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Development of a new calorimetry with high-granularity, dual-readout and excellent timing - Energy resolution evaluation by simulation -

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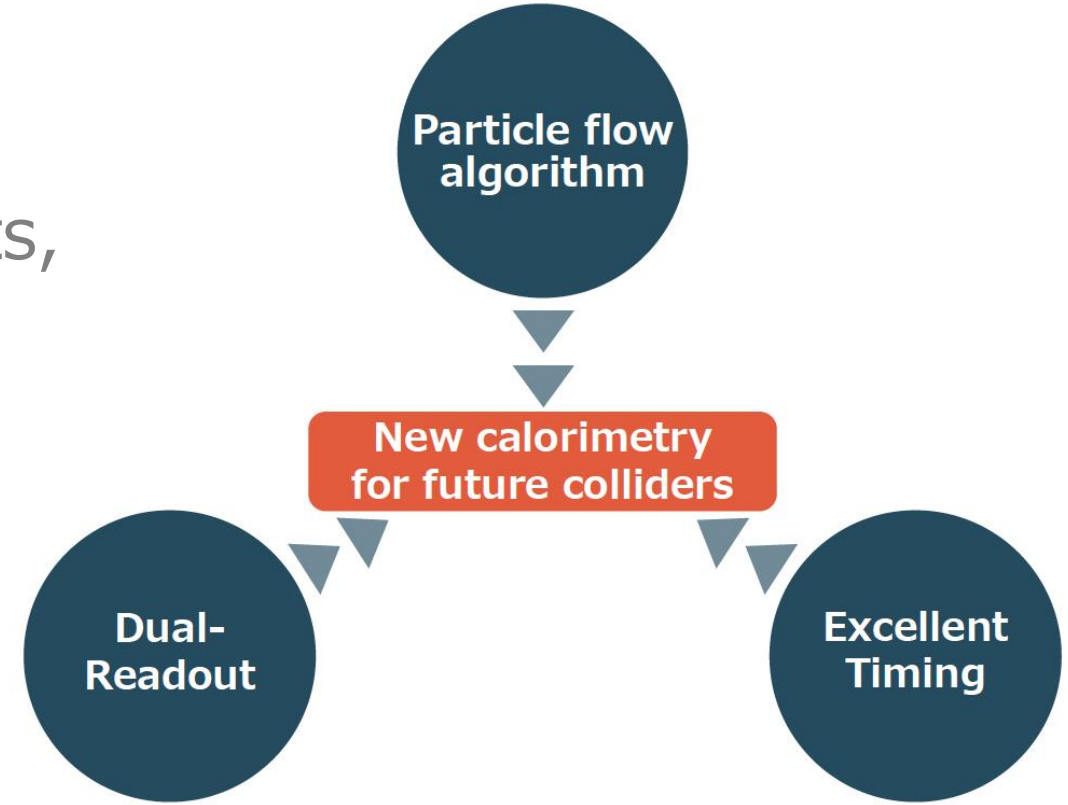
Introduction

New calorimetry development

To realize high energy resolution for jets,

- Combine two sophisticated calorimetry; Particle flow algorithm (PFA) & dual-readout.
- Add excellent timing information for improving PFA.

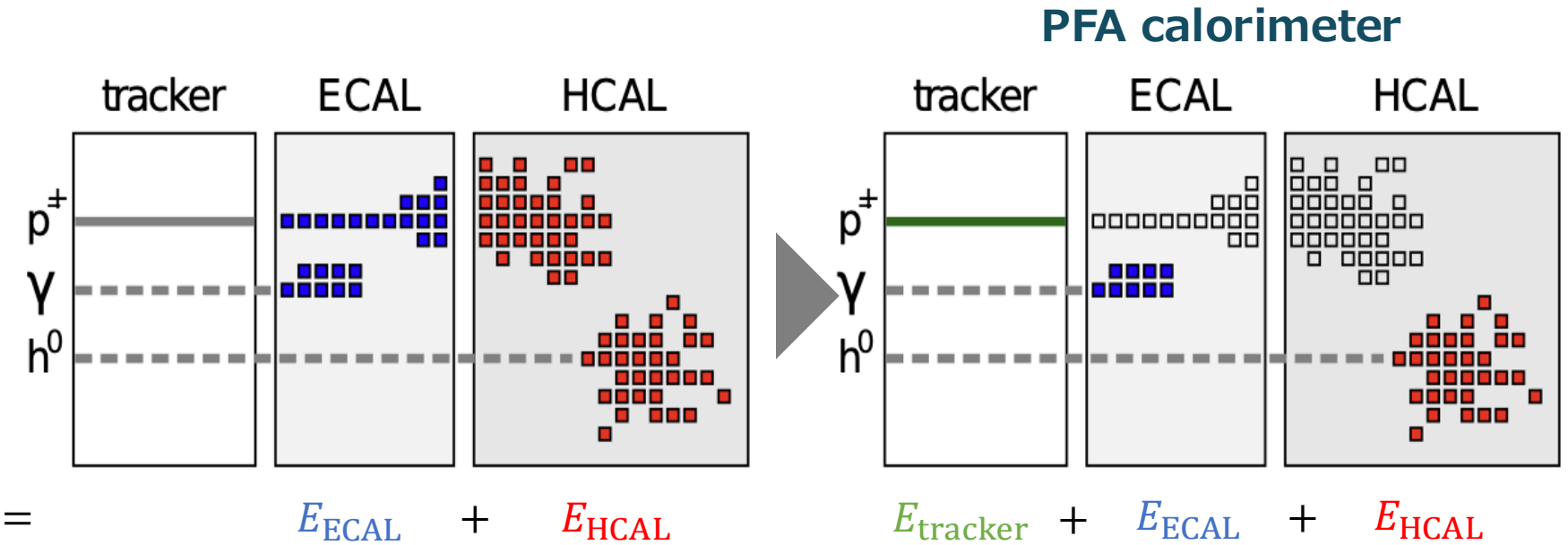


$p^{\pm}$: Charged particle

γ: Photon

h^0: Neutral hadron

Particle flow algorithm (PFA)



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

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

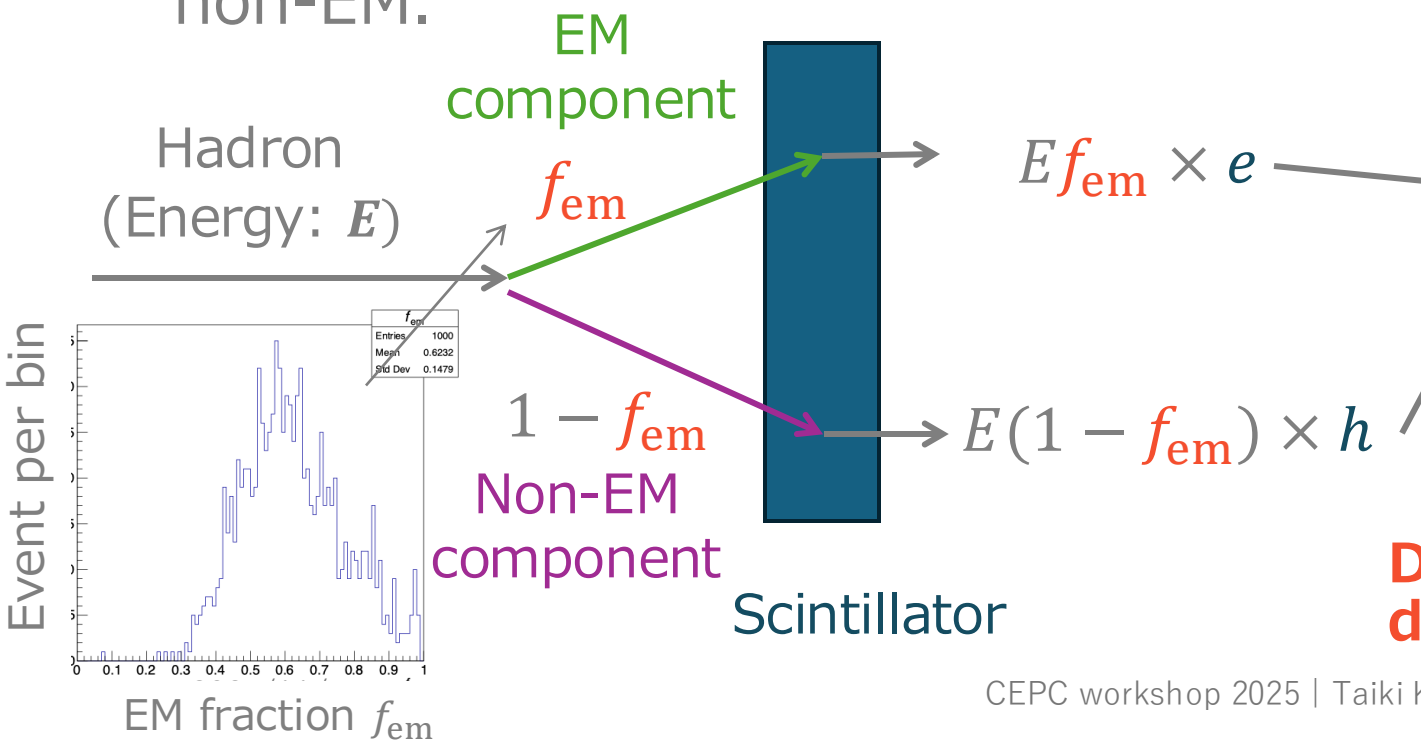
$$E = E_{\mathrm{tracker}} + E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}}$$

- Tracking of each particle and identification of particle type.
- Measurement with best suited detectors depending on particle types.
- For exact classification, high-granular calorimeter is required.

Conventional HCAL

Feature of hadron shower:

- Hadron shower has two components; electromagnetic (EM) and non-EM components.
- The fraction of EM component, f_{em} , fluctuates from event to event.
- The ratio of deposited energy to signal (e, h) differs between EM and non-EM.



Hadron signal:

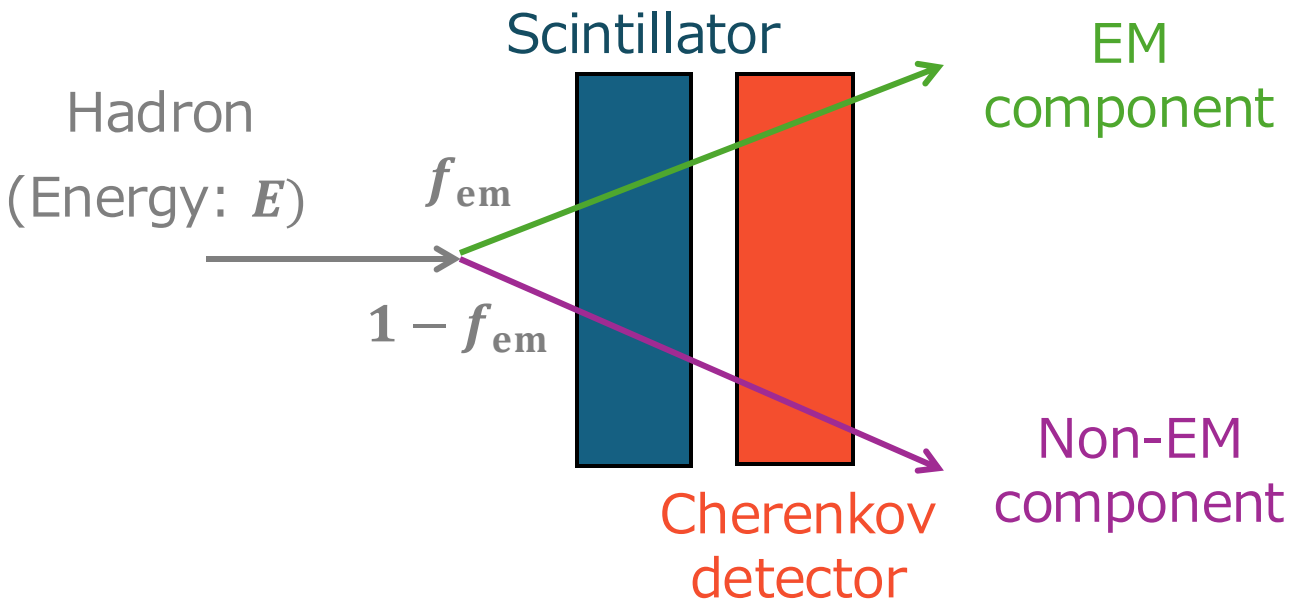
$$E f_{\mathrm{em}} \times e + E(1 - f_{\mathrm{em}}) \times h$$

$$= eE\left[f_{\mathrm{em}} + (1 - f_{\mathrm{em}}) \times \frac{h}{e}\right]$$

Degradation of the energy resolution due to this fluctuation.

Dual-readout (DR)

- Simultaneously read out showers with detectors having distinctly different response ratios (h/e), such as scintillator and Cherenkov detector.
- Using the difference h/e with two detectors, identify the EM fraction event-by-event and exact energy like solving the system below.



EM scaled — EM — Non-EM

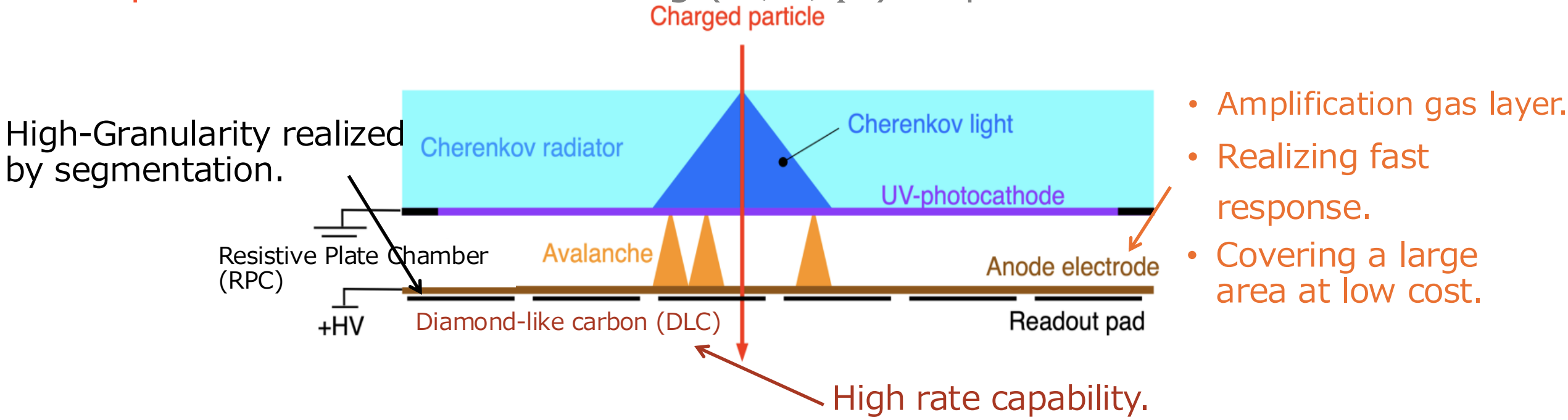
$$\begin{cases} S = E\cdot\left[f_{\mathrm{em}} + \left(\frac{h}{e}\right)_s (1-f_{\mathrm{em}})\right] \\ C = E\cdot\left[f_{\mathrm{em}} + \left(\frac{h}{e}\right)_c (1-f_{\mathrm{em}})\right] \end{cases}$$

$e, h, \left(\frac{h}{e}\right)$: known as independent with initial particle types & incoming energy

$$E = \frac{S-\chi C}{1-\chi} \qquad \left(\chi = \frac{1-\left(\frac{h}{e}\right)_s}{1-\left(\frac{h}{e}\right)_c}\right)$$

Excellent-timing

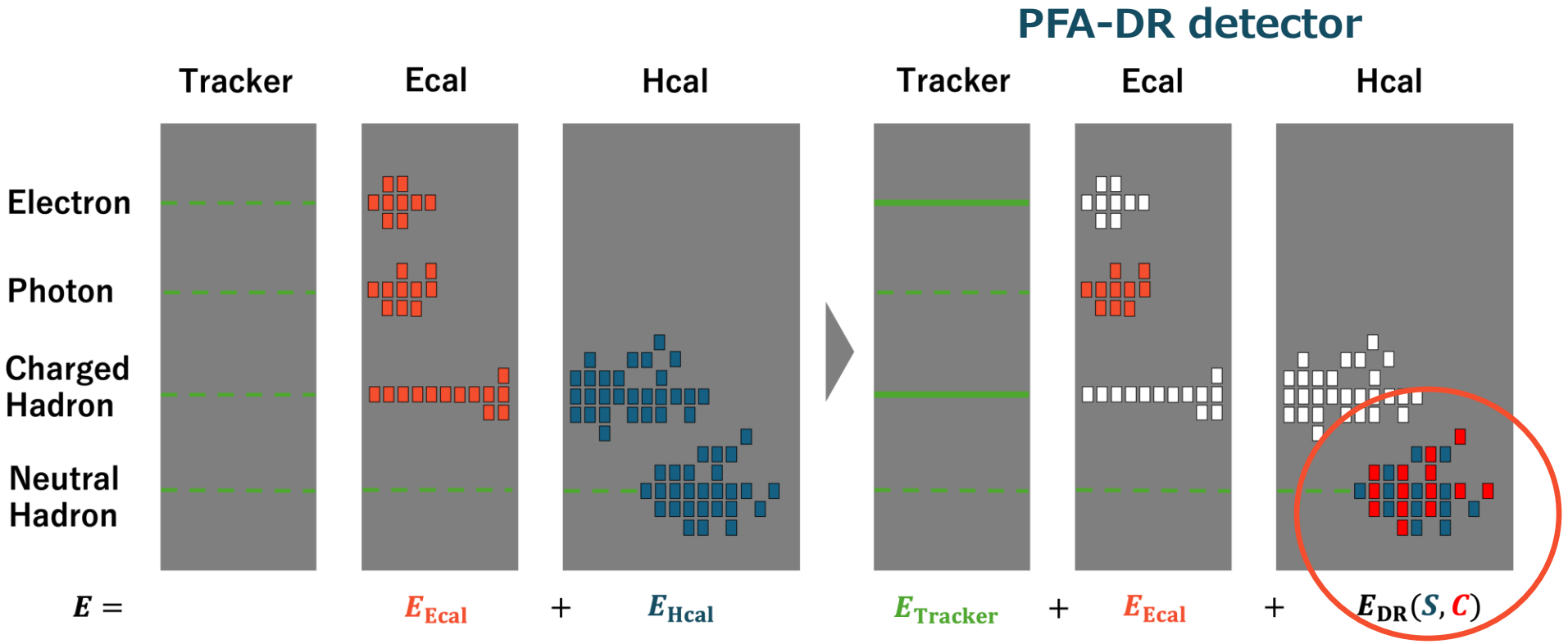
- Utilize a fast time response of Cherenkov light emission in Cherenkov detector used for the DR.
- Cherenkov detector by gaseous photomultiplier based resistive plate chamber for fast timing ($\mathcal{O}(10)$ ps) response.



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

Current status

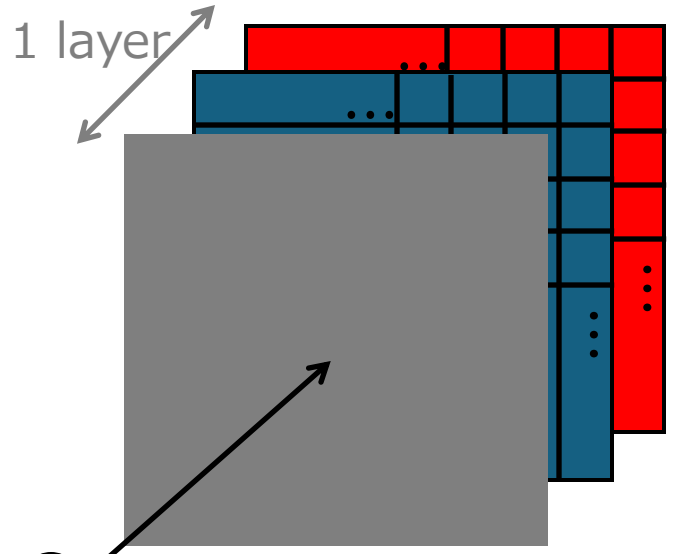
To combine PFA & DR detector, evaluate the performance of high-granular DR HCAL with single hadron by simulation.



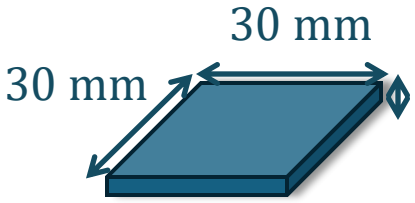
Performance evaluation of DR HCAL

Setup

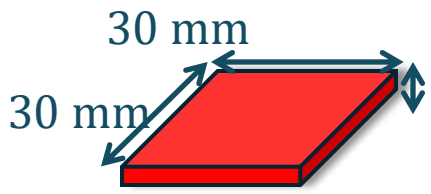
- Used iLCSoft.
- CALICE AHCAL-like setup.
- 3 setups with same depth and different sampling frequency.



10~100 GeV (at 10 GeV intervals.)

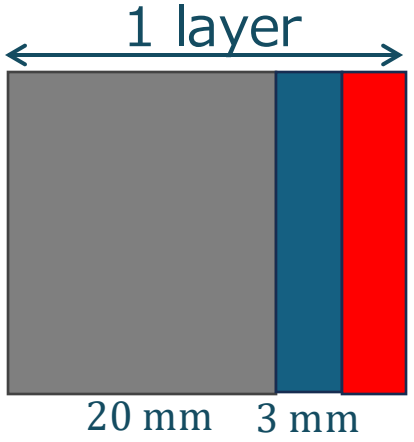


Scintillator tile

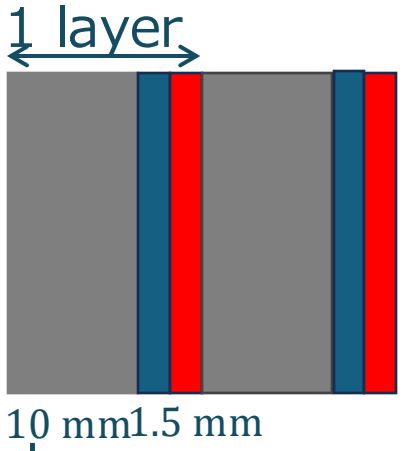


Cherenkov tile

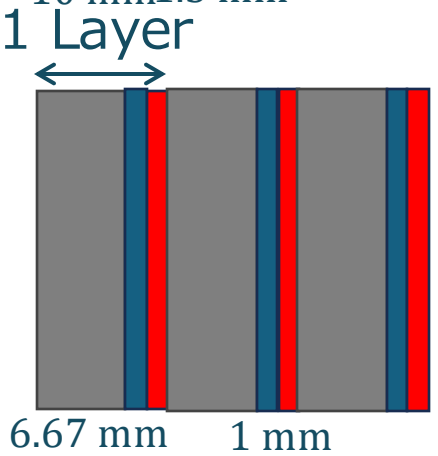
Tot: 60 layers
($\sim 8\,\lambda_{\mathrm{int}}$)



Tot: 120 layers



Tot: 180 layers

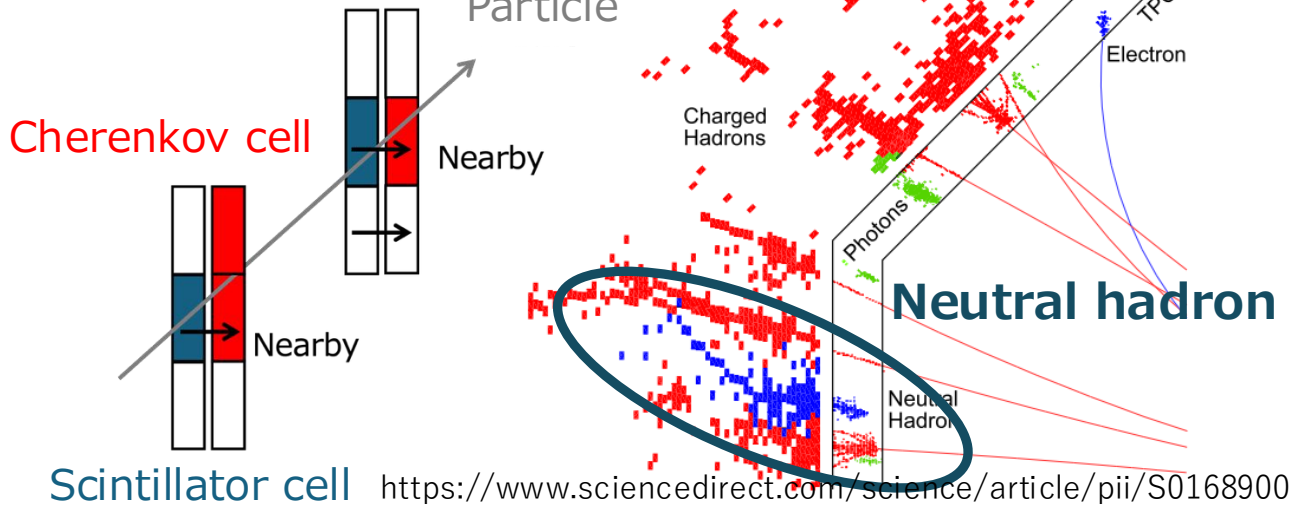


Analysis

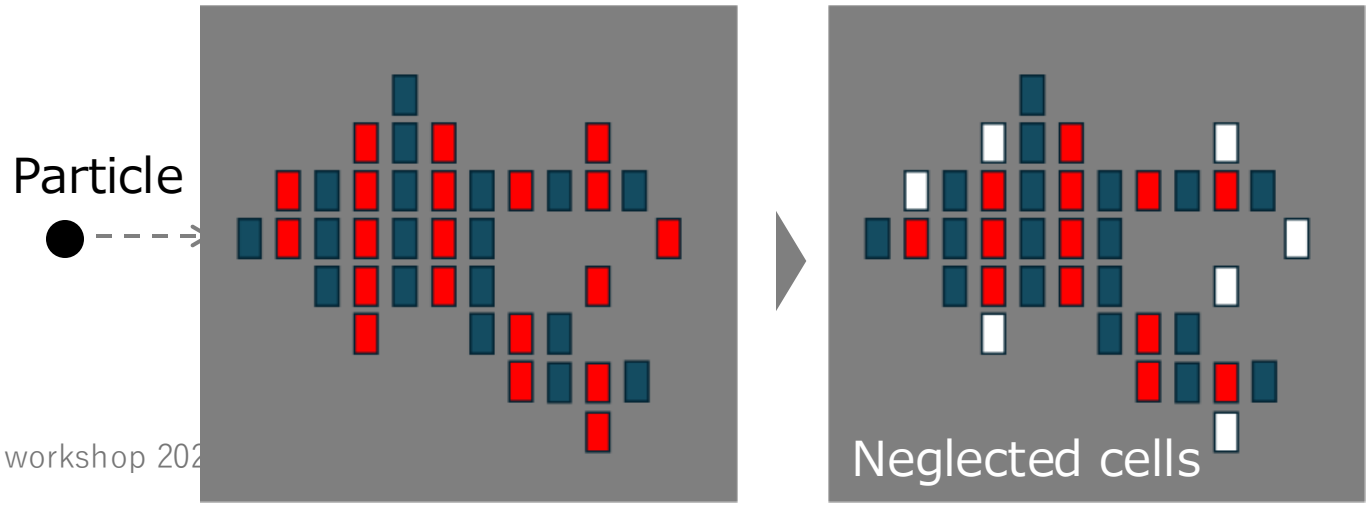
- DR analysis:

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

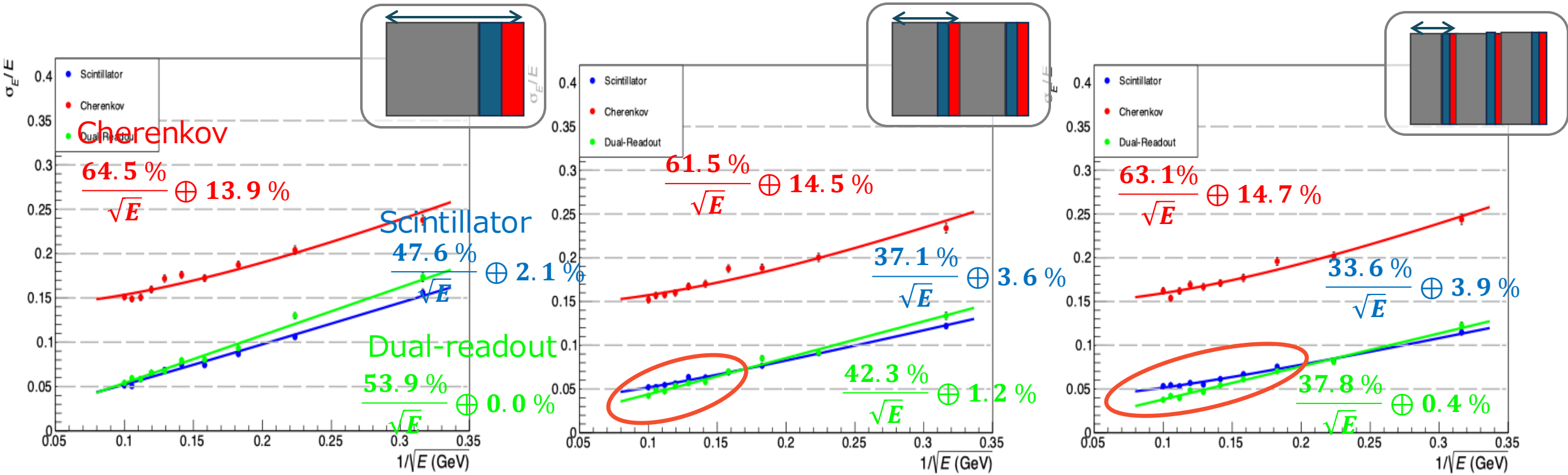
  - Estimate $\chi = (S - E_{in})/(C - E_{in})$ with known E_{in} (initial particle energy).
  - Reconstruct $E = \frac{S - \chi C}{1 - \chi}$ with estimated χ.
- "PFA-compatible" DR analysis:
  - Need to associate Cherenkov hits with Neutral hadron particle flow objects in final state of jets.
  - Only use nearby Cherenkov hits from scintillator hits' location.



https://www.sciencedirect.com/science/article/pii/S0168900212011734

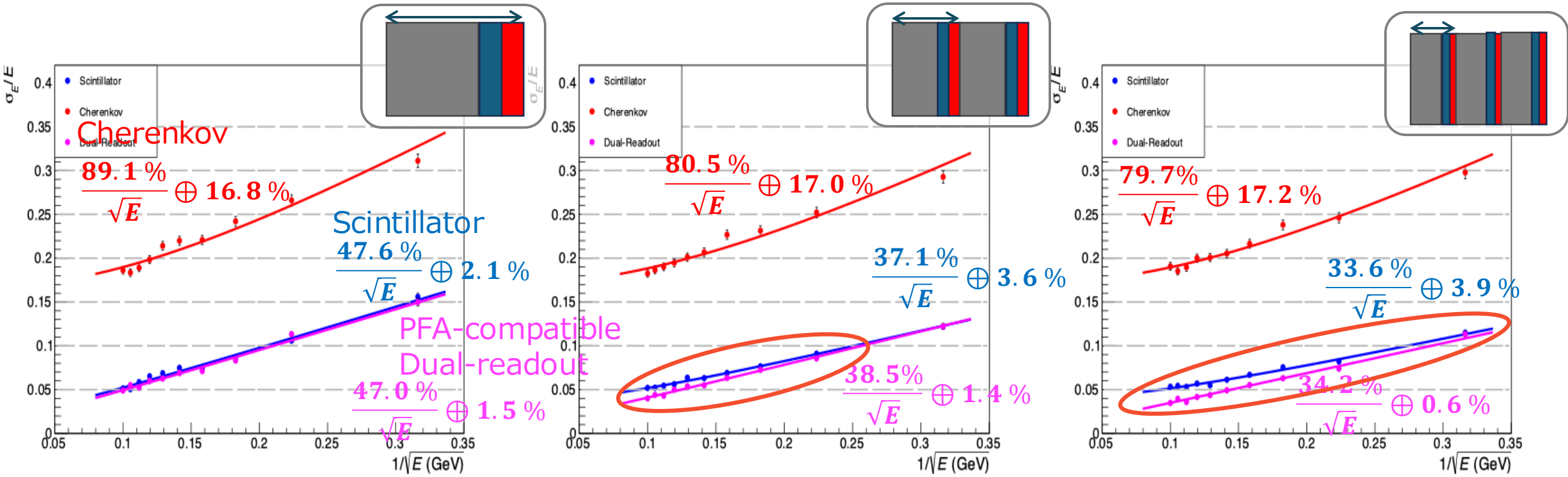


Energy Resolution by DR for K_L^0:



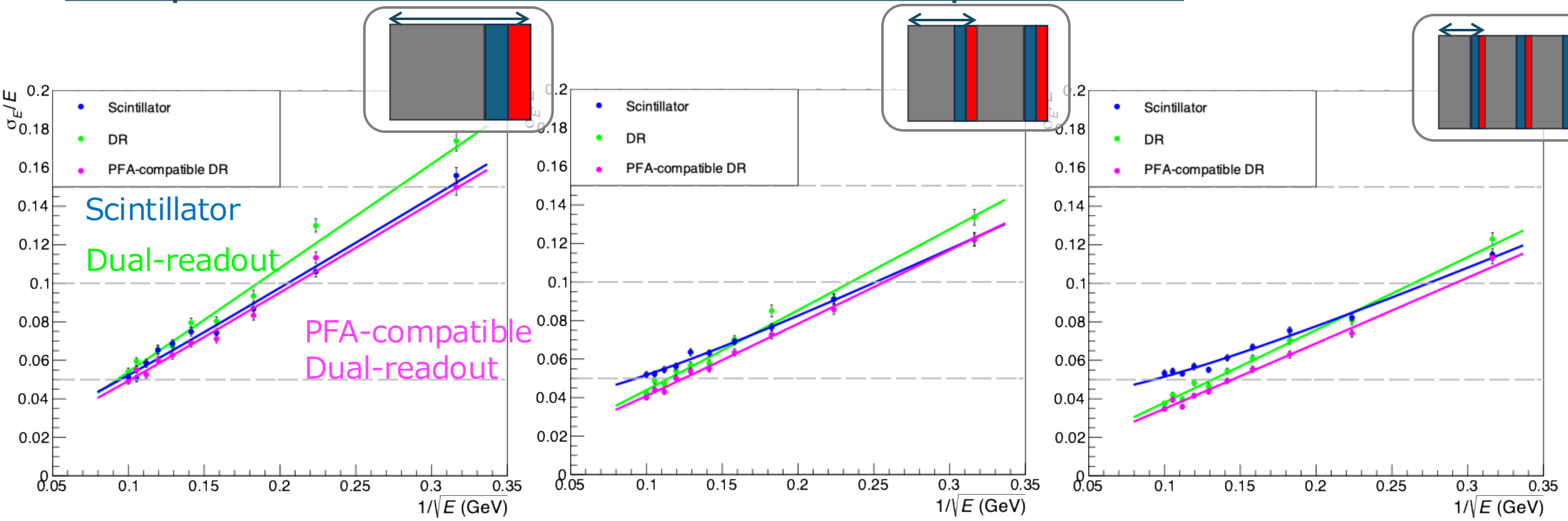
Improvement by DR especially in high energy region.

Energy resolution by PFA-compatible DR for K_L^0:



Also, improvement by DR especially in high energy region.

Comparison between DR and PFA-compatible DR



PFA-compatible DR resolutions are better than usual DR resolutions.

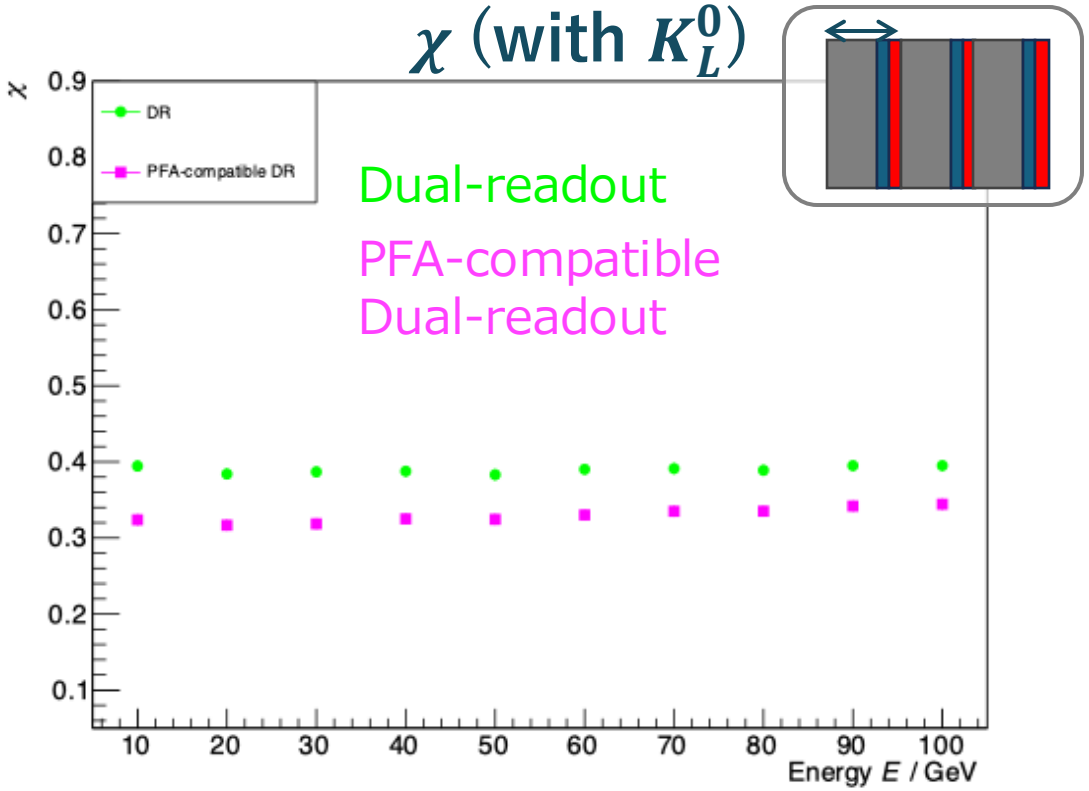
Difference between DR & PFA-compatible DR

- $\left(\frac{h}{e}\right)_C$ decreases. $\left(\chi = \frac{1-\left(\frac{h}{e}\right)_S}{1-\left(\frac{h}{e}\right)_C}\right.$ decreases.)

- Decrease of $\left(\frac{h}{e}\right)_C$ makes more distinct difference between two $\left(\frac{h}{e}\right)_{S,C}$.

$$S = E \cdot [f_{\mathrm{em}} + \underbrace{\left(\frac{h}{e}\right)_s}_{\sim 0.6}(1 - f_{\mathrm{em}})]$$

$$C = E \cdot [f_{\mathrm{em}} + \underbrace{\left(\frac{h}{e}\right)_c}_{\sim 0.3 \rightarrow \text{smaller}}(1 - f_{\mathrm{em}})]$$



- Clear difference in $\left(\frac{h}{e}\right)$ between the two signals allows to more exactly identify and eliminate f_{em}, leading to an expected improvement in the DR performance.

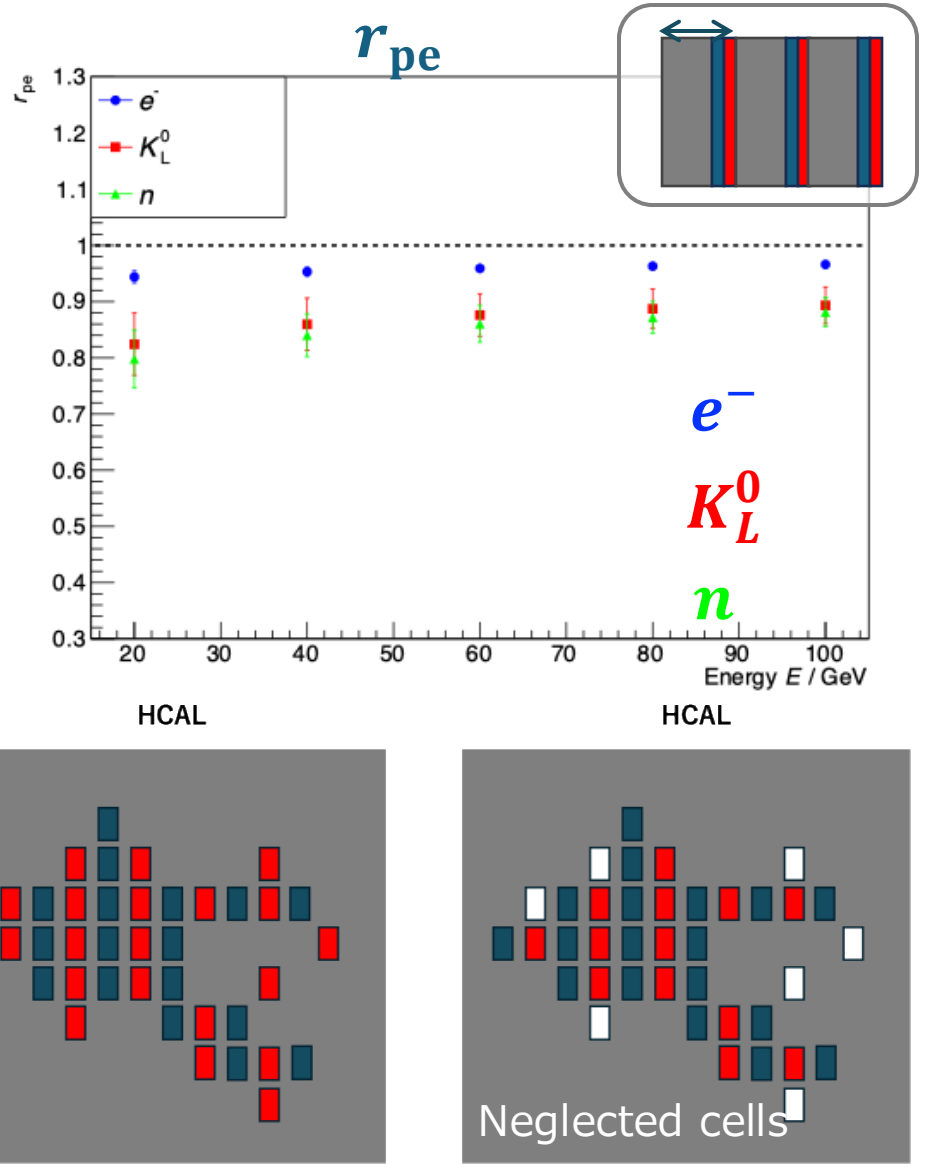
- The reason why $\left(\frac{h}{e}\right)_C$ decreases when only using near Cherenkov hits from scintillator hits:

- Looking at a ratio:

$$r_{\mathrm{pe}} = \frac{\#\ \mathrm{Only\ selected\ Cherenkov\ pe}}{\#\ \mathrm{All\ Cherenkov\ pe}},$$

more selectively Cherenkov hits in EM shower when getting near Cherenkov hits from scintillator hits' location.

$\left(\frac{h}{e}\right)_C \longrightarrow$ Effectively ignoring hits in hadronic shower and getting low.



- Because EM showers are more compact, selecting Cherenkov hits only near scintillator hits are expected to tend to emphasize the EM component.

Conclusion

Summary

- As a first step of developing a new calorimetry that integrates PFA, DR, and excellent timing, evaluated the performance of highly granular DR HCAL (CALICE AHCAL-like setup) by simulation.
- As a result, an improvement in energy resolution by DR at high energy region was observed for several detector setups.
- In particular, the PFA-compatible DR, which takes advantage of the high granularity, showed a potential improvement in energy resolution compared to the conventional DR.

Outlook

- Explore the optimal detector configuration for DR HCAL, such as the choice of absorber material, detector structure and so on.
- The current PFA-compatible DR uses Cherenkov hits only within a fixed distance from scintillator hits. Further improvement in DR performance is expected if successfully selecting only hadronic components more effectively .
- Evaluate PFA-DR analysis for jets at the full detector scale.