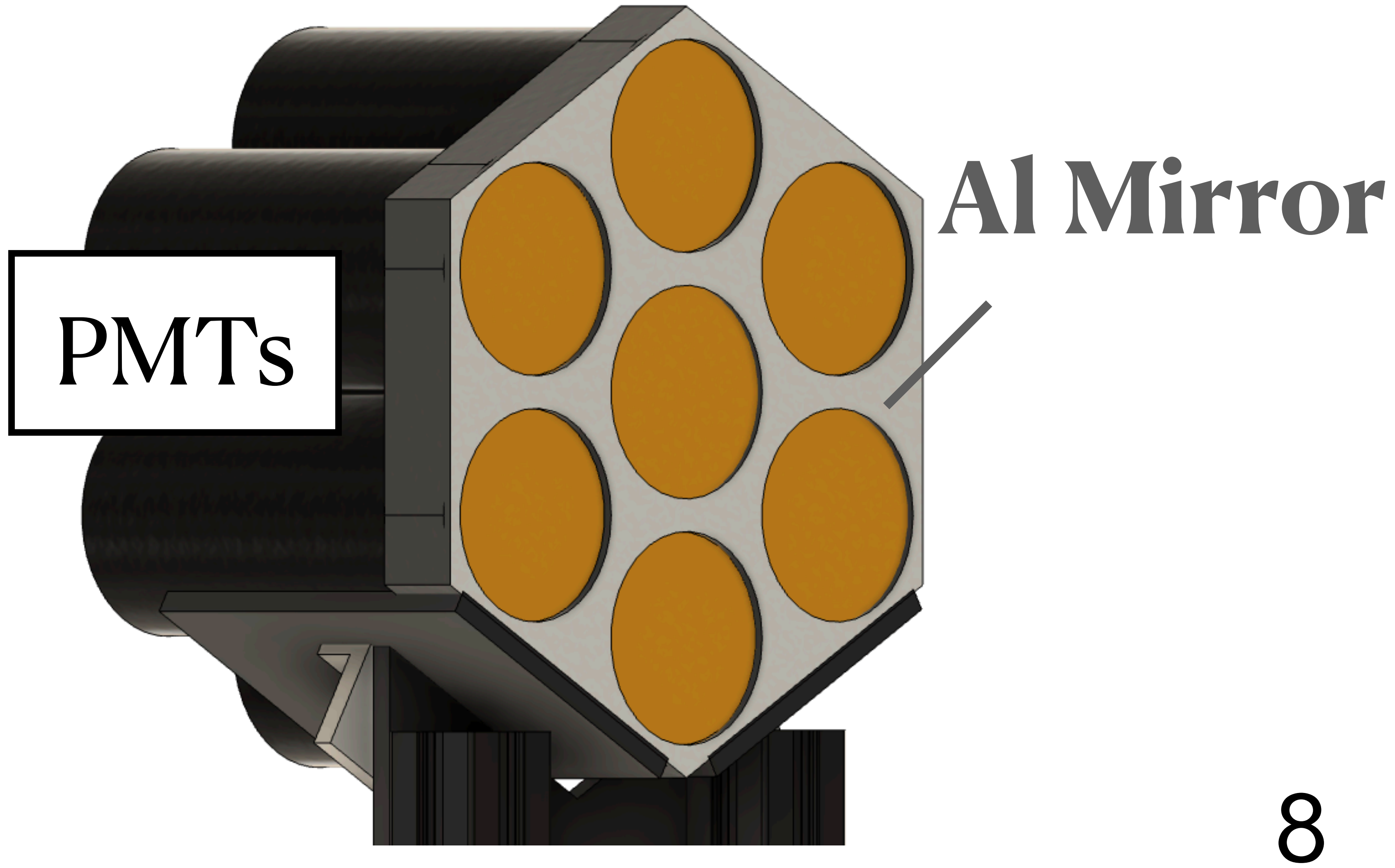
- Read out by several PMTs

⇒ **Good S/N, Radiation hard (⇔ MPPC)**

- Al Mirror outside of photocathode

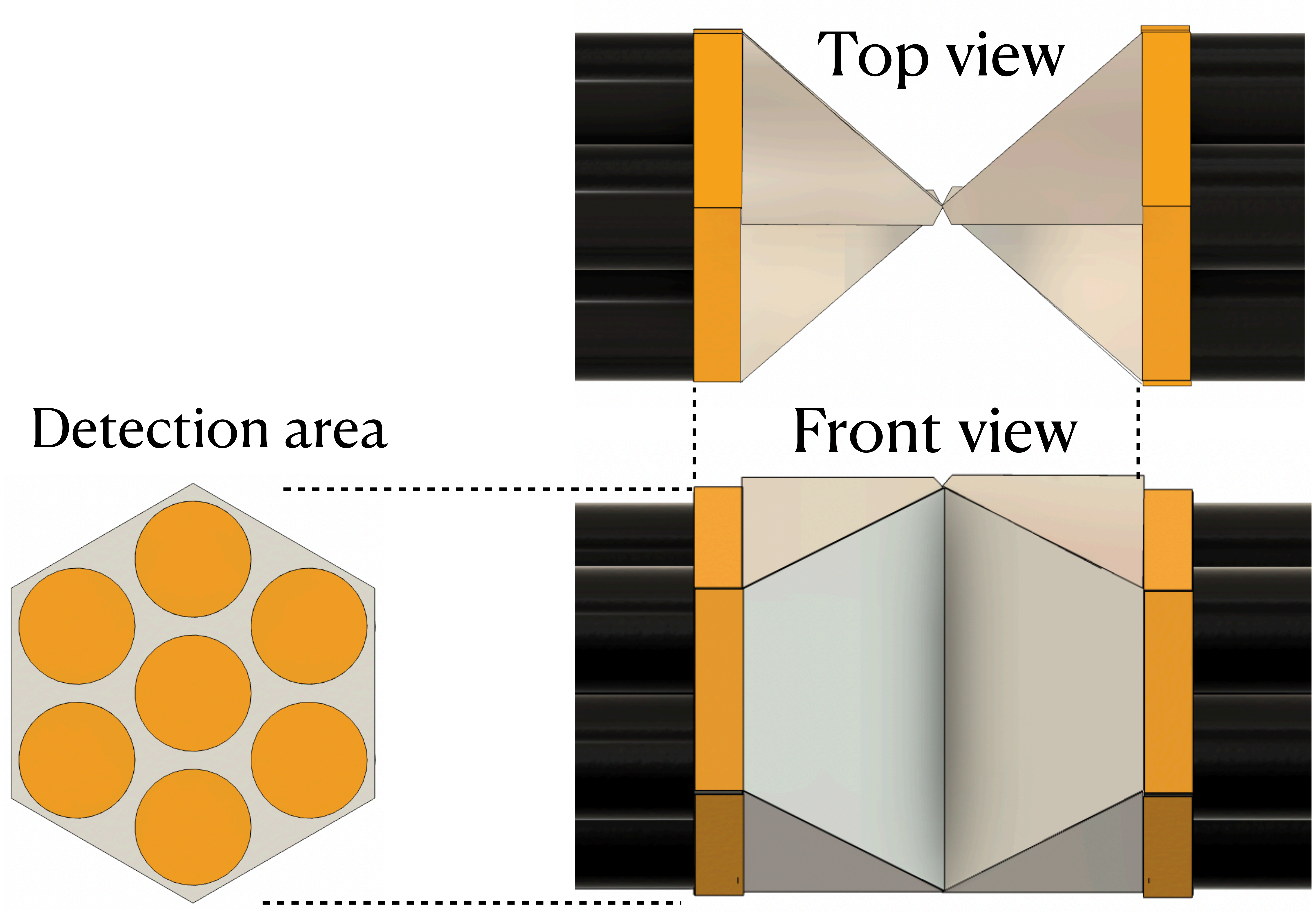
⇒ **increases light yield** (× 1.25)

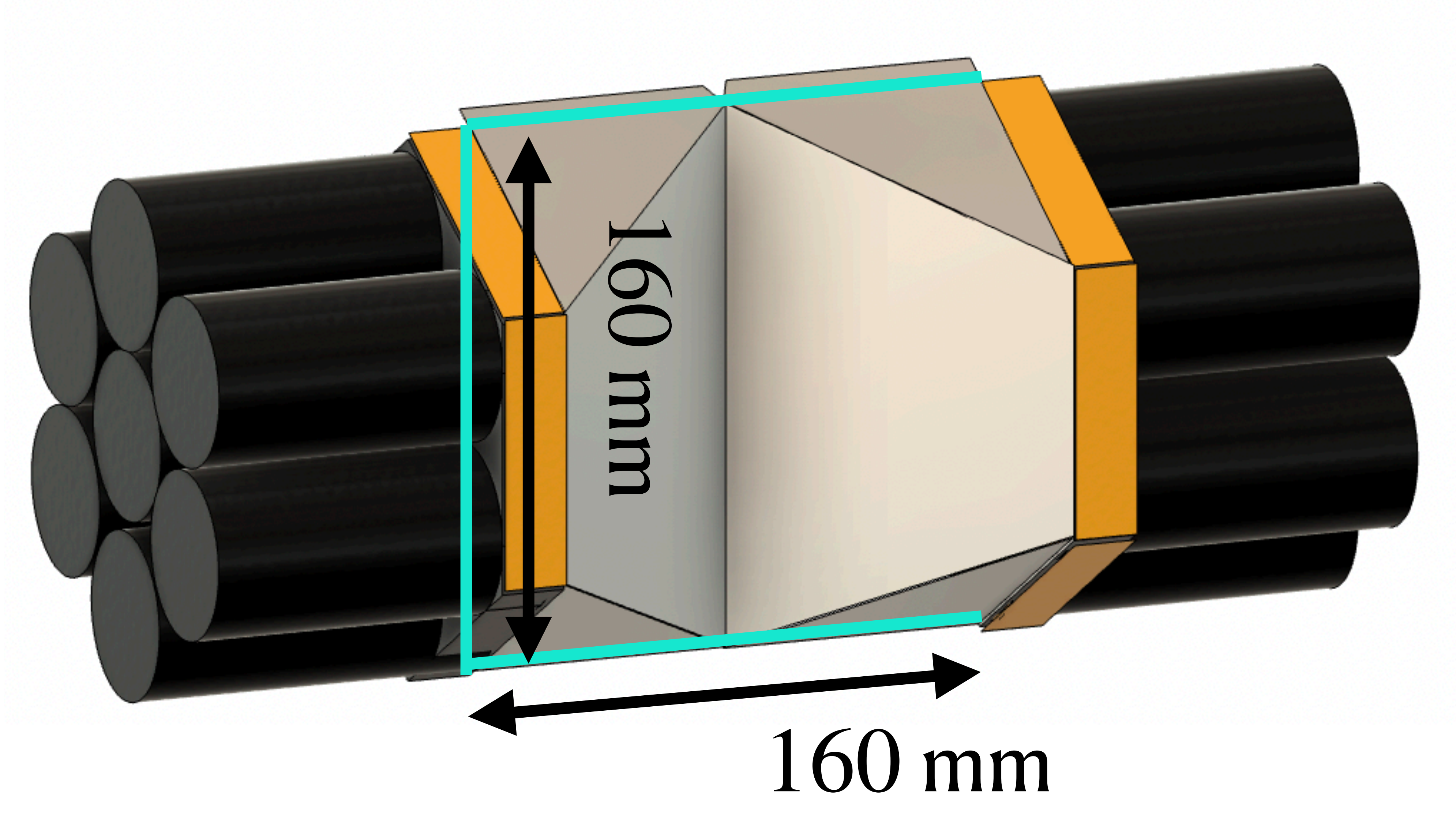




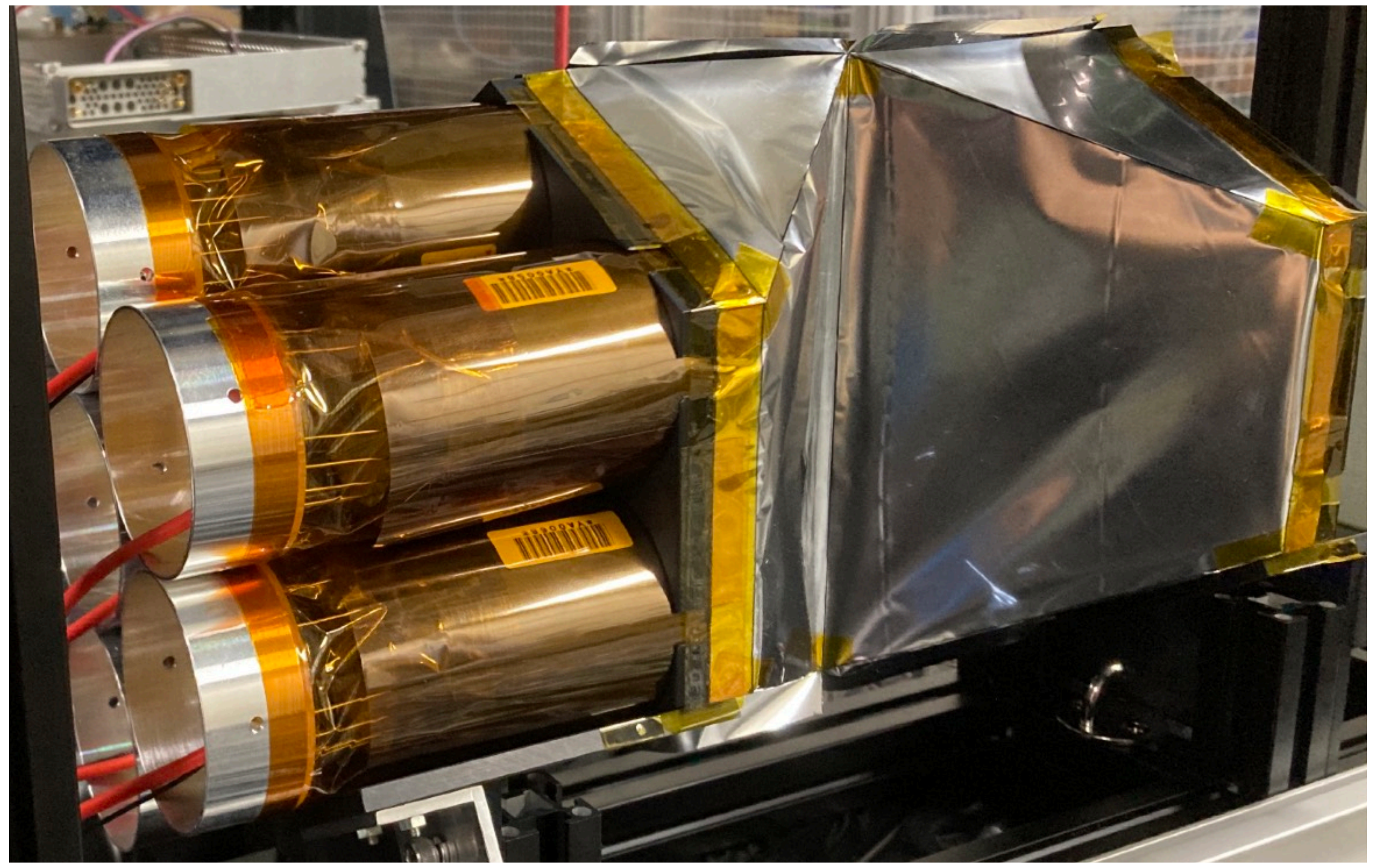
Design of reflector

- Make this structure by 12 μmT Al mylar





Photograph

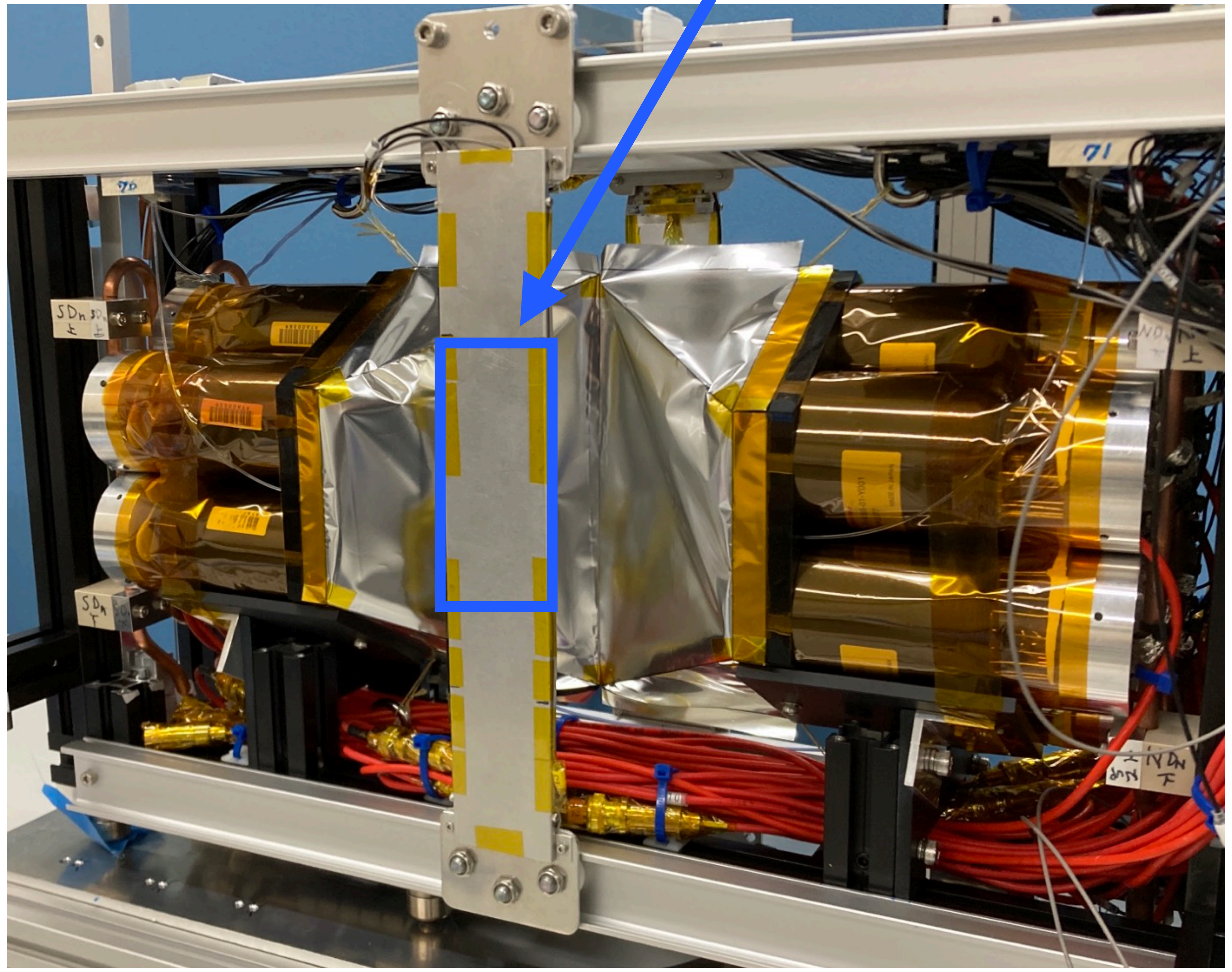


- Use 7 PMTs per side ⇒14 PMTs in total

Installation of filmUCV

- **Installed a new version of UCV(FilmUCV) in May** 2023
- **Installed movable trigger counters at the same time**

to evaluate Performance of FilmUCV directly

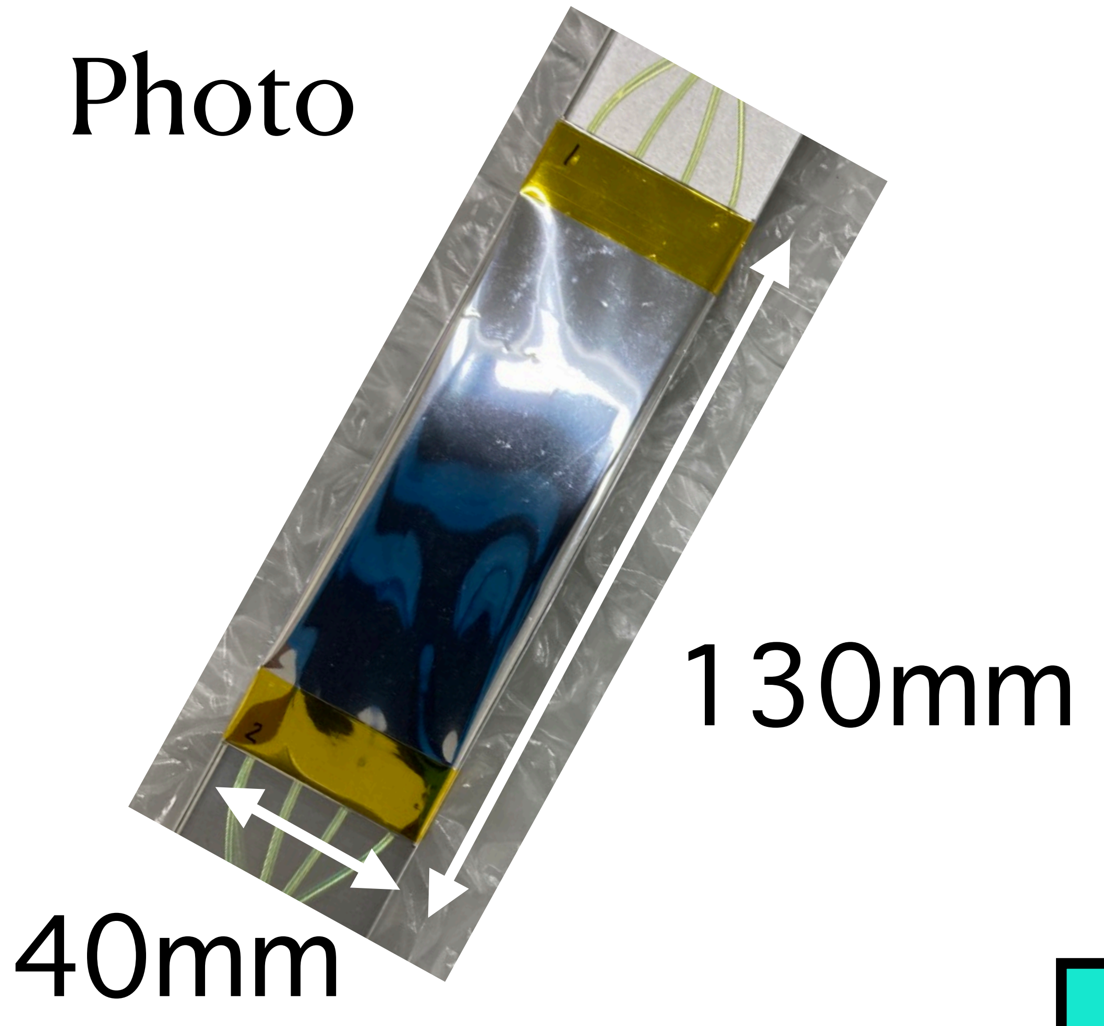


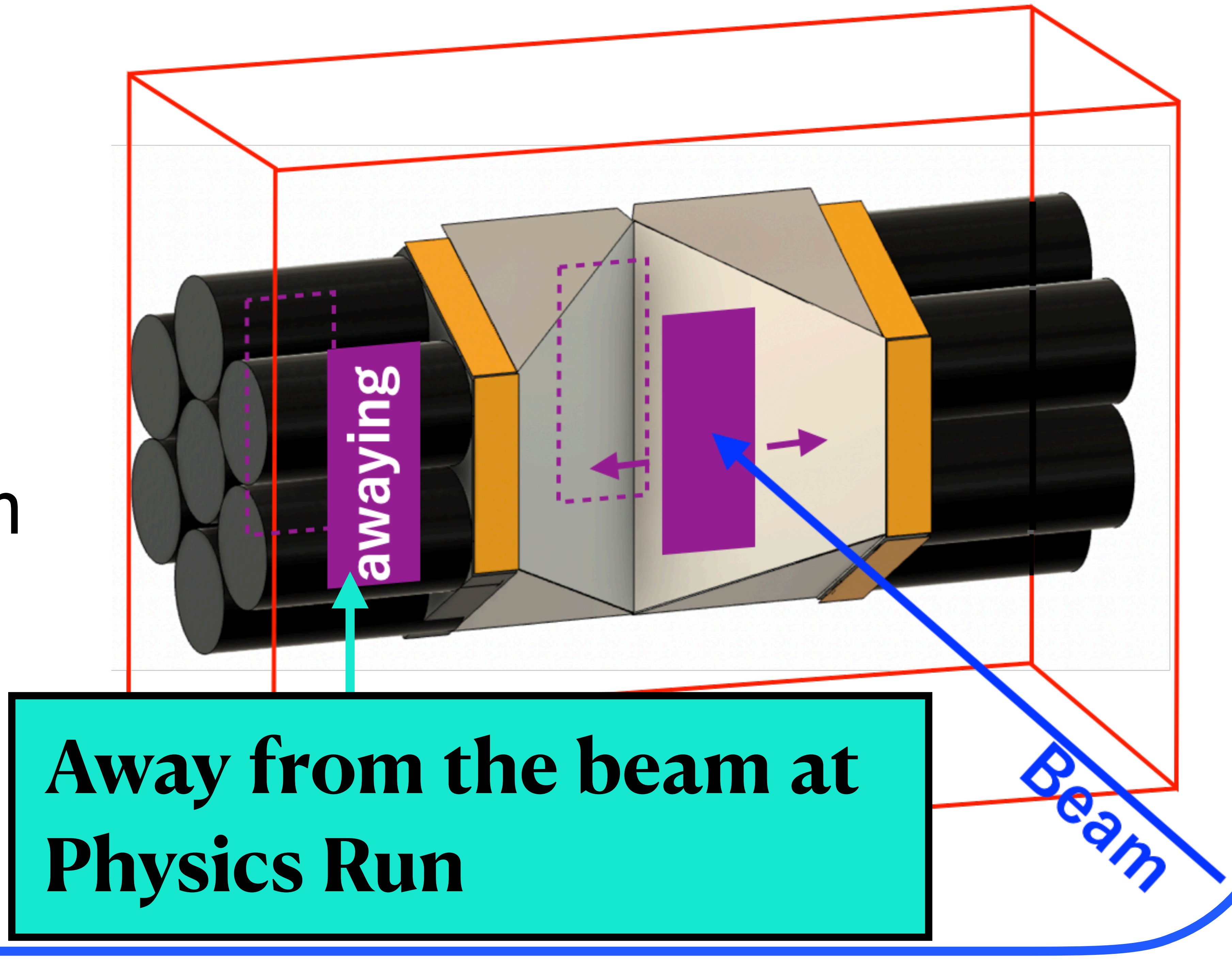
Movable trigger counter

Developed by K. Kotera (Osaka Univ.)

- Read out scintillation light by MPPCs
- Can move trigger counters

Photo





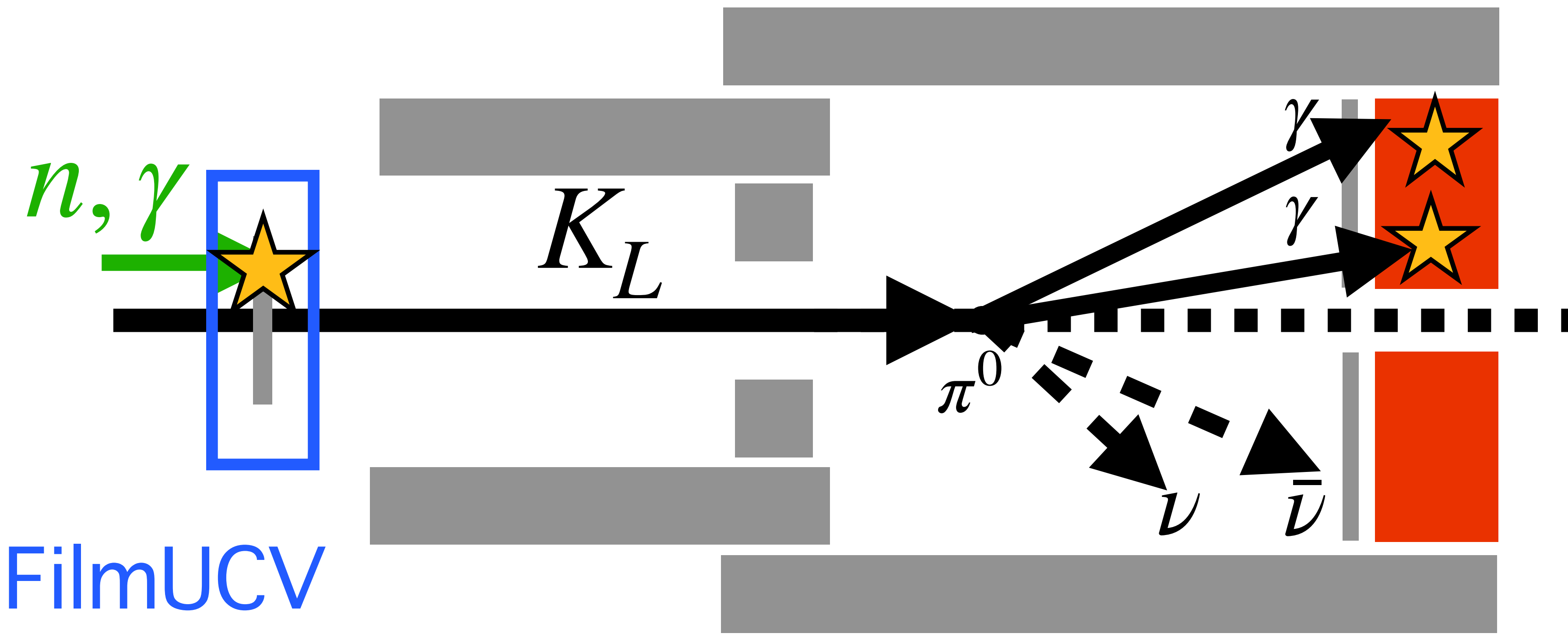
In Summer 2023, **we took the data for FilmUCV**

What we wanted to check about filmUCV using 2023 data

1. **Performance of filmUCV (light yield, inefficiency)**

2. **Increase of probability of losing signal events (Accidental loss)**

- Due to ① High counting rate of FilmUCV itself
  ② Scattered neutral particle hitting other veto detector (on going)

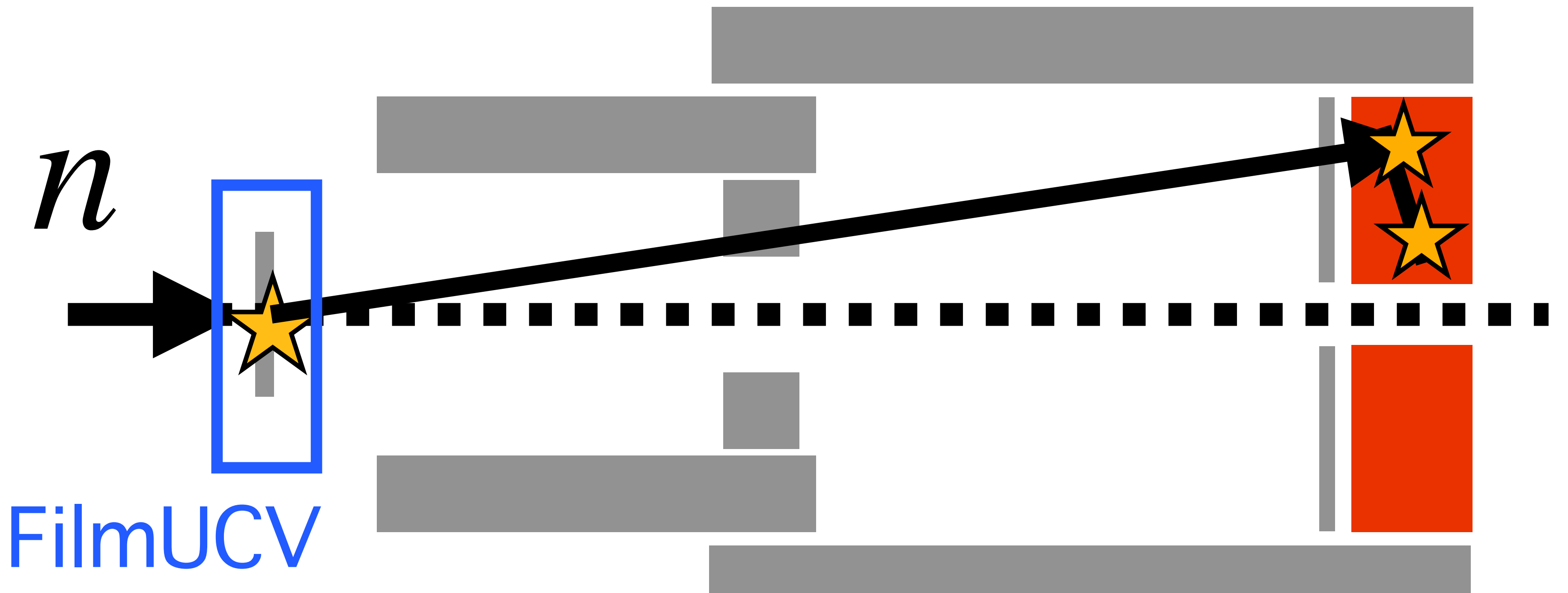


e.g.) Case ①

3. **Increase of other backgrounds**

- Due to scattering of neutral particle

⇒ **check the change of increase thanks to less material budget**



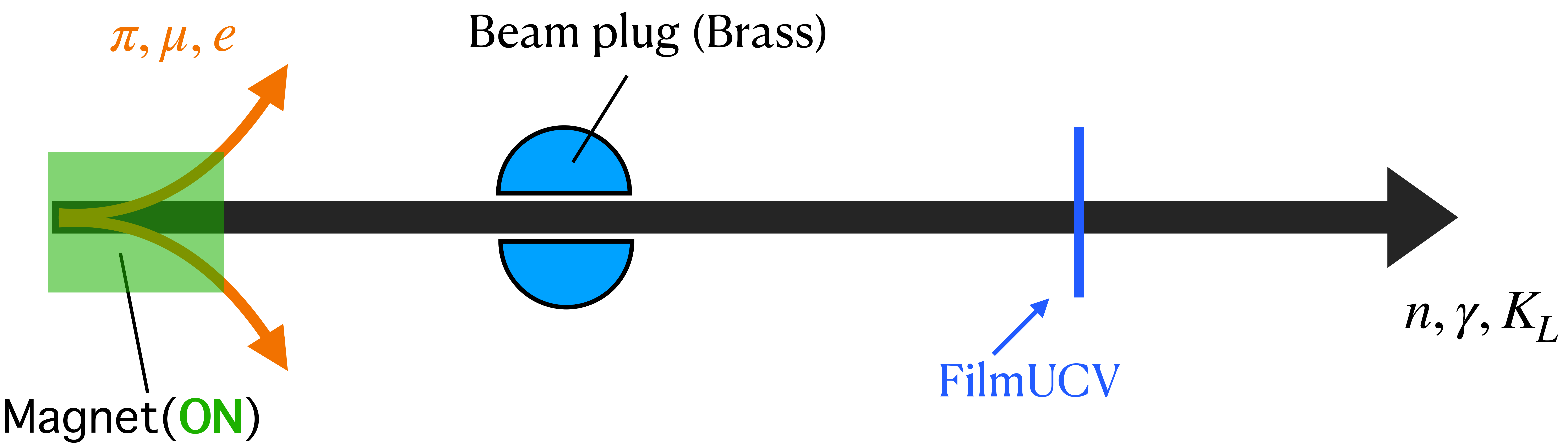
e.g.) Neutron background

Performance of filmUCV

Special data taking for performance evaluation

Took the special data to evaluate FilmUCV performance directly in 2023 run

Schematics of beam line : **Physics run**

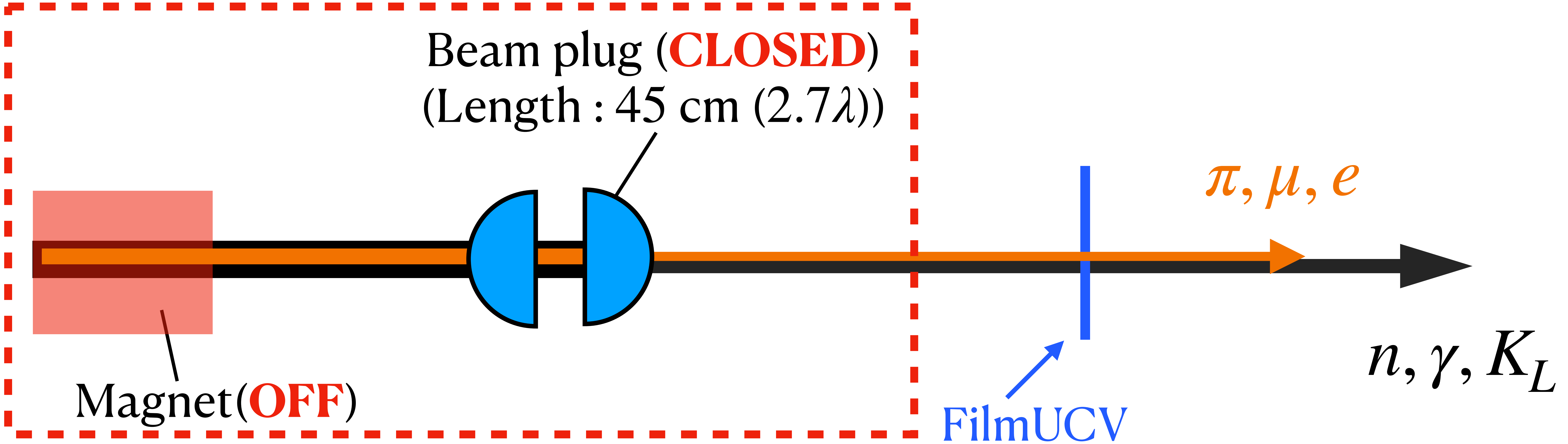


	Physics run
$F_{\text{charged}}/F_{\text{neutral}}$ (MC)	3.6×10^{-4}

Special data taking for performance evaluation

Took the special data to evaluate FilmUCV performance directly in 2023 run

Schematics of beam line : **Special run**



1. Turned **OFF** Magnet
2. **Closed** beam plug

$F_{charged}/F_{neutral}$ (MC)	Physics run	**Special run**
	3.6×10^{-4}	1.6×10^{-2}

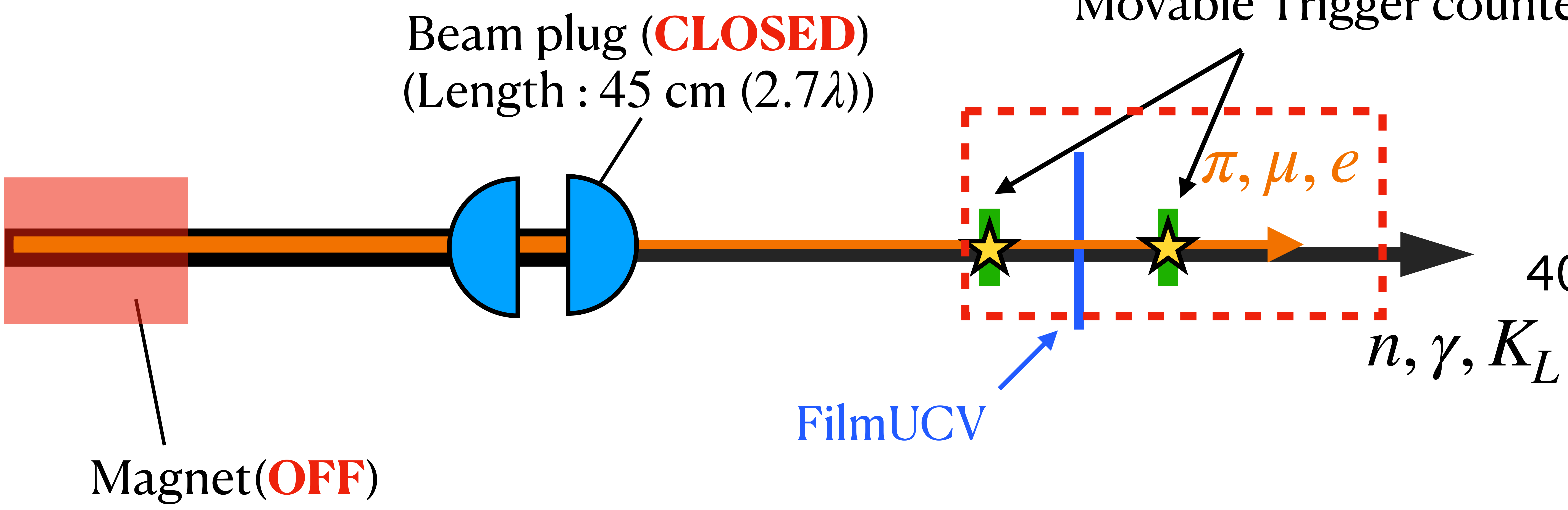
$\times 40$

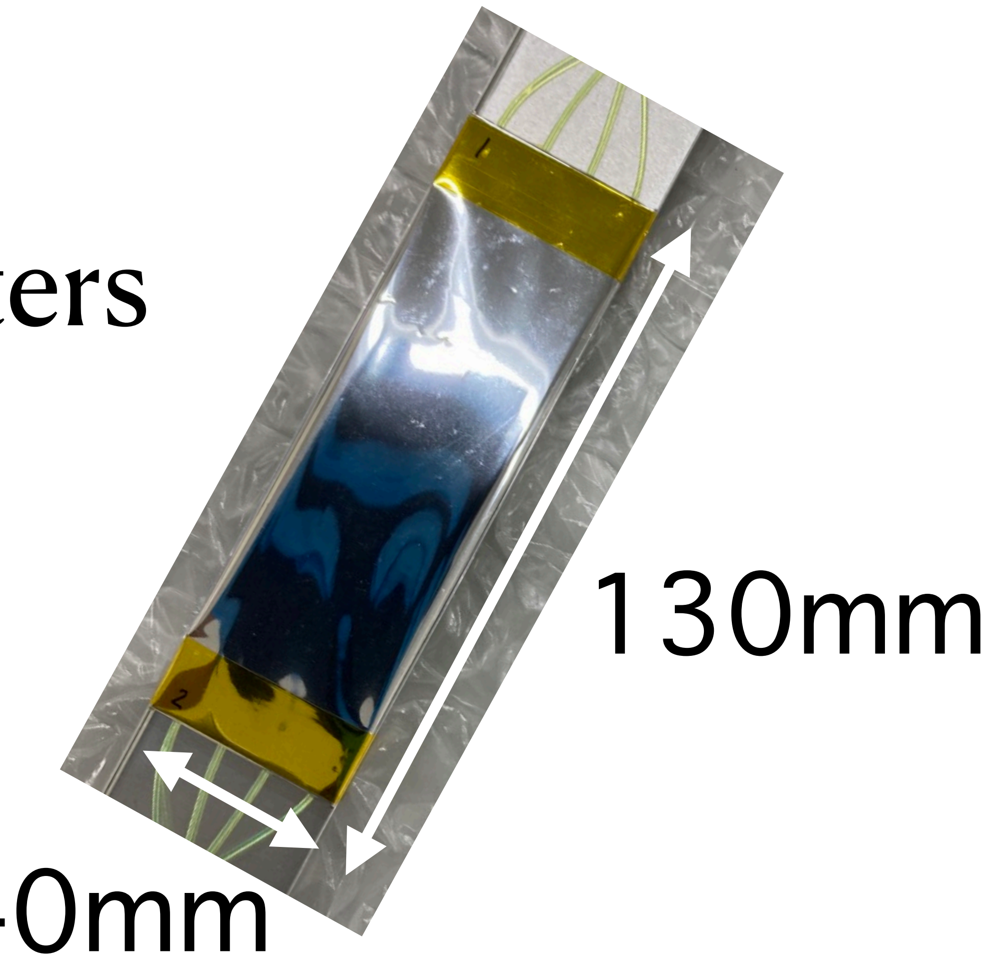
→ **Enhanced Minimum Ionizing Particles(MIPs)**

Special data taking for performance evaluation

Took the special data to evaluate FilmUCV performance directly in 2023 run

Schematics of beam line : **Special run**

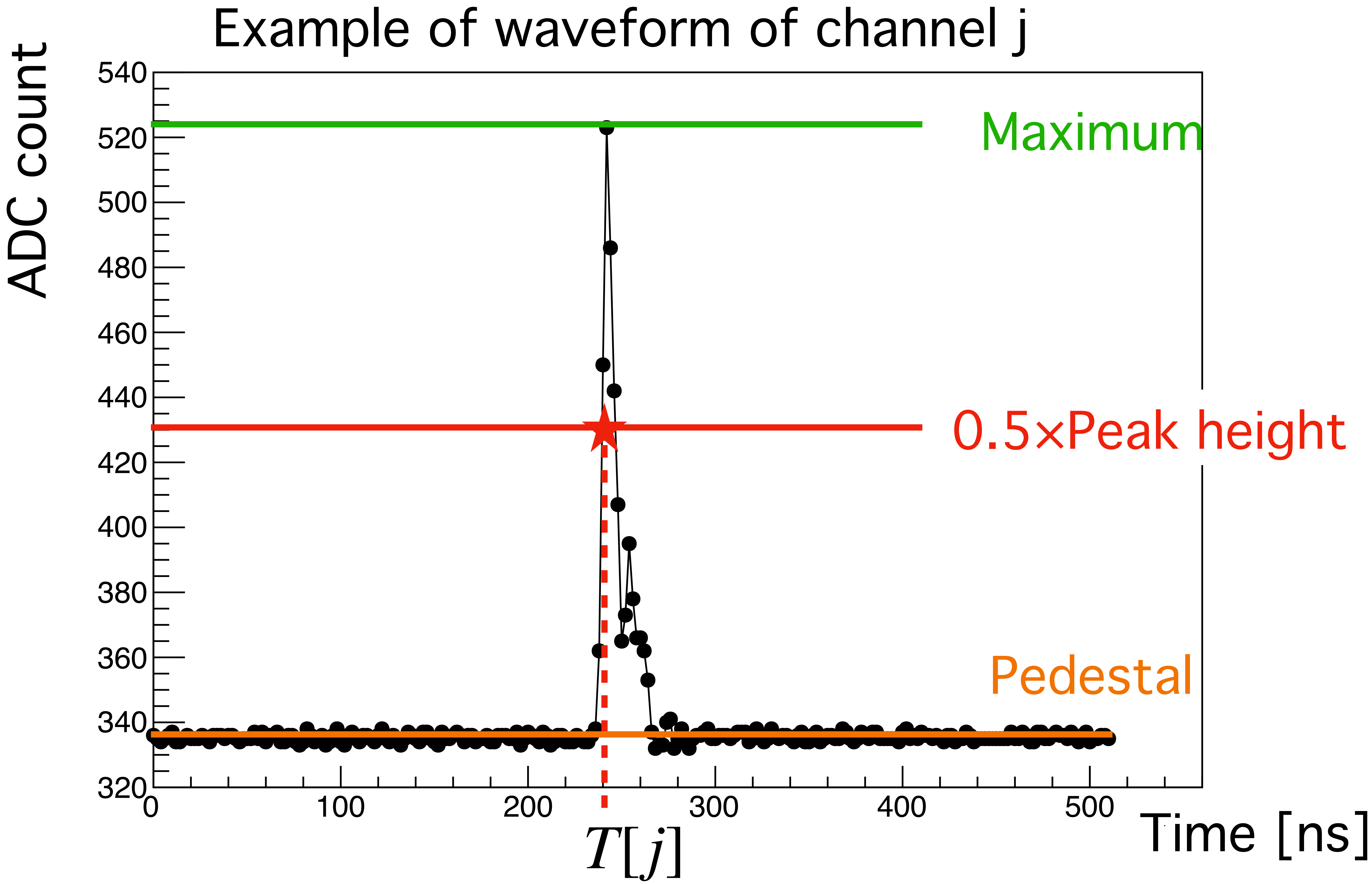




1. Turned **OFF** Magnet
2. **Closed** beam plug
3. Trigger : coincidence of movable trigger counters

➡ **Can collect the data efficiently that MIPs pass through FilmUCV**

Definition of light yield and timing



Light yield : Peak height = Maximum - Pedestal

Timing $T[j]$: the timing that exceeded the half of Peak height (Constant Fraction Timing)

Evaluation of light yield and inefficiency

Light yield = Peak Height   Time = Constant Fraction Time

Light yield

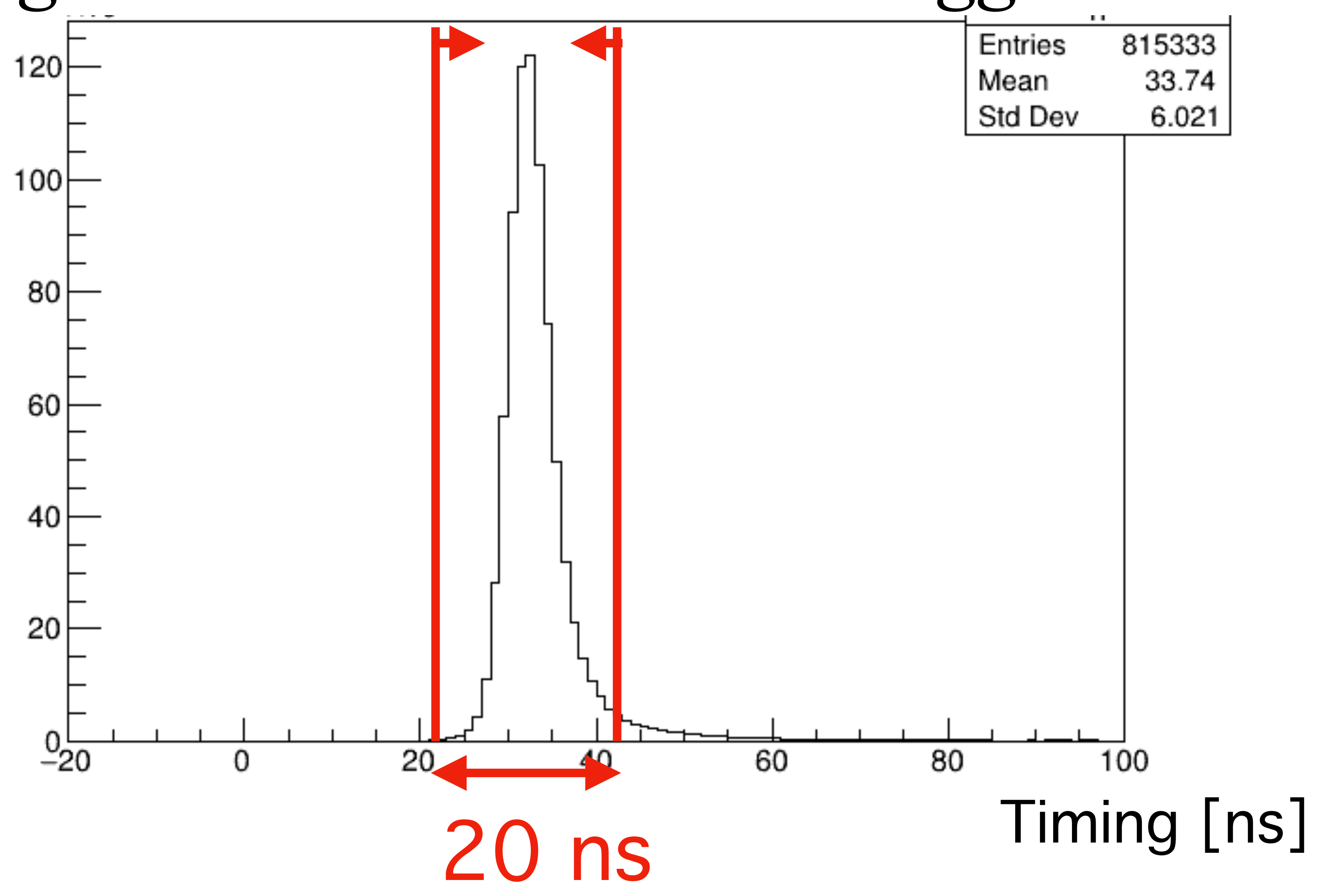
- Find peak in each channel in a 20 ns time window
- **Convert Peak height to # of photoelectrons** with 1p.e. calibration data

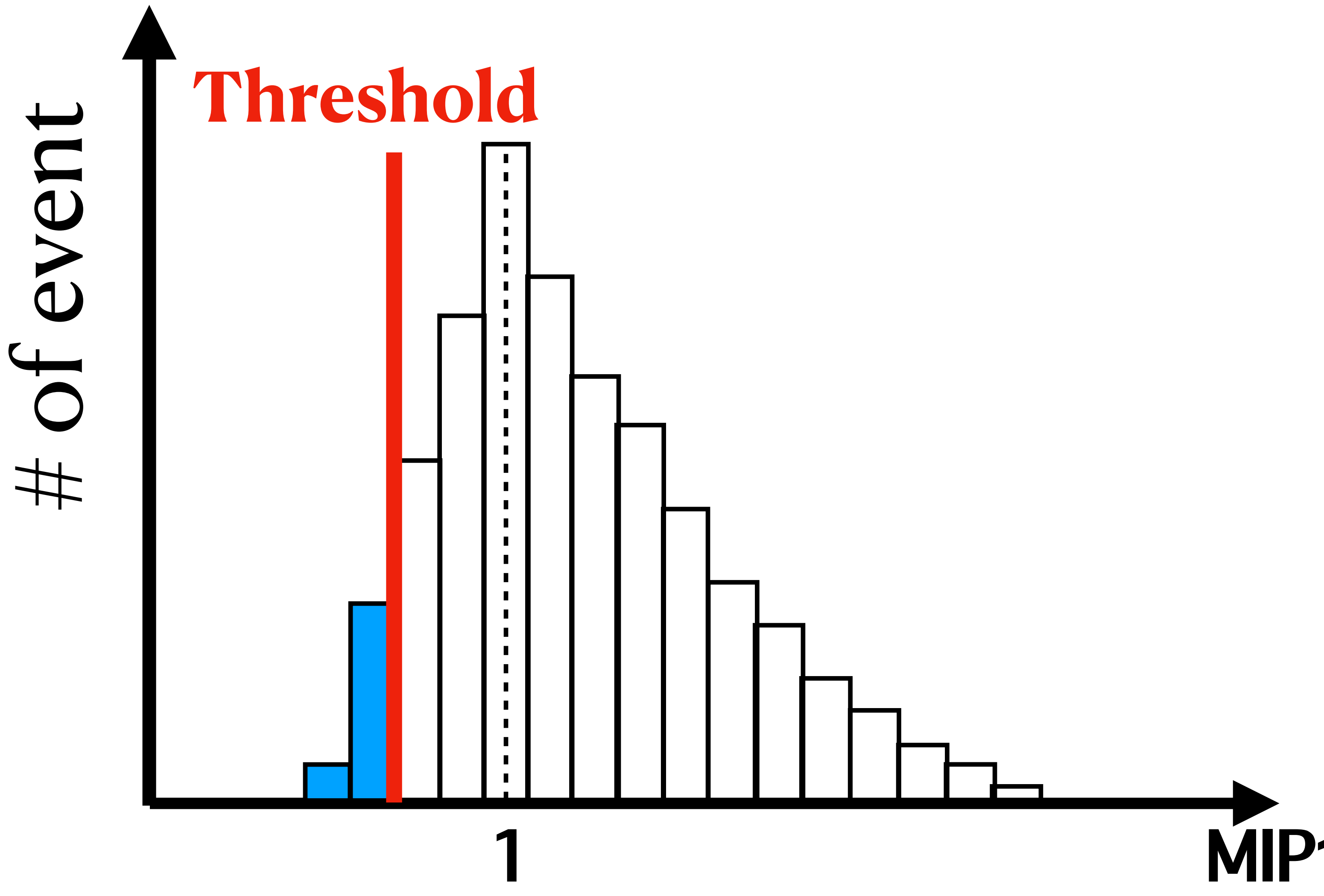
- Calculate **total light yield of UCV by summing for each channel**

Inefficiency

- Inefficiency = $\frac{\textbf{\# of event (< threshold)}}{\textbf{\# of total event}}$

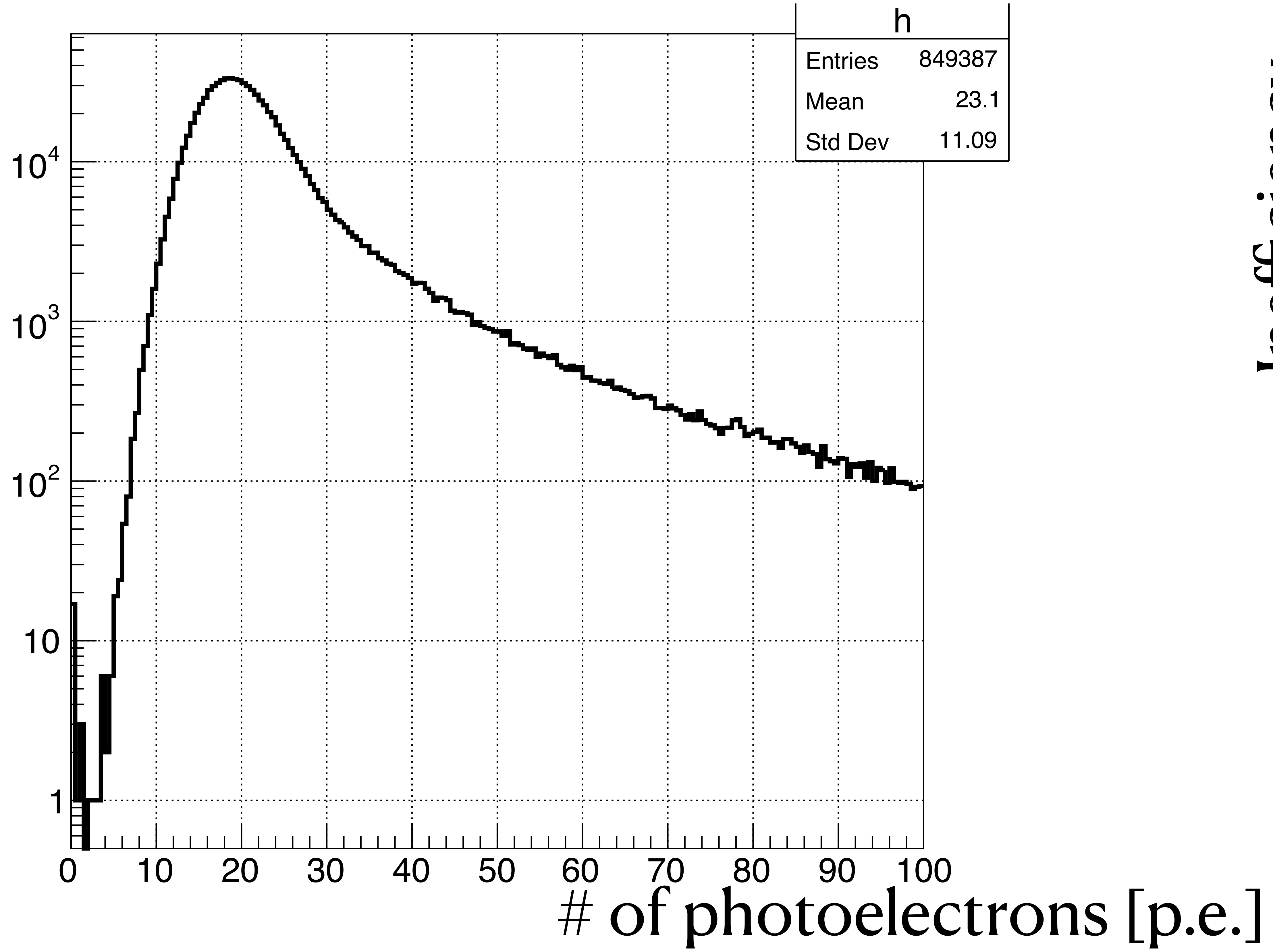
Timing between a channel and trigger counter



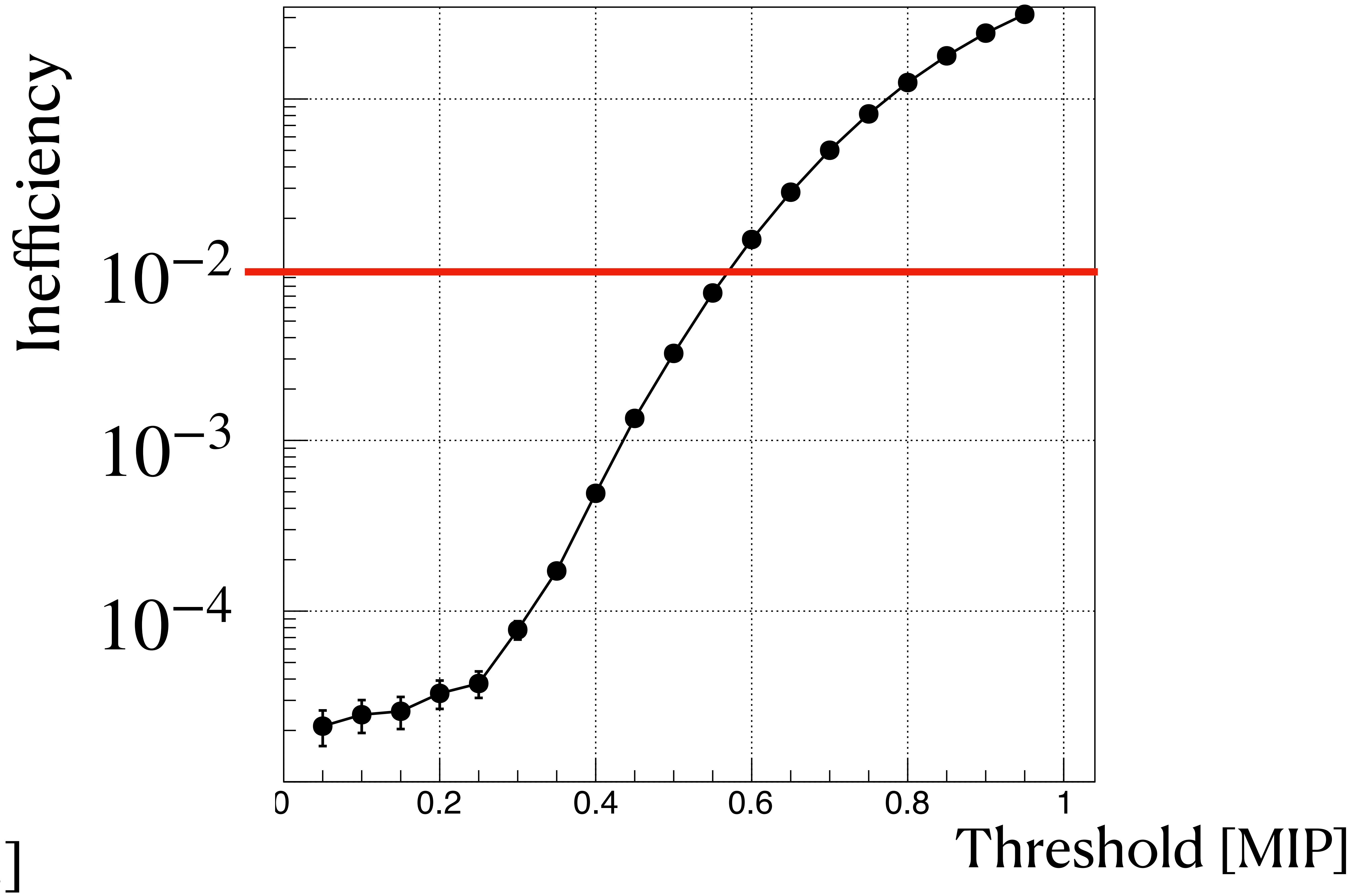


Result of light yield and inefficiency

Distribution of # of photoelectrons



Inefficiency



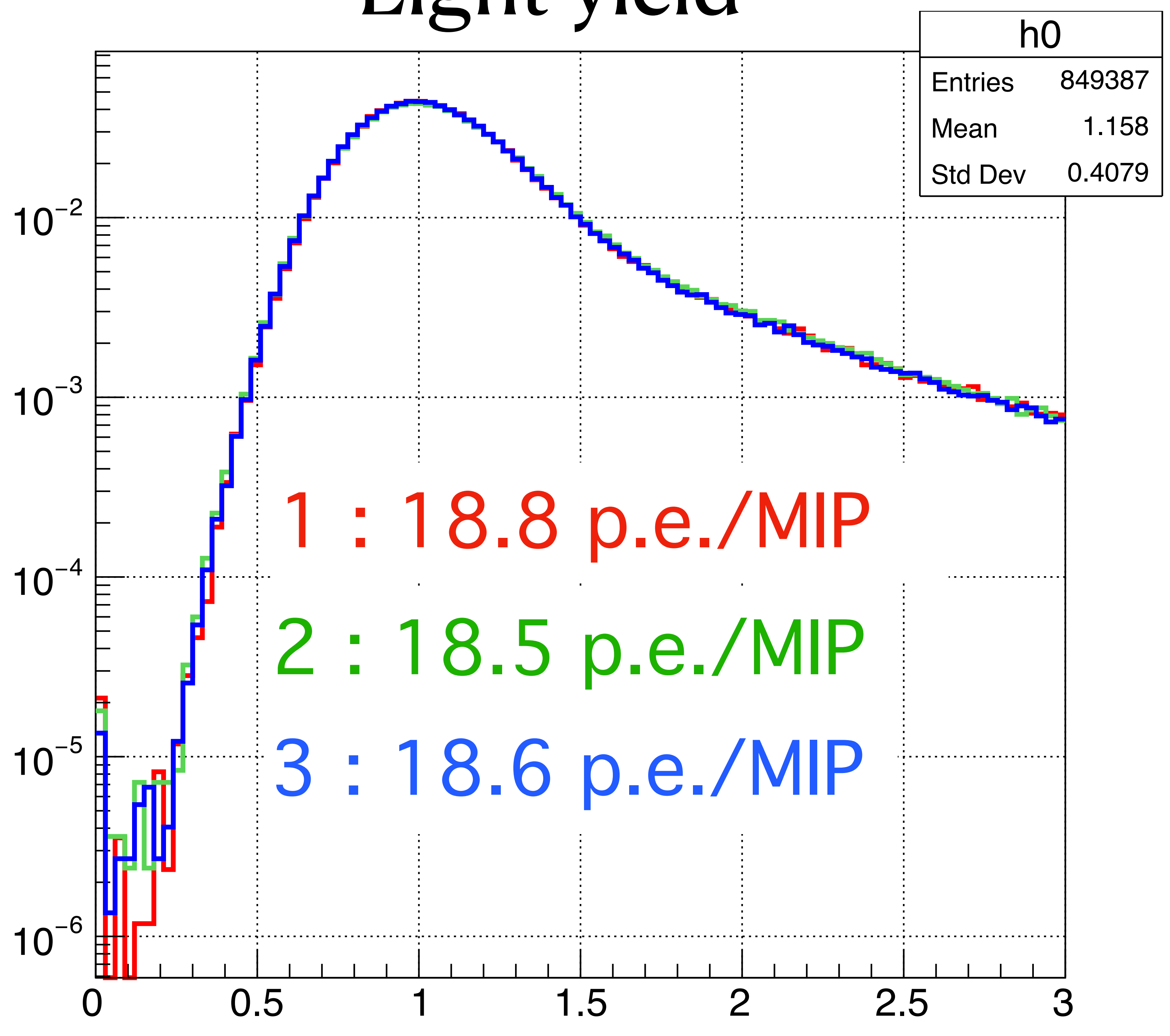
- Light yield : (18.86 ± 0.013) p.e./MIP
- Inefficiency : Achieved < 1% inefficiency at < 0.55 MIP threshold

➡ **Obtained the performance as expected**

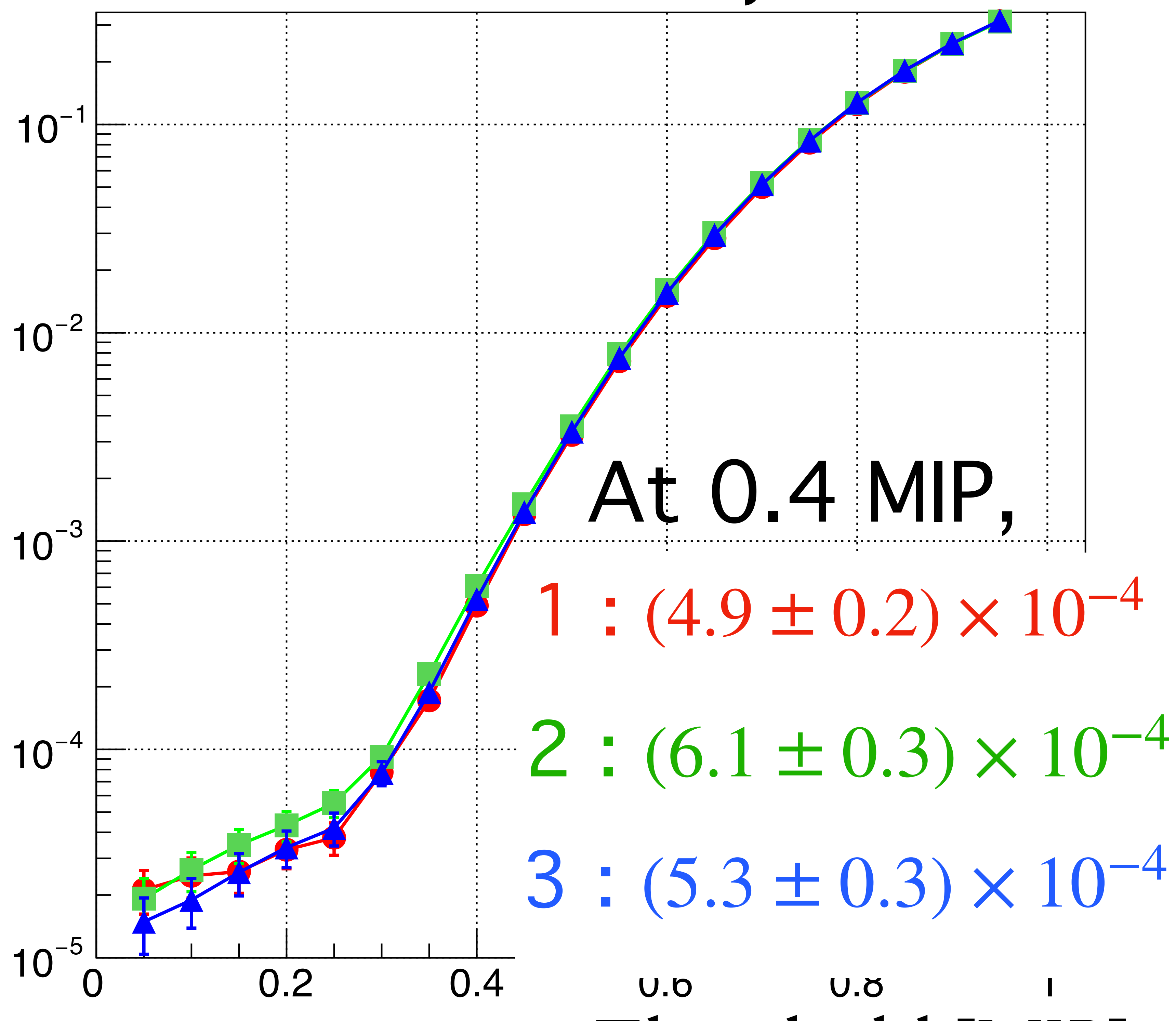
Uniformity of performance

- Also checked uniformity of performance **by changing the position of trigger counter**

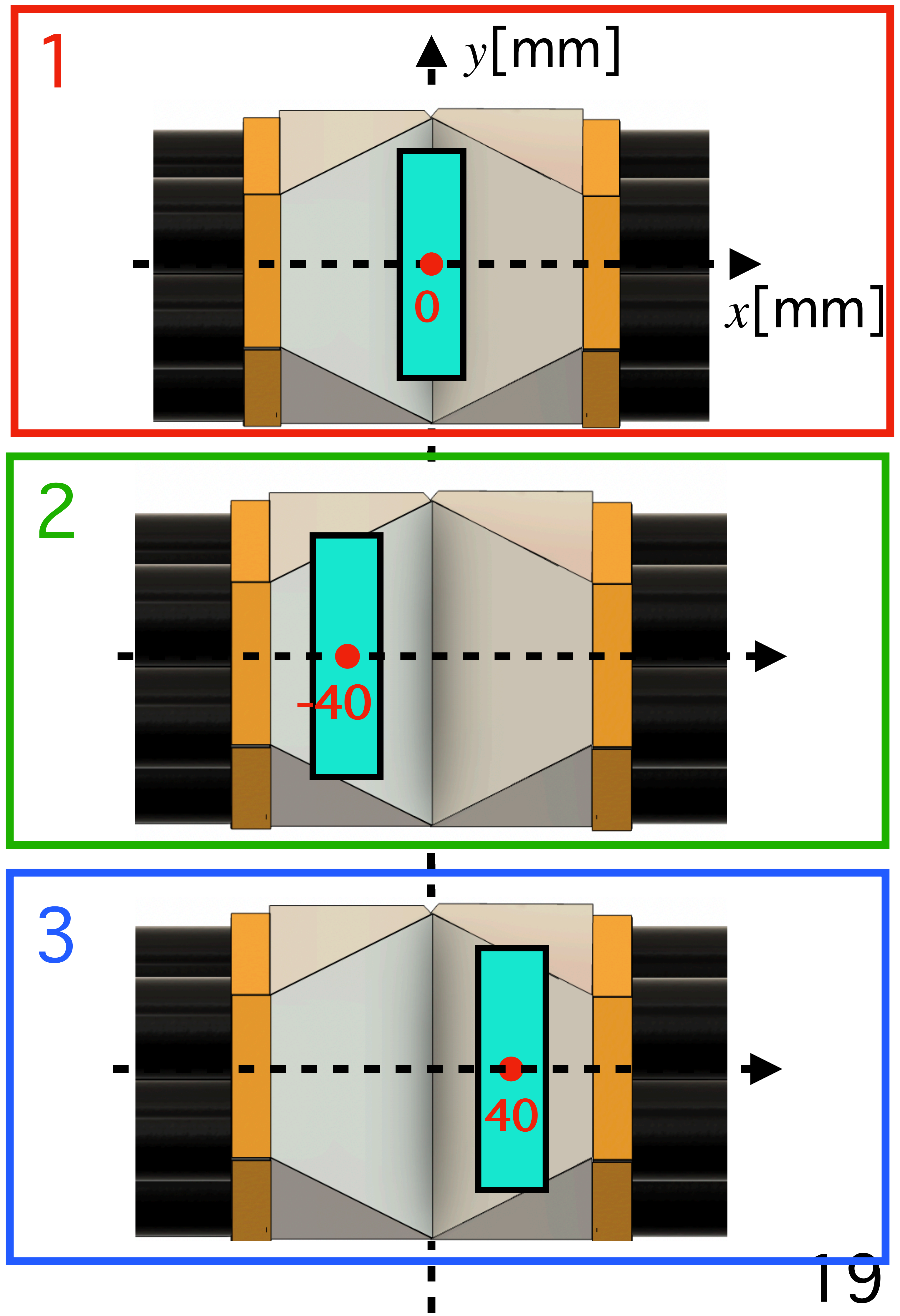
Light yield



Inefficiency



Front view



Confirmed Enough uniformity

Evaluation of timing resolution

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

⬇

- Calculated the FilmUCV timing (T_{UCV})

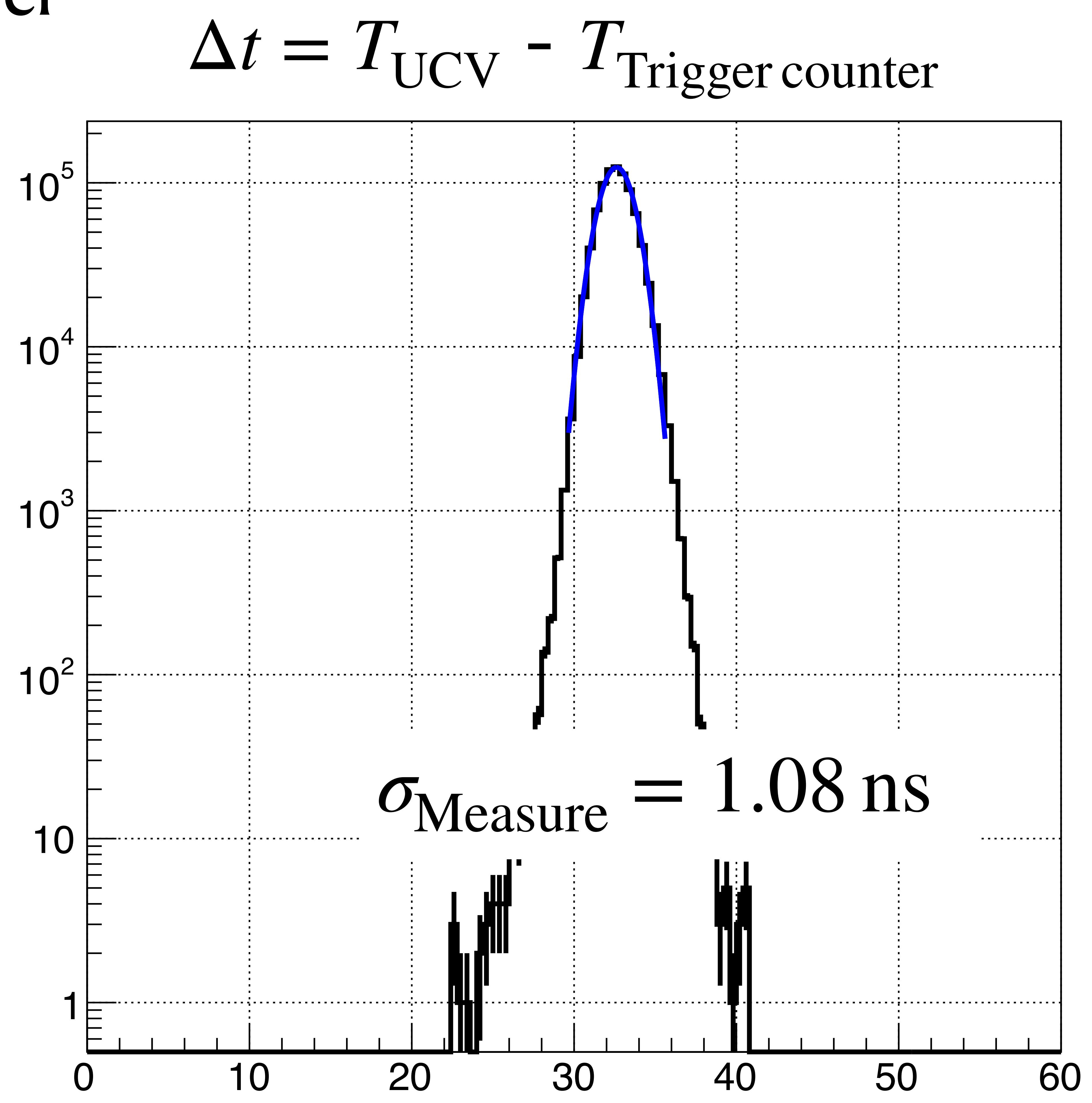
Definition : Average weighted by light yield

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

$T[j]$: timing of channel j $N_{\mathrm{p.e.}}[j]$: light yield of channel j

⬇

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



By subtracting the timing resolution of Trigger counter ($\sigma_{\mathrm{Trigger\ counter}} = 0.38$ ns)

$$\sigma_{\mathrm{UCV}} = (1.012 \pm 0.001)\ \mathrm{ns}$$

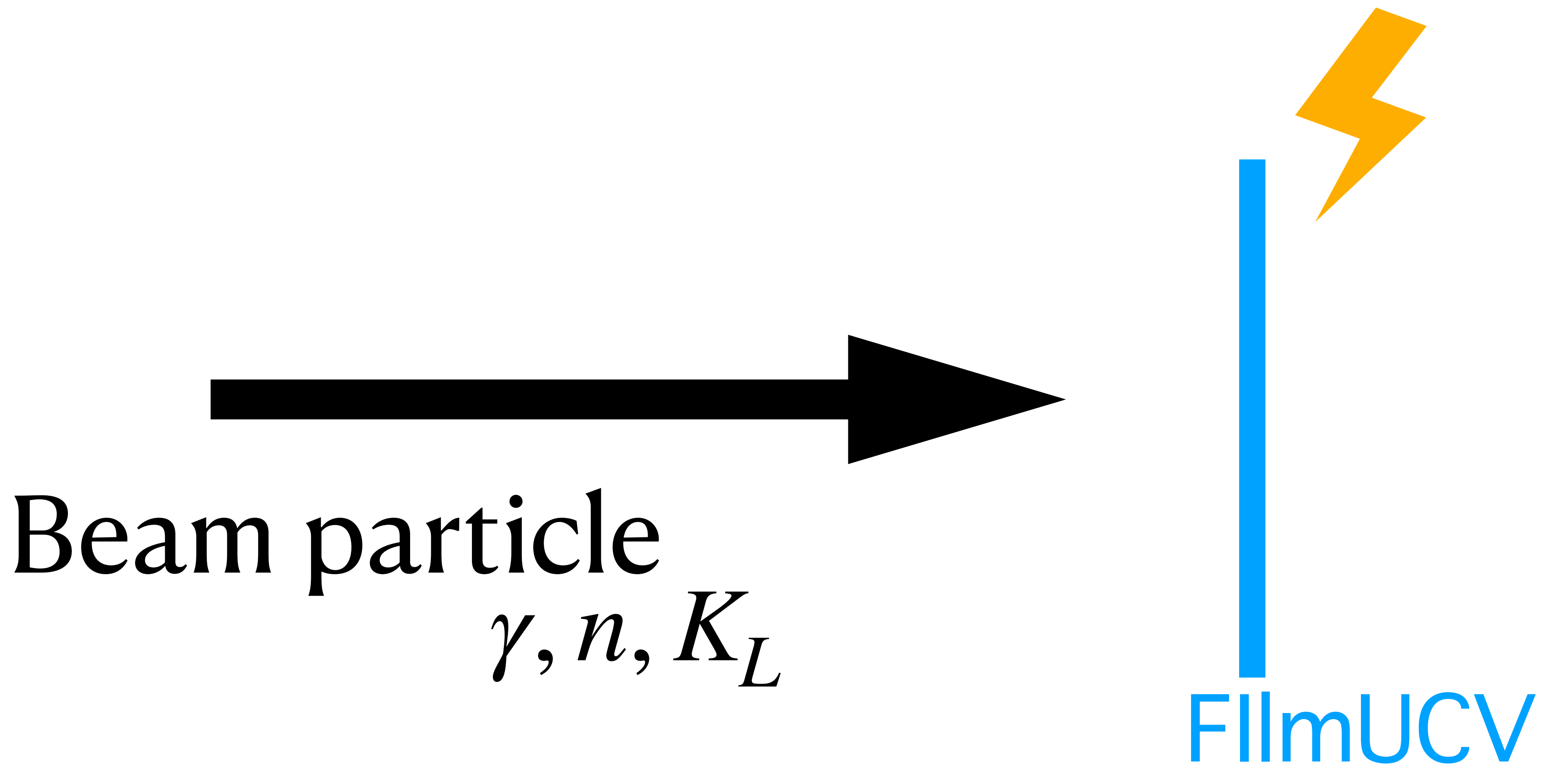
Accidental loss of filmUCV

Evaluation of accidental loss at filmUCV

- Accidental Loss L : Probability of losing signal events

$$L = 1 - \exp(-Rw)$$

R : Hit rate at FilmUCV w : Time window for veto

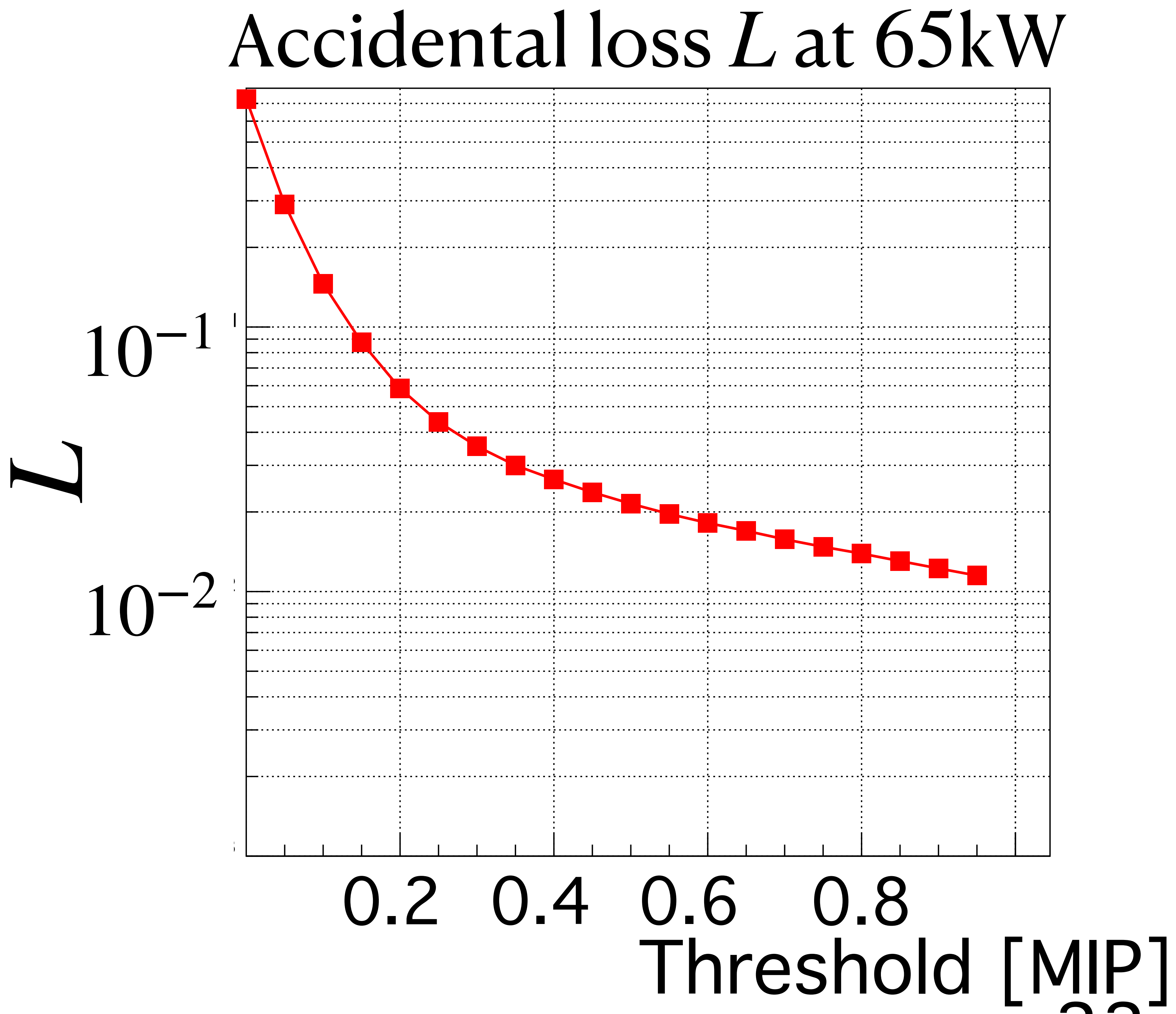


- Calculated R
  using **Random trigger (CLOCK) data at physics run**

Evaluated L with $w = 20$ ns
(Assumed that Beam structure is flat)

- L **:** 2.65**% at** 0.4 **MIP threshold ->NOT same as expected**
  (Expectation: L = 1.5% at 0.4 MIP threshold)

→ **Under investigation**



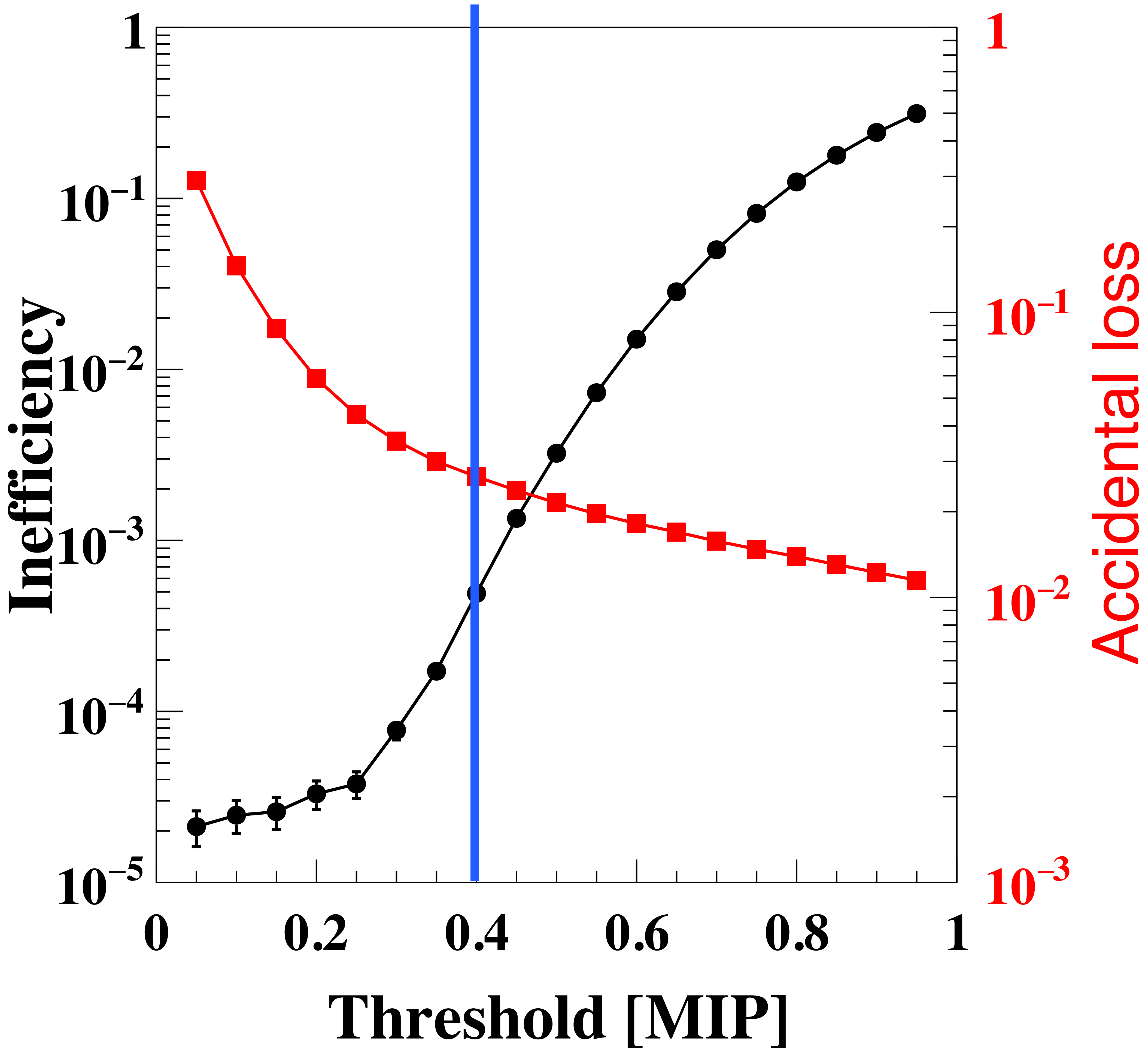
Rejection power against K^+ BG

- When Setting threshold = 0.4 MIP,

Accidental loss : 2.65%
Inefficiency : $(4.8 \pm 0.2) \times 10^{-4}$

K^+ BG rejection — w/ FilmUCV

#BG(K^+)/#Signal(SM) : **0.007**



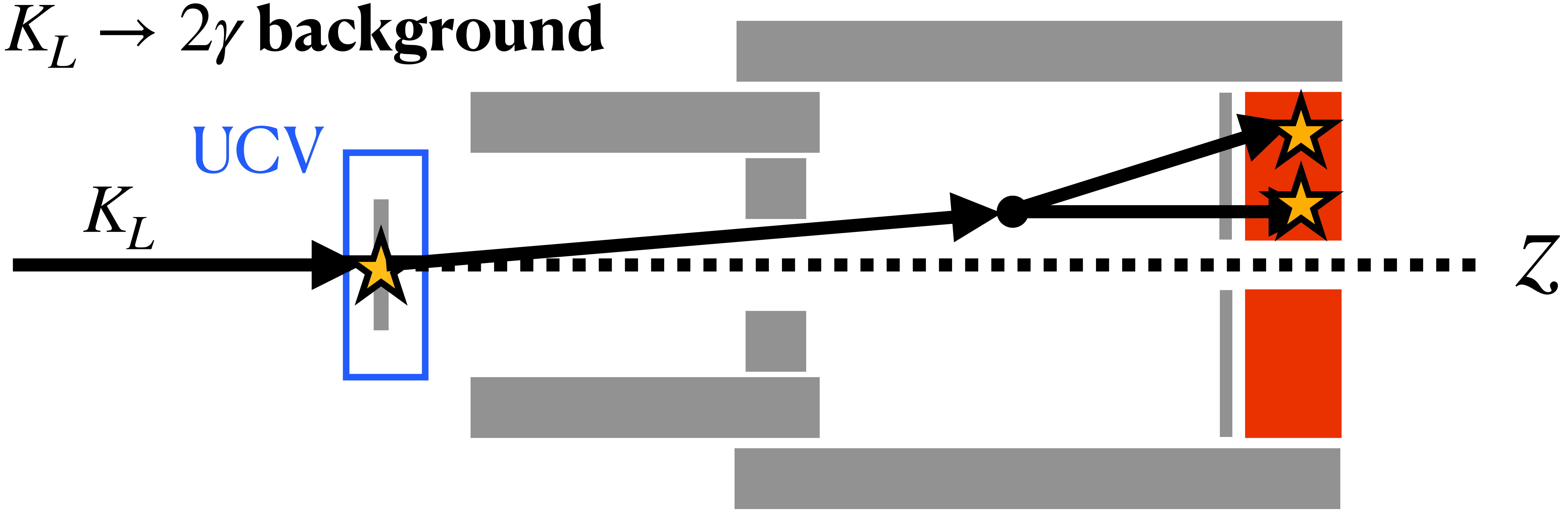
→ **Can eliminate K^+ background**

Increase of other backgrounds

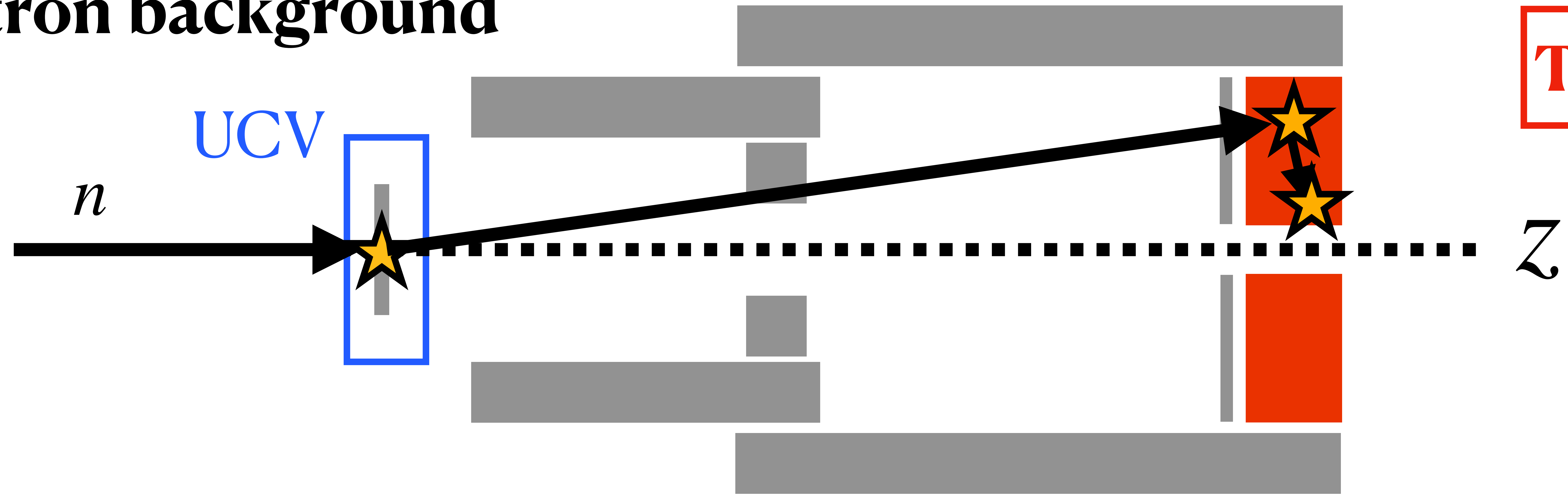
Increase of other backgrounds

Neutral particles (K_L, n) are scattered in UCV ⇒ **Increased 2 types of backgrounds**

1. **Halo $K_L \to 2\gamma$ background**



2. **Neutron background**



Today's contents

Increase of neutron background

Goal

\# of neutron BG $\propto$ neutron flux

⇒**Check change of neutron flux thanks to the change of UCV's material budget**

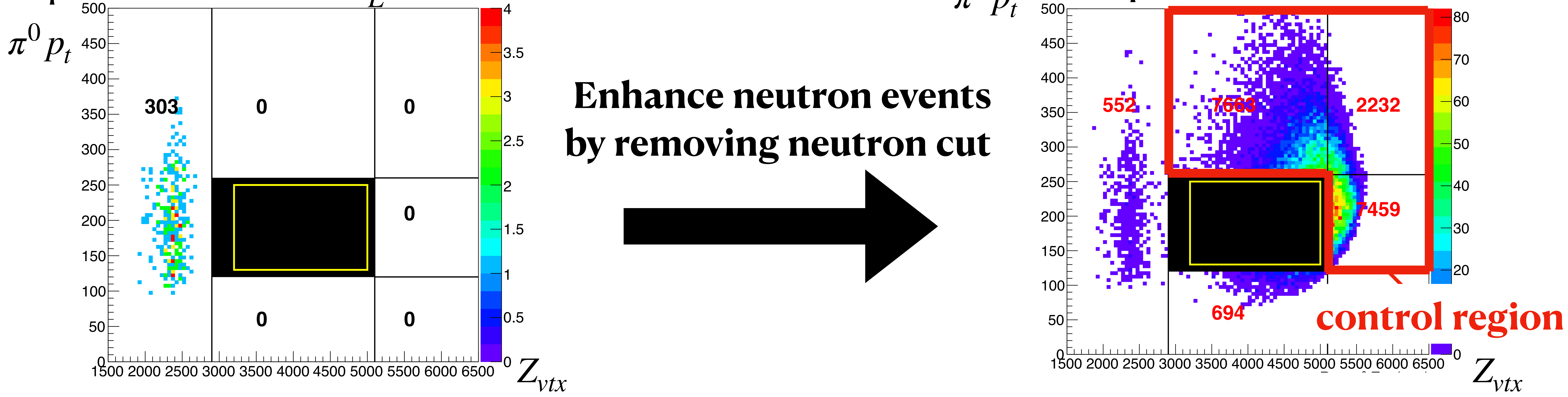
(0.5 mmT → 0.2 mmT)

- Estimated neutron flux using physics data

1. Counted # of events in **control region** of Pt-z plot ($N_{\rm obs}$)

Pt-z plot with all cut for $K_L \to \pi^0 \nu \bar{\nu}$ search

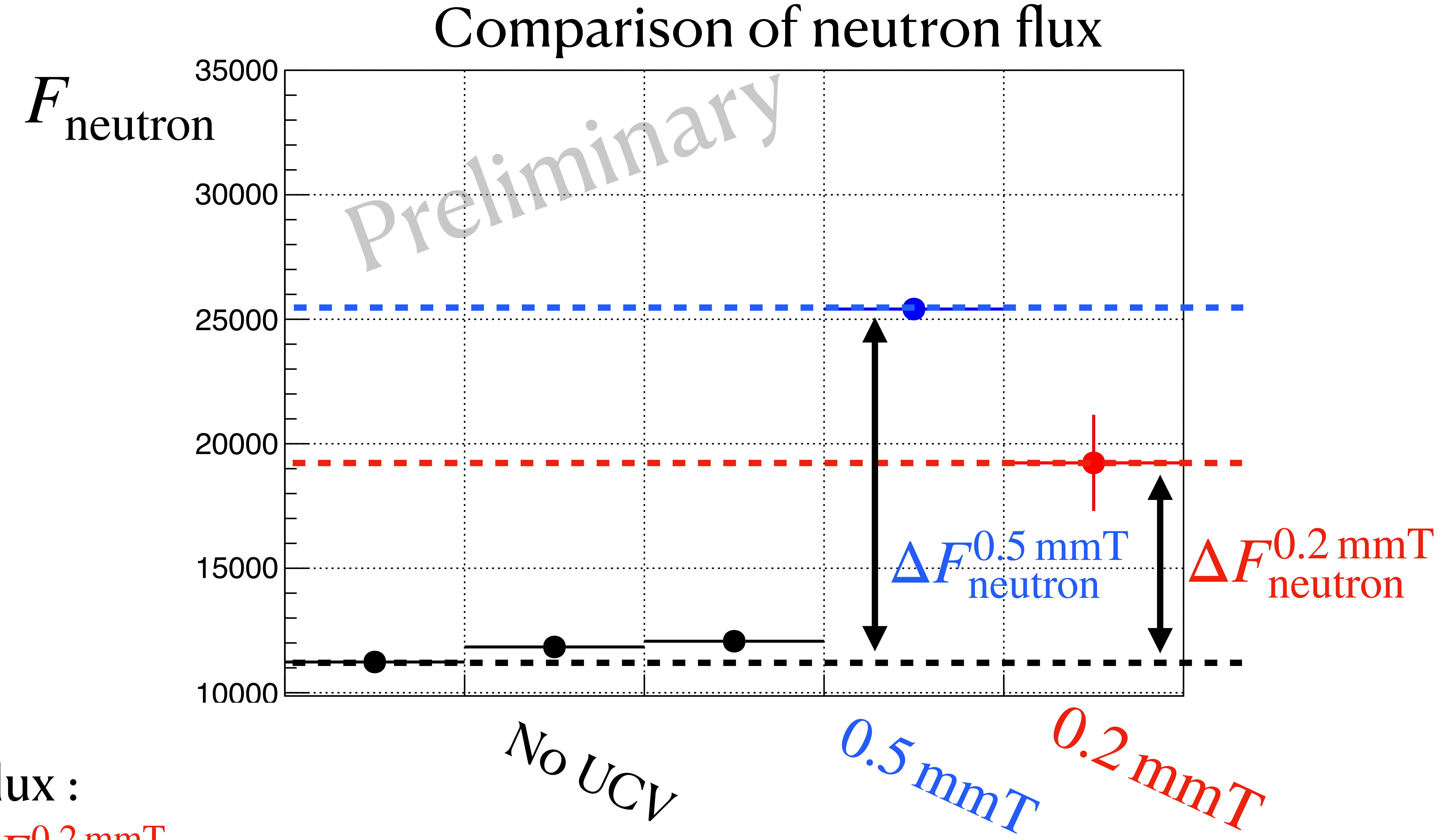
Pt-z plot w/o neutron cut



2. Defined neutron flux as $F_{\rm neutron} = N_{\rm obs}/A/{\rm POT}[10^{19}]$

A : **Acceptance** POT : **Accumulated Proton On Target**

Result of neutron flux comparison



Change of flux :

$$\frac{\Delta F^{0.2\,\text{mmT}}_{\text{neutron}}}{\Delta F^{0.5\,\text{mmT}}_{\text{neutron}}} = 0.56 \pm 0.14$$

$\Rightarrow$ **Same as expectation within uncertainty**

(Expectation : 0.41)

Conclusion

- Installed new charged particle detector using 0.2 mmT scintillator (filmUCV)

Performance

- Light yield : 18.8 p.e./MIP ✔
- Inefficiency : $(4.8 \pm 0.2_{\text{stat.}}\ {}^{+0.15}_{-1.0}\ {}_{\text{syst.}}) \times 10^{-4}$ at 0.4 MIP threshold ✔
- Timing resolution : 1.01 ns ✔

⇒ **Can eliminate K^+ BG**

Accidental loss

- Accidental loss : 2.6 % ➡ **Under investigation**

Increase of other background

- Same as expectation for neutron background ✔

Backup

CKM matrix

$$V_{\rm CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$
$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$\lambda \equiv \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}$$
$$A \equiv \frac{1}{\lambda}\left|\frac{V_{cb}}{V_{us}}\right|$$
$$\rho \equiv \Re\left\{\frac{V_{ub}^*}{A\lambda^3}\right\}$$
$$\eta \equiv \Im\left\{\frac{V_{ub}^*}{A\lambda^3}\right\}$$

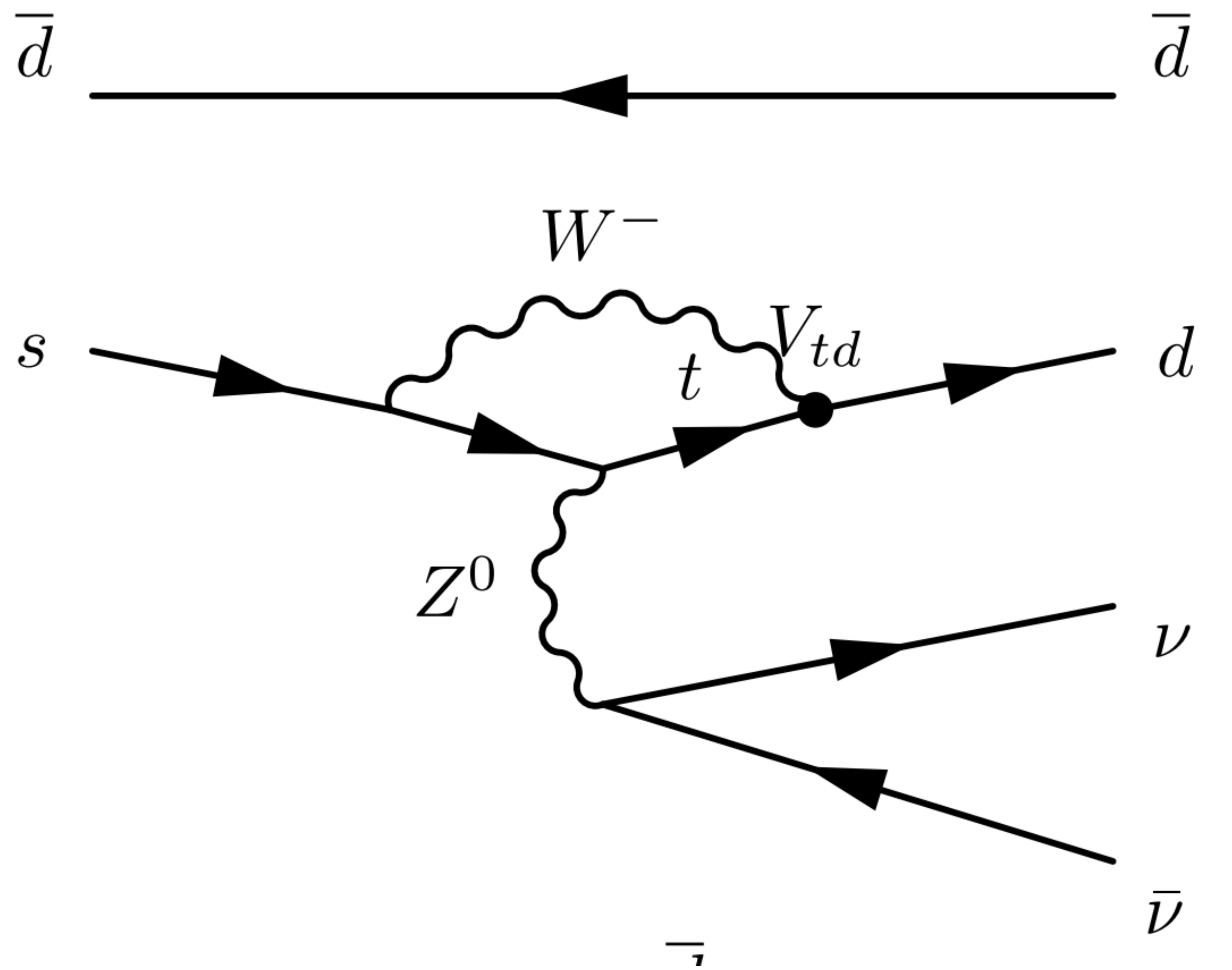
$$\lambda = 0.22453 \pm 0.00044$$
$$A = 0.836 \pm 0.015$$
$$\bar{\rho} = 0.122^{+0018}_{-0.017}$$
$$\bar{\eta} = 0.355^{+0.012}_{-0.011}$$

$K_L \to \pi^0 \nu\bar{\nu}$ decay

Amplitude of $K_L \to \pi^0 \nu\bar{\nu}$ decay

$$A(s \to d\nu\bar{\nu}) \sim \boxed{\frac{m_t^2}{M_W^2}\lambda_t} + \frac{m_c^2}{M_W^2}\ln\frac{M_W}{m_c}\lambda_c + \frac{\Lambda_{\text{QCD}}^2}{M_W^2}\lambda_u$$

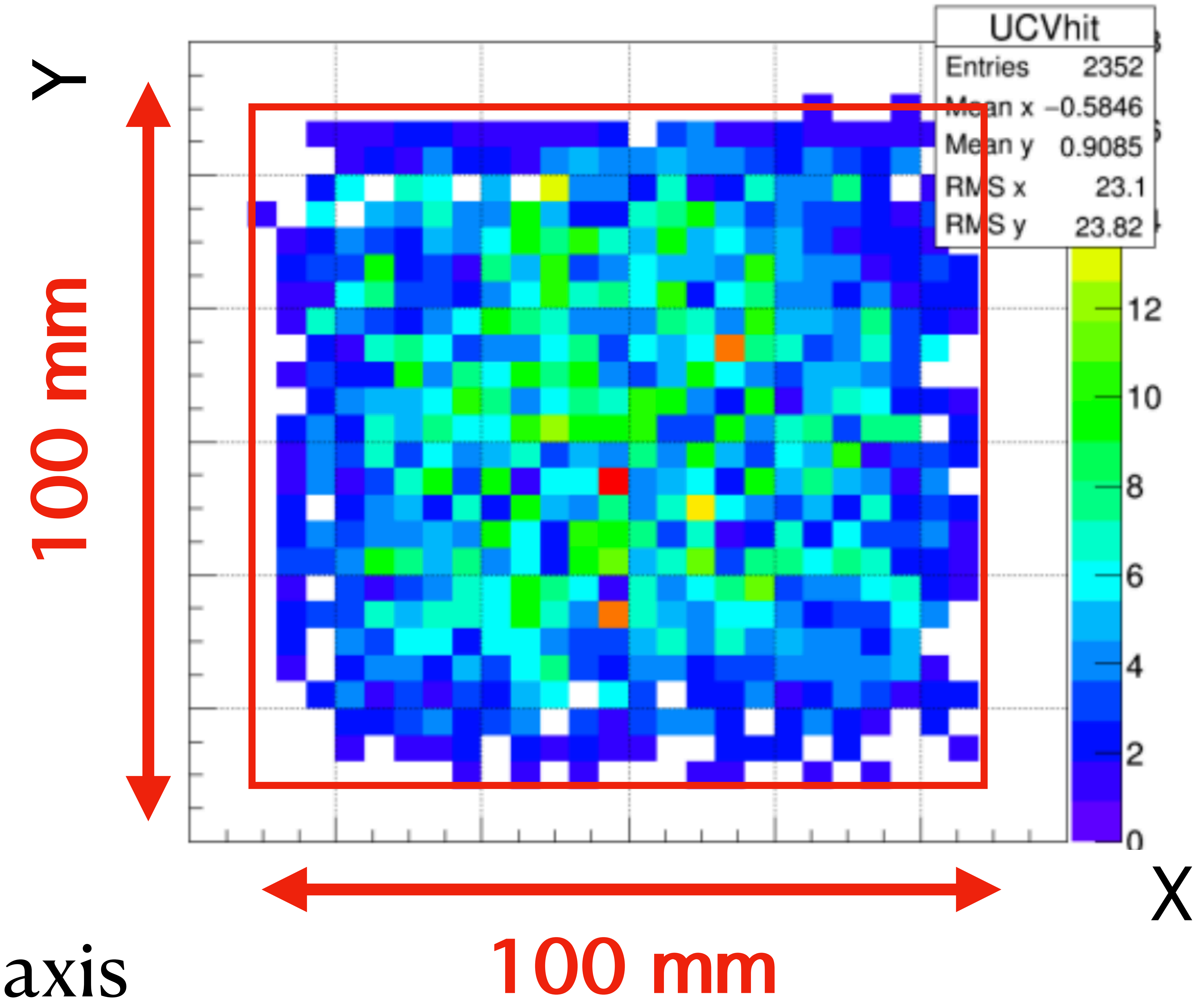
Large contribution
due to the large mass of top (68%)



$$\begin{aligned}
A\left(K_L \to \pi^0\nu\bar{\nu}\right) &\sim \frac{1}{\sqrt{2}}\left(A\left(K^0 \to \pi^0\nu\bar{\nu}\right) - A\left(\bar{K}^0 \to \pi^0\nu\bar{\nu}\right)\right) \\
&\propto V_{ts}V_{td}^* - V_{ts}^*V_{td} \\
&\sim -A\lambda^2(A\lambda^3(1-\rho+i\eta) - A\lambda^3(1-\rho-i\eta)) \\
&= -i2A^2\lambda^5\eta \\
&\propto \eta.
\end{aligned}$$

K+ profile

MC simulation



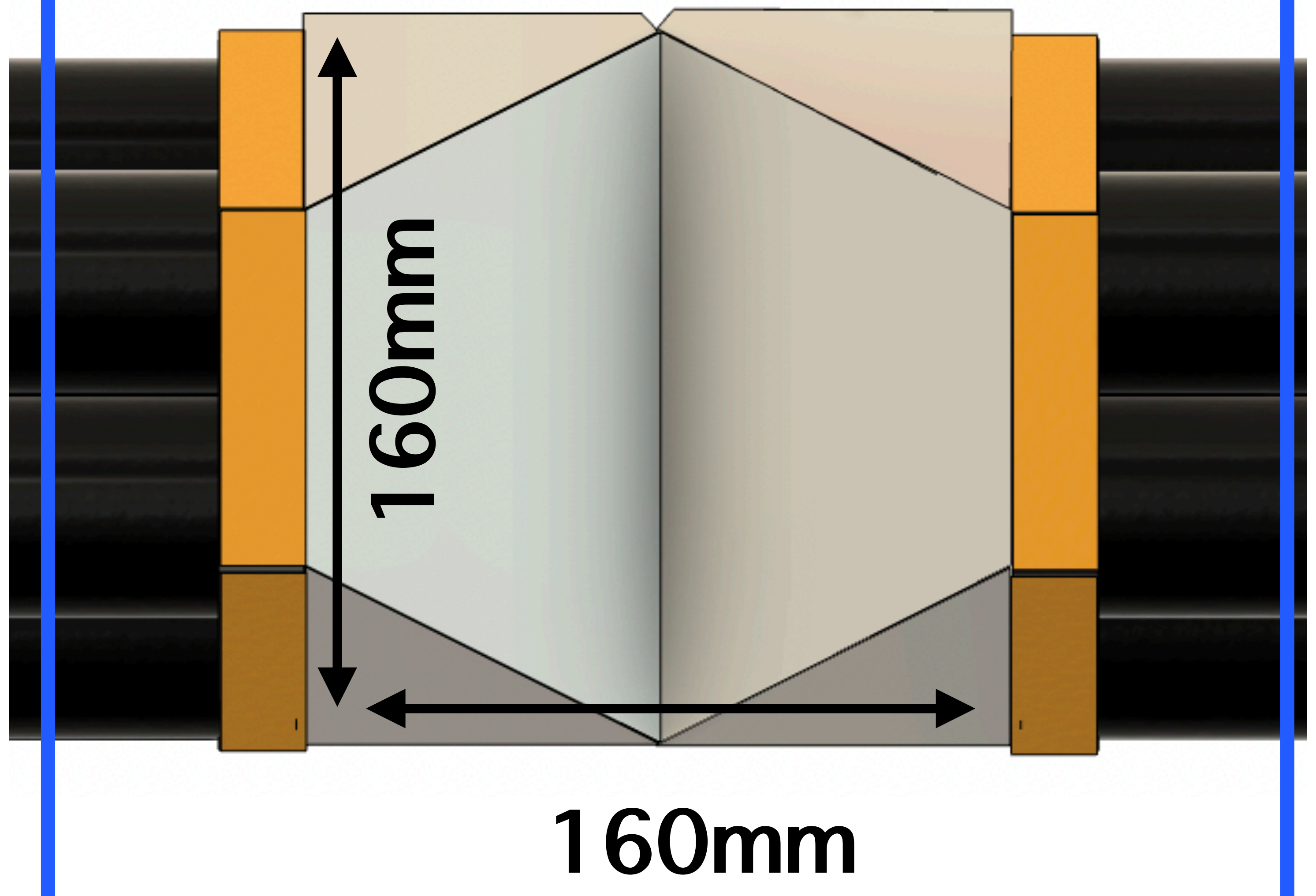
Z : Beam axis

Channel configuration

FilmUCV

- Use **sum Amplifier**
  ⇒**Sum** 2 **PMT signals** on the same side

Ch0 : (0, 1)
Ch1 : (2, 3)
Ch2 : (4, 5)
Ch3 : (6)

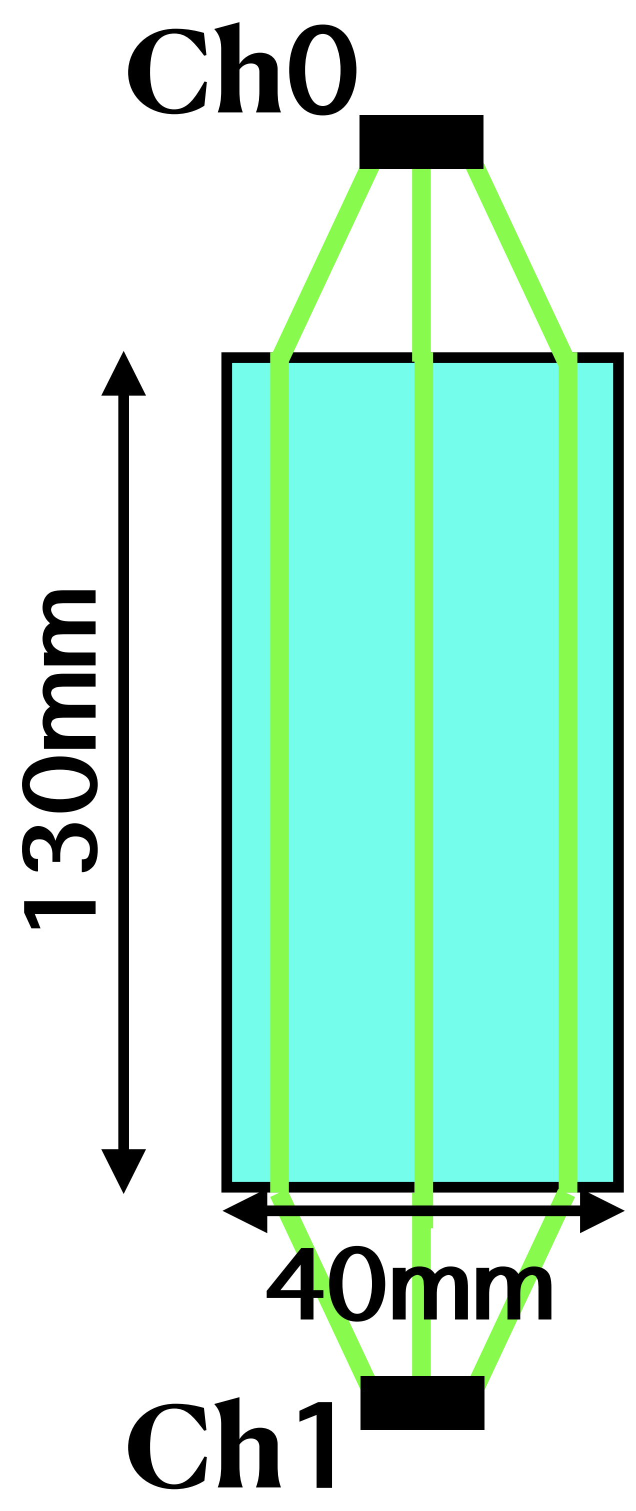


Total 8 ch

Ch4 : (7, 8)
Ch5 : (9, 10)
Ch6 : (11, 12)
Ch7 : (13)

Movable Trigger counter

- Readout two MPPCs through WLS fibers

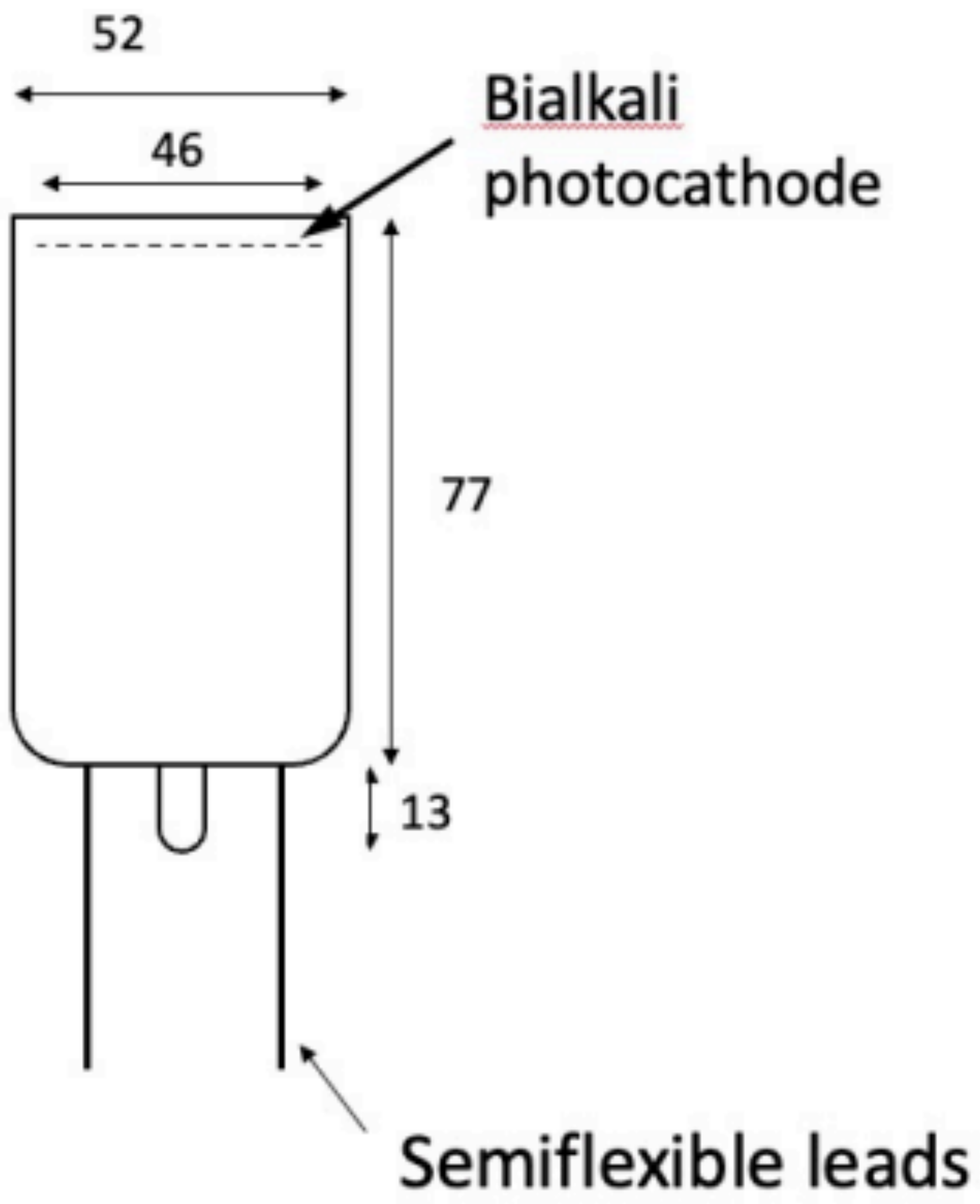


PMT used in FilmUCV

R14095-01

- **Compact PMT (ϕ52mm)**
- **Can count single photoelectron**
- 10 stage dynode
- No assembly type
  -> Current PMT base was prepared by A.Kitagawa(Osaka University)
- QE = 28% at 420 nm

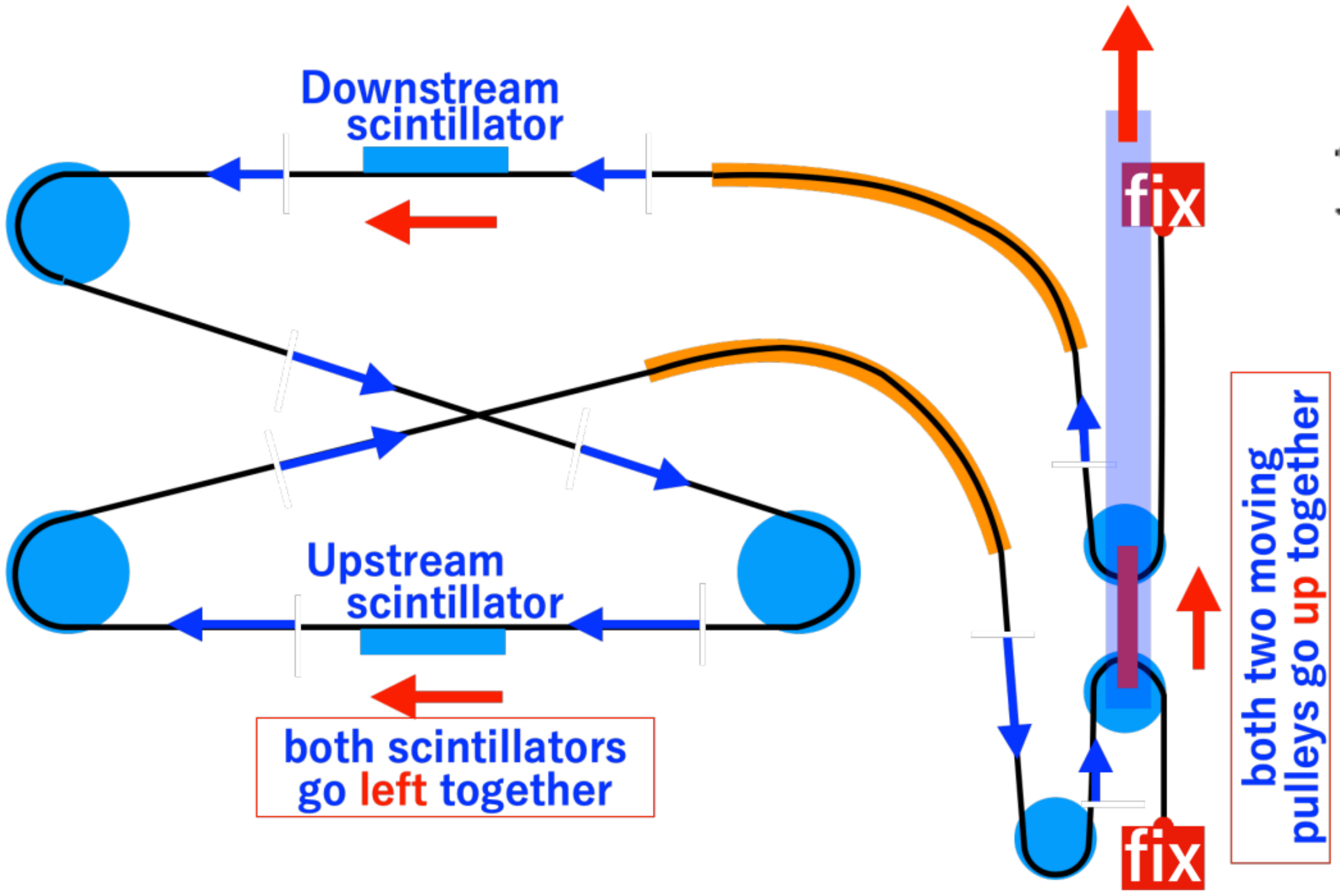
Hamamatsu Photonics
R14095-01

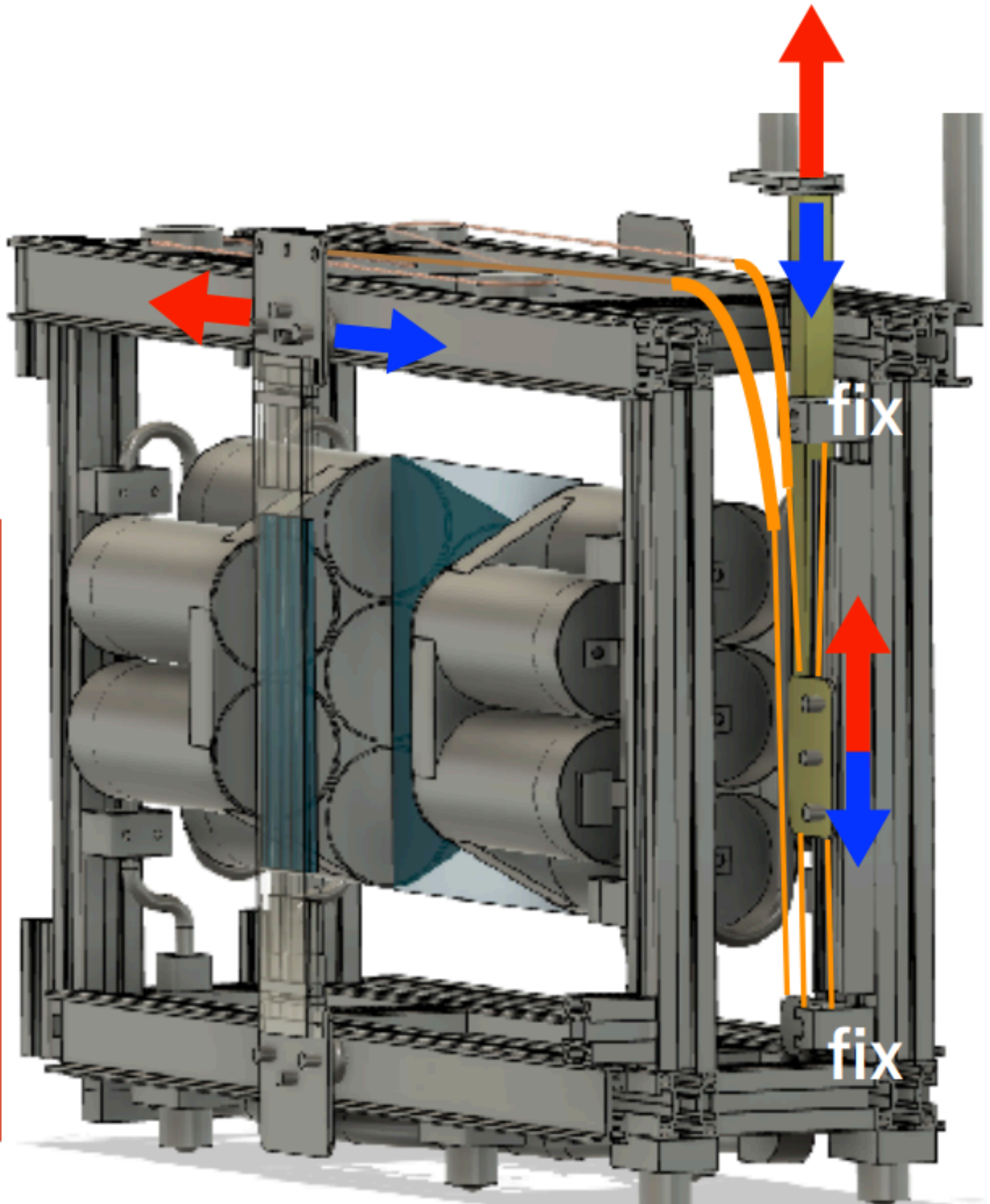


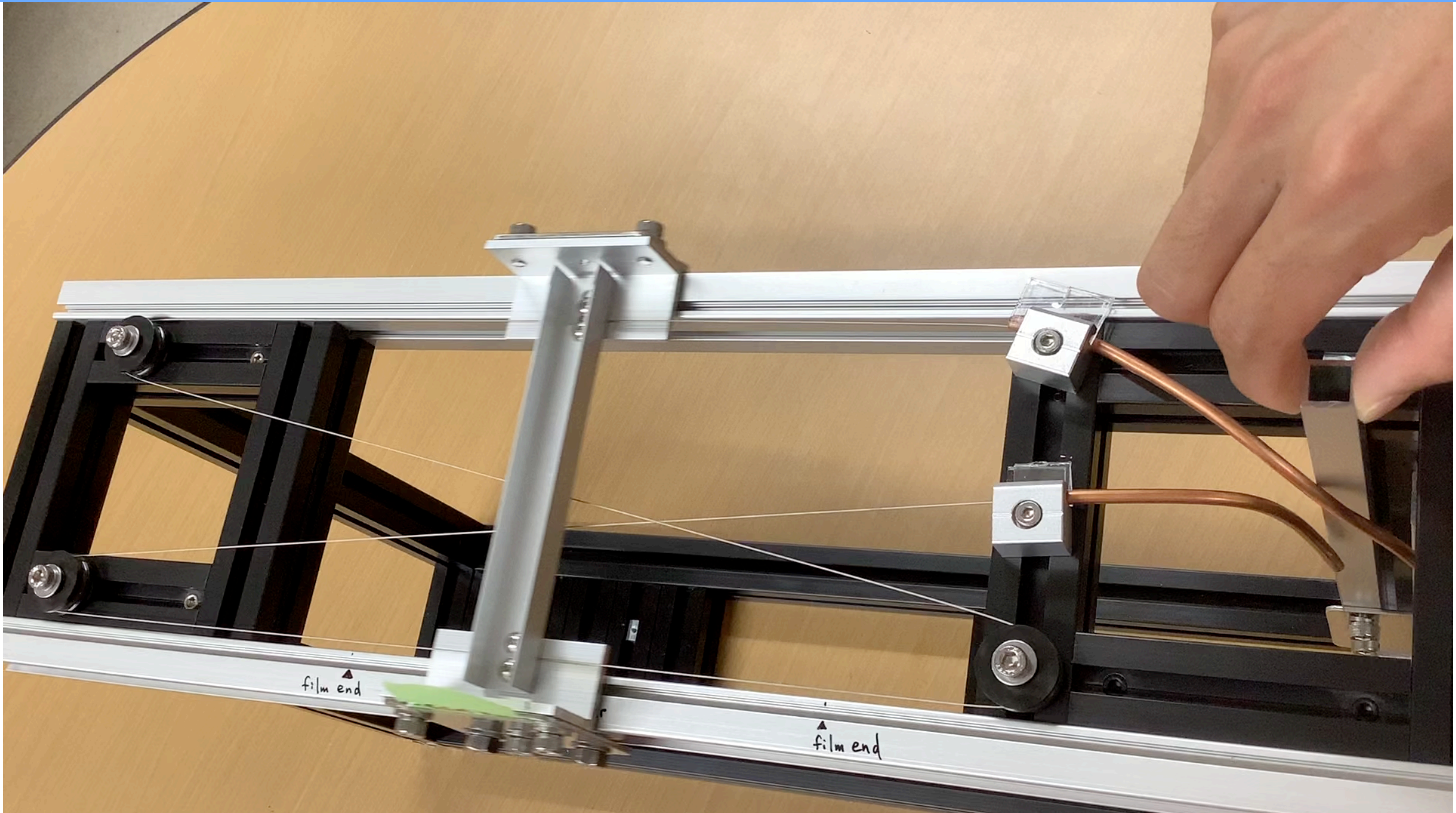
How to move

I did not want to use a spring or something with wire··· but

System of **a both-end fixed wire** and pulleys can transfer vertical movement of rod to the horizontal movement of trigger counters



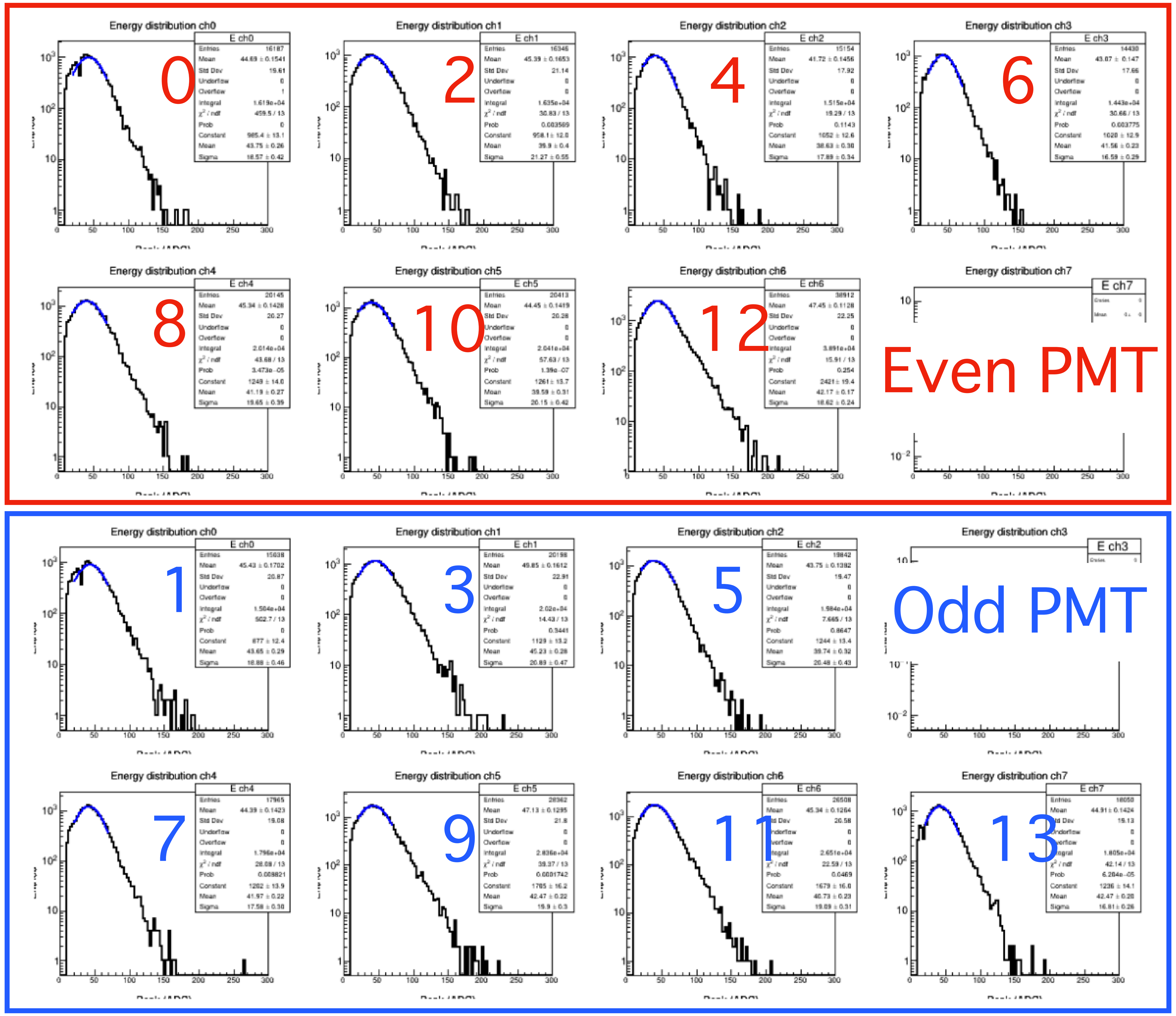


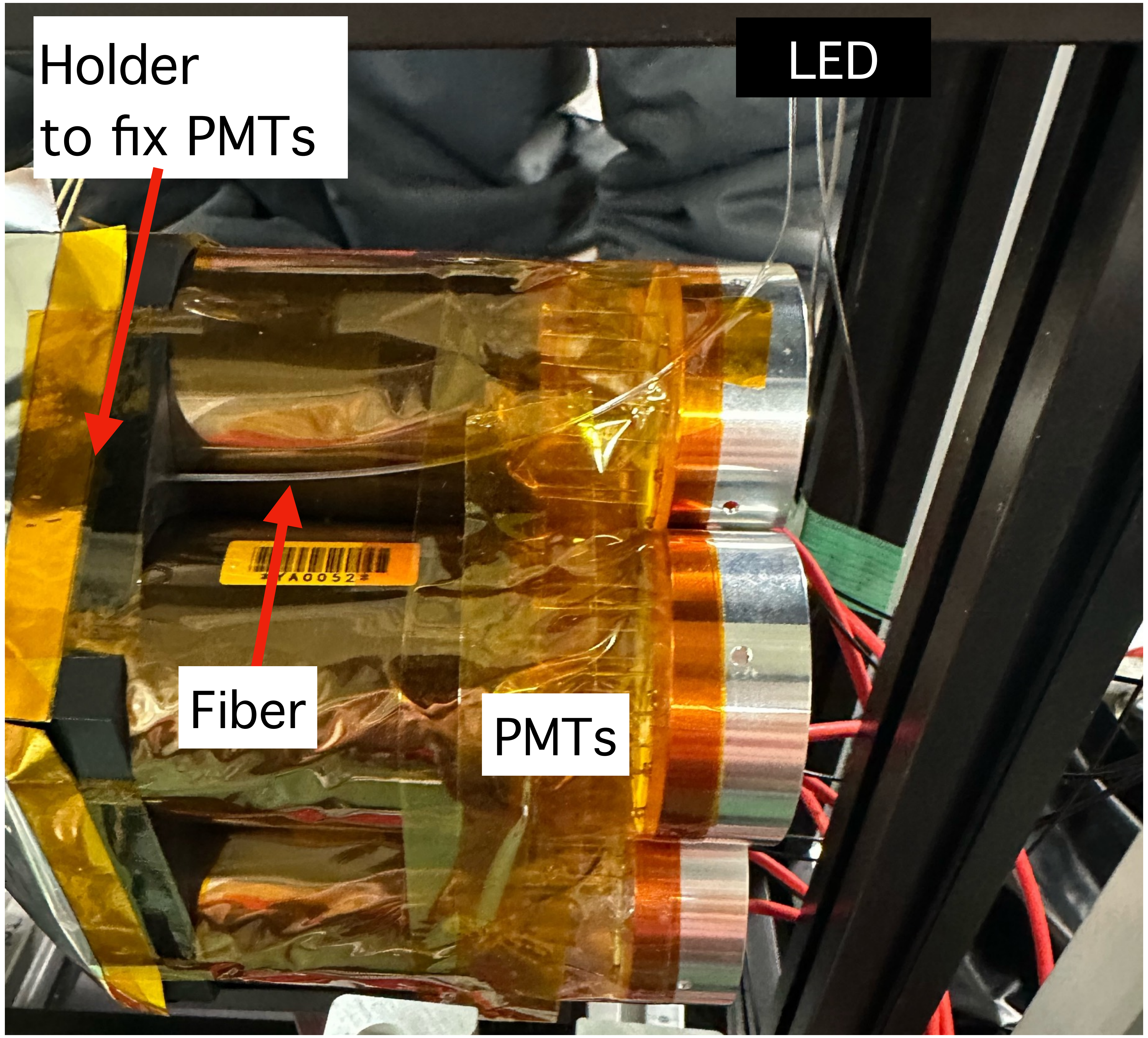

film end
film end

1 p.e. calibration

1 p.e. calibration (in case of Peak height)

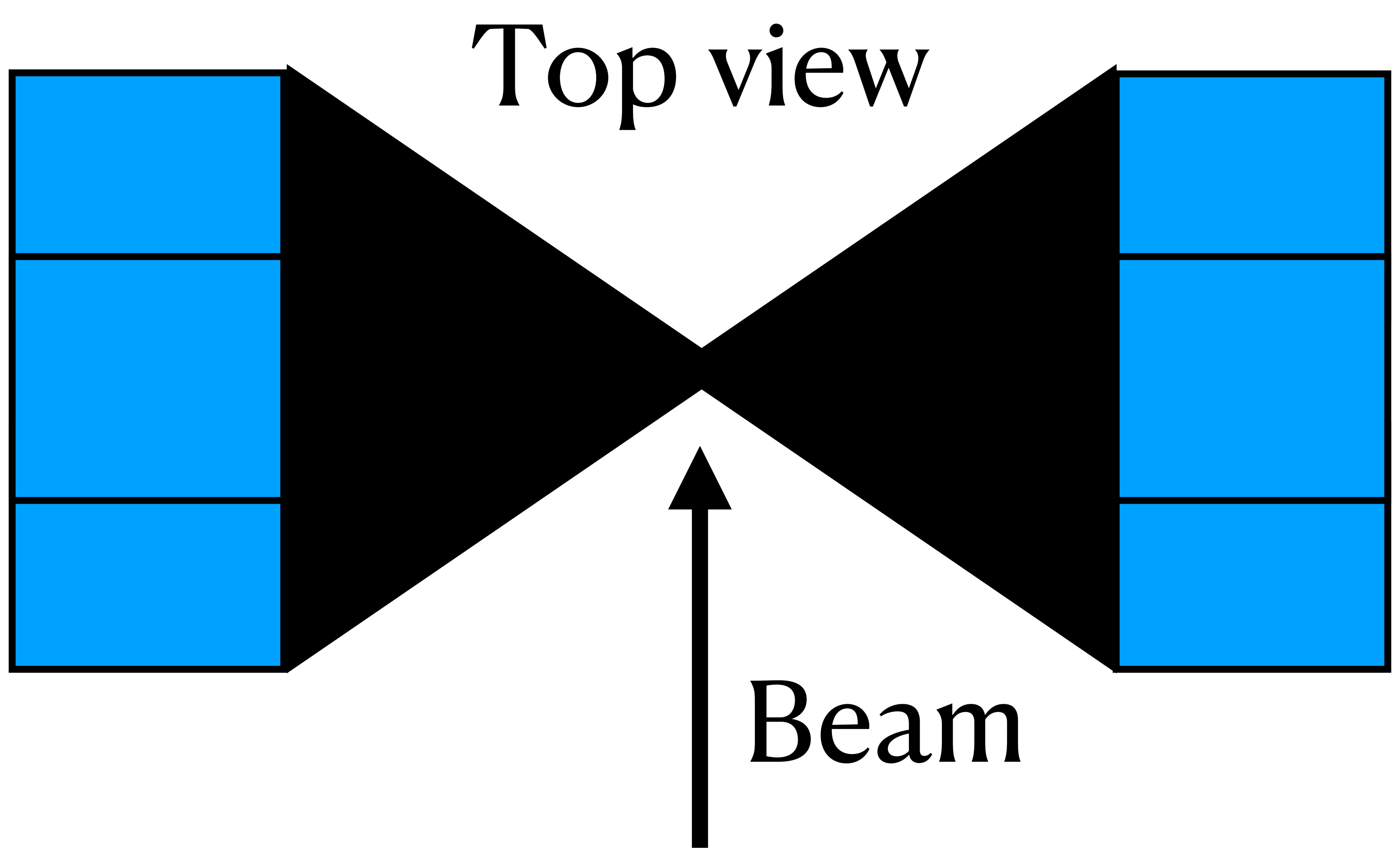
- 1 p.e. peak = 40 ADC counts within 5%

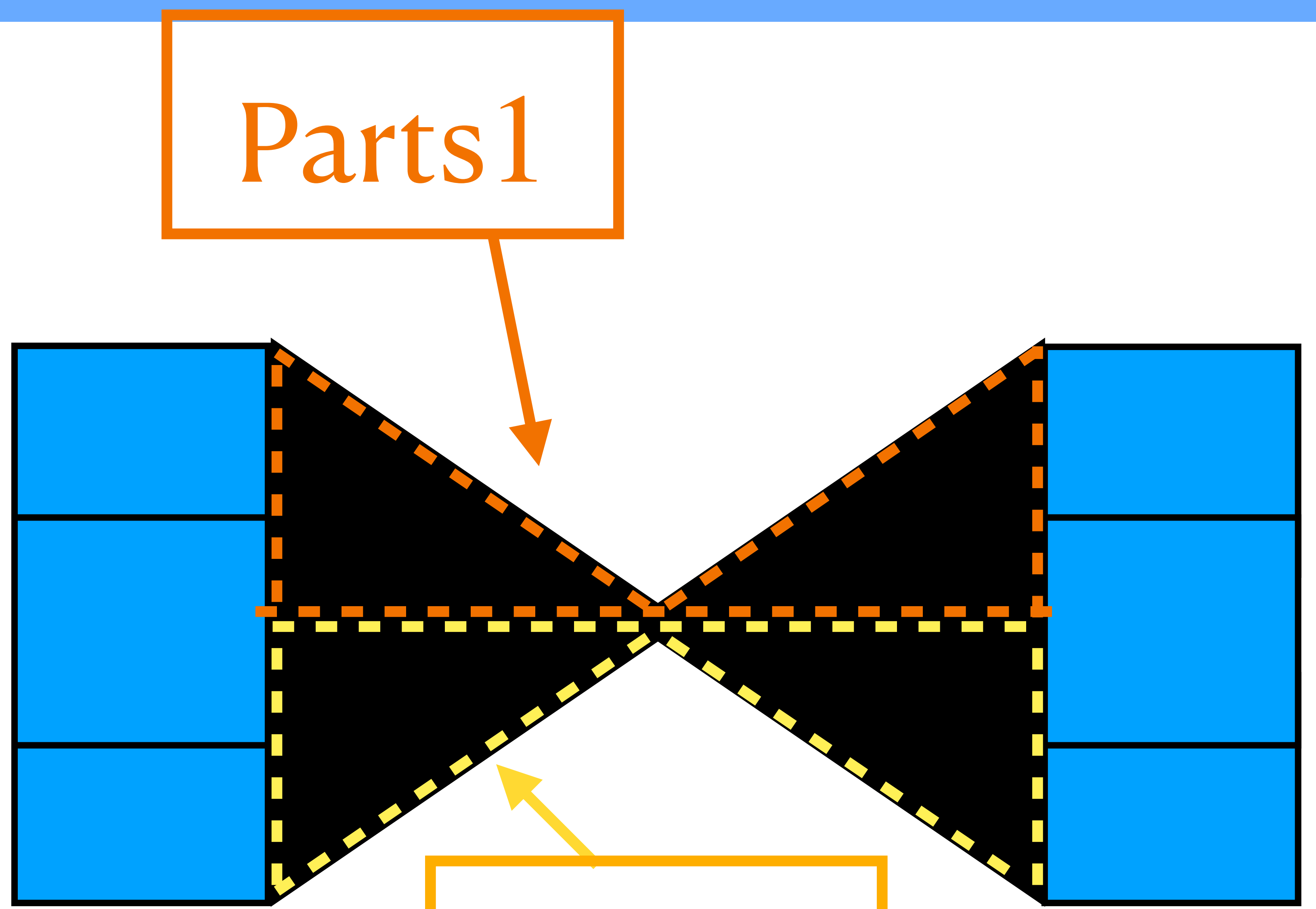


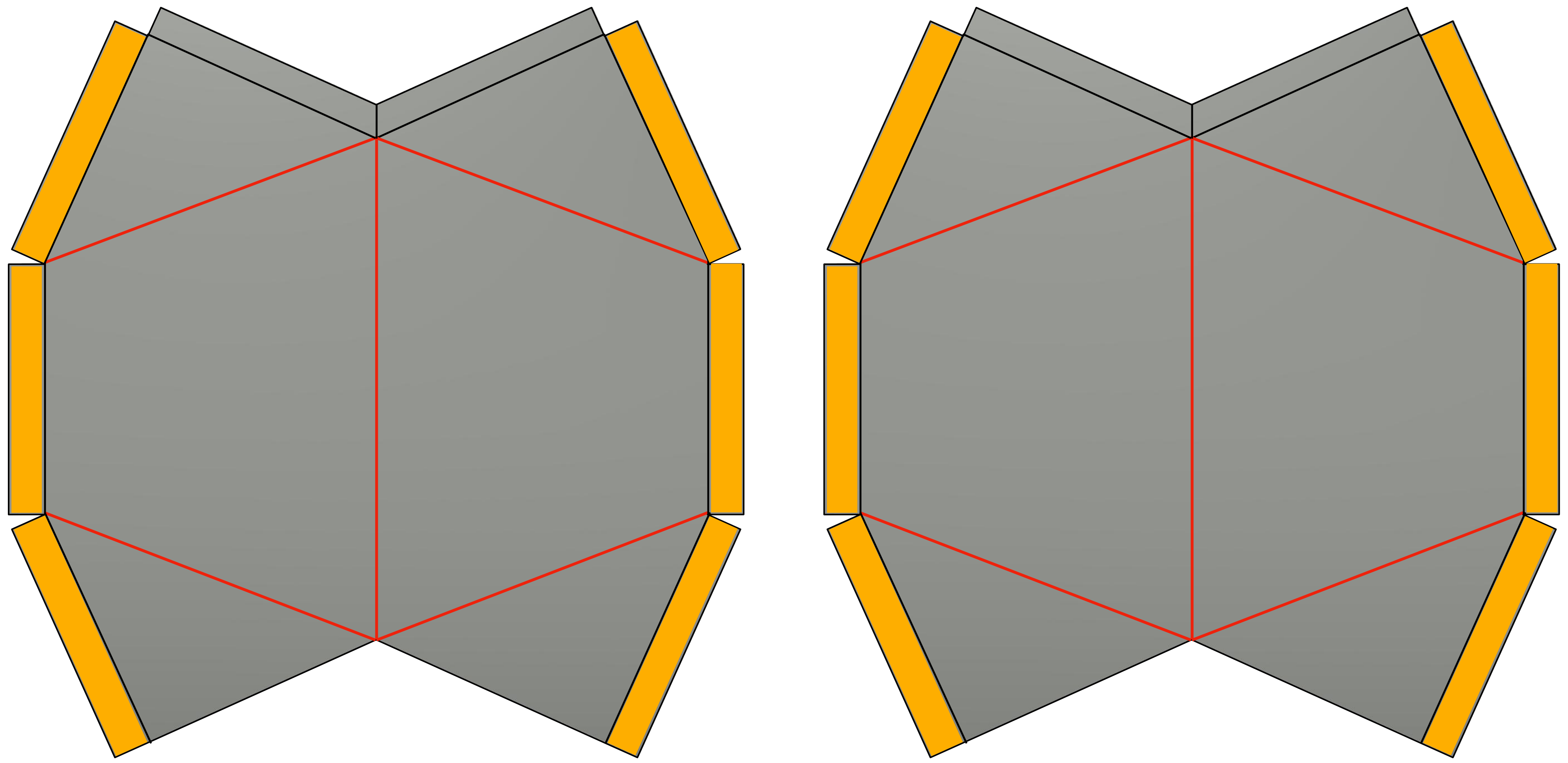


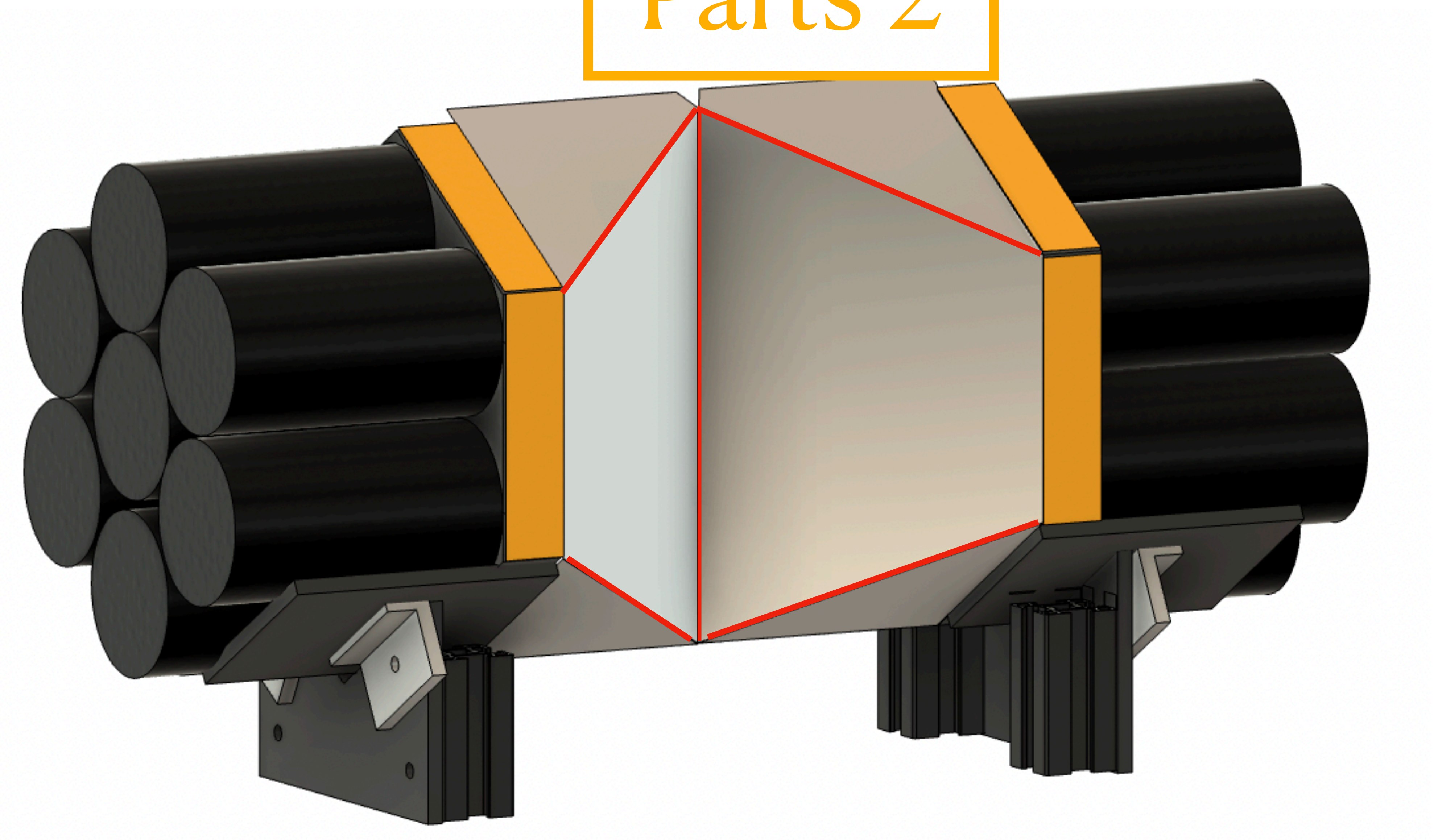
Assembly of Al mylar

Divide it into two parts









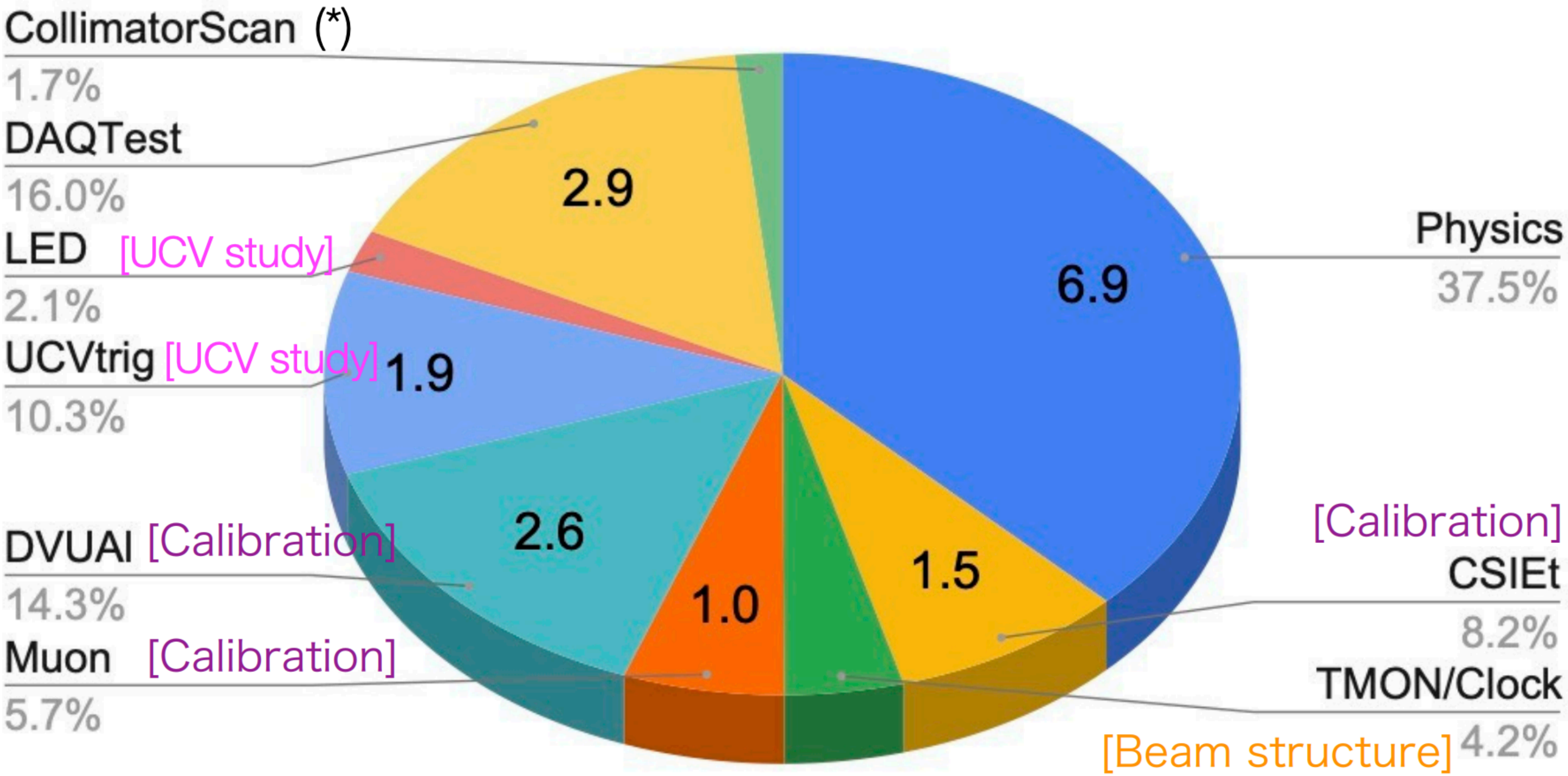
- Fold red line and fix parts of orange to holder with Kapton tape

Data taking in Summer 2023

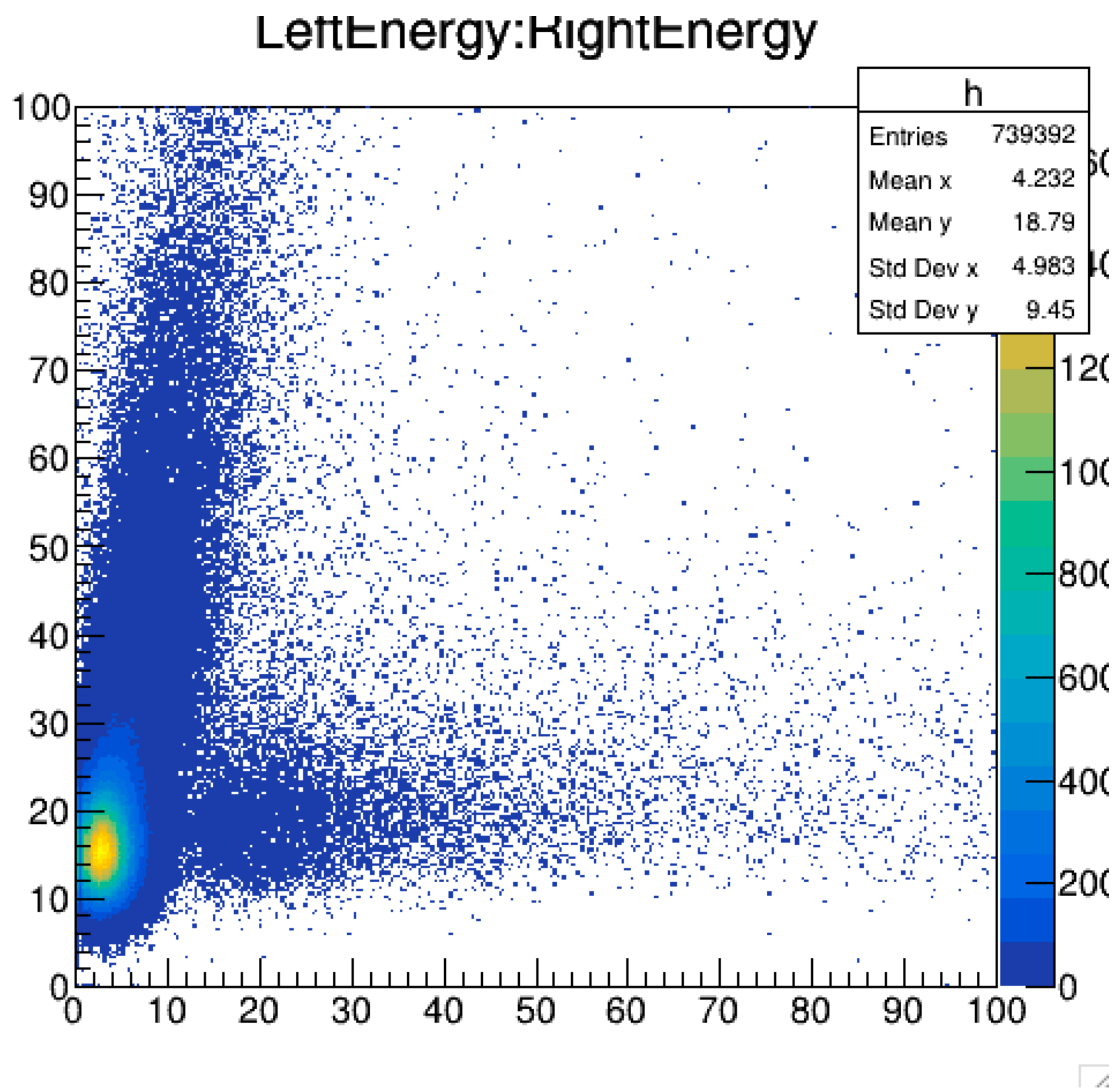
- Beam usage : 1 night @ 30 kW, ~1 day @ 50 kW
- Accumulated physics data : 1.4×10^{17} POT (0.5% of 2021 data)

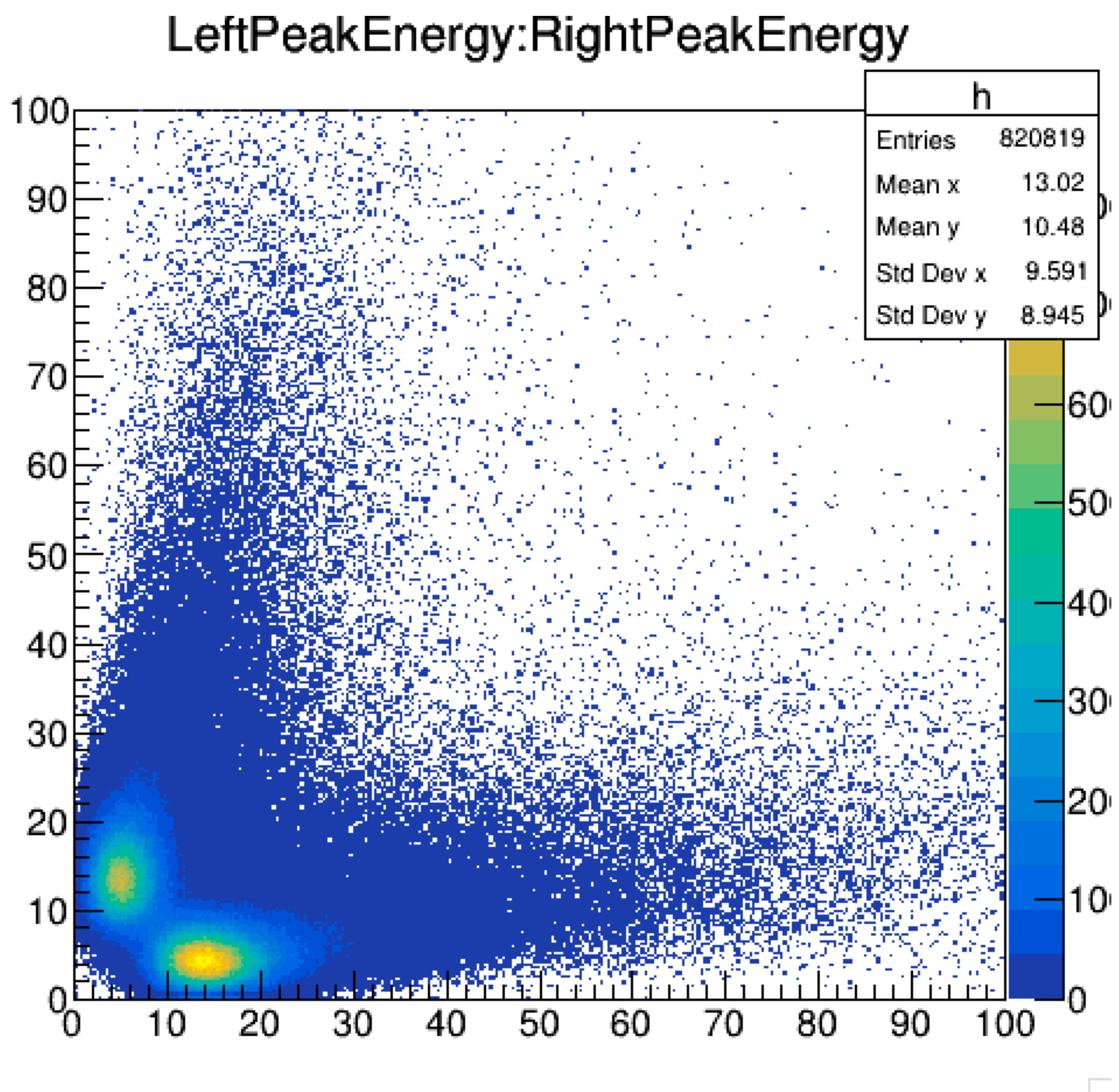
Minimum Goal of the beam time

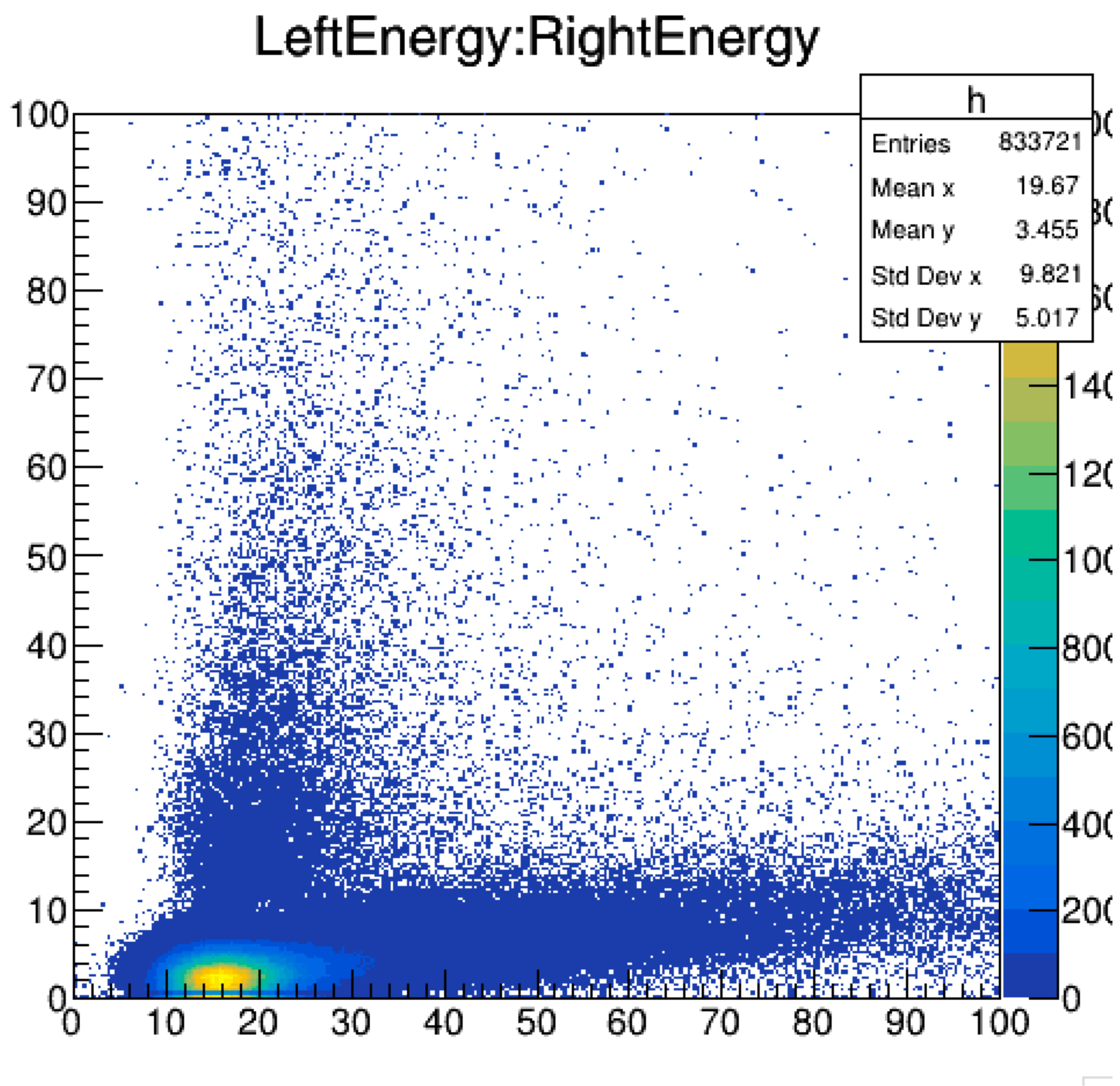
- **Evaluation of performance of filmUCV (including UCV effect)**
- Establishment of newDQ



Correlation between right and left

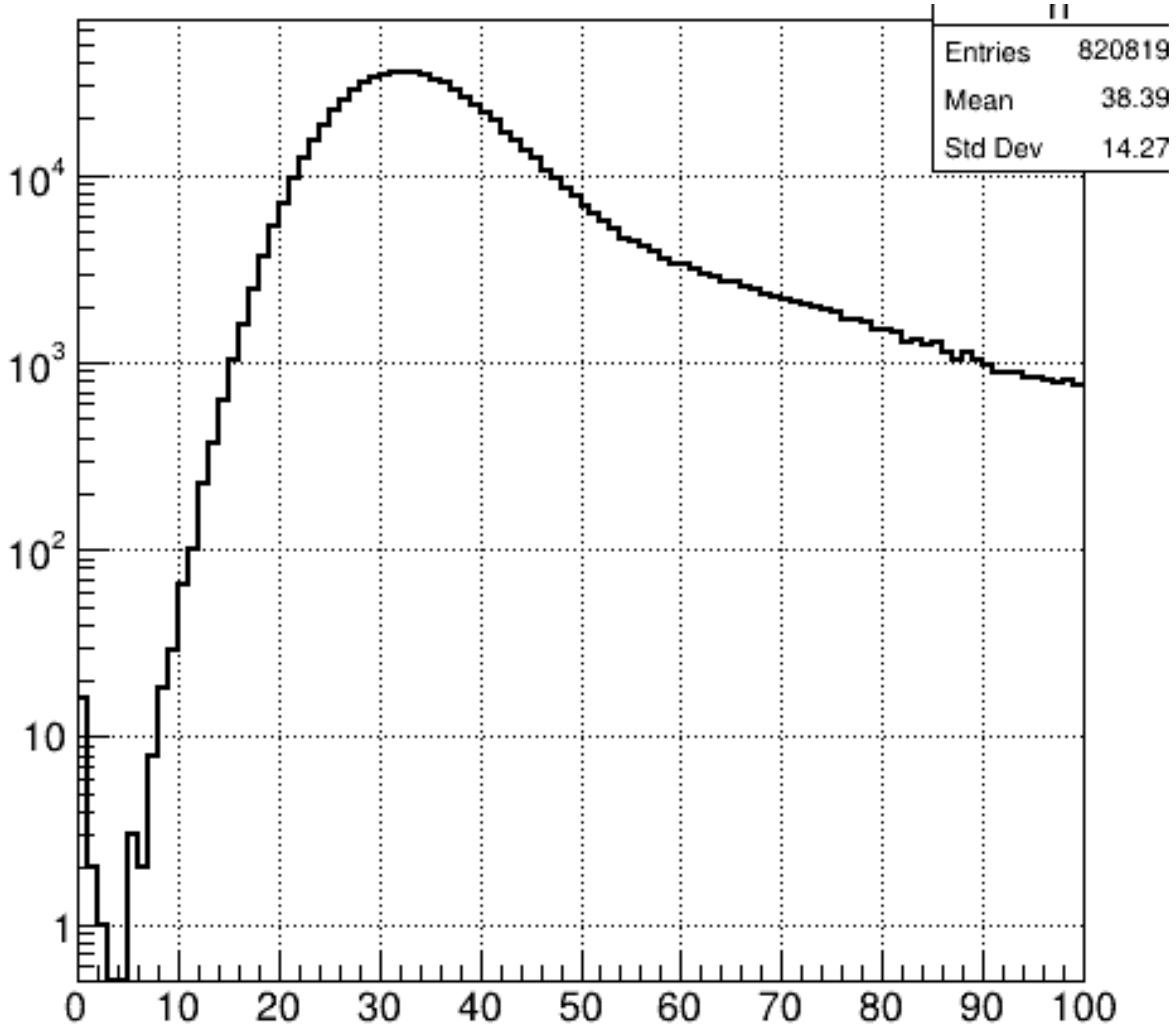






Light yield (IntegratedADC)

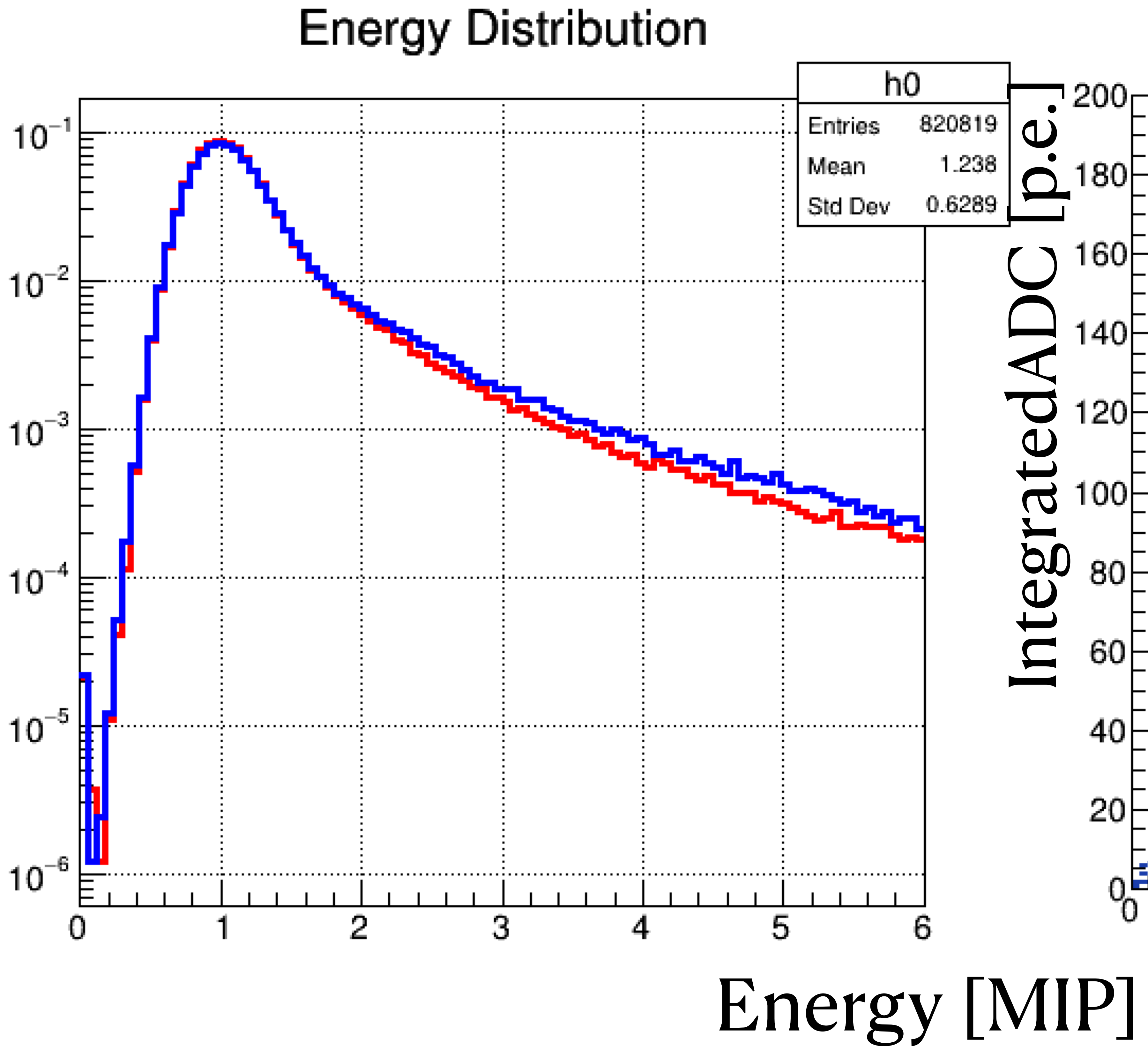
Distribution of # of photoelectron



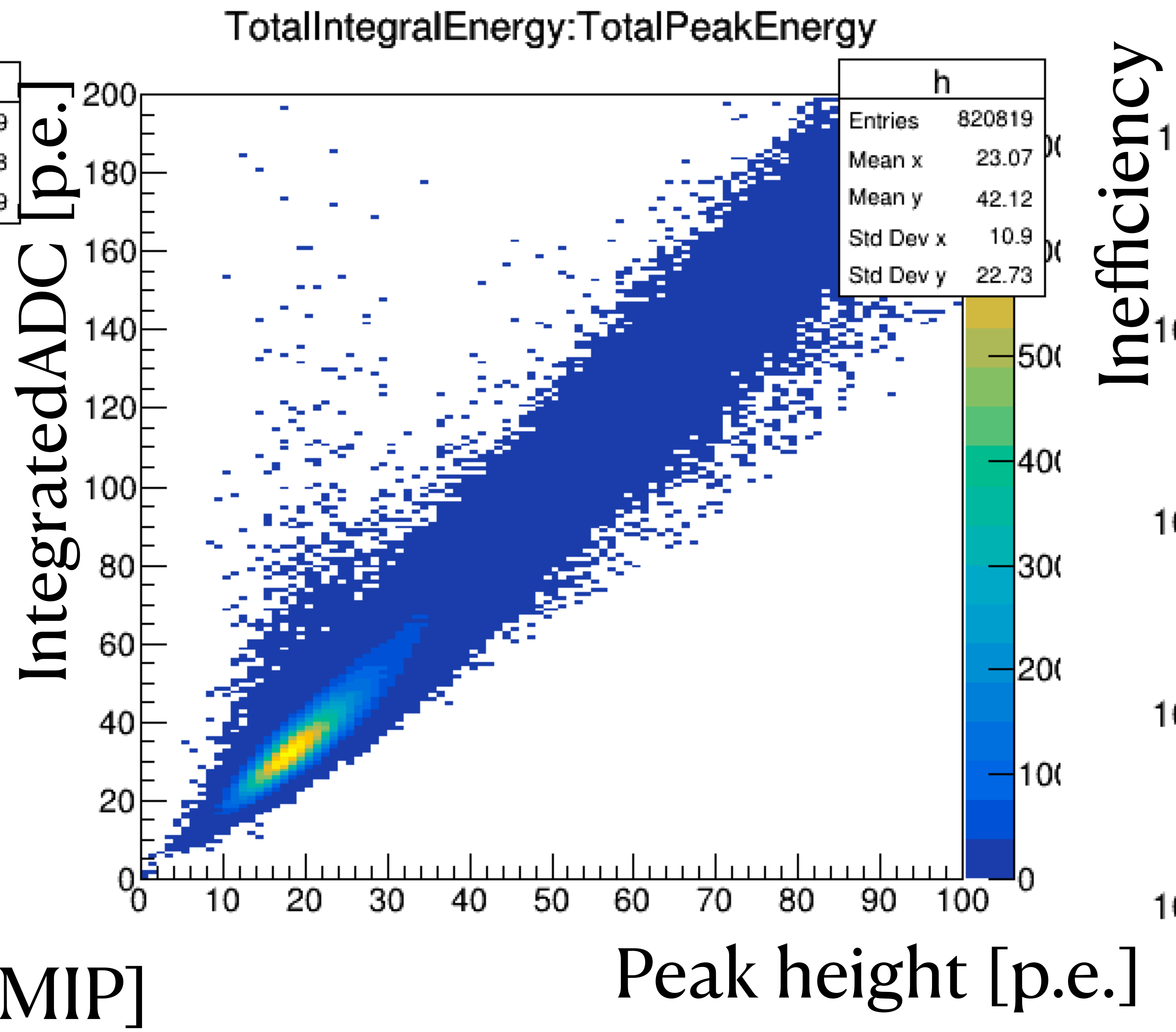
- Light yield : MIP peak = (32.48±0.03) p.e./MIP (IntegratedADC)
- Next page : inefficiency, comparison between peak height and IntegratedADC

Comparison

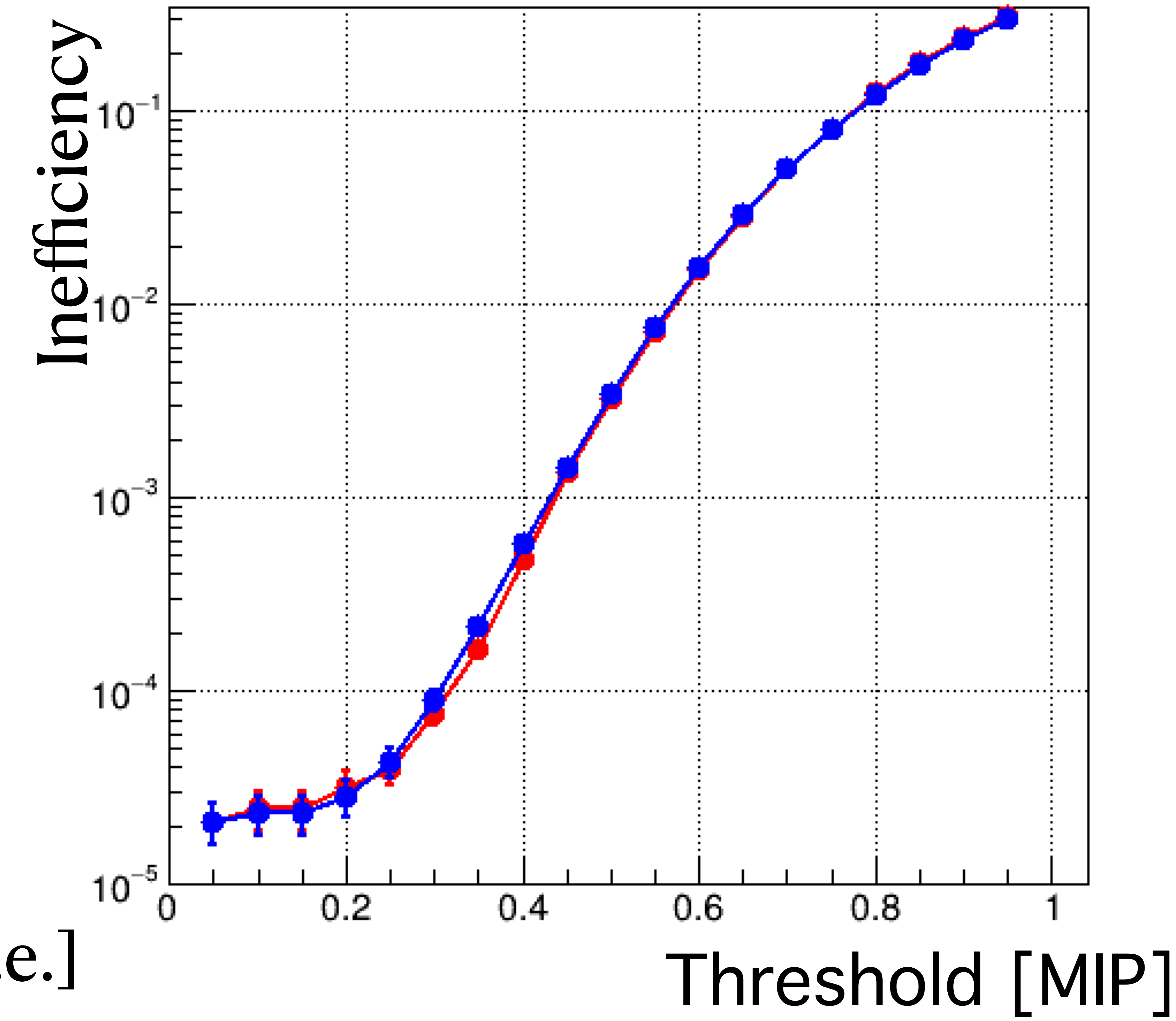
Energy



Correlation



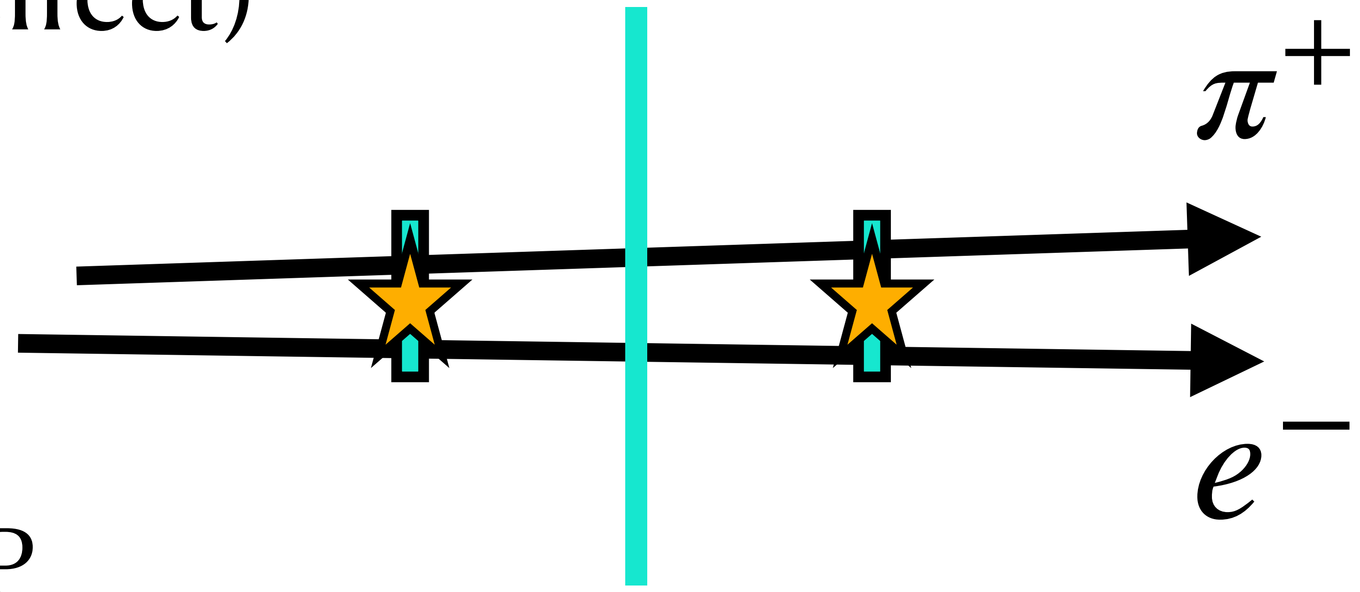
Inefficiency



- No large difference between IntegratedADC and peak height in terms of inefficiency

Systematic uncertainty of effect of 2 MIP effect

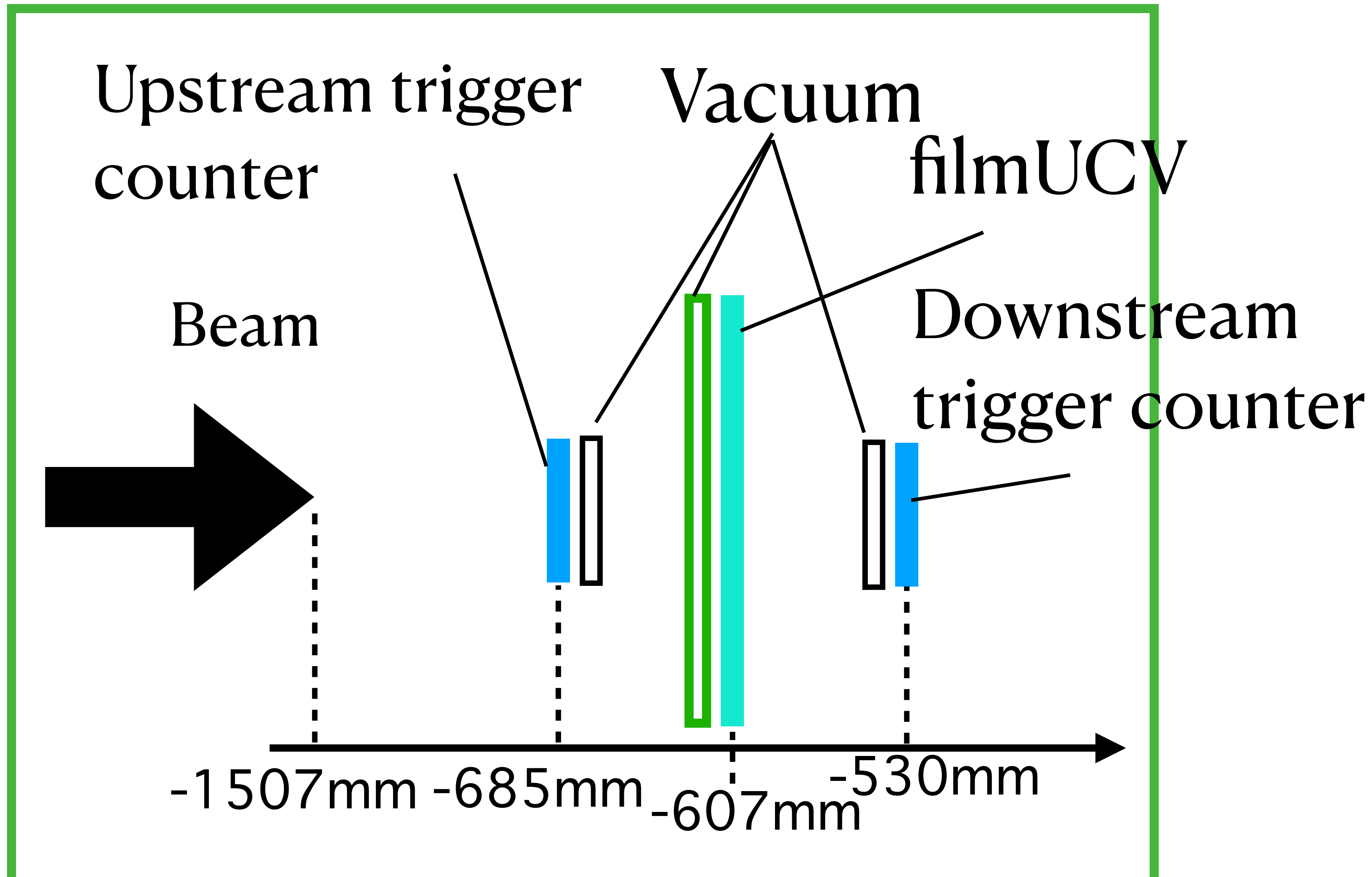
- Counted # of charged particles passing through filmUCV at vacuum layer at first
  $\Rightarrow$ The events of ≥ 2 charged particles : 8% (Don't consider quenching effect)
  But there is no clear MIP contribution in Data -> **a few % at most**
- Decided uncertainty as the change when 2MIP contribution is subtracted

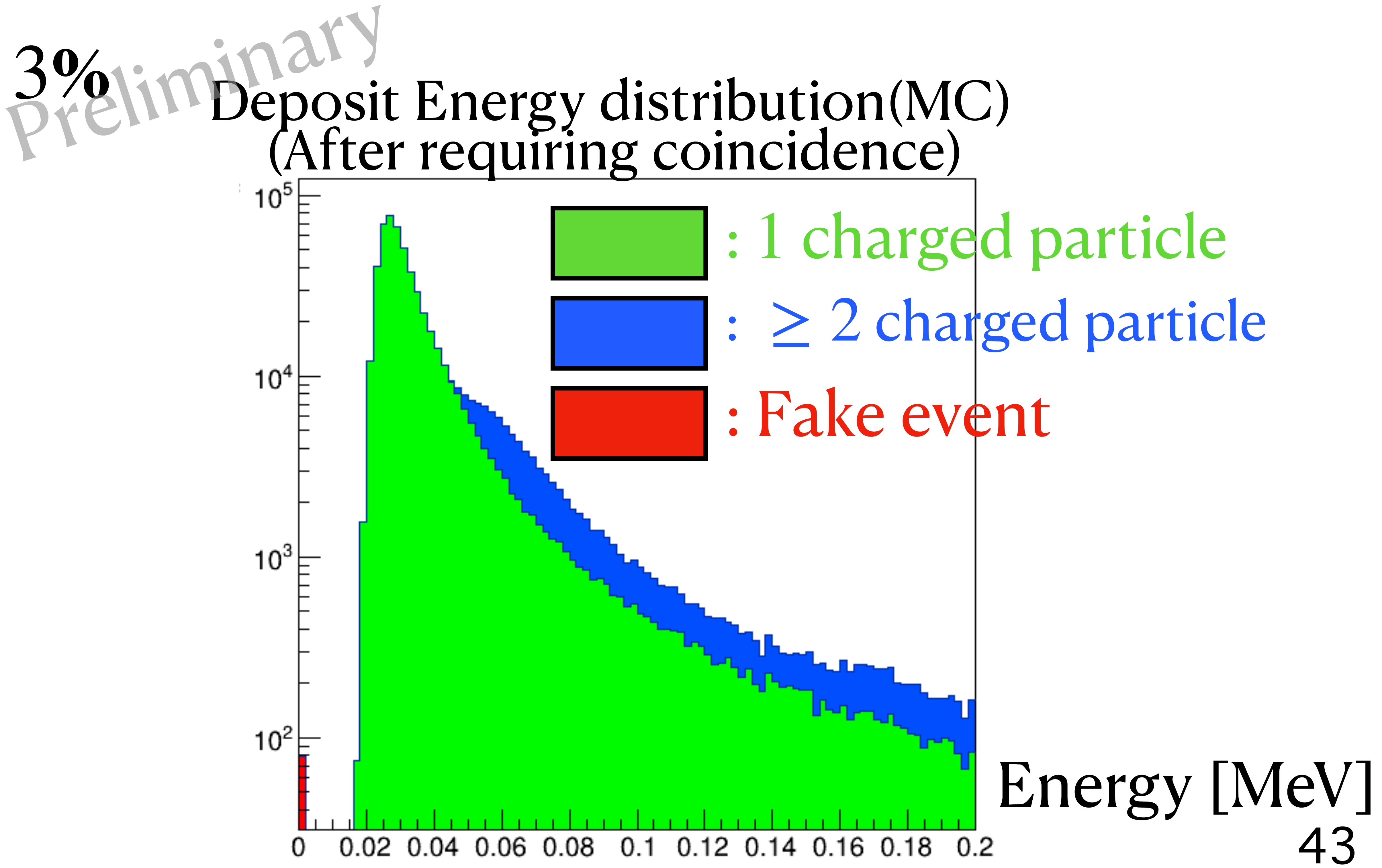


$$0.97\eta_{\text{true}} + 0.03\eta_{\text{true}}^2 = \eta_{\text{Measure}}$$

η_{true} : True inefficiency against 1 MIP
η_{Measure} : Measured inefficiency

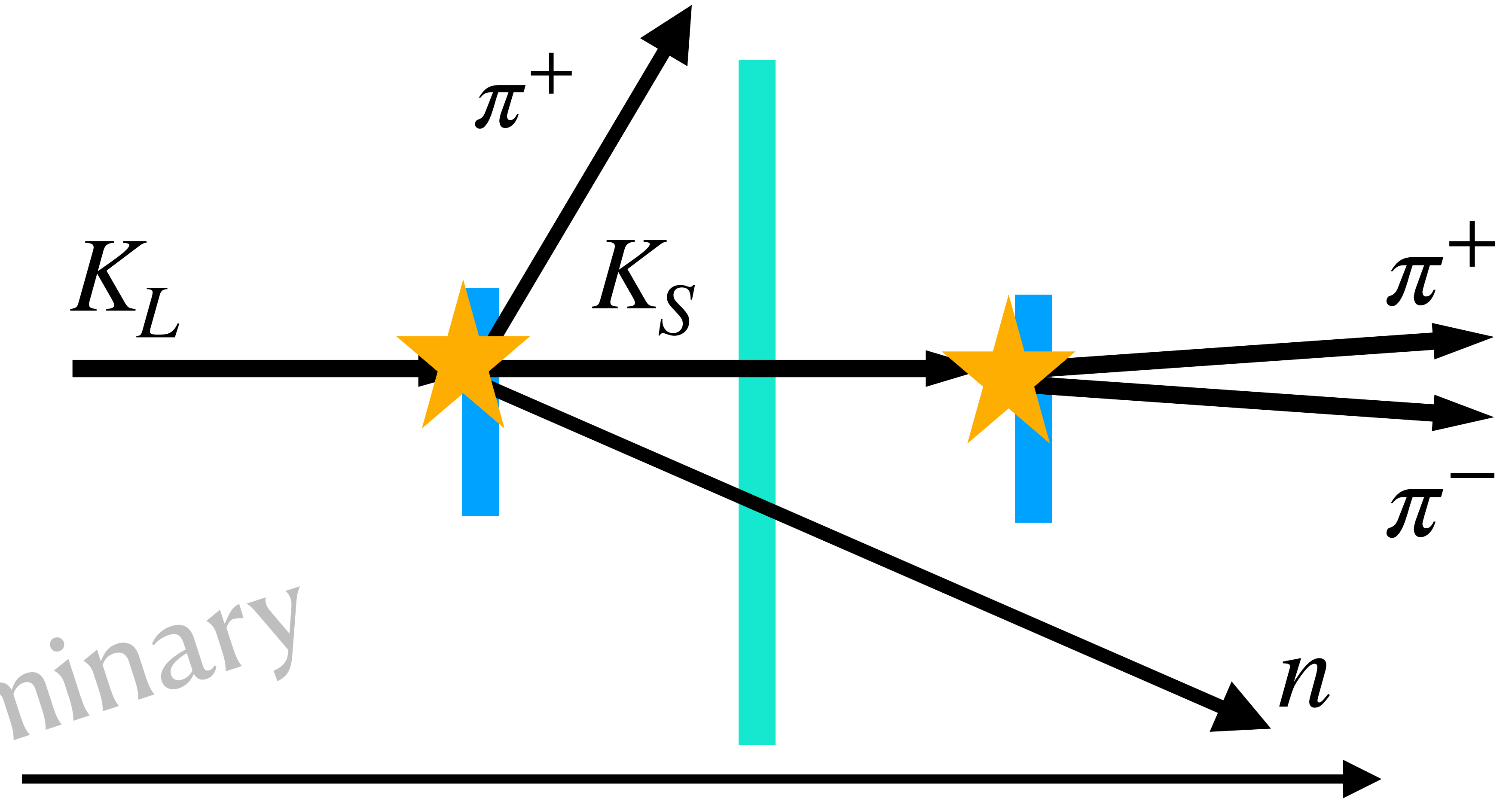
$\Rightarrow$ **Uncertainty of inefficiency (at 0.4 MIP) : 3%**





Effect of underestimation : Fake inefficiency

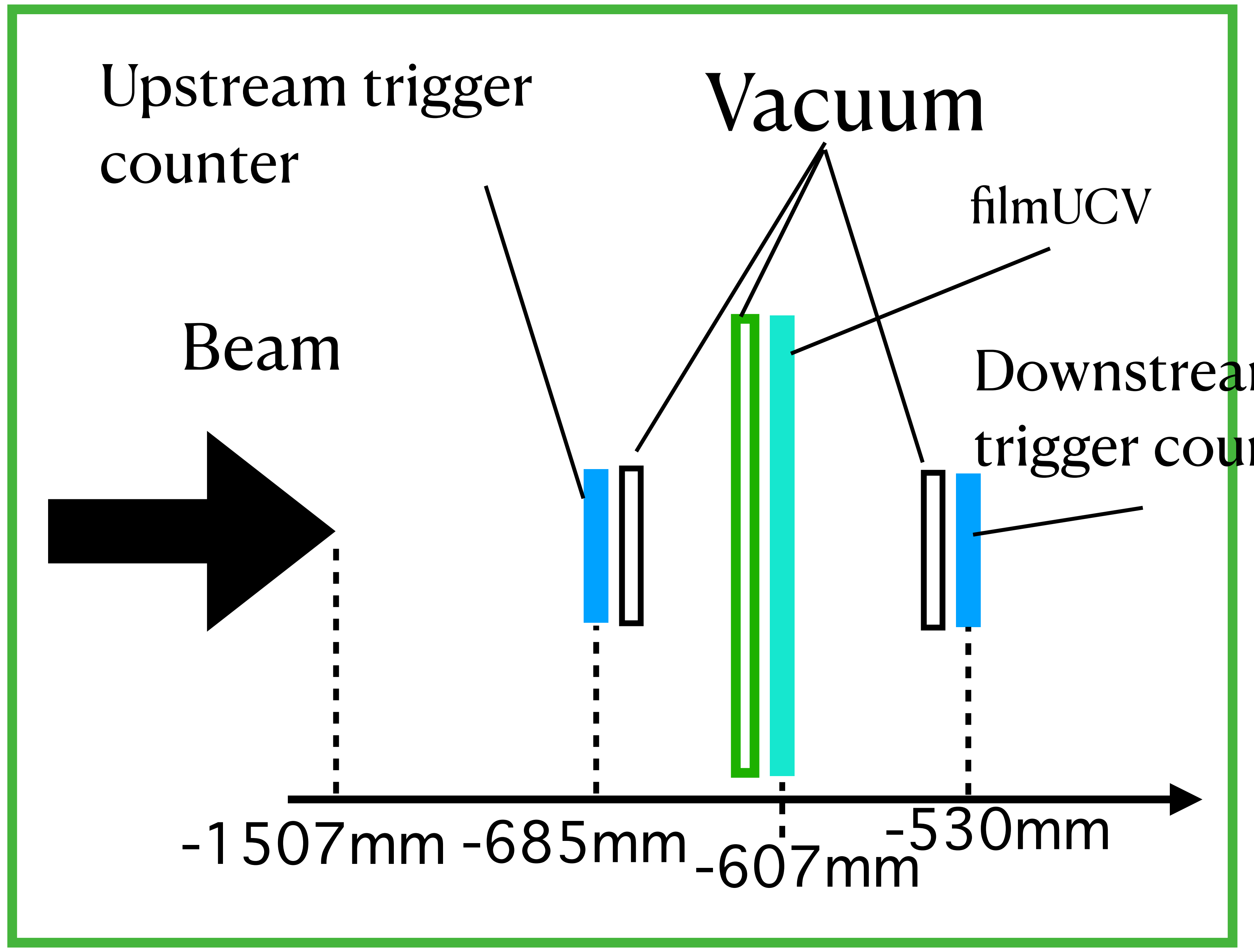
- Fake event : Events which neutral particle pass through filmUCV although charged particle pass through both trigger counters



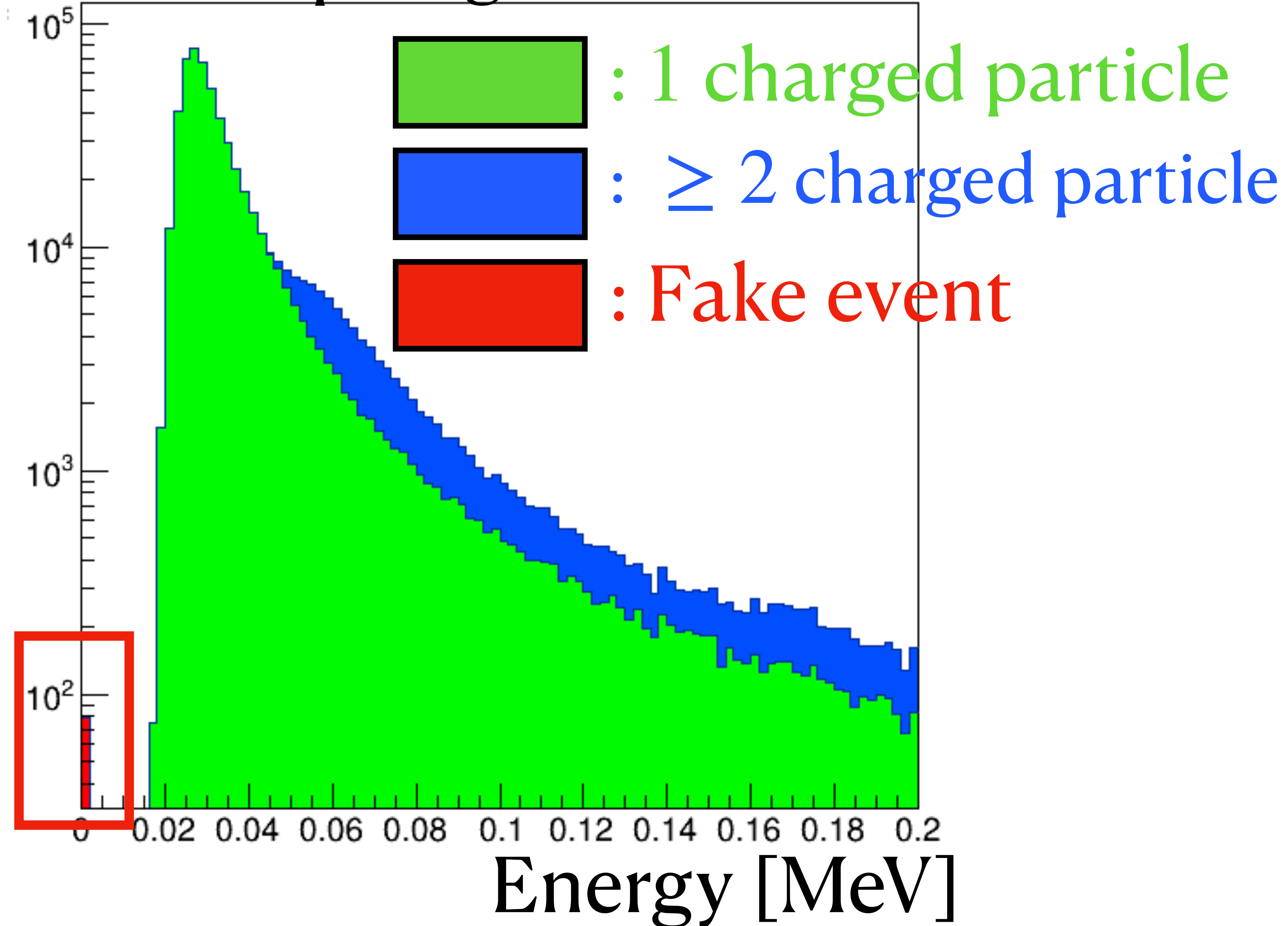
$\Rightarrow$ Fake event : 0.01 %
(Don't consider quenching effect)

$\Rightarrow$ **Uncertainty of inefficiency at 0.4 MIP : -23 %**

Preliminary



Deposit Energy distribution(MC)
(After requiring coincidence)

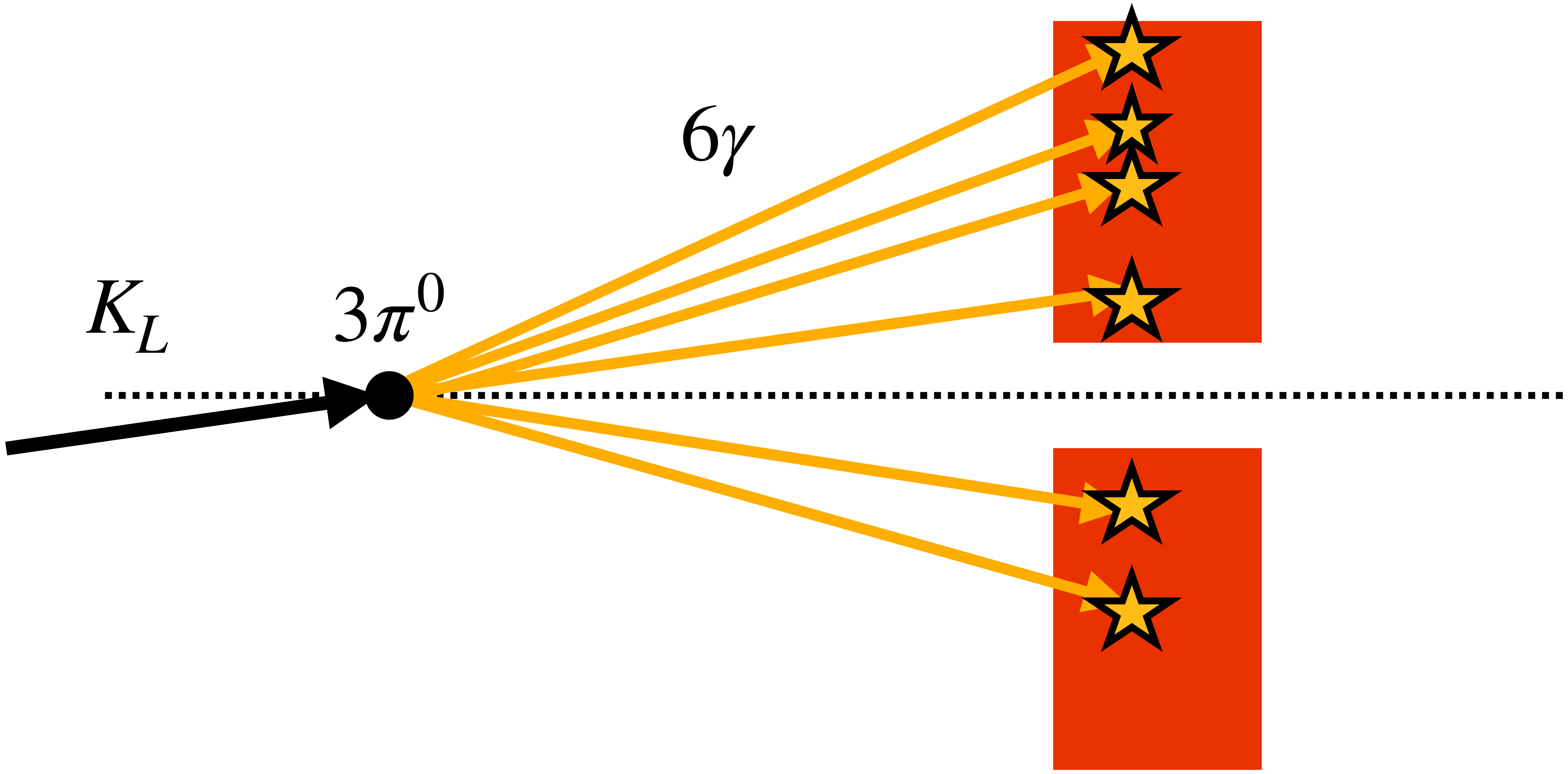


Estimation of halo K_L flux (1)

Estimate halo K_L flux using $K_L \rightarrow 3\pi^0(6\gamma)$ decay

- High Branching Fraction (20 %)
- Require 6 clusters in Calorimeter -> small background

➡ Best mode for halo K_L flux measurement



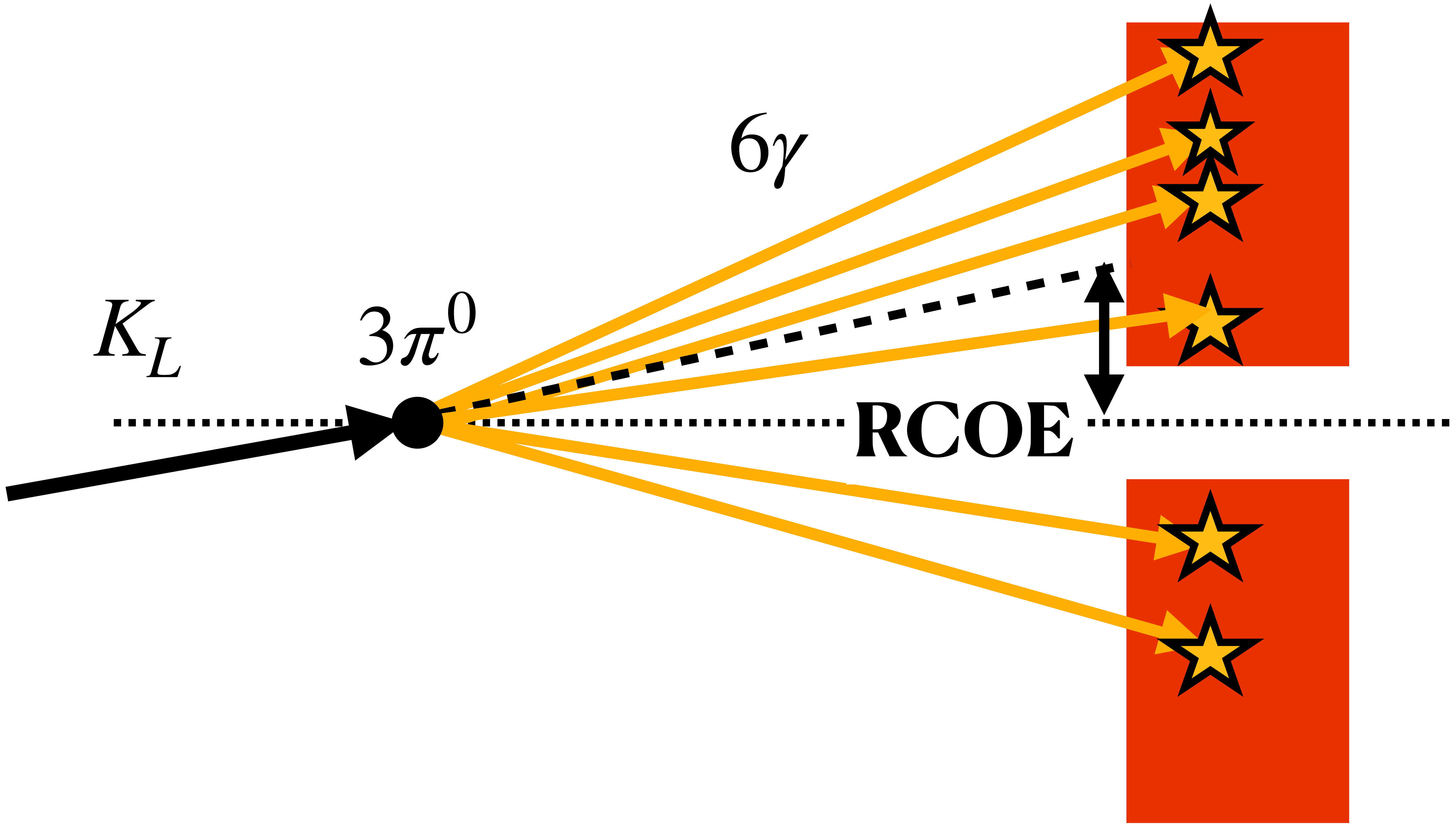
Estimation of halo K_L flux (2)

Definition of halo K_L events

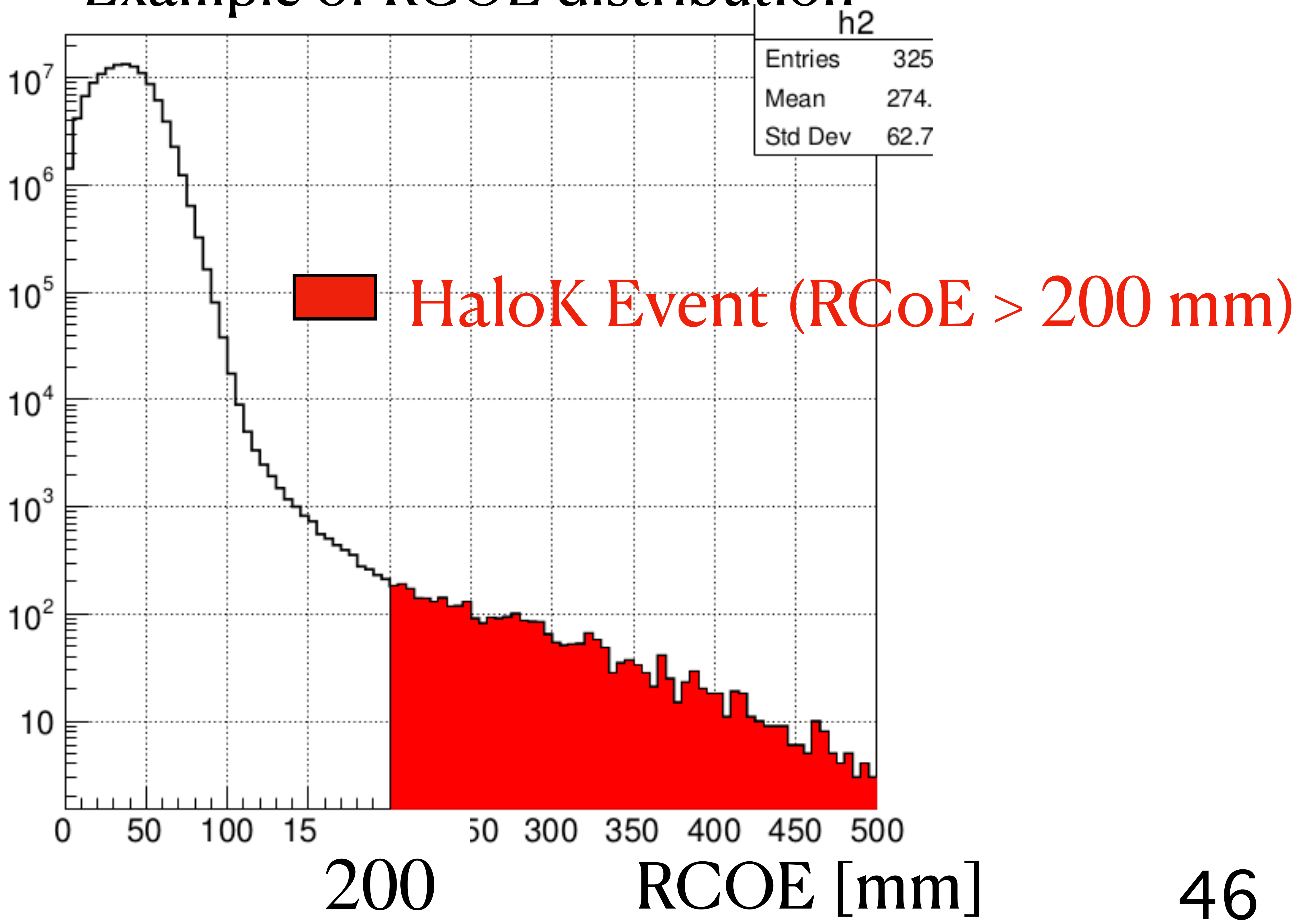
- Use the **R**adius of **C**enter **O**f **E**nergy (RCOE)

$$\mathrm{RCOE} = \sqrt{X_{\mathrm{COE}}^2 + Y_{\mathrm{COE}}^2} \qquad X_{\mathrm{COE}} = \frac{\sum x_i E_i}{\sum E_i} \qquad Y_{\mathrm{COE}} = \frac{\sum y_i E_i}{\sum E_i}$$

Halo K_L Events = Events with (RCOE > 200 mm)

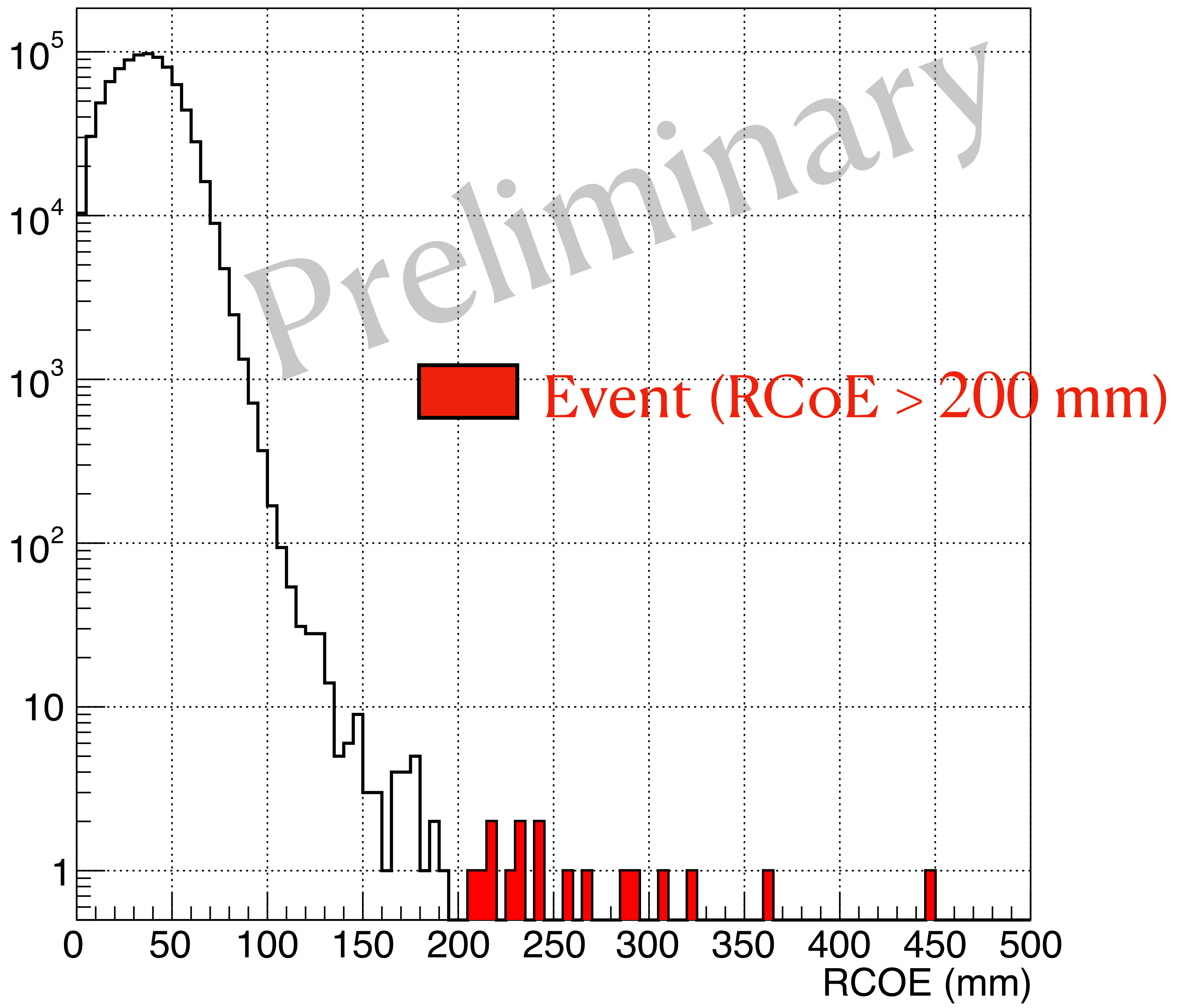


Example of RCOE distribution



Current result of comparison of Halo K_L flux

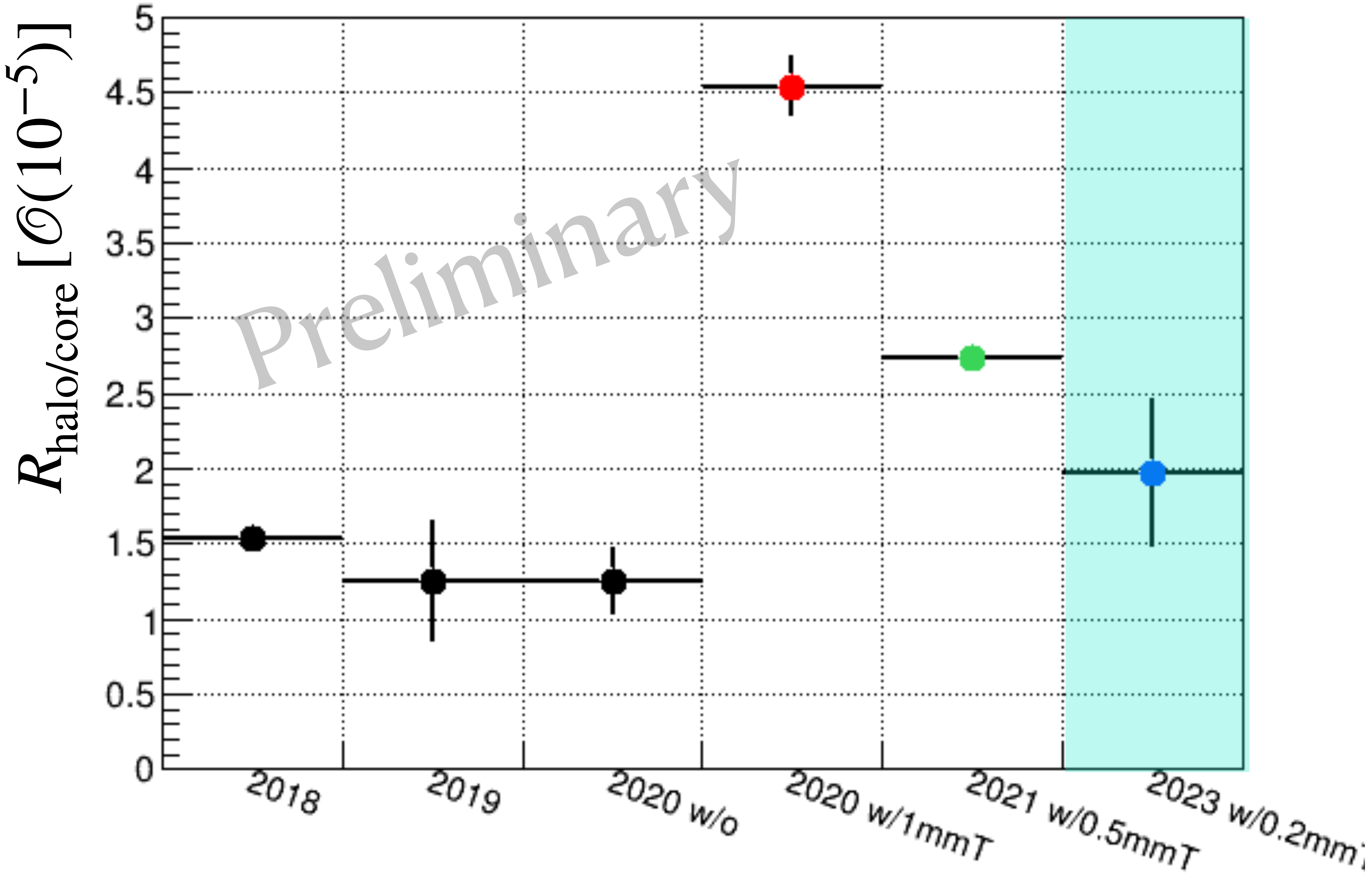
RCOE distribution in RUN90



$N_{\text{core}}: 8.6 \times 10^5 \quad N_{\text{halo}}: 17$

$\Rightarrow R^{\text{RUN90}}_{\text{halo/core}} = (2.0 \pm 0.5) \times 10^{-5}$

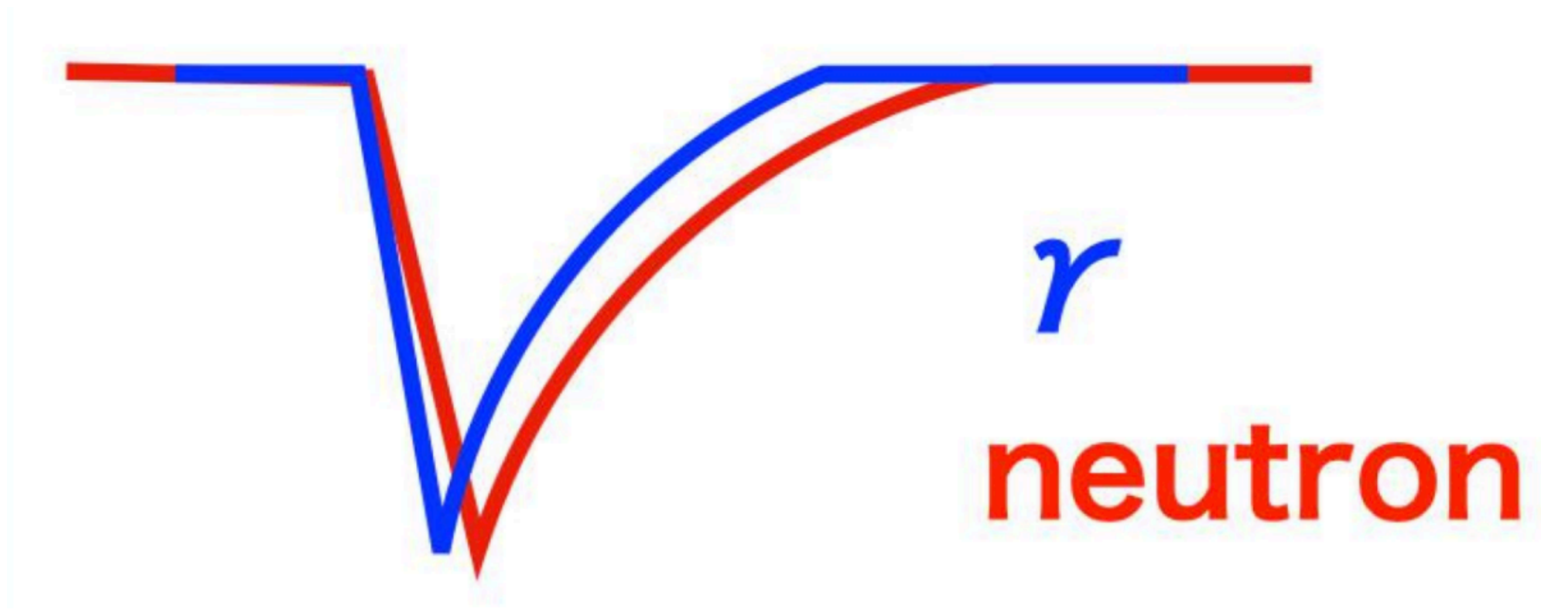
Comparison of $R_{\text{halo/core}}$

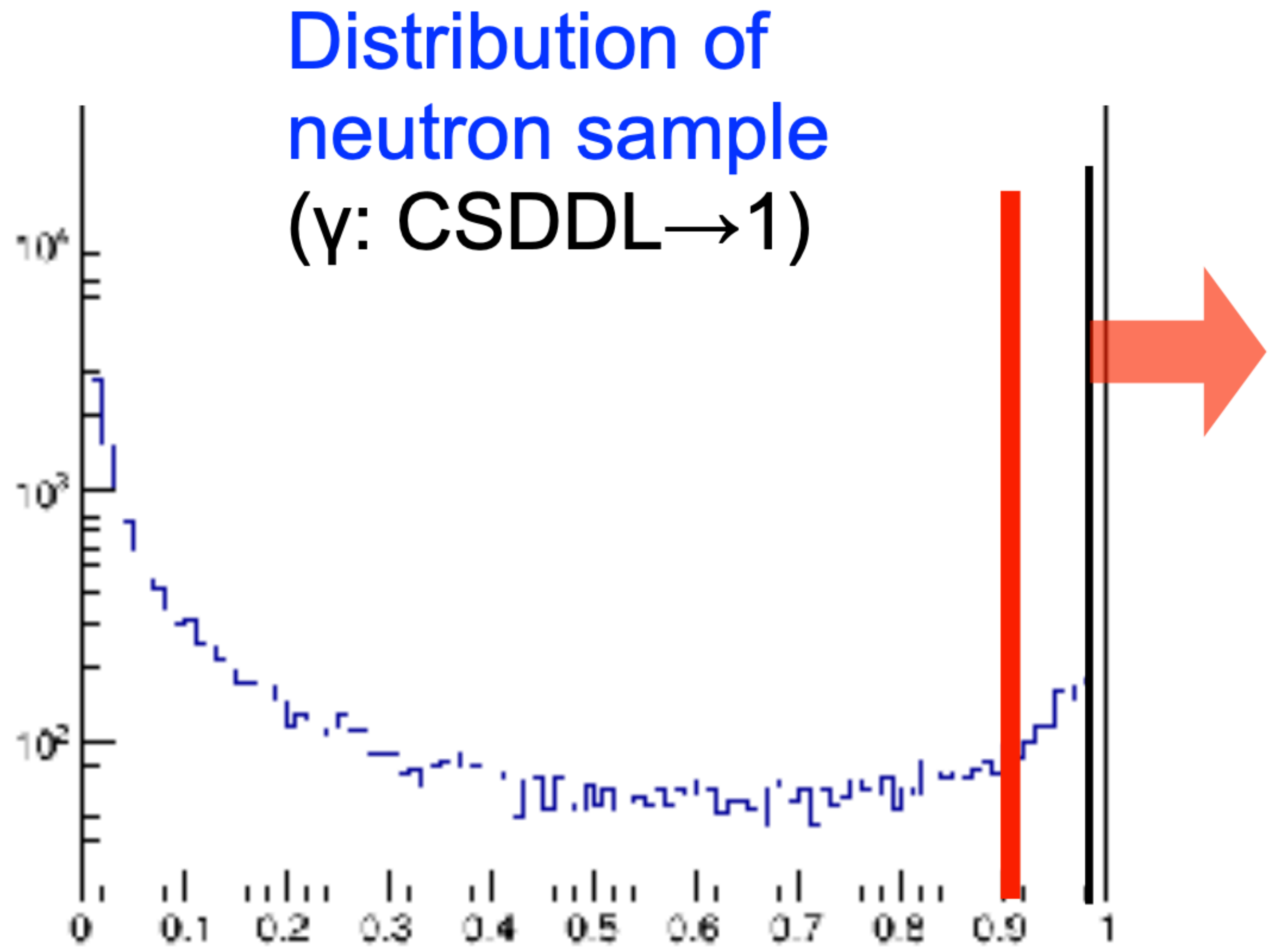


$$\frac{\Delta F^{\text{RUN90}}}{\Delta F^{\text{RUN87}}} = 0.45 \pm 0.38 \quad \left(\text{Expectation}: \frac{0.224\,\text{mmT(Sci. + mylar)}}{0.55\,\text{mmT}(25^\circ\,\text{tilted})} = 0.41\right)$$

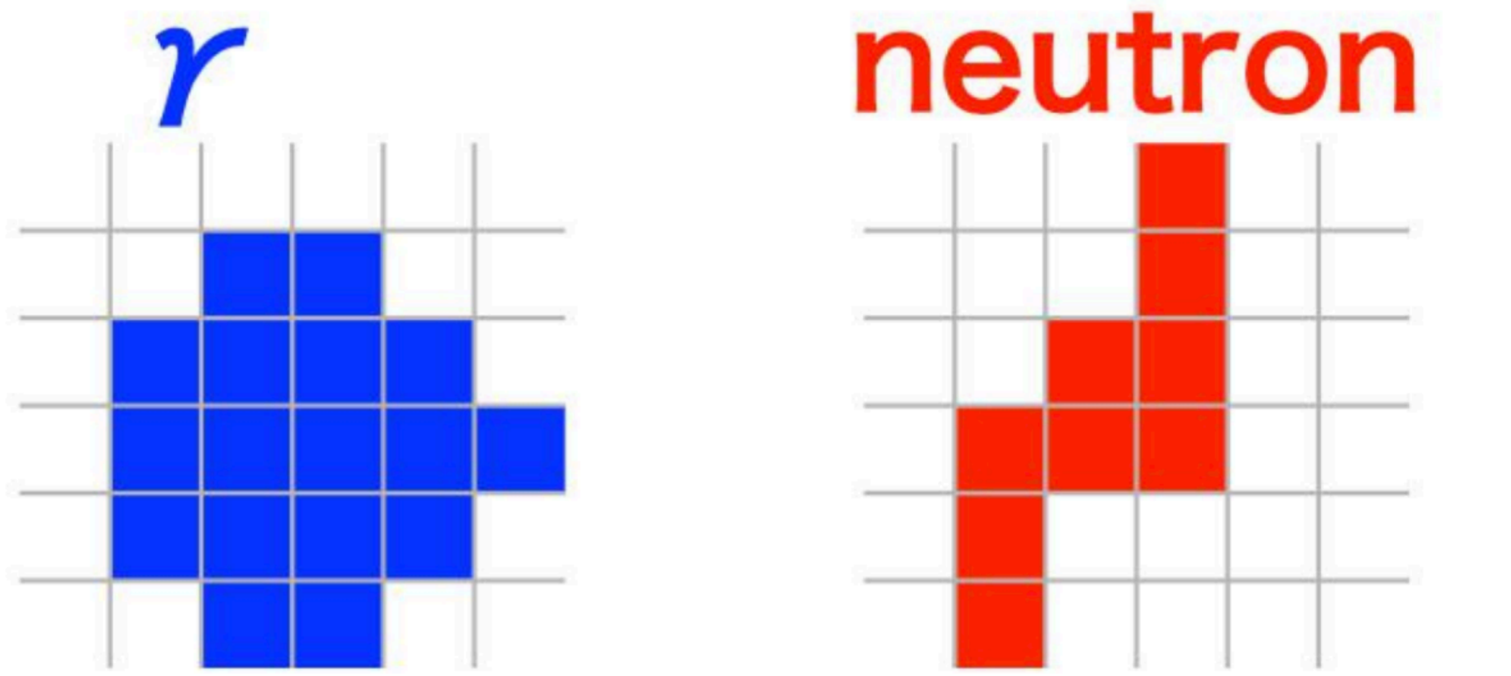
Cut for neutron background

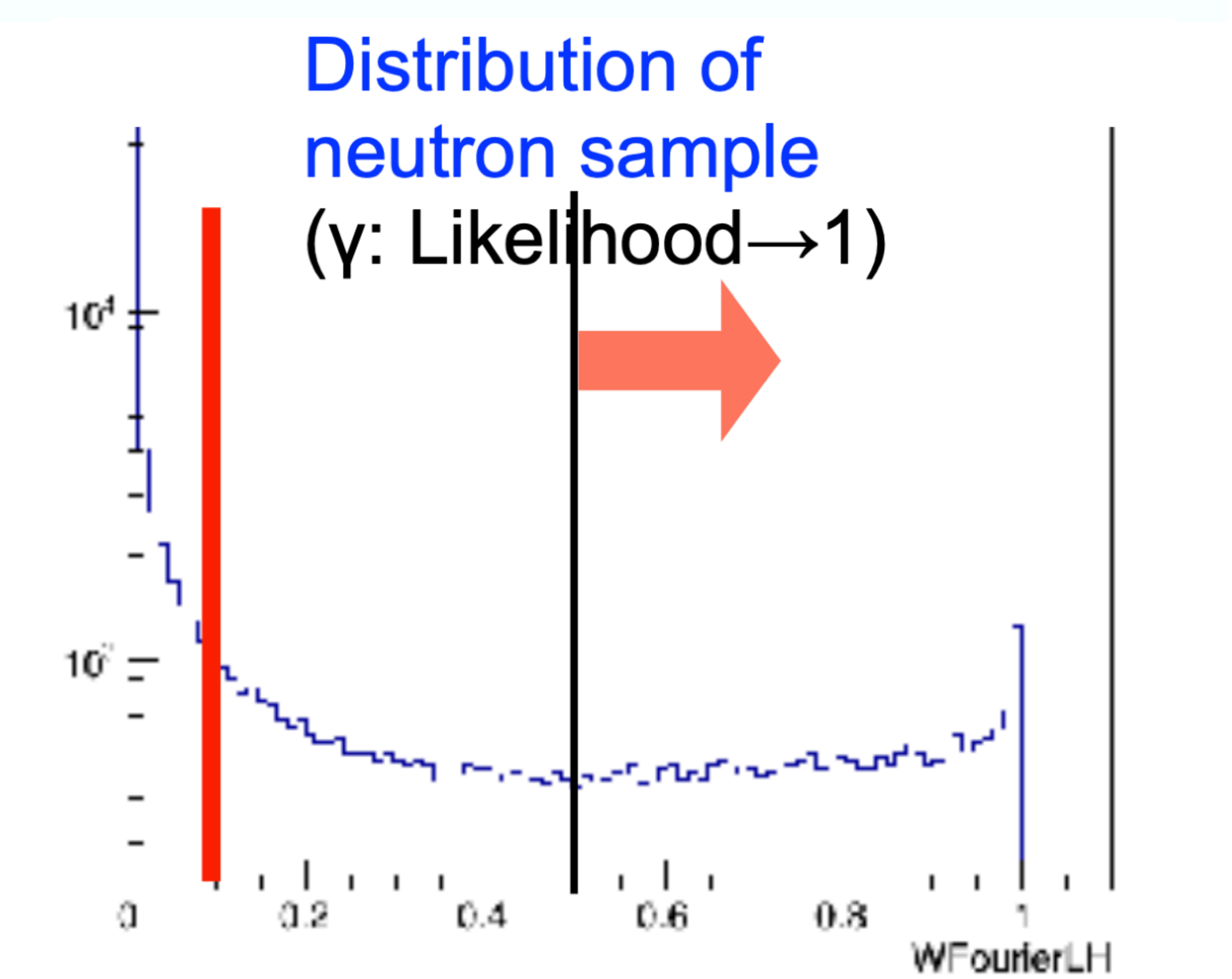
Pulse Shape Discrimination



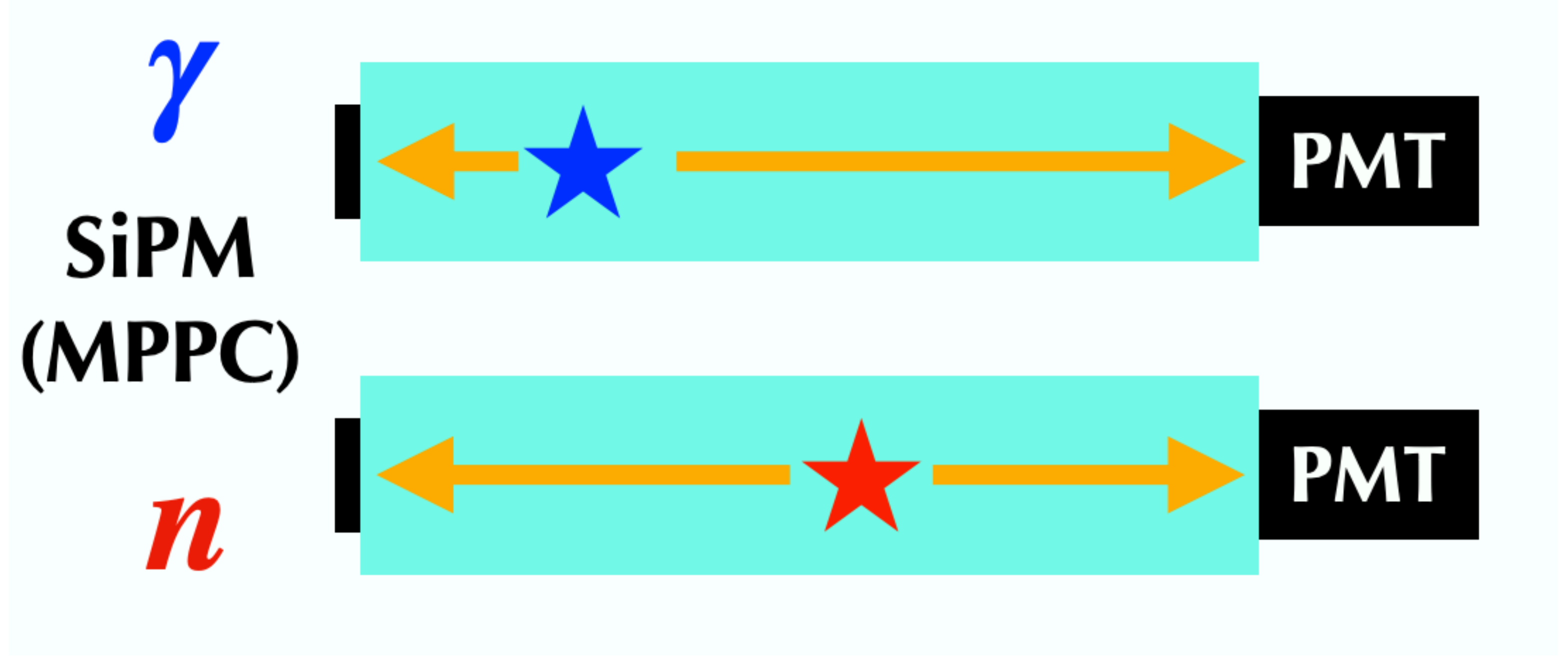


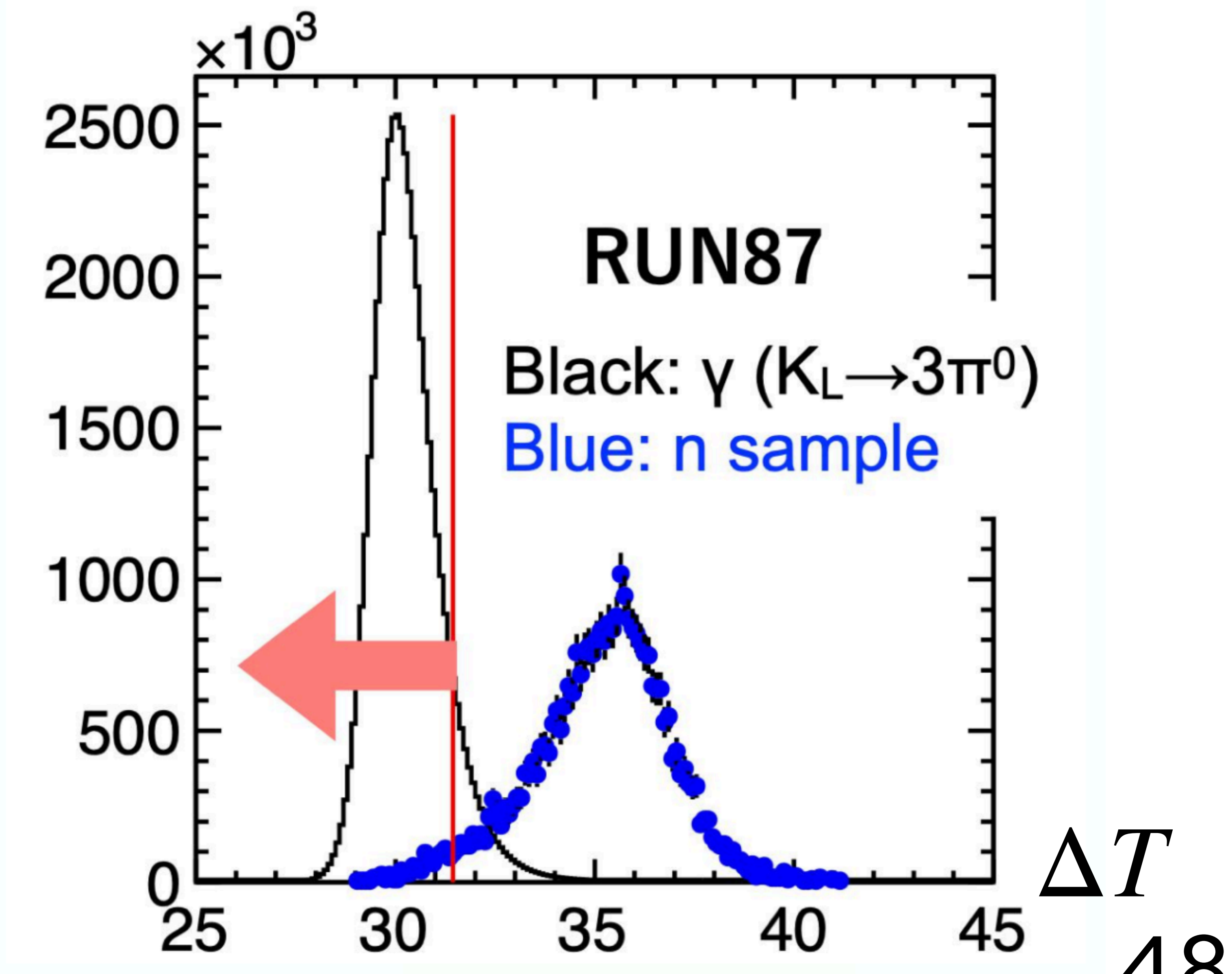
Cluster Shape Discrimination





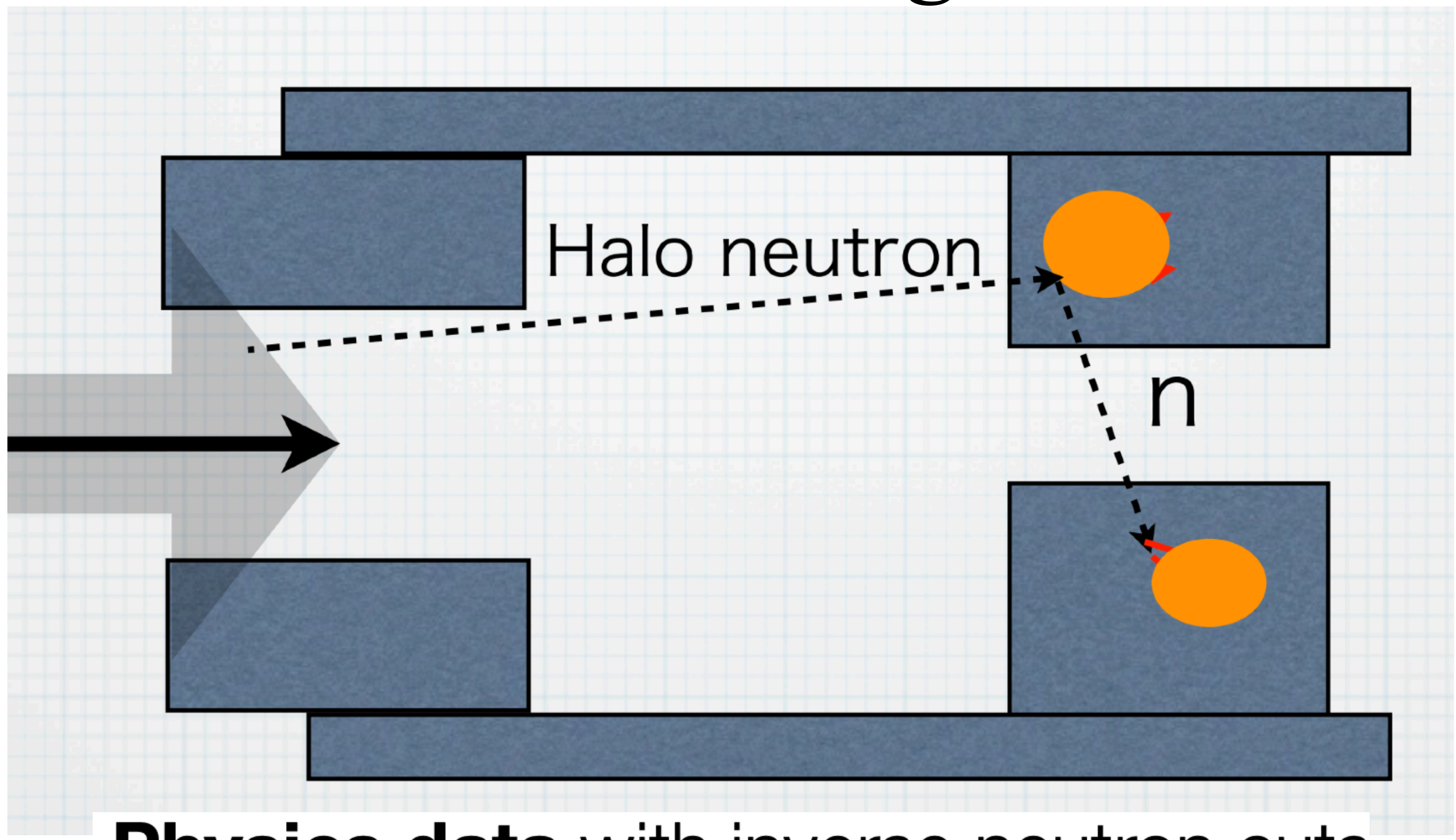
Both-end Read out



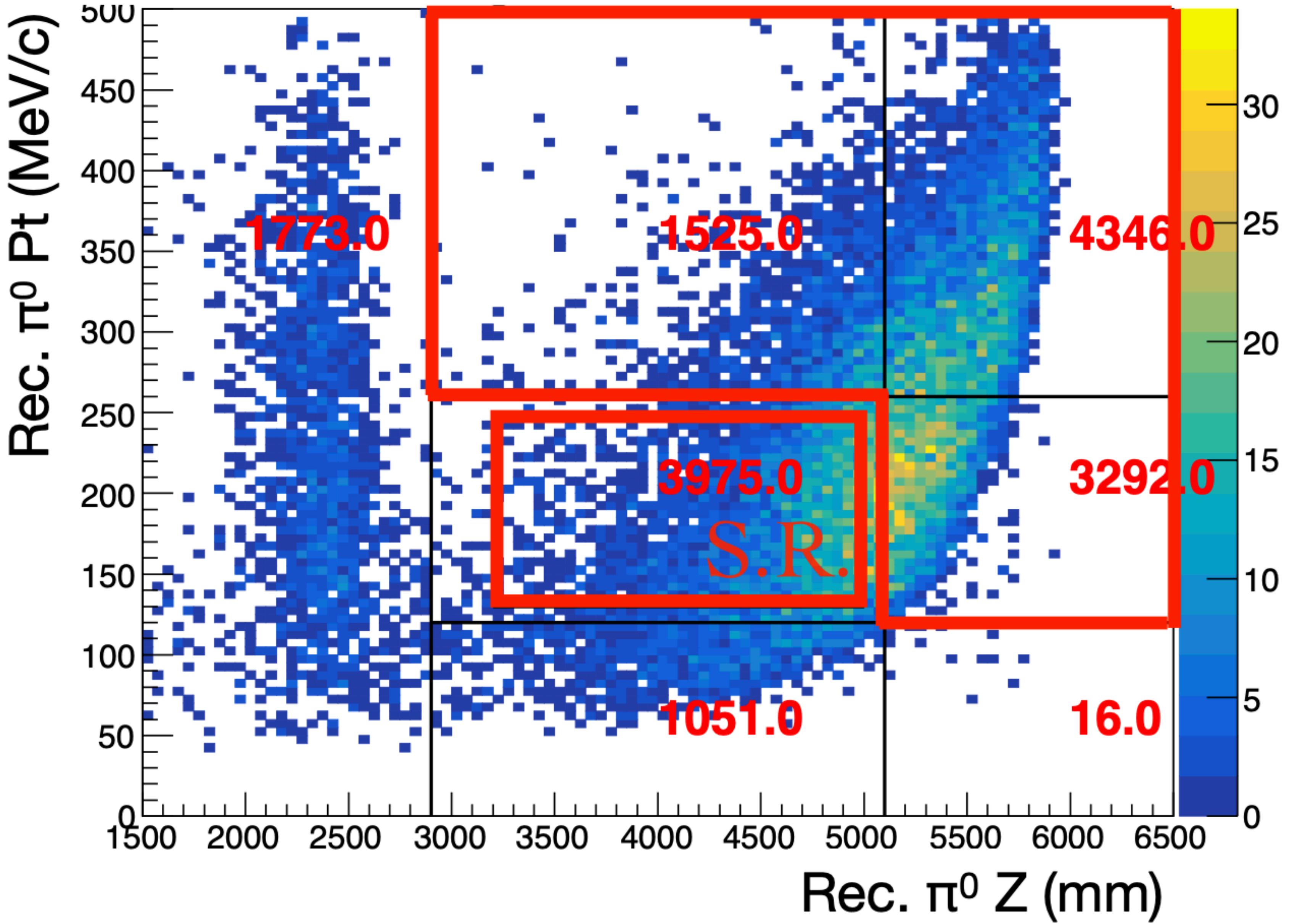


Control data for neutron background

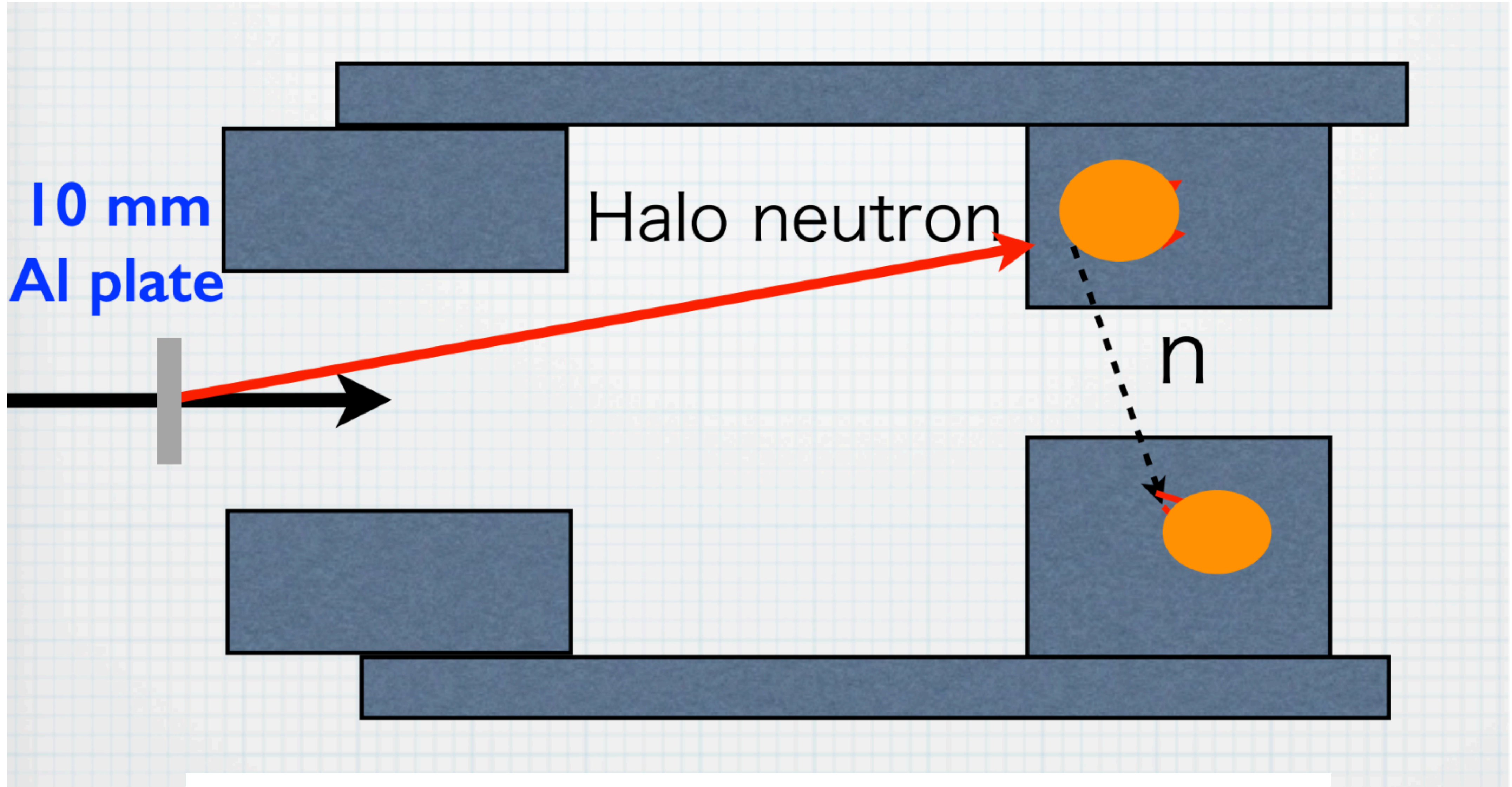
Neutron background



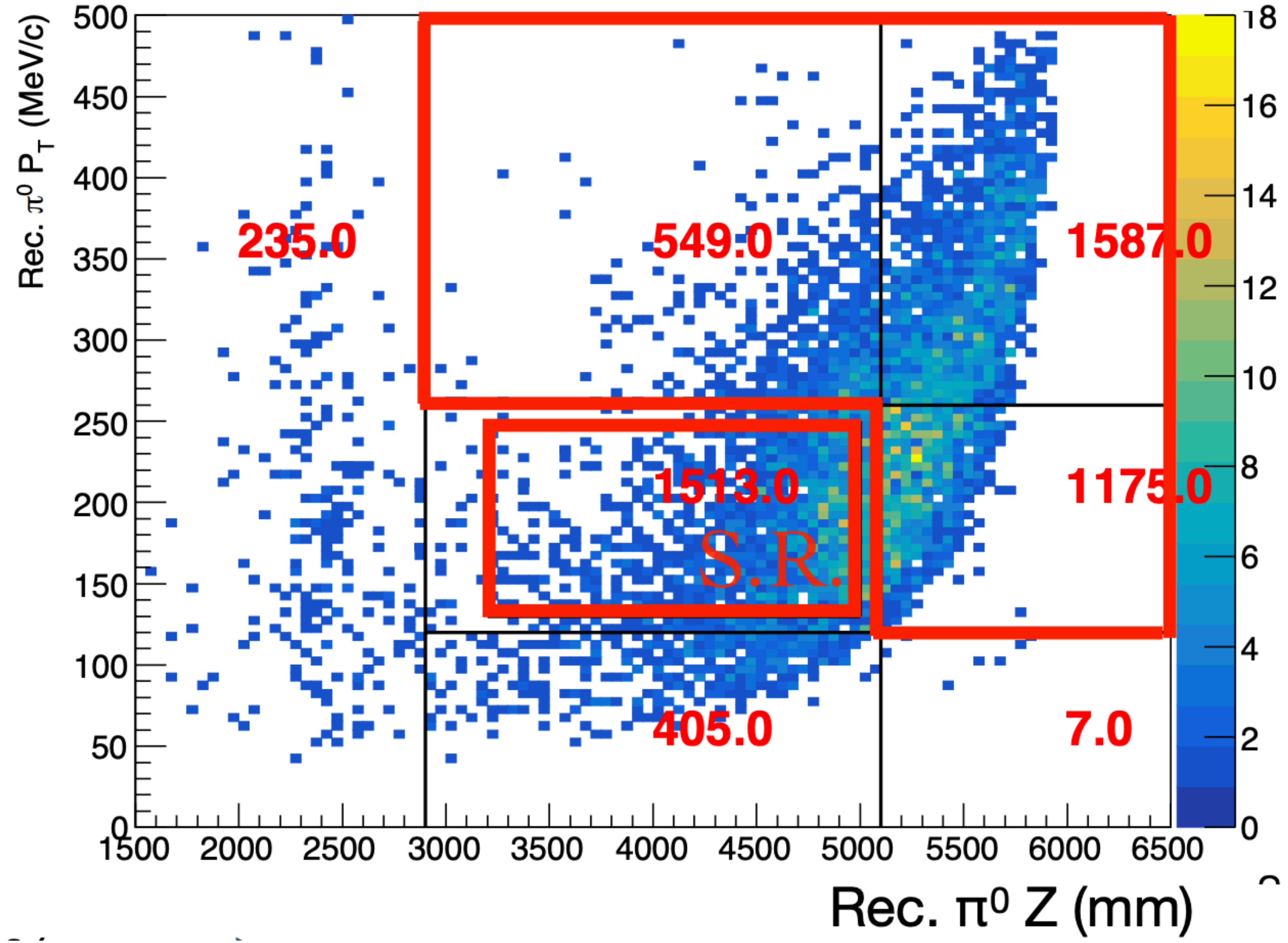
Physics data with inverse neutron cuts



Control data



Control data (Al target data)



Latest result of $K_L \to \pi^0 \nu \bar{\nu}$ search

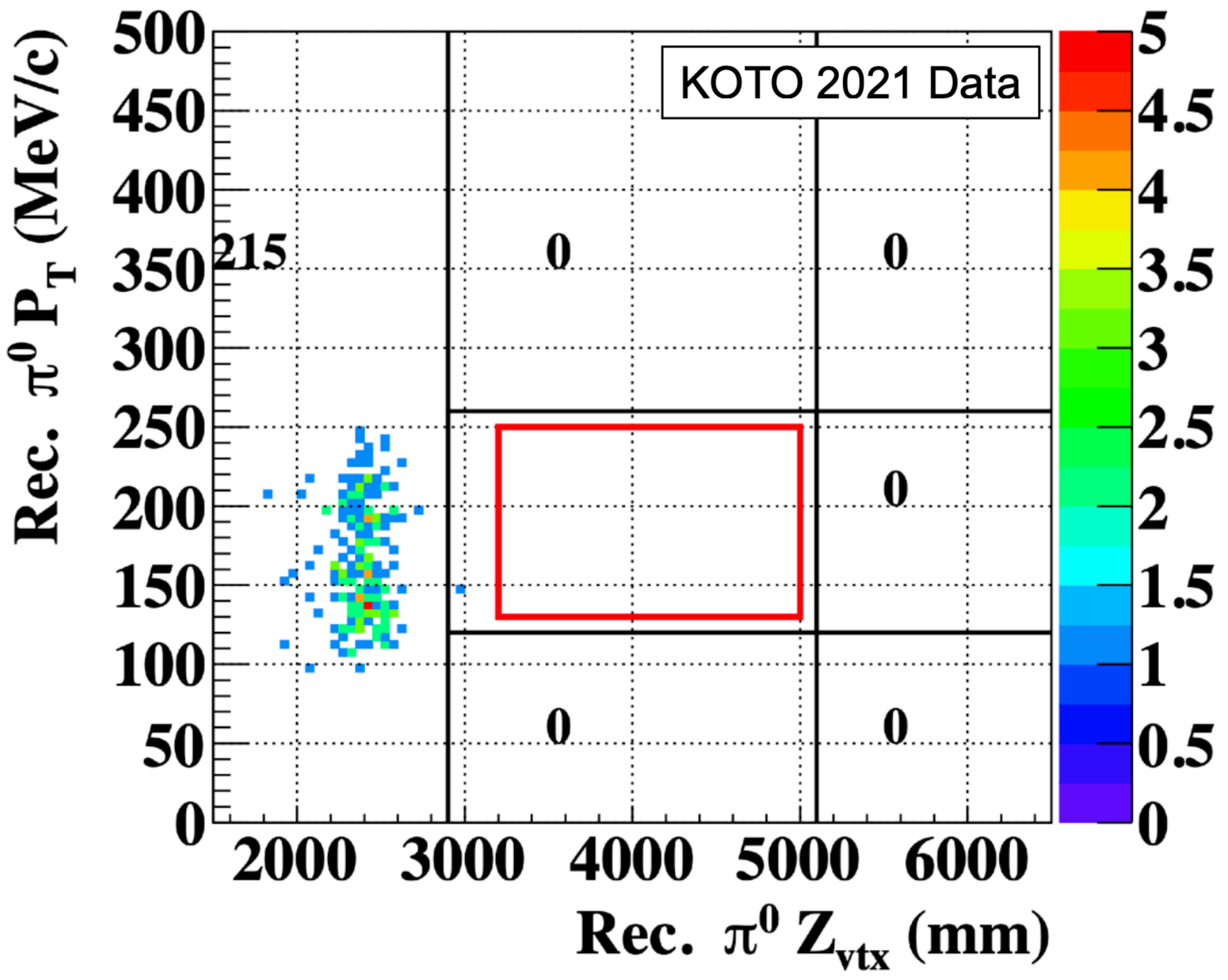
- **No signal candidates** were observed in the signal region.
- Set the upper limit to be

  BR($K_L \to \pi^0 \nu\nu$) < 2.0×10^{-9}

  at 90% confidence level.

  - Corresponding to SES×2.3 based on Poisson statistics.

Preliminary



This result was firstly presented at IPNS and J-PARC Joint seminar on September 6, 2023

We are preparing the paper of the 2021 data analysis.

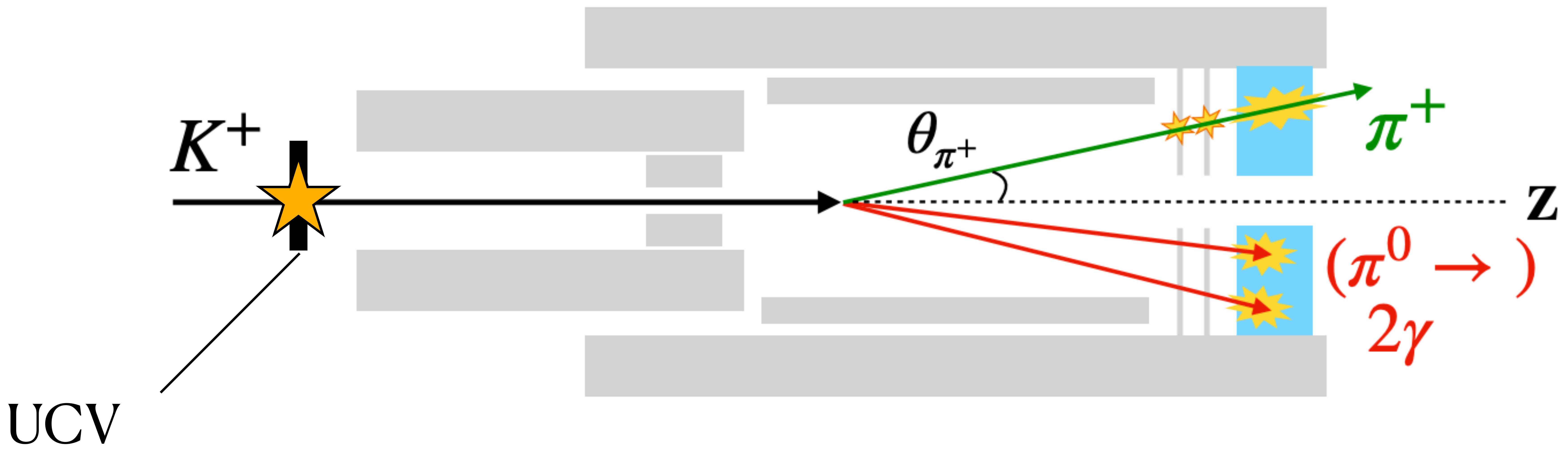
https://kds.kek.jp/event/48881/contributions/252904/attachments/175352/231977/KOTO_pac37-rel.pdf

Background table in 2021 data analysis

Source	Estimated value
Upstream π^0	$0.064 \pm 0.050\ (stat.) \pm 0.006\ (syst.)$
$K_L \to 2\pi^0$	$0.060 \pm 0.022\ (stat.)\ ^{+0.051}_{-0.060}\ (syst.)$
$K^\pm$	$0.043 \pm 0.015\ (stat.)\ ^{+0.004}_{-0.030}\ (syst.)$
Scattered and halo $K_L(\to 2\gamma)$	$0.022 \pm 0.005\ (stat.) \pm 0.004\ (syst.)$ $0.018 \pm 0.007\ (stat.) \pm 0.004\ (syst.)$
Hadron cluster BG	$0.024 \pm 0.004\ (stat.) \pm 0.006\ (syst.)$
η production in CV	$0.023 \pm 0.010\ (stat.) \pm 0.006\ (syst.)$
Sum	$0.255 \pm 0.058\ (stat.)\ ^{+0.053}_{-0.068}\ (syst.)$

https://kds.kek.jp/event/48881/contributions/252904/attachments/175352/231977/KOTO_pac37-rel.pdf

Inefficiency measurement using $K^+ \to \pi^+\pi^0$



- 3 clusters in the calorimeter
- 1 charged particle hit in the charged veto detector (CV)
- No energy deposition in any other veto detectors