Fast optical photon transportation in GEANT4

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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.

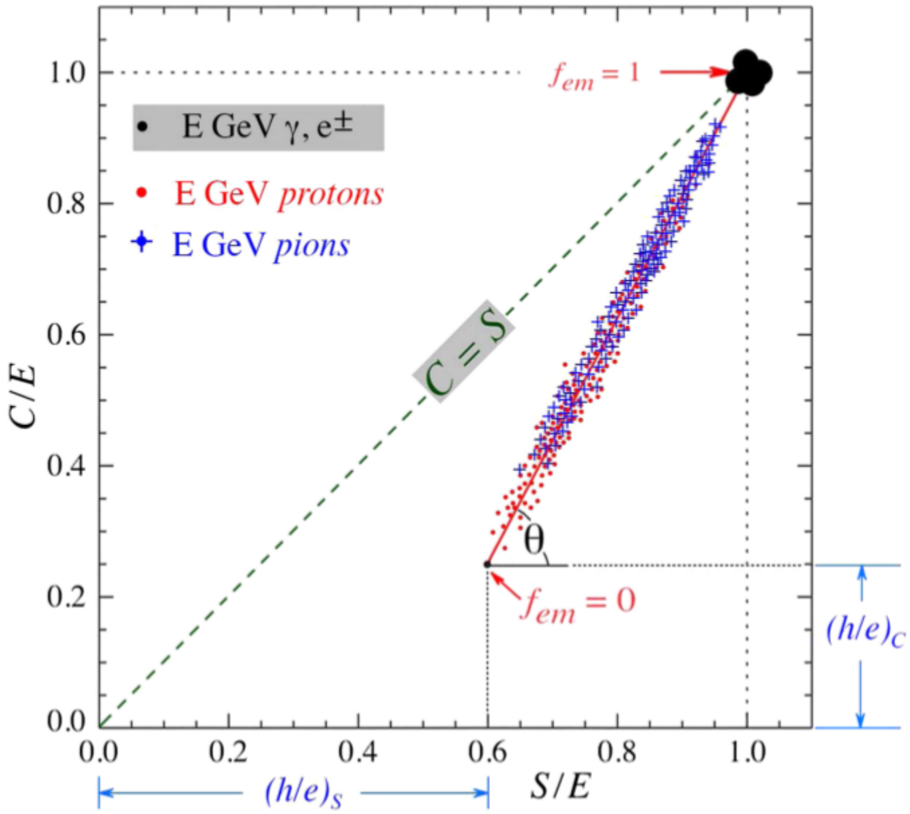
$$S = E[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})],$$

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

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

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

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



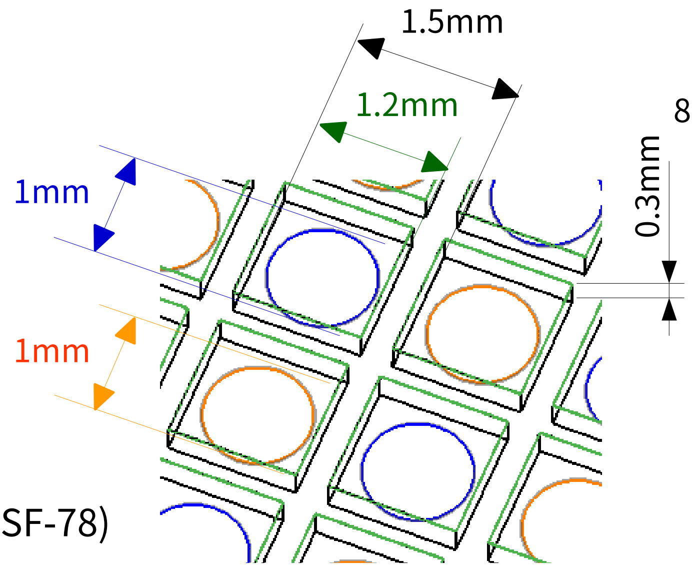
Energy measured from scintillation channel vs Cerenkov channel for EM particle, π & p.

- 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.
- Dual-readout calorimeter is a main detector of IDEA detector concept, which is being discussed in CDR of both FCC-ee & CEPC at one of the interaction points.

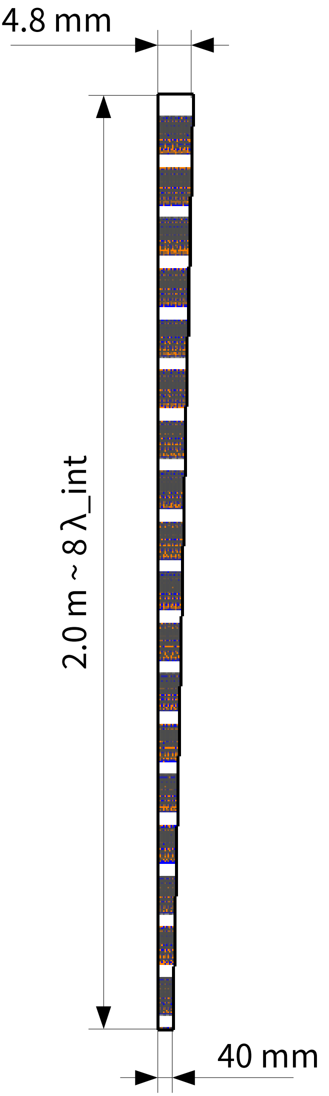
GEANT4 simulation setup (1)

GEANT4 simulation setup – Geometry

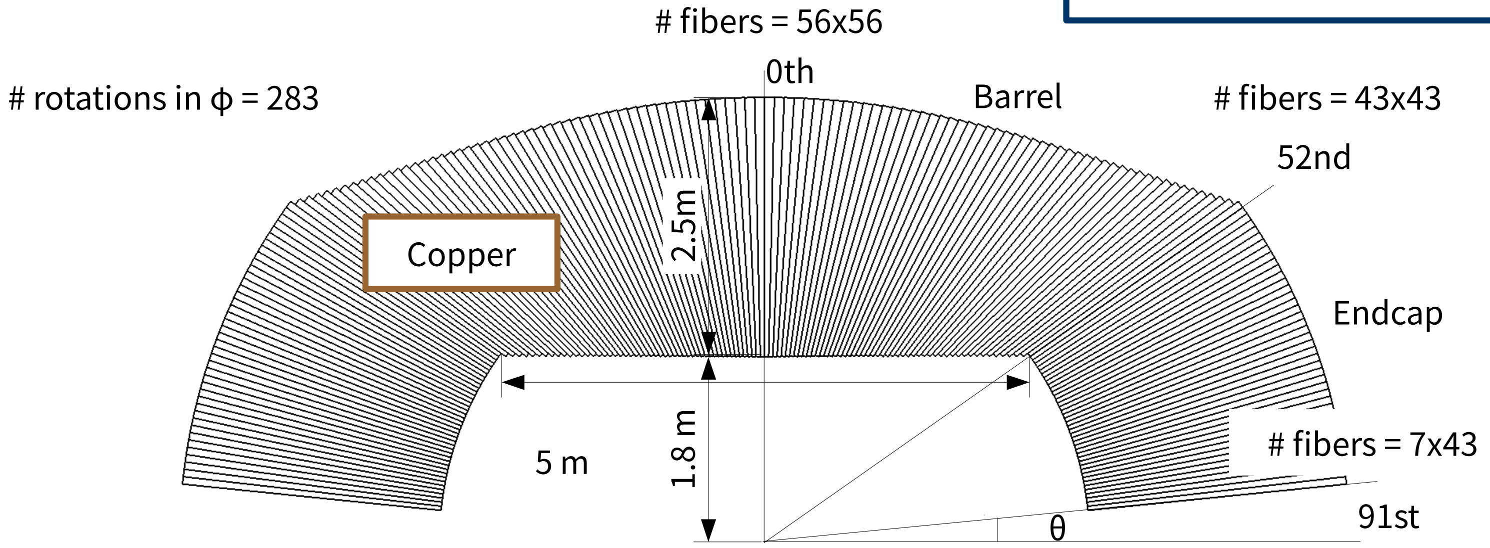
- A projective 4π ‘wedge’ geometry.
- Covers up to $|\cos(\theta)| < 0.995$ ($|\eta| < 3.0$) with no cracks.
- A Cu tower with a depth of about 2.0 m (~ 8 λ_int).
- O(1000) fibers implemented per tower.
  - Cerenkov(C) fiber: PMMA (Eska SK40)
  - Scintillation(S) fiber: Polystyrene(PS) (Kuraray SCSF-78)
- High granularity SiPM array (Hamamatsu S13615-1025N)



Rear end of a tower



Side view of 0th tower

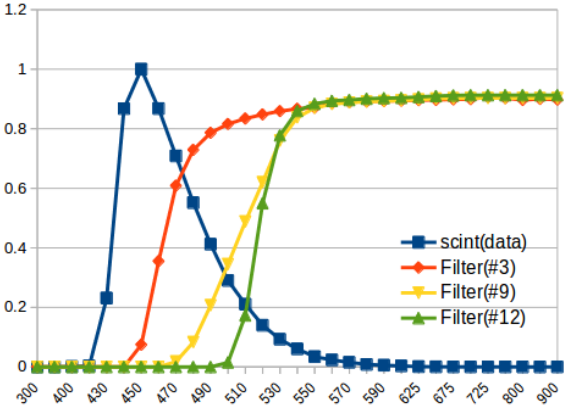


x-z view of dual-readout calorimeter

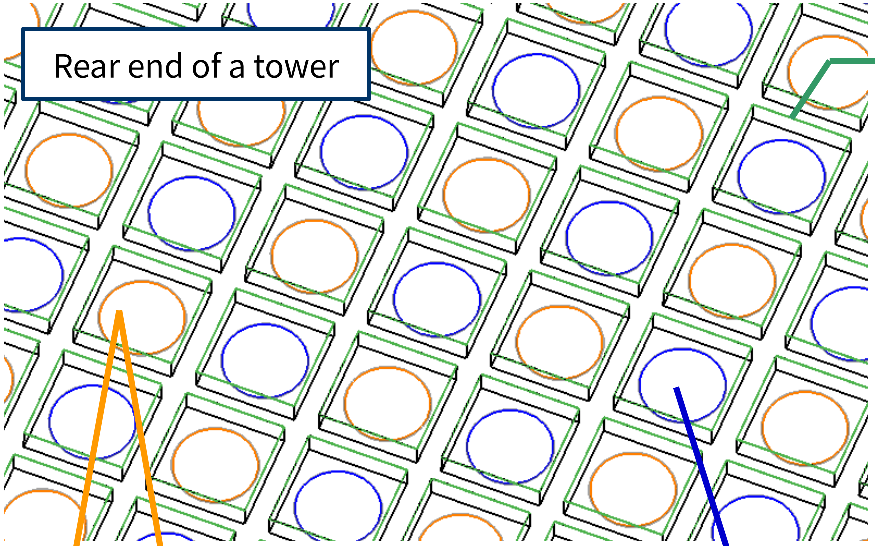
GEANT4 simulation setup (2)

GEANT4 simulation setup – Optical physics [Github]

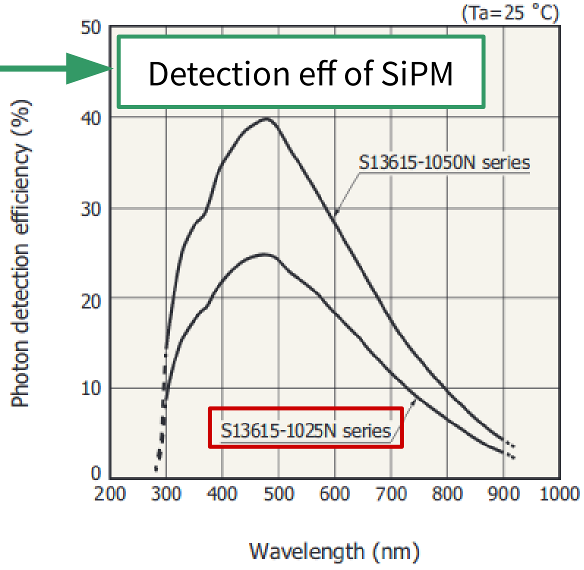
Transmission eff of filters



Rear end of a tower



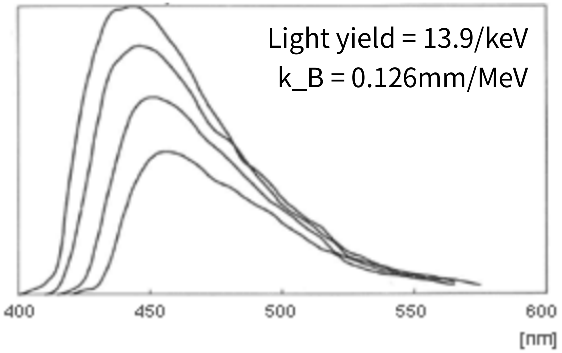
Detection eff of SiPM



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

Attenuation loss of Polystyrene (PS) & PMMA

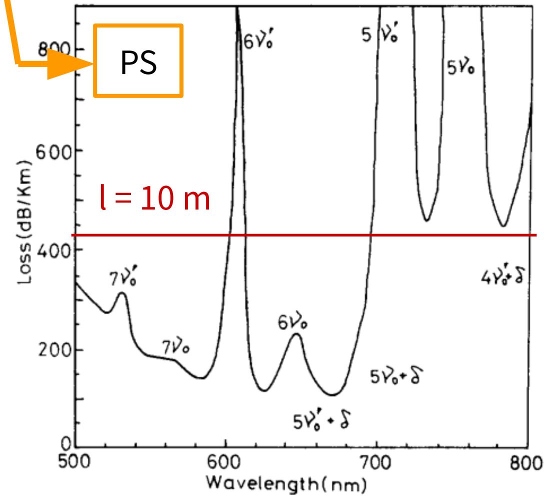
Scintillation spectra of PS



Light yield = 13.9/keV

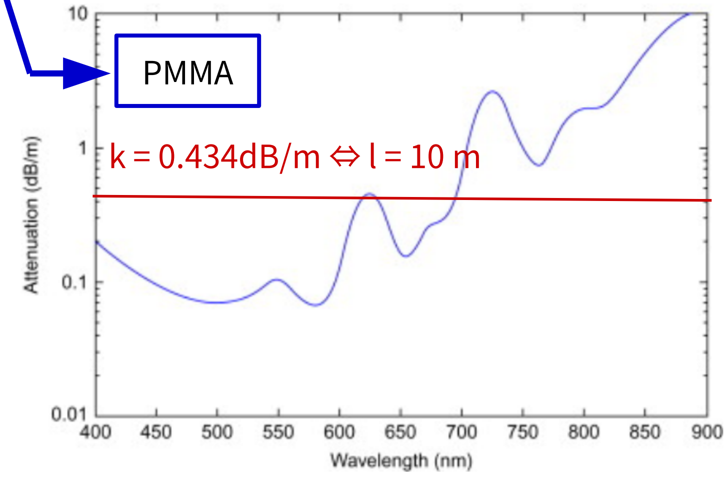
k_B = 0.126mm/MeV

PS



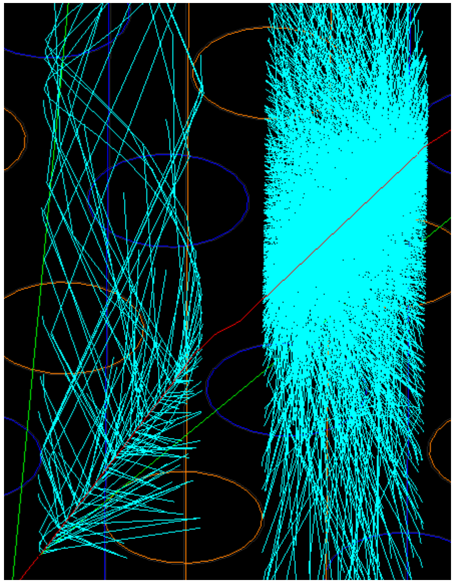
l = 10 m

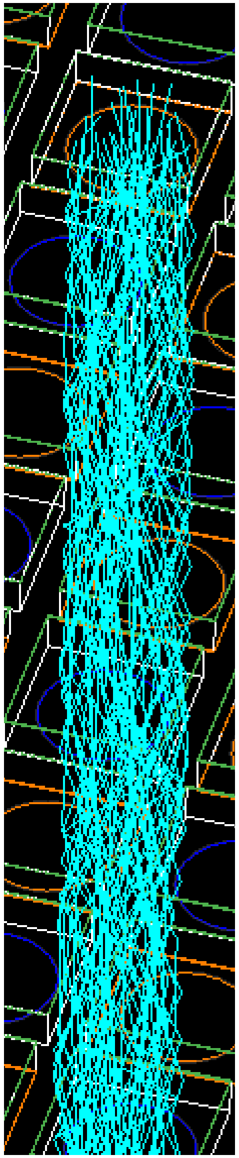
PMMA



k = 0.434dB/m ⇔ l = 10 m

Detail vs CPU consumption





Details needed to simulate dual-readout calorimeter

- Cerenkov & scintillation processes.
- Light attenuation of Polystyrene & PMMA.
- Transmission of optical surfaces, e.g. yellow filter, SiPM.
- Total internal reflection inside optical fibers.
  - Numerical aperture is important for Cerenkov channel.

CPU consumption for tracking optical photons

- A drawback for detailed simulation is CPU consumption caused by tracking optical photons.
- Single photon generates ~ O(10k) tracks for tracking, while there are ~ O(10k) optical photons per GeV of incident particle, results ~ O(100M) tracks per GeV.
- It takes 304 ± 88 min in average to produce an event!
  - Tested 1000 of 20 GeV electron events at institutional server.

- Needs smart & efficient way to transport optical photons while preserving the details needed to simulate dual-readout calorimeter.

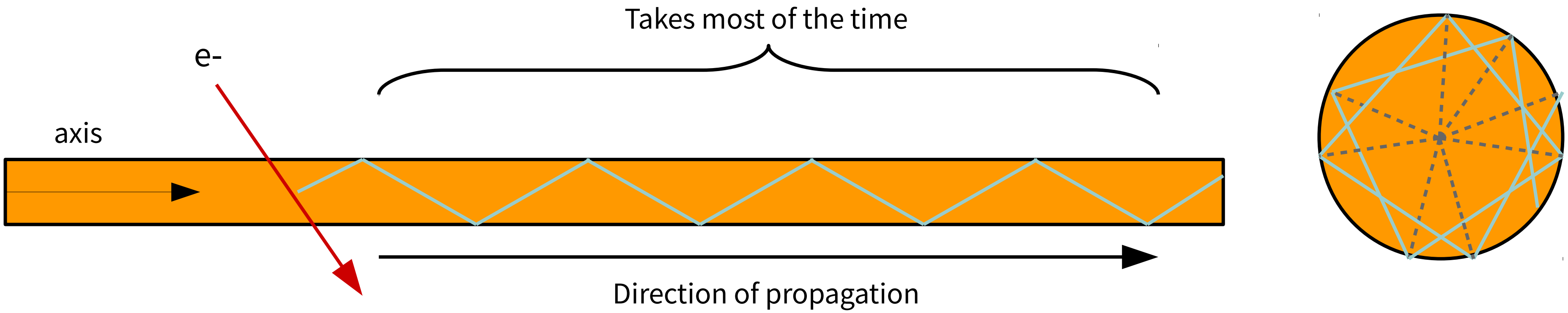
Postulates

Postulates for fast optical photon transportation

- The best way to achieve it is letting GEANT4 to do all necessary calculations, while avoiding introducing any unnecessary user code or external library.
- Most of the CPU consumption is caused by tracking intermediate optical photons between the generation & the moment when it escapes optical fibers.
- All processes of interest occur at the end of fibers except generation, total internal reflection, and absorption of optical photons.

Postulates from the characteristics of optical fibers

- An optical photon within numerical aperture will keep doing total internal reflection, unless it gets absorbed.
- An incident angle to the facet normal of the boundary & length of individual track of a optical photon will remain same through whole transportation.
- Core & cladding of fibers are circular shape with polished surface.

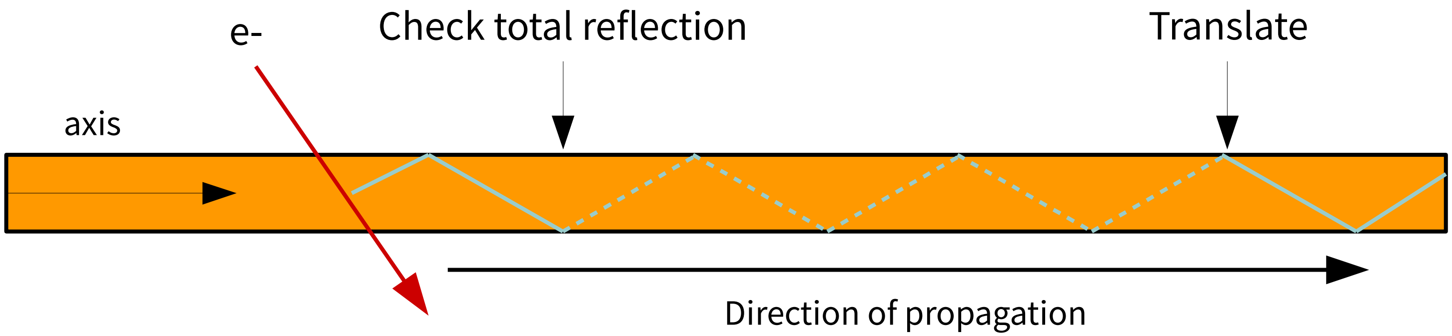


Main idea

Main idea for fast optical photon transportation

- Not all intermediate transportation step are needed for the simulation.
- Sufficient to ensure that the optical photon experiences total internal reflection a couple of times.
- Absorption probability can be calculated separately, once per optical photon.

- Thus intermediate steps can be skipped by
  - 1. Trigger the Fastsim model if corresponding track is resulted by total internal reflection.
  - 2. Estimate the target point of translation using track information.
  - 3. Check whether optical photon survives without getting absorbed until it reaches estimated point.
  - 4. Translate the track and set member variables using estimated information on-the-fly.



Trigger the Fastsim model

Safety checks before triggering the model & translating the track

- Translating a wrong track to a random position should be always avoided.
- Several safety checks have been made at G4VFastSimulationModel::ModelTrigger(const G4FastTrack&) [Github].
  - 1. A particle definition of the track should be optical photon.
  - 2. The track should not be a stopped track i.e. waiting to be killed.

    track→GetTrackLength() ≠ 0
  - 3. The track should experienced total internal reflection at least a couple of times [Github].

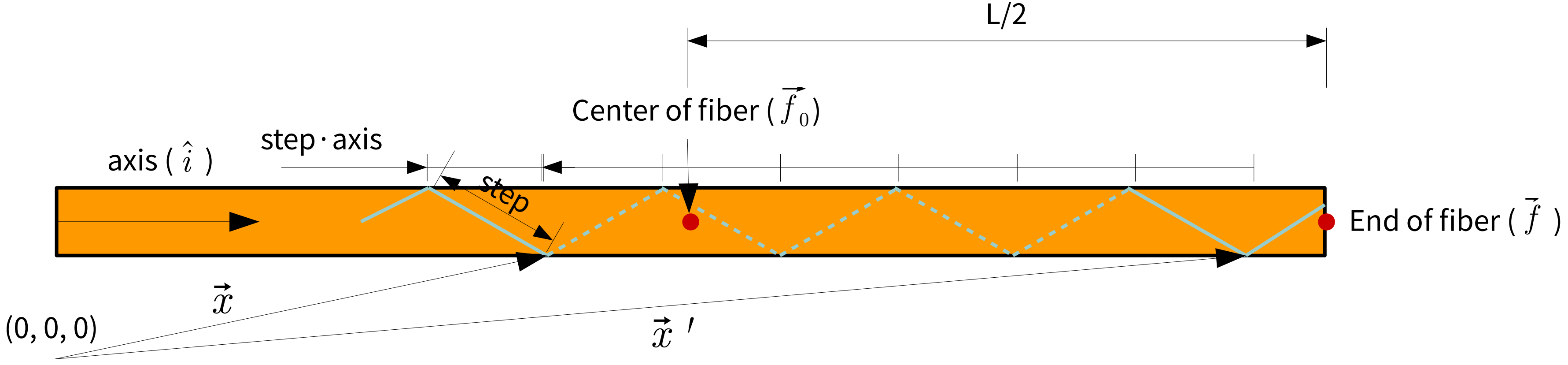
    G4OpBoundaryProcess→GetStatus() == G4OpBoundaryProcessStatus::TotalInternalReflection

- Above checks are critical to make sure not to crash GEANT4, or the result physically makes sense.
- Actions that have to be taken from the user side are
  - Making optical fibers G4Region.
  - Letting the Fastsim model know the material of fiber core & length of fibers.

Estimating the target point

Estimating the target point of translation for fast optical photon transportation

- Based on the postulate that the step length of individual track remains same throughout whole transportation, the point of translation can be estimated easily.
- $\vec{f} = \vec{f}_0 + L/2\,\hat{i}$
- $\vec{f}_0$ & $\hat{i}$ can be obtained by G4TouchableHandle (touchable→GetHistory()→GetTopTransform().Inverse().TransformPoint/Axis(x, y, z))
- # of expected reflections = std::floor($\frac{(\vec{f}-\vec{x})\cdot\hat{i}}{\overrightarrow{step}\cdot\hat{i}}$)
- $\vec{x}\,' = \vec{x} + (\overrightarrow{step}\cdot\hat{i})\,\hat{i} \times$ # of expected reflections
- $t\,' = t$ + step/velocity $\times$ # of expected reflections
- User can require n times more total internal reflections by using (# of expected reflections – n).
  - n = 2 is sufficient to make sure everything works.
- If # of expected reflections < n, do nothing.



Checking absorption

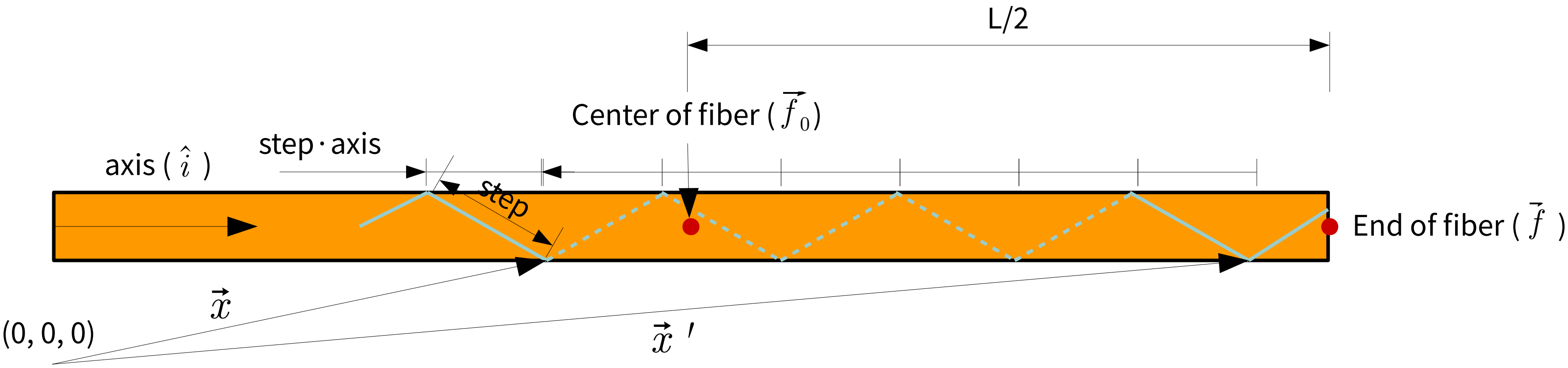
Checking absorption probability of an optical photon

- Skipping intermediate tracking of optical photon forces to check absorption probability by the model.
- In GEANT4, interaction probability with a matter of a particle is given as a ‘lifetime’ as a unit of interaction length.

  i.e., # of interaction length left = -std::log(G4UniformRand())
- The particle is killed when the travel length exceeds # of interaction length left.

- For a fast transported optical photon, absorption can be checked via
  - # of expected reflections × steplength / attenuation length > # of interaction length left
- Attenuation length of a material can be accessed using G4MaterialPropertyTable.

```
matPropTable→GetProperty(kABSLENGTH)→Value( momentum )
```



Translating the stack

Translating the track

- Once the target point is estimated & optical photon survives absorption check, translate the track using G4VFastSimulationModel::DoIt(const G4FastTrack&, G4FastStep&) [Github].
- Set member variables of the G4FastStep using set(propose) functions,

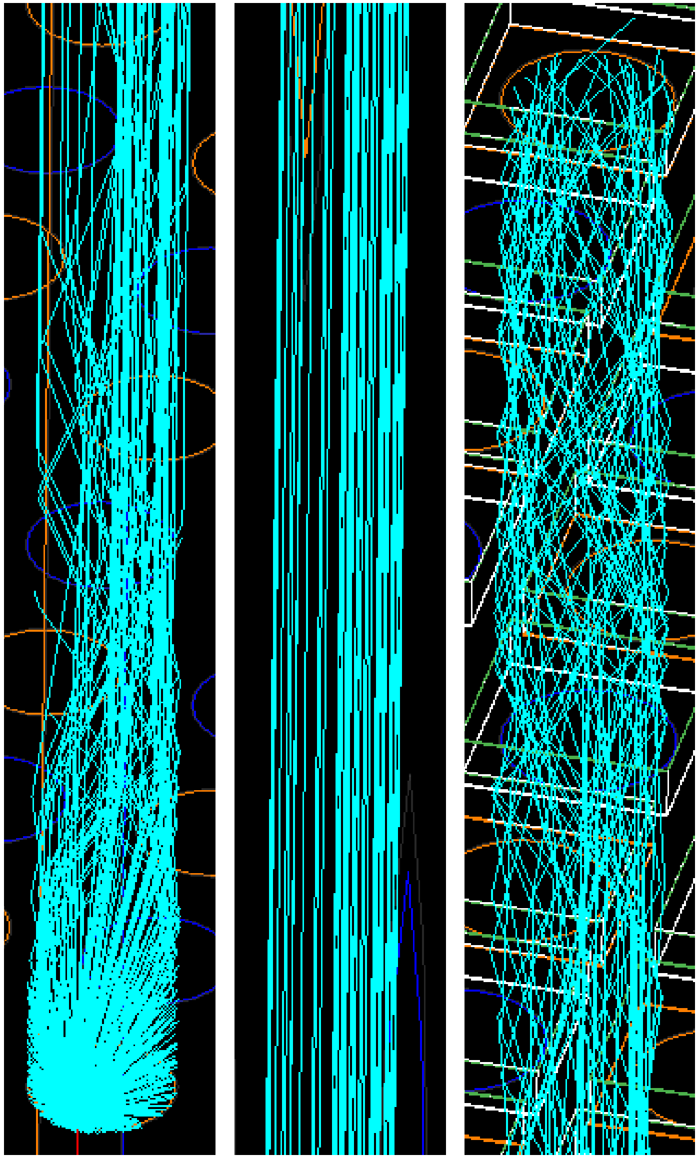
  e.g. position, global time, kinetic energy, momentum direction, and polarization.

- Position, global time are set based on the estimated point of translation.
- Other member variables are copy of the original track.

Demonstration & Validation

Demonstration of fast optical photon transportation

- Visualized translating tracks of optical photons from scintillation process to the end of the scintillation fiber.
- A 100 keV electron is shot to a scintillation fiber.
- The idea of translating a track using G4VFastSimulationModel works.

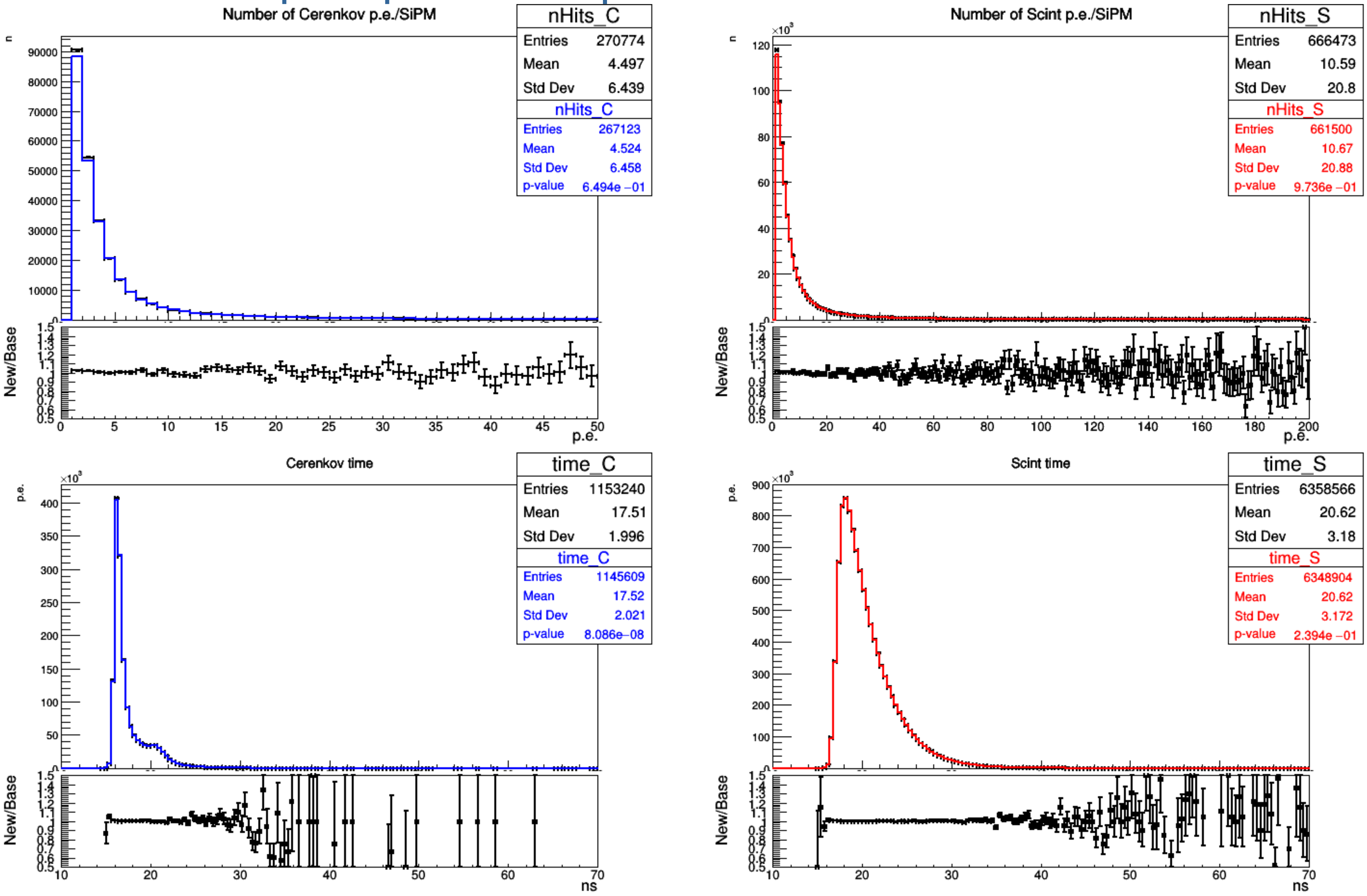


Validation of fast optical photon transportation

- To validate that it reproduces the result of full tracking well at the energy scale of interest, compared the distribution of optical photons detected at sensitive detector (SiPM) using 1000 of 20 GeV electron events.
- Distributions of interest, for each channel (S & C)
  - # of detected optical photons / SiPM
  - # of detected optical photons vs wavelength
  - # of detected optical photons vs global time

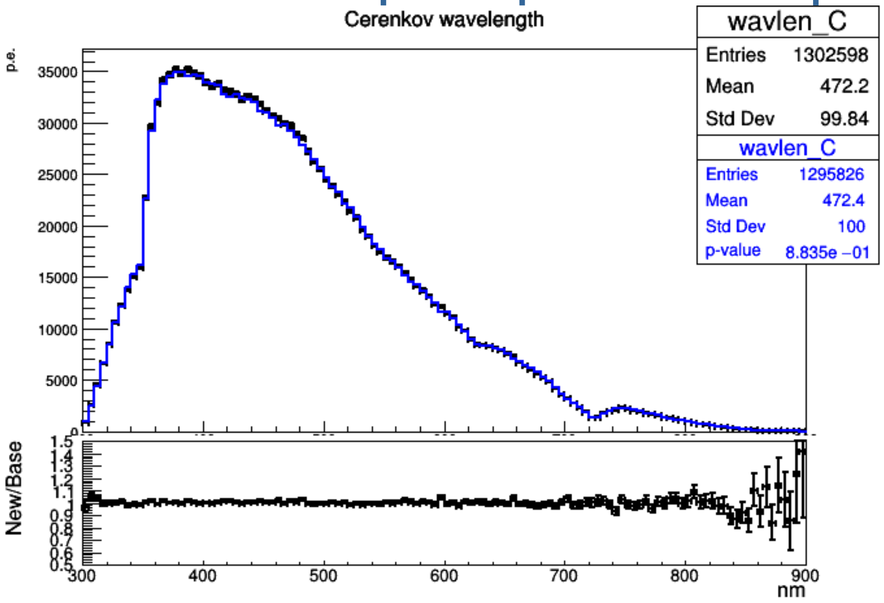
Fast vs full tracking

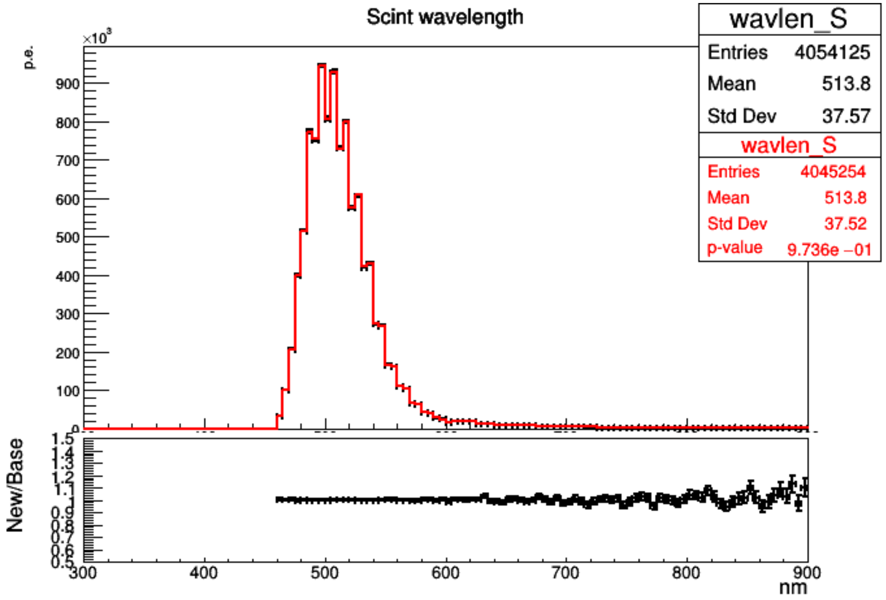
Validation of fast optical photon transportation



Fast vs full tracking

Validation of fast optical photon transportation





- Fast optical photon transportation nicely reproduces the distributions of full tracking for the number & wavelength of detected optical photons.
- Also it gives decent results for timing of detected optical photons.

CPU consumption improvement

Improvement in CPU consumption using fast optical photon transportation

- Gain in computing side by skipping intermediate total internal reflections is tremendous.
- It takes 4.62 ± 1.17 min in average to produce an event (tested with 1000 of 20 GeV electron events).
- While it was 304 ± 88 min when using full tracking with the same server.

- Almost ~ 70 times faster than full tracking!
- Attractive results considering the details kept for the simulation of dual-readout calorimeter.

Summary

Dual-readout calorimeter & optical physics

- Dual-readout calorimeter utilizes both Cerenkov & scintillation processes.
- Simulation of light attenuation, transmission efficiency, numerical aperture are essential.

Fast optical photon transportation

- Full tracking of optical photon is not affordable in computing point of view.
- An optical photon within fiber can be transported fast based on several postulates.
- The idea is implemented using standalone GEANT4 & minimal code on the G4VFastSimulationModel.
- Fast optical photon transportation gives decent results with 70 times boost of computing speed.
- Fastsim model of optical fiber can be applied to the more generic case potentially if it satisfies the postulates.

Asking for comments

- Impression to the idea, things we might be missing, technically alarming points, more checks wish to see, etc.
- We kindly ask for your comments or advices.

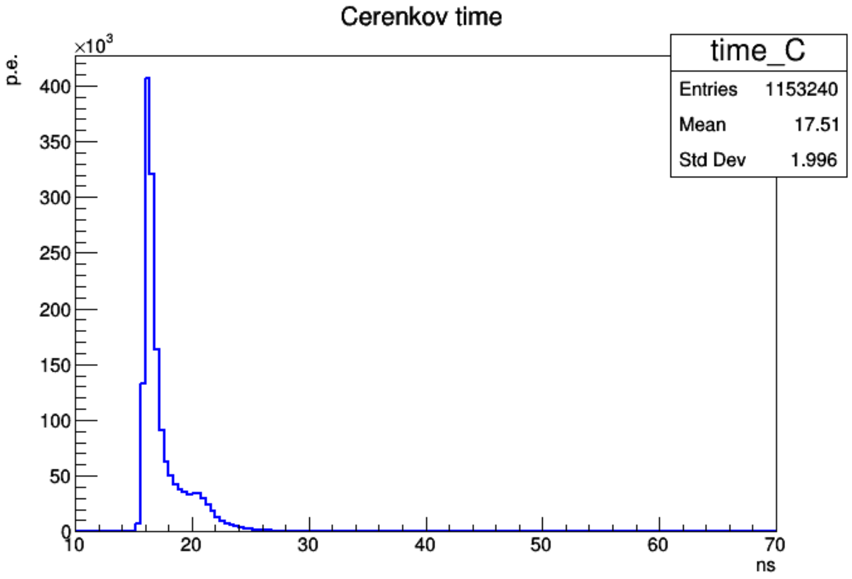
Thank you!

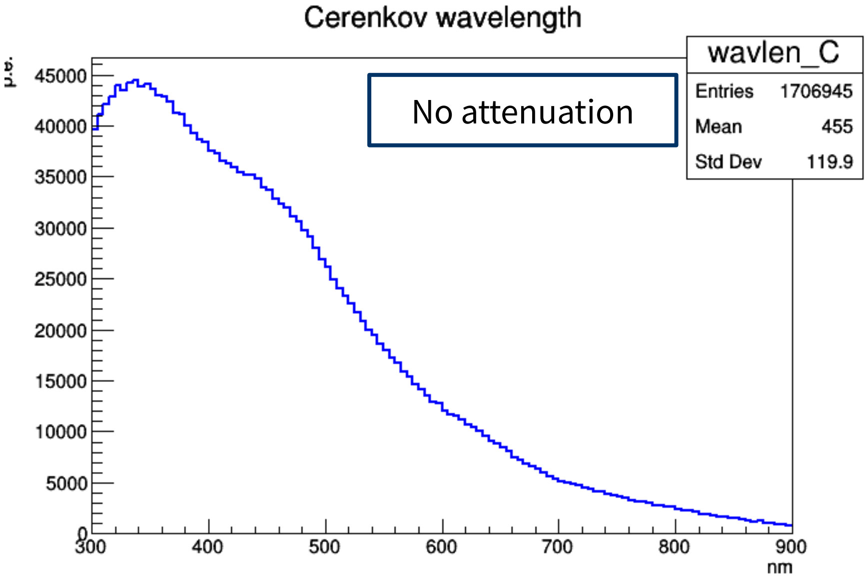
Backups

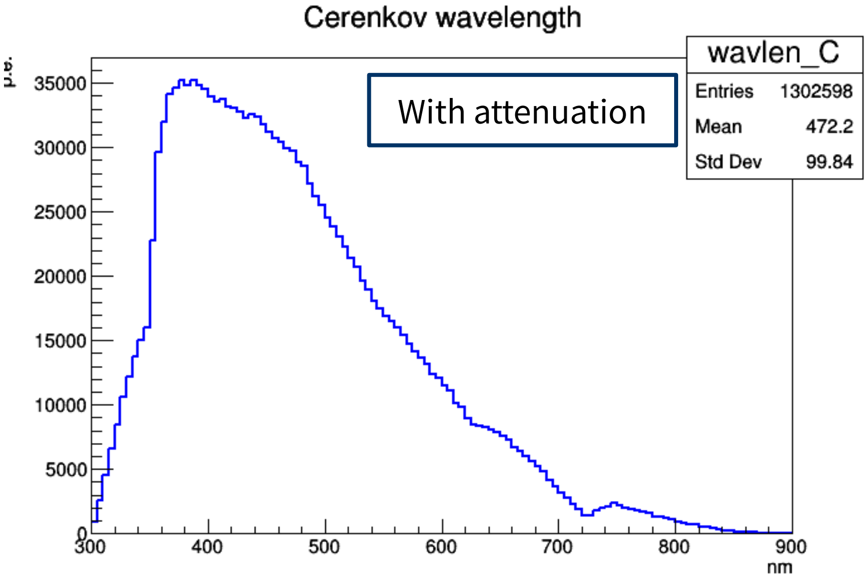
Cerenkov channel

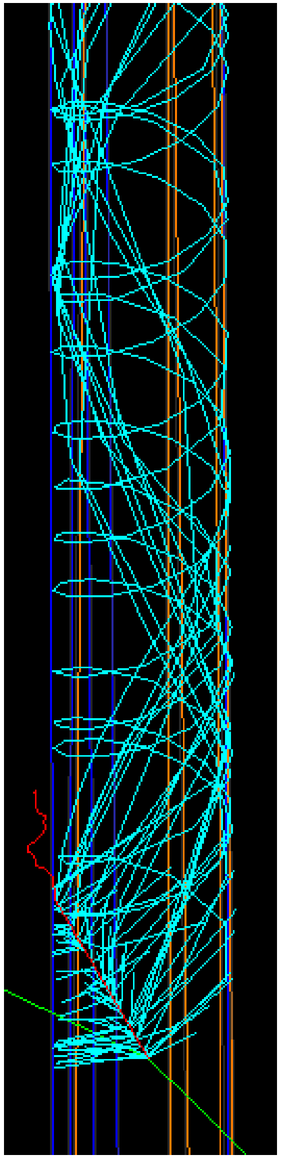
Characteristics of Cerenkov channel

- There are two components within numerical aperture of Cerenkov fiber; fast & slow.
- Fast component gives larger yield while slow component gives smaller.
- Dips on the distribution of Cerenkov wavelength are caused by the attenuation of fibers.
- Detection efficiency of SiPM gives extra minor contribution.





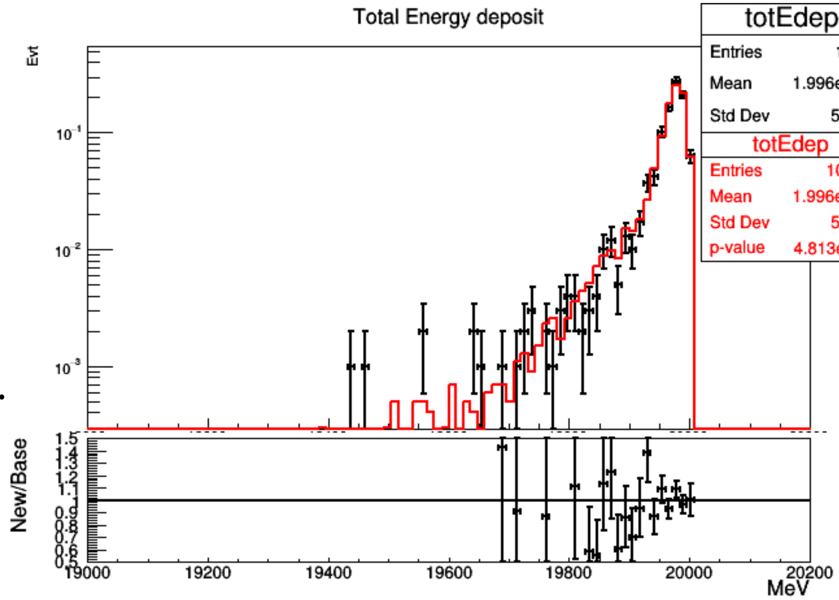


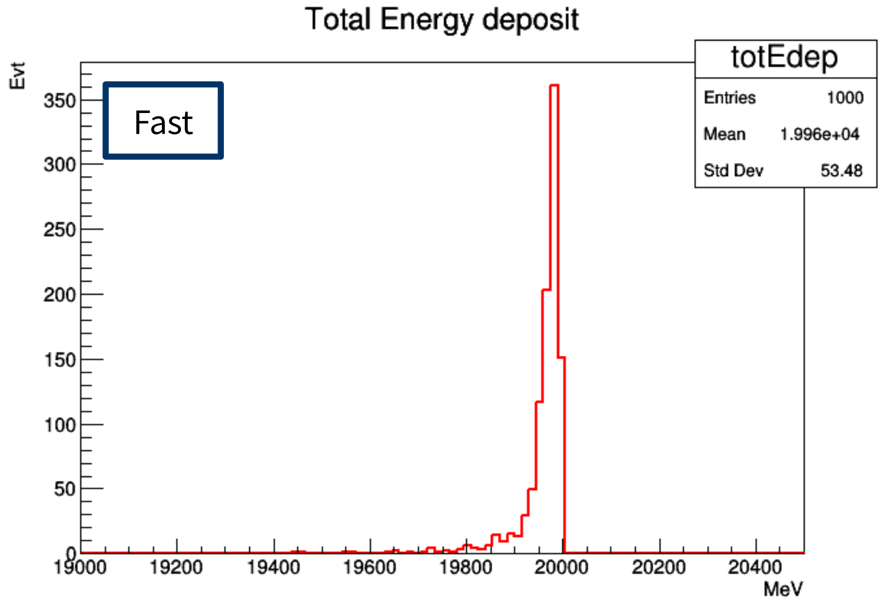


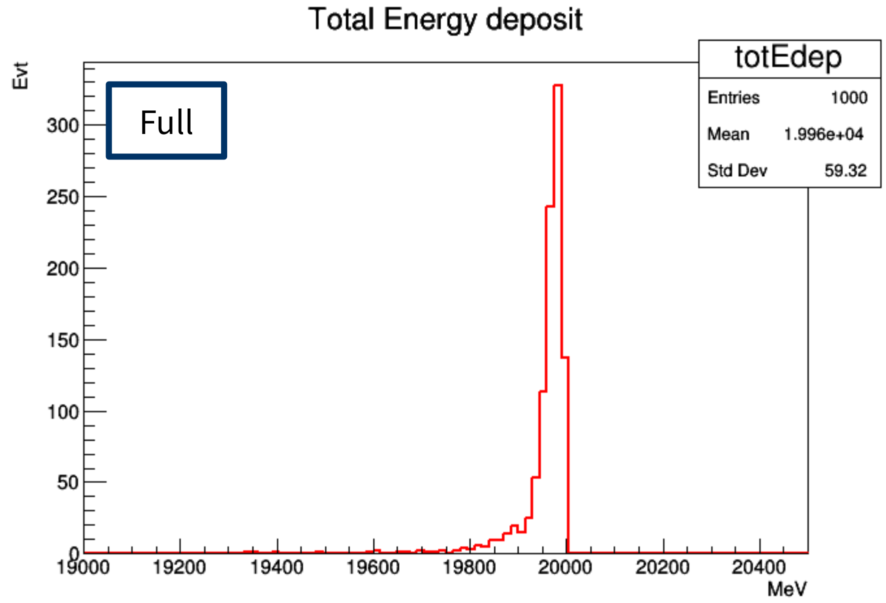
Energy deposits

Validation of fast transportation

- Total energy deposits shows no noticeable difference between fast & full tracking of optical photons, considering the # of events simulated.
- Total energy deposit from the fast optical transported result shows no significant difference when it is compared to the result with optical physics turned-off.







Light attenuation correction

Light attenuation correction

- π+ can go deep inside tower compared to e-.
- 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

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

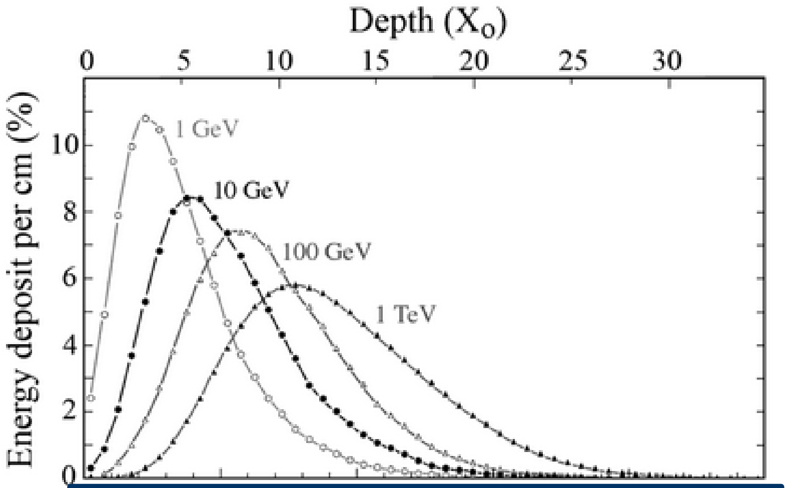
TOF of π+ in vacuum/tower

$$t_v = \frac{2.0\,m - x}{v}$$

Propagation time of optical photons

$$t_{max} = t_v + t_c = \frac{2.0 - x}{v} + \frac{x}{0.3\,m/ns} + \frac{1.8\,m}{0.3\,m/ns}$$

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.
- Estimate v using e- evts & plug-in v to estimate x for π+ evts

$$v = \frac{2.0\,m - 0.1368\,m}{t_{max} - \frac{0.1368\,m}{0.3\,m/ns} - \frac{1.8\,m}{0.3\,m/ns}}$$

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

- Estimating x can be done via either S channel or C channel.

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

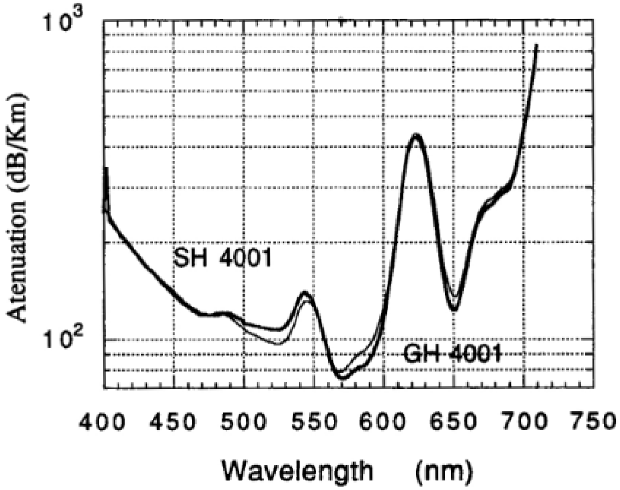
Material properties

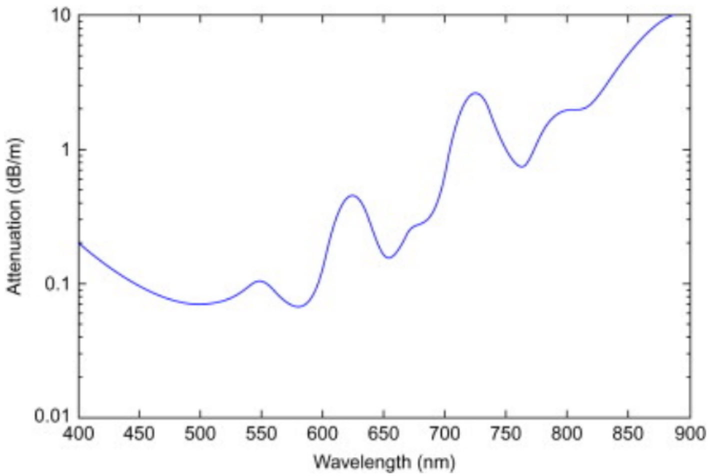
Photon energy

- 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





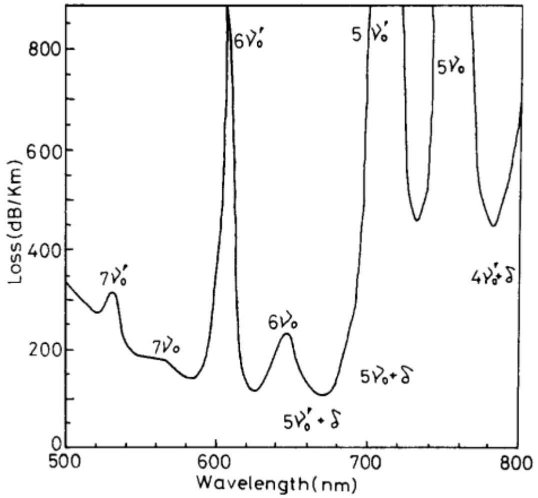
Material properties

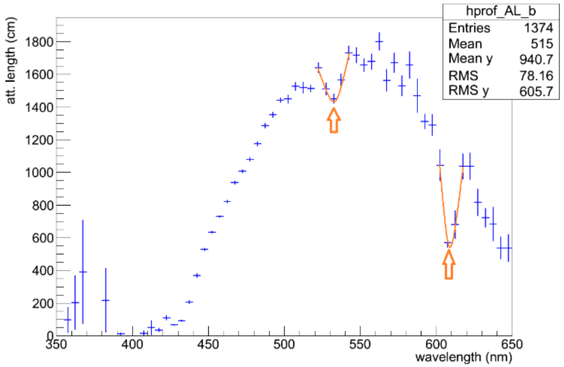
Fluorinated polymer

- 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)

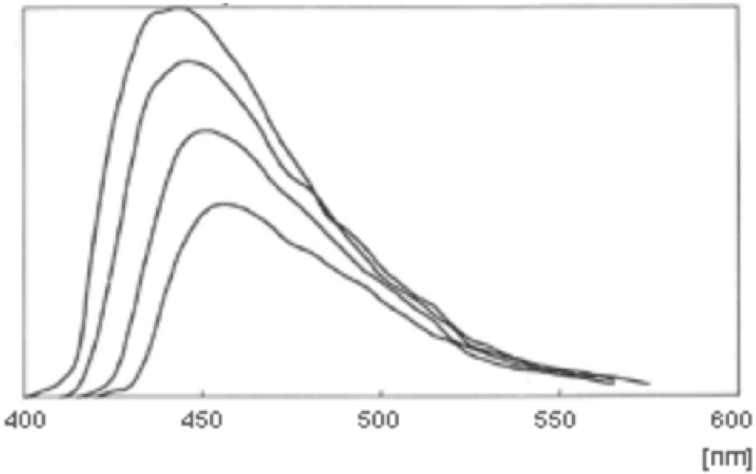




Material properties

Polystyrene

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

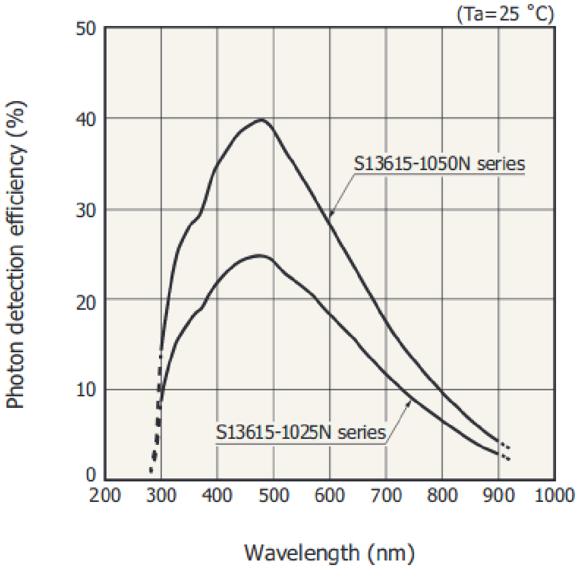


Glass, Air

- 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

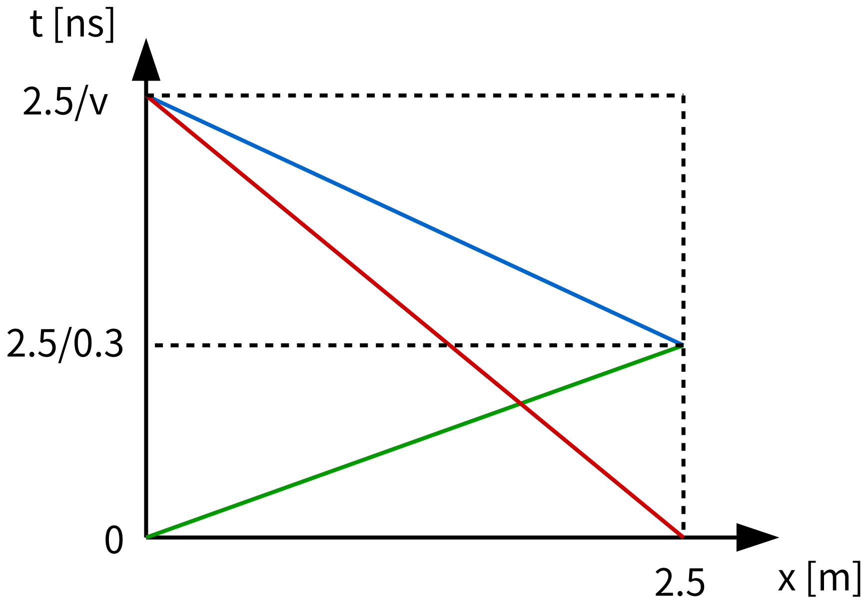
$$t_v = \frac{2.5\,m - x}{v}$$

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

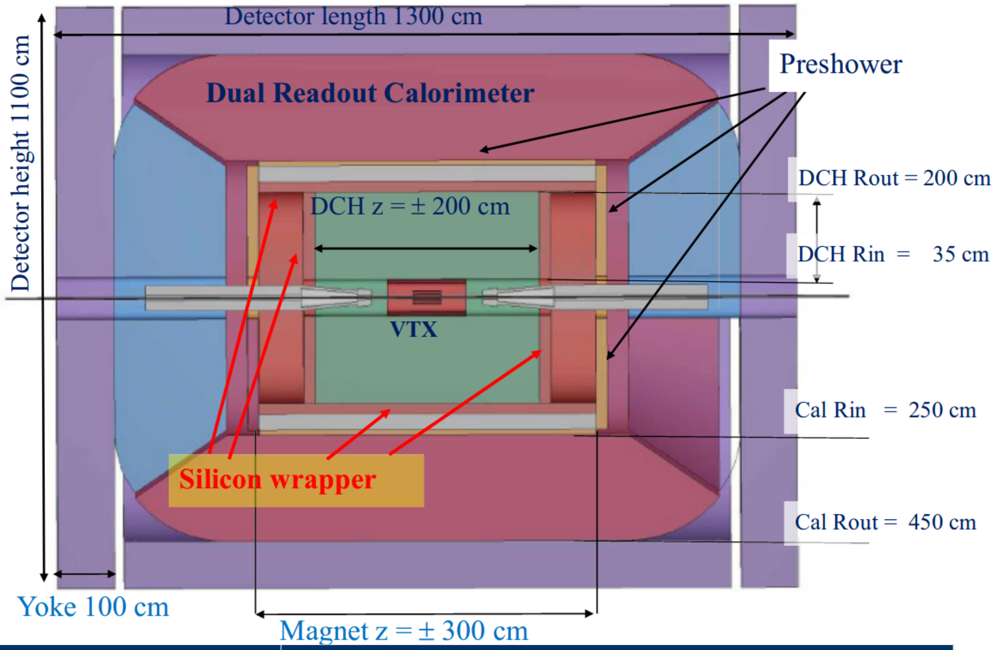
- The detection time of optical photons can be represented as the sum of TOF of π+ & propagation time of optical photons within fibers.
- Average velocity of optical photons can be estimated by exploiting well-known longitudinal profile of EM showers.
- Note: TOF of π+ in vacuum is ignored in the graph.



IDEA detector

IDEA detector concept

- At FCC-ee & CEPC, there will be two types of detectors based on the two different concepts for two IPs.
- IDEA detector is being discussed in conceptual design report (CDR) of BOTH FCC-ee & CEPC, as a detector located at an IP of FCC-ee and CEPC.
- Dual-readout calorimeter is a main calorimeter of IDEA detector which detects both EM & hadronic components.



CLD detector (FCC-ee)	Baseline detector (CEPC)	IDEA detector (FCC-ee & CEPC)
Silicon pixel vertex detector	Silicon pixel vertex detector	Silicon pixel vertex detector
Silicon tracker (inner & outer)	Silicon inner tracker	Drift chamber tracker
	TPC surrounded by external silicon tracker	Passive material radiator with MPGD layer
Si-W ECAL	Si-W ECAL	2 T solenoid
Scintillator-steel HCAL	GRPC HCAL	**Dual-readout calorimeter**
2 T solenoid	3 T solenoid	
RPC chambers with a steel yoke interleaved	Flux return yoke embedded with a muon detector	Muon chambers embedded in the magnet yoke

Title

Text

$$formula$$