Follow-up for synchronization study

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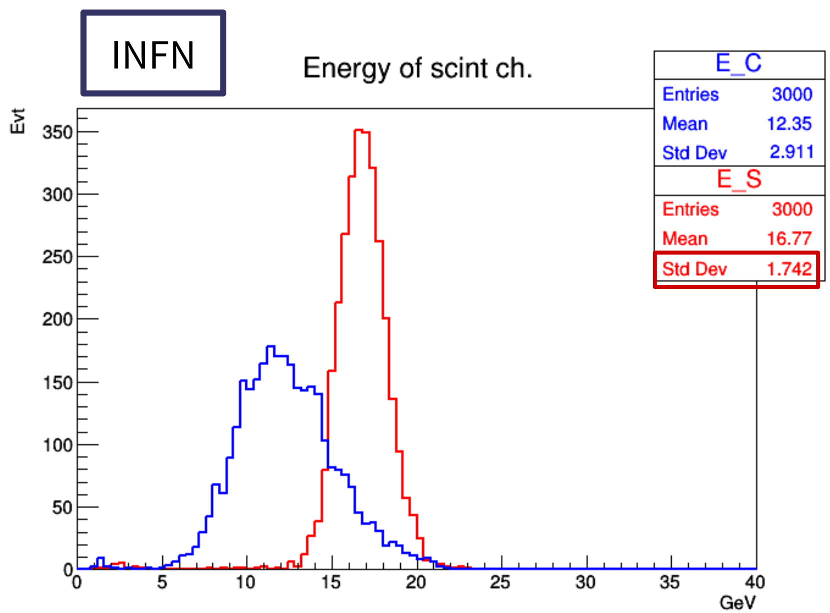
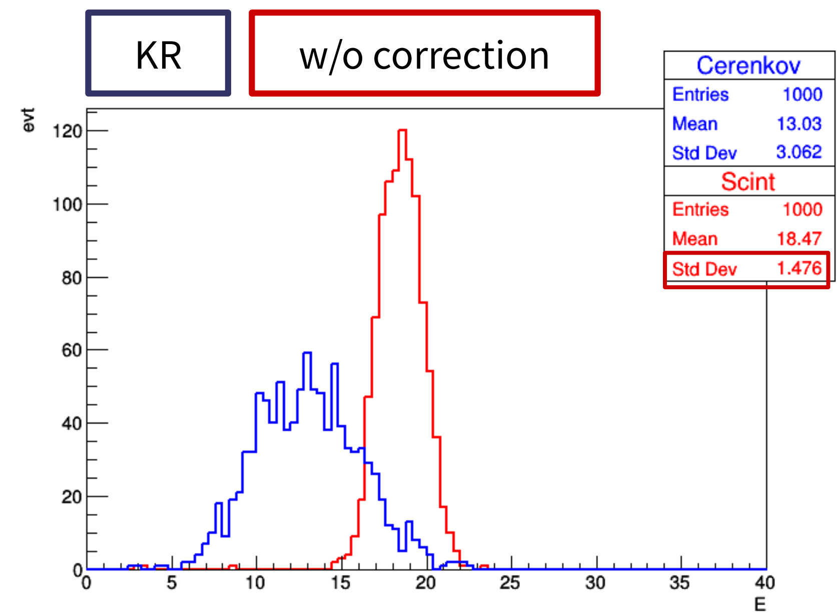
Introduction

Follow-up for synchronization study

- In the last meeting [link], it was shown that the resolutions of dual-readout corrected energy from the two packages were similar IF we synchronize the calibration procedure.
- However, there was a remaining question that the responses of scintillation channel were so different, aside from the dual-readout corrected energy.

- The candidates for the difference in scintillation channels are discussed in this meeting.
- Note that for KR package, plots are shown w/o light attenuation correction during the remaining slides, although the light attenuation effect is still simulated by GEANT4.





Light yield

Difference in light yields between two packages

- The most notable difference between two packages is light yield of scintillation channel.

- The light yield of scintillation channel for KR package is a result of combination of 1) light yield of polystyrene, 2) scintillation spectrum of polystyrene, 3) attenuation length of polystyrene, 4) spectrum of PDE of SiPM, and 5) transmittance spectrum of the yellow filter (see backup S12 for the details).
- Discovered a big difference in the transmittance spectrum of the yellow filter while reviewing above settings.

Tower		1	2	3	4	5	6	7	8	9	10
KR	Scint	1131.16	1128.69	1129.40	1137.81	1133.72	1128.75	1129.48	1135.76	1130.36	1098.79
	Ceren	73.0705	73.4569	72.9496	73.6362	73.3276	73.3702	73.1823	73.3276	73.2939	73.1464
INFN	Scint	401.369	400.112	400.761	399.881	399.500	401.441	400.672	400.411	401.741	400.074
	Ceren	102.219	102.206	102.052	101.903	101.907	102.047	102.503	101.744	102.281	102.145

Spectra of scintillation channel

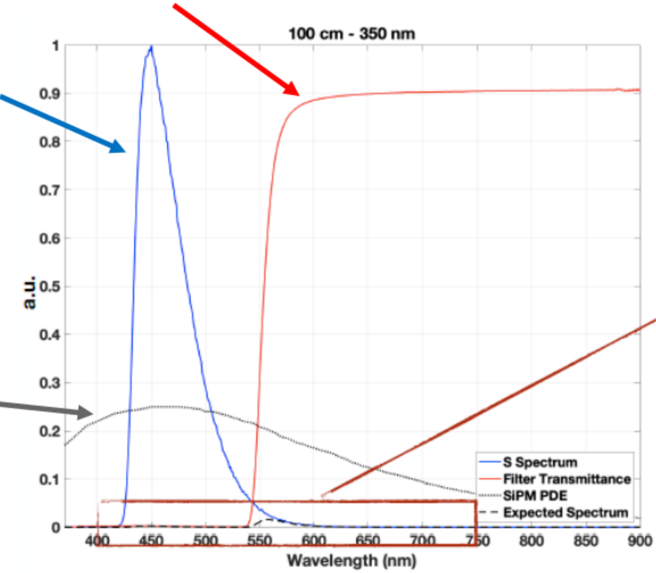
Scintillation spectrum & transmittance spectrum of yellow filter

From Romualdo's

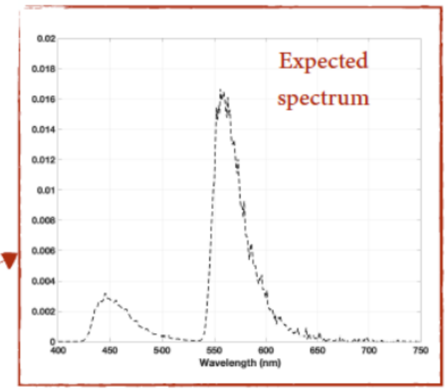
Scintillating fiber: emitted light spectrum (measured)

Yellow filter: transmittance spectrum (measured)

SiPM: Photodetector efficiency (from datasheet)

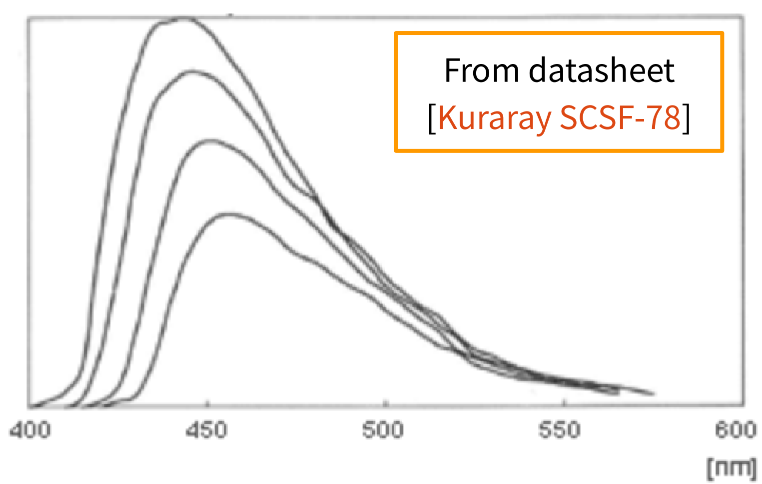


Expected spectrum and its attenuation



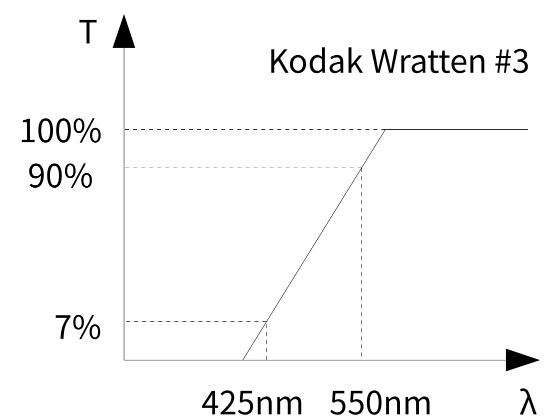
Attenuation $\left(\frac{A_{noFilter}}{A_{Filter}}\right) = 77\ times$

From our's



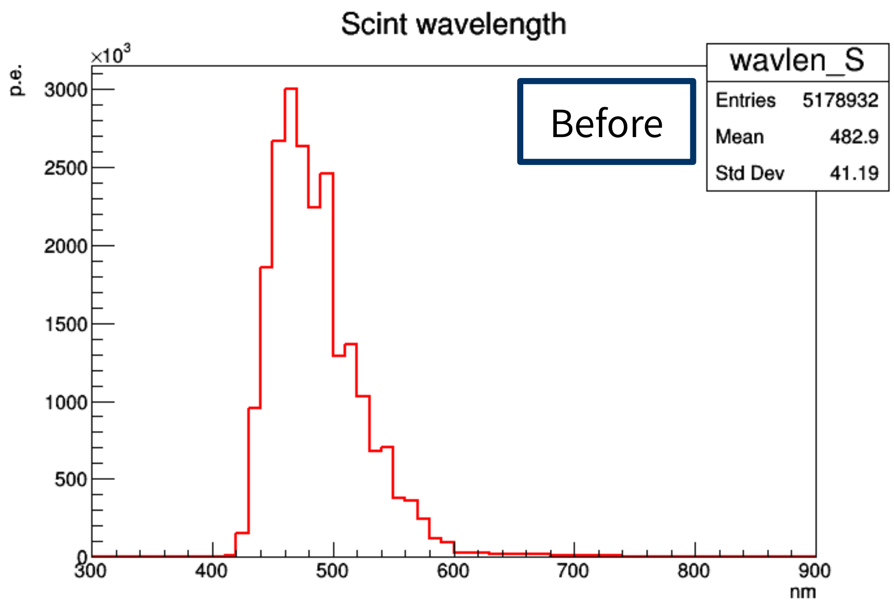
From datasheet [Kuraray SCSF-78]

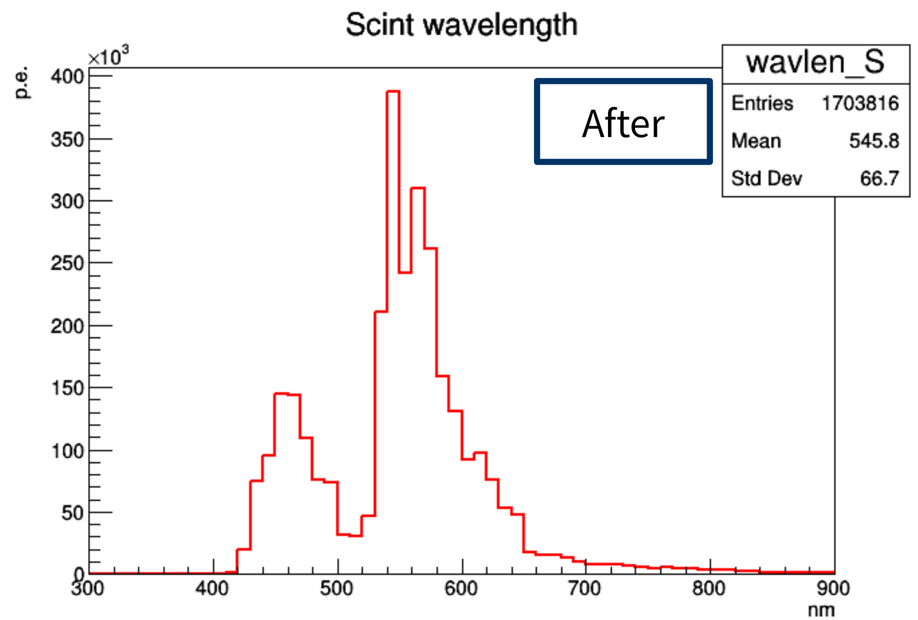
Transmission eff of filter



Spectra of scintillation channel

Comparison of before & after synchronization of yellow filter w/ 20 GeV e-





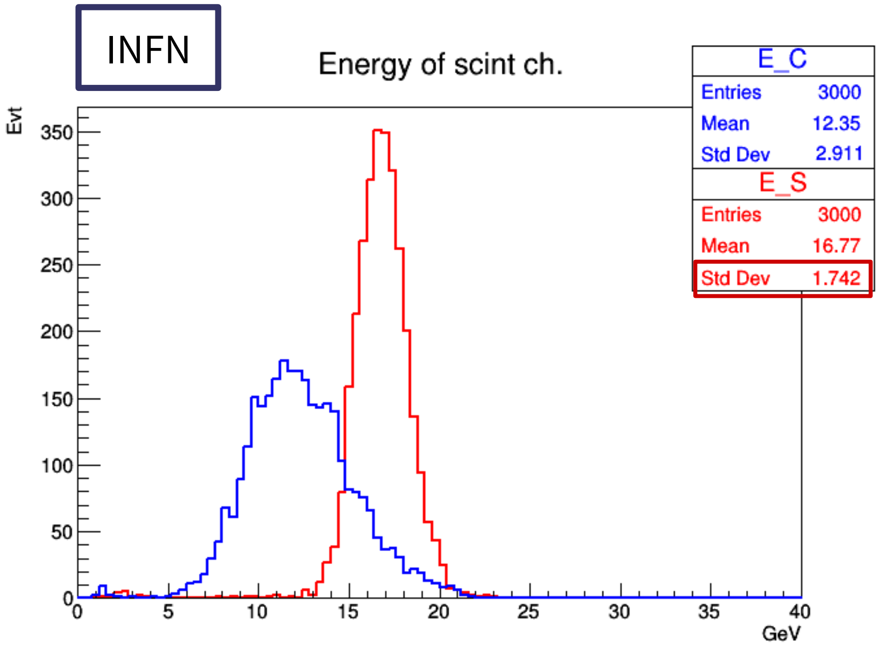
- Checked the spectrum of scintillation channel before (our previous setup) & after synchronizing the yellow filter.
- After the rough synchronization (data interpolated with 25nm step) of the yellow filter, the spectrum of scintillation channel shows similar distribution, with drastically decreased light yield (1130 → 154).

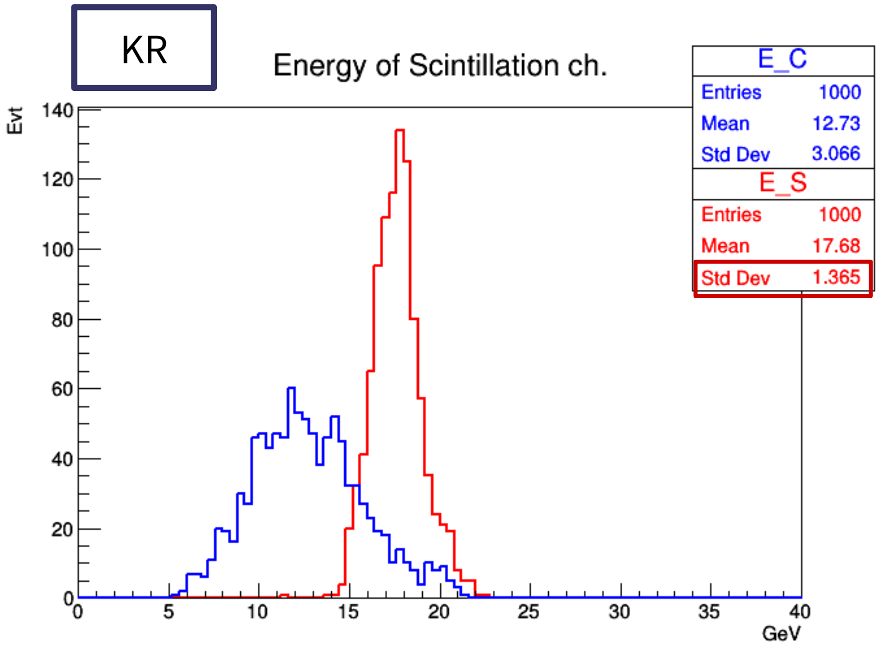
  (more accurate simulation will be delivered later, with 10nm step at turn-on region)

- Difference in the spectrum may indicate that each simulation is based on the different yellow filter.

Energy distribution

Energy distribution of scintillation channel after sync yellow filter w/ 20 GeV π+

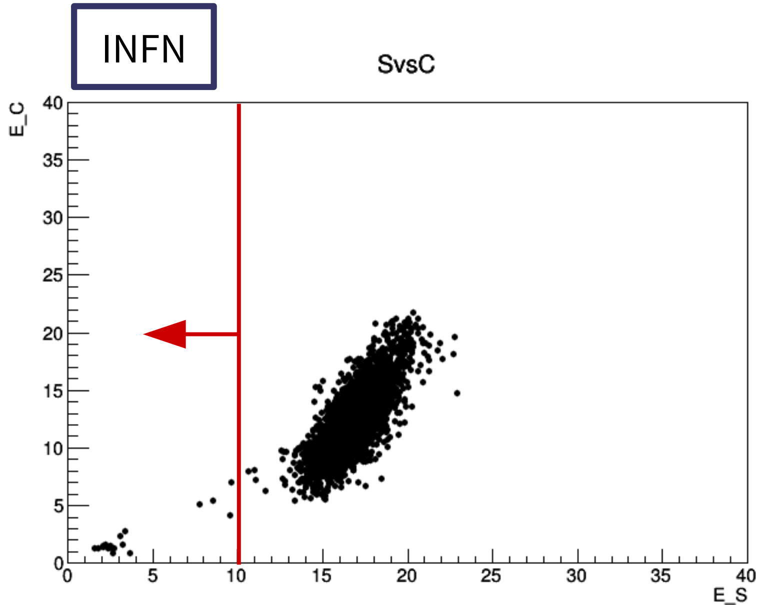


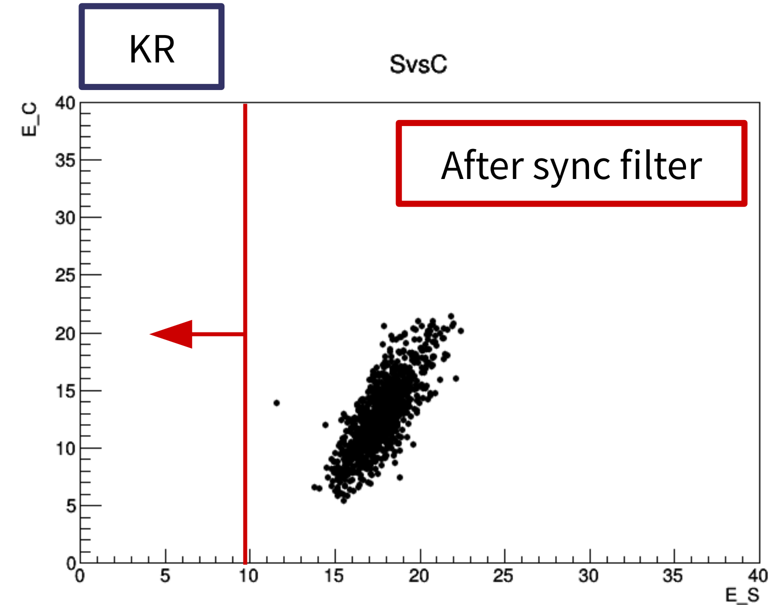


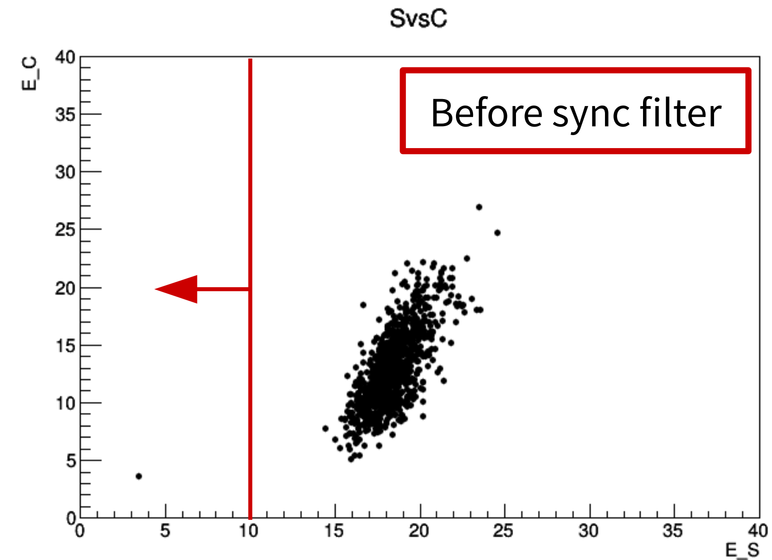
- Although the spectrum of yellow filter is responsible for the difference in light yield, however, still standard deviation of estimated energy shows large difference even after the synchronization of the yellow filter.
- Another candidate is responsible for this difference.

Outliers

Outliers at the low energy region w/ 20 GeV π+



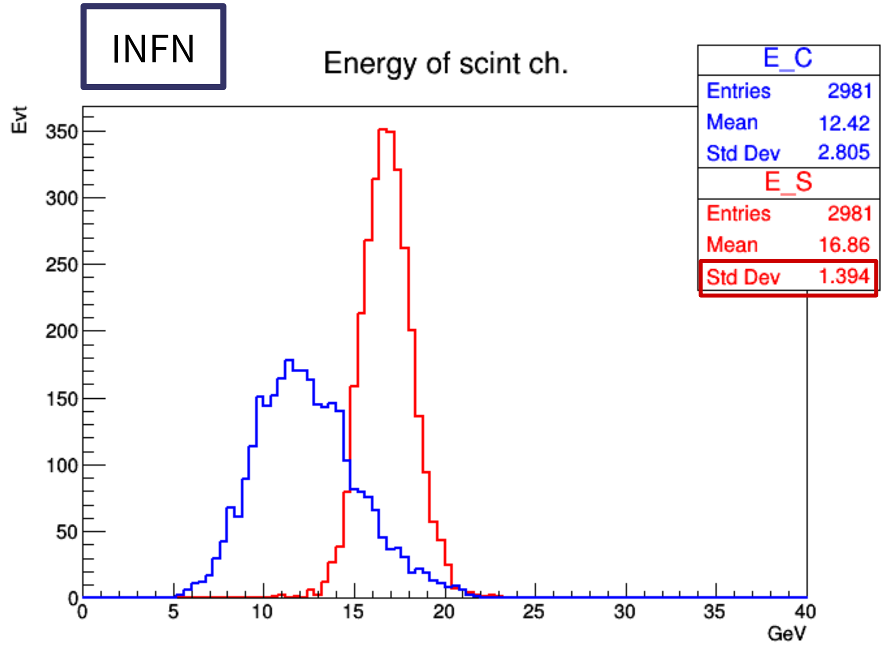


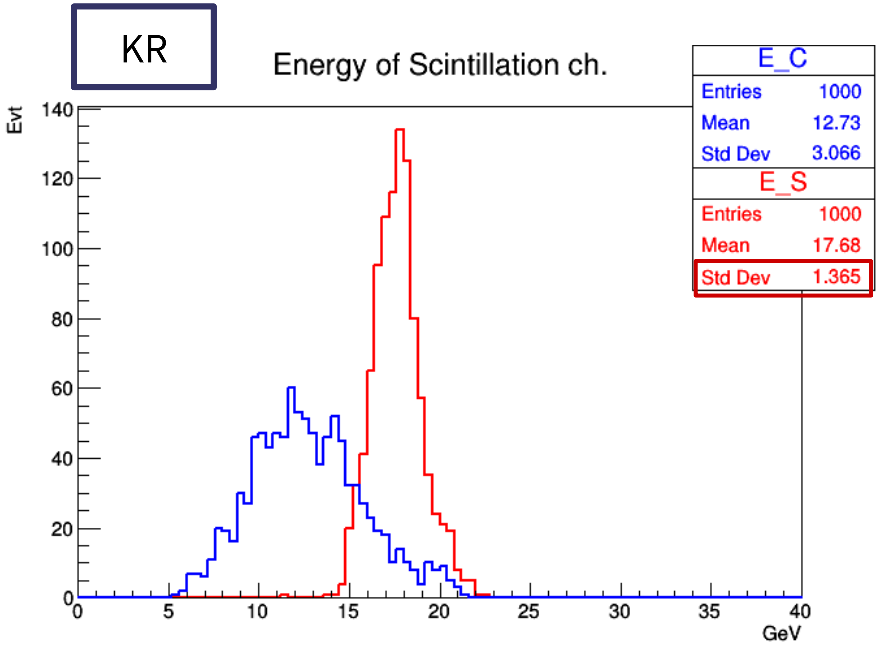


- One more notable difference between two packages is an existence of outliers at the low energy region.
- To check the impact of outliers on the standard deviation of energy distribution, compared the distribution after excluding events with E_S < 10 GeV.

Energy distribution

Energy distribution of scintillation channel w/ 20 GeV π+ after excluding outliers





- After excluding outliers with E_S < 10 GeV, the standard deviation of scintillation channel shows similar results.
- This indicates that the outliers may responsible for the difference in scintillation channel between two packages.
- This also explains the reason why we observed the difference in scintillation channel, but not for dual-readout corrected energy; We take standard deviation for scintillation channel, but we fit with Gaussian for dual-readout corrected energy.

- Question – Why outliers (~ 1%) occur?

Summary

Differences in scintillation channel between two simulations

- Setup for the spectrum of yellow filter may responsible for the difference in light yield.
- Outliers at the low energy region may responsible for the difference in standard deviation of energy distribution.

Remaining questions

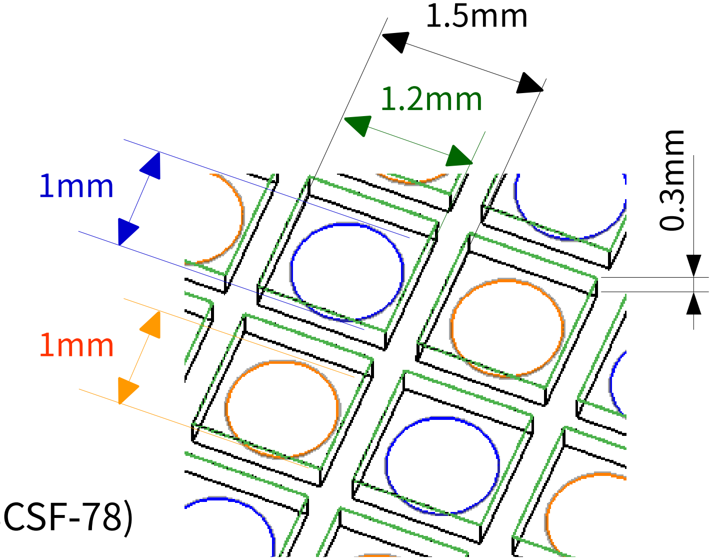
- Model of the filter used to setup each simulation.
- Origin of outliers (whether it is technical or not).

Backups

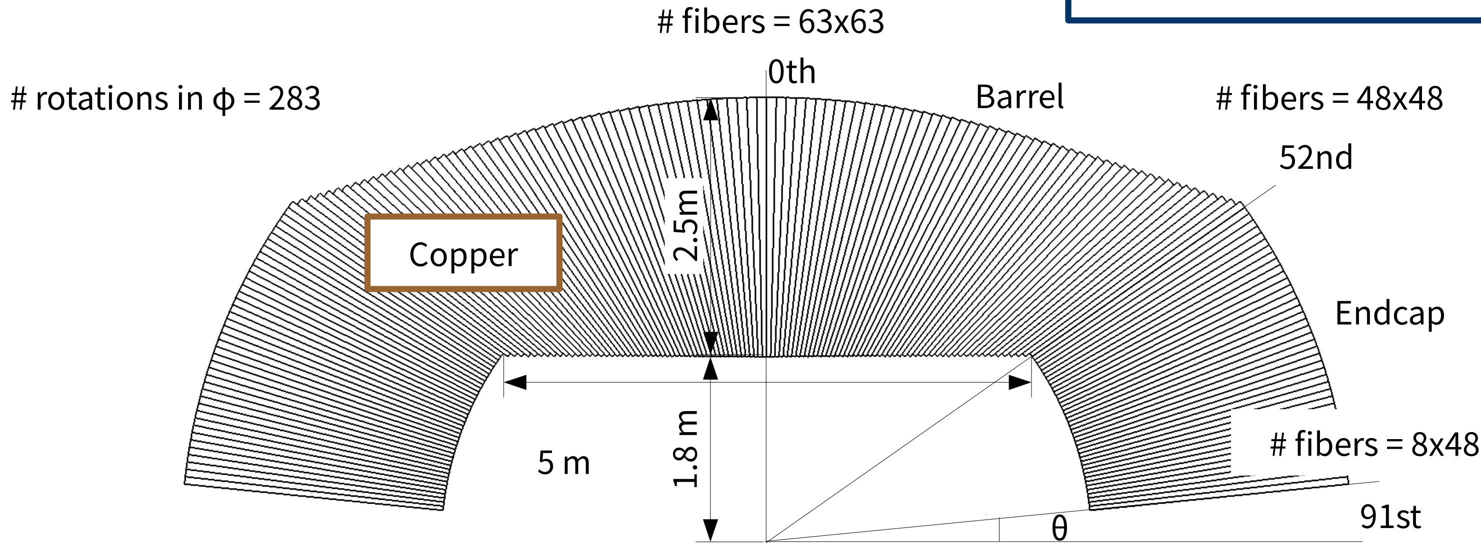
GEANT4 simulation setup (1)

GEANT4 simulation setup – Geometry

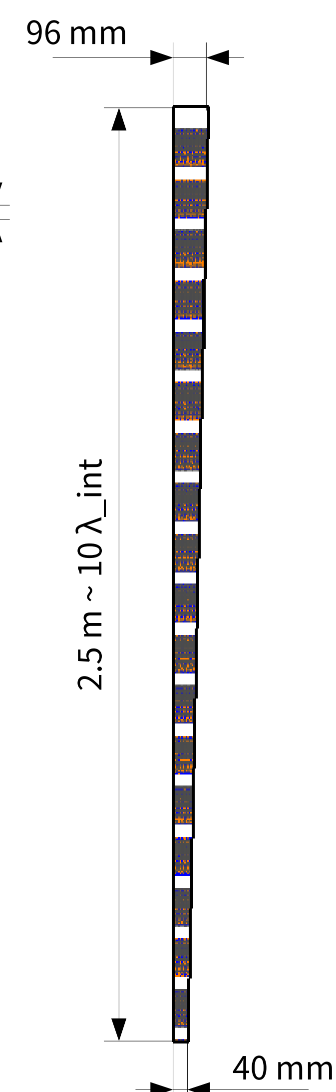
- A projective 4π 'wedge' geometry.
- Covers up to |cos(θ)| < 0.995 (|η| < 3.0) with no cracks.
- A Cu tower with a depth of about 2.5 m (~ 10 λ_int).
- O(1000) fibers implemented per tower.
  - Cerenkov(C) fiber: PMMA (Eska SK40)
  - Scintillation(S) fiber: Polystyrene(PS) (Kuraray SCSF-78)
- High granularity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



Rear end of a tower



x-z view of dual-readout calorimeter

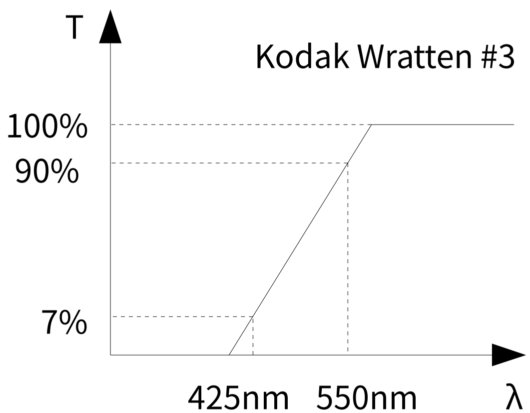


Side view of 0th tower

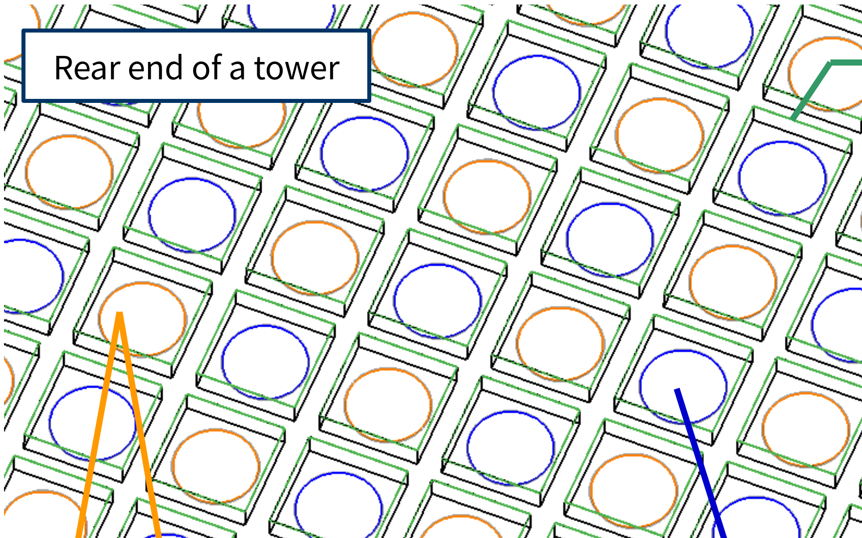
GEANT4 simulation setup (2)

GEANT4 simulation setup – Optical physics

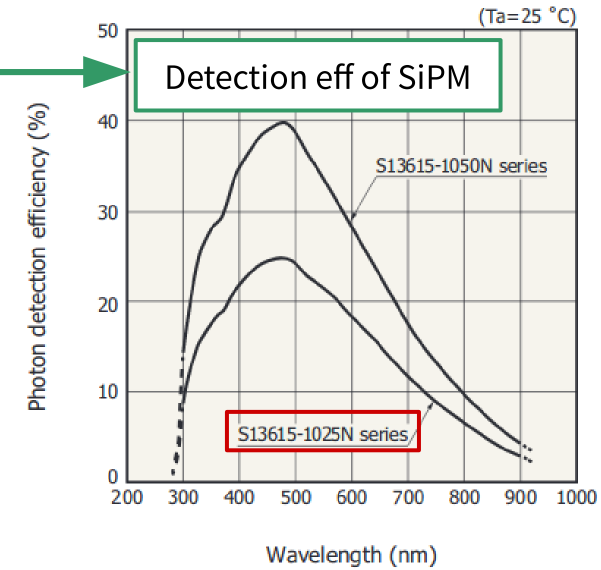
Transmission eff of filter



Rear end of a tower

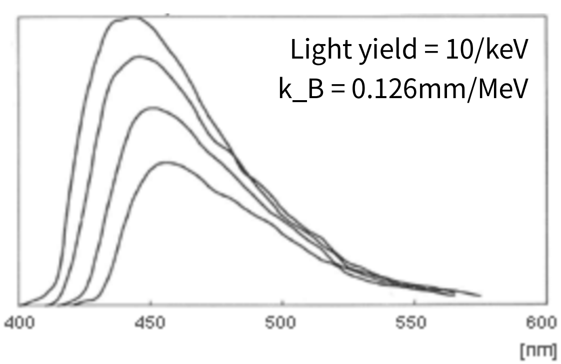


Detection eff of SiPM



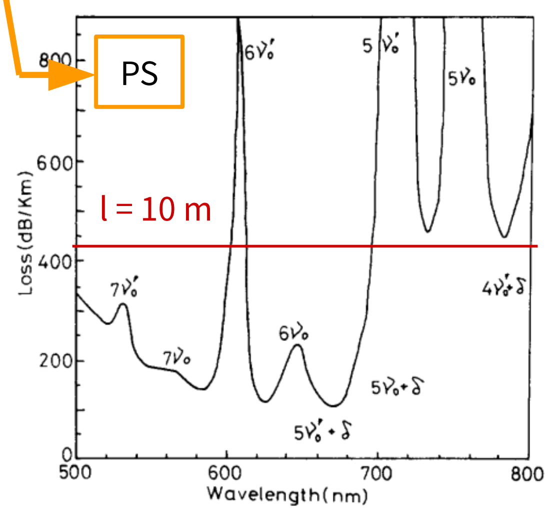
Attenuation loss diverges at 400nm → applied filter to S channel to mitigate it

Scintillation spectra of PS

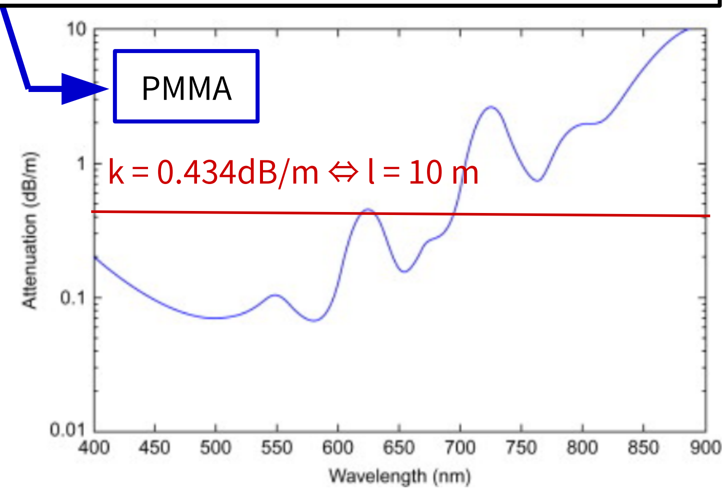


Attenuation loss of Polystyrene (PS) & PMMA

PS



PMMA



Calibration

Calibration procedure

- Used 1cm x 1cm 20 GeV electron beam parallel to the target tower
  - For INFN package: Direction of the beam & the tower is identical up to 9 digits.
  - For Korean package: Direction of the beam & the tower is exactly identical.
- Extracting equalization constants
  - Eq. constant = # of p.e. counted in the channel / MC truth energy deposited in the target tower
- Applying scale factor
  - Using equalization constants solely does not provide correct energy measurement for whole shower.
  - Uniform scale factor is applied to equalization constants to correct energy, using 20 GeV electron events.
  - Beam setup used for estimating scale factor is different from the that used for calibration.
    - Used 1cm x 1cm 20 GeV electron beam, with $(\theta, \phi) = (1.5°, 1.0°)$ inclination regarding to the axis of the 1^{st} tower in the right.
    - This beam setup is maintained for energy measurements for electrons and pions after the calibration.

Macros

Macro used for calibration for n-th tower

```
/run/numberOfThreads 1
#
# Initialize kernel
/run/initialize
#
# Kinematics:
#
/gps/particle e-
/gps/energy 20 GeV
/gps/position 0 0 0 cm
/gps/pos/type Plane
/gps/pos/shape Square
/gps/pos/rot1 0 0 1
/gps/pos/halfx 0.5 cm
/gps/pos/halfy 0.5 cm
/gps/ang/type beam1d
/gps/direction 0.9995663085 0 0.029448173248
#
/run/beamOn 3000
```

sin((1/2+n)*(π/4)/40)

cos((1/2+n)*(π/4)/40)

Macros

Macro used for measuring energy of electrons & pions

```
/run/numberOfThreads 1
#
# Initialize kernel
/run/initialize
#
# Kinematics:
#
/gps/particle pi+
/gps/energy 50 GeV
/gps/position 0 -4.363766 -6.546 cm
/gps/pos/type Plane
/gps/pos/shape Square
/gps/pos/rot1 0 0 1
/gps/pos/halfx 0.5 cm
/gps/pos/halfy 0.5 cm
/gps/ang/type beam1d
/gps/direction 0.999199957 0.0174524 0.03598416
#
/run/beamOn 3000
```

250cm*tan(1.0°)

250cm*tan(1.5°)

sin(1.5°+1/2*(π/4)/40)

cos(1.5°+1/2*(π/4)/40)*sin(1.0°)

cos(1.5°+1/2*(π/4)/40)*cos(1.0°)

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.

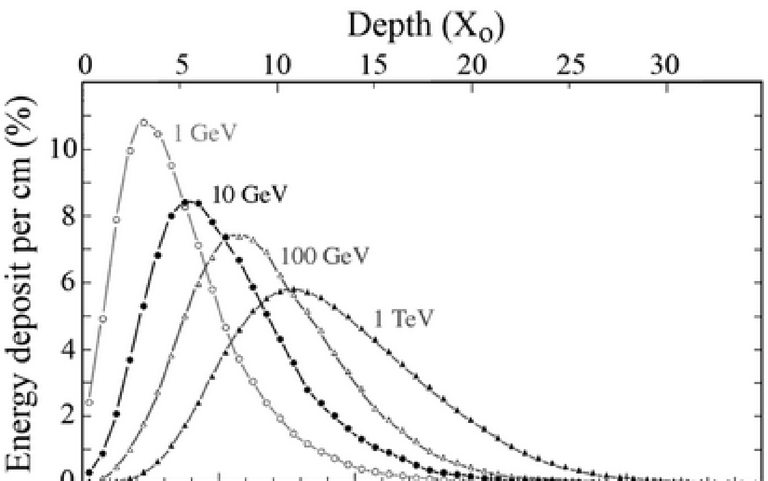
Shower depth as a function of time

- 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.

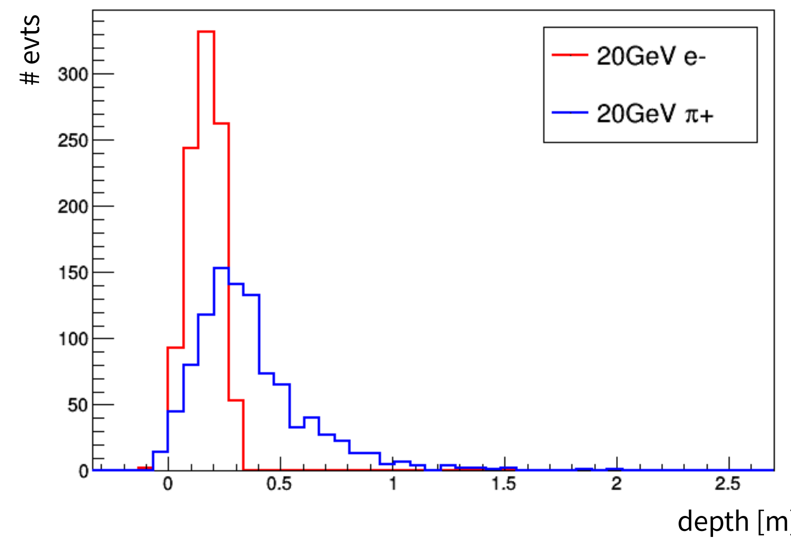
$$v = \frac{2.5\,m - 0.1368\,m}{t_{max} - \frac{0.1368\,m}{0.3\,m/ns} - \frac{1.8\,m}{0.3\,m/ns}}$$

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

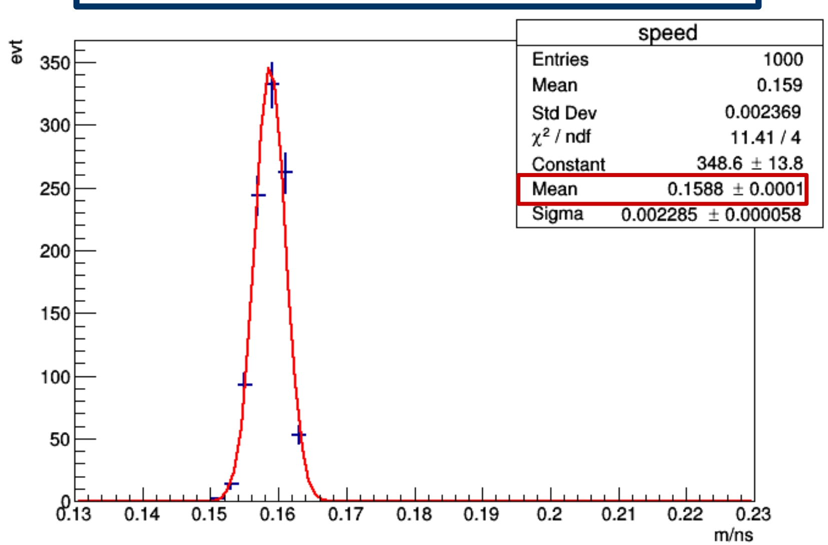
$$E = E_{6.33\,X_0} \exp\frac{x - 6.33\,X_0}{\lambda_{eff}}$$

- Removing the exponential term corrects the attenuation loss.

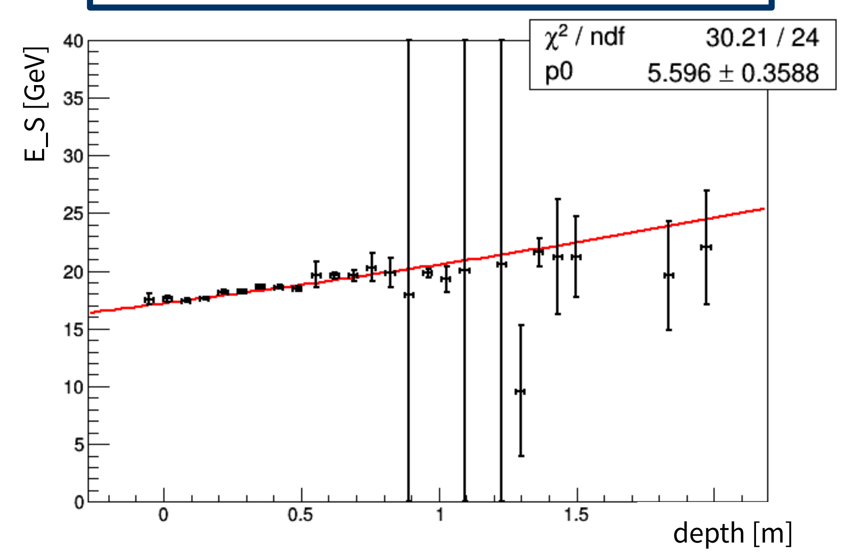
Shower depth of 20 GeV e- & π+



Velocity of optical photon v within fibers



Avg E_S vs shower depth for 20GeV π+



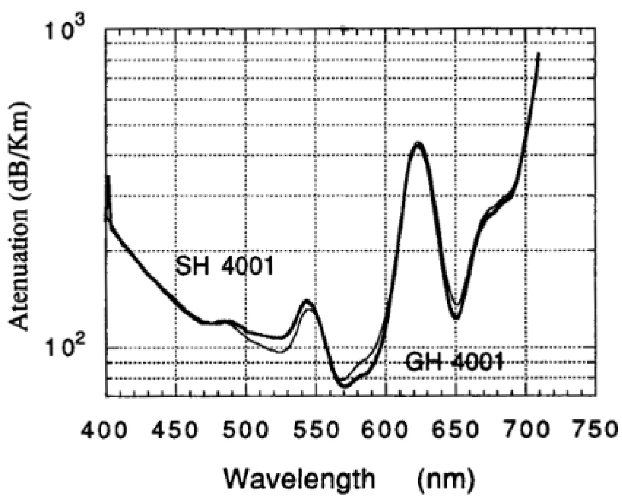
Material properties

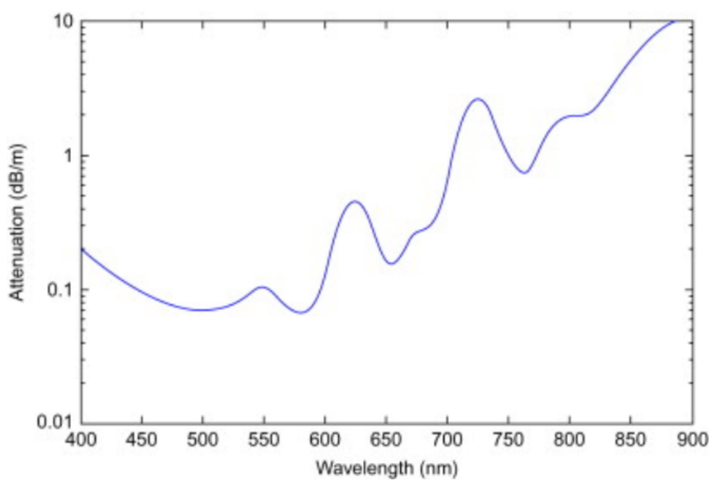
Photon energy

- 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





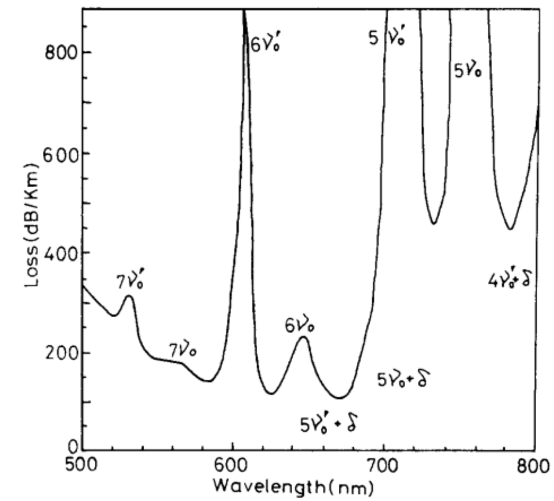
Material properties

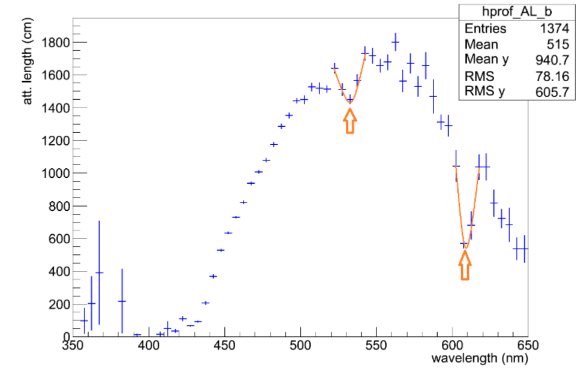
Fluorinated polymer

- 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, 012 (SCSF-78 LHCb Sci-Fi tracker R&D TDR)
  - kuraray scintillating fiber manufacturer (SCSF-78)

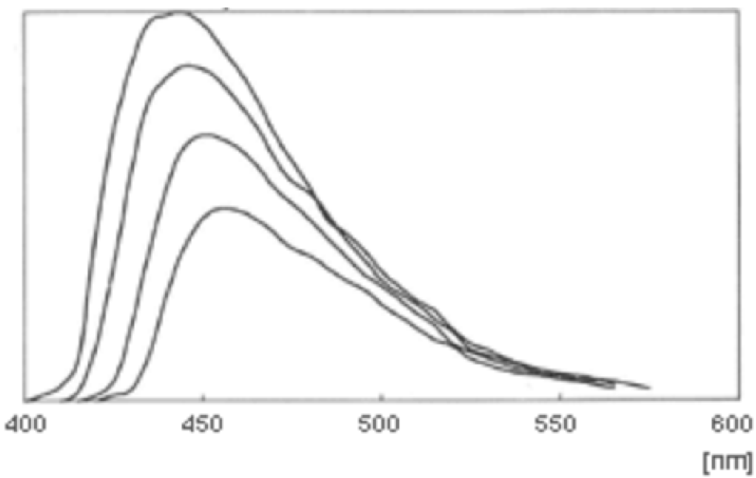




Material properties

Polystyrene

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

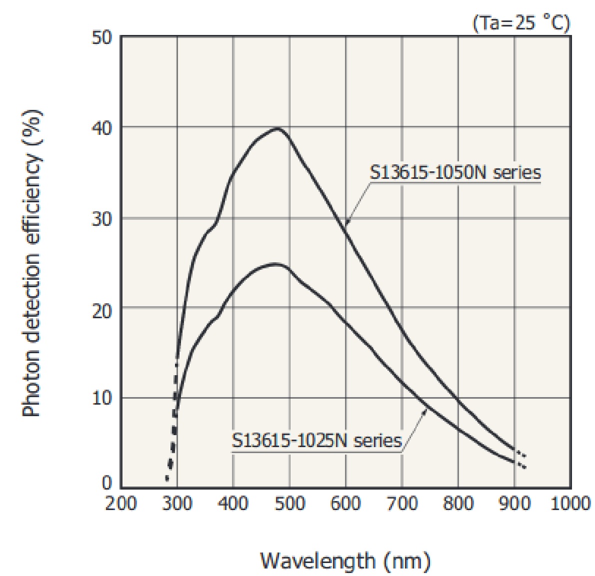


Glass, Air

- 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

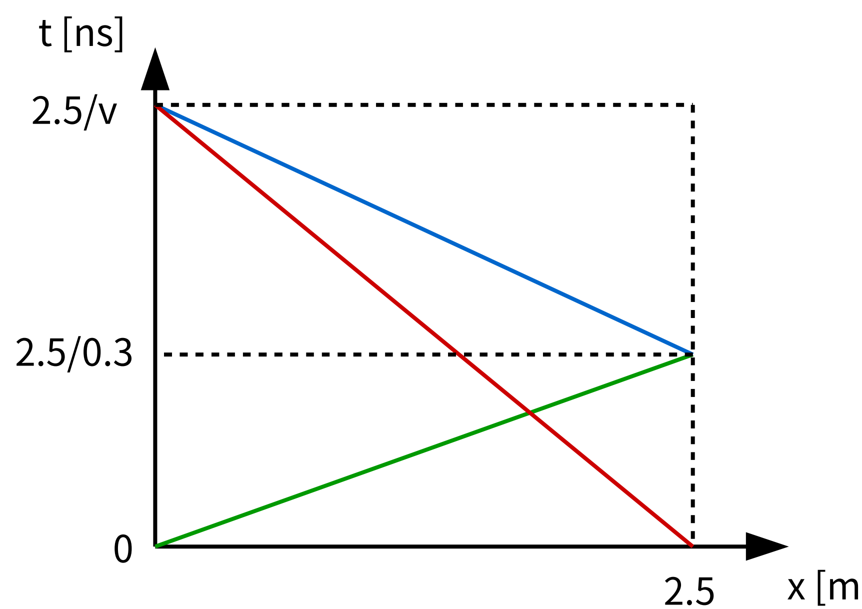
Light attenuation correction

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

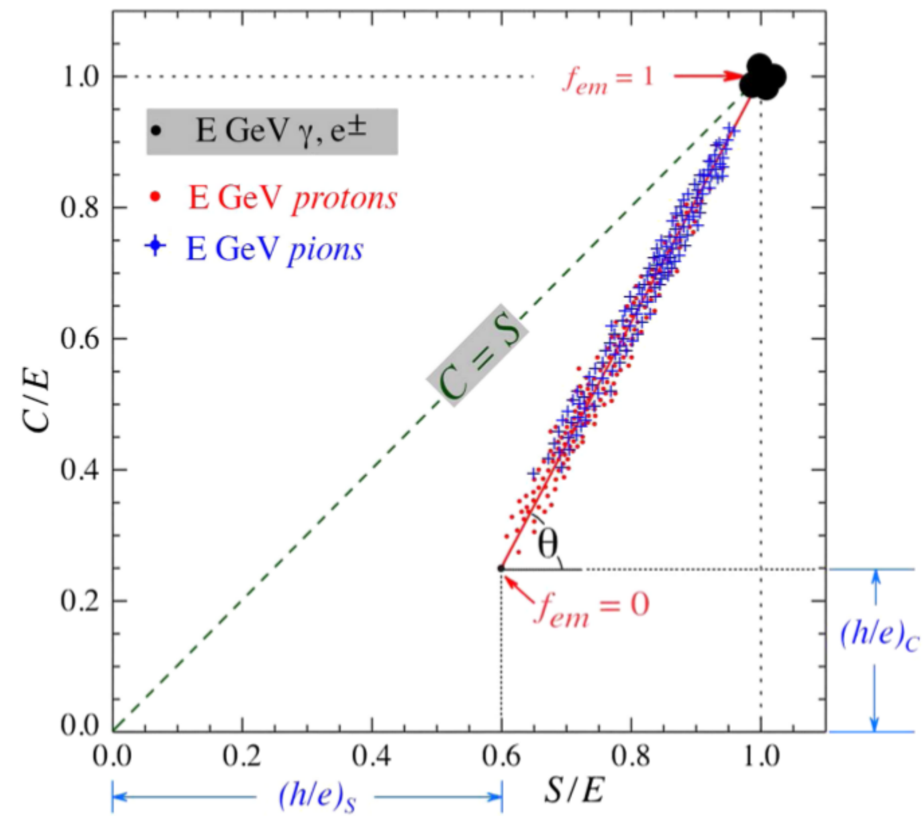
$$S = E[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})],$$

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

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

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

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



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

- 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.

Title

Text

$$formula$$