LCWS2024 International Workshop on Future Linear Colliders

Development of next-generation calorimeter combining high-granularity and dual-readout calorimeter with psec-timing

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Fermilab KEK SHINSHU UNIVERSITY ICEPP The University of Tokyo NIU

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Outline

- Concept of next-generation calorimeter
- Sub-detector development
  - Cherenkov detector
  - Scintillation detector
- Performance study by simulation
- Summary and prospect

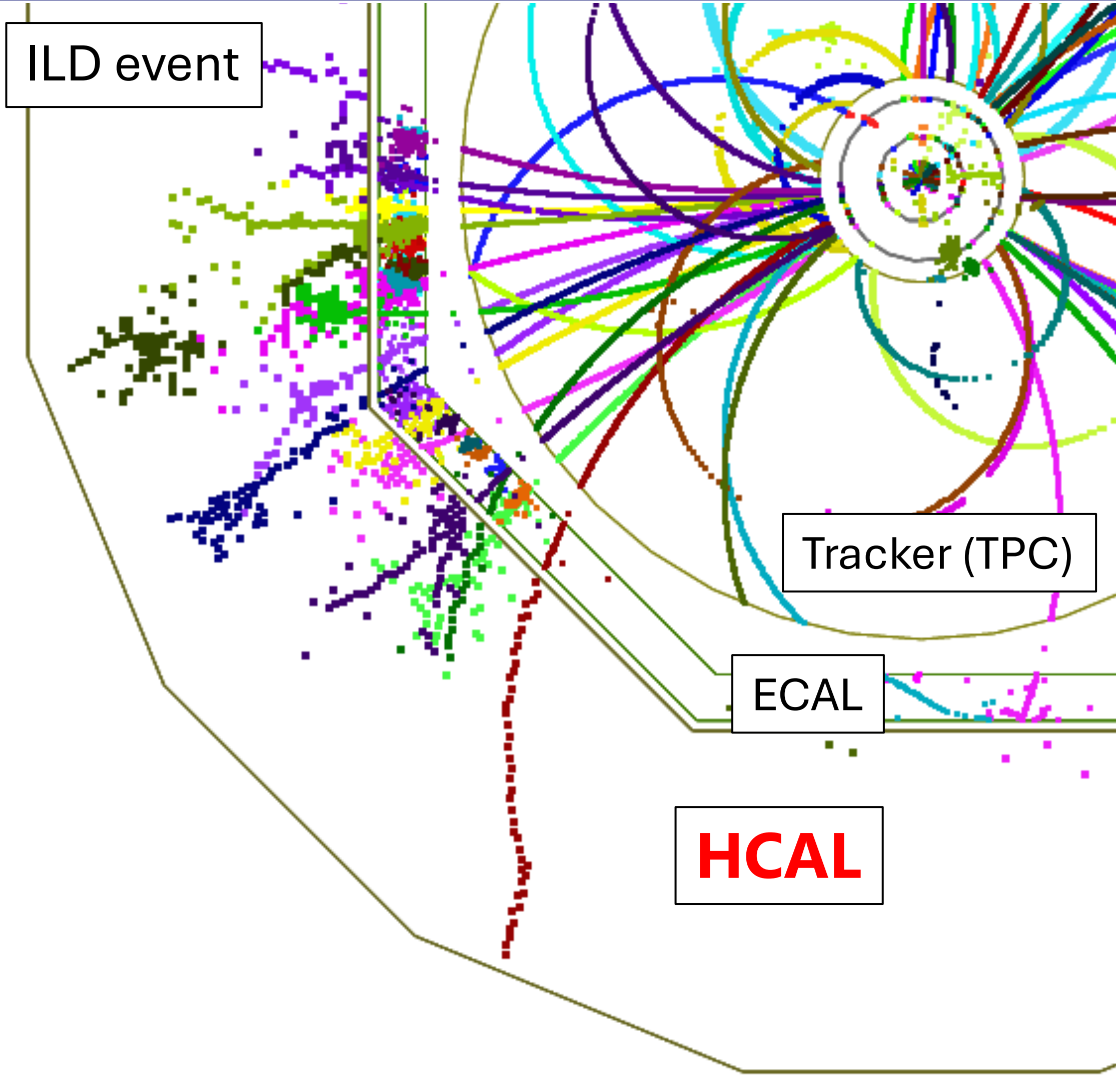
Concept of Next-generation Calorimeter

Calorimeter in collider experiment

We should focus on precision measurement of the Higgs sector for the next-generation collider experiments

- Most of the final state includes multiple jet
- Jet energy resolution is crucial for modern collider experiment
  - ~ 3% for broad energy scale
  - 70% of energy deposit in hadron calorimeter
  - However, energy resolution of HCAL is poor

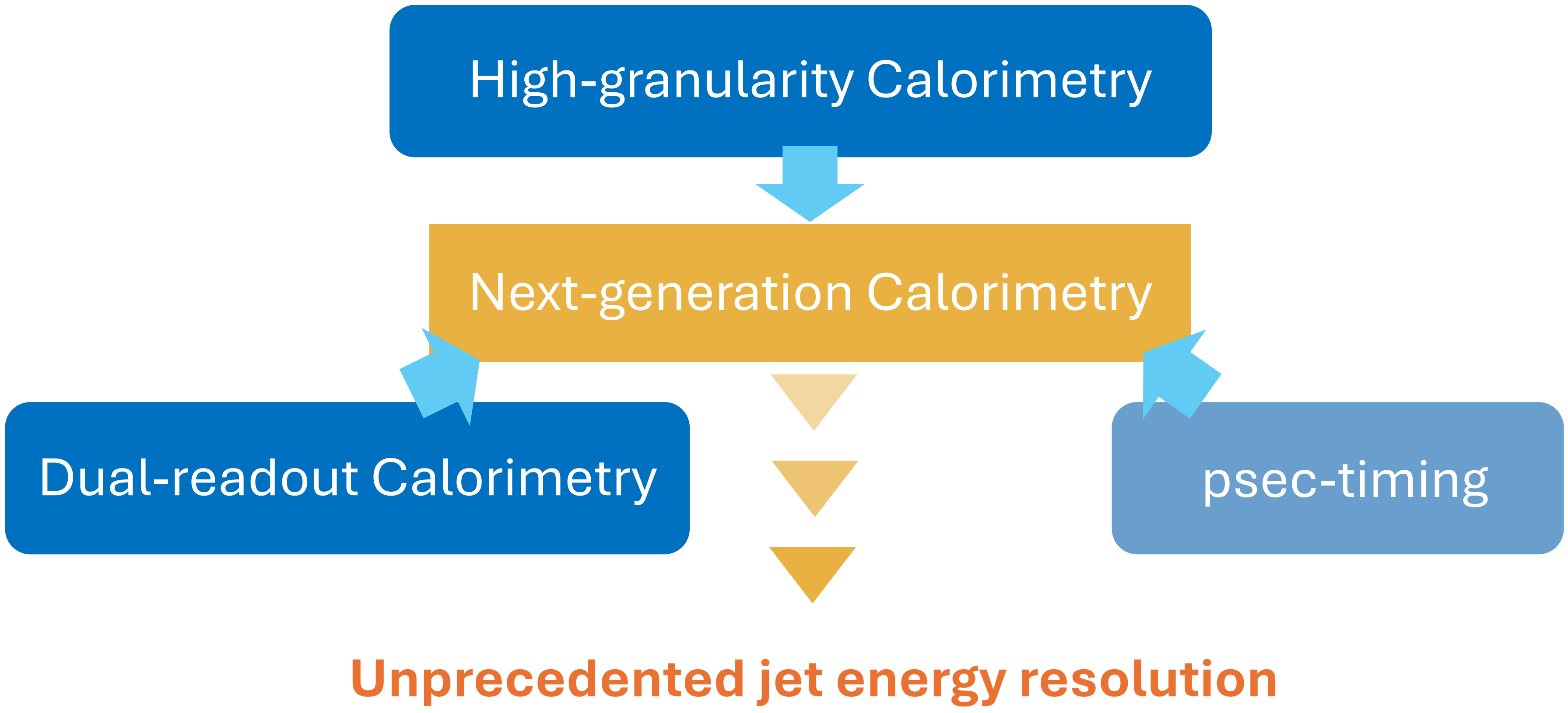
    → Due to complex interaction by hadrons



https://www-jlc.kek.jp/~miyamoto/evdisp/html/index.html

Concept of next-generation calorimeter

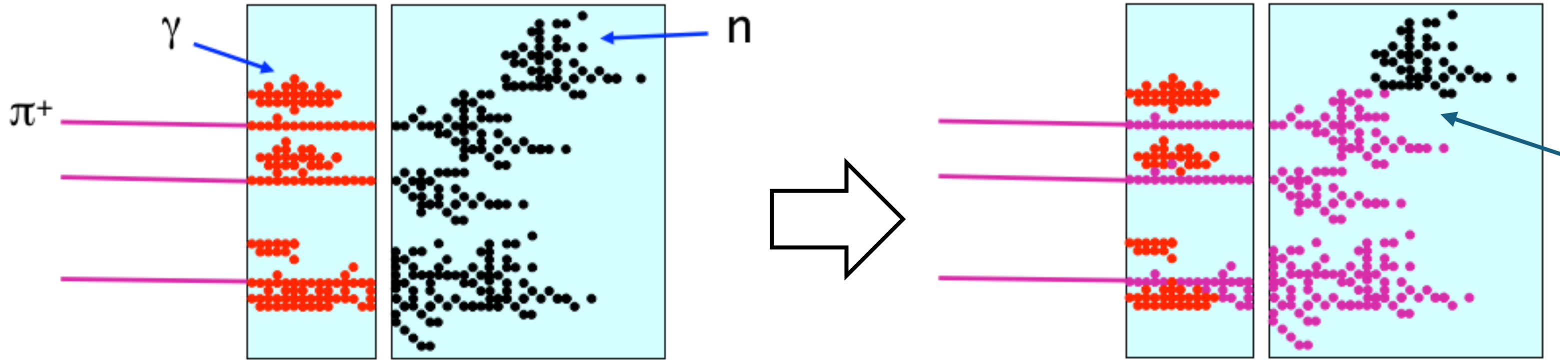
Combine two calorimeter technology in corporation with psec-timing



High-granularity

Particle flow algorithm

Use best suited detector for energy measurement considering particle species



$E_{JET} = E_{ECAL} + E_{HCAL}$

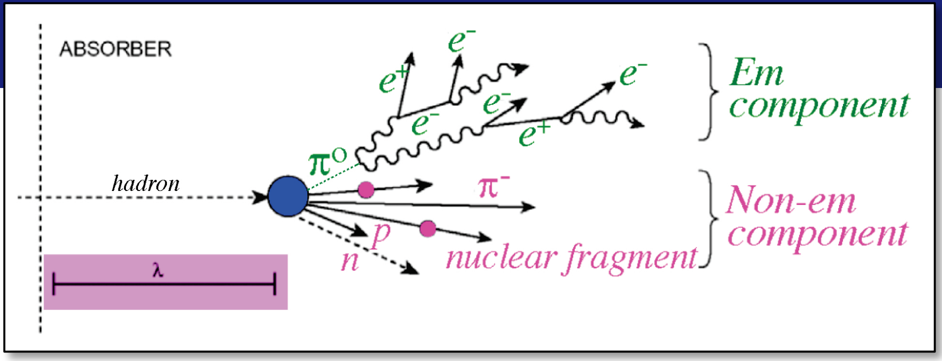
$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

Granularity required to separate different showers

Drawback: Large number of channels

▶ Mainly cultivated by CALICE collaboration

Dual-readout



Energy compensation of hadronic shower by scintillation and Cherenkov radiation

" event-by-event measurement of f_{em} "

$$S = E \cdot \left[f_{\mathrm{em}} + \left(\frac{h}{e}\right)_s (1 - f_{\mathrm{em}})\right]$$

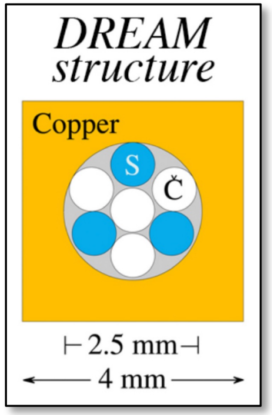
$$C = E \cdot \left[f_{\mathrm{em}} + \left(\frac{h}{e}\right)_c (1 - f_{\mathrm{em}})\right]$$

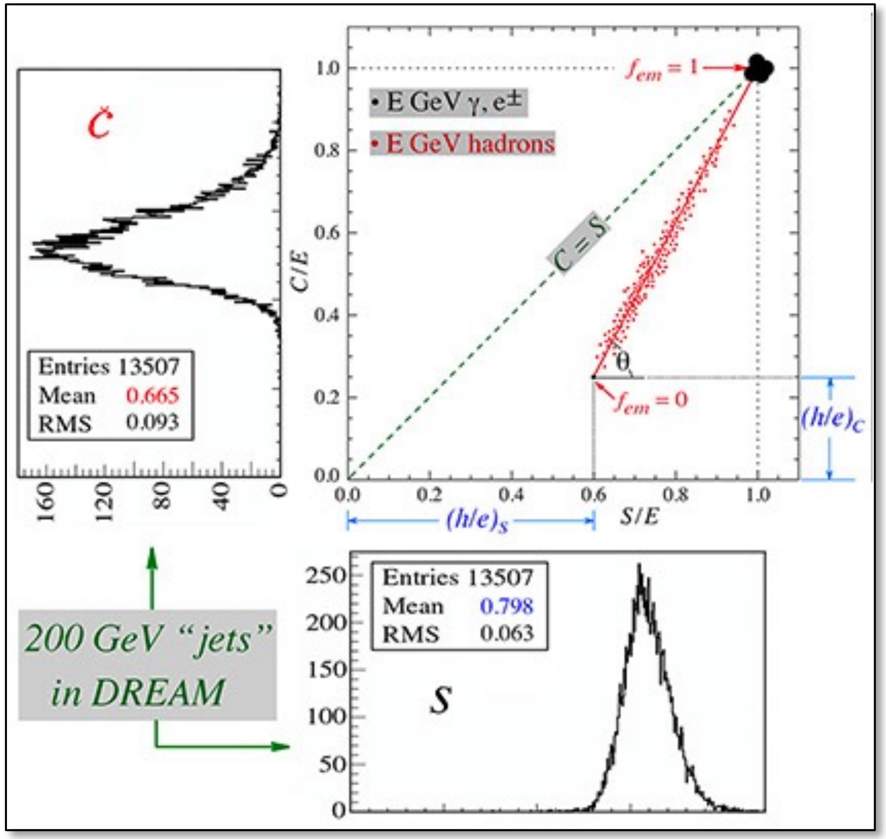
▶

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

Independent of f_{em}

- $\left(\frac{h}{e}\right)_S, \left(\frac{h}{e}\right)_C$: 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.



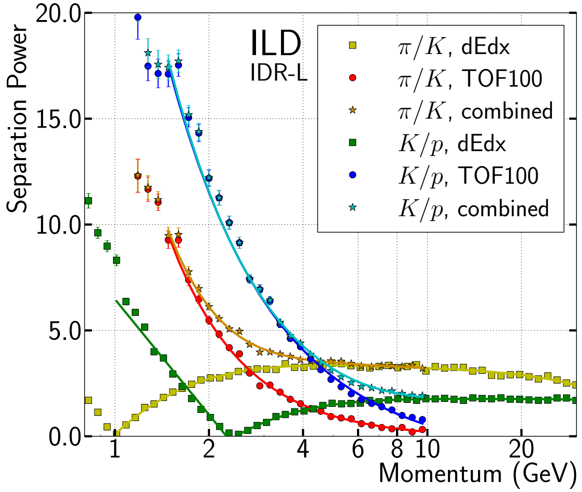


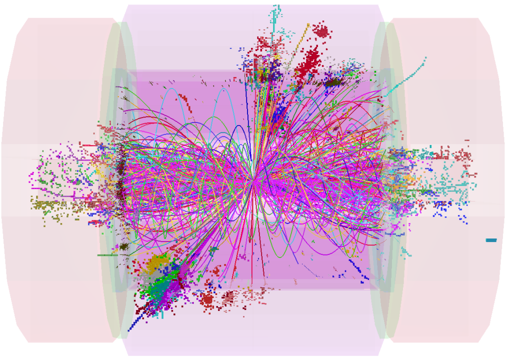
▶ Mainly studied by DREAM and RD52 collaboration
*Fiber-based calorimeter

psec-timing

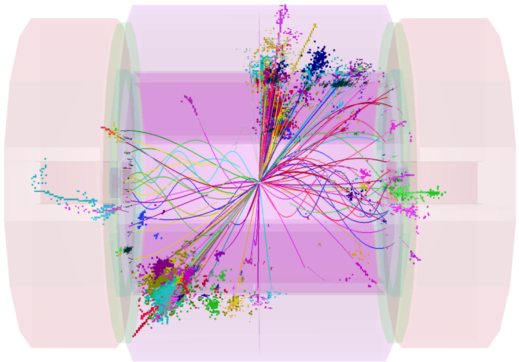
Timing as additional information

- PID by TOF
- Timing cut by detected time in calorimeter
  - Pile-up reduction
  - Reject off-timing background
- Timing as additional input for PFA
  - Clustering by hit timing in calorimeter



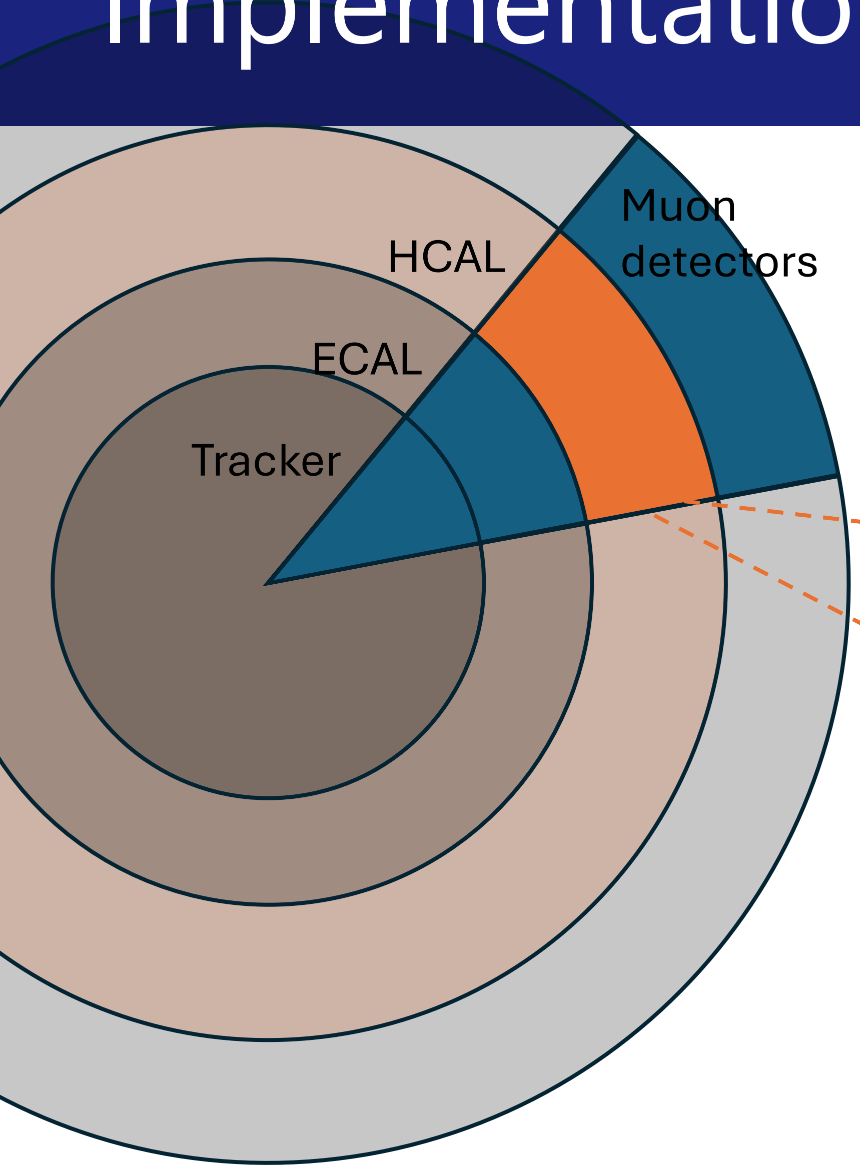


w/o timing cut



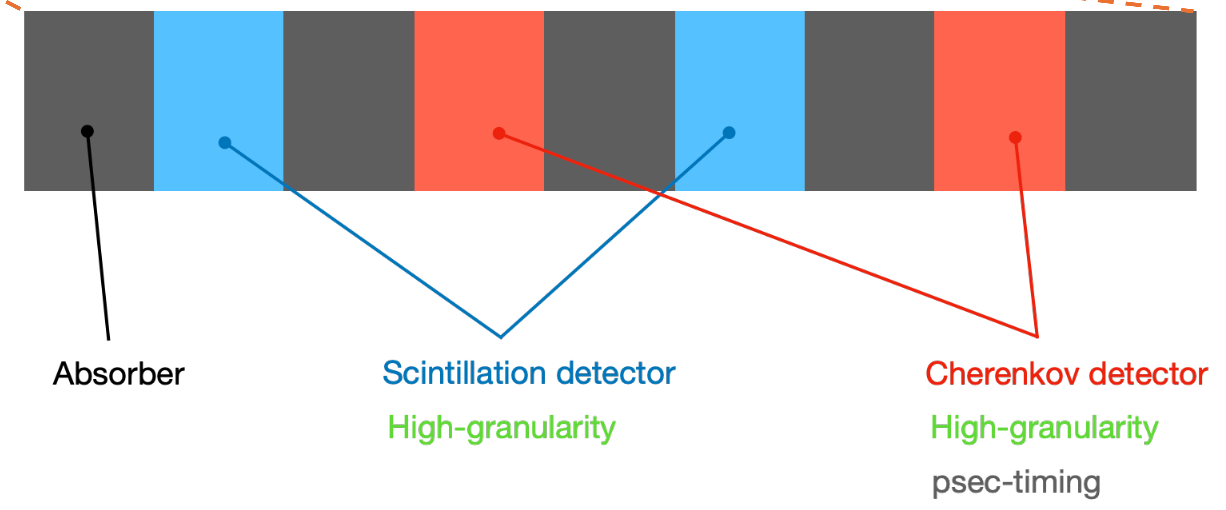
w/ timing cut

Implementation



Simulation study of performance by combination of PFA + dual-readout and psec HCAL

Sub-detector development



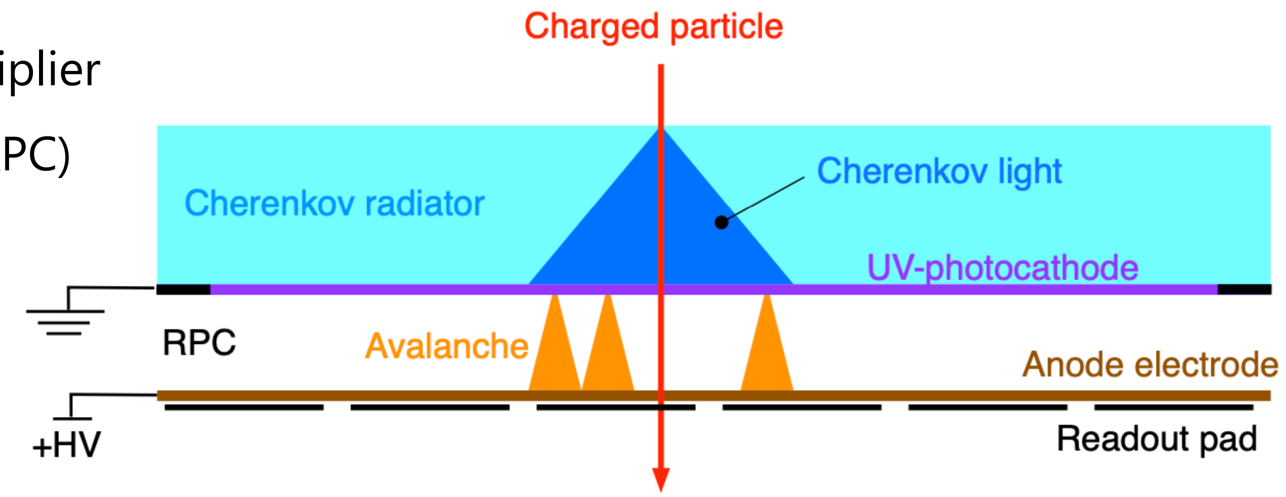
Sub-detector Development

- Cherenkov detector
- Scintillation detector

Cherenkov detector

➢ Requires granular readout and psec-timing

- Cherenkov radiator coupled to Gaseous photomultiplier
- Electron amplification by resistive plate chamber (RPC)
  - ✓ Fast timing
  - ✓ Simple structure → Large area by low cost
  - ✓ Readout segmentation

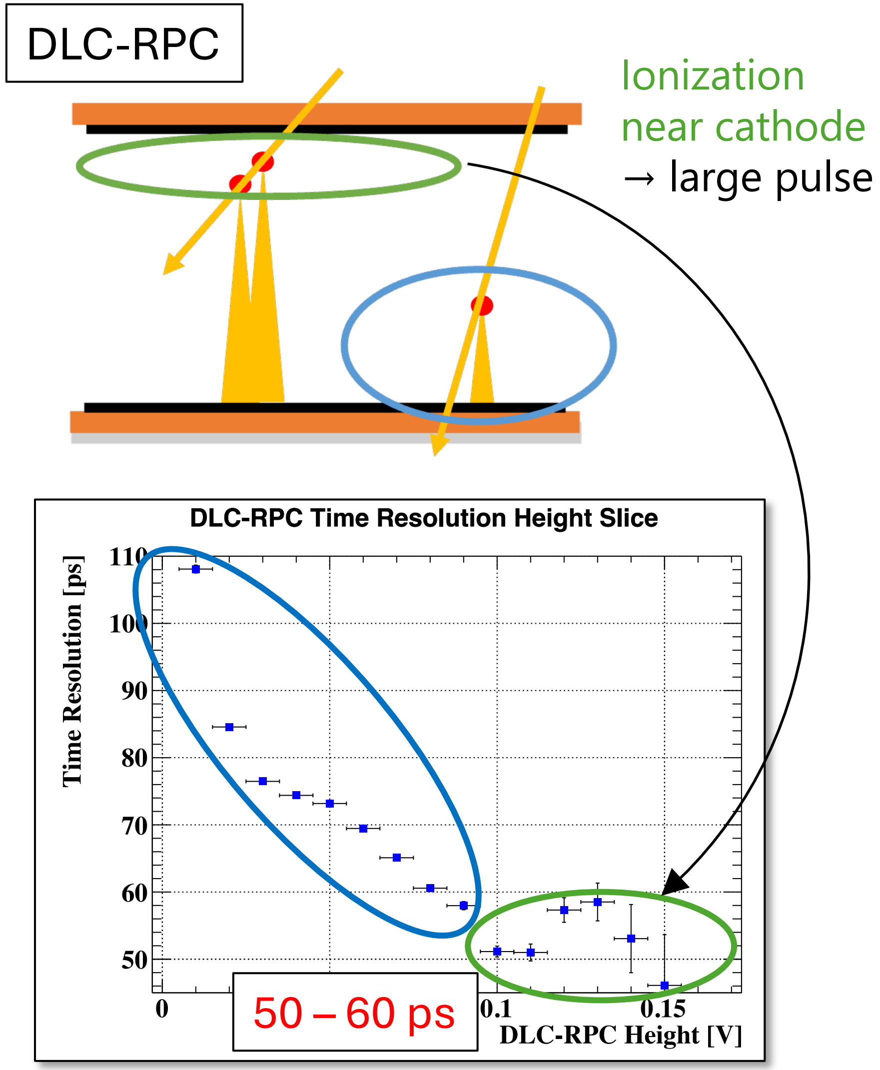


- Diamond-Like Carbon as resistive electrode (DLC-RPC)
  - ✓ High-rate-capability > 1 MHz/cm^2
  - ✓ DLC sputtered on polyimide = “film” electrode

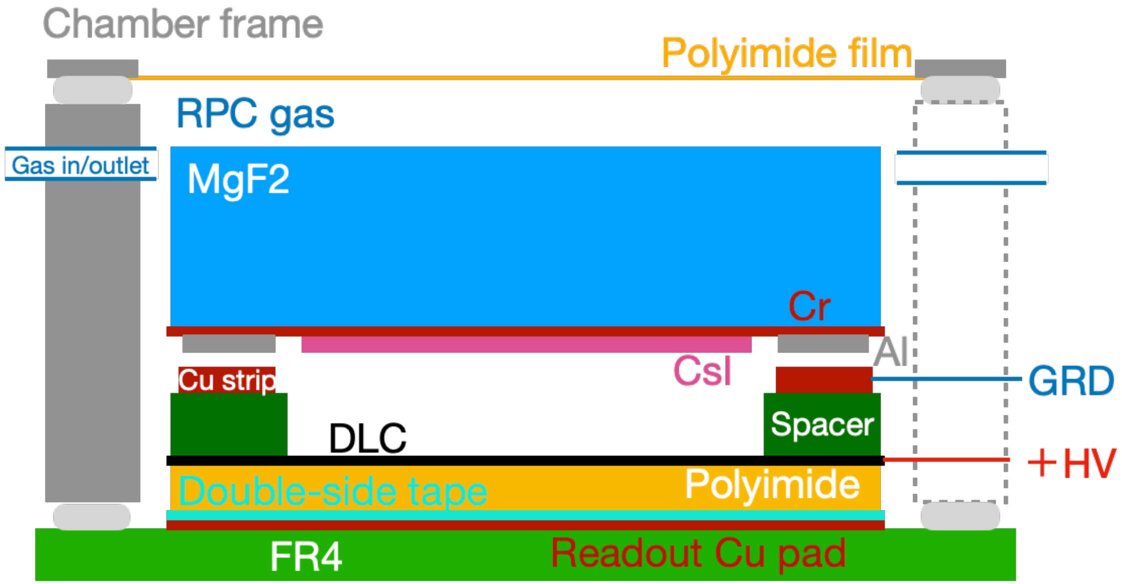
Cherenkov detector

- $\sigma_t = 50 - 60$ ps for large pulses in DLC-RPC (gap thickness 200 μm)
  - < 1 ionization electron cluster generated by single charged particle
  - Average 2.8 primary electron in a cluster
  - 80 – 100 ps for single primary electron generated near cathode
    → close situation for single photoelectron (p.e.) in Cherenkov detector

- Considering 10 p.e. for Cherenkov detector, it estimates 20 – 30 ps
  - 10 p.e. achieved by similar concept detector: PICOSEC (Micromegas-based)
  - RPC signal contamination and photon-feedback could affect performance



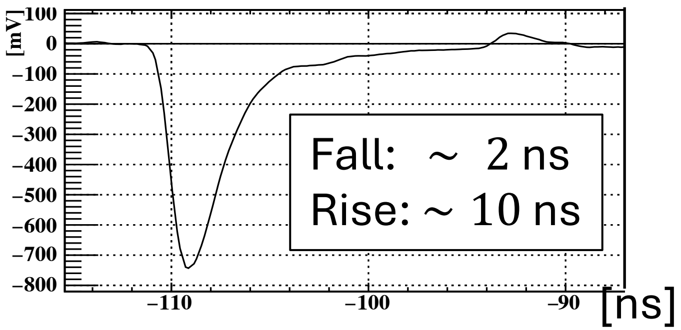
Cherenkov detector



First prototype constructed

Signal data taken by 5 GHz waveform digitizer

Sample waveform



Configurations

Radiator	MgF_2	2.4 mm
Photocathode	CsI	18 nm
Conductive layer	Cr	3 nm
Contact layer	Al	100 nm
Resistive layer	DLC	100 nm
Active area	-	2x1 cm^2
RPC gap	Kapton Plastic Cu	200 μm
RPC gas	R134a SF_6 C_4H_{10}	93% 1% 6%

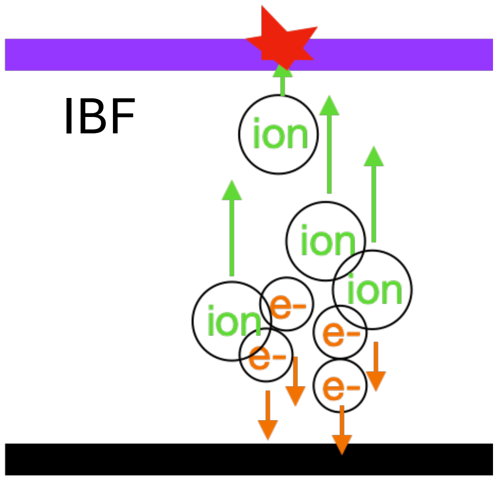
Cherenkov detector

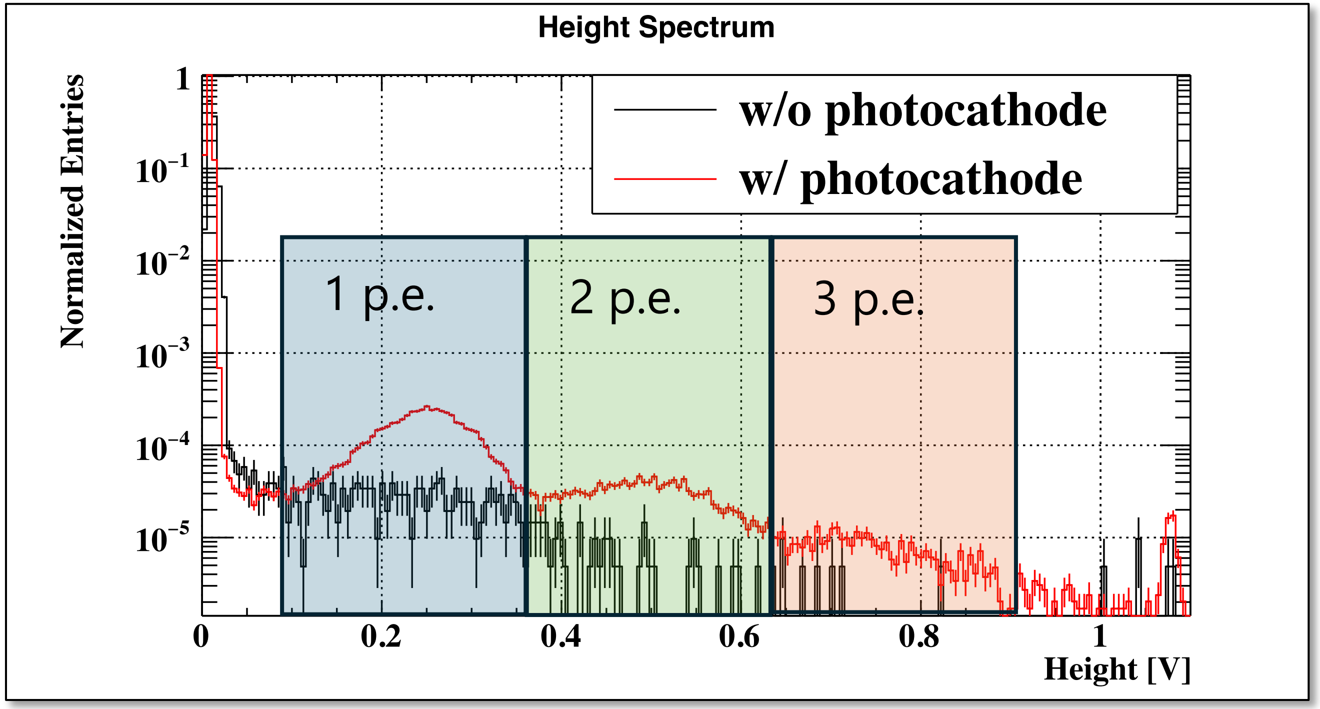
👍 Successfully observed Cherenkov light signal!

👍 Discrete peaks of #p.e. in height(charge) spectrum = photon counting capability

👎 Low #p.e.

- Ion-backflow (IBF)?
  → robust photocathode required
- Failure in the handling of photocathode?





Cherenkov detector

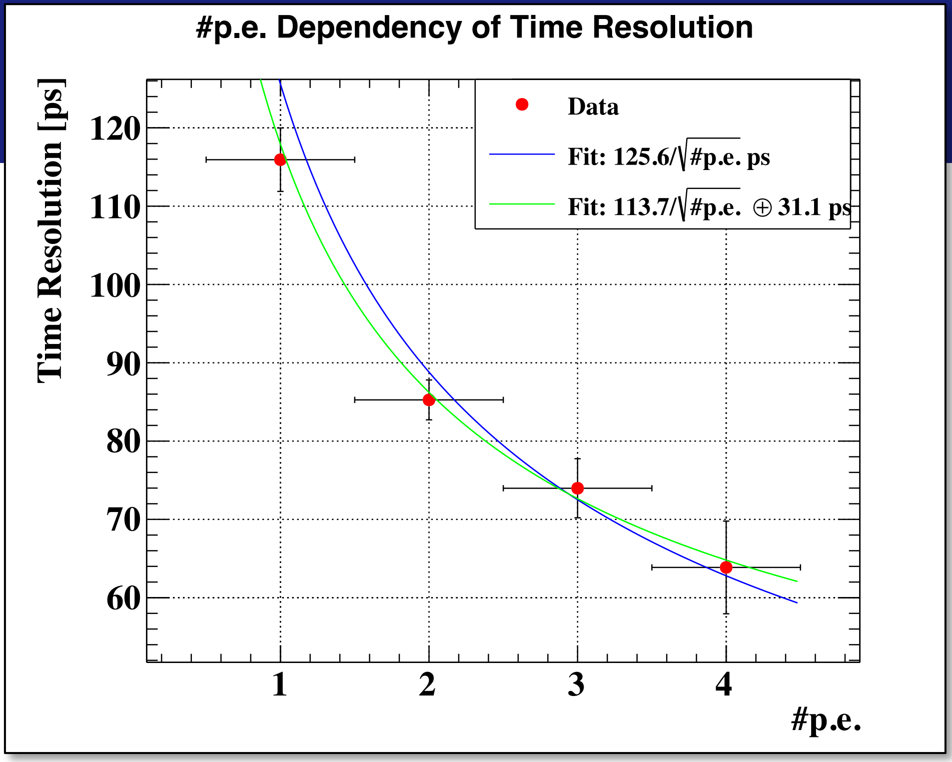
Time resolution depends on #p.e.

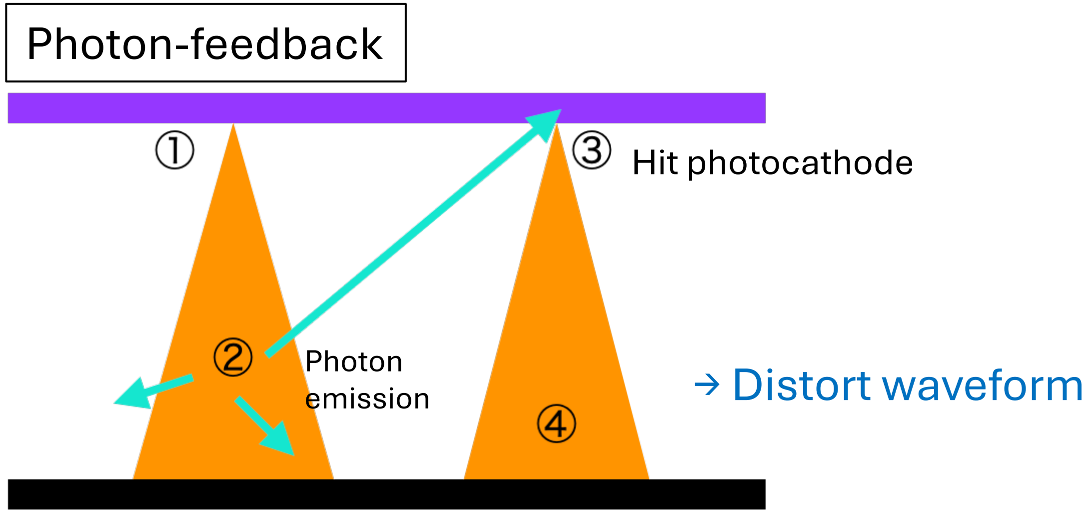
- $126/\sqrt{\#\mathrm{p.e.}}$ or $114/\sqrt{\#\mathrm{p.e.}} \oplus 31.1$ ps
- 40-50 ps for 10 p.e., 30-40 ps for 20 p.e.
- RPC signal contamination ($\sim 50\%$),
  Photon-feedback (PFB)
  → Possible reason of discrepancy to estimated value

➢ Improvement planned

- Reduce gap thickness → mitigate RPC contamination
- Switch to robust photocathode → mitigate PFB

The construction technique been established
→ Moving on to the upgrade of the detector





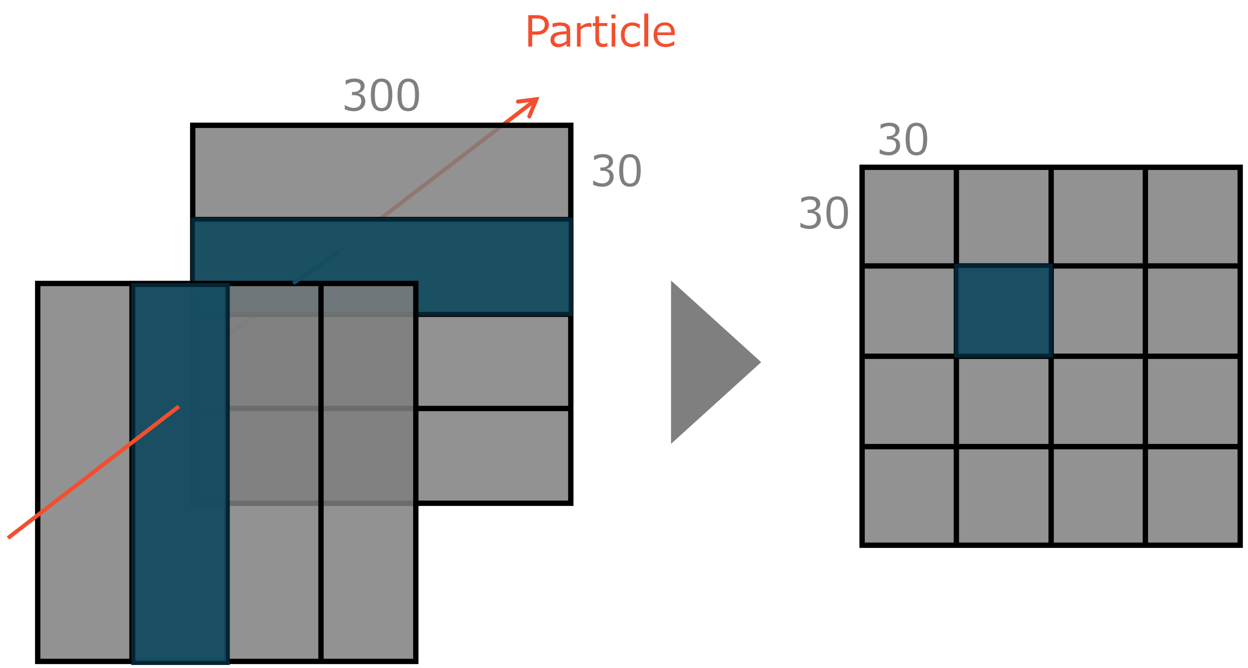
Scintillation detector

➢ Granular readout but moderate number of channels

Place strip scintillator in orthogonal way and realize virtual cell

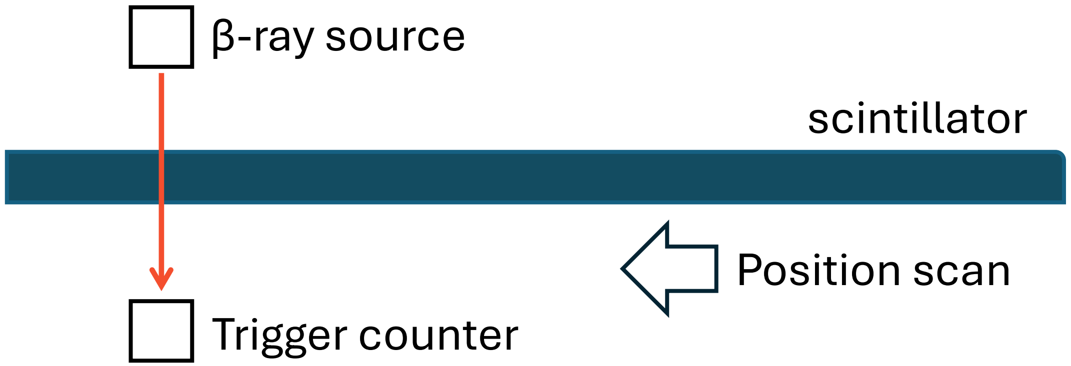
- Concept already proven in 45 x 5 mm^2 strip for ECAL (Virtual segmentation of 5 x 5 mm^2)
- Test if it works for large size: 300 x 30 mm^2

→ See if light yield and its uniformity is sufficient

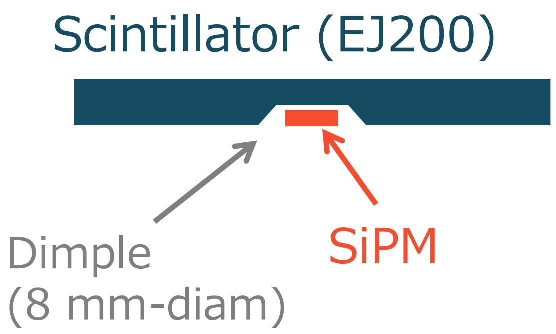


Scintillation detector

Setup



1. Single SiPM



2. Double SiPMs

👍 mitigate ghost hist by charge, timing difference

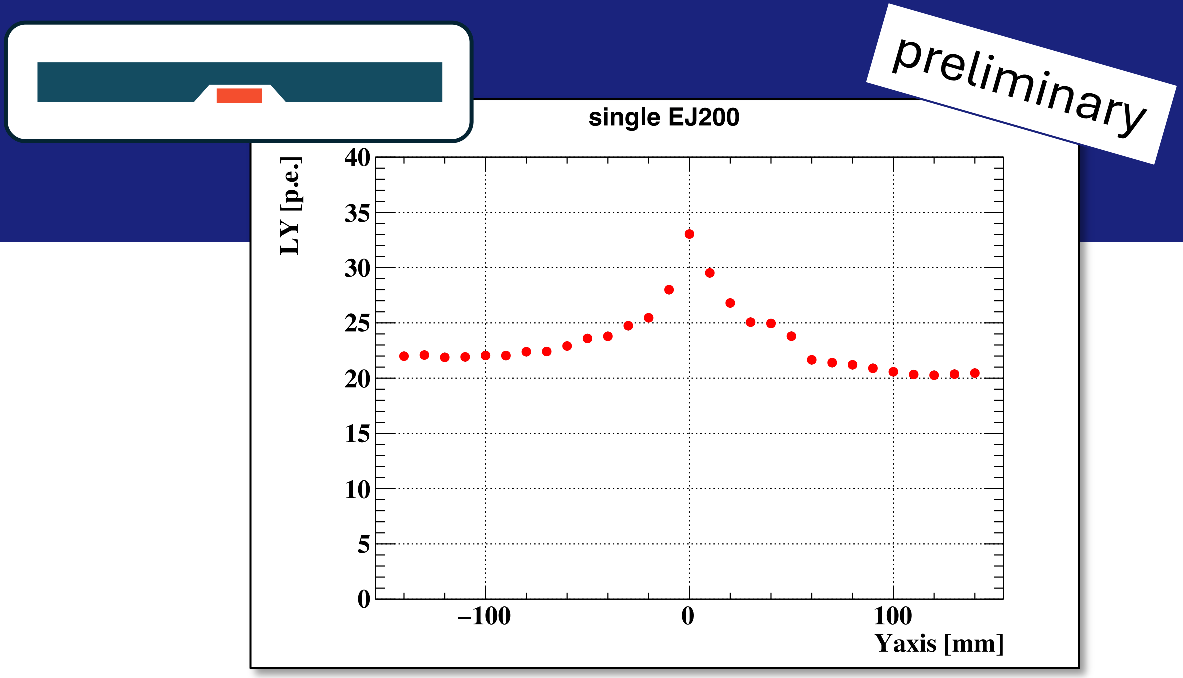
👎 Double the #channels

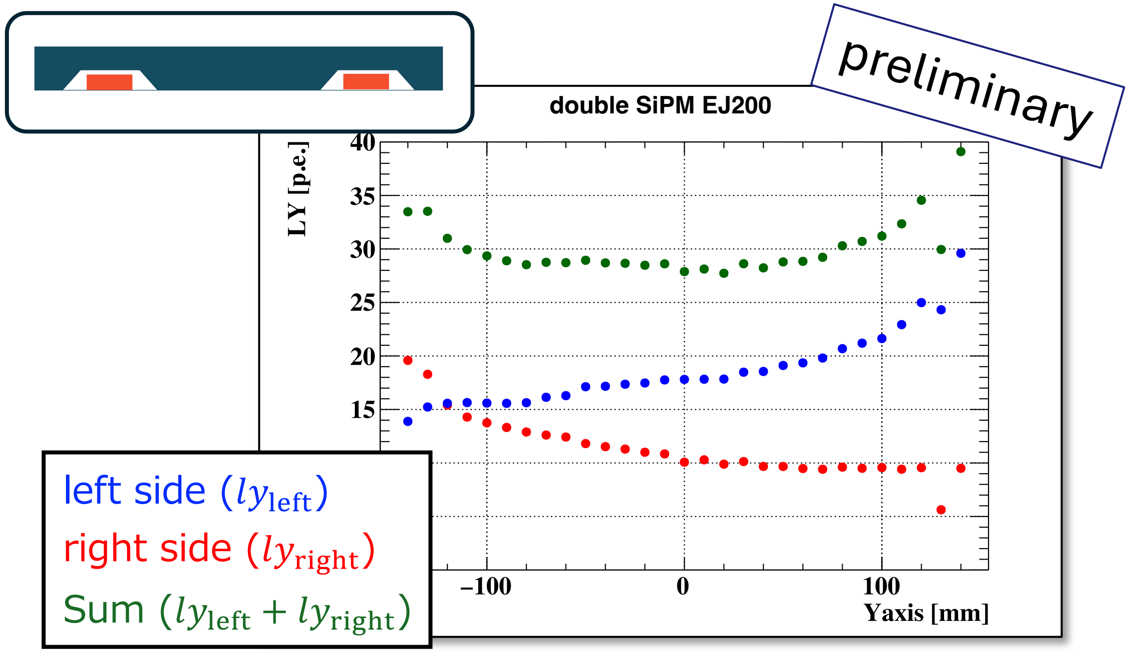
Scintillation detector

Result

- Sufficient light yield + good uniformity for both configuration
  - Non-uniformity around SiPM can be mitigated by dimple design
- Study for performance evaluation of position reconstruction using charge and time difference in a single strip bar ongoing

*Asymmetry in Y axis to be investigated

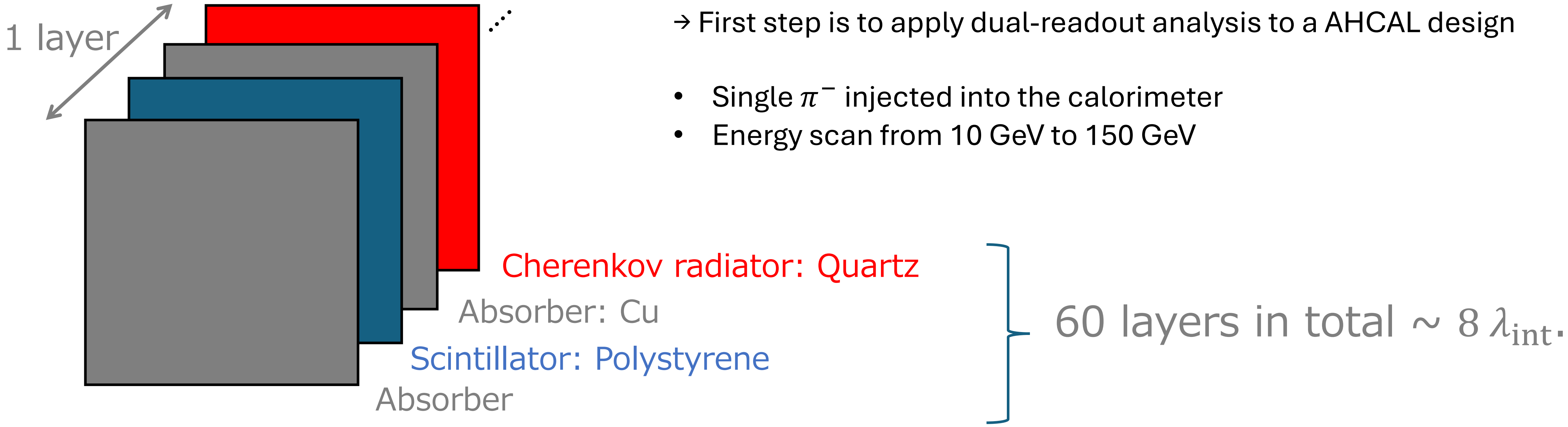




Performance Study by Simulation

Setup

- Simulation study targeting to understand the performance of combination of high-granularity and dual-readout calorimetry, adding timing information to the analysis

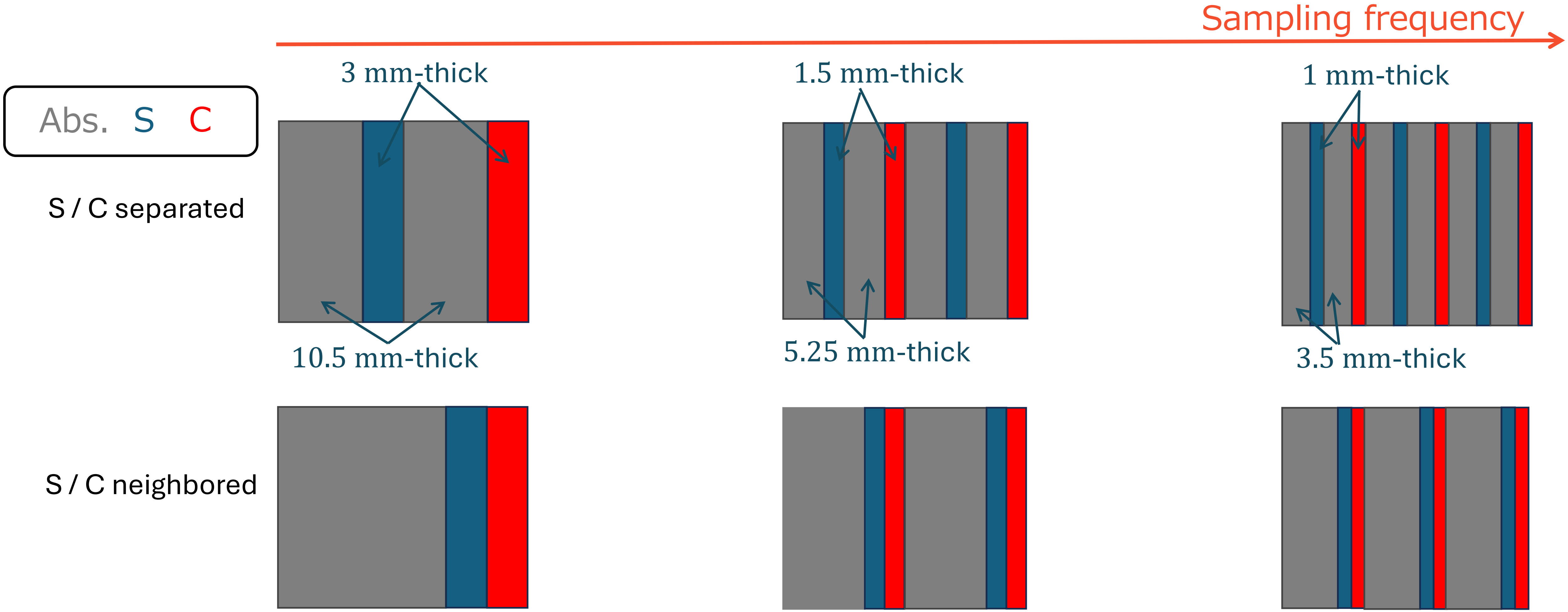


CALICE AHCAL as baseline design
Switch half of scintillation layers to Cherenkov layers
→ First step is to apply dual-readout analysis to a AHCAL design

- Single π^- injected into the calorimeter
- Energy scan from 10 GeV to 150 GeV

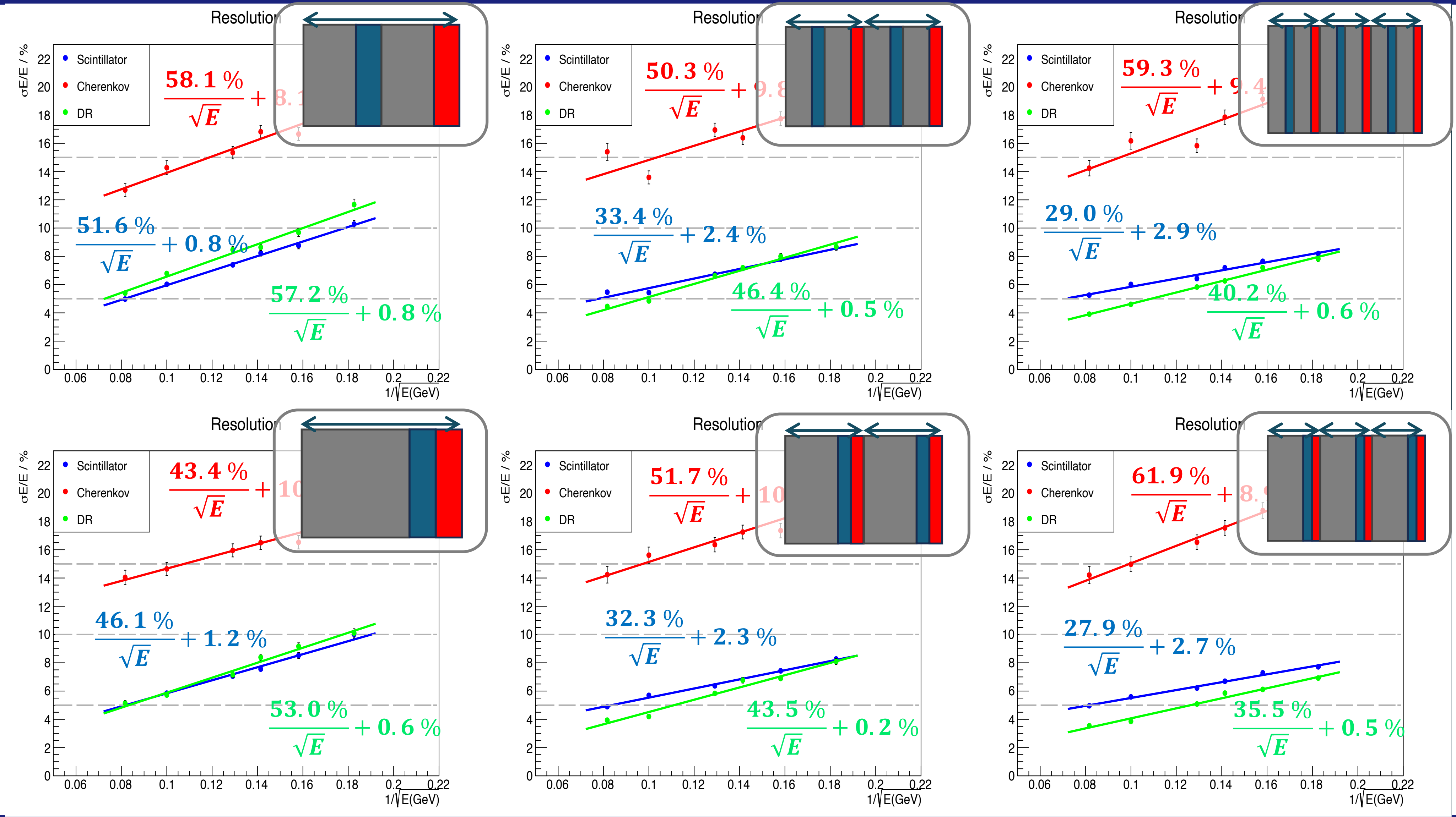
Setup

Compare different configuration to understand the behavior of dual-readout analysis

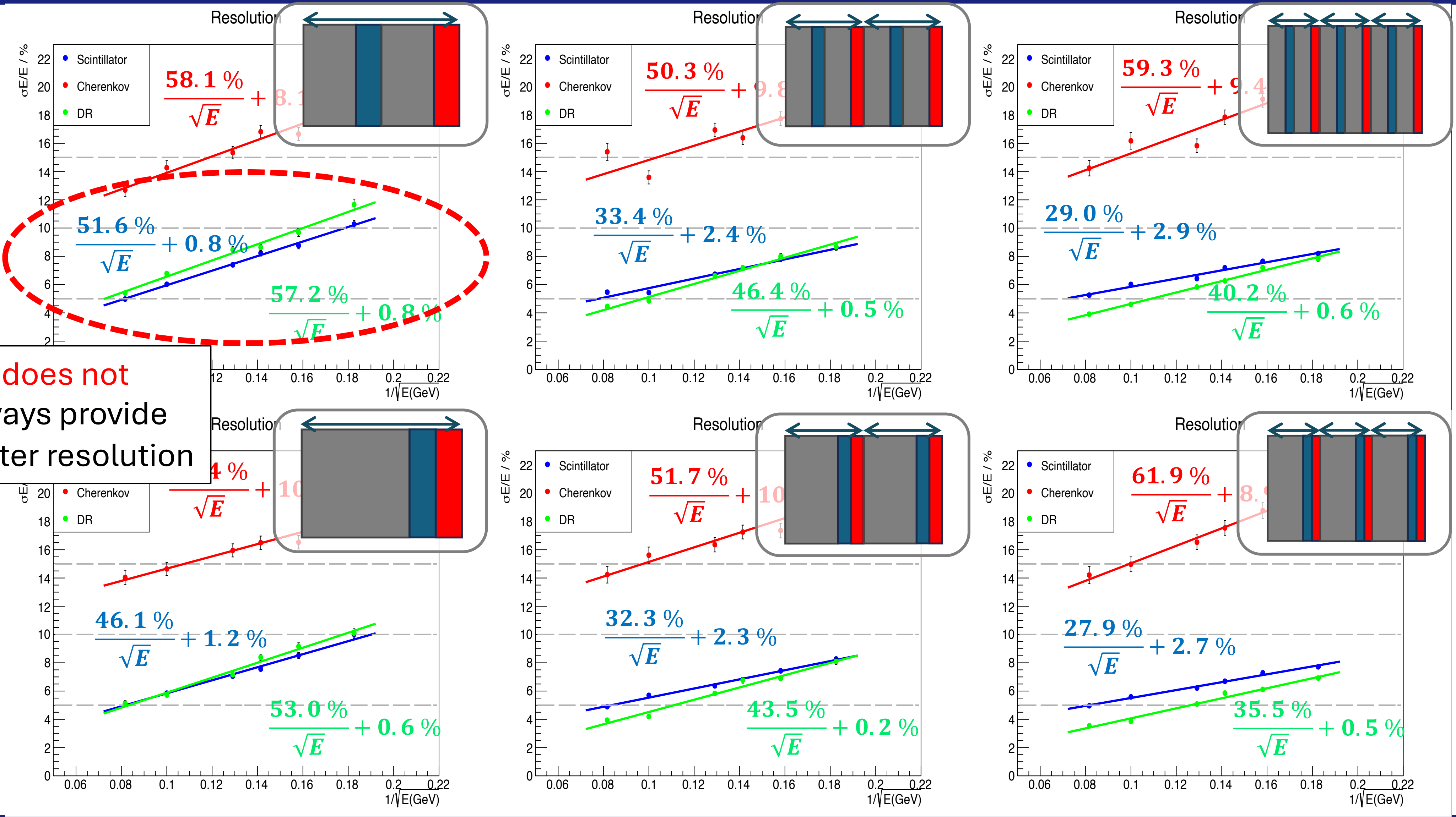


* The total thickness of each layers are the same

Dual-readout analysis

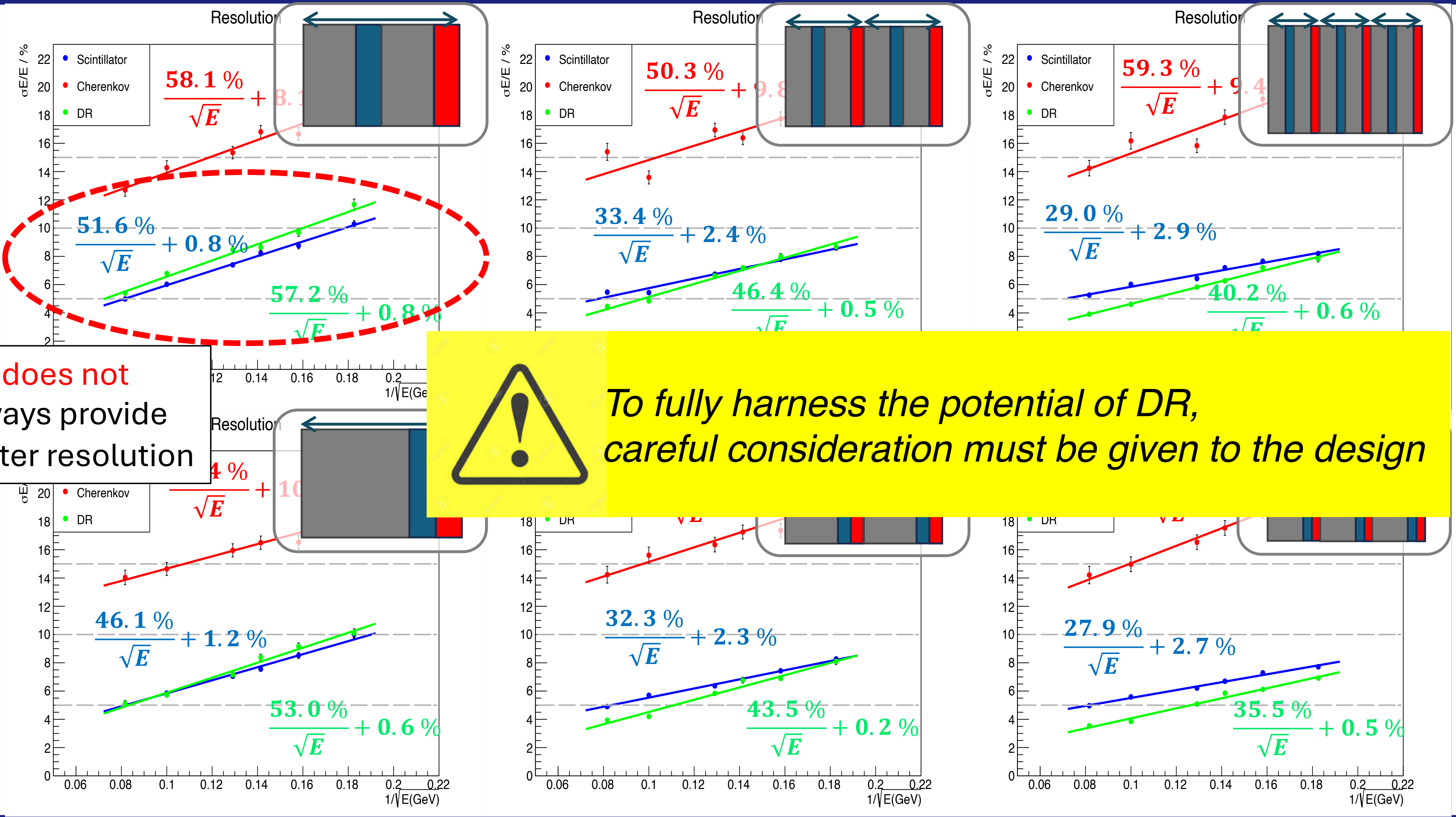


Dual-readout analysis



DR does not always provide better resolution

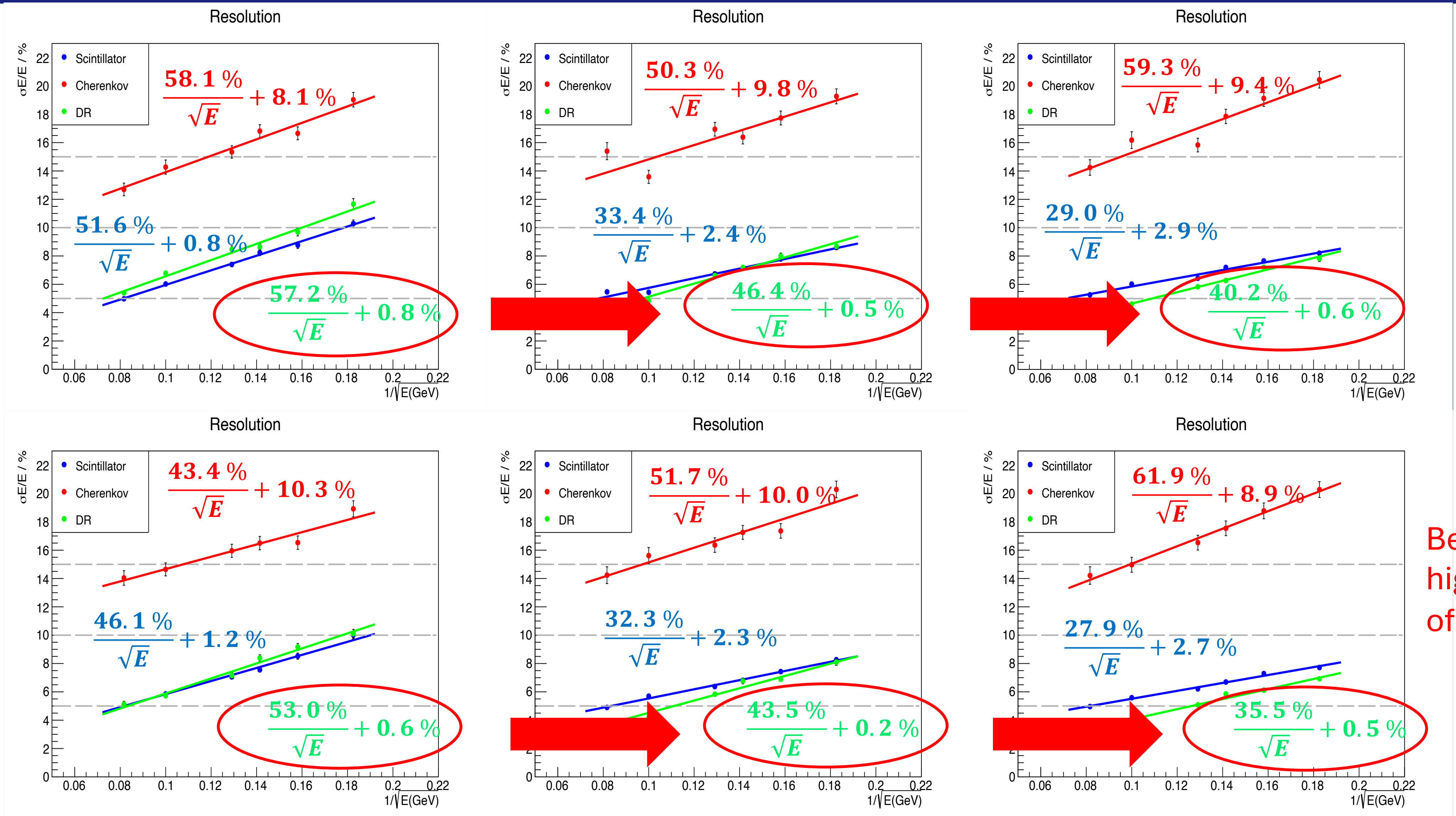
Dual-readout analysis



DR **does not** always provide better resolution

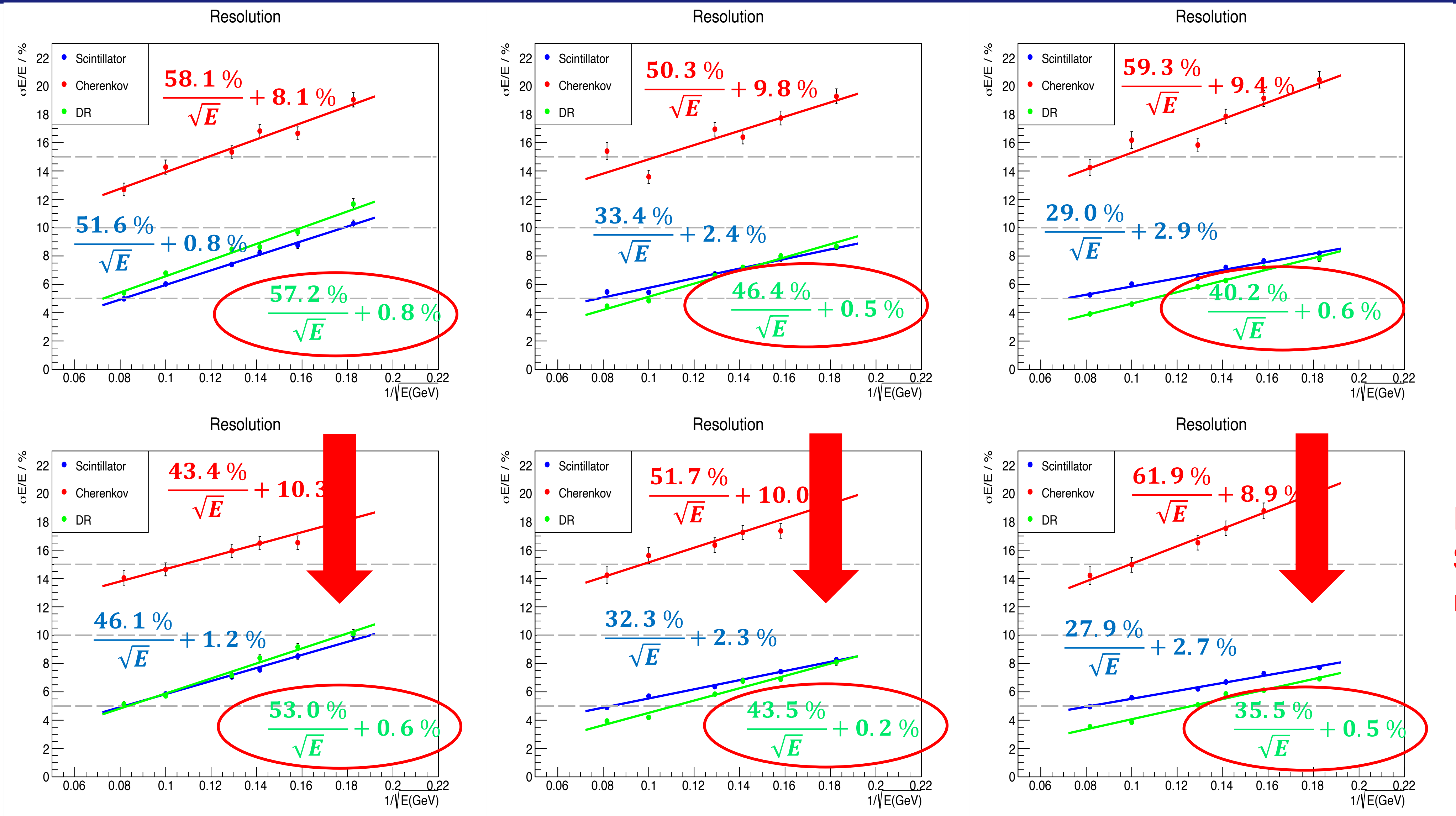
To fully harness the potential of DR, careful consideration must be given to the design

Dual-readout analysis



Better in
high frequency
of sampling layers

Dual-readout analysis

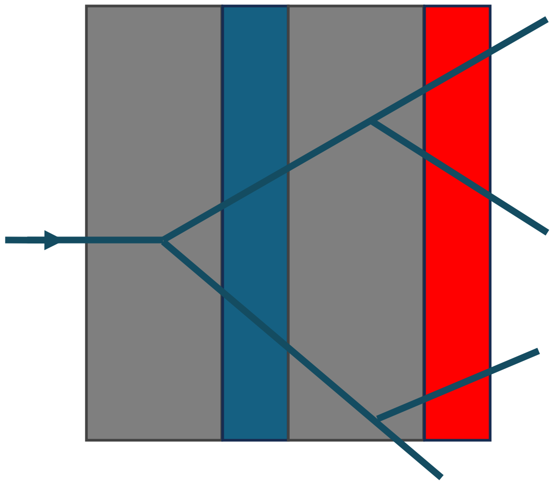


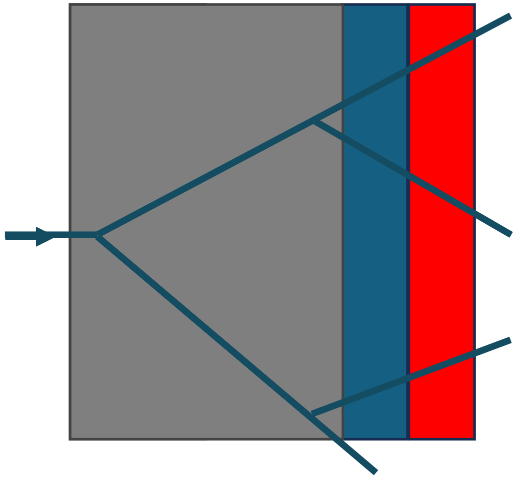
Better for S and C neighbored

Discussion

S / C config.

	Separated		Neighbored
Correlation:	0.56	▶	0.66
$\frac{\sigma_{E_{DR}}}{E_{DR}} / \frac{\sigma_S}{S}$:	1.14	▶	1.01

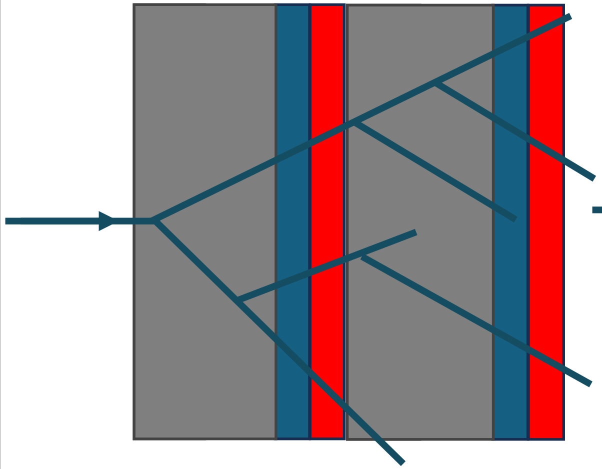

Separated

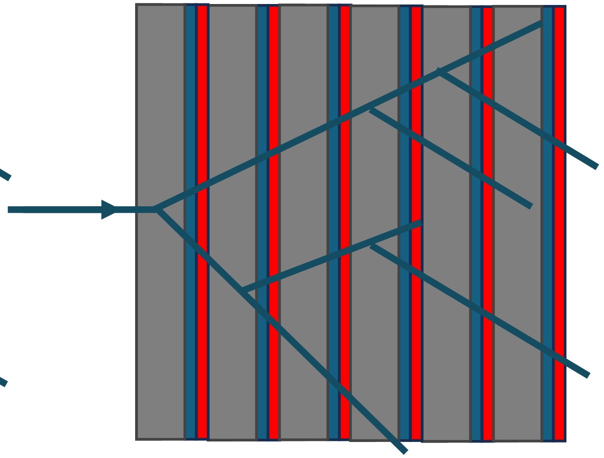

Neighbored

More likely to observe the same shower

Sampling frequency

Low freq.		High freq.
0.66	▶	0.77
1.01	▶	0.82


Low freq.

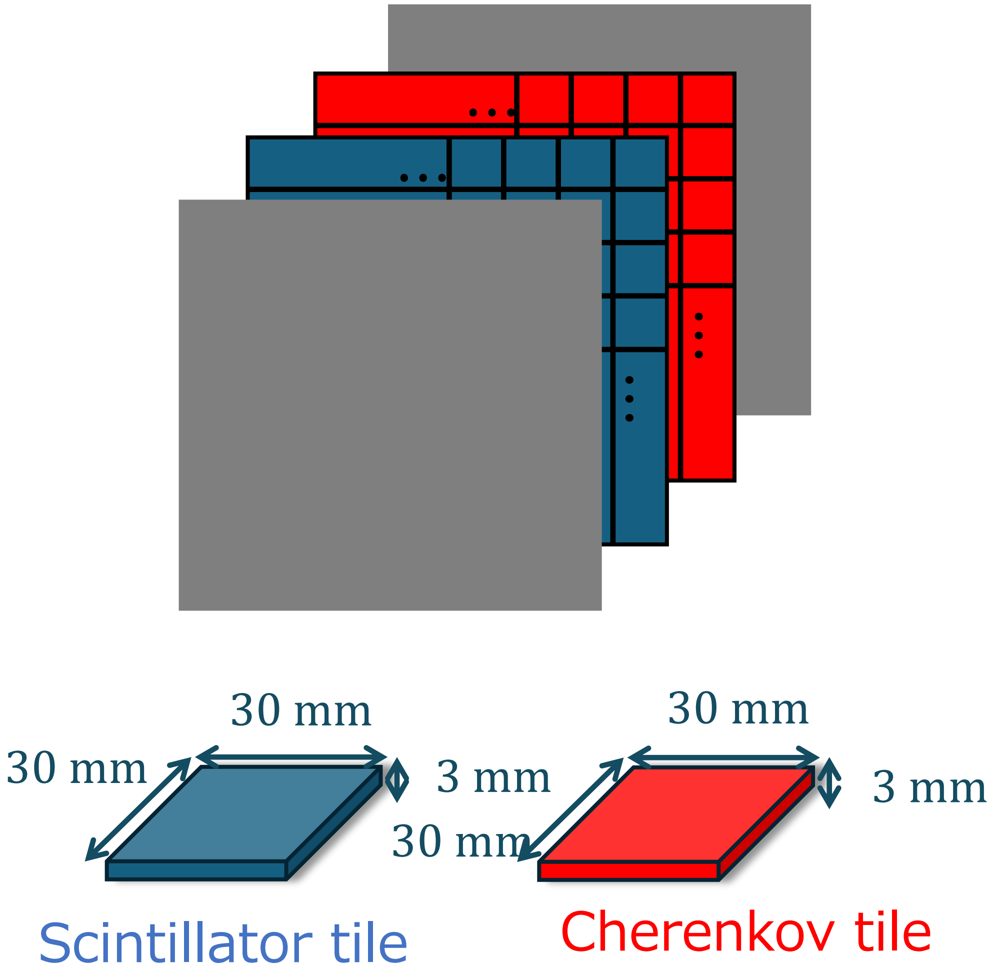

High freq.

Measures better profile of the shower

→ Further study to investigate the best configuration

Prospect for the simulation

- ✓ Investigation of better configuration for DR
- ✓ Create a framework for PFA + DR
  - Segmentation for each layer in calorimeter
  - ILD configuration as baseline
- ✓ Add timing information to PFA



Summary and Prospect

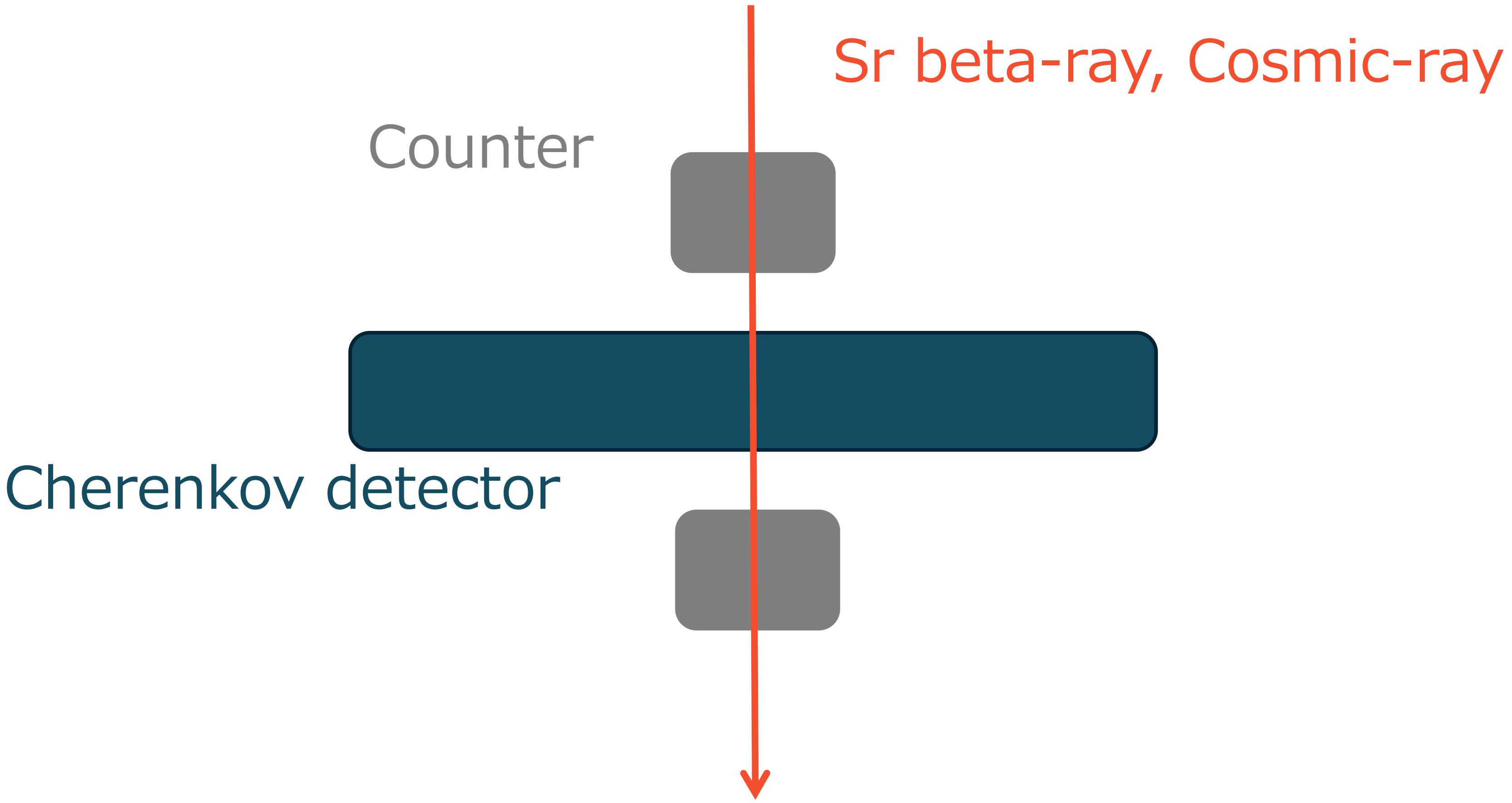
- Development of next-generation calorimetry that combines high-granularity and dual-readout in addition of psec-timing
- R&D for sub-detectors ongoing
  - Cherenkov detector has proved its detector principle
  - Scintillation detector has shown its sufficient light yield and
- Simulation study has provided the direction of calorimeter configuration
- S and C combined system to be tested in testbeam facility to study overall performance

Thank you!

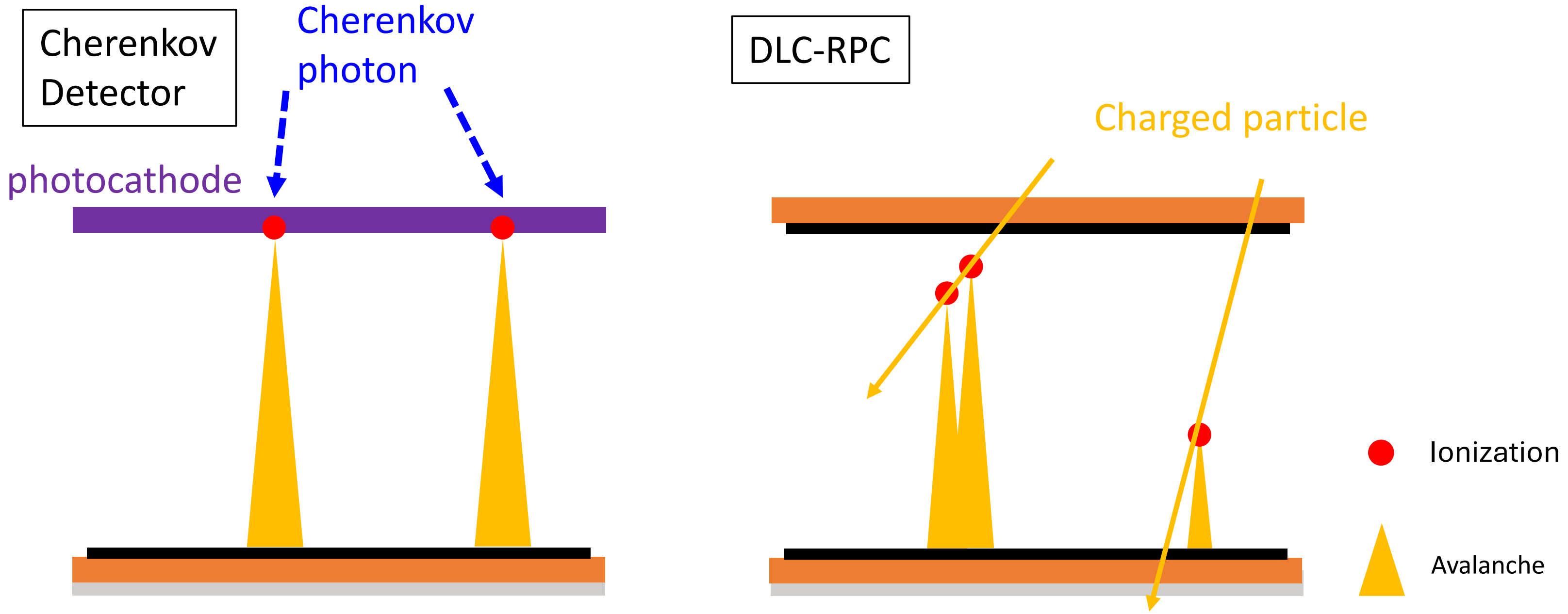
Backups

DLC-RPC Cherenkov detector

Experimental setup

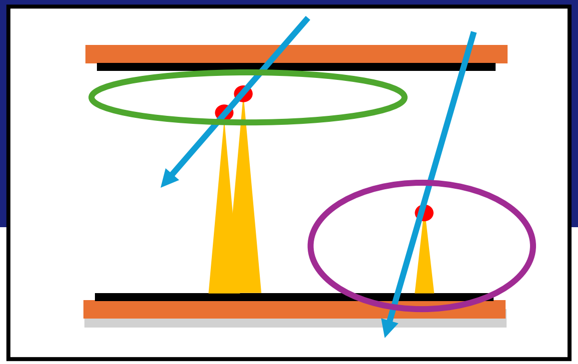


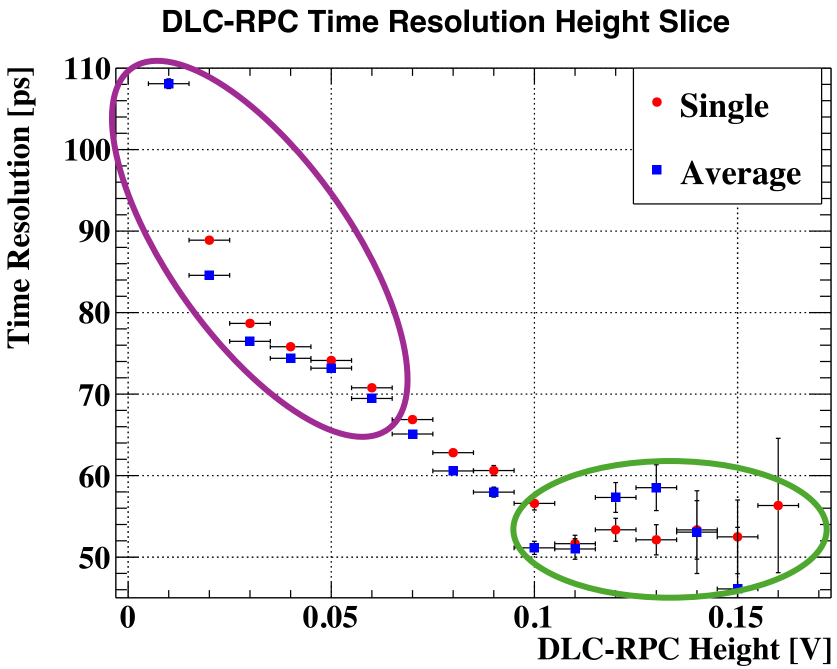
Difference of signal generation process

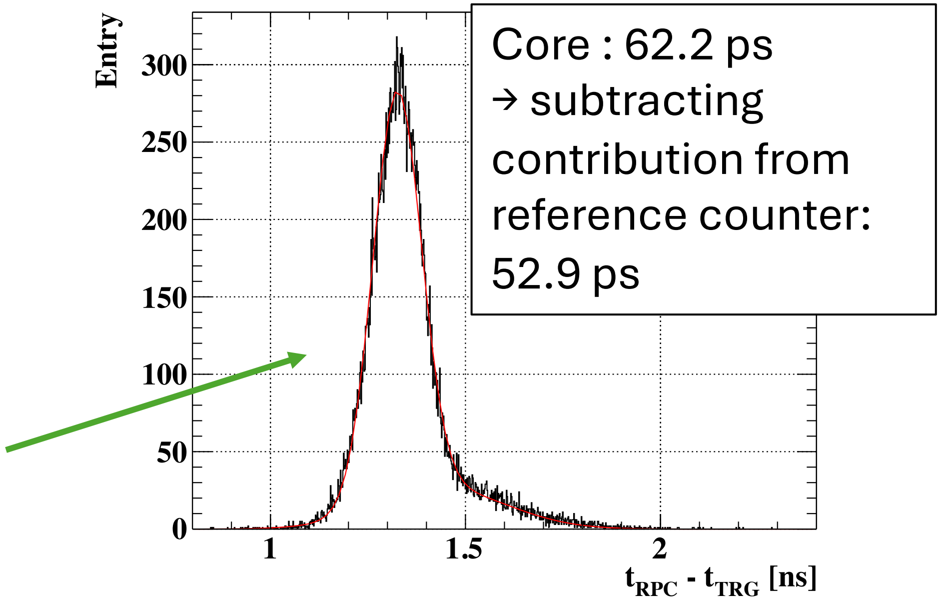


Consider:

- Correlation of signal height and starting position of avalance
- #clusters
- #primary electrons

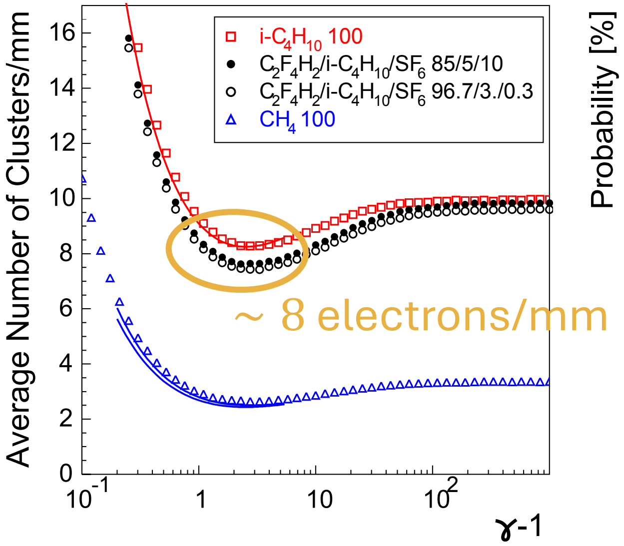



DLC-RPC Time Resolution Height Slice
Time Resolution [ps]
DLC-RPC Height [V]
Single
Average
110
100
90
80
70
60
50
0
0.05
0.1
0.15

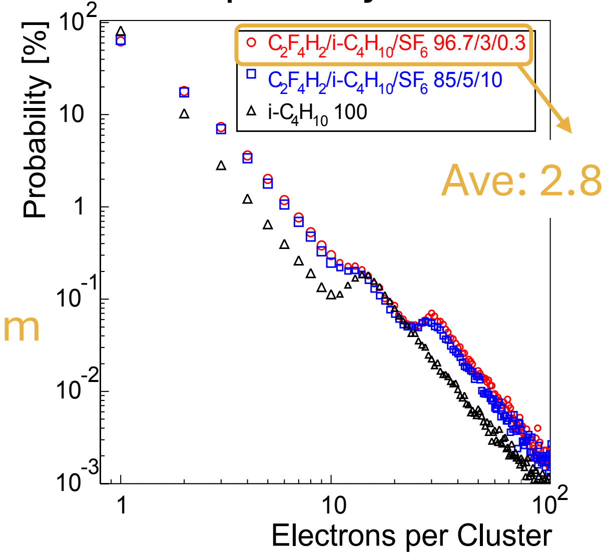

Core : 62.2 ps
→ subtracting contribution from reference counter: 52.9 ps
Entry
t_{RPC} - t_{TRG} [ns]
300
250
200
150
100
50
0
1
1.5
2

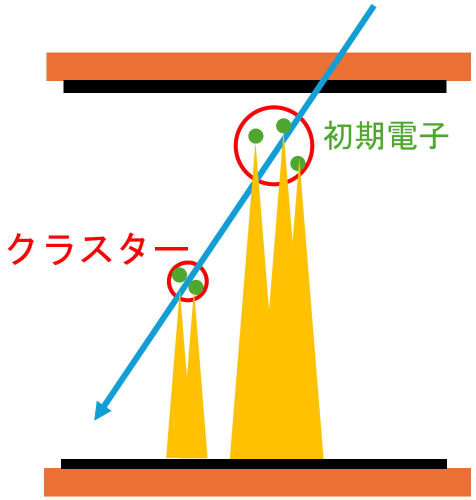
Cluster and primary electrons

#clusters



#primary electrons



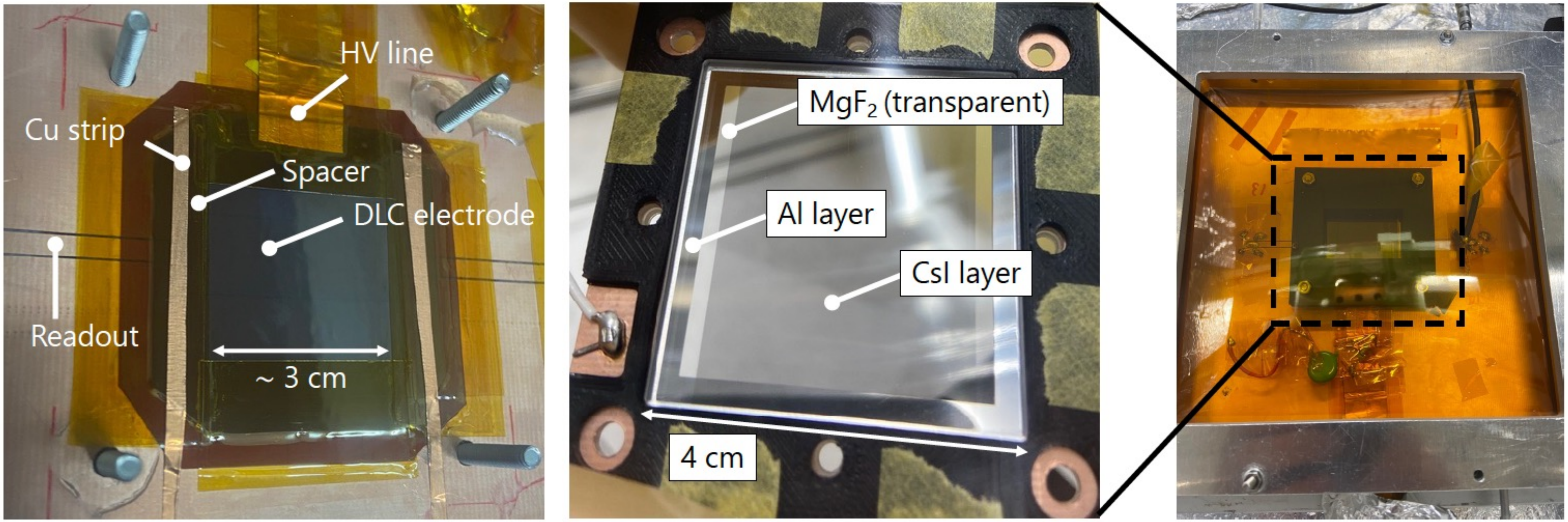


https://doi.org/10.1016/S0168-9002(03)00337-1

- #clusters
  - ^{90}Sr β-ray: $\gamma - 1 \sim 1 \rightarrow \sim 2$ clusters / 200 μm
  - Clusters that can be grow to signal: some 10% → #cluster ~1
- #Primary electrons: 2.8 electrons / cluster

Detector photo

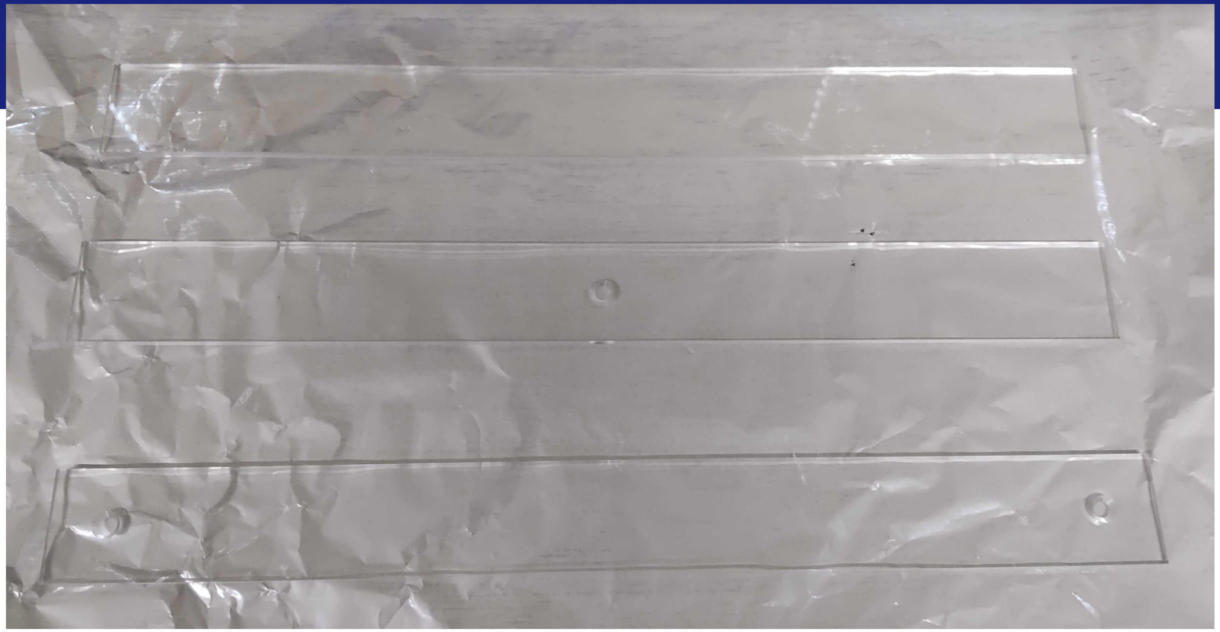
DLC (anode) electrode | Photocathode electrode | Detector Chamber

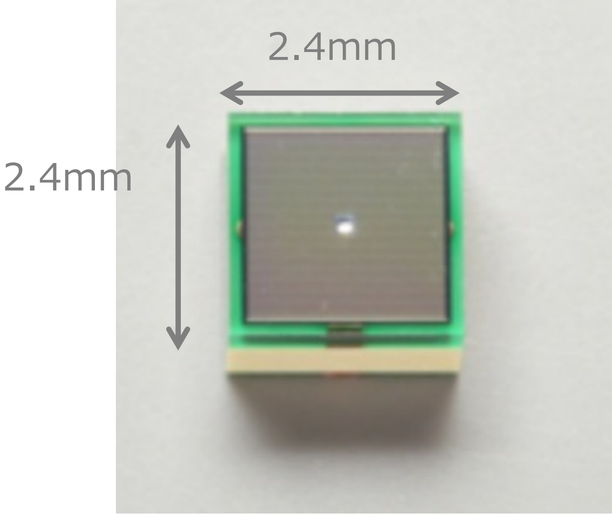


Scintillator strip

Strip and SiPM

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

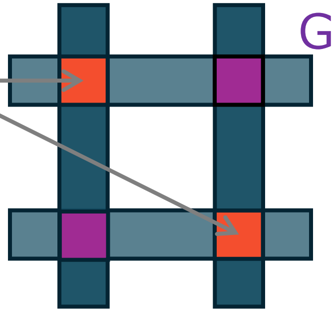




- Optimization of the strip design.
- Checking the light yield and uniformity with position scan using Sr90 beta-ray.

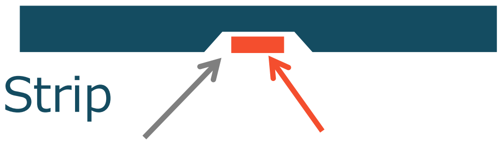
Strip material candidates

	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

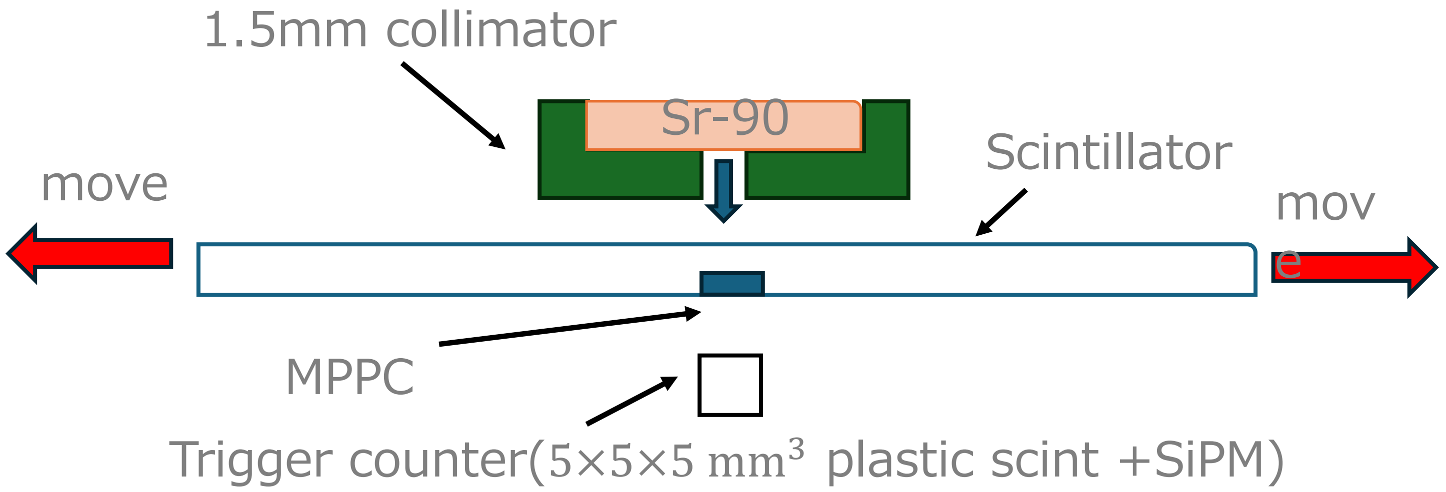


2. Double SiPMs

3. Double SiPMs at each side

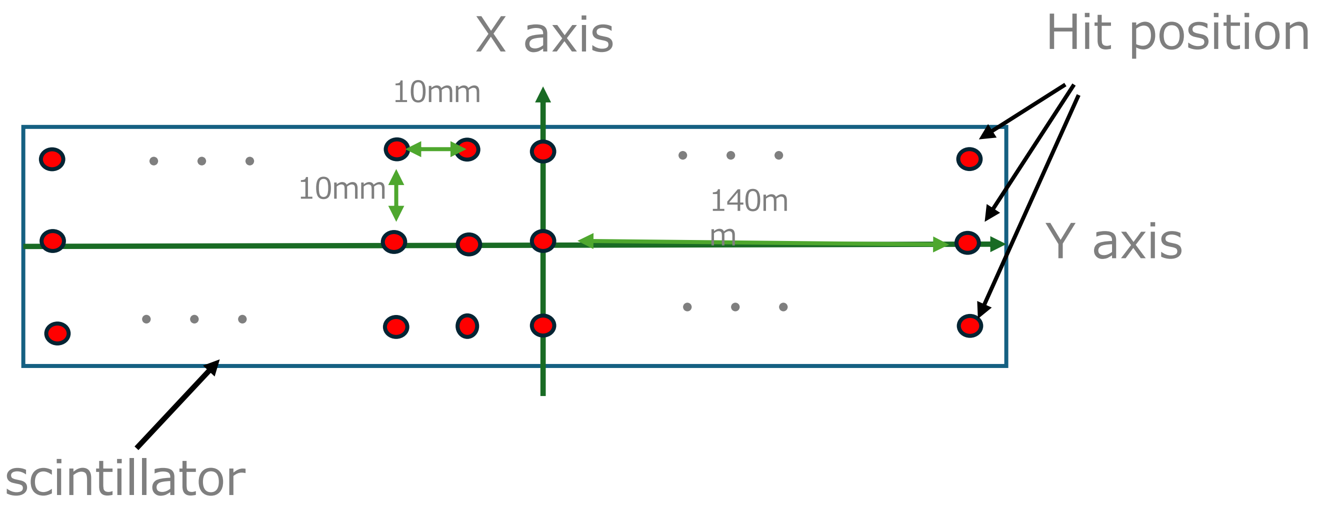
2 & 3 setups are motivated for hit position reconstruction to mitigate ghost hits.

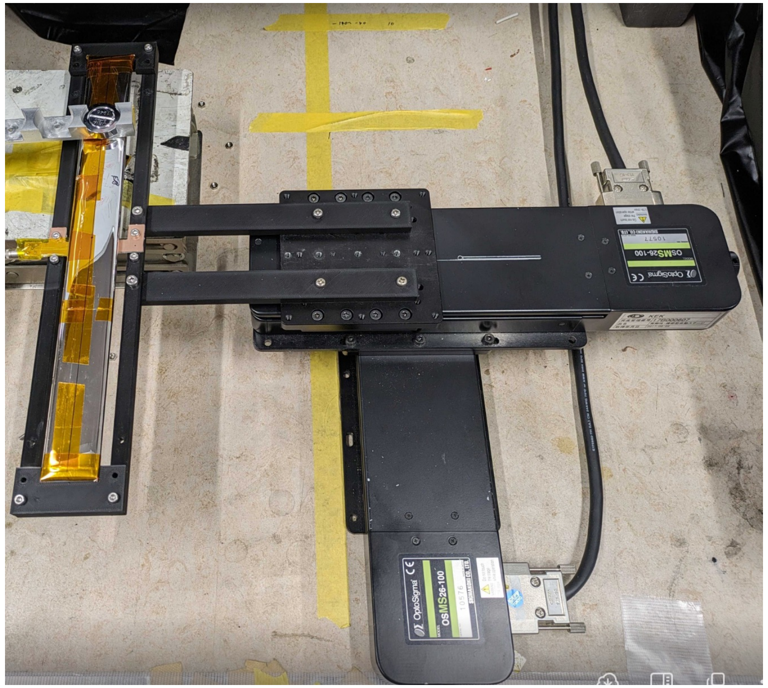
Experimental setup of position scan



Strip response measured with β from Sr-90

2D position scan with x-y moving stage



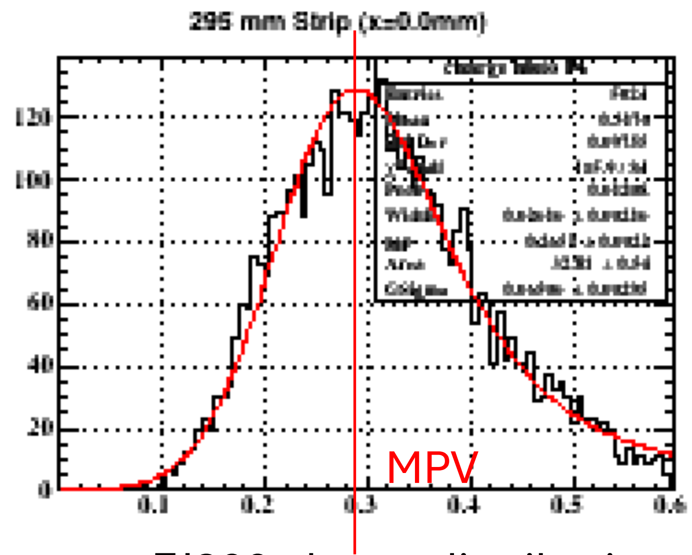


Analysis method

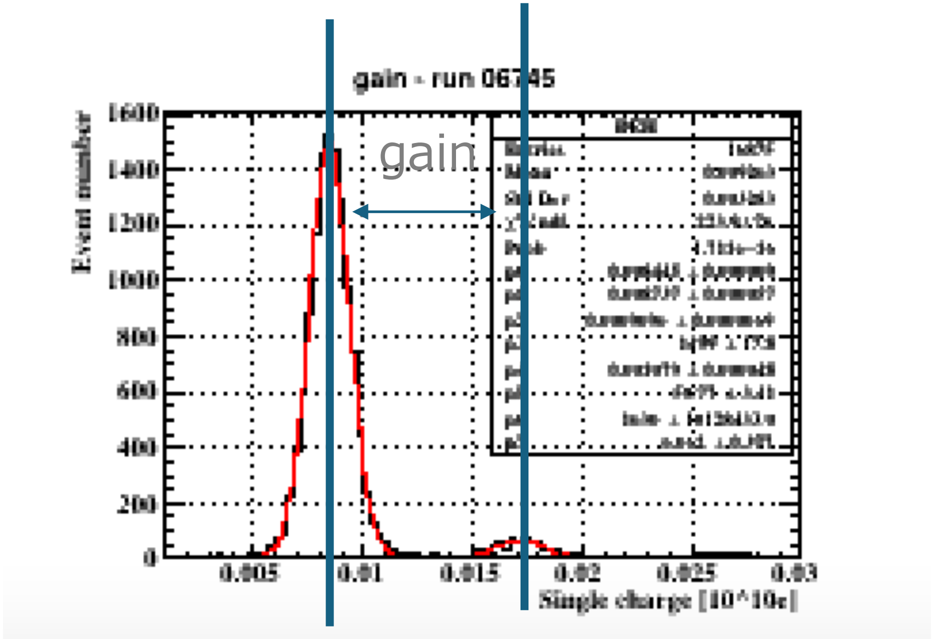
$$\text{Light Yied} = \frac{(\text{charge of scintillation})}{\text{gain}}$$

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

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



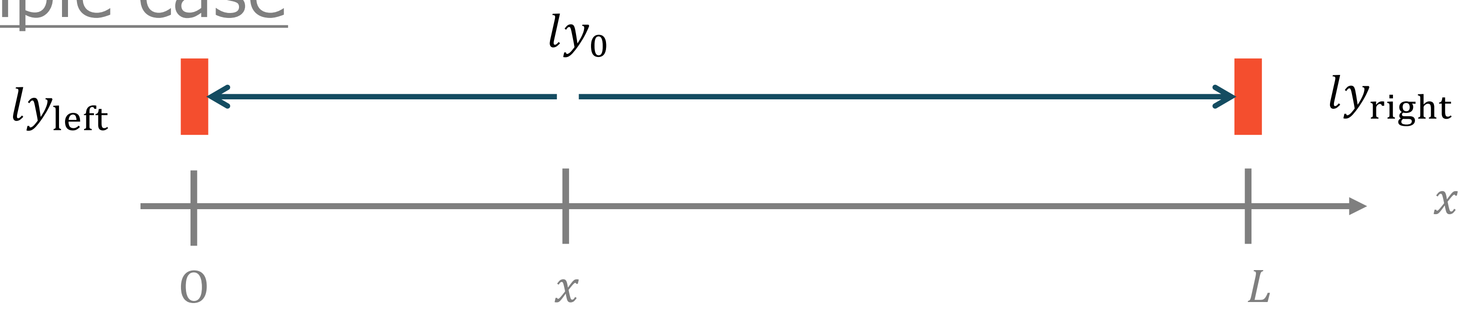
EJ200 charge distribution



Why a geometrical mean?

- For uniformly reconstructing light yield.

<u>Simple case</u>

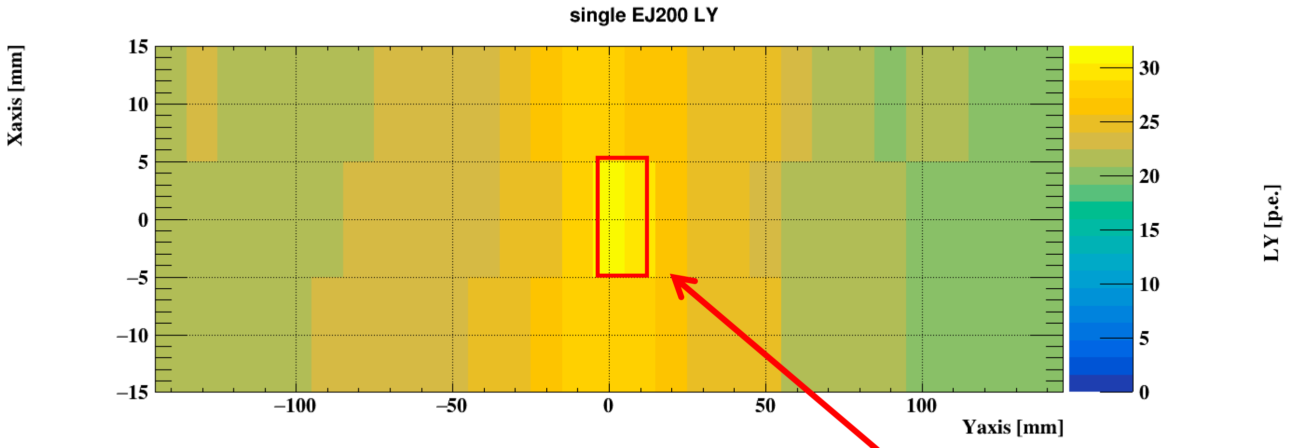


Attenuation length: λ

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

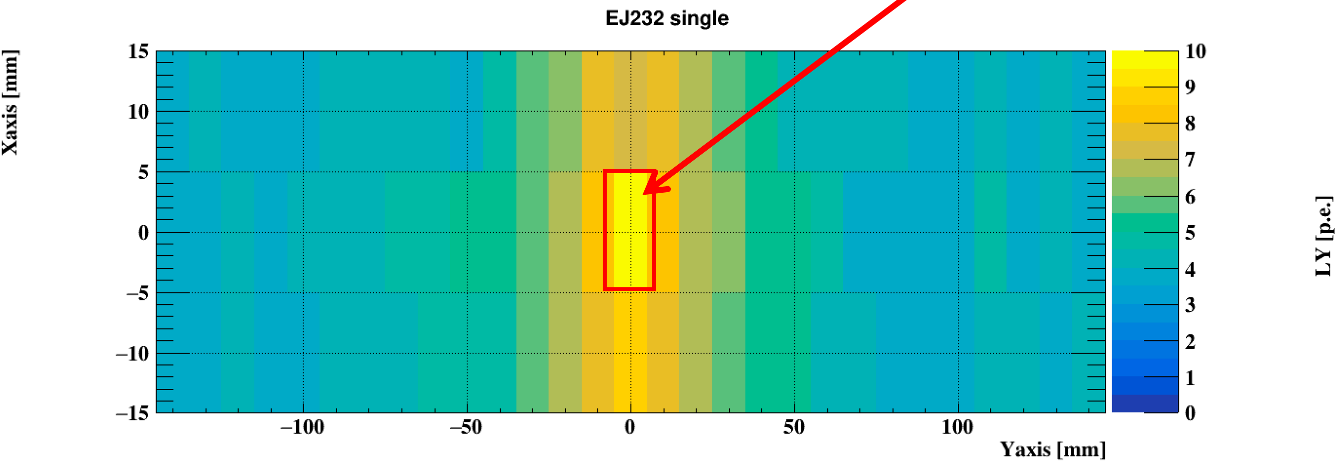
Single readout (EJ200 & EJ232)

EJ200 single light yield



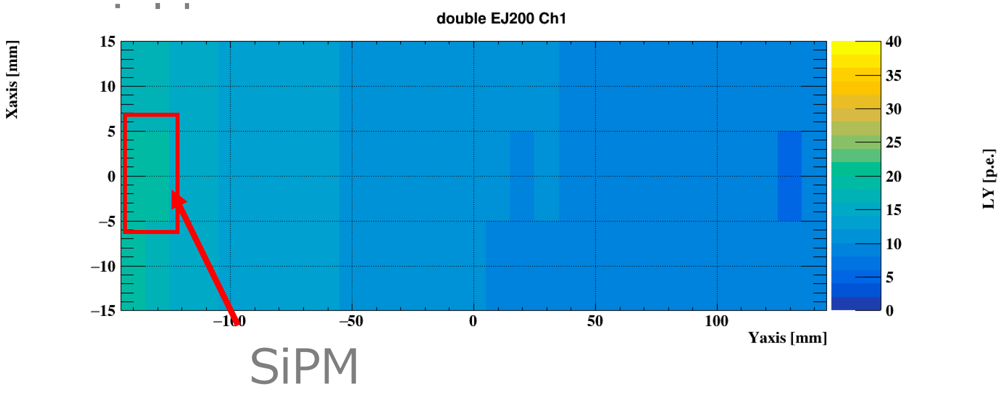
EJ232 single light yield

Dimple and SiPM

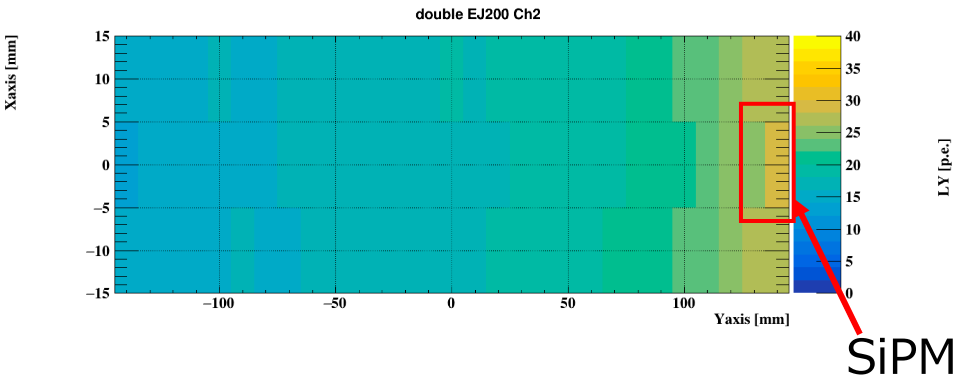


Double readout (EJ200)

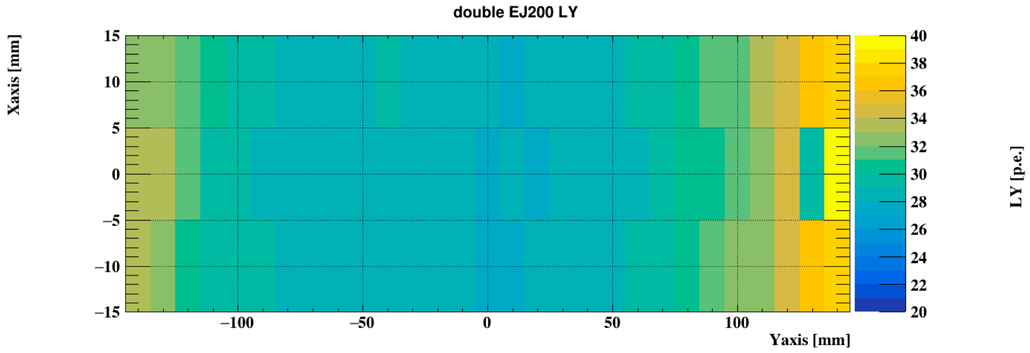
Ch1 light



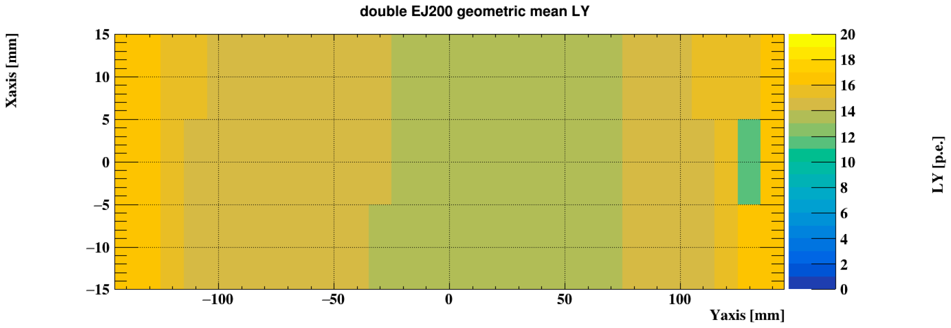
Ch2 light yield



ch1 and ch2 sum

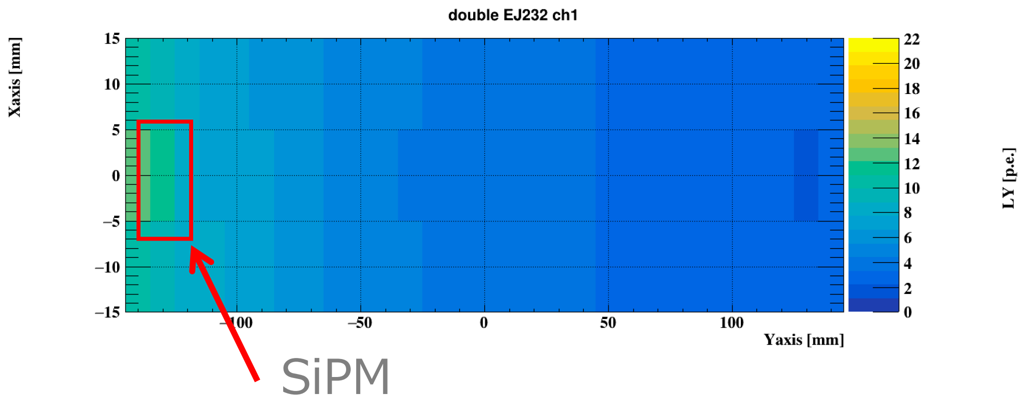


ch1 and ch2 geometric mean

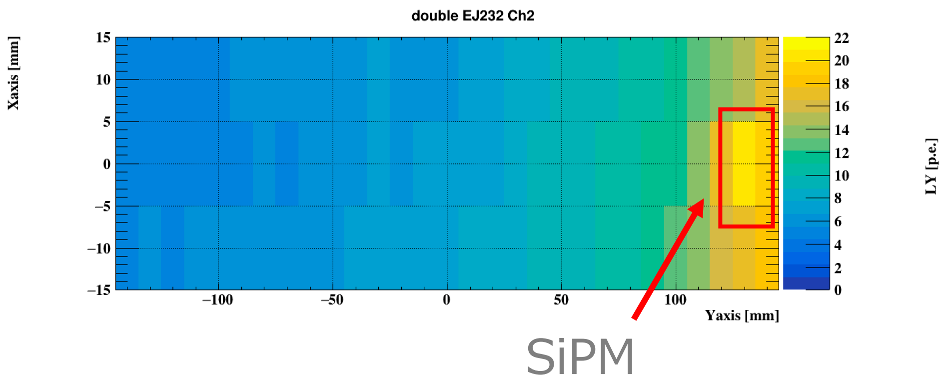


Double readout (EJ232)

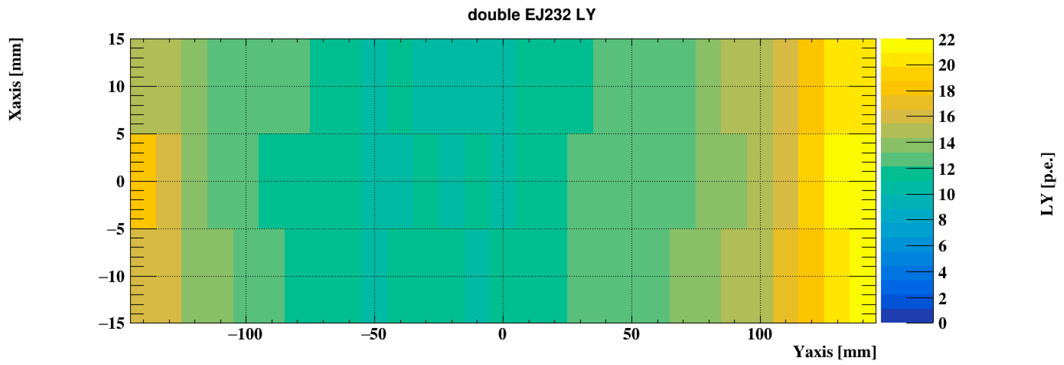
Ch1 light yield



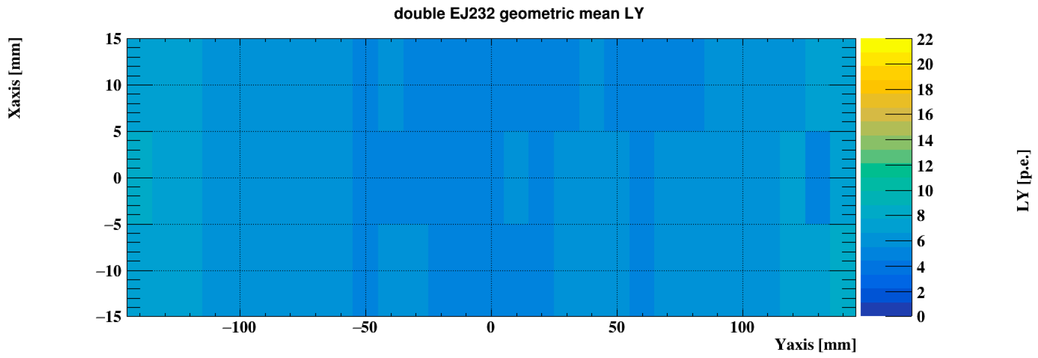
Ch2 light yield



Ch1 and ch2 sum

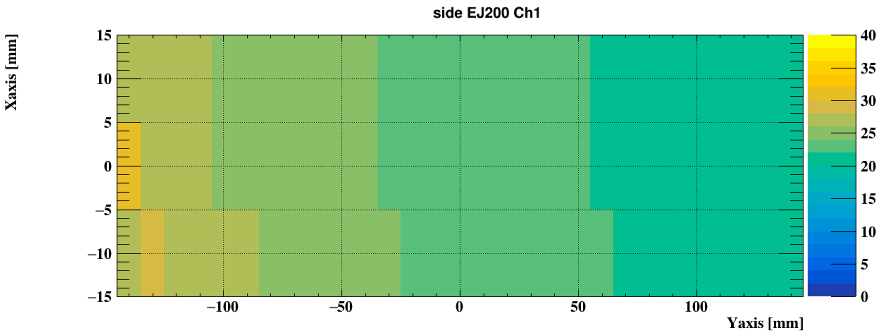


ch1 and ch2 geometric mean

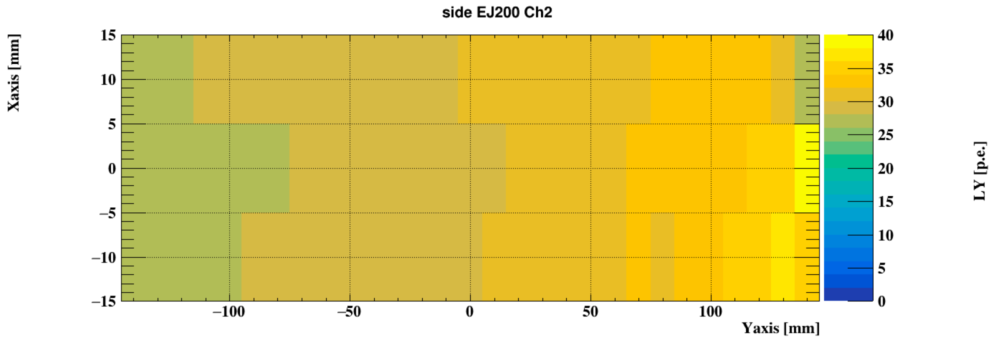


Side readout (EJ200)

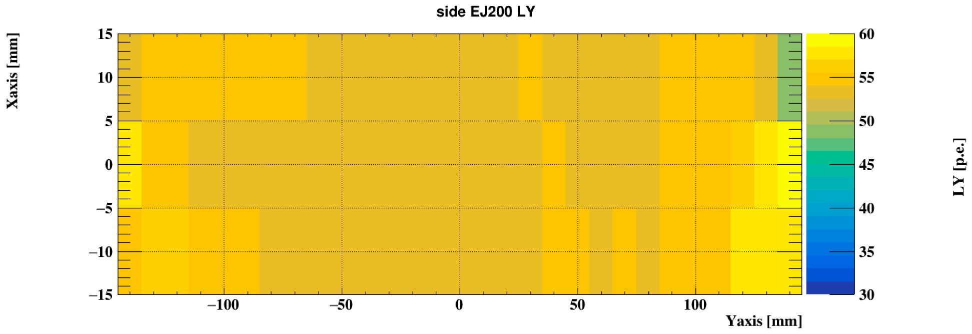
Ch1 at left side



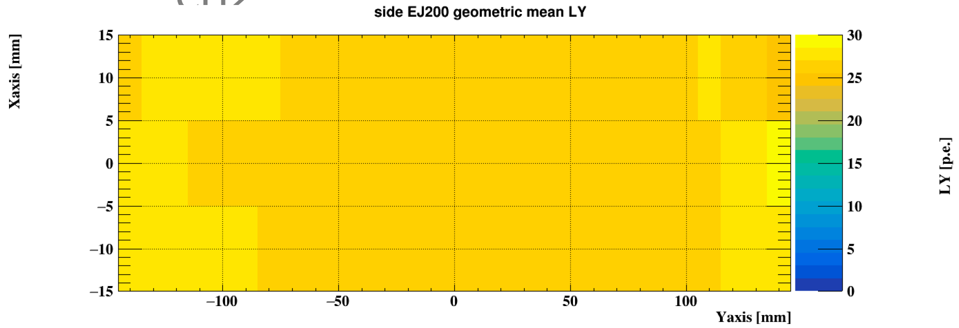
Ch2 at right side



Ch1 and ch2 sum

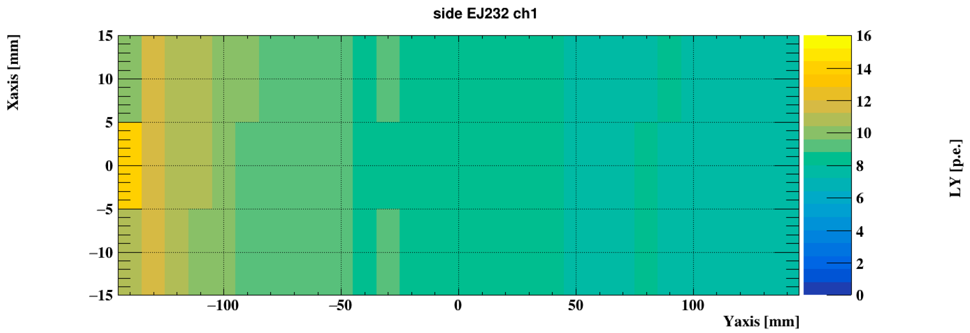


Geometric mean ch1 and ch2

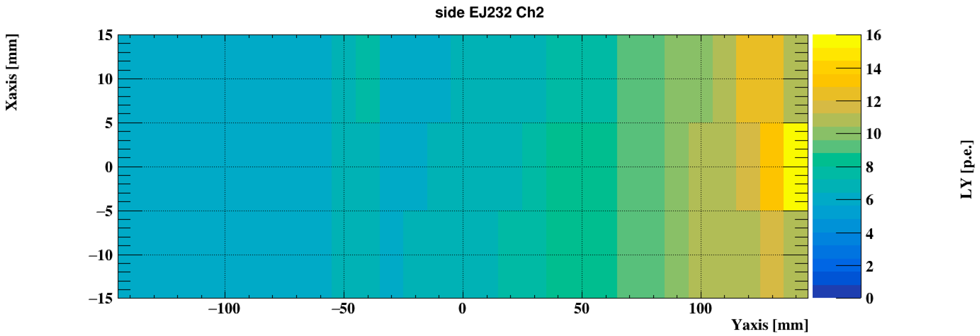


Side readout (EJ232)

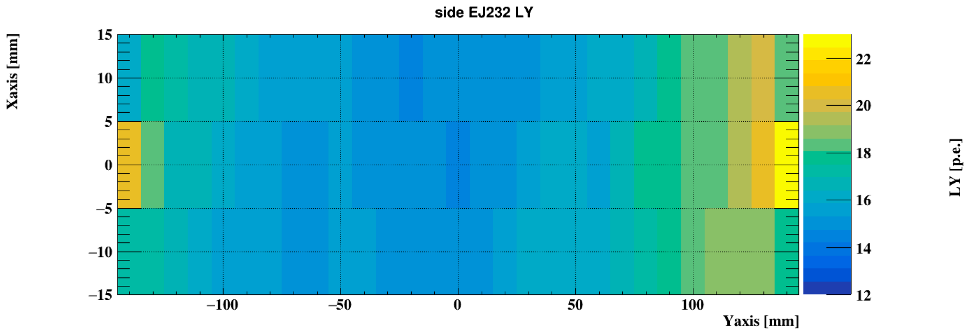
Ch1 at left side



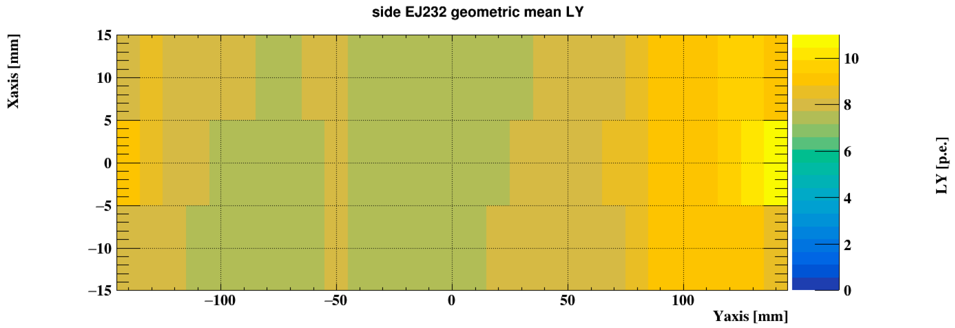
Ch2 at right side



Ch1 and ch2 sum



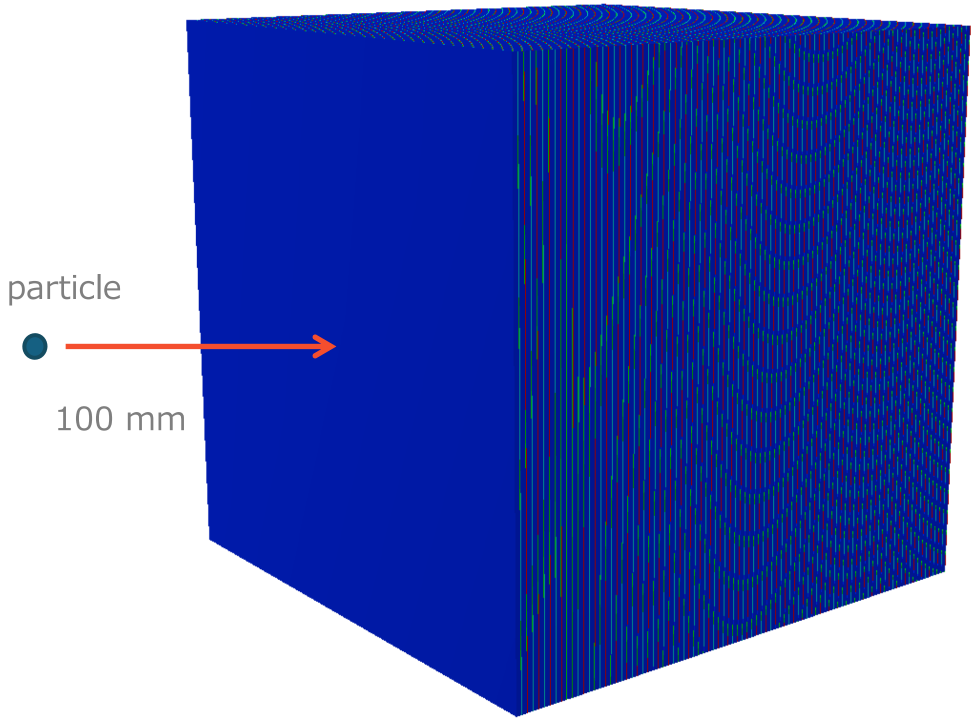
Geometric mean ch1 and ch2

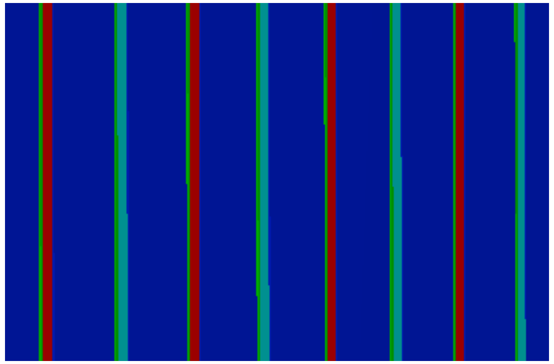


Simulation

Simulation setup

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

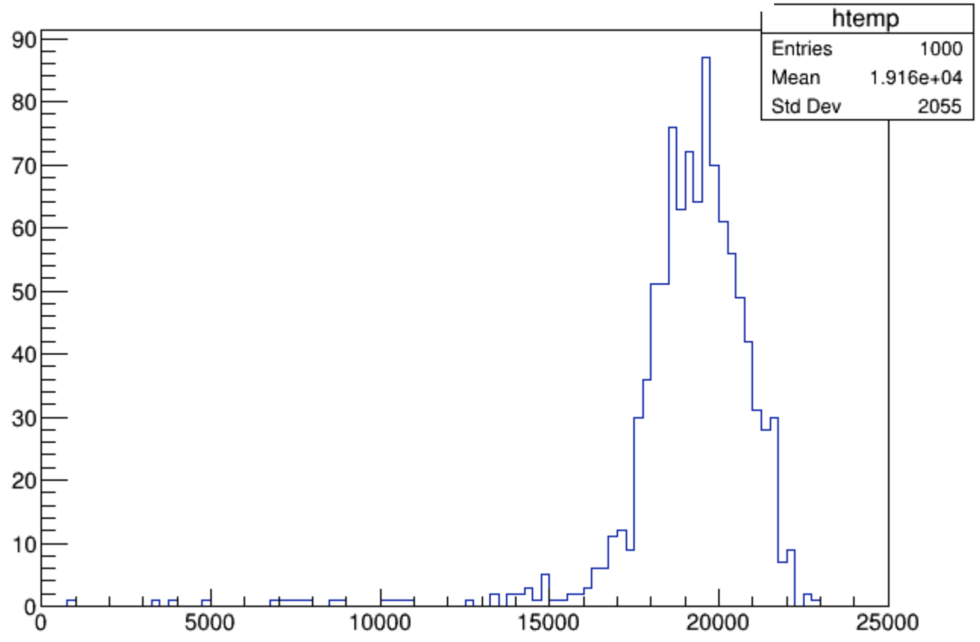




Scintillator signals

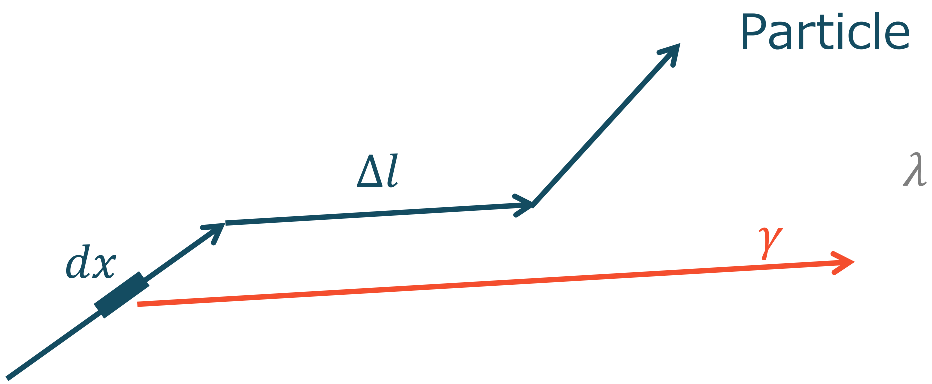
- Use p.e. assuming MPPC linear response.
- #p.e. = 0.0005 / MIP (3 mm thick)

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



Cherenkov signals

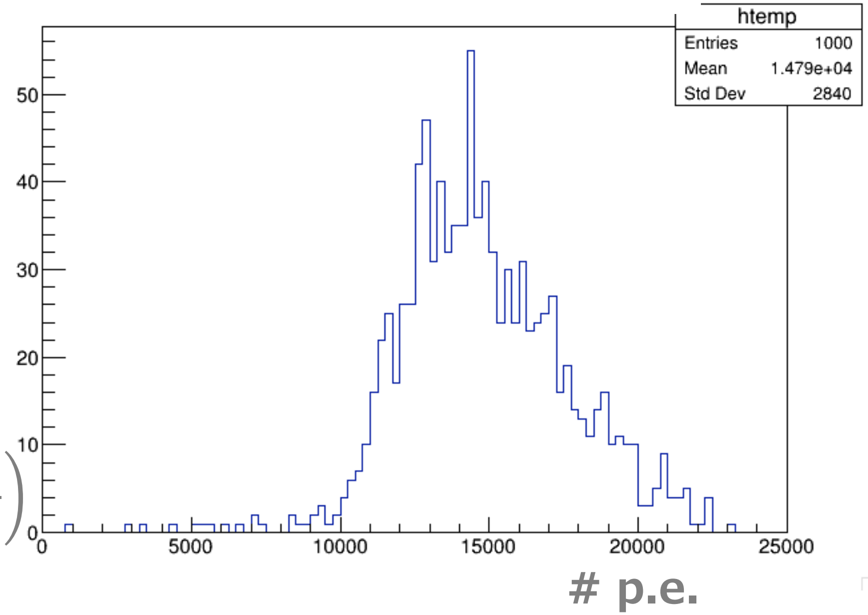
- The number of generated Cherenkov photons:



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

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

60 GeV π^-



- # 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

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

- NIFS-V made from NIKON.

Impurities

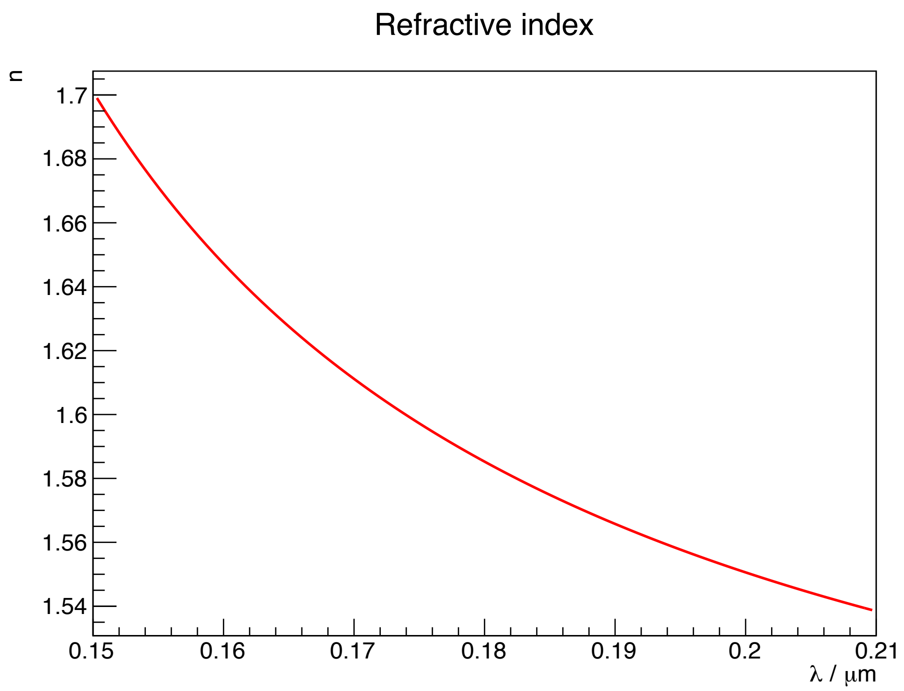
OH	< 100 ppm	Al	< 0.2 ppb
Li	< 0.2 ppb	Ti	< 0.2 ppb
Na	< 0.2 ppb	Cr	< 0.2 ppb
K	< 0.2 ppb	Fe	< 0.2 ppb
Mg	< 0.2 ppb	Cu	< 0.2 ppb
Ca	< 0.2 ppb		

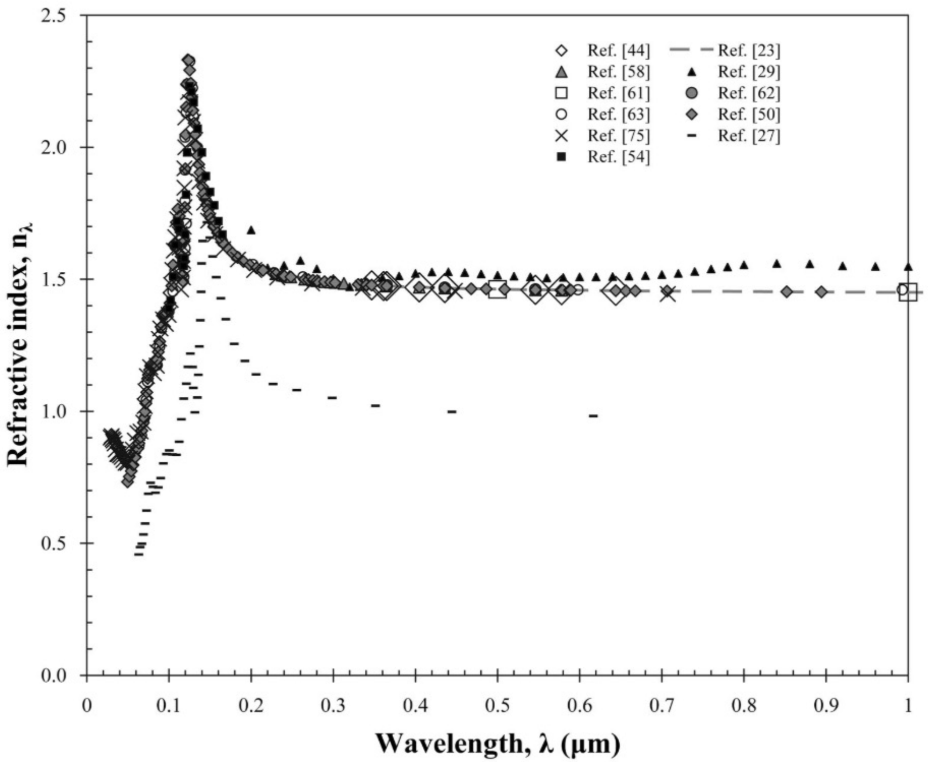
  - Refractive index

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

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





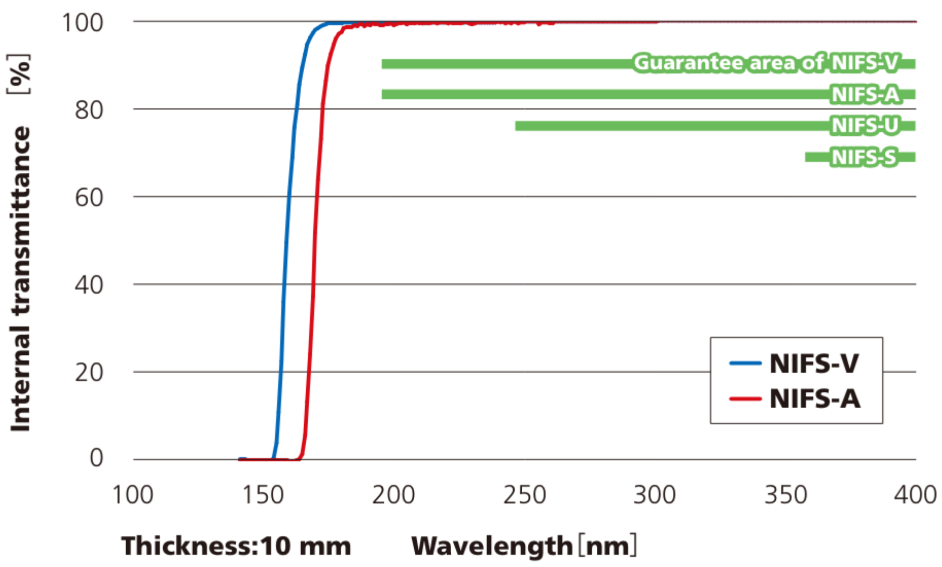
https://www.seas.ucla.edu/~pilon/Publications/AO2007-1.pdf

• Internal transmittance.

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

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

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



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

- CsI photocathode

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

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

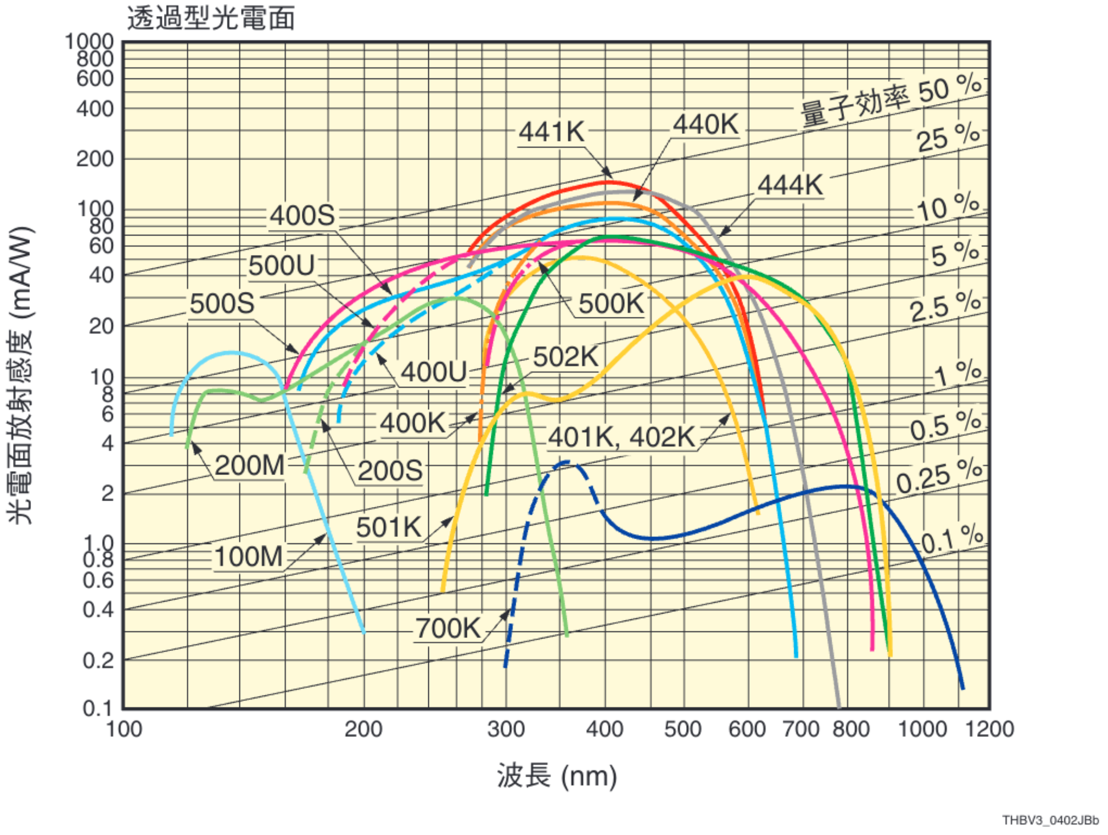


図 4-2(b) 透過型各種光電面分光感度特性

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.

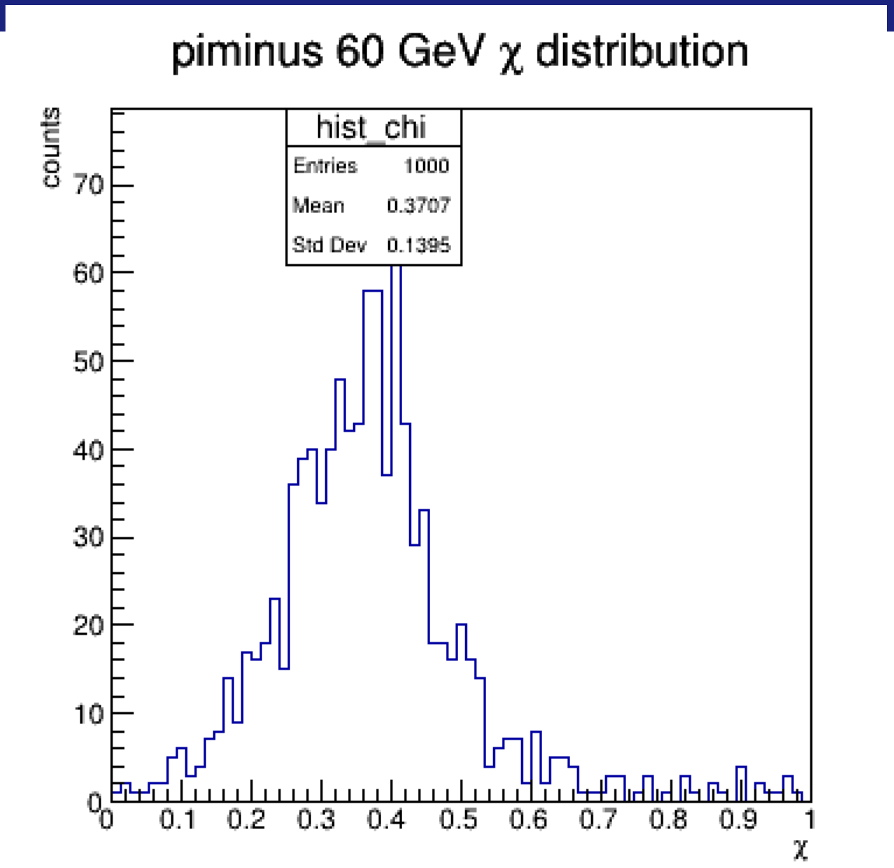
$$(\text{Reconstructed hadron energy}) = \frac{1}{k} \cdot (\text{Output hadron signals})$$

χ estimation

Using initial particle energy and solving

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

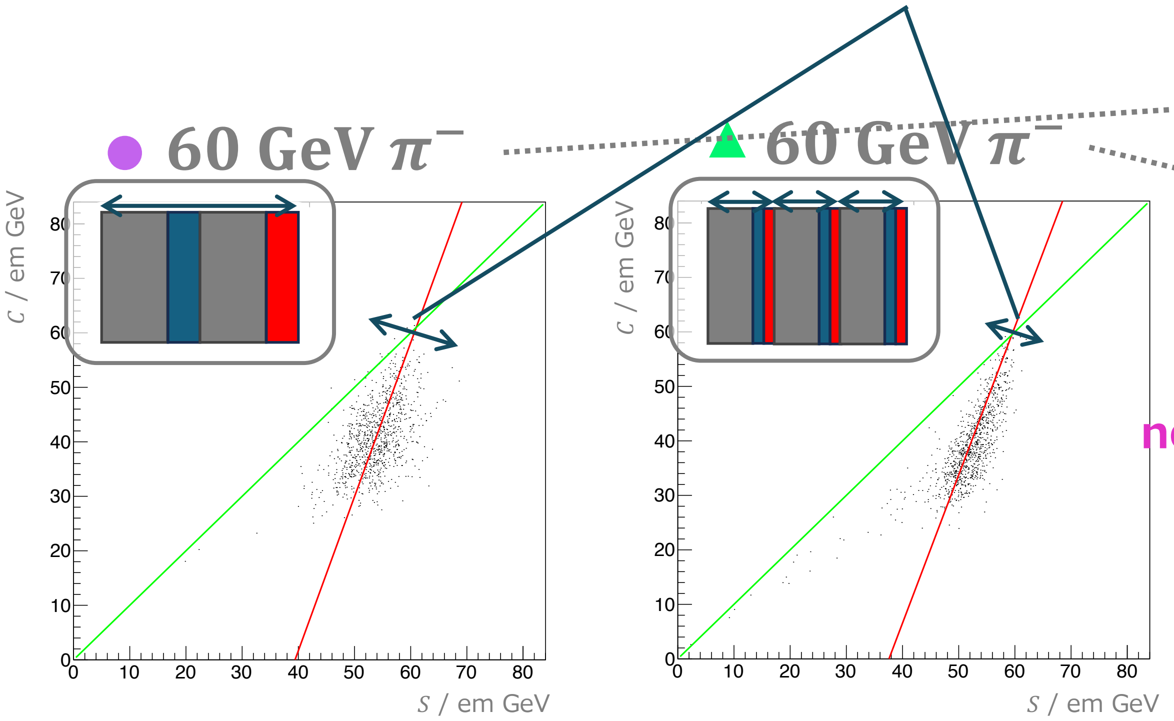
(use most probable value)



Discussion

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

Corresponding to the Dual-Readout resolution



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