Fibre-based, Capillary Tube Dual-Readout Calorimeter

TB Analysis and Simulation

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On behalf of the IDEA Dual-Readout Calorimeter Group

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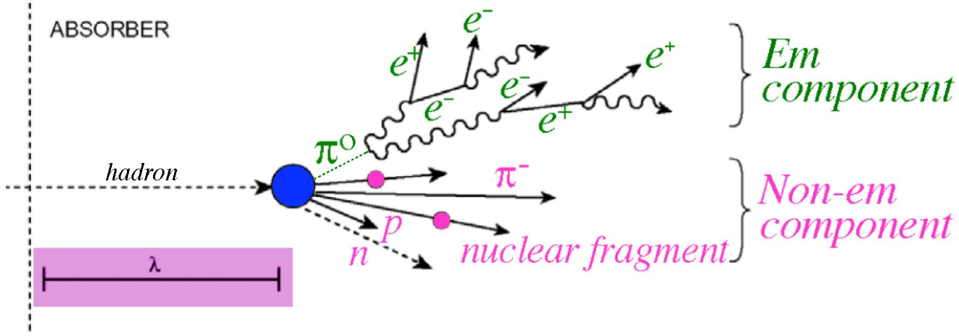
Dual-Readout Calorimetry [reference]

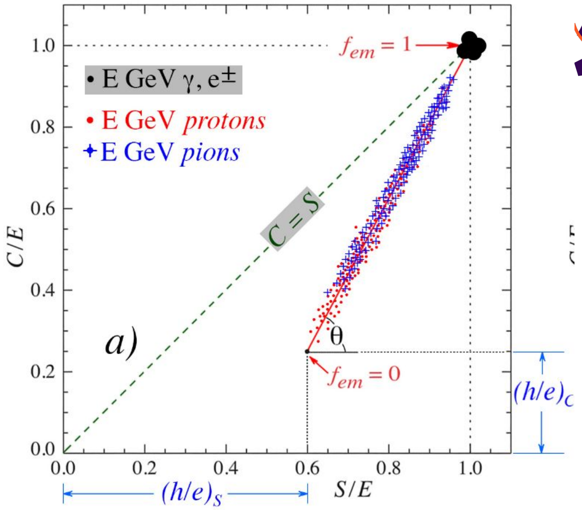
- Large fluctuations in fraction of **EM component** (f_{EM}) for hadronic showers
- If calorimeter response to **EM part** different from that to **non-EM part** (h/e ≠1): Energy resolution of calorimeter **largely limited by** f_{EM}
- Dual-Readout calorimetry allows to remove fluctuations by **correcting for** f_{EM} **event-by-event** using **two readout channels with different h/e**
  - Exploit complementary information about shower development
  - **Scintillation** and **Cherenkov** channel

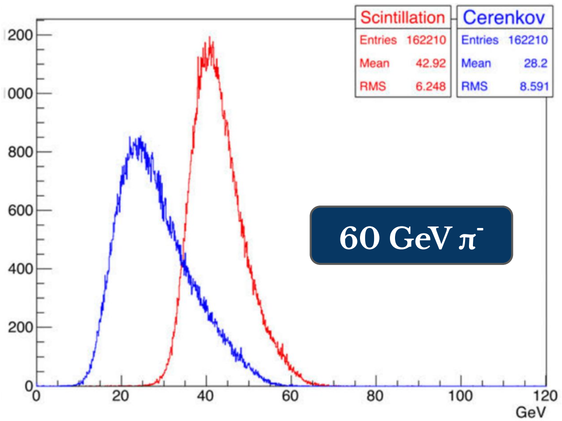


$$E = \frac{S - \chi C}{1 - \chi} \qquad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

Dual-Readout Calorimetry [reference]

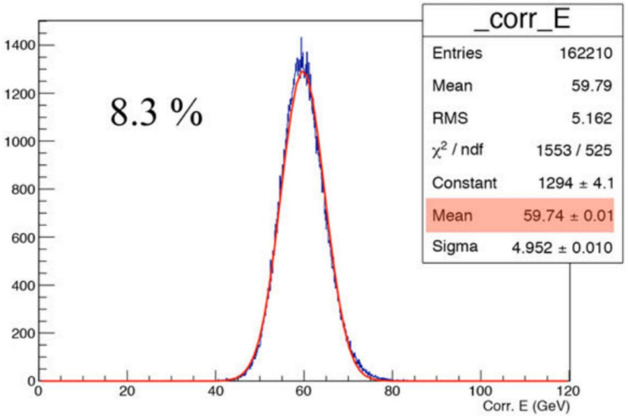
- Calibration with electrons of known energy for both em and hadronic showers
  - Potential to use as ECAL and HCAL combined
  - Universal for all hadron types
- Restored Gaussian and linear response to hadrons
- Improved energy resolution



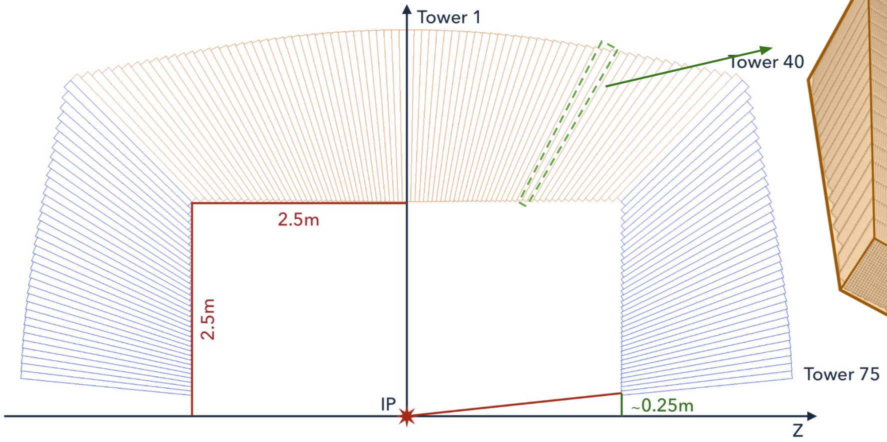


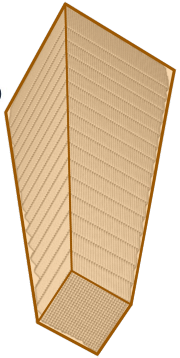
60 GeV π^-

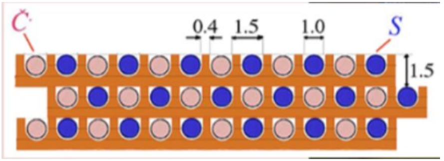
DR-formula

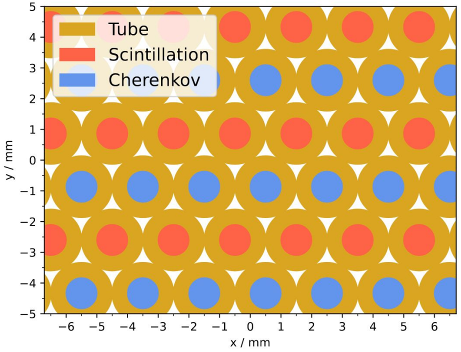


IDEA Dual-Readout Calorimeter [reference]









- Geometry built from projective towers
- O(100M) fibres embedded in absorber in longitudinal direction
- Absorber material being investigated (copper, brass, steel, …)
- Tower geometries, based on chessboard or **honeycomb** layout of fibres, available
- High transverse granularity
  - Excellent angular resolution
  - Lateral shower shape sensitivity
- No longitudinal segmentation out of the box
- For both **EM** and **HAD** calorimetry
  - Option with dedicated crystal ECAL in front

2021 Testbeam (Bucatini Prototype) [reference]

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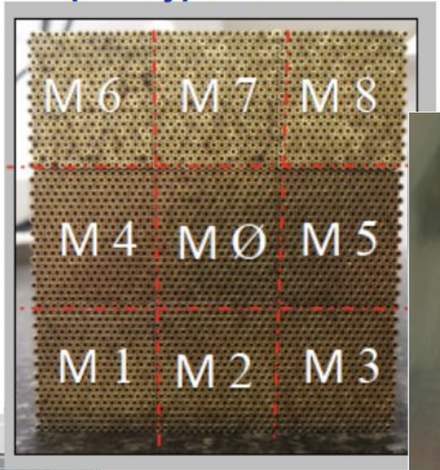
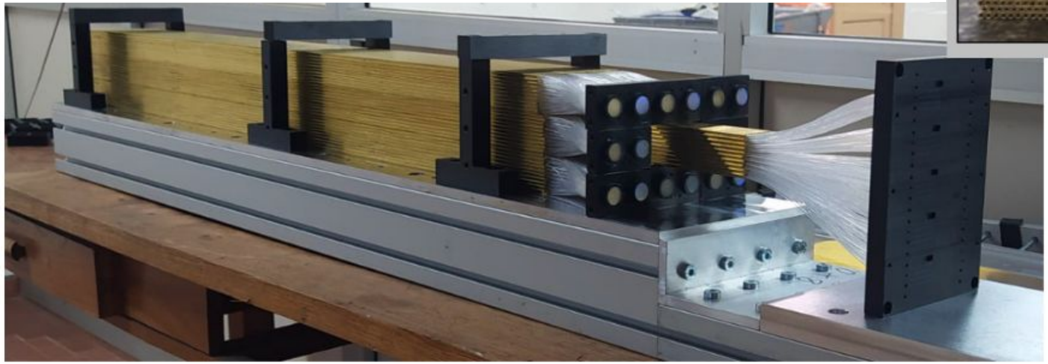
- Prototype based on **capillary brass tubes** of 2 mm outer diameter
  - Housing 1 mm diameter fibre
- Dimension to contain **EM shower** (10x10x100 cm^3) to 94% up to energies of 100 GeV
- 9 towers, each containing 16x20 capillary tubes
  - laid out in alternating rows of scintillating (S) and Cherenkov (C) fibres
- M0 read out with **one SiPM per fibre**
- M1-8 with **two PMTs each** (one for bundled C, one for bundled S)
- Test beams at SPS in 2021 & 2023 (10-120 GeV e$^+$)

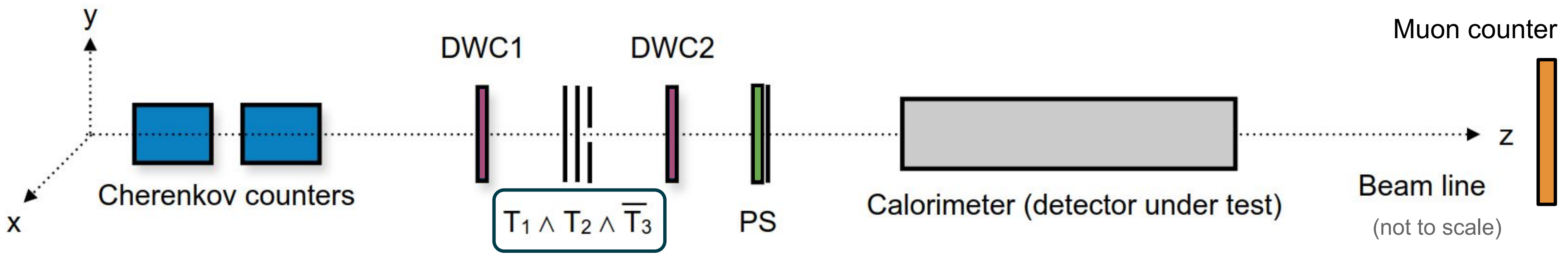
Full prototype - 9 towers



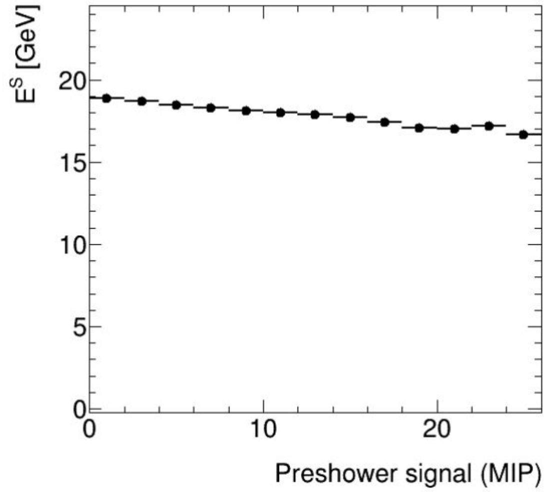
A single tower



SPS 2021 Test Beam Setup [reference]

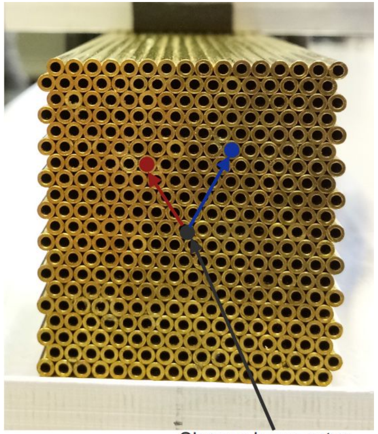


- Positron beam highly **contaminated with hadrons**
- **Cherenkov counters** only reliable up to 30 GeV
  - Need to rely on **Preshower** to make positron selection
- **Preshower** placed far from front face of **calorimeter** due to access restrictions
  - Induced shower leakage
- **Delay wire chambers** with limited (~2 mm) spatial resolution



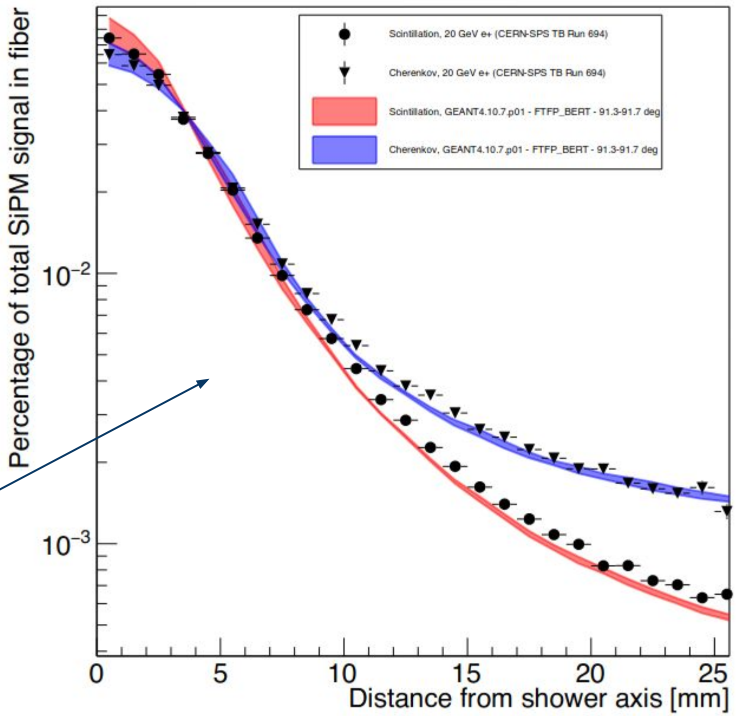
Lateral Shower Shape Measurement [reference]

- Need to confirm ability to reconstruct shower structure with testbeam prototype
- Lateral Profile: average signal carried by single fibre located at distance *r* from shower barycenter
- Compare testbeam results with simulation of prototype in Geant4



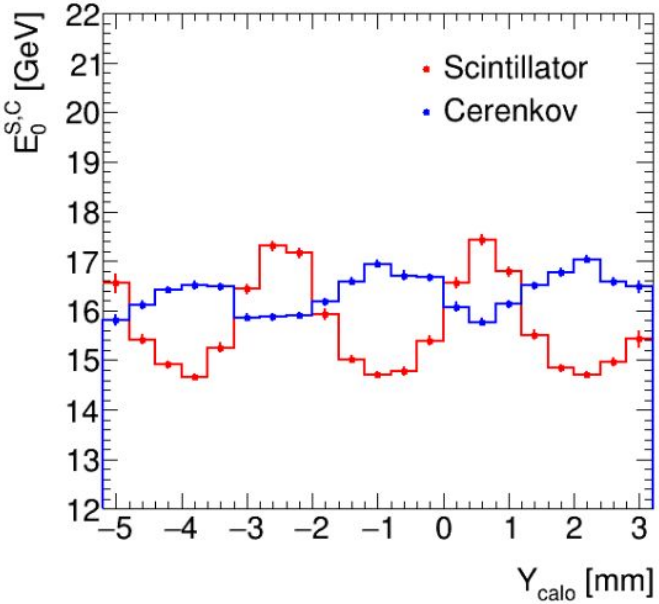
- **Good agreement with G4 simulation**
- **Shower barycenter reconstruction to $\mathcal{O}$(mm) possible**

CERN SPS 20 GeV e^+ - GEANT4 (log scale)

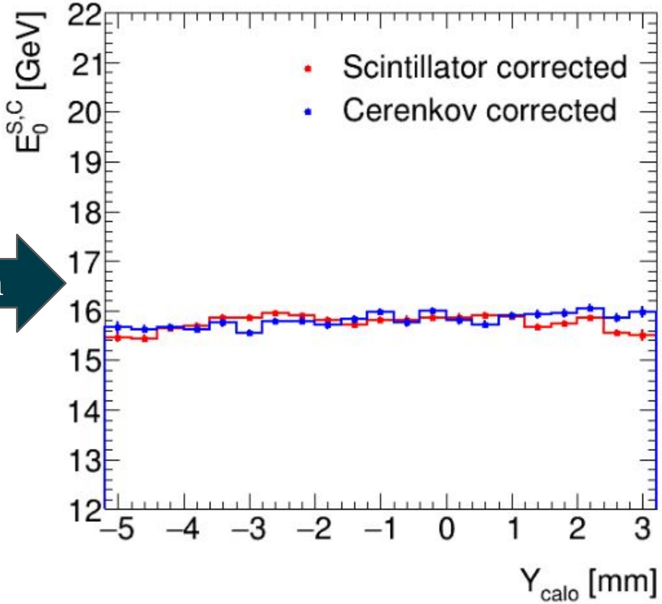


Energy Modulation [reference]

- Observing signal modulation in Y_{calo} (shower barycentre)
  - Dependence on impact point
  - Introduce correction based on incident row

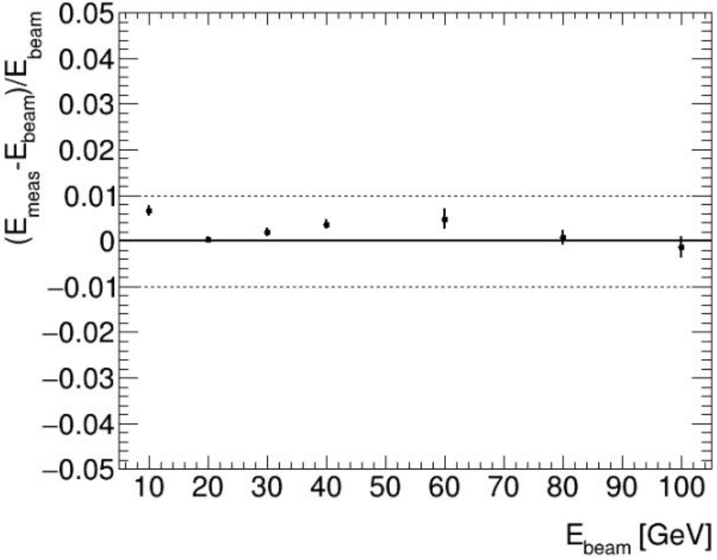


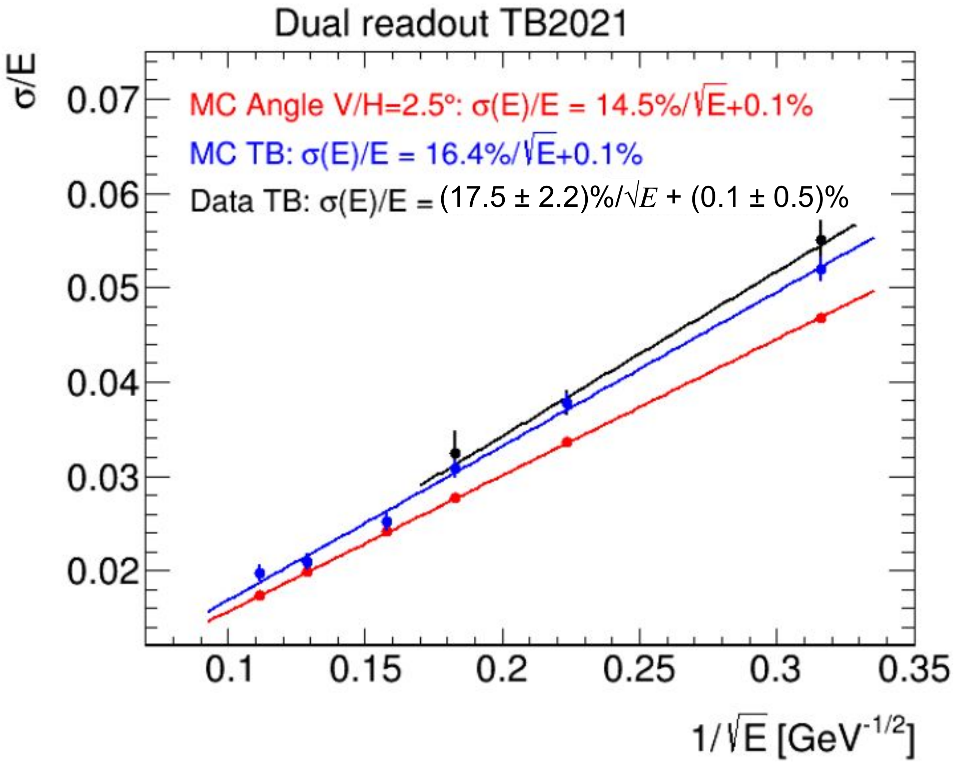
row correction



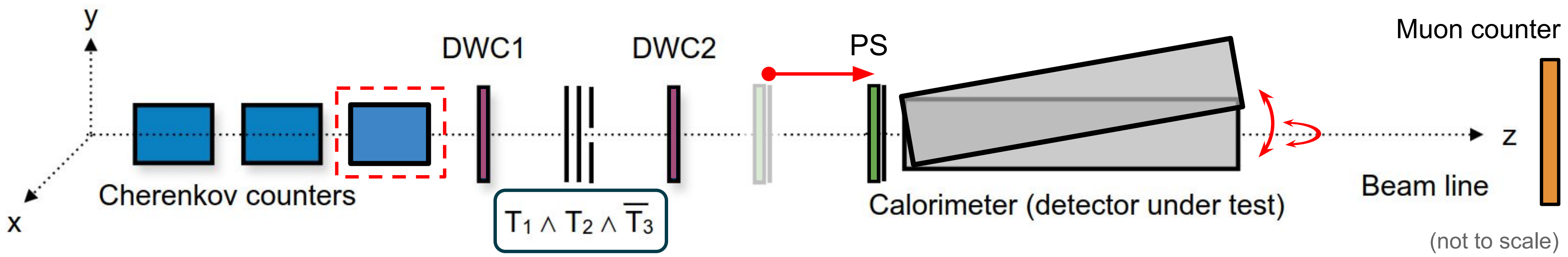
Energy Resolution Results [reference]

- After calibration of towers with one 20 GeV run and Y_{calo} correction:
  - Lineratity well within 1%
- ~17% stochastic term
  - simulation predicts 14% achievable



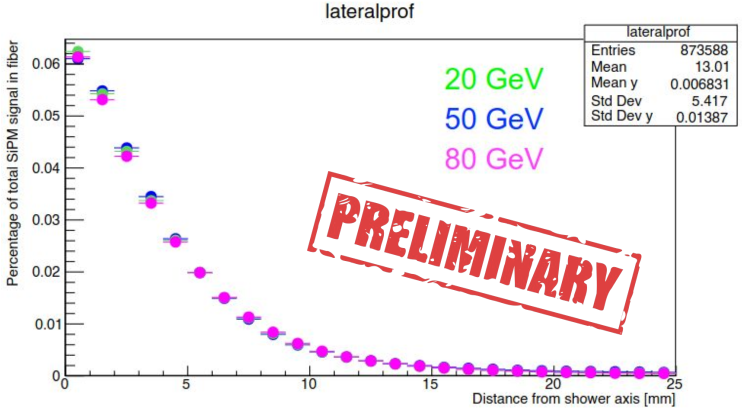


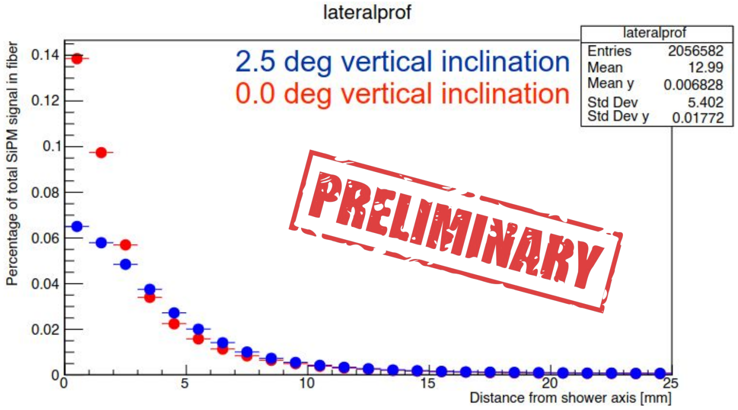
SPS 2023 Test Beam Setup



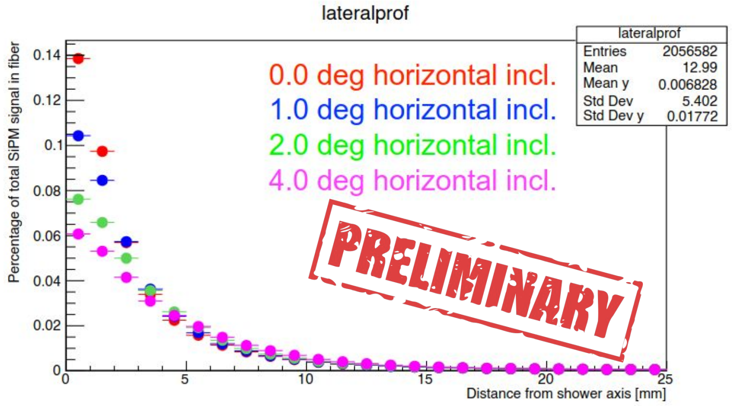
- Mostly similar setup
- Addressed some of the issues of 2021 test beam
  - Added third **Cherenkov counter**
  - New, properly working **delay wire chamber**
  - Moved the **Preshower** closer to calorimeter
  - Allowed for vertical and horizontal rotation of the **prototype**
- Shown results are *preliminary*

TB2023 Results: Lateral Shower Shapes

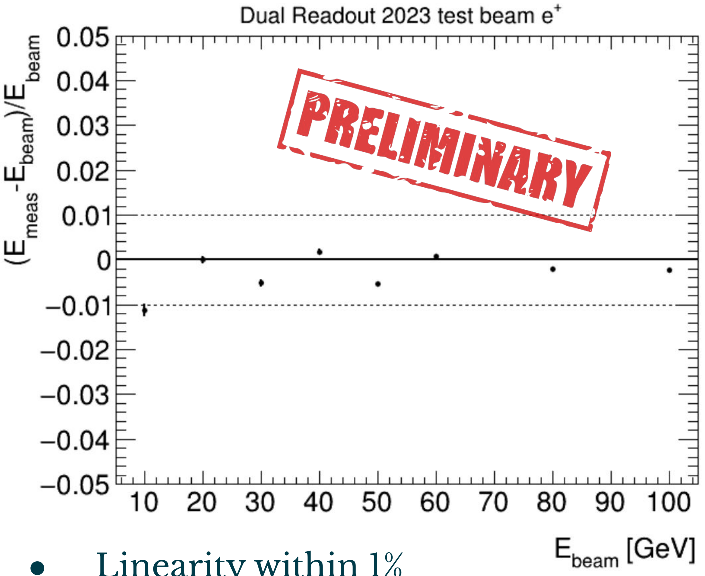




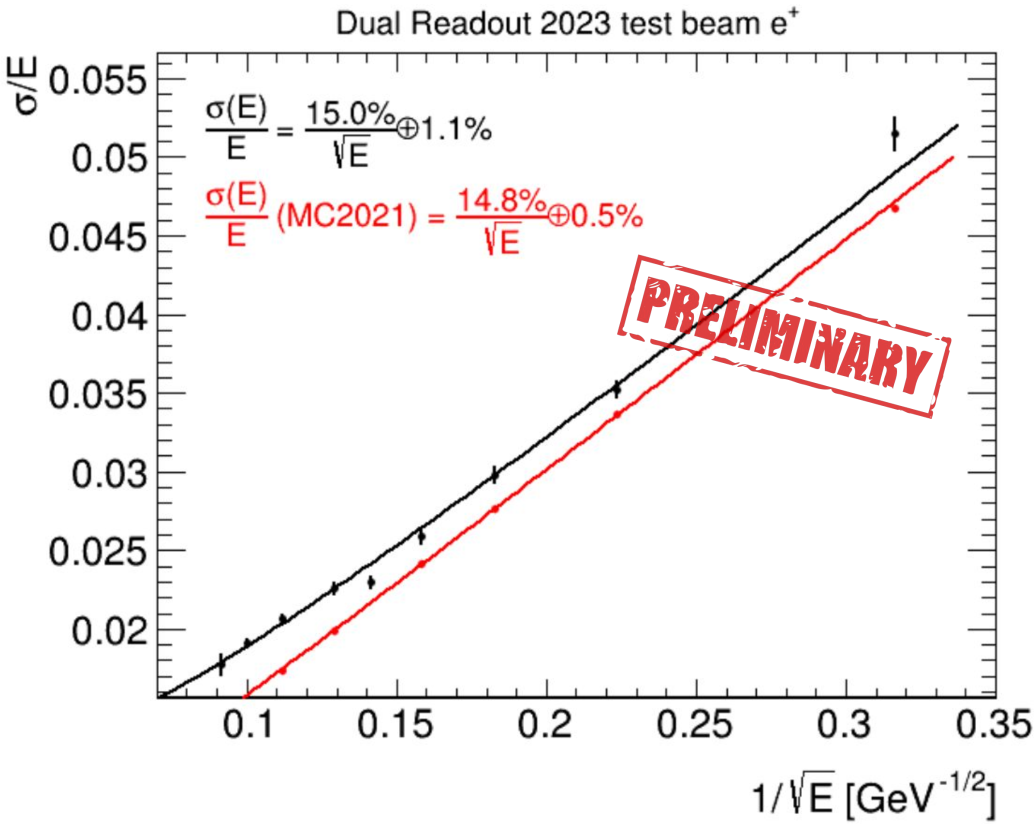
- Lateral shower profile largely independent of incident energy
- Strong dependence on vertical and horizontal rotation of calorimeter with respect to beam
    - Shower develops over more fibres



TB2023 Results: Energy Linearity and Resolution

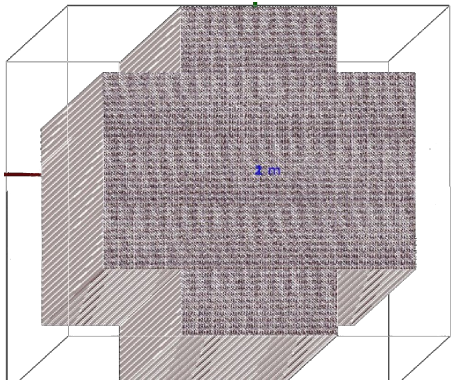


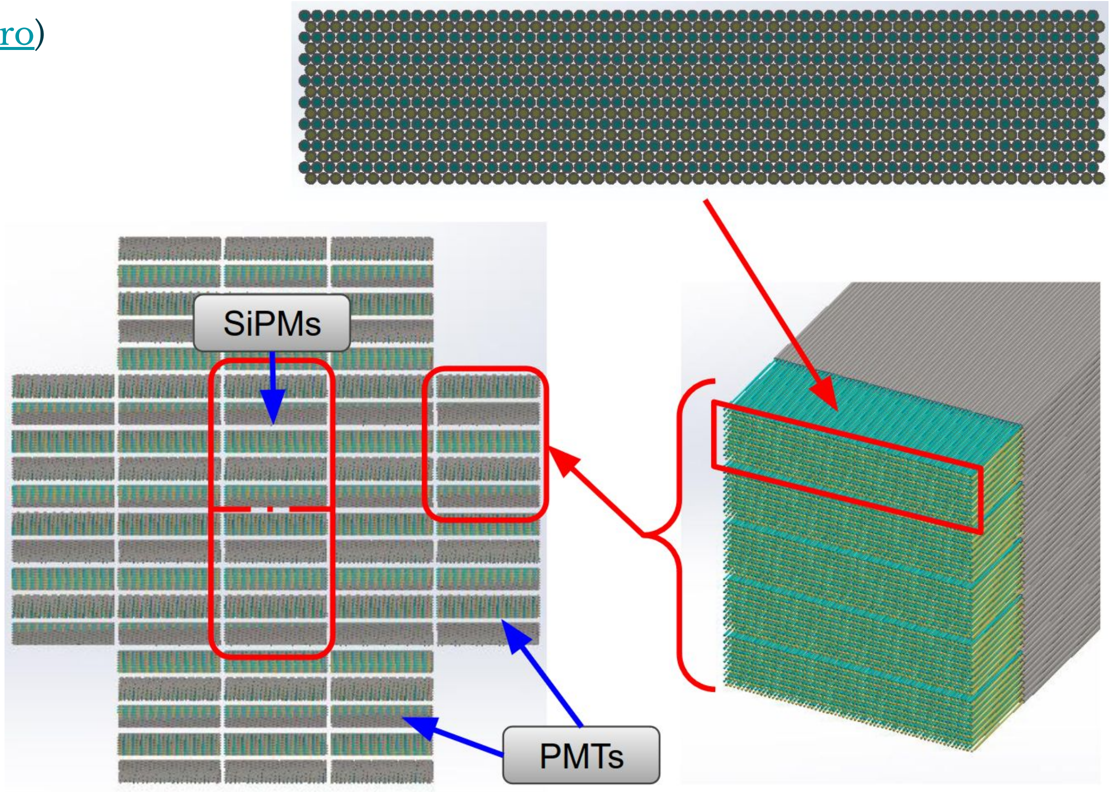
- Linearity within 1%
- Resolution looks promising
  - Large constant term due to beam energy uncertainty
  - Electronic noise term needs to be understood



HiDRa (High resolution, highly granular Dual-Readout demonstrator)

- Prototype for hadronic shower containment under construction (see talk by Romualdo Santoro)
- 65 x 65 x 250 cm^3
- 80 minimodules, each 16x64 tubes
- Mixed SiPM and PMT readout
  - 10240 SiPMs
  - 2 PMTs per minimodule
- Started to study geometry in simulation

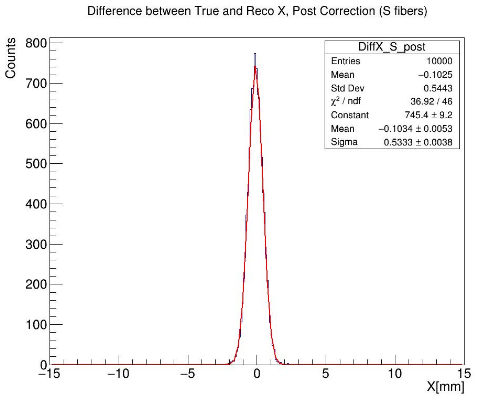




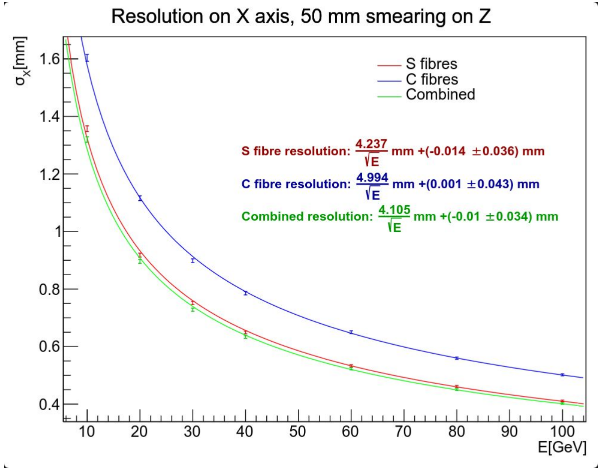
HiDRa: Spatial Resolution

$$x_{\text{Bar}} = \frac{\sum_i E_i x_i}{\sum_i E_i} \qquad y_{\text{Bar}} = \frac{\sum_i E_i y_i}{\sum_i E_i}$$

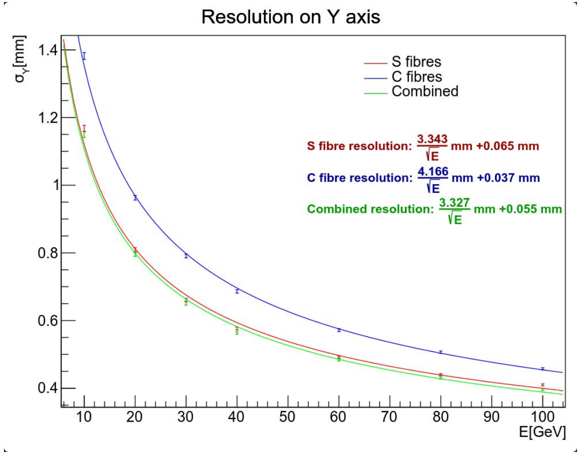
- Reconstruction of shower barycentre from SiPMs
- Grouping of fibres has **minimal effect** on spatial resolution



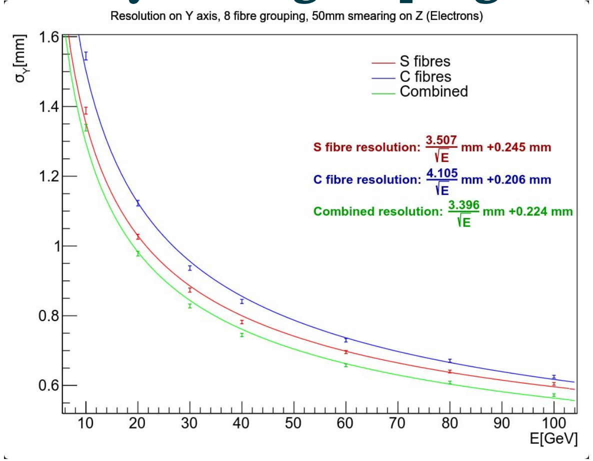
x direction



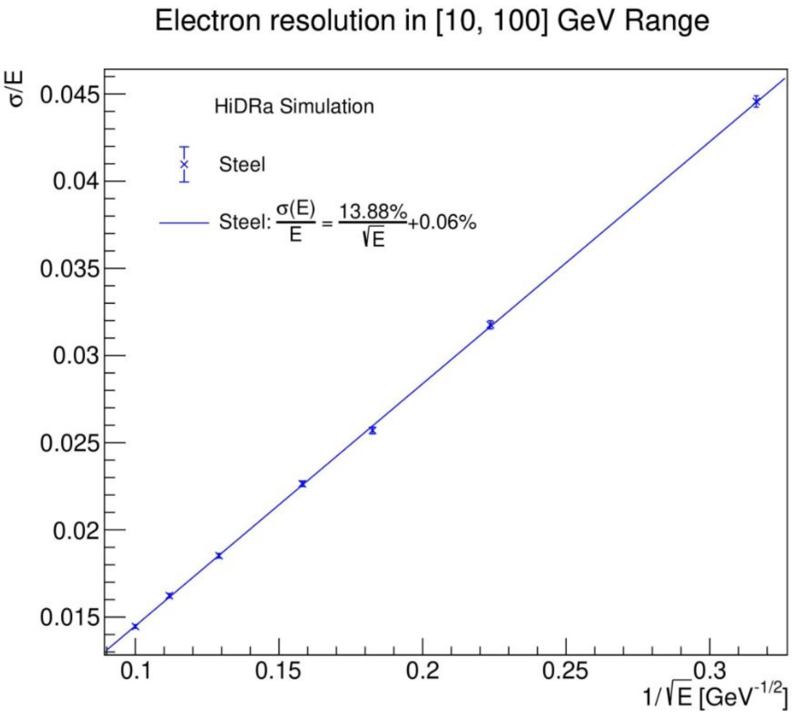
y, no grouping

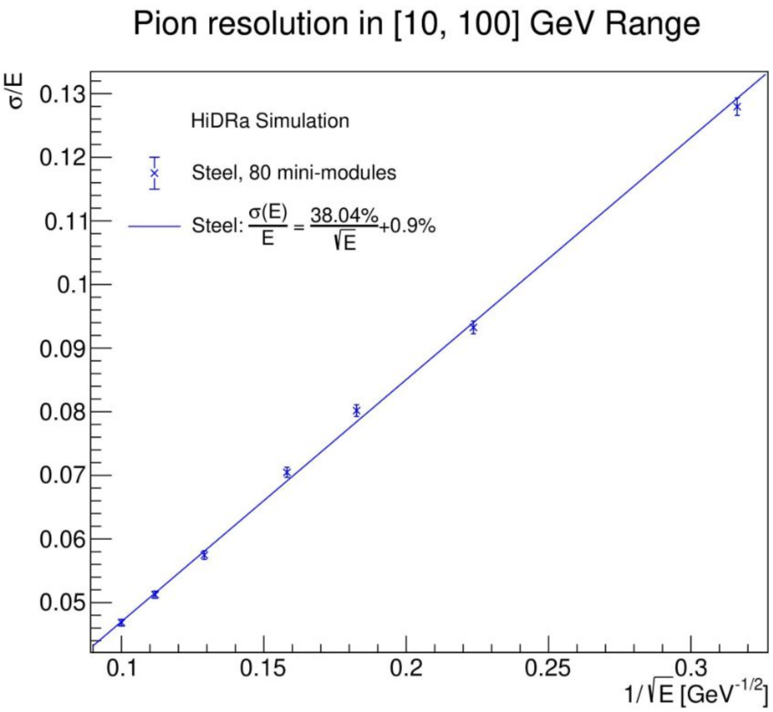


y, with grouping



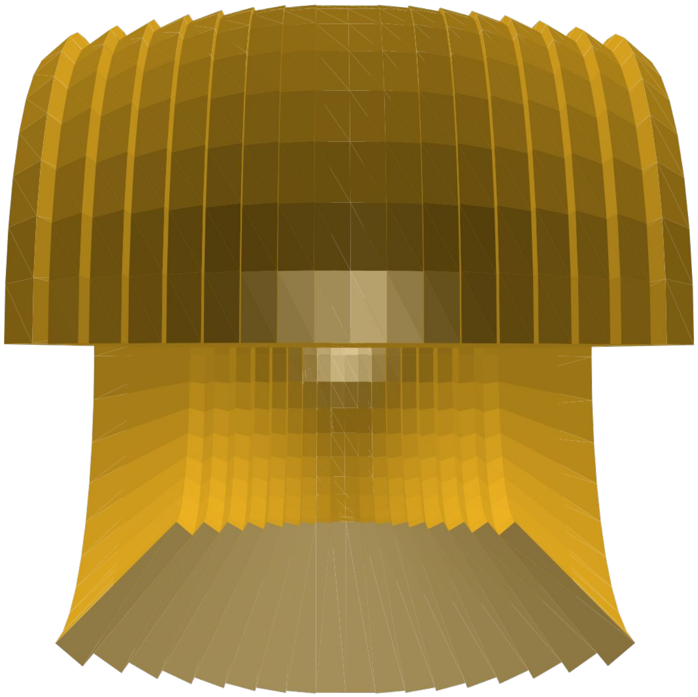
HiDRa: Single Particle Energy Resolution [reference]





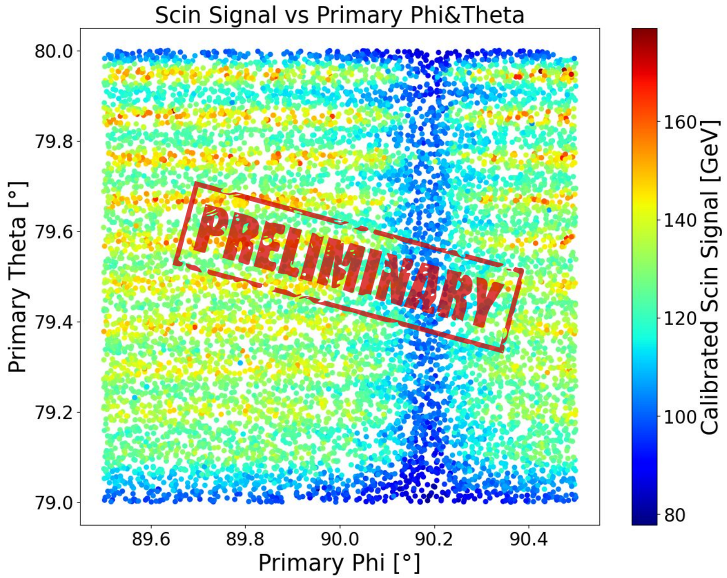
- EM resolution in line with expectations
- First estimate of hadronic energy resolution
  - somewhat limited by leakage (mostly lateral)

Full Detector Simulation



Towers enlarged for visualisation purposes

- First full detector simulation with capillary tubes under "construction"
- Using DD4hep simulation framework
- First results to come soon



Summary

- Two successful test beam campaigns with electromagnetic prototype
  - Positron showers [10-120 GeV at SPS]
  - TB2021 results recently published
- Hadronic prototype under construction
  - Partial characterisation with test beam at SPS in August
  - Expected to be fully finished by end of year
- Test beam data used to validate Geant4 simulation
  - Results for Hidra prototype seem promising
- Full Simulation of IDEA calorimeter with capillary tubes under development

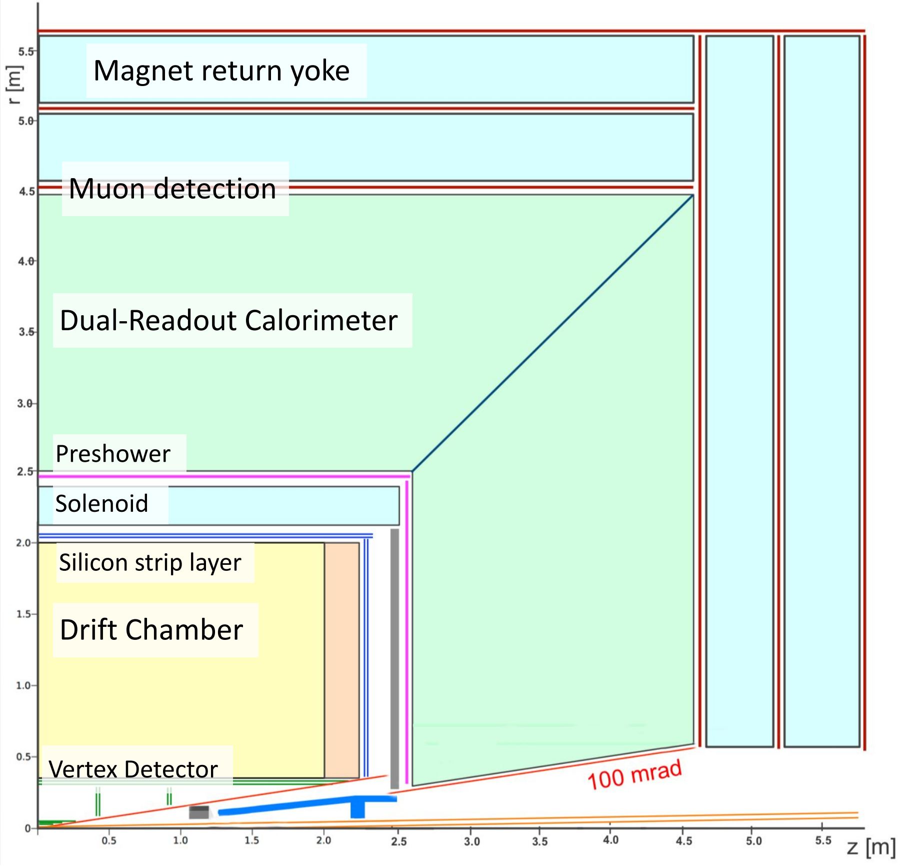
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA no 101004761.

Thank you for your attention!

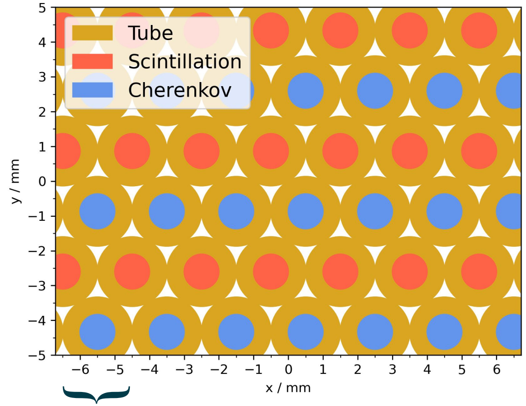
Backup-Slides

IDEA (Innovative Detector for Electron-positron Accelerators) [reference]

- Detector concept for future circular leptonic collider
- Key components:
  - Vertex detector: silicon pixels based on MAPS
  - low material Drift Chamber
  - Silicon micro-strip layer
  - Thin Solenoid: 0.7 X_0 and 0.16 λ_{int} , 2 T
  - Preshower: μ-RWELL placed behind absorber (barrel: Solenoid, forward region: Lead plate)
  - Single Dual-Readout Calorimeter: for both **EM** and **HAD** calorimetry
    - Option to have crystal ECAL being explored
  - Muon detection: μ-RWELL in 3 layers
  - Magnet return yoke



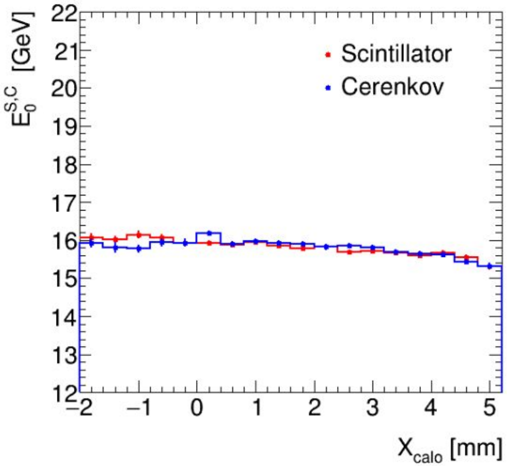
Positron Position & Energy Measurement [reference]

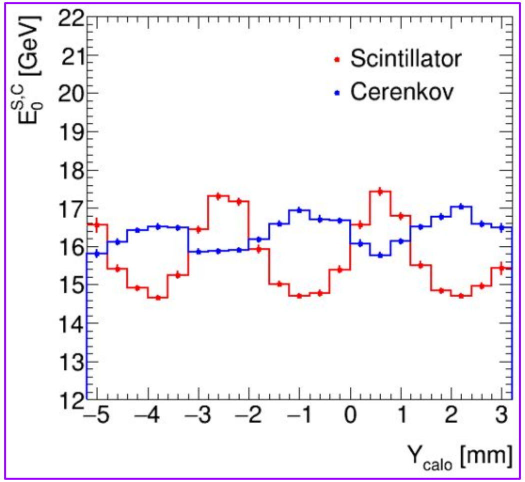


2 mm:
DWCs not precise enough

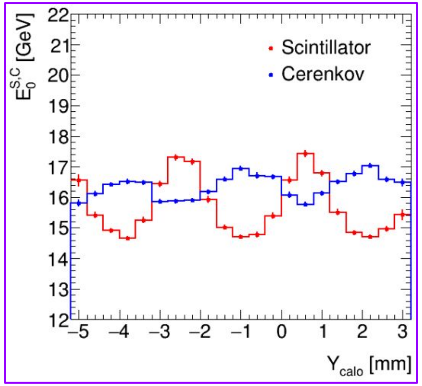
Use barycentre of shower (central tower only):

$$X_{\mathrm{CALO}} = \frac{\sum_i x_i E_i}{\sum_i E_i} \qquad Y_{\mathrm{CALO}} = \frac{\sum_i y_i E_i}{\sum_i E_i}$$



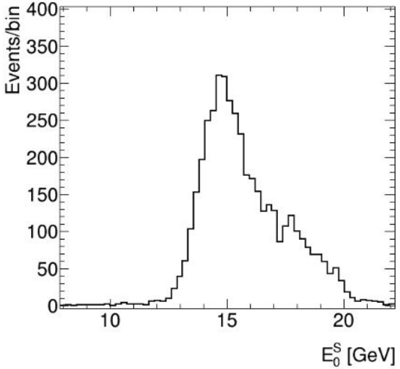


Energy Modulation [reference]

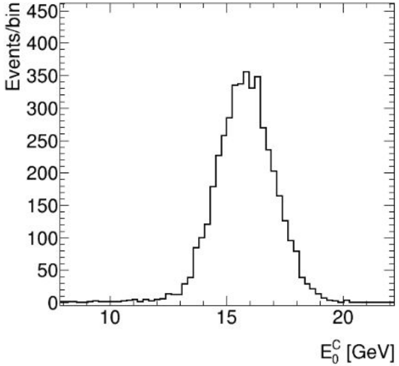


non-Gaussianity

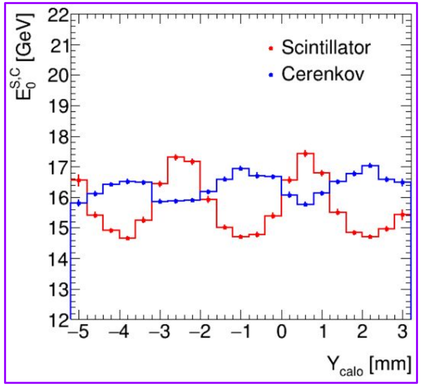
Scintillation



Cherenkov

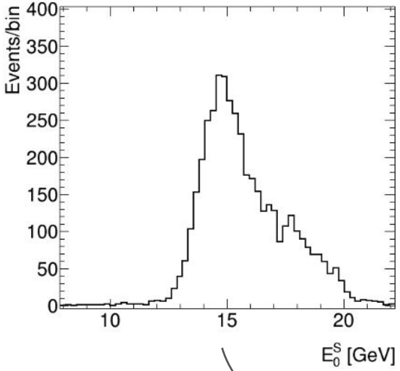


Energy Modulation [reference]

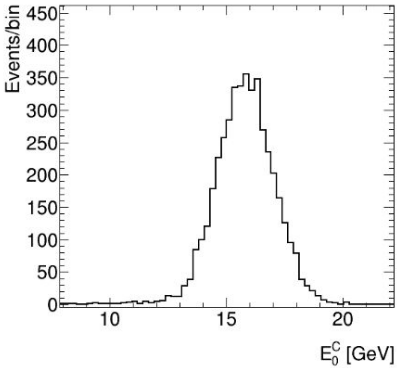


non-Gaussianity

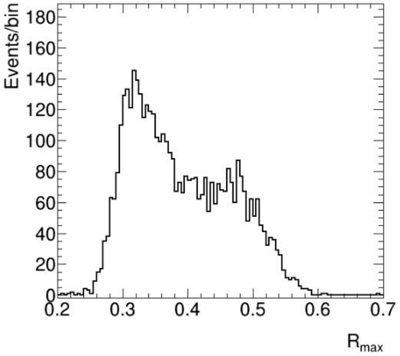
Scintillation

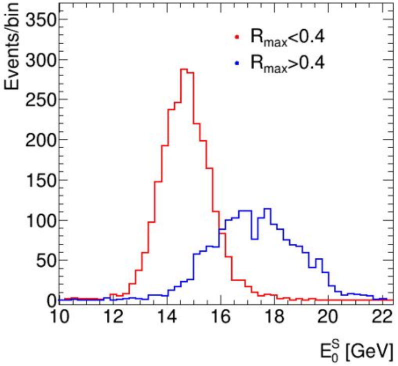


Cherenkov

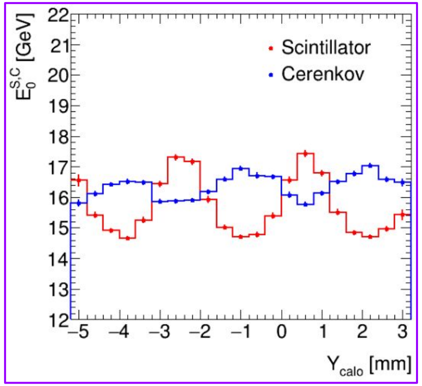


$$R_{\text{max}} = \frac{\text{Energy in row with highest S signal}}{\text{Total S Energy}}$$



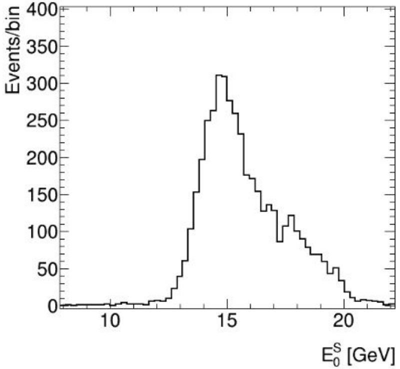


Energy Modulation [reference]

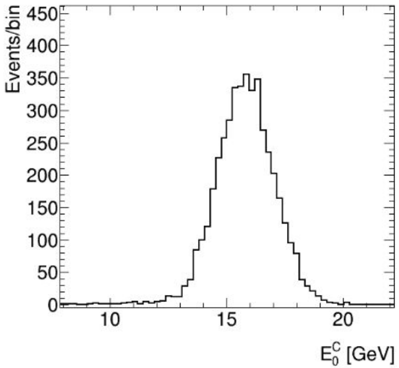


non-Gaussianity

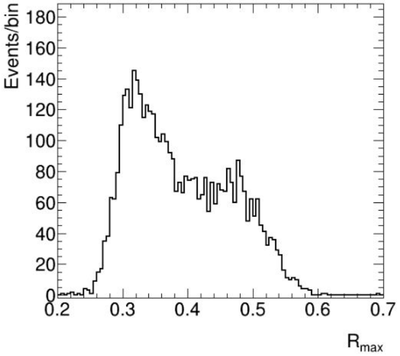
Scintillation



Cherenkov

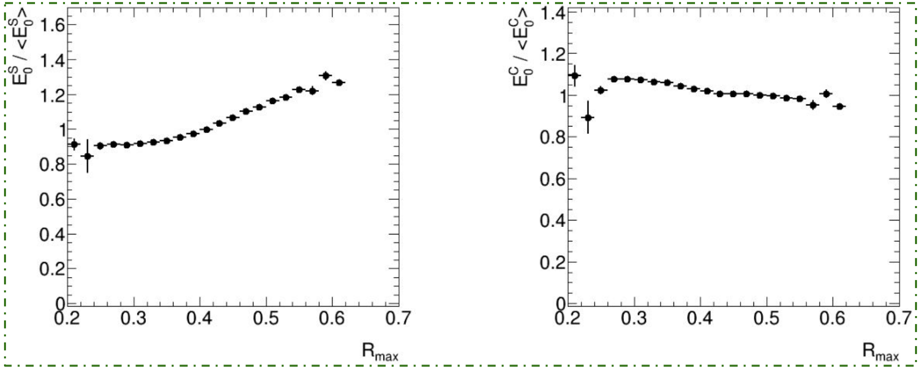


$$R_{\text{max}} = \frac{\text{Energy in row with highest S signal}}{\text{Total S Energy}}$$

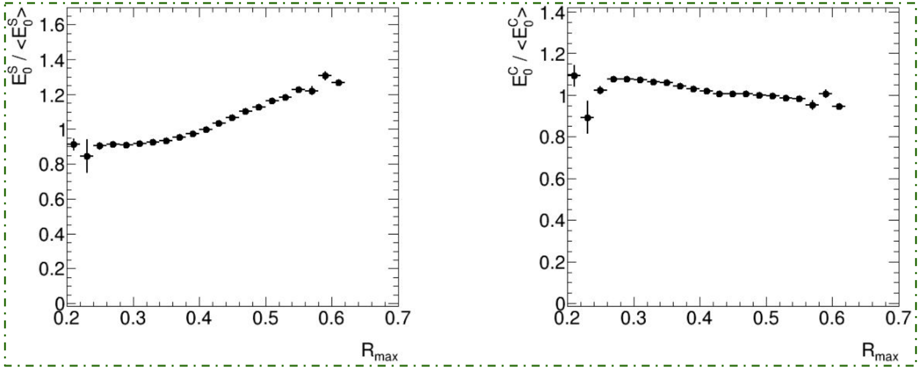


Scintillation

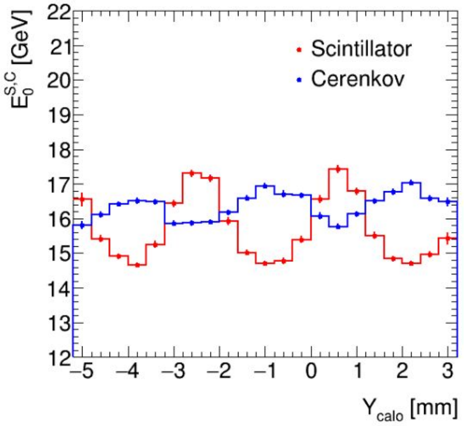
Cherenkov



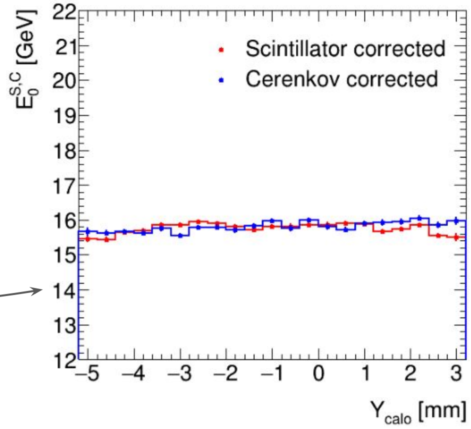
Modulation Correction [reference]

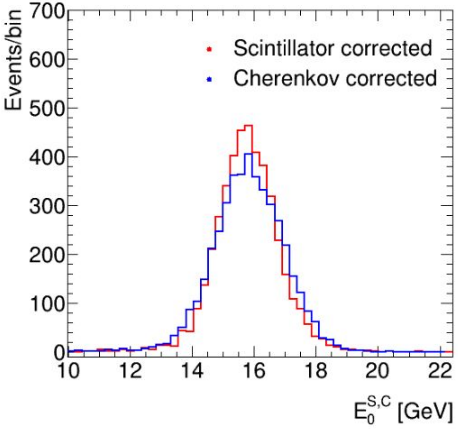


Describe with polynomial to get correction factor



correction applied





HiDRa Leakage

- ➢ Lateral leakage has major impact on energy resolution
- ➢ Longitudinal leakage leads to low-reconstructed-energy events