GEANT4 simulation of the dual-readout calorimeter for the CEPC

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Computing resource provided by KISTI & KNU

Dual-readout calorimeter

The dual-readout calorimetry

- The major difficulty of measuring energy of hadronic shower comes from the fluctuation of EM fraction of a shower, f_em.
- f_em can be measured by implementing two different channels with different h/e response in a calorimeter.

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right],$$

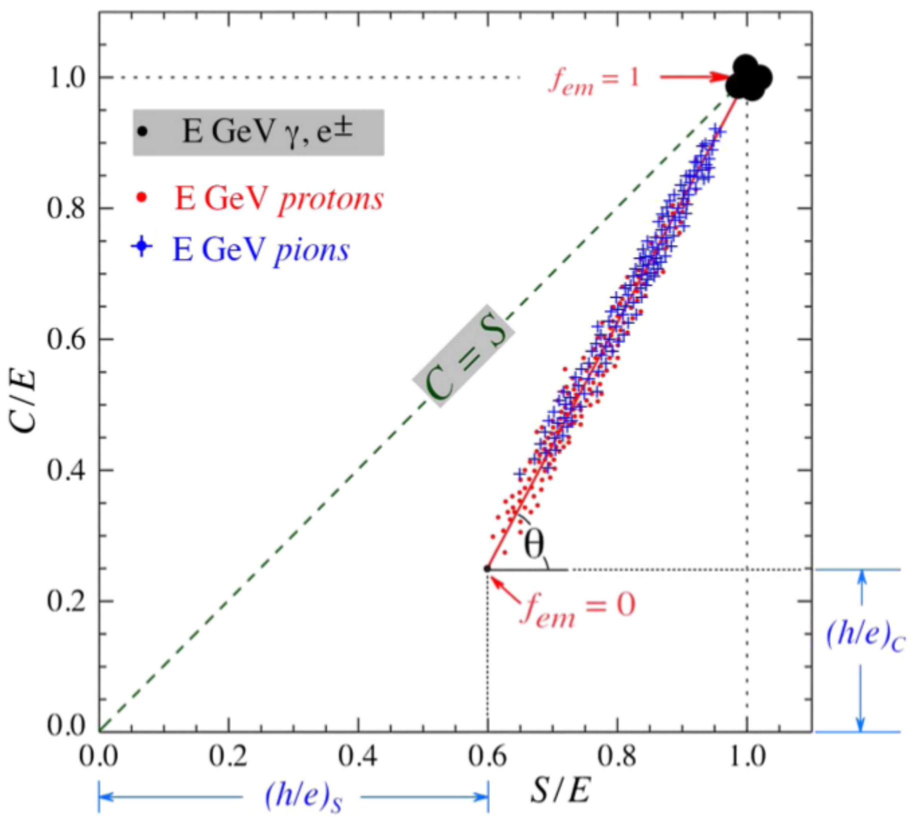
$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1 - f_{em})\right].$$

$$f_{em} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1 - (h/e)_S] - [1 - (h/e)_C]}$$

$$\cot\theta = \frac{1 - (h/e)_S}{1 - (h/e)_C} \equiv \chi,$$

$$E = \frac{S - \chi C}{1 - \chi}.$$

- Dual-readout calorimeter offers high-quality energy measurement for both EM particles and hadrons.
- Excellent energy resolution for hadrons can be achieved by measuring f_em and correcting the energy of hadron event-by-event.

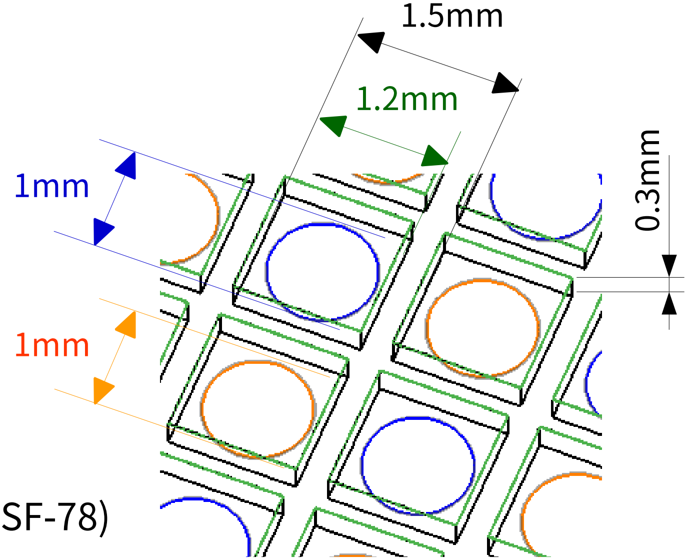


Energy measured from scintillation channel vs Cerenkov channel for EM particle, π & p.

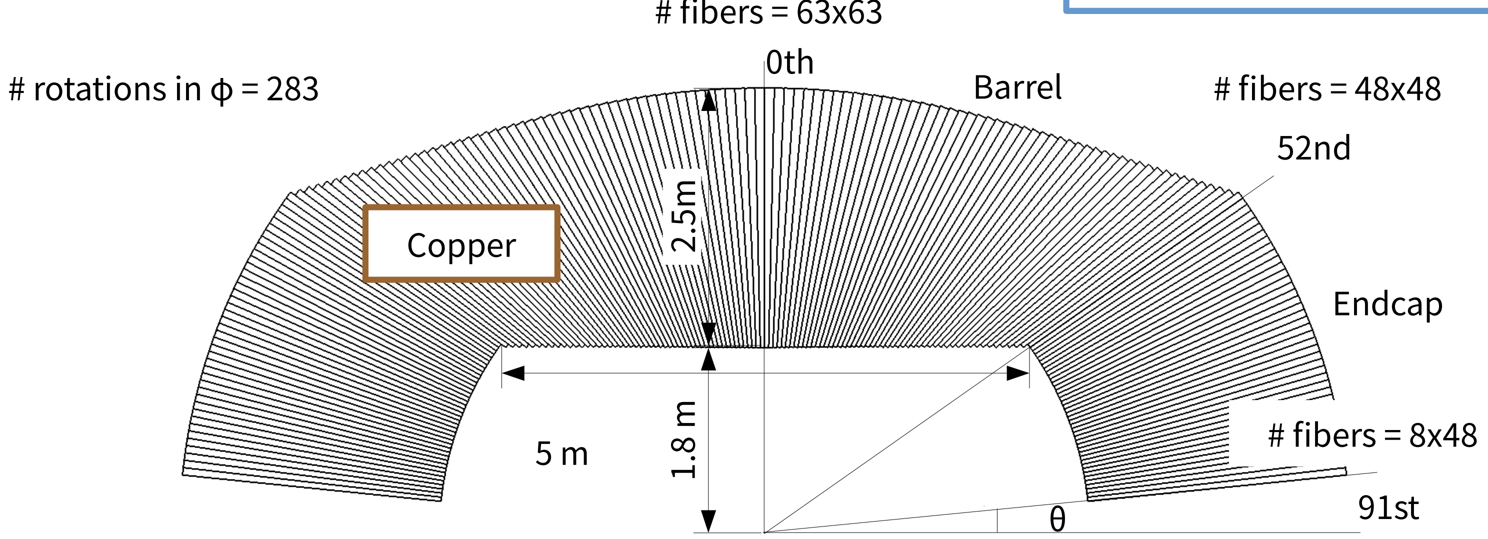
GEANT4 simulation setup (1)

GEANT4 simulation setup – Geometry

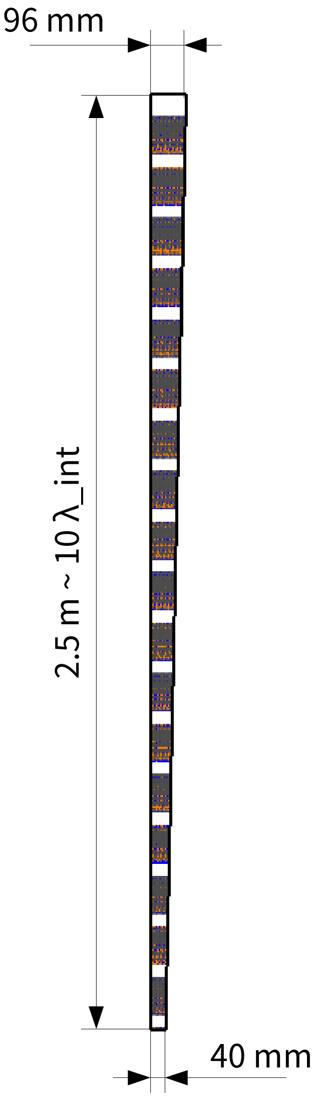
- A projective 4π ‘wedge’ geometry.
- Covers up to |cos(θ)| < 0.995 (|η| < 3.0) with no cracks.
- A Cu tower with a depth of about 2.5 m (~ 10 λ_int).
- O(1000) fibers implemented per tower.
    - Cerenkov(C) fiber: PMMA (Eska SK40)
    - Scintillation(S) fiber: Polystyrene(PS) (Kuraray SCSF-78)
- High granularity SiPM array (Hamamatsu S13615-1025N)



Rear end of a tower



x-z view of dual-readout calorimeter

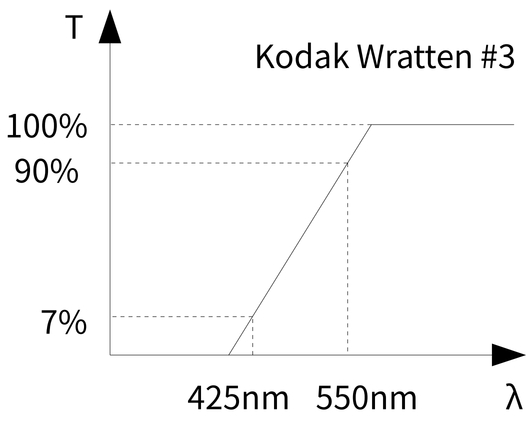


Side view of 0th tower

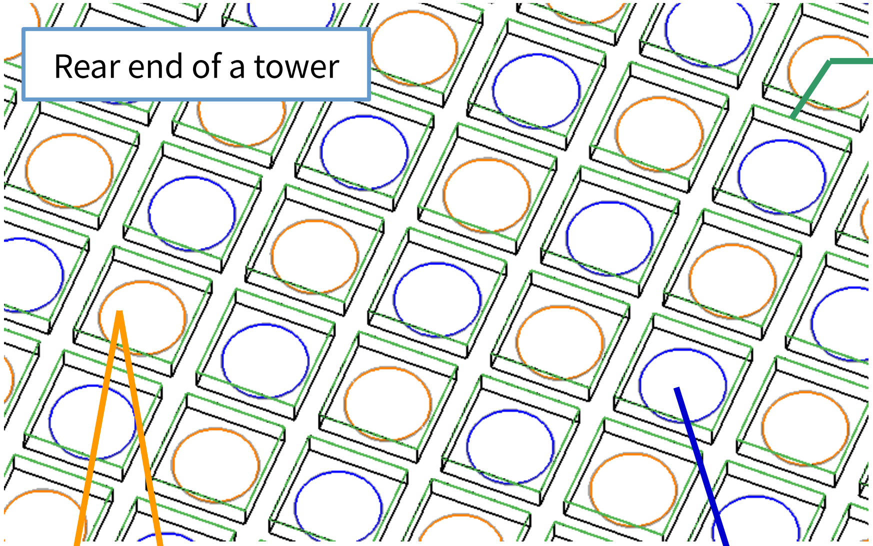
GEANT4 simulation setup (2)

GEANT4 simulation setup – Optical physics

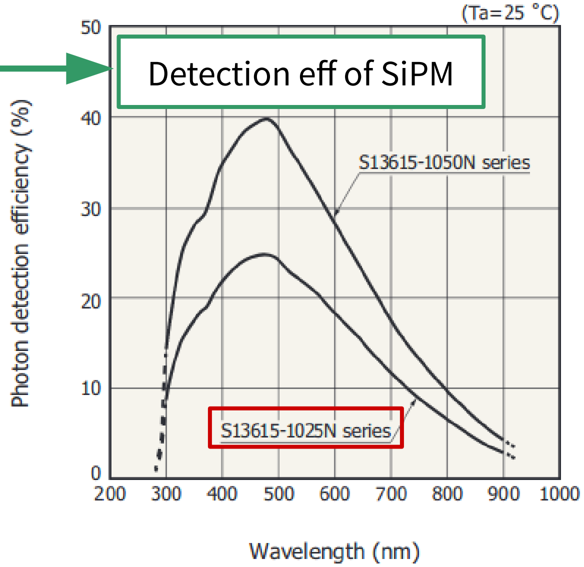
Transmission eff of filter



Rear end of a tower

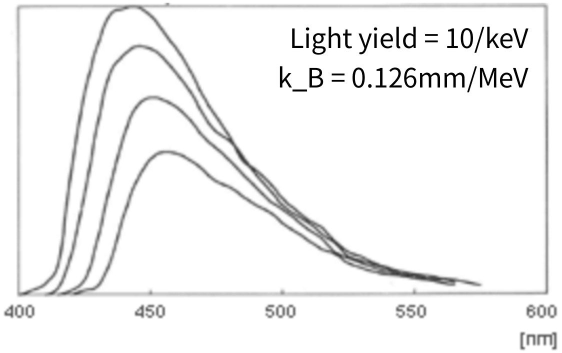


Detection eff of SiPM



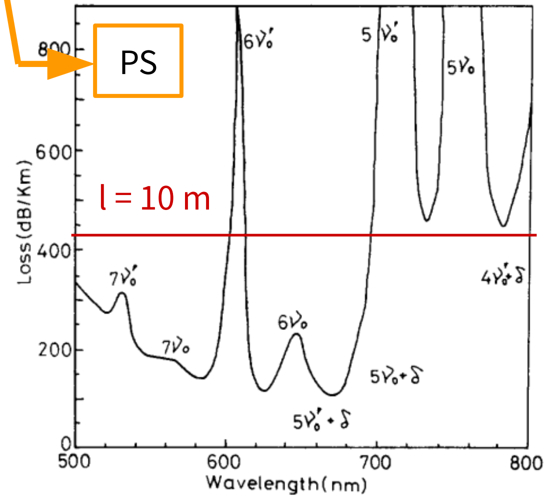
Attenuation loss diverges at 400nm → applied filter to S channel to mitigate it

Scintillation spectra of PS



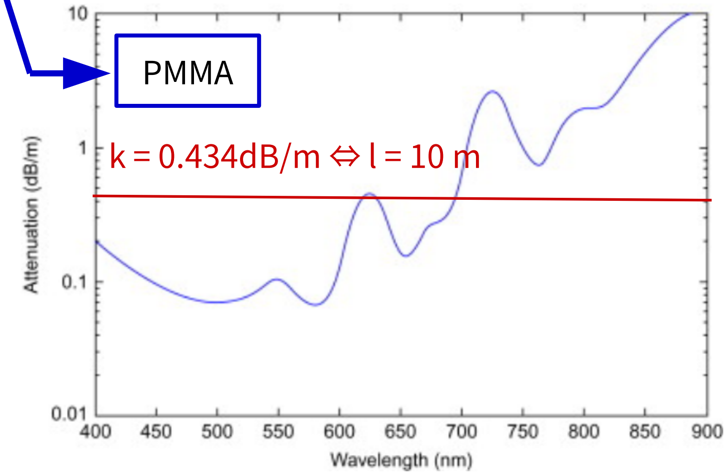
Light yield = 10/keV
k_B = 0.126mm/MeV

Attenuation loss of Polystyrene (PS) & PMMA



PS

l = 10 m



PMMA

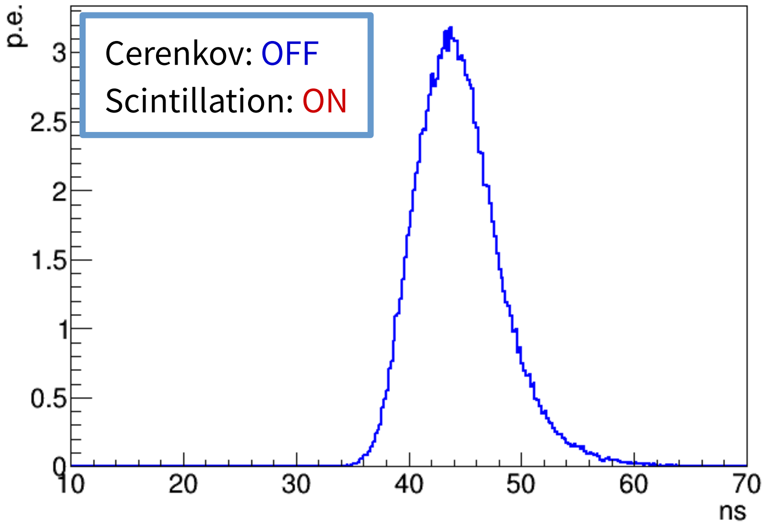
k = 0.434dB/m ⇔ l = 10 m

Optical cross-talk correction

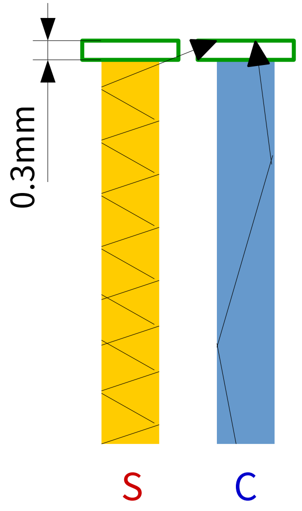
Optical cross-talk (S → C) correction

- Optical X-talk can occur since the thickness of SiPM is not zero.
- X-talk effect from Cerenkov to scintillation channel is minimal, however the effect from scintillation to Cerenkov channel may cause visible effects.
- X-talk effect was checked by simulating 20 GeV e- events, by turning off Cerenkov effect while keeping scintillation effect on.
- X-talk is corrected by applying cut-off for Cerenkov channel with detected time later than 34ns.

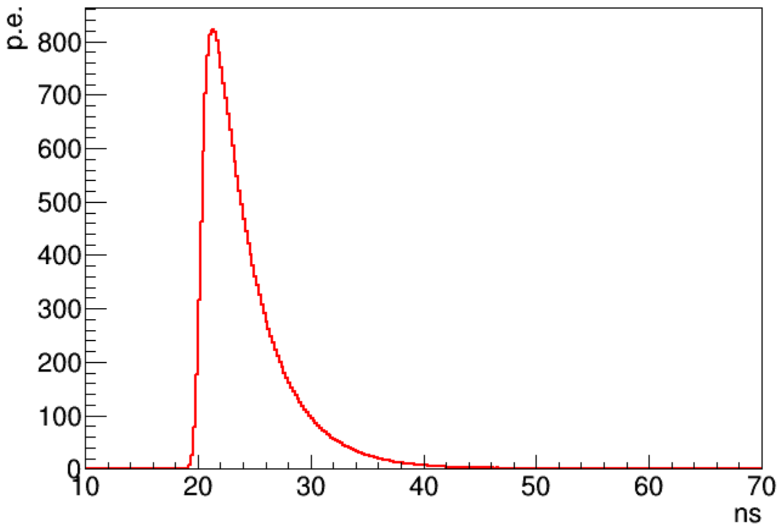
Cross-talk effect (S → C)



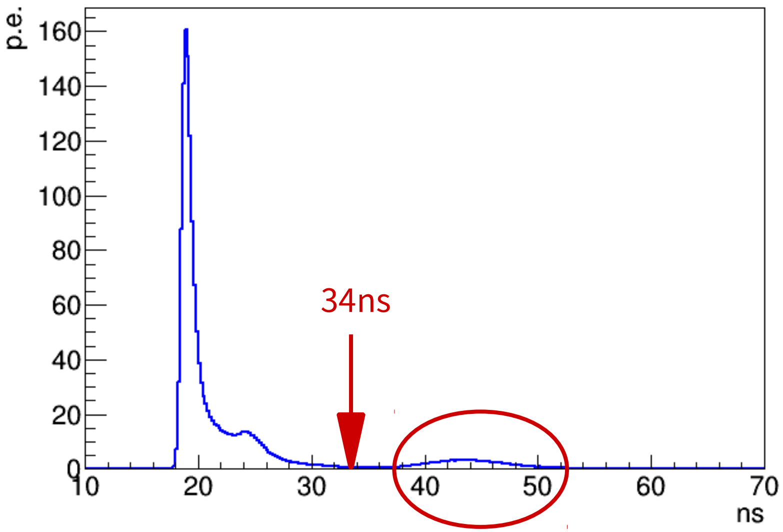
X-talk mechanism



Avg # of p.e. / 0.2 ns for S channel



Avg # of p.e. / 0.2 ns for C channel

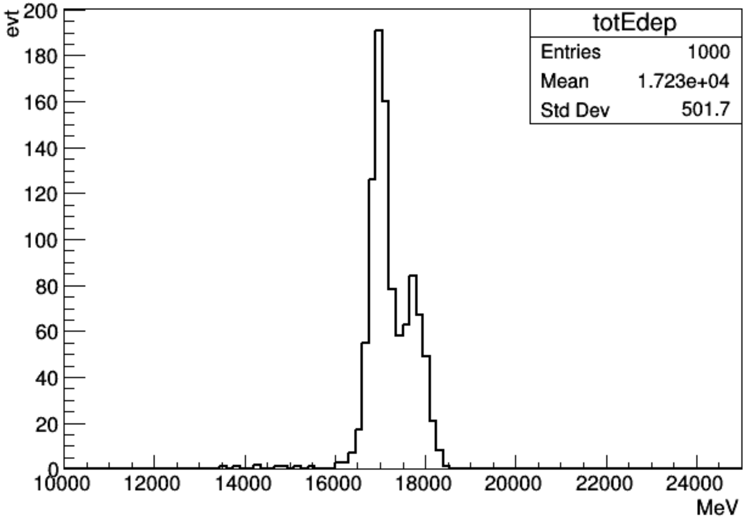


Calibration procedure

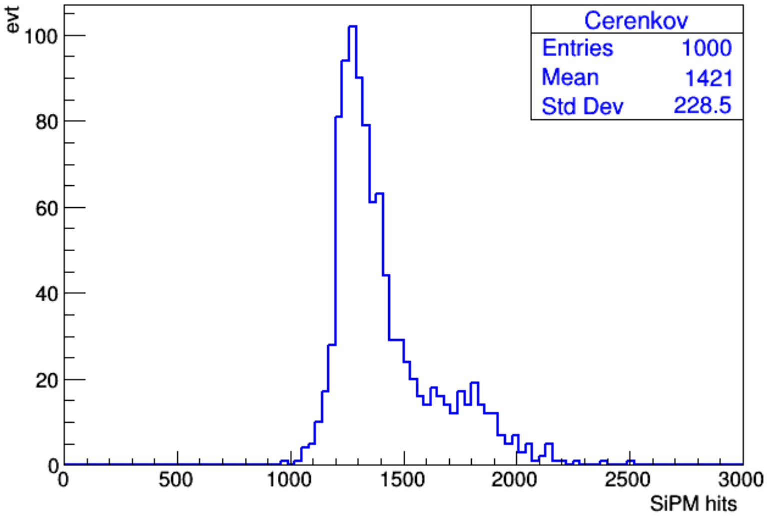
Calibration procedure using 20GeV e- events

- Using 1cm x 1cm e- beam perpendicular to the tower, estimate
  - 1. The total energy deposit located in the tower.
  - 2. # of p.e. counted from Cerenkov channel in the tower.
  - 3. # of p.e. counted from scintillation channel in the tower.
- From the energy deposit located in the tower & p.e. counted from each channel, eventually the amount of response per GeV of the tower can be estimated.
- Repeat for every tower in η direction.

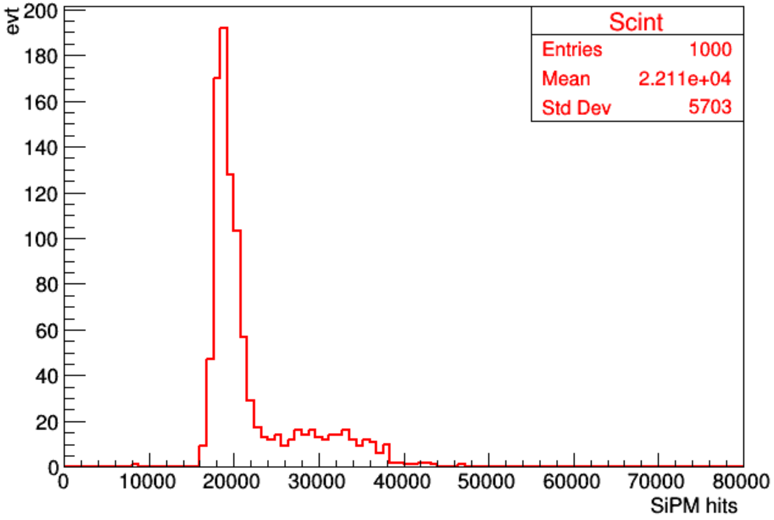
Energy deposit for 20GeV e- (0th tower)



# of p.e. for C channel (0th tower)



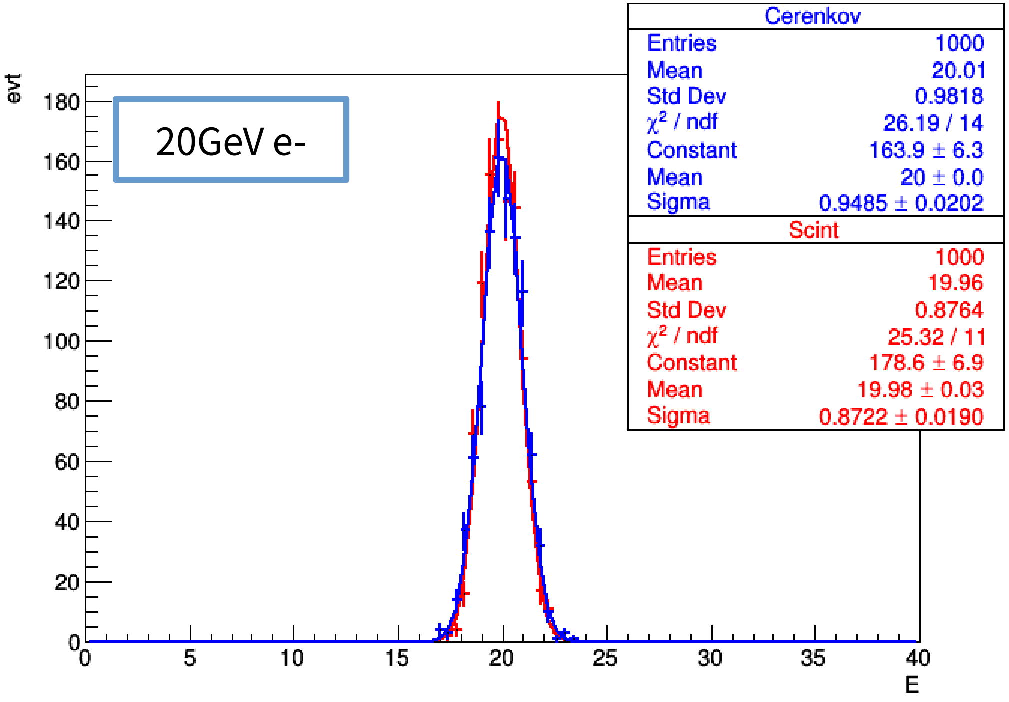
# of p.e. for S channel (0th tower)

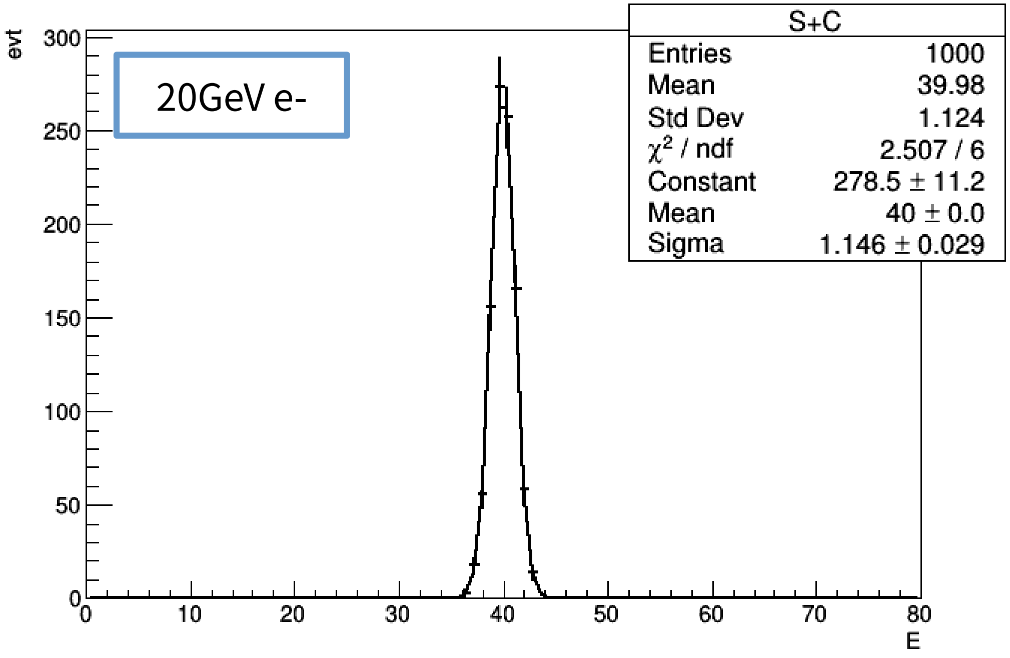


Energy response for e- events

Energy response for e- events

- Energy response of dual-readout calorimeter is estimated using calibrated towers.
- Used 1cm x 1cm e- beams with (Δθ, Δϕ) = (1.5°, 1.0°) incident angle.
- Response of Cerenkov, scintillation channel and sum of two channels are fitted with Gaussian.

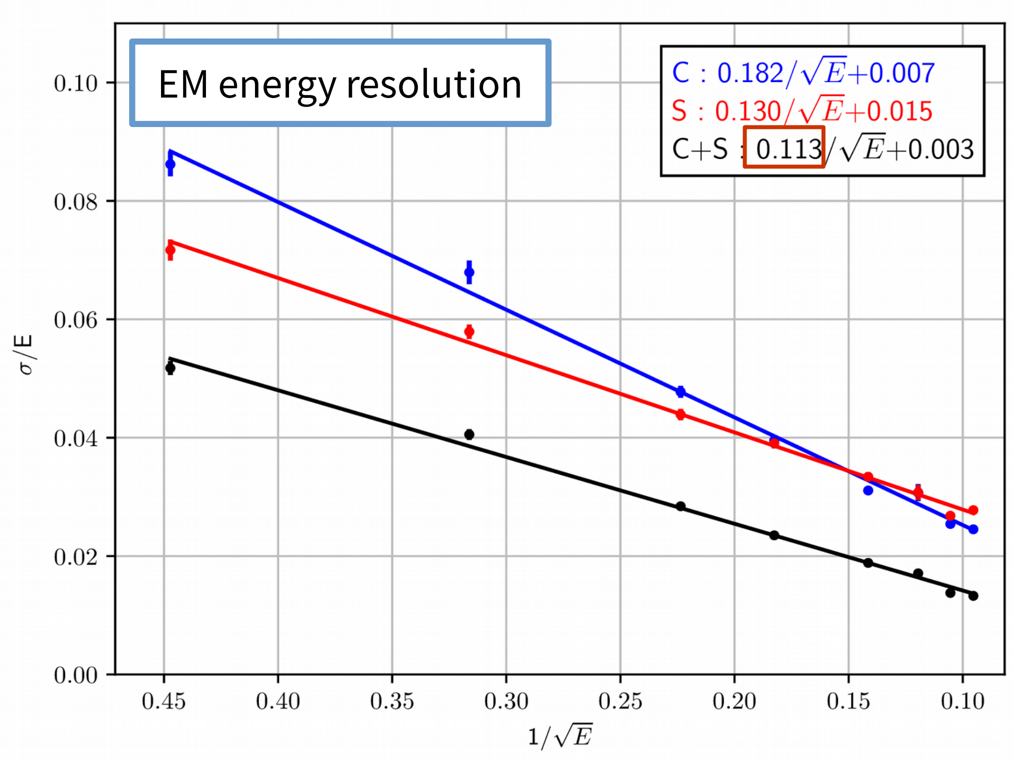


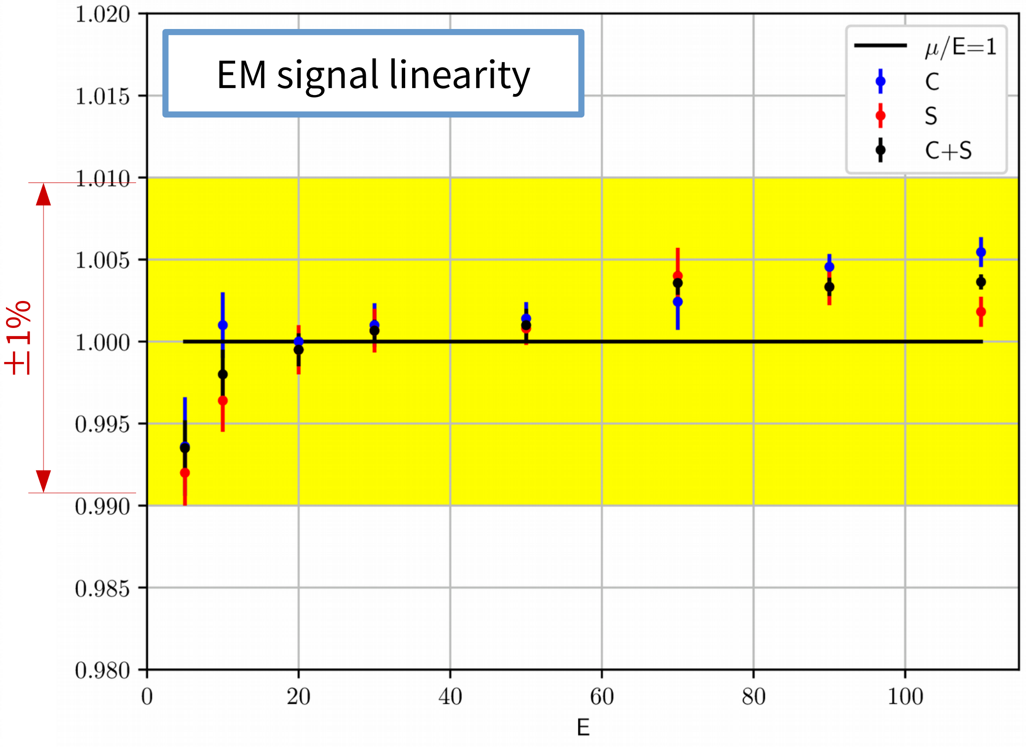


EM energy resolution

EM energy resolution

- Measured EM energy resolution with 5 to 110 GeV electrons.
- Energy resolution is scaled to 1/√E.
- Stochastic & constant term of the energy resolution can be obtained by linear fitting.
- Stochastic term of energy resolution to EM shower is ~ 11%.
- Measured energy is linear to electron energy within ± 1%.





Light attenuation correction (1)

Light attenuation correction

- π+ can go deep inside tower compared to e-.
- Although filters are applied to S channel to mitigate the light attenuation, energy measured from S channel should be corrected to take into account of attenuation properly.
- Can be corrected by measuring the shower depth event-by-event, using time structure of the scintillation signal.

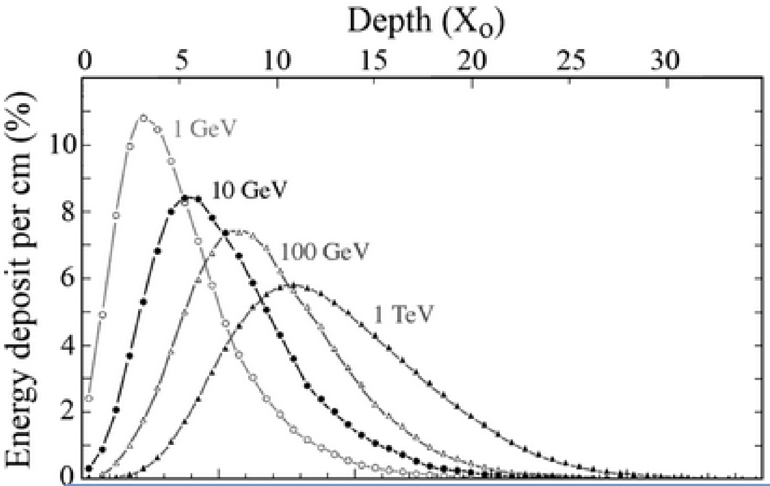
Shower depth as a function of time

- Shower depth x can be represented as a function of detection time

$$t_c = \frac{1}{0.3\,m/ns}x + \frac{1.8\,m}{0.3\,m/ns}$$ TOF of π+ in vacuum/tower

$$t_v = \frac{2.5\,m - x}{v}$$ Propagation time of optical photons

$$t_{max} = t_v + t_c = \frac{2.5 - x}{v} + \frac{x}{0.3\,m/ns} + \frac{1.8\,m}{0.3\,m/ns}$$ Detection time



Longitudinal profile of EM shower (EGS4)

Estimation of average optical photon velocity

- The average velocity of optical photons (v) can be estimated by calculating effective radiation length of the tower & exploiting well-known longitudinal profile of EM showers.

	Cu	PS	PMMA
Volume (%)	65.1	17.45	17.45
X0 (cm)	1.436	41.31	34.07
X0_eff (cm)	2.1613		

Light attenuation correction (2)

Light attenuation correction

- Estimated avg velocity of optical photons using 20GeV e- evts.

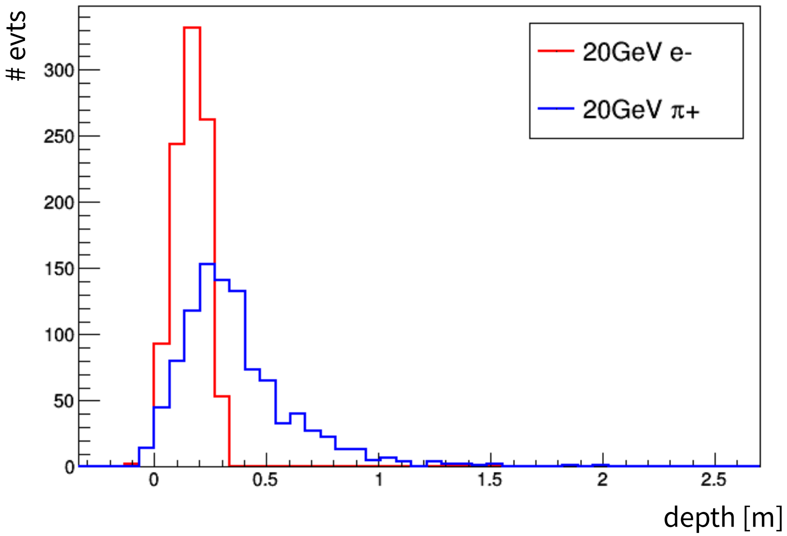
$$v = \frac{2.5\,m - 0.1368\,m}{t_{max} - \frac{0.1368\,m}{0.3\,m/ns} - \frac{1.8\,m}{0.3\,m/ns}}$$

- Shower depth can be estimated event-by-event.
- Average measured energy shows exponential dependency on the depth of a shower.

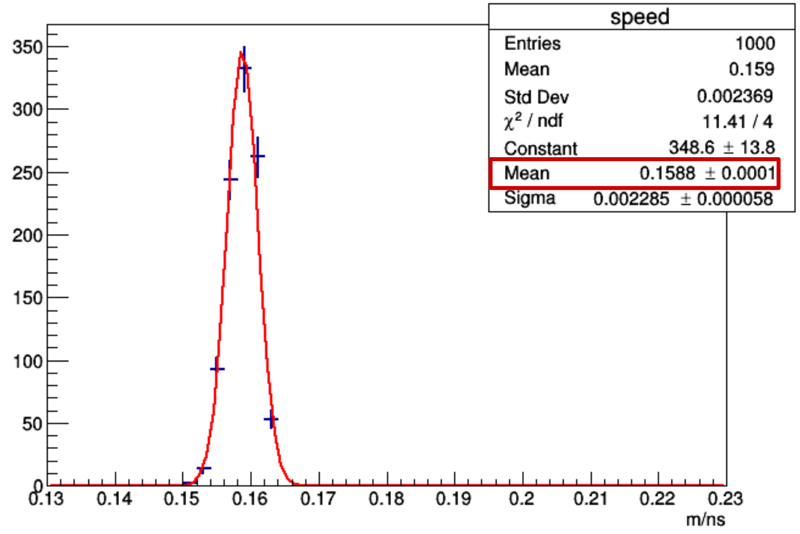
$$E = E_{6.33\,X_0} \exp \frac{x - 6.33\,X_0}{\lambda_{eff}}$$

- Removing the exponential term corrects the attenuation loss.

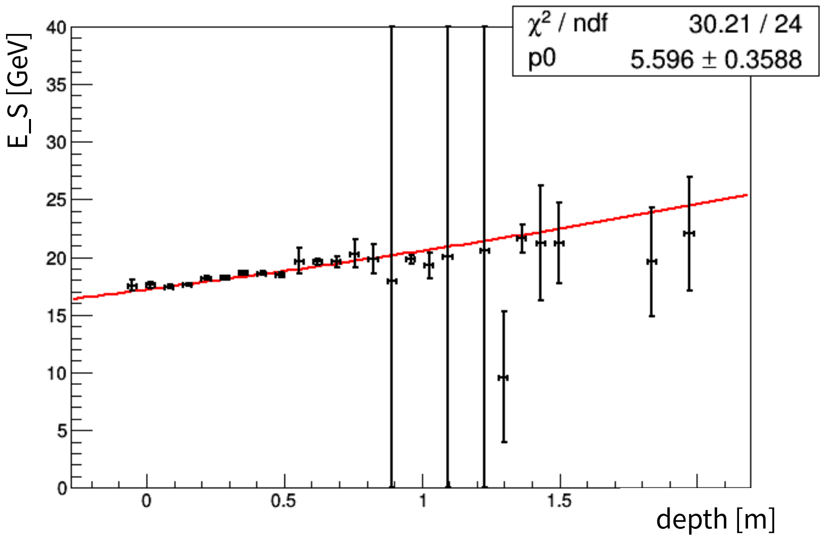
Shower depth of 20 GeV e- & π+



Velocity of optical photon v within fibers



Avg E_S vs shower depth for 20GeV π+



Dual-readout correction constant

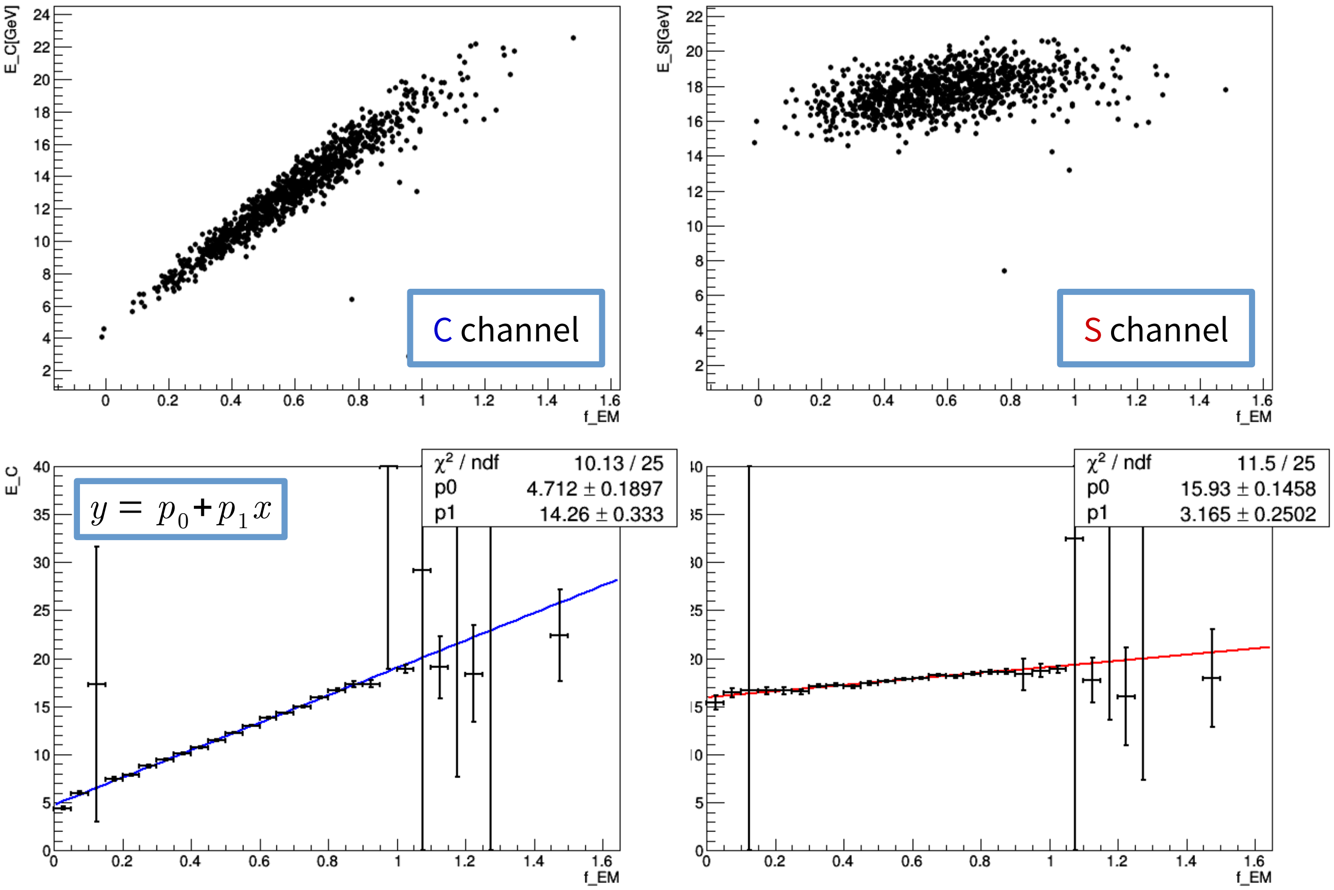
Estimating dual-readout correction constant χ using 20GeV π+

- Starting from initial values of (h/e)_C & (h/e)_S, calculate f_em.
- Using calculated f_em, the relation between energy response & f_em can be profiled for C & S channel.
- Linear fitting of profiled relation returns h/e of each channel.
- Estimated h/e of each channel eventually converges while repeating above steps.
- Dual-readout correction constant can be calculated from h/e.

$$f_{\mathrm{em}} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1-(h/e)_S] - [1-(h/e)_C]}.$$

$$\frac{h}{e} = \frac{p_0}{p_0 + p_1}$$

$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} \equiv \chi$$

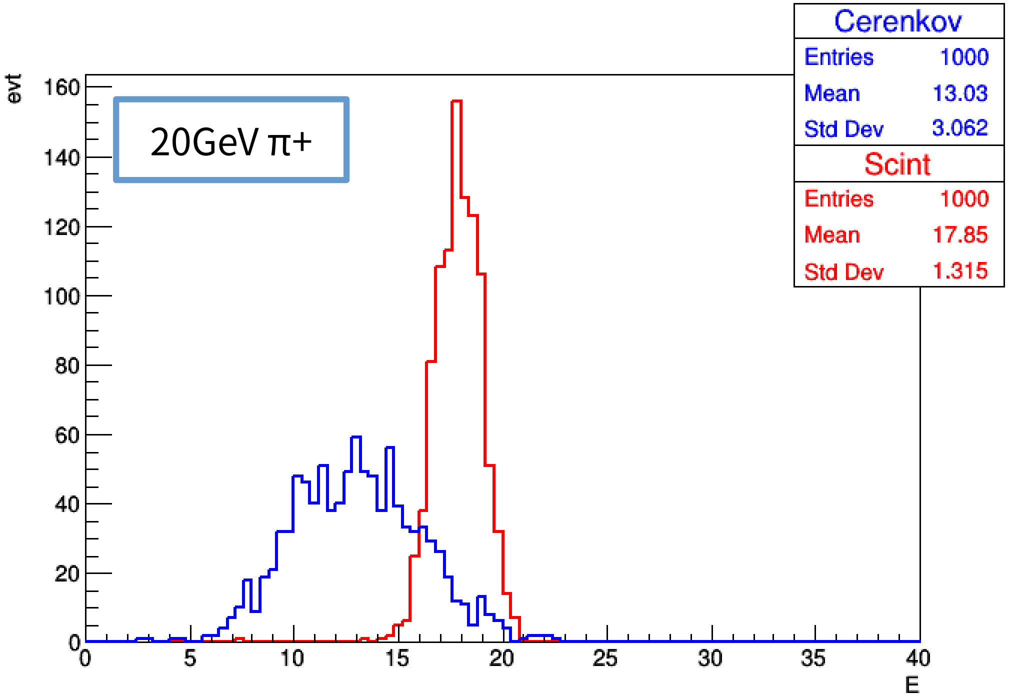


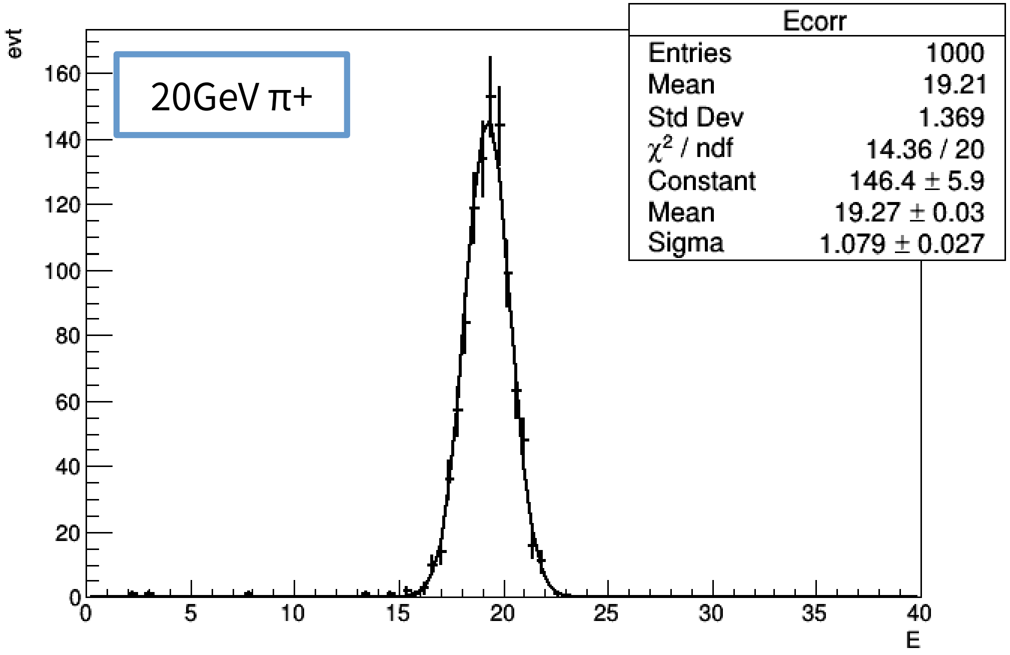
	Cerenkov	Scintillation
h/e	0.2484	0.8342
χ	0.2206	

Energy response for π+ events

Energy response for π+ events

- Energy response of dual-readout calorimeter for π+ beam is estimated.
- Both light attenuation correction & dual-readout correction are applied.
- Dual-readout correction improved the linearity of energy response.

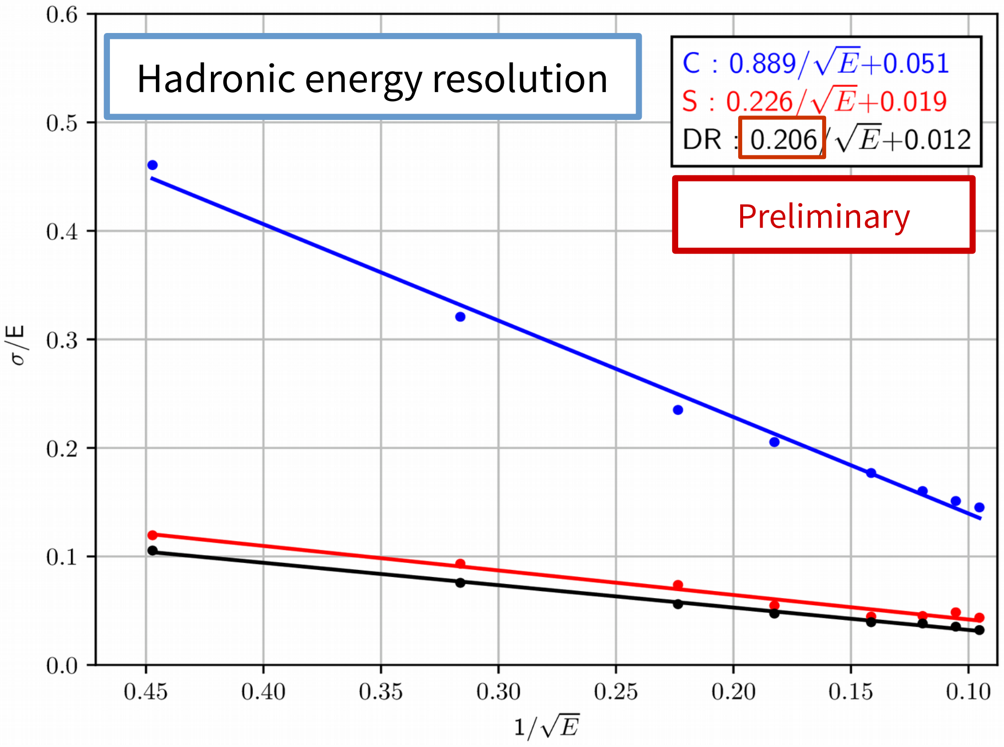


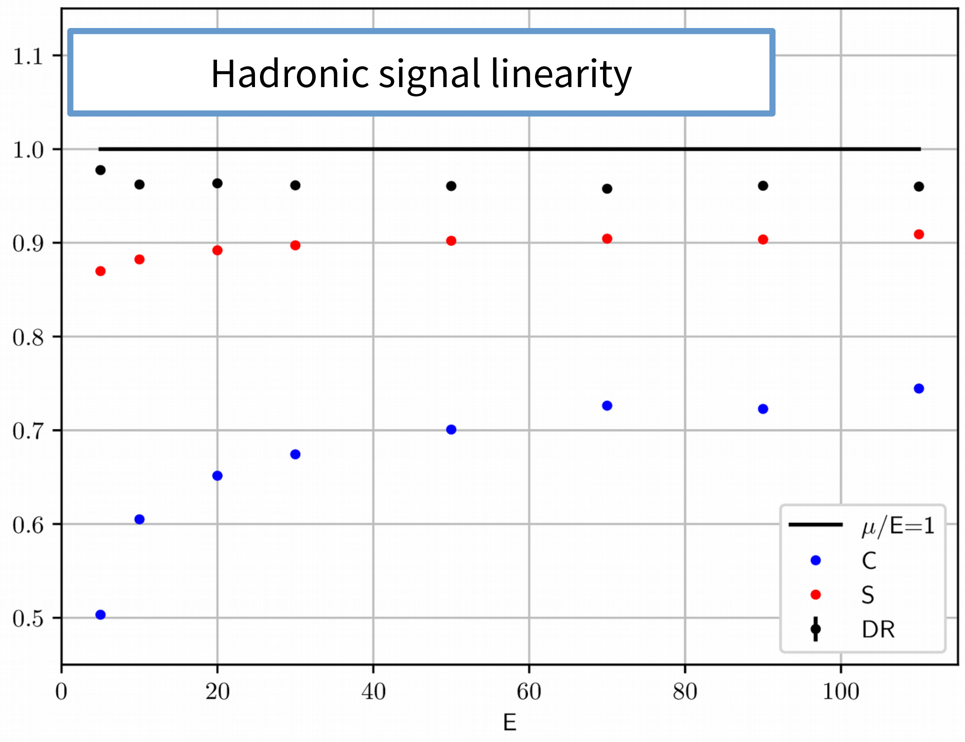


Hadronic energy resolution

Hadronic energy resolution (preliminary results)

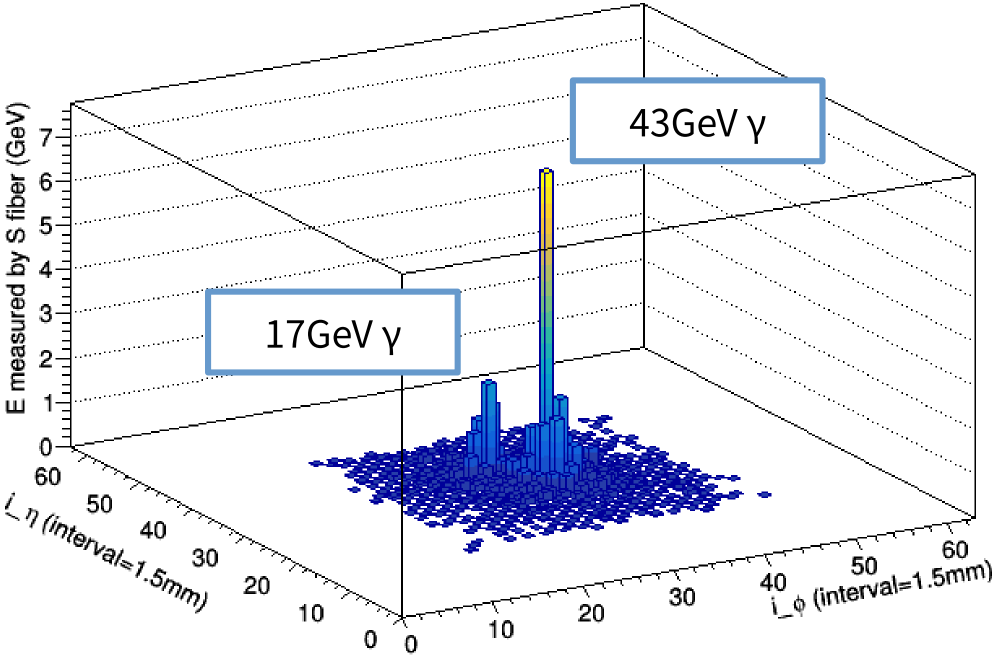
- Measured hadronic energy resolution with 5 to 110 GeV pions.
- Energy resolution is scaled to 1/√E.
- Stochastic & constant term of the energy resolution can be obtained by linear fitting.
- Stochastic term of energy resolution to hadronic shower ~ 21%.





High-granularity demonstration

High-granularity demonstration of the dual-readout calorimeter using $\pi^0 \to \gamma\gamma$



43GeV γ

17GeV γ

Energy measured by a scintillation fiber from 60 GeV π^0

- With 1.5mm interval between fibers, the dual-readout calorimeter is able to detect energy deposits of γγ from 60GeV π^0 as separated clusters (corresponds to lorentz factor $\gamma \sim 444$, opening angle $\theta \sim 3.5$ mil).

Summary

Dual-readout calorimeter for the CEPC

- Dual-readout calorimeter provides a method to measure energy of both EM & hadronic particles with excellent energy resolution.
- GEANT4 simulation of dual-readout calorimeter is performed in great detail.
- Predicted EM energy resolution of GEANT4 simulation is 11%/√E with almost 0 constant term, and the calorimeter responses are linear within 1% uncertainty.
- To take into account the attenuation properly, the depth of shower maximum is measured event-by-event and light attenuation correction is applied to scintillation channel.
- According to GEANT4 simulation results, the dual-readout calorimeter can achieve 21%/√E with linear calorimeter response for single hadrons.
- The dual-readout calorimeter is expected to be able to distinguish $\gamma\gamma$ from 60 GeV π^0 by high granularity design.

Future plans

- Measure energy resolution to multi-particle state such as jet.
- Reconstruct W & Z using $W/Z \to jj$ events.
- Measure position resolution

Backups

More on corrections

Dual-readout correction constant & h/e from convergence

Iter	0	1	2	3	4	5	6	7	8
(h/e)_C	0.21	0.2545	0.2463	0.2465	0.2465	0.2466	0.2483	0.2445	0.2484
(h/e)_S	0.77	0.8452	0.8378	0.8387	0.8348	0.8424	0.8366	0.8420	0.8342
X	0.291	0.2076	0.2152	0.2140	0.2192	0.2092	0.2174	0.2091	0.2206

Light attenuation correction

$$t_c = \frac{1}{0.3\,m/ns}x + \frac{1.8\,m}{0.3\,m/ns}$$

TOF of π+ in vacuum/tower

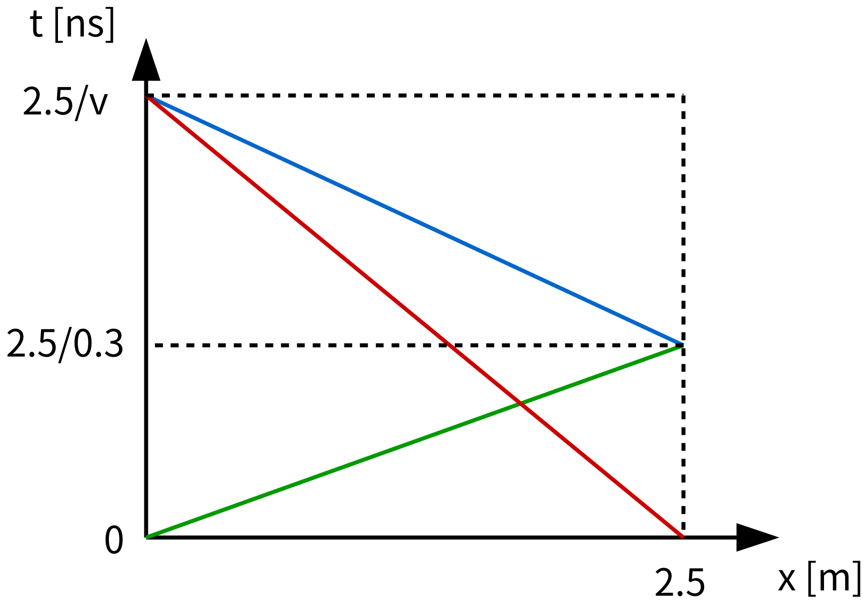
$$t_v = \frac{2.5\,m - x}{v}$$

Propagation time of optical photons

$$t_{max} = t_v + t_c = \frac{2.5 - x}{v} + \frac{x}{0.3\,m/ns} + \frac{1.8\,m}{0.3\,m/ns}$$

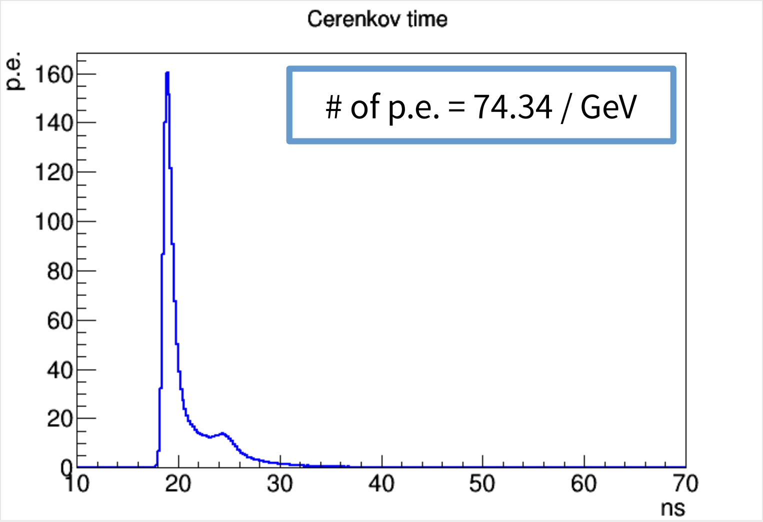
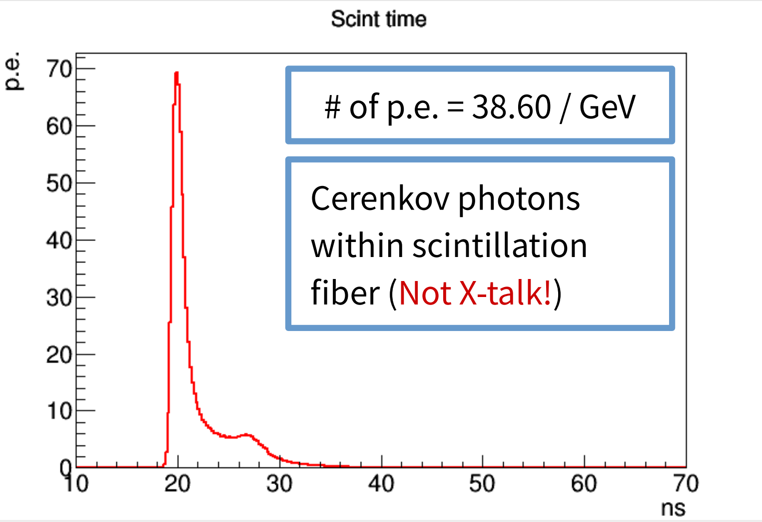
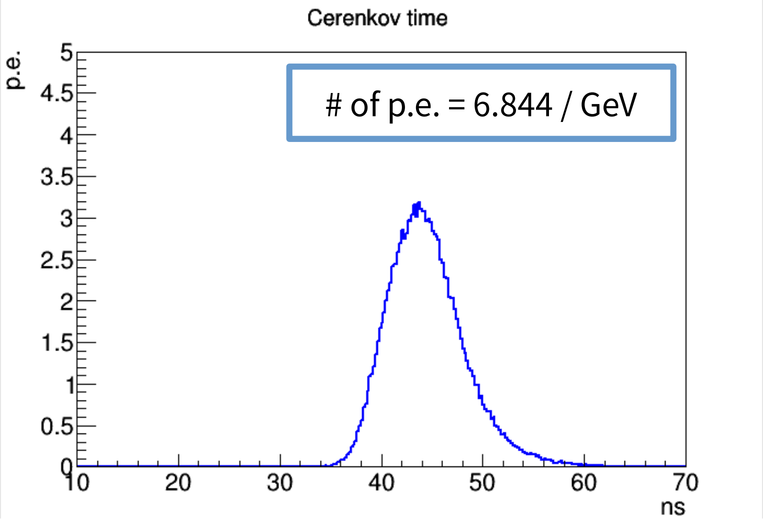
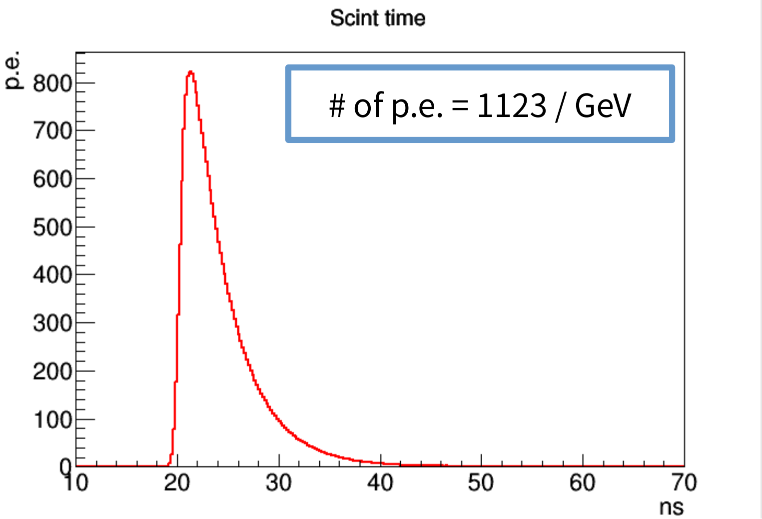
Detection time

- The detection time of optical photons can be represented as the sum of TOF of π+ & propagation time of optical photons within fibers.
- Average velocity of optical photons can be estimated by exploiting well-known longitudinal profile of EM showers.
- Note: TOF of π+ in vacuum is ignored in the graph.



Optical cross-talk

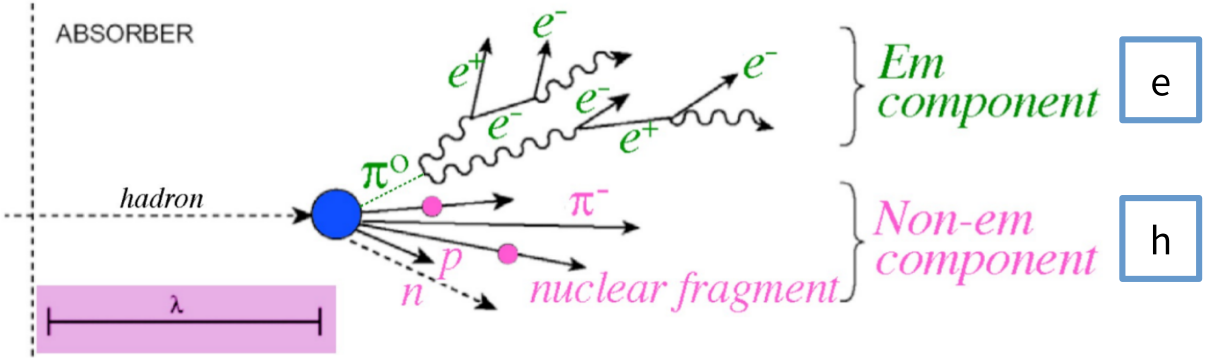
Optical cross-talk of Cerenkov & scintillation channels

	Cerenkov	Scintillation
Cerenkov: ON Scintillation: OFF	 # of p.e. = 74.34 / GeV	 # of p.e. = 38.60 / GeV Cerenkov photons within scintillation fiber (Not X-talk!)
Cerenkov: OFF Scintillation: ON	 # of p.e. = 6.844 / GeV	 # of p.e. = 1123 / GeV

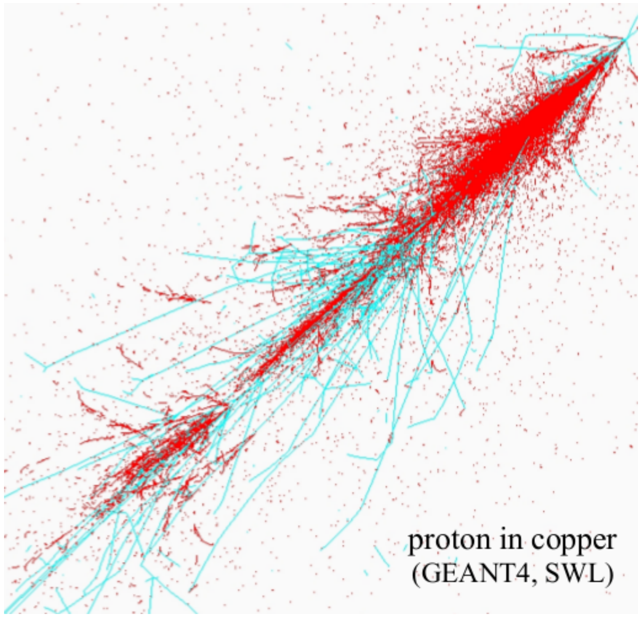
Difficulty of HCAL

Difficulty of hadronic calorimetry

- Hadronic (non-EM) component of a shower is consist of:
  - Charged hadrons (π, K, …) 20 %
  - Nuclear fragments (p) 25 %
  - Neutrons & soft γ's 15 %
  - Break-up of nuclei (invisible) 40 %
- The main fluctuation is EM fraction fluctuation between π± & π0 (γγ).
- Secondary fluctuation is nuclear binding energy losses.



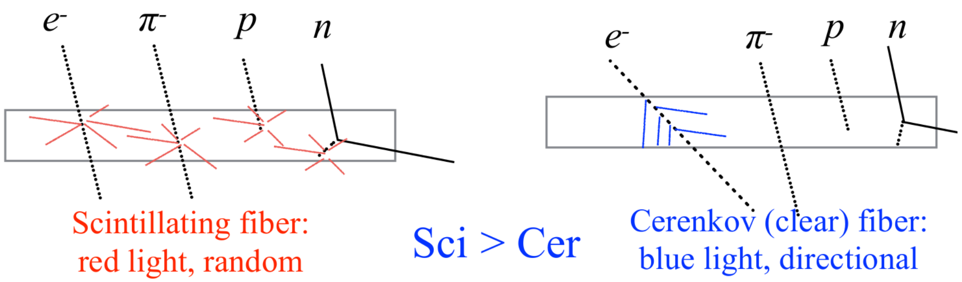
Typical shower initiated by a hadron consists of both EM and hadronic component.


proton in copper
(GEANT4, SWL)

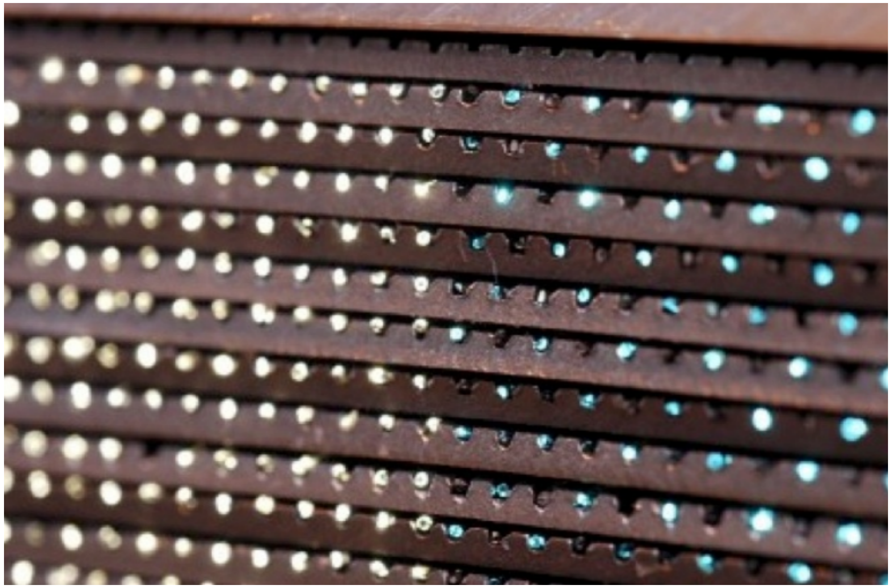
Scintillation & Cerenkov fibers

The main difference between scintillation & Cerenkov fibers

- Scintillation fiber
  - Emits red light in random directions.
  - Responds to both EM & hadronic particles.
- Cerenkov fiber
  - Emits blue light in a direction collimated to the incident particle.
  - Responds to mainly EM particles only.



Schematic diagram of how scintillation & Cerenkov fiber responds to each fiber.



Picture of scintillation (left) and Cerenkov (right) fibers emitting lights.

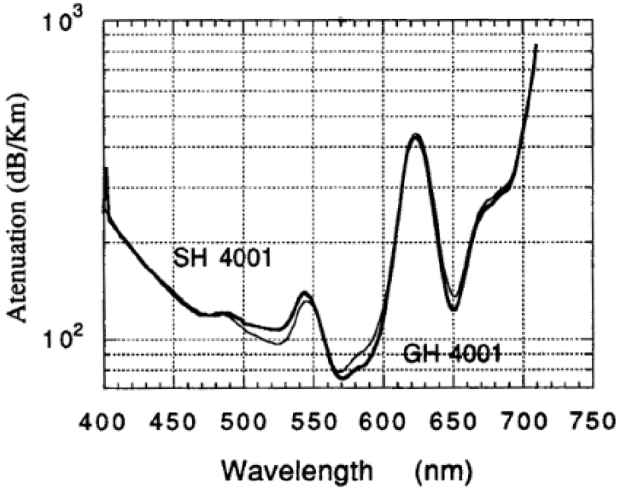
Material properties

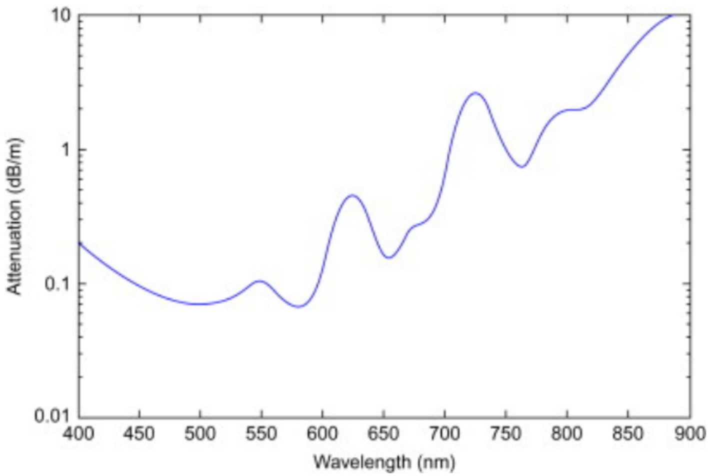
Photon energy

- The energy window of optical photons is set to 900-300 nm (1.37760-4.13281 eV) with 25 nm step.

PMMA

- RI
  - refractiveindex.info (G. Beadie, M. Brindza, R. A. Flynn, A. Rosenberg, and J. S. Shirk. Refractive index measurements of poly(methyl methacrylate) (PMMA) from 0.4-1.6µm, Appl. Opt. 54, F139-F143 (2015))
- Attenuation
  - sciencedirect (Silvio Abrate, Handbook of Fiber Optic Data Communication (4th Ed.), 2013)
  - Eska POF manufacturer





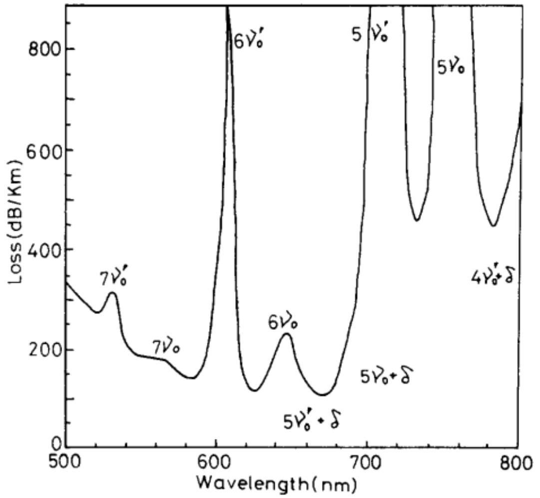
Material properties

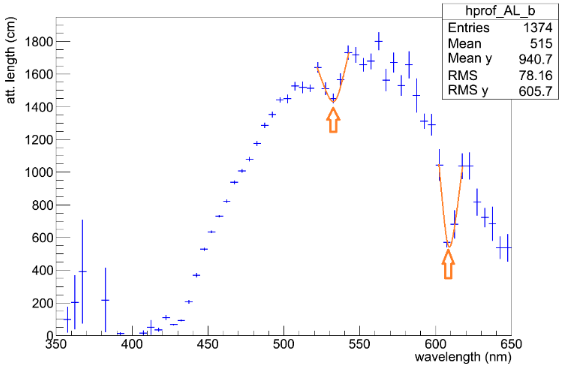
Fluorinated polymer

- RI
  - RD52 paper (N. Akchurin, et al., Nuclear Instruments and Methods in Physics Research, A762 (2014), pp. 100-118.)
  - Set to single value (1.42).

Polystyrene

- RI
  - refractiveindex.info (N. Sultanova, S. Kasarova and I. Nikolov. Dispersion properties of optical polymers, Acta Physica Polonica A 116, 585-587 (2009))
- Attenuation
  - J. Applied Physics (T. Kaino, M. Fujiki, and S. Nara, Low-loss polystyrene core-optical fibers, Journal of Applied Physics 52, 7061 (1981))
  - LHCb-PUB-2015-011 (SCSF-78 for LHCb Sci-Fi tracker R&D TDR)
  - kuraray scintillating fiber manufacturer (SCSF-78)

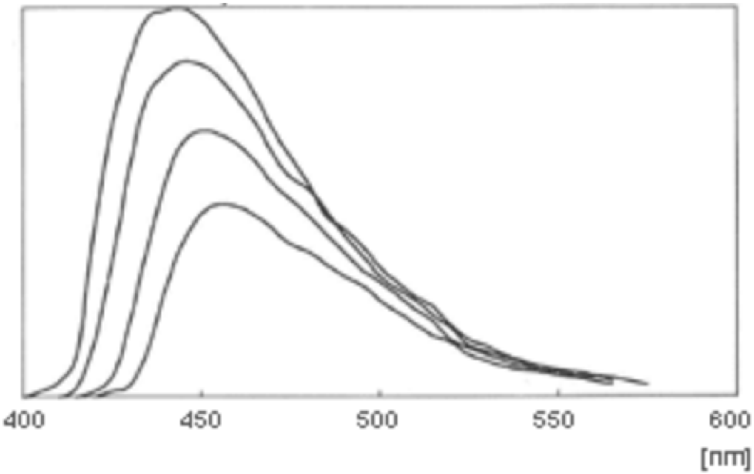




Material properties

Polystyrene

- Emission spectrum, decay constant
  - kuraray scintillating fiber manufacturer (SCSF-78)
  - Decay constant = 2.8 ns
- Birks constant
  - k_B = 0.126 mm/MeV

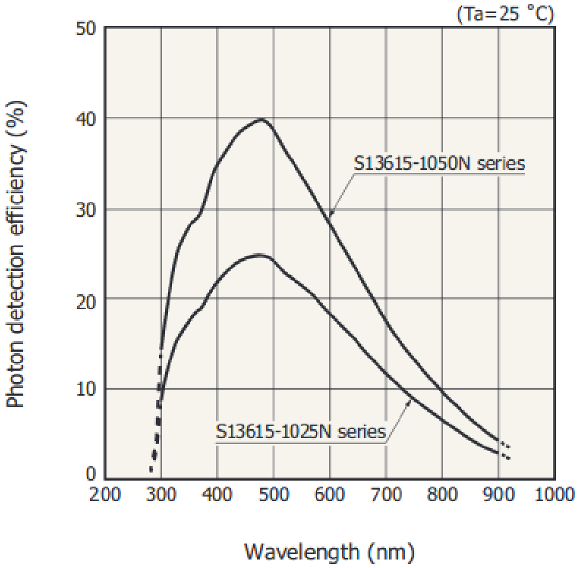


Glass, Air

- RI
  - 1.52, 1.0
- Attenuation
  - 420 cm, N/A

PDE (Photon Detection Efficiency)

- Hamamatsu S13615-1025N series



Title

Text

$$formula$$