IDEA Dual-readout calorimeter in Key4hep

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on behalf of the dual-readout calorimeter team

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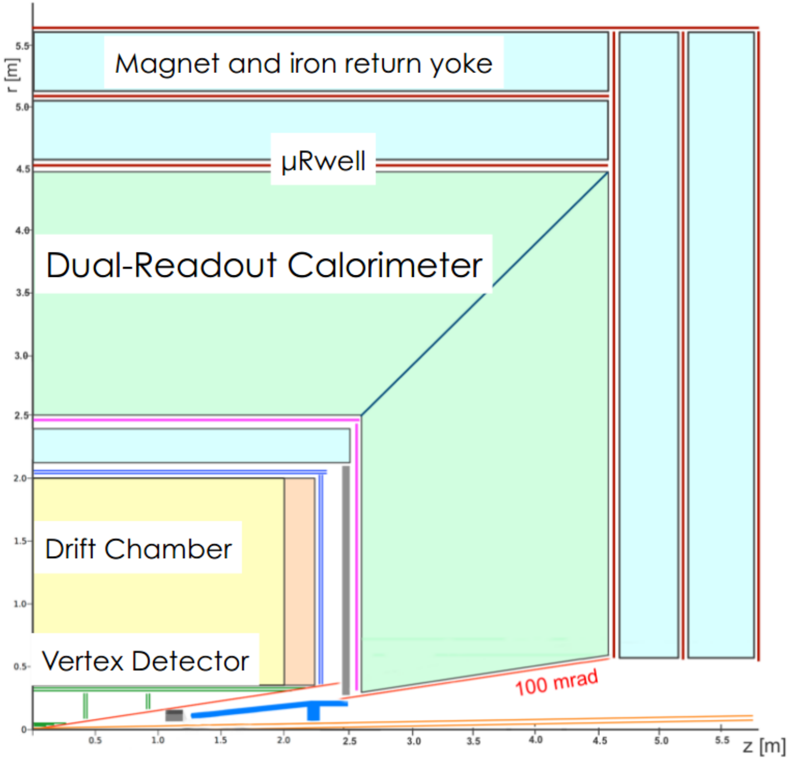
FUTURE CIRCULAR COLLIDER

IDEA detector

Concepts of the IDEA detector

- Silicon vertex detector
- Ultra-light drift chamber with a low material budget ~ $O(10^{-2})\ X_0$
  → minimize interaction within tracker volume
- Thin (~ 0.7 X_0), 2 T solenoid inside the calorimeter
- Dual-readout calorimeter + preshower
  - Good EM & excellent hadronic energy resolution
    (crystal option also provides exceptional EM energy resolution)
- μ-RWELL muon chambers



Dual-readout calorimeter

Dual-readout calorimetry

- The major difficulty of measuring energy of hadronic showers 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

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

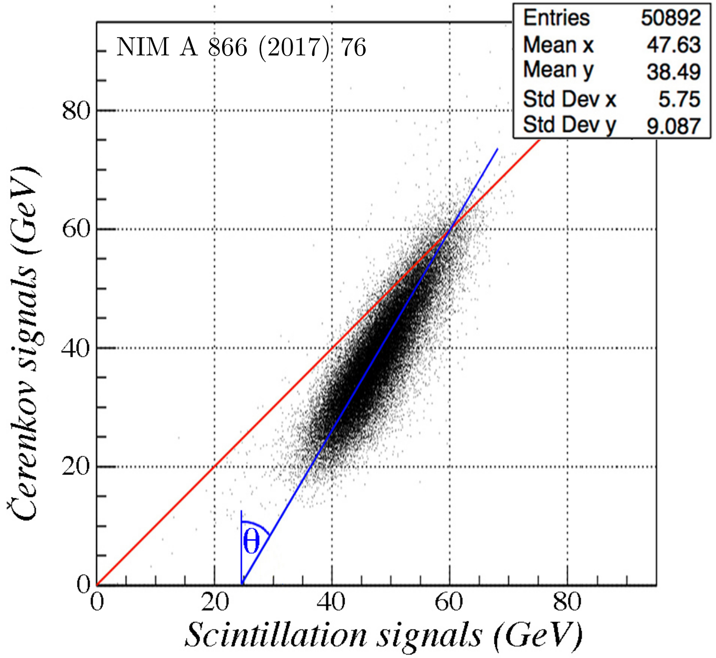
$$C = E[f_{em} + (\frac{h}{e})_C (1 - f_{em})]$$

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

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

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

- Excellent energy resolution for hadrons can be achieved by measuring f_{EM} and correcting the measurement event-by-event
- Dual-readout fiber-sampling calorimeter is a key element of the IDEA detector concepts

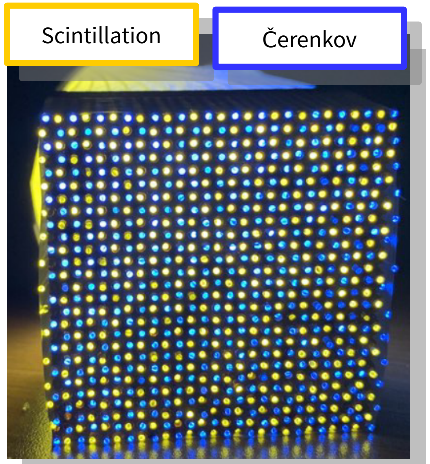


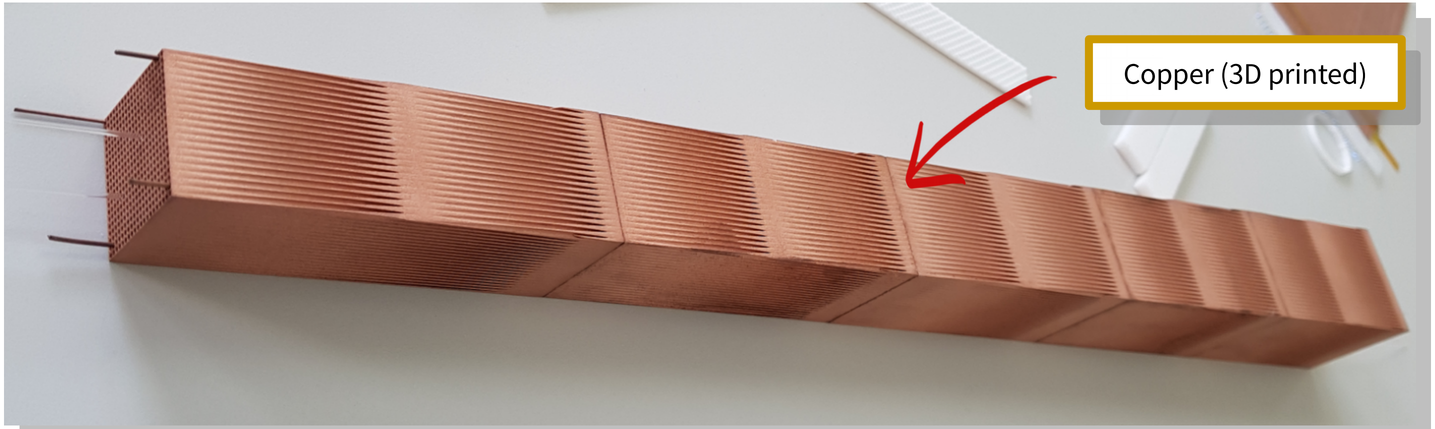
E_S vs $E_{\check{C}}$ with the RD52 lead fiber calorimeter for 60 GeV pions at CERN SPS H8

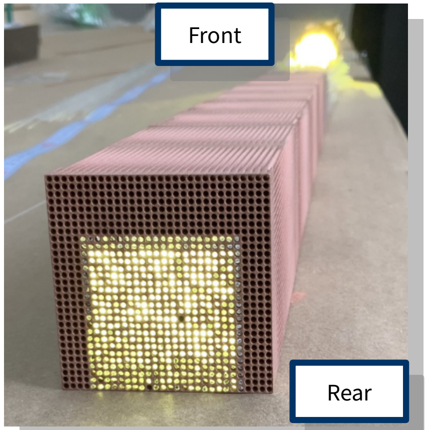
Dual-readout calorimeter

- 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

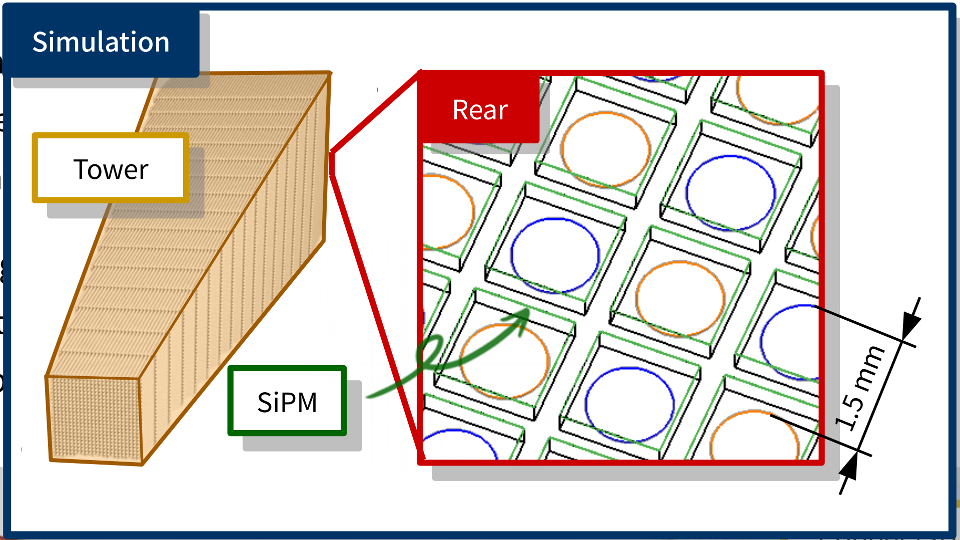


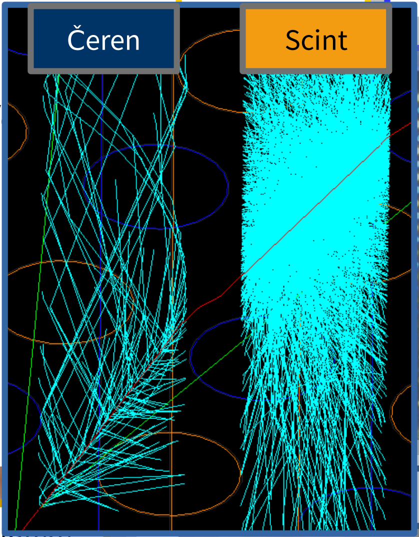


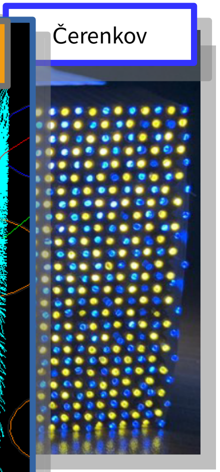


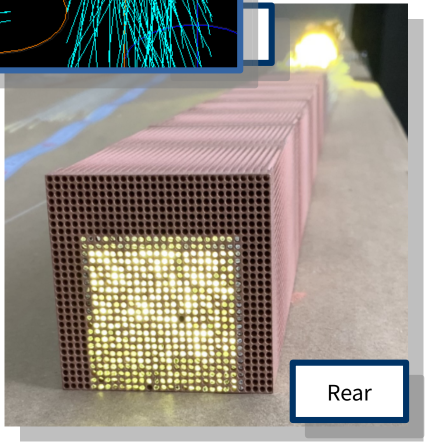
Dual-readout calorimeter

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





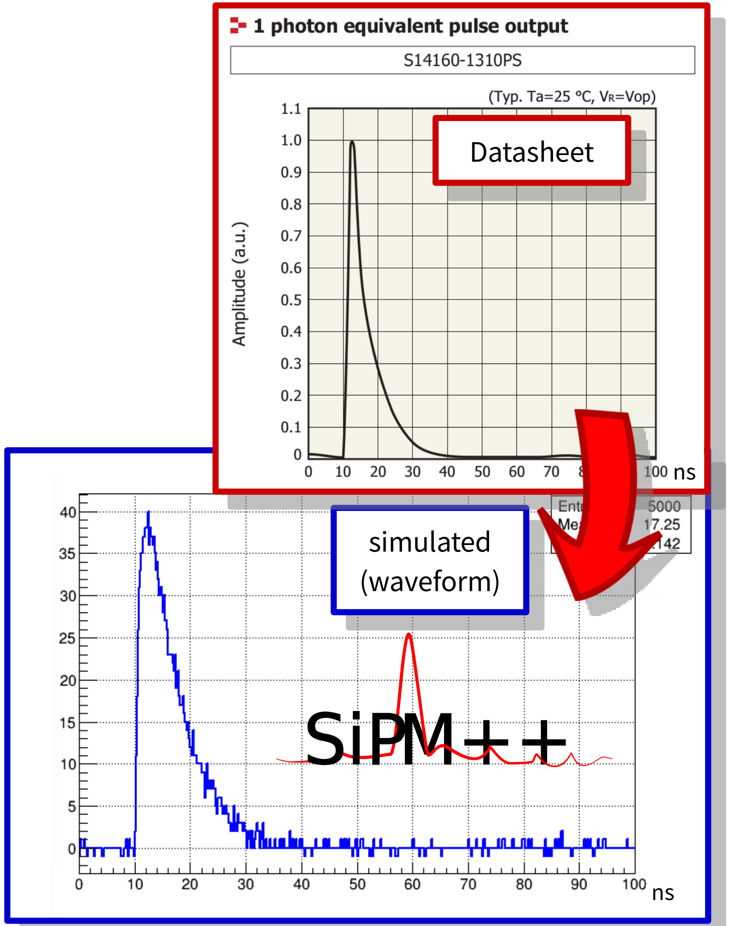


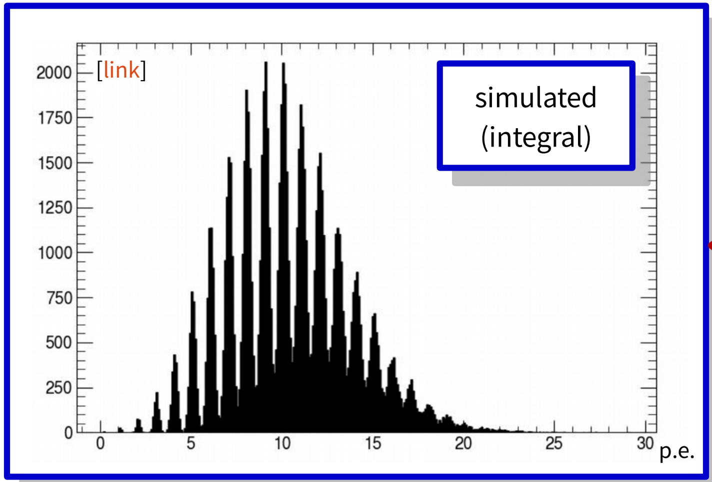


SiPM emulation

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, …
- Included in the Key4hep stack as an external library

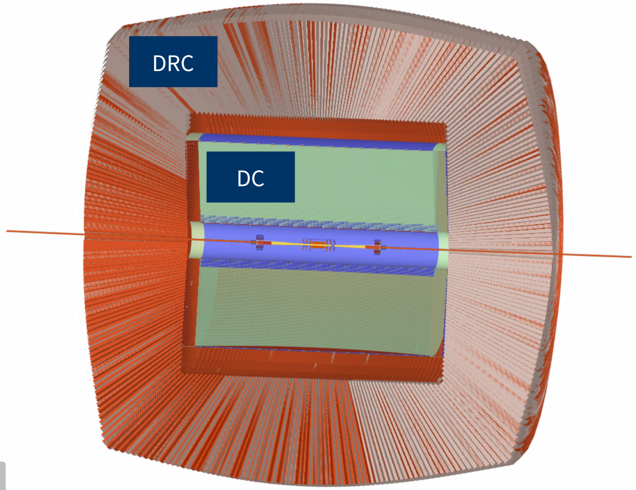


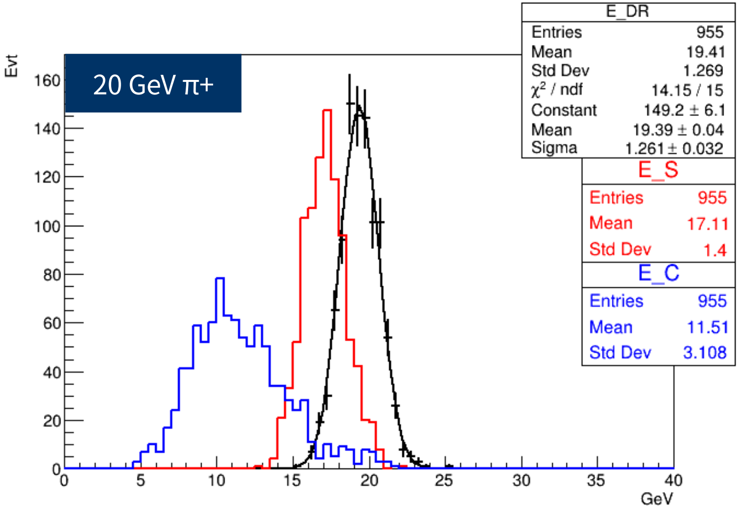


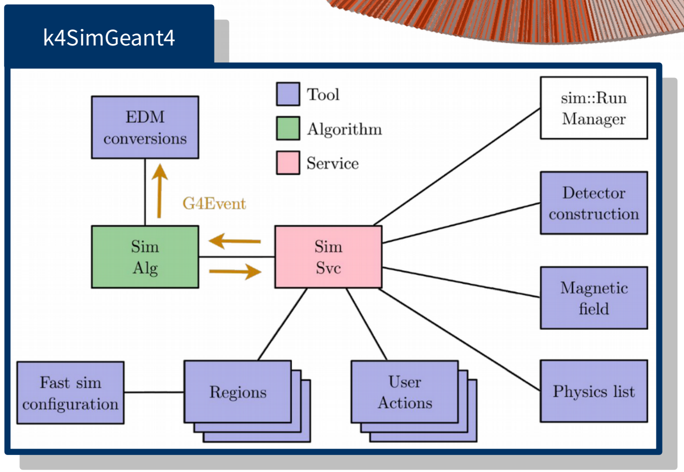
Dual-readout technique with Key4hep

A brief look at the dual-readout performance

- A full-scale 4π geometry has been implemented into DD4hep [git]
- Interfaced to G4 via k4SimGeant4, including a module for optical transportation
- Sensitive detectors are interfaced to EDM4hep – common event data model across Key4hep community
- Preliminary results show reasonable agreement with standalone G4 simulations



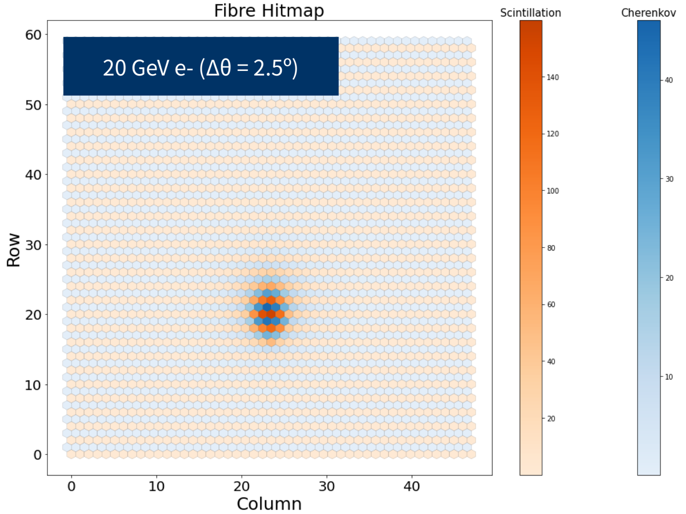


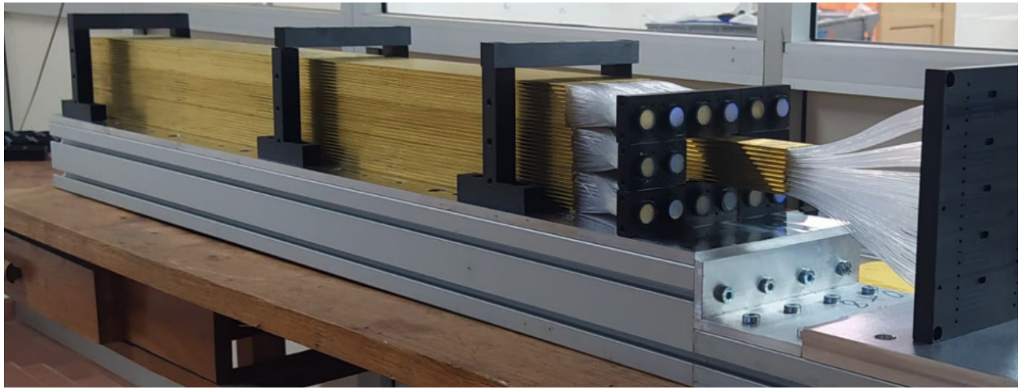


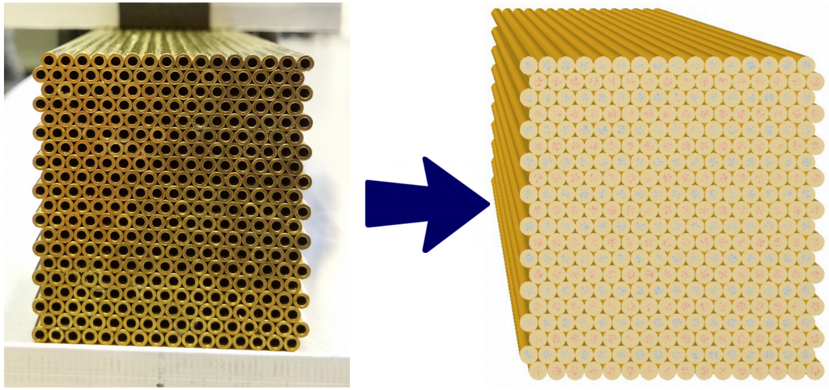
Bucatini calorimeter

Bucatini module with DD4hep

- A variety of options for DRC are being tested to answer physics & engineering challenges – Bucatini module is one of the major testbeds
- It has been extensively tested at beam sites in DESY & SPS [arXiv] 2021 (also planned for this Summer)
- Also working on implementing Bucatini module into DD4hep (hardware → software) [link]



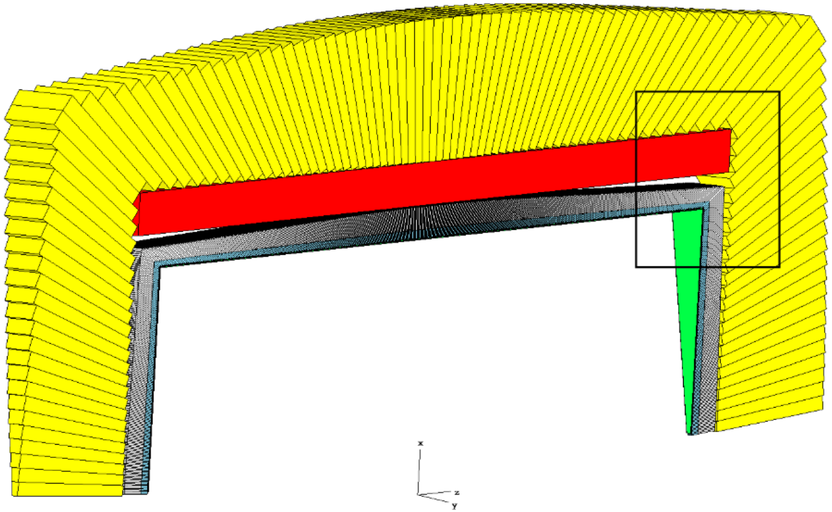


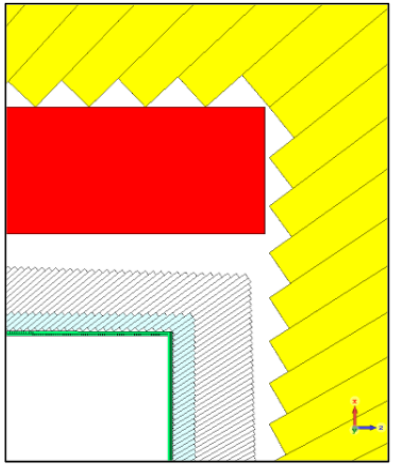


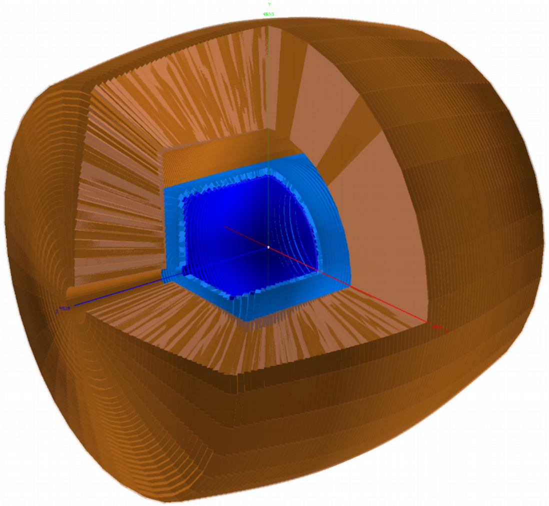
Crystal DRC

Crystal option with DD4hep

- An alternative option that provides excellent EM resolution
- 1 X_0 timing layer (LYSO) + 2 layers of PbWO4 crystals inside the IDEA magnet [JINST]
- Dual-readout technique with crystals can be carried out using different wavelengths of Čerenkov & scintillation light
- Detector geometry with crystal option has also been implemented in DD4hep [git]







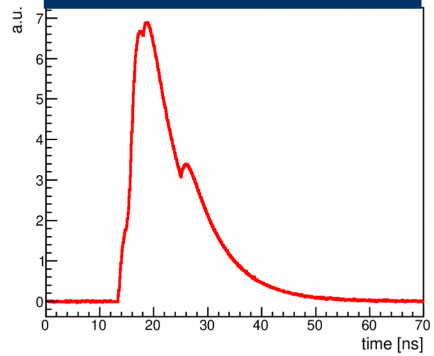
Reconstruction with Key4hep

Reconstructing & displaying calo hits

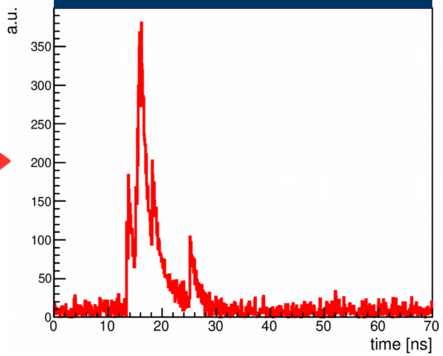
- Reconstruction codes are implemented as Gaudi algorithms
  - (traditional) 2D dual-readout correction
  - Novel 3D reco using Fourier analysis with timing [git][CALOR]

  → can be put together with other key4hep services & sequences
- Able to promote the resulting EDM4hep calorimeter hits for usage in other key4hep software, e.g. Phoenix event display

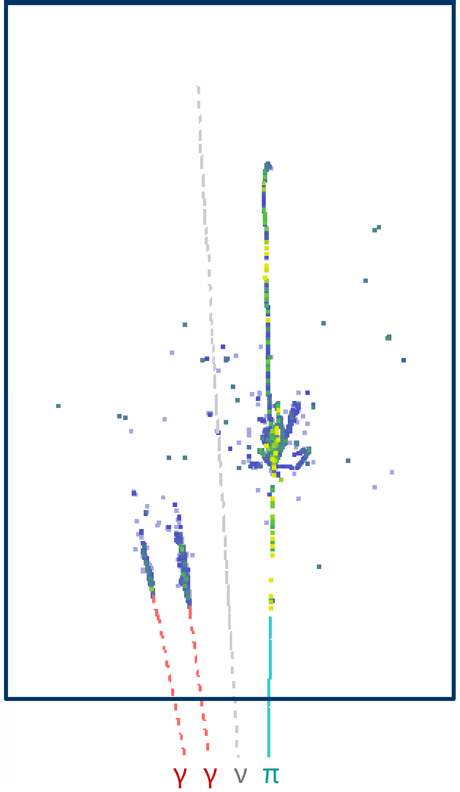
(Toy) Raw waveform



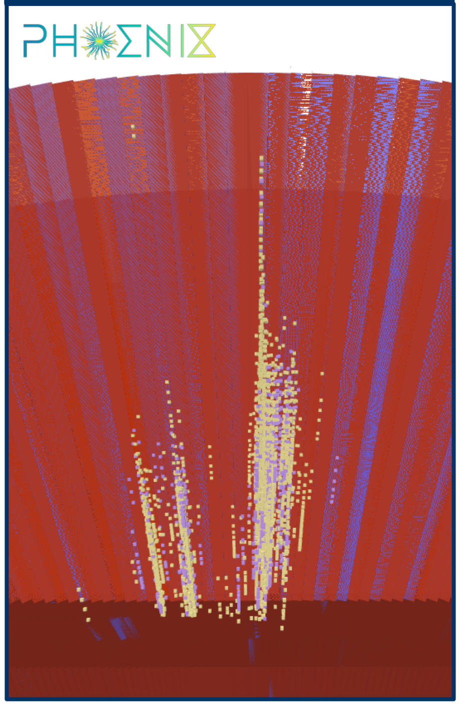
Processed waveform



20 GeV $\tau^- \to \pi^- \pi^0 \nu$ (MC truth)



20 GeV $\tau^- \to \pi^- \pi^0 \nu$ (Reco C/S)



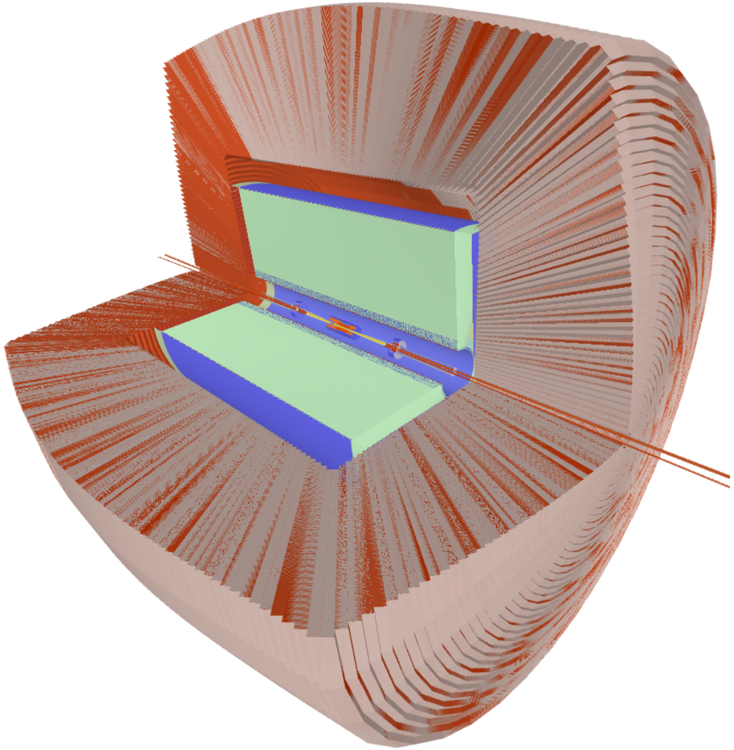
Summary

Dual-readout calorimeter and Key4hep

- DRC has migrated its components to Key4hep successfully
  - Detector description
  - Simulation interface & event data model
  - Digitization & reconstruction

- A wide variety of dual-readout communities are seeking to reach the Key4hep infrastructure (Bucatini, crystal DRC, …)
- The team is now working on further integration
  → consolidating SW organization to Key4hep repositories
  (k4geo, k4SimGeant4, k4RecCalorimeter)

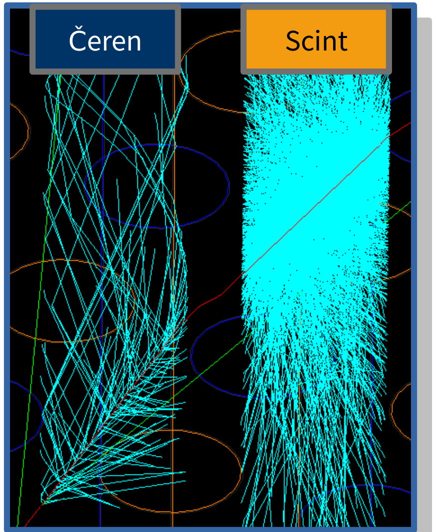
- Anticipating synergies with other Key4hep softwares by benefiting common infrastructures (event display, clustering algorithm, …)



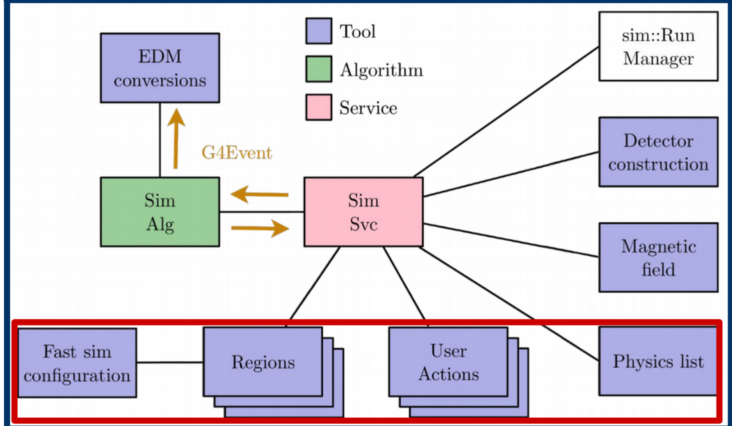
Backups

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

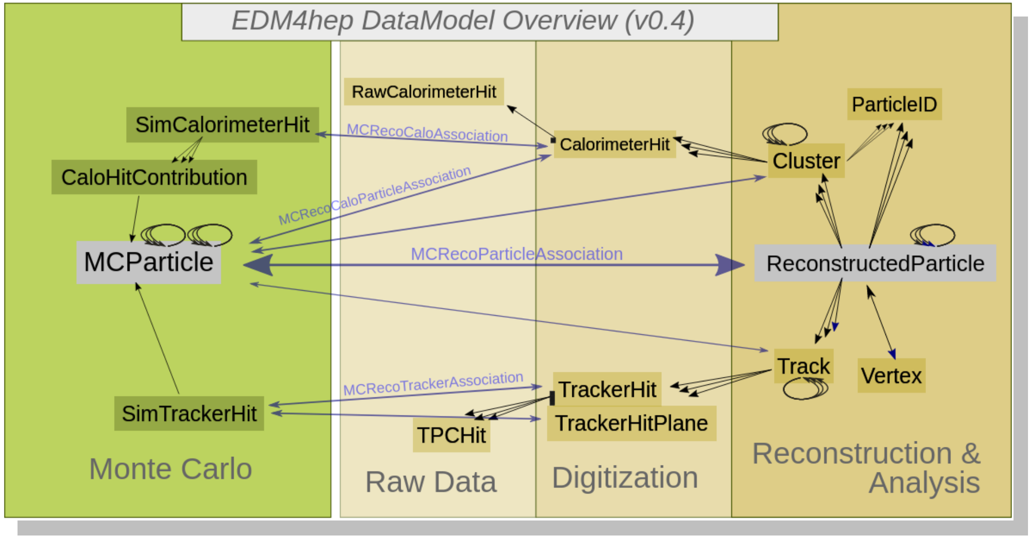
```
regionTool = SimG4FastSimOpFiberRegion("fastfiber")
opticalPhysicsTool = SimG4OpticalPhysicsList("opticalPhysics", fullphysics="SimG4FtfpBert")
physicslistTool = SimG4FastSimPhysicsList("Physics", fullphysics=opticalPhysicsTool)

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
)
```

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)

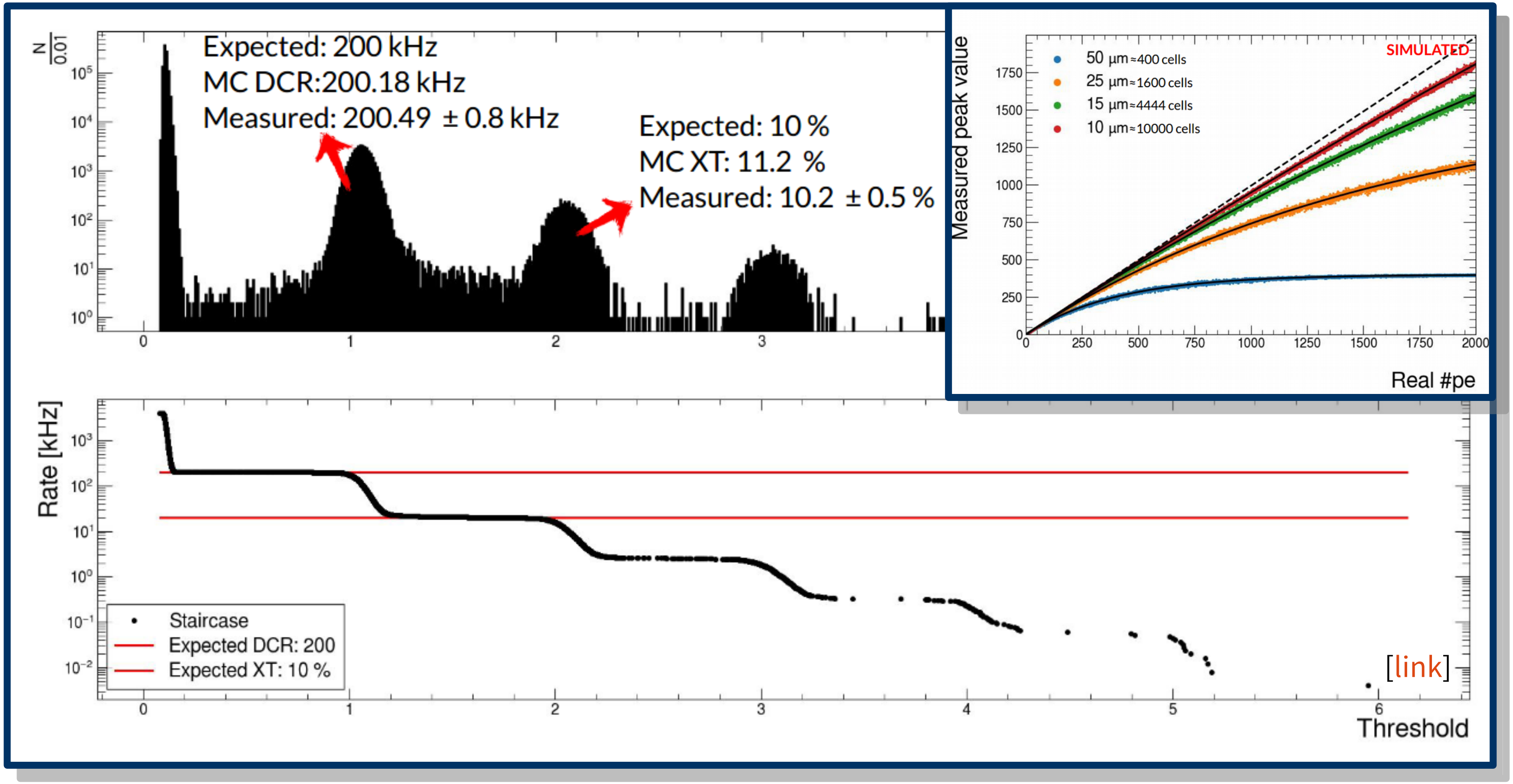
- Interfaced G4Event/G4VHit of the DRC simulation to EDM4hep calorimeter hits



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
)
```

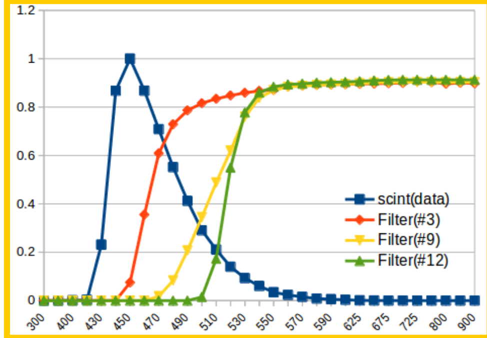
SiPM emulation



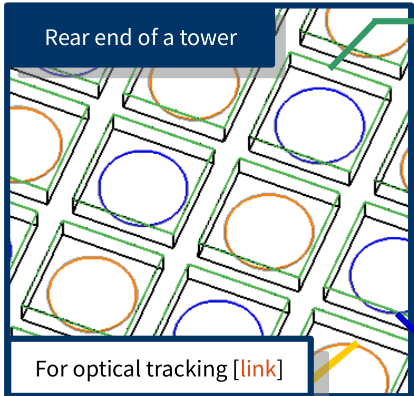
[link]

Optical properties in simulation

Transmission eff of filters

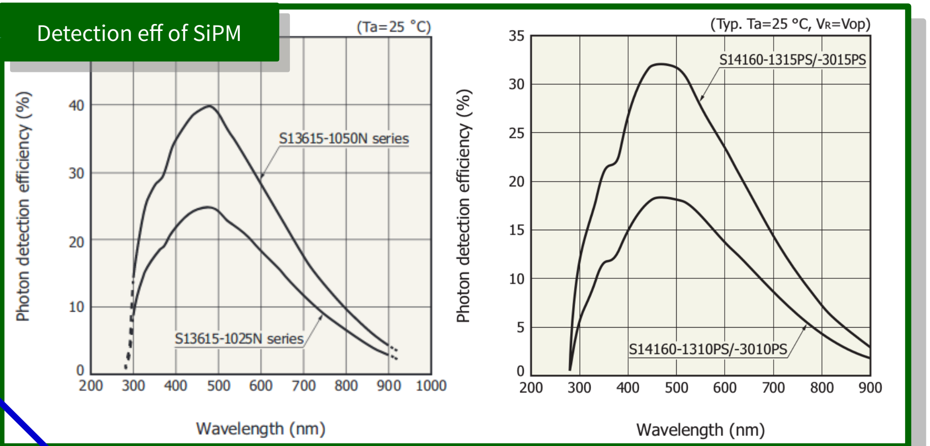


Rear end of a tower



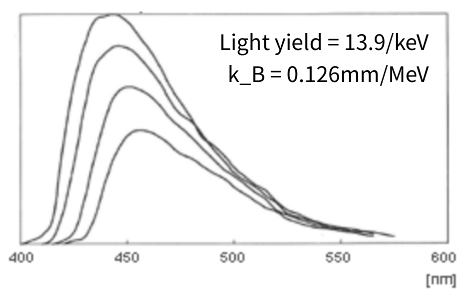
For optical tracking [link]

Detection eff of SiPM



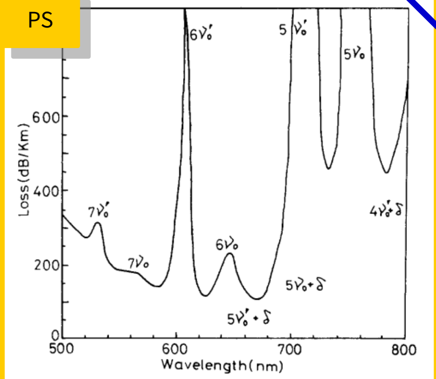
Attenuation loss diverges at 400nm → applied filter to S channel to mitigate it

Scintillation spectra of PS

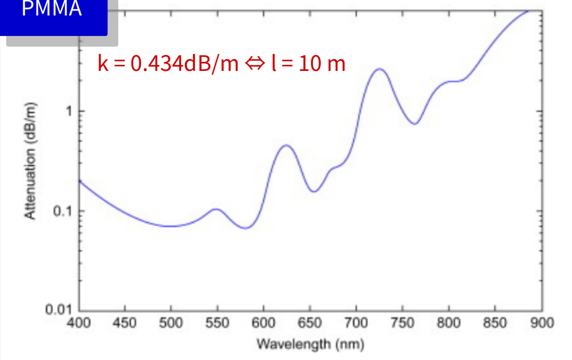


Attenuation loss of Polystyrene (PS) & PMMA

PS



PMMA

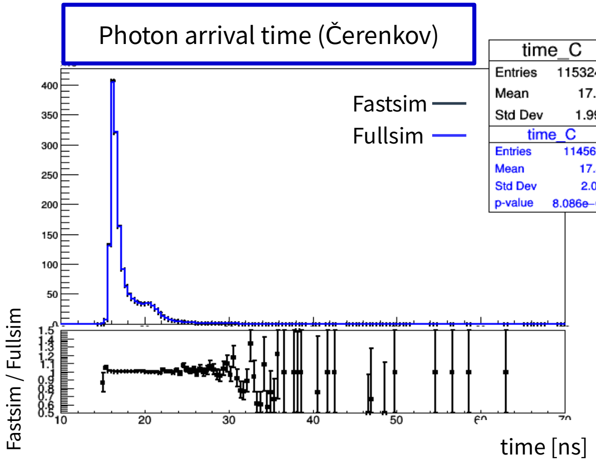


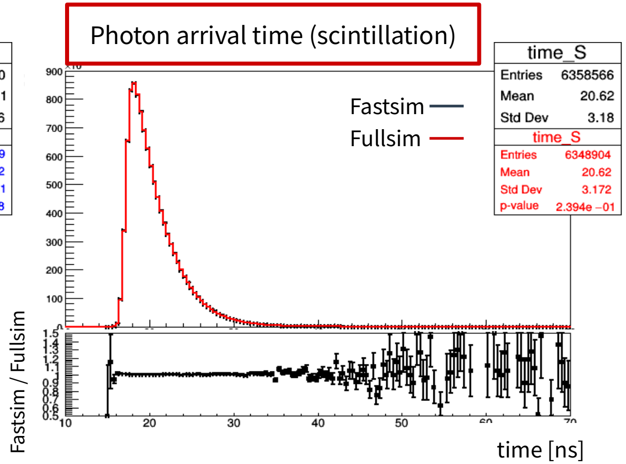
Speeding up optical photon tracking

Fast optical photon tracking

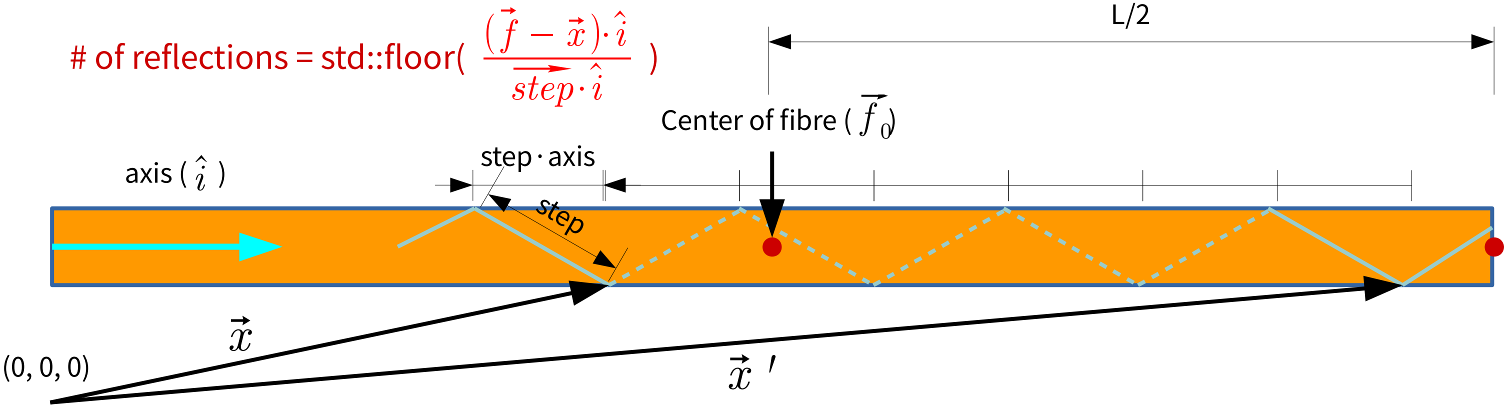
- Tracking optical photons is necessary, however it dominates CPU consumption
- Optical photons inside fibers can be tracked efficiently, by skipping intermediate steps

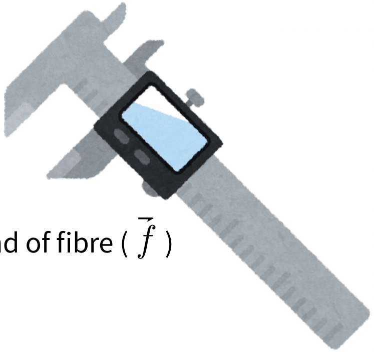
  → developed fastsim for optical photons (presented at GEANT4 R&D meeting [link])





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





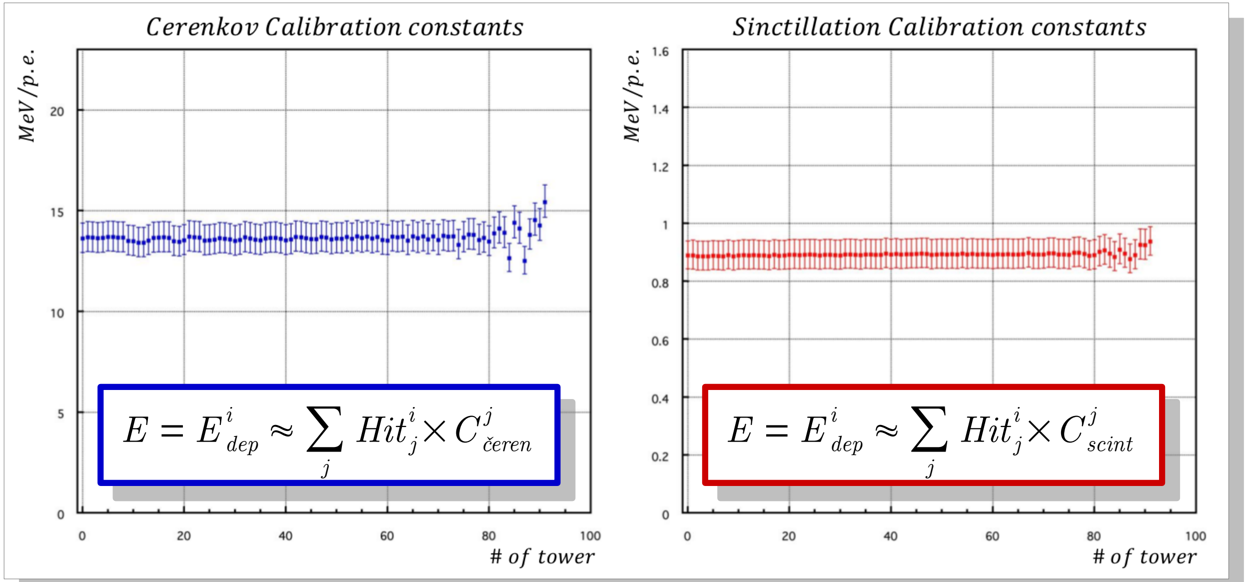
Calibration

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

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

$$\Rightarrow \begin{bmatrix} E^0_{dep} \\ E^1_{dep} \\ \vdots \\ E^{90}_{dep} \\ E^{91}_{dep} \end{bmatrix} = \begin{bmatrix} Hit^0_0 & Hit^0_1 & \cdots & Hit^0_{90} & Hit^0_{91} \\ Hit^1_0 & Hit^1_1 & & Hit^1_{90} & Hit^1_{91} \\ \vdots & & \ddots & \vdots & \\ Hit^{90}_0 & Hit^{90}_1 & & Hit^{90}_{90} & Hit^{90}_{91} \\ Hit^{91}_0 & Hit^{91}_1 & \cdots & Hit^{91}_{90} & Hit^{91}_{91} \end{bmatrix} \begin{bmatrix} C^0 \\ C^1 \\ \vdots \\ C^{90} \\ C^{91} \end{bmatrix}$$



Longitudinal shower shape

Shower shape & timing – SiPM waveform

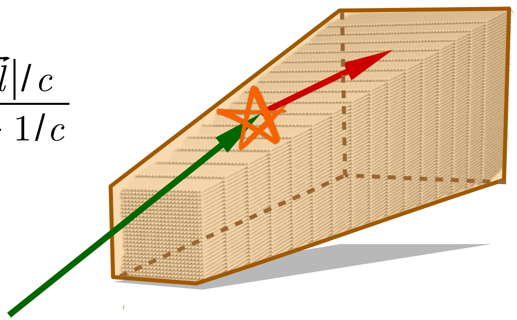
- Unsegmented calorimeter fully depends on the timing to reconstruct longitudinal shower shape
- Is dV/dt → dE/dx possible?

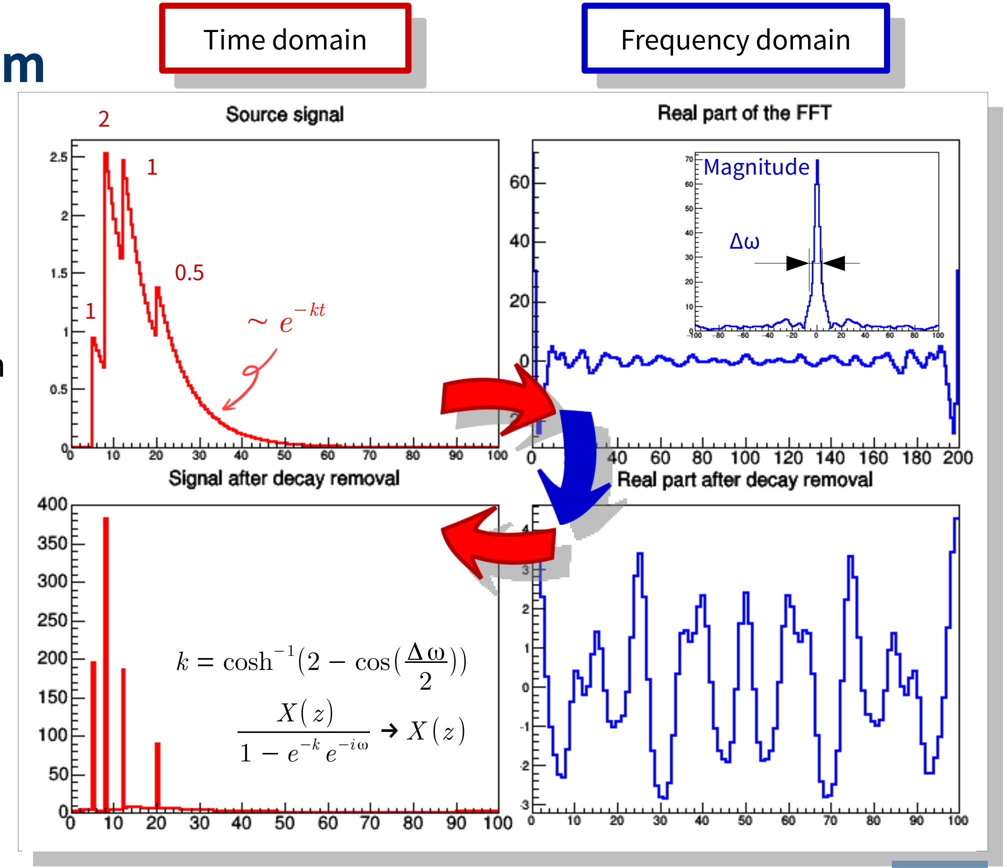
  → very challenging due to many hidden layers
- A SiPM yields exponentially decaying waveform to 1 photon
- FFT can be used to mitigate exponential tail, while preserving time translation & amplitude information

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

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

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



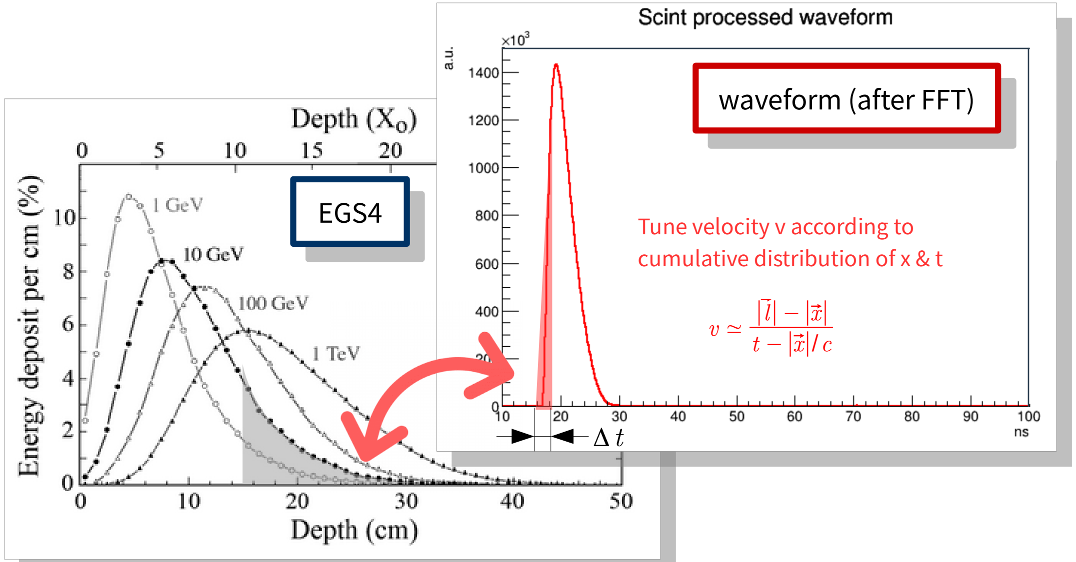


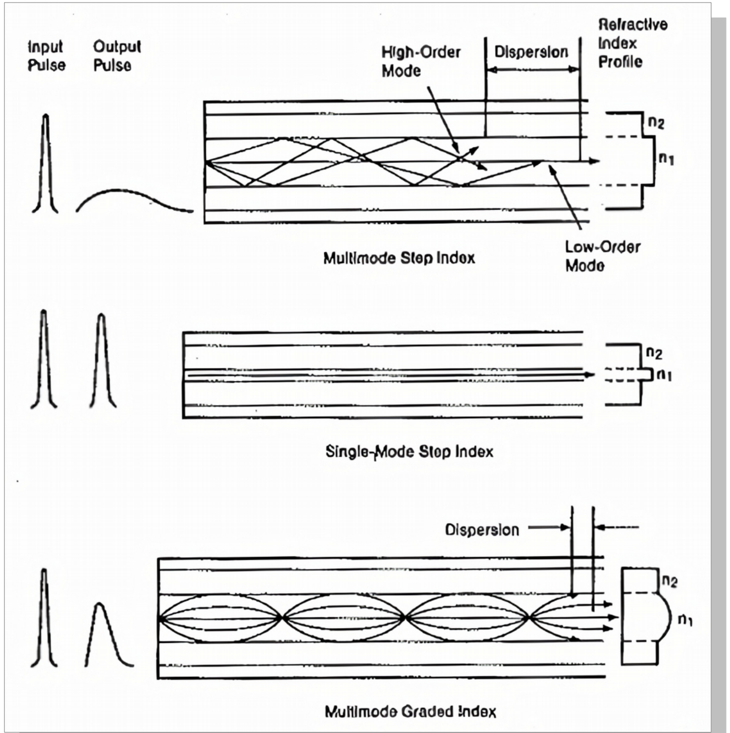
Longitudinal shower shape

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