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CALOR 2024 Tsukuba

Development of High-Granularity Dual-Readout Calorimetry with psec Timing

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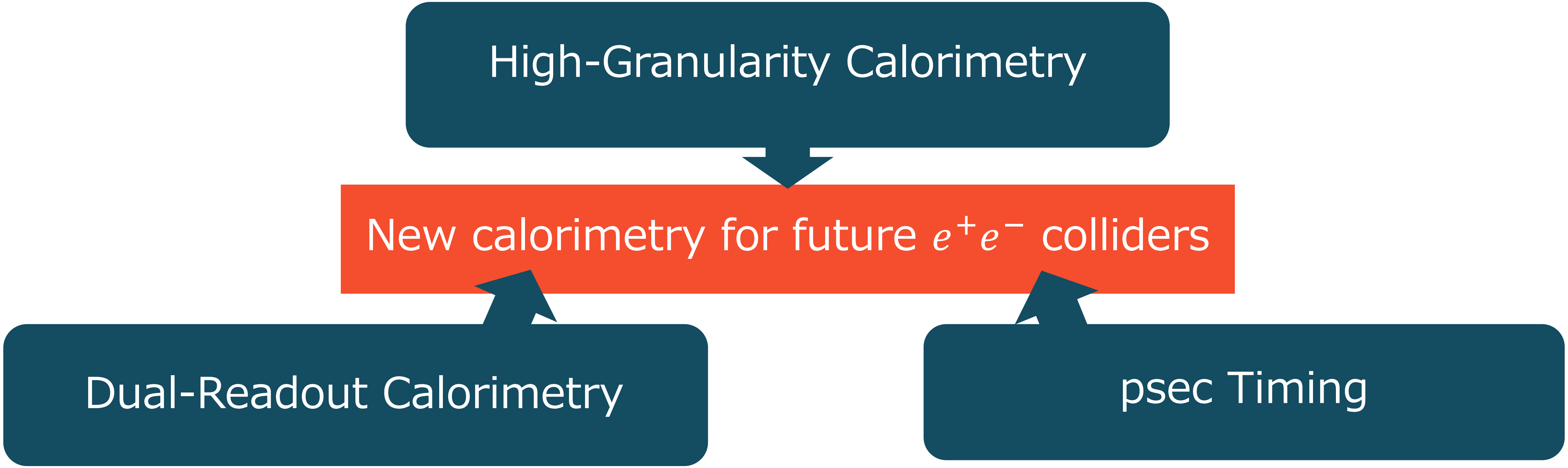
Outline

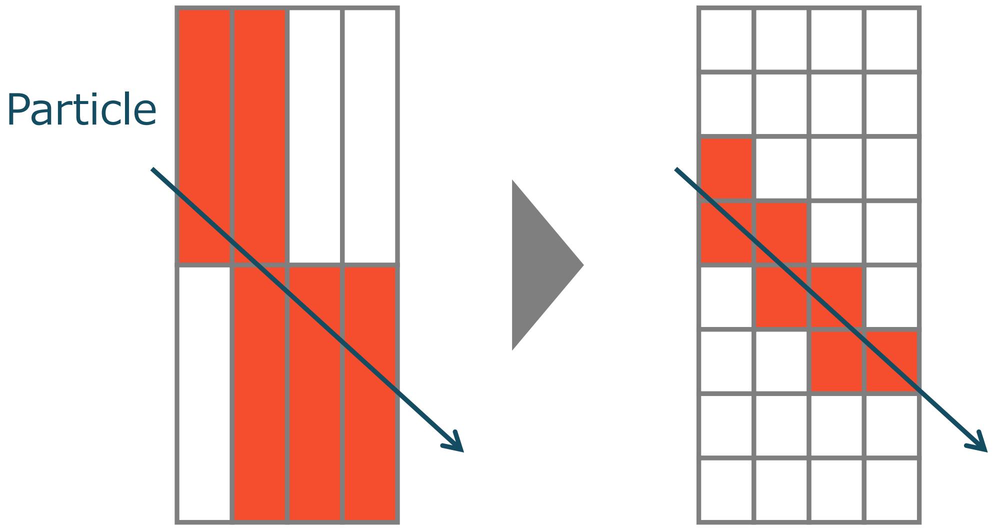
- ◆ Concept
- ◆ Performance Evaluation by Simulation
- ◆ Scintillation Detector Development
- ◆ Cherenkov Detector Development
- ◆ Summary and Prospect

Concept

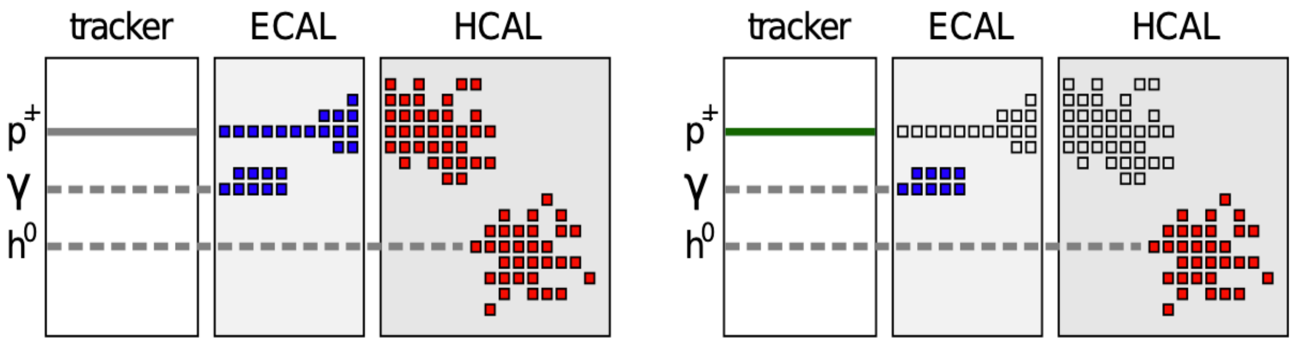

High-Granularity Calorimetry
New calorimetry for future e^+e^- colliders
Dual-Readout Calorimetry
psec Timing

High-Granularity

Highly Granular calorimeter



Particle Flow Algorithm



$$E = E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}} = E_{\mathrm{tracker}} + E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}}$$

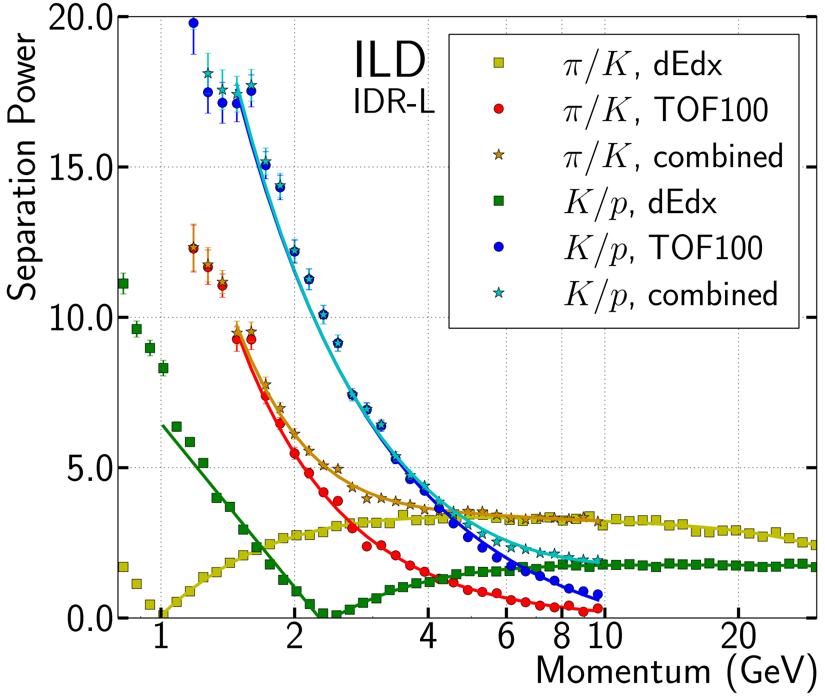
https://www.desy.de/~ohartbri/TOP/thesis_oskar_master.pdf

- High granularity for identifying particles and their track to execute Particle Flow Algorithm (PFA).
- Measurement with best suited detectors depending on particle types.

psec-Timing

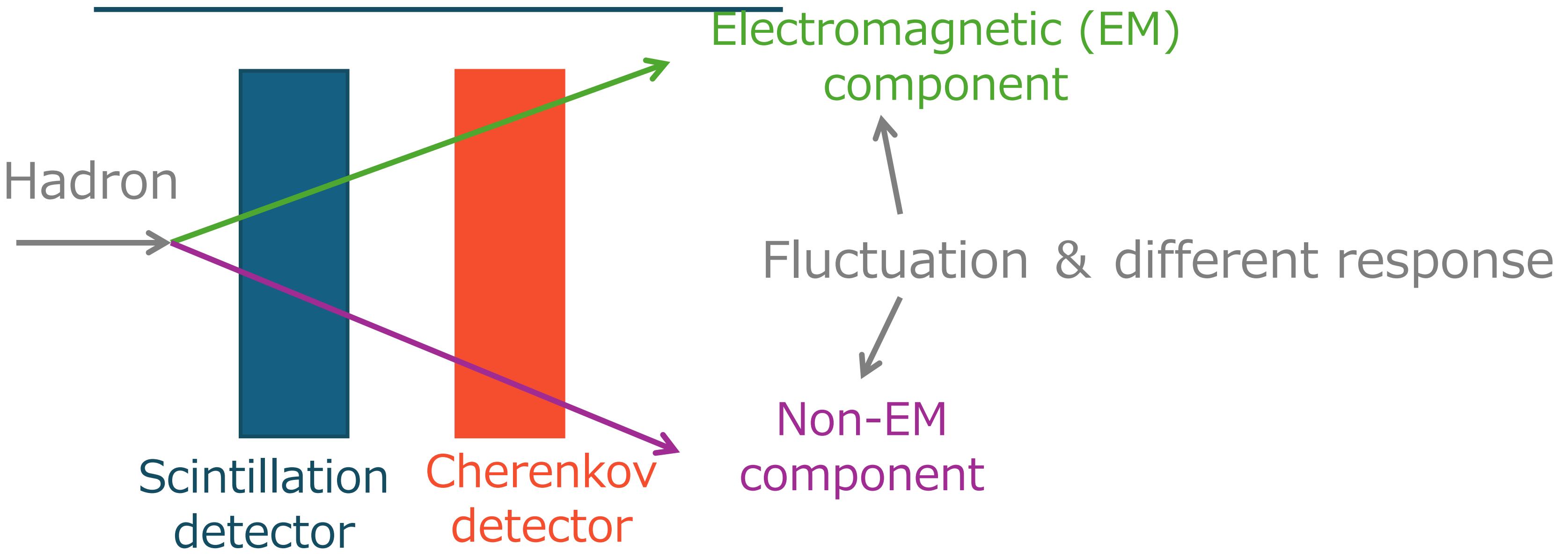
- Improvement of particle identification by time of flight (TOF).
- Reduction of background.
- Improvement of PFA.

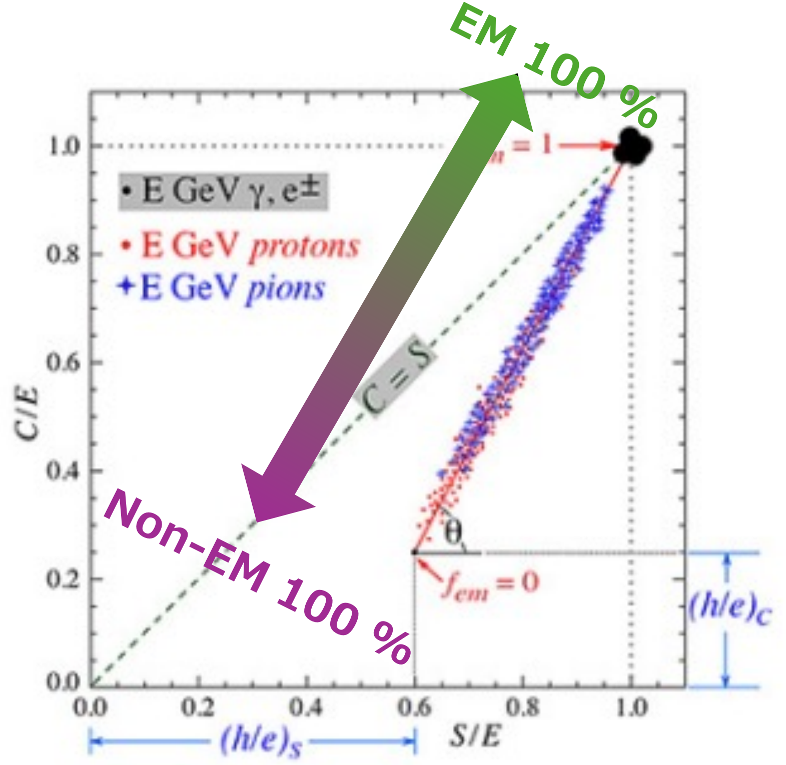
Separation Power



https://cds.cern.ch/record/2717327

Dual-Readout





(Lee, S., Livan, M. and Wigmans, R.(2018). Nucl. Instr. and Meth. A882, 148.)

To improve energy resolution of hadronic shower with Scintillation detector & Cherenkov detector.

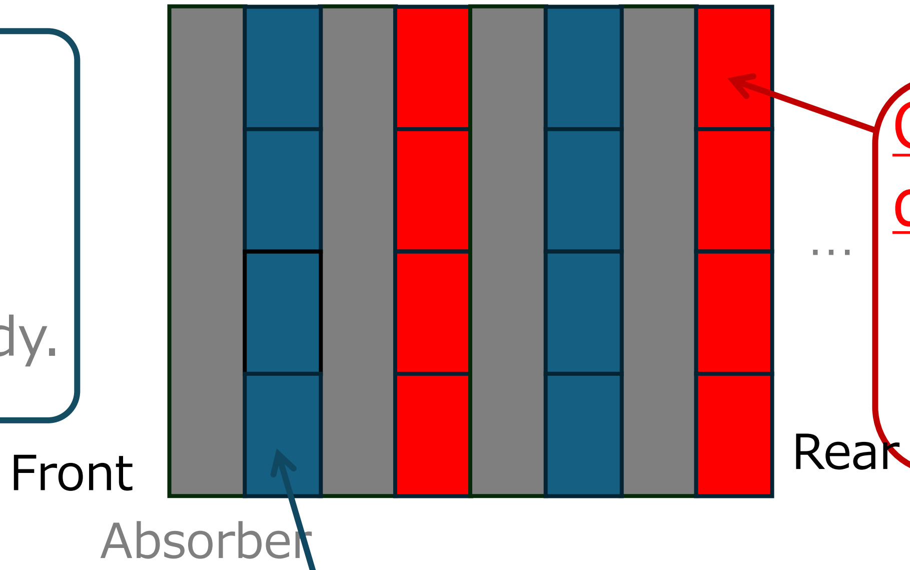
$$\begin{cases} S = E \cdot \left[f_{\mathrm{em}} + \left(\frac{h}{e}\right)_S (1 - f_{\mathrm{em}})\right] \\ C = E \cdot \left[f_{\mathrm{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\mathrm{em}})\right] \end{cases}$$

▶ $$E = \frac{S - \chi C}{1 - \chi} \left(\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C} \right)$$

- $\left(\frac{h}{e}\right)_S, \left(\frac{h}{e}\right)_C$: Conversion efficiency of Non-EM signals to EM signals (independent with energy and particle type).
- E: Initial particle energy.
- f_{em}: Energy ratio of EM component to E.

Overall design and research items

Hadron calorimeter



Overall Simulation

High-granularity, dual-readout and psec timing detector performance study.

Cherenkov Detector layer development

High-granularity and psec timing resolution detector.

Scintillation Detector layer development

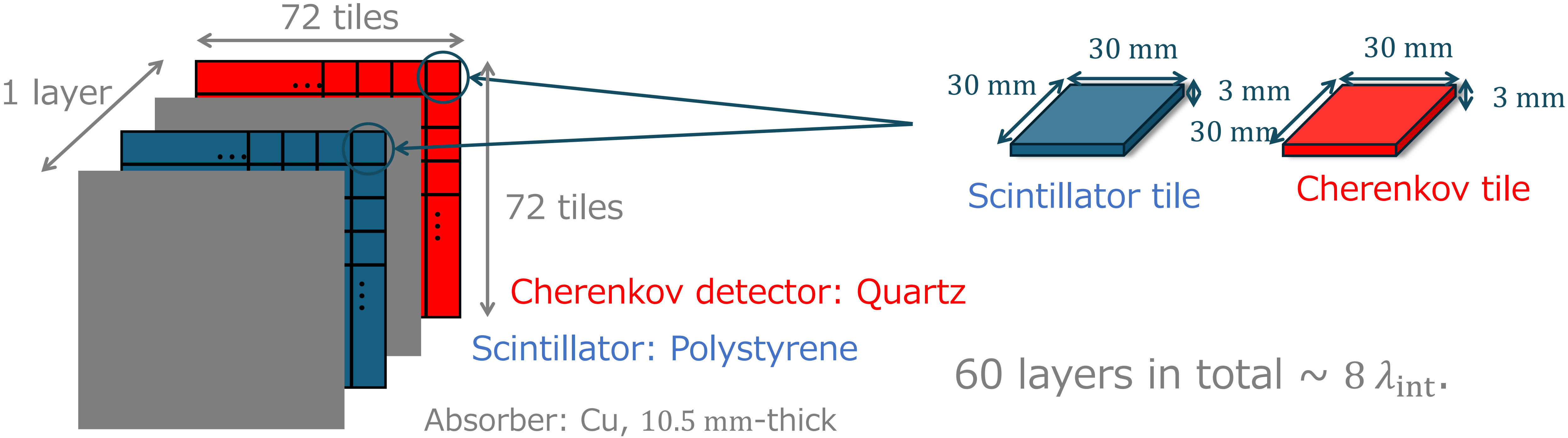
High-granularity detector.

Performance Evaluation by Simulation

Studying dual-readout performance for single π^- energy resolution with this setup (not including psec Timing).

(Use DD4hep and its interface to Geant4 to describe geometry, materials)

Reference Setup (CALICE AHCAL-like tiles)

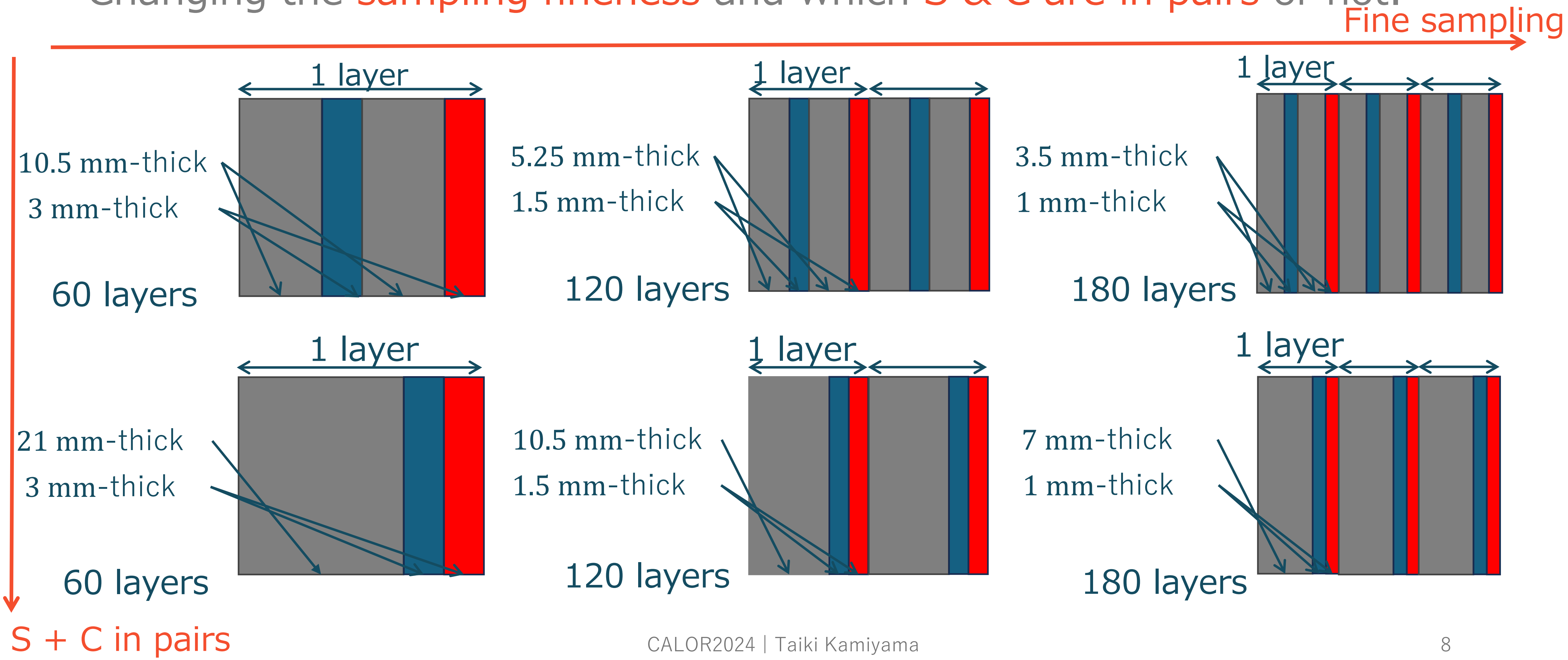


60 layers in total ~ 8 λ_{int}.

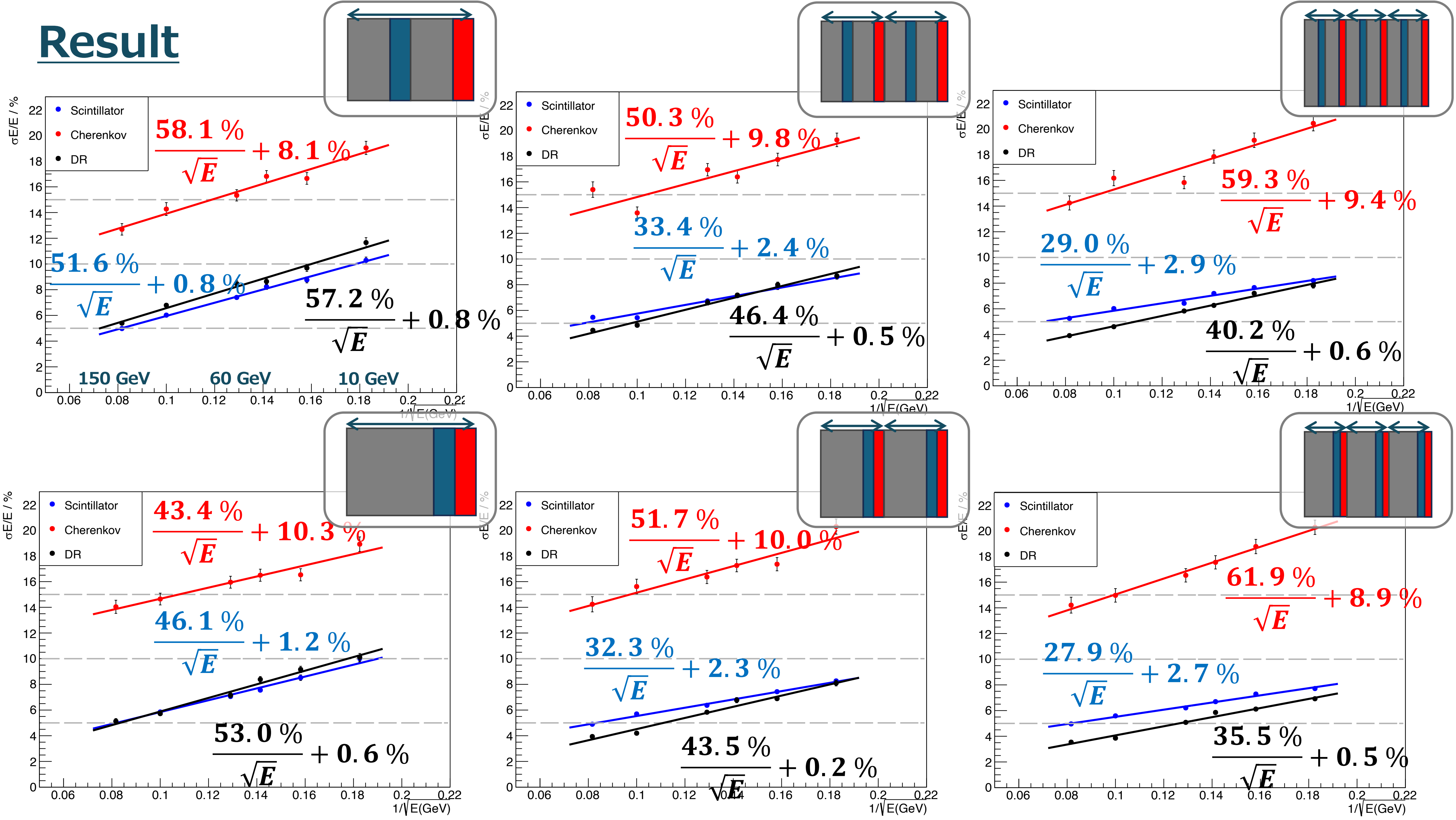
Comparison with different configurations

Cu
Polystyrene
Quartz

- The same total thickness of each material.
- Changing the sampling fineness and which S & C are in pairs or not.



Result

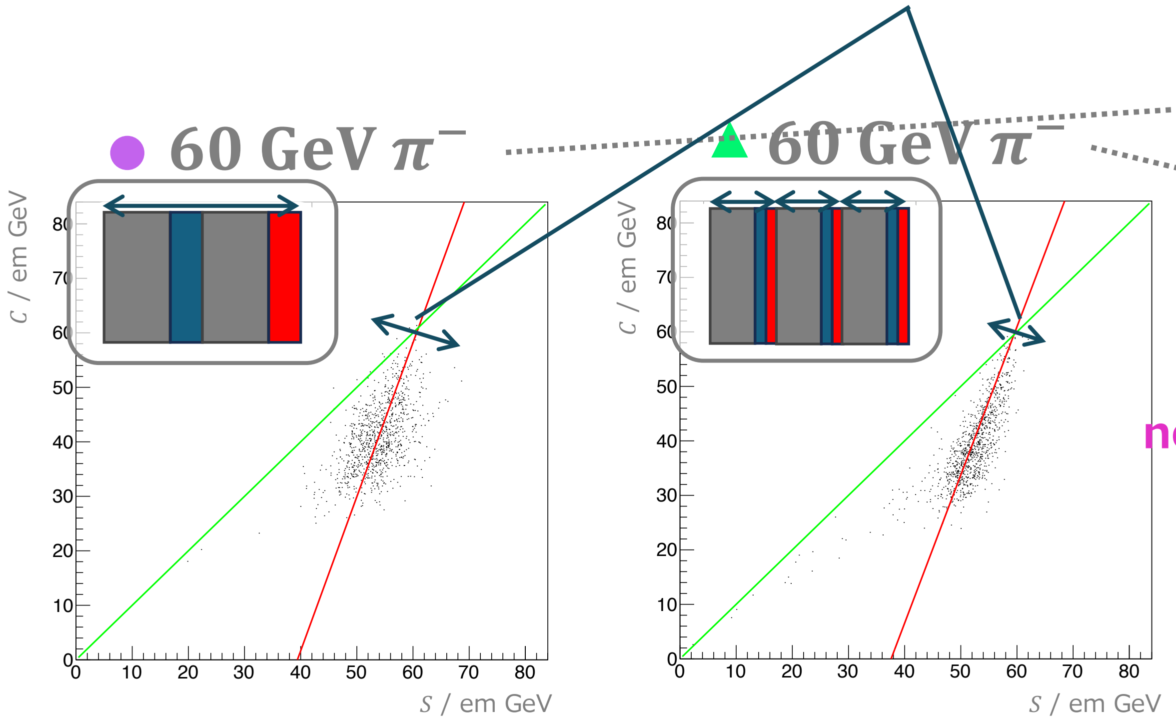


Scintillator
Cherenkov
DR
σE/E / %
1/√E(GeV)
150 GeV
60 GeV
10 GeV
58.1 %/√E + 8.1 %
51.6 %/√E + 0.8 %
57.2 %/√E + 0.8 %
50.3 %/√E + 9.8 %
33.4 %/√E + 2.4 %
46.4 %/√E + 0.5 %
59.3 %/√E + 9.4 %
29.0 %/√E + 2.9 %
40.2 %/√E + 0.6 %
43.4 %/√E + 10.3 %
46.1 %/√E + 1.2 %
53.0 %/√E + 0.6 %
51.7 %/√E + 10.0 %
32.3 %/√E + 2.3 %
43.5 %/√E + 0.2 %
61.9 %/√E + 8.9 %
27.9 %/√E + 2.7 %
35.5 %/√E + 0.5 %

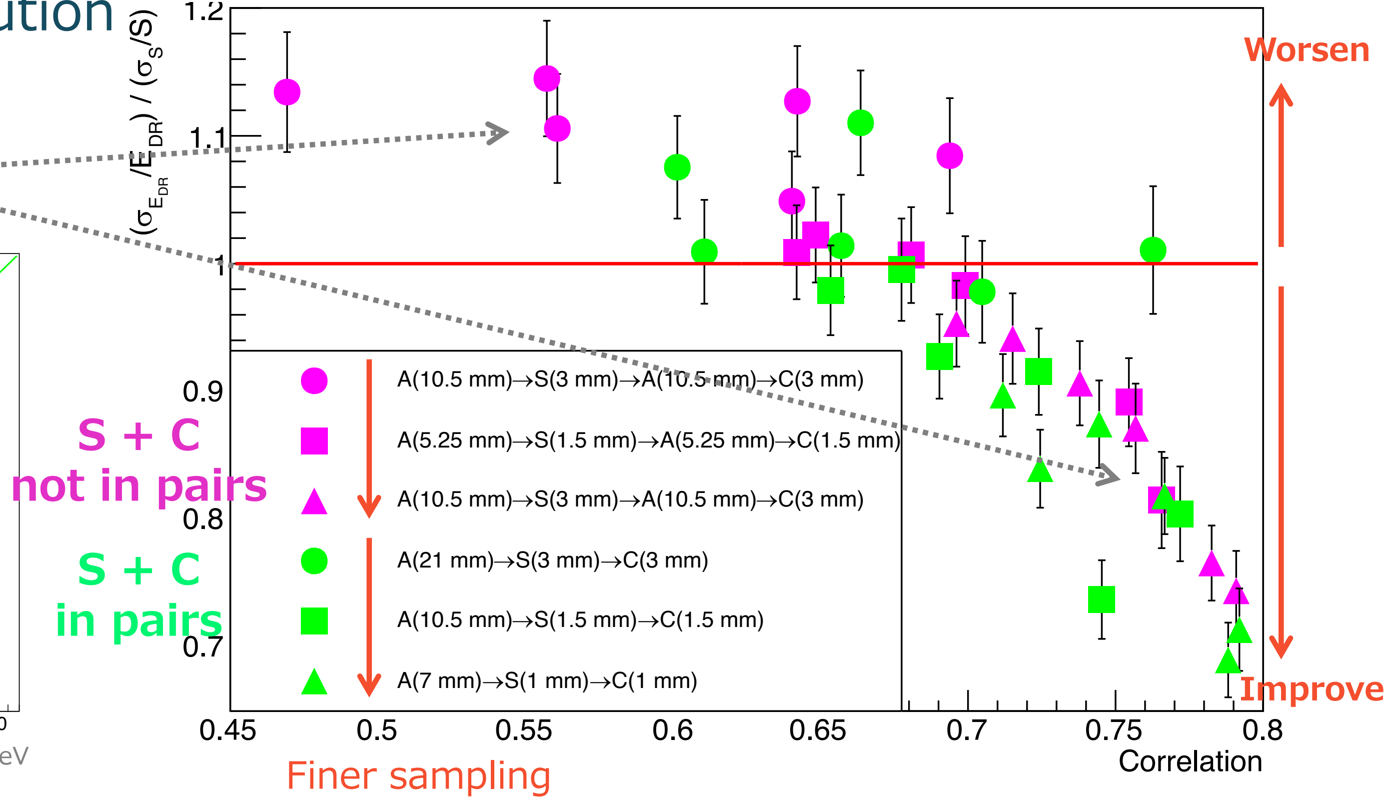
Discussion

Better Dual-Readout performance with higher correlation between Scintillator signals and Cherenkov signals.

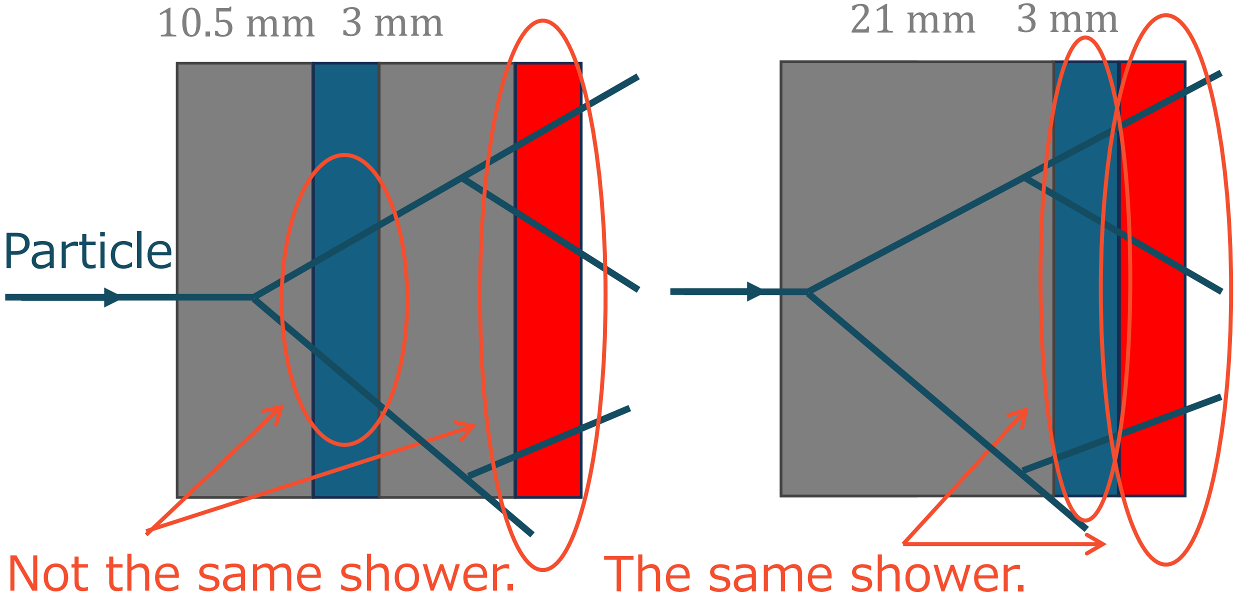
Corresponding to the Dual-Readout resolution



Correlation vs Resolution Improvement $\left(\frac{\sigma_{E_{DR}}}{E_{DR}} \,/\, \frac{\sigma_S}{S}\right)$



S + C in pairs



Correlation:	0.56	▶	0.66
Improvement:	1.14		1.01

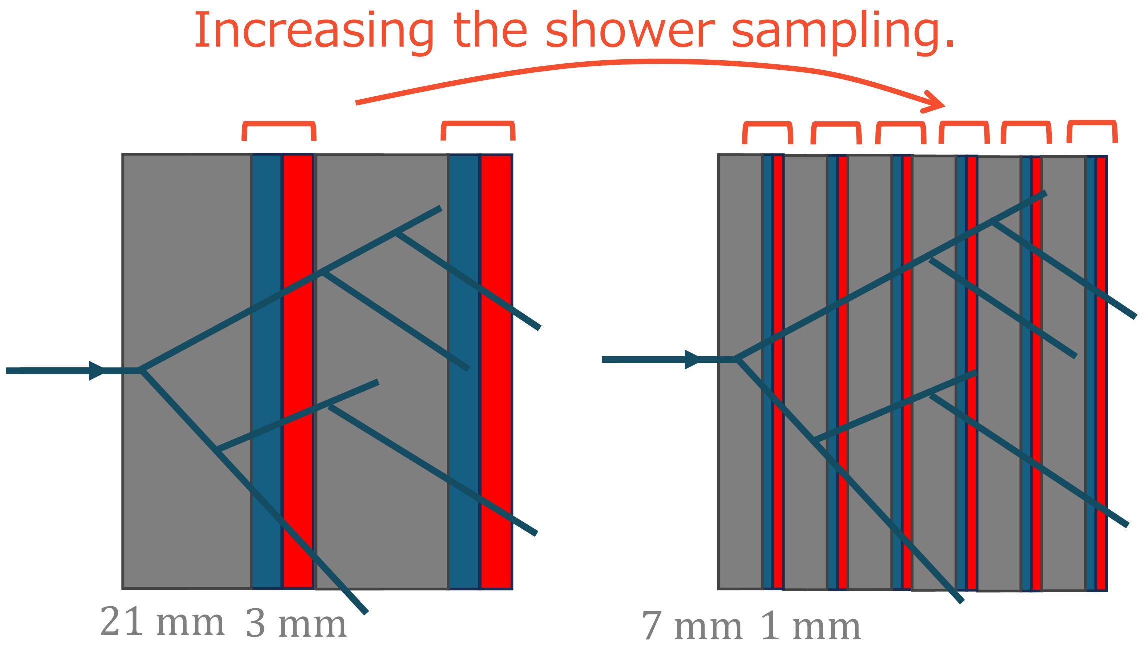
$(\frac{\sigma_{E_{DR}}}{E_{DR}} / \frac{\sigma_S}{S})$

"Homogeneous" reading the shower with Scintillators and Cherenkov detectors in S + C in pairs setups.

▼

Higher the correlation.

Fine sampling



Correlation:	0.66	▶	0.77
Improvement:	1.01		0.82

$(\frac{\sigma_{E_{DR}}}{E_{DR}} / \frac{\sigma_S}{S})$

Less affected by shower fluctuation with finer sampling.

▼

Higher the correlation.

Scintillation Detector Development

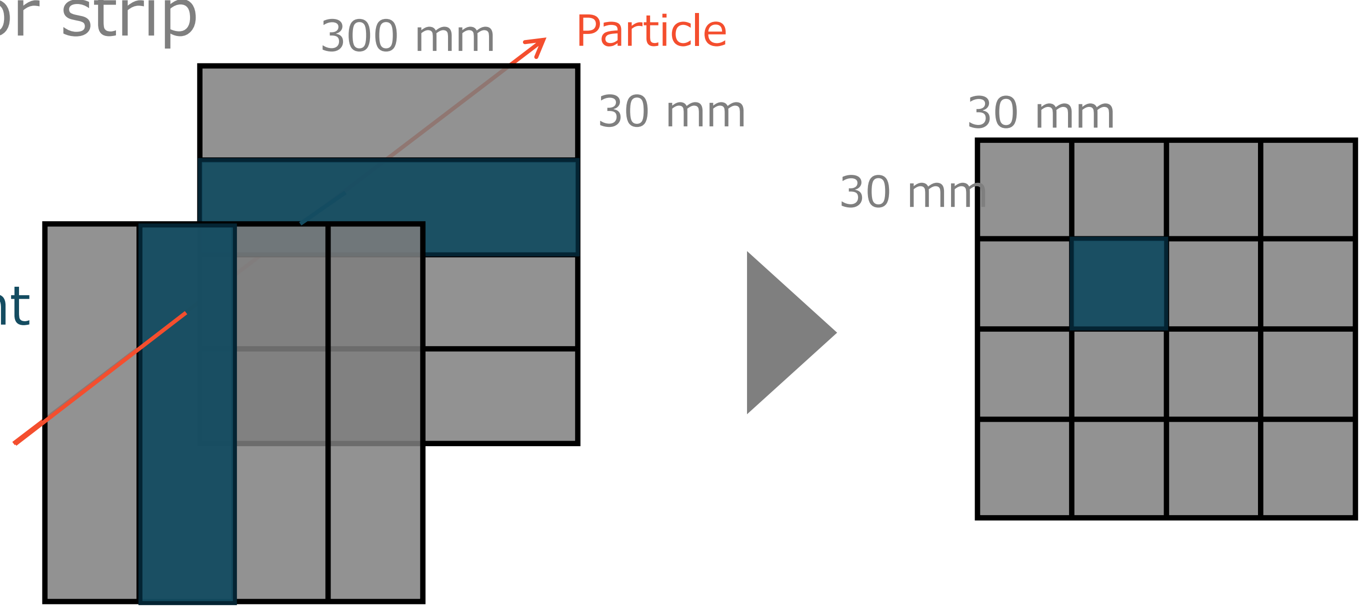
(Poster by H. Ogawa)

Requirement

High- granularity

Concept

Scintillator strip



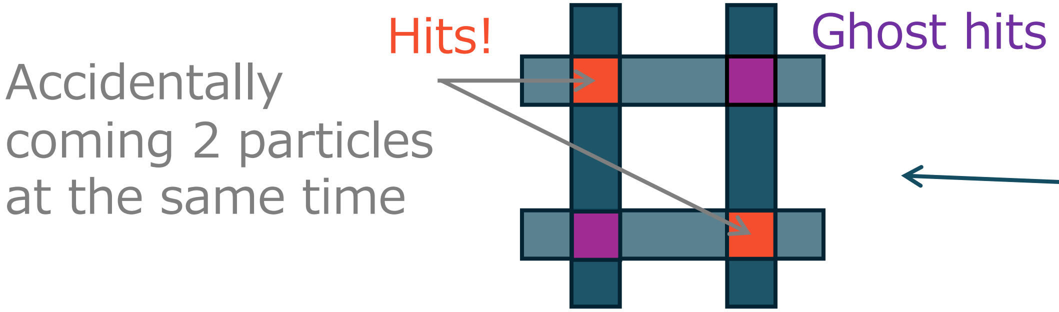
Laying in different directions.

Effective High-Granularity ($30{\times}30\ \mathrm{mm}^2$) reducing readout channels.

- Optimization of the strip design.
- Checking the light yield and uniformity with position scan using Sr90 beta-ray.

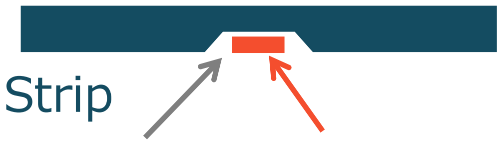
Strip material candidates

	EJ200	EJ232
Light yields [photons/1MeV]	10,000	8,400
Attenuation length [cm]	380	17
rise time [ns]	0.9	0.35
charactaristic	standard	fast



Readout candidates

1. Single SiPM

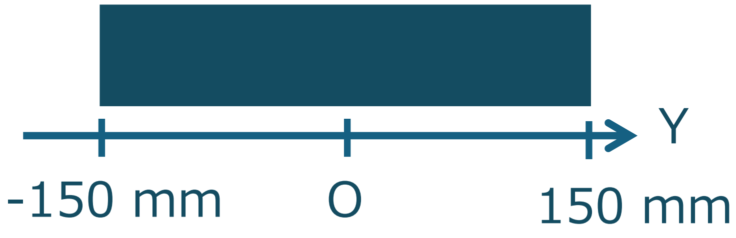


2. Double SiPMs

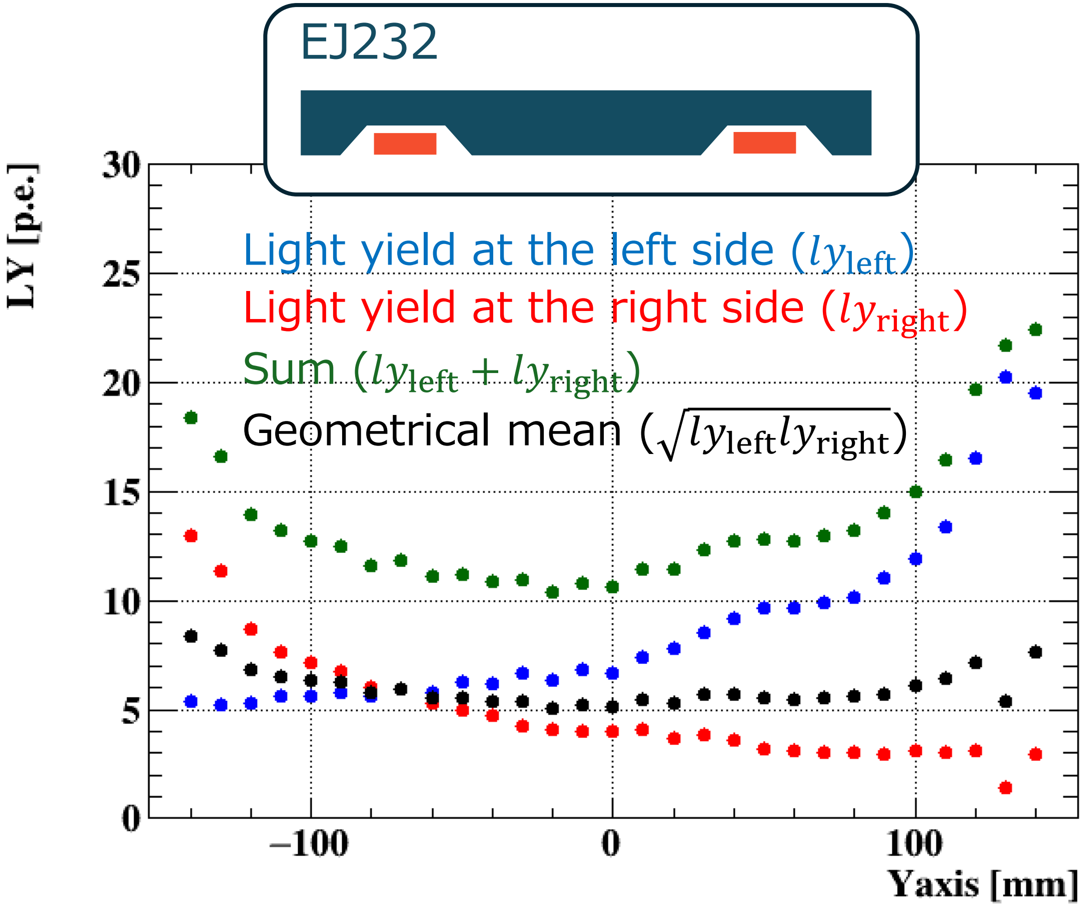
3. Double SiPMs at each side

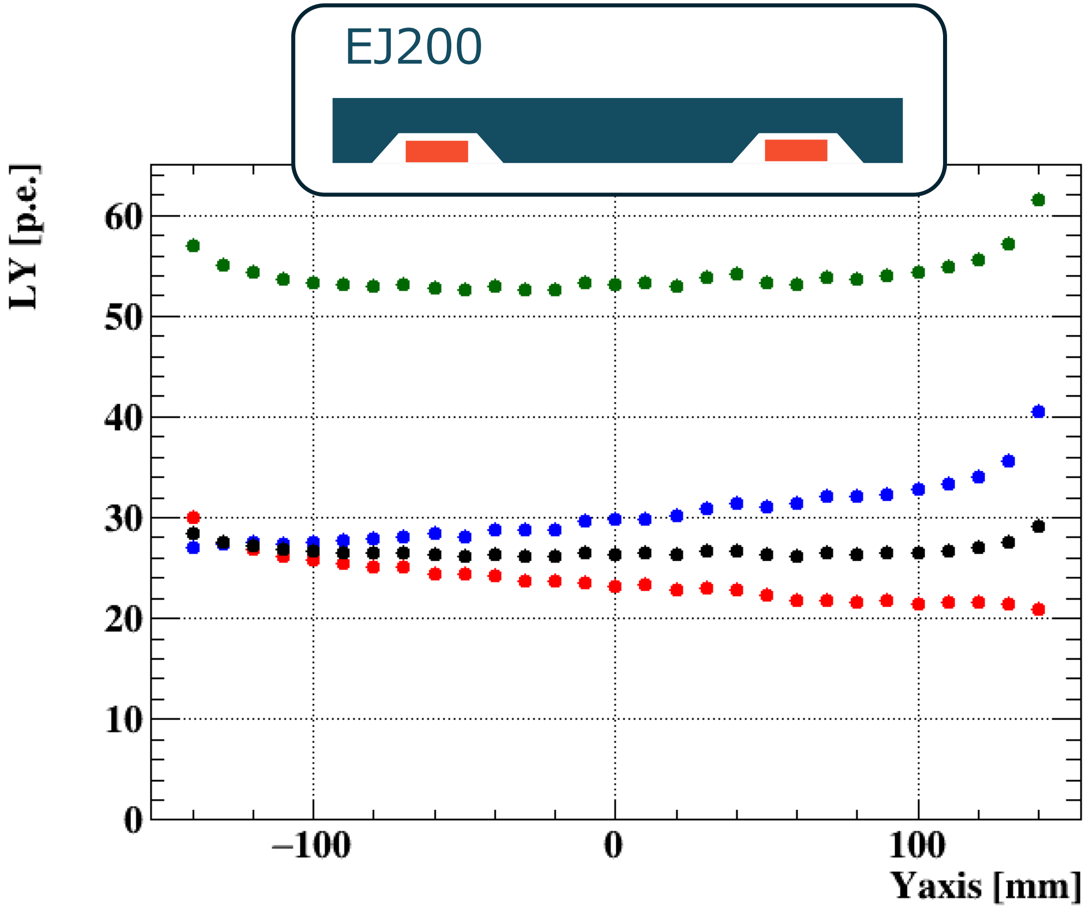
2 & 3 setups are motivated for hit position reconstruction to mitigate ghost hits.

Light yield and uniformity



- ✓ Sufficient light yield and good uniformity for EJ200.
- ✓ L-R asymmetry to be investigated.





Cherenkov Detector Development

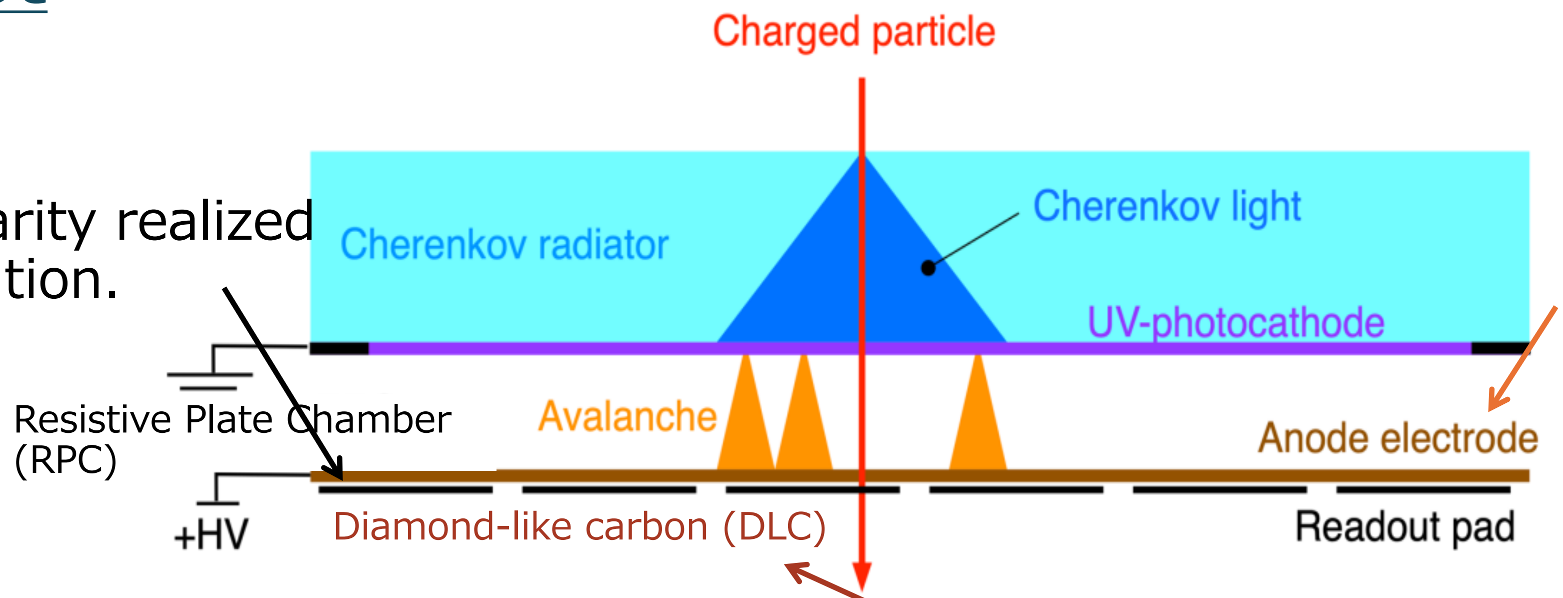
(Poster by W. Li)

Requirements

High-granularity & psec timing

Concept

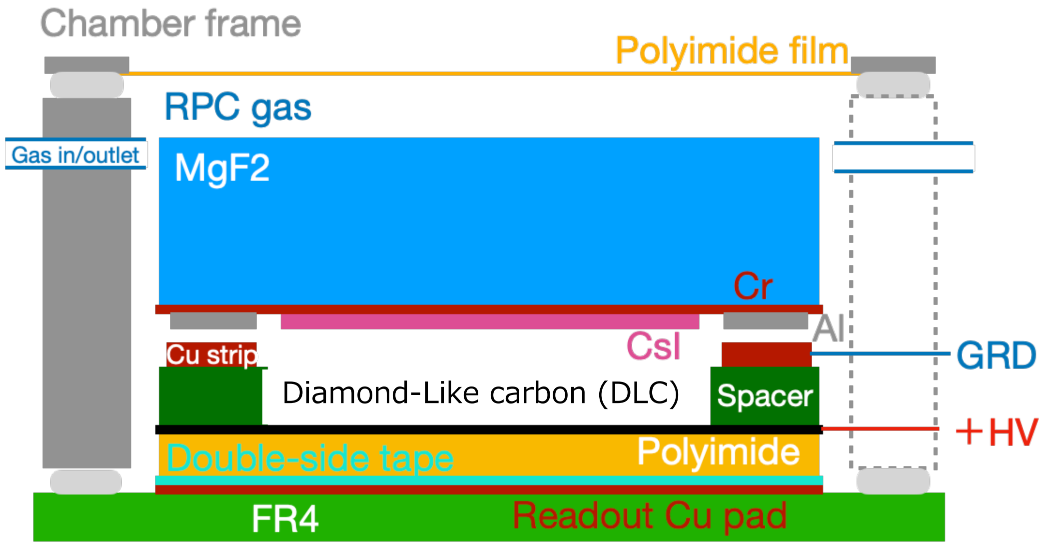
High-Granularity realized by segmentation.

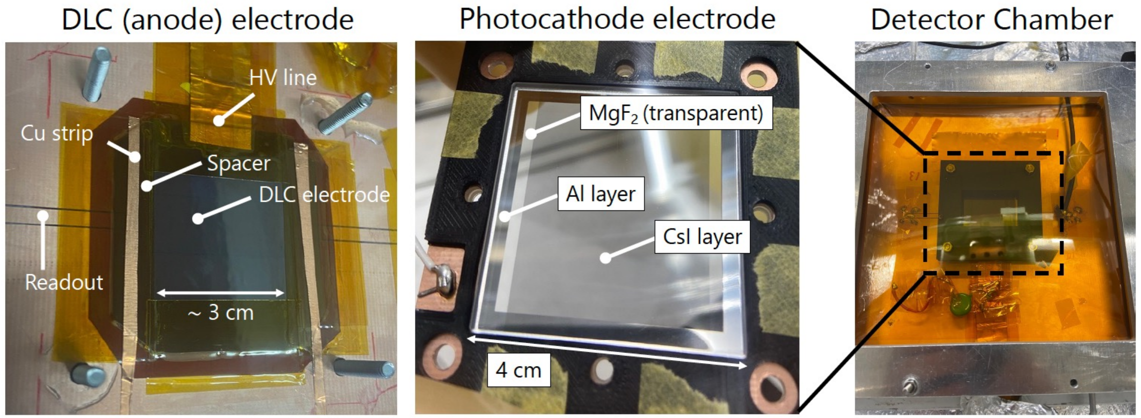


- Amplification gas layer.
- Realizing fast response.
- Covering a large area at low cost.

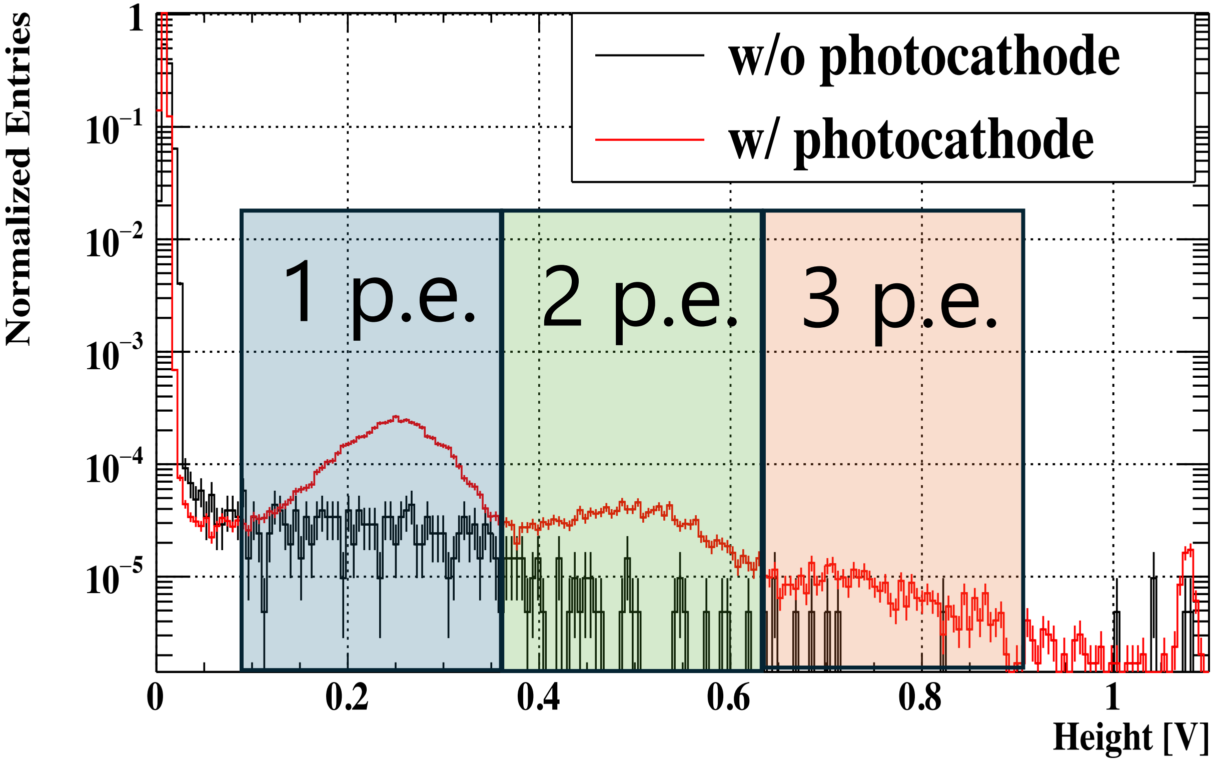
High rate capability.

Cherenkov signal observed with a prototype.



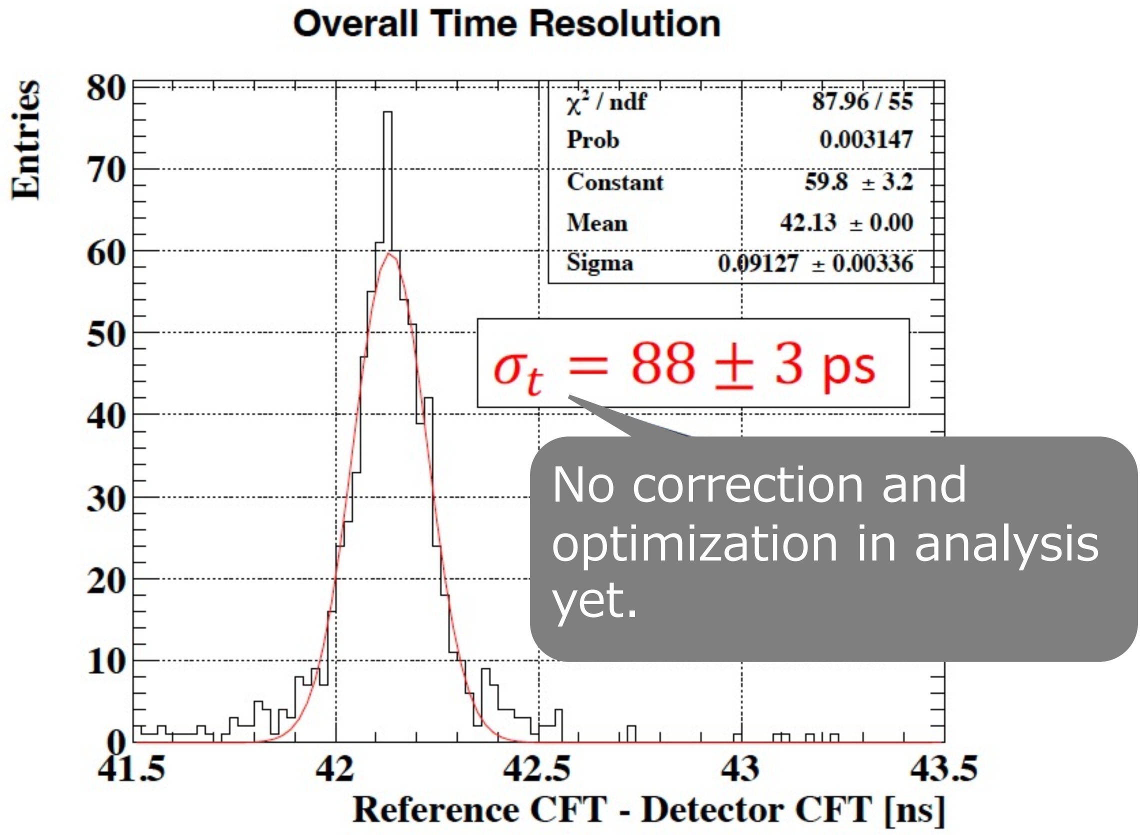


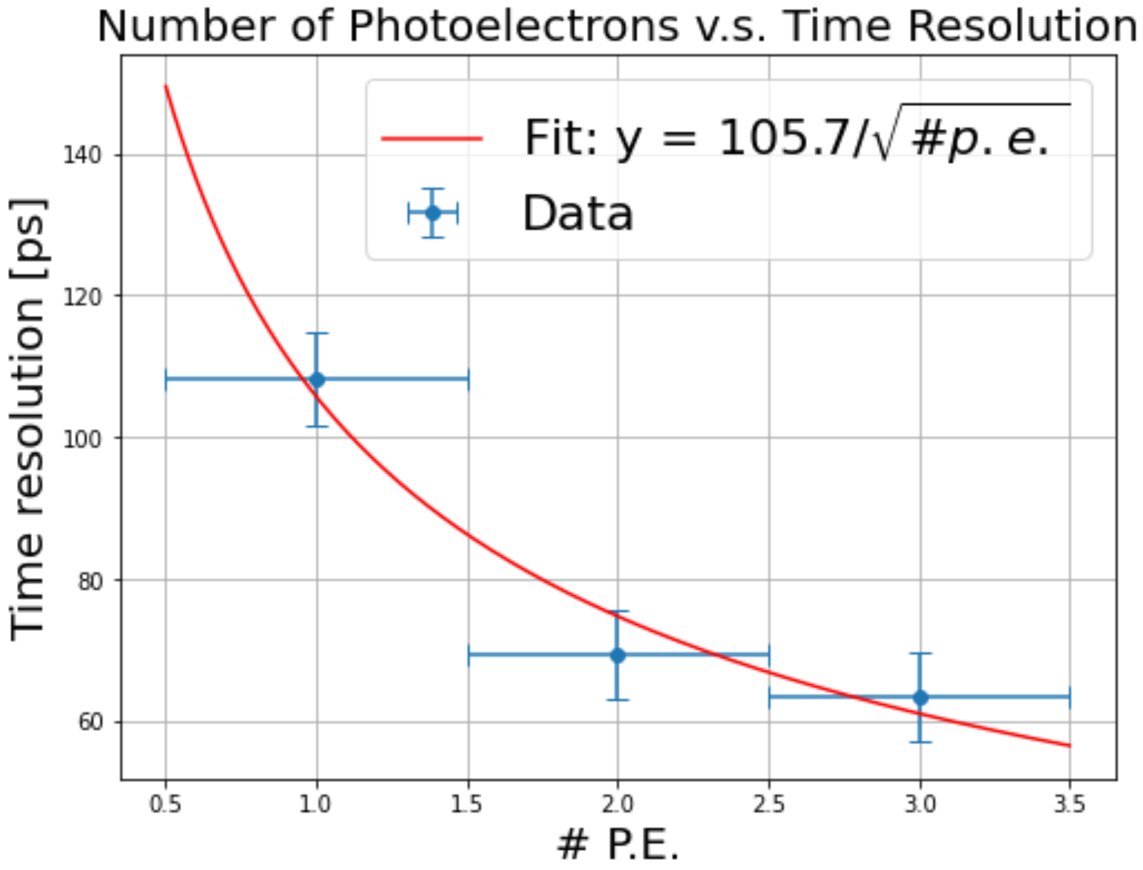
Charge spectrum in a Sr90 beta-ray test



Preliminary timing performance in a cosmic-ray test.

- QE of CsI photocathode seems lower than expected.
- $10\ \mathrm{p.e.}$s required for time resolution of $30\ \mathrm{ps}$.





3. Summary and Prospect

Developing High-Granularity Dual-Readout Calorimetry with psec Timing.

Simulation

Studying Dual-Readout performance of CALICE AHCAL-like setup.

Performance study also with high-granularity (PFA) and psec timing.

Scintillation Detector

Measuring the light yield with several strip configurations.

Planning to optimize the strip design.

Cherenkov Detector

Checking the operation of the DLC-RPC Cherenkov detector with High-Granularity & psec timing.

Planning to optimize the hardware design.

Beam test with combined prototype at KEK or Fermilab.

Backup

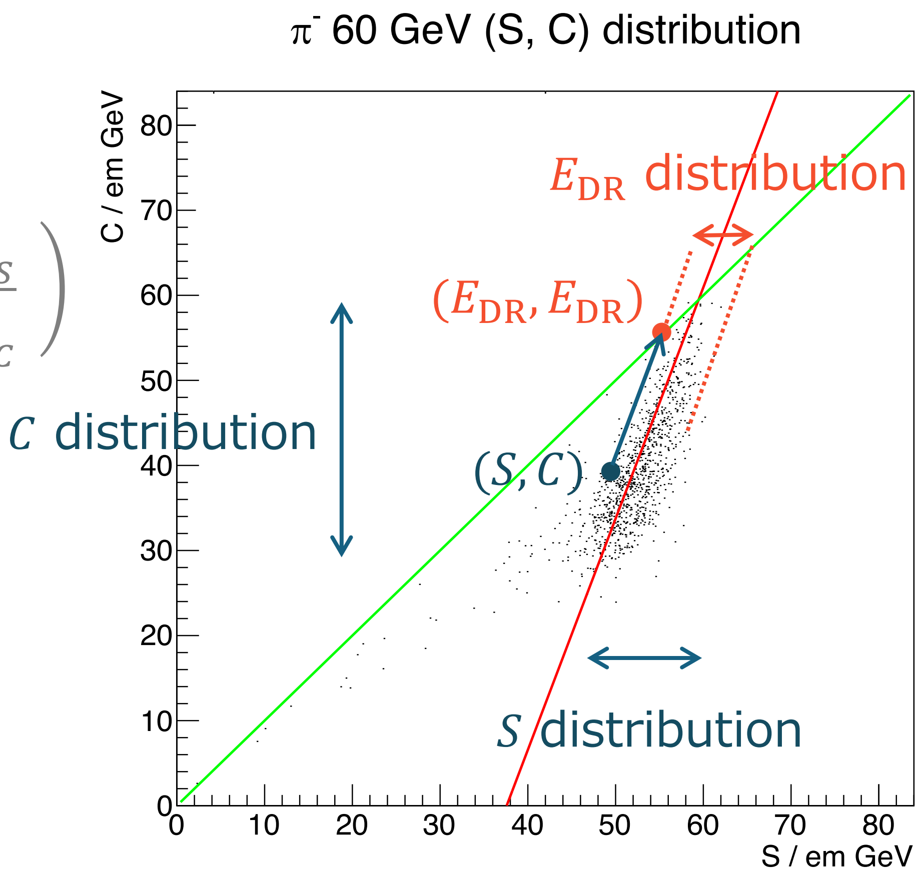
Dual-Readout

Dual-Readout analysis

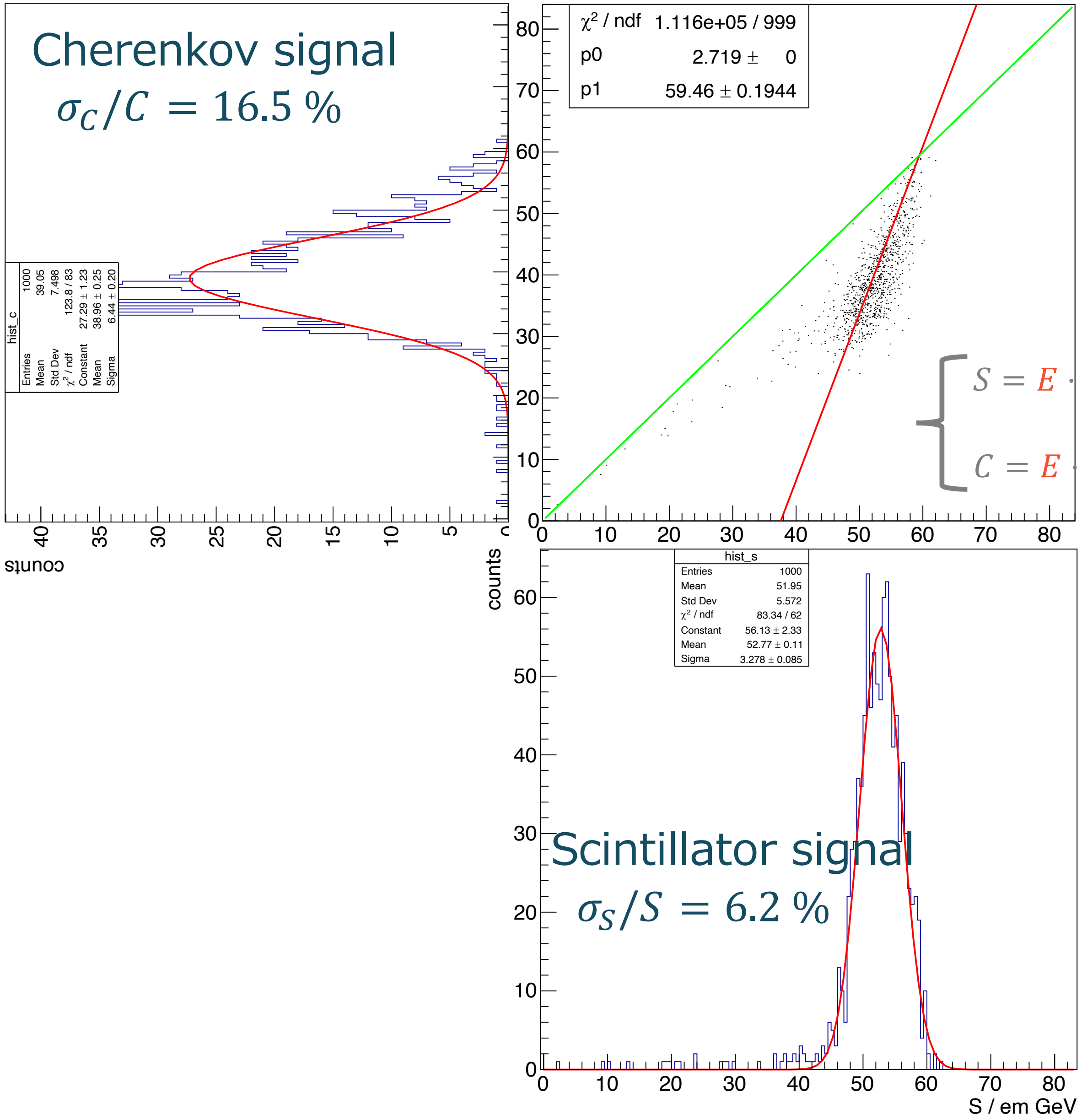
- Dual-Readout method:

$$\begin{cases} S = E \cdot \left[f_{\mathrm{em}} + \left(\frac{h}{e}\right)_s (1 - f_{\mathrm{em}})\right] \\ C = E \cdot \left[f_{\mathrm{em}} + \left(\frac{h}{e}\right)_c (1 - f_{\mathrm{em}})\right] \end{cases} \Rightarrow E_{\mathrm{DR}} = \frac{S - \chi C}{1 - \chi} \left(\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C} \right)$$

- In graphically understanding →



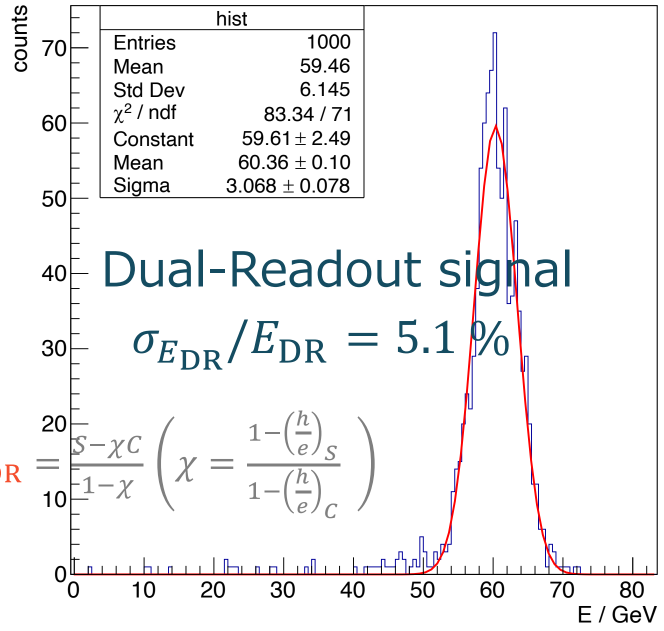
π^- 60 GeV (S, C) distribution



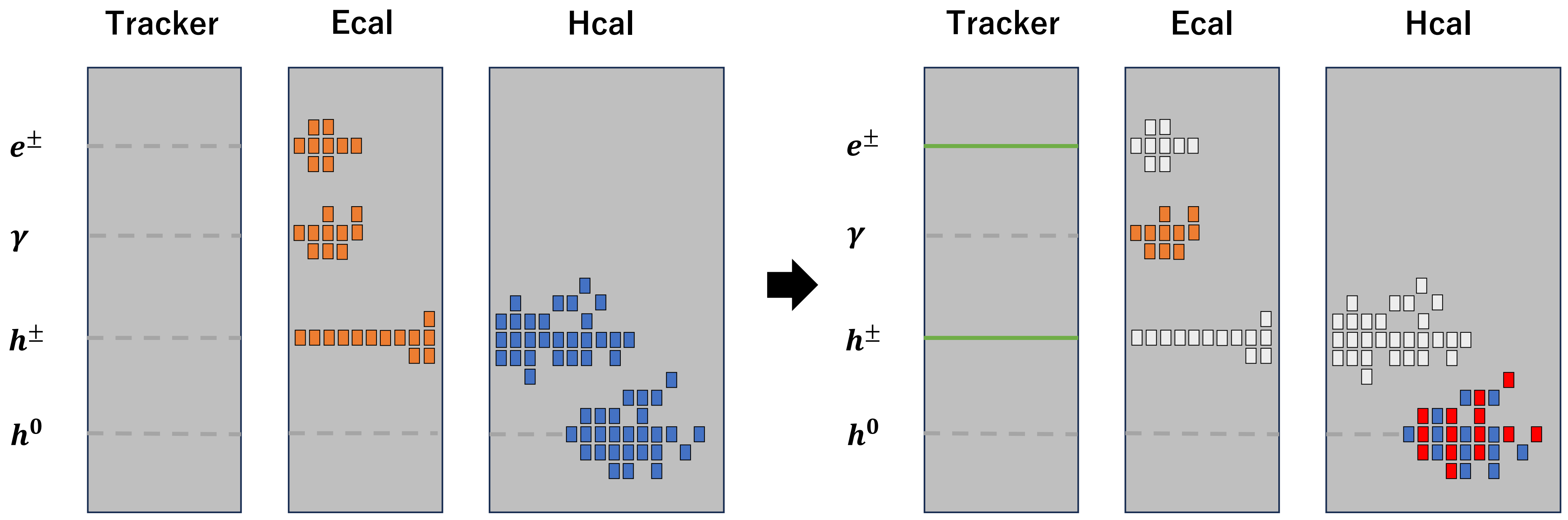
$$\begin{cases} S = E \cdot \left[f_{\text{em}} + \left(\frac{h}{e}\right)_S (1 - f_{\text{em}}) \right] \\ C = E \cdot \left[f_{\text{em}} + \left(\frac{h}{e}\right)_C (1 - f_{\text{em}}) \right] \end{cases}$$

$$E_{\text{DR}} = \frac{S - \chi C}{1 - \chi} \quad \left(\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C} \right)$$

π^- 60 GeV Dual-Readout



Concept of a new calorimeter



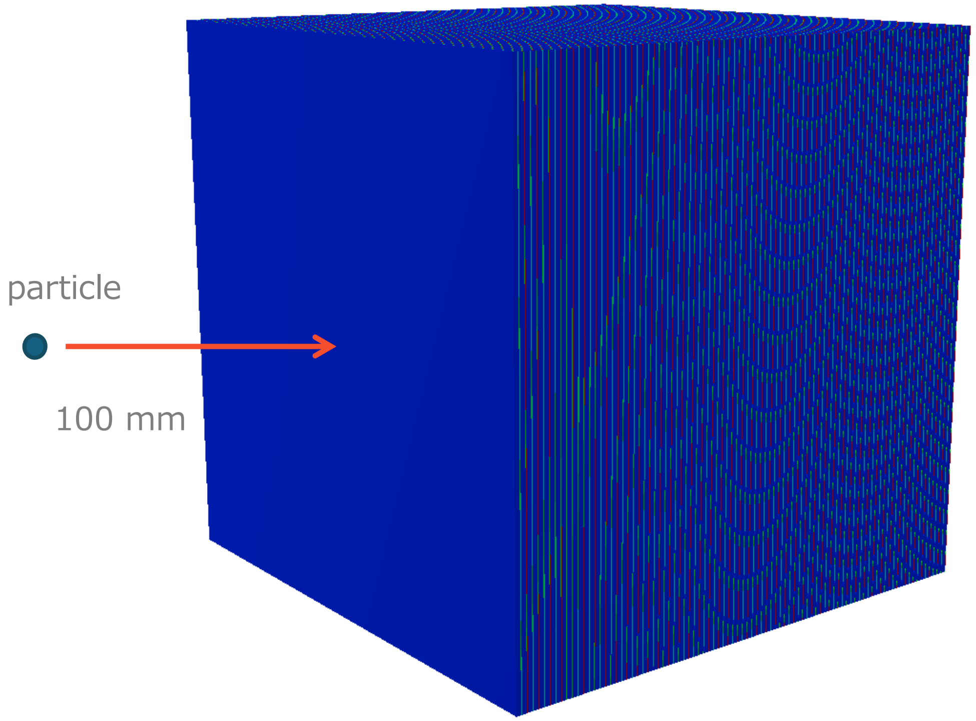
$E = E_{\mathrm{Ecal}} + E_{\mathrm{Hcal}}$

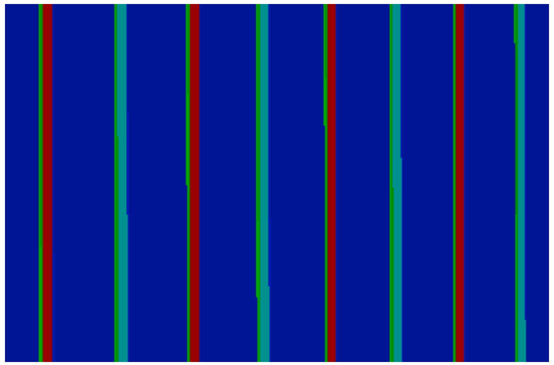
$E = E_{\mathrm{Tracker}} + E_{\mathrm{Ecal}} + E_{\mathrm{DR}}(S, C)$

Simulation

Simulation setup

Launch single 1000 events of e^-, π^- with $30, 40, 50, 60, 100, 150$ GeV into the center of the detector.

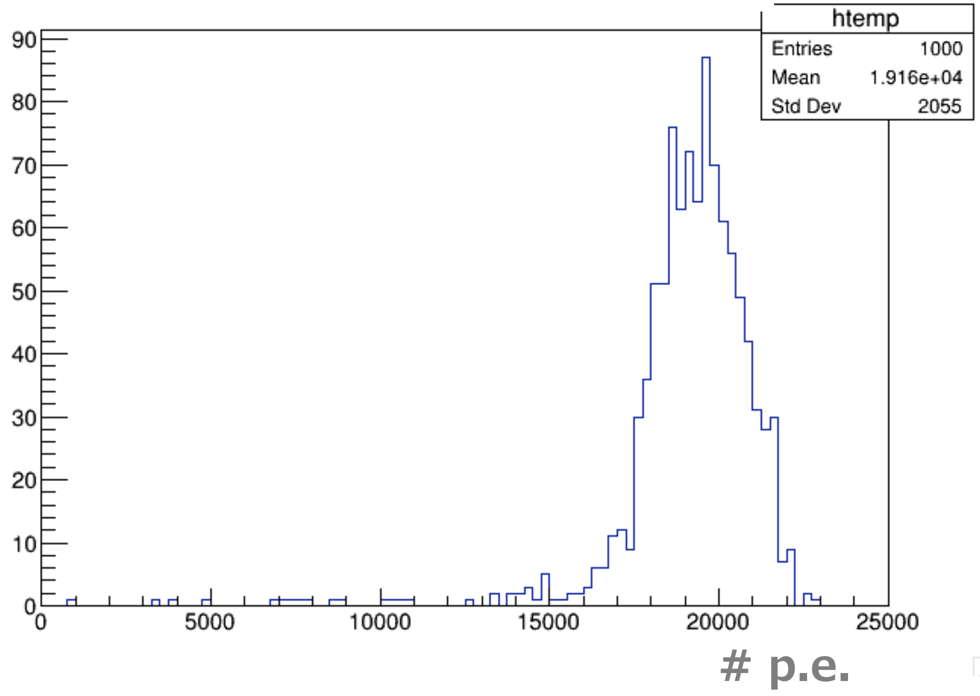




Scintillator signals

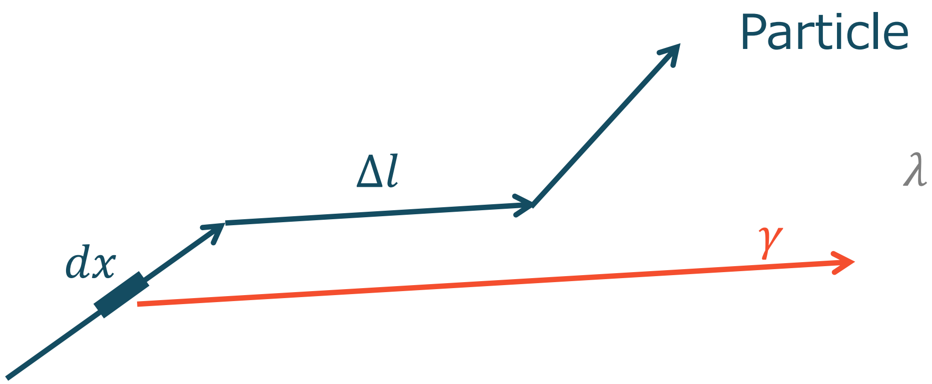
- Use p.e. assuming MPPC linear response.
- #p.e. = 0.0005 / MIP (3 mm thick)

$60\ \mathrm{GeV}\ \pi^{-}$



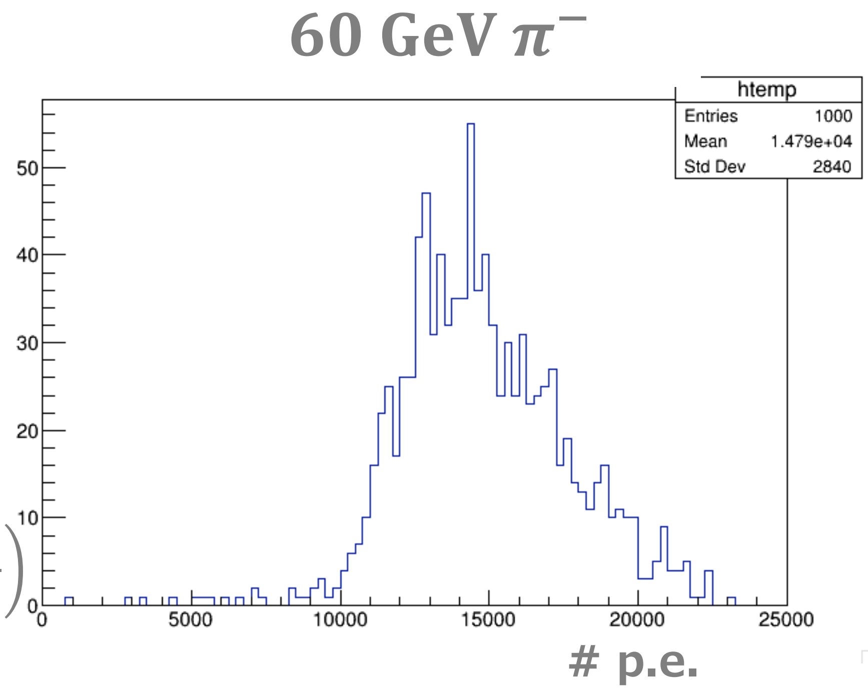
Cherenkov signals

- The number of generated Cherenkov photons:



$$\lambda = \lambda \sim \lambda + d\lambda, \quad dx,$$

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi Z^2\alpha}{\lambda^2}\left(1 - \frac{1}{n^2(\lambda)\beta^2}\right)$$



- # Digitized detected Cherenkov photons
  - Mean: $\hat{N}_{\mathrm{det}} = \Delta l \cdot \int_{\lambda_{\mathrm{min}}}^{\lambda_{\mathrm{max}}} \frac{2\pi Z^2\alpha}{\lambda^2}\left(1 - \frac{1}{n^2(\lambda)\beta^2}\right) \cdot \mathrm{QE}(\lambda) d\lambda$
  - Digitized: N_{det} = gRandom→Poisson($\hat{N}_{\mathrm{det}}$)

N: the number of Cherenkov photons

x: particle path length

λ: wavelength of Cherenkov photons

α: Fine-structure constant

Z: charge

- NIFS-V made from NIKON.

https://www.nikon.com/business/components/assets/pdf/sio2-e.pdf

Impurities

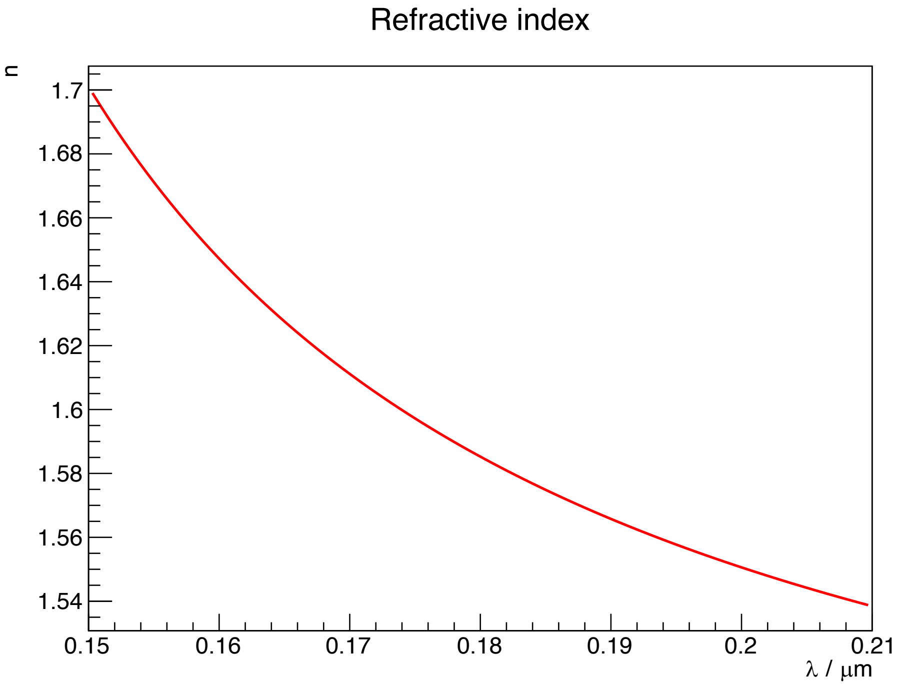
OH	< 100 ppm	Al	< 0.2 ppb
Li	< 0.2 ppb	Ti	< 0.2 ppb
Na	< 0.2 ppb	Cr	< 0.2 ppb
K	< 0.2 ppb	Fe	< 0.2 ppb
Mg	< 0.2 ppb	Cu	< 0.2 ppb
Ca	< 0.2 ppb		

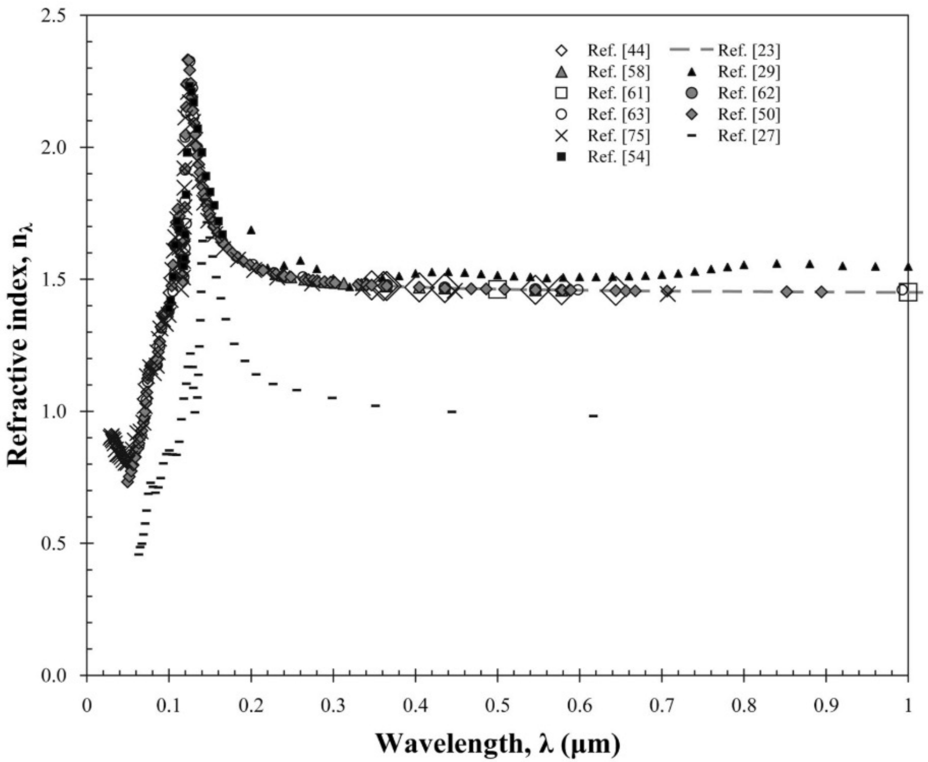
- Refractive index

$$n^2-1=\frac{P_1\lambda^2}{\lambda^2-Q_1}+\frac{P_2\lambda^2}{\lambda^2-Q_2}+\frac{P_3\lambda^2}{\lambda^2-Q_3}+\frac{P_4\lambda^2}{\lambda^2-Q_4}$$

Dispersion Coefficients *7	
P_1	6.40349086E-01
P_2	3.74308316E-01
P_3	8.97505390E-02
P_4	9.08924481E-01
Q_1	4.25379400E-03
Q_2	1.27798420E-02
Q_3	1.40044370E-02
Q_4	9.93231891E+01

- Checking refractive index





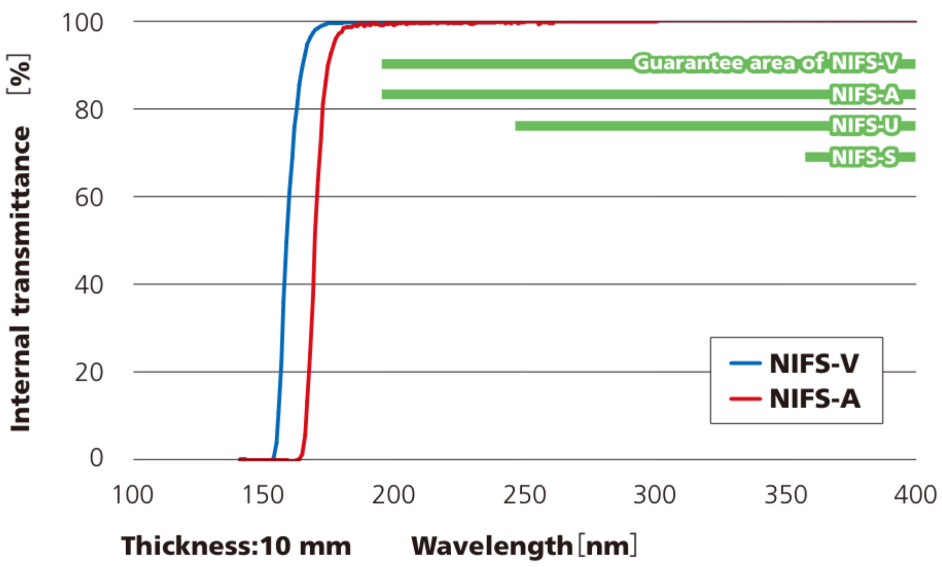
https://www.seas.ucla.edu/~pilon/Publications/AO2007-1.pdf

- Internal transmittance.

$$T[\%] = 0\ (\lambda < 150\ \mathrm{nm} = \lambda_{\mathrm{min}})$$

$$T[\%] = 10 \cdot (\lambda - 150\ \mathrm{nm})\ \ (\lambda < 160\ \mathrm{nm})$$

$$T[\%] = 100\ (\lambda \geq 160\ \mathrm{nm})$$



https://www.nikon.com/business/components/assets/pdf/sio2-e.pdf

- CsI photocathode
  - Assume ~ 10 %.
  - $\lambda < 200\ \mathrm{nm} = \lambda_{\mathrm{max}}$.

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/PMT_handbook_v4J.pdf

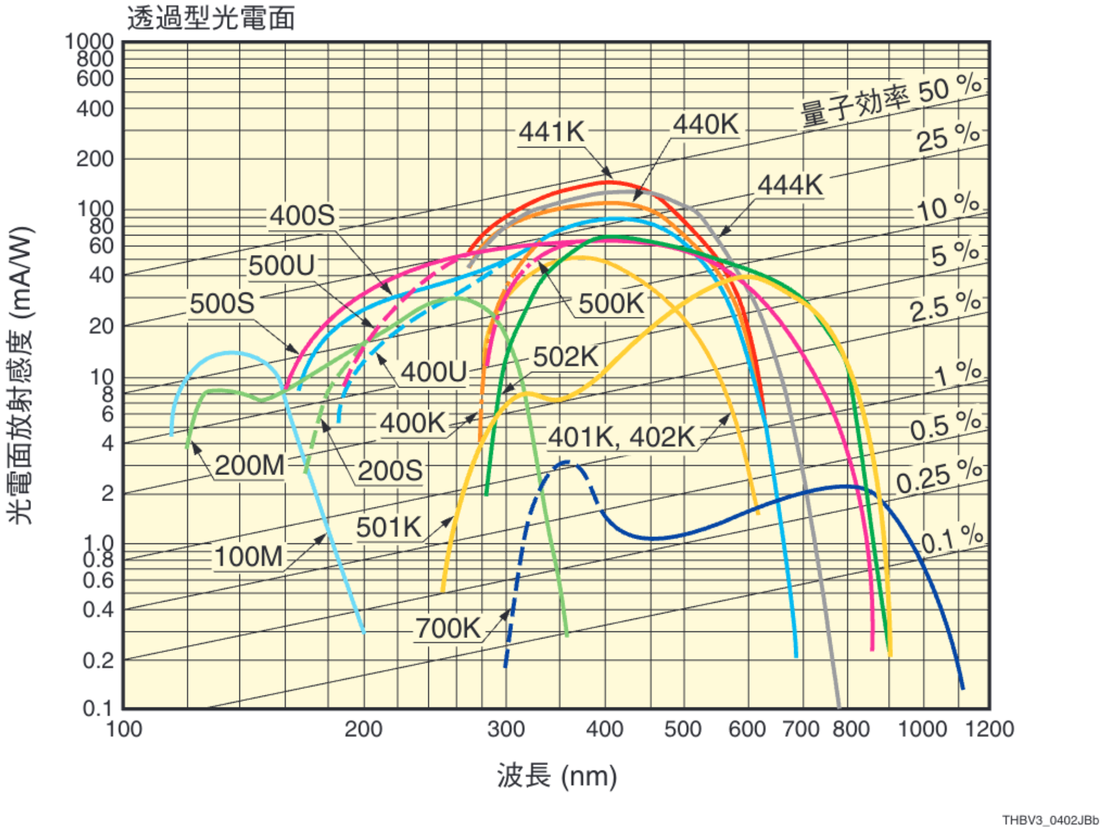


図 4-2(b) 透過型各種光電面分光感度特性

Calibration with EM component

- Showers caused by e^- has only EM components.

$$(\text{Output signals}) = k \cdot (\text{Initial particle energy})$$

- Using this k, reconstructing initial hadron energy from output hadron signals.

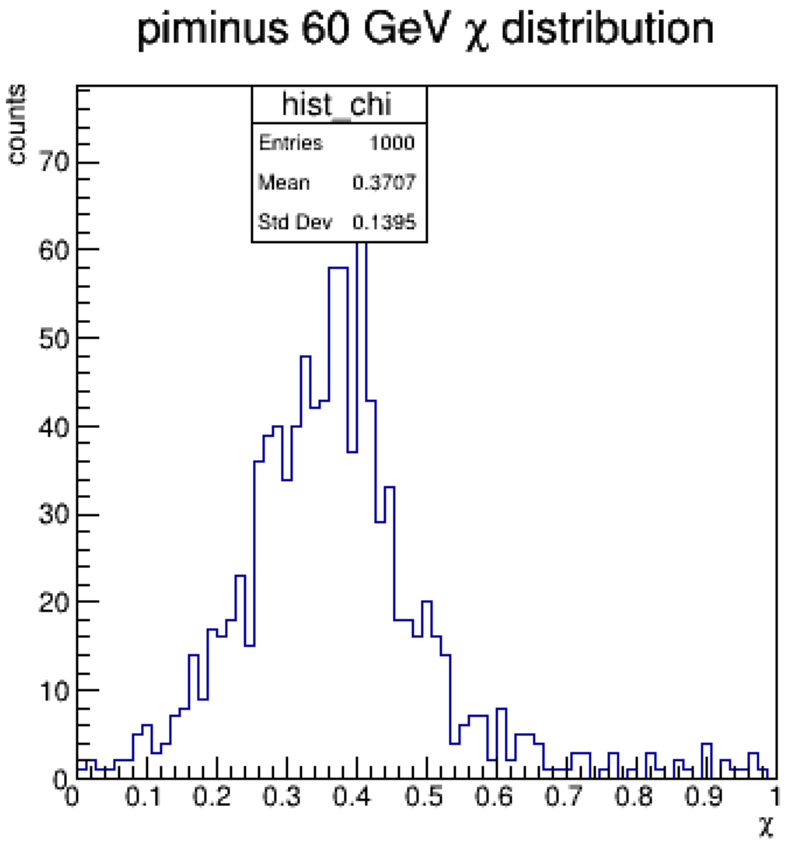
$$(\text{Reconstructed hadron energy}) = \frac{1}{k} \cdot (\text{Output hadron signals})$$

χ estimation

Using initial particle energy and solving

$$\chi = (S - E)/(C - E).$$

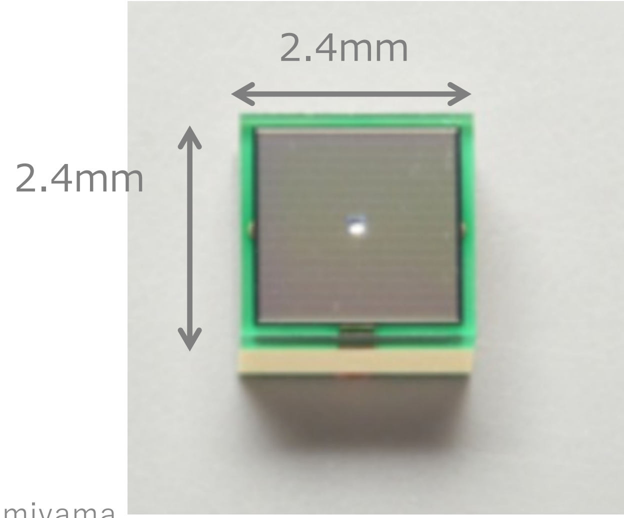
(use most probable value)



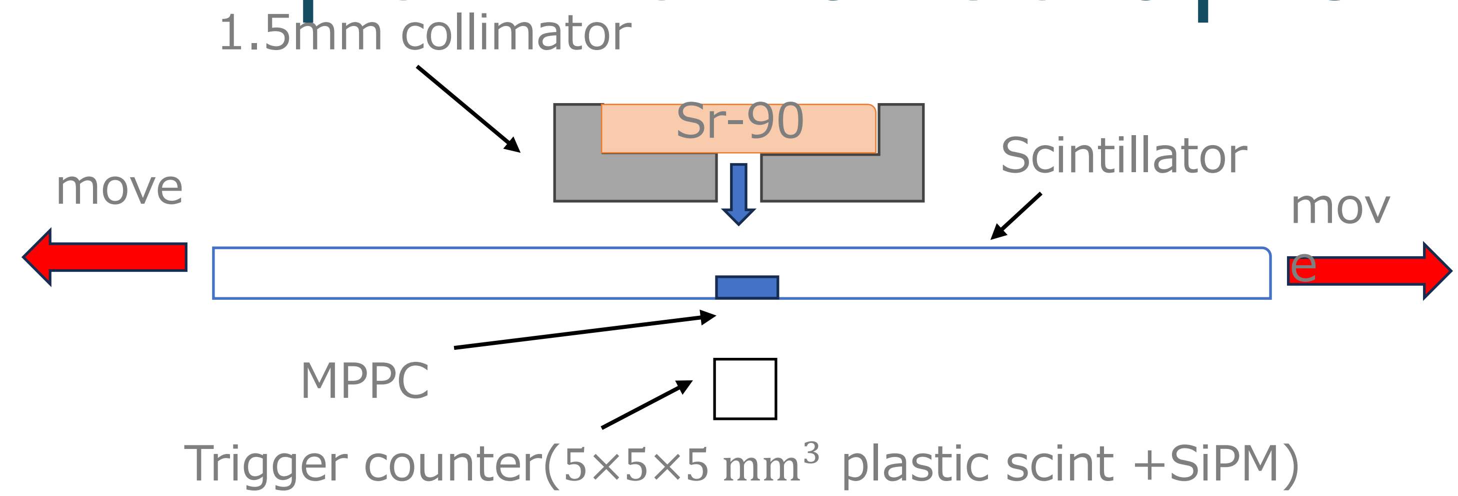
Scintillator strip

Strip and SiPM

- Scintillator
  - ELJEN EJ200, EJ232
  - 295mm×30mm×3mm
- SiPM
  - MPPC S13360-2050VE

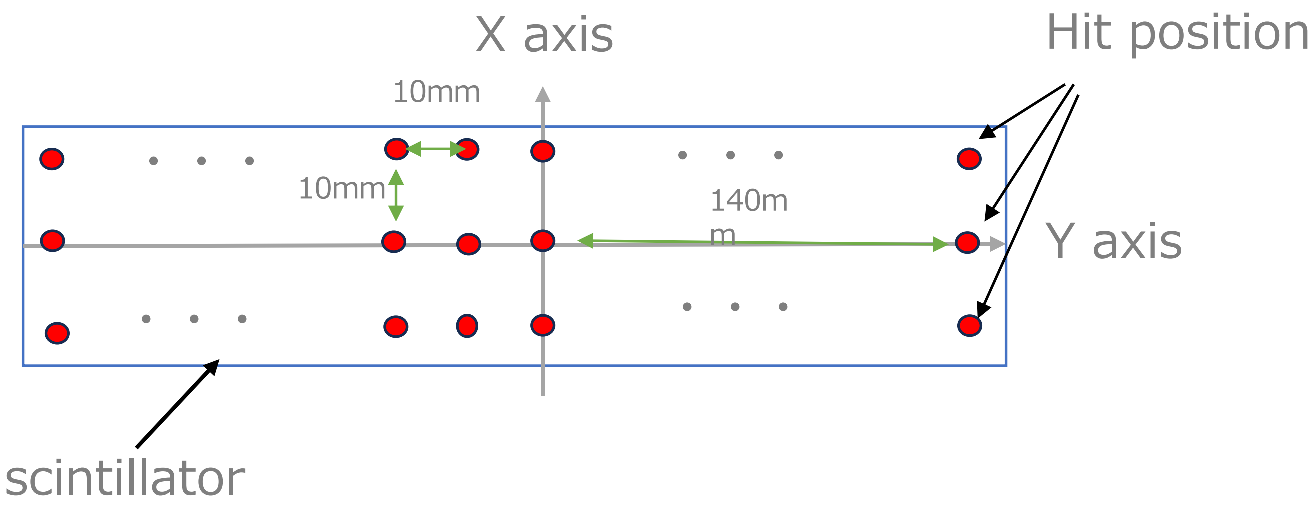


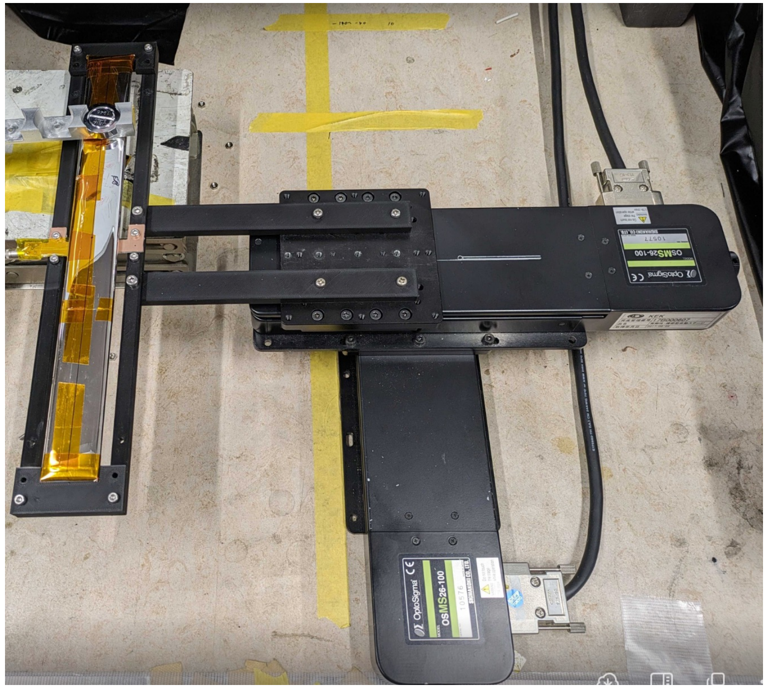
Experimental setup of position scan



Strip response measured with β from Sr-90

2D position scan with x-y moving stage



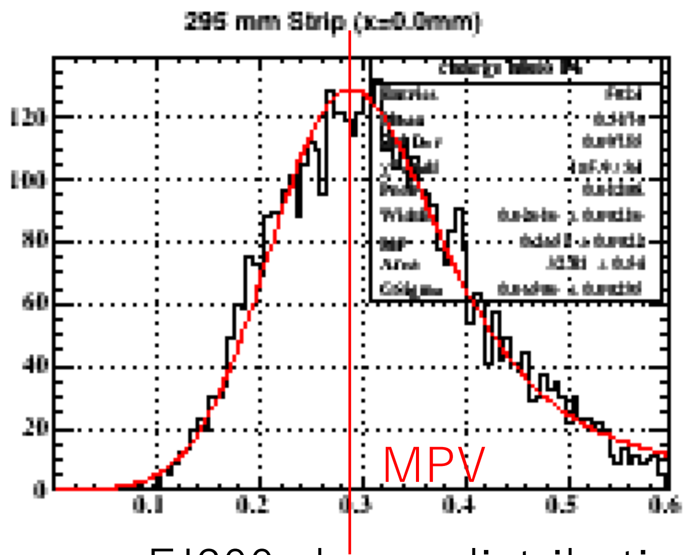


Analysis method

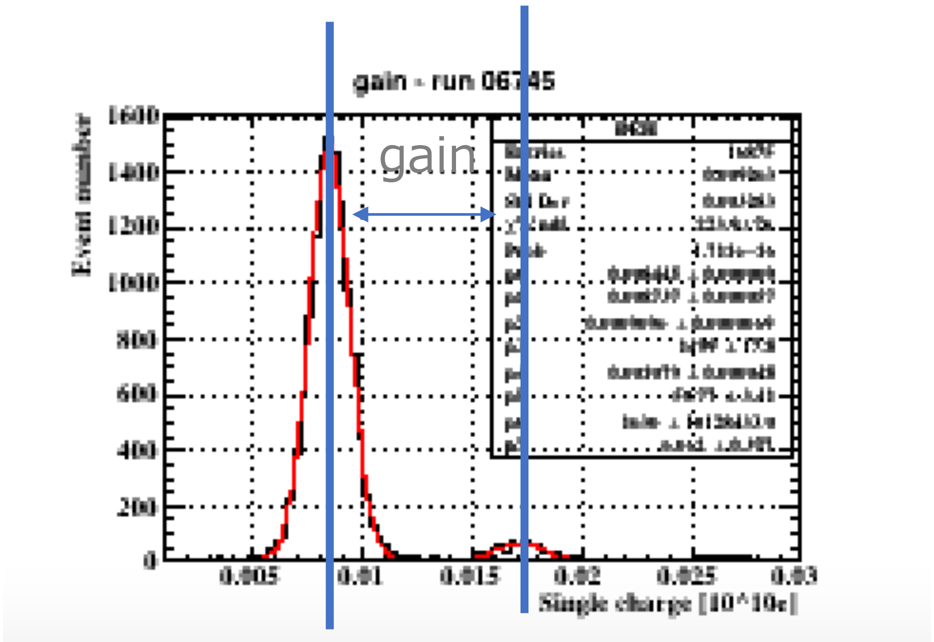
$$\text{Light Yied} = \frac{(\text{charge of scintillation})}{\text{gain}}$$

$$\text{Sum light yield} = (\text{Ch1 light yield}) + (\text{Ch2 light yield})$$

$$\text{Geometric mean lihgt yield} = \sqrt{(\text{Ch1 light yield}) \times (\text{Ch2 light yield})}$$



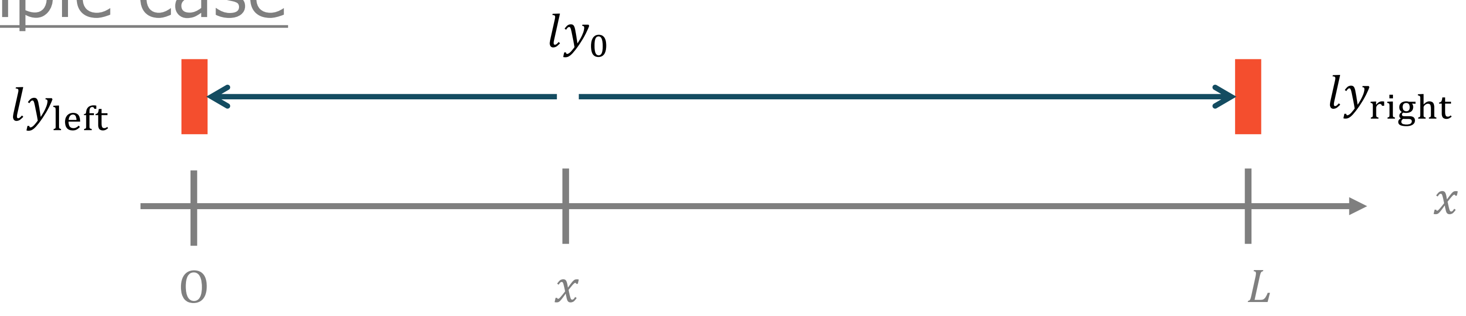
EJ200 charge distribution



Why a geometrical mean?

- For uniformly reconstructing light yield.

<u>Simple case</u>

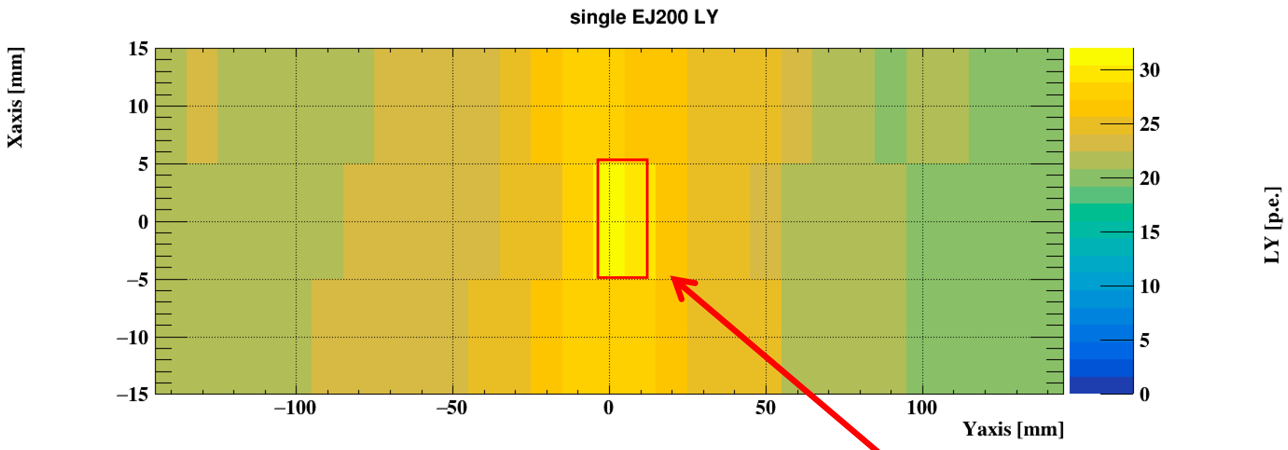


Attenuation length: λ

- Mean: $\frac{ly_{\mathrm{left}}+ly_{\mathrm{right}}}{2} = \frac{ly_0}{2}(e^{-\frac{x}{\lambda}} + e^{-\frac{L-x}{\lambda}})$
- Geometrical Mean: $\sqrt{ly_{\mathrm{left}} \cdot ly_{\mathrm{right}}} = ly_0 e^{-\frac{L}{2\lambda}}$

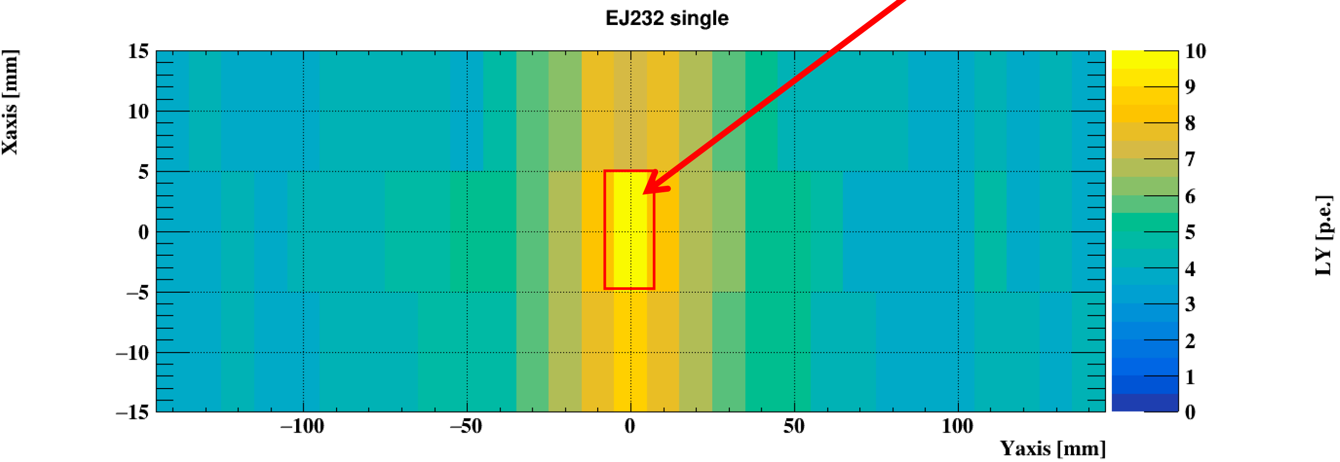
Single readout (EJ200 & EJ232)

EJ200 single light yield



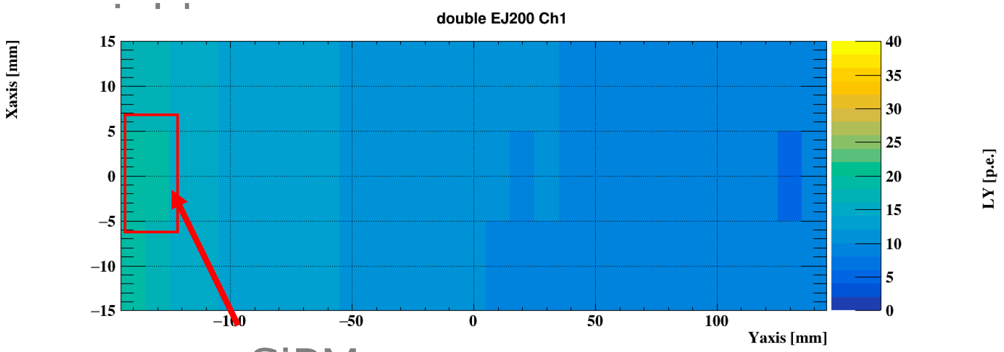
EJ232 single light yield

Dimple and SiPM



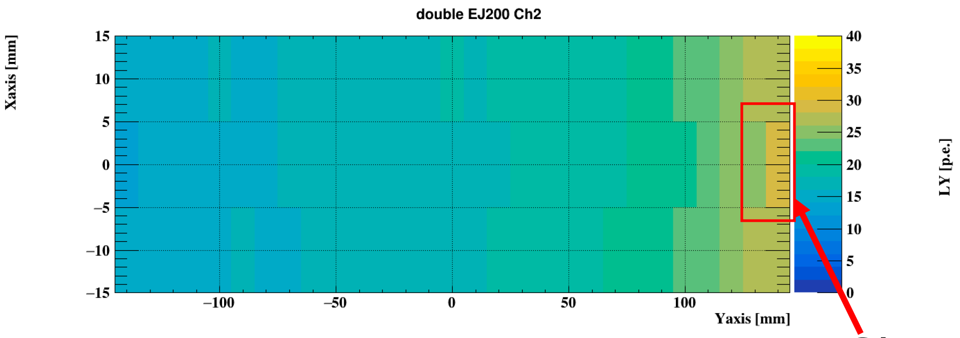
Double readout (EJ200)

Ch1 light



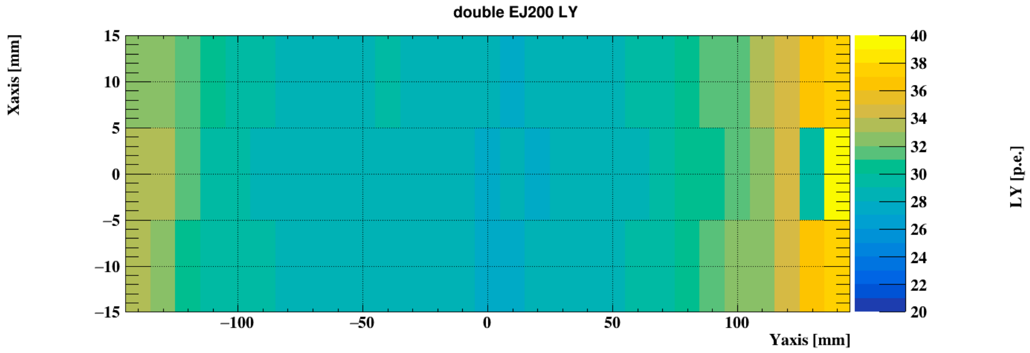
SiPM

Ch2 light yield

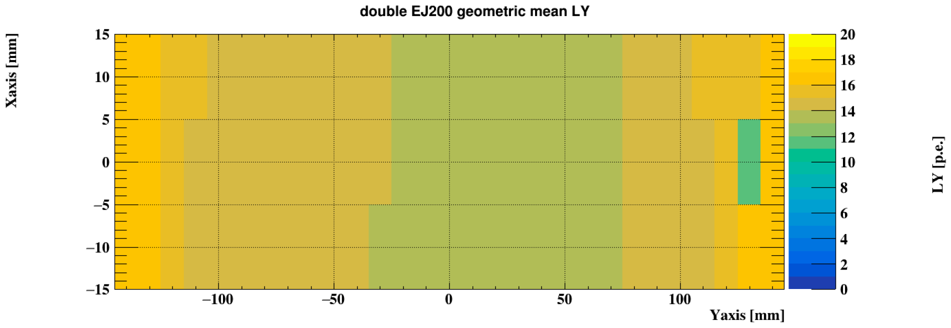


SiPM

ch1 and ch2 sum

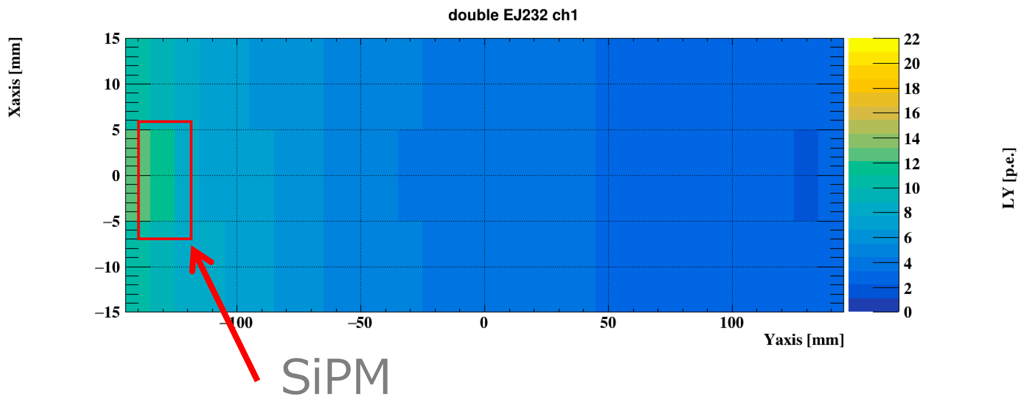


ch1 and ch2 geometric mean

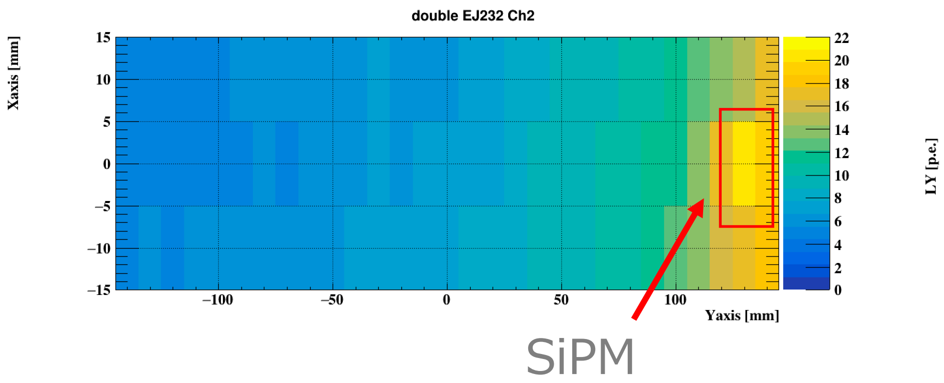


Double readout (EJ232)

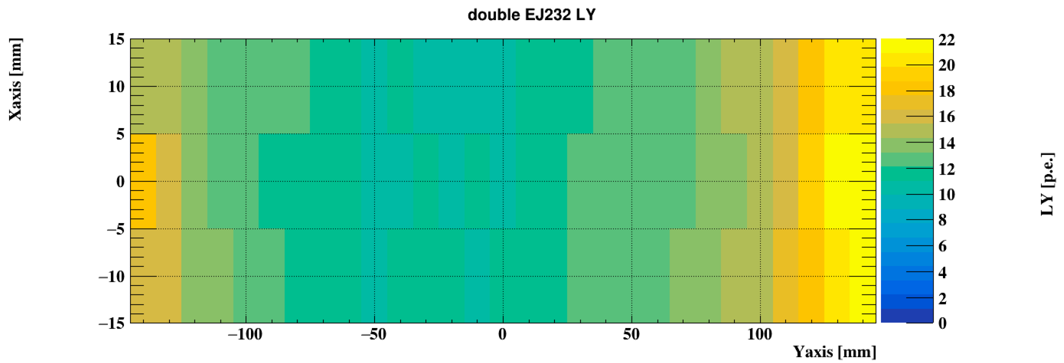
Ch1 light yield



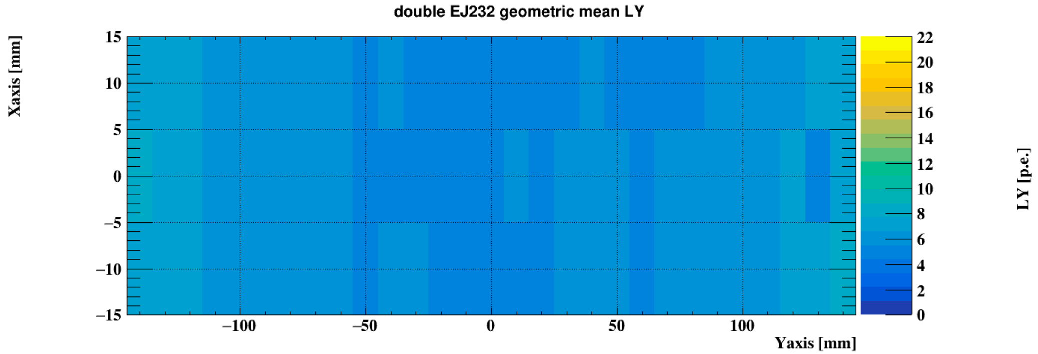
Ch2 light yield



Ch1 and ch2 sum

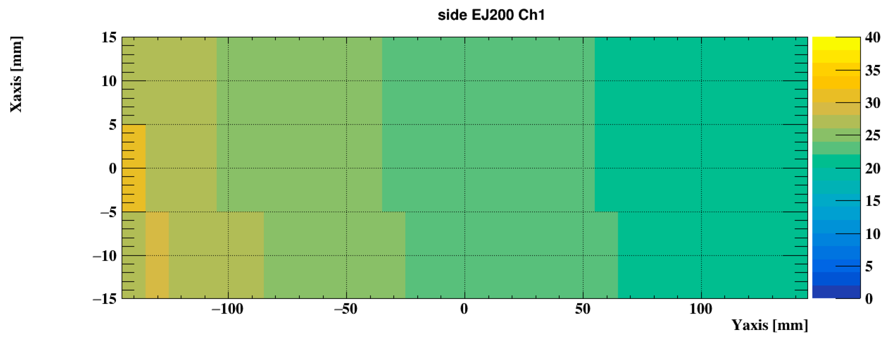


ch1 and ch2 geometric mean

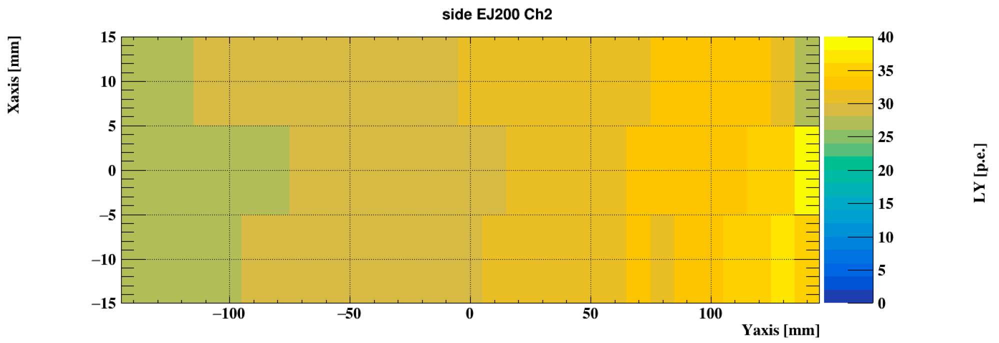


Side readout (EJ200)

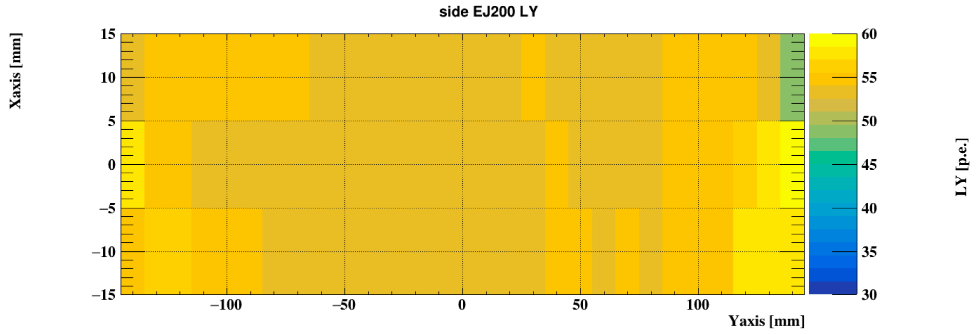
Ch1 at left side



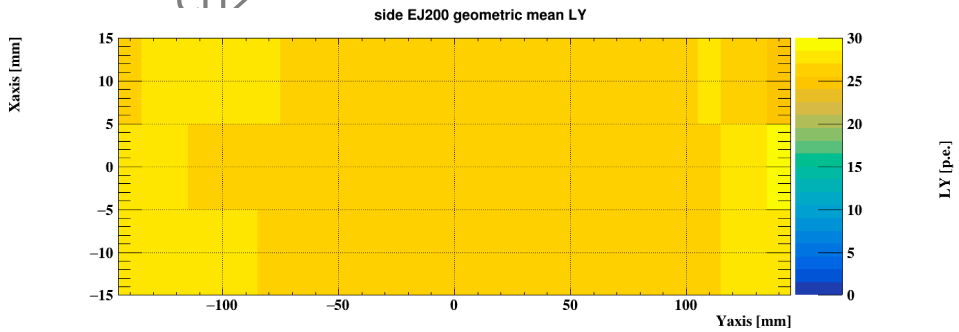
Ch2 at right side



Ch1 and ch2 sum

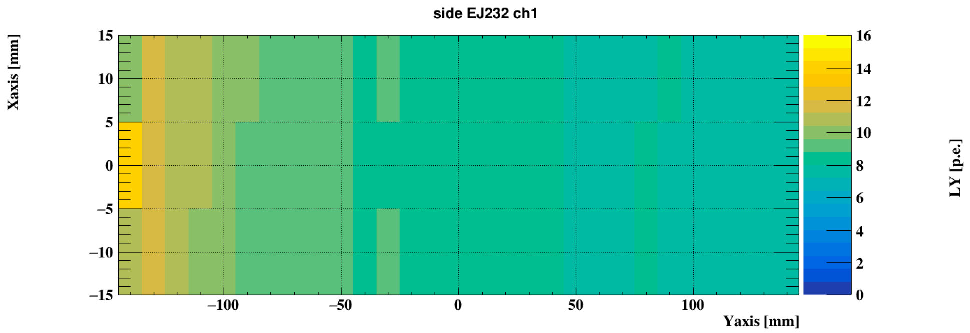


Geometric mean ch1 and ch2

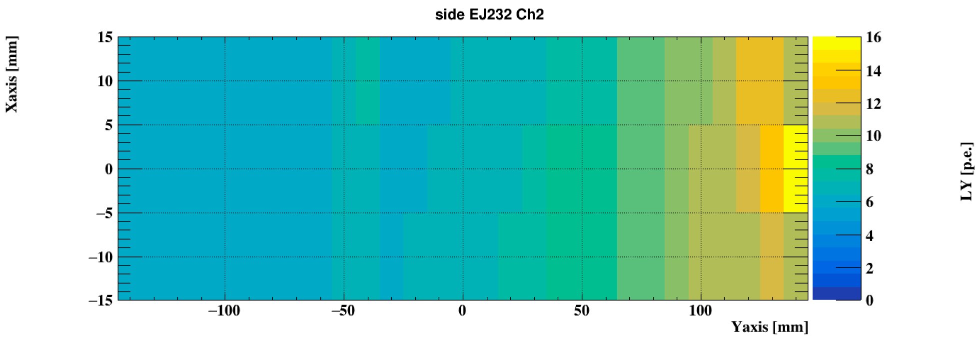


Side readout (EJ232)

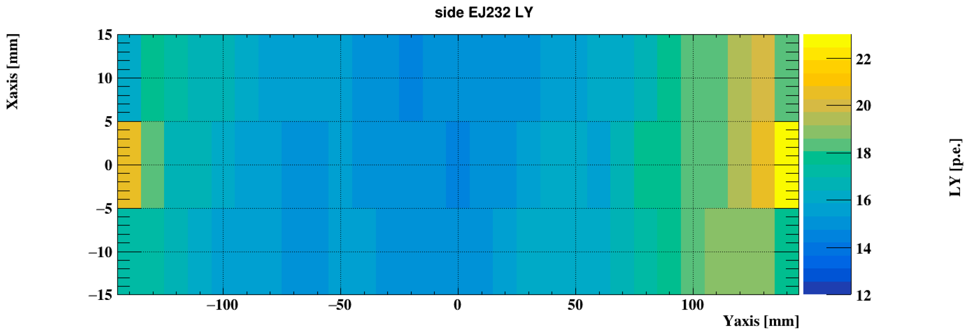
Ch1 at left side



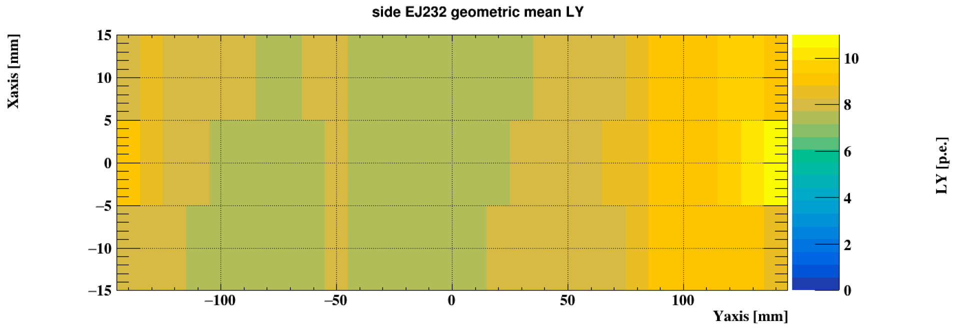
Ch2 at right side



Ch1 and ch2 sum

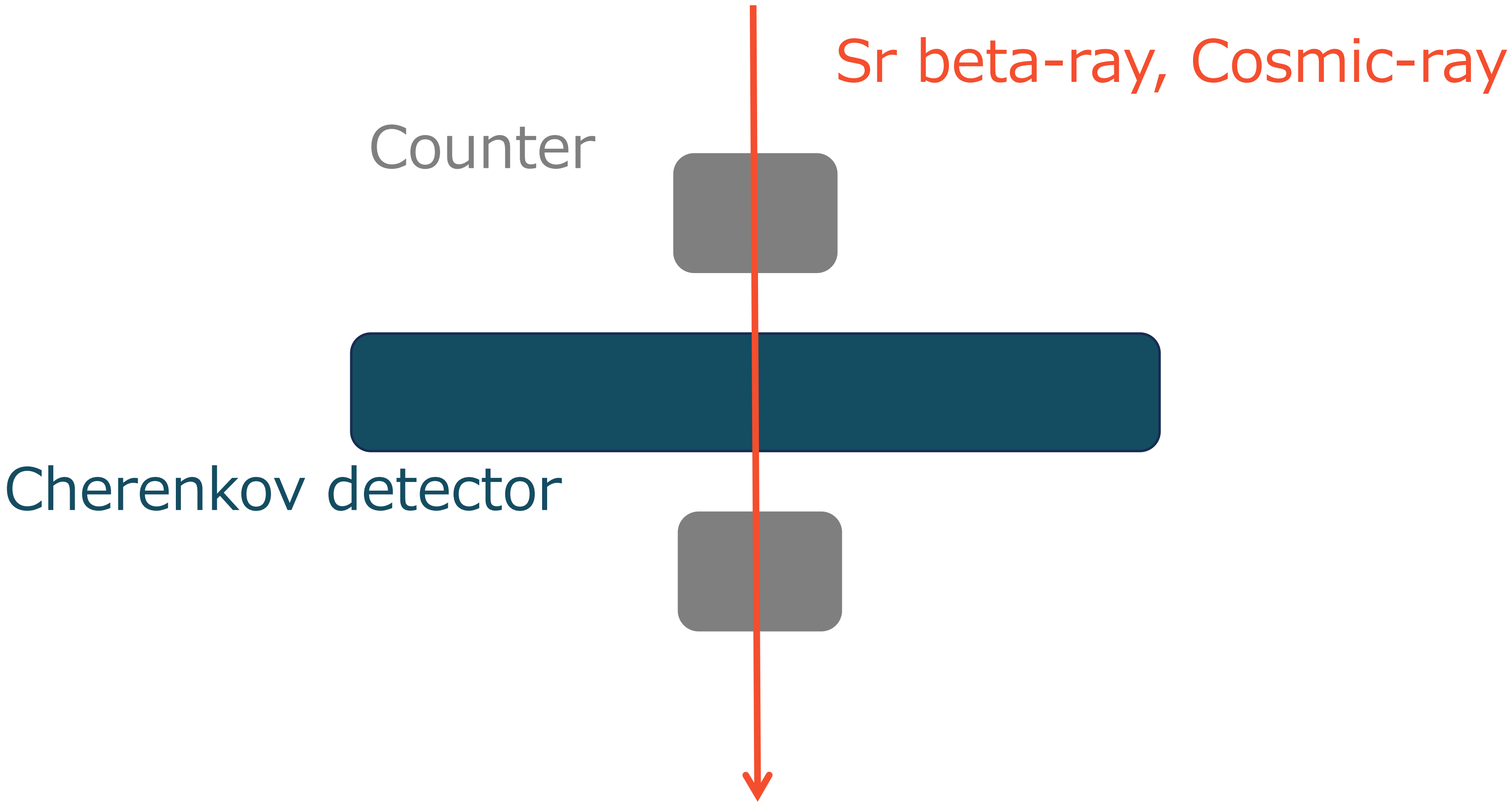


Geometric mean ch1 and ch2



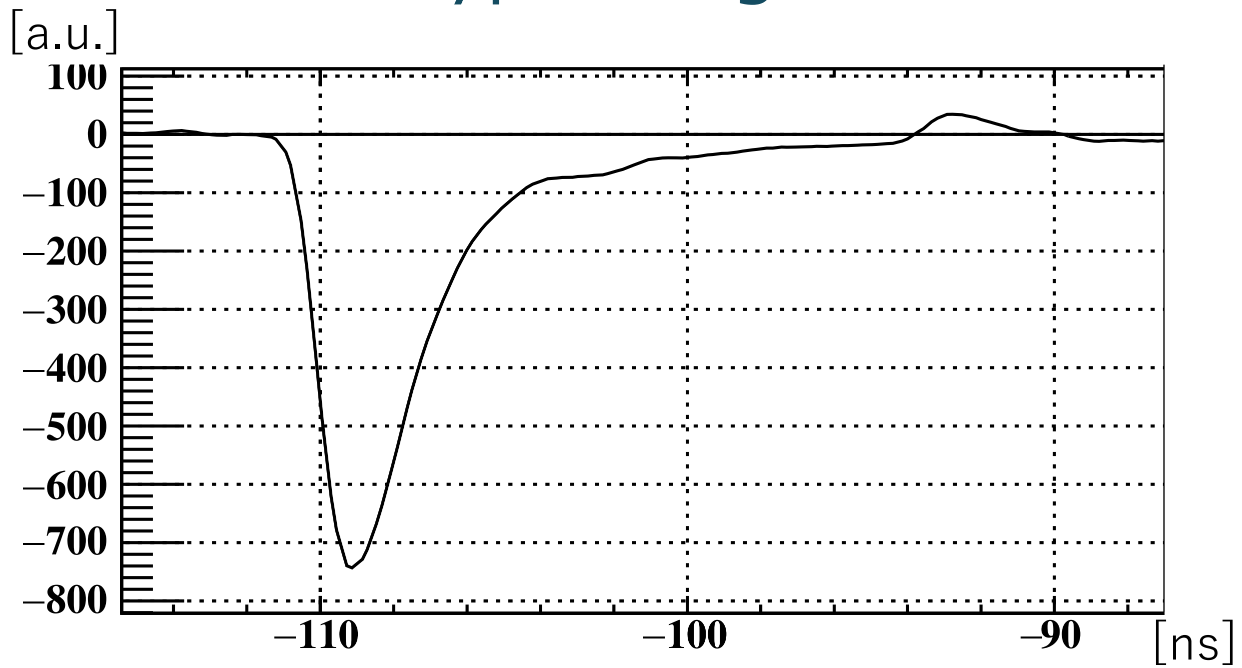
DLC-RPC Cherenkov detector

Experimental setup

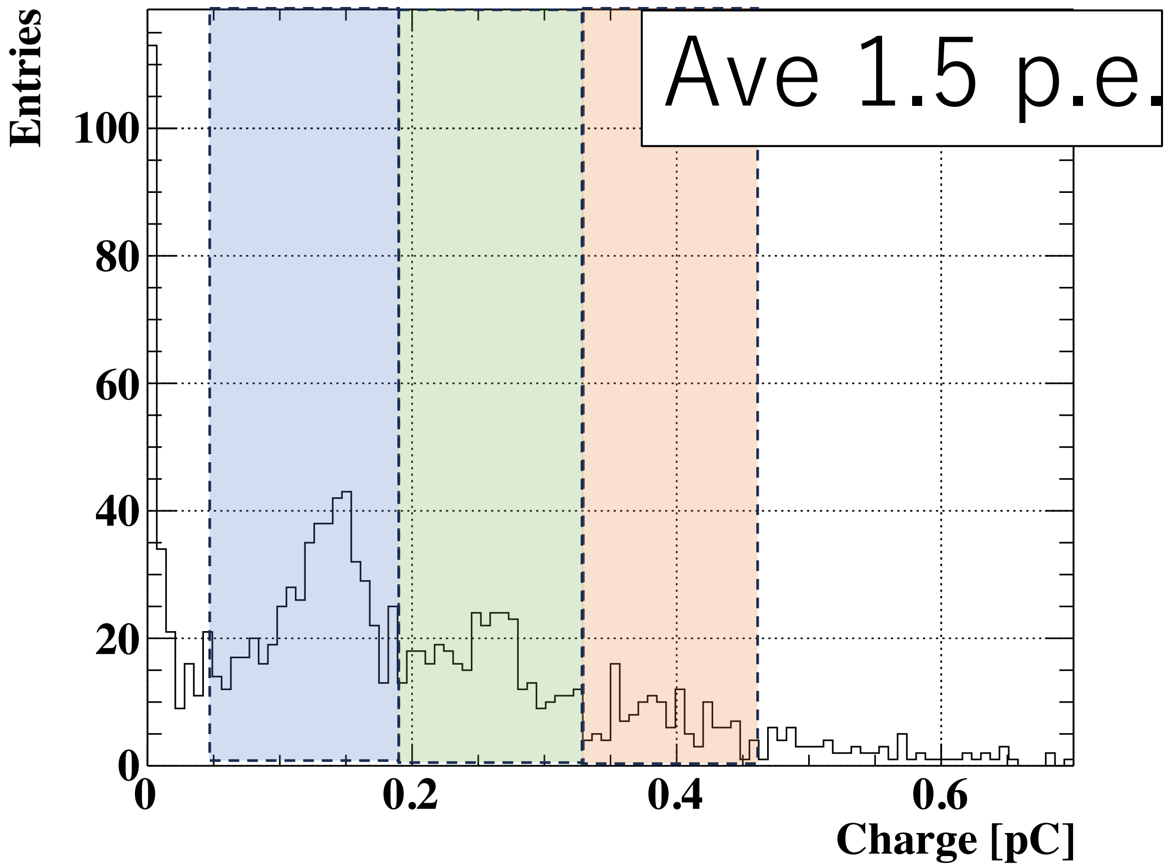


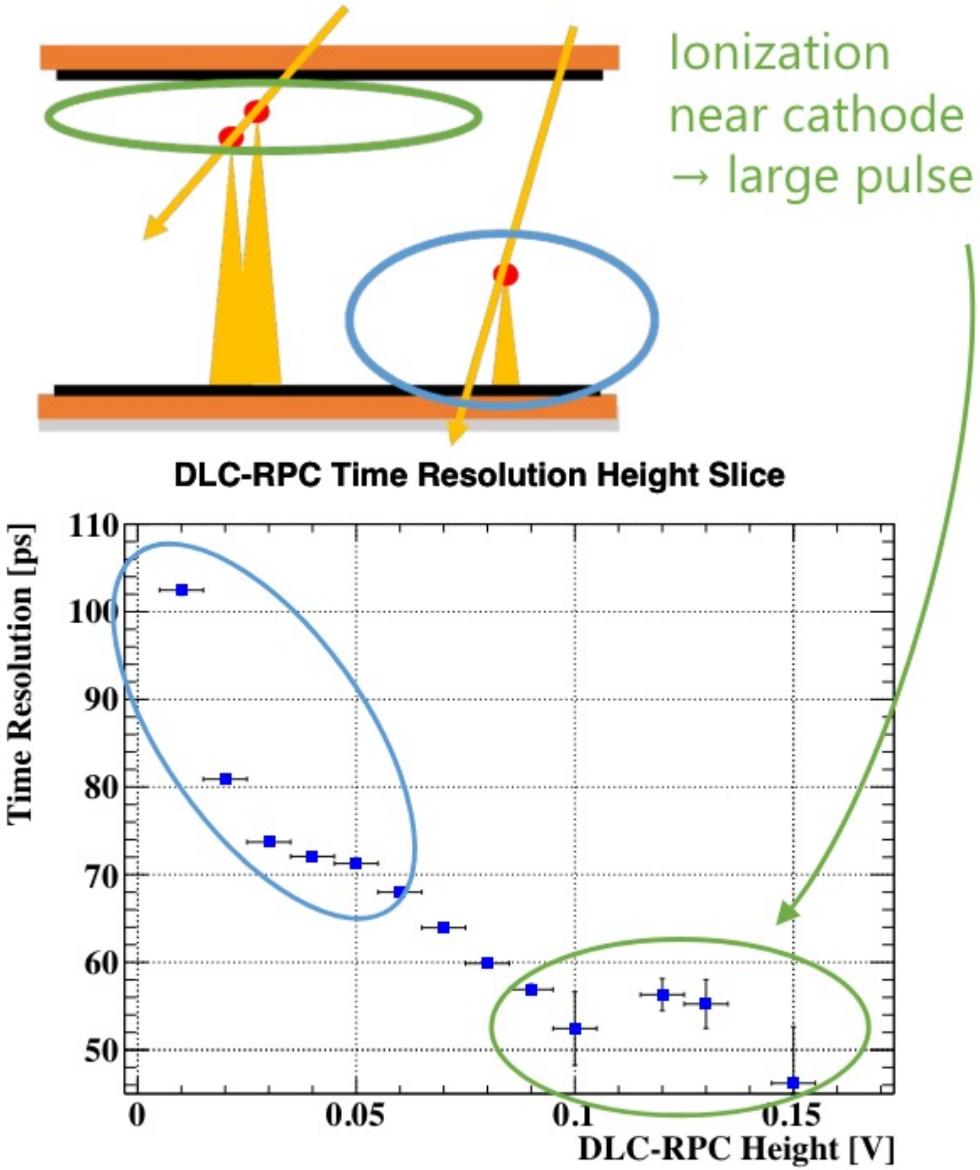
Data

Typical signal



Cosmic-ray test




Ionization
near cathode
→ large pulse
DLC-RPC Time Resolution Height Slice
Time Resolution [ps]
110
100
90
80
70
60
50
0
0.05
0.1
0.15
DLC-RPC Height [V]