Dual-Readout Calorimetry latest studies

***Lorenzo Pezzotti*, Iacopo Vivarelli**
CERN (EP-SFT) & Sussex University

On behalf of the
IDEA Dual-Readout Calo Group

INFN RD_FCC Collaboration Meeting - SW Session
15-16/12/2021

EDM4HEP & KEY4HEP

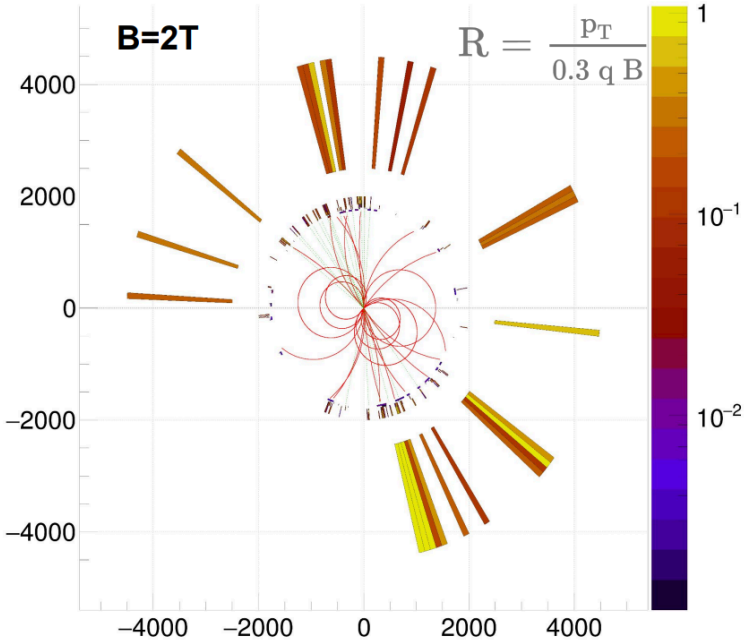
towards particle flow in dual-readout calorimeters

Towards a particle flow approach for DR

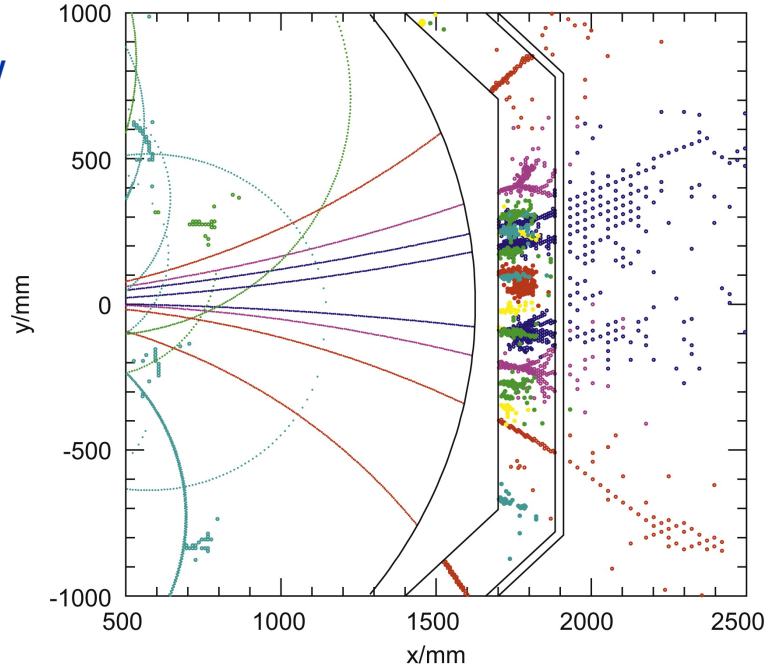
- Particle flow (PF) can further enhance jet resolution and PID capabilities with respect to our benchmarks.
- At the calorimeter level, it needs the concept of *cluster*, to reduce the multiplicity of input channels from the single fibers.
- 2-dimensional information only, provided by default in the fibre calorimeter, may be enough. A recent presentation of Sang Yun Koh showed the potential of timing for 3-dimensional reconstruction [link].

Proto-particle-flow reconstruction with the IDEA DR full-sim.

See Marco's talk after this one.



Particle Flow in ILD.



Work program

Use widely shared software tools that introduce the concept of hit (truth, digitized), cluster, track: event data model ✓

↓

Perform a reconstruction step to produce clusters from fiber hits ✓

↓

Apply DR at the cluster level to obtain a calorimeter input at the correct scale ✗

↓

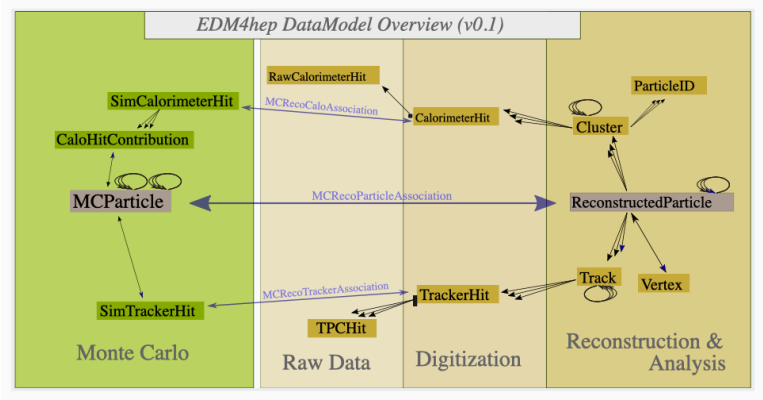
Apply a PF algorithm (PANDORA, DNN, etc.) ✗

Ongoing work

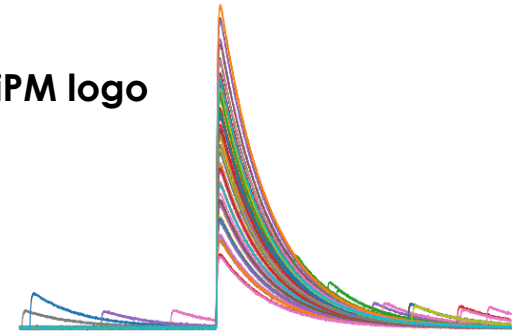
Work program

Use widely shared software tools that introduce the concept of hit (truth, digitized), cluster, track: event data model

- [EDM4HEP] is the event data model that is used in FCC and CEPC frameworks.
- The output of the european simulation is producing edm4hep output routinely:
  - check the EDM4HEP branch of the code introducing relevant dependencies.
- In parallel, a [digitisation model] to include the SiPM response to the incoming light from the fibre was developed at Insubria University.



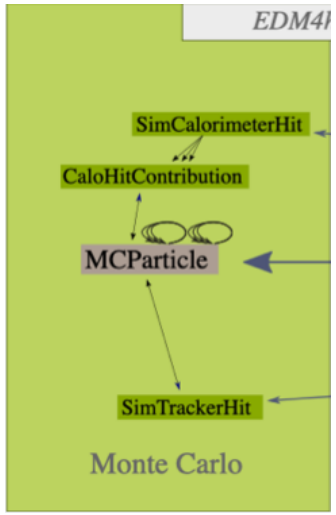
SimSiPM logo



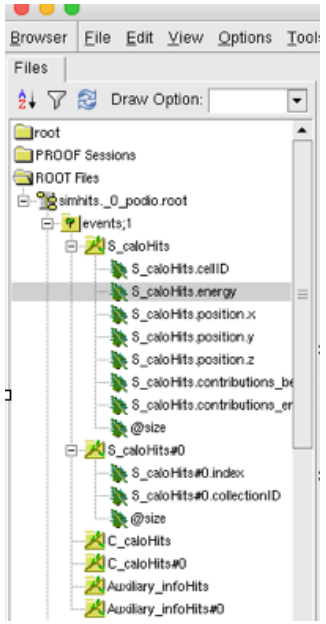
Ongoing work

Work program

Use widely shared software tools that introduce the concept of hit (truth, digitized), cluster, track: event data model



- From radiation-matter interaction (GEANT4) to hit-level data output:
  - Each fibre is represented by a **SimCalorimeterHit,** essentially position, energy and a list of pointers to
    - **CaloHitContribution** - individual G4 hit (position, energy and time of arrival of photons to SiPM).
      - Time of arrival estimated from **global G4 hit time and distance to SiPM**, also possible to include full light propagation in GEANT4.
  - Two **SimCalorimeterHit containers** are written (scintillation and Cherenkov signals).
  - An auxiliary container contains informations about leakage, total energy deposited, etc.

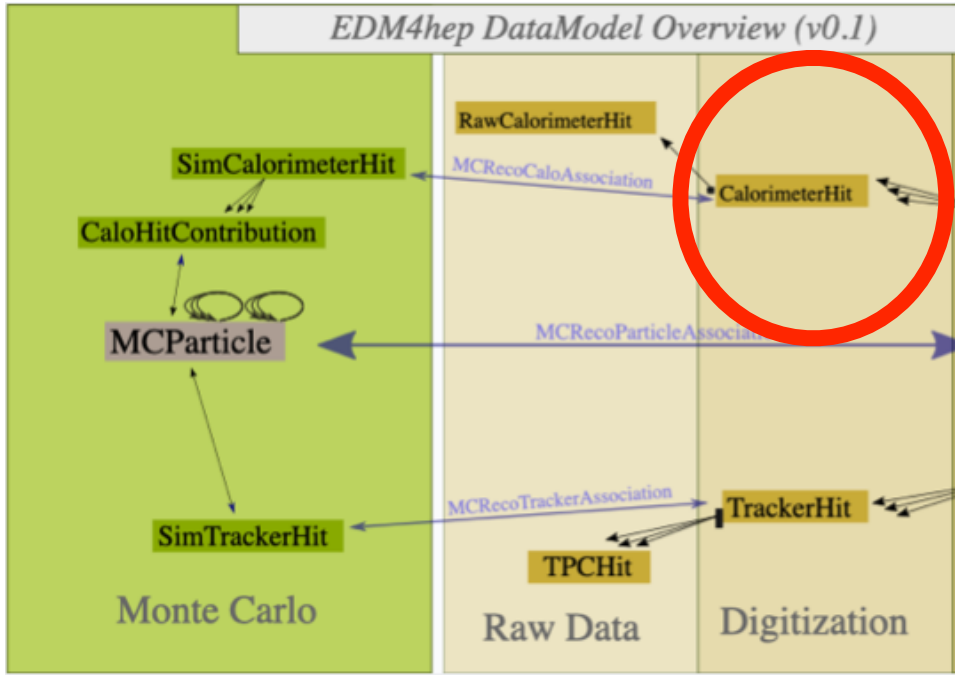


Ongoing work

Work program

Use widely shared software tools that introduce the concept of hit (truth, digitised), cluster, track: event data model

- From hit-level data output to digitized signals:
  - Digitization package available [here], as a dedicated branch. Part of the DRCalo package (working on top of the key4hep stack).
  - It takes the **SimCalorimeterHit containers**, applies SiPM simulation and writes out a **CalorimeterHit** container.
  - It is a hook to the Insubria digitization package.

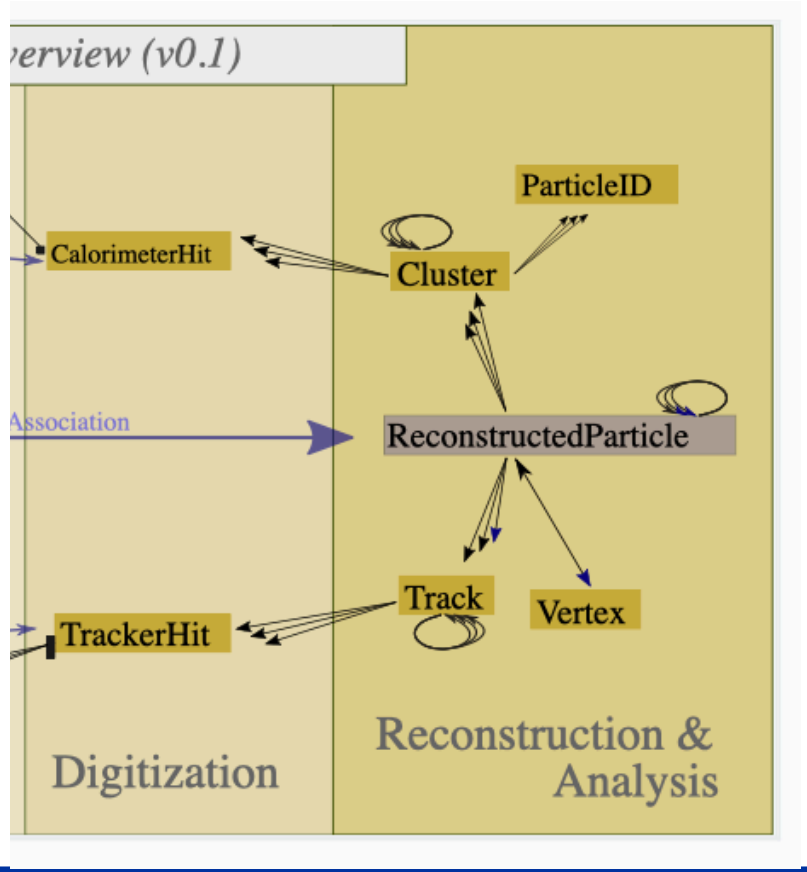


Ongoing work

Work program

Perform a reconstruction step to produce clusters from fiber hits

- From digitized signals to reconstructed objects:
  - In progress…
  - Construct a grid of *calo towers* with defined (η, ϕ) and a hash to quickly access their position.
  - Cluster together calo towers with a three-threshold scheme:
    - A seed (energy above E_{seed}) starts a cluster.
    - Neighboring towers expand the cluster. If their threshold above E_{expand}, their neighbors also expand the cluster.



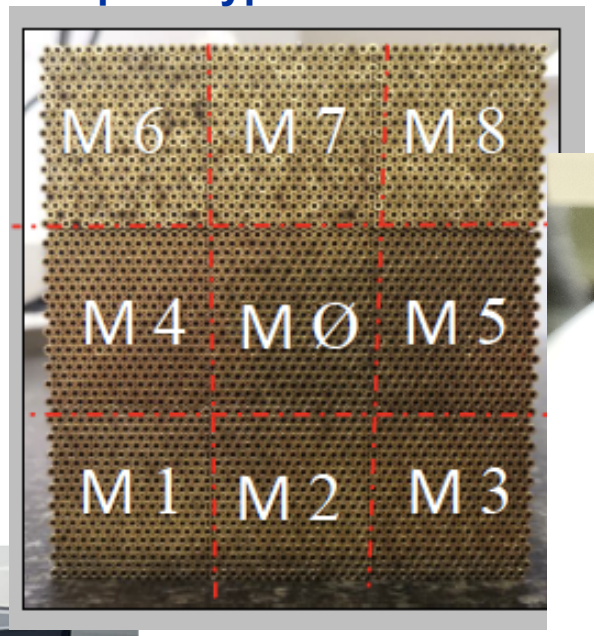
GEANT4 validation

exploiting the 2021 beam tests

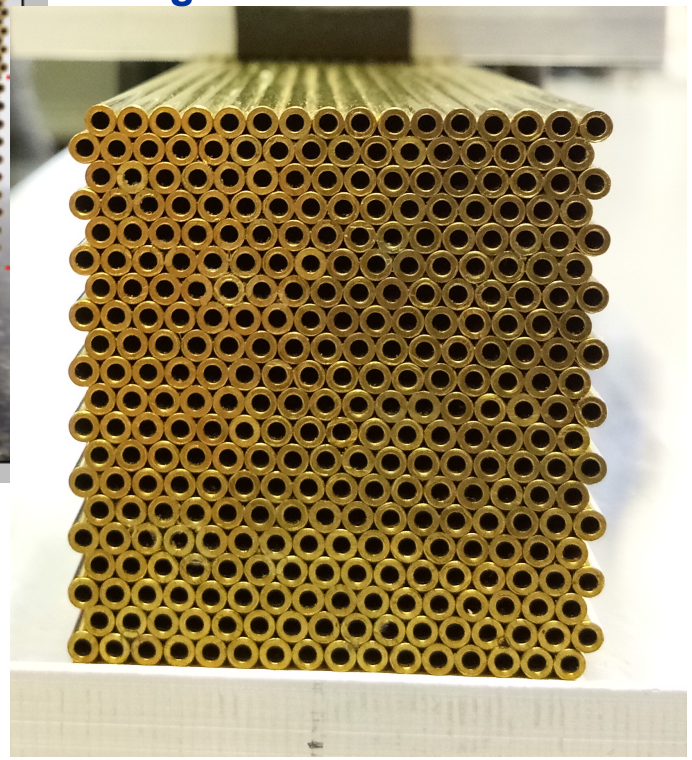
The 2020 dual-readout prototype

- In 2020/2021 a new capillary-tube-based dual-readout prototype was built. Specifics:
  - Electromagnetic dimensions of 10x10x100 cm^3.
  - 9 towers, each containing 16x20 capillaries (160 Cherenkov and 160 Scintillating).
  - Capillary tube outer diameter of 2 mm and inner diameter of 1.1 mm. 1-mm-thick optical fibers.
- Goal: millimeter 2-dimensional shower-shape reconstruction in dual-readout calorimeters.

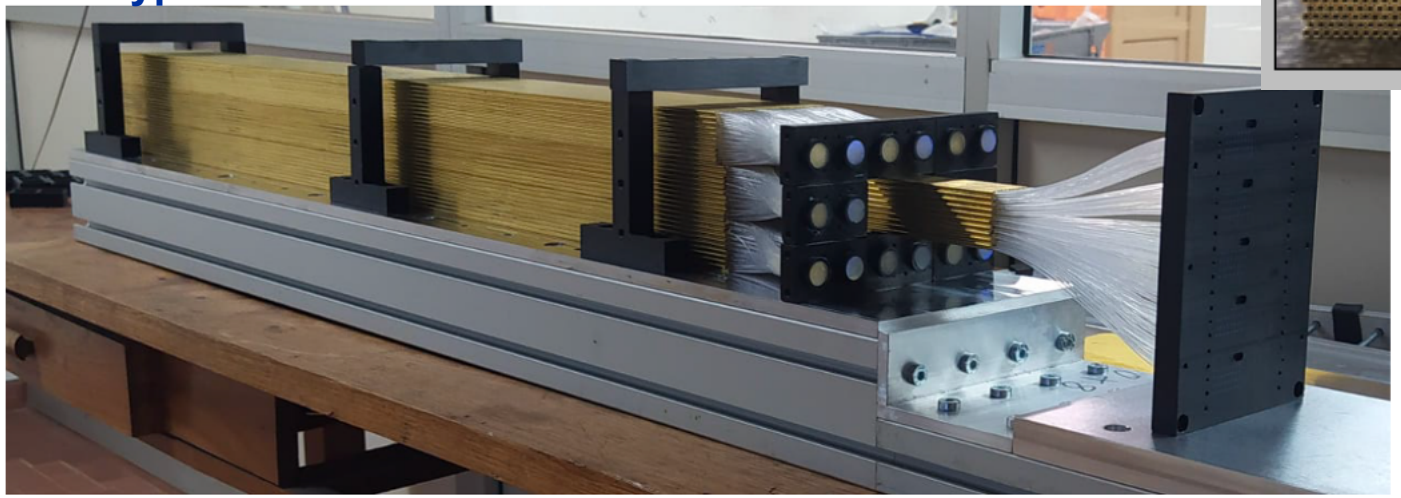
Full prototype - 9 towers



A single tower



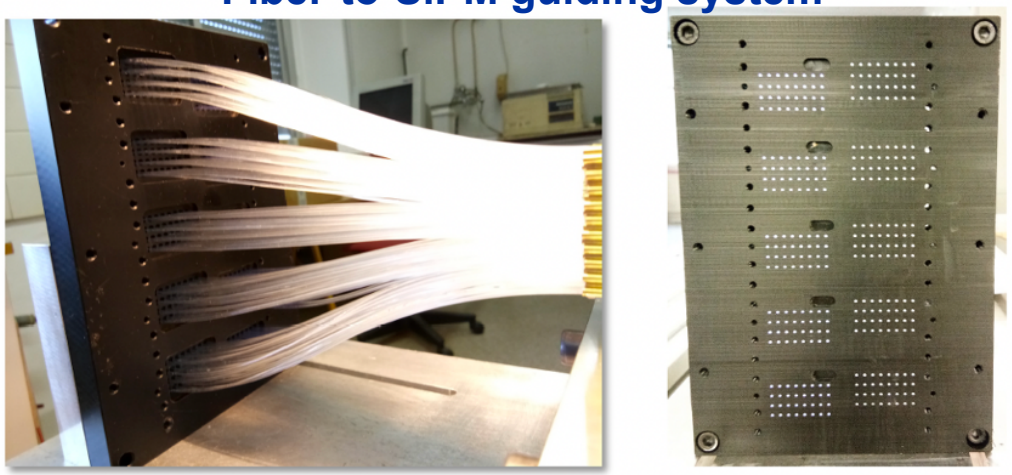
Prototype rear end

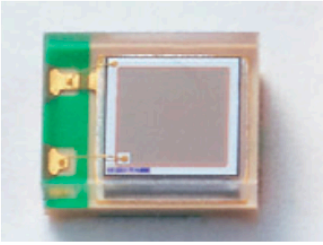


The 2020 dual-readout prototype readout system

- Superior granularity achieved using a hybrid readout system:
  - 320 SiPMs in the central tower independently read-out using
    - 5 FEE readout boards, operated in self-trigger mode.
  - Surrounding 8 towers read-out by two PMTs per tower providing an independent Cherenkov and Scintillation light readout.

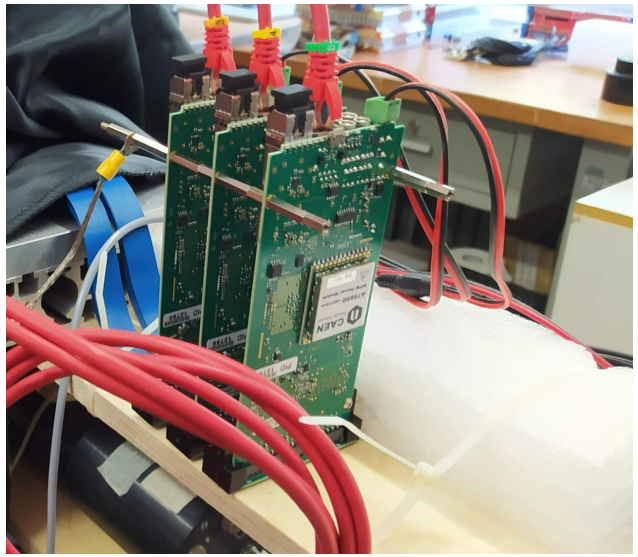
Fiber-to-SiPM guiding system





Hamamatsu SiPM: S14160-1315 PS
Cell size: $15\ \mu m$

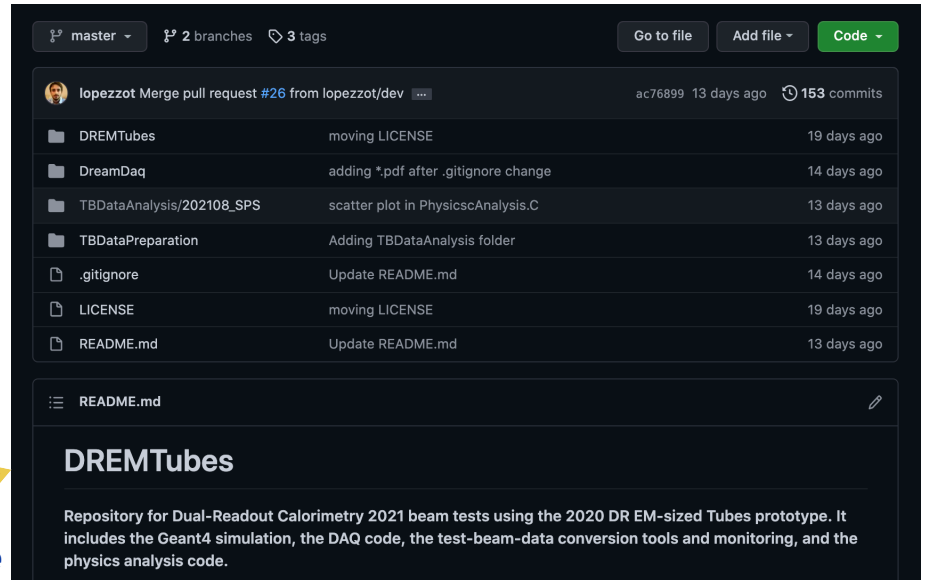
Front end board housing 64 SiPM



Readout Boards CAEN A5202

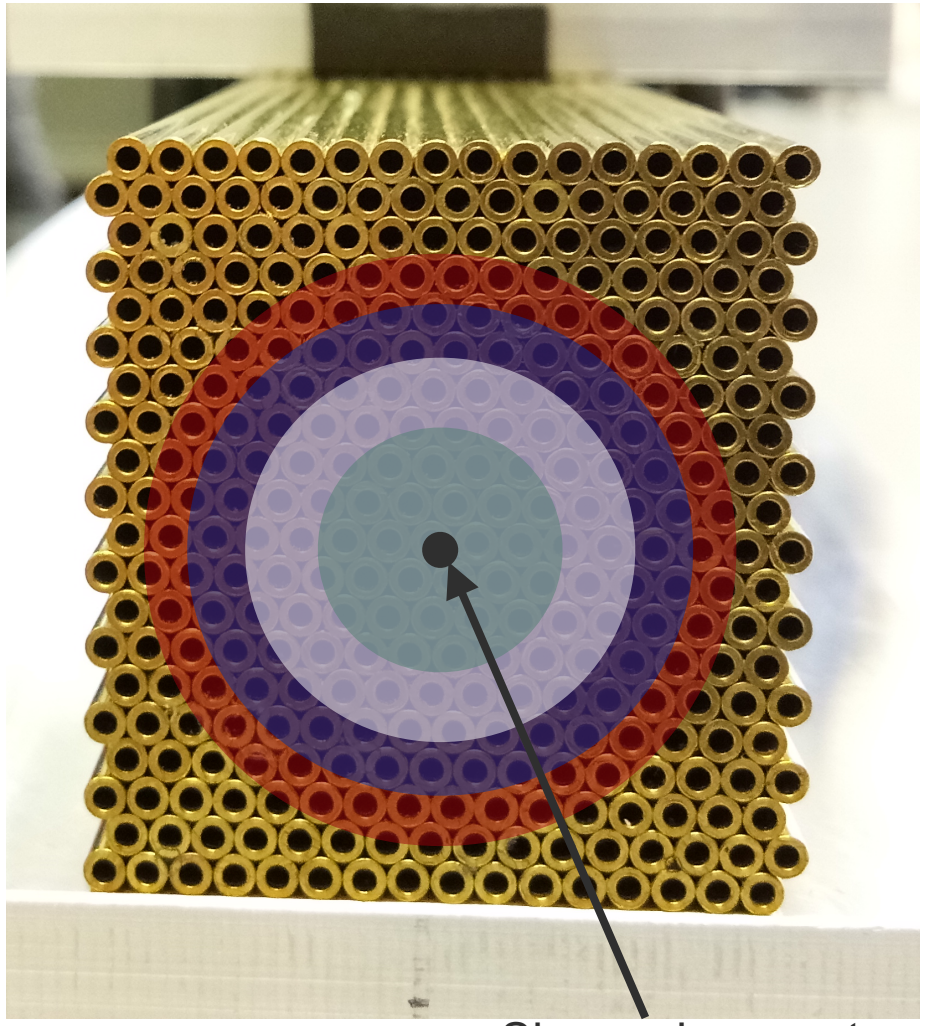
The 2021 test beam software

- The 2021 dual-readout calorimeter software is located in a new GitHub repo:
  - [github] (currently in v1.3.1)
- Divided into four sub-repos:
  - DREAMDaq/ → Test beam data acquisition code *Contact: Roberto Ferrari*
  - TBDataPreparation/ → Converters from raw data to analysis ntuples *Contacts: Lorenzo Pezzotti, Iacopo Vivarelli, Andrea Negri Edoardo Proserpio and Romualdo Santoro*
  - TBDataAnalysis/ → Macros for high-level-objects analysis *Contacts: Lorenzo Pezzotti, Iacopo Vivarelli, Edoardo Proserpio and Romualdo Santoro*
  - DREMTubes/ → GEANT4 test-beam simulation *Contact: Lorenzo Pezzotti*



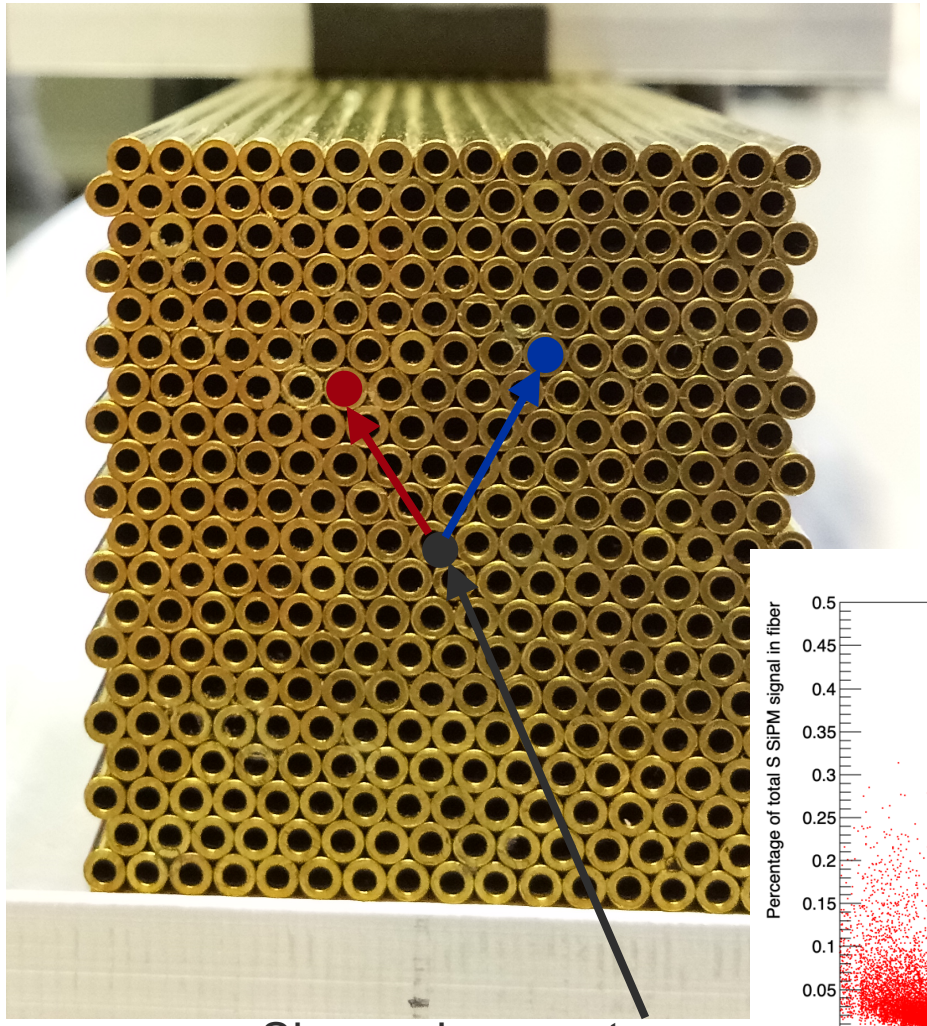
Star me

How to measure e^+ shower shapes

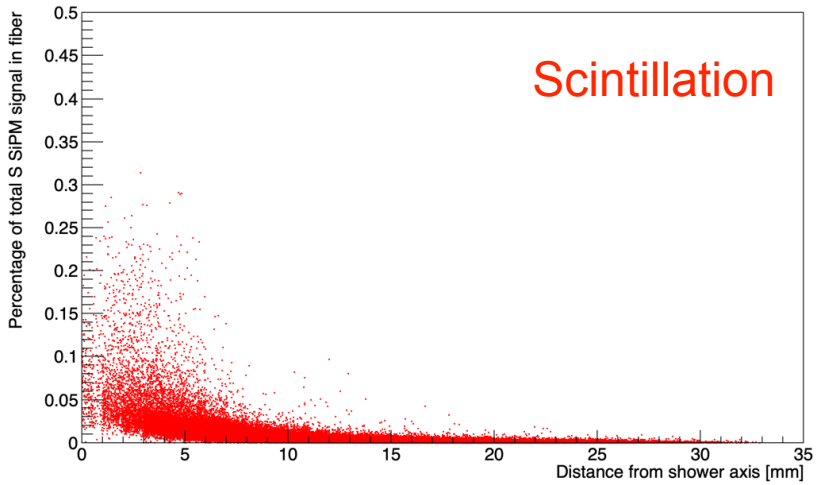


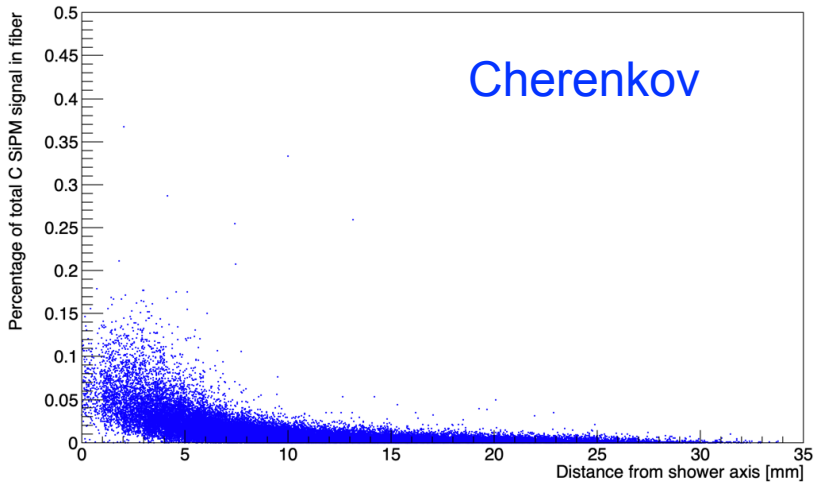
- Radial profile, *i.e.* the average signal located in a radial shell centered on the beam axis.
- Measurement:
  - For every event, we calculate the barycenter position and the percentage of signal in a radial shell $r_i < r < r_{i+1}$ centered on it.
  - We plot the average value over multiple events per each shell.
- Note:
  - Up to now only the SiPM information is used (no PMT signals involved).
  - Scintillation and Cherenkov signals are divided by the total SiPM signal (S and C),
    i.e. the signal containment for Tower-0 is not used.

How to measure e^+ shower shapes

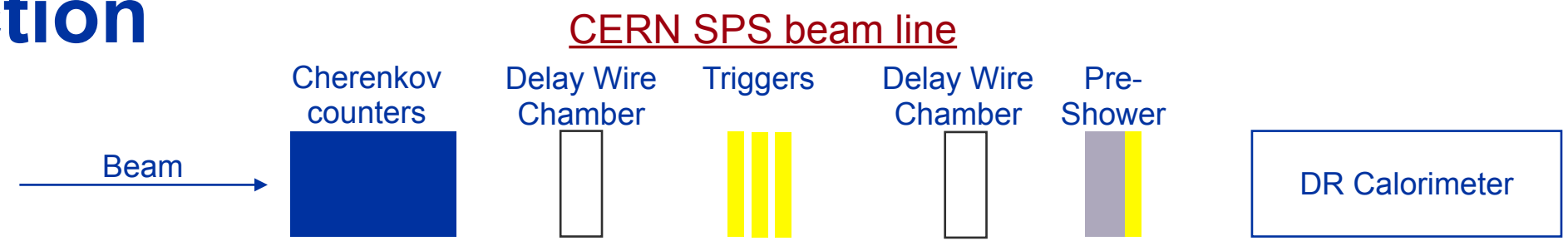


- Lateral profile, *i.e.* the average signal carried by a fiber located at a distance r from the shower barycenter.
- Measurement:
  - For every event, and for every fiber we populate a scatter plot (signal *vs.* distance).
  - Lateral profiles are extracted as average values for every x-bin (ROOT::TProfile).



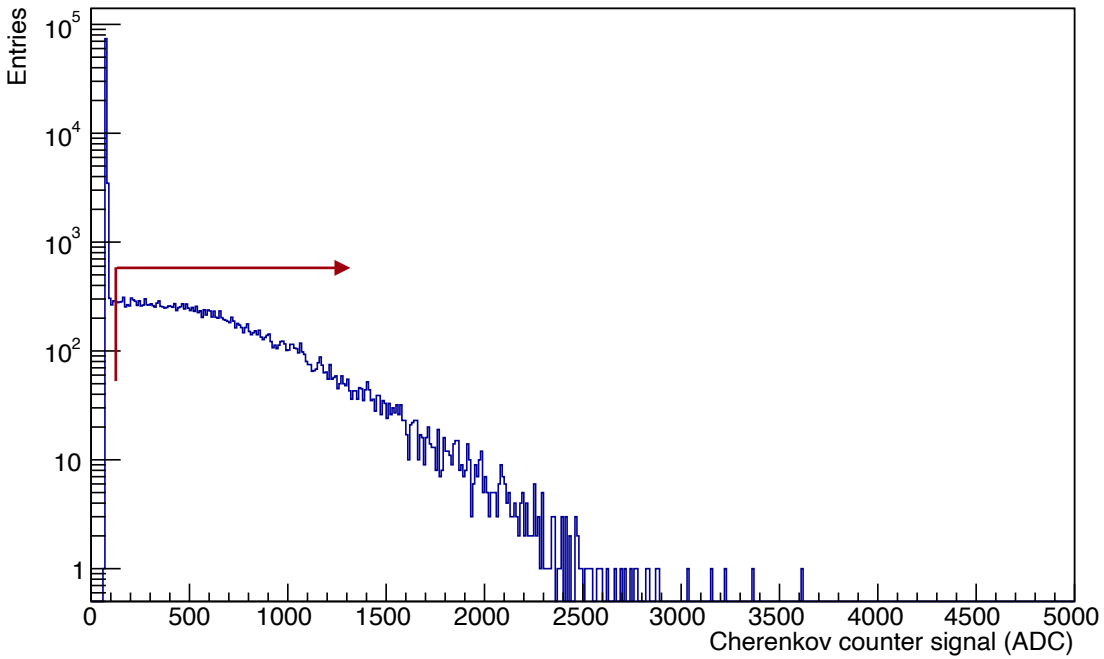


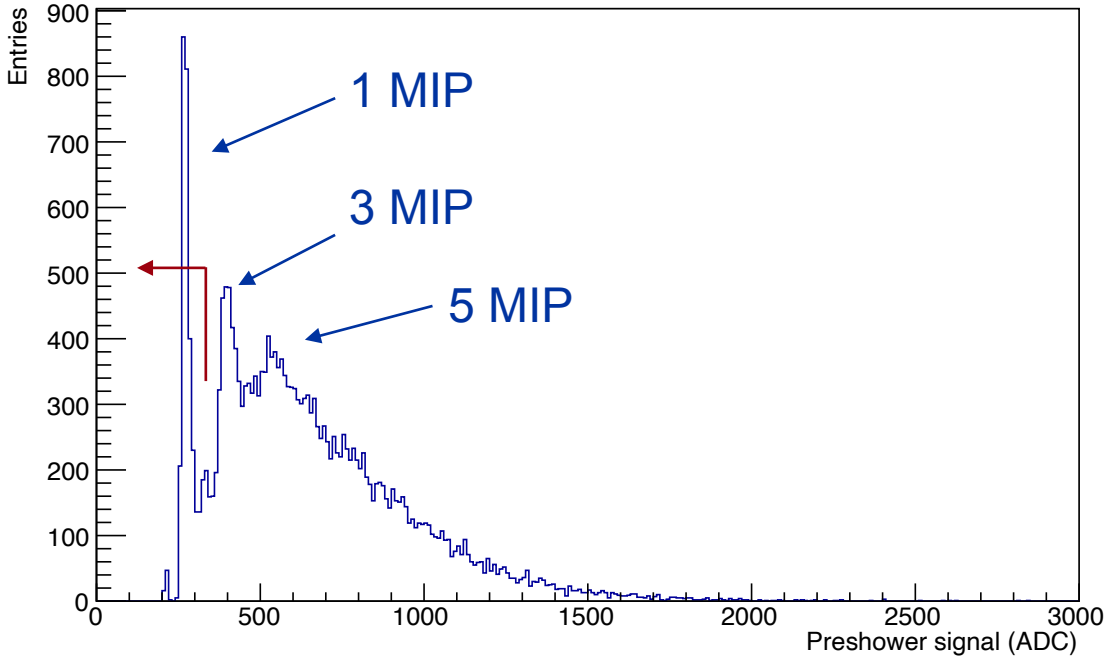
Events selection



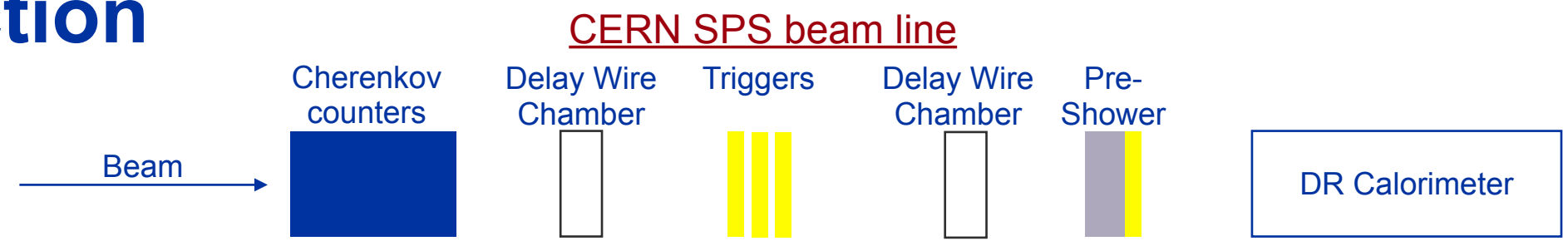
Select e^+ in SPS beams as events for which the Cherenkov counter signal is > 90 ADC.

Select e^+ for which a signal compatible with 1 MIP is recorded in the preshower scintillator.

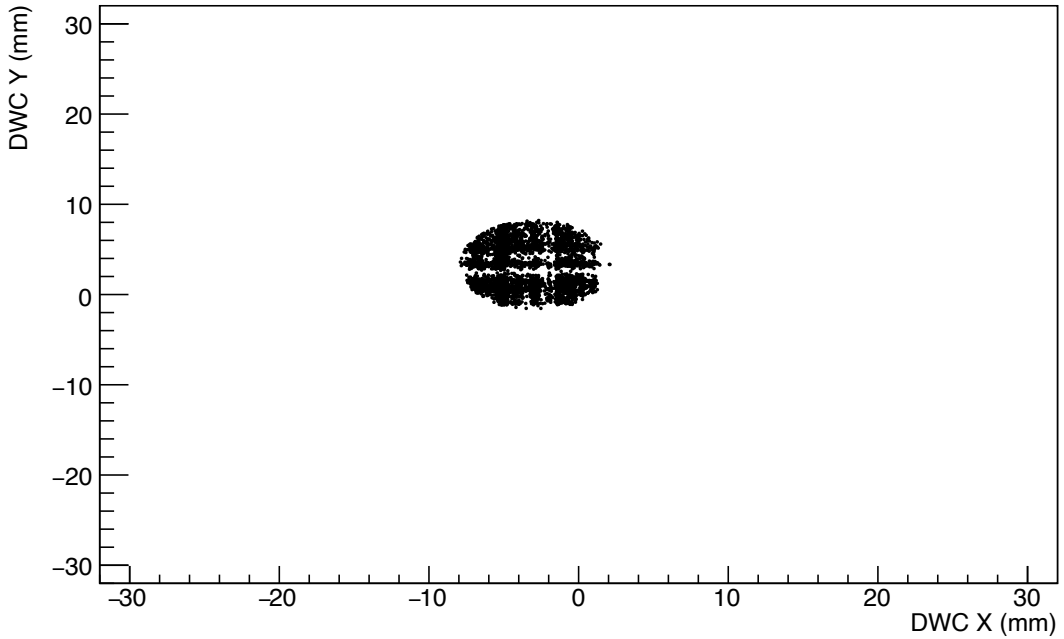




Events selection



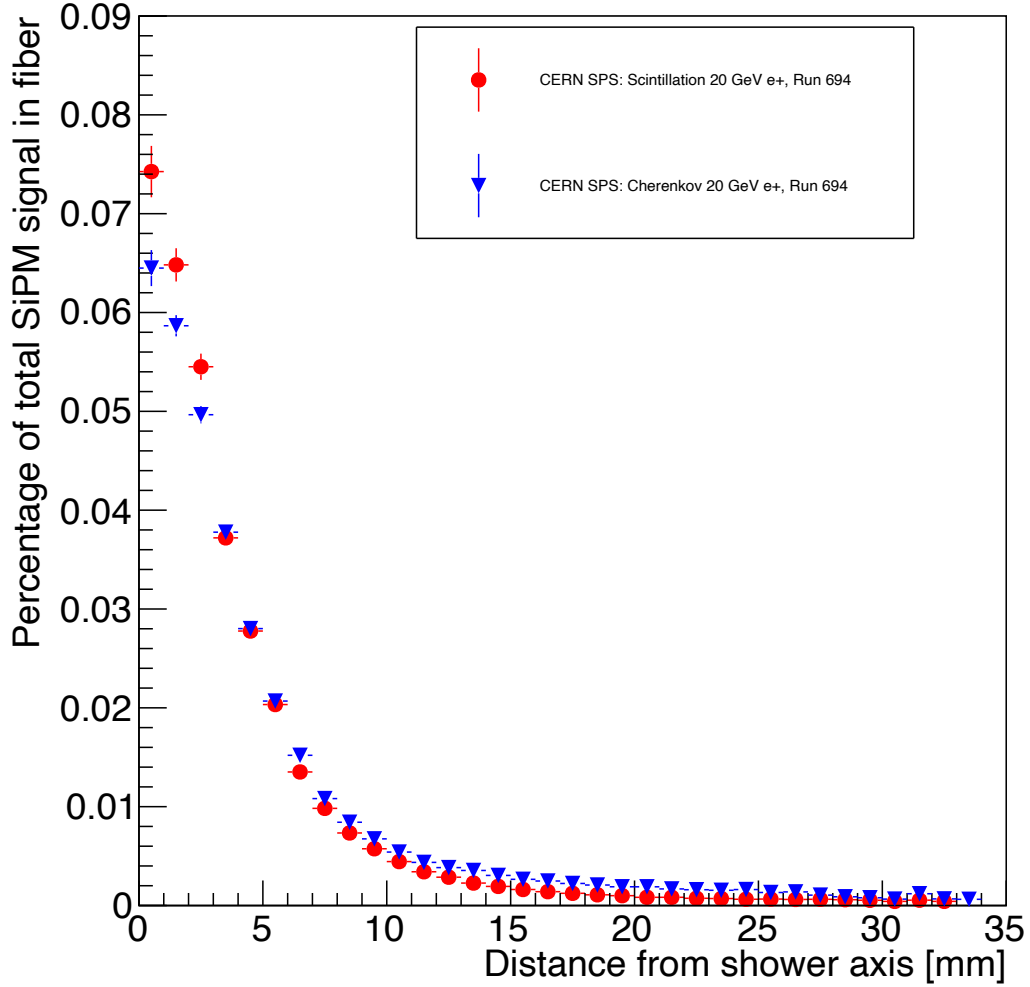
Select a 5 mm radius beam spot with both Delay Wire Chambers (DWC).



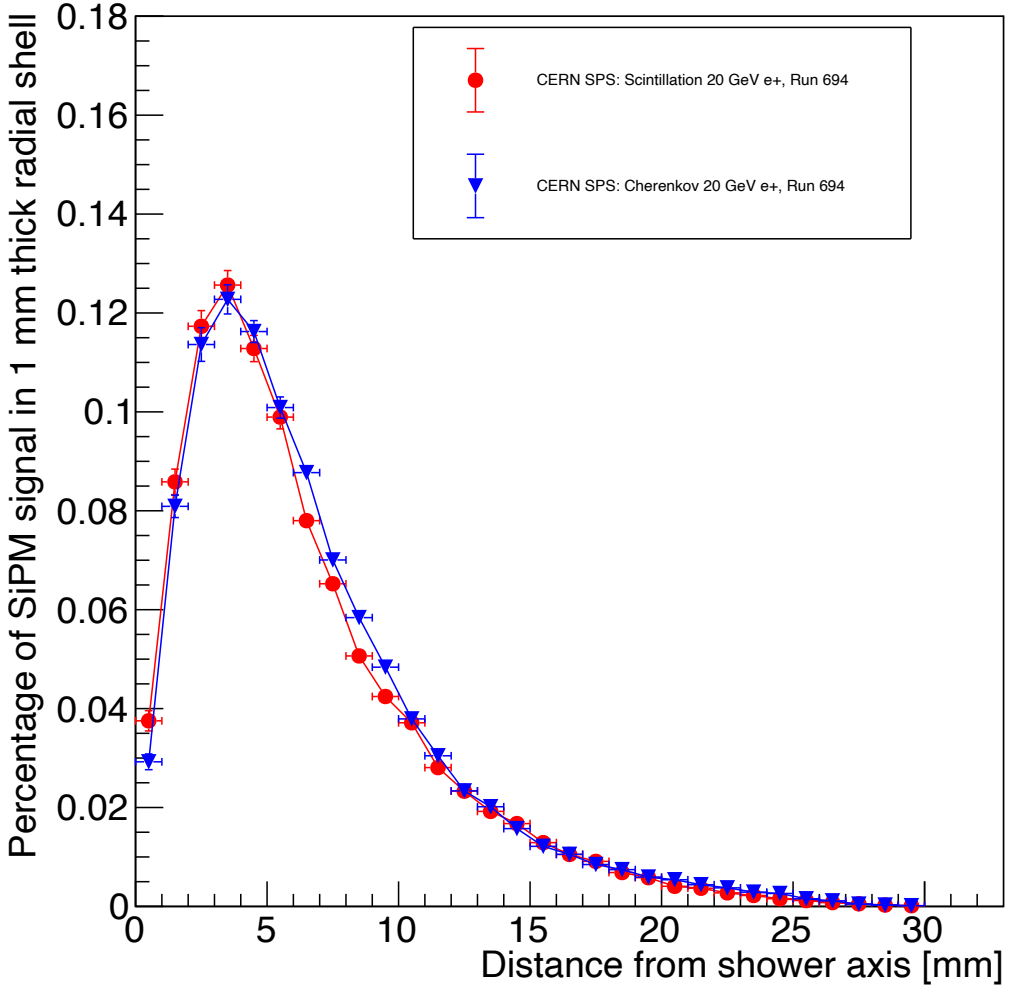
Preliminary results

20 GeV e^+ shower profiles (CERN TB)

Lateral profile



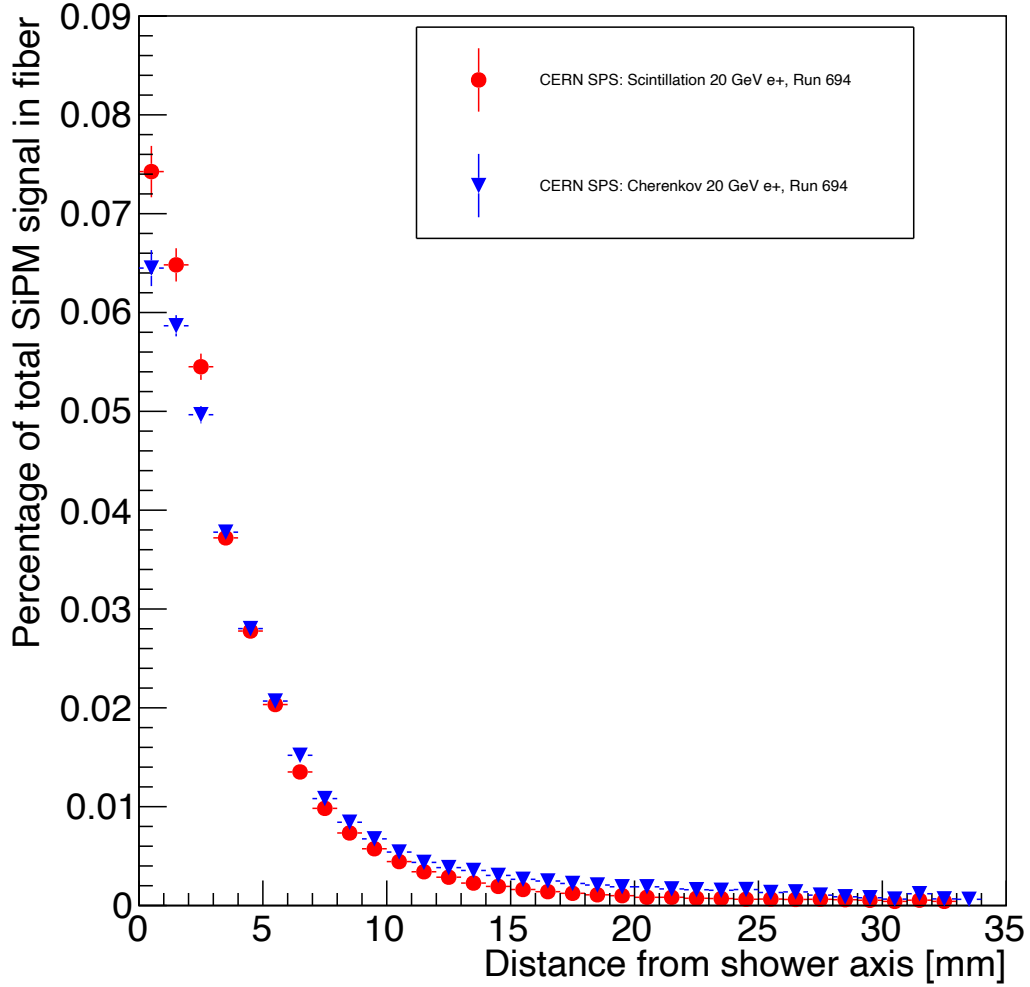
Radial profile



Preliminary results

20 GeV e^+ shower profiles (CERN TB)

Lateral profile

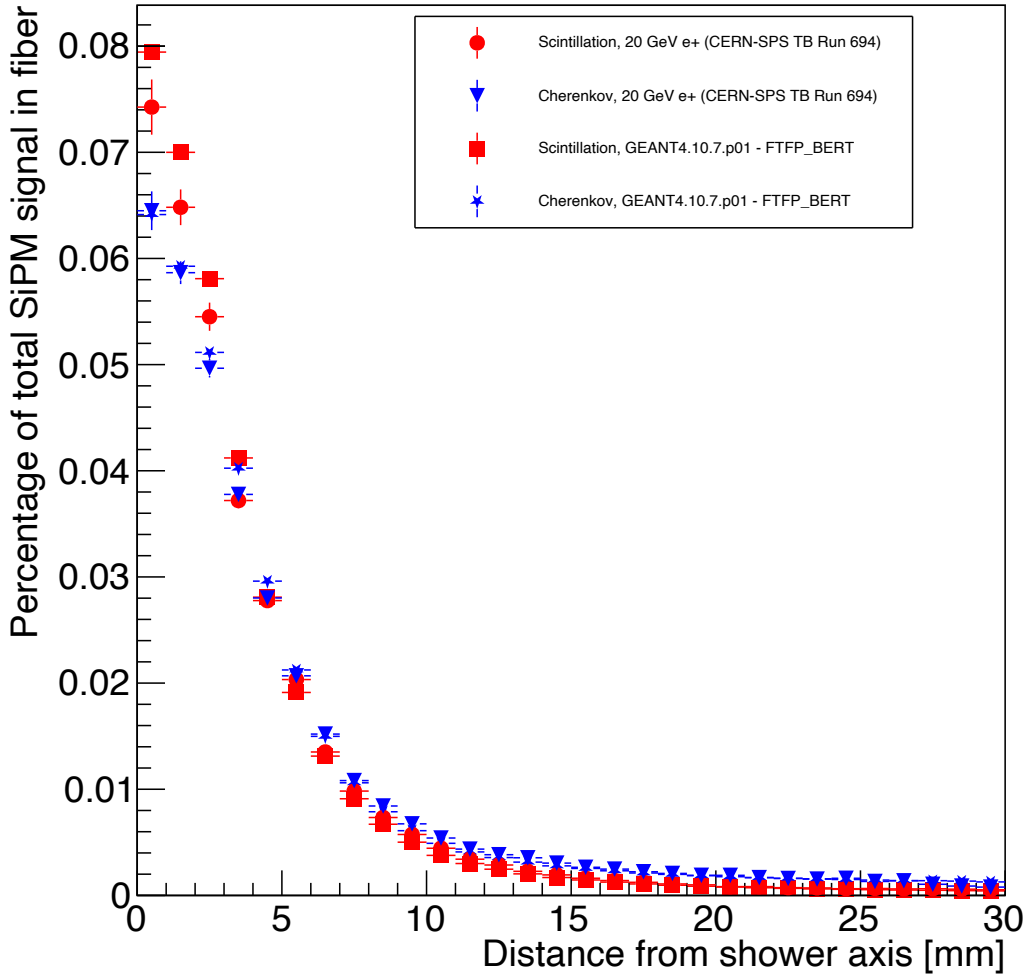


- Possible to provide a 1 millimeter sampling of e^+ showers up to a distance of $\simeq 3$ cm from the shower axis.
- The Scintillation and Cherenkov profile discrepancy was already measured in [article]. But its scaling with the 2020 prototype was largely unpredictable.
- Error bars represent 68% confidence level.

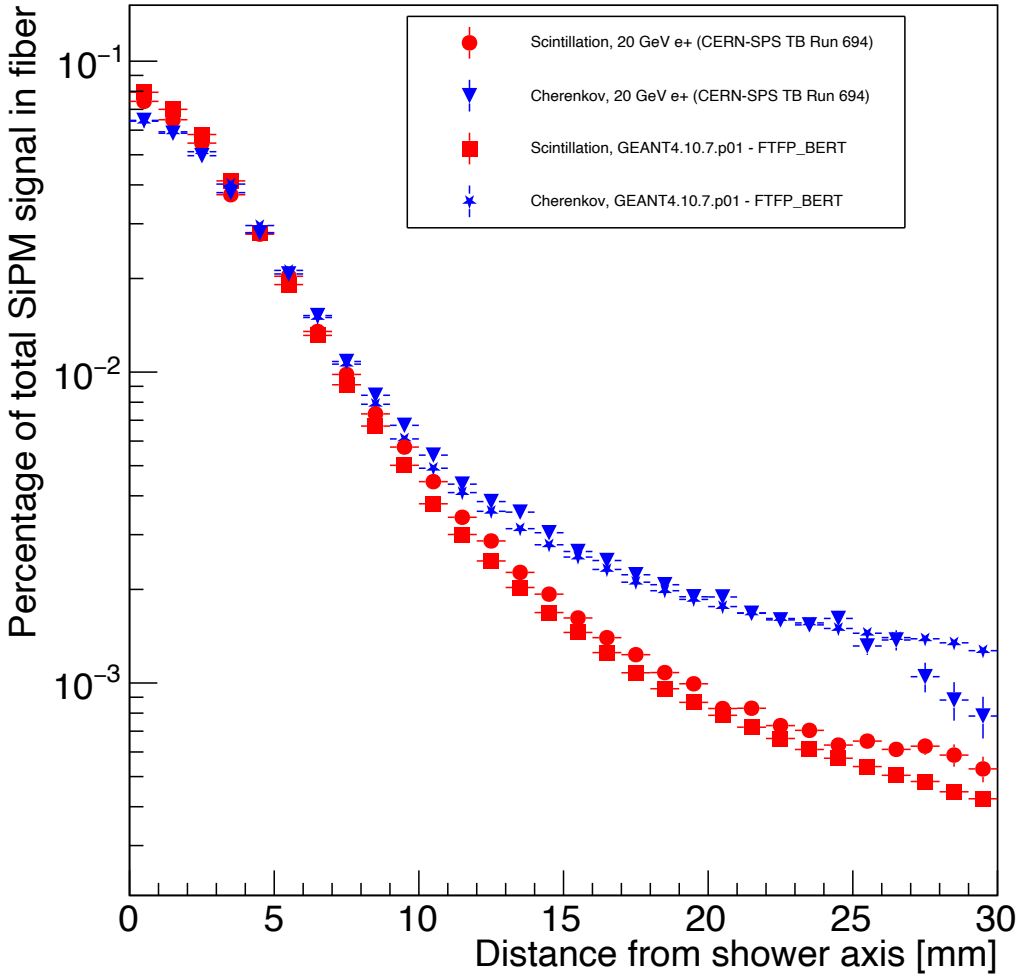
Preliminary results

GEANT4 comparison

Lateral profile - TB Data & GEANT4



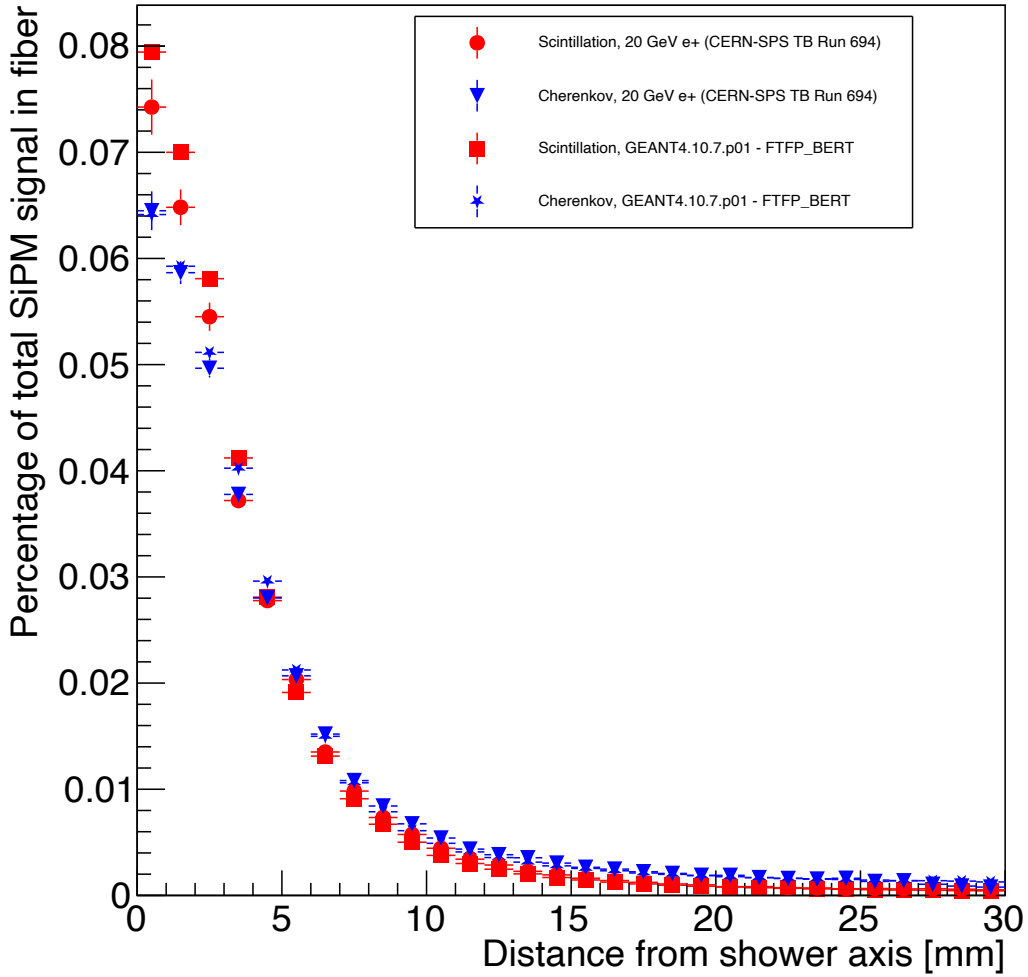
Lateral profile log scale - TB Data & GEANT4



Preliminary results

GEANT4 comparison

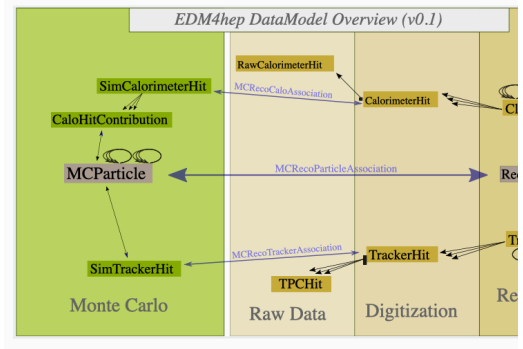
Lateral profile - TB Data & GEANT4

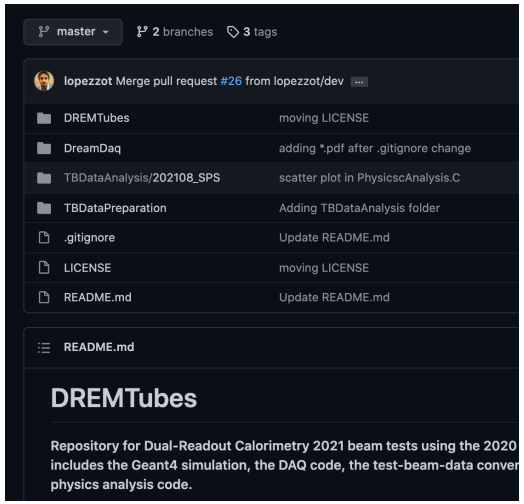


- Note:
  - Still needed to quantify systematic errors on the GEANT4 results.
    - Largely due to the error on the relative angle between the calorimeter and the beam axis.
  - Almost every point from GEANT4 is statistically compatibile ($\pm 3\sigma$) with the experimental measurement.

Take Home

- Towards particle flow in dual-readout calorimeters:
  - Several benchmarks with a traditional dual-readout calorimetry approach have been provided in the last three years (PID, single particles, jets, …).
  - A particle-flow-like approach could further improve the performance. We suggest using:
    - EDM4hep as our event data model, coupled to the digitization package.
- Validating dual-readout calorimetry simulation on test-beam data:
  - Code for test-beam analysis and simulation is available and ready-to-use.
  - Very encouraging preliminary results recently obtained while comparing GEANT4 and test beam data.





Join our bi-weekly dual-readout calorimetry meeting:
- idea-dualreadout@cern.ch - https://indico.cern.ch/category/10684/
- Roberto Ferrari & Romualdo Santoro (HW conveners), Iacopo Vivarelli & Lorenzo Pezzotti (SW conveners)