Q-Wall, a Novel Quartz-Cherenkov Calorimeter Concept

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Motivation

Electromagnetic calorimetry in the forward regions of collider detectors is particularly challenging:

- Radiation levels are dramatically high
- Particle multiplicity is high rendering the particle separation a significant challenge
- Time resolution requirements are high for a clear discrimination of beam and physics-related events

Therefore, the future and upgrade forward detectors need:

- Improved EM energy resolution,
- Increased transverse segmentation and
- Refined time response.

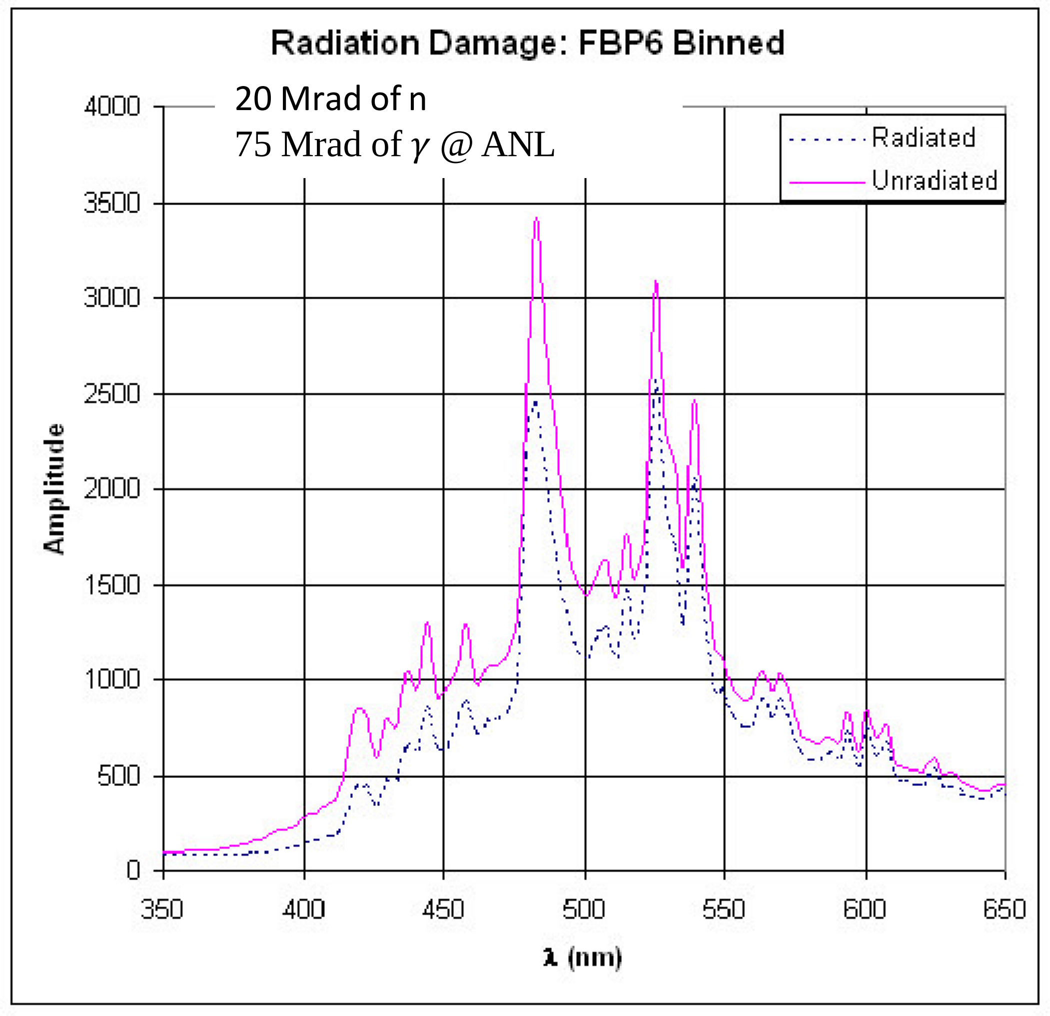
Possible Implementation

An immediate use case is the CMS Hadron Forward (HF) Calorimeters. Although the HF calorimeters are extremely radiation-hard with its steel-quartz fiber structure, a dedicated electromagnetic section upstream of HF would offer several advantages:

- Improvement of transverse segmentation to manage pileup and better define jets,
- Improved timing information to counteract pile-up,
- Enhanced measurement of the electromagnetic component of incident jets,
- Enhanced vertex reconstruction of events in the forward region,
- Mitigation of radiation damage to HF,
- Production of a tag for incoming isolated muons,
- Reduction of punch-through backgrounds into the HF calorimeters, and
- A renewed interest in forward physics.

The Q-Wall Concept

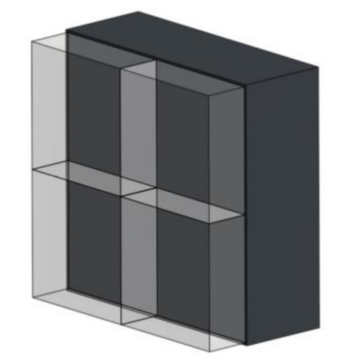
Detectors that utilize quartz Cherenkov radiators coupled to fast and radiation-hard photodetectors are exceptionally well-suited to meet the requirements.



- Quartz is extremely radiation-hard

- Microchannel Plates (MCPs) and photomultiplier tubes (PMTs) are attractive options as photodetectors of Q-Wall with their relatively high efficiencies, high gains and low transit time spreads.

The simplest design would be quartz blocks coupled to multi-anode PMTs.

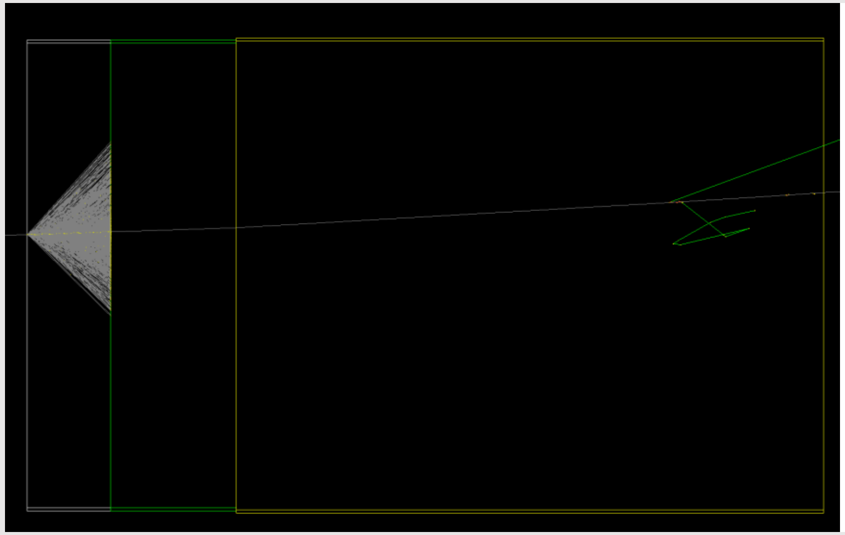


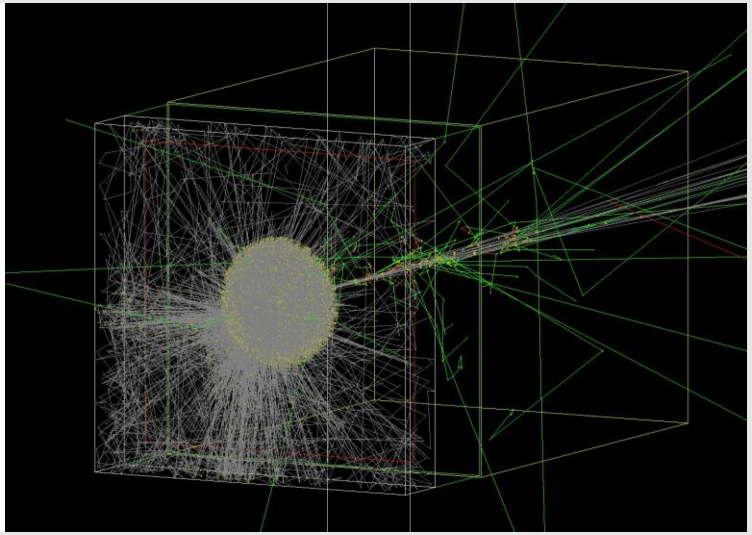
Single Q-Wall module

The Q-Wall Concept

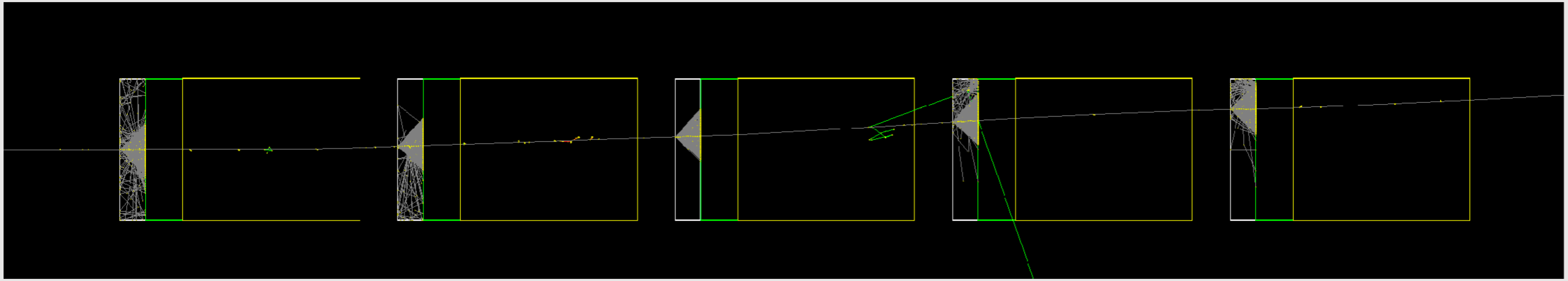
The design integrates radiation-resistant quartz tiles/blocks with equally resilient PMTs. As charged particles traverse the quartz array, they produce Cherenkov light, which is then captured and measured by the PMTs.

A muon traversing a single Q-Wall cell





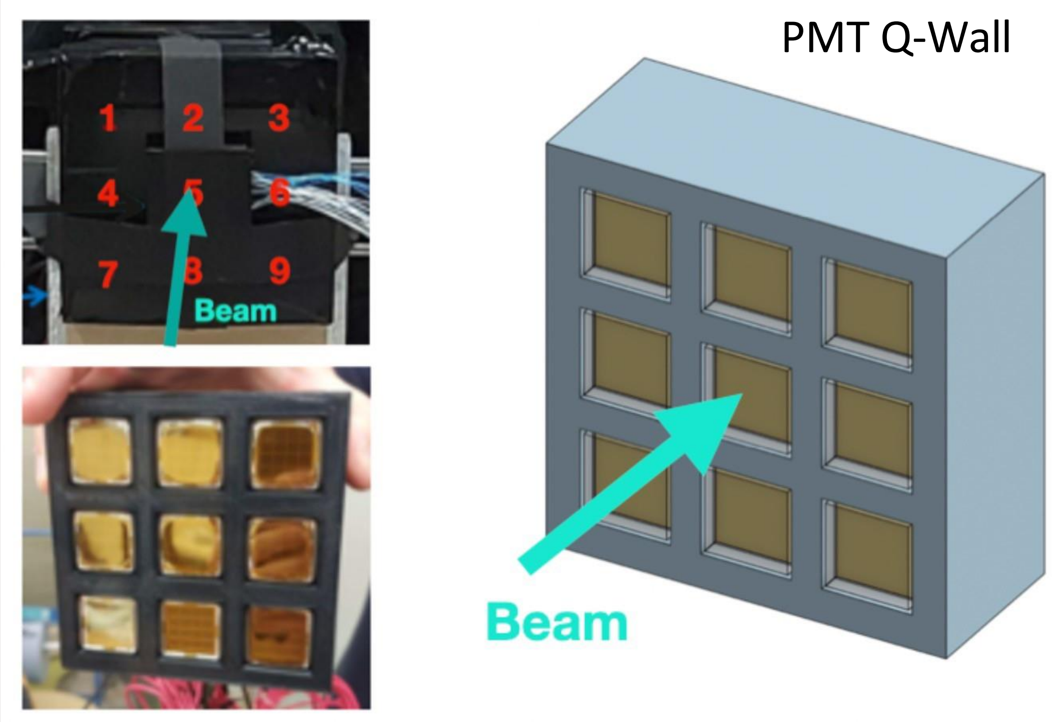
A muon traversing five consecutive Q-Wall cells interspersed with 1 X_0 Fe absorbers



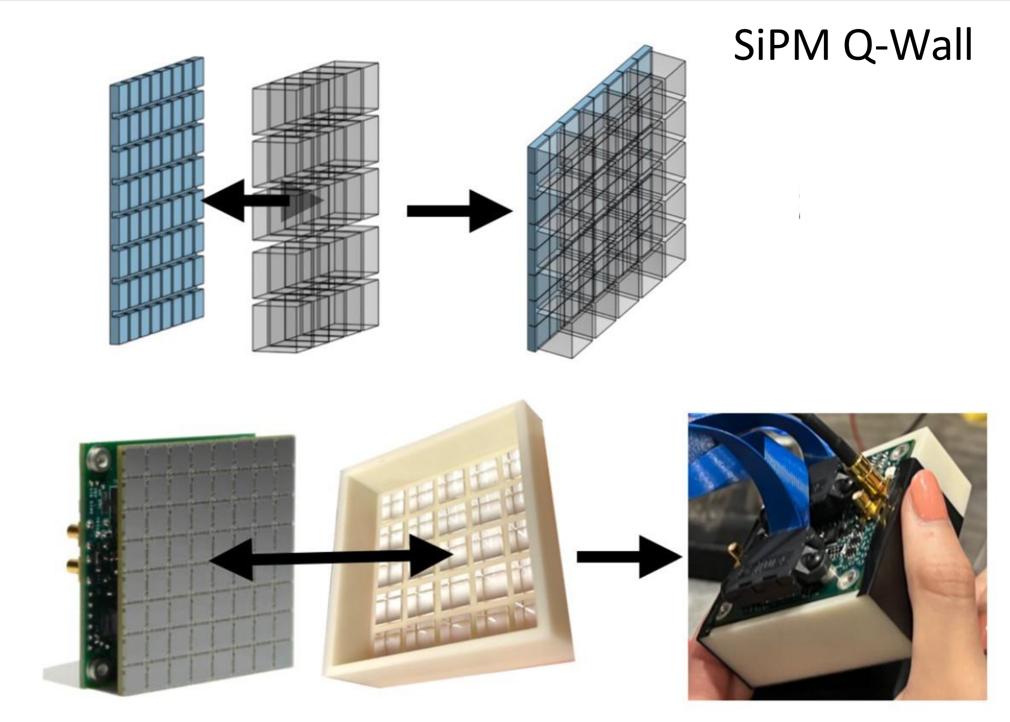
Development and Testing of Q-Wall Modules

In order to validate the suitability of the Q-Wall concept for electromagnetic calorimetry, we constructed a Q-Wall module with ultraviolet transmitting plexiglass tiles and multi-anode PMTs.

In addition, we constructed another Q-Wall module with matrices of Silicon Photomultipliers (SiPMs) coupled with small borosilicate glass cubes in order to explore the effect of high lateral segmentation (not baseline design).



PMT Q-Wall



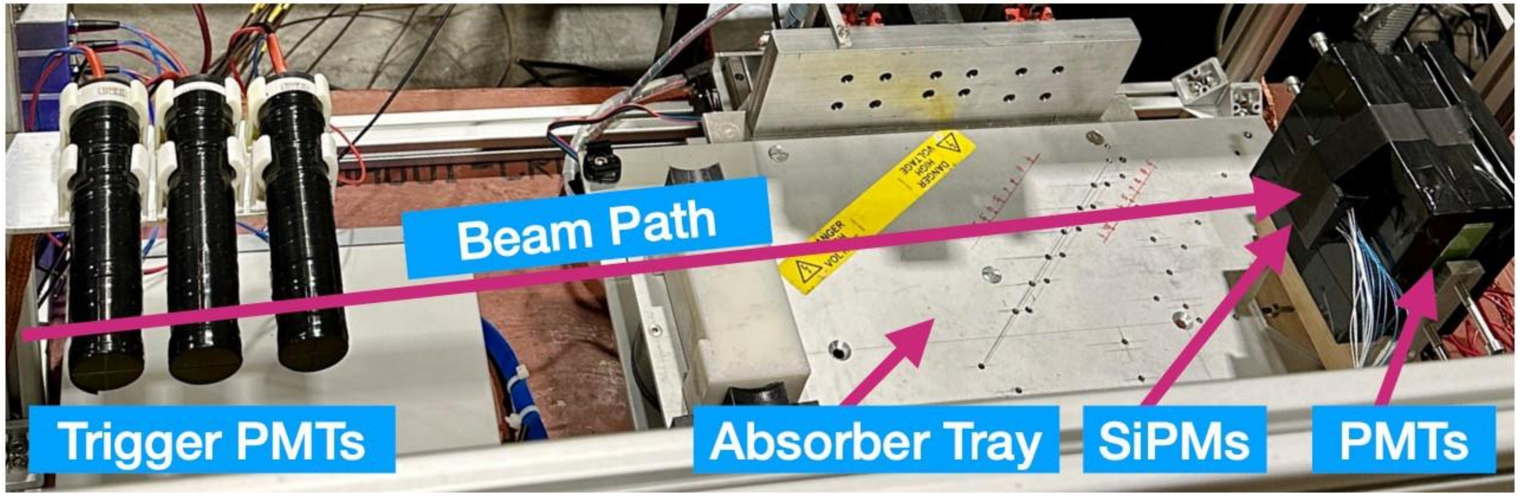
SiPM Q-Wall

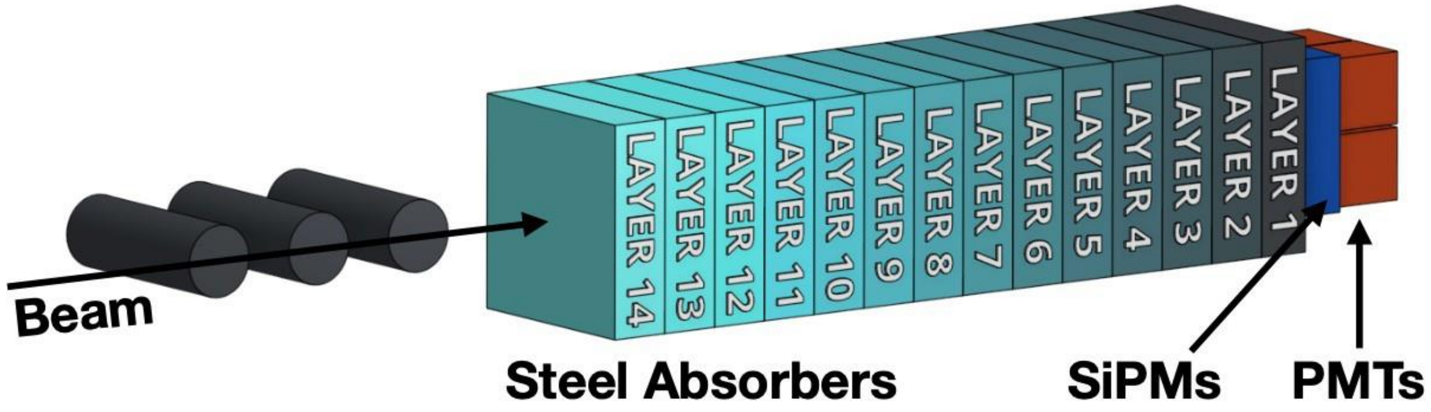
Beam Test Setup

The electromagnetic shower development was mimicked by the variable upstream absorber amount. Different PMTs were used in different test campaigns: Hamamatsu R7600 and R 5900. The SiPMs in the SiPM Q-Wall module were Onsemi C Series 6 x 6 mm in an 8 x 8 array.

CERN SPS beam line

40 - 100 GeV/c electron beams



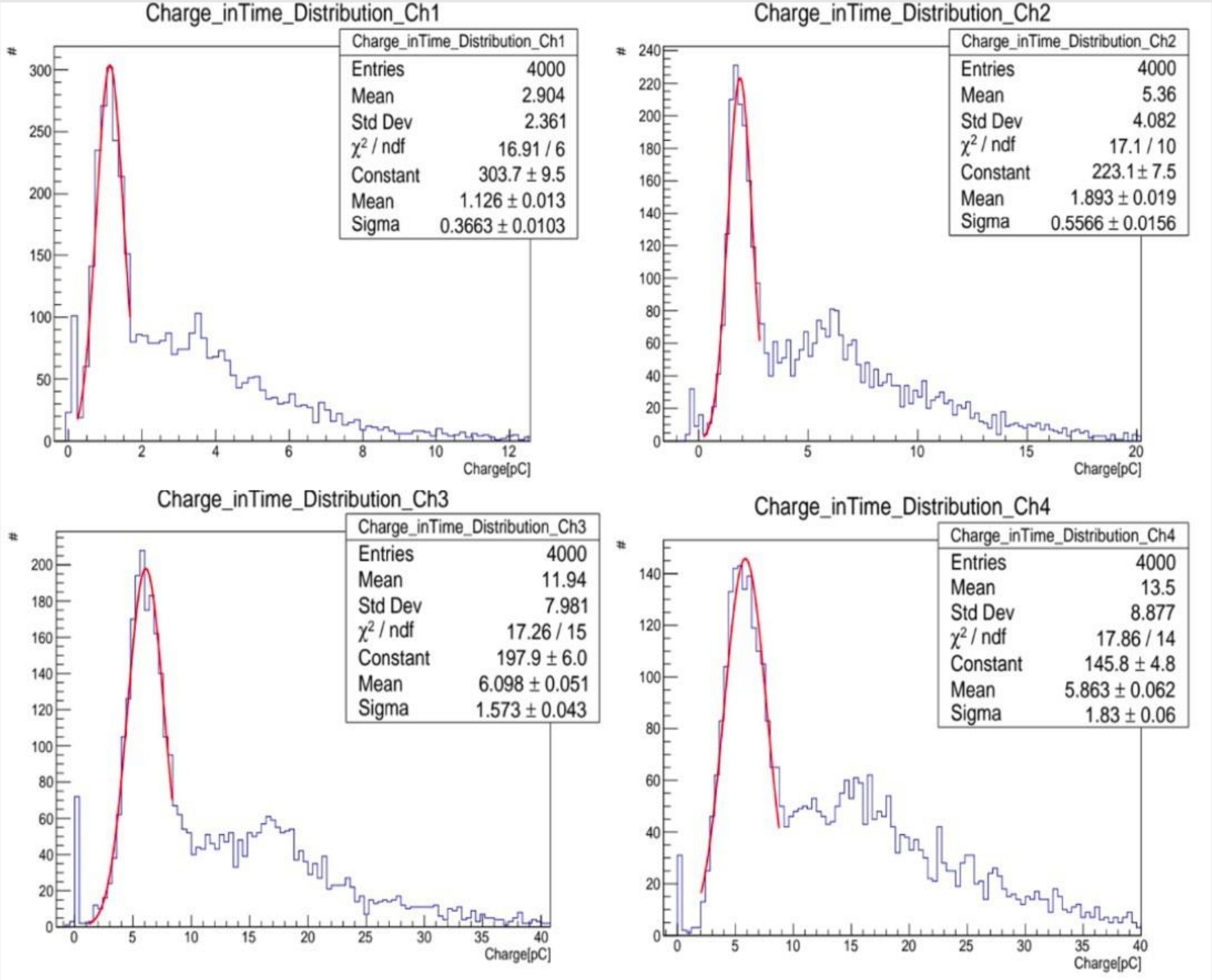


Beam Test Setup

Two test campaigns were conducted in 2022 and 2023. Components of the test setup:

- Beam-Defining Telescope: Trigger creation and coincidence verification.
- $XY\phi$ Motion Table: A remote controlled motion table allowed precise XY positioning and scanning across the detector surfaces and for placement of steel absorber plates.
- SiPMs Paired with Borosilicate Glass Cubes: 64 SiPMs (2022) or 9 SiPMs (2023) with 1 cm borosilicate glass cubes.
- PMTs Paired with Plexiglass Tiles: A collection of 4 PMTs (2022) or 9 PMTs (2023) with quartz tiles.
- A DAQ System: A VME ADC DAQ recorded signals from the PMTs, and a Vertilon IQSP582 was used with the SiPMs. A NIM crate was used to create and provide triggers to the VME and Vertilon DAQs. High voltage was provided by a LeCroy HV4032A to the PMTs. A Vertilon SIB464 SiPM interface board provided low voltage to the SiPMs.

Calibration with MIPs



Charge_inTime_Distribution_Ch1	
Entries	4000
Mean	2.904
Std Dev	2.361
χ^2 / ndf	16.91 / 6
Constant	303.7 ± 9.5
Mean	1.126 ± 0.013
Sigma	0.3663 ± 0.0103

Charge_inTime_Distribution_Ch2	
Entries	4000
Mean	5.36
Std Dev	4.082
χ^2 / ndf	17.1 / 10
Constant	223.1 ± 7.5
Mean	1.893 ± 0.019
Sigma	0.5566 ± 0.0156

Charge_inTime_Distribution_Ch3	
Entries	4000
Mean	11.94
Std Dev	7.981
χ^2 / ndf	17.26 / 15
Constant	197.9 ± 6.0
Mean	6.098 ± 0.051
Sigma	1.573 ± 0.043

Charge_inTime_Distribution_Ch4	
Entries	4000
Mean	13.5
Std Dev	8.877
χ^2 / ndf	17.86 / 14
Constant	145.8 ± 4.8
Mean	5.863 ± 0.062
Sigma	1.83 ± 0.06

Beam centered on each PMT individually to measure the MIP signal.

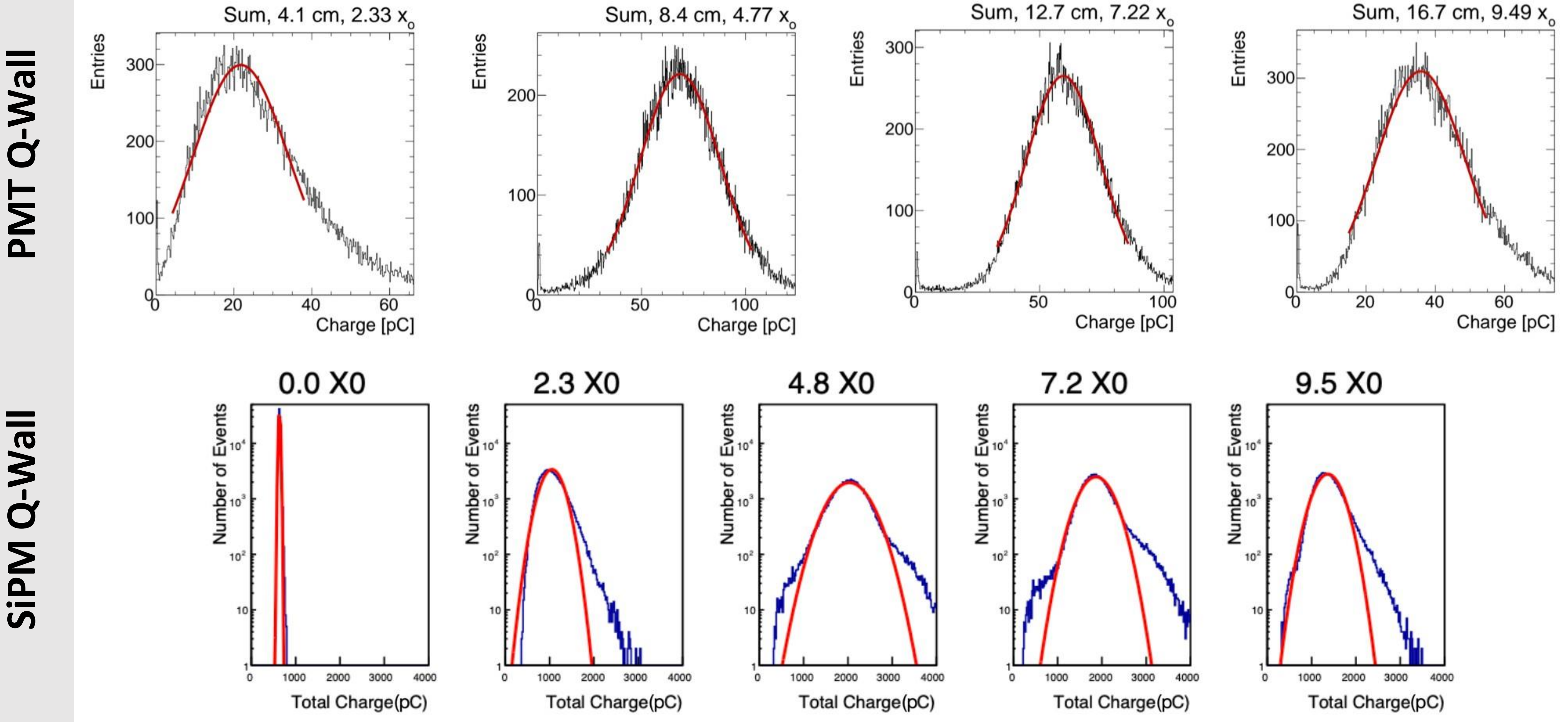
50 GeV/c electron beam was used with no upstream absorbers.

Ch1, Ch2 ➔R5900
Ch3, Ch4 ➔R7600

Well-defined MIP peaks

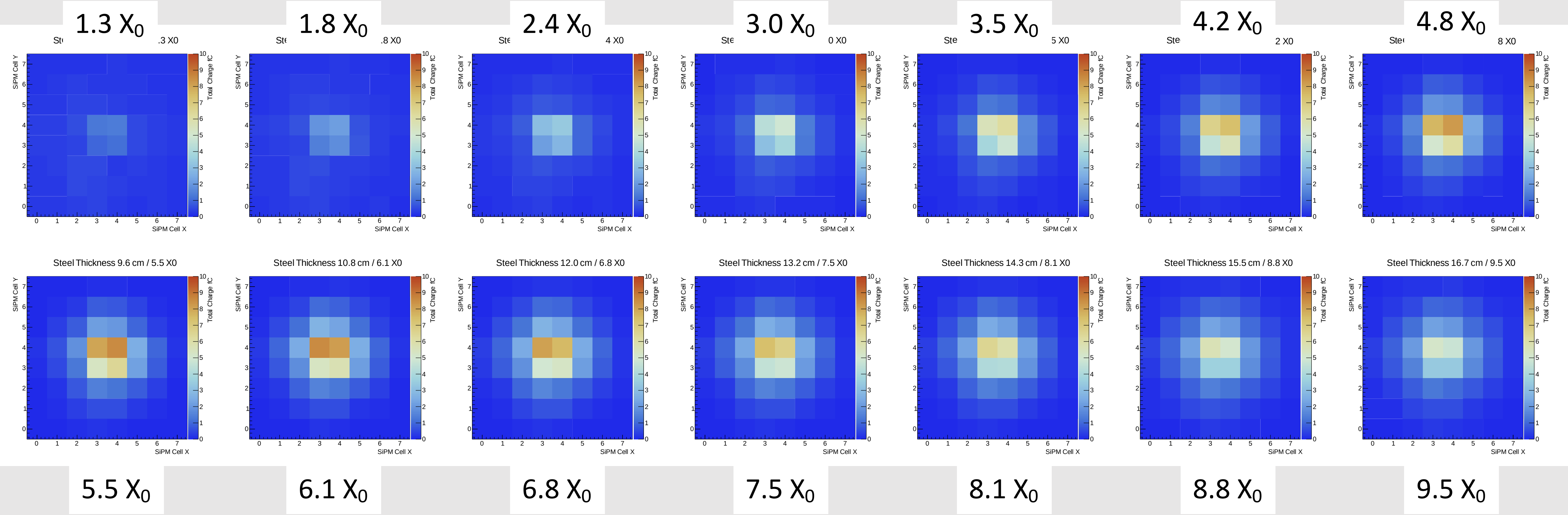
Total Charge Distributions of the Q-Wall Modules

50 GeV/c electron beam



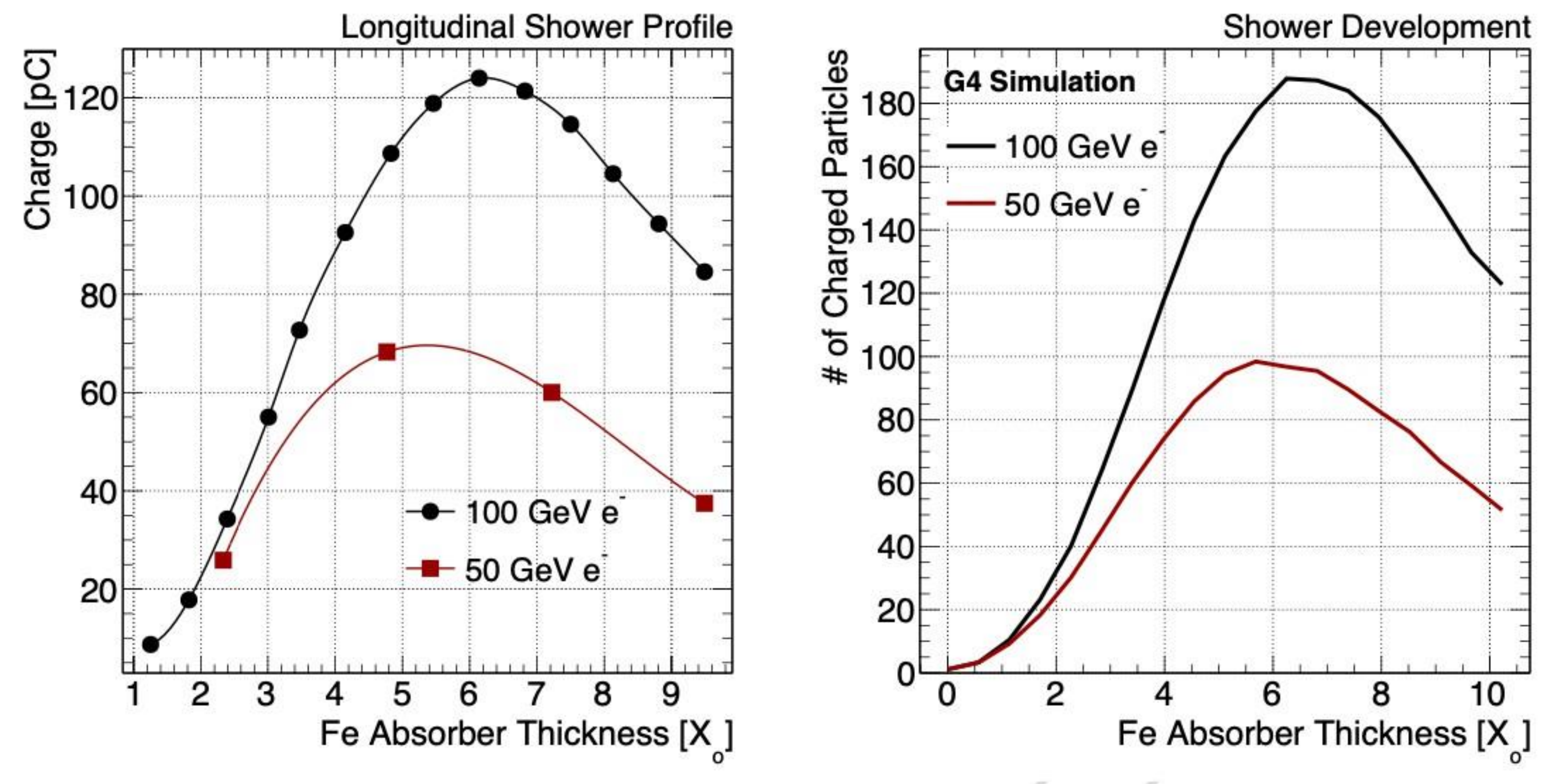
Longitudinal Shower Development

Normalized total charge in each SiPM pixel of the 8 x 8 array with 100 GeV electrons.



Longitudinal Shower Profiles with PMT Q-Wall Module

The profiles scale with the energy; shower maxima are at the expected locations.

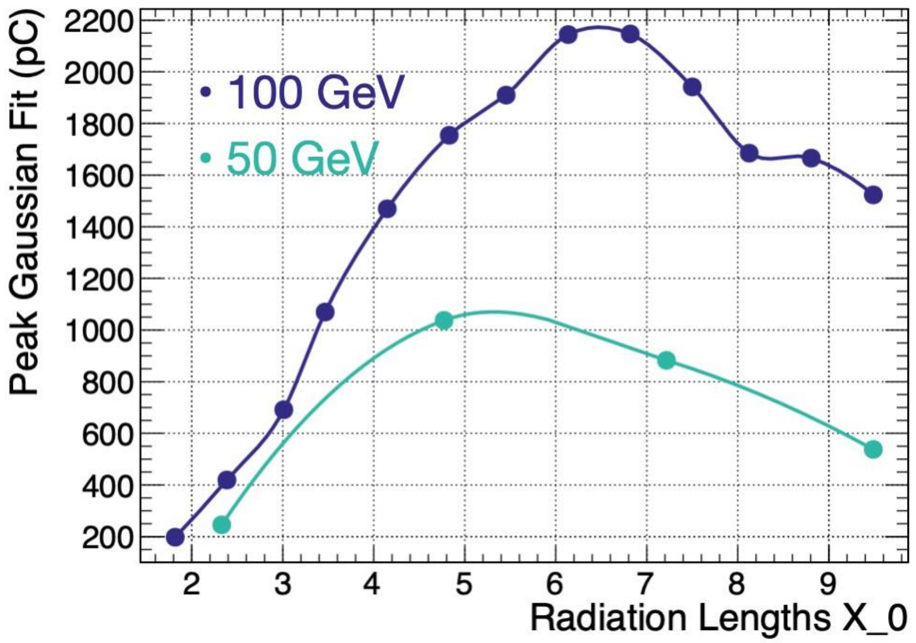


The simulations are along the line of the measurements. Full digitization of the simulated response is underway.

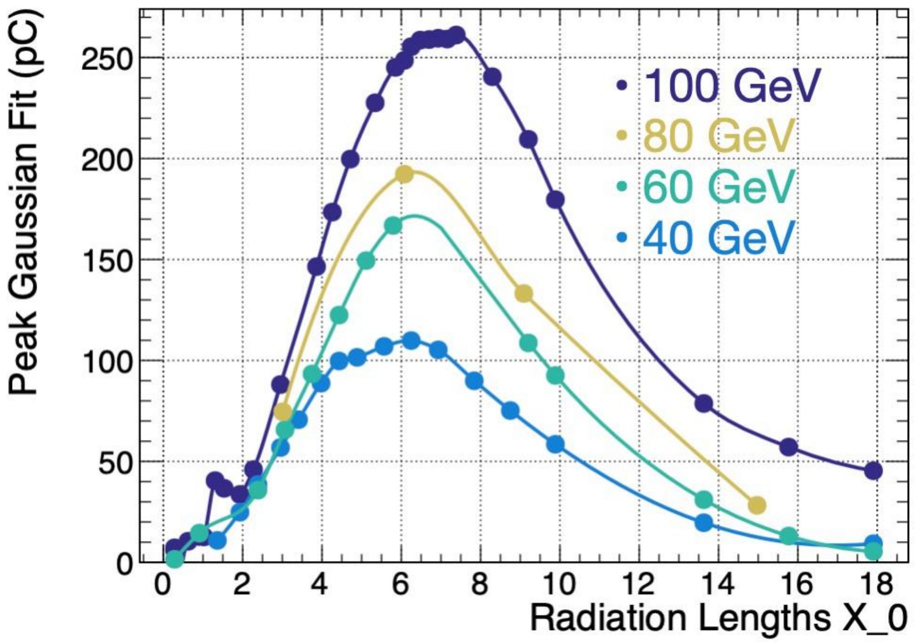
Longitudinal Shower Profiles with SiPM Q-Wall Module

Compatible profiles were obtained with significantly different setups. Finer longitudinal granularity is better for longitudinal shower development sampling. MC work is underway.

2022
8 x 8 array

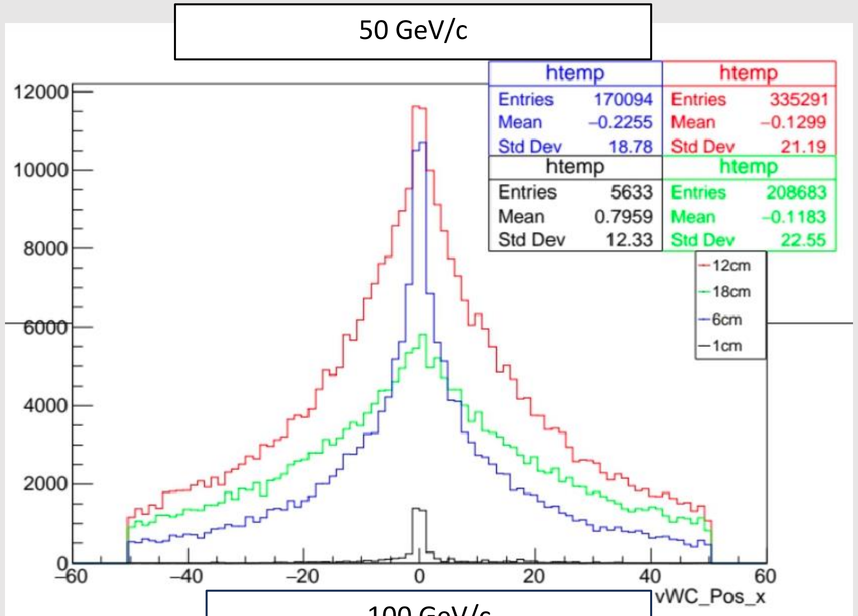


2023
3 x 3 array

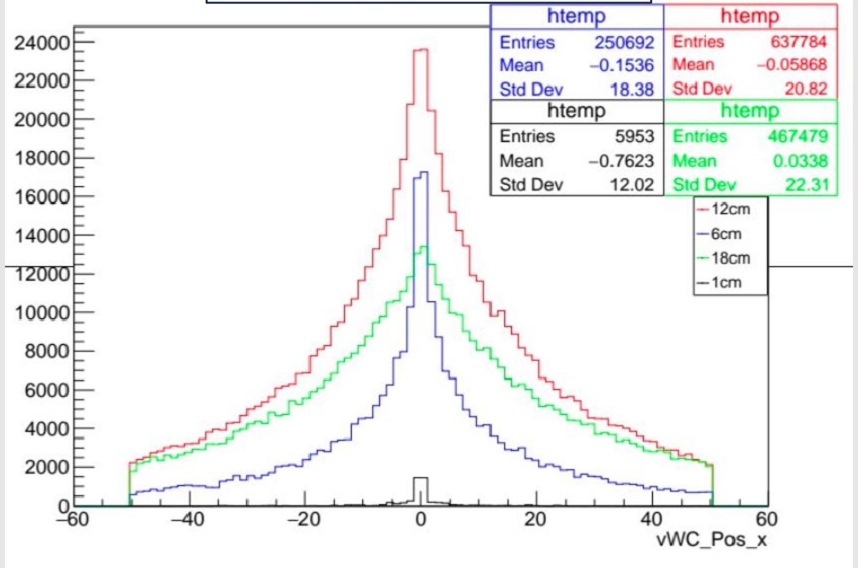


Radial Shower Shapes

50 GeV/c



100 GeV/c



Radial shower shapes were simulated at various shower depths (number of charged particles as a function of the radial distance from the incident particle direction):

- 1 cm (0.57 X_0),
- 6 cm (3.41 X_0),
- 12 cm (6.82 X_0) and
- 18 cm (10.23 X_0).

Transverse shower development simulation is within expectations (Moliere radius of iron is 17.2 mm).

Data-MC matching is underway (needs accurate signal digitization).

Conclusions

The first modules of a Q-Wall electromagnetic calorimeter was constructed with quartz tiles and PMTs/SiPMs and tested with electron beams.

The performance of the first modules is within expectations and is qualitatively reproduced with simulations. Further simulation studies including the full digitization of the response and the response of a full-scale calorimeter are underway.

The photodetector is an integral part of the calorimeter. Alternatives to PMTs such as microchannel plates could provide further features such as higher timing resolution.

Developing specialized photodetectors could enhance the functionality of Q-Wall calorimeters e.g. higher sensitivity to neutrons and using tungsten absorbers.

The Q-Wall concept provides a viable choice for electromagnetic calorimetry in high radiation environments.