# GEANT4 simulation of the dual-readout calorimeter

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# Introduction

## Features of GEANT4 simulation of dual-readout calorimeter

- GEANT4-level
  - Based on the RD52 copper tower with 2.5m length, round shape endcap.
  - Fully simulated optical physics
    - G4Cerenkov process.
    - G4Sintillation process (heavy CPU load!).
    - Detection efficiency of SiPMs.
    - Attenuation length of Cerenkov, scintillation fiber cores.
    - Scintillation spectrum of polystyrene.
    - Applied the filter (Kodak Wratten #3) for scintillation channel.

  → References on backups

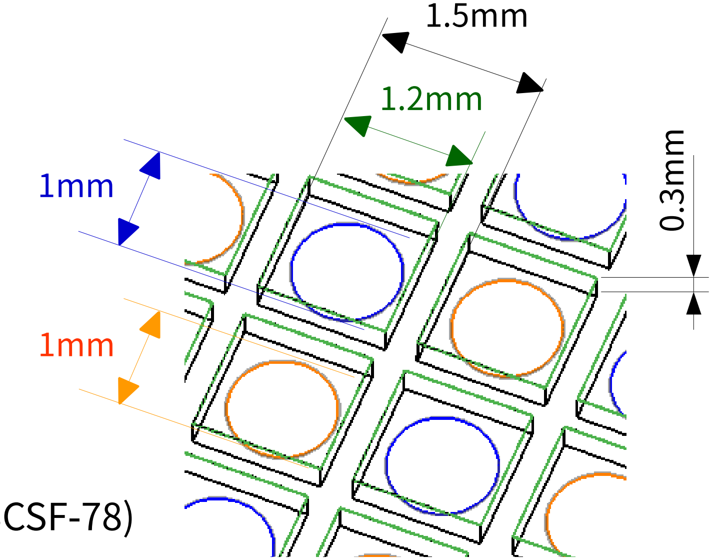
- Analysis-level
  - Optical photon cross-talk correction.
  - Light attenuation correction.
  - Dual-readout correction constant $\chi$ measured internally (using simulation results).

- Github [https://github.com/SanghyunKo/dual-readout/tree/frozen_WGR16]

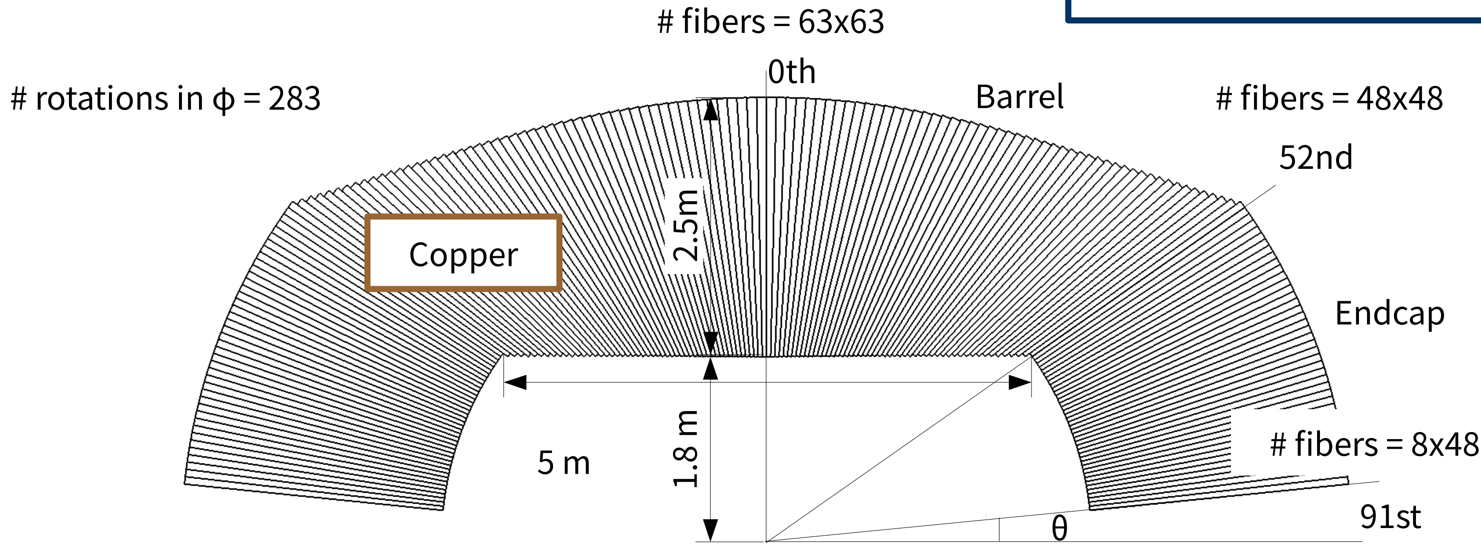
# GEANT4 simulation setup (1)

## GEANT4 simulation setup – Geometry

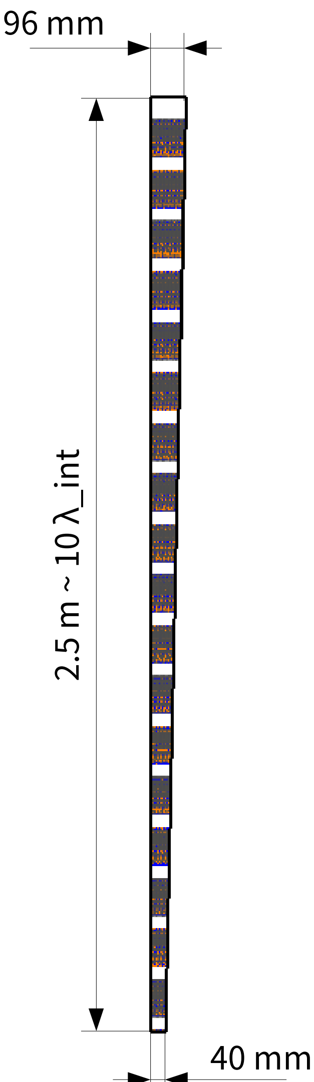
- A projective 4π ‘wedge’ geometry.
- Covers up to |cos(θ)| < 0.995 (|η| < 3.0) with no cracks.
- A Cu tower with a depth of about 2.5 m (~ 10 λ_int).
- O(1000) fibers implemented per tower.
  - Cerenkov(C) fiber: PMMA (Eska SK40)
  - Scintillation(S) fiber: Polystyrene(PS) (Kuraray SCSF-78)
- High granularity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




Rear end of a tower




x-z view of dual-readout calorimeter

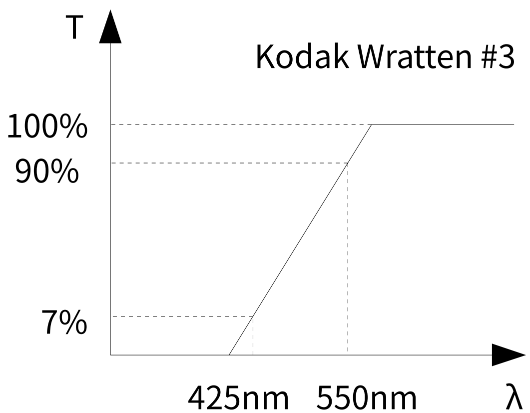



Side view of 0th tower

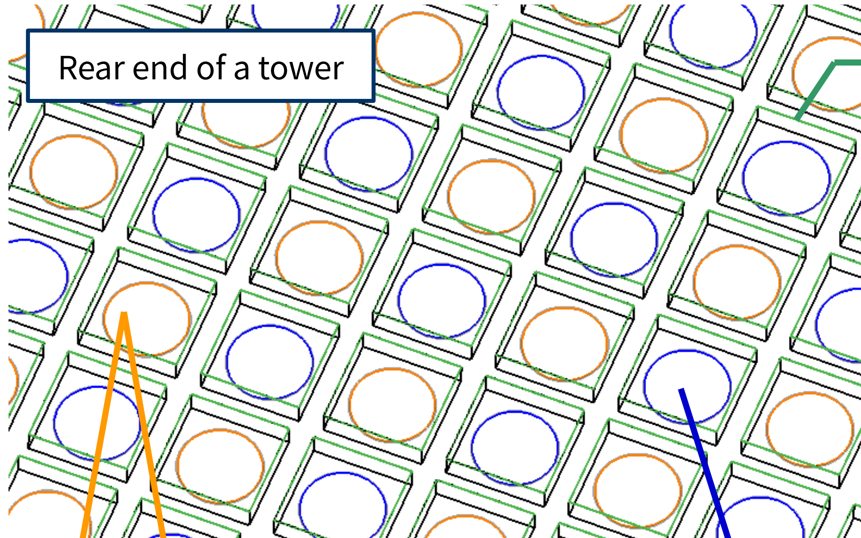
# GEANT4 simulation setup (2)

## GEANT4 simulation setup – Optical physics

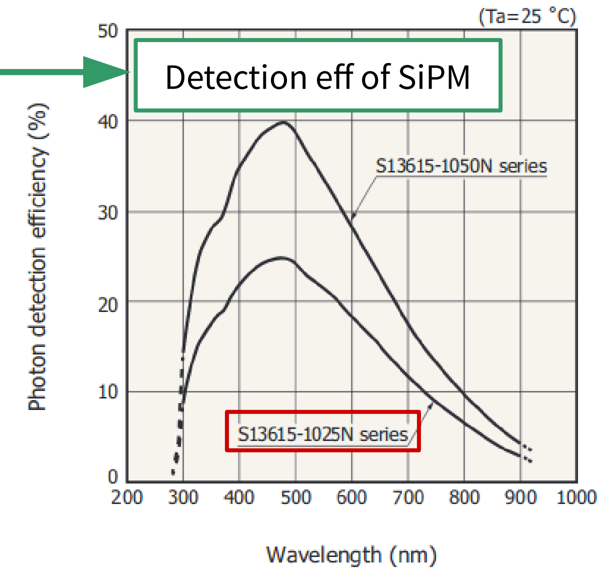
Transmission eff of filter




Rear end of a tower

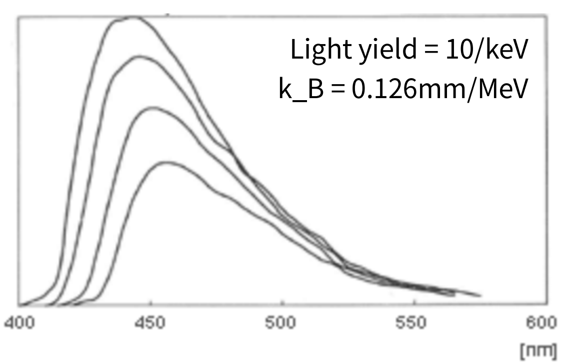


Detection eff of SiPM



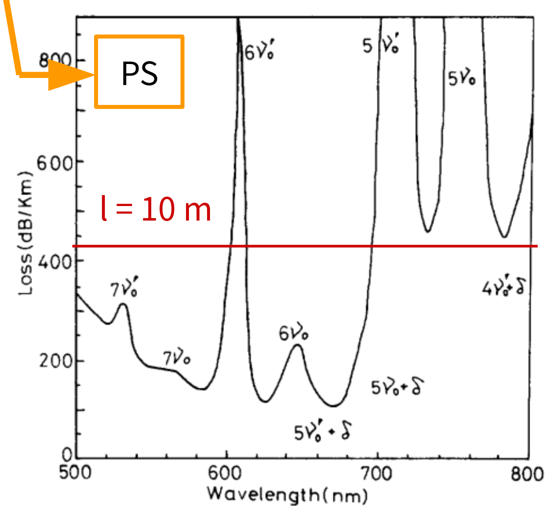

Attenuation loss diverges at 400nm → applied filter to S channel to mitigate it

Scintillation spectra of PS

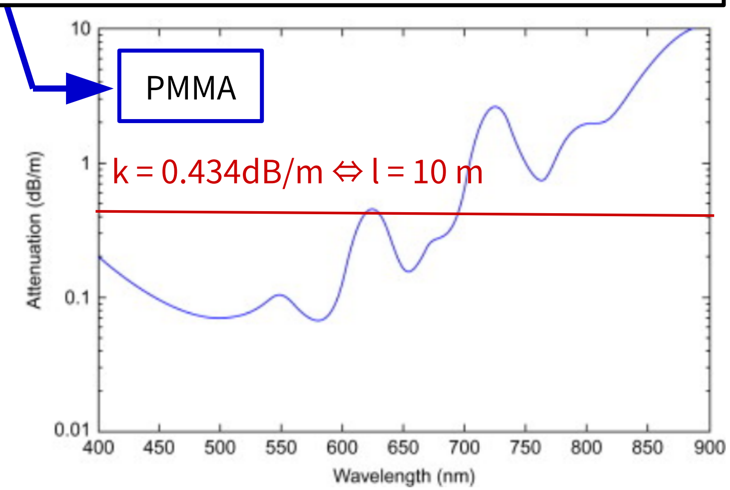



Attenuation loss of Polystyrene (PS) & PMMA

PS




PMMA

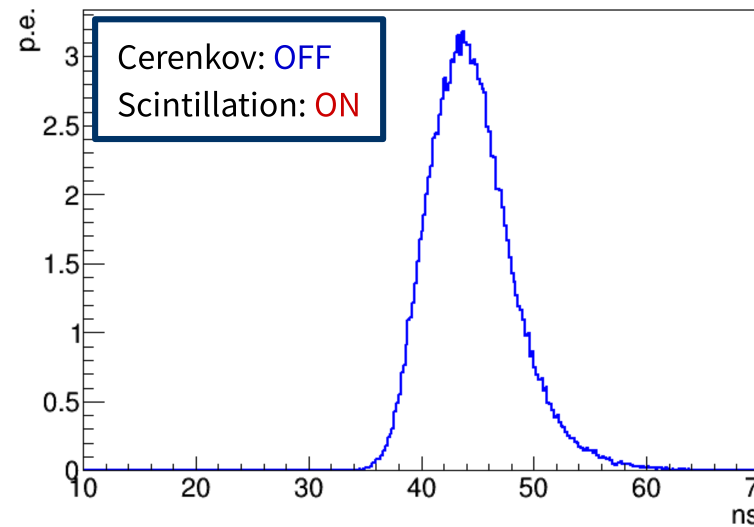


# Optical cross-talk correction

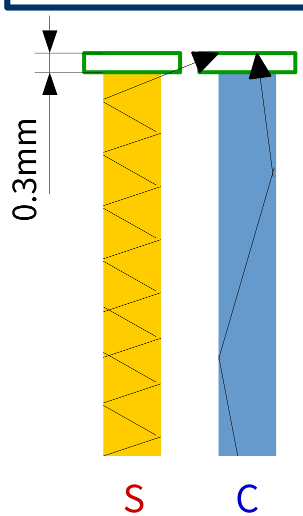
## Optical cross-talk (S → C) correction

- 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.

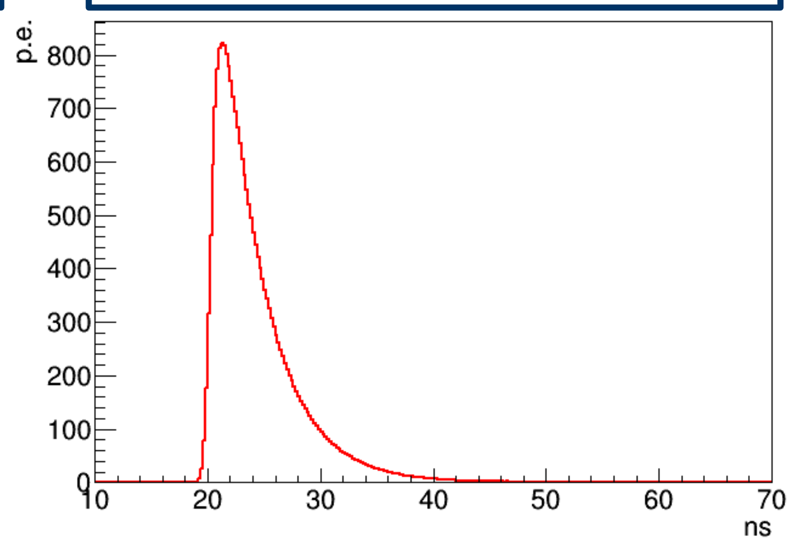
Cross-talk effect (S → C)



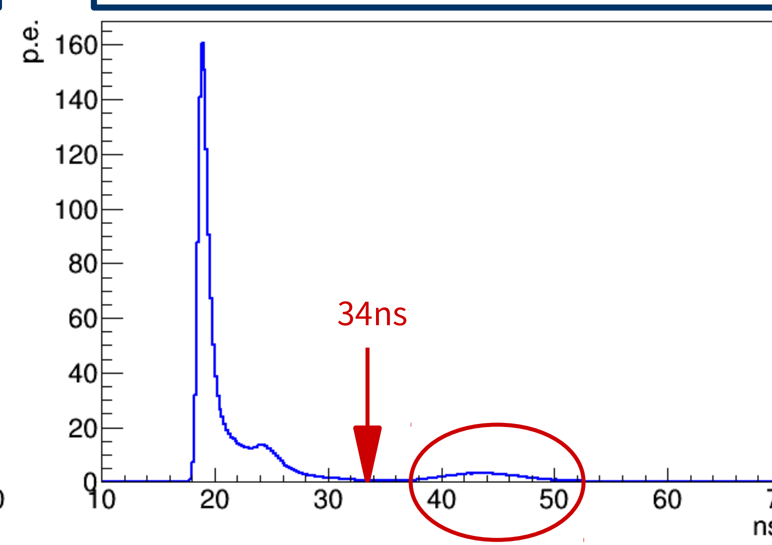

X-talk mechanism




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

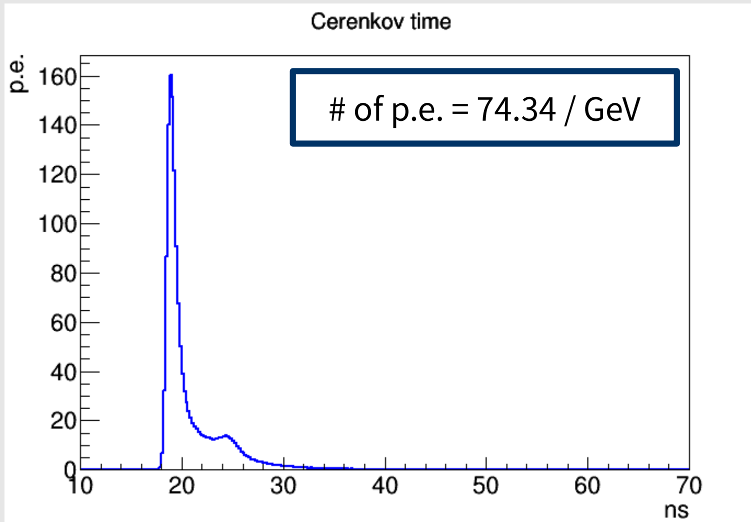
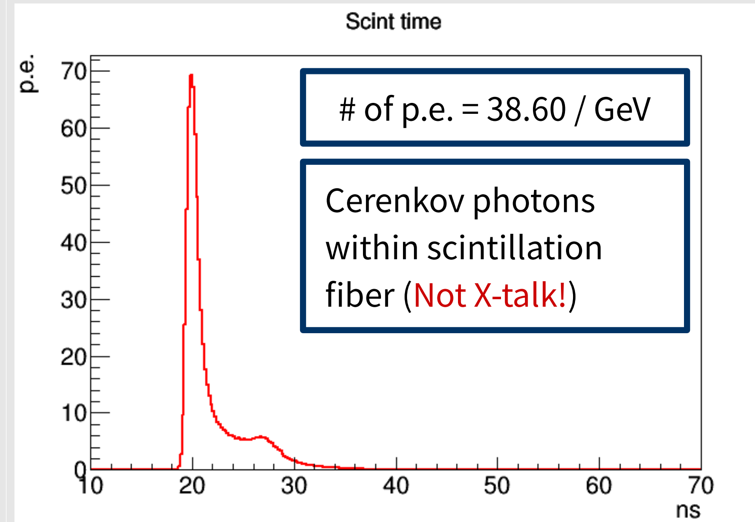
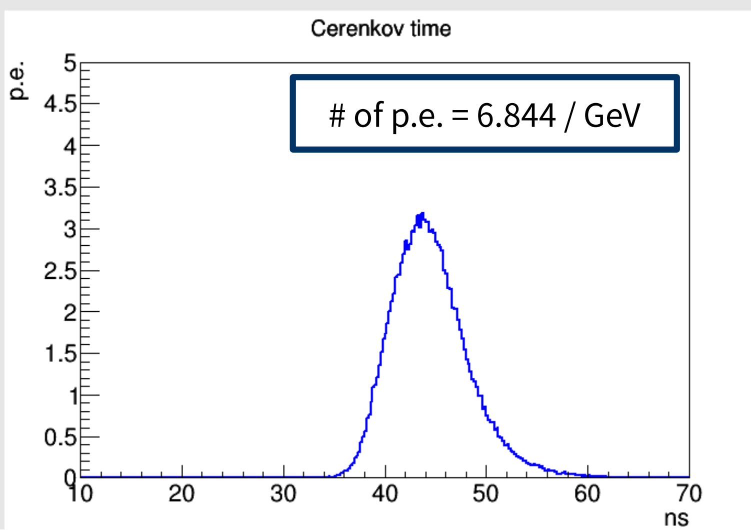
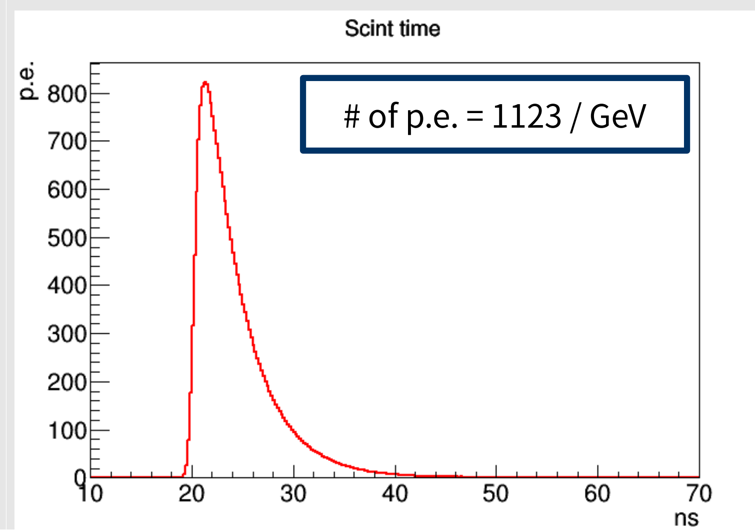



Avg # of p.e. / 0.2 ns for C channel



# Optical cross-talk

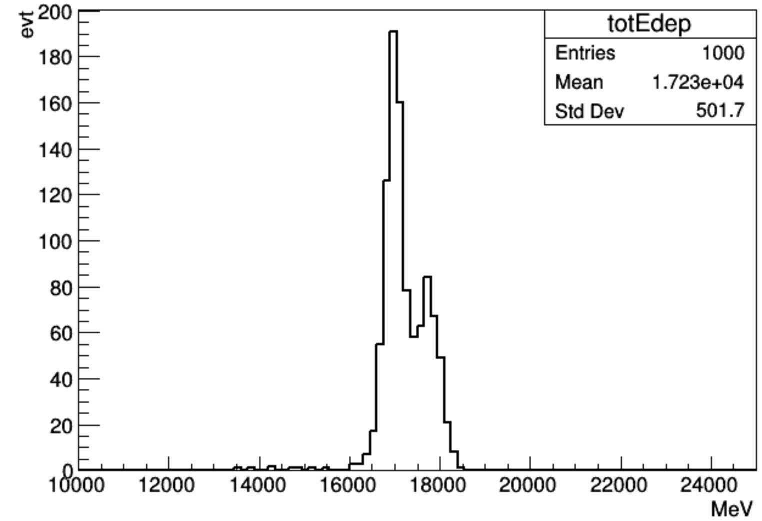
## Optical cross-talk of Cerenkov & scintillation channels

| | Cerenkov | Scintillation |
|---|---|---|
| Cerenkov: ON<br>Scintillation: OFF |   |   |
| Cerenkov: OFF<br>Scintillation: ON |   |   |

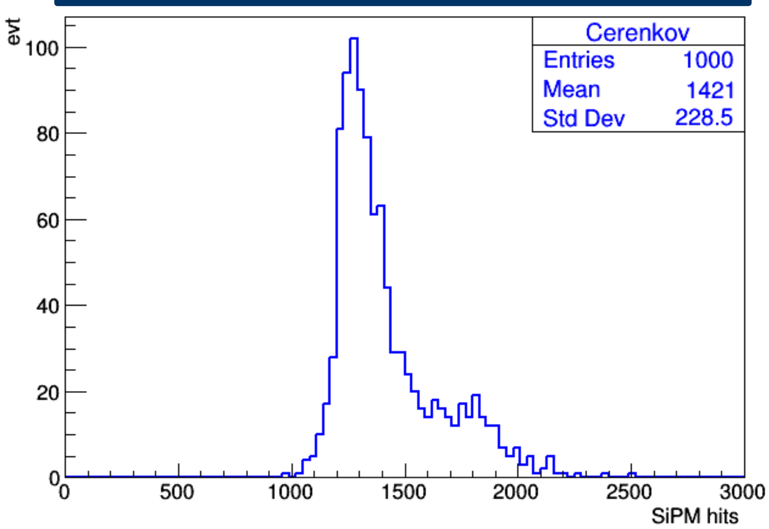
## Calibration procedure using 20GeV e- events

- 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.

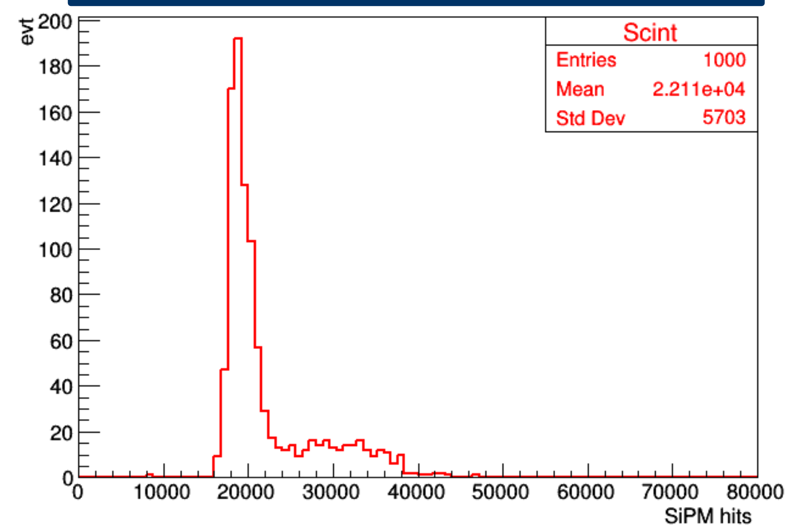
Energy deposit for 20GeV e- ($0^{th}$ tower)




# of p.e. for C channel ($0^{th}$ tower)



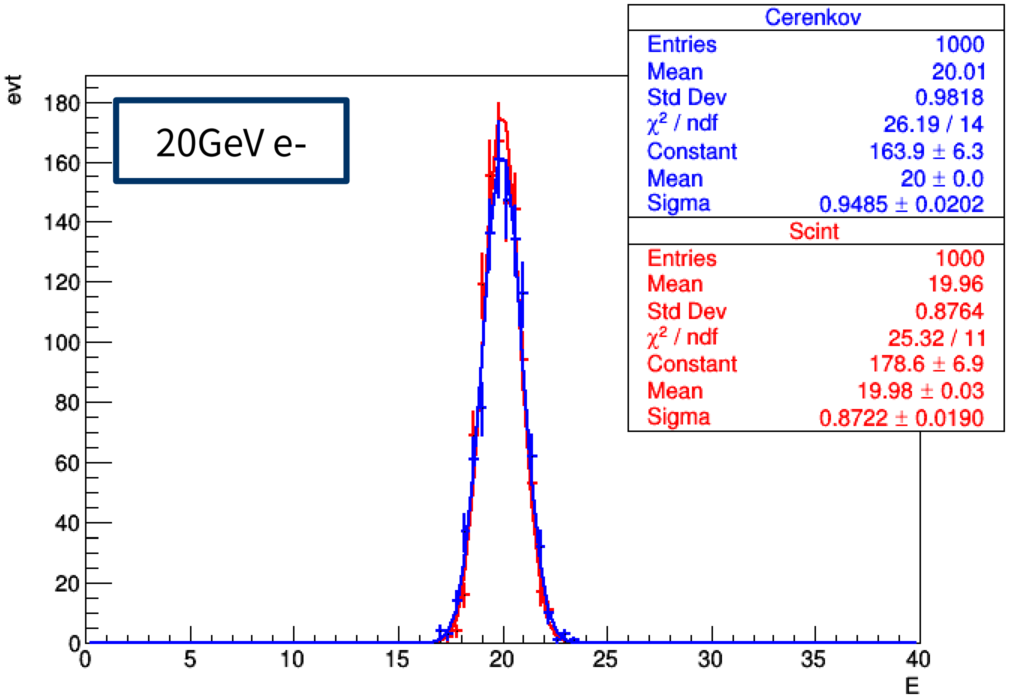

# of p.e. for S channel ($0^{th}$ tower)

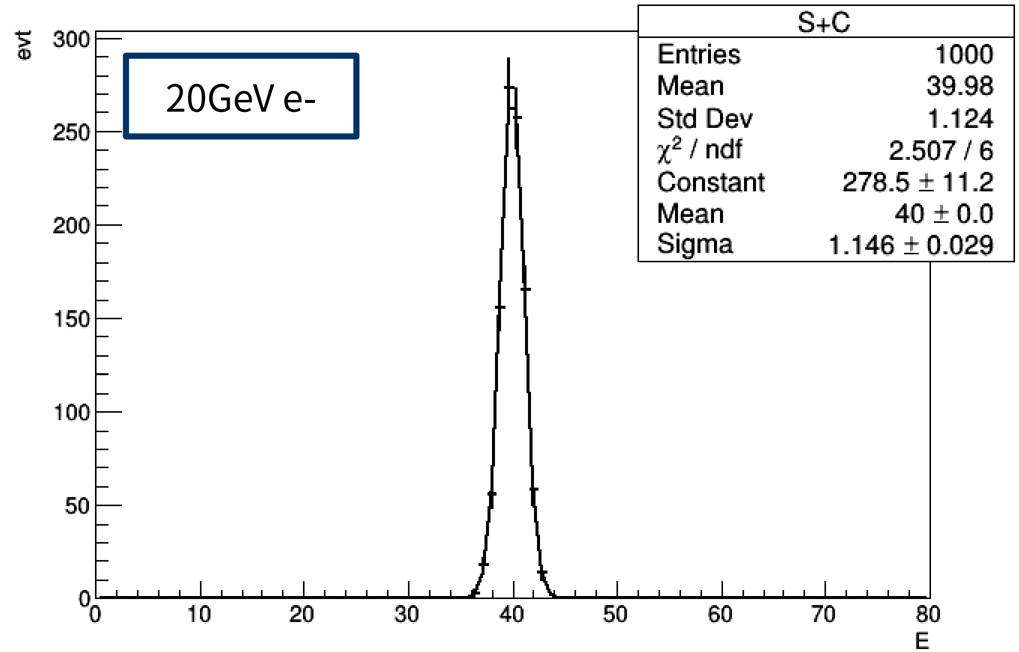


# Energy response for e- events

## Energy response for e- events

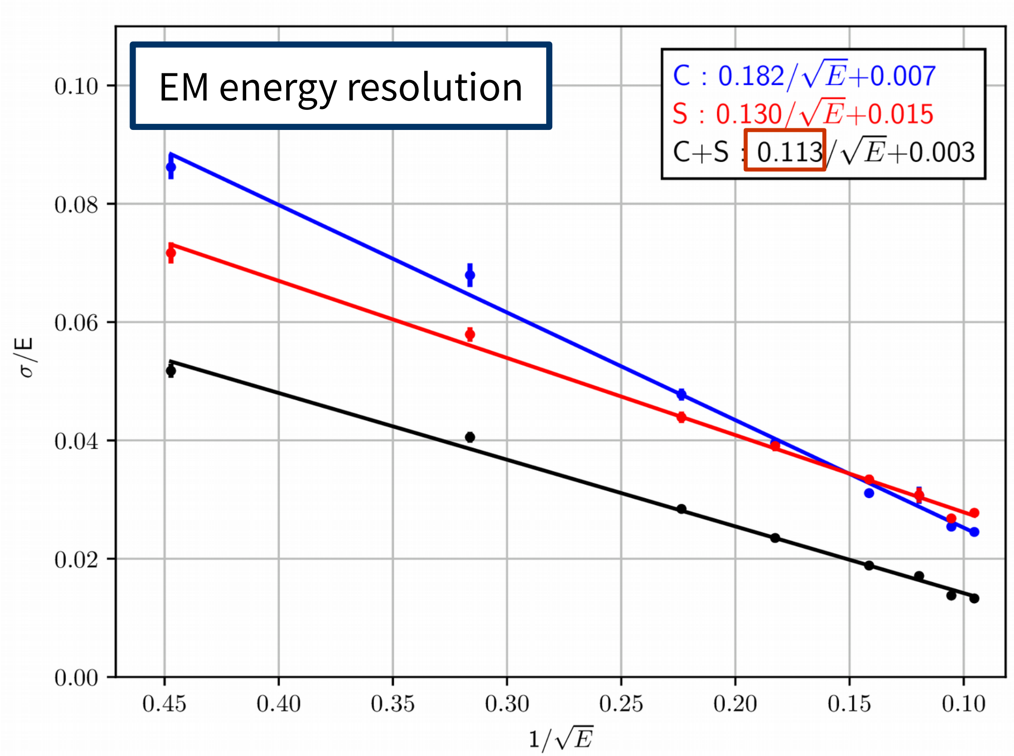
- Energy response of dual-readout calorimeter is estimated using calibrated towers.
- Used 1cm x 1cm e- beams with (Δθ, Δϕ) = (1.5°, 1.0°) incident angle.
- Response of Cerenkov, scintillation channel and sum of two channels are fitted with Gaussian.

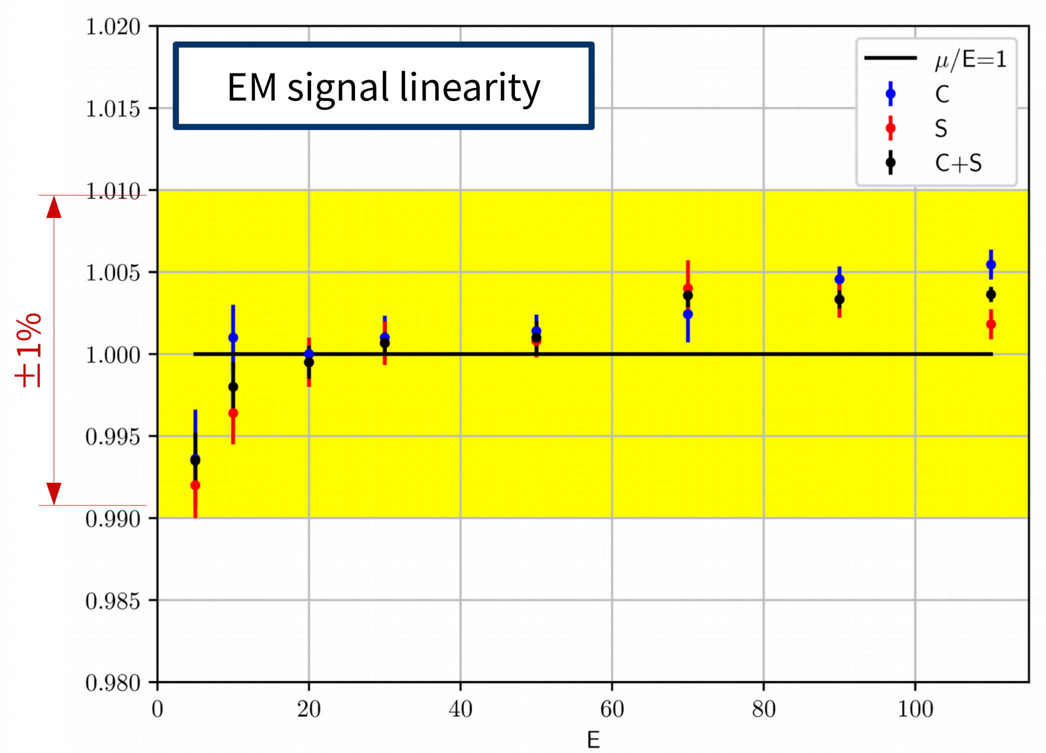


## EM energy resolution

- 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

- 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.

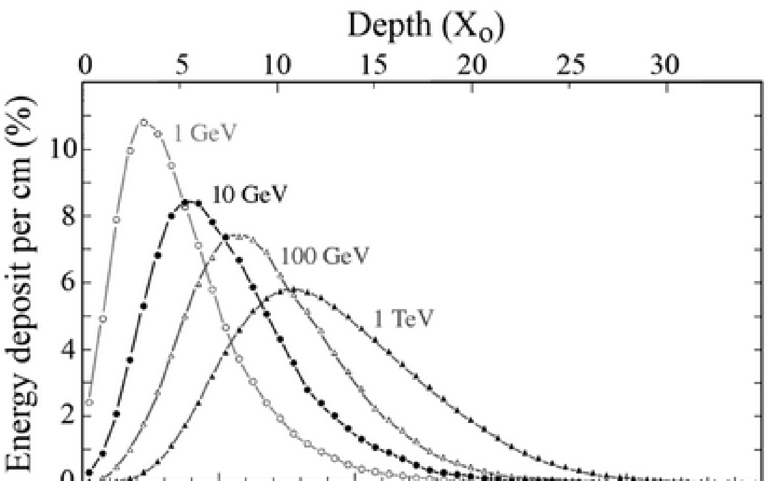
## Shower depth as a function of time

- 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.

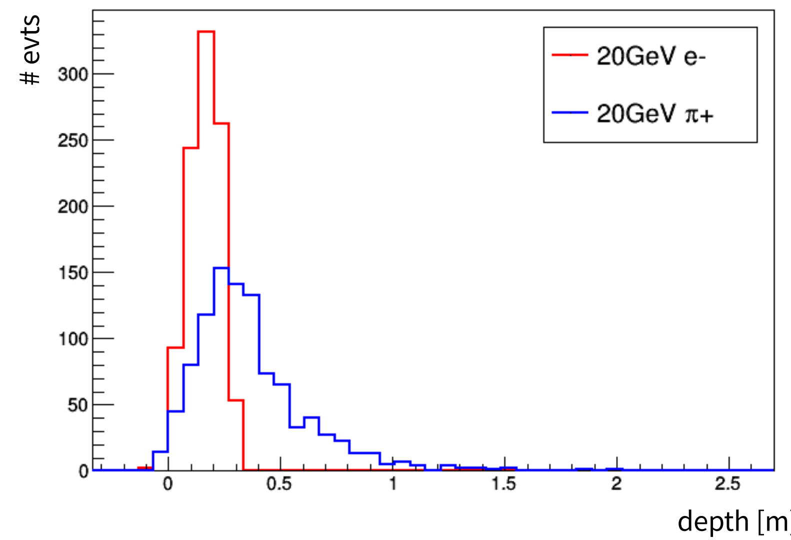
$$v = \frac{2.5\,m - 0.1368\,m}{t_{max} - \frac{0.1368\,m}{0.3\,m/ns} - \frac{1.8\,m}{0.3\,m/ns}}$$

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

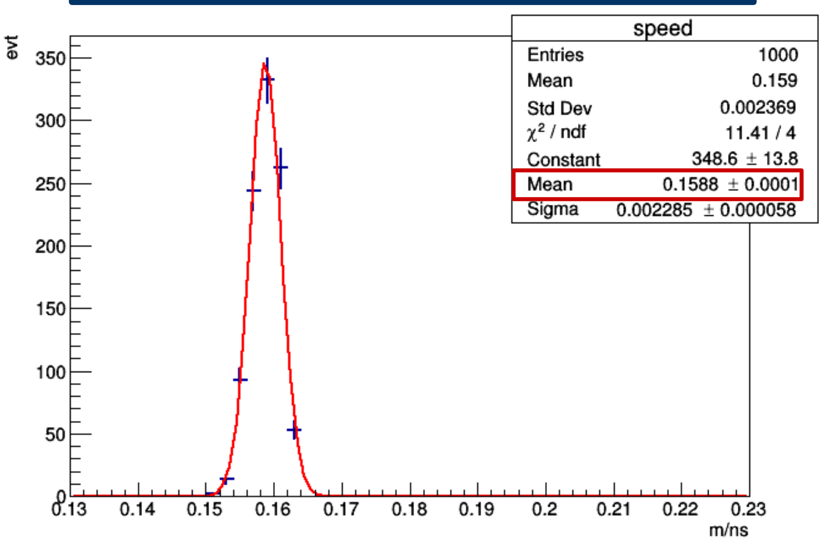
$$E = E_{6.33\,X_0} \exp\frac{x - 6.33\,X_0}{\lambda_{eff}}$$

- Removing the exponential term corrects the attenuation loss.

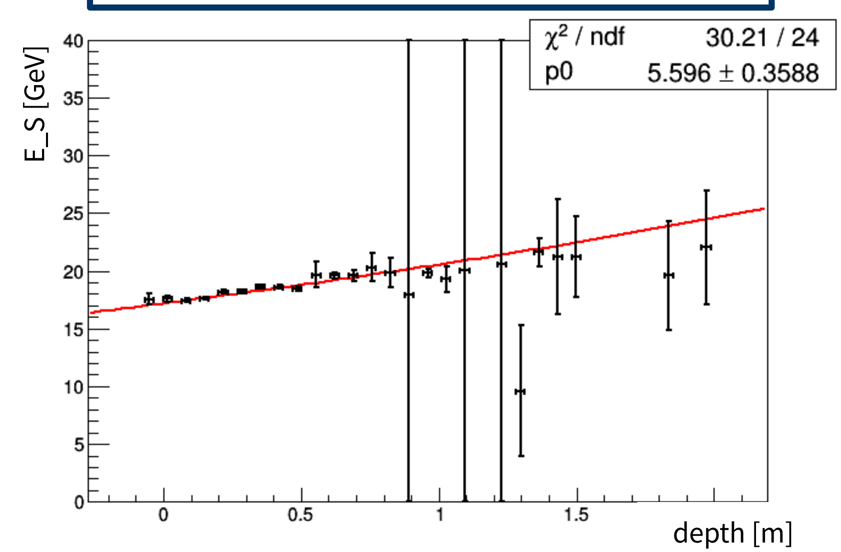
Shower depth of 20 GeV e- & π+




Velocity of optical photon v within fibers




Avg E_S vs shower depth for 20GeV π+



# Dual-readout correction constant

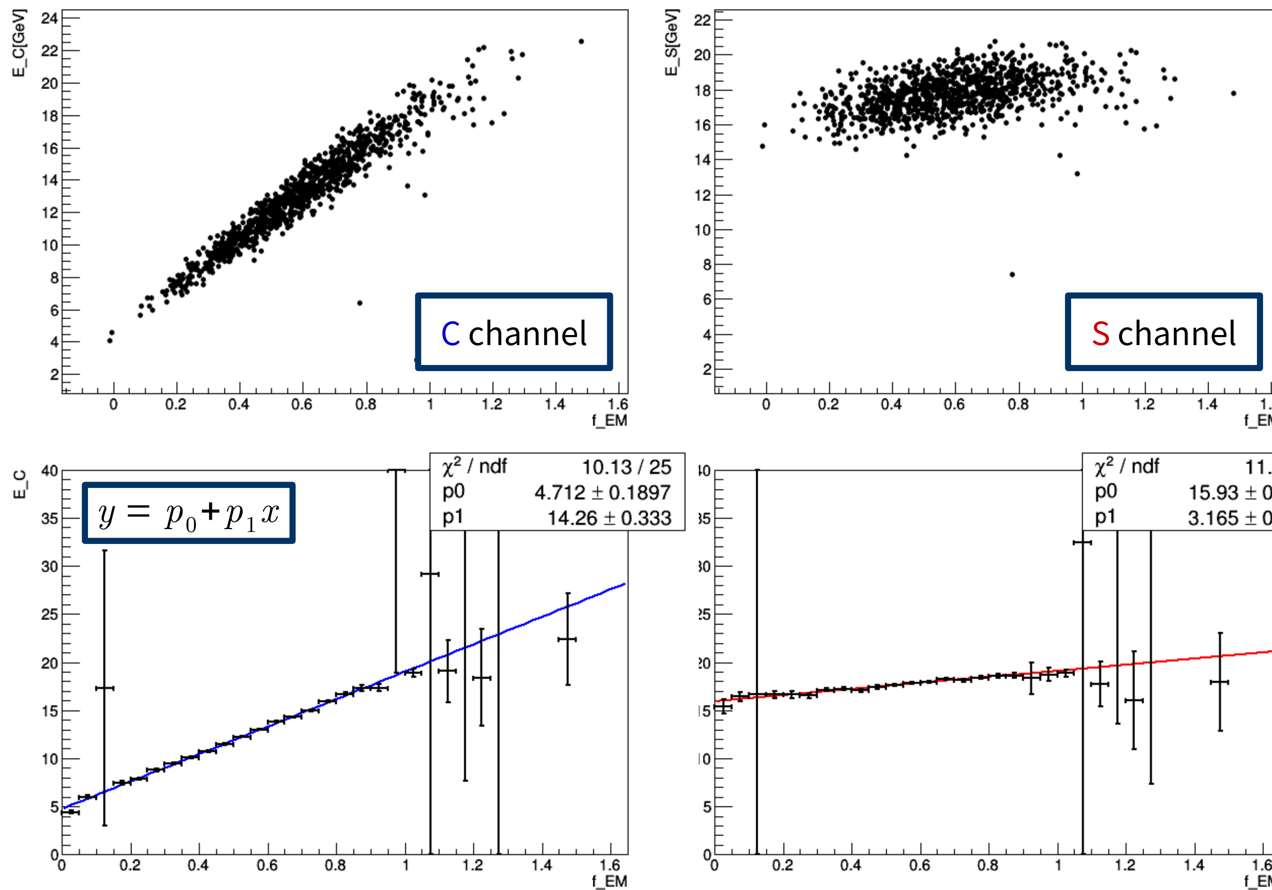
## Estimating dual-readout correction constant χ using 20GeV π+

- 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.

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

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

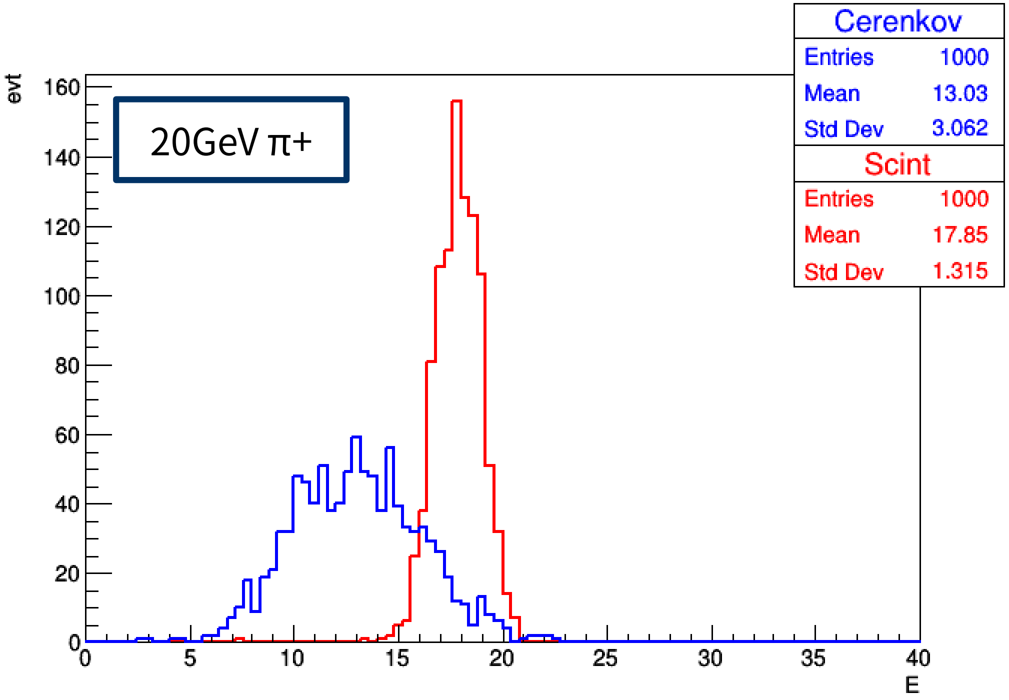
$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} \equiv \chi$$

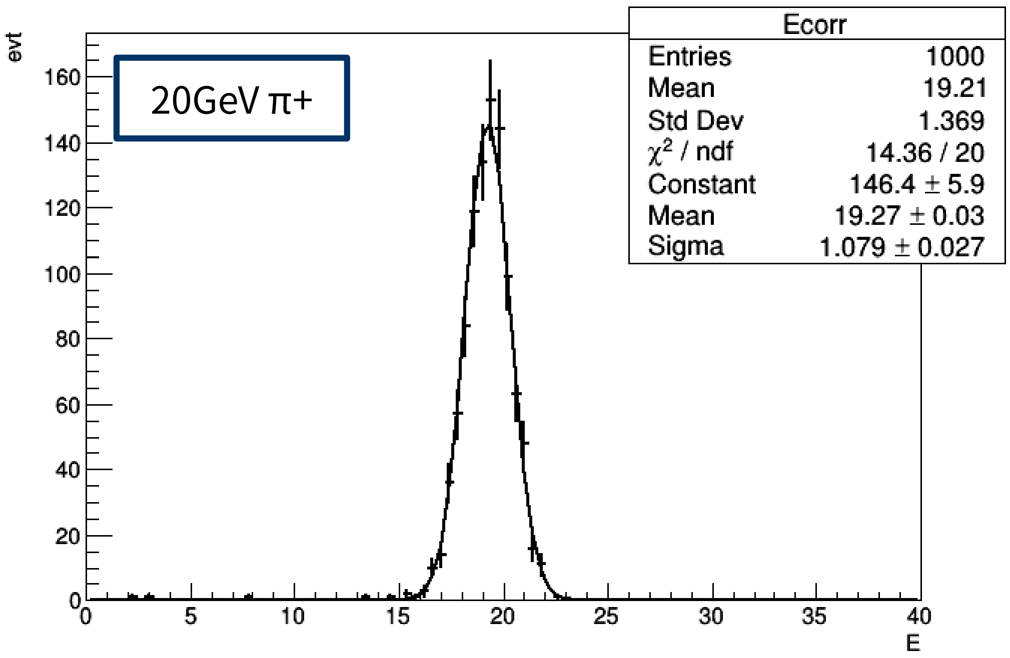



| | Cerenkov | Scintillation |
|---|---|---|
| h/e | 0.2484 | 0.8342 |
| χ | 0.2206 | |

## Energy response for π+ events

- Energy response 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.

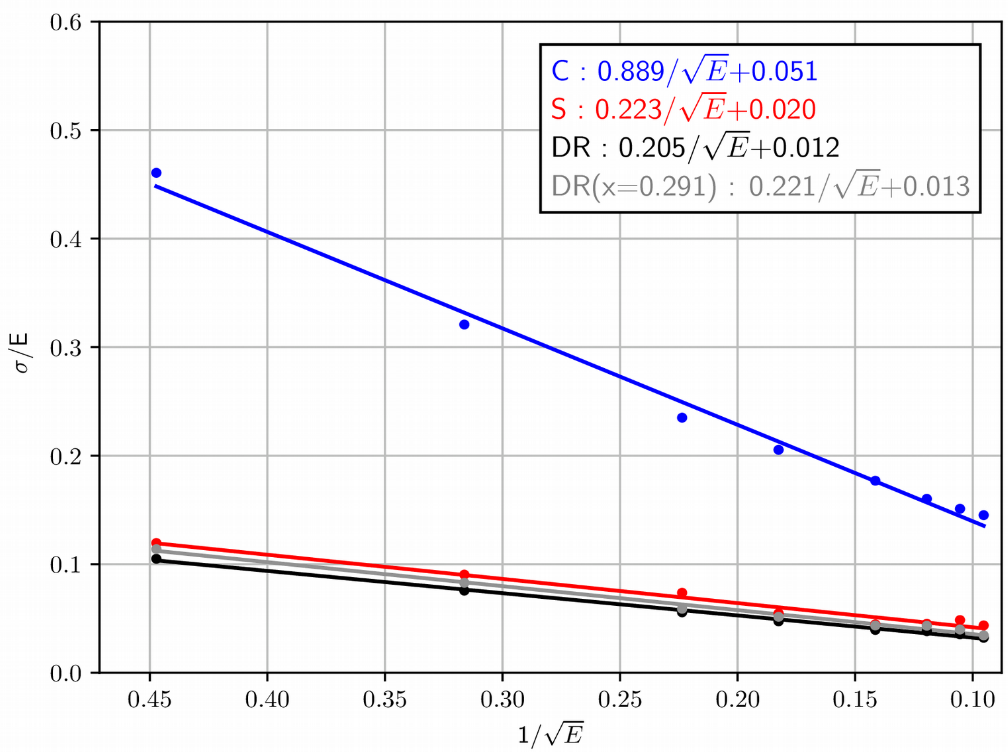


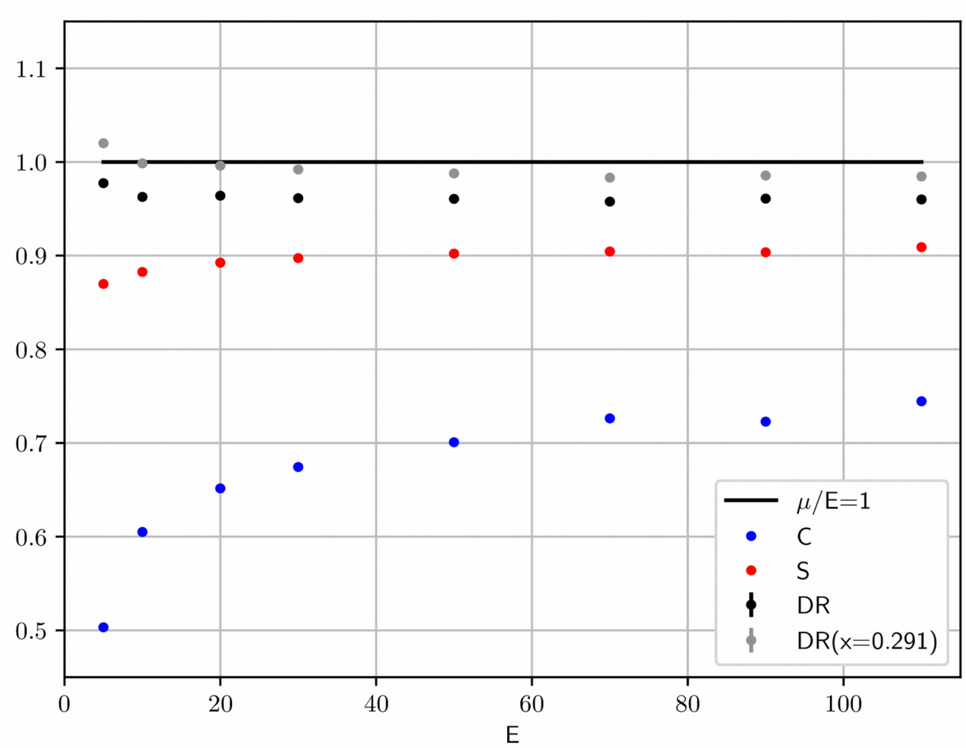



# Hadronic energy resolution

## Hadronic energy resolution

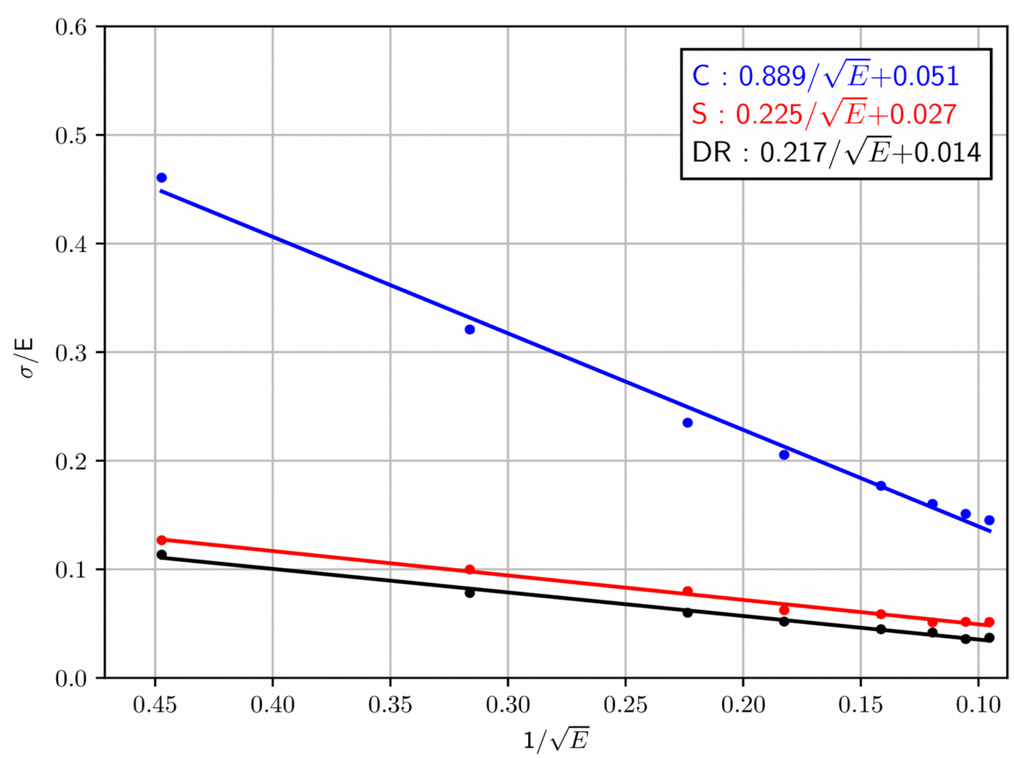
- Measured hadronic energy resolution with 5 to 110 GeV pions.
- Energy resolution is scaled to 1/√E.
- Stochastic & constant term of the energy resolution can be obtained by linear fitting.
- Stochastic term of energy resolution to hadronic shower ~ 21%.
- Energy resolution with χ = 0.291 was appended for cross-check.

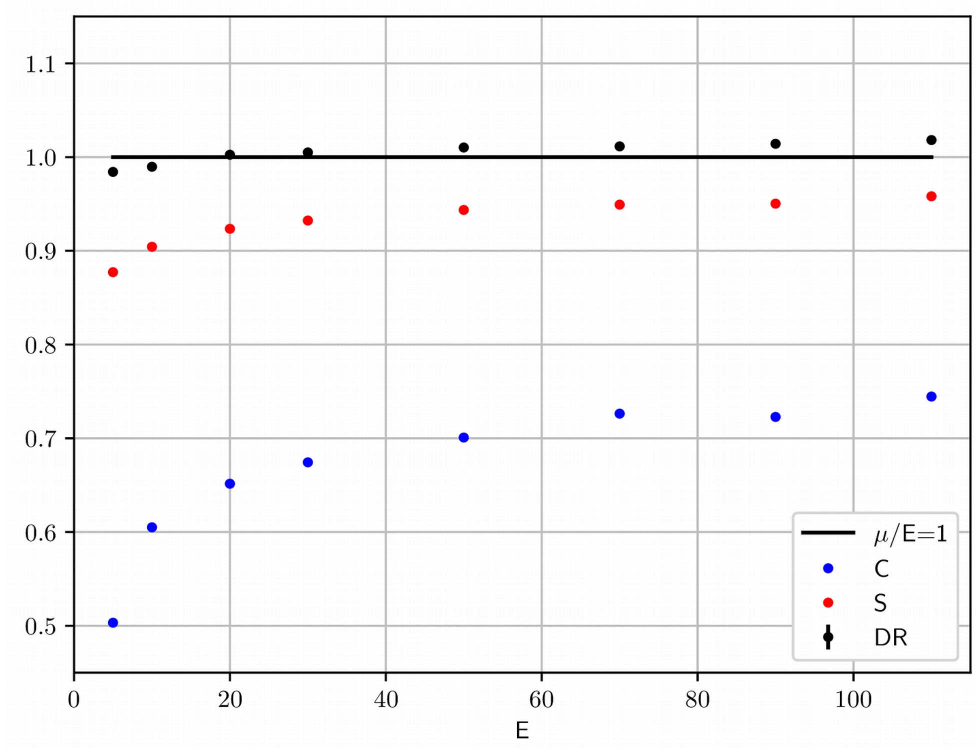


## Hadronic energy resolution (w/o light attenuation correction)

- Hadronic energy resolution without light attenuation correction was measured as well for cross-check.
- Light attenuation correction improves the energy resolution ~ 1%p as it improves the linearity of the response.



# Summary

## GEANT4 simulation of the dual-readout calorimeter

- A study on GEANT4 simulation has been done with 2.5m long copper tower based on RD52.
- Optical physics processes (both Cerenkov & scintillation) fully simulated with GEANT4.
- Optical cross-talk was observed and corrected for Cerenkov channel.
- Energy resolution for e- is ~ 13%/√E for scintillation only and ~ 11%/√E for S+C.
- Light attenuation correction is applied for hadronic events.
- Dual-readout correction constant χ was measured internally using GEANT4 (0.22).
- Energy resolution for π+ is ~ 21%/√E, and light attenuation correction & the choice of χ can give 1 – 2 %p deviations, respectively.

## Next step

- Measure jet energy resolution using Fastjet anti-kT clustering with fully simulated optical physics.
- Measure angular resolution with fully simulated optical physics.
- Test the geometry with tower length shorter than 2.5m (e.g. 2.0m).
- Test an alternative absorber material (e.g. Pb).

# Backups

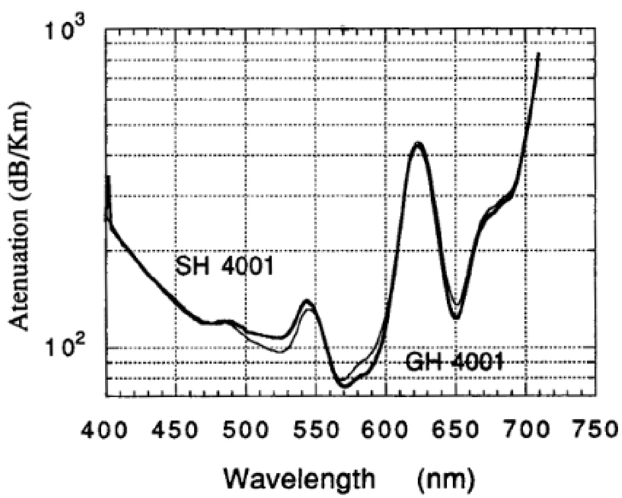
# Material properties

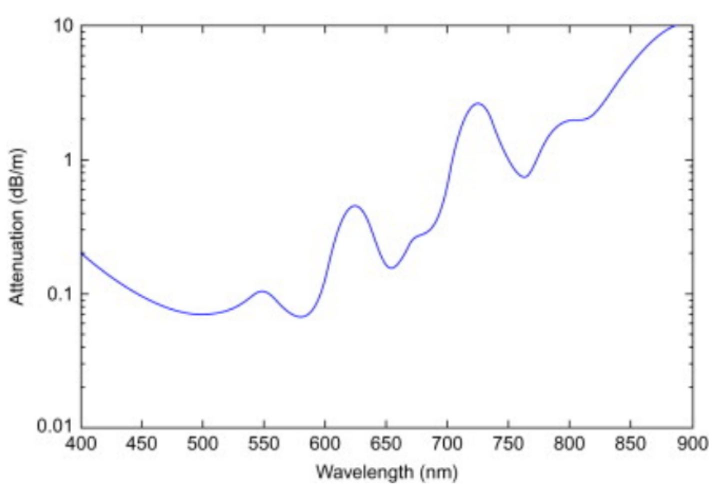
## Photon energy

- 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



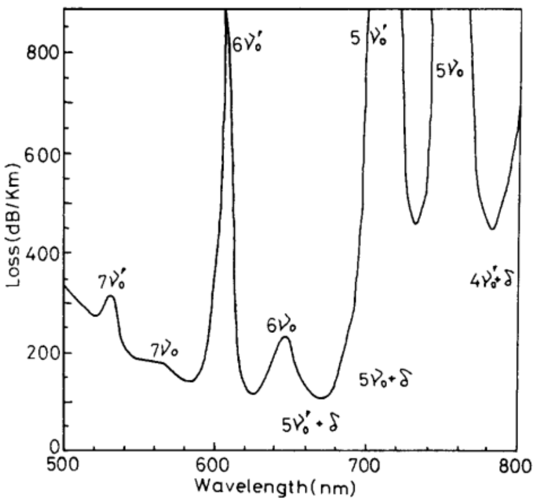
# Material properties

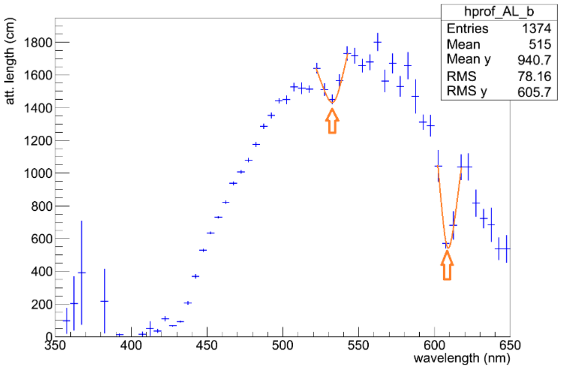
## Fluorinated polymer

- 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)

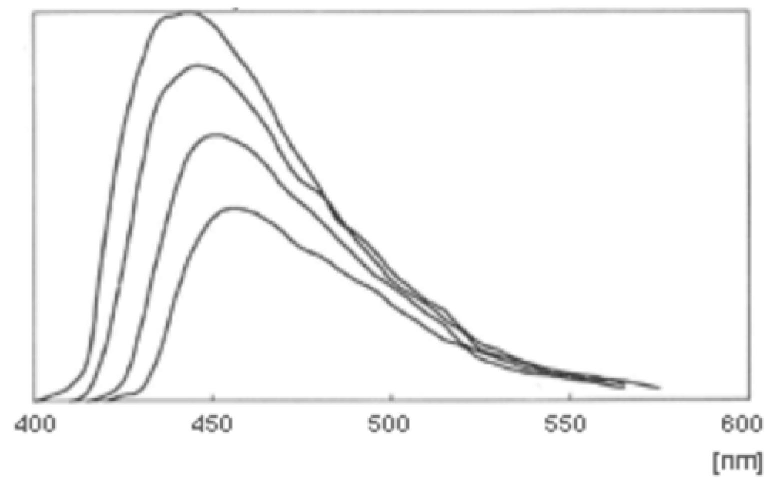


# Material properties

## Polystyrene

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

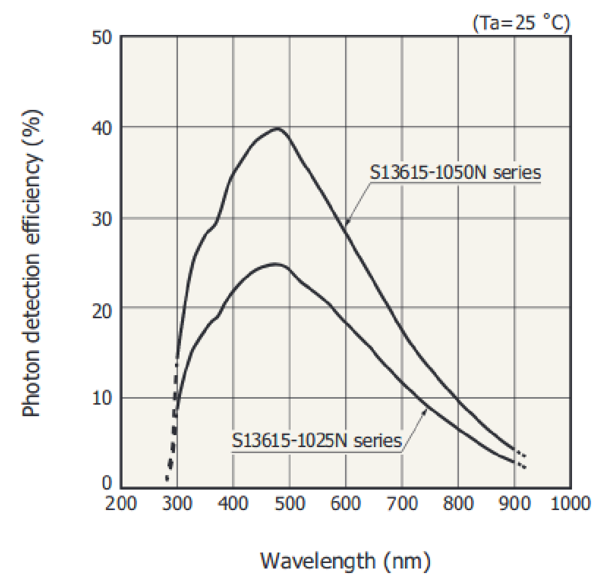



## Glass, Air

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

## PDE (Photon Detection Efficiency)

- Hamamatsu S13615-1025N series



# 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 |

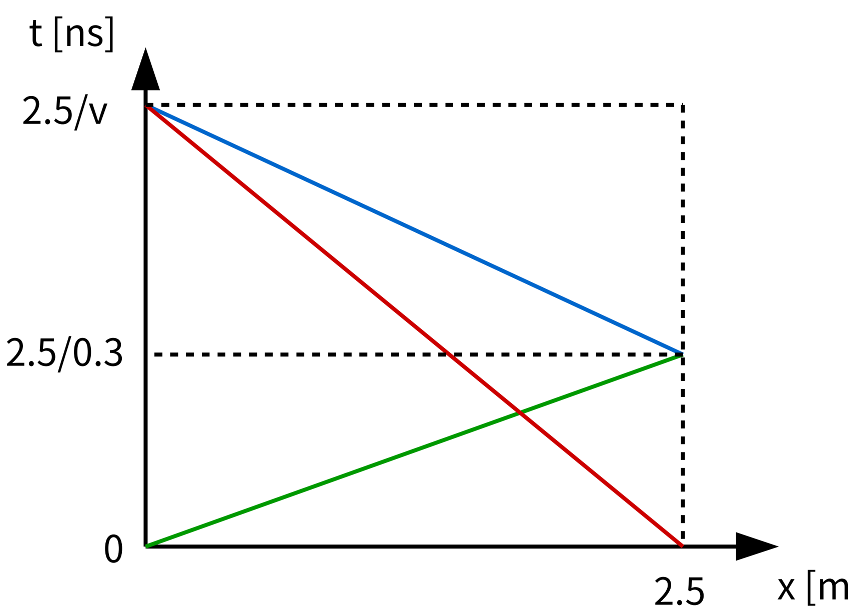
## Light attenuation correction

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



# 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.

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

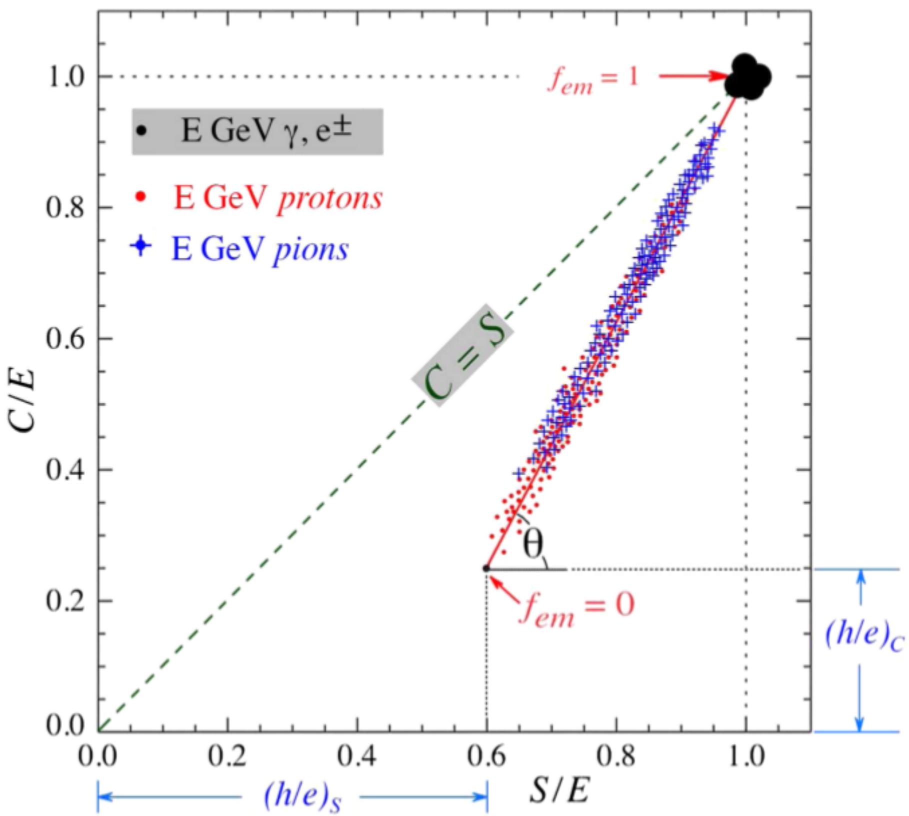
$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1-f_{em})\right].$$

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

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

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

- 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.