Reconstruction of 3D shower shape with the dual-readout calorimeter

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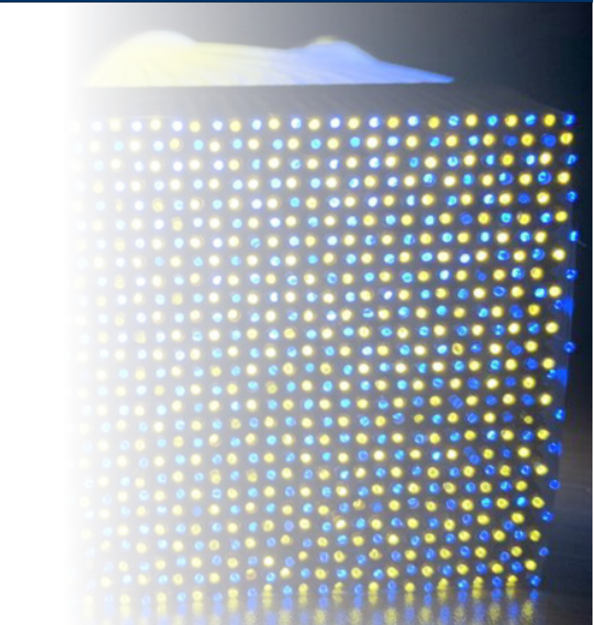
on behalf of the dual-readout calorimeter team

18th May 2022, CALOR2022



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

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

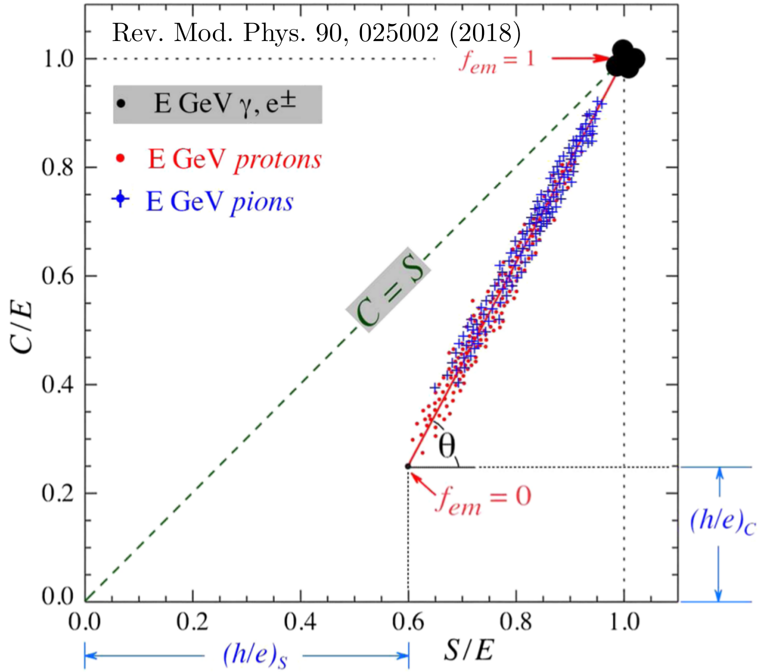
$$C = E[f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em})]$$

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

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

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

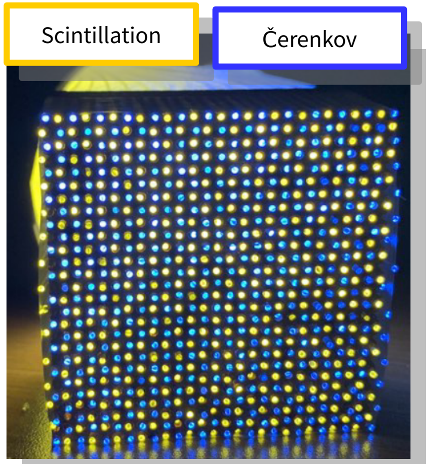
- Excellent energy resolution for hadrons can be achieved by measuring f_em and correcting the measurement event-by-event
- Dual-readout fiber-sampling calorimeter is a key element of the IDEA detector concepts

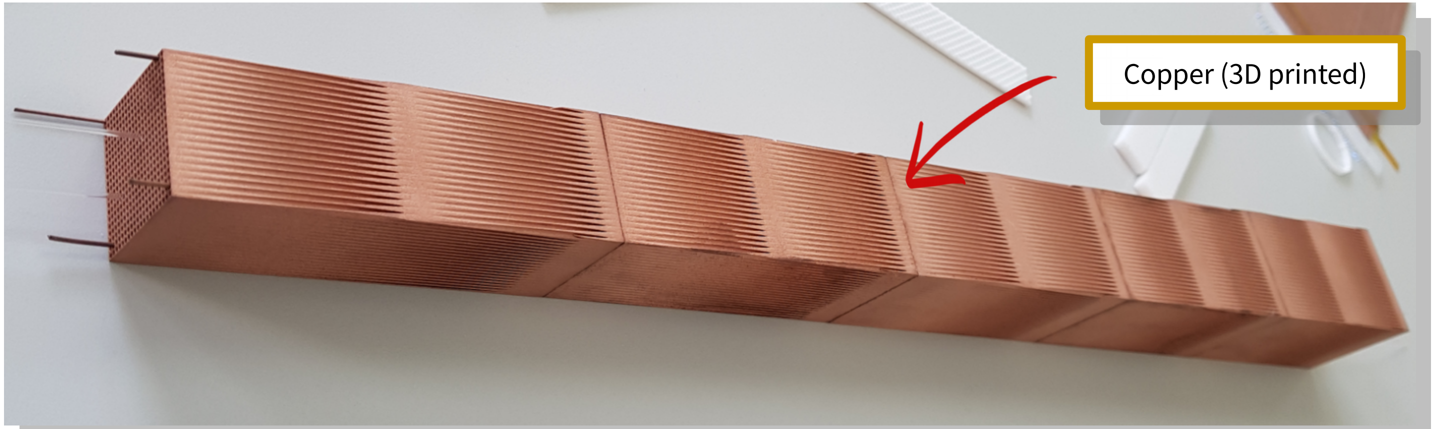


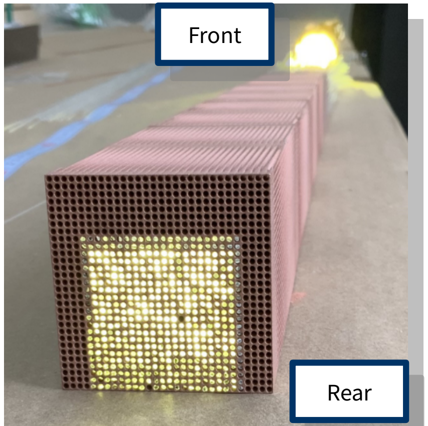
Energy measured from scintillation channel vs Čerenkov channel for EM particle, π & p

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

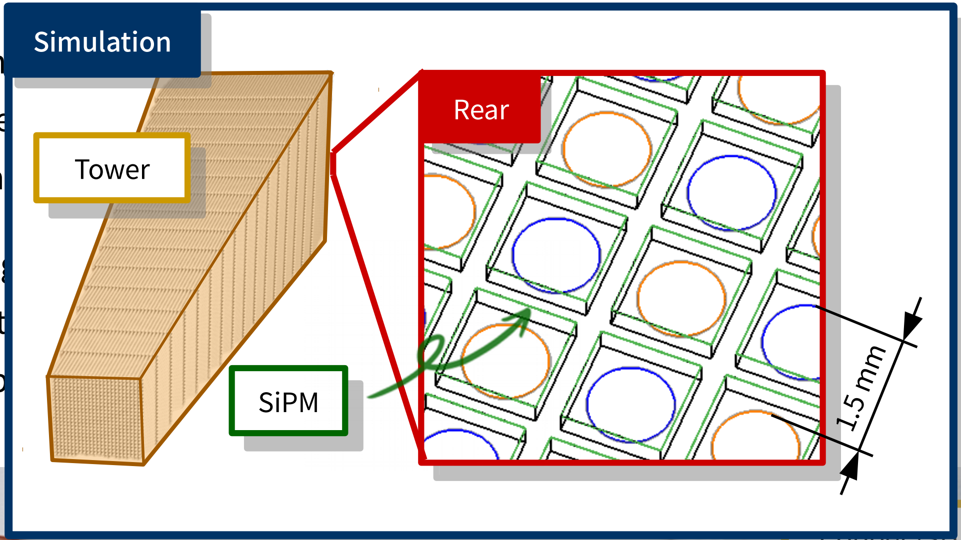


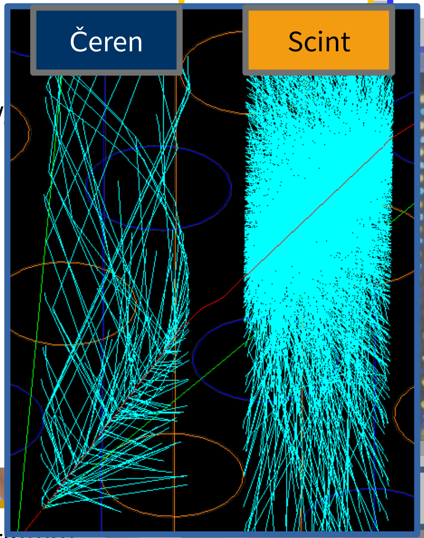


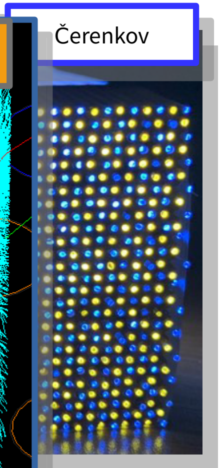


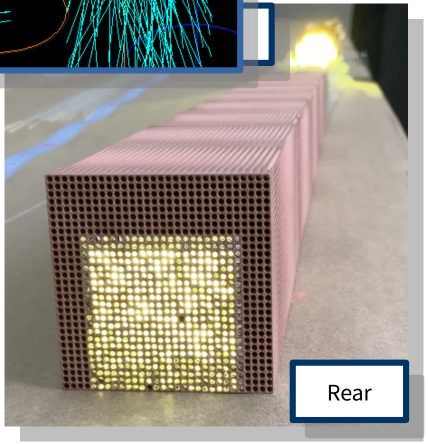
Dual-readout calorimeter

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





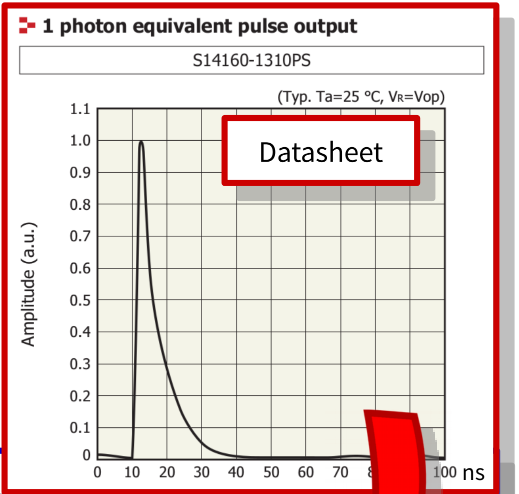


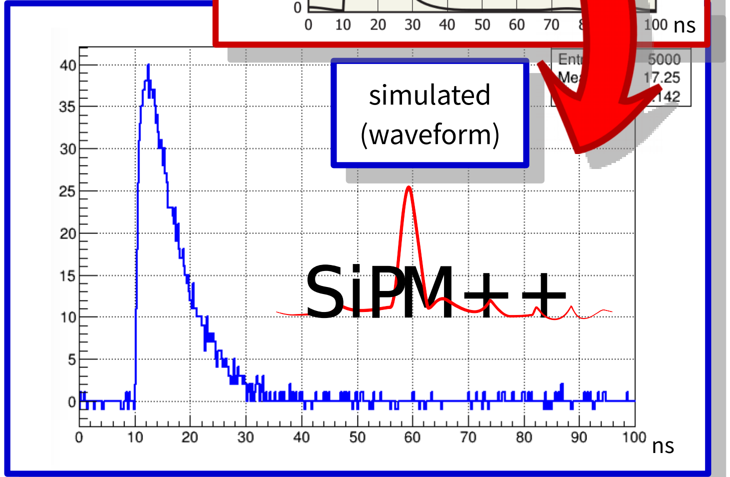


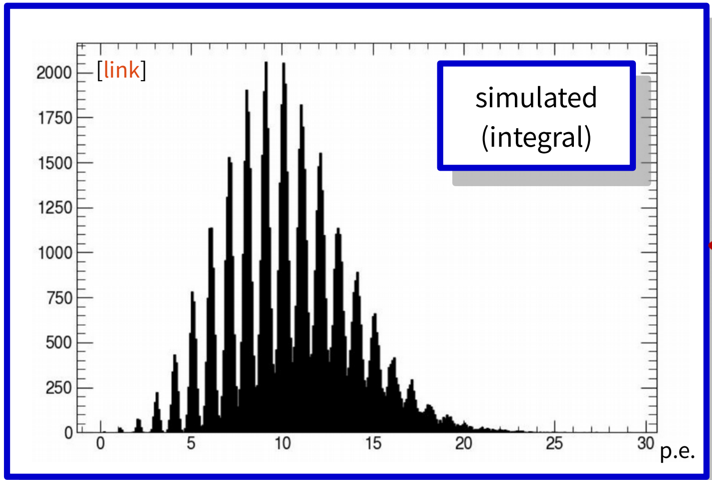
SiPM emulation

Simulating SiPM response with SimSiPM

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



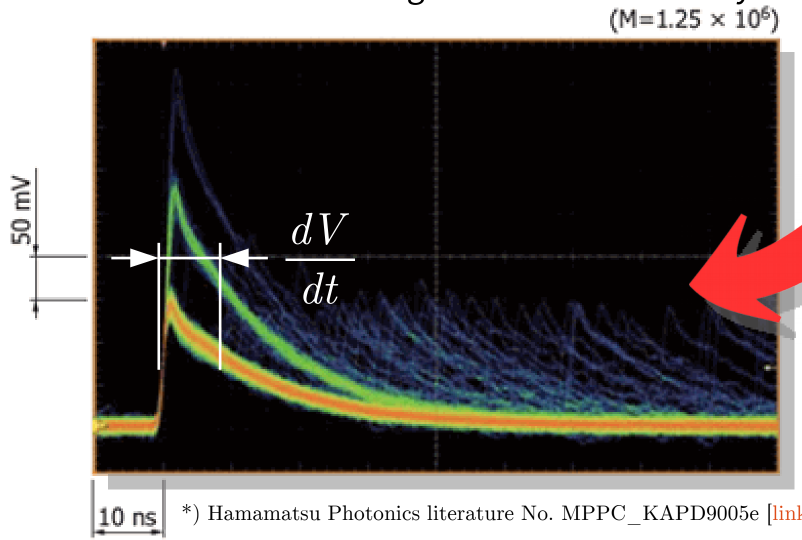




Shower shape & timing

Breaking down timing

- For fiber-sampling calorimeters, the conventional approach to get longitudinal info is taking the time of peak/arrival
  → ignores details aside from shower maximum depth
- Full recovery of longitudinal shower shape
  → utilization of entire timing structure is necessary



*) Hamamatsu Photonics literature No. MPPC_KAPD9005e [link]

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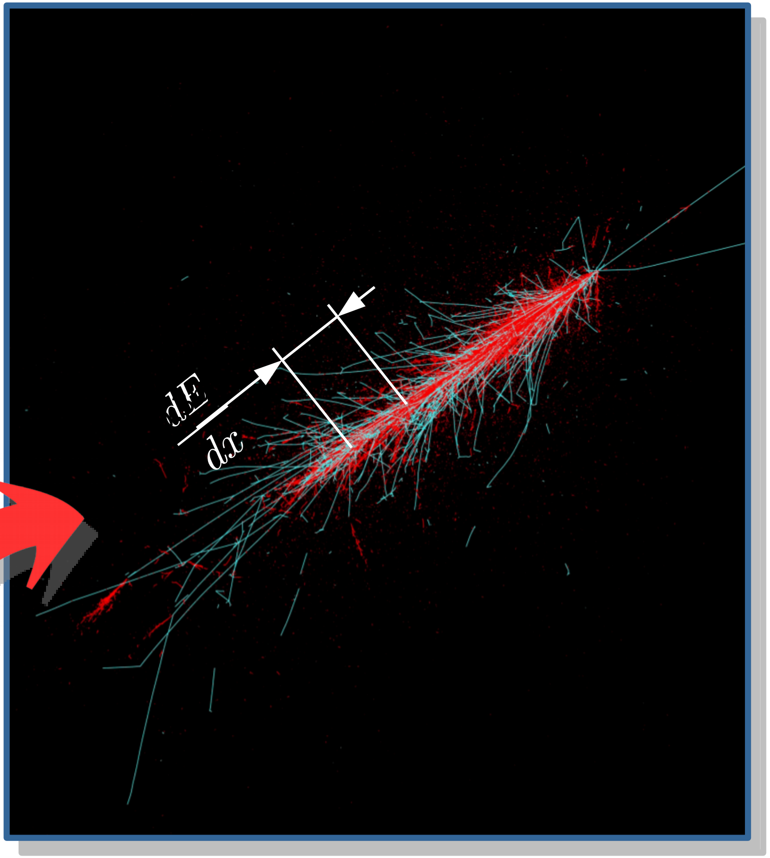


Longitudinal shower shape

Shower shape & timing – SiPM waveform

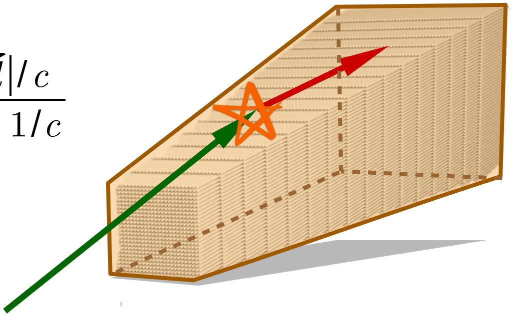
- Unsegmented calorimeter fully depends on the timing to reconstruct longitudinal shower shape
- Is dV/dt → dE/dx possible?

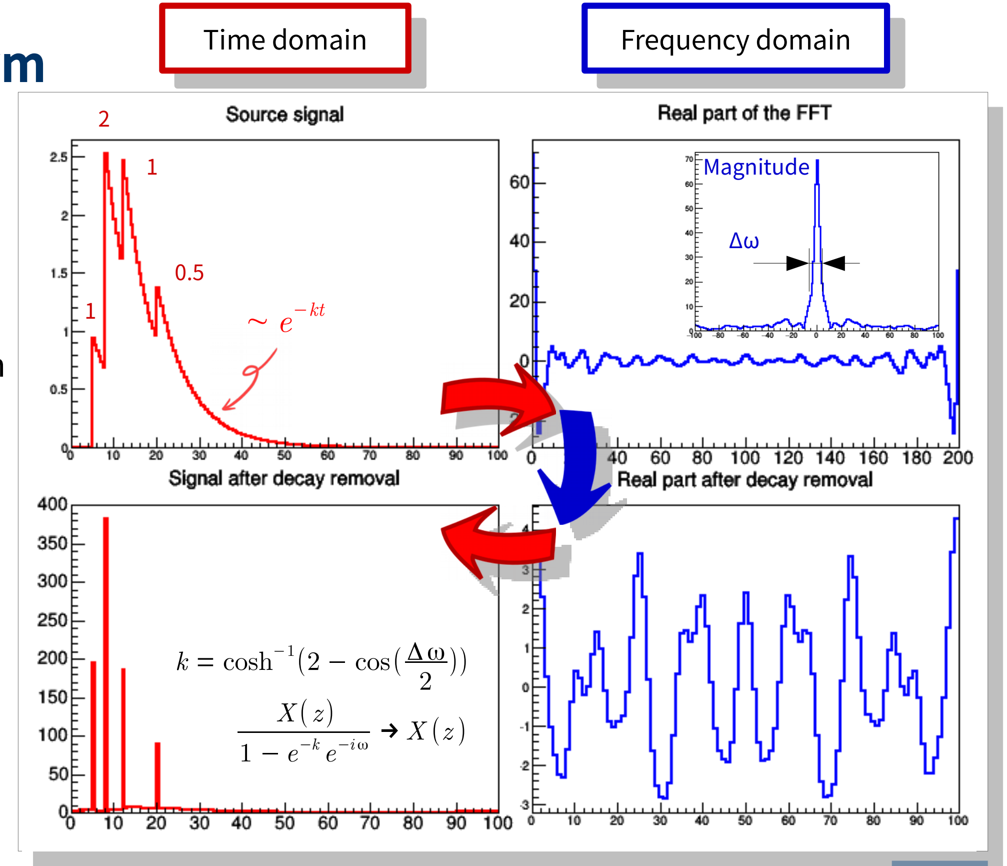
  → very challenging due to many hidden layers
- A SiPM yields exponentially decaying waveform to 1 photon
- FFT can be used to mitigate exponential tail, while preserving time translation & amplitude information

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

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

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



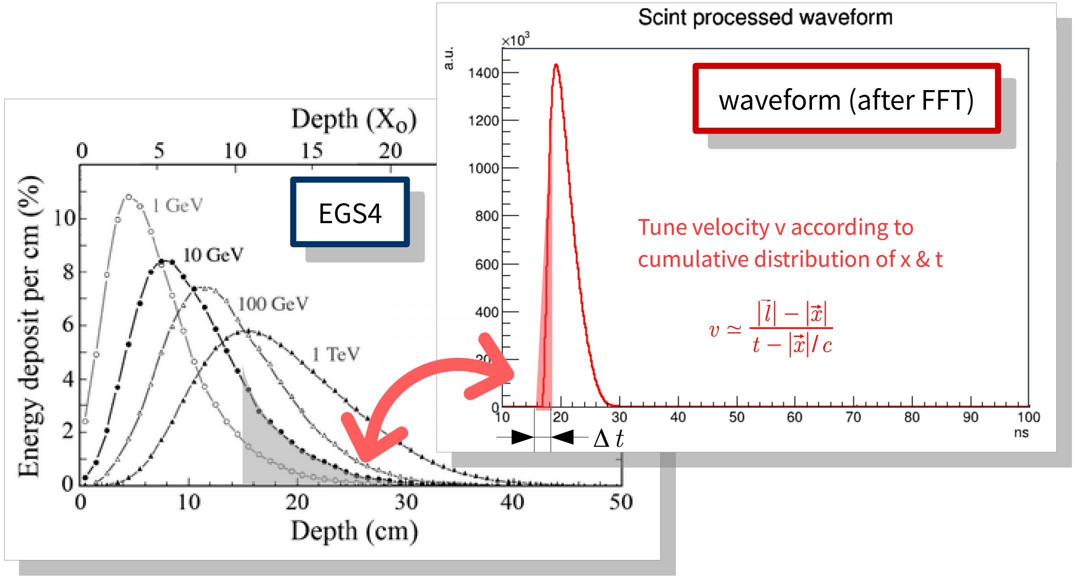


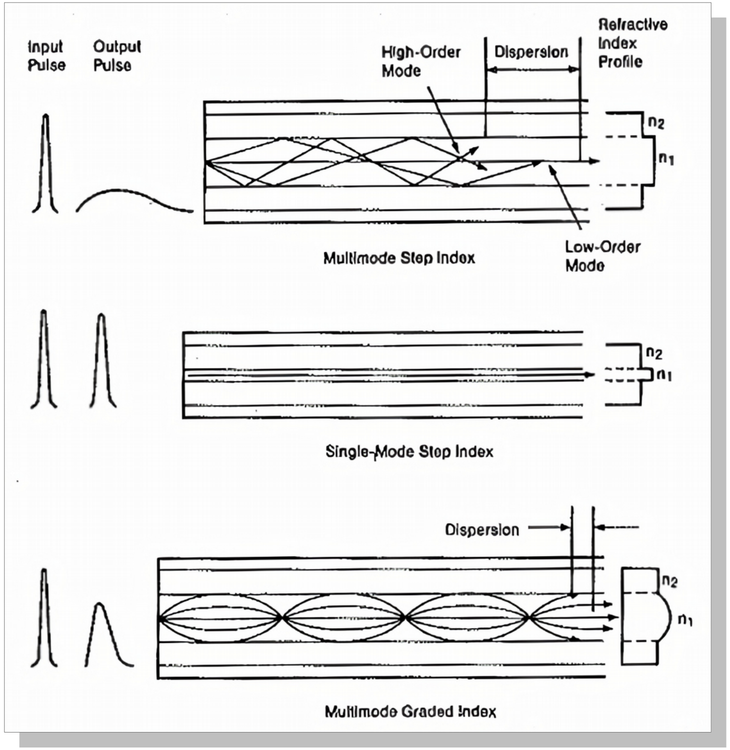
Longitudinal shower shape

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



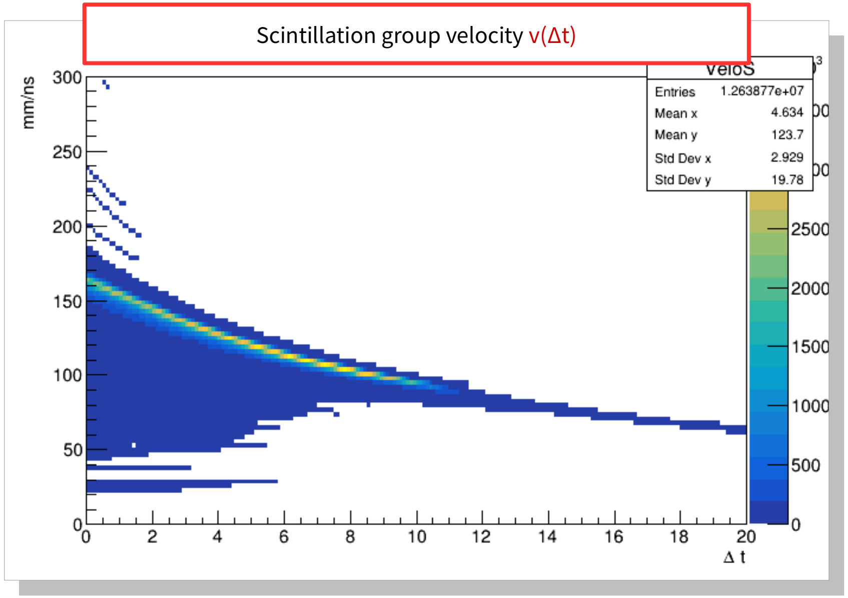


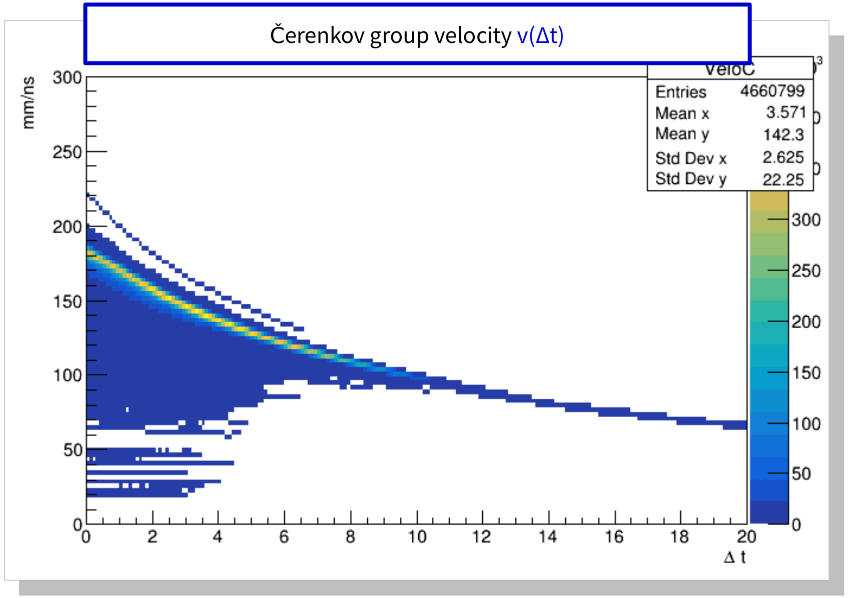
Modal dispersion

Group velocity modeling

- Assign slower group velocity for the late-components at $t = t_0 + \Delta t$ (ToA)
- Apply tuning according to cumulative distribution of dE/dx & dV/dt with 20 GeV e-

  → profile group velocity for every fiber by assuming the longitudinal shape (EM shower template)





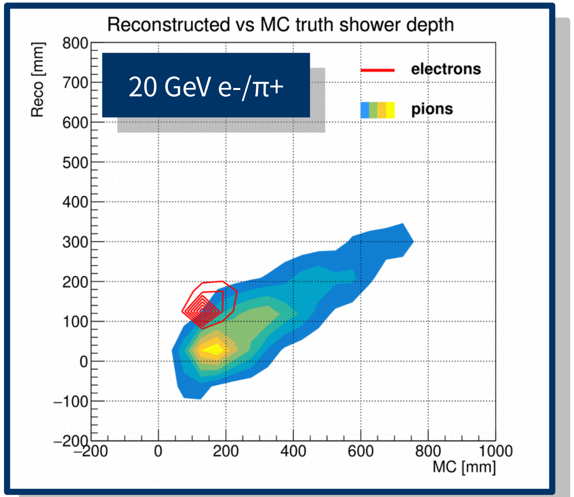
Longitudinal shower shape

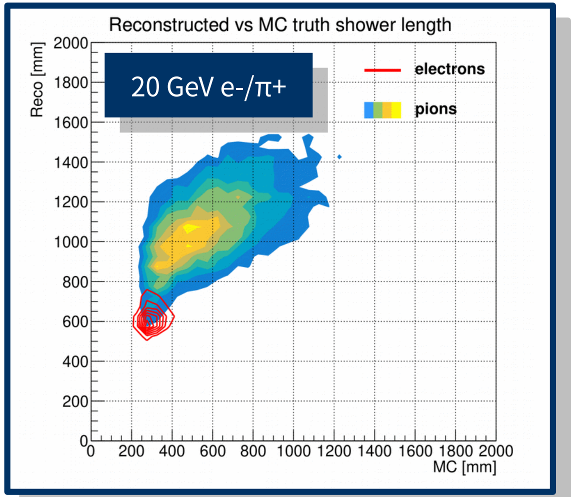
Longitudinal shower depth & length

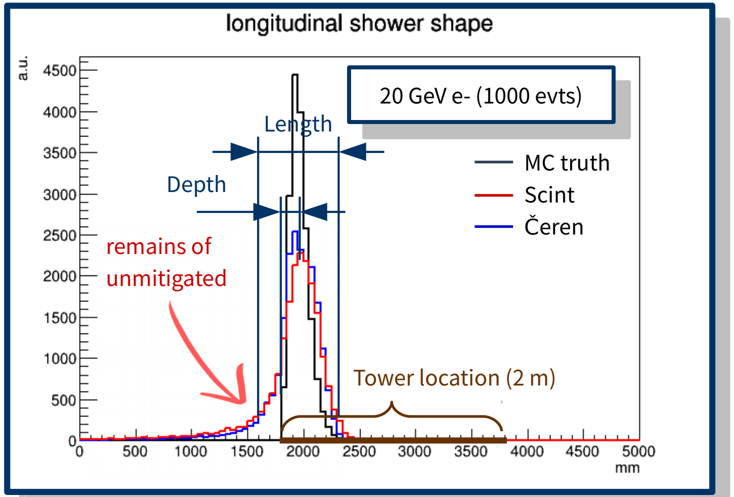
- Able to obtain linear correlation of both shower depth & length simultaneously
  - Depth shows good correlation between MC vs Reco
  - Length shows moderate correlation

  → 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

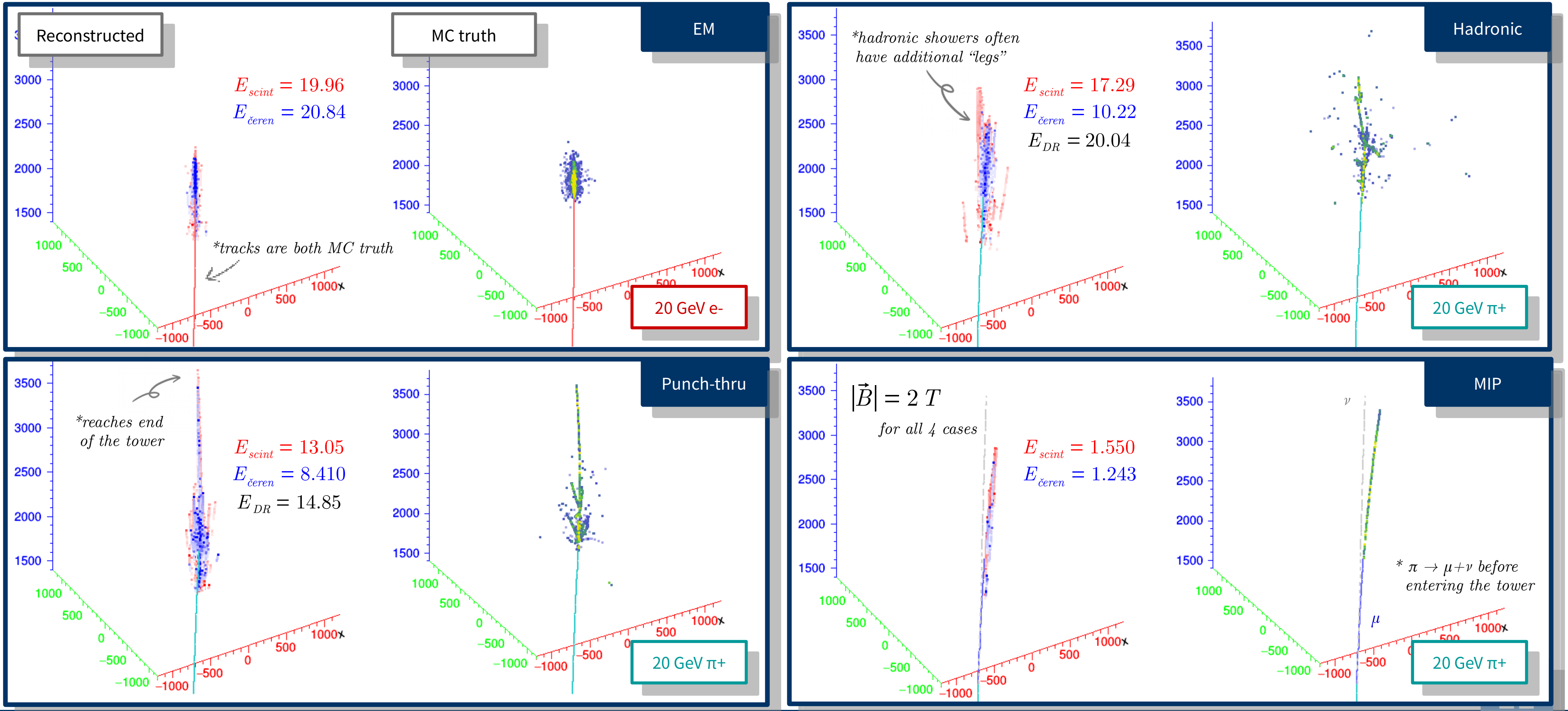






*) contributed to Snowmass21 white paper arXiv:2203.07286

3D reconstruction



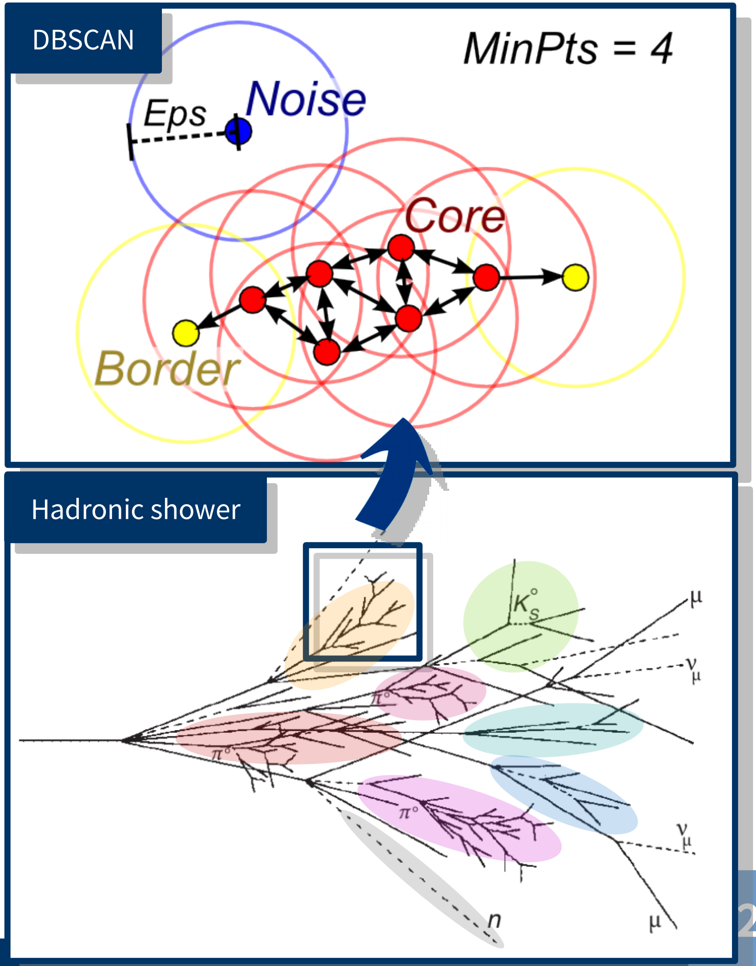
Shower substructure

Probing shower substructure with DBSCAN

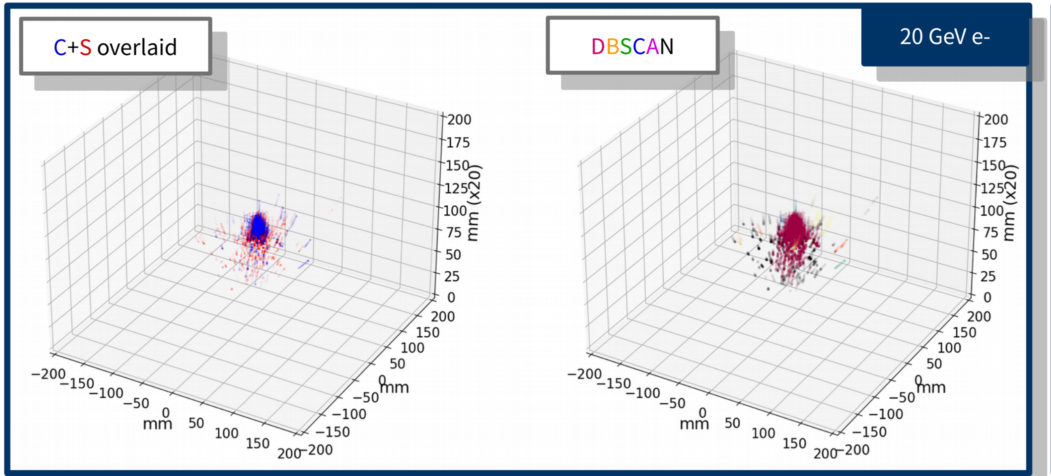
- start to look into basic properties with 3D shower shape
  → counting the # of substructures

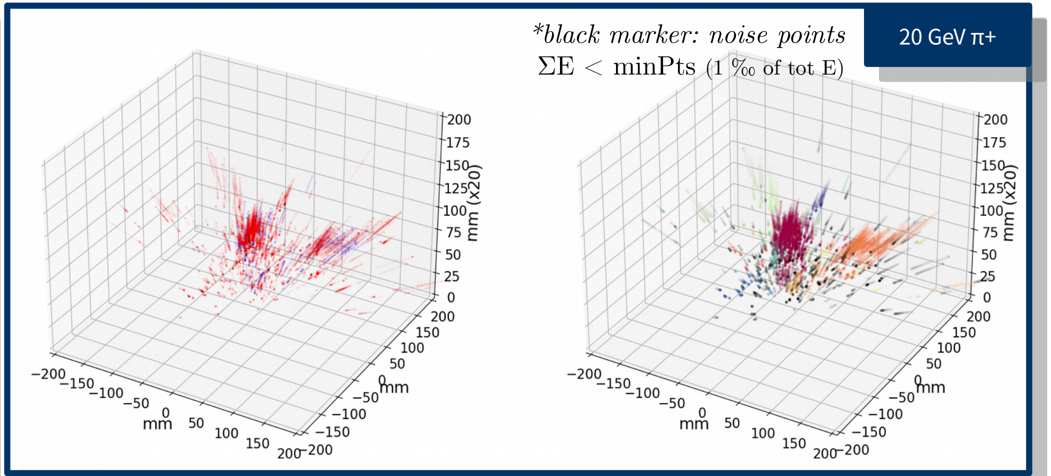
- DBSCAN (density-based clustering) has useful characteristics to cluster (hadronic) shower substructures
  - 1) does not require the # of clusters a priori
  - 2) suitable for arbitrary-shaped clusters
  - 3) able to weight each point

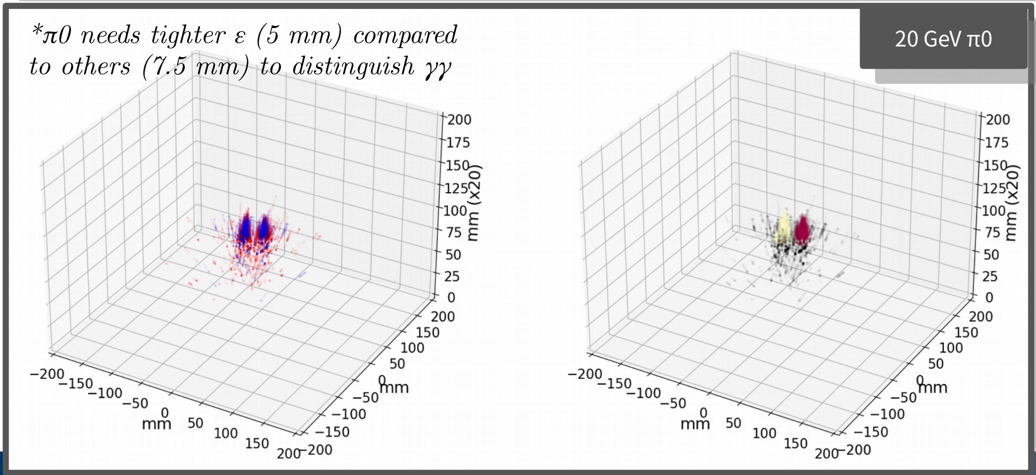
- However, DBSCAN does not consider different lateral (1.5 mm) & longitudinal (100 ps ≈ 4 cm) binning accuracy
  - scale the longitudinal direction by the factor of 20 to match the accuracy of each direction

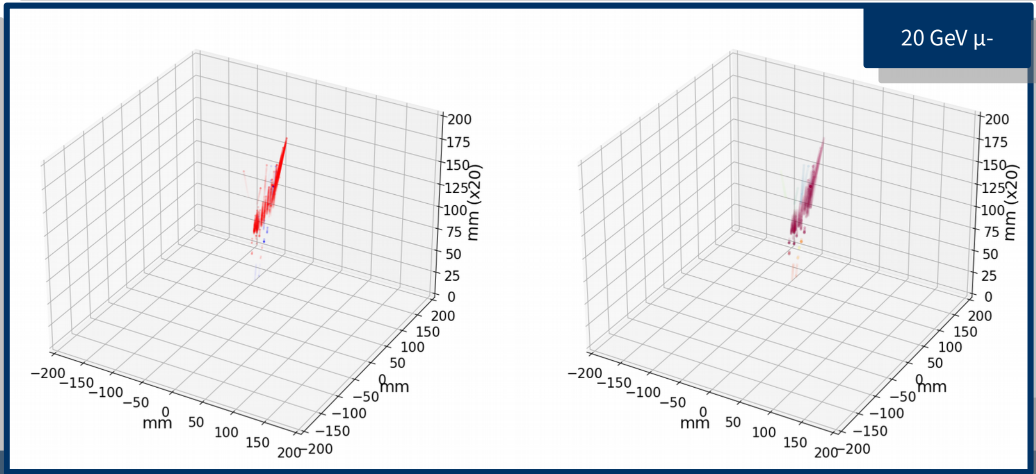


Shower substructure





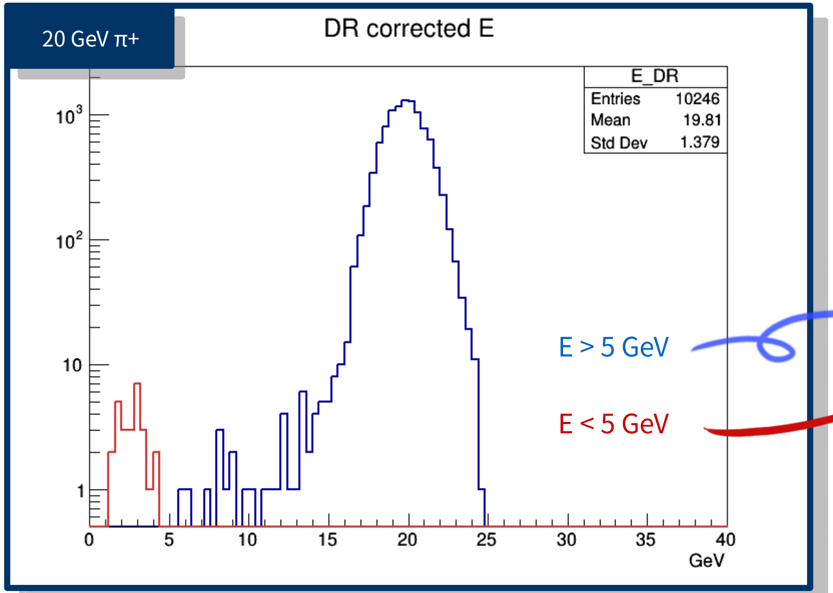


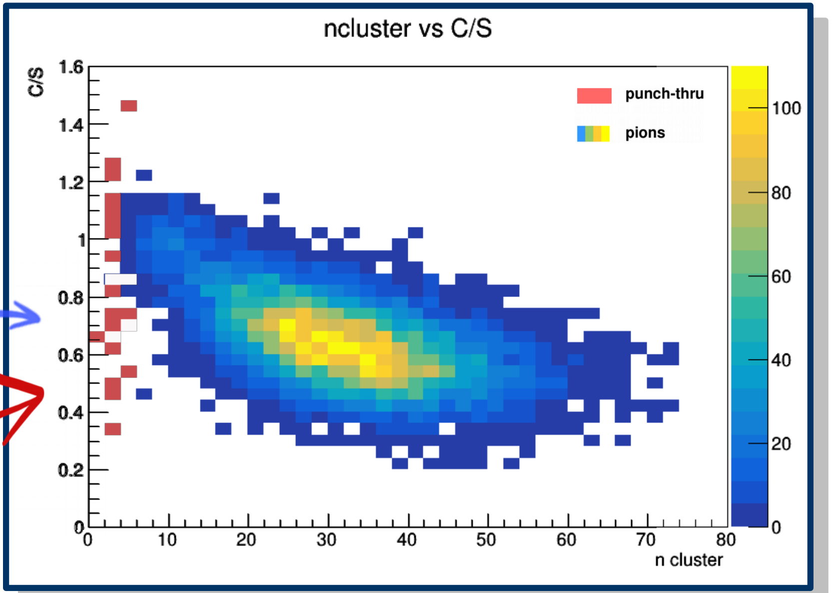


of clusters vs C/S

Hadronic punch-thru ID via substructure clustering

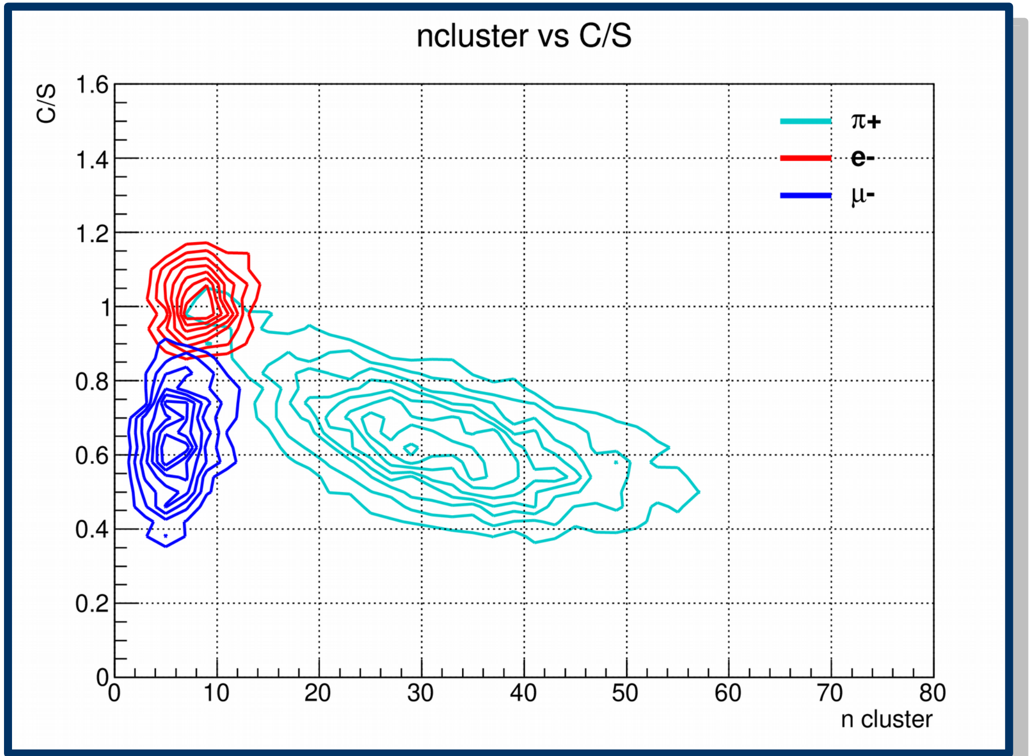
- # of clusters provides an orthogonal source of the information
- mixing it with the classic C/S of DRC can bring insights to the behavior of showered particles
  → hadronic particle showers to fully EM component, punch-thru, .etc

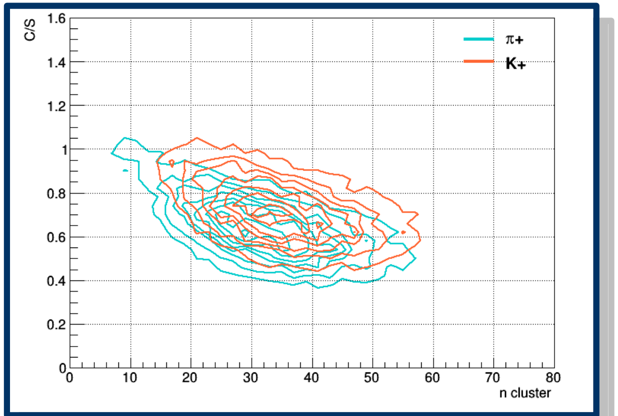


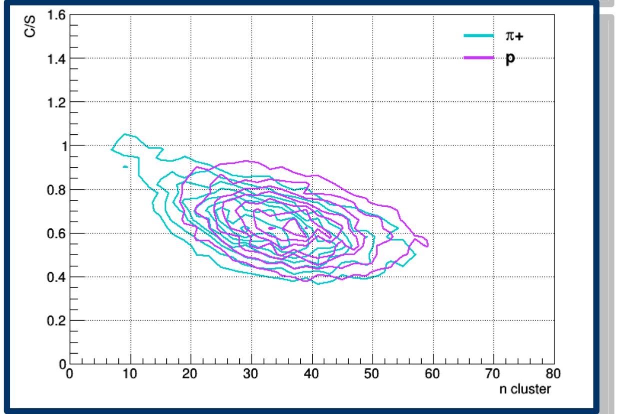


of clusters vs C/S

Particle ID with substructure clustering



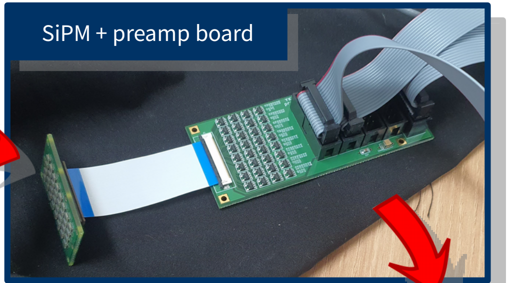


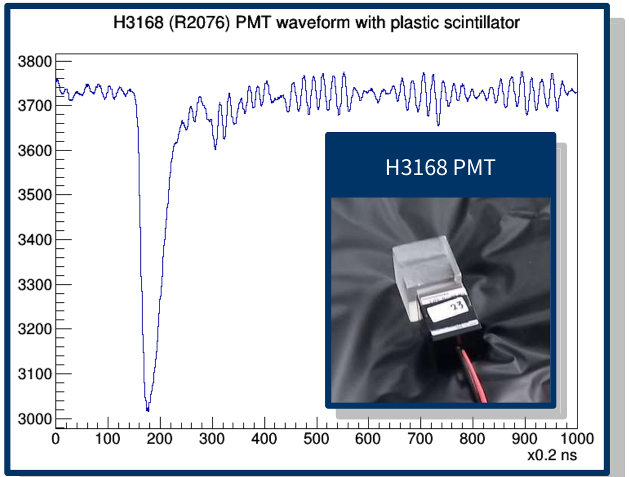


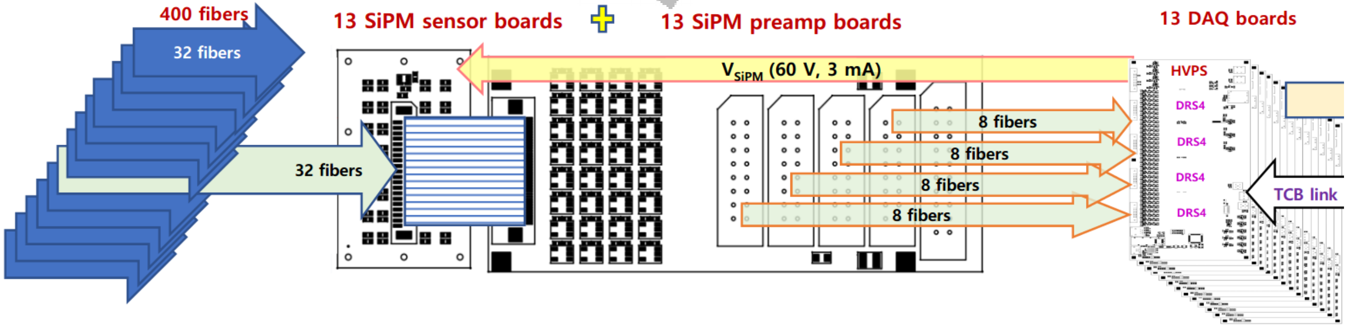
Hardware efforts

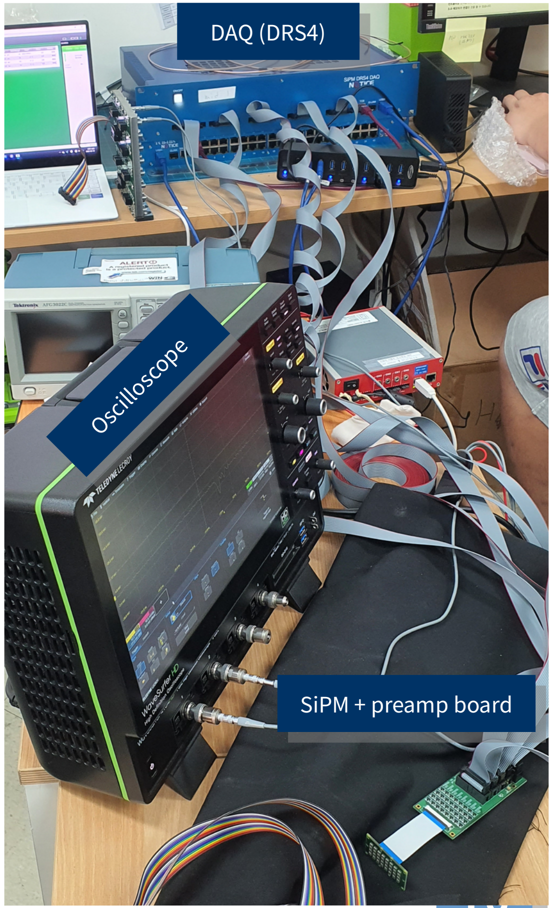
Towards the proof of concept

- Started lab tests with SiPM + readouts
- Plan to collect waveforms at SPS H8 in August (in prescaled mode – 67kB/32ch per event)







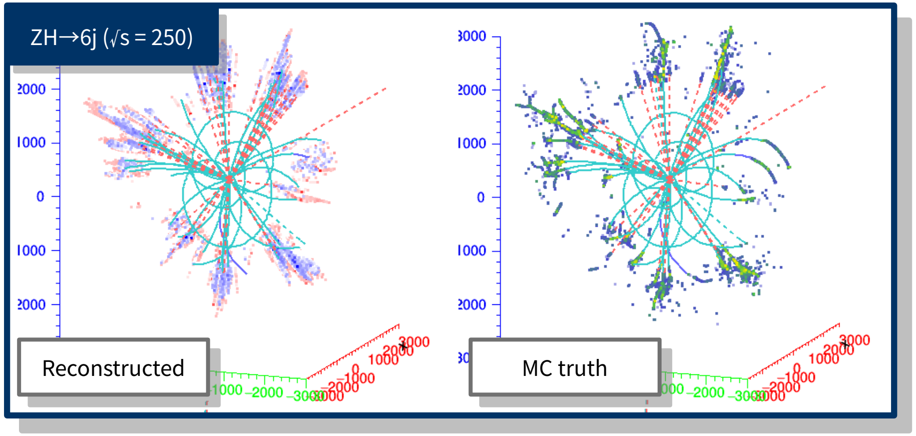


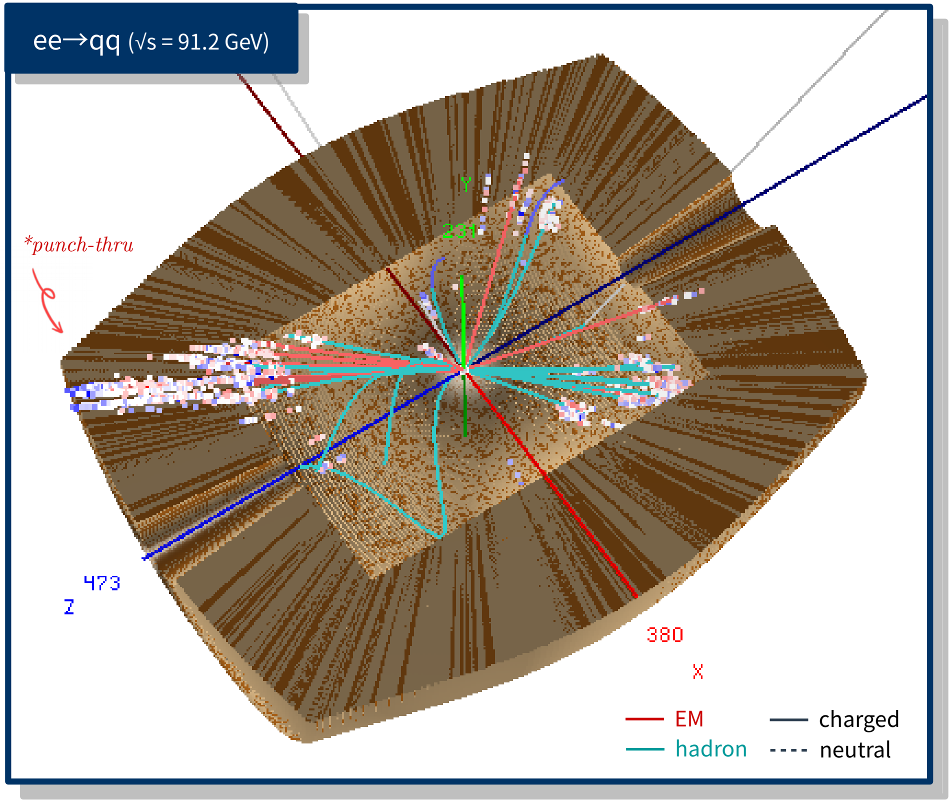
Summary

Longitudinal & 3D reconstruction

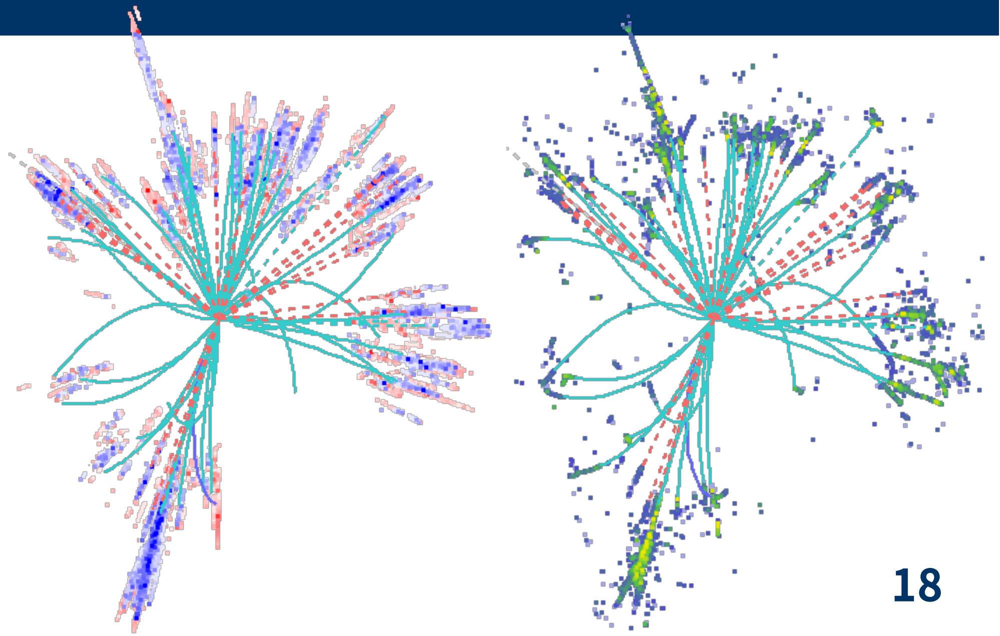
- Dual-readout calorimeter has shown excellent performance with simulations through past years
- Developing novel ideas to exploit timing information for longitudinal & 3D reconstruction

  → first 3D reconstruction with fiber-sampling calorimeter
- Many exciting challenges are ahead of us…





Backups



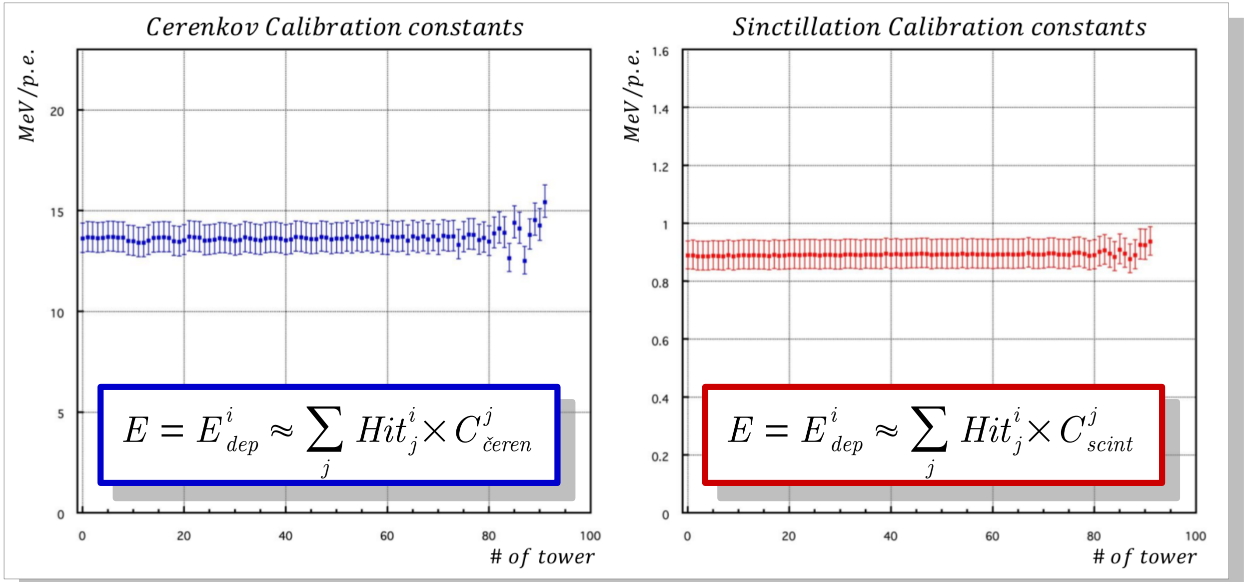
Calibration

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

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

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



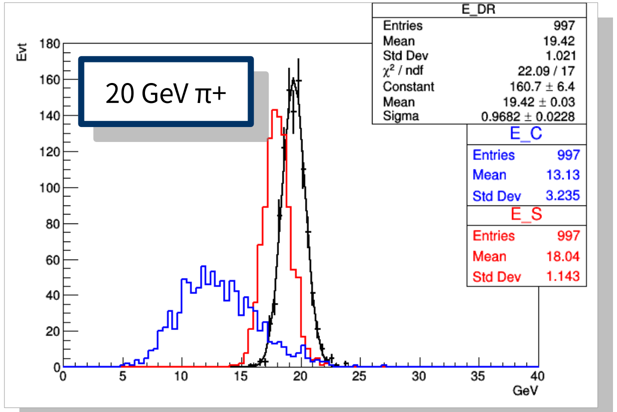
$$E = E^i_{dep} \approx \sum_j Hit^i_j \times C^j_{čeren}$$

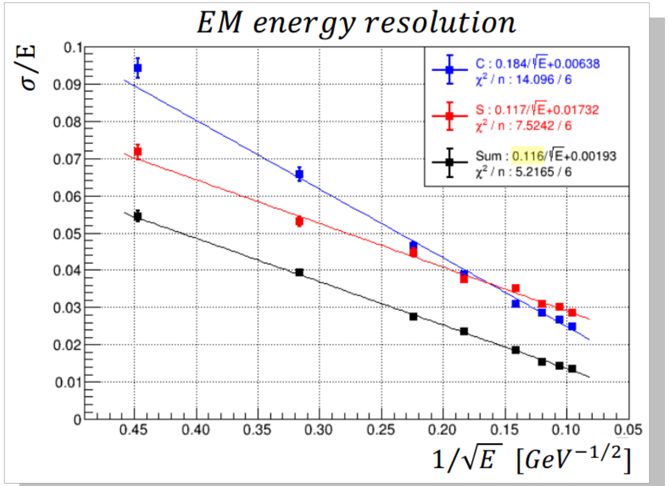
$$E = E^i_{dep} \approx \sum_j Hit^i_j \times C^j_{scint}$$

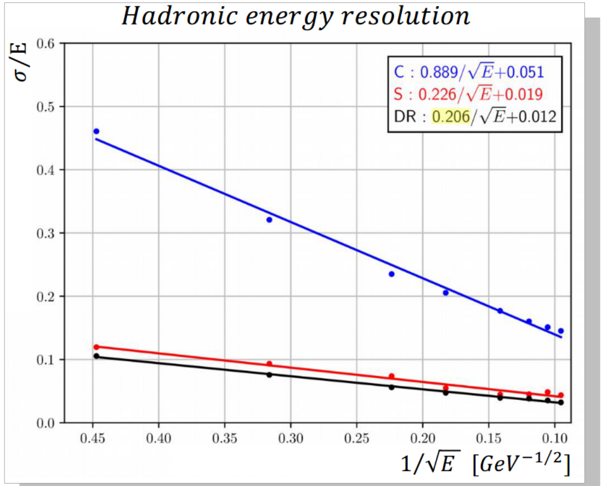
Energy resolution

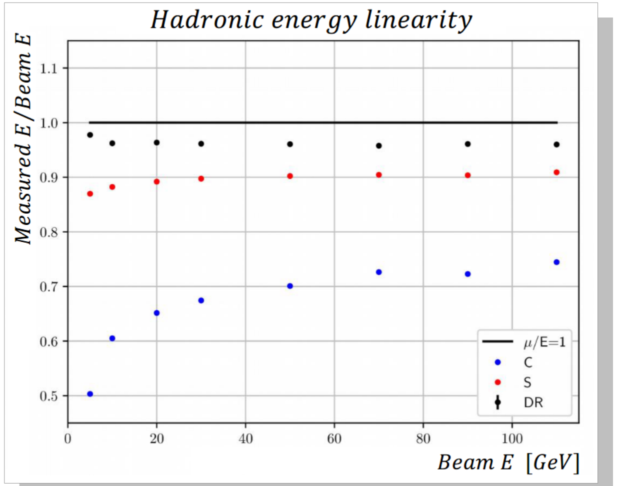
Estimation of energy resolution with GEANT4

- GEANT4 shows excellent energy resolution for both EM & hadronic showers
  → 11.6%/√E (EM) 20.6%/√E (Hadronic)
- Moving forward to demonstrate energy resolution with the beam test data
  → details presented by INFN colleagues [link]





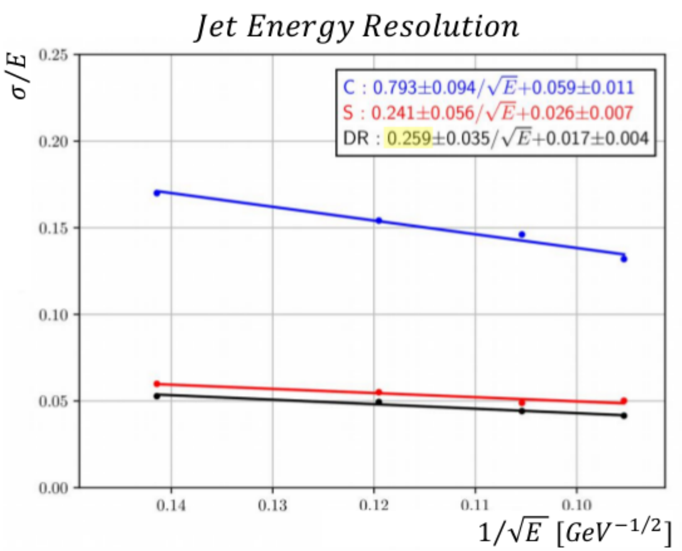


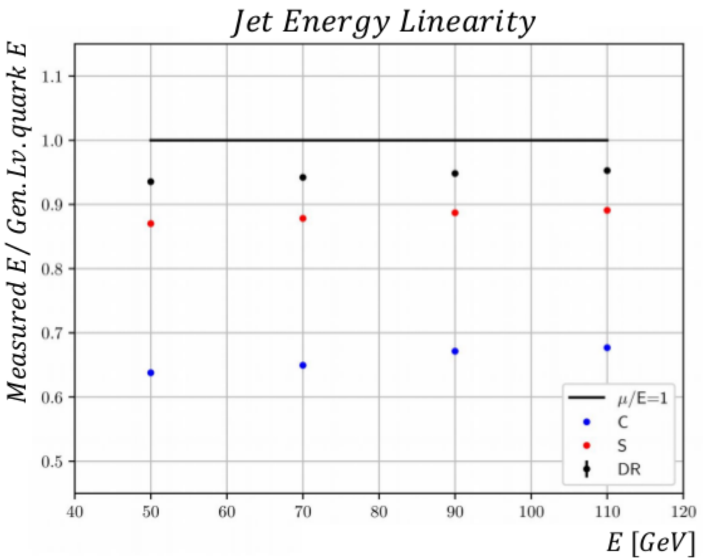


Jet energy resolution

JER with ee → uu events

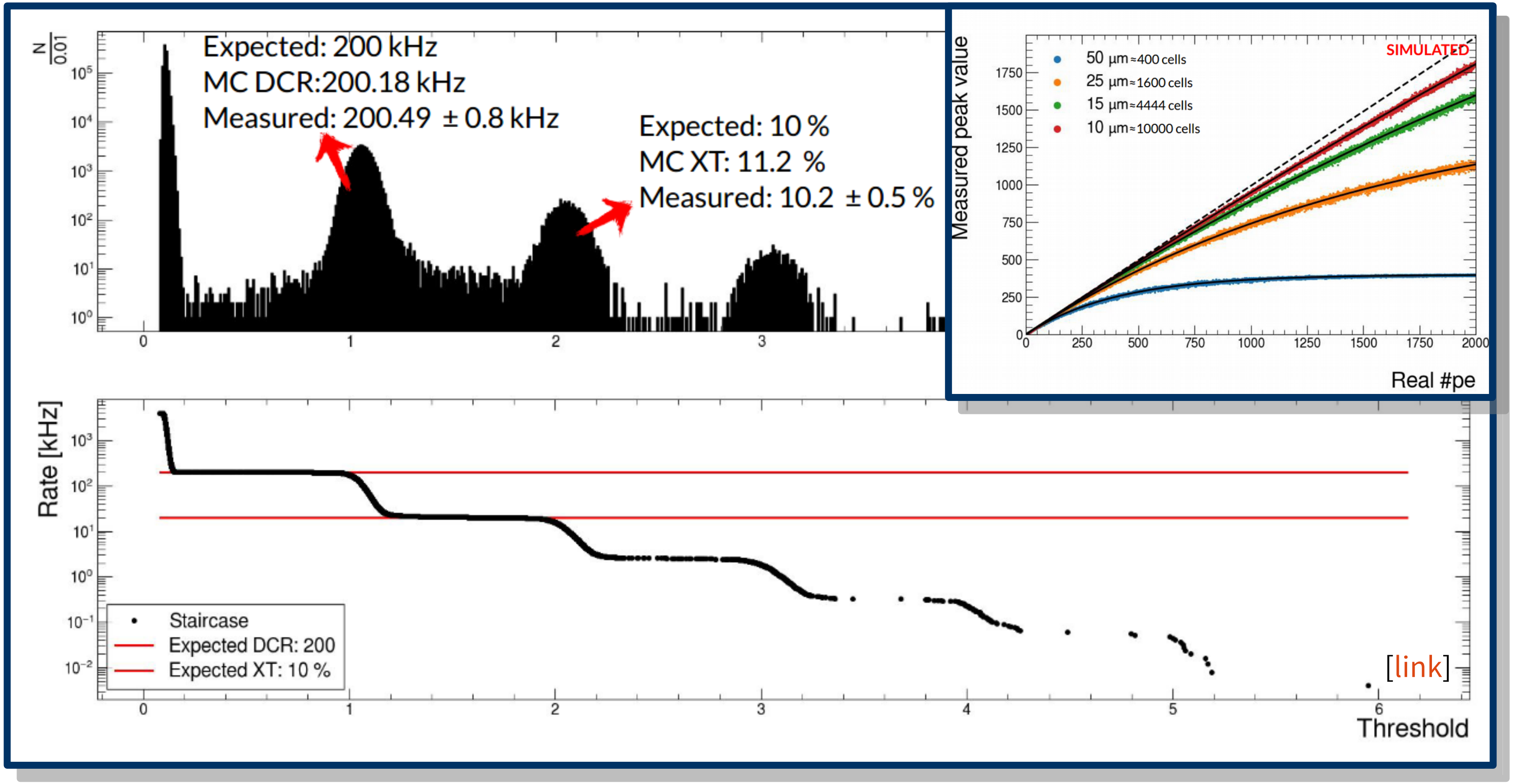
- Resolution is scaled to $1/\sqrt{E}$.
- Stochastic term and constant term of resolution is estimated by linear fitted result





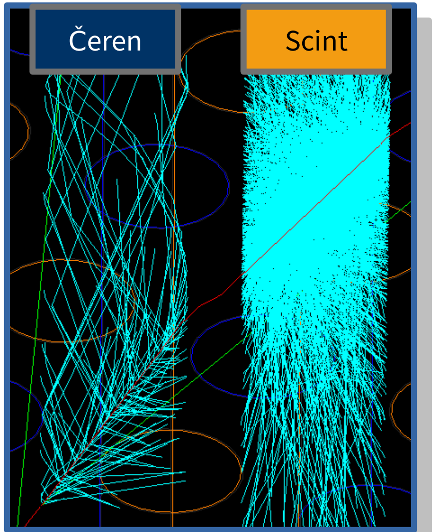
- Stochastic term for jet energy resolution is **~26%**.
- JER for 100GeV jet is ~3.1%. It satisfies requirement which proposed at CDR of FCC-ee and CEPC.

SiPM emulation

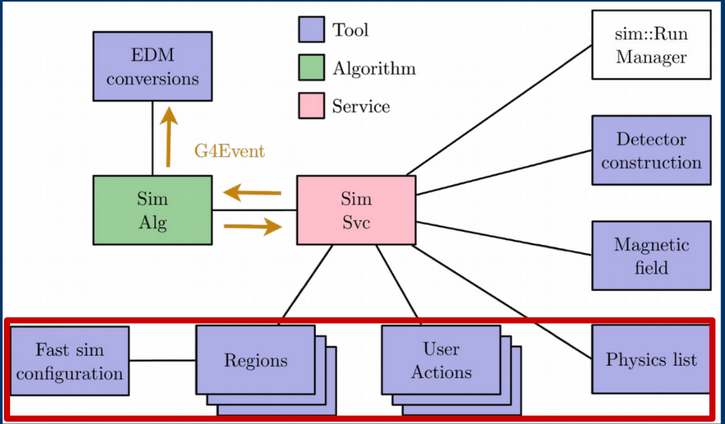


Optical physics simulation

- 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

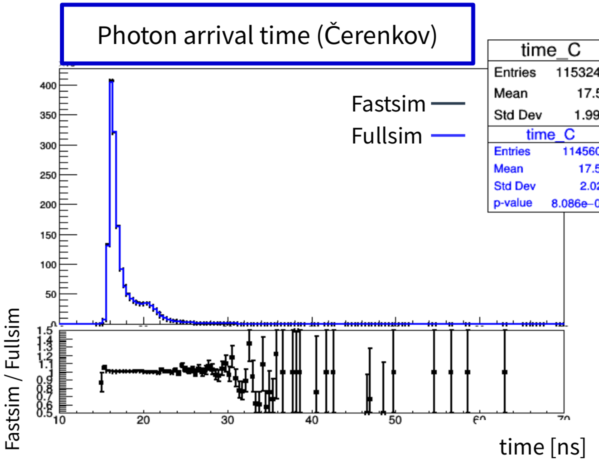
```
regionTool = SimG4FastSimOpFiberRegion("fastfiber")
opticalPhysicsTool = SimG4OpticalPhysicsList("opticalPhysics", fullphysics="SimG4FtfpBert")
physicslistTool = SimG4FastSimPhysicsList("Physics", fullphysics=opticalPhysicsTool)

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
)
```

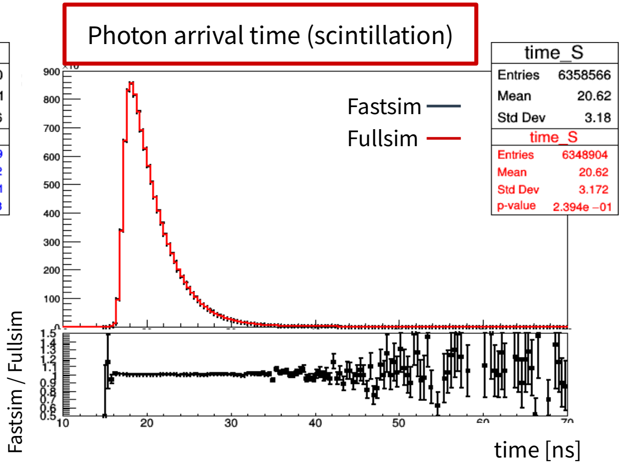
Speeding up optical photon tracking

Fast optical photon tracking

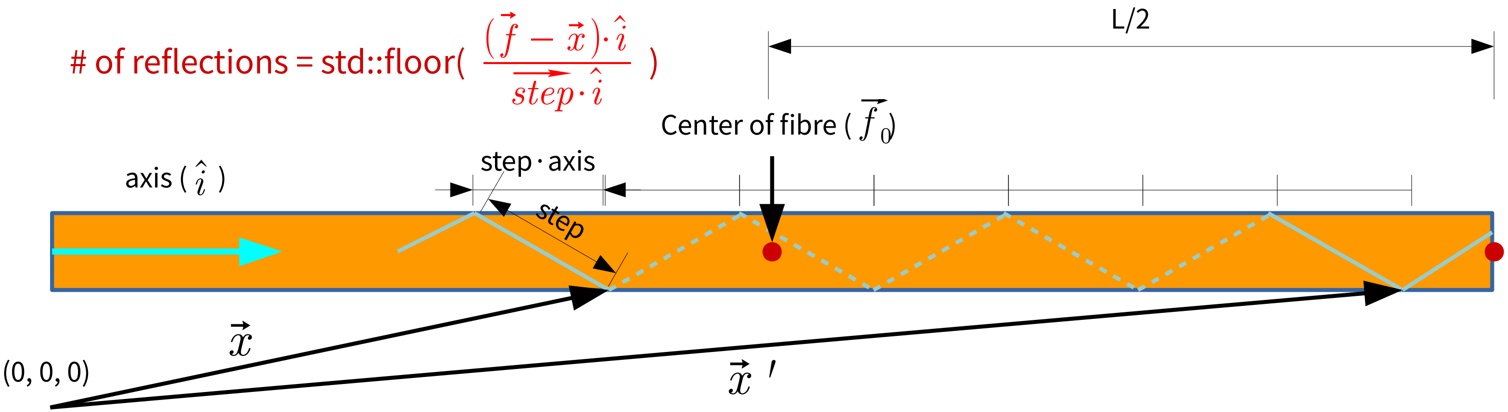
- Tracking optical photons is necessary, however it dominates CPU consumption
- Optical photons inside fibers can be tracked efficiently, by skipping intermediate steps

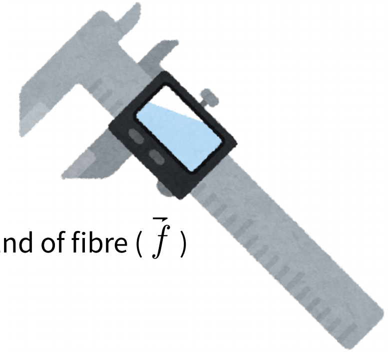
  → developed fastsim for optical photons (presented at GEANT4 R&D meeting [link])





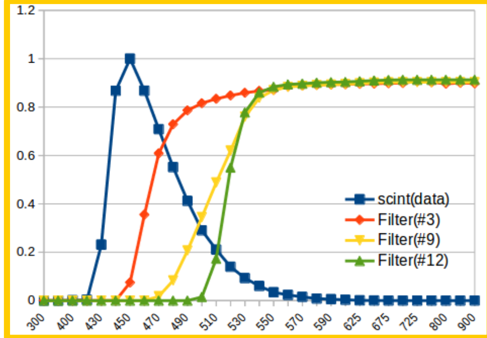
# of reflections = std::floor($\frac{(\vec{f}-\vec{x})\cdot\hat{i}}{\vec{step}\cdot\hat{i}}$)



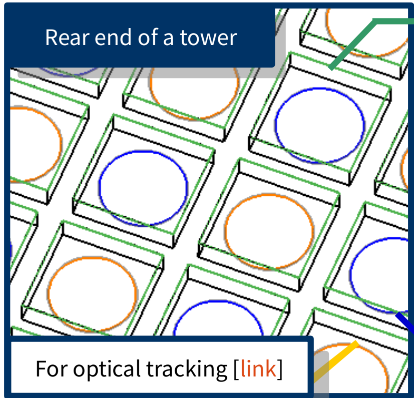


Optical properties in simulation

Transmission eff of filters

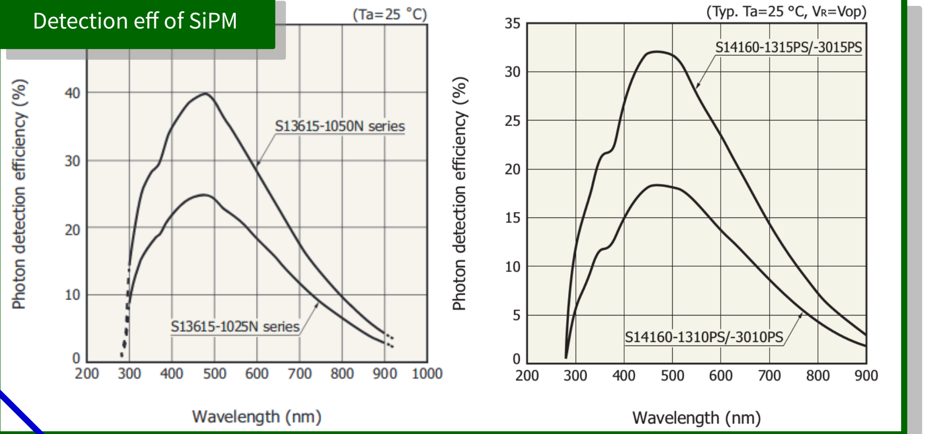


Rear end of a tower



For optical tracking [link]

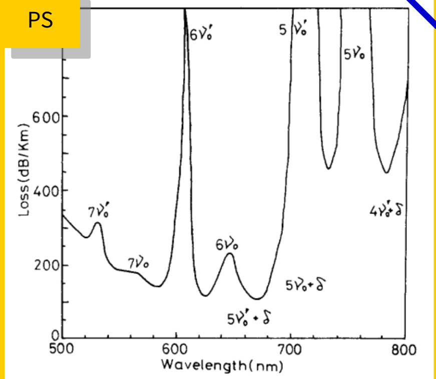
Detection eff of SiPM



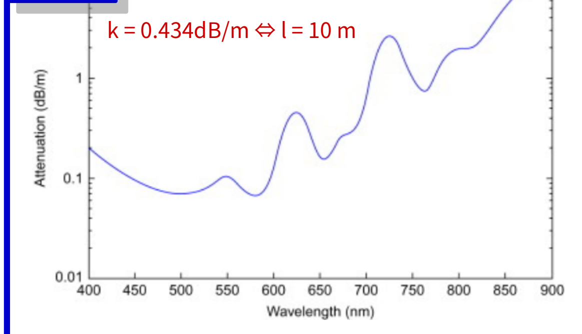
Attenuation loss diverges at 400nm → applied filter to S channel to mitigate it

Attenuation loss of Polystyrene (PS) & PMMA

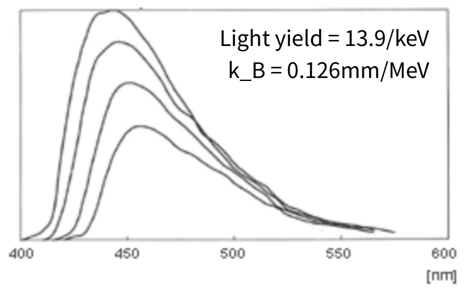
PS



PMMA



Scintillation spectra of PS



Backups – to be updated