Updates on dual-readout fibre calorimeter development

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on behalf of the Dual-Readout group - ECFA DRD 6 Collaboration
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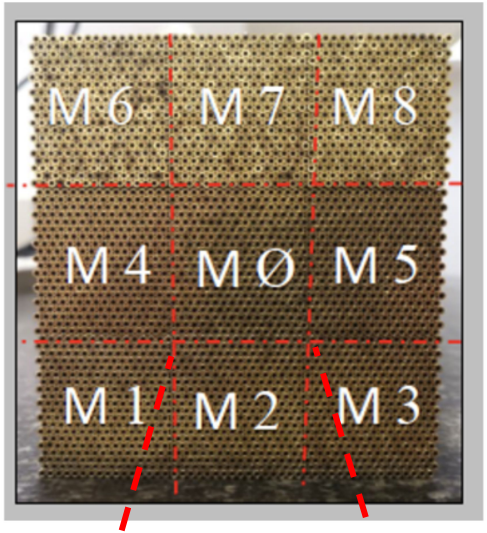
Recap on previous results

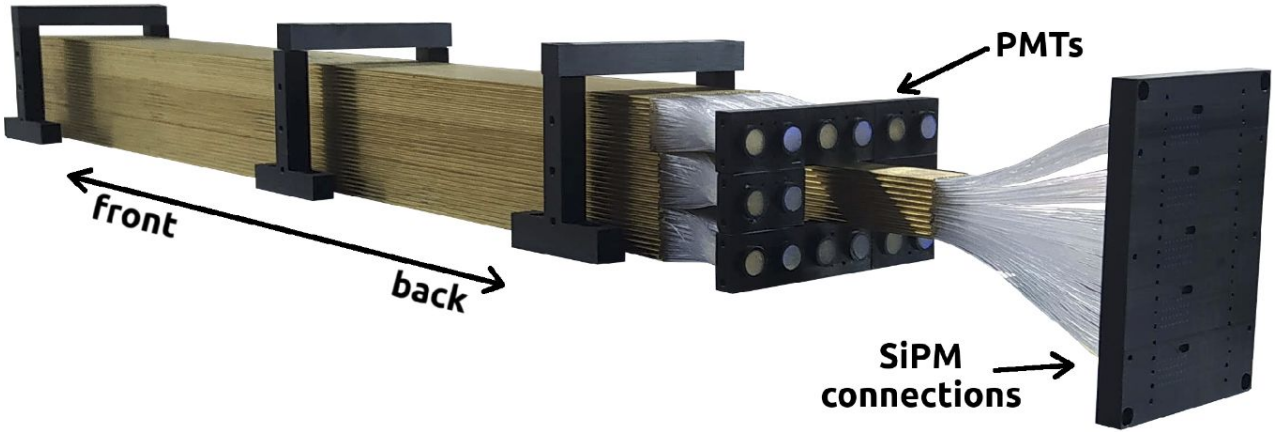
First high-granularity DR prototype built in 2021 and tested at CERN SPS
→ Results in [DOI 10.1088/1748-0221/18/09/P09021]

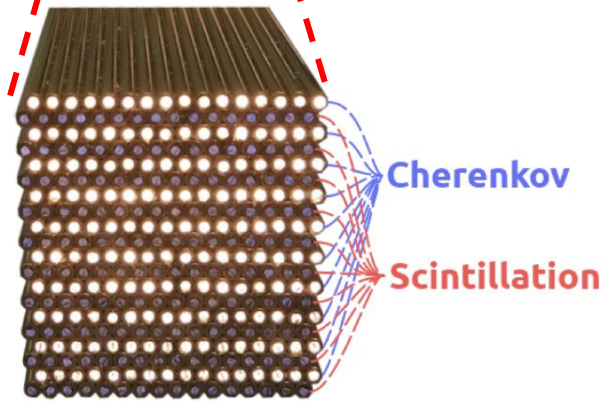
9 modules made of 16x20 brass capillaries → 10x10x100 cm^3 volume

Tube inner diameter: 1.1 mm, outer diameter: 2 mm

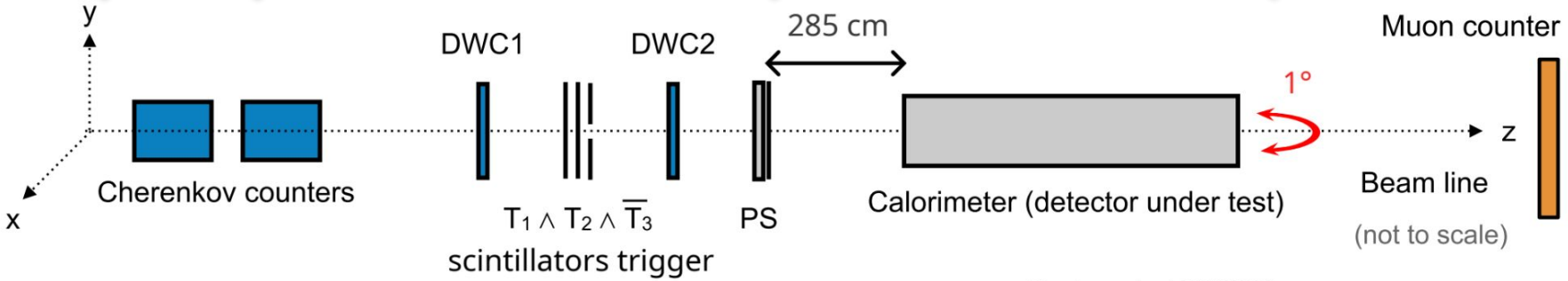
Alternating rows of scintillating and clear (→ Cherenkov) optical fibres







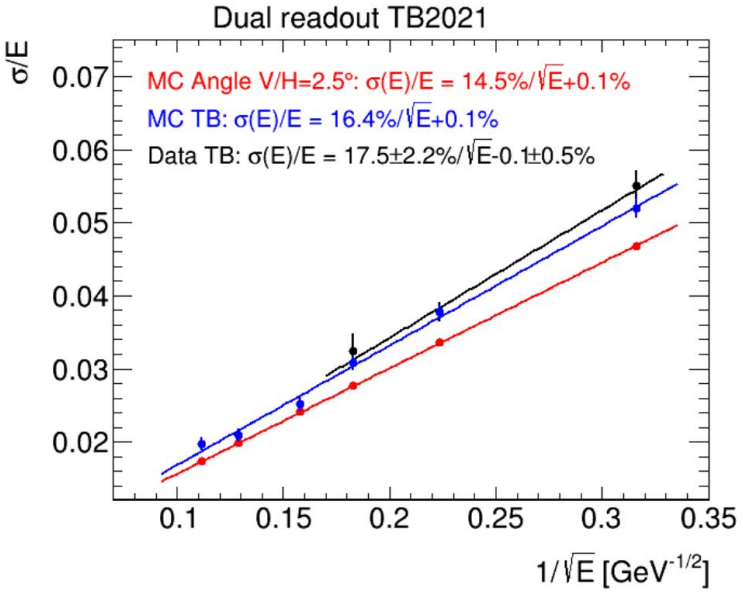
Recap on previous results (2021 test beam)



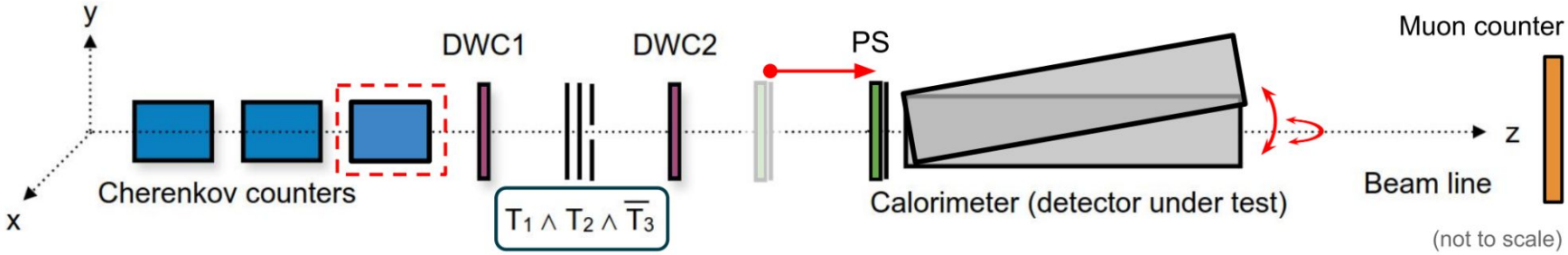
A few issues arose during data-taking:

- High contamination of hadrons in positron beam
- Lateral leakage of em showers induced by preshower positioned far from calorimeter
- Not sufficient calorimeter tilting (1° along vertical direction) → signal dependence on beam impact position due to channeling effects
- Resolution only estimated below 30 GeV (preshower out, positron selection made only with Cherenkov counters)

Data well described by Geant4 simulation reproducing TB setup: it suggested that better resolution could be achieved with larger tilting and closer preshower detector



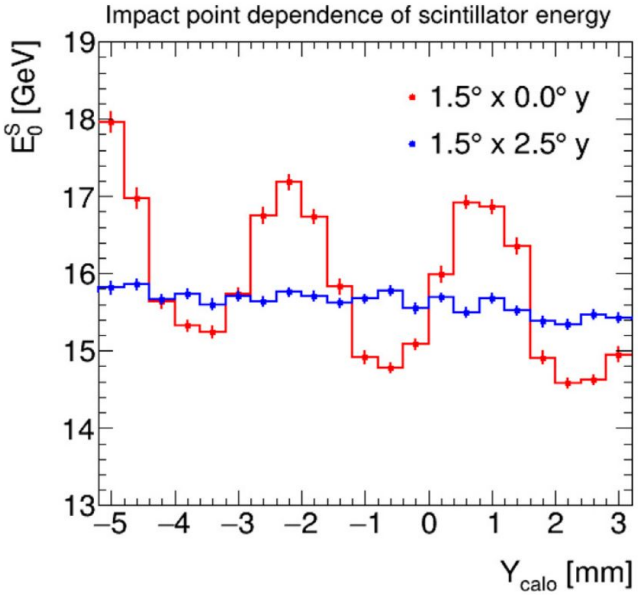
Results from 2023 test beam



Improved test beam setup with respect to previous one:

- Improved positron beam purity
- Added third Cherenkov counter, preshower closer to calorimeter, better working delay wire chambers for beam impact point position
- Two vertical tilting angles (0° and 2.5°) and horizontal angle scan
  Energy scan for resolution measurement taken with 2.5° tilting in both horizontal and vertical directions

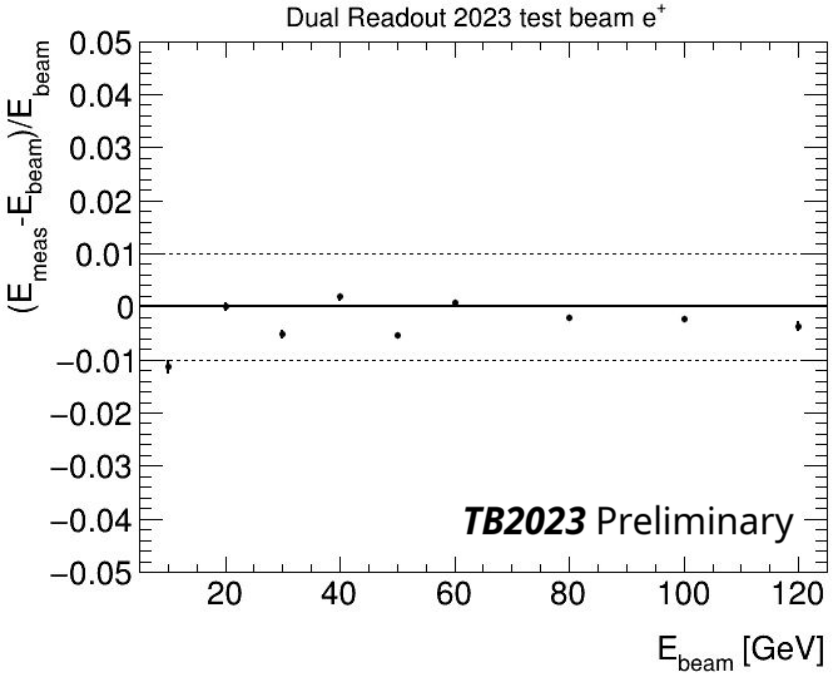
Analysis of the collected data close to be finalised, paper in preparation

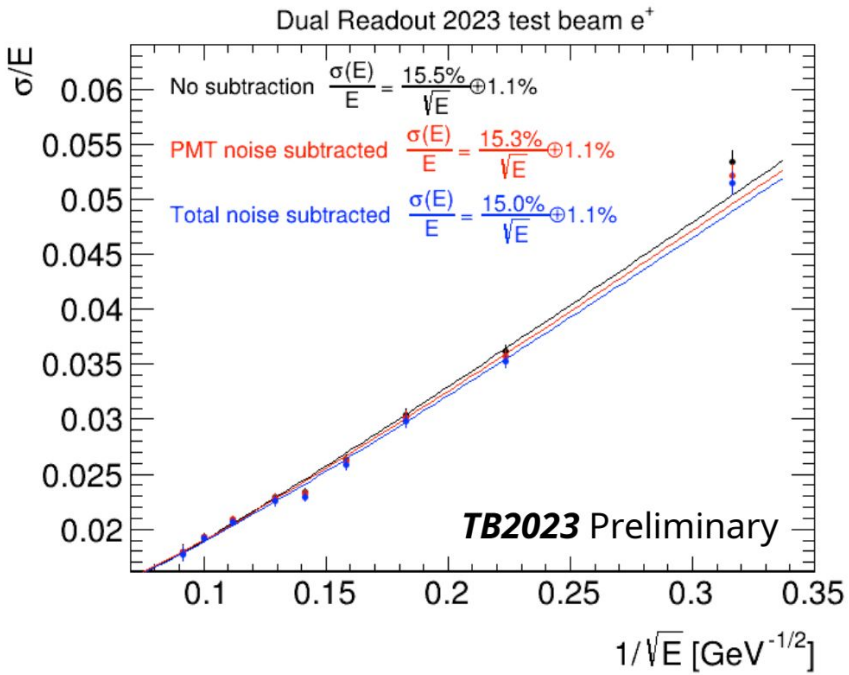


Results from 2023 test beam

Linear response within 1% in the whole [10, 120] GeV energy range, and energy resolution close to value predicted by the simulation

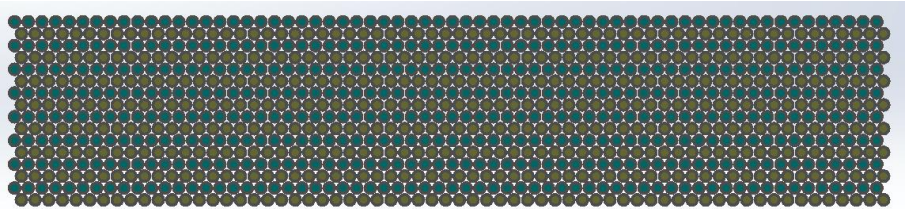
- Larger constant term compatible with beam energy spread suggested by SPS experts
- Detailed work on better understanding of noise produced by SiPMs ongoing





HiDRa prototype

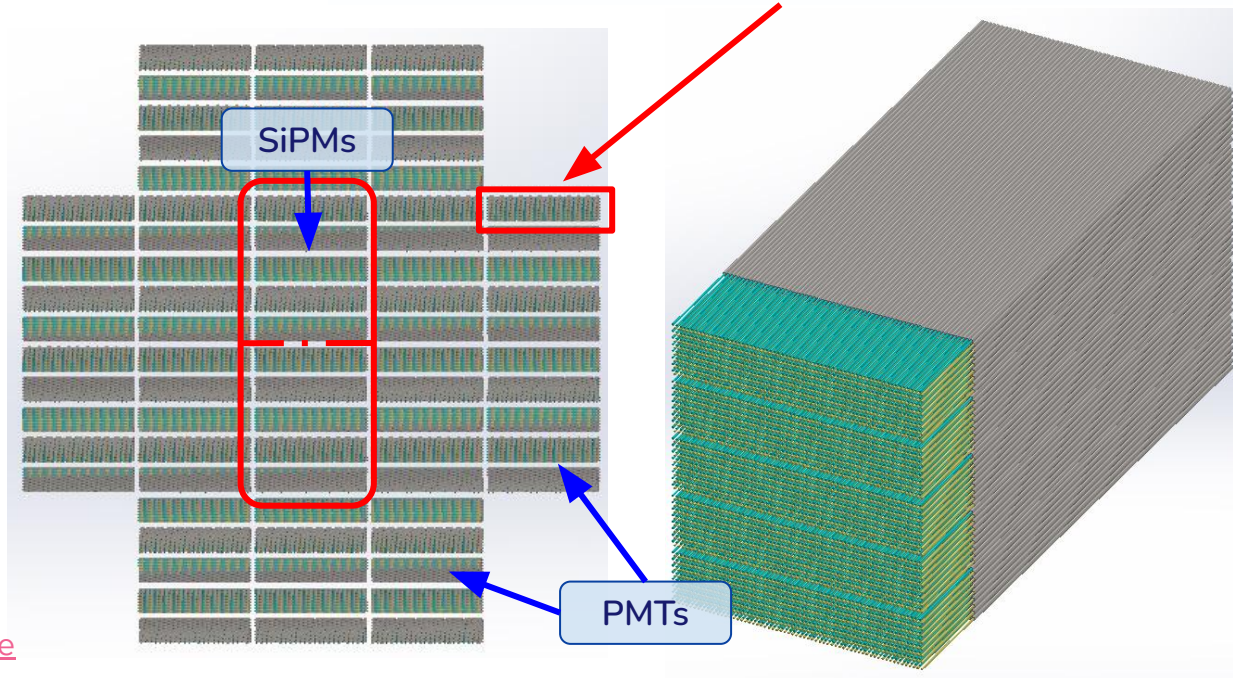
Each external module read out by two PMTs, one for S fibres and the other for C fibres (512 fibres each)



Size: 65 × 65 × 250 cm^3
(almost) fully contained hadron showers
80 modules, each made of 16 x 64 steel capillaries

Mixed SiPM and PMT readout
→ Cost/Performance optimisation
→ Significant increase in DAQ complexity (10240 SiPMs)

Aiming to identify a scalable and cost-effective solution for dual-readout calorimeter building, in preparation for IDEA experiment proposal



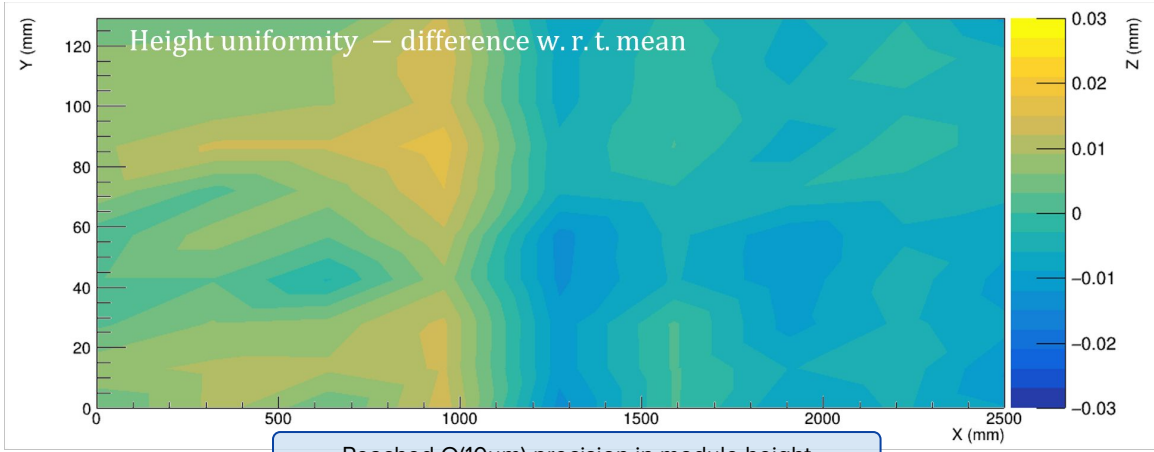
Design and a few results briefly described here

Prototype Construction

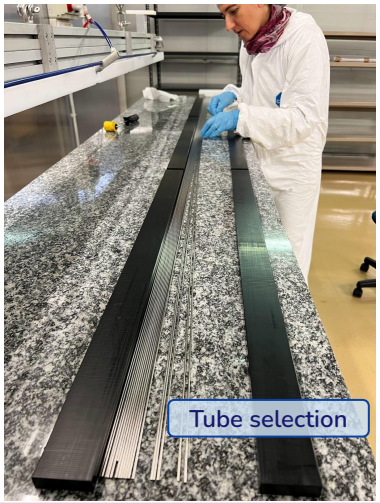
Currently 47/80 modules assembled
41 already loaded with fibres

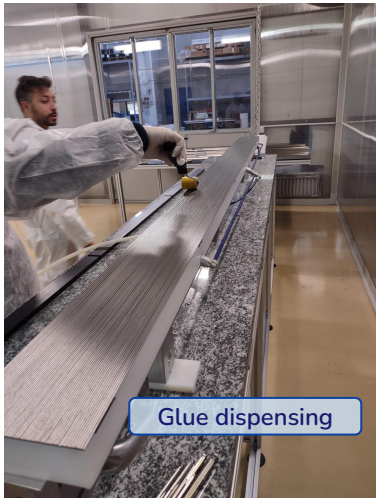
Semi-automatic system for planarity measurement shows excellent uniformity

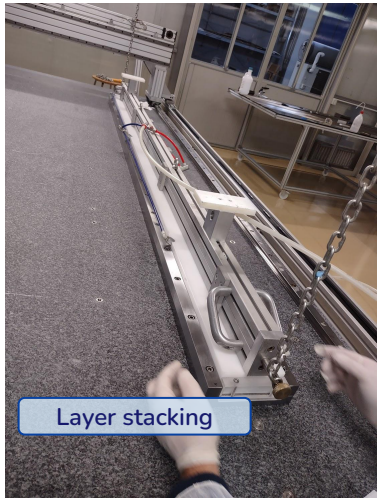
Bottleneck is fibre loading

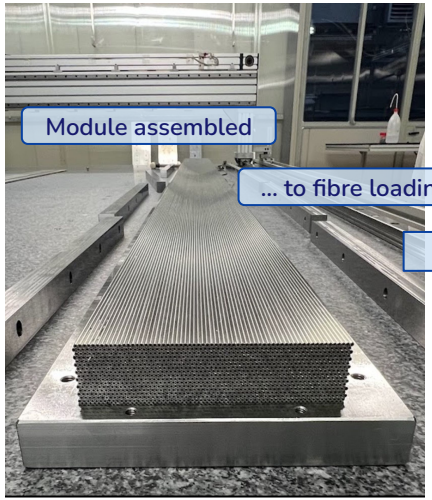


Reached O(10μm) precision in module height







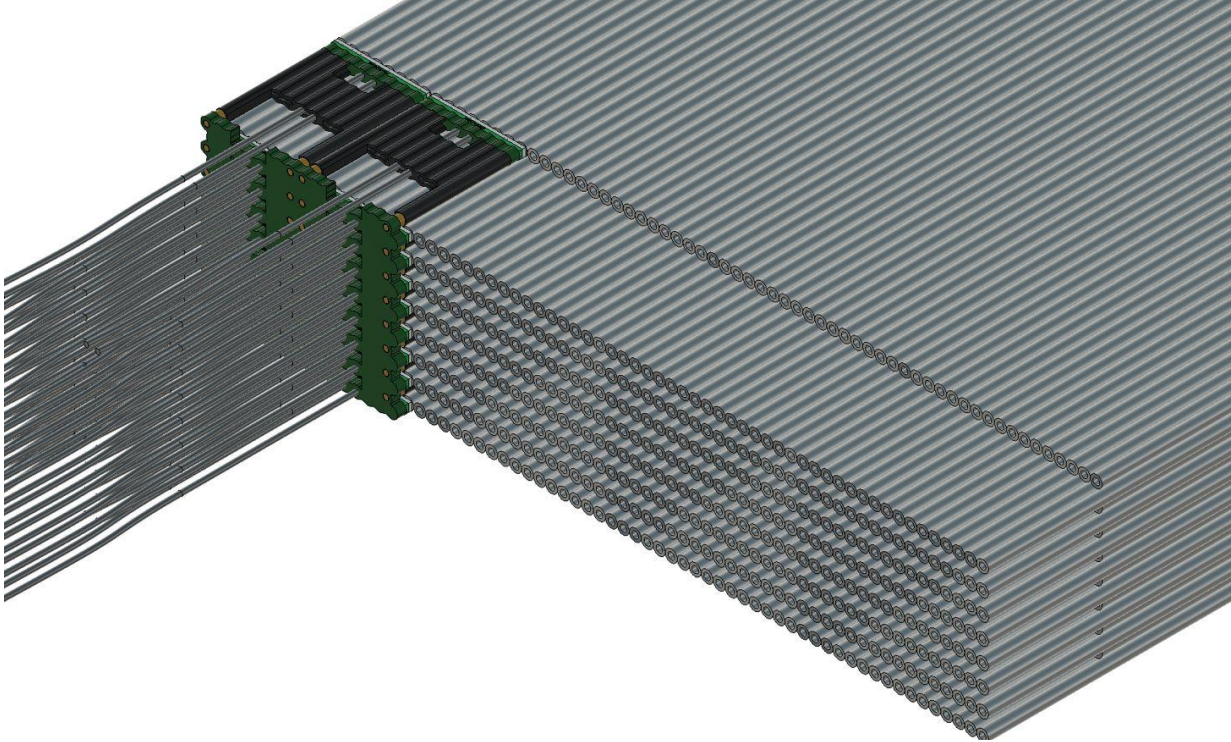


SiPM Integration

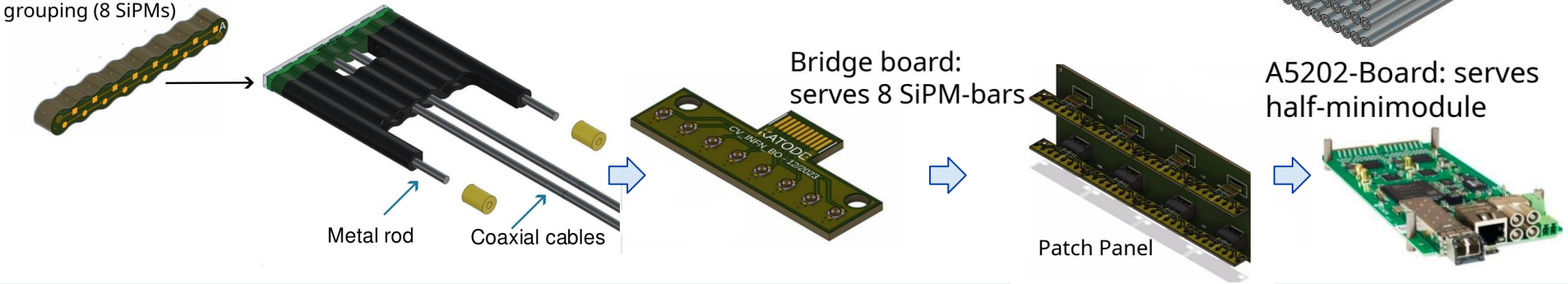
Custom electronics design required by limited space behind calorimeter

Grouping of SiPM signals from 8 same-type fibres into one readout channel performed directly on frontend boards (analog sum)

SiPMs shipped, integration to be demonstrated soon with dummy and then real components



mini FE-board with integrated grouping (8 SiPMs)



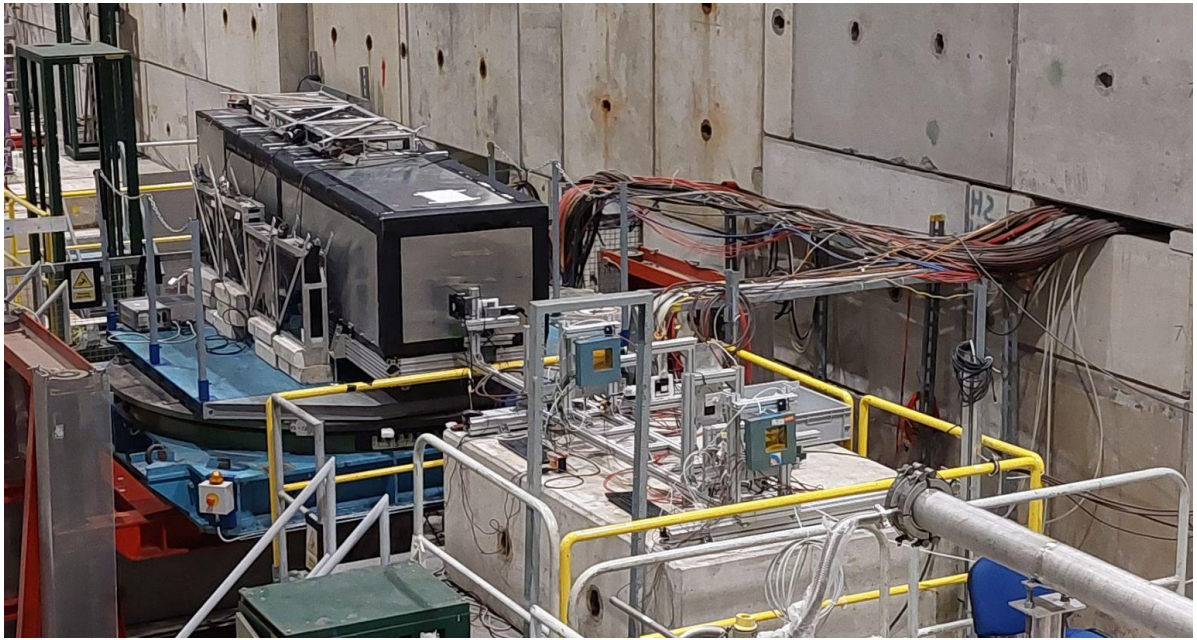
2024 Test Beam

First characterisation of new prototype on beam at the end of August

Partially completed calorimeter with 36/80 modules, using PMT-only readout
→ Dual-Readout Almost Granular Object (DRAGO) prototype

12 x 3 modules, ~ 38.4 x 33.9 x 250 cm^3
Containment for hadron showers: ~ 87%
(estimated through Geant4 simulation)

TS55	TC55	TS54	TC54	TS53	TC53
TS45	TC45	TS44	TC44	TS43	TC43
TS35	TC35	TS34	TC34	TS33	TC33
TS25	TC25	TS24	TC24	TS23	TC23
TS16	TC16	TS15	TC15	TS14	TC14
TS17	TC17	TS00	TC00	TS13	TC13
TS10	TC10	TS11	TC11	TS12	TC12
TS20	TC20	TS21	TC21	TS22	TC22
TS30	TC30	TS31	TC31	TS32	TC32
TS40	TC40	TS41	TC41	TS42	TC42
TS50	TC50	TS51	TC51	TS52	TC52
TS60	TC60	TS61	TC61	TS62	TC62



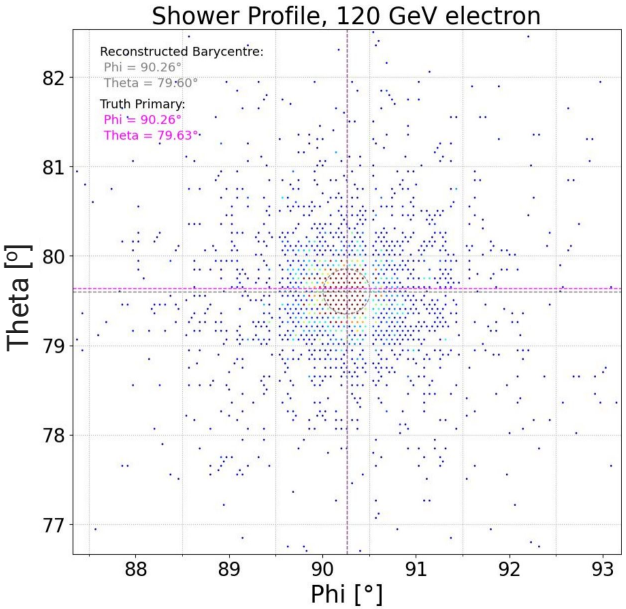
Data analysis ongoing for electron, muon and pion beams
Identification of a calibration procedure suitable for HiDRa
Results will be useful for a first simulation tuning with real prototype data

Other ongoing activities

Extensive Geant4 simulation campaign for performance estimation for both HiDRa and the IDEA calorimeters (to be updated with prototype information)

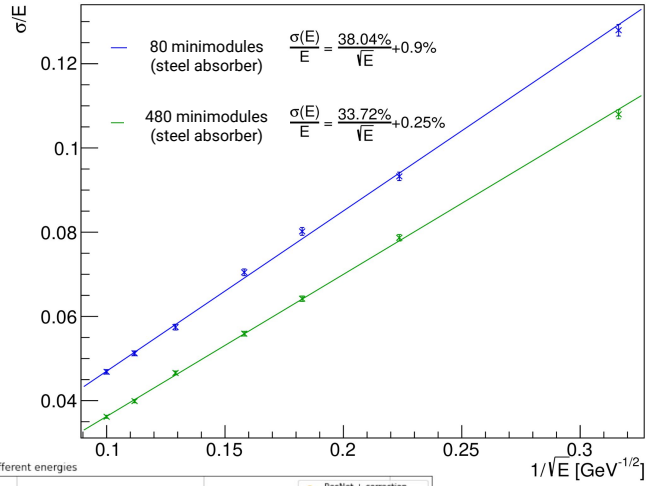
Development of IDEA calorimeter DD4HEP-based full-sim (see L. Pezzotti presentation)

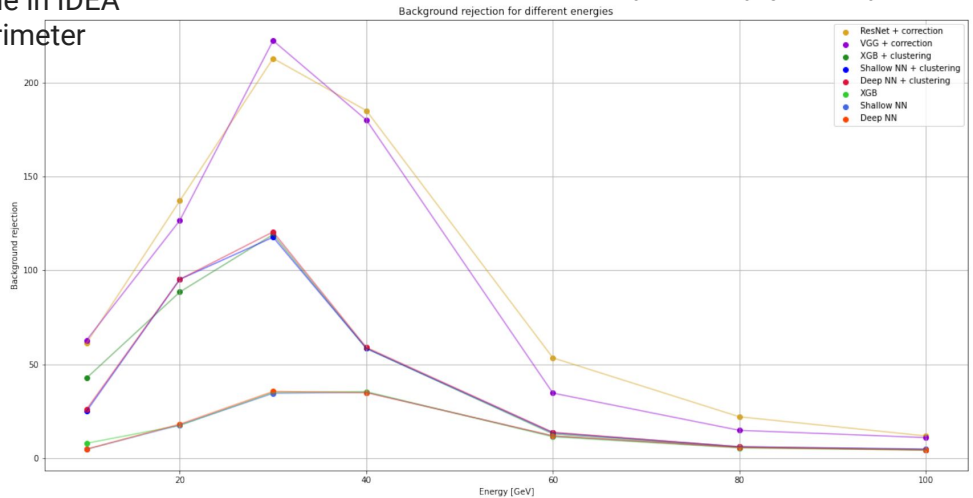
Machine learning application based on highly granular calorimeter information



A. Centeno, em shower profile in IDEA calorimeter

Pion resolution in [10, 100] GeV Range





G. Salsi π^0/γ separation using XGBoost, DNNs and CNNs

Summary

- Efforts being put on construction and characterisation of prototypes with design viable for the IDEA calorimeter
- Dual-readout technique allows for good measurements of both em and hadronic showers with a longitudinally unsegmented calorimeter (+ crystal option to further improve em shower resolution)
    - Performance for electromagnetic showers demonstrated with test beam data to be ~close to expected with small scale prototype
    - Prototype capable of hadron shower containment under construction. Reliable assembly technique identified, and SiPM integration to be tested soon.
    - Beam test of partially-completed prototype at the end of summer 2024, data analysis ongoing
- Software-based activities ongoing in parallel, including DD4Hep & Geant4 simulations, Machine Learning techniques

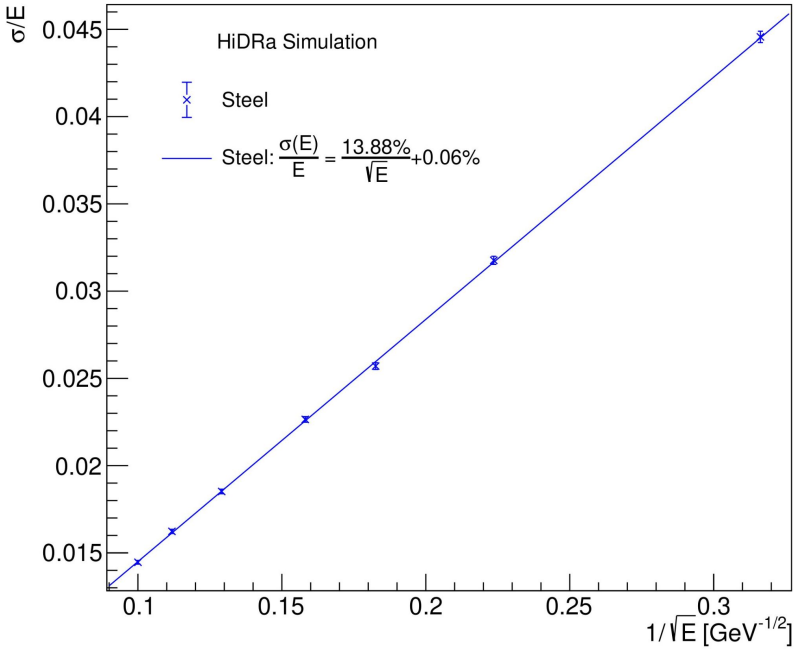
BACKUP

HiDRa performance studies

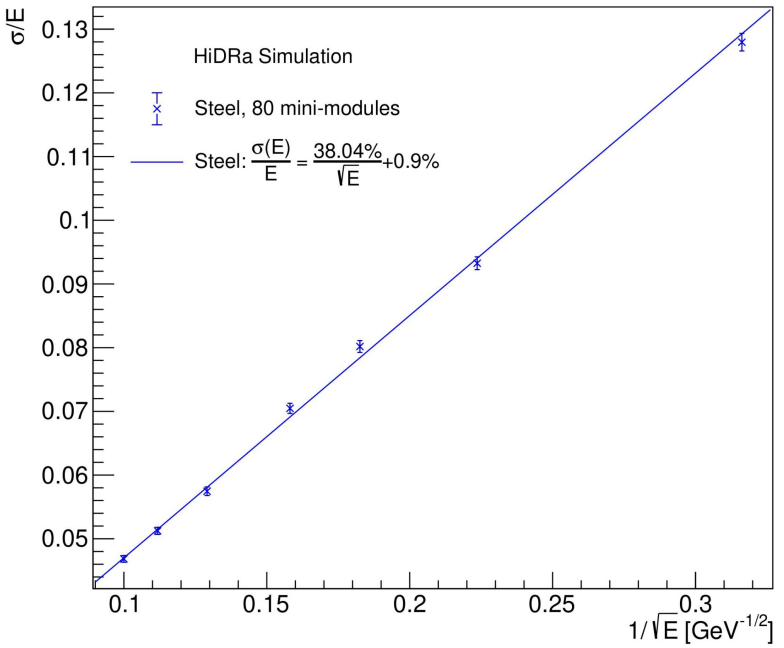
➔ See more results on Geant4-based simulations for both HiDRa prototype and the IDEA dual-readout calorimeter in Andreas' poster

Geant4 simulation-based energy resolution, for electrons and pions

Electron resolution in [10, 100] GeV Range

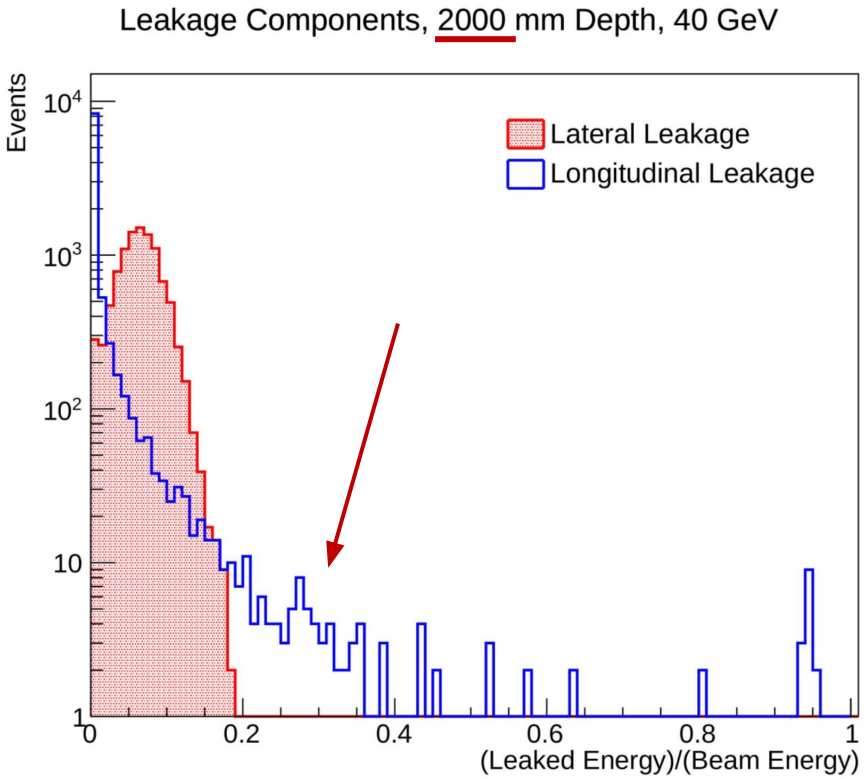


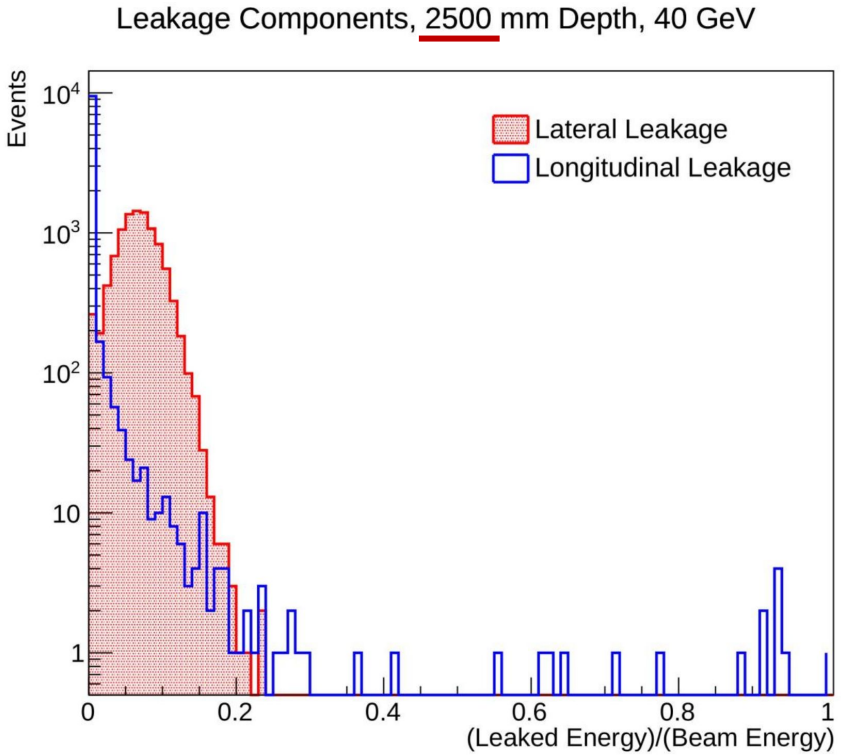
Pion resolution in [10, 100] GeV Range



HiDRa Leakage studies

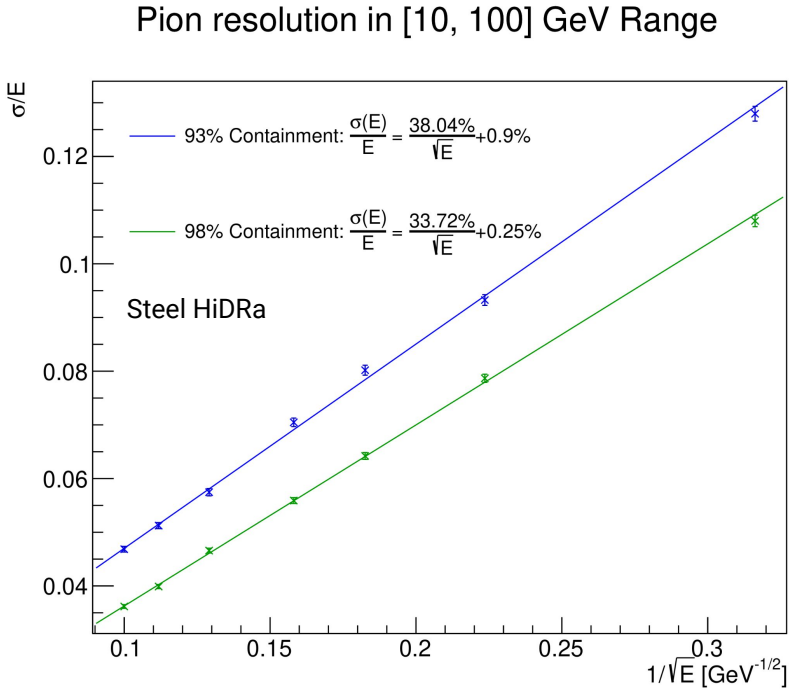
- Lateral leakage has major impact on energy resolution
- Longitudinal leakage leads to low-reconstructed-energy events

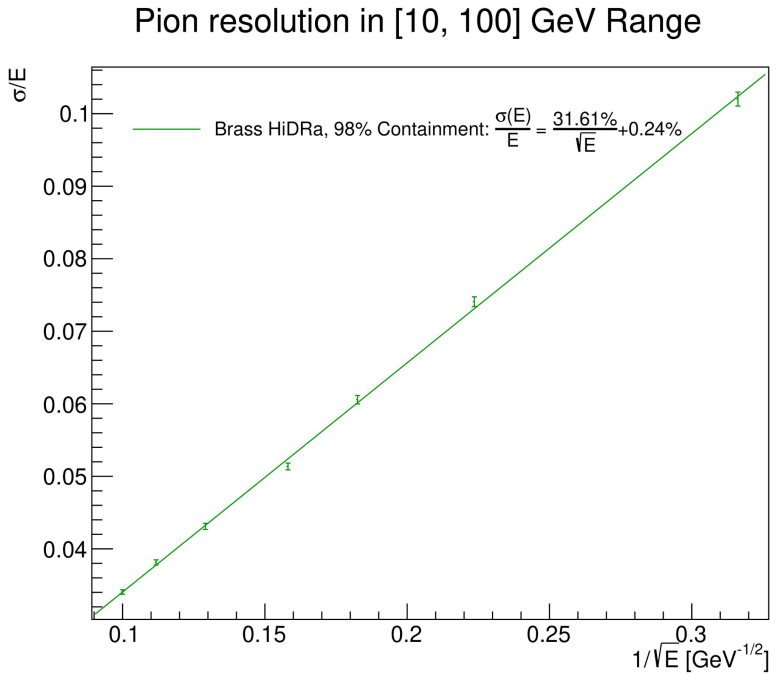




HiDRa energy resolution

Dependence of the energy resolution for hadrons on the overall containment
Add mini-modules in the simulation to estimate resolution for larger calorimeters

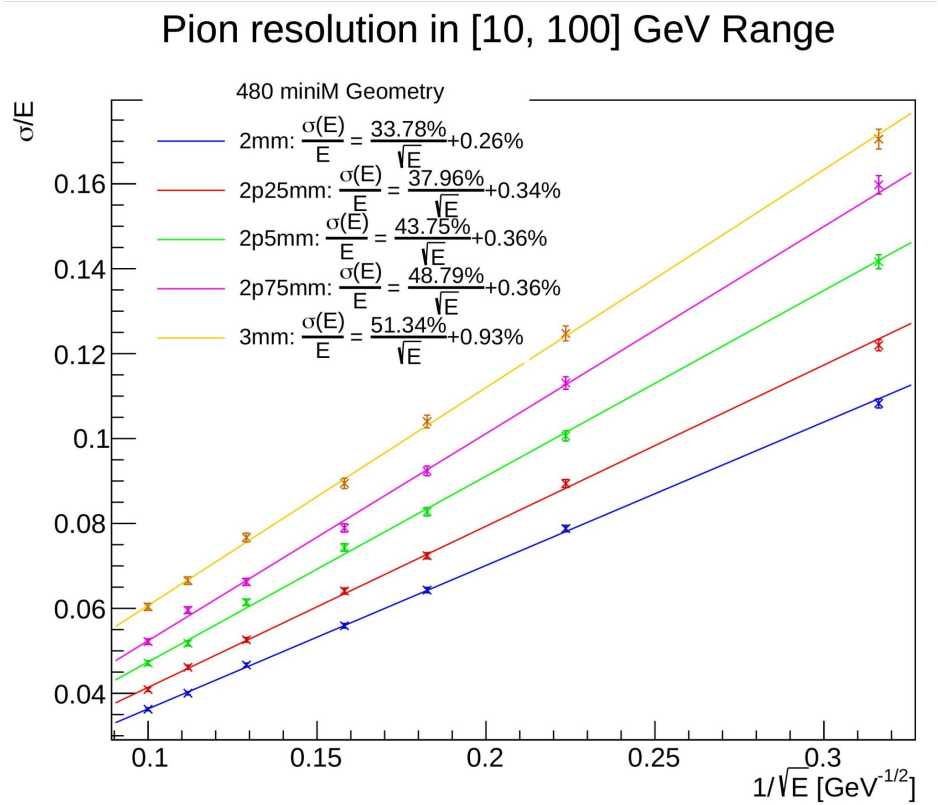




Resolution Vs Sampling Fraction

See the effect of increasing the capillary absorber outer diameter in the G4 simulation

Using the same geometry (480 mini-modules here) if one increases the outer diameter also the whole prototype containment increases

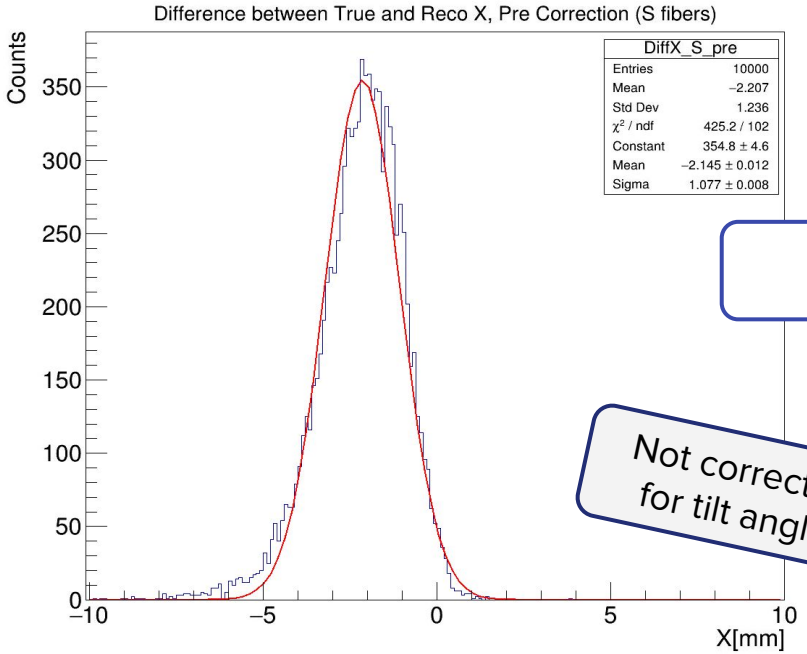


HiDRa space resolution

Reconstruct coordinates through centre-of-gravity method
Plots obtained with independent SiPM information

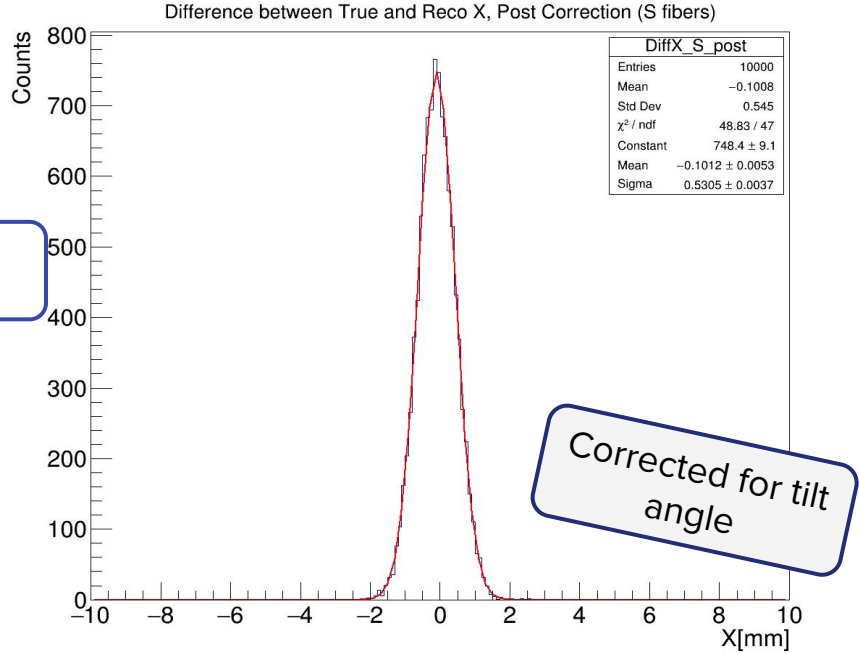
$$x_{\mathrm{Bar}} = \frac{\sum_i E_i x_i}{\sum_i E_i} \qquad y_{\mathrm{Bar}} = \frac{\sum_i E_i y_i}{\sum_i E_i}$$

Correct calorimeter tilting effect (2.5° in both X and Y directions) assuming MC truth knowledge of shower barycenter along Z axis



60 GeV electrons

Not corrected for tilt angle



Corrected for tilt angle

HiDRa space resolution (e^+)

Reconstruct coordinates through centre-of-gravity method

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

Calorimeter tilting effect (2.5° in both X and Y directions) corrected assuming MC truth knowledge of shower barycenter along Z axis with 5 cm gaussian smearing

Molière radius in HiDRa: ~24.7 mm → marginal impact of 8 channel grouping (16 mm)