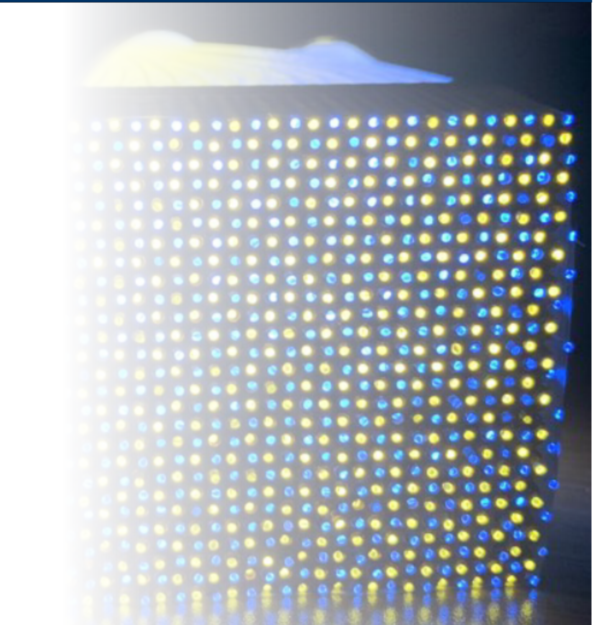
Dual-readout calorimeter software migration to Key4HEP

Sanghyun Ko (sanghyun.ko@cern.ch)

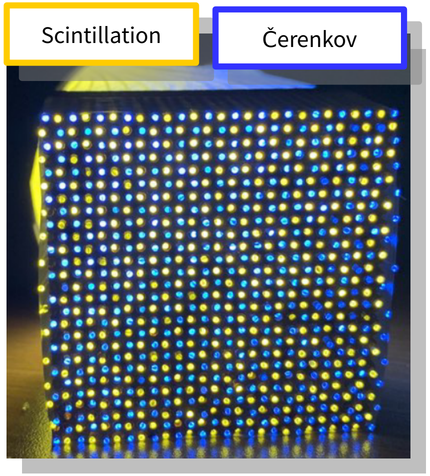
Seoul National University

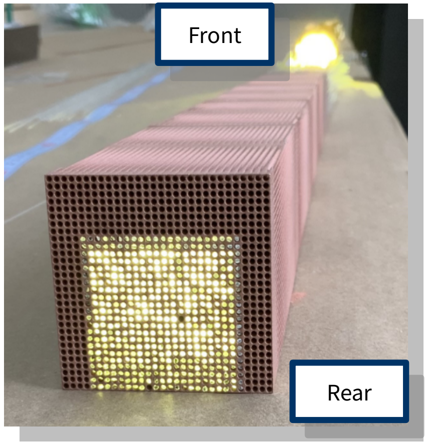
On behalf of the **IDEA Dual-readout calorimeter team**



Dual-readout calorimeter

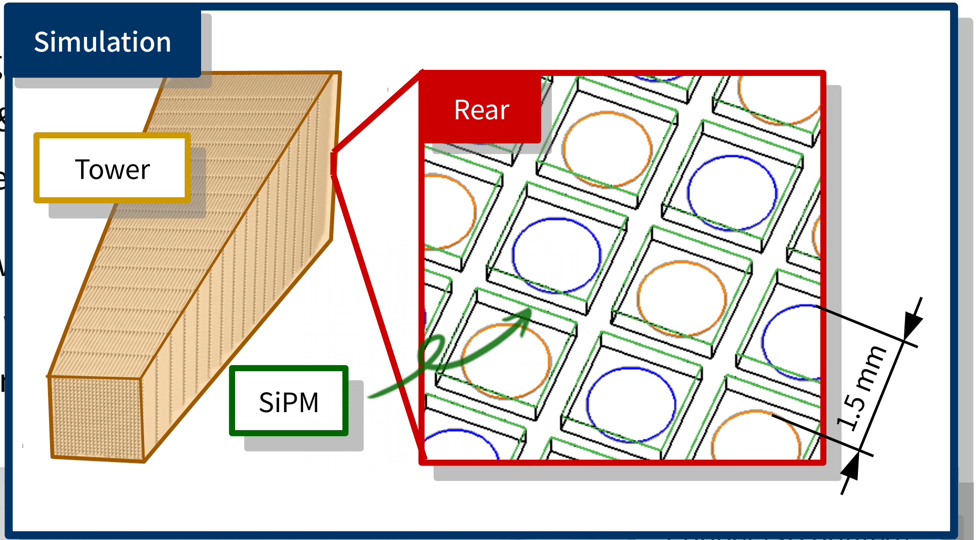
- Longitudinally unsegmented fiber-sampling calorimeter
  → measure both EM & hadronic components with two different channels in h/e
  → excellent energy resolution for hadrons via event-by-event correction
- Projective geometry with a uniform sampling fraction
  → fine unit structure with high granularity
  → more fibers in the rear than the front

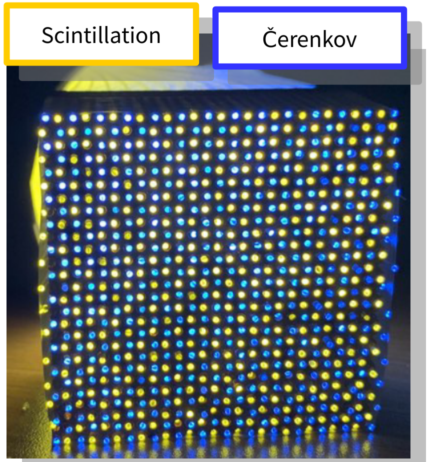


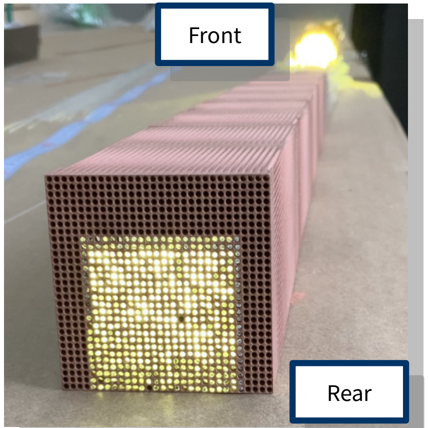


Dual-readout calorimeter

- Longitudinally unseg
  → measure both EM &
  → excellent energy re
- Projective geometry w
  → fine unit structure
  → more fibers in the r





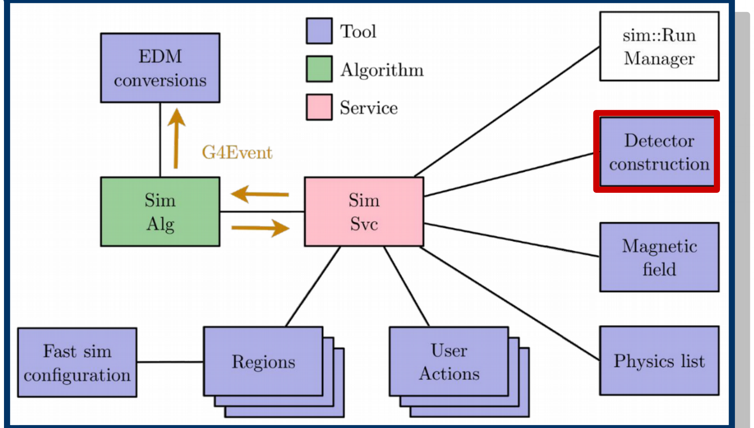


DD4hep migration

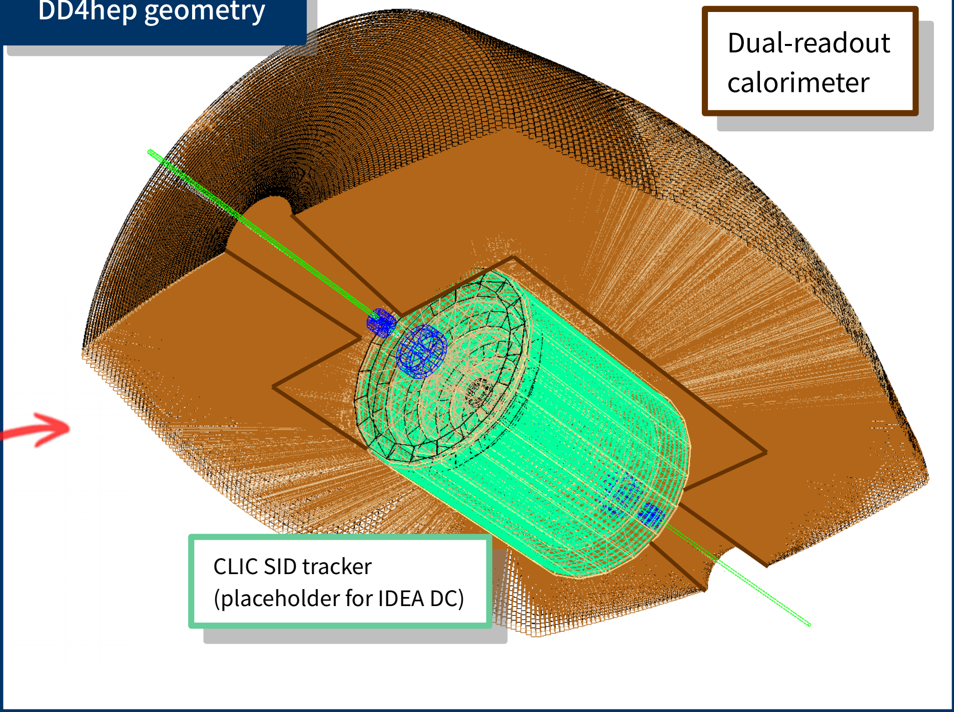
- Key4hep – common SW stack for FCC, ILC, CLIC, CEPC
- DD4hep is a main framework for the detector description

- Implemented IDEA dual-readout calo in DD4hep [git]
- Migration of IDEA drift chamber is on-going [link]

k4SimGeant4

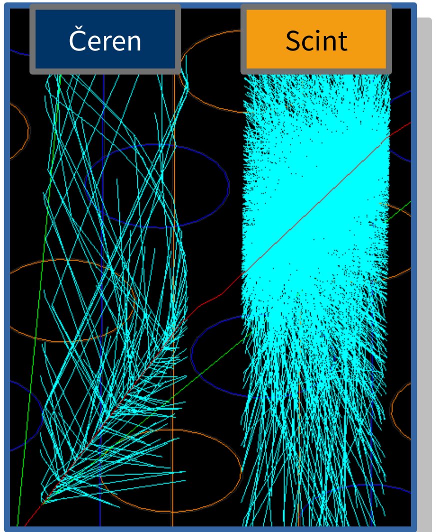


DD4hep geometry

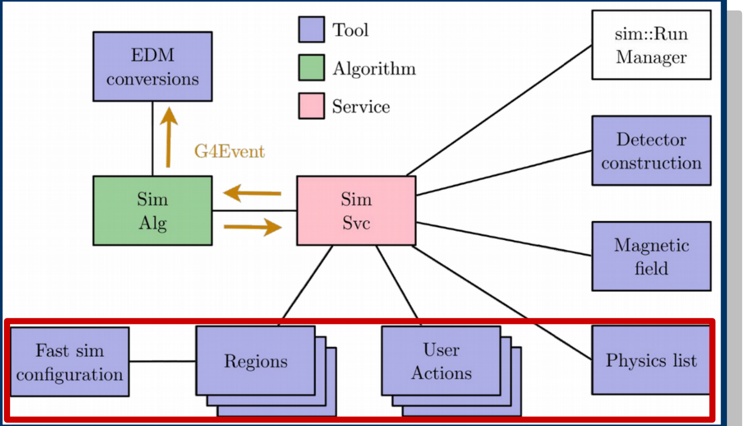


Optical physics simulation

- 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

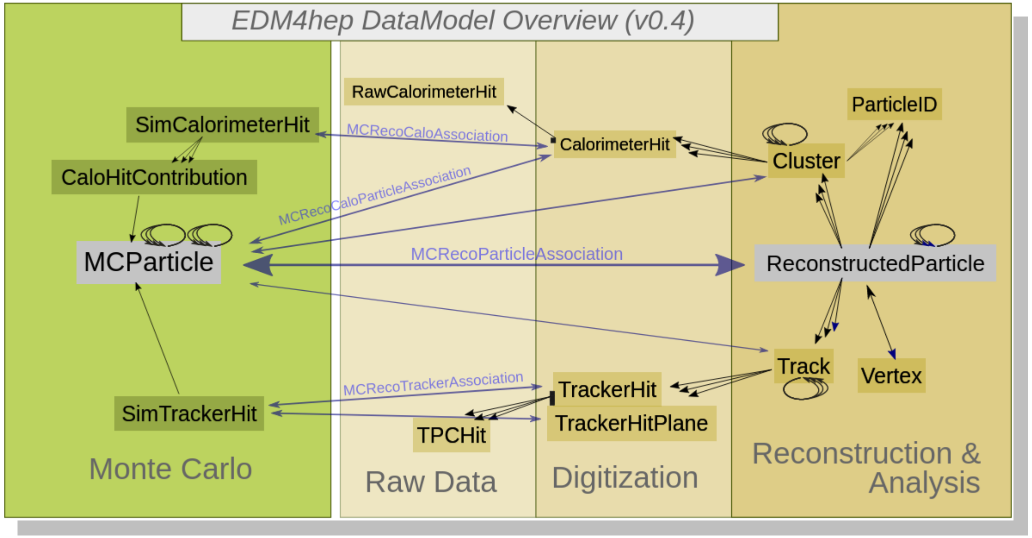
```
regionTool = SimG4FastSimOpFiberRegion("fastfiber")
opticalPhysicsTool = SimG4OpticalPhysicsList("opticalPhysics", fullphysics="SimG4FtfpBert")
physicslistTool = SimG4FastSimPhysicsList("Physics", fullphysics=opticalPhysicsTool)

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
)
```

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



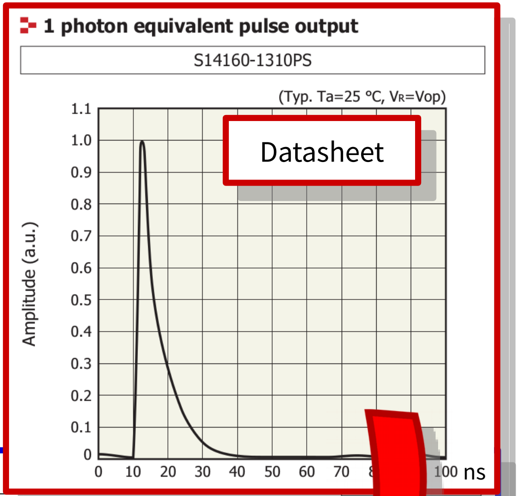
Data	EDM4hep class
MC truth (Edep)	edm4hep::SimCalorimeterHit
Readout (# of p.e.)	edm4hep::RawCalorimeterHit
Digitization (# of ADC)	edm4hep::RawCalorimeterHit
Reco (2D/3D)	edm4hep::CalorimeterHit

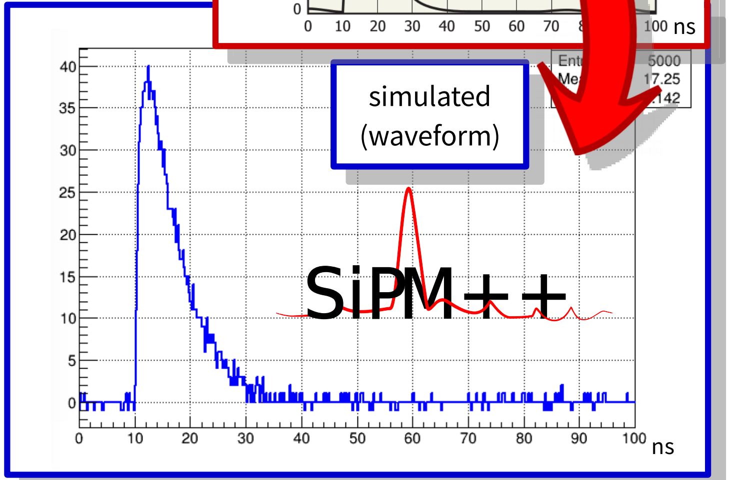
```
from Configurables import SimG4SaveDRcaloHits, SimG4SaveDRcaloMCTruth
saveDRcaloTool = SimG4SaveDRcaloHits("saveDRcaloTool", readoutNames = ["DRcaloSiPMreadout"])
saveMCTruthTool = SimG4SaveDRcaloMCTruth("saveMCTruthTool") # need SimG4DRcaloActions

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

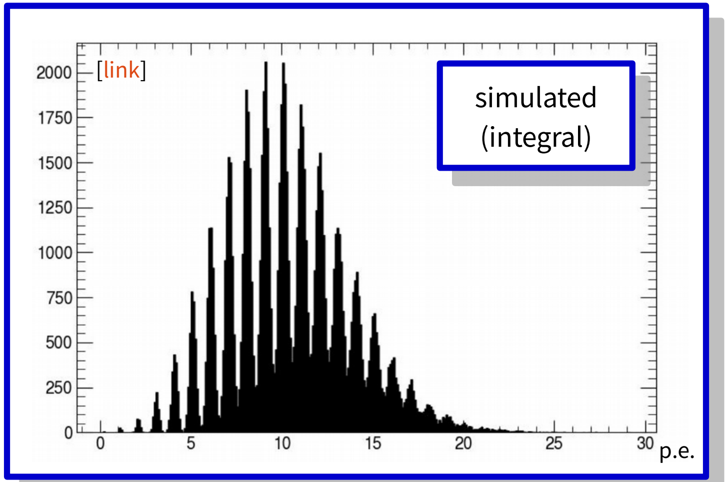
SiPM simulation

Simulating SiPM waveform with SimSiPM

- SiPM is a main photodetector candidate → developed simulation library [link]
- Parameterized inputs from the datasheet (dark counts, crosstalk, afterpulses, …)
- Generic c++/python library, implemented into Gaudi [code]
  - uses custom Podio data model for describing waveform [code]
    → plan to move to podio::UserDataCollection (new feature from v00-13-02)





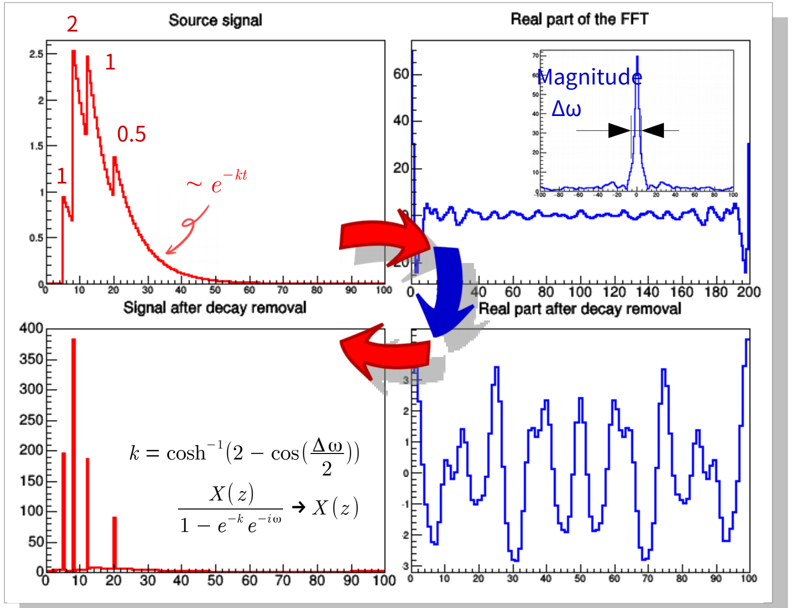


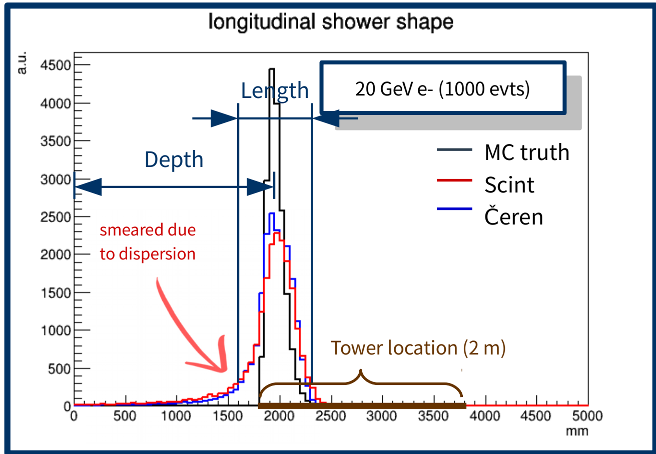
3D reconstruction

- Unsegmented calorimeter extensively depends on the timing to reconstruct longitudinal shower shape
- Signal processing algorithm implemented into Gaudi [link][code] to reconstruct longitudinal shower shape from SiPM waveforms
- Longitudinal shower shape with excellent lateral granularity
  → 3D reconstruction
- Complete chain of GEN → SIM → DIGI → RECO within Key4hep

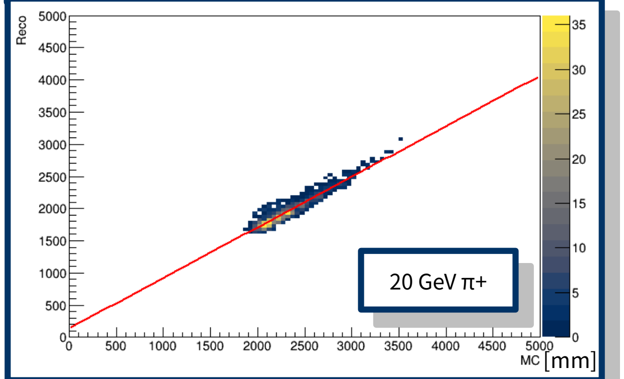
Time domain

Frequency domain



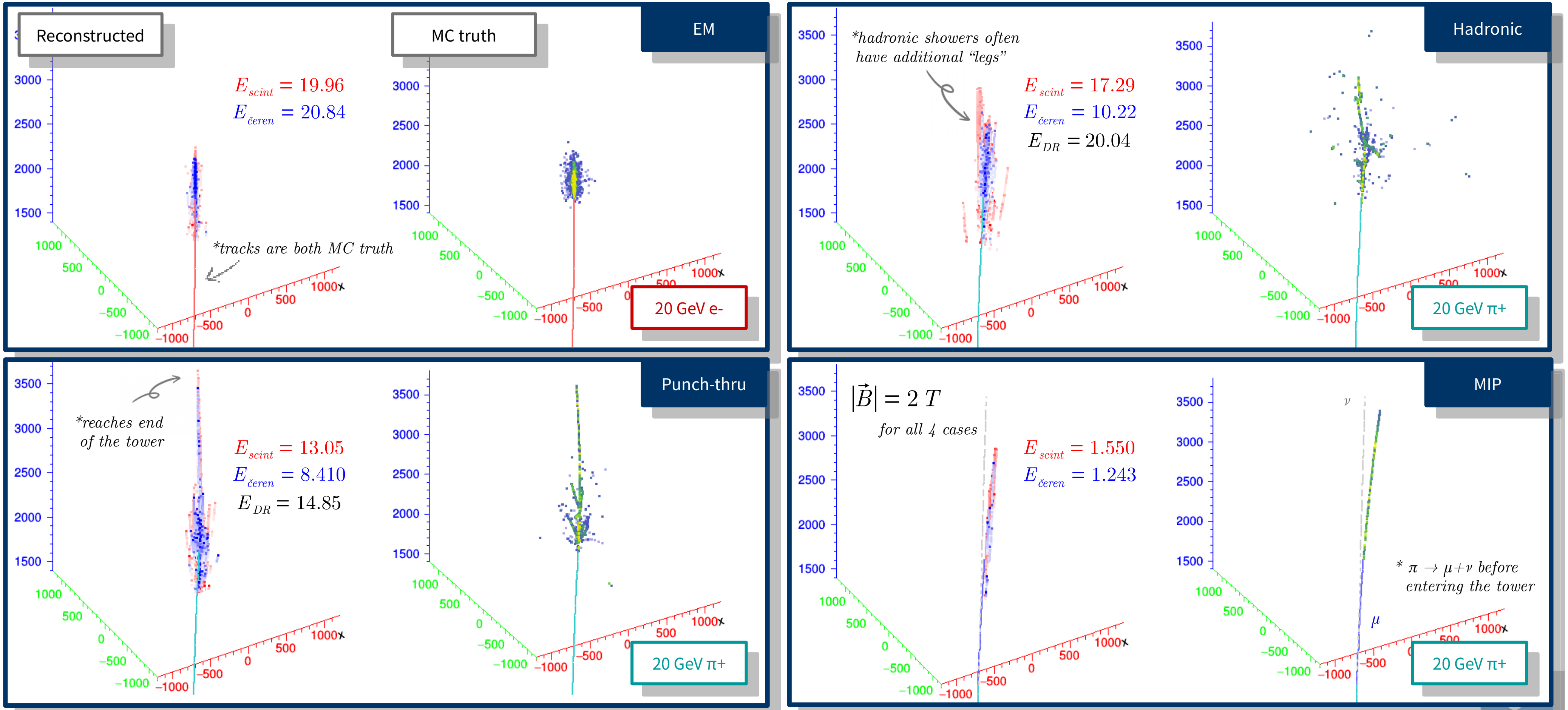


Depth



	Simulation setup
Timing resolution	Ideal (assume ~ O(10 ps))
Sampling rate	100 ps

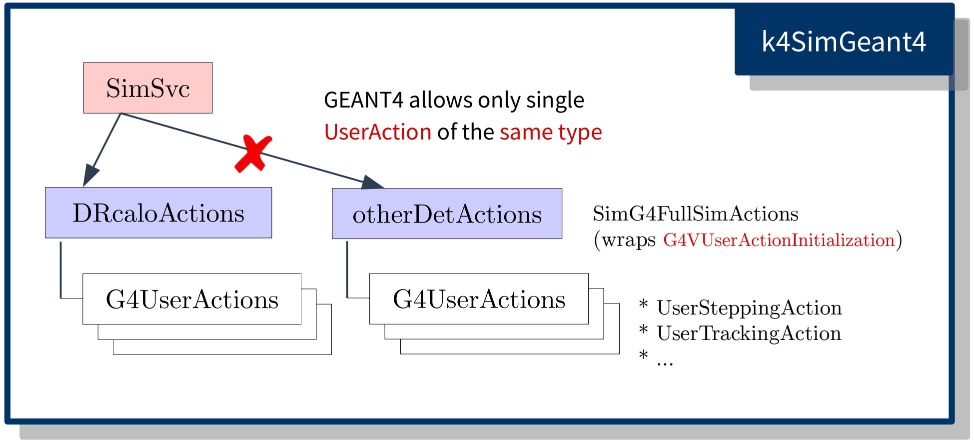
3D reconstruction

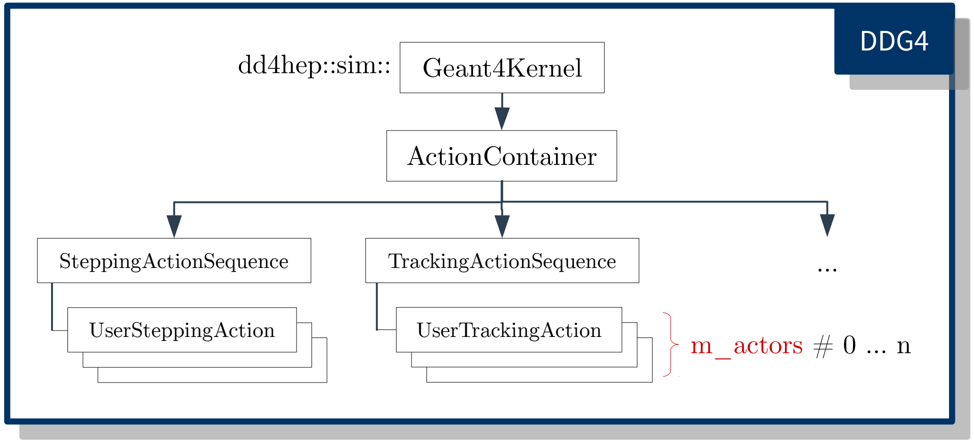


GEANT4 User Actions

Incorporating GEANT4 User Actions in Key4hep

- Utilization of G4UserActions is essential for Dual-readout calorimeter
  (efficient manipulation of optical photons, retrieving MC truth energy deposits, .etc)
- Standalone simulation of DRC with Key4hep is outstanding, yet needs to be improved for the full-scale detector simulation
  → Incorporating multiple User Actions of the same type is not allowed
  → DDG4's approach using Action Containers/Sequences can be a potential candidate to solve the issue



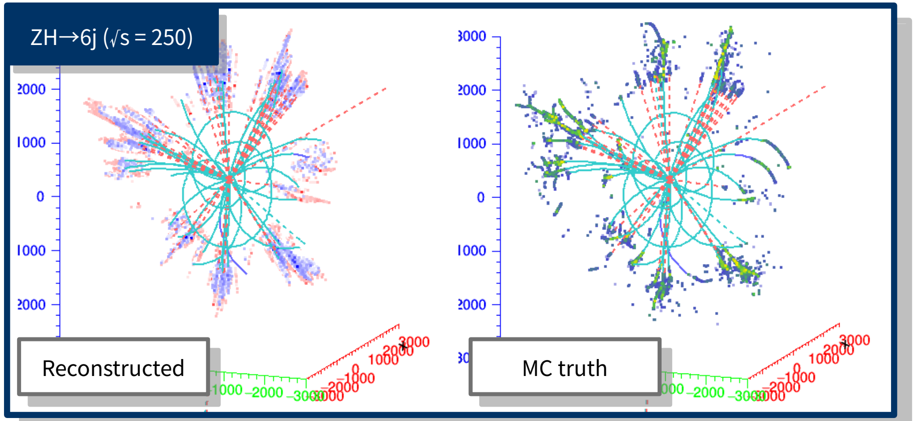


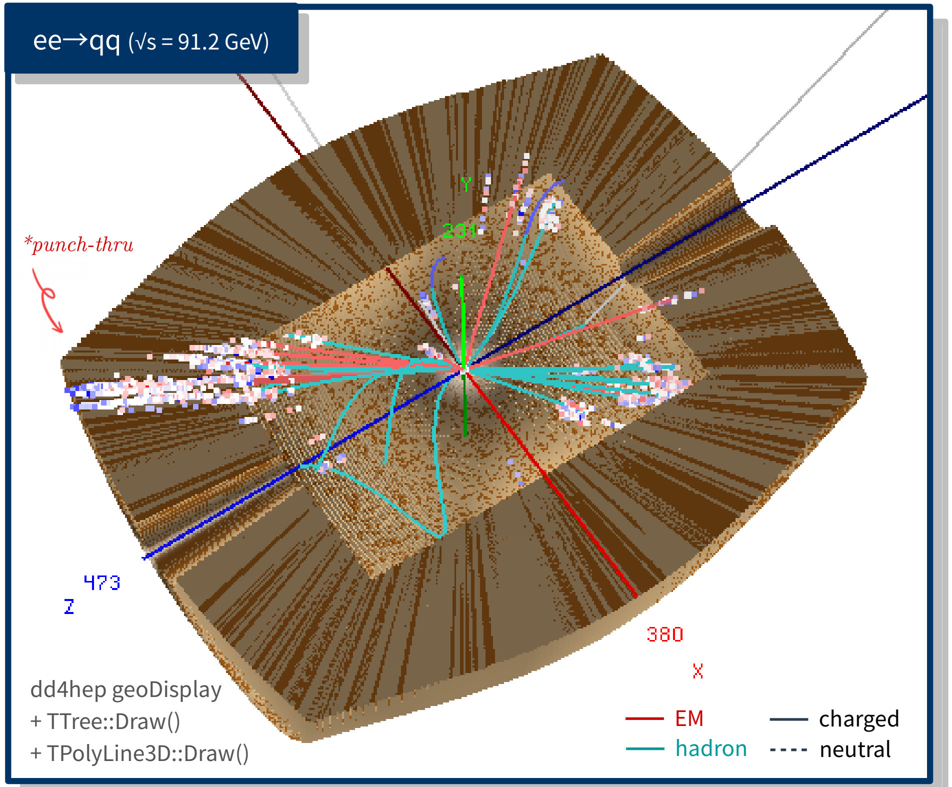
Visualization

Event display for EDM4hep

- Visualization is the most intuitive way to understand the detector's response to a given physics process
- Albeit an universal data model & broad user community, the event display software for EDM4hep is still absent
- Participating as stakeholders of a visualization tool would be essential for next-generation detectors

  (3D imaging calorimetry, 4D tracking, …)





Summary

Migration of Dual-readout calorimeter to Key4hep

- The (standalone) IDEA Dual-readout calorimeter has been successfully migrated to the Key4hep framework

  → Many developments have happened since the last FCC physics workshop
  - (continued) migration of the geometry to DD4hep
  - Adopt EDM4hep for the data model
  - Develop Gaudi Tool for the digitization/reconstruction

Towards full-scale IDEA detector simulation

- Few steps remain to be prepared for the full-scale detector simulation

  → incorporating multiple GEANT4 user actions
- Having common ground for the framework can be synergic for both detector & SW communities – e.g., clustering

Backups

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

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

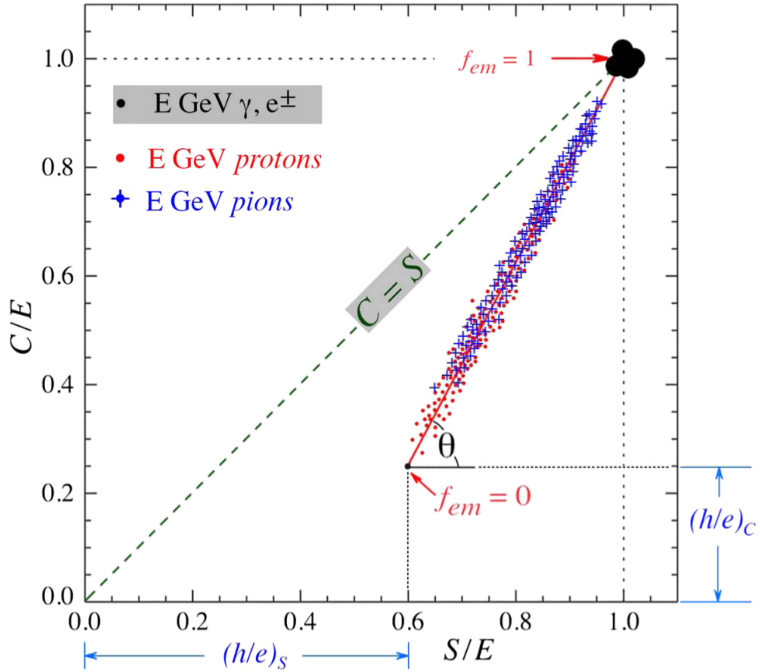
$$C = E[f_{em} + (\frac{h}{e})_C (1 - f_{em})]$$

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

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

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

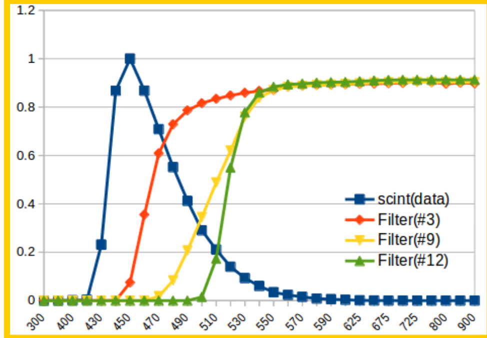
- Excellent energy resolution for hadrons can be achieved by measuring f_em and correcting the measurement event-by-event
- Dual-readout fiber-sampling calorimeter is a key element of the IDEA detector concepts



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

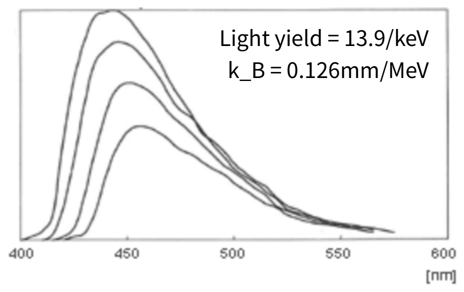
Optical properties in simulation

Transmission eff of filters

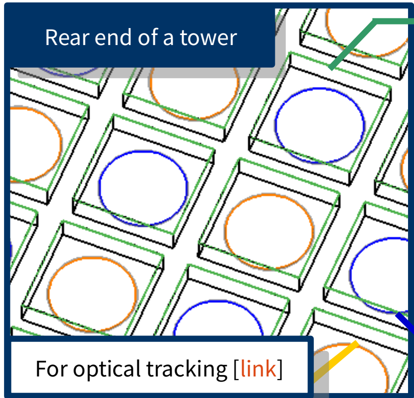


Attenuation loss diverges at 400nm → applied filter to S channel to mitigate it

Scintillation spectra of PS

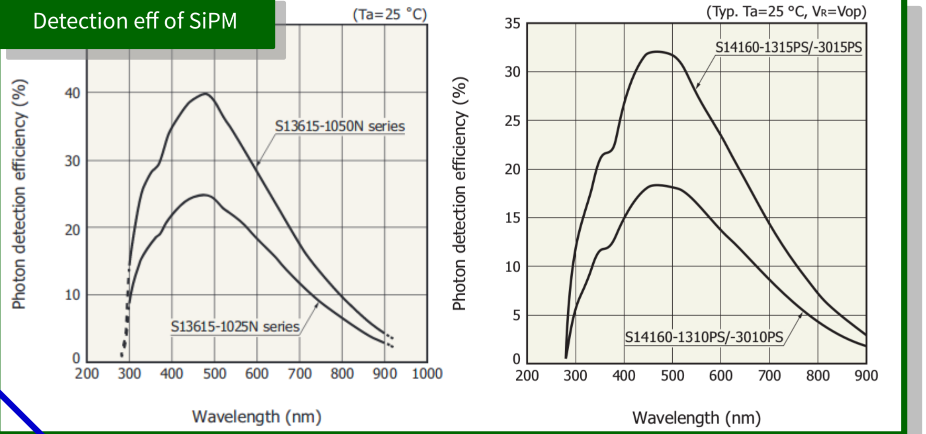


Rear end of a tower



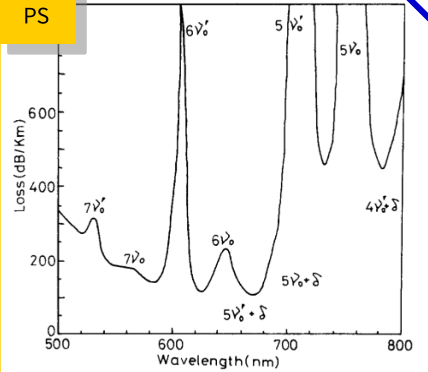
For optical tracking [link]

Detection eff of SiPM

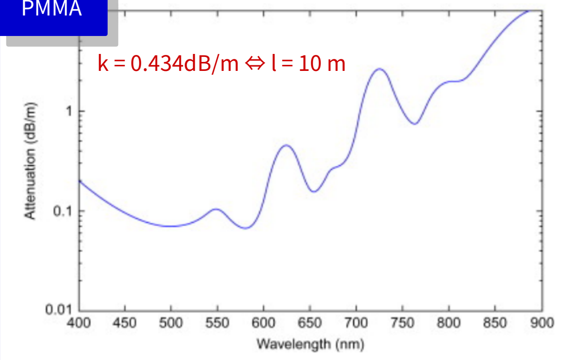


Attenuation loss of Polystyrene (PS) & PMMA

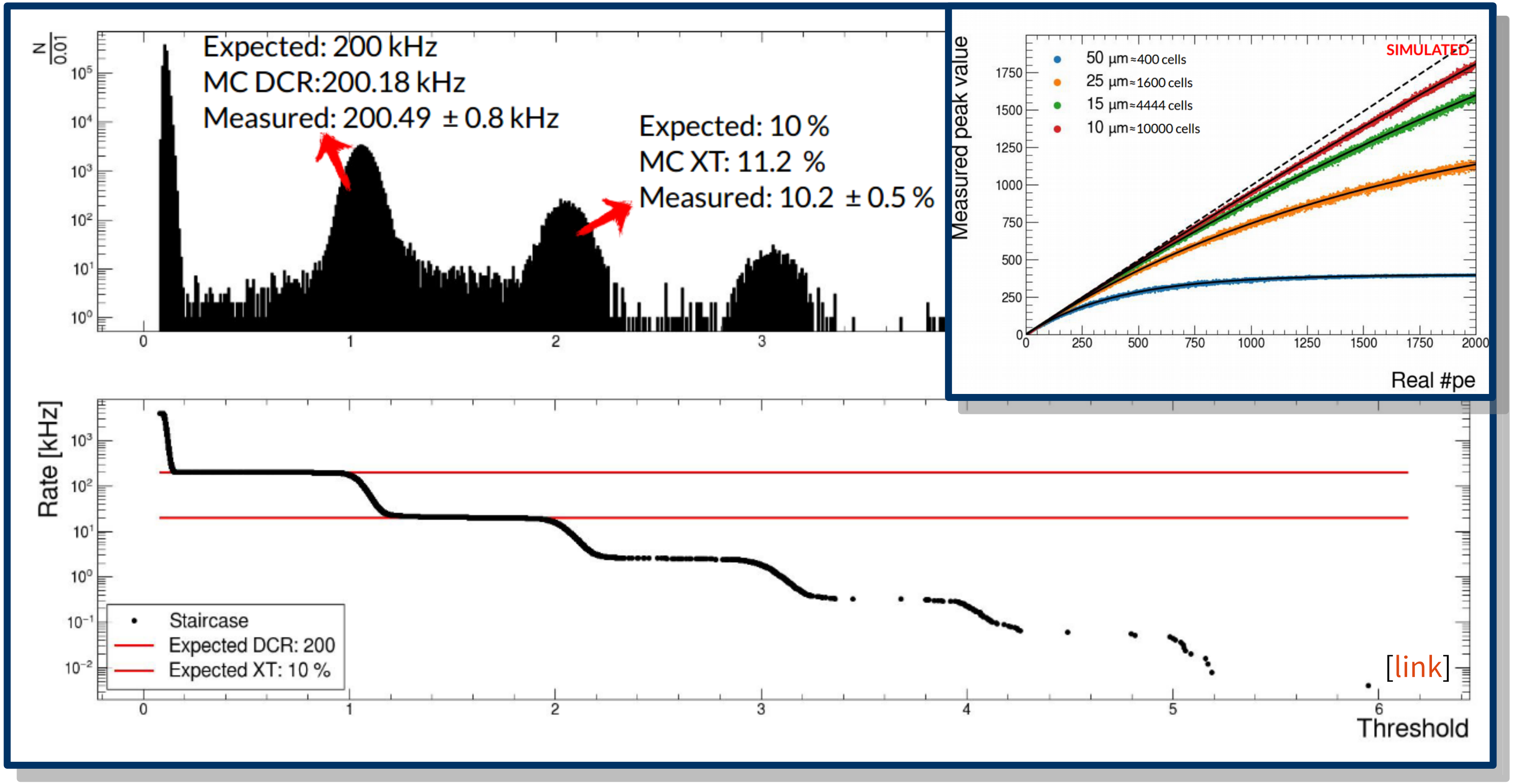
PS



PMMA



SiPM emulation



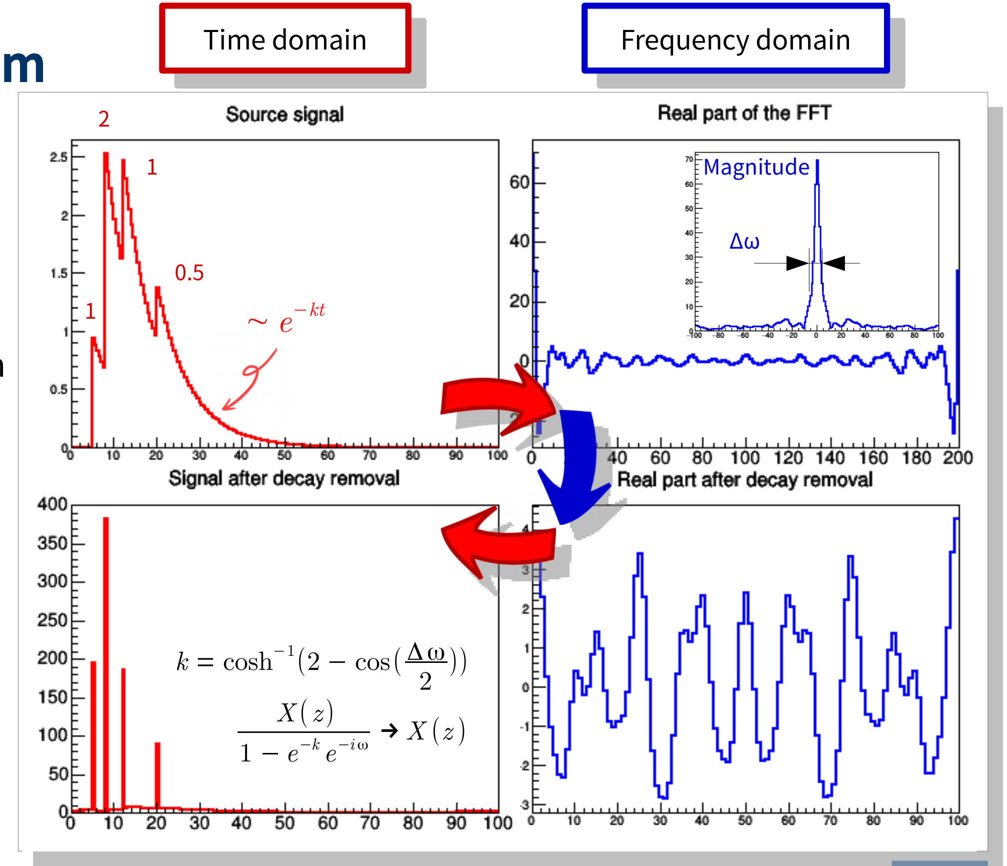
[link]

Longitudinal shower shape

Shower shape & timing – SiPM waveform

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

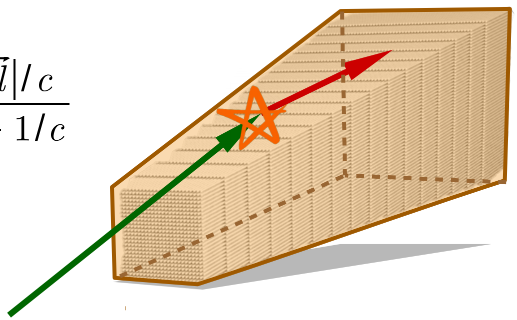
  → very challenging due to many hidden layers
- A SiPM yields exponentially decaying waveform to 1 photon
- FFT can be used to mitigate exponential tail, while preserving time translation & amplitude information



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

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

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

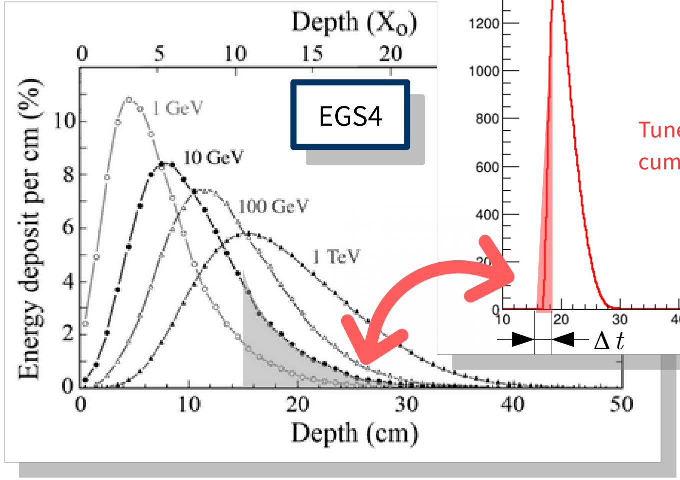


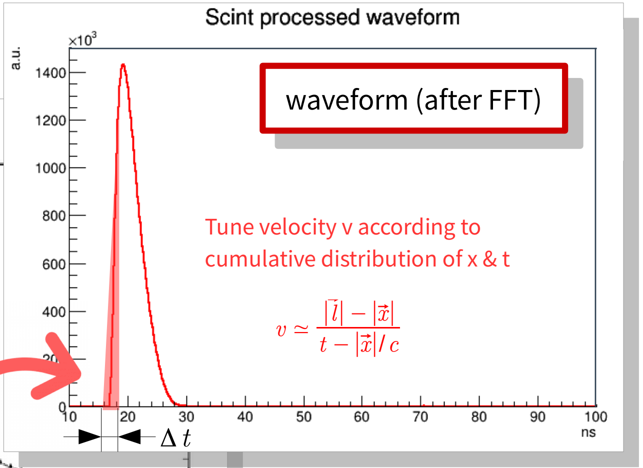
Longitudinal shower shape

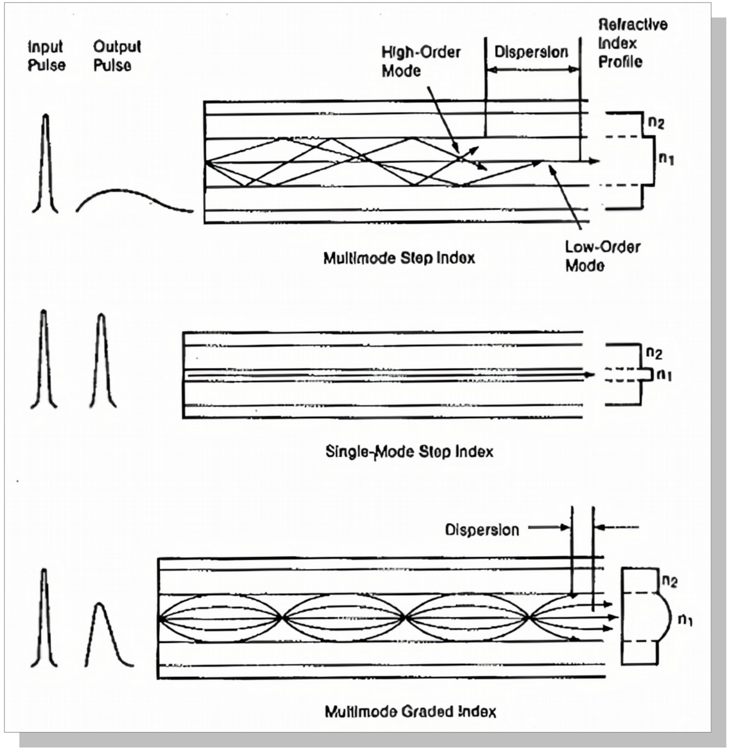
Shower shape & timing – Dispersion

- 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







Longitudinal shower shape

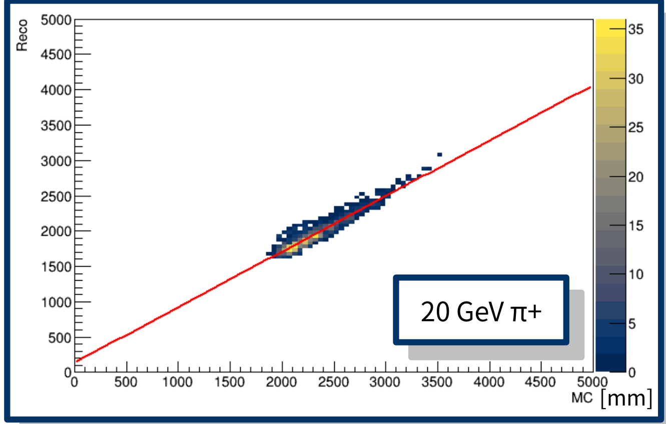
Longitudinal shower depth & length

- Able to obtain linear correlation of both shower depth & length simultaneously
  - Depth shows good correlation between MC vs Reco
  - Length shows moderate correlation

  → remains of unmitigated shower head (mainly dispersion)
- Longitudinal shape with excellent lateral granularity → 3D reconstruction

	Simulation setup
Timing resolution	Ideal (assume ~ O(10 ps))
Sampling rate	100 ps

Depth



Length