DRC implementation in Key4hep

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DRC repository

Standalone DRC

- Currently, all components of DRC simulation belong to the single repository [HEP-FCC/dual-readout]
  - Geometry (Detector)
  - Full simulation (DRsim)
  - Digitization (DRdigi)
  - Reconstruction (DRreco)
  - Analysis (analysis)

Key4hep repositories

- Each component is scattered over multiple repositories
- Geometry [key4hep/k4geo]
  or [HEP-FCC/FCCDetectors]
- Full simulation [HEP-FCC/k4SimGeant4]
- Reconstruction [HEP-FCC/k4RecCalorimeter]
- Analysis [HEP-FCC/FCCAnalyses] (based on RdataFrame)
- Configurations [HEP-FCC/FCCSW]

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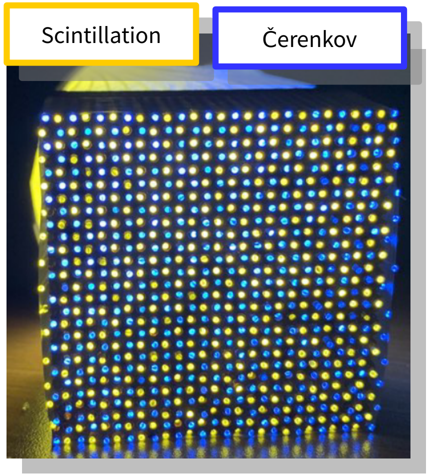
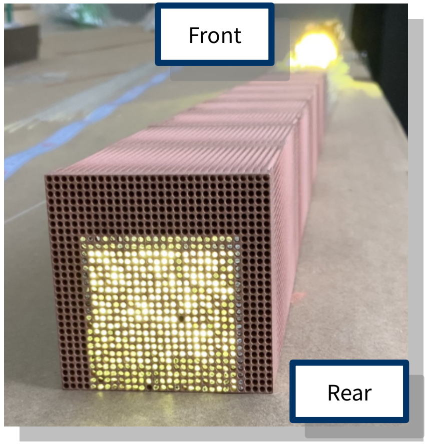
Dual-readout calorimeter

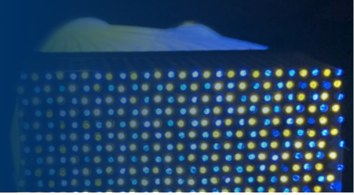
- Longitudinally unsegmented fiber-sampling calorimeter
  → measure both EM & hadronic components with two different channels in h/e
  → excellent energy resolution for hadrons via event-by-event correction

- Projective geometry with a uniform sampling fraction
  → fine unit structure with high granularity
  → more fibers in the rear than the front

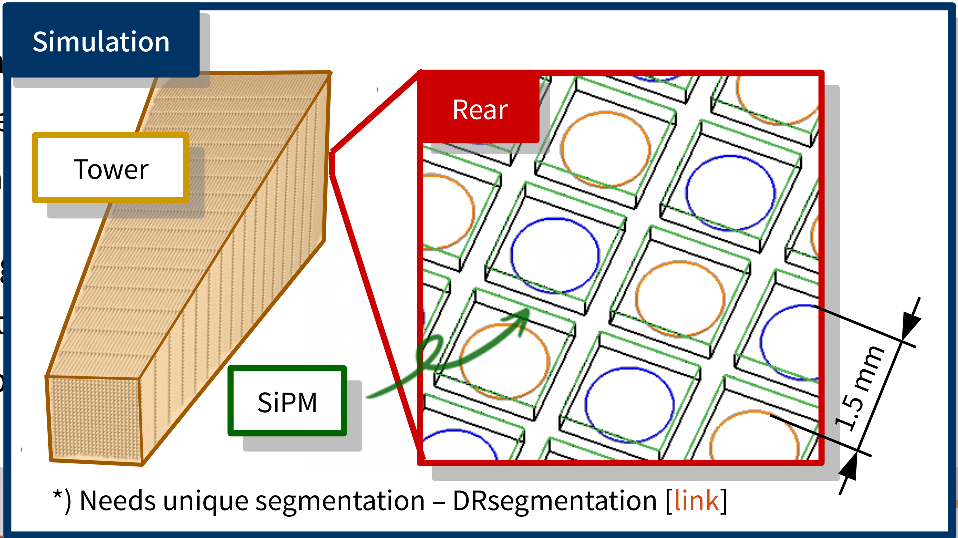


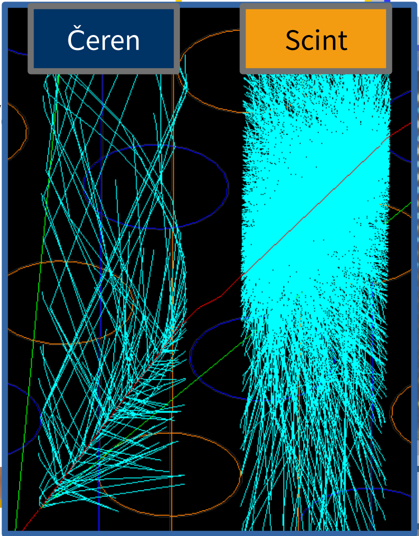


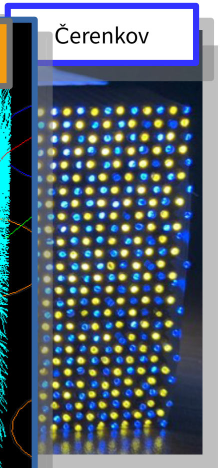
Dual-readout calorimeter

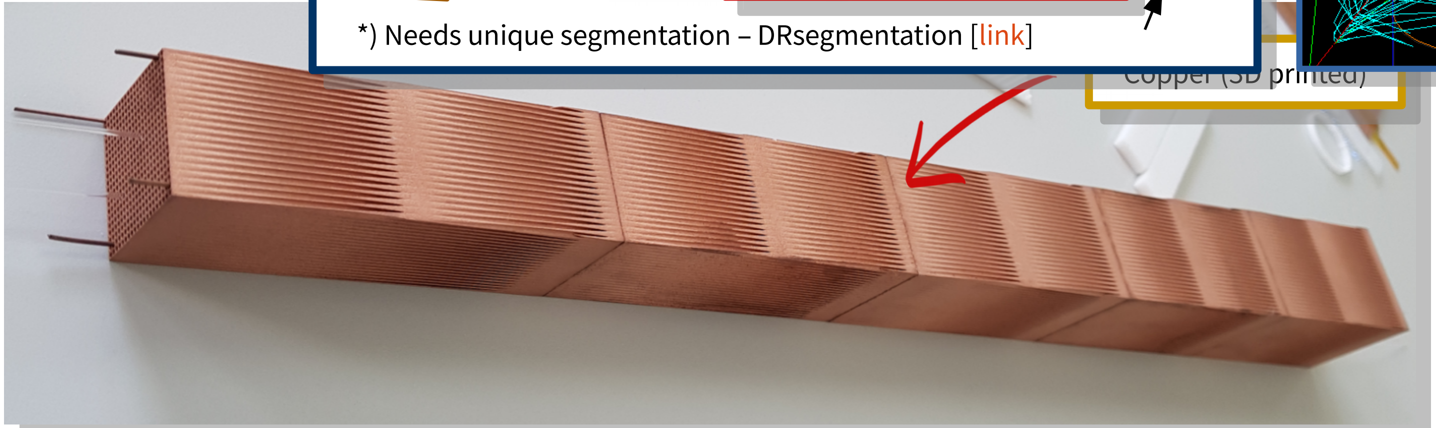


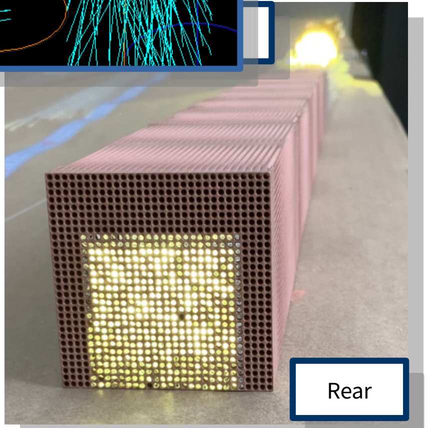
- Longitudin
  → measure h/
  → excellen
- Projective
  → fine unit
  → more fib











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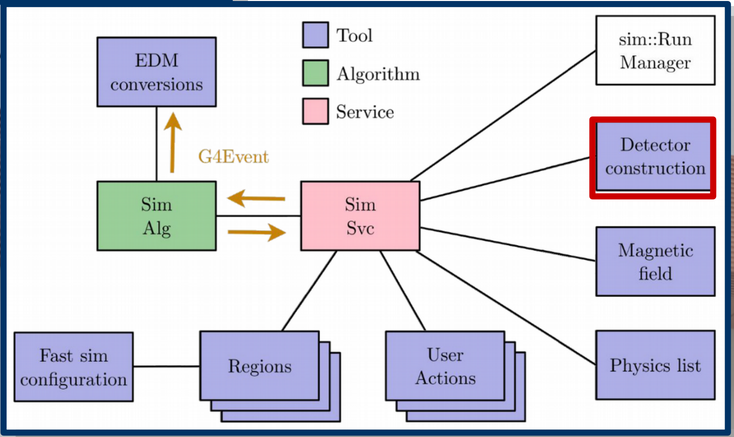
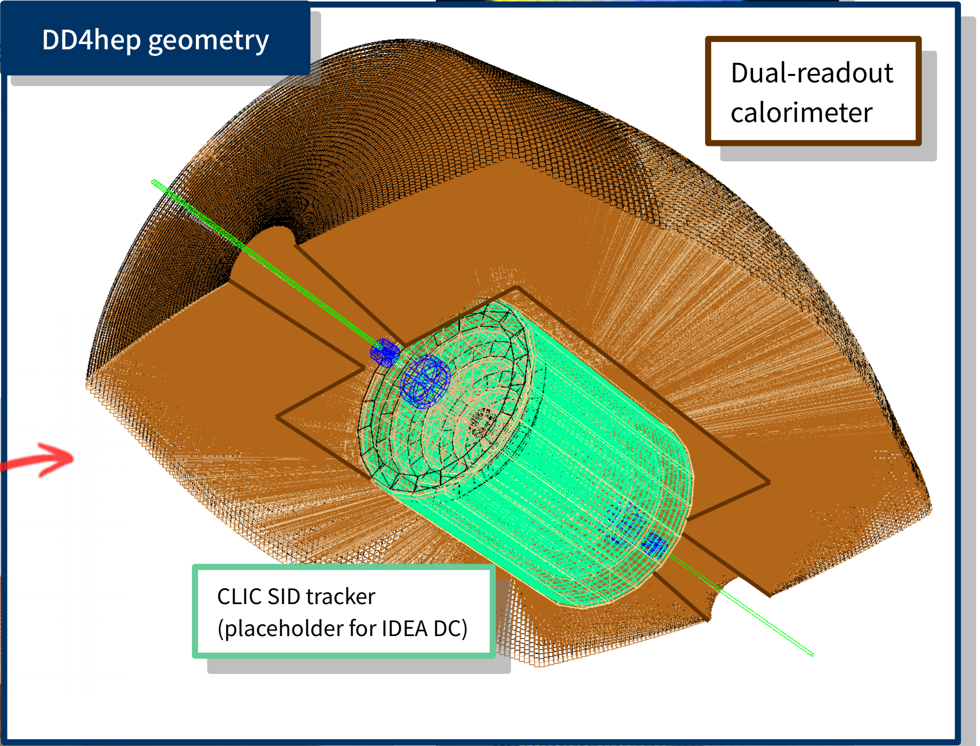
k4SimGeant4

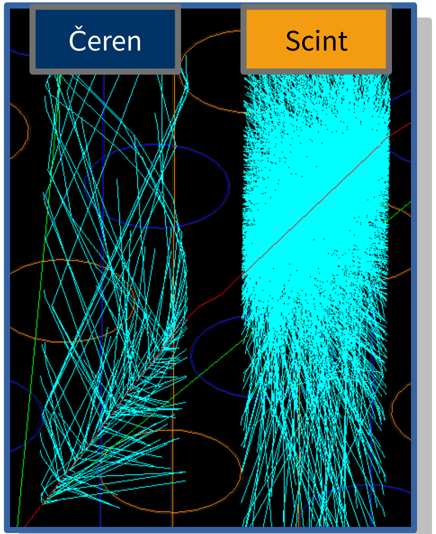


DD4hep geometry

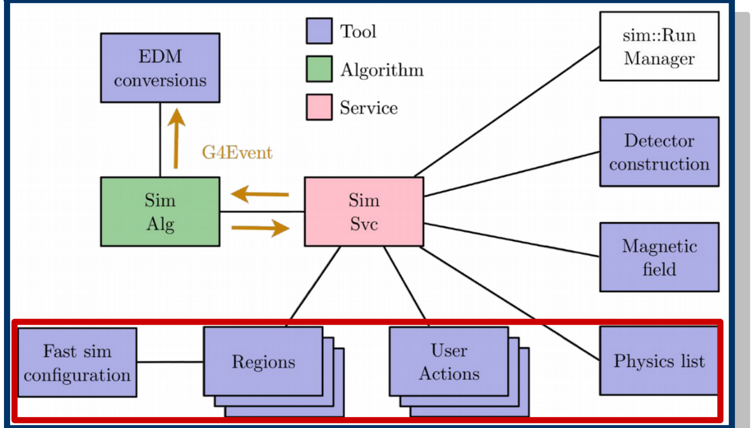


Optical physics simulation

- Timing is crucial for longitudinally unsegmented calorimeter to measure shower depth
- Optical physics gives detailed timing information, but at a high cost of CPU
- Incorporating modularized G4 Physics Lists to achieve detail & speed simultaneously
  - FTFP_BERT (full simulation)
    - + GEANT4 optical physics [code] (inactive in default G4)
    - + Fastsim module applied to optical photons [link][code]



k4SimGeant4



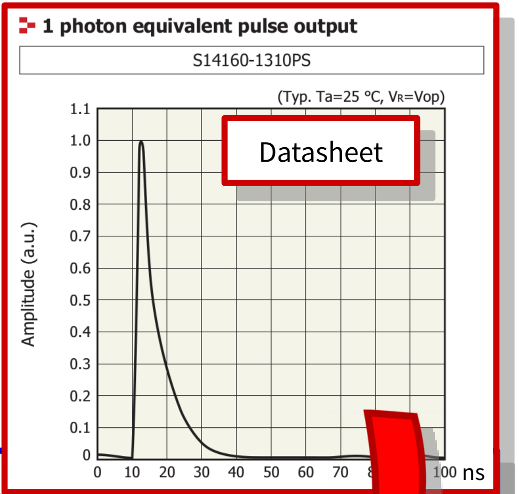
k4run configuration

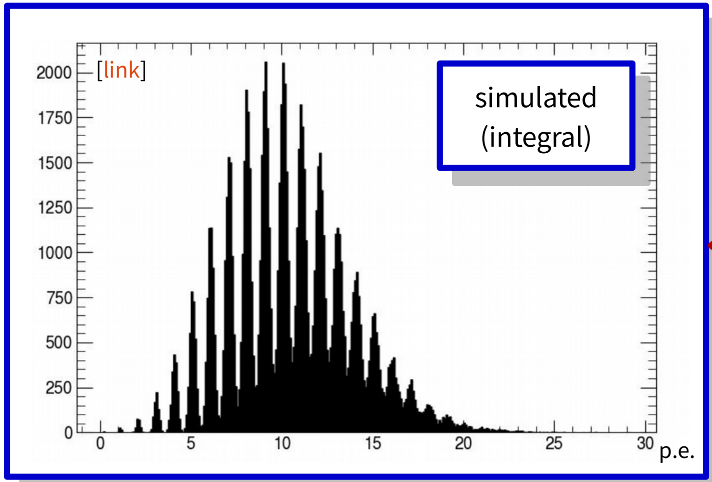
```
regionTool = SimG4FastSimOpFiberRegion("fastfiber")
opticalPhysicsTool = SimG4OpticalPhysicsList("opticalPhysics", fullphysics="SimG4FtfpBert")
physicslistTool = SimG4FastSimPhysicsList("Physics", fullphysics=opticalPhysicsTool)

from Configurables import SimG4DRcaloActions
actionTool = SimG4DRcaloActions("SimG4DRcaloActions")

# Name of the tool in GAUDI is "XX/YY" where XX is the tool class name and YY is the given name
geantservice = SimG4Svc("SimG4Svc",
  physicslist = physicslistTool,
  regions = ["SimG4FastSimOpFiberRegion/fastfiber"],
  actions = actionTool
)
```

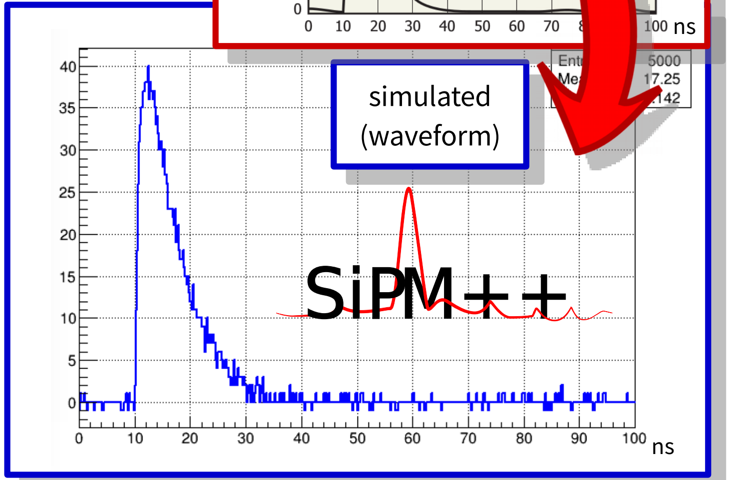
SiPM emulation

Simulating SiPM response with SimSiPM

- SiPM is a major candidate for the photodetector
  → SiPM simulation library is developed [link][FCCSW meeting]
- Parameterized inputs from the datasheet
  → Dark counts, crosstalk, afterpulses, saturation, noise, …
- Implemented in the simulation with Hamamatsu S14160-1310PS

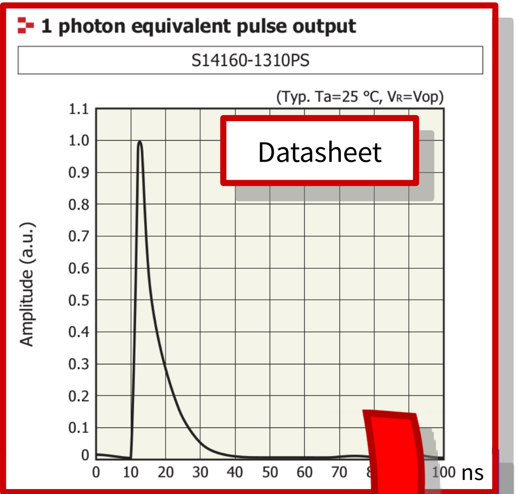


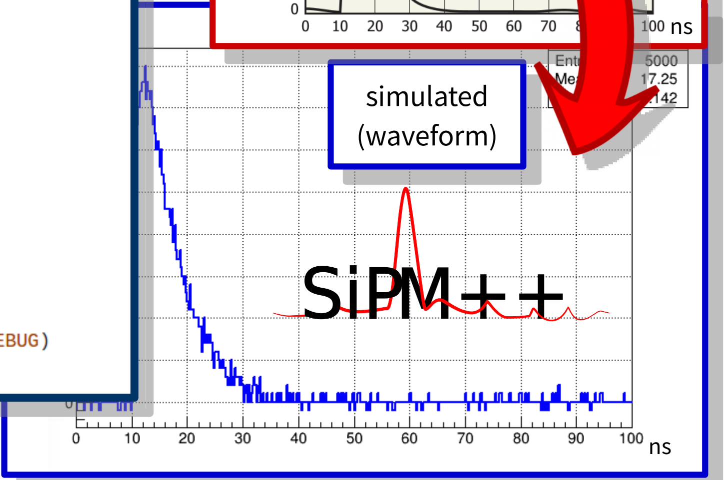




SiPM emulation

```
from Configurables import PodioInput
podioinput = PodioInput("PodioInput", collections = ["RawTimeStructs", "RawCalorimeterHits",

from Configurables import DigiSiPM
digi = DigiSiPM("DigiSiPM",
  # Hamamatsu S13615-1025
  signalLength = 500.,
  SiPMsize = 1.,
  DCR = 100e3,
  Xtalk = 0.03,
  sampling = 0.1,
  recovery = 20.,
  cellpitch = 25.,
  afterpulse = 0.03,
  falltimeFast = 50.,
  risetime = 1.,
  SNR = 30.,
  gateLength = 240.,
  OutputLevel = DEBUG
)

from Configurables import PodioOutput
podiooutput = PodioOutput("PodioOutput", filename = "digi.root", OutputLevel = DEBUG)
podiooutput.outputCommands = ["keep *"]
```





Summary

DRC implementation in Key4hep

- The DRC is implemented in DD4hep
  → its projective geometry requires an unique DDsegmentation module

- Full simulation of DRC utilizes a detailed simulation of optical physics
  → developed fast simulation module to ease intense CPU usage

- Emulation of SiPM is implemented in Gaudi module
  → processing signal waveform is vital for digitization

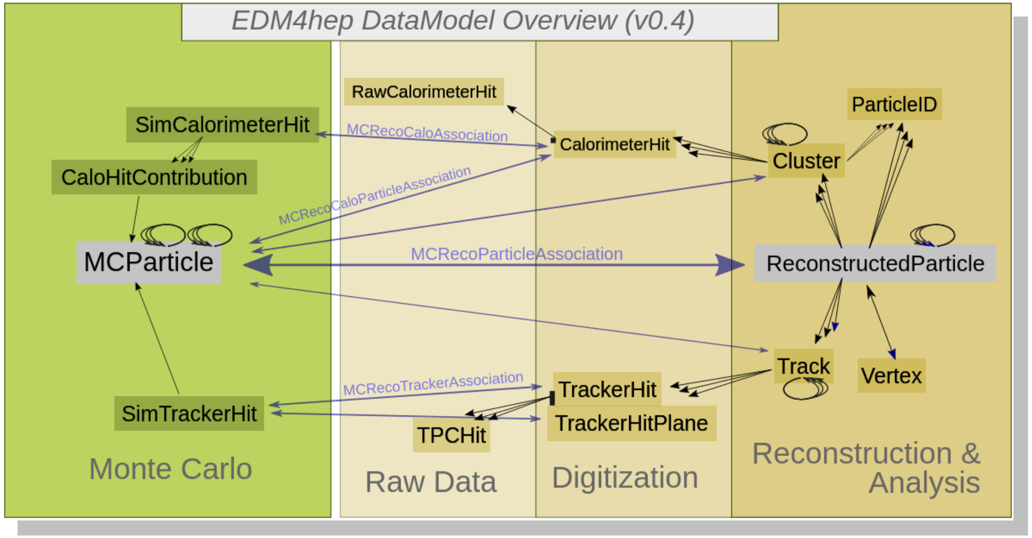
Backups

EDM4hep

Migration to EDM4hep

- EDM4hep is a common EDM that can be used by all communities in the Key4hep project
  → aim to boost synergy between associated SW (simulation, clustering, event display, .etc)

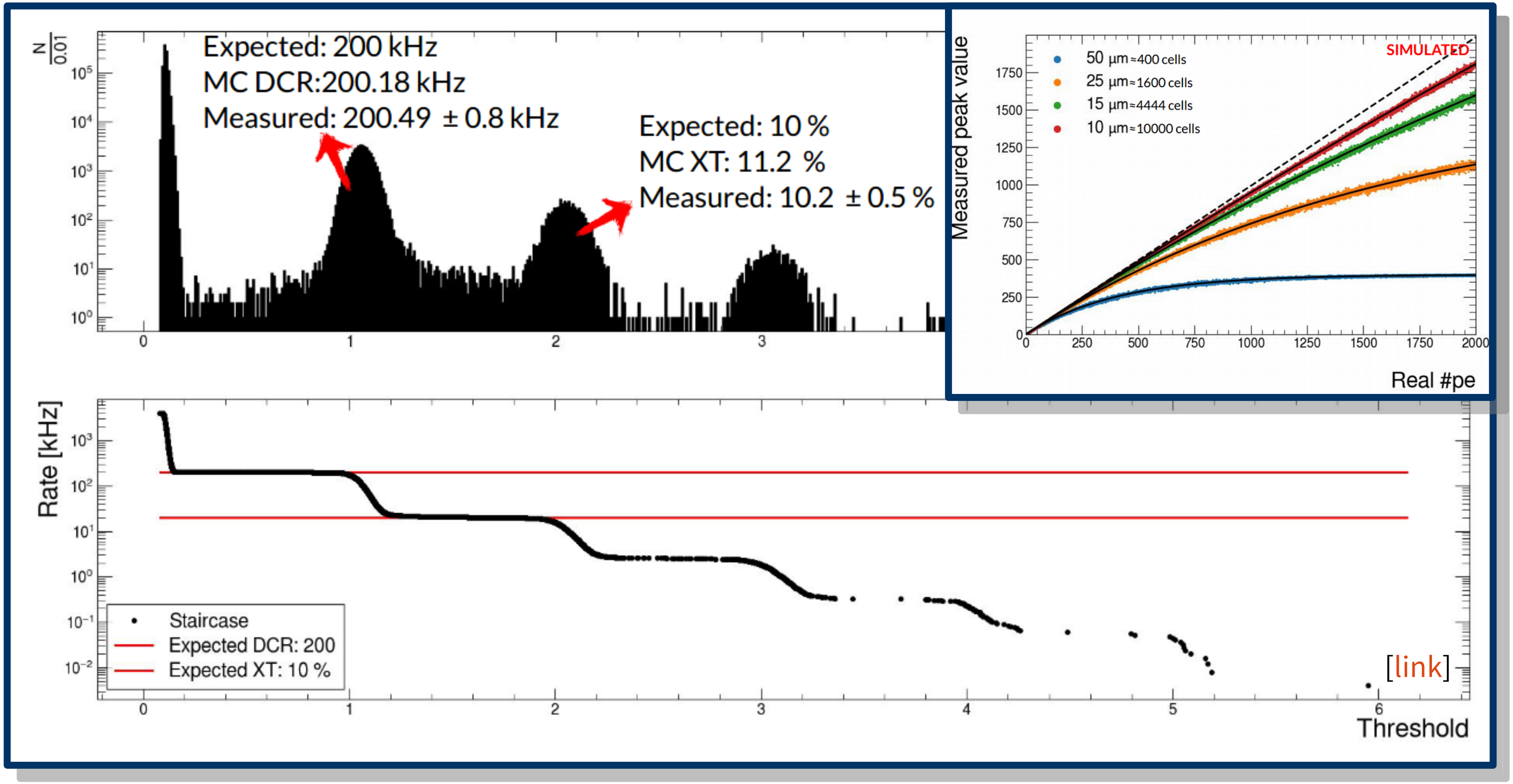
- Interfaced G4Event/G4VHit of the DRC simulation to EDM4hep calorimeter hits



Data	EDM4hep class
MC truth (Edep)	edm4hep::SimCalorimeterHit
Readout (# of p.e.)	edm4hep::RawCalorimeterHit
Digitization (# of ADC)	edm4hep::RawCalorimeterHit
Reco (2D/3D)	edm4hep::CalorimeterHit

```
from Configurables import SimG4SaveDRcaloHits, SimG4SaveDRcaloMCTruth
saveDRcaloTool = SimG4SaveDRcaloHits("saveDRcaloTool", readoutNames = ["DRcaloSiPMreadout"])
saveMCTruthTool = SimG4SaveDRcaloMCTruth("saveMCTruthTool") # need SimG4DRcaloActions

geantsim = SimG4Alg("SimG4Alg",
  outputs = [
    "SimG4SaveDRcaloHits/saveDRcaloTool",       → # of p.e.
    "SimG4SaveDRcaloMCTruth/saveMCTruthTool"    → MC truth Edep
  ],
  eventProvider = edmConverter
)
```

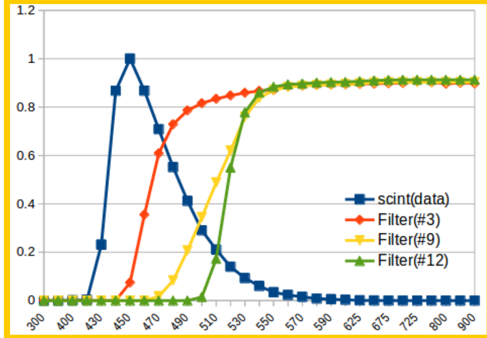
SiPM emulation



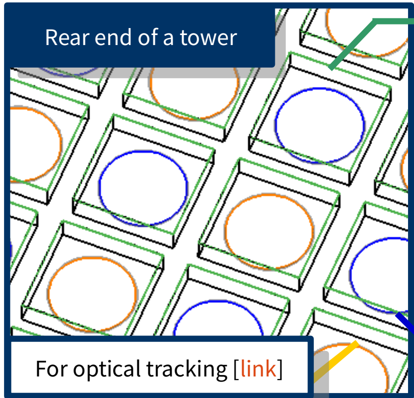
[link]

Optical properties in simulation

Transmission eff of filters

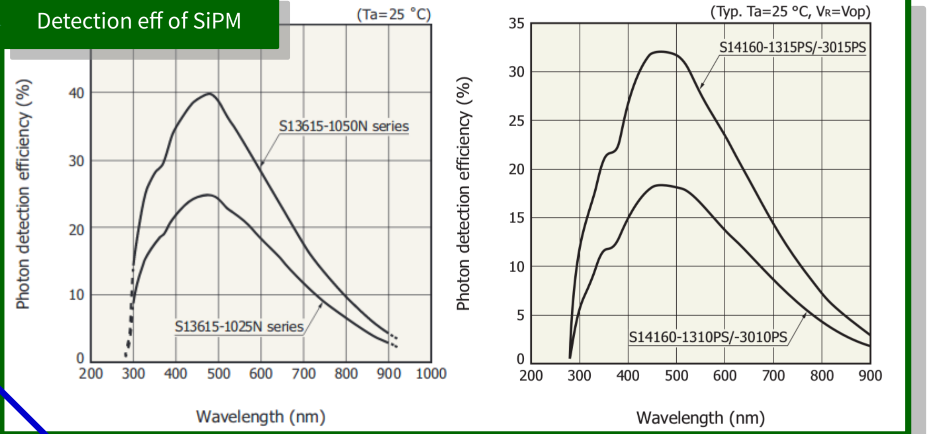


Rear end of a tower



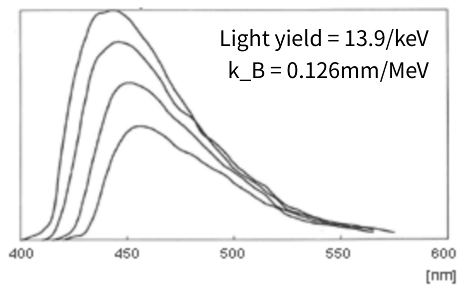
For optical tracking [link]

Detection eff of SiPM



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

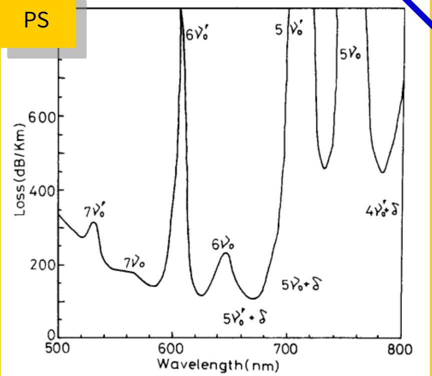
Scintillation spectra of PS



Light yield = 13.9/keV
k_B = 0.126mm/MeV

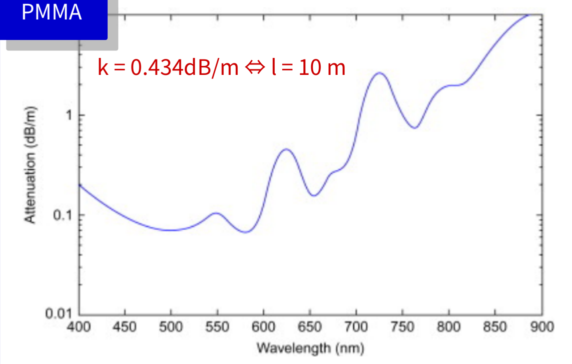
Attenuation loss of Polystyrene (PS) & PMMA

PS



PMMA

k = 0.434dB/m ⇔ l = 10 m

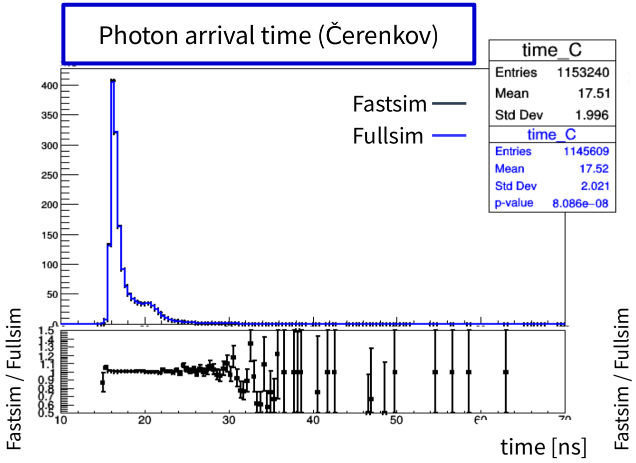


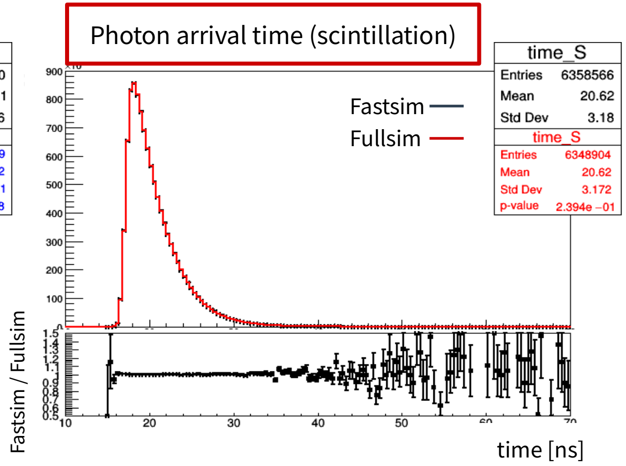
Speeding up optical photon tracking

Fast optical photon tracking

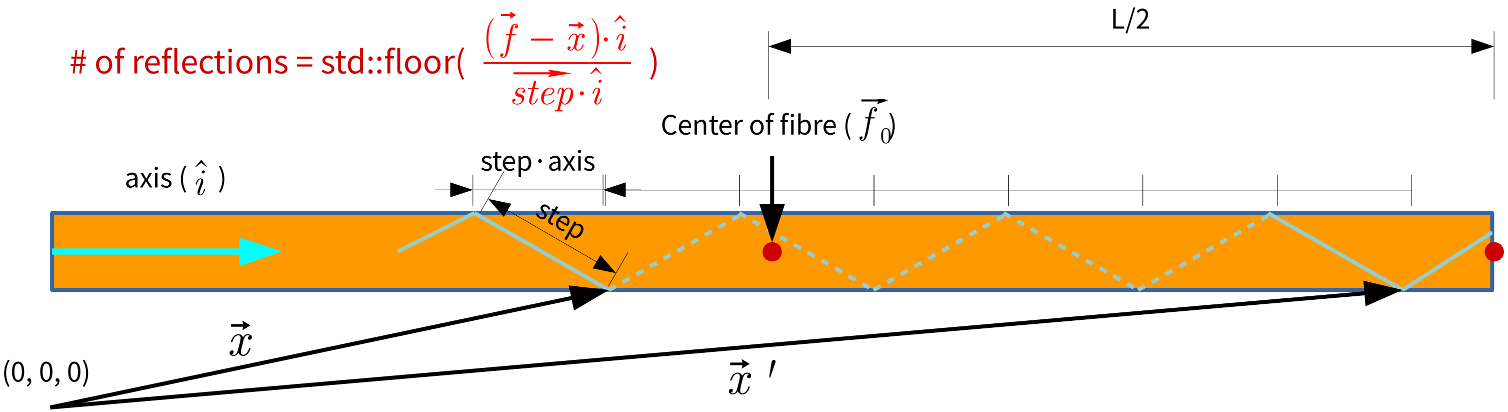
- Tracking optical photons is necessary, however it dominates CPU consumption
- Optical photons inside fibers can be tracked efficiently, by skipping intermediate steps

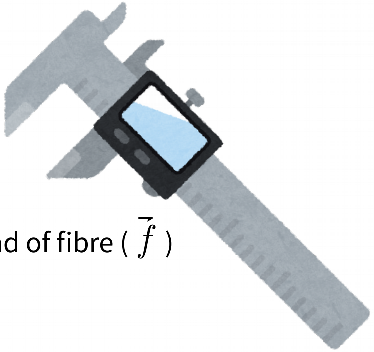
  → developed fastsim for optical photons (presented at GEANT4 R&D meeting [link])





# of reflections = std::floor($\frac{(\vec{f} - \vec{x}) \cdot \hat{i}}{\vec{step} \cdot \hat{i}}$)





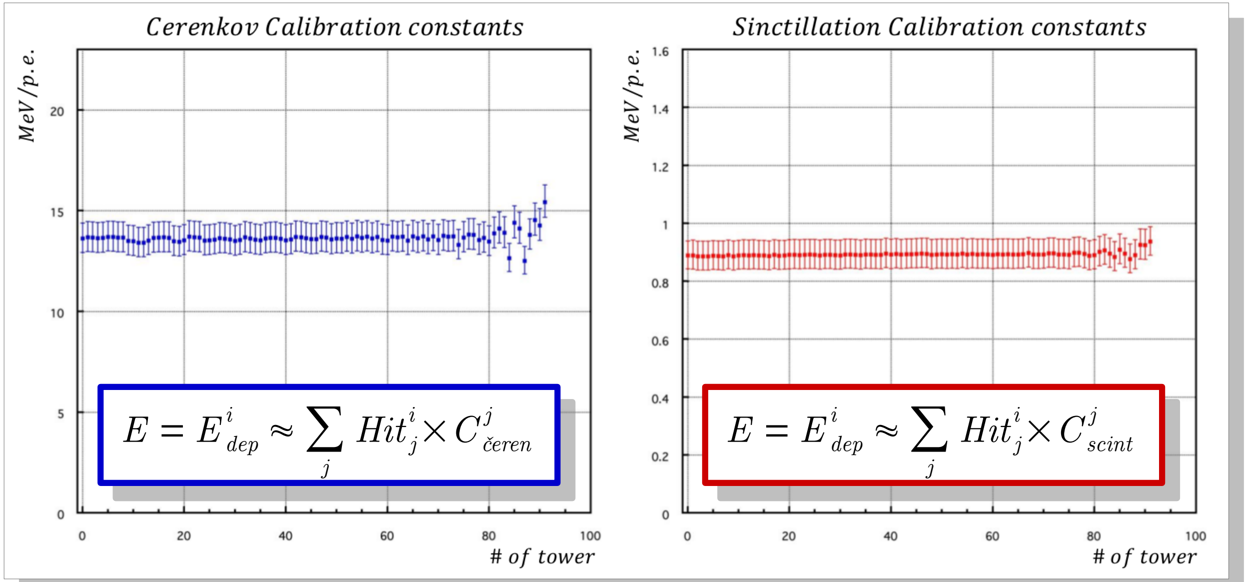
Calibration

Calibration using 20 GeV e-

- Measure Energy deposit, scintillation p.e. & Čerenkov p.e. at i-th tower (0^{th} - 91^{st})
- Energy can be expressed as a linear combination with simulations of 92 towers
  → Estimate calibration constants
- Uniform calibration constants as a function of the tower number

$$\boldsymbol{Energy} = \sum_{i=0}^{92} \boldsymbol{Hit}_{i^{th}\ tower} \times \boldsymbol{Calibration\ constant}^{i^{th}\ tower}$$

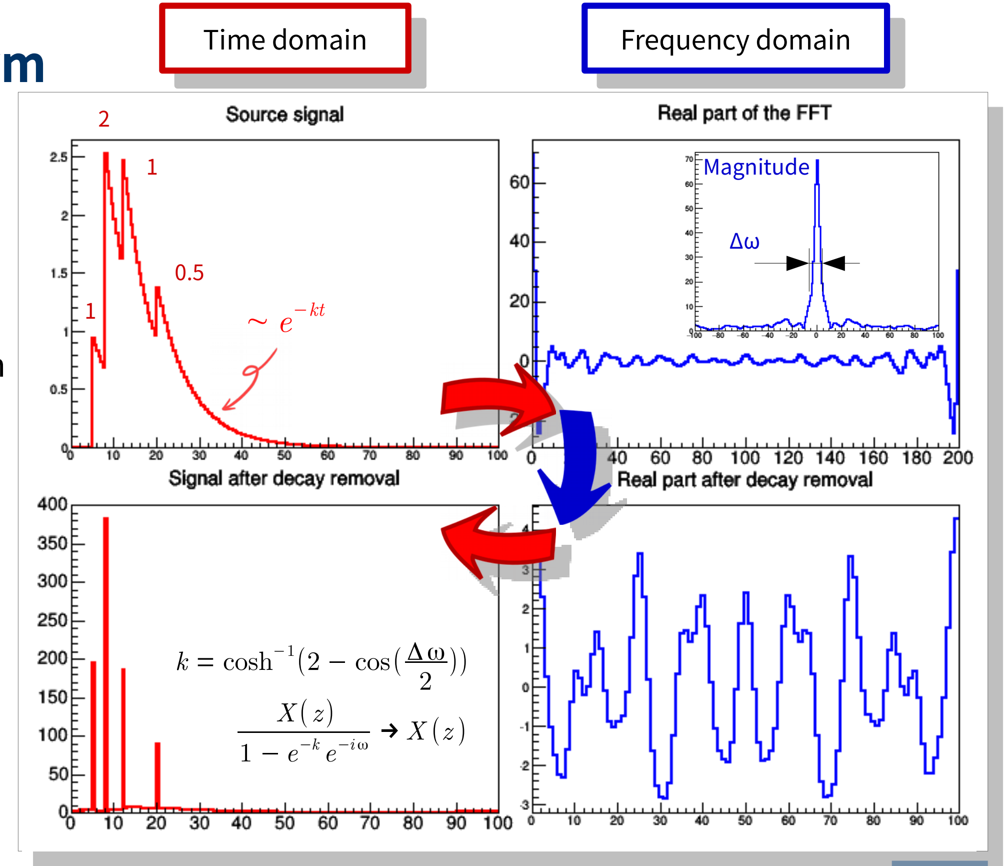
$$\Rightarrow \begin{bmatrix} E^{0}_{dep} \\ E^{1}_{dep} \\ \vdots \\ E^{90}_{dep} \\ E^{91}_{dep} \end{bmatrix} = \begin{bmatrix} Hit^{0}_{0} & Hit^{0}_{1} & \cdots & Hit^{0}_{90} & Hit^{0}_{91} \\ Hit^{1}_{0} & Hit^{1}_{1} & & Hit^{1}_{90} & Hit^{1}_{91} \\ \vdots & & \ddots & \vdots & \\ Hit^{90}_{0} & Hit^{90}_{1} & & Hit^{90}_{90} & Hit^{90}_{91} \\ Hit^{91}_{0} & Hit^{91}_{1} & \cdots & Hit^{91}_{90} & Hit^{91}_{91} \end{bmatrix} \begin{bmatrix} C^{0} \\ C^{1} \\ \vdots \\ C^{90} \\ C^{91} \end{bmatrix}$$



Longitudinal shower shape

Shower shape & timing – SiPM waveform

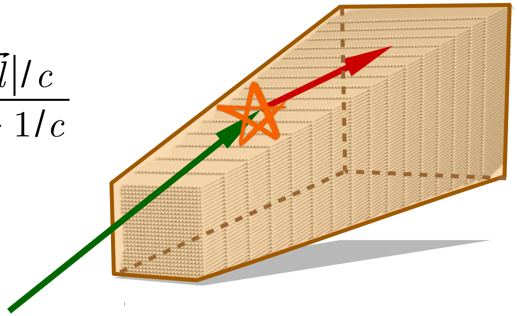
- Unsegmented calorimeter fully depends on the timing to reconstruct longitudinal shower shape
- Is dV/dt → dE/dx possible?
  → very challenging due to many hidden layers
- A SiPM yields exponentially decaying waveform to 1 photon
- FFT can be used to mitigate exponential tail, while preserving time translation & amplitude information



Deposit position $(\vec{x})$ Photon propagation $(\vec{k})$

$$t = \frac{|\vec{x}|}{c} + \frac{|\vec{k}|}{v} \qquad |\vec{k}| \simeq \frac{t - |\vec{l}|/c}{1/v - 1/c}$$

$$\vec{x} \simeq \vec{l} - \frac{t - |\vec{l}|/c}{1/v - 1/c}\,\hat{k}$$

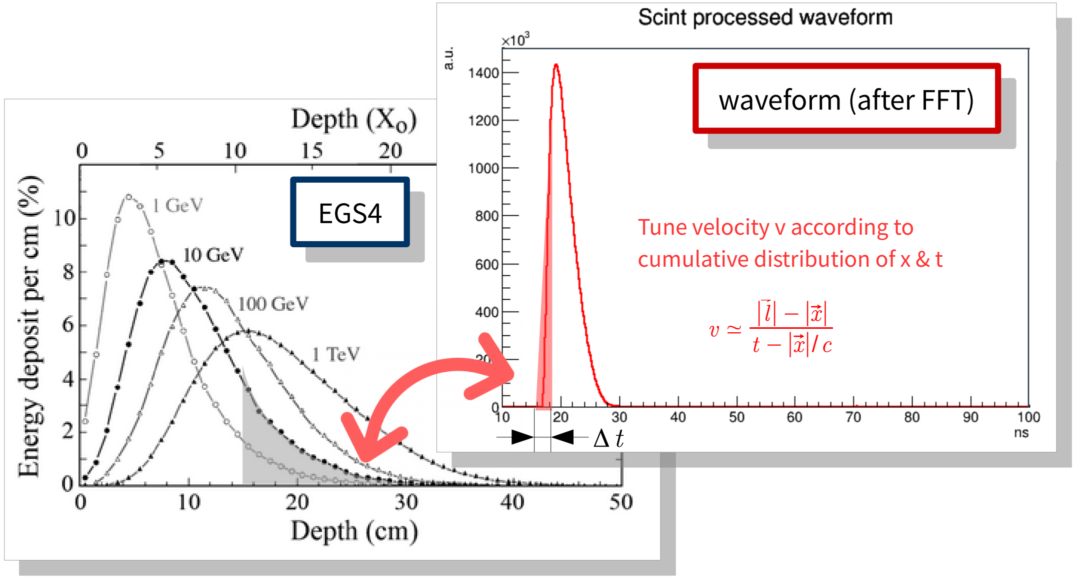


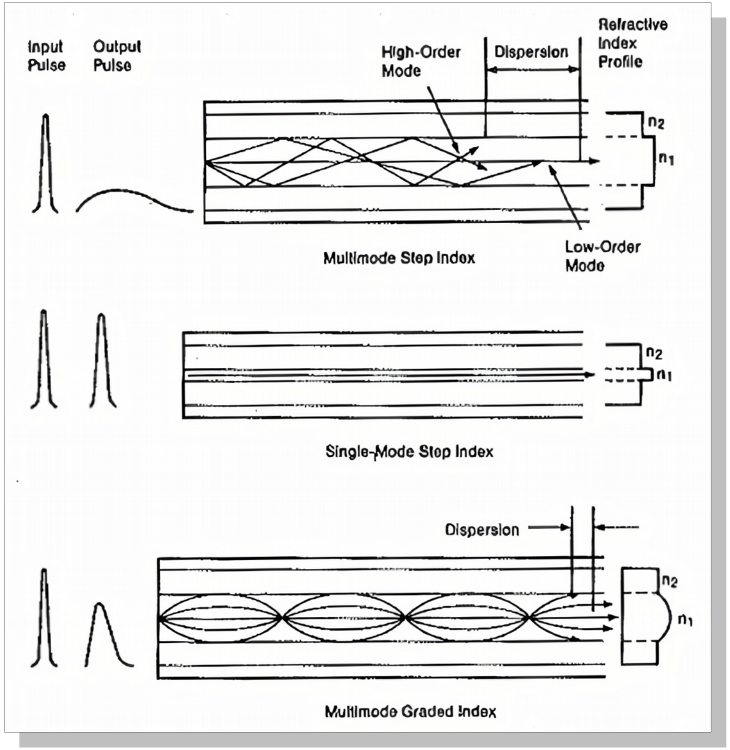
Longitudinal shower shape

Shower shape & timing – Dispersion

- Waveform is unlikely a shower shape even after FFT processing
- Late-component of the timing is dominated by the modal dispersion
- Mitigate dispersions by using slower phase velocity for late-components

  → Tune group velocity as a function of Δt using EM shower





3D reconstruction