Gran Collage

Le 8 attività INFN nel programma DRD6

CryoDBDCal

DRD6 - WP3 Meeting - 05/03/2024

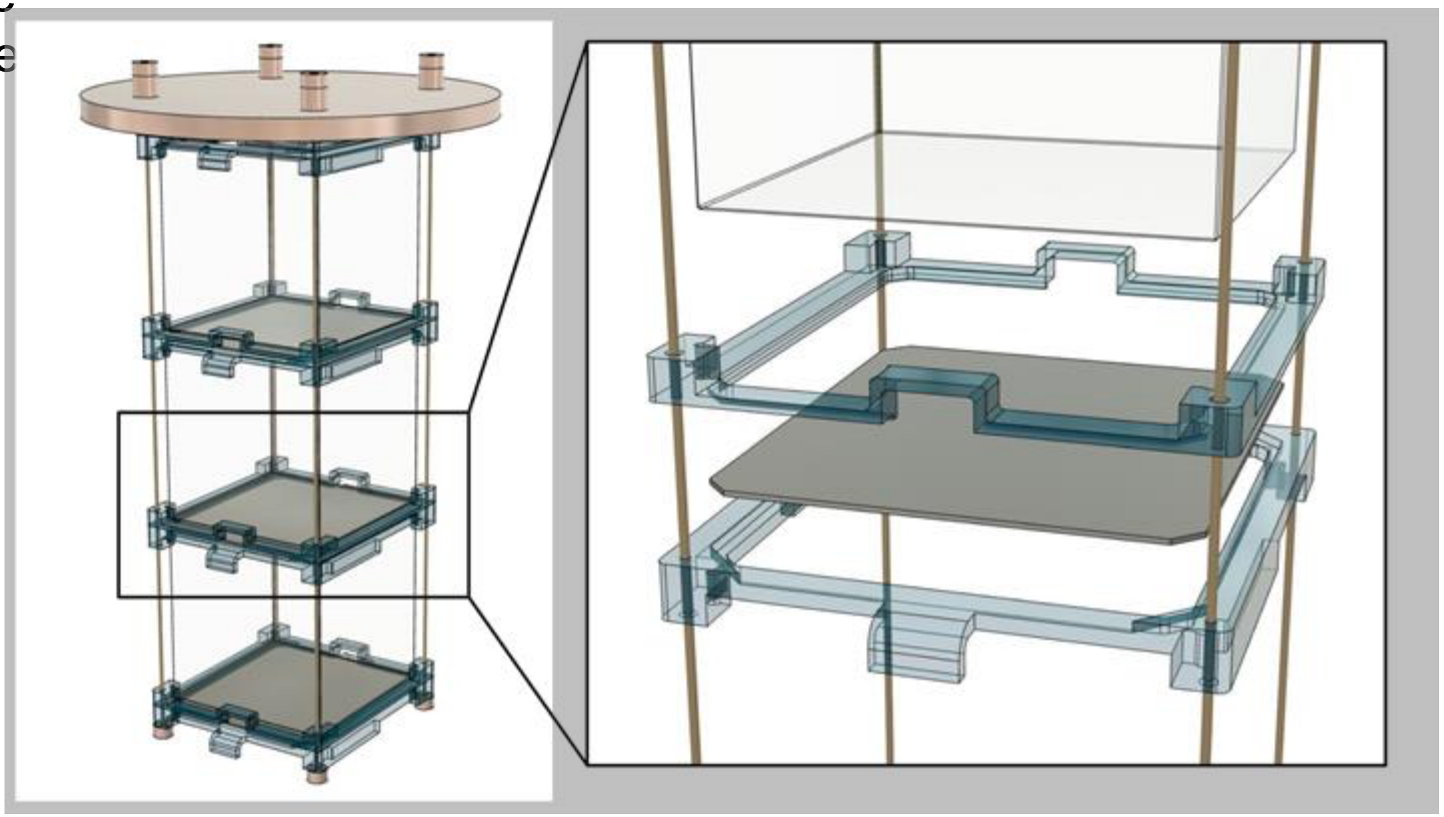
Matteo Biassoni - INFN Milano-Bicocca

D 3.17

Demonstrate that a complete detector with “full size” crystals can be operated with 3D-printed plastic structure and scintillation light can be read with current cryogenic light detectors technology

Currently working on second prototype with non-scintillating structure to validate plastic material at cryogenic temperature

- confirm detector performance
- confirm mechanical properties @mK temperature



Synergies:

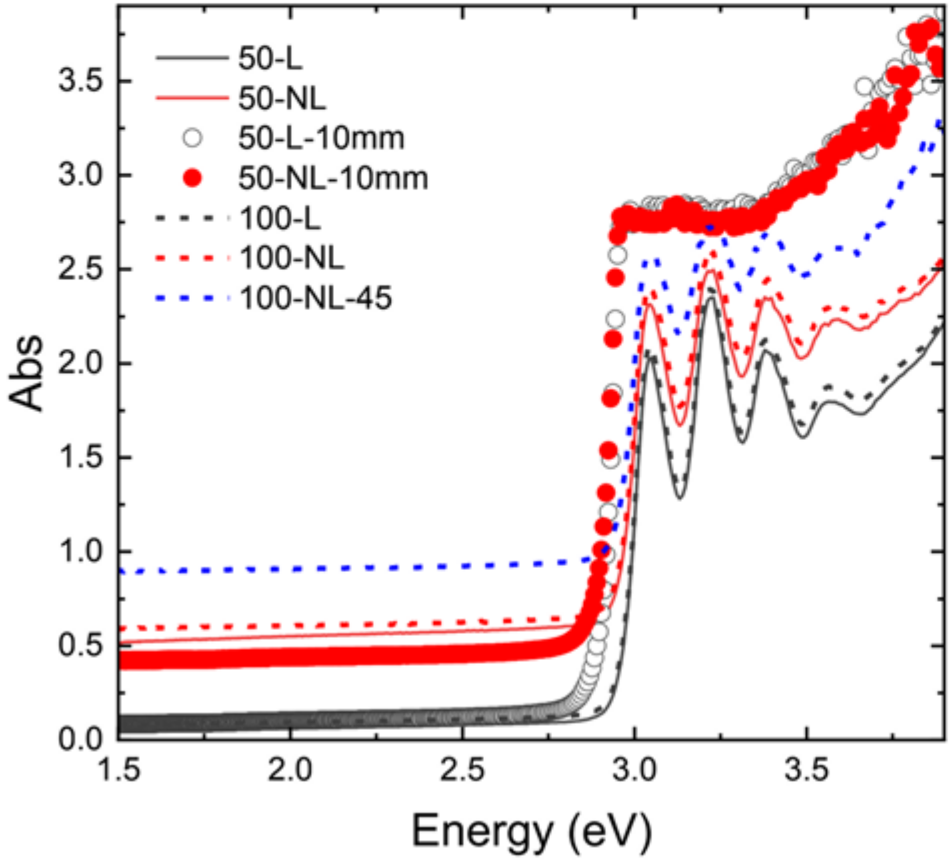
- 3DSpark PRIN2022 Grant
- CUORE/CUPID/CUPID-1ton with 100Mo and/or 130Te

D 3.17 - continued

Demonstrate that commercial resin can be doped to implement scintillation.

Currently working on:

- optical characterization of legacy resin to choose best scintillating die
- procedure for reproducible polymerization outside additive manufacturing machine for fast testing of scintillation



Synergies:

- 3DSpark PRIN2022 Grant
- CUORE/CUPID/CUPID-1ton with 100Mo and/or 130Te

D 3.17 - continued

Demonstrate that commercial resin fulfills radiopurity requirements

Done:

- ICPMS measurements

Currently working on:

- HPGe counting

Sample	Th content	U content	K content
	Unit (ppt)	Unit (ppt)	Unit (ppb)
resin 3D printer	< 1	3 ± 1	780 ± 234

Synergies:

- 3DSpark PRIN2022 Grant
- CUORE/CUPID/CUPID-1ton with 100Mo and/or 130Te

M 3.21

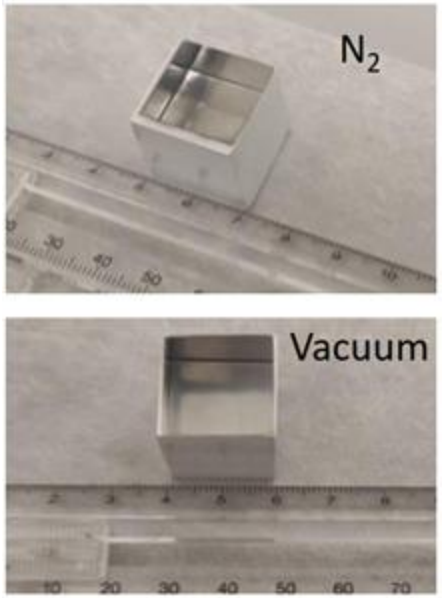
Study doping/coating of crystals for cryogenic calorimeters to improve scintillation/light collection

Done:

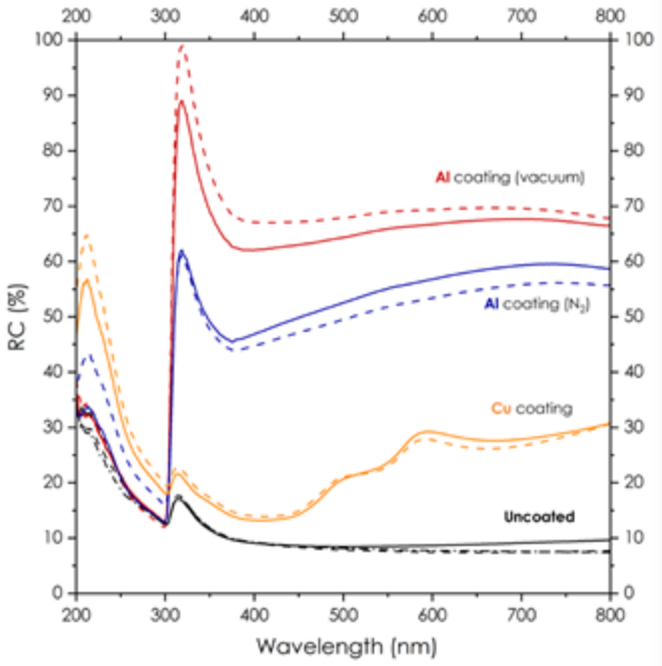
- effect of Cu and Ag doping of LMO crystals with optical characterization (non-cryogenic)

Currently working on:

- cryogenic test of surface reflecting coatings to understand impact on bolometric performance



Al coated LMO crystals



Synergies:

- COLD PRIN2020
- CUORE/CUPID/CUPID-1ton with 100Mo and/or 130Te

3dSPARK

3d-printed Scintillating Polymer Assembly for Rare events at milliKelvin temperature

Matteo Biassoni[1], Davide Chiesa[1,2], Leonard Imbert[1]

[1] INFN Milano-Bicocca
[2] Dip. Fisica G. Occhialini, Università di Milano-Bicocca

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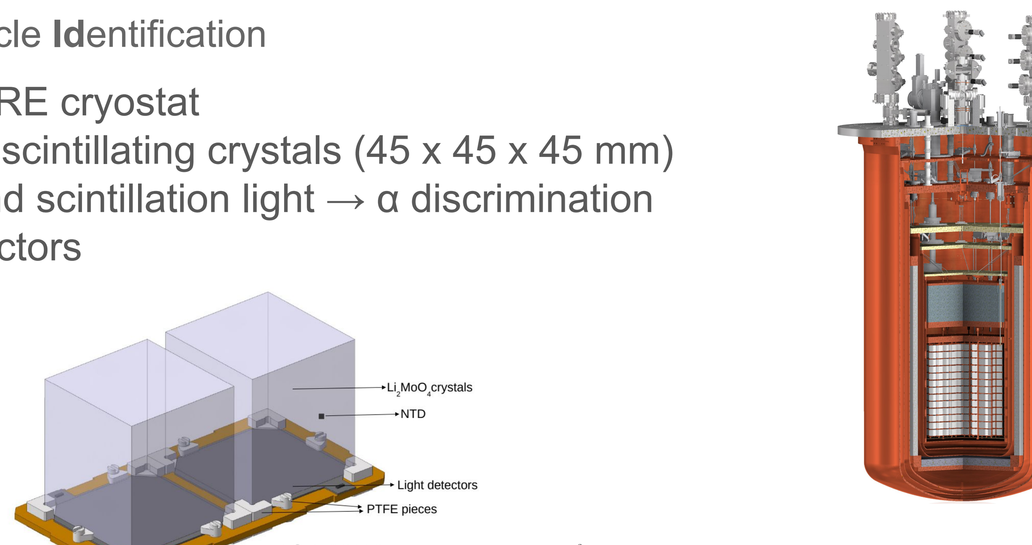
Università degli Studi di Milano Bicocca

CUPID: the next generation bolometric 0νββ decay experiment

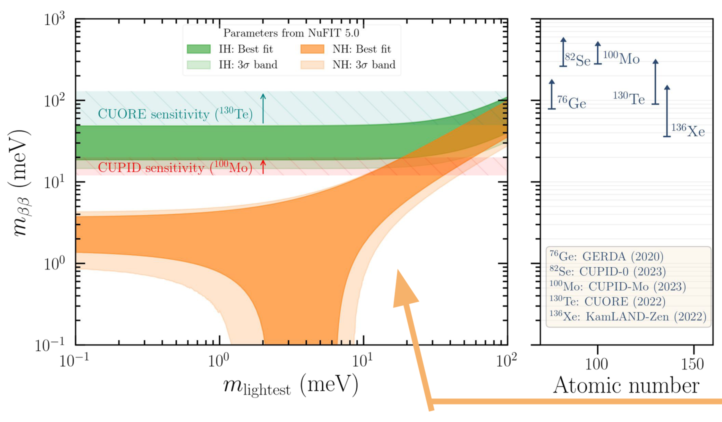
CUORE Upgrade with Particle Identification

- Will operate in the CUORE cryostat
- 1596 $Li_2{}^{100}MoO_4$ (LMO) scintillating crystals (45 x 45 x 45 mm)
- Dual read out of heat and scintillation light → α discrimination
  ↳using Ge light detectors



- ^{100}Mo, $Q_{\beta\beta}$ = 3034 keV
- ^{100}Mo mass = 240 kg

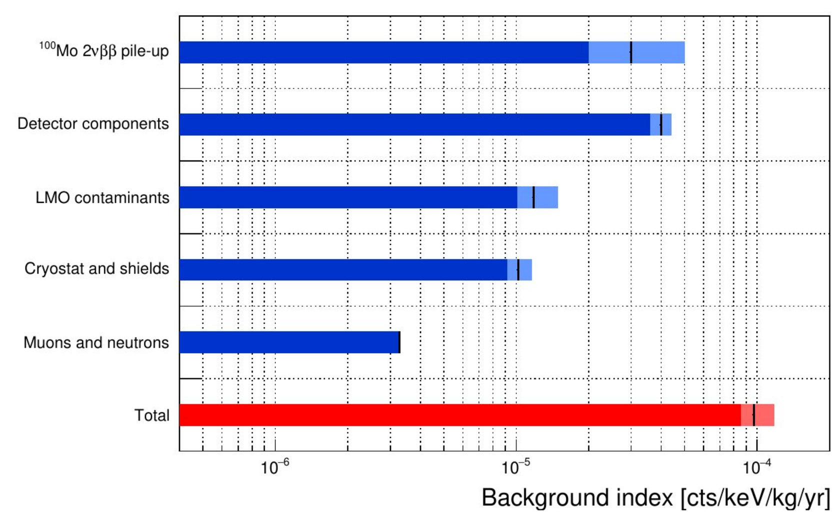
Goal:
- Fully probe the "Inverted Hierarchy" region
- Discovery sensitivity:
  - $T_{1/2}$ (^{100}Mo 0νββ) > 10^{27} yr
  - $m_{\beta\beta}$ < 12 – 20 meV



↳Need to reach a background index of 10^{-4} cts/keV/kg/yr

CUPID estimated background

Background reductions compared to CUORE:
- Particle identification
- Muon veto
- Increased $Q_{\beta\beta}$ value for reduced γ/β backgrounds



Background induced by natural radioactivity are estimated based on the CUORE and CUPID-Mo background models

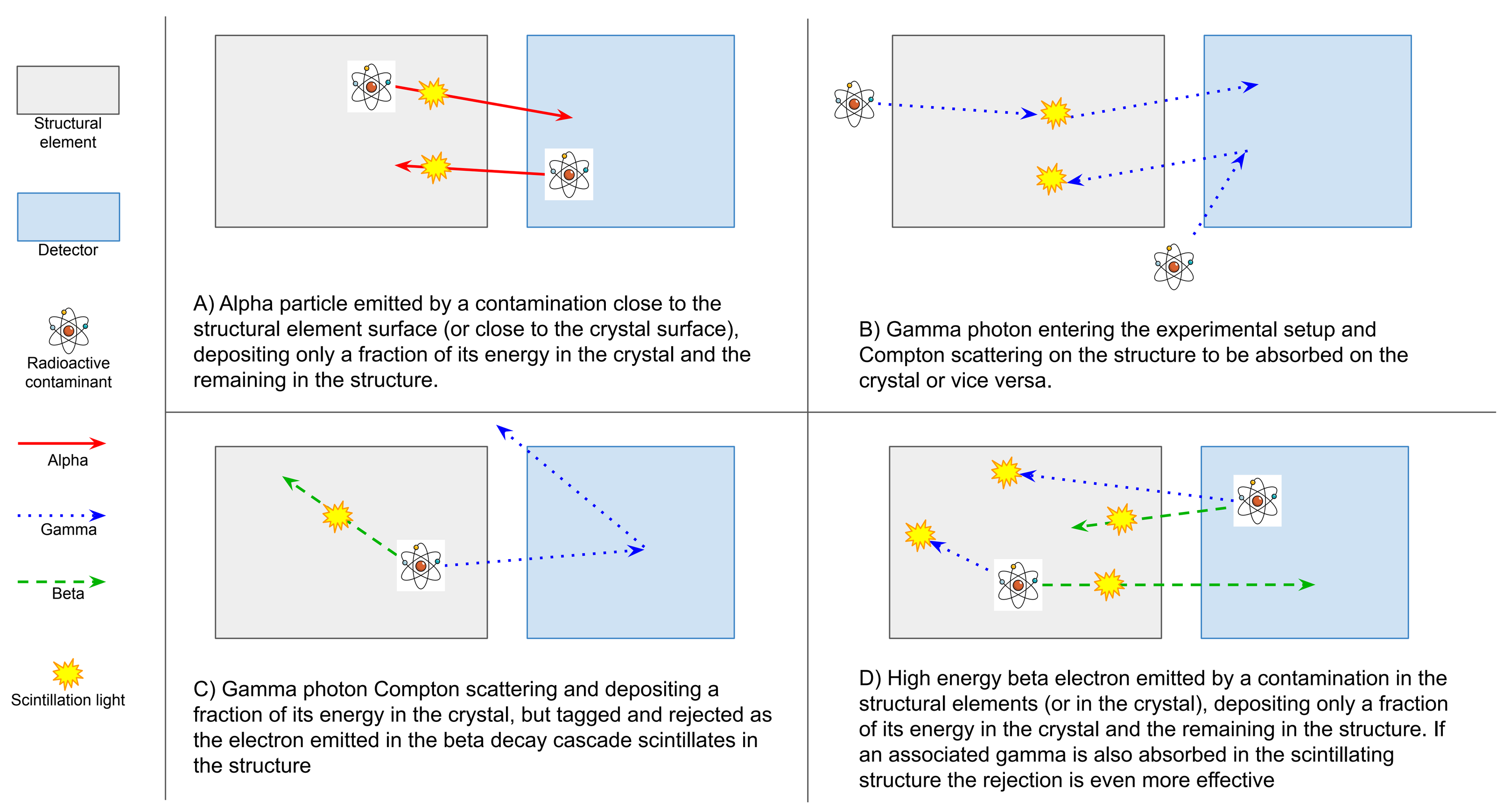
- Detector components
  - Dominated by the surface contamination of the mechanical structure
- LMO contaminants
  - Dominated by the surface contamination
- Cryostat and shields
  - Background from γ compton scattering
- Muons and neutrons
  - Based on initial design and MC simulation

~ 70 % of the total background
Can be decreased with a polymer-based assembly

- ^{100}Mo 2νββ pile-up
  - From measured performances of Neganov-Trofimov-Luke light detectors

Need to decrease the background for next to next generation experiment to explore the "Normal Hierarchy" region

Concept: active mechanical structures



A) Alpha particle emitted by a contamination close to the structural element surface (or close to the crystal surface), depositing only a fraction of its energy in the crystal and the remaining in the structure.

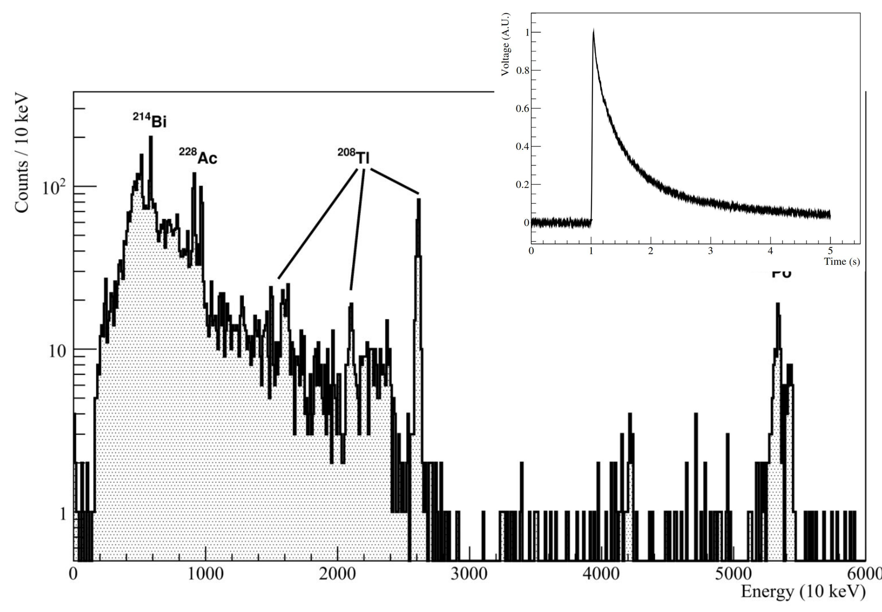
B) Gamma photon entering the experimental setup and Compton scattering on the structure to be absorbed on the crystal or vice versa.

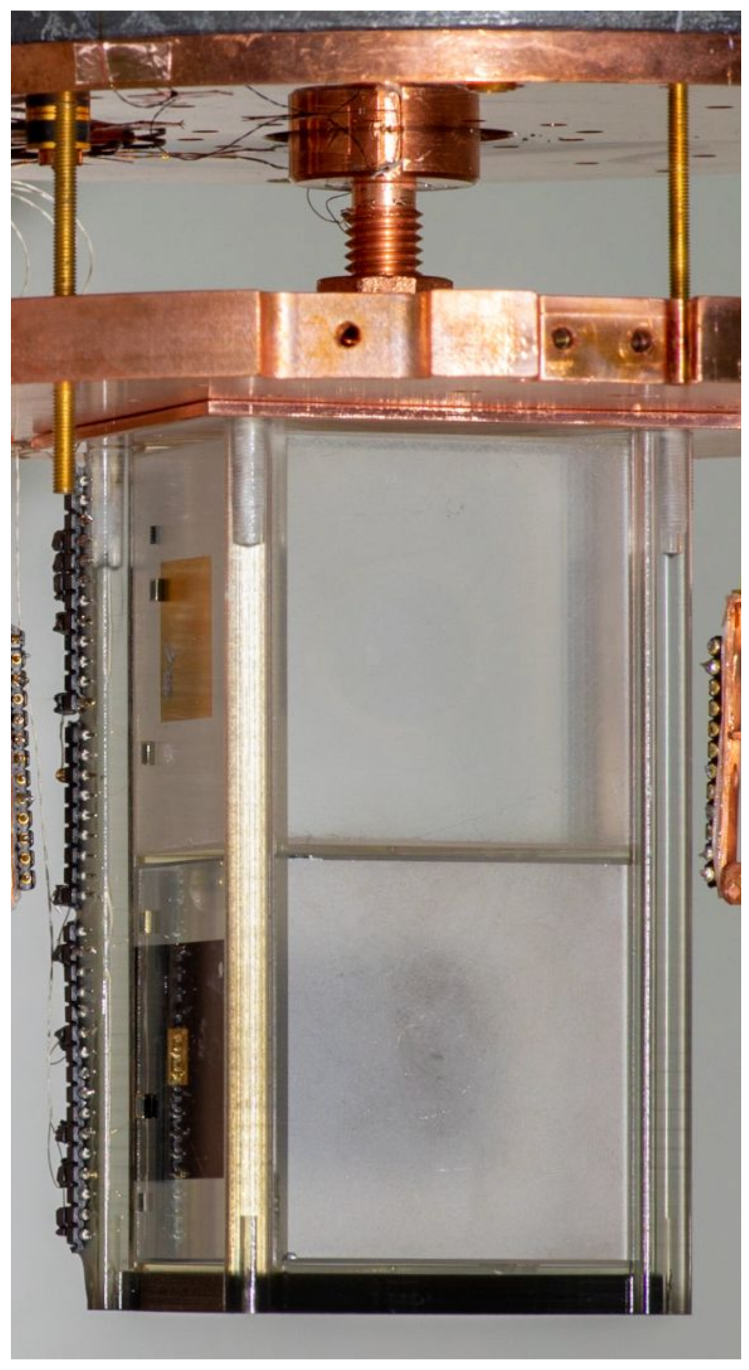
C) Gamma photon Compton scattering and depositing a fraction of its energy in the crystal, but tagged and rejected as the electron emitted in the beta decay cascade scintillates in the structure

D) High energy beta electron emitted by a contamination in the structural elements (or in the crystal), depositing only a fraction of its energy in the crystal and the remaining in the structure. If an associated gamma is also absorbed in the scintillating structure the rejection is even more effective

State of the art

- Proof-of-principle measurement performed with small (1 cm^3) and large (5 cm^3) TeO_2 crystals
- Off-the-shelf 3D printable transparent resin (no scintillation)
- No thermalization issues observed (thermalization happens mainly through readout wires)
- Intrinsic thermal gain (100-250 muV/MeV) and pulse shape compatible with traditional setups
- Satisfactory energy resolution (5-20 keV FWHM @2615 keV)





Eur. Phys. J. Plus (2023) **138**: 384 https://doi.org/10.1140/epjp/s13360-023-03991-6

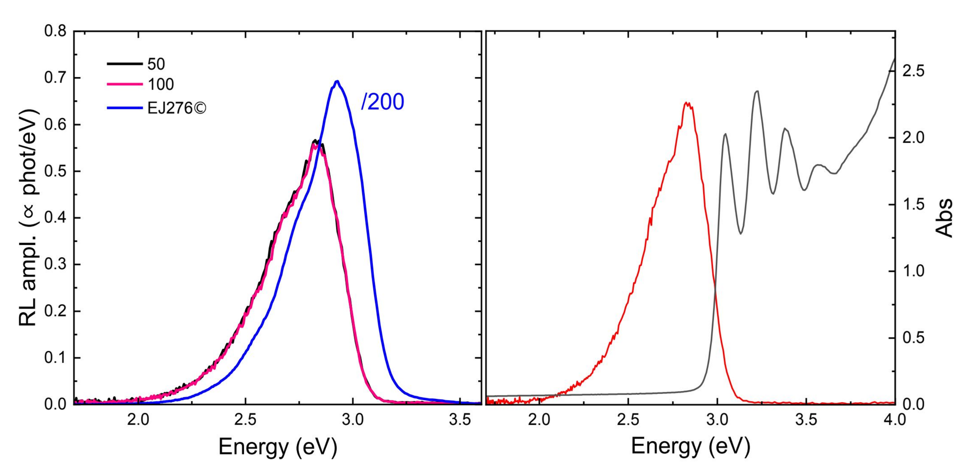
Material choice and characterization

REQUIREMENTS:
- Radiopurity of raw material
- 3D-printable:
  - stereolithography (SLA) allows zero-contact manufacturing
  - more freedom in the design to minimise amount of material
- low-Z, low-density to minimize gamma interaction probability
- low procurement and manufacturing cost

Customize with scintillating compound

Characterize optical and mechanical properties at cryogenic temperatures

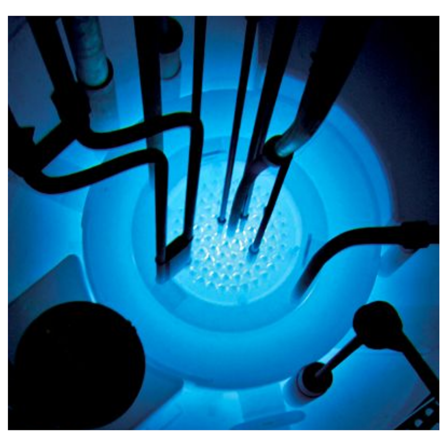
Off-the-shelf products with industrial technology available

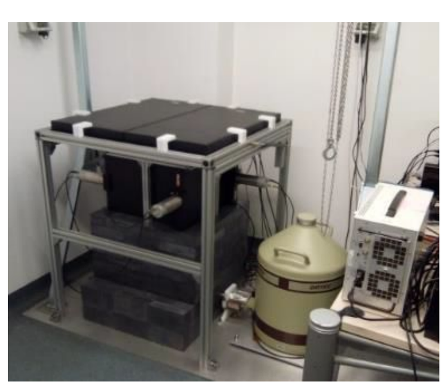


Radio-luminescence and optical absorption of commercial UV-curing resin candidate

Material screening

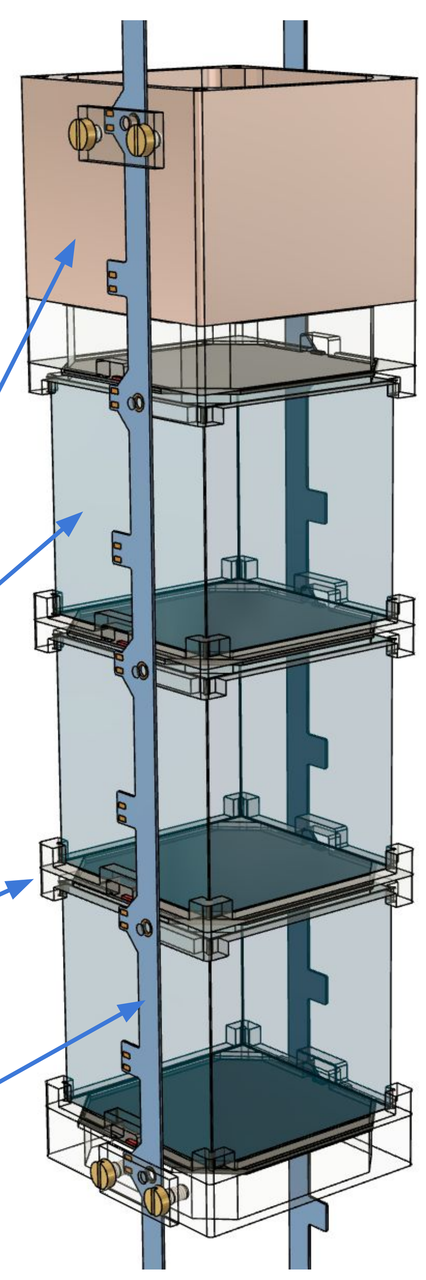
- Neutron Activation Analysis (NAA) at the TRIGA Mark II reactor in Pavia.
  - Irradiation with thermal neutron flux up to ~10^{13} $cm^{-2}s^{-1}$.
  - HPGe spectroscopy analysis of activated samples at Milano-Bicocca Radioactivity Lab.
  - Typical sensitivities down to sub-ppt (<10^{-12} g/g) in the search for ^{40}K, ^{238}U and ^{232}Th contaminations.
- HPGe screening measurements @LNGS:
  - complementary to NAA, to detect the daughters of ^{238}U and ^{232}Th decay chains (e.g. ^{226}Ra, ^{228}Ra, ^{228}Th)
  - relatively long measurements (~1 month)
  - sensitivities down to ~ 10^{-10} – 10^{-11} g/g





Demonstrator design and operation

PROJECT GOALS:
- build and run a prototype with full-size crystals (TeO_2 or Li_2MoO_4), scintillating plastic and light detectors
- demonstrate detector performance (base temperature, energy resolution, time resolution)
- demonstrate background rejection capabilities with structure scintillation

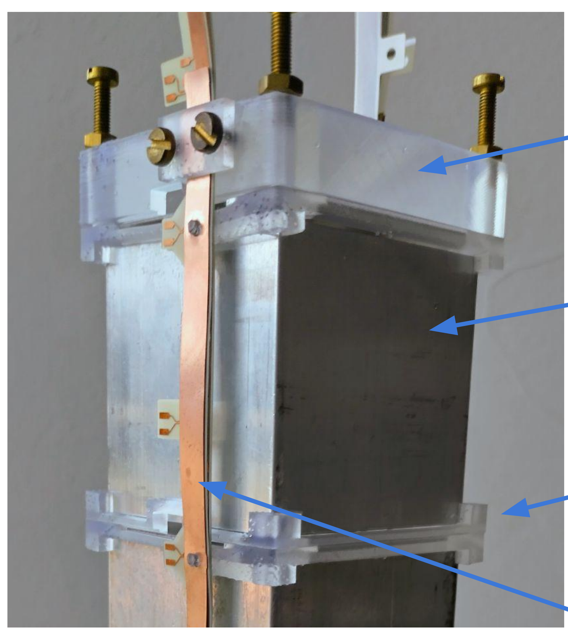


Cryostat interface

Crystal

Scintillating frame

CuPEN (scintillating) readout wiring



Mock-up for assembly, bonding and mechanical tests. Design still to be optimised for light collection

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU – Project Title 3dSPARK: 3d-printed Scintillating Polymer Assembly for Rare events at milliKelvin temperature – 2022C7ESM3 - Grant Assignment Decree No. 974 adopted on June 30, 2023 by the Italian Ministry of Ministry of University and Research (MUR).

Status of MPGD-Hcal

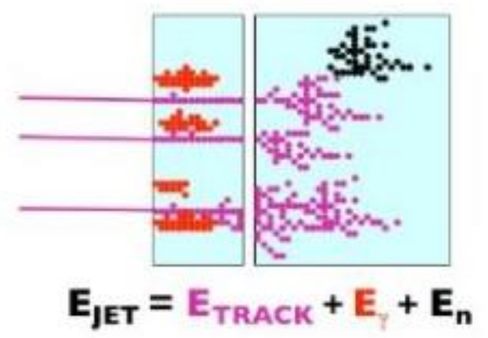
M. Ali[1,7], M. Alviggi[5], M. Bianco[6], M. Biglietti[4], M. Buonsante[1,2], M. Borysova[3], A. Colaleo[1,2], M. T. Camerlingo[1], M. Della Pietra[5], R. Di Nardo[4], L. Generoso[1,2], P. Iengo[5], M. Iodice[4], L. Longo[1], M. Maggi[1], L. Moleri[3], F. Nenna[1,2], A. Pellecchia[1], R. Radogna[1,2], G. Sekhniaidze[5], F. M. Simone[1,2], **A. Stamerra**[1,2], R. Venditti[1,2], P. Verwilligen[1], D. Zavazieva[3], A. Zaza[1,2]

[1] INFN Bari
[2] University of Bari
[3] Weizmann institute of science
[4] INFN Roma 3
[5] INFN Napoli
[6] CERN
[7] University of Padova

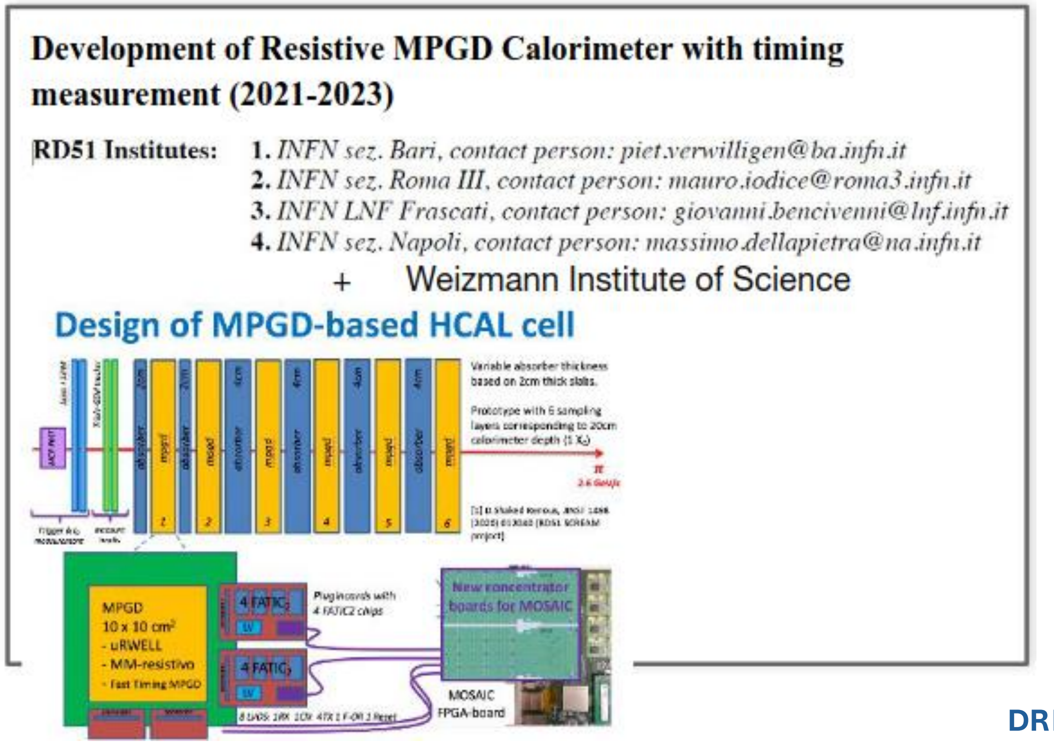
MPGD-HCal at Future colliders

- Current tendency for R&D on calorimeters:
  High Granularity for Particle Flow
  - 5D calorimeter --> (x,y,z, t) + Energy reconstruction

- Current technology: Silicon, Scintillators, RPCs as active layers



GOAL for future colliders:
Jet energy resolution for Z/H separation:
σ_E /E< 3% - 4%
→ 60%/sqrt(E) for HCal



Proposal: adopting state-of-the-art **resistive MPGDs** as active layers of sampling calorimeter → investigated within the context of the Muon Collider experiment

Project initiated in 2021 within the RD51 collaboration and currently framed within the DRD6/DRD1 collaborations and supported by PNRR Calorhino

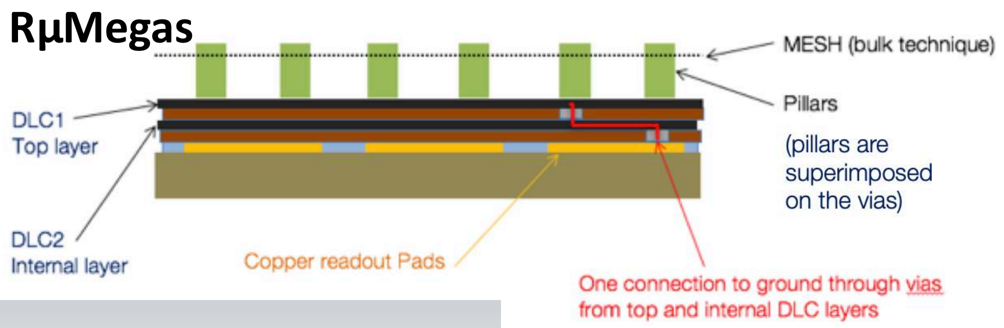
MPGD-based HCAL for Muon Collider

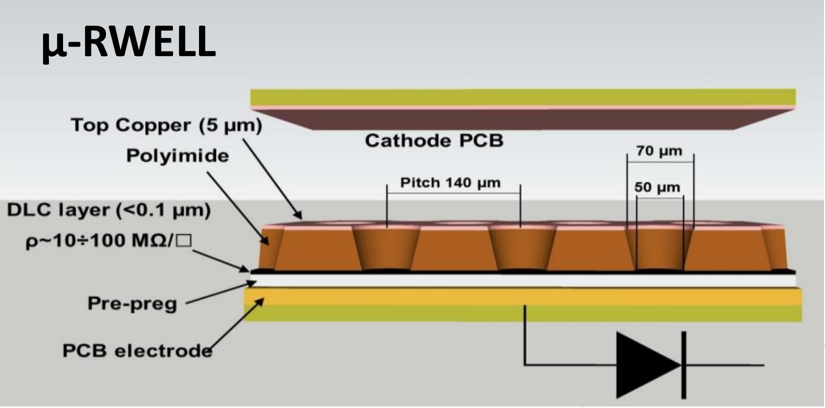
Why resistive MPGDs for calorimeters?

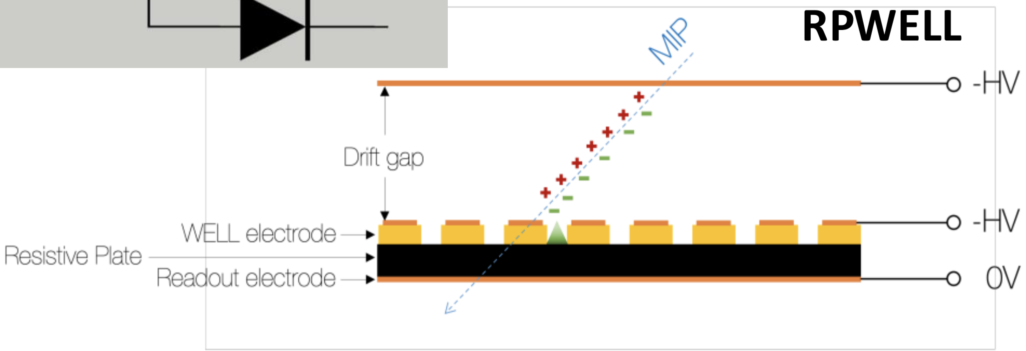
- Cost-effective for large area instrumentation
- Radiation hardness (up to few C/cm^2)
- High rate-capability O(MHz/cm^2)
- Readout granularity at-will (~cm^2 or less)
- Space resolution O(100μm) → Low pad multiplicity
- Response uniformity
- Operational stability (low discharge rate)
- Time resolution with MIPs of few ns
- Large community developing these detectors

concept already proposed by **CALICE** and **SCREAM** collaboration investigated the sampling calorimeter with RPCs and μMegas and inherited by ALEPH

3 MPGD technologies studied in this project







Challanges for MPGD usage in calorimetry and goals of the R&D

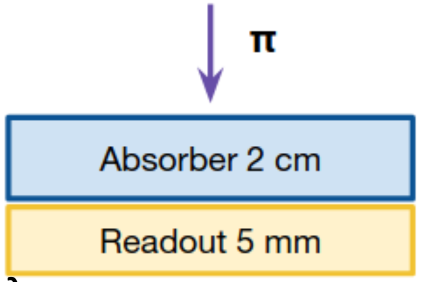
- develop prototype of 50x50 cm^2-100x100 cm^2 active area to minimize dead areas
- guarantee uniform response
- precisely evaluate the time resolution

HCal standalone simulation

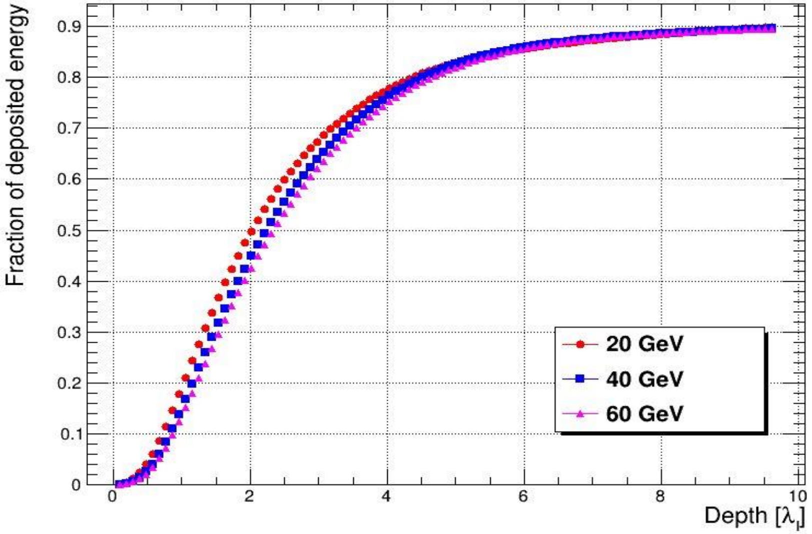
Standalone Geant4 simulation technology-independent

- Geometry of single layer:
  - 2 cm of iron for absorbers
  - 5 mm gas (Ar/CO_2)
- Readout granularity 1x1 cm^2

λ ~ 26 cm



Result: longitudinal containment in 10 λ, transversal in 3 λ



Energy resolution simulated in two scenarios:

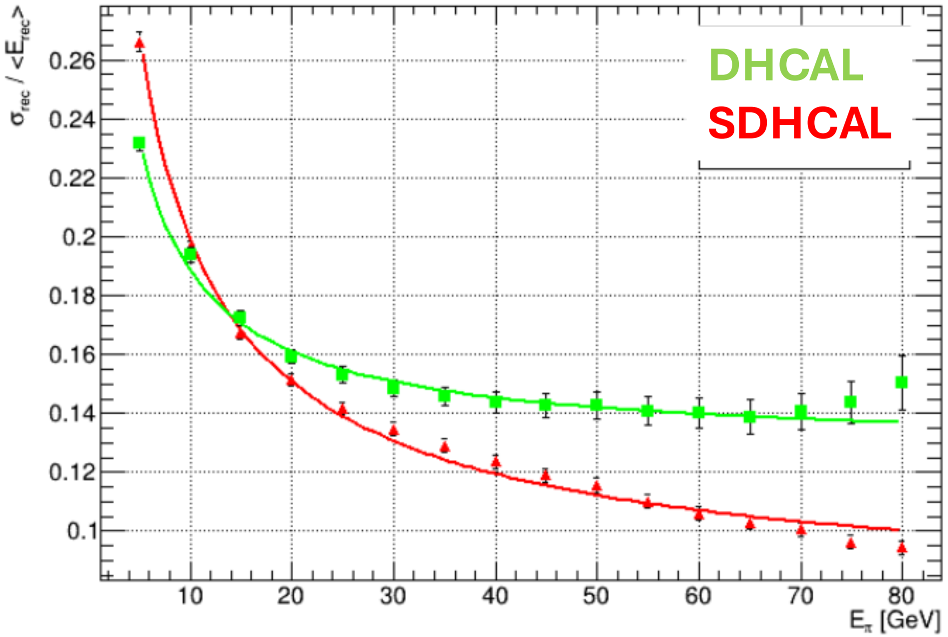
- **Digital** calorimeter: shower energy proportional to total number of hits
- **Semi-digital** calorimeter: hits are weighted based on three thresholds (using CALICE thresholds) $E_\pi = \alpha N_1 + \beta N_2 + \gamma N_3$

Result:

- resolution at **8%** for E_π ~ 80 GeV with semi-digital readout
- resolution **saturates** at **14%** for E_π ~ 30 GeV for digital readout

$$\frac{\sigma_{rec}}{E_{rec}} = \frac{S}{\sqrt{E_\pi}} \oplus C$$

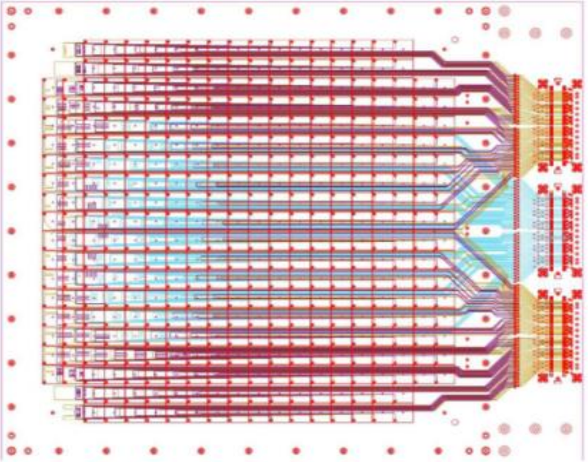
	DHCAL	SDHCAL
S	0.44 ± 0.01	0.58 ± 0.01
C	0.14 ± 0.02	0.07 ± 0.02

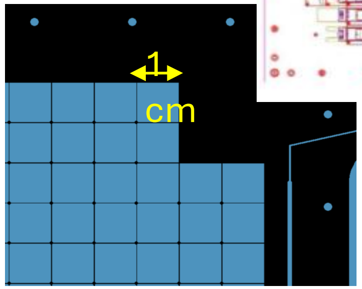


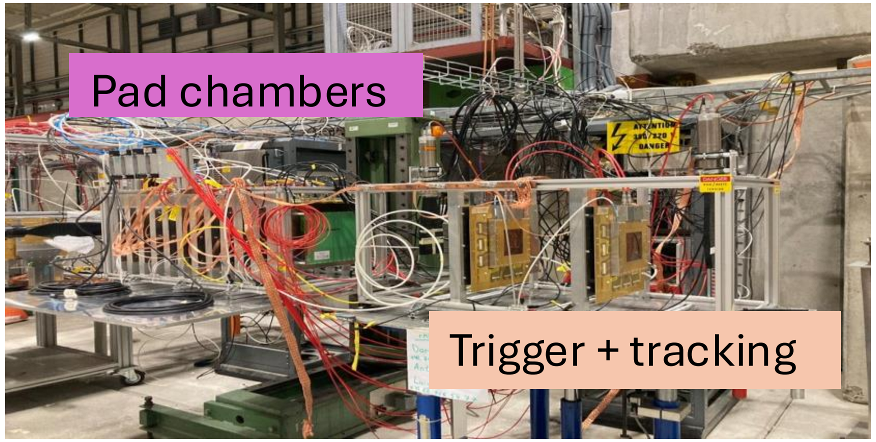
Characterization in test beams at SPS

No absorbers

MPGD technologies:
- 7 μRWELL
- 4 resistiv RμMegas
- 1 RPWELL
- Detector **layout**: 20x20 cm^2
- ~6 mm drift gap
- **Common readout** board: 1x1cm^2 pad

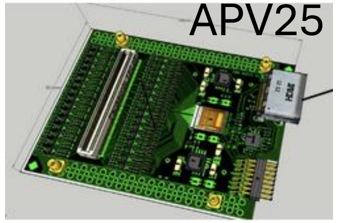


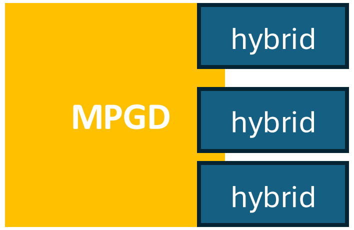


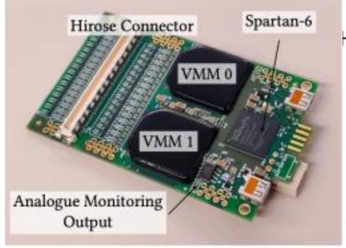


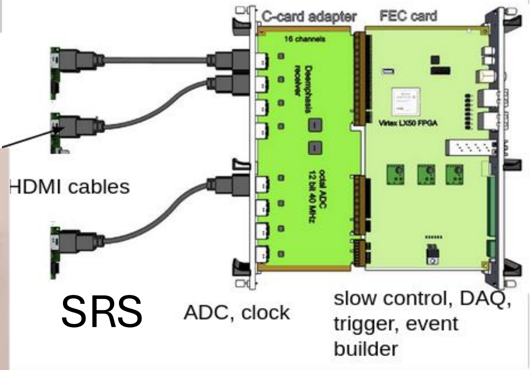
GOAL: Test of readout layers in terms of response to MIPs
- Pad chambers under test (RμMegas, μ-RWELL, RPWELL)
- $Ar/CO_2/CF_4$: μRWELL - $Ar/CO_2/iC_4H_{10}$: RμMegas / RPWELL
- Particles O(100GeV) μ beam

2 different hybrids tested with SRS back-end:
- APV25
- VMM hybrids tested in 1 μ-RWELL in a different test beam (thanks to DRD1 collaboration)





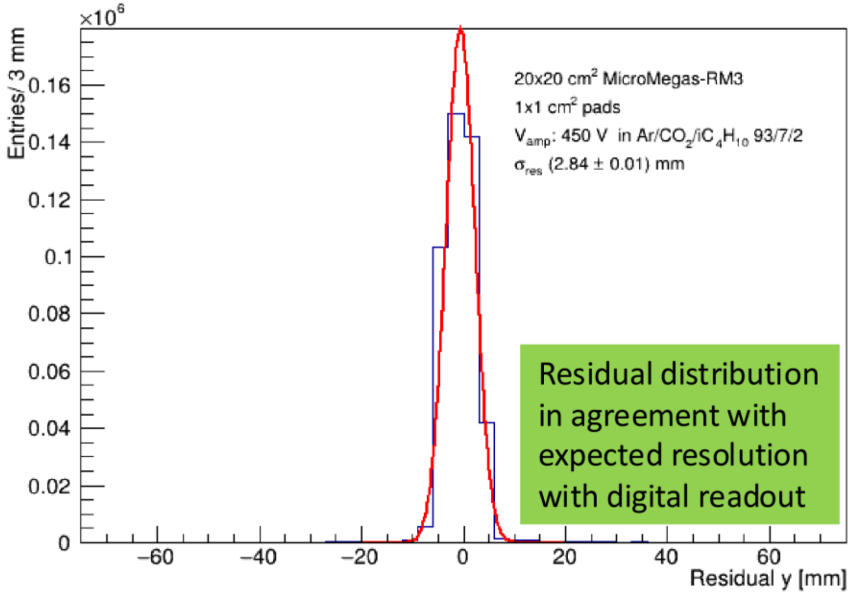




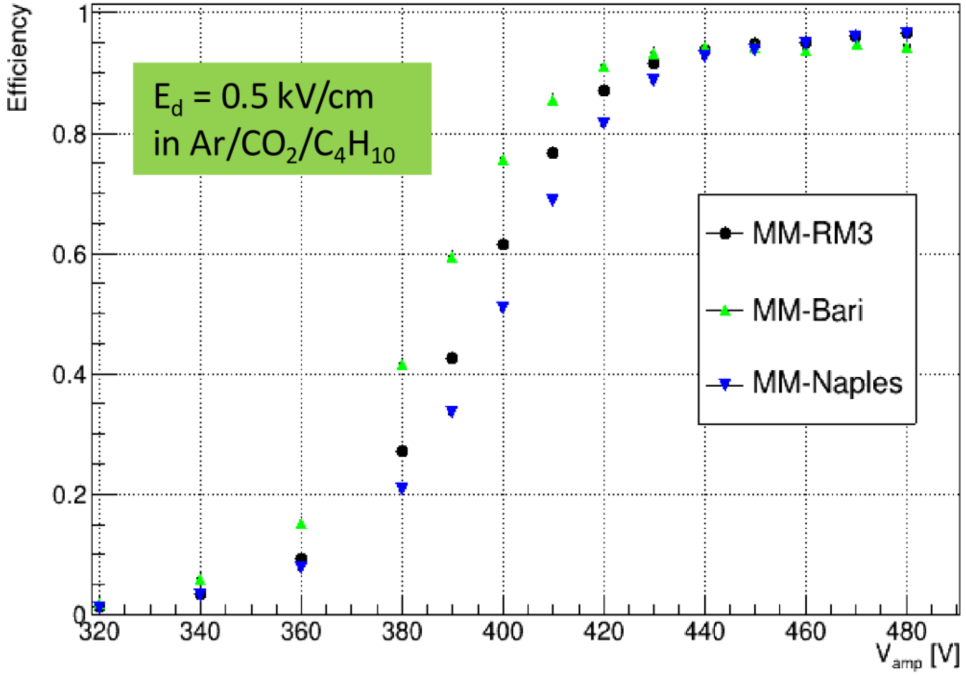
Performance to MIPs

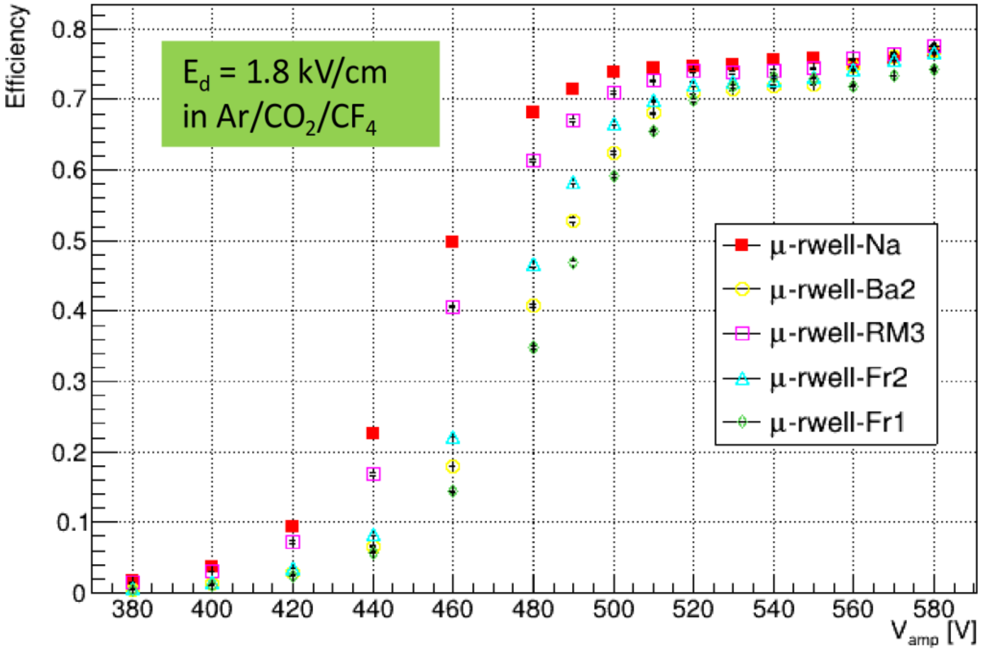
Reconstruction:

- Observed high probability of **cross-talk** between pads
  Due to routing of readout lines from pads to front-end
- Patched **offline** by clustering pads based on charge sharing fraction
- Tracks built with 2 tracking μMegas (256 μm pitch)



Plateau efficiency: about **95% for μMegas, 75% for μ-RWELL, 90% for RPWELL**
Response uniformity: 10% RμMegas, 16% μ-RWELL, 22% RPWELL





Detector	Uniformity (%)
MM-RM3	$(12.3 \pm 0.8)\%$
MM-Na	$(11.6 \pm 0.8)\%$
MM-Ba	$(8.0 \pm 0.5)\%$
RPWELL	$(22.6 \pm 4.7)\%$
μrw-Na	(11.3 ± 1.0) %
μrw-Fr2	$(16.2 \pm 1.7)\%$
μrw-Fr1	$(16.3 \pm 1.1)\%$

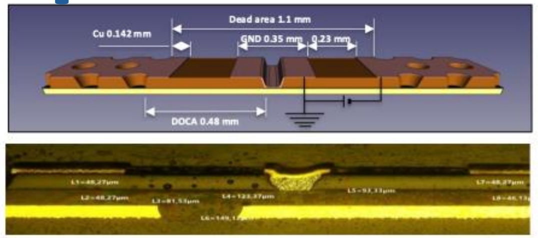
Investigation on inefficiency of µRWELL

Inefficiency of **µ-RWELL** due to **PEP-Groove** introducing dead areas

- **Locally very high** efficiency
- PEP lines introduce a **region of ~ 1 mm with ~50% efficiency drop**
- At **increasing drift** field, efficiency drop region **gets thinner and smaller**

Excluding PEP areas, the efficiency is up to 95%

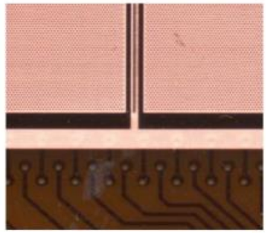
→ **Optimization of drift field** to be repeated

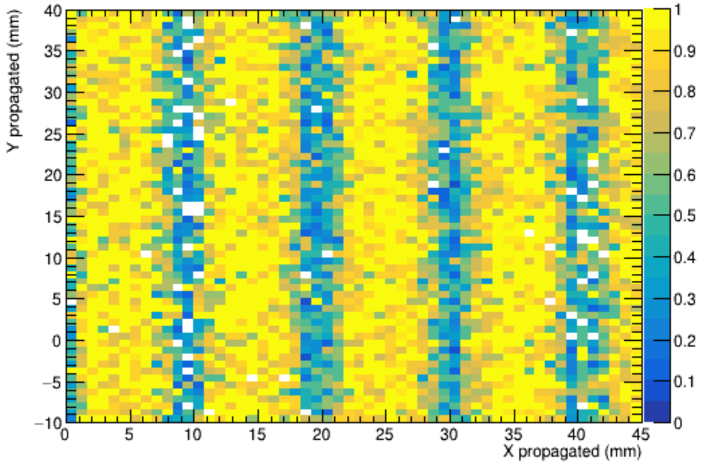


2022

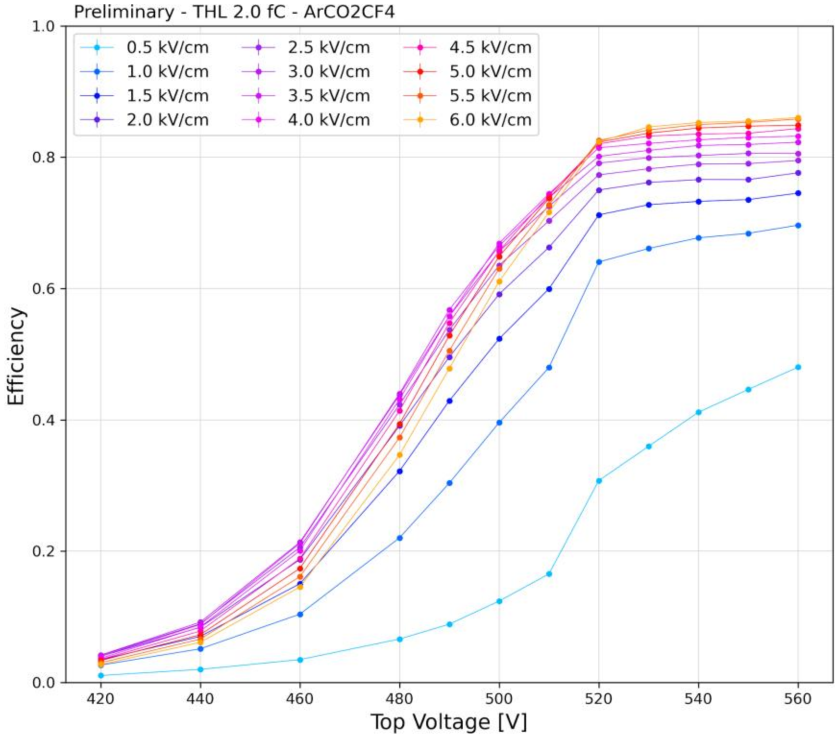
PEP-Groove:
DLC grounding through conductive groove to ground line
Pad R/O = 9×9mm²
Grounding:
- Groove pitch = 9mm
- width = 1.1mm

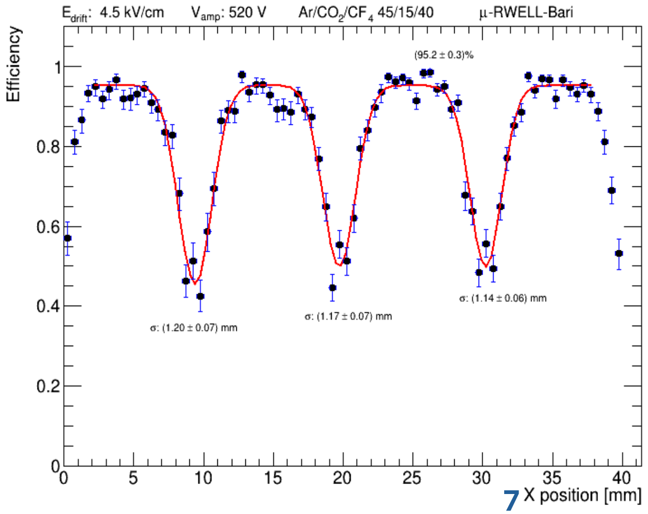
→ 84% geometric acceptance





New prototypes will follow
DOT grounding scheme





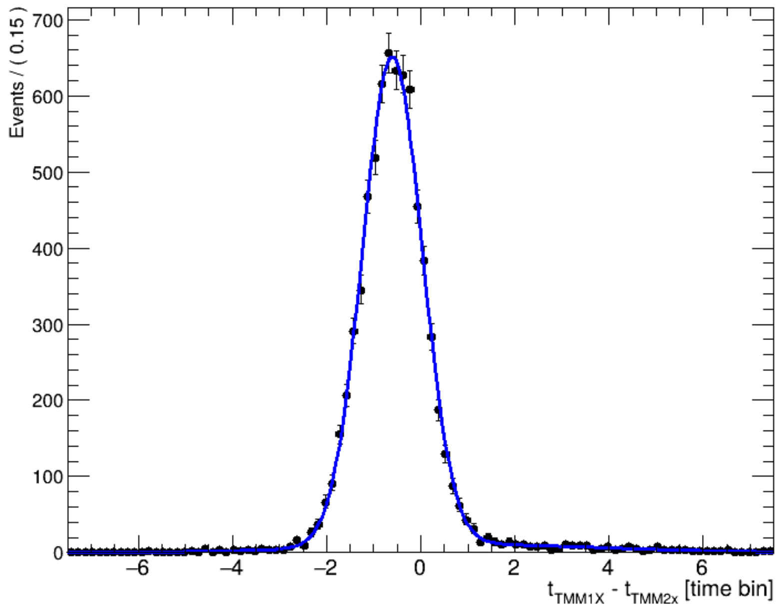
Results from tests with VMM

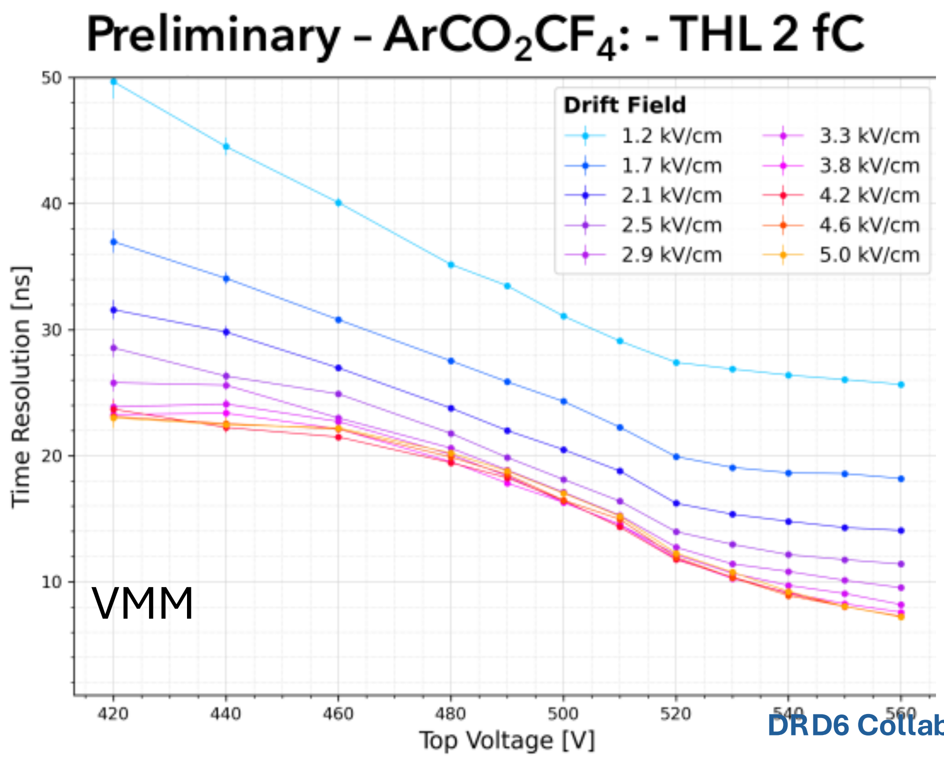
- **Rate** *(1 night data taking with APV → two spills with VMM)*
- Lower **thresholds** reachable (down to 0.8 fC)
- **Consistent results** obtained with VMM and APV

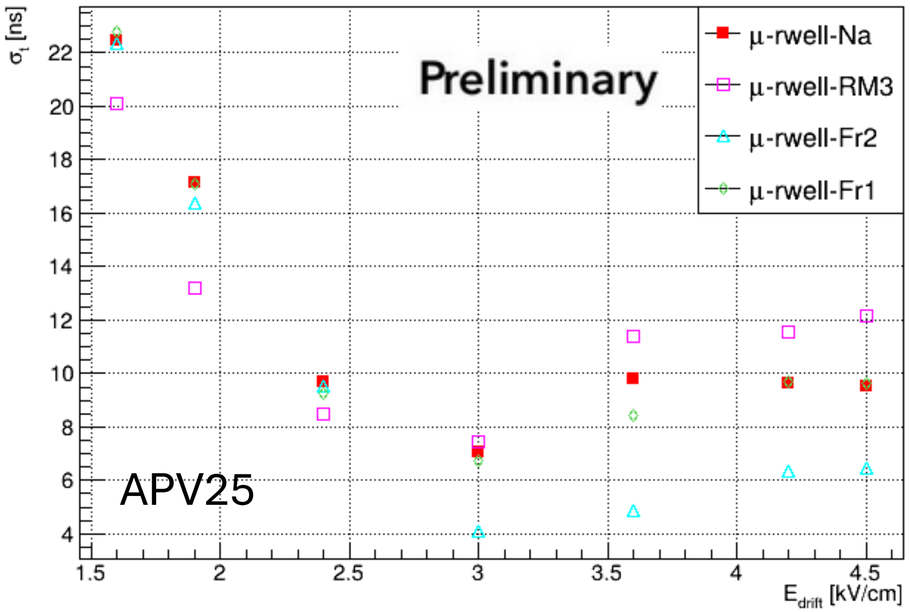
Time resolution to MIPs

- Time for channel obtained
  - from the fit of rising edge of signals for APV25
  - time of the signal peak for VMM
- Time resolution for detectors measured using tracking system as reference
- Gaussian fit of $\Delta t = t_{det} - t_{track}$ → $\sigma_{mis} = \sigma_{det} \oplus \sigma_{track}$

Time resolution for μ-RWELLs can reach **a few ns** in $Ar/CO_2/CF_4$ with proper drift field (3 – 3.5 kV/cm)

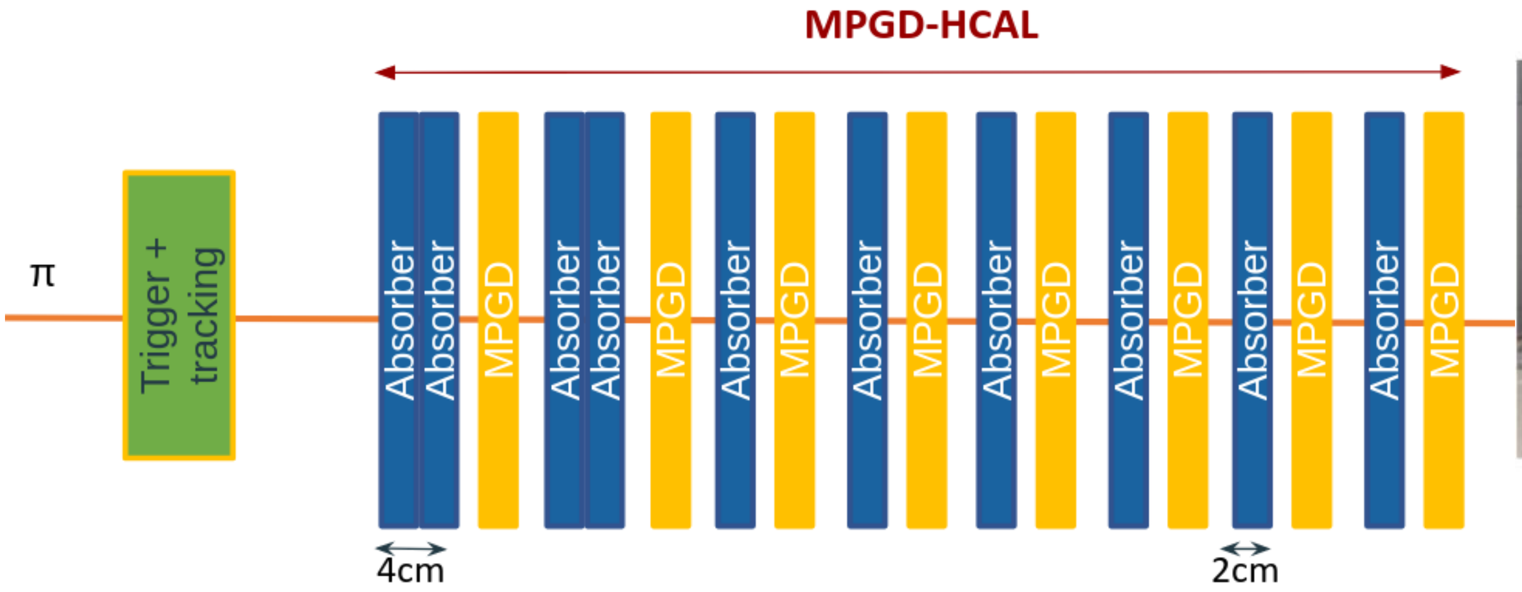


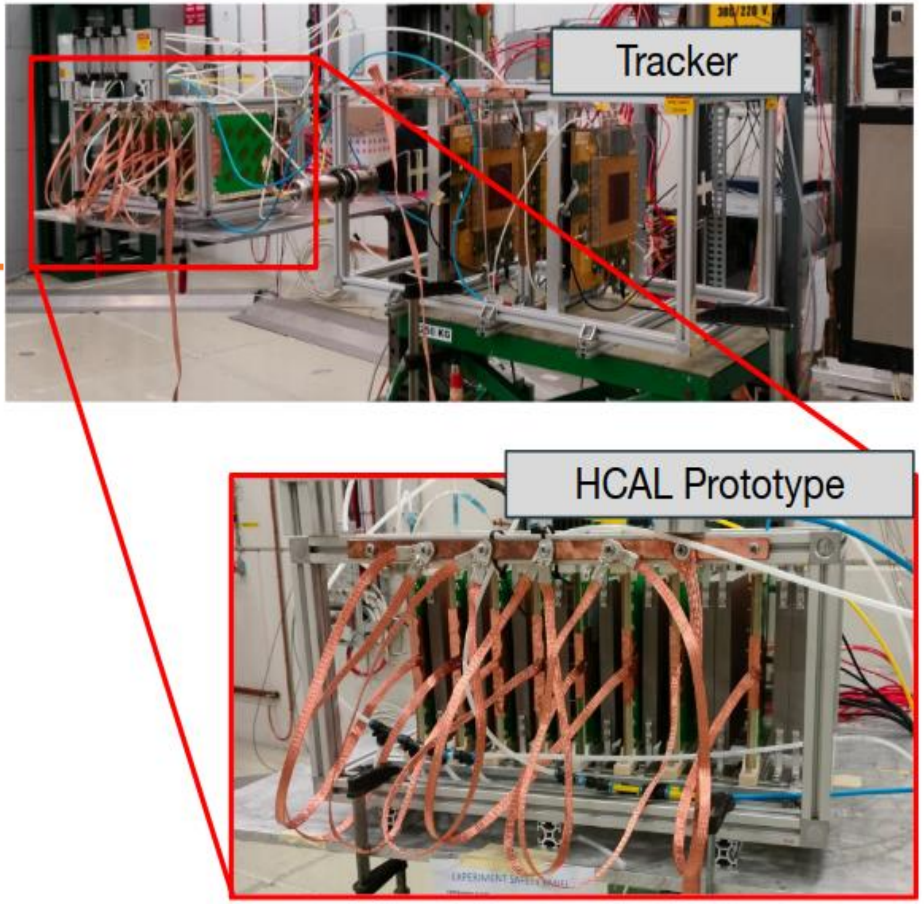




MPGD-HCAL prototype

With absorbers





HCAL prototype ~ 1 λ_I (8 active layers) tested under pion beam at PS

Data taking based on analog FE (APV25 + SRS)

Runs at different π^- energy (up to 11 GeV)

- Two TB campaigns: August 2023, July 2024
- Data analysis **ongoing**
- Developed G4 simulation for comparison with TB prototype

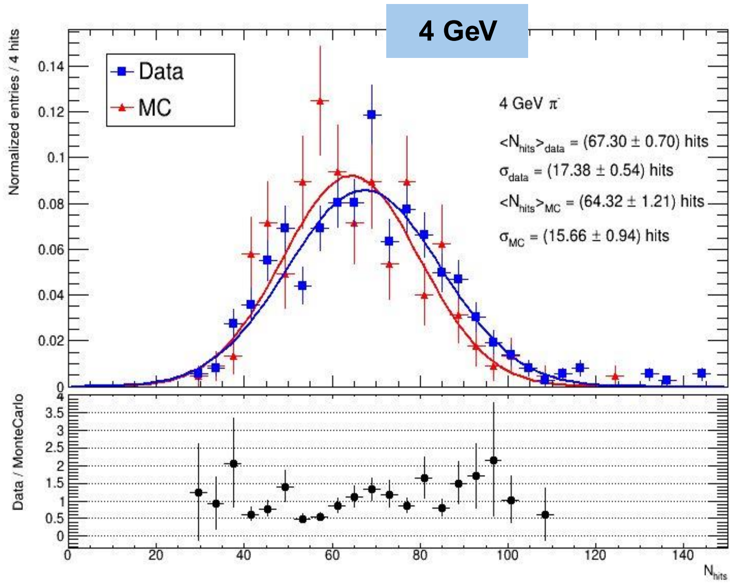
Pion shower studies 2023 data

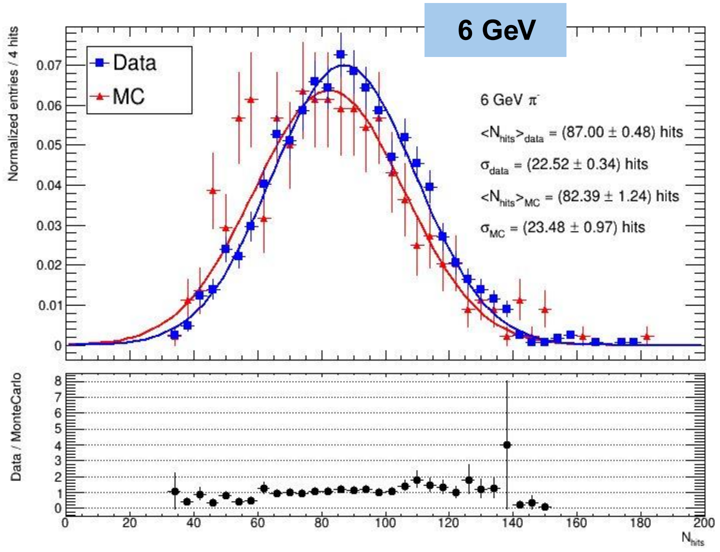
Issues for 2023:

- problematic electronics for the first 2 MPGD layers
  → taken into account for data/MC comparison
- many dead channels in electronics
- Detectors operated at high gain saturating electronics
  →no charge information

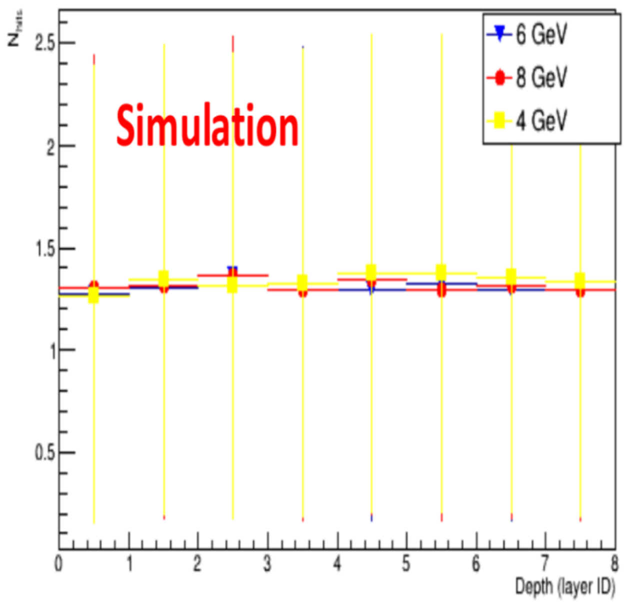
Preliminary results for digital readout (hit charge not used)

- MIP events identified as having at most 4 pads per layer
- Good **data/MC comparison** in number of hits per shower

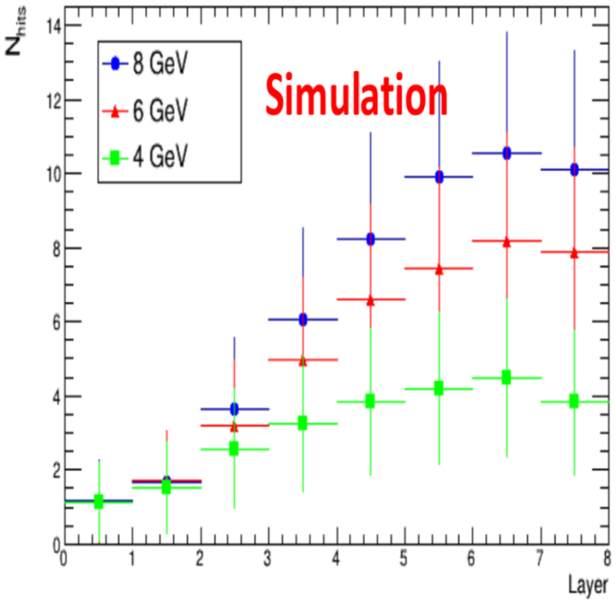




MIP-like events



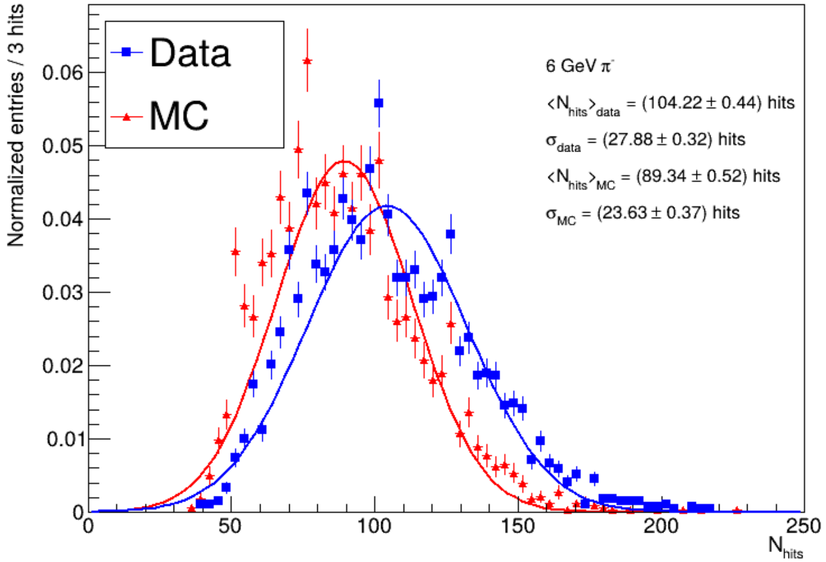
Shower events

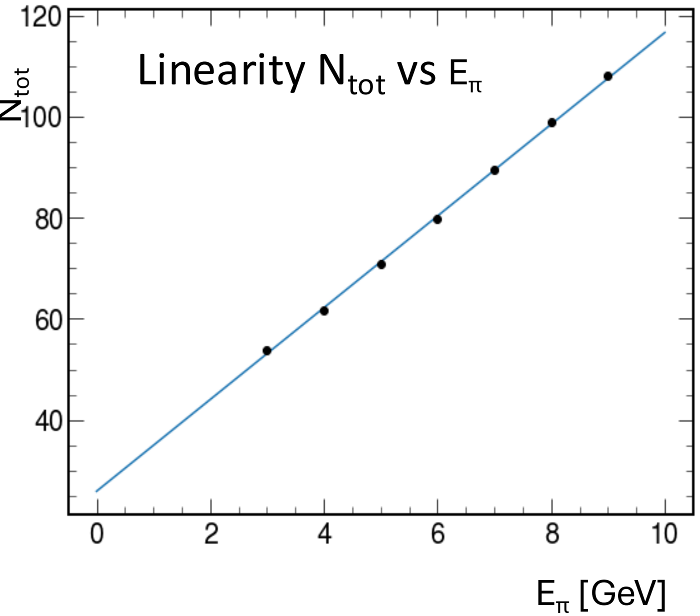


Pion shower studies 2024 data

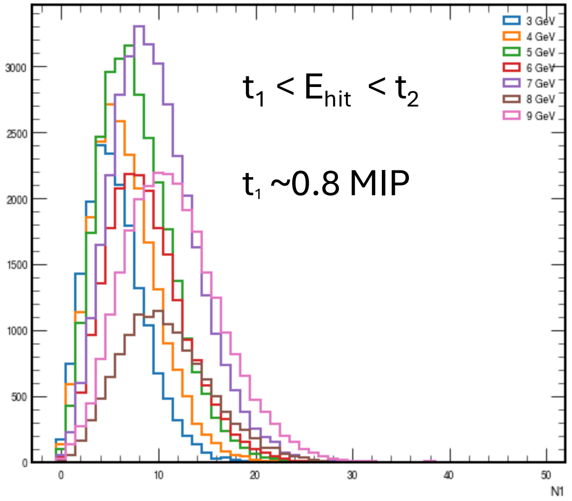
- Different **event selection** criteria are under investigation:
  - Shower events selected requiring at least 4 hits in each active layer
  - Cut on Q = std of cluster size x cluster charge (Q is expected to be high for shower events)
- Plans to improve shower selection (not good Data/MC agreement)
  → initial data-cleaning using tracking system for MIPs identification
  → further rejection of non-contained showers

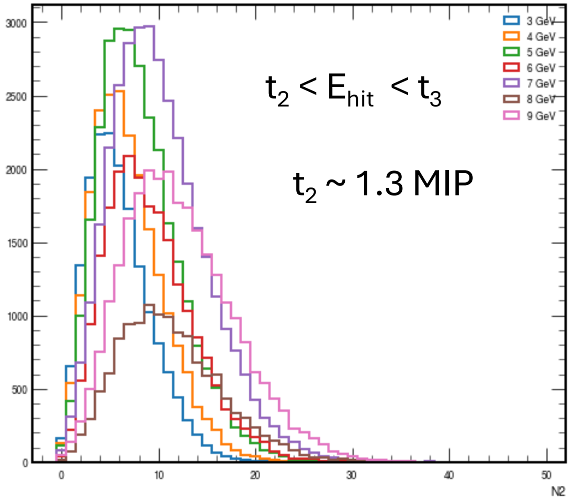
ongoing

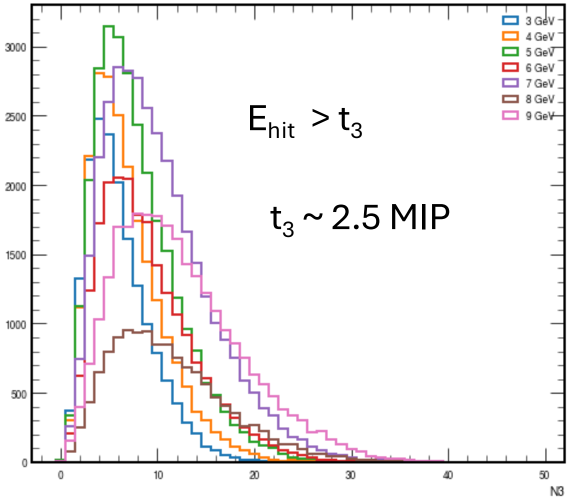




- Ongoing threshold (t_1, t_2, t_3) optimization studies for semidigital approach to shower reconstruction







Ongoing...

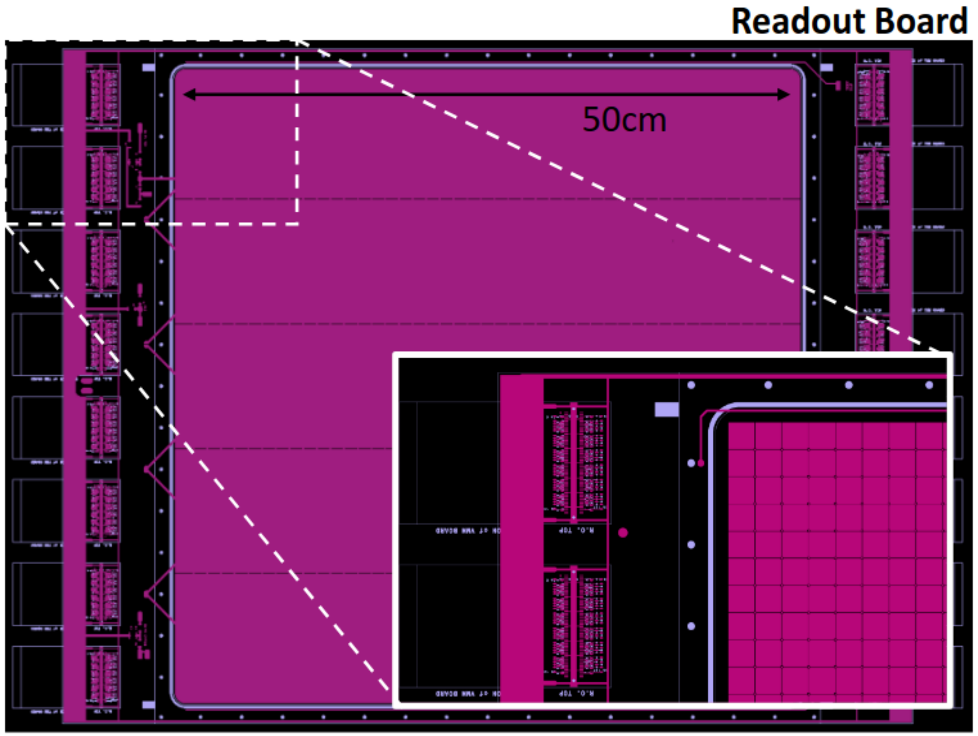
Plans for next months

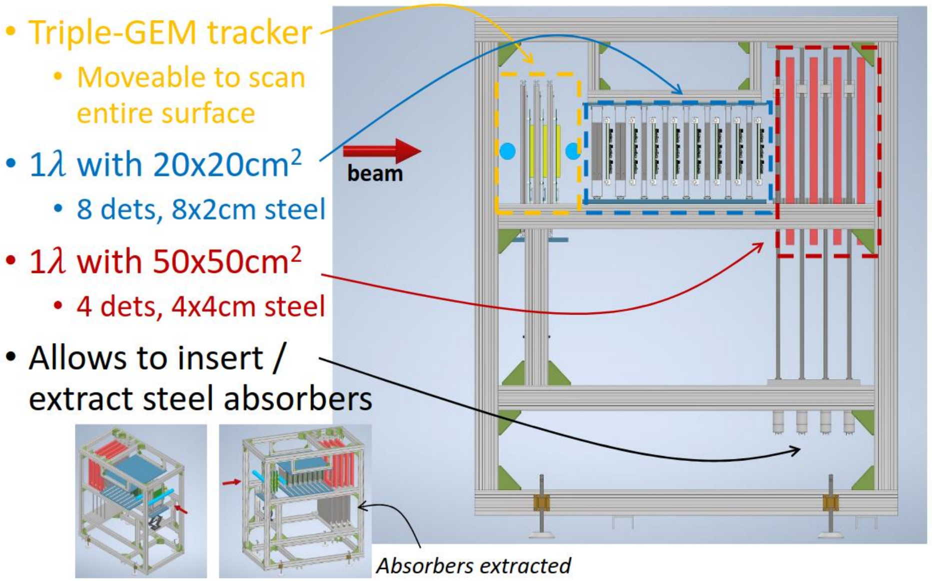
Hardware development:

- Development of a new cell **prototype of ~ 2 λ**:
  → 8 old 20 x 20 cm^2 chambers + 4 **new 50 x 50 cm^2** chambers (currently under production):
  - *121 mm^2 pads, read out by 16 APV/VMM cards*
  - 2 RµMegas
  - 2 µRWELLs with most recent grounding system
- Drift gap optimization studies for timing improvements
- Development of a mechanical structure holding the entire setup
- Test beam campaign with DRD6 foreseen in Fall 2025
- Common test beam with Crilin (MuCol ECAL) next year
- Continuing integration with VMM and testing new chips (FATIC3, CALOROC?)

Analysis development:

- Energy resolution measured in digital mode
- Threshold optimization for semi-digital mode
- Study of timing within calorimeter system



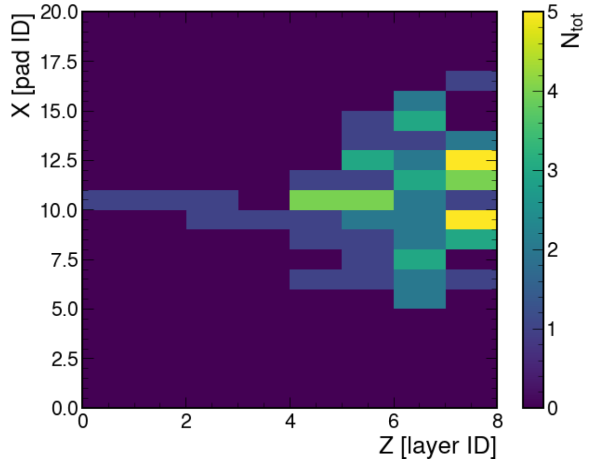


Conclusions

Development of MPGD-HCAL ongoing in **simulations** and **hardware**

- Tested 12 MPGDs and small cell calorimeter within RD51 **common project** and **PNRR Calorhino**
- In 2024 we consolidated previous 2023 results with present prototypes in two test beams:
  - SPS: efficiency and acceptance, response uniformity, field optimizations, time resolution
  - PS: test of a fully equipped 8 MPGD layers prototype

  Analysis focusing on timing and energy resolution now for calorimeter prototype
- First integration with VMM performed, with good results and compatible with APV25

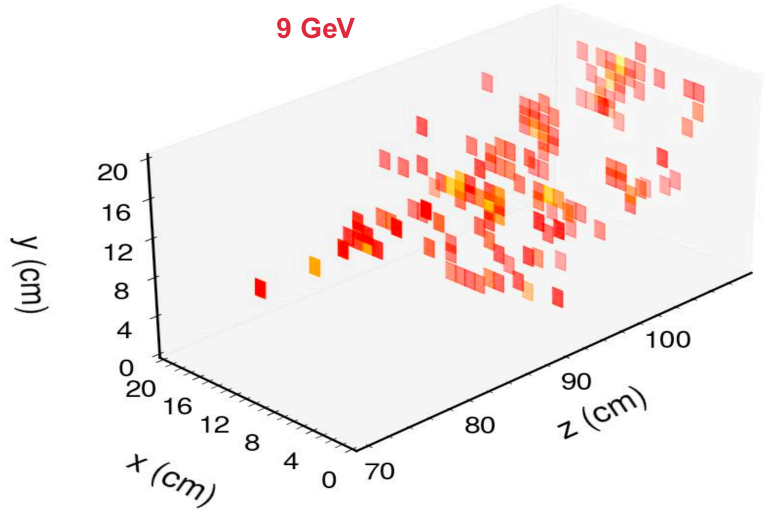


Next to come

New 50 x 50 cm^2 chambers with improved readout board routing under production

- 2 Micromegas
- 2 µRWELLs with most recent grounding system

- Test beam campaign with DRD6 foreseen in Fall 2025



Long term plans

- Understanding suitable technology (Micromegas, µRWELL, RPWELL)
- R&D for eco-gas mixtures to replace the ones currently used
- Electronics: new chips will be tested
- Producing **50×100 cm^2 detectors**
- Producing detectors with **integrated electronics and cooling**

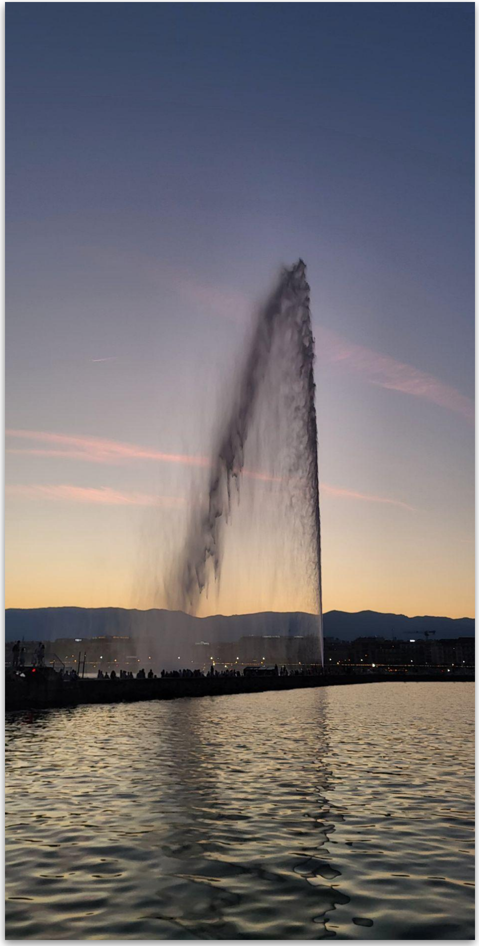
We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1 .1, Call for tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU– Project Title: CALORHINO – CUP 53D23000990006-CALORHINO - Grant Assignment Decree No. 974 adopted on 30/06/2023 by the Italian Ministry of Ministry of University and Research (MUR)

Task 3.2.2:
R&D on Picosecond SpaCal Technology

Loris Martinazzoli[1]
on behalf of the Task 3.2.2 group
(CERN, Institute of Physics of the Czech Academy of Sciences,
University of Barcelona, IFIC Valencia, University of Milano-Bicocca,
IJCLab Orsay, LPC Clermont-Ferrand, LPC Caen, IP2I Lyon)

[1] CERN, Geneva, Switzerland

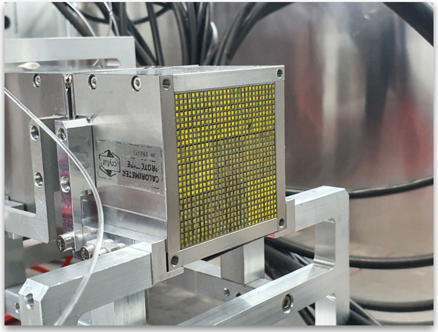
DRD6 Collaboration Meeting
CERN, Geneva
31st October 2024

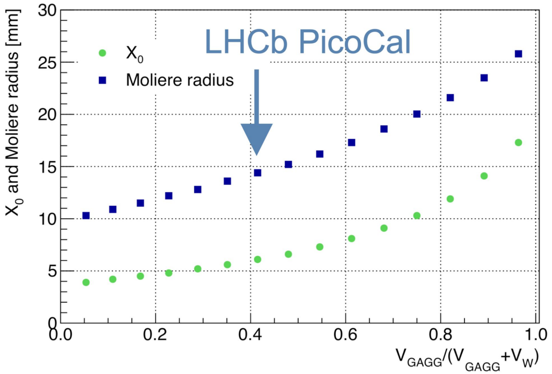


A Spaghetti Calorimeter

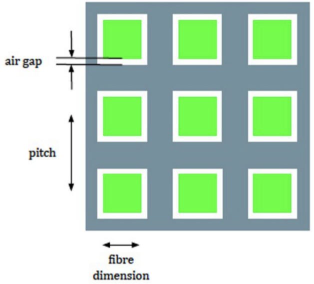
Energy resolution and X0/Molière radius **tunable**

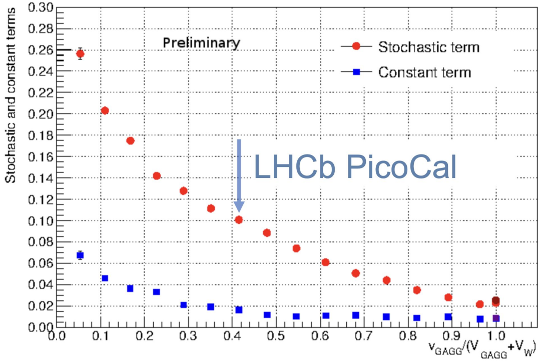
- Lower cost than homogeneous calorimeters
- Can be adapted to meet requirements for **LHCb PicoCal, Higgs factory, FCC-hh, fixed-target experiments** at the intensity frontier





Fibres scintillate and transport light
- No WLS ⇒ faster scintillation ⇒ **timing**





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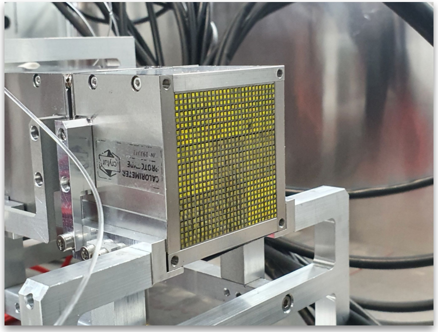
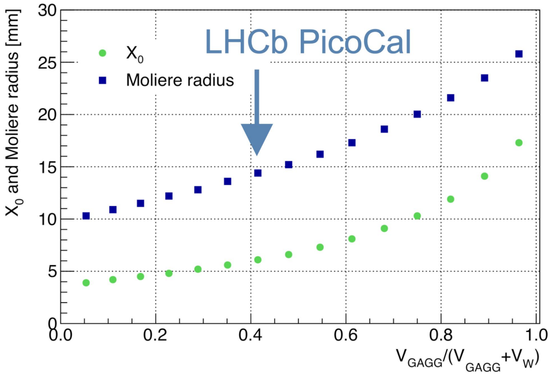


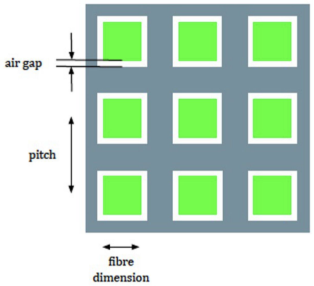


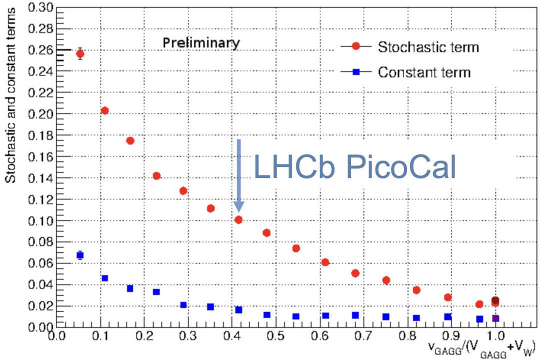
Fibres scintillate and transport light

- No WLS ⇒ faster scintillation ⇒ **timing**

Key challenges:

- **Radiation hardness** ⇒ Crystals for hadron colliders, radiation tolerant organic scintillators
- **Small cell size** ⇒ dense absorber, e.g. Tungsten
- **Fast photon detectors** ⇒ MCD-PMTs, SiPMs ...





Planned Activities in 2024-2026

		D3.7	Tungsten and lead absorbers for module-size prototypes	2024
	M3.11		Design of optimised light guides	2025
		D3.8	Set of crystal samples, SPIDER ASIC prototype	2026
SpaCal	M3.12		Specification of photon detector and improved simulation framework available	2026
		D3.9	Module-size prototypes (significantly larger than EM showers) built and validated in beam tests	>2026

Planned Activities in 2024-2026

SpaCal		D3.7	Tungsten and lead absorbers for module-size prototypes	2024
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		D3.9	Module-size prototypes (significantly larger than EM showers) built and validated in beam tests	>2026

One clear goal:

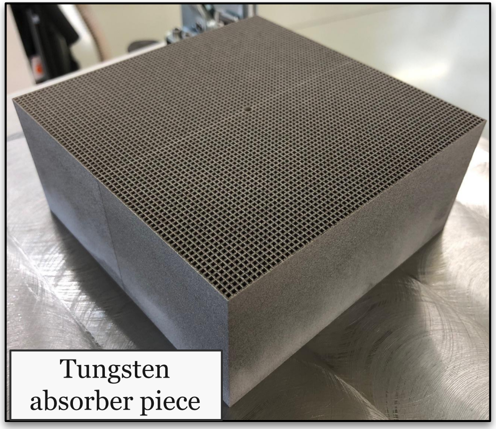
*Build and validate **module-size SpaCal** prototypes with **W** absorber and crystal/organic fibres and **Pb** absorber with organic fibres **by 2028***

Absorbers and Light Guides

! Deliverable D3.7 achieved !

Produced:
- 3D-printed **Tungsten** absorber
- Cast **Lead** absorber

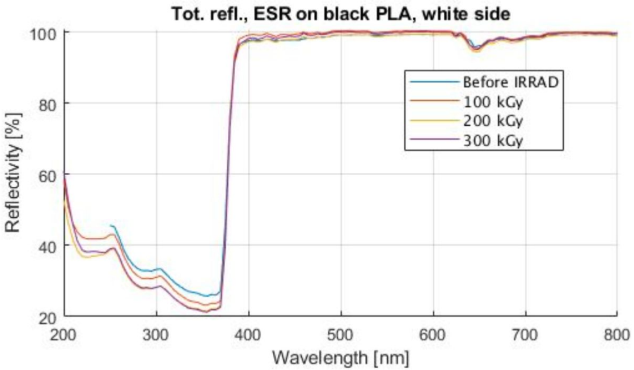
R&D on absorber production continuing


Tungsten absorber piece

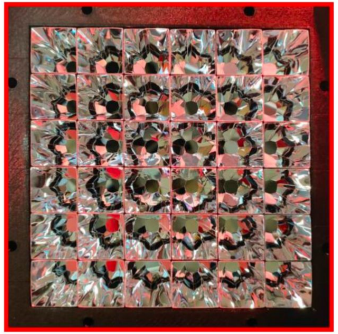

Lead absorber piece (new!)

Concept for **radiation-hard “hollow” light guides** demonstrated.

Extensive optimisation ongoing via:
- Laboratory measurements
- Ray-tracing simulations
- Testbeams



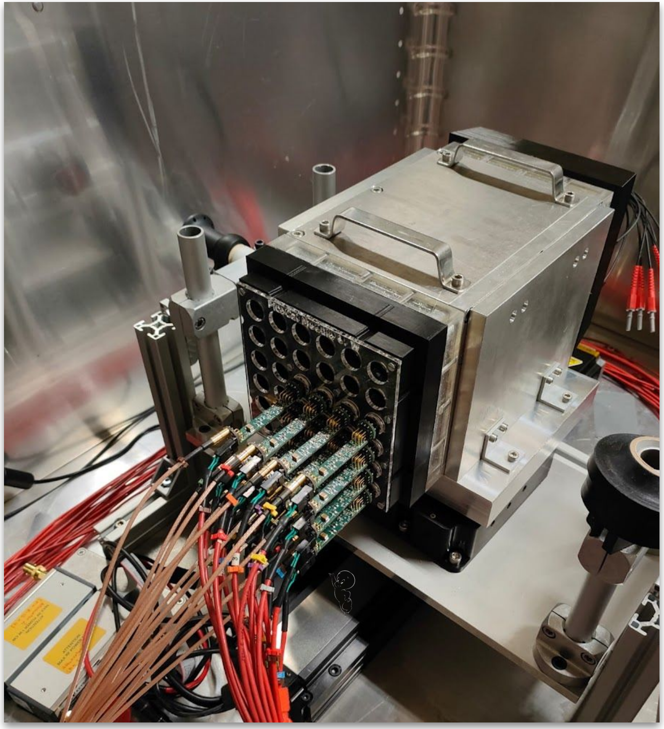
Radiation hard light guides



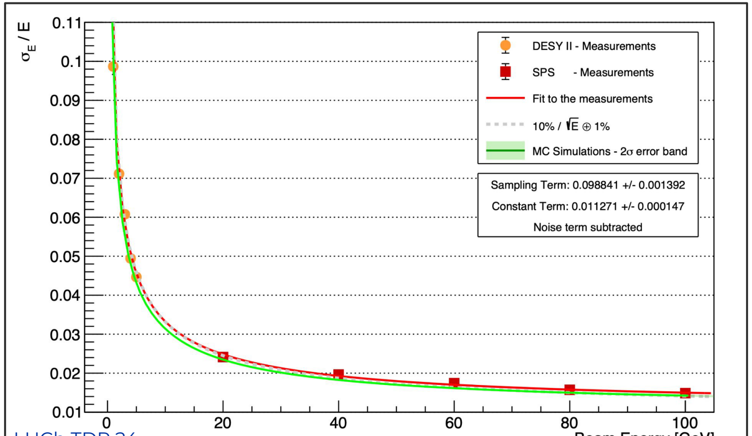
Current Status: SpaCal with W Absorber

- 12x12x19 cm^3 **Tungsten** absorber 3D printed
- 1x1 mm^2 Single-cladded **Kuraray SCSF-78** polystyrene fibres
- **Single-sided readout**

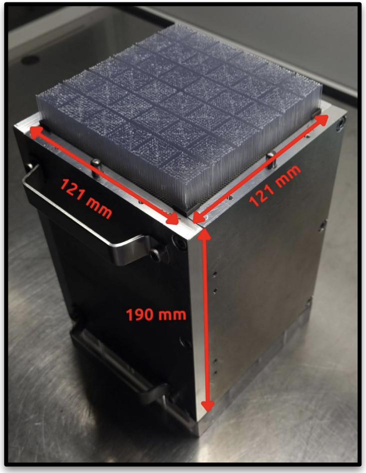
- Testbeam measurements at
  DESY II, Hamburg and SPS, CERN
- Excellent **agreement with Monte Carlo simulations**



Energy Resolution (DESY & SPS, R14755U-100)



LHCb TDR 24

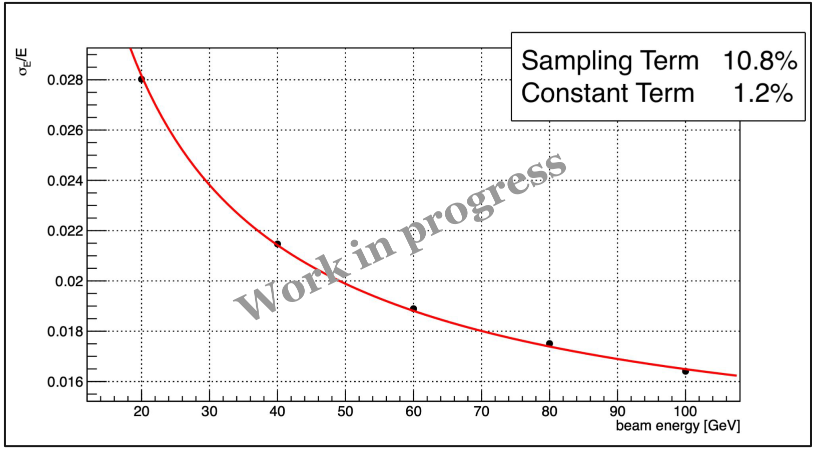


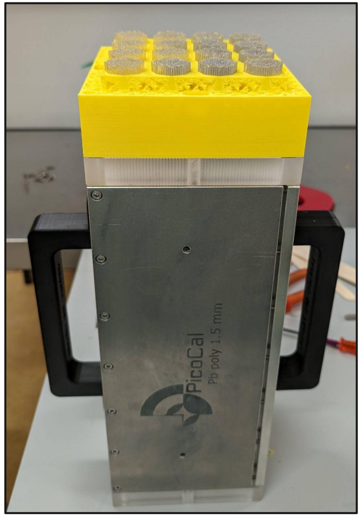
Current Status: SpaCal with Pb Absorber

- 12x12x30 cm^3 cast **Lead** absorber
- 1.5 mm^2 diameter **Kuraray 3HF (green)** polystyrene fibres
  - Better radiation hardness than blue fibres
  - All multi-cladded but for one cell
- **Single-sided readout**

- First testbeam at SPS, CERN in 2024
  - Preliminary results in good agreement with expectations

Energy Resolution (SPS, R11187)

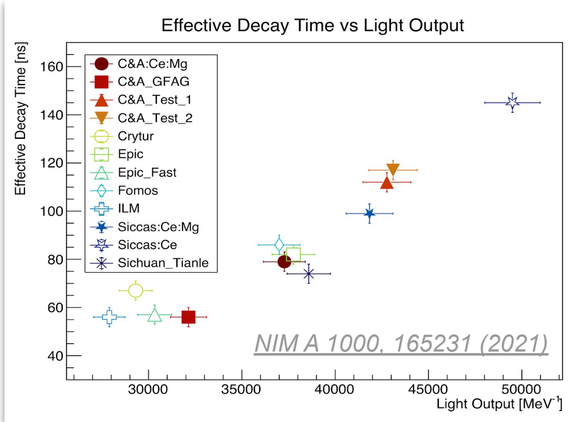


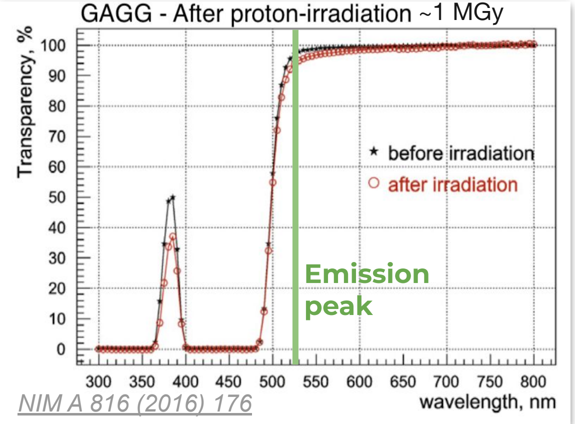


Crystal Properties and Optimisation

Garnet crystals are:
- bright and fast
- radiation-hard
- tunable scintillation properties

Flexible scintillator, tunable to the application!

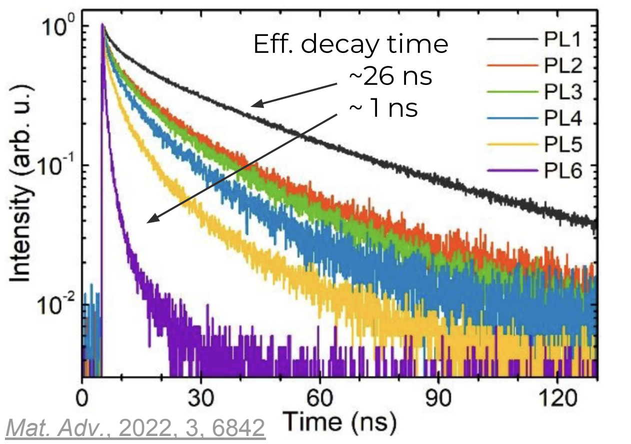


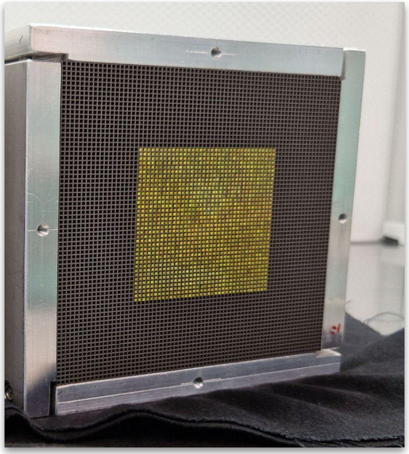


Successful tests of ultra-acceleration with heavy Ce/Mg doping
- Joint R&D CERN, FZU, Vilnius
- No major loss in time resolution

Collaboration with **Task 3.4.1 “*Scintcal*”**
Future R&D: optimisation of crystal growth and composition

New prototype assembled with accelerated GAGG ⇒ Tested in October 2024...
... Analysis ongoing





SPIDER ASIC

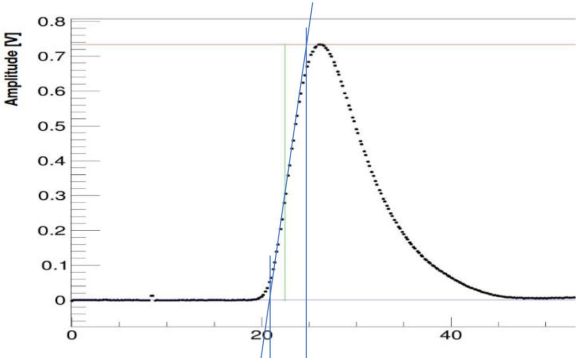
ASIC dedicated to timing in high-rate environments (e.g. HL-LHC):

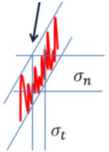
- Time measurement in E_T = [50MeV, 5 GeV]
  - Target **15 ps** for E_T = [1 GeV, 5 GeV]

- Based on **Switch-Capacitor-Arrays (SCA)** CMOS 65 nm technology
  - Configurable sampling rate > 2.5 GS/s
  - 8 samples to compute Constant Fraction Discrimination (CFD)
  - Best solution for wide dynamic range
  - R&D on correction for saturation (extends the dynamic range)

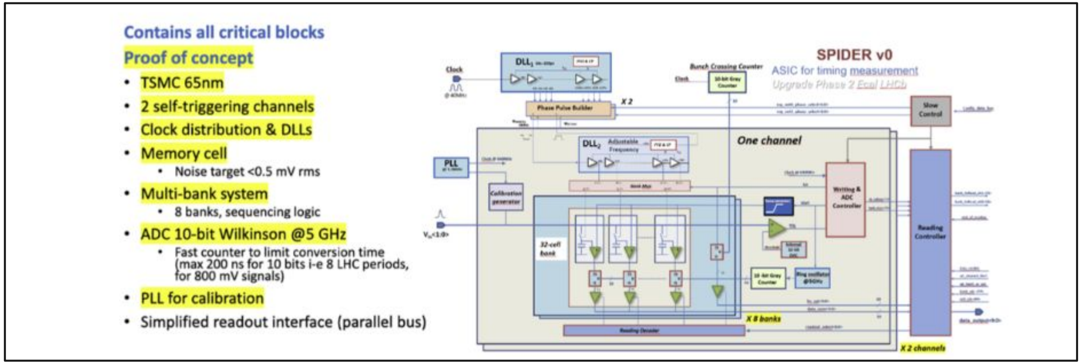
- Design compatible with **40 MHz and 50% occupancy**
  - R&D ongoing **towards 100% occupancy**
  - Option to send the **full digitised pulse** to the backend

- First tests in the lab in 2025
- First prototype in **testbeam in 2026**





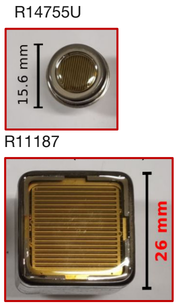
$$t \geq \frac{\sigma_V}{\left(\frac{dV}{dt}\right) max} \qquad \sigma_t \geq \frac{T_{LR}}{SNR}$$

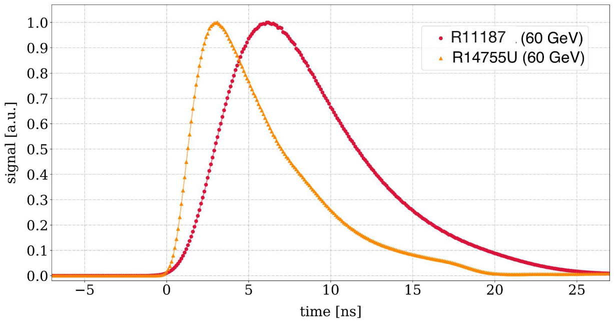


Photon Detectors Performance

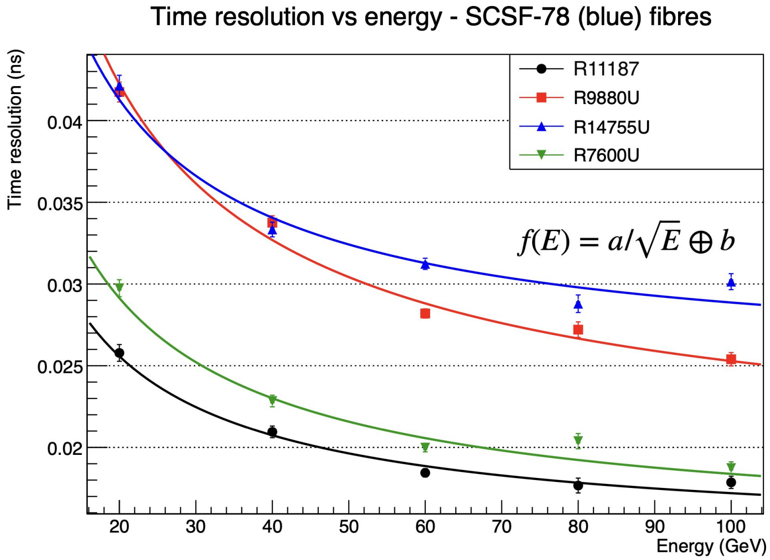
Undertook comparative study of different **photodetectors** to measure their **contribution to time resolution**:

- first results for **Single-sided readout**
- 1 light guide - 4 MCD PMTs (Hamamatsu)
  - Wide range of **gain**, **time transit spread**, and single photoelectron **response**





Time resolution **below 20 ps** at high energy for some PMTs

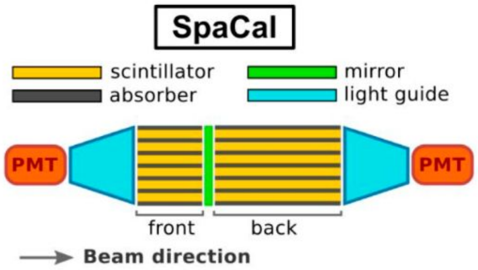


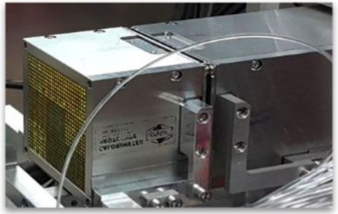
Studying:

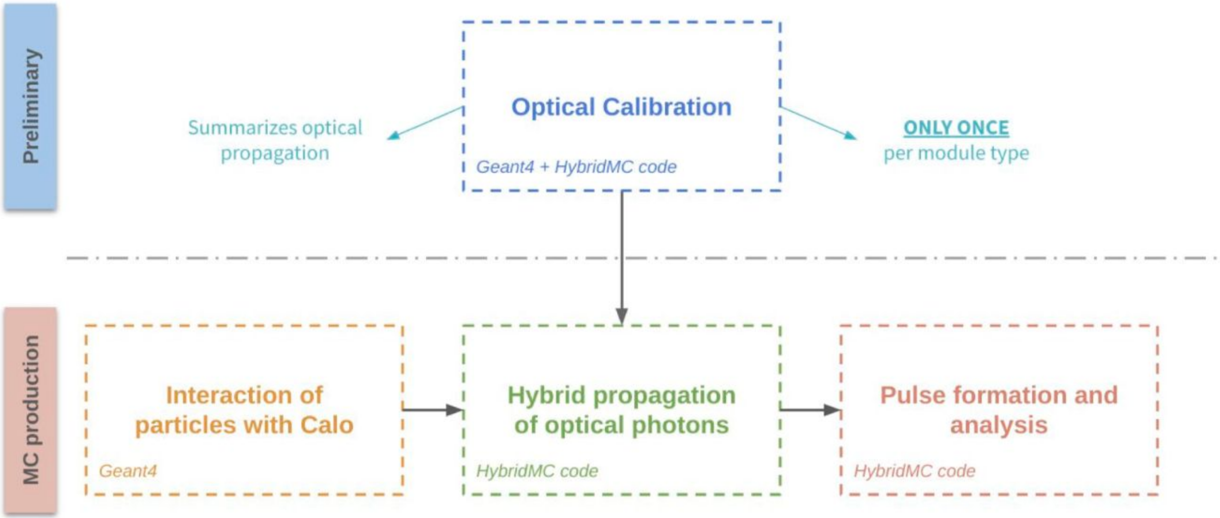
- **contributions** of the PMT to the fit parameters
- **new techniques** to maximise information extraction from the **pulse shape**

Simulation Framework

Developed for detailed simulation of SpaCal and Shashlik technologies, moving transport of optical photons **outside of Geant4**

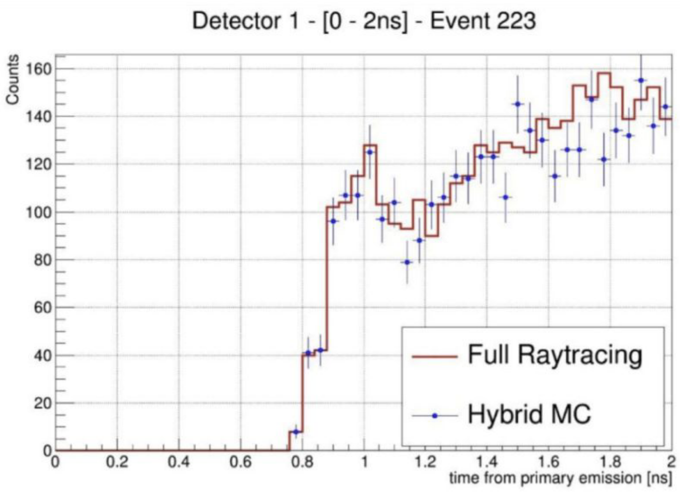






- Preliminary characterization with a special full ray-tracing run → **optical calibration**
  - Optical photons produced over a grid of points, propagated and collected at the exit of the modules
  - Histograms of the extracted photons are recorded
- Fundamental features of optical transport are **encoded in the histograms** (extraction efficiency, time distribution)
- Optical calibration needs to be performed **only once per module type** (so CPU time doesn't matter)

Simulation Framework



Technology	Type	Full ray-tracing *[s/GeV] of $e^{\pm}/\gamma$*	HybridMC *[s/GeV] of $e^{\pm}/\gamma$*	Gain
SpaCal	*W-GAGG*	990 ± 20	9.4 ± 0.1	~100
	Pb-Polystyrene	3600 ± 100	2.28 ± 0.04	~1500
	W-Polystyrene	1070 ± 20	2.88 ± 0.04	~400
Shashlik	–	1800 ± 30	3.83 ± 0.09	~500

- **Excellent agreement** with standard full ray tracing
- Substantial **gain in computation time**: from **100x** to **1500x** times faster
  - Allows to perform physics benchmark studies at LHC Run 5 conditions in reasonable time
- Validated with **testbeam experimental measurements** of Shashlik and SpaCal prototypes

R&D ongoing to achieve CPU time compatible with *full-scale experiment simulation framework*, e.g. LHCb

Summary and Next Steps

SpaCal is a **flexible technology** that can meet the needs of a variety of HEP experiments

- **Tunable** X_0, R_M, and energy resolution
- **Time resolution** better than 20 ps for high-energy electron beams

- Task's goal is to build module-size prototypes by 2028
    - **well on schedule** (already met some deliverables)

Intense **R&D** ongoing **covering multiple topics**, e.g. new fast GAGG tested at SPS

- Feasibility study for the usage of SiPMs at Higgs factories planned
    - **ideal for collaboration with other tasks**

- Many other strong synergies and areas of collaborations, including:
  scintillating materials, **simulation software**, **fast photodetectors**, …

Task 3.1.2 - MAXICC: Maximum Information Crystal Calorimetry for future e^+e^- colliders

R. Hirosky[1], M. Lucchini[2]

[1] University of Virginia, USA

[2] INFN & University of Milano-Bicocca, Italy

on behalf of the Calvision / MAXICC groups

DRD6 Collaboration Meeting

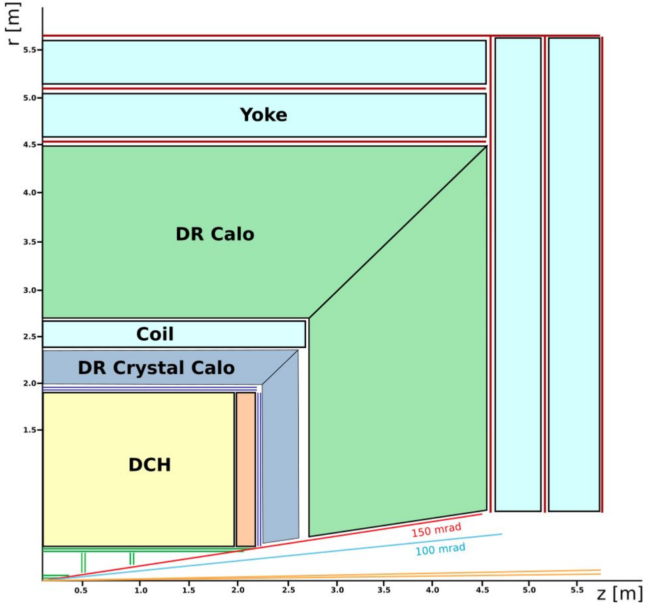
31 October 2024

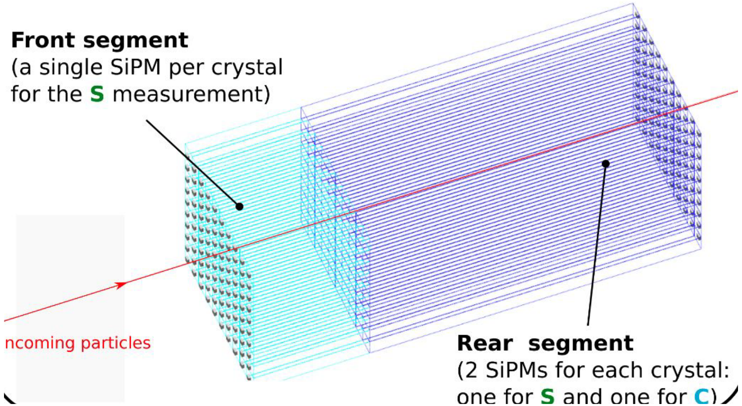
Overview of the project

- Evaluate the potential and the feasibility of integrating a **cost-effective** **homogeneous** **dual-readout** **segmented** crystal **EM** calorimeter in the IDEA detector

- First studies and concept descriptions in:
  - [2020 *JINST* **15** P11005]
  - [2022 *JINST* **17** P06008]

- Activity at 360 degrees:
  - Simulation studies (from standalone to full sim)
  - R&D on technology and proof-of-principle
  - Prototyping of a calorimetric module





Teams and resources involved

- Interest and efforts growing since 2023
  - **INFN**:
    - Coordination within the RD_FCC italian collaboration and national grants
    - Milano-Bicocca, Napoli, Perugia
  - **CALViSION**:
    - A DOE funded project bringing together several US institutions
    - Maryland, Princeton, UVa, Caltech, FNAL, ANL, SLAC*, Michigan, Catholic University of America*, Brandeis*, Stonybrook*, Rutgers*, TTU. MIT, Baylor*, Purdue, Caltech
  - CERN (Switzerland) with the support of European widening project TWISMA (GA 101078960)
  - IN2P3-IP2I (France)

- Currently estimating ~8 FTE of person power (with most people at <50%)
- Yearly budget until 2026 to continue R&D and build full containment EM prototype

Milestones and deliverables

From the DRD6 proposal

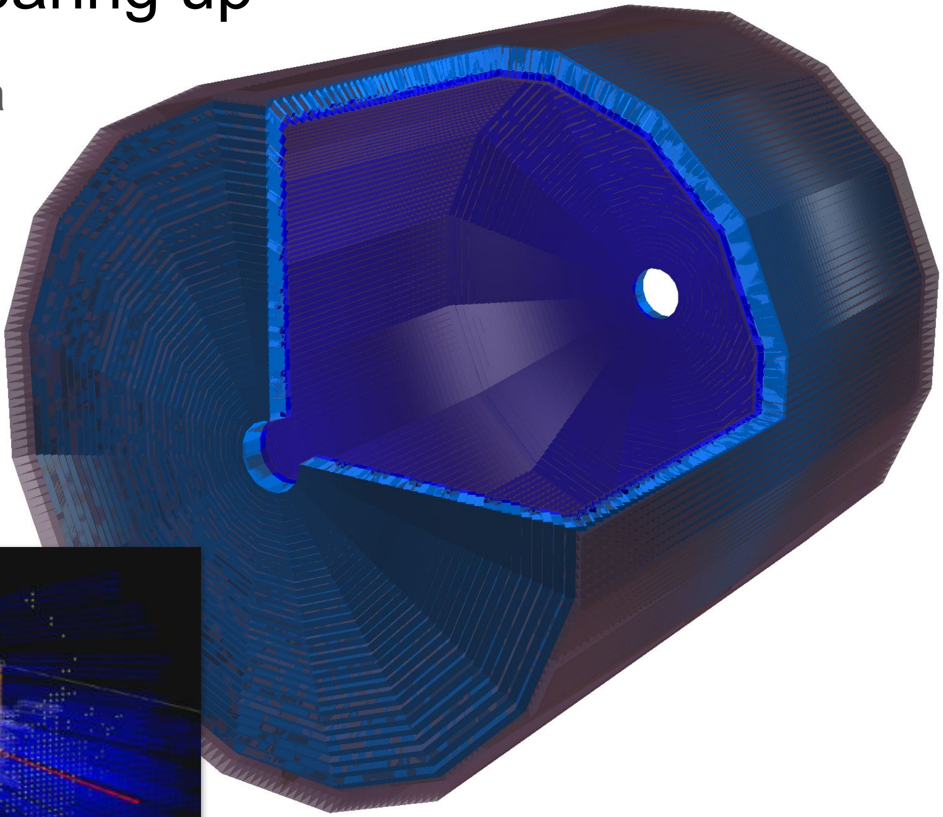
	Milestone	Deliverable	Description	Due date
MAXICC	M3.5		Completion of qualification tests on components and selection of crystal, filter and SiPM candidates for prototype	2025
	M3.6		Report on the characterisation of crystal, SiPM and optical filter candidates and their combined performance for Cherenkov readout	2025
		D3.3	Full containment dual-readout crystal EM calorimeter prototype and testbeam characterisation	2026
	M3.7		Joint testbeam of EM module prototype with dual-readout fibre calorimeter prototype (DRCAL)	>2026

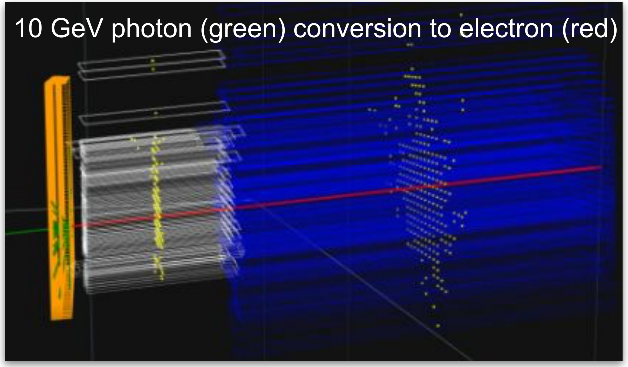
- Original list of milestones and deliverables remains valid and the schedule unchanged as of today
- Aiming at a first test on full containment prototype by the end of 2025

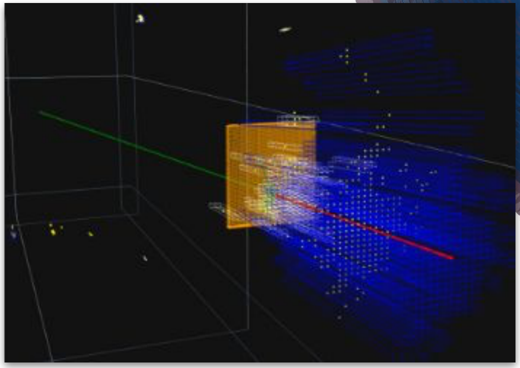
Highlights from 2024

Implementation in key4hep gearing up

- Great progress in 2024 in developing a fully differentiable detector geometry and simulation in key4hep (github)
    - SiPMs and digitized readout implemented
    - ML angular resolution and e/gamma regression studies underway
    - Integration with IDEA detector underway
    - See W.Chung at CALOR2024



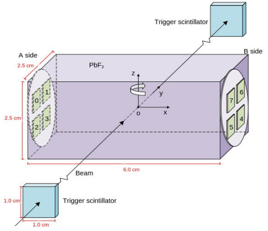


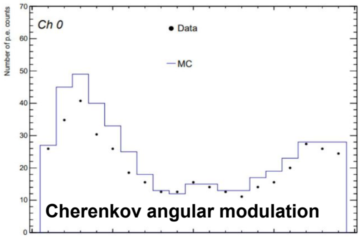


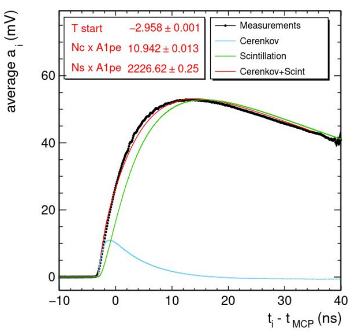
W.Chung
(Princeton University)

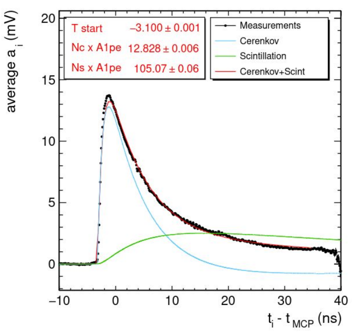
Results from 2023 test beam work

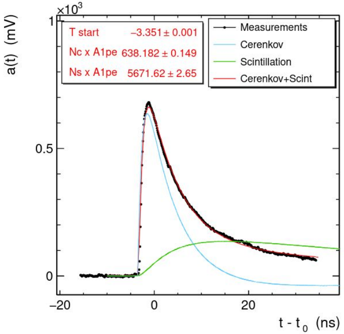
- Focused on tests to validate optical photon modeling using PbF2 and BGO
  - Study light collection efficiency vs impact angle in PbF2 (pure Cherenkov radiator) [recent paper here]
  - Initial tests of S/C light light collection and light tracing modeling in BGO [recent paper here]
  - Successful discrimination of Cherenkov and scintillation photons using pulse shape

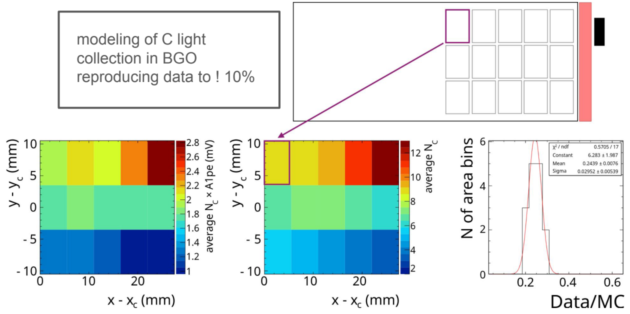






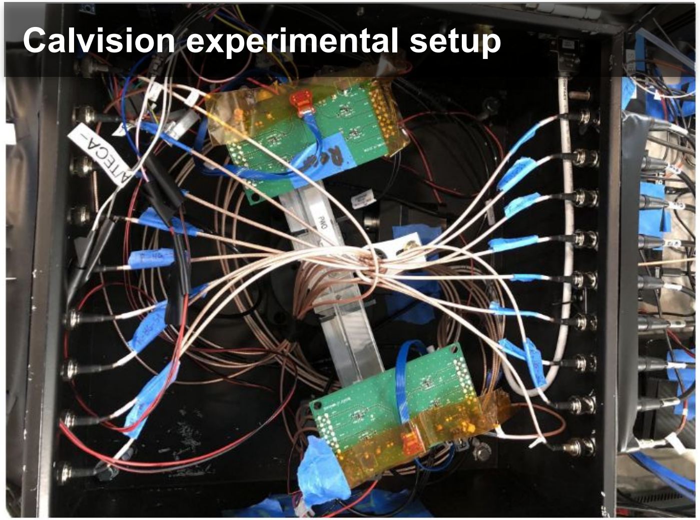


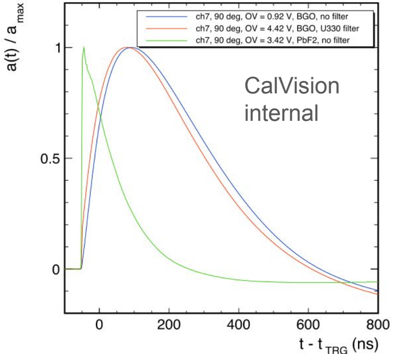


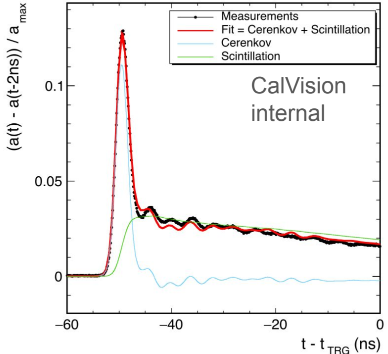


Test beam at DESY (April 2024)

- Focus on large crystals with improved SiPM readout and better optical coupling
  - Repeating study on PbF2 and BGO with better SiPMs and testing more crystal flavors (PWO, heavy glasses, ...)
  - Test of different filters using silicon cookies as optical interface, Broadcom SiPMs

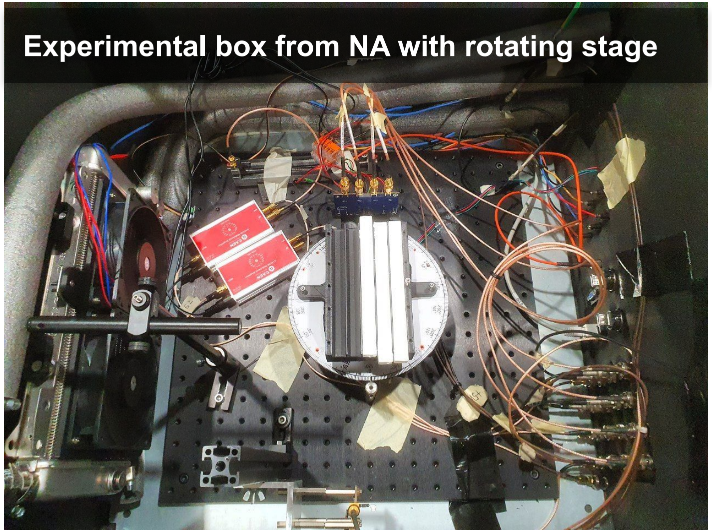


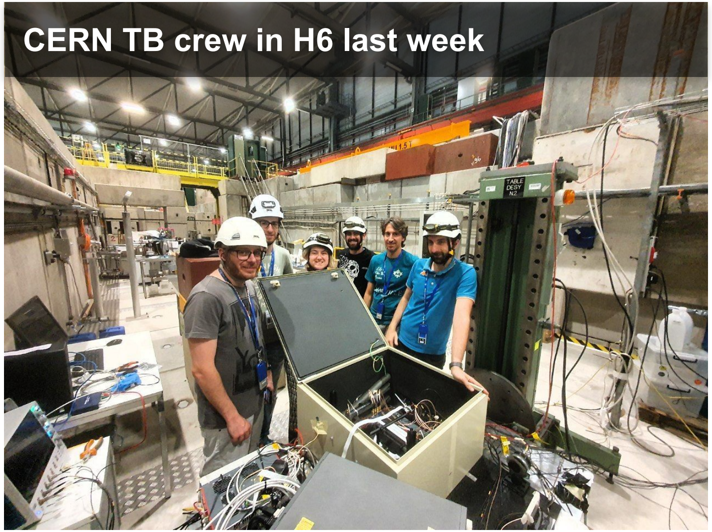


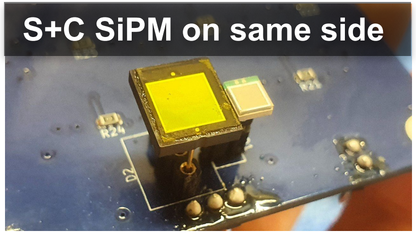


Test beam at CERN (July 2024)

- Testing close-to-nominal crystal geometry and longitudinal segmentation
- Tests with electrons (10-100 GeV), muons, hadrons
- Tested a variety of filters and crystals to assess Cherenkov yield as a function of of beam angle
- **Plenty of useful data to steer the next R&D steps** and technological choices for the prototype construction


Experimental box from NA with rotating stage

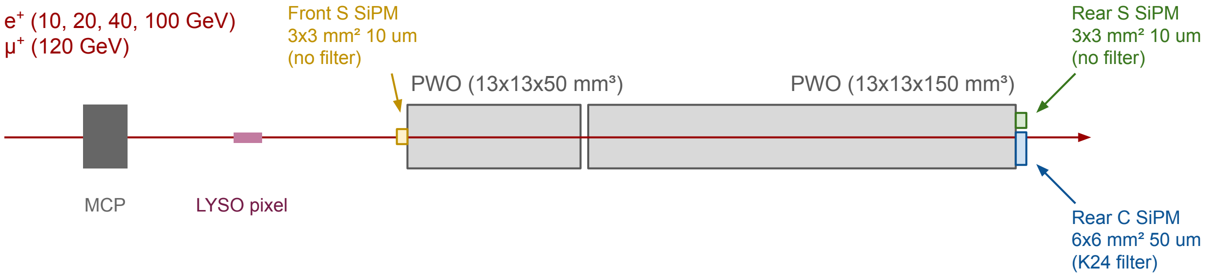

CERN TB crew in H6 last week

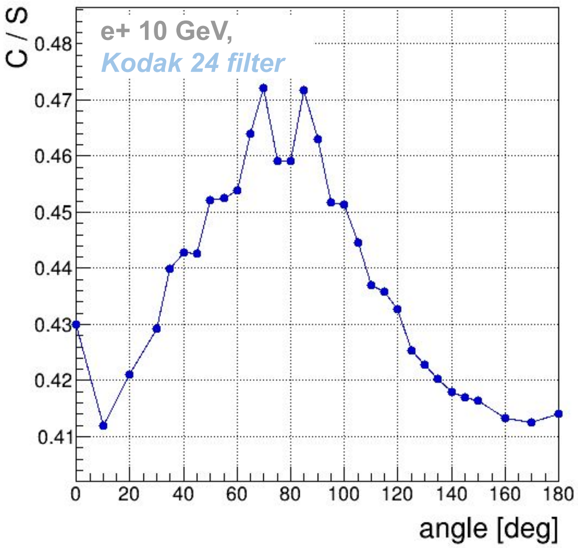

S+C SiPM on same side

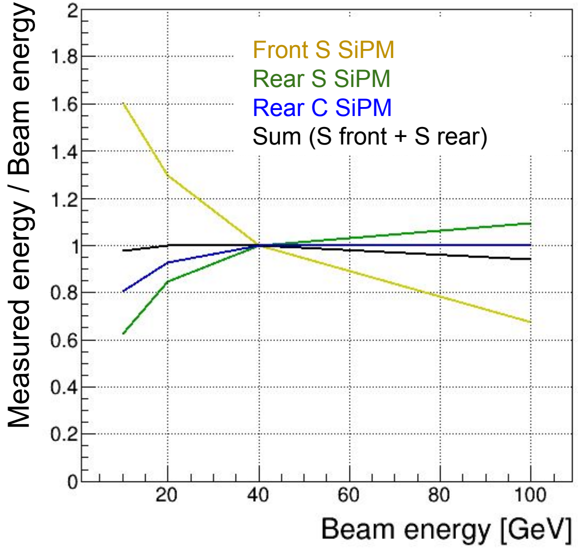

Ultrathin filters on Hamamatsu SiPMs

Preliminary results from CERN July 2024 TB

- **Angular scans** (rotating crystal wrt to beam) to study C/S variation
- **Electron energy scan** to evaluate longitudinal displacement of shower maximum using front and rear crystal
- **Assessing dynamic range** required for SiPMs and electronics



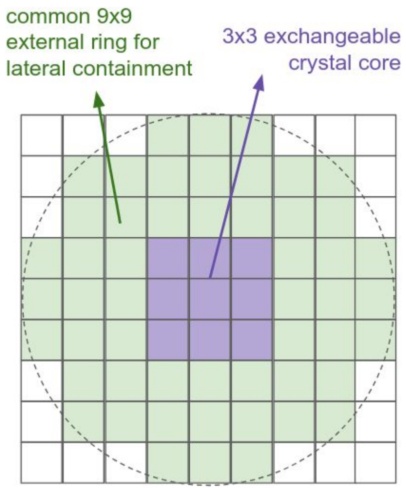




Plans for 2025

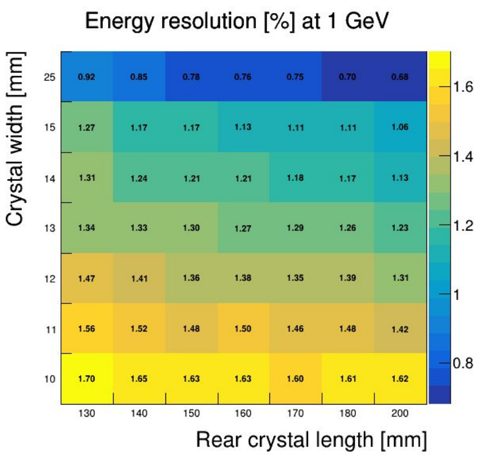
Strategy towards multi-channel prototype

- Lab and beam test results from 2024 will inform the choice of a baseline technology to **build a full containment EM calorimeter prototype (~200 channels, ~2R_M)**
- **Plan to build two main prototypes using complementary technologies:**
  - PWO-based:
    - fast crystal (10 ns)
    - shortest X_0 and smaller R_M
    - readout of cherenkov photons in the infrared region
  - BGO-based:
    - slower crystal (300 ns) but larger scintillation light output,
    - readout of cherenkov photons possible also in the UV region
    - C/S discrimination through pulse shape possible



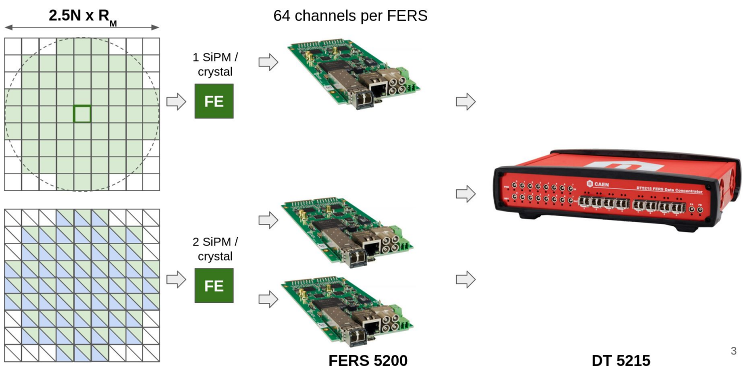
- Possible additional flavors:
  - Central crystal matrix could be replaced with other crystals/filters/SiPMs (e.g. BSO)
  - Front crystal segment with boosted transverse granularity than rear segment

PWO-based prototype

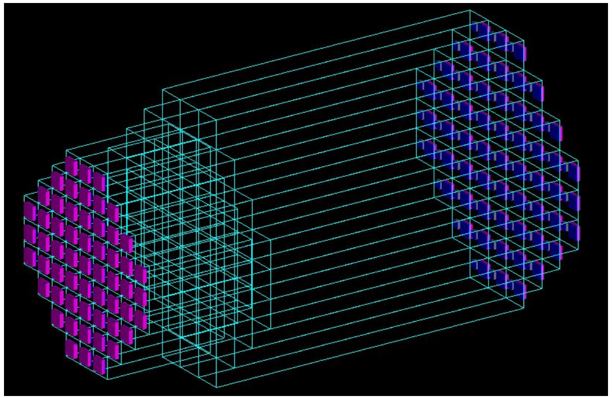


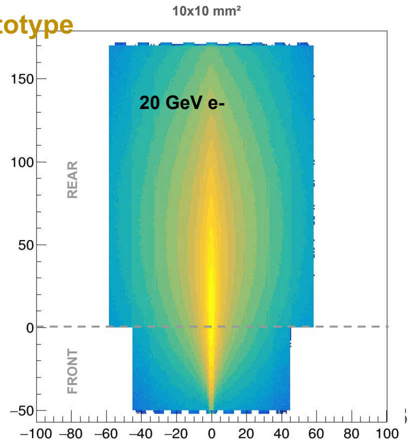
- Layout optimization (crystal dimensions) ongoing
- Procurement of FERS-5200 + DT5215 CAEN electronics for readout completed, purchase of crystals and SiPMs in early 2025
- Design of mechanical support and front-end about to start
- Plan to use DAQ/readout system common to HIDRA (fiber dual-readout calorimeter) prototype for optimal integration

Prototype readout schematics



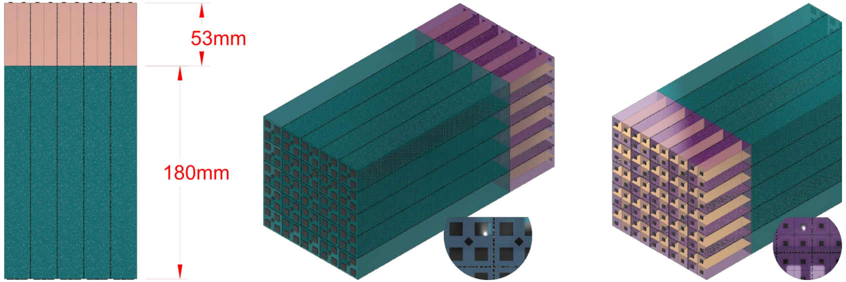
Geant4 simulation of prototype

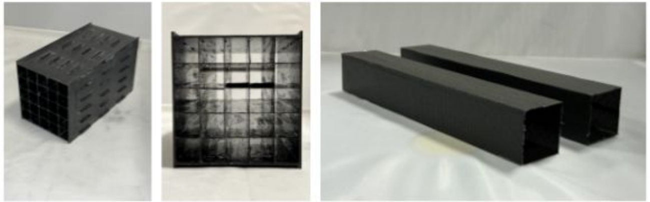


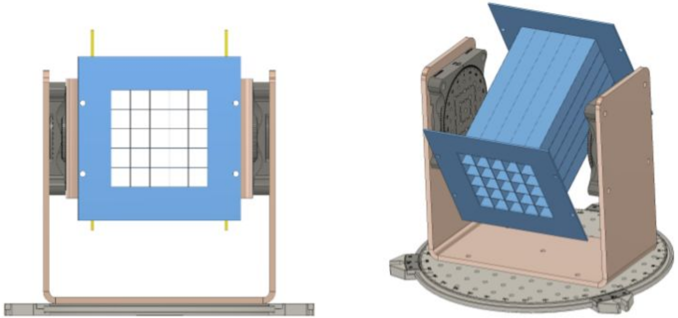


BGO-based prototype

- **BGO** matrix: $22X_0$ deep, $5X_0 \times 5X_0$ lateral with $1X_0$ and $\frac{1}{4}X_0$ lateral granularity
  - Crystal purchase in progress (expected to arrive and complete testing in spring)
- **Carbon fiber alveolar, mechanic support, and cooling options, R&D in progress**
- **Studies to improve electronics** (e.g. linearity) over next 6-8 months
  - Similar readout w/ FERs 5200 for front section, **most likely DRS or NALU HDSoc for rear section**
- Form factors and mechanics of electronics for EM containment scale will be challenging







Summary

- **R&D to optimize dual-readout** in scintillating crystals using optical filters and SiPM is **progressing well** thanks to successful beam tests in 2024

- **Construction and lab tests of two full containment prototypes is planned during the first half of 2025, then test on beam**
  - 2-week test beam slot requested at SPS (H6) for late September 2025!

- **A broad R&D program** to achieve the demonstration of this calorimetric technique using a full scale EM calorimeter prototype **by the next european strategy for particle physics update** is being pursued
  - aiming at a combined test beam with fiber dual-readout calorimeter from 2026

DRCal overview and status

Romualdo Santoro
on behalf of the DRCal Collaboration

Università dell'Insubria and INFN – Milano

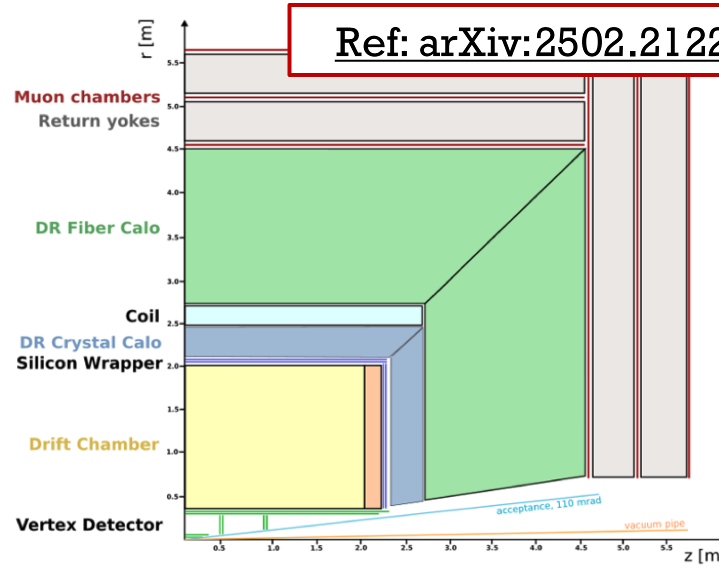
DRCal Collaboration and main R&Ds

- South Korea → projective fibre-sampling calorimeter demonstrator
- Europa: INFN, Sussex University → fibre-sampling calorimeter demonstrator
- U.S. → exploiting time information for effective longitudinal segmentation and improved energy reconstruction using neural networks
- Important synergies
  - Custom trigger board (low latency ~ 10 ns)
  - Common DaQ (EUDAQ)
  - Good sharing of Test Beam time slots
  - Common simulation framework (Overview of IDEA Full simulation: L. Pezzotti)
  - DRD4: monolithic SPADs (ASPIDES project supported by INFN)
- Target experiments
  - Next generation of leptonic colliders in the IDEA detector concept framework

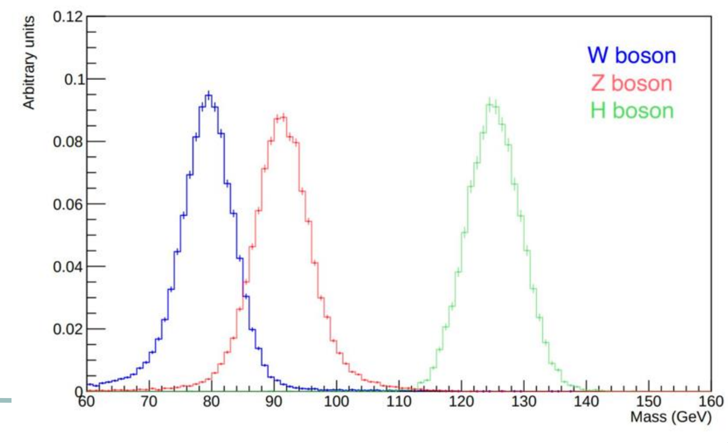
IDEA: detector concept

- Beam pipe: R ≈1.0 cm
- Highly transparent tracking
  - Si pixel vertex detector (monolithic technology)
  - Drift Chamber
  - Si wrappers (strips)
- Dual-readout crystal ecal: ≈ 22 X_0
- Thin superconducting solenoid: 3 T
- Dual-readout calorimetry 2 m / 7 λ_{int}
- Muon chambers
  - μ-RWELL in return yoke

Ref: arXiv:2502.21223



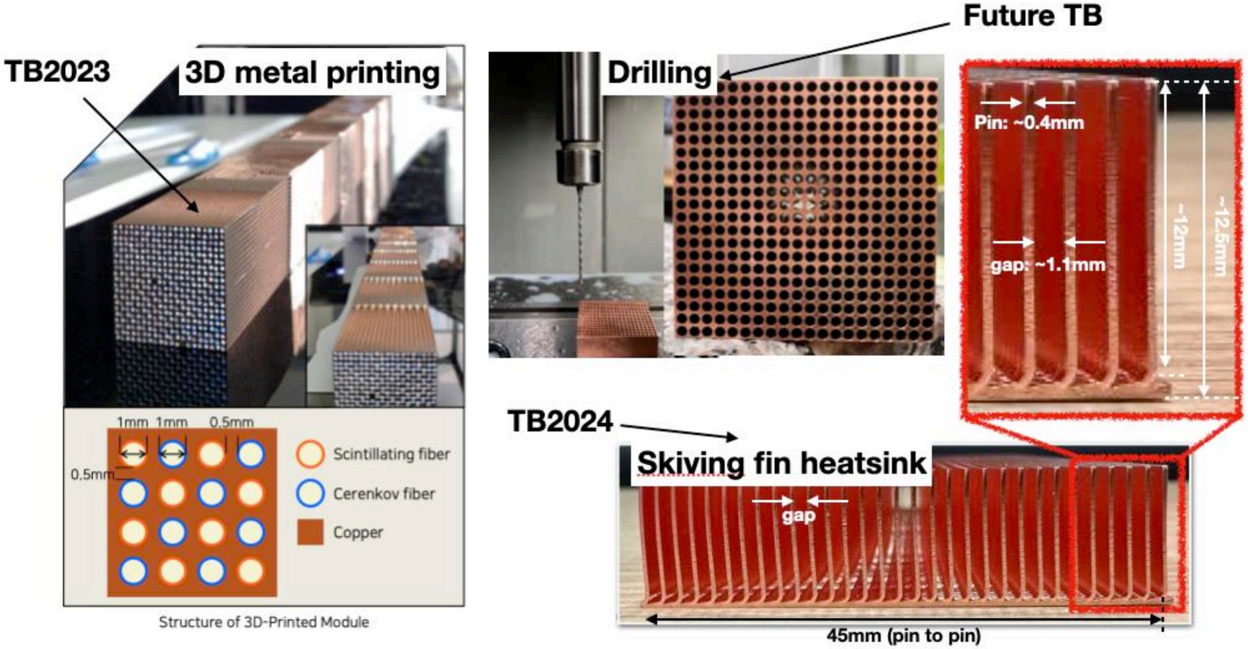
Target jet-jet mass resolution $\frac{\sigma}{E} = \frac{30\ \%}{\sqrt{E}}$

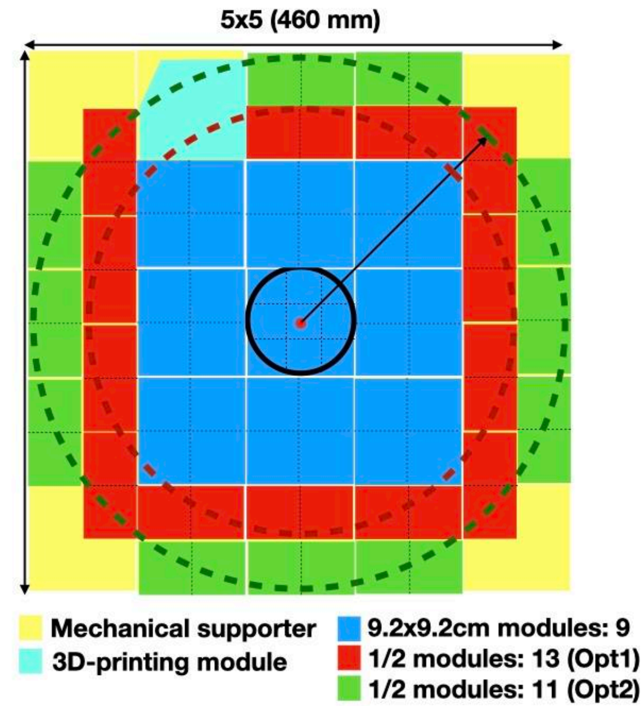


R&D in South Korea

- Different options under study:
  - Absorber production and assembly procedure
  - Fibre types (round, square, single/double cladding)
  - Light sensors (PMT, MCP-PMT, SiPM)

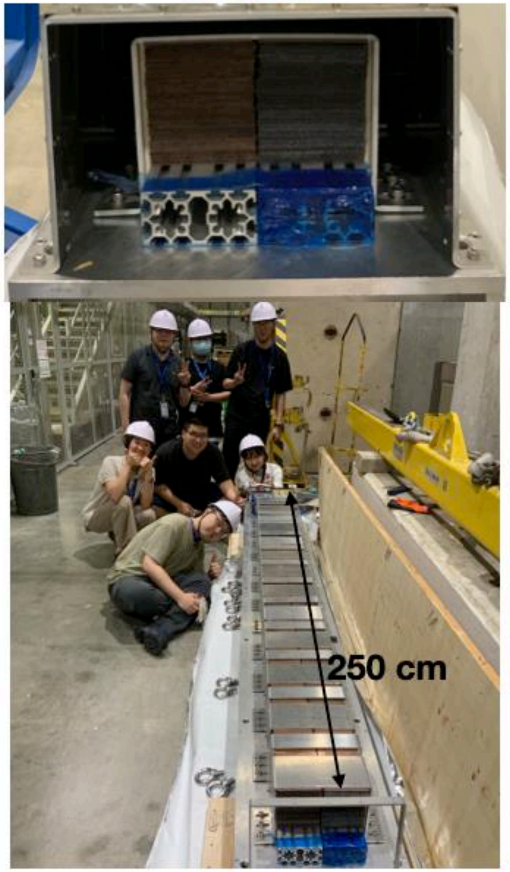
Goal: Hadronic-size prototype





R&D in South Korea

TB 2022



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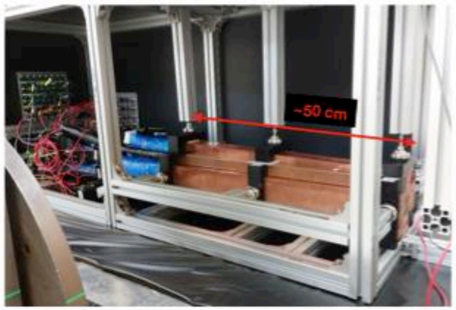
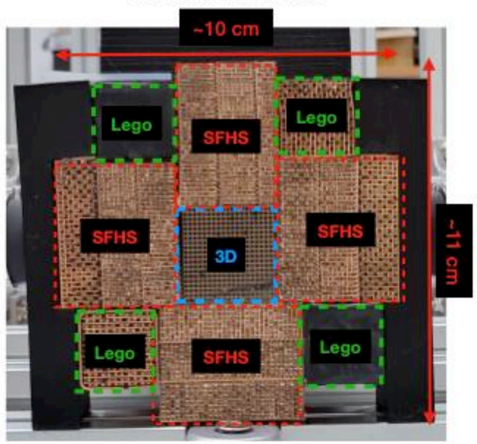


Side view of DRC module



Upstream view of DRC module

TB 2024

30x30x250 cm

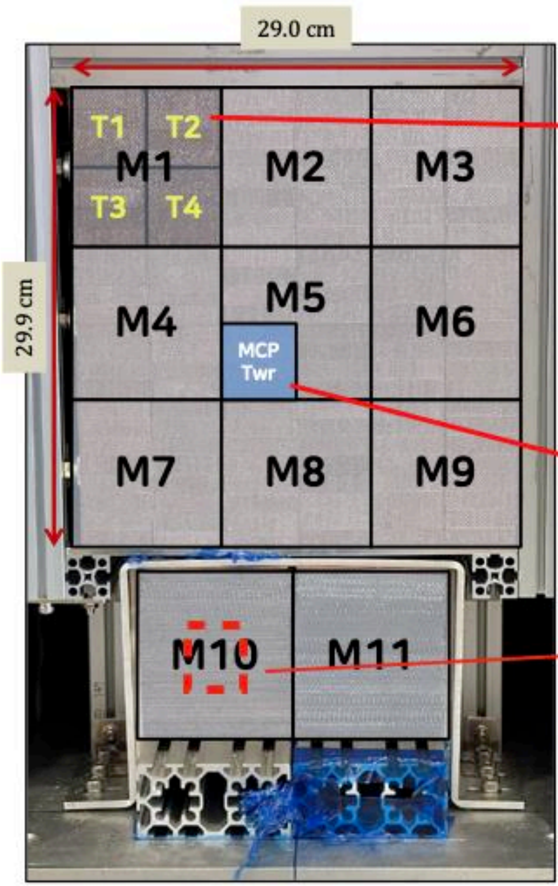
TB 2022 module

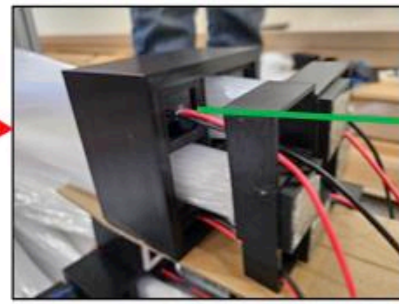
- Larger prototype:
  - Copper based
  - Almost 90% lateral containment for hadrons
  - Almost $10\lambda_I$

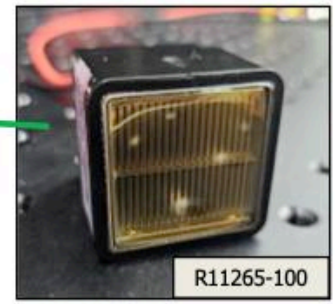
X_0	λ_I	Sampling Fraction
2.92 cm	27.91 cm	S=5.10%, C=5.77%

R&D in South Korea

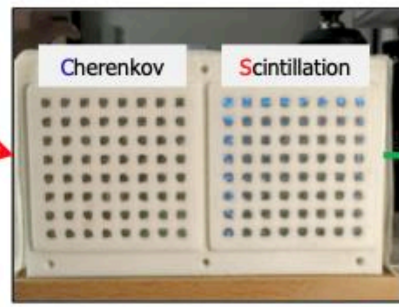
- High granularity solutions: MCP-PMT (128 ch) vs SiPM (400 ch)

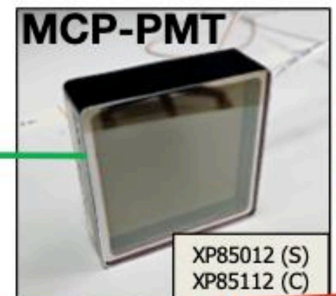






SiPM





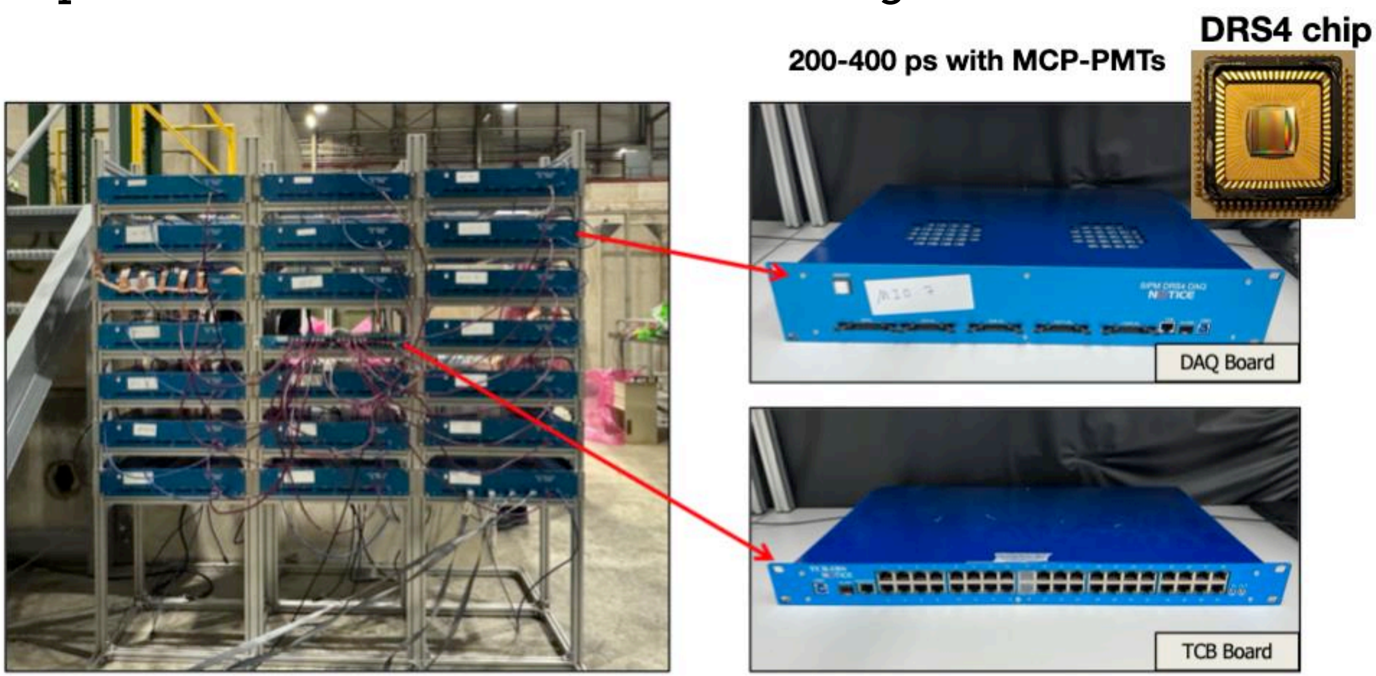
MCP-PMT (talk 12.07)

S-ch: 200
C-ch: 200
on the center of M10

- The DRC module is divided to '**tower**' unit, each tower is bundled to single readout channel. (Square type PMT, Hamamatsu R11265-100)
- On M5-T3, **MCP-PMT** is attached, which provides high granularity, dividing single tower into 64 channels. (XP85012, XP85112)

R&D in South Korea

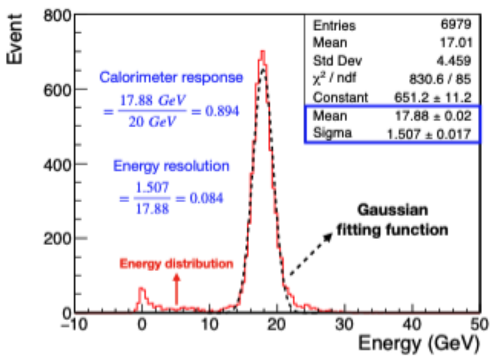
- Custom DAQ system: 20 DAQ boards and 1 TCB board (to control multi DAQ boards)
- Redout based on DRS4 (32 channel / board)
- Powerful performance obtained during test-beam campaign
- Upgrade plan is under discussion for faster timing resolution

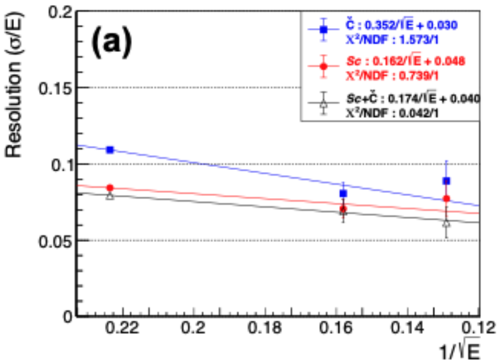


R&D in South Korea

- Analyses and paper preparation

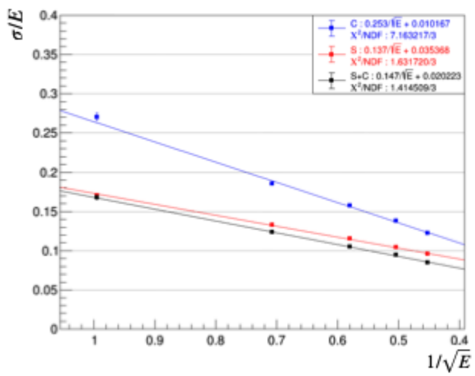
TB 2022

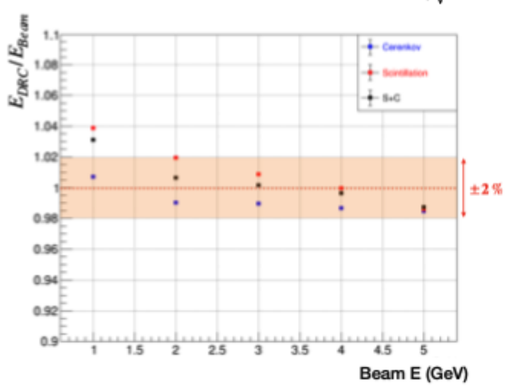




Submitted to Journal of Subatomic Particles and Cosmology (Elsevier)

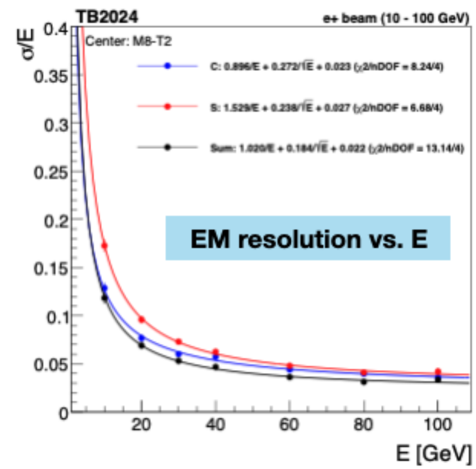
TB 2023

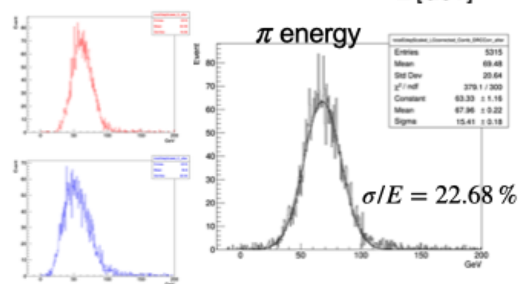




Presented at CALOR 2024

TB 2024



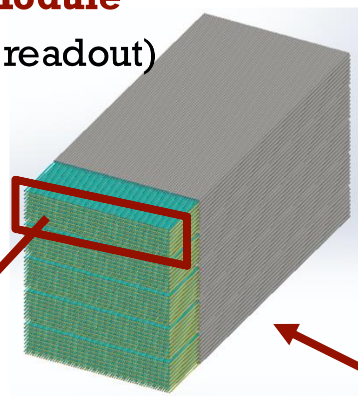


Very Preliminary

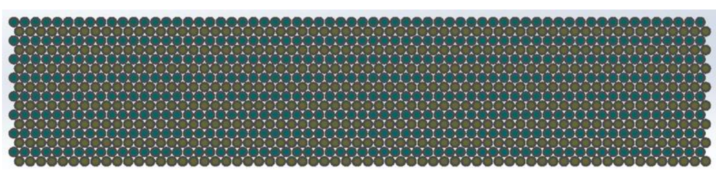
R&D in Europe: HiDRa

The Low Granular Module

5 Mini-modules (PMT readout)
~ 13 x 13 x 250 cm^3



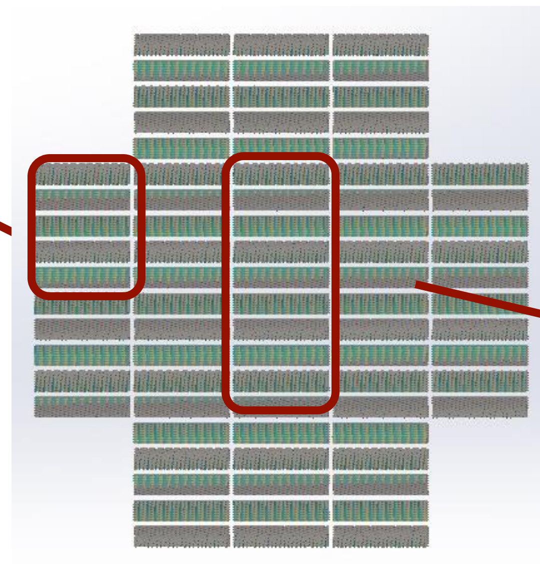
The mini-module



64 x 16 stainless steel capillaries: 2 mm outer diameter and 2.5 m long. Scintillating and clear fibres (alternated in rows) to apply the dual-readout method

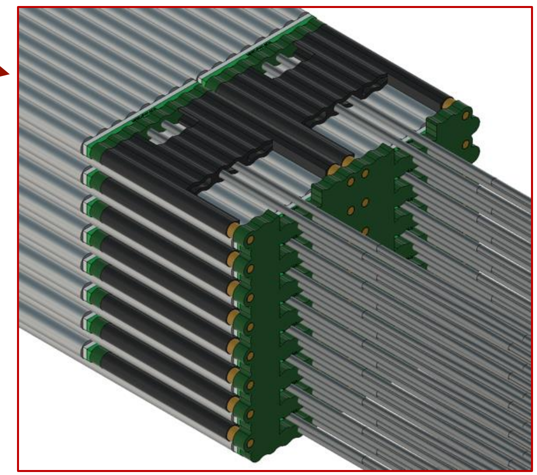
The HiDRa prototype

Designed to be scalable and large enough to measure hadronic performances



The High Granular Module

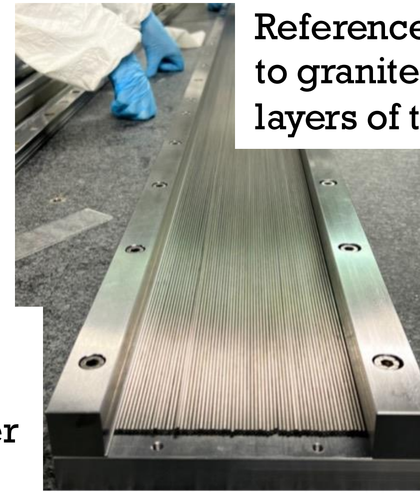
Two central modules read out with 10k SiPMs (one per fibre)



Challenging integration requiring precise assembly procedure and compact components (i.e. SiPMs, services and mechanical support) to fit in the back of the calorimeter

Construction technique

High quality tube selection:
Accurate measurement of thickness, straightness, length, and internal diameter (pass/fail test with fibre insertion)



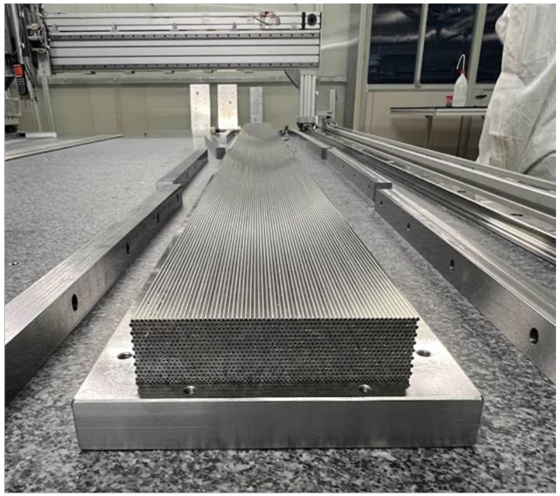
Reference structure anchored to granite table for stacking layers of tubes

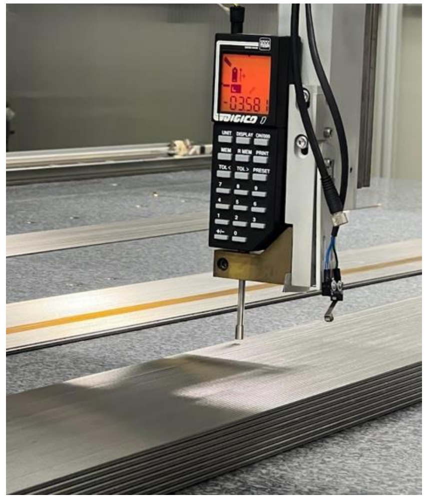
Vacuum + double-sided tape for tube handling

Glue dispensing and tube alignment and positioning

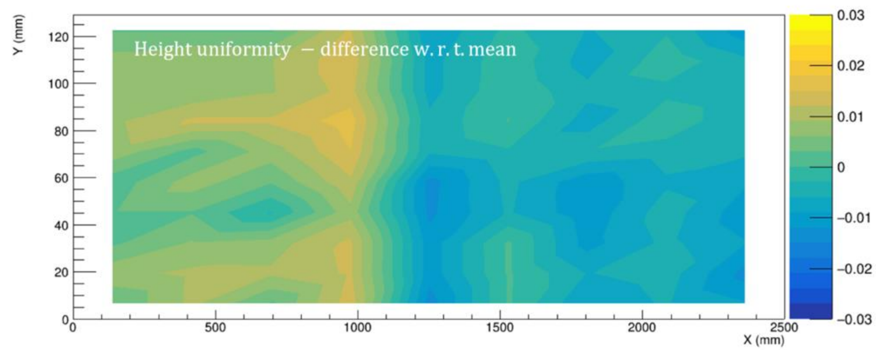
Construction technique and mechanical precision

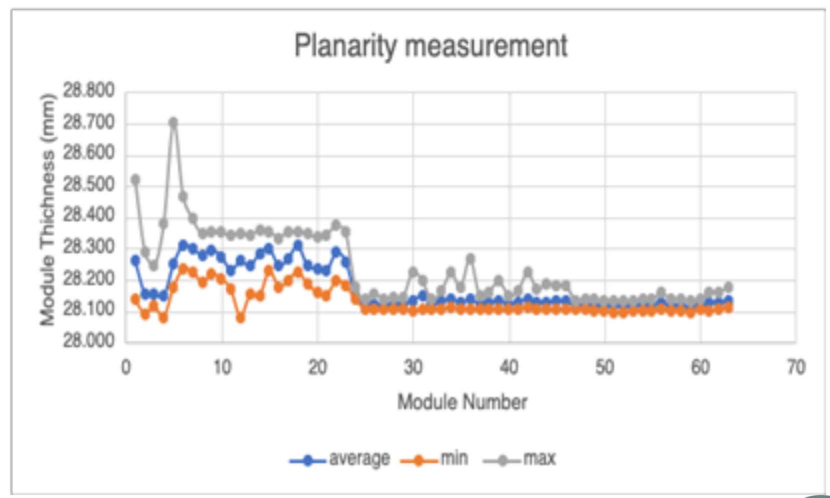
Semi-automatic system for planarity measurement: 90 measurements per mini-module





O (10 μm) precision on the mini-module height (calor2024)

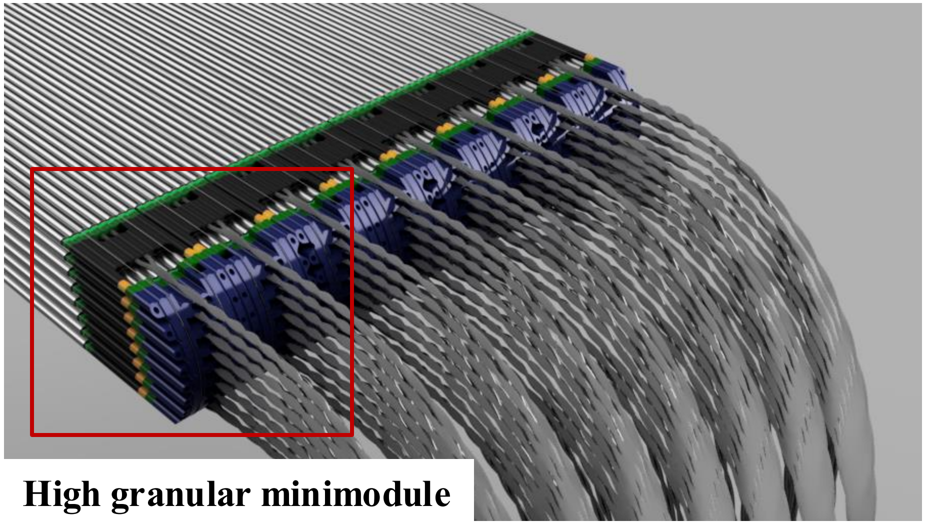


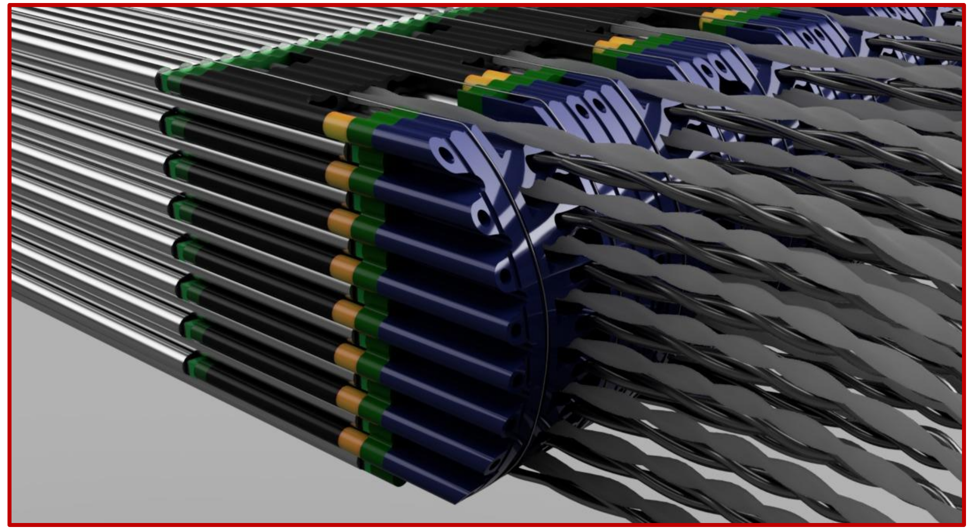


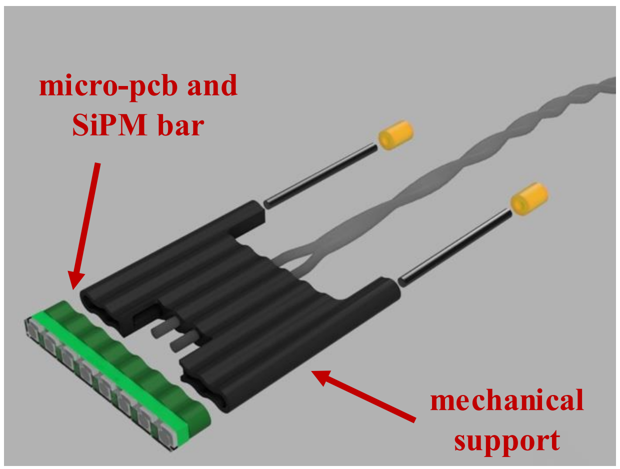
Production started in November 2023:

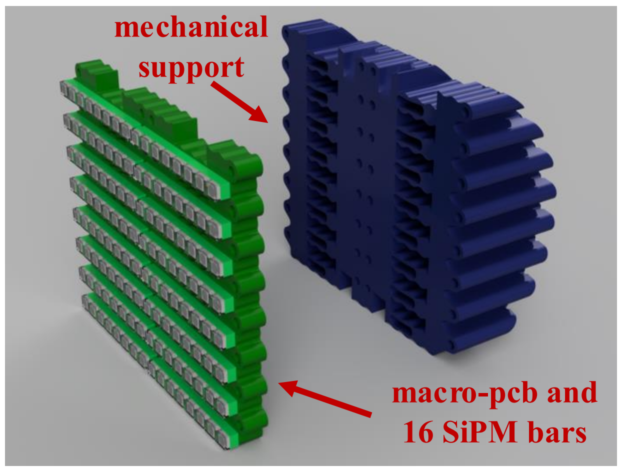
- LG minimodules (PMT readout)
  - all glued
  - 50/70 loaded with fibres (36 qualified on beam in 2024)
- HG minimodules (SiPM readout)
  - procedure qualified with dummy components (see later)
  - ready to start the production

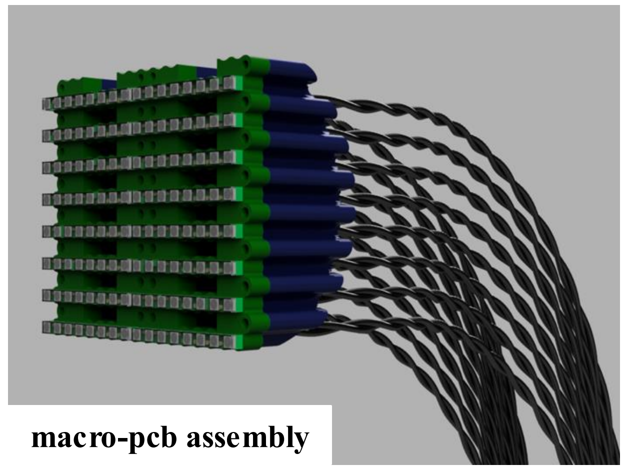
HG: from design …



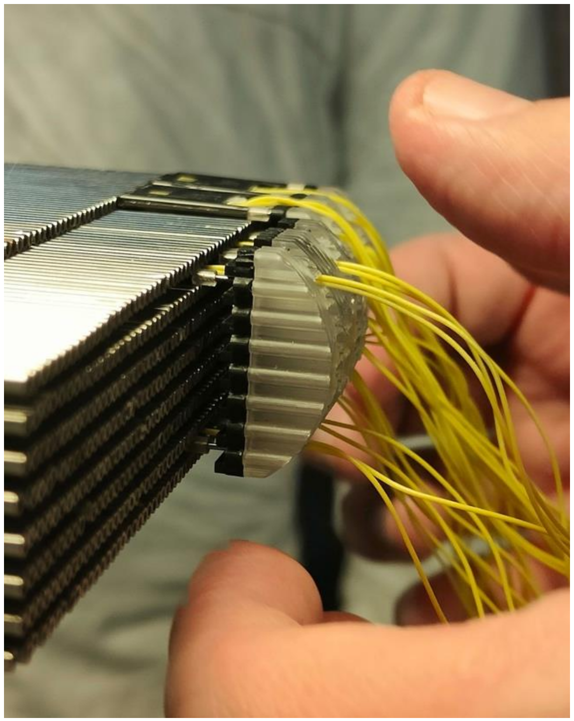


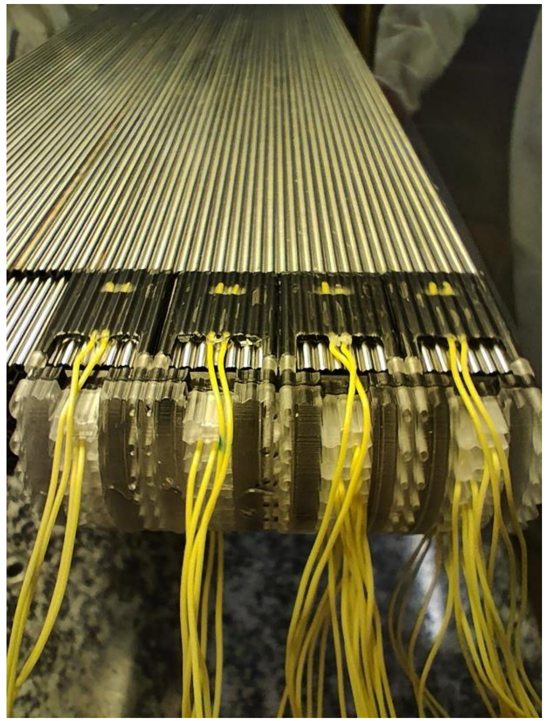


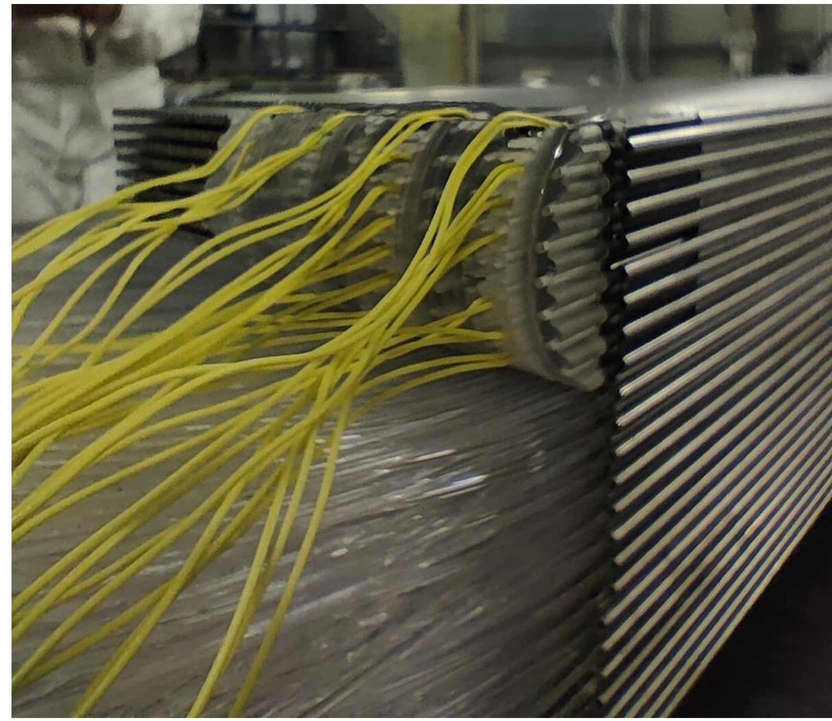




… to assembly with dummy components



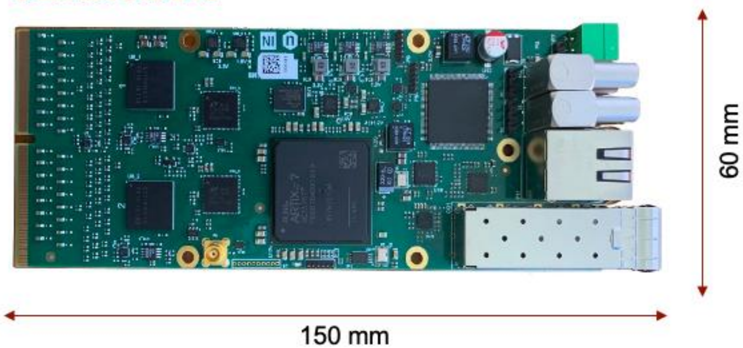




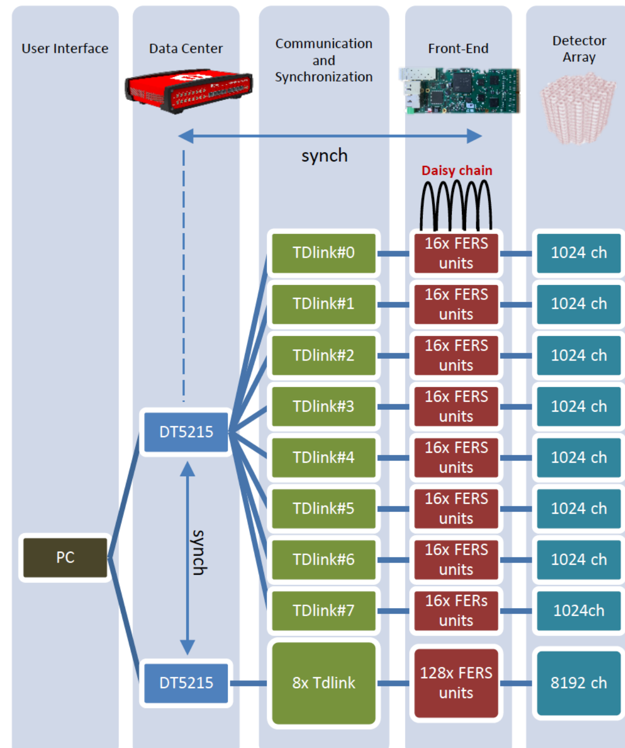
SiPM readout strategy

- The high granular module is operated with the Caen FERS system (5200) and the A5202 readout boards

FERS: A5202

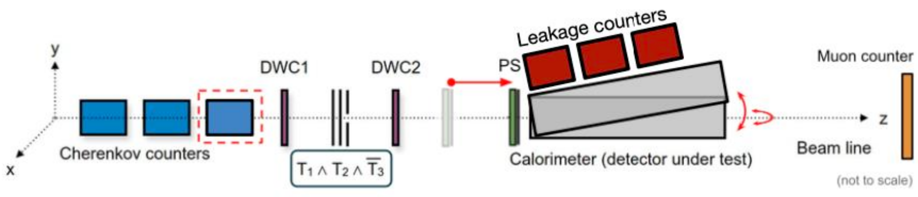


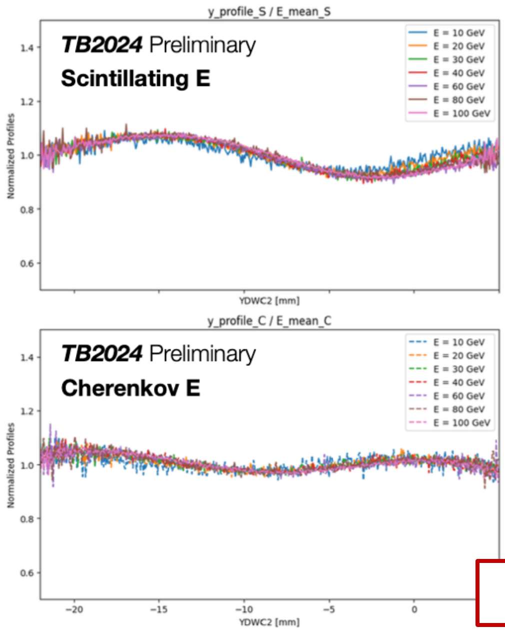
- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout (6.25 Gbit/s)



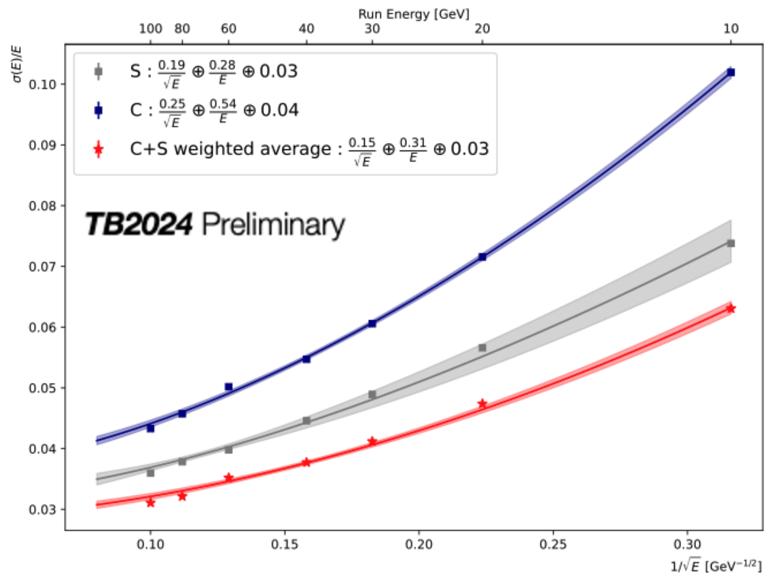
TB 2024 @ CERN SPS with partially completed hadronic-shower-size calorimeter

- Low Granular modules qualification on beam:
  - 36 HiDRa minimodules, 3 columns x 12 rows: ≈ 39 X 39 x 250 cm^3
  - Nominal angle of 2.5° (x and y axis) with the beam
  - PMT-readout only





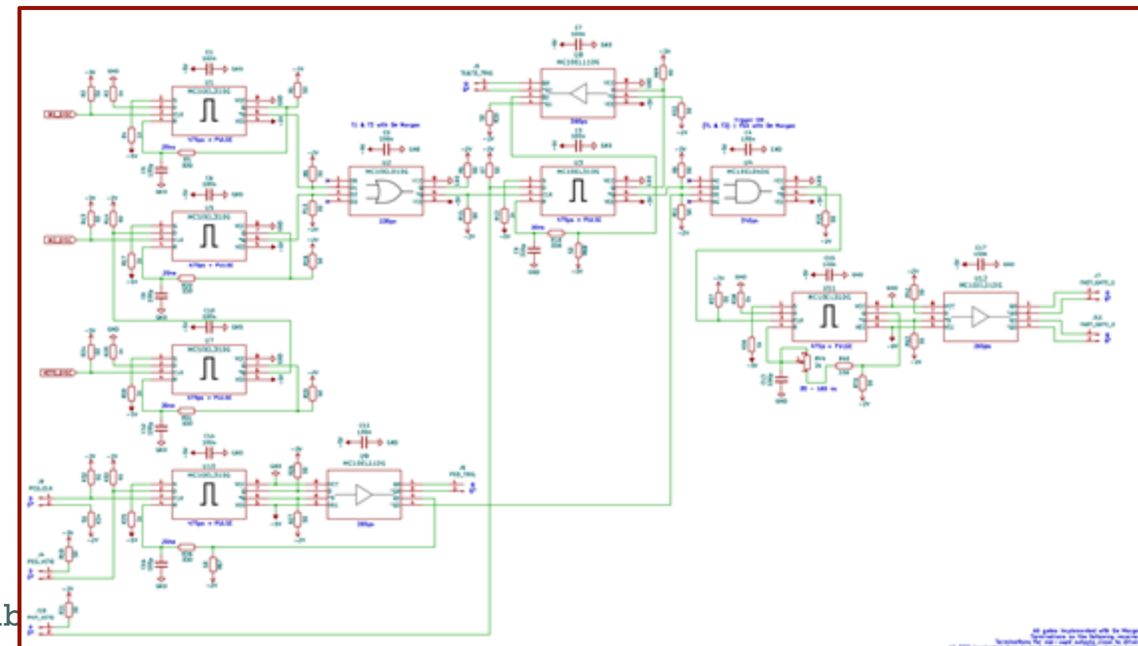
- The dependence of the energy response versus the particle impact point is under study
- Energy resolution measured after applying the dependency correction



L. Nasella @ VCI2025

Custom trigger board

- Low latency trigger board (~ 10 ns) (designed in Pavia)
  - ECL logic
  - Inputs: 3 analogue signals (coincidence and veto) and 3 digital signals (2 vetoes and 1 pedestal trigger)
  - Outputs: 2 fast gates (tunable duration) and 2 digital flags (Physic / pedestal)
- Prototype expected by mid-May
- Final version by end of September



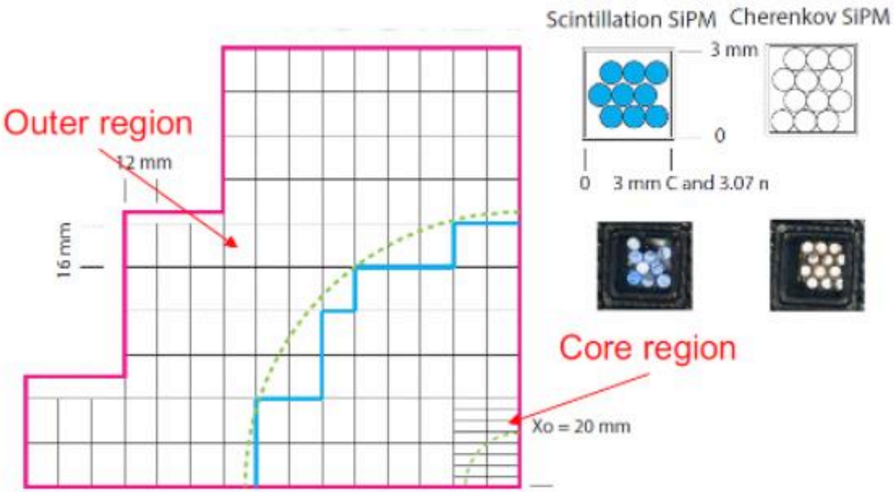
R&D in US: DREAM refurbishing

Dual-readout fiber calorimeter with longitudinal segmentation based on timing.

- Different types of information from large number of channels need to be integrated and collected in a unified manner (EUDAQ)

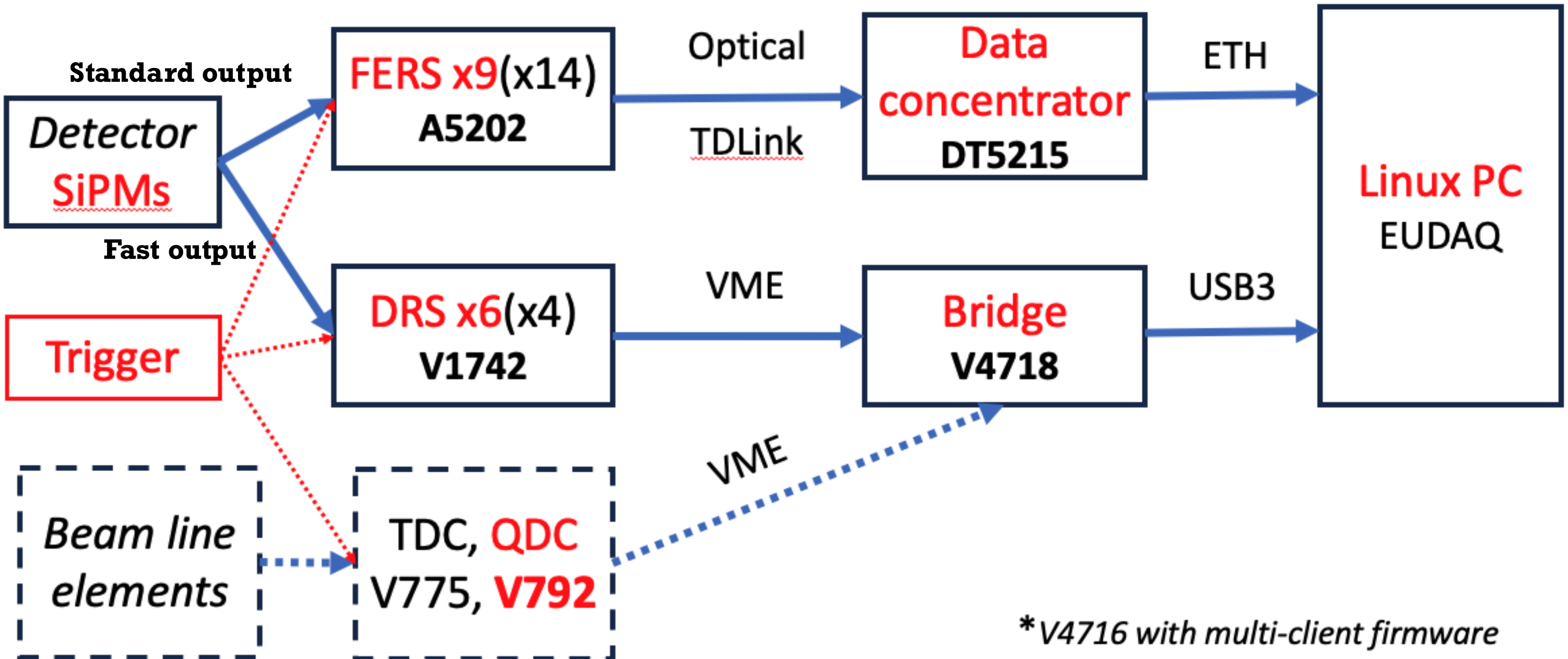
Outer region - 768 Ch – SiPM Std (FERS)
Core region – 128 Ch Std (FERS), 128 Fast (DRS)

Refurbishing in progress



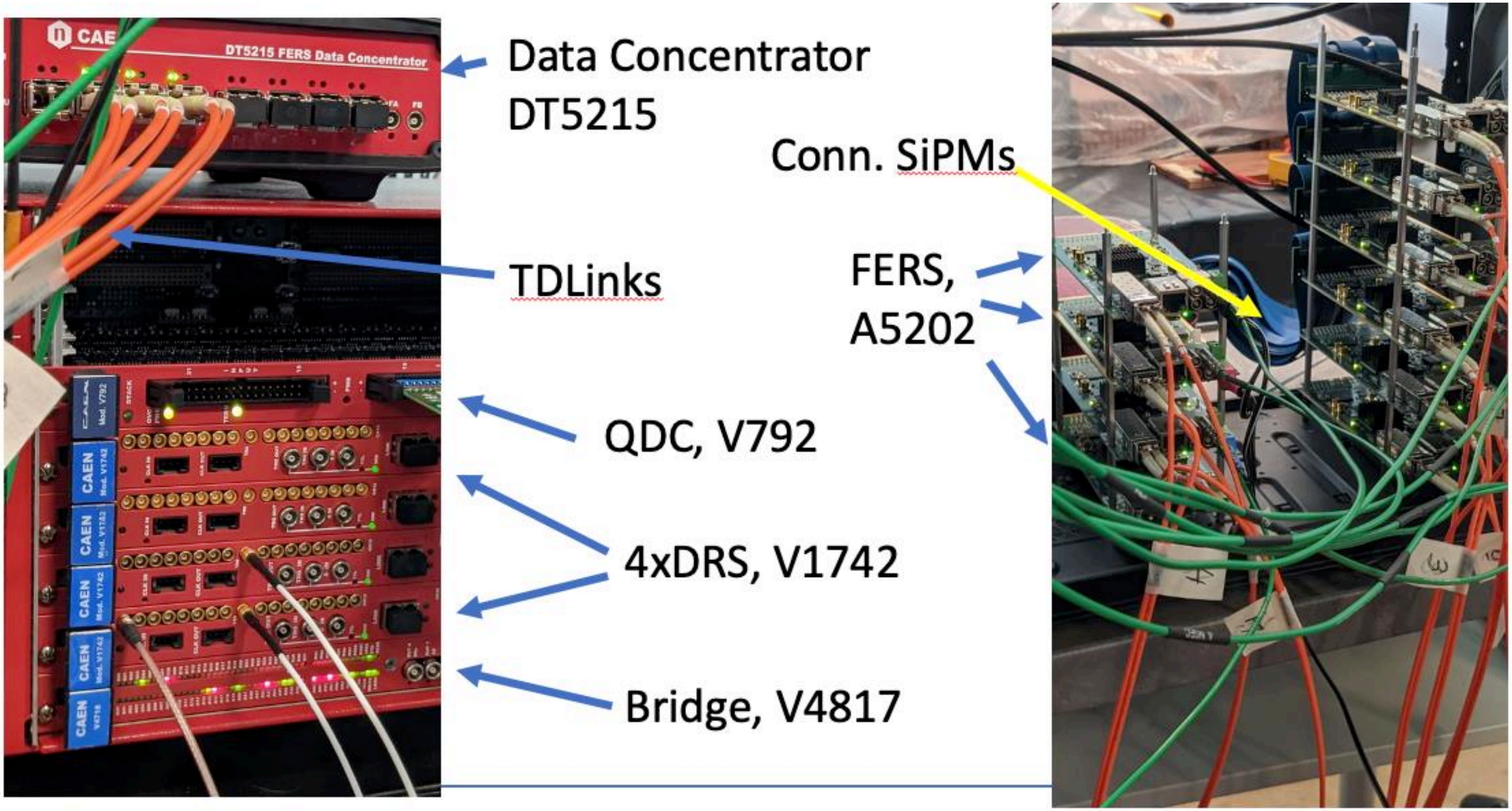
	SiPM	Sensitive area	SiPM Output	readout
Outer Region	OnSemi J-Series	6x6 cm^2	Standard + fast (180 ps)	standard (FERS)
Core region	OnSemi J-Series	3x3 cm^2	Standard + fast (90 ps)	Std (FERS) + fast (DRS)

R&D in US: readout strategy



*V4716 with multi-client firmware (2024051500) – DRS + QDC,TDC

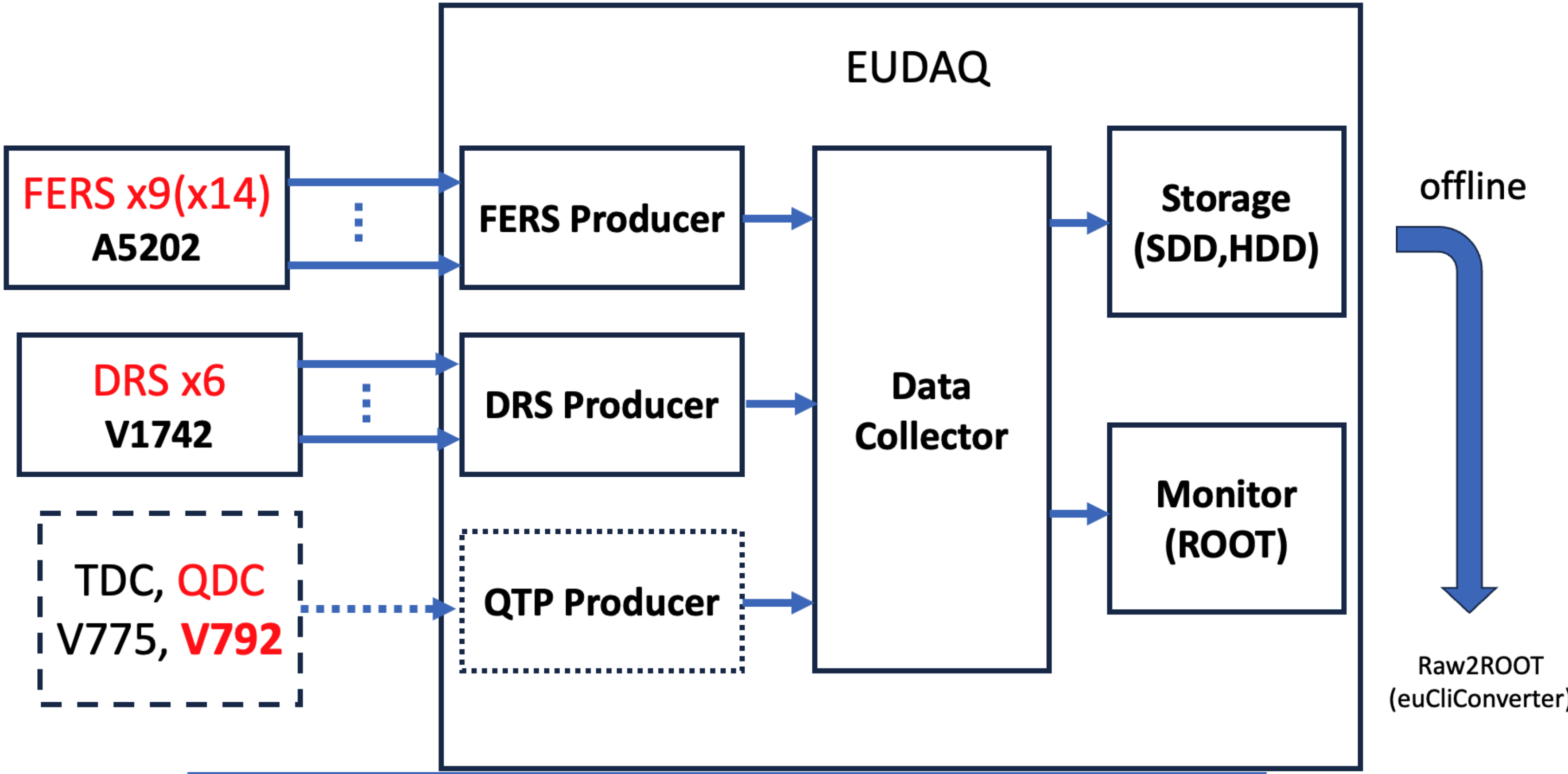
R&D in US: readout electronics



[Jordan Damgov @ DRD6 DAQ SW meeting]

DAQ developments in EUDAQ

Readout electronics partitioning in EUDAQ

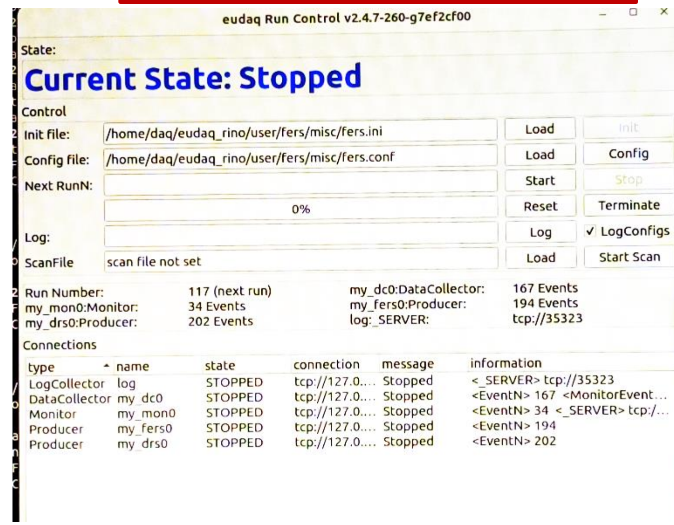


Jordan Damgov @ DRD6 DAQ SW meeting

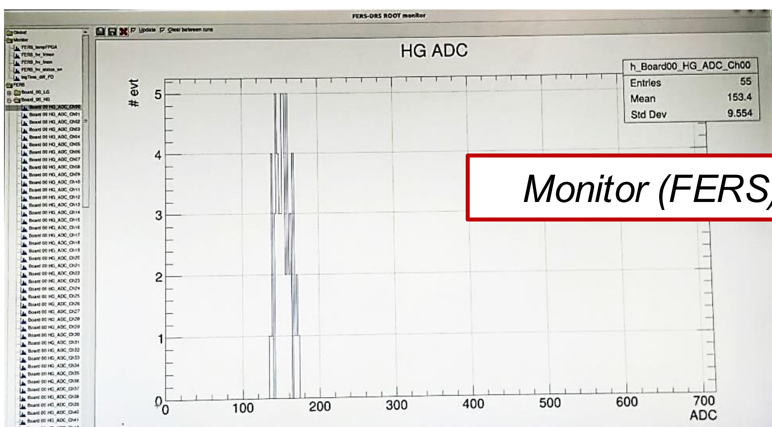
Implementation for DRS and FERS

- Started from Rino Persiani work, incorporating FERS into EUDAQ
  - https://github.com/rinopersiani/eudaq_rino
- US developments: https://github.com/jdamgov/eudaq_tb2024

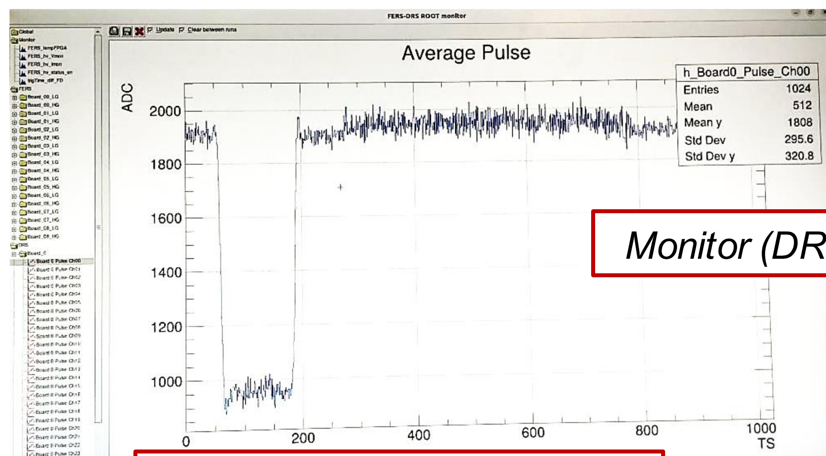
Run control



- CAEN libraries and Drivers:
  - CAENComm-v1.7.0
  - CAENDigitizer-v2.17.3
  - CAENVMElib-4.0.2
  - FERSlib from Janus5202-3.6.0
  - V4718-USB-Drv and libusb.



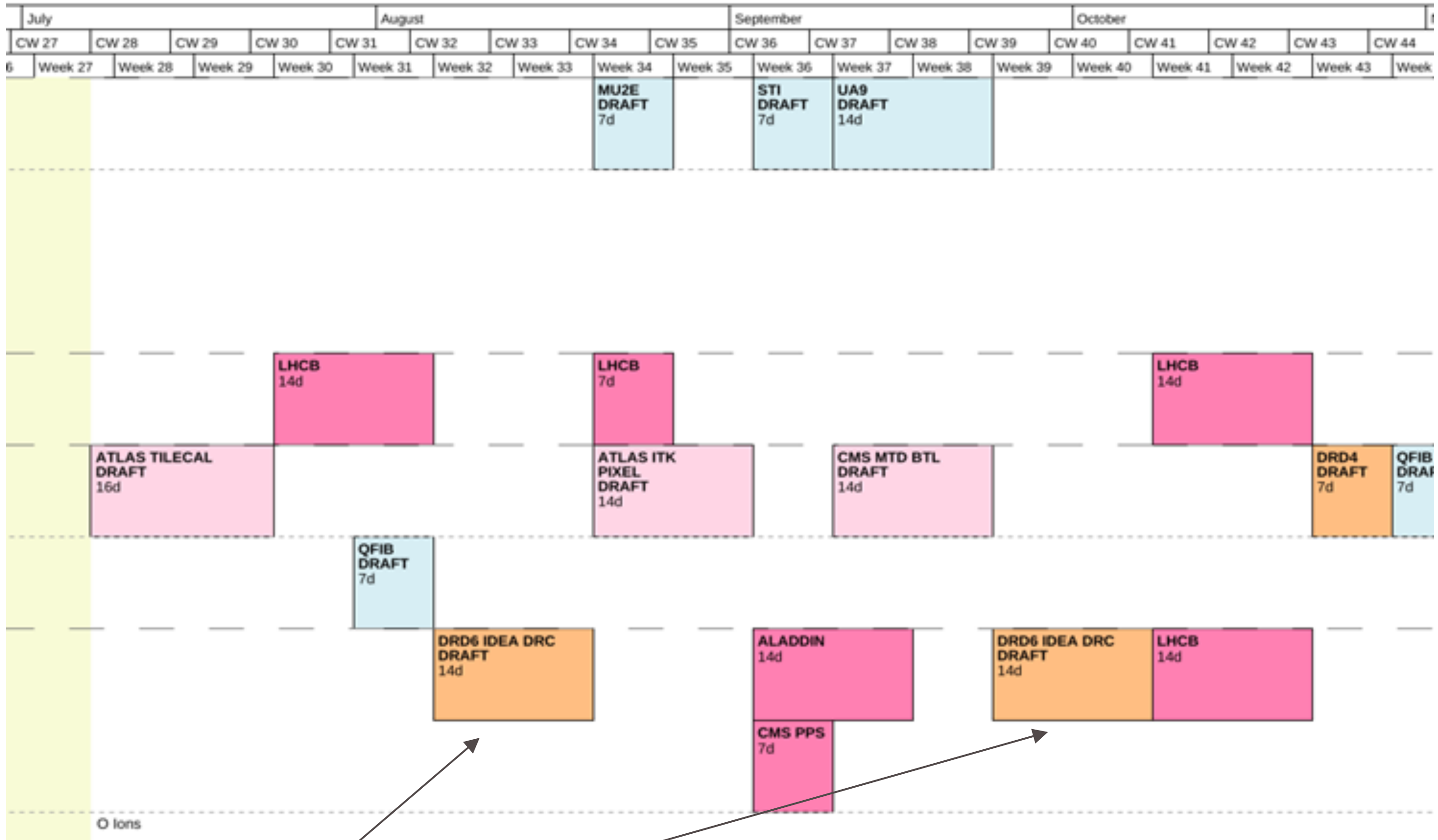
Monitor (FERS)



Monitor (DRS)

Jordan Damgov @ DRD6 DAQ SW meeting

Test beam schedule at SPS in 2025



DRCal: main user in H8

Digital SiPM Platform for High Energy Physics

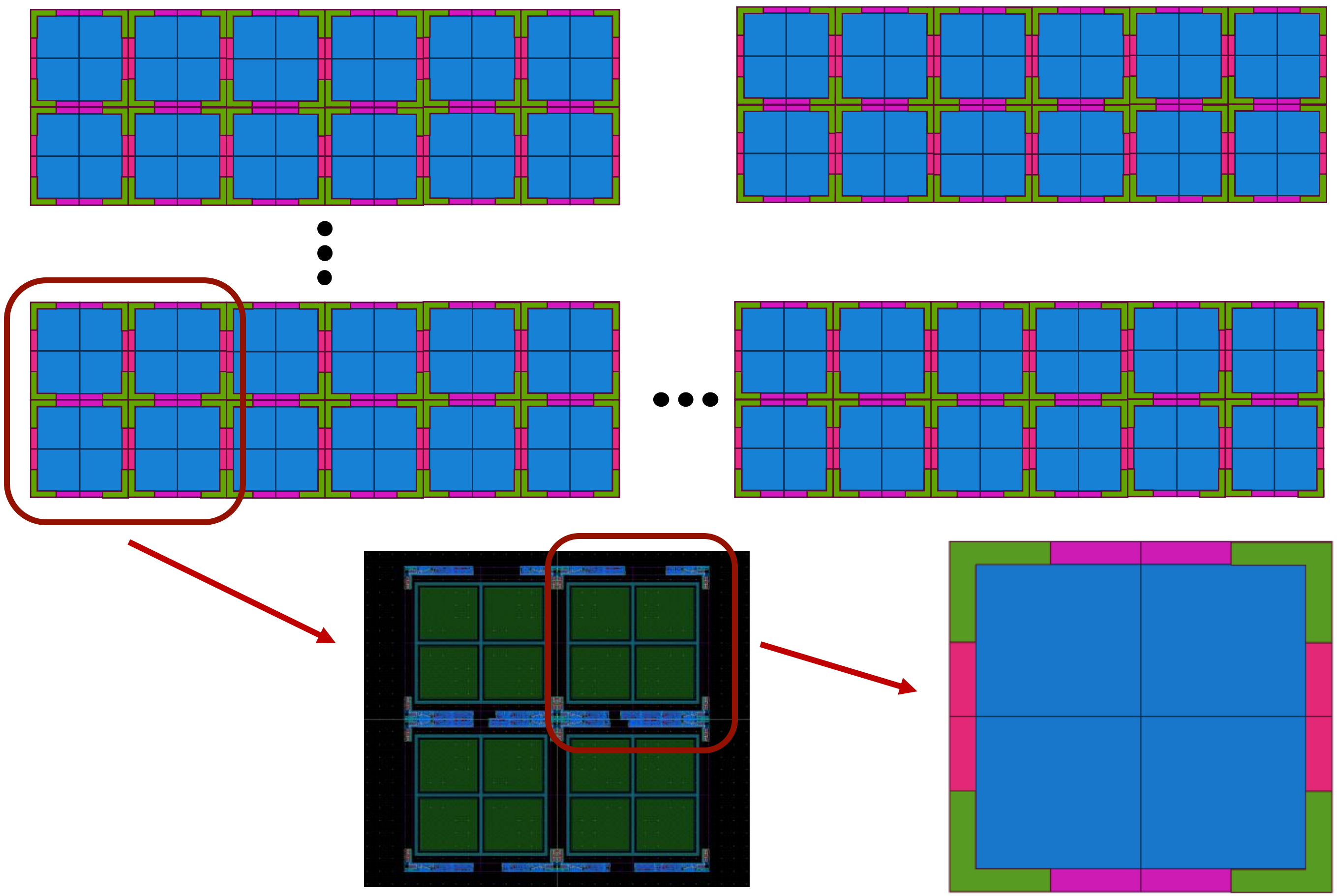
- ASPIDES is a two-year project funded by INFN (2025), coordinated by L. Ratti (INFN-PV)
- Goal: development of monolithic SiPMs in CMOS technology detectors with embedded functionalities (dSiPM)
  - Photon counting with wide dynamic range ($\approx 30\mu m$ pitch)
  - Fully digital output
  - ToA and ToT with resolution better than 100 ps
  - Threshold adjustment capabilities for noise rejection
  - Possibility to enable/disable individual micro-cells and global signal to enable/disable the array
- Study of radiation damage and operation at cryogenic temperatures
- Modelling of new SPAD devices with improved performance in radiation environment and at cryogenic temperatures
- Submission planned for Q4 2025 (LFoundry 110 nm, 6 metal layers)

ASPIDES

L. Ratti @ DRD4 WP1 meeting

Design is on-going

16 x 16 array, made of elementary clusters of 2x2 cells

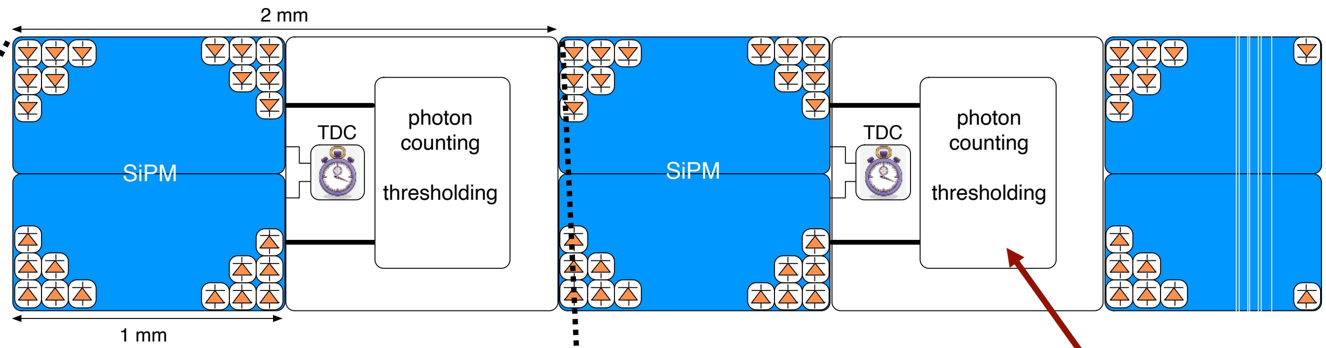


Basic building macro for the matrix

- Front-end
- SPAD active region
- Routing region
- Counter and NAND tree

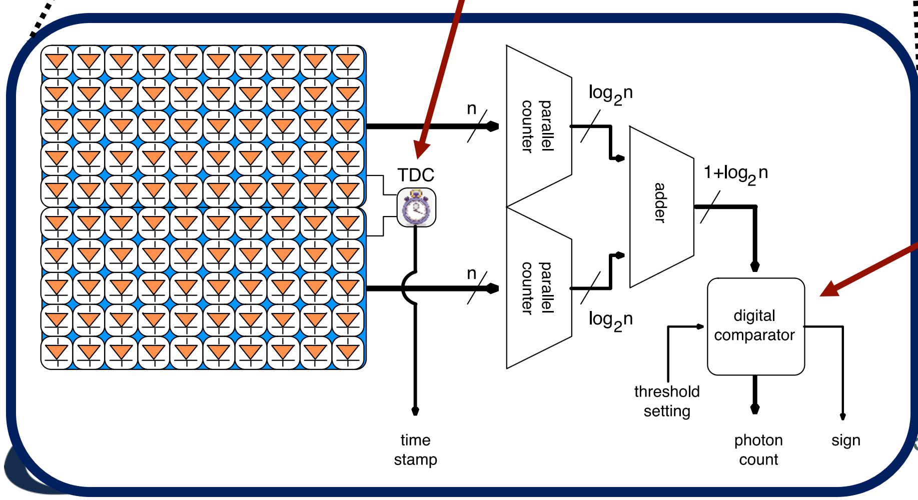
Demonstrator for DR calorimetry

1 Module = 8 dSiPMs 1x1 mm^2, interspaced by 2 mm



TDC close to the signal source: possibility to set a threshold on triggering signal

Electronics placed in the inter-SiPM region, taking advantage of the HiDRa geometry



Threshold: virtually any value can be set

In summary

- The DRCal R&D, at this stage, goes in several directions
  - Innovative absorber production to guarantee good quality and affordable cost
  - Assembly solutions that could be considered for large scale production
  - Different fibres and light sensors
  - Different readout architectures and analysis techniques
- Synergies and common efforts are growing, hopefully we will have combined test beam in the coming years
- New solutions to improve robustness and scalability are also being evaluated

To follow up the R&D, subscribe:
e-groups.cern.ch and idea-dualreadout@cern.ch

CRILIN overview and status

Davide Zuliani

Università degli Studi di Padova and INFN-Padova

on behalf of the CRILIN group

<ins>**DRD Calo 2025 Collaboration Meeting - IJCLab, Orsay**</ins>

Co-funded by the European Union

G.A. No. 101094300 and 101004730

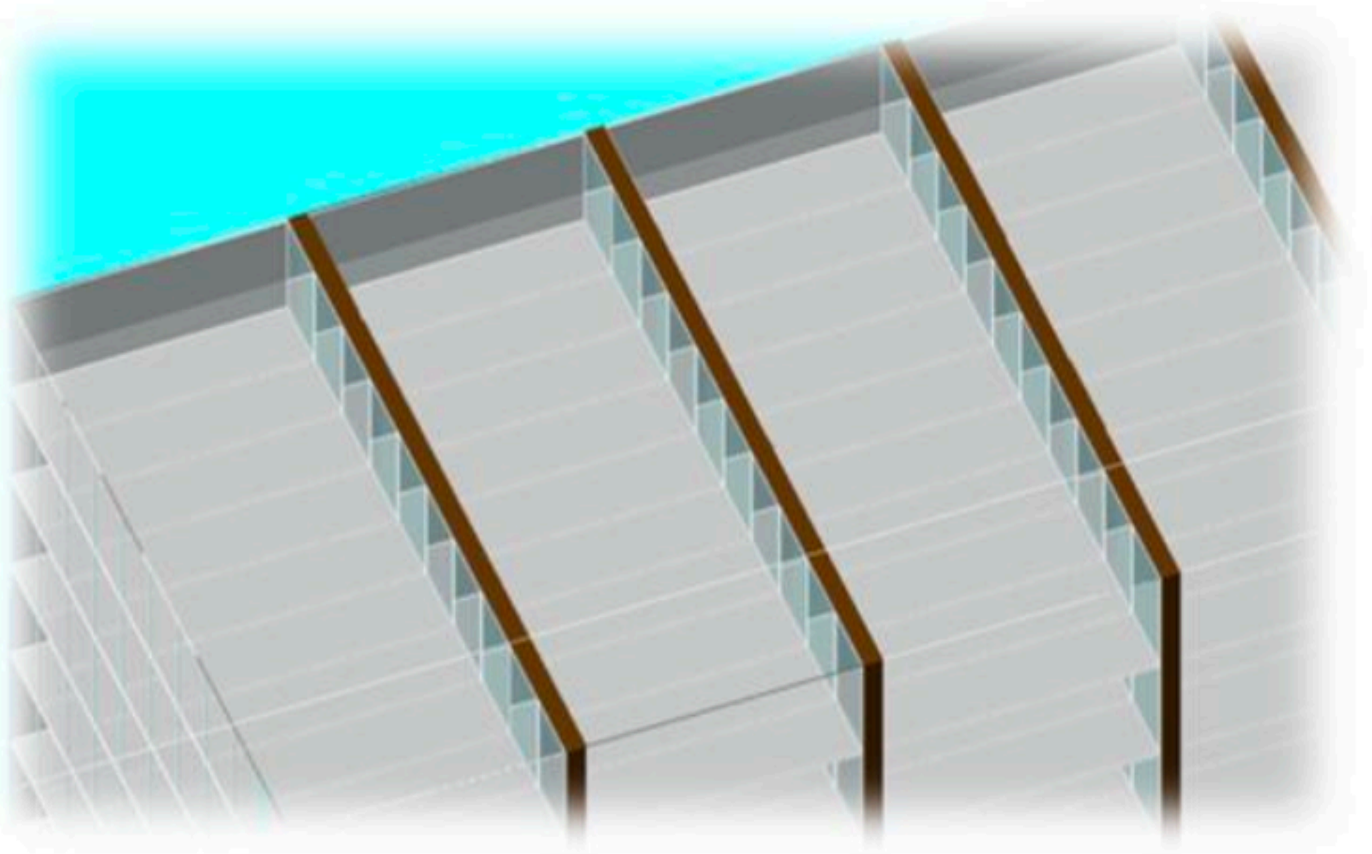
The CRILIN calorimeter

- CRILIN is a **semi-homogeneous** electromagnetic calorimeter made of **crystal matrices** interspaced and readout by **SiPMs**
- Each crystal is independently readout by **2 channels**, each consisted of **2 SiPMs in series**

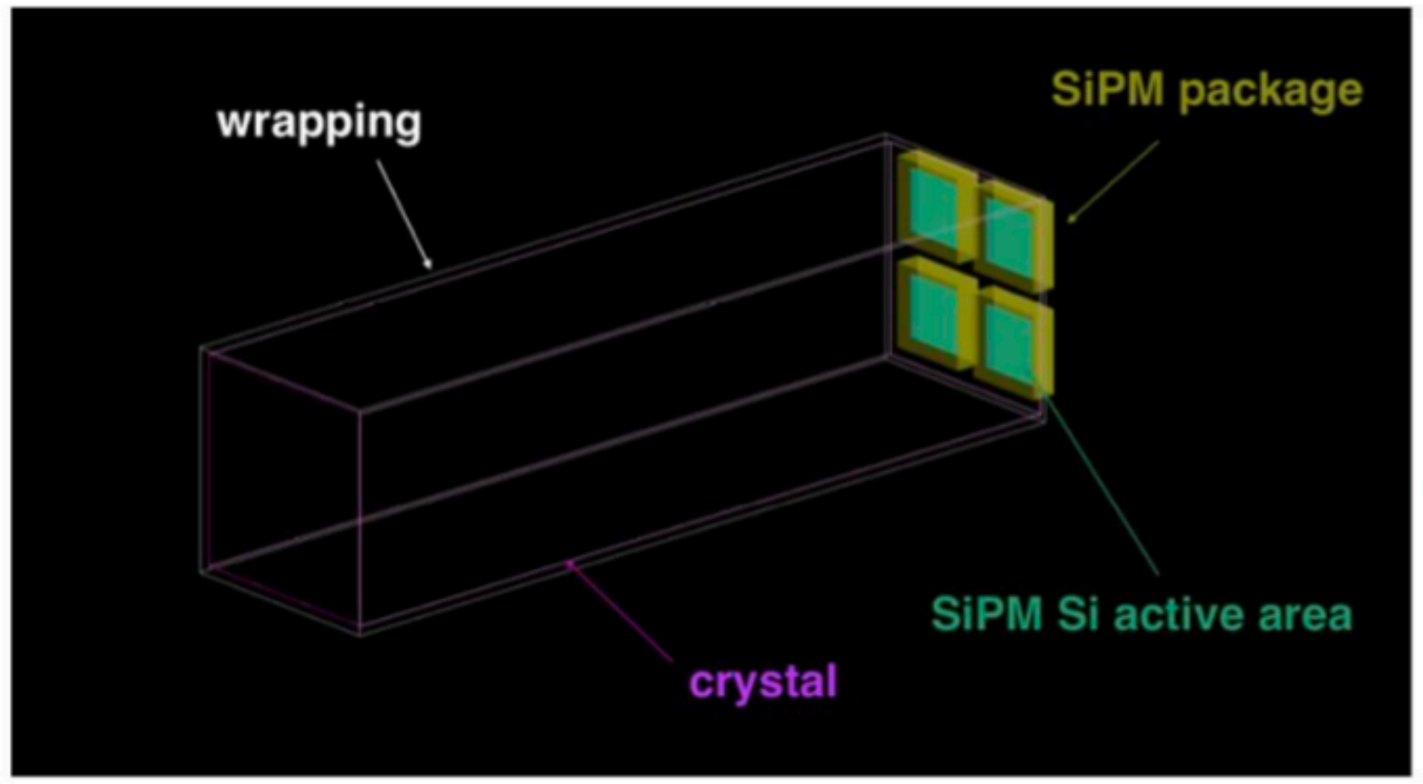
- Choice of the crystal: **PbF_2: high density** → compact calorimeter
  fast response →Cherenkov radiation

- Alternatives: **$PbWO_4$-UF** and **LYSO**

- **Good candidate** to match the calorimeter requirements for the Muon Collider



✓ **Longitudinal segmentation** **6 crystal layers (26 X_0)**	✓ **High granularity** **Cell size O(1cm²)x4 cm³**
✓ **Excellent time resolution** **Fast signals**	✓ **Radiation hardness** **Both PbF_2 crystal and SiPMs**



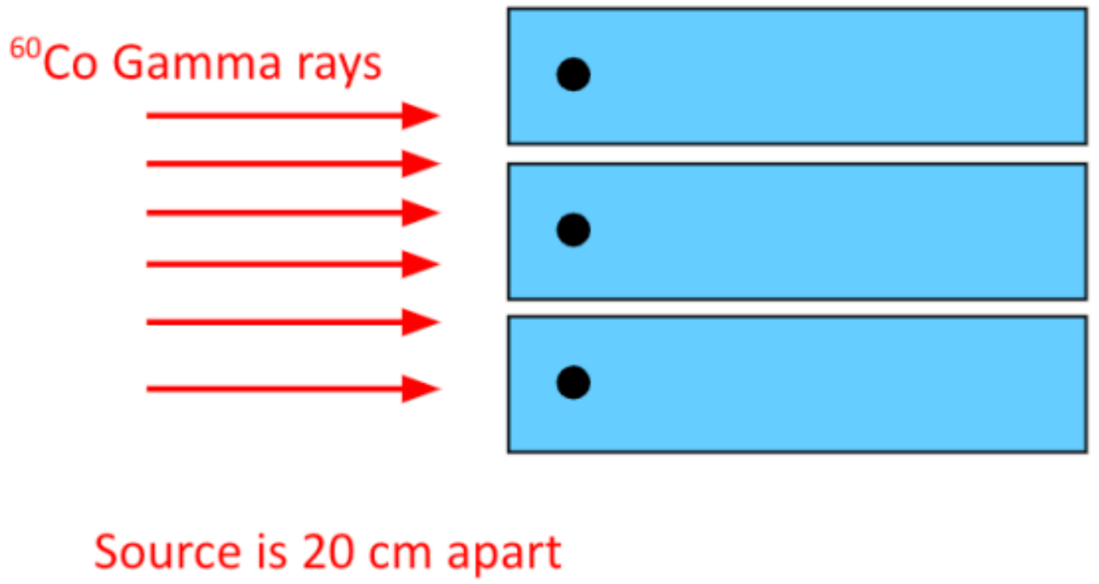
https://inspirehep.net/literature/2625951

Overview of recent results

Crystal radiation hardness

- **Radiation hardness** of PbF_2 and $PbWO_4$-UF ($1x1x4\ cm^3$) checked for:
  - TID up to 1000kGy @ Calliope facility, ENEA-Casaccia
  - 14 MeV neutrons @ Frascati Neutron Generator, ENEA-Frascati, up to $10^{13} n/cm^2$

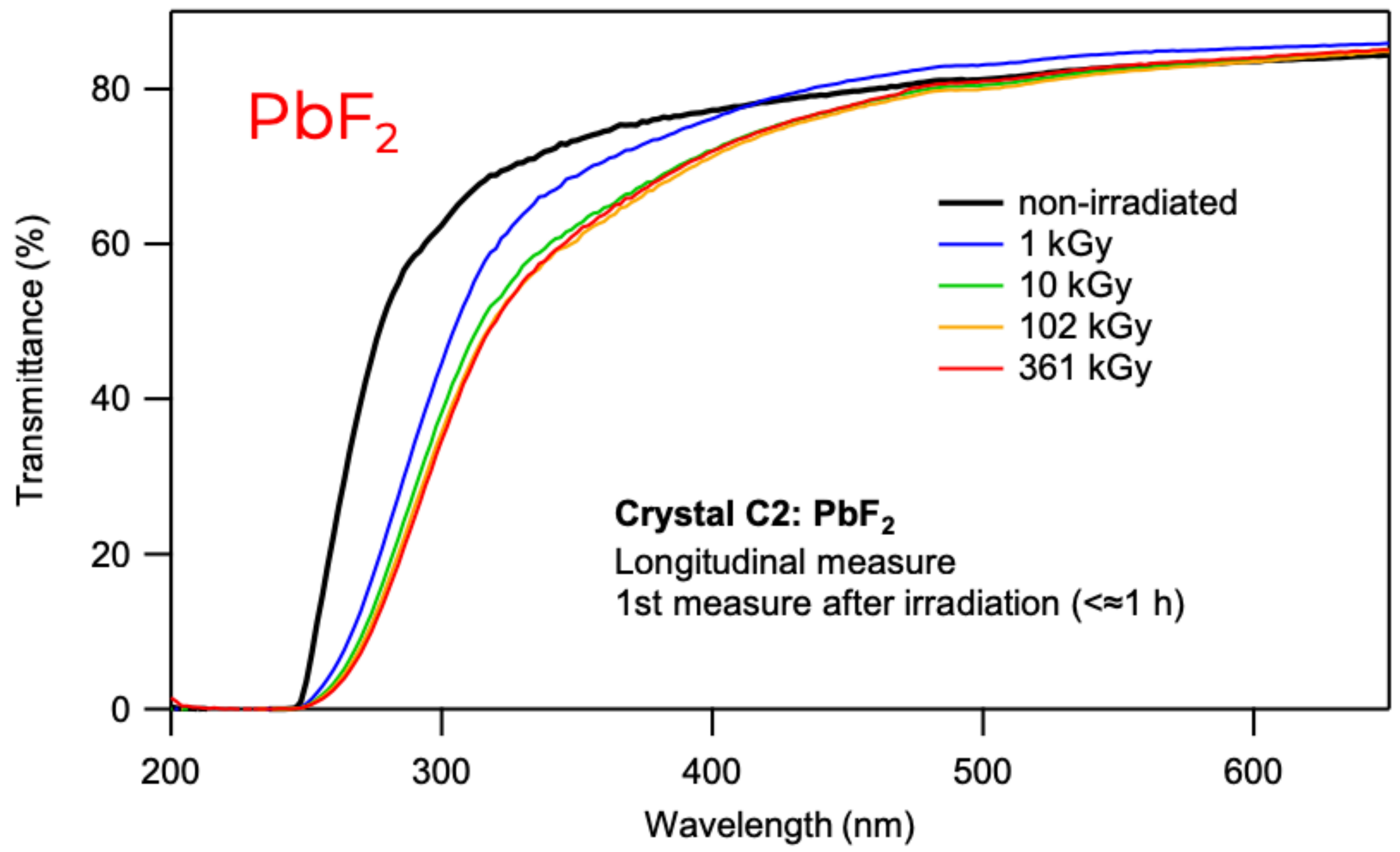
https://inspirehep.net/literature/2753375

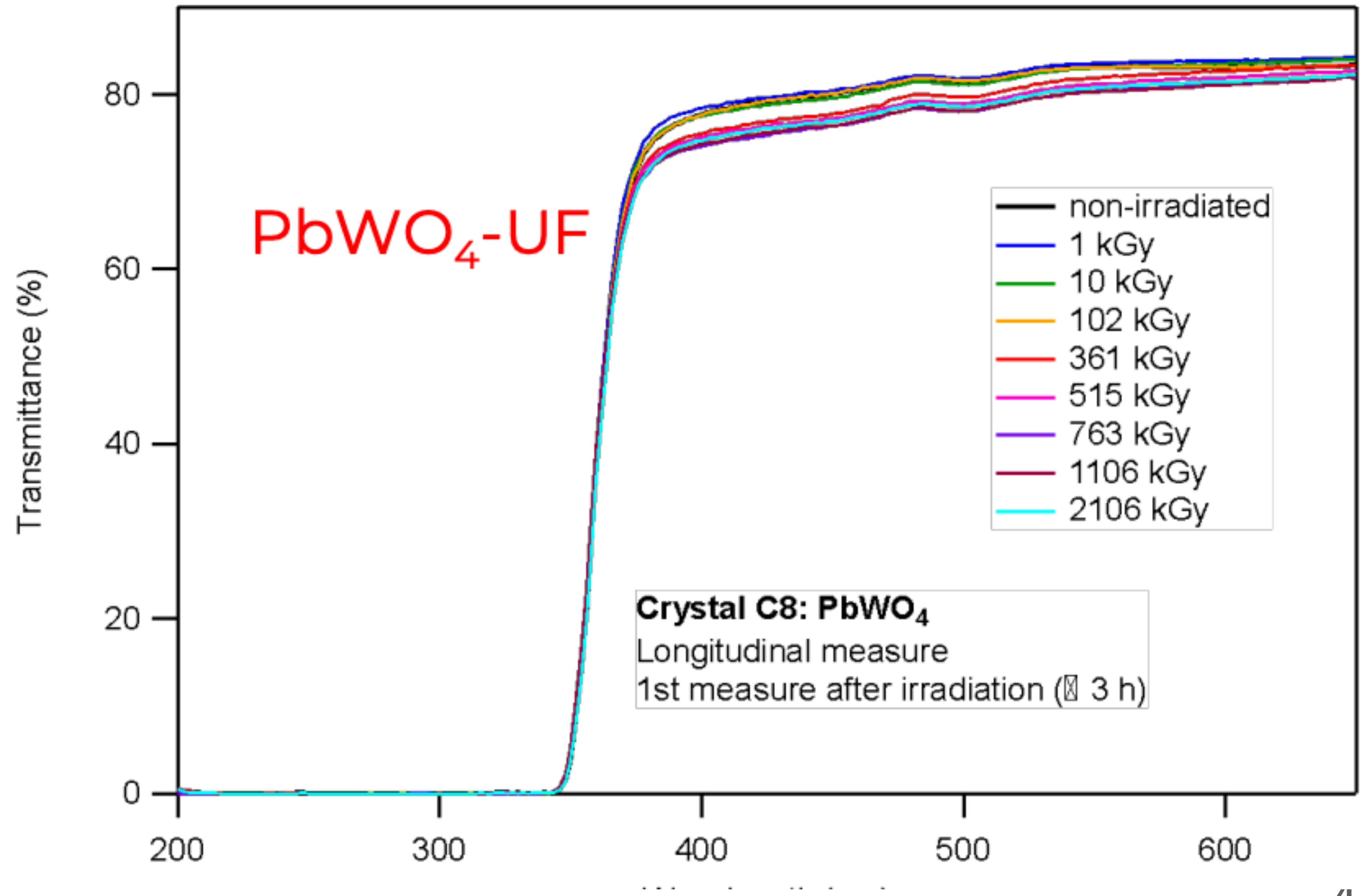


Crystal	PbF_2	PWO-UF
Density [g/cm^3]	7.77	8.27
Radiation length [cm]	0.93	0.89
Molière radius [cm]	2.2	2.0
Decay constant [ns]	-	0.64
Refractive index at 450 nm	1.8	2.2
Manufacturer	SICCAS	Crytur

PWO-UF (ultra-fast):
Dominant emission with $\tau < 0.7$ ns
M. Korzhik et al., NIMA 1034 (2022) 166781

- For PbF_2:
  - **after a TID > 350 kGy no significant decrease** in transmittance observed.
  - Transmittance after neutron irradiation showed no deterioration
- For $PbWO_4$-UF:
  - **after a TID > 2 MGy no significant decrease** in transmittance observed.





SiPM radiation hardness

- **Neutron irradiation**: 14 MeV neutrons with a total fluence of 10^{14}n/cm^2 for 80 hours
- **Two SiPMs models**:

10 μm pixel-size (Hamamatsu S14160-3010PS)

15 μm pixel-size (Hamamatsu S14160-3015PS)

- Extrapolated from I-V curves at a 3 different temperatures:
  - **Currents** at different operational voltages
  - **Breakdown voltages**

For the expected radiation level the best SiPMs choice are the **10 μm pixel-size** for a minor **dark current contribution**.

Before irradiation:

SiPM pixel-size	V_{br} [V]	I(V_{br}+4V) [nA]	I(V_{br}+6V) [nA]	I(V_{br}+8V) [nA]
15 μm	78.00±0.01	35.03±0.01	80.50±0.01	152.35±0.01
10 μm	80.97±0.01	23.89±0.01	42.58±0.01	70.80±0.01

After irradiation:

15 μm pixel-size

T [°C]	V_{br} [V]	I(V_{br}+4V) [mA]	I(V_{br}+6V) [mA]	I(V_{br}+8V) [mA]
-10 ± 1	75.29 ± 0.01	$\boxed{12.56 \pm 0.01}$	30.45 ± 0.01	46.76 ± 0.01
-5 ± 1	75.81 ± 0.01	14.89 ± 0.01	32.12 ± 0.01	46.77 ± 0.01
0 ± 1	76.27 ± 0.01	17.38 ± 0.01	33.93 ± 0.01	47.47 ± 0.01

10 μm pixel-size

T [°C]	V_{br} [V]	I(V_{br}+4V) [mA]	I(V_{br}+6V) [mA]	I(V_{br}+8V) [mA]
-10 ± 1	76.76 ± 0.01	$\boxed{1.84 \pm 0.01}$	6.82 ± 0.01	29.91 ± 0.01
-5 ± 1	77.23 ± 0.01	2.53 ± 0.01	9.66 ± 0.01	37.51 ± 0.01
0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

https://inspirehep.net/literature/2753375

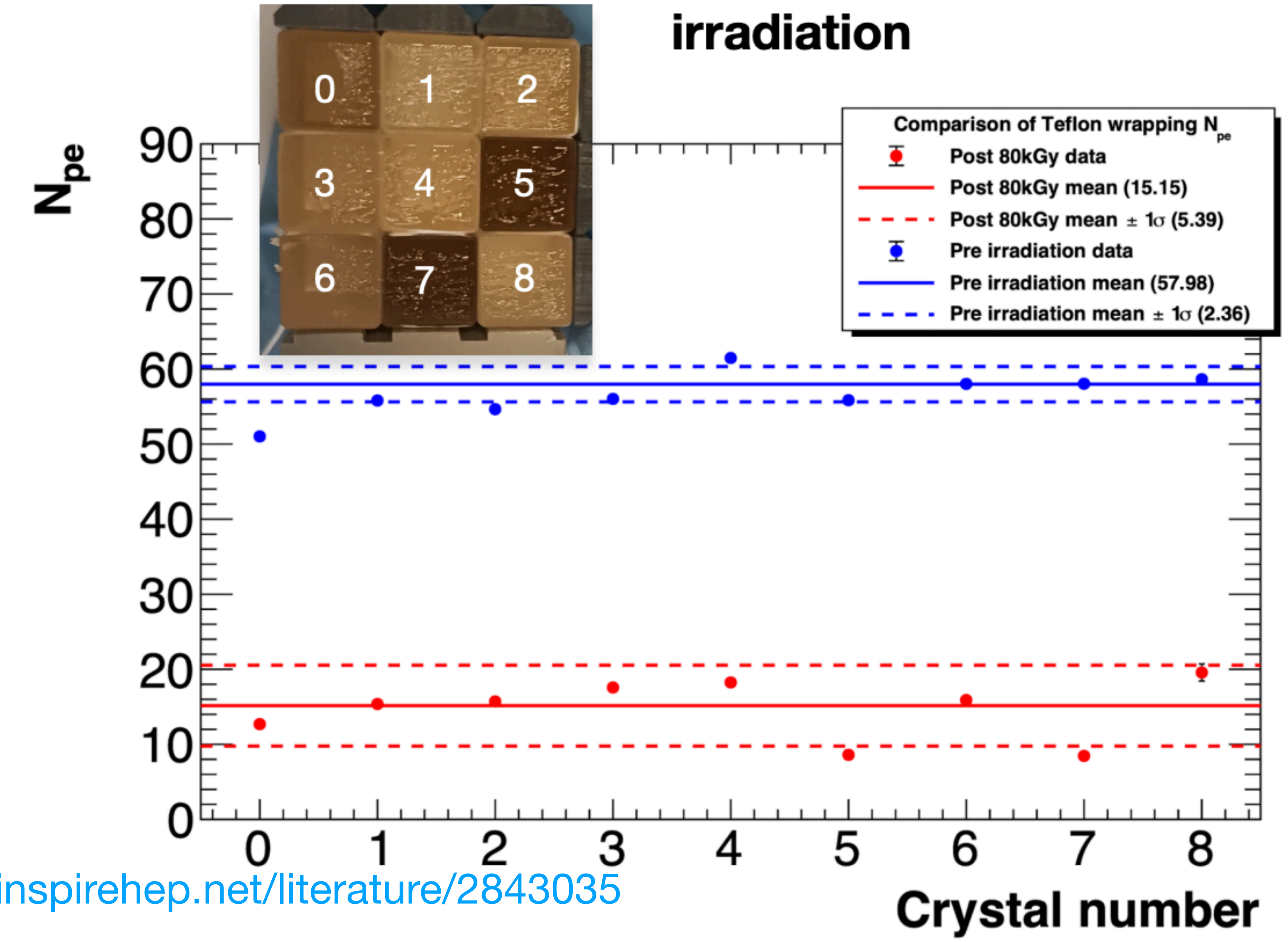
Light-yield loss

- To further extend the radiation tolerance studies, a test of the **Light Yield loss** after **Gamma ray irradiation** were performed
- **Two different wrappings tested, <u>Teflon</u> and <u>Mylar</u>**
- **Light Yield loss** evaluated through variation in **charge** and **number of photo-electrons** (N_{pe})

10 times the expected radiation at the Muon Collider!

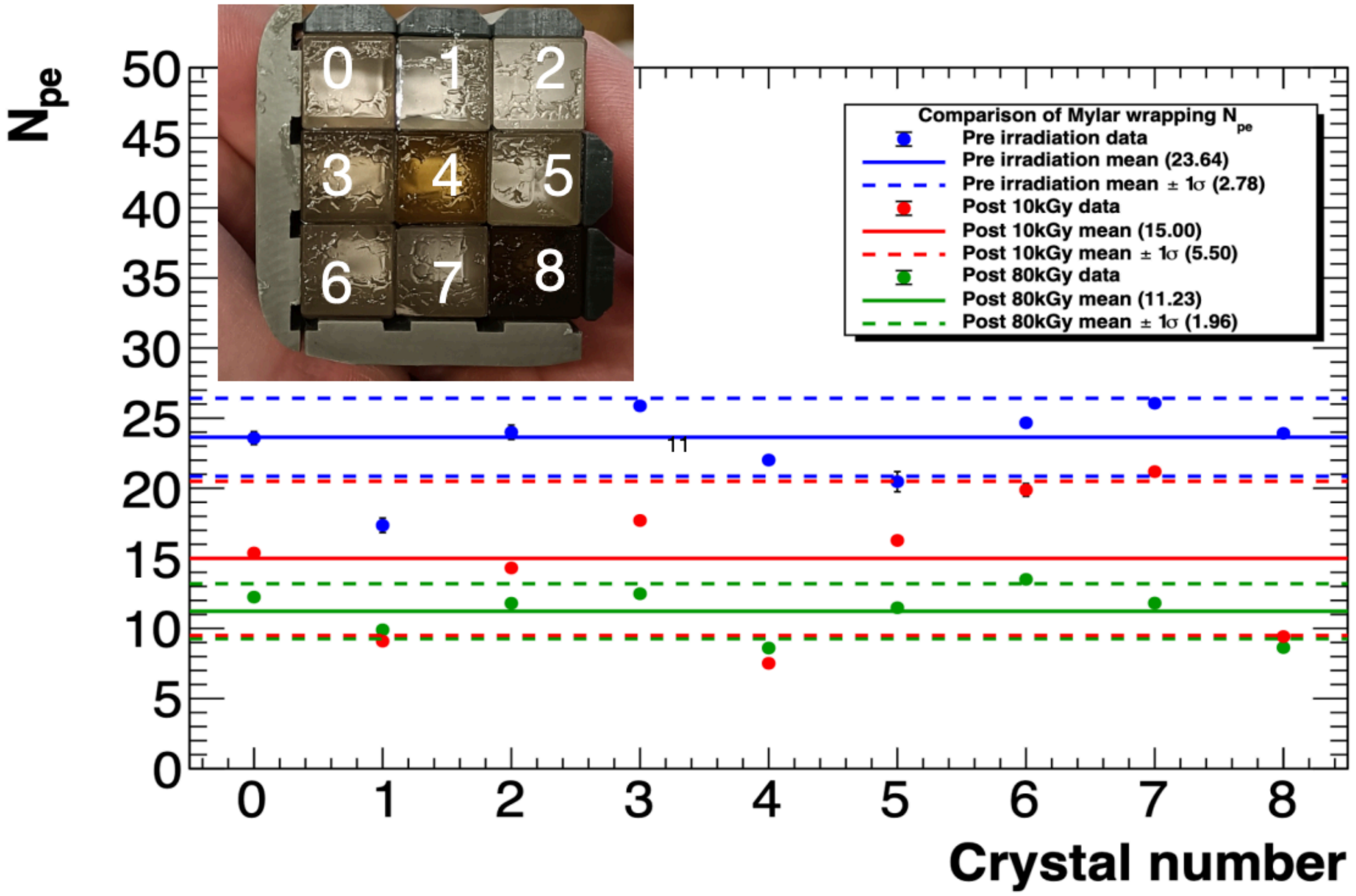
Telfon wrapping

Npe values of PbF_2 pre and post 80 kGy irradiation



Mylar wrapping

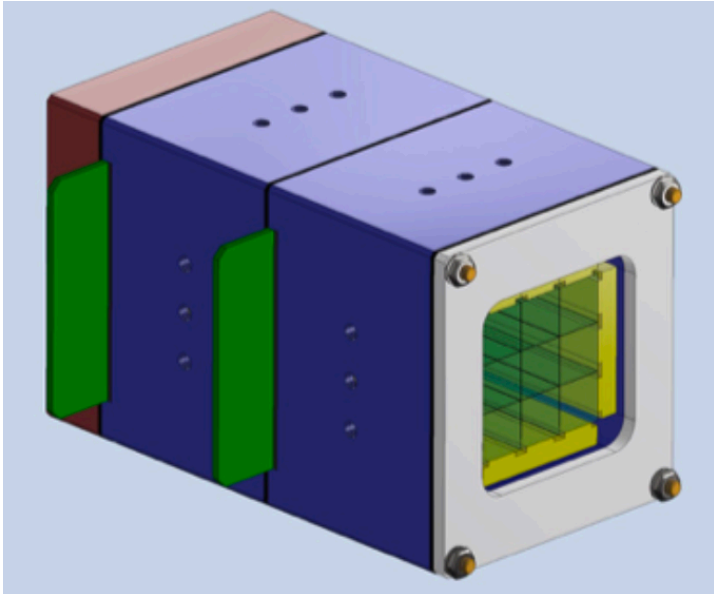
Npe values of PbF_2 pre, after 10 kGy and after 80 kGy irradiation



https://inspirehep.net/literature/2843035

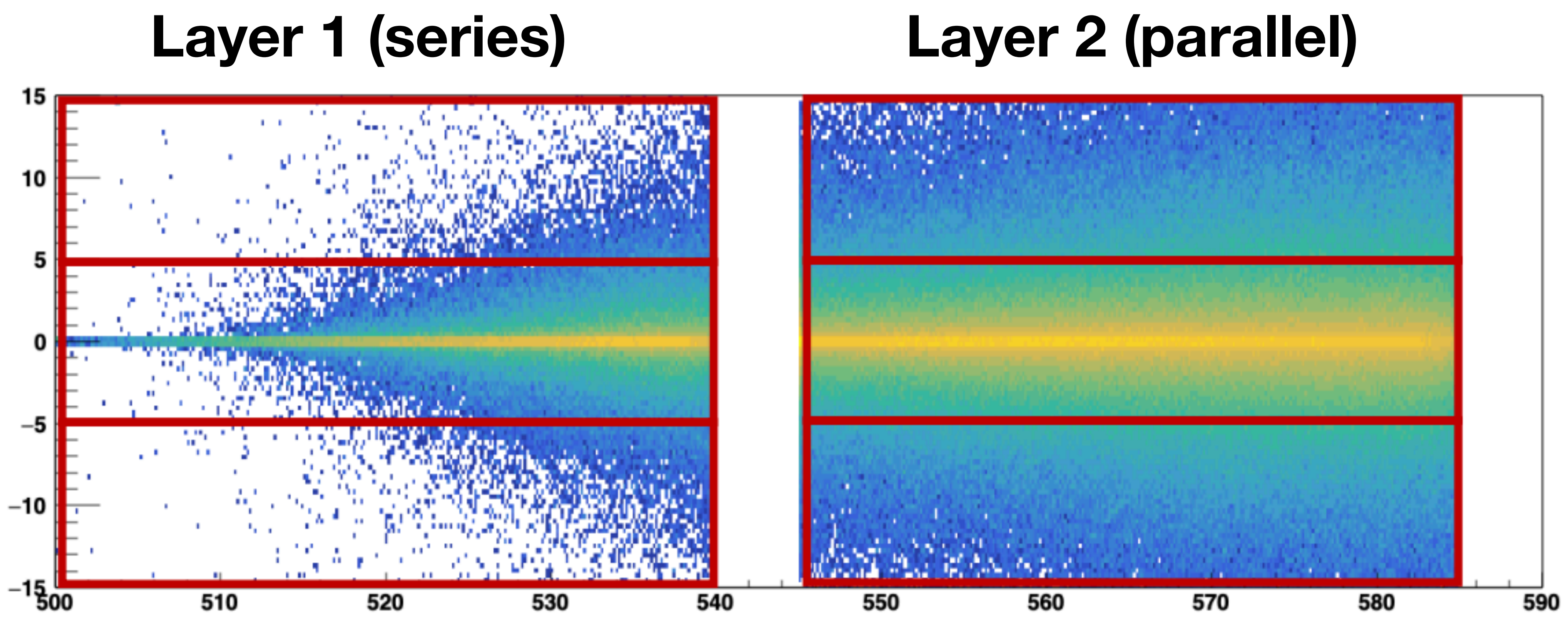
Energy deposition: TB vs. simulations

Proto-1 (2 crystal layers totaling **8.5 X_0**) is not deep enough to fully contain the electromagnetic shower, making energy resolution studies unfeasible

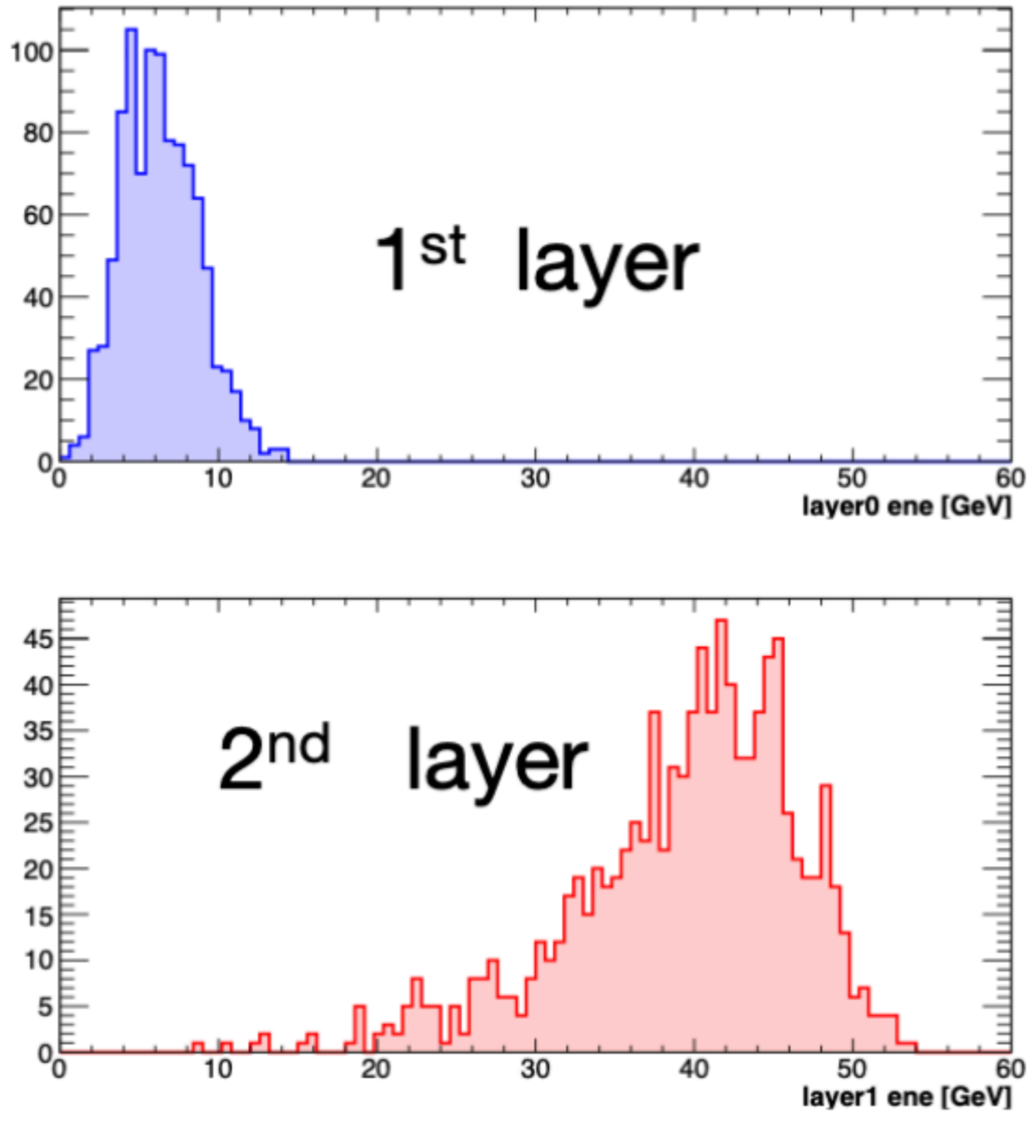


Will be possible with new larger prototype, now under construction

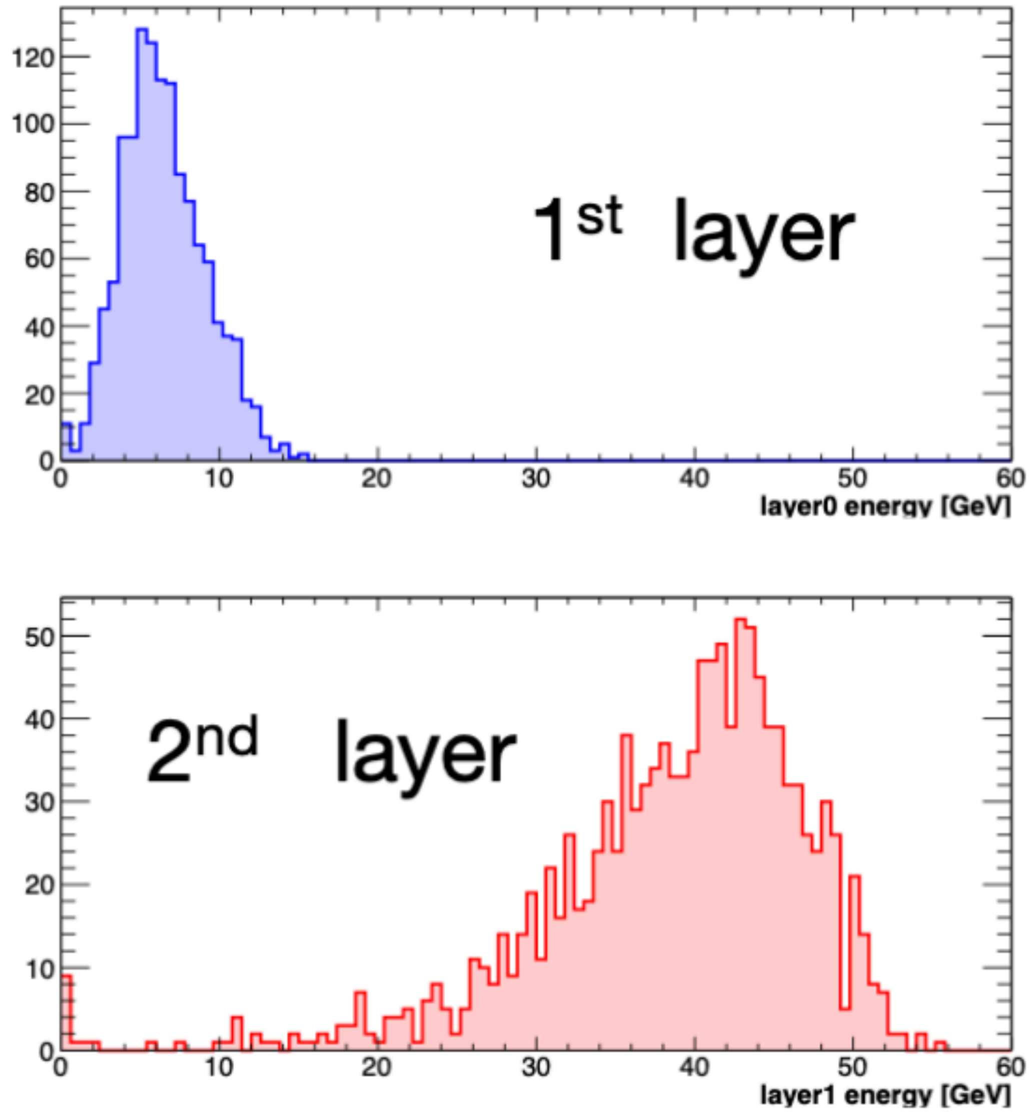
MC
120 GeV e^-

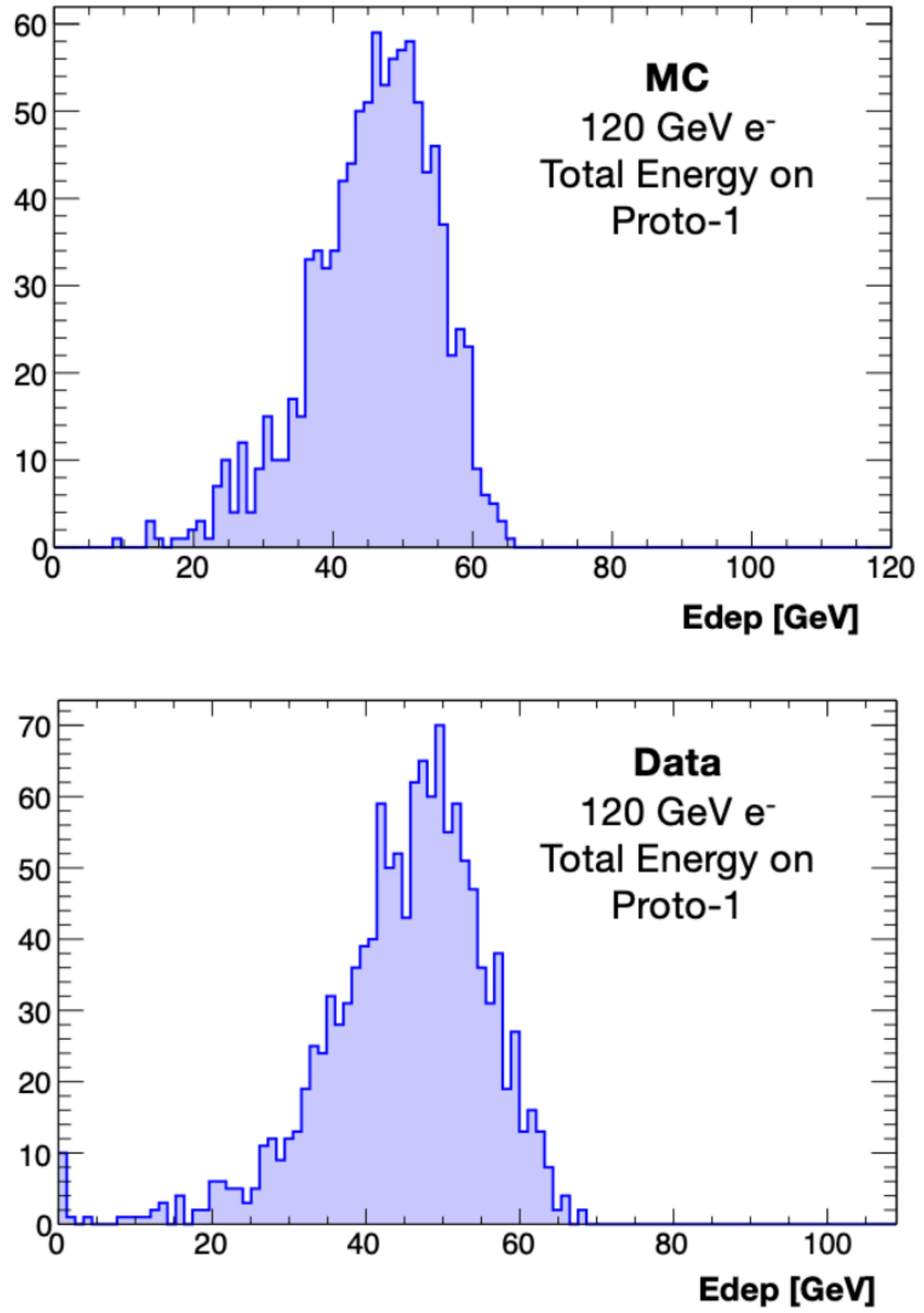


MC
120 GeV e^-



DATA
120 GeV e^-

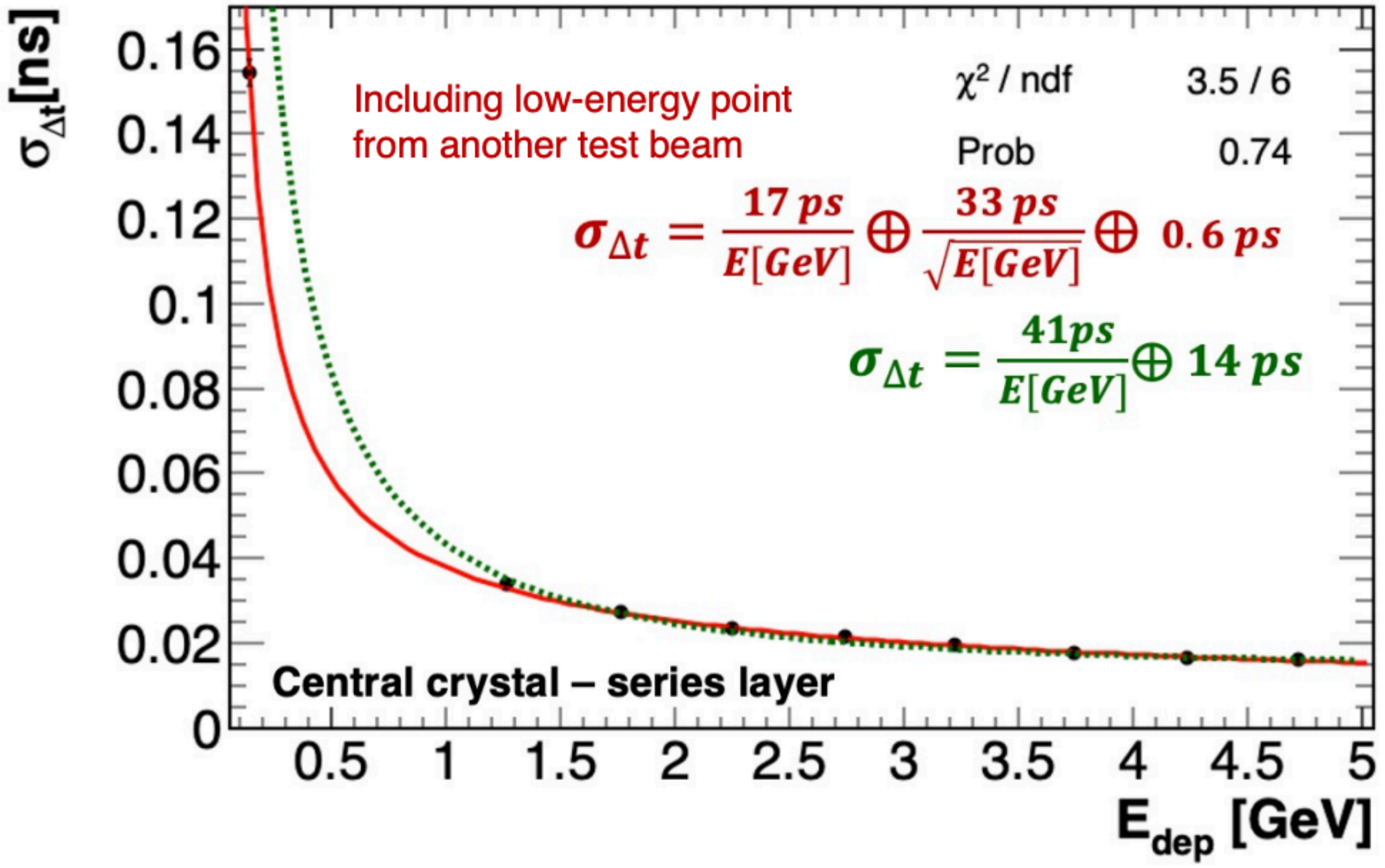


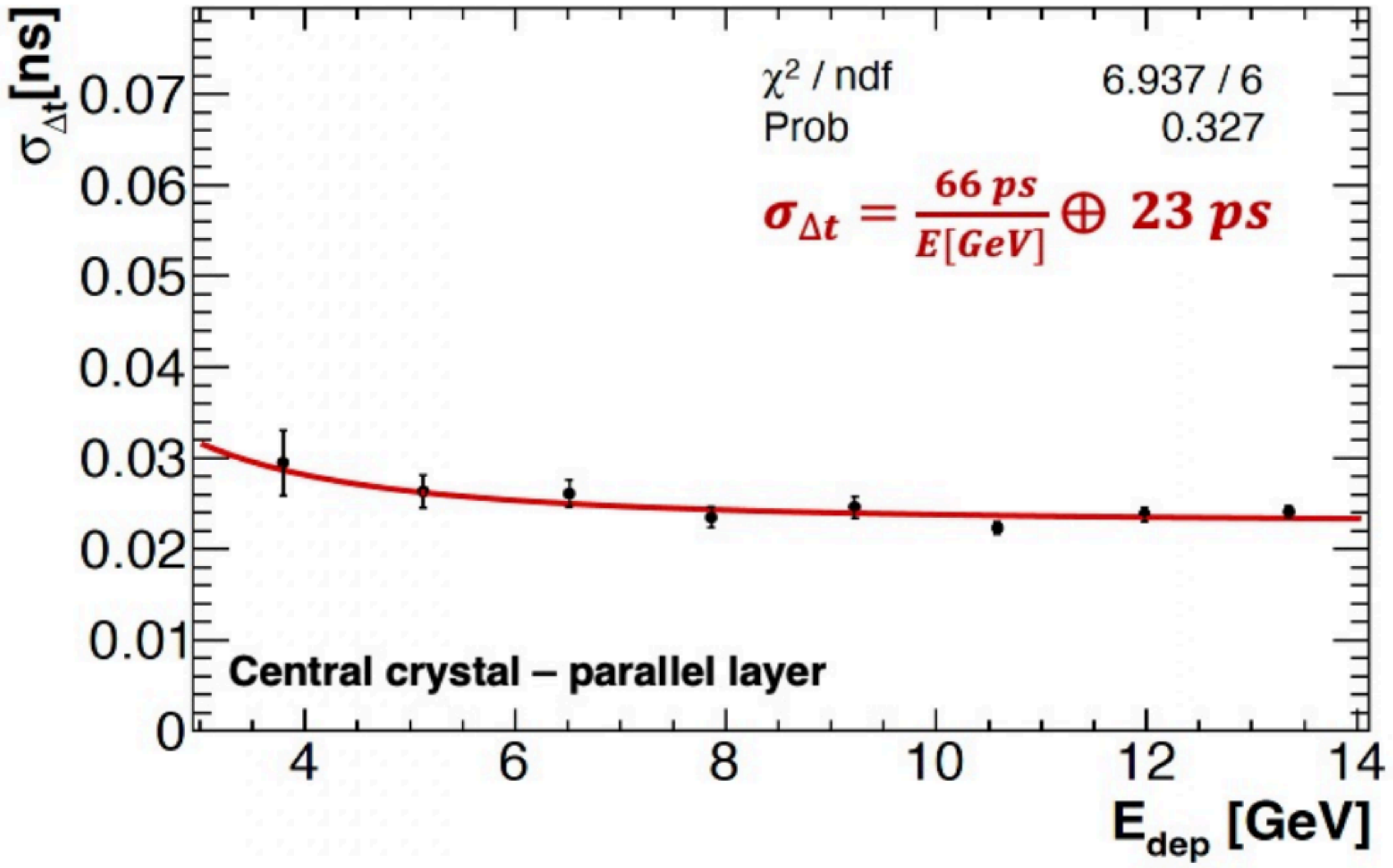


Important result:

- Great **agreement** between MC simulation studies and experimental data from the test beam on the energy deposited in the prototype
- **Validation of the simulation model**

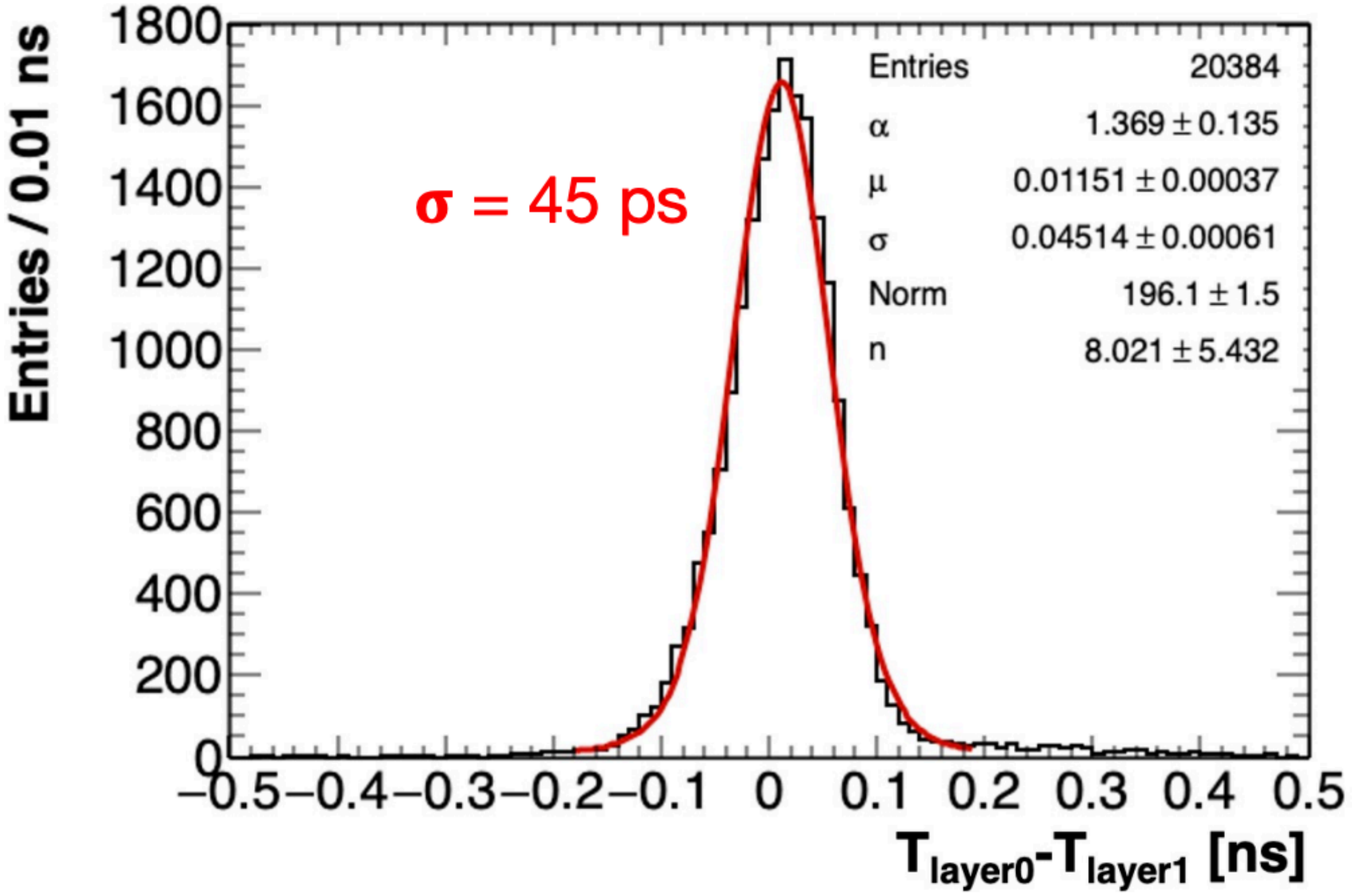
Timing resolution studies





Time resolution evaluated by the time difference of the two channels of the **central crystal of the 3x3 matrices**

- **Outstanding time resolution** of **O(20 ps)** was achieved in both the case of the **series layer** and the **parallel layer**
- **Excellent results** using central crystals of **different layers** with **σ_t=45ps**. Time resolution dominated by the 2 SiPM board **synchronization jitter O(32ps)**



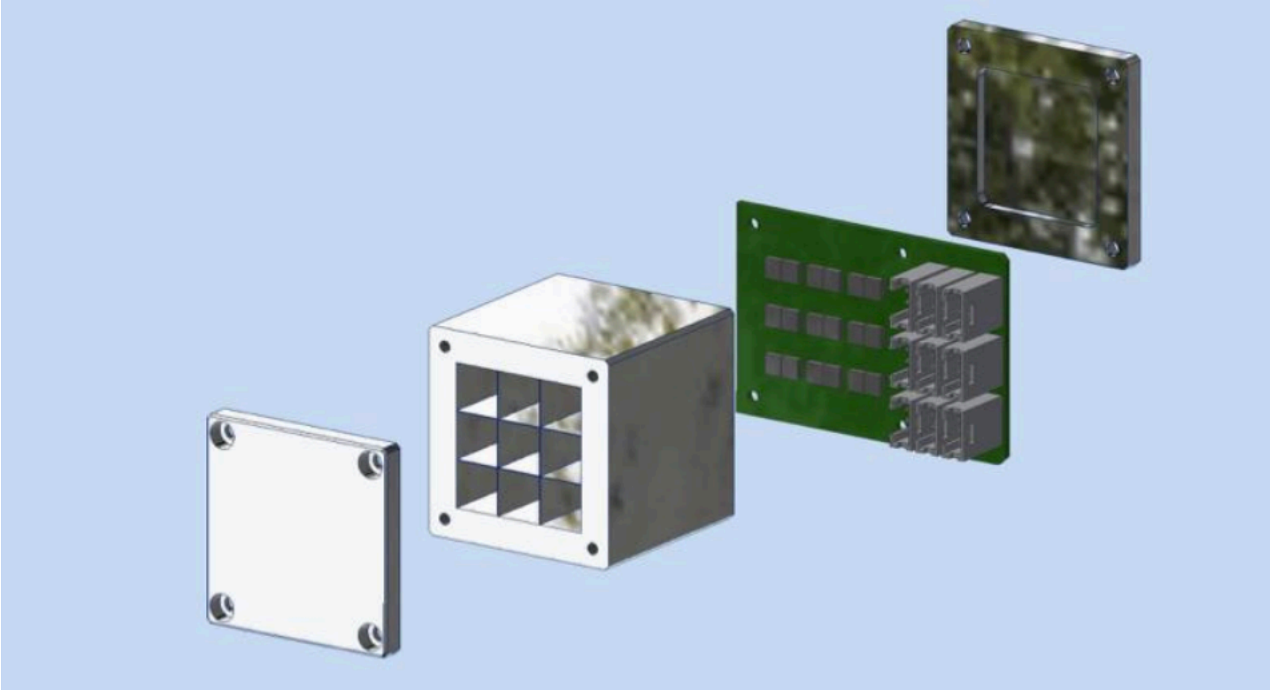
Results in agreement with future colliders requirements!

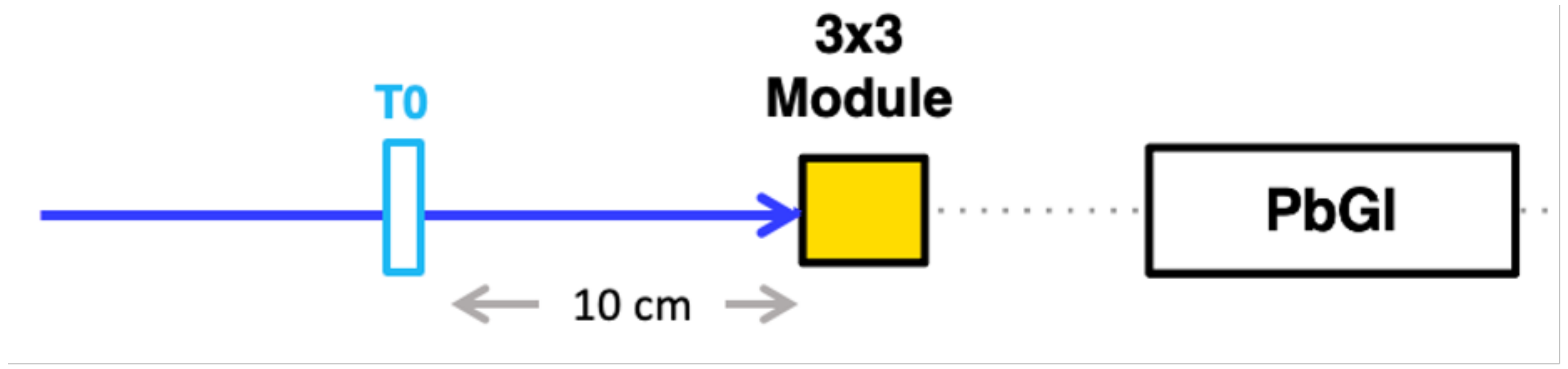
Plans for 2025

Two TB campaigns

Week 19

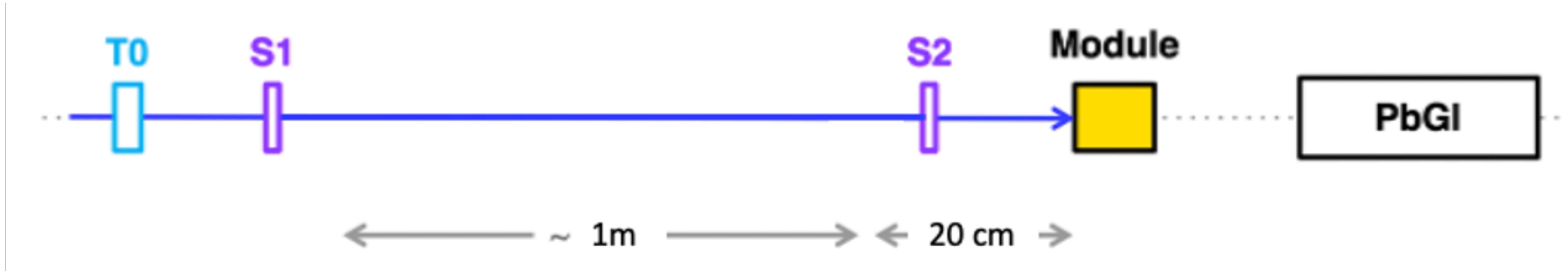
- 3x3 prototype under test for new FEE checks and **comparisons between acquisition methods**:
  - Custom FEE with CAEN v1742 flash ADC digitizers
  - CAEN DT5203 board with integrated amplification electronics and picoTDC → test time over threshold
- Different **wrapping** and **paint solutions** to optimize light reflections





Week 39

- Same setup as week 19 + testing of **2 beam monitor sensors** for spatial resolution and efficiency performances



Two TB campaigns: beam request

Particle type	Electron/positron
Momentum	20-150 GeV (20 GeV intervals)
Intensity/spill	10^3 particles/spill
Purity	As high as possible (70% minimum)
Spot dimension	few mm in both x and y
Beam divergence	< 90 μrad in both x and y

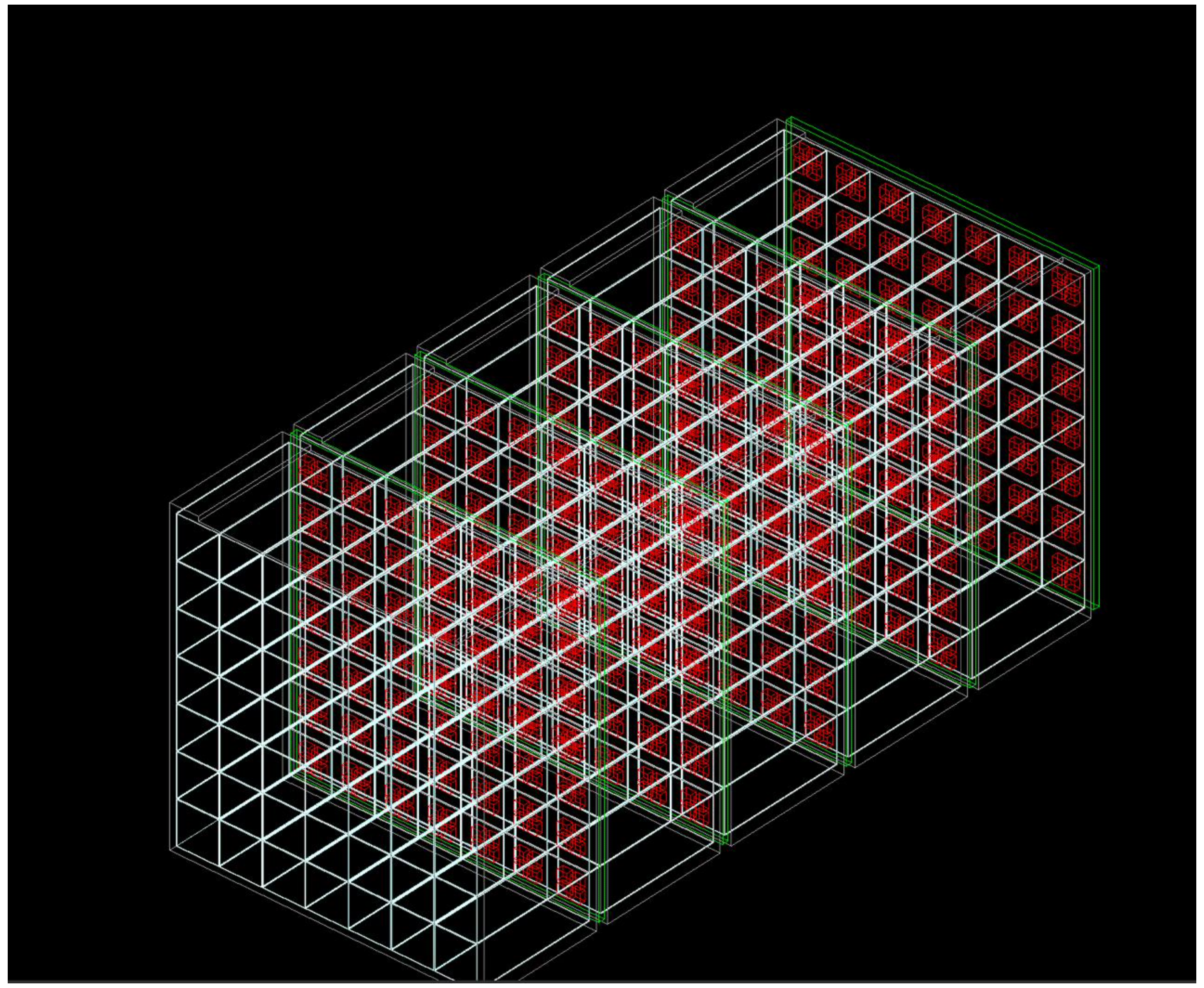
Notes:

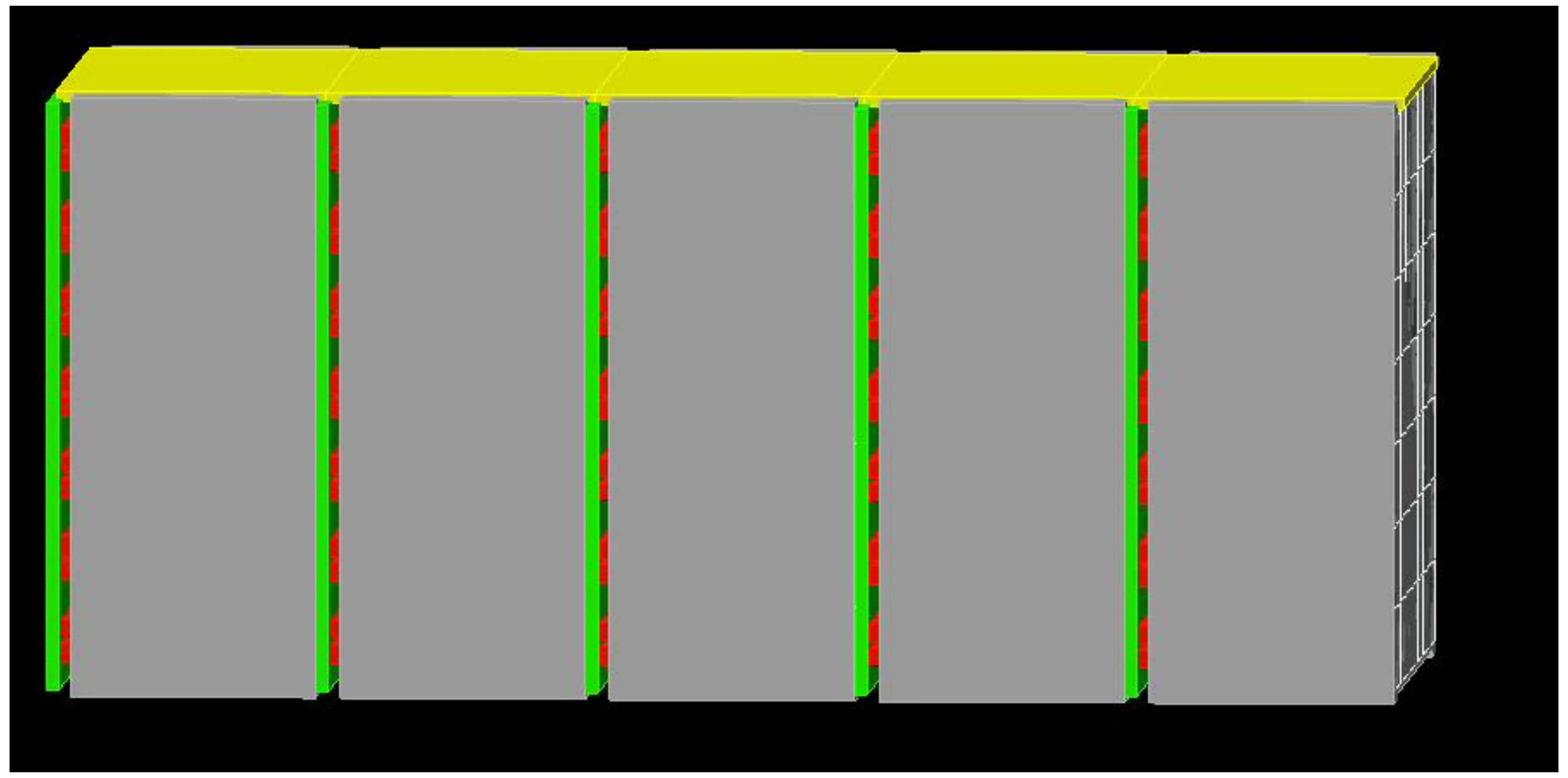
- Purity is the most important parameter, followed by intensity (10^3 -10^4 particles/spill)
- Possible brief request for parallel muon beam file (mips)
- No tagged photon foreseen running this year

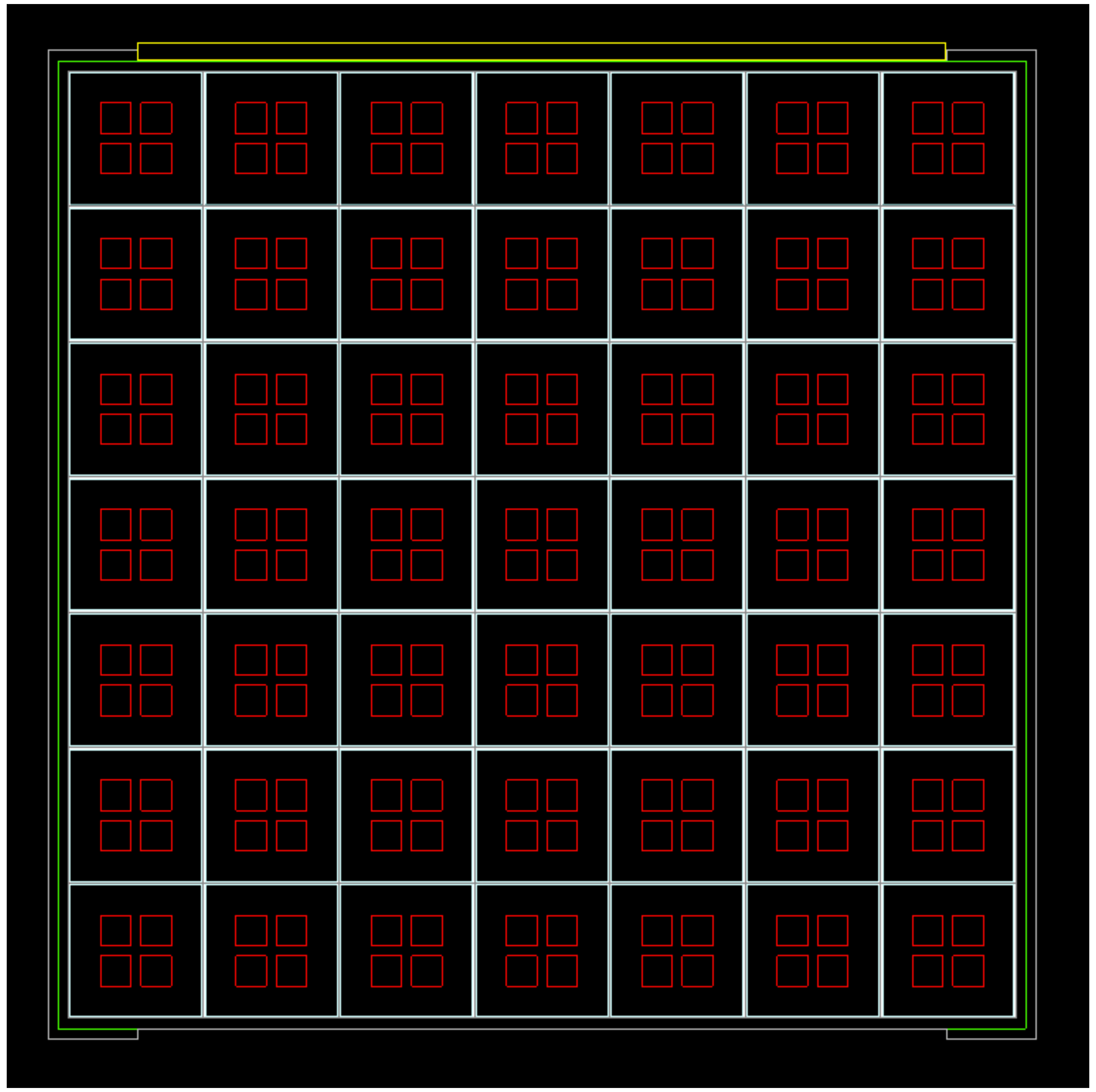
New 7x7 CRILIN module: design

- **New 7x7 crystals x5 layers CRILIN module** has been designed and studied using simulations
  - Bigger crystals (13x13x40 mm^3), 100 μm tolerance
  - 100 μm printing per side
  - Aluminum separation, max 200 μm per side
  - Maximum 2 mm aluminum external envelope to hold the module
  - Space for Kapton strip for output signal

→ **Design close to the final module to be placed in the calorimeter!**

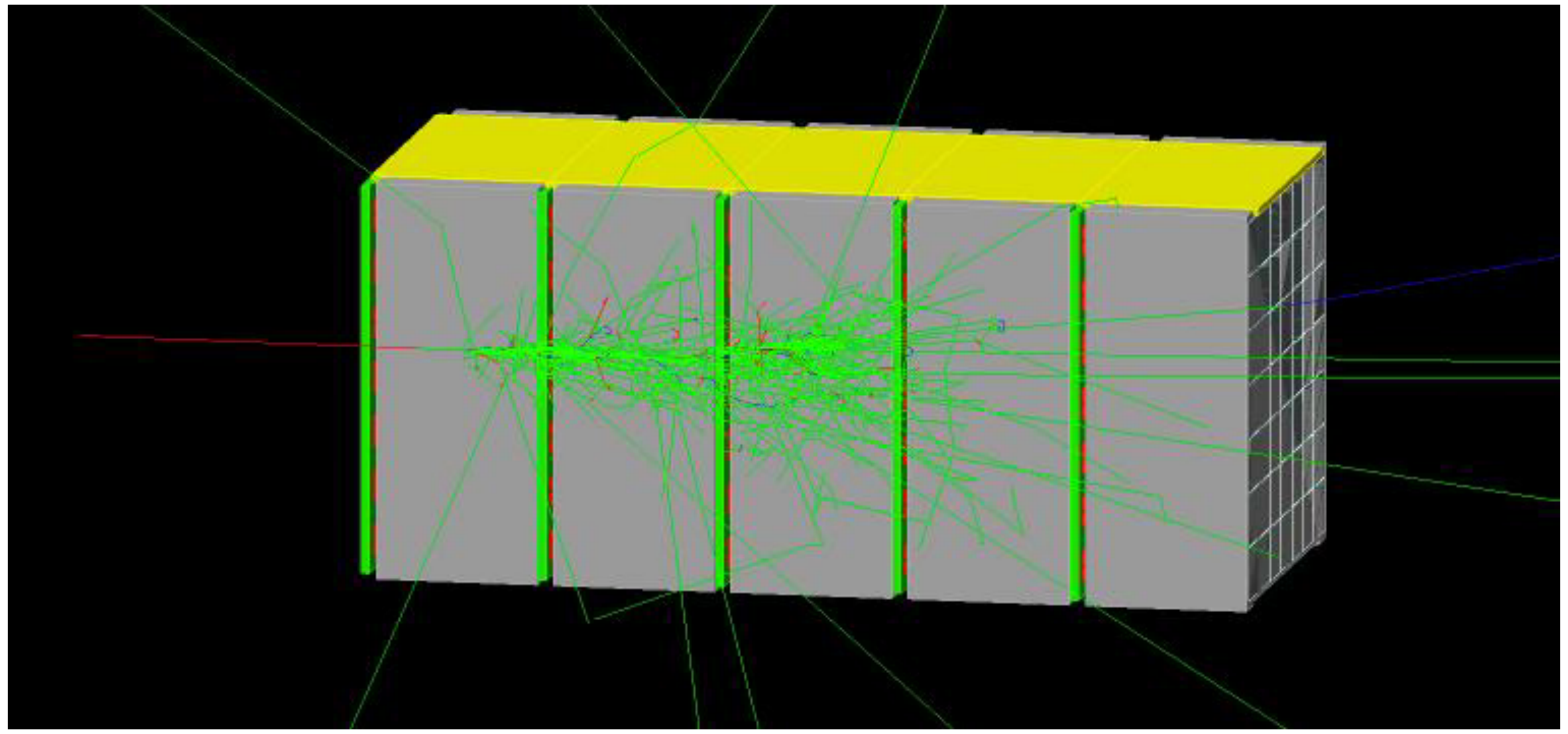




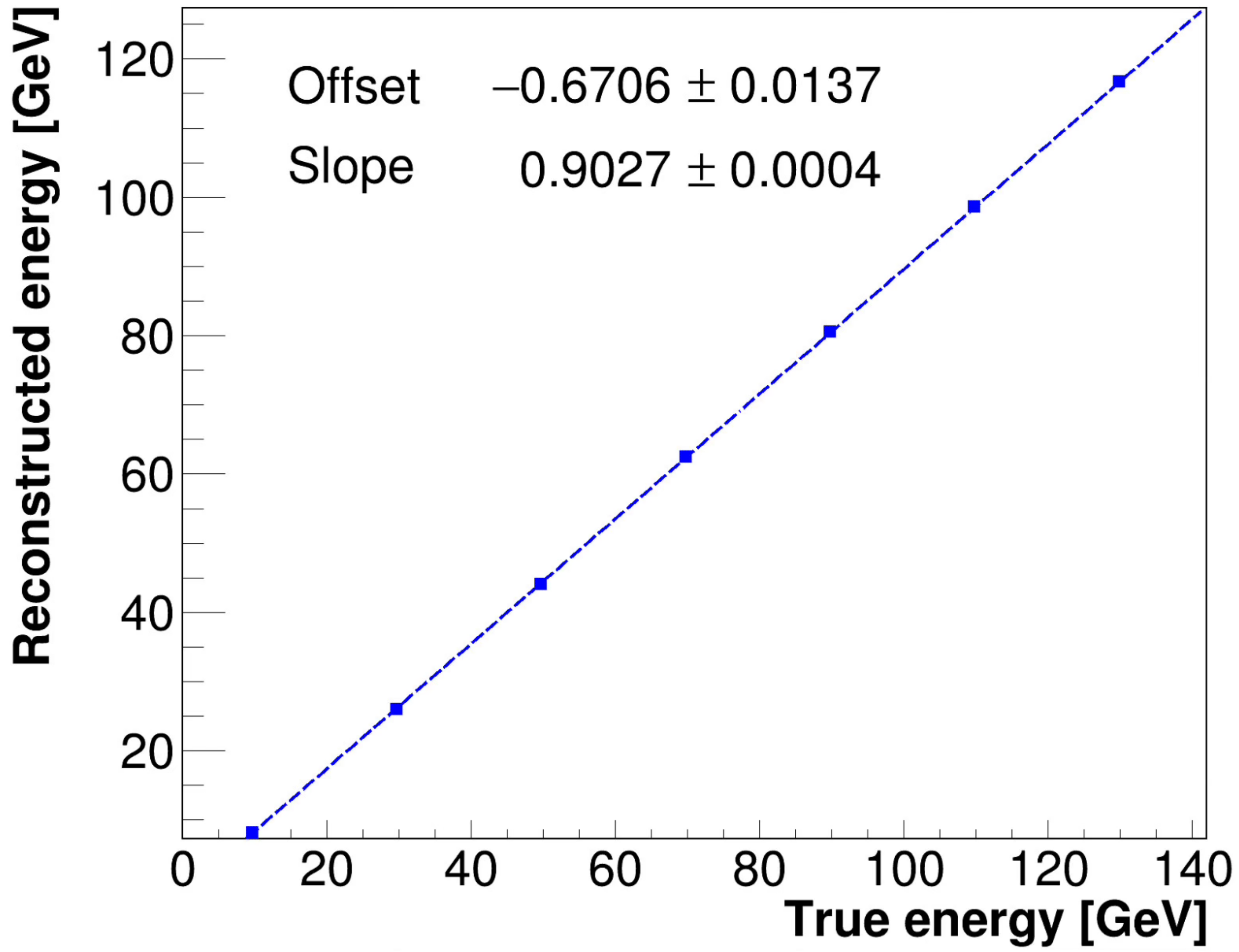


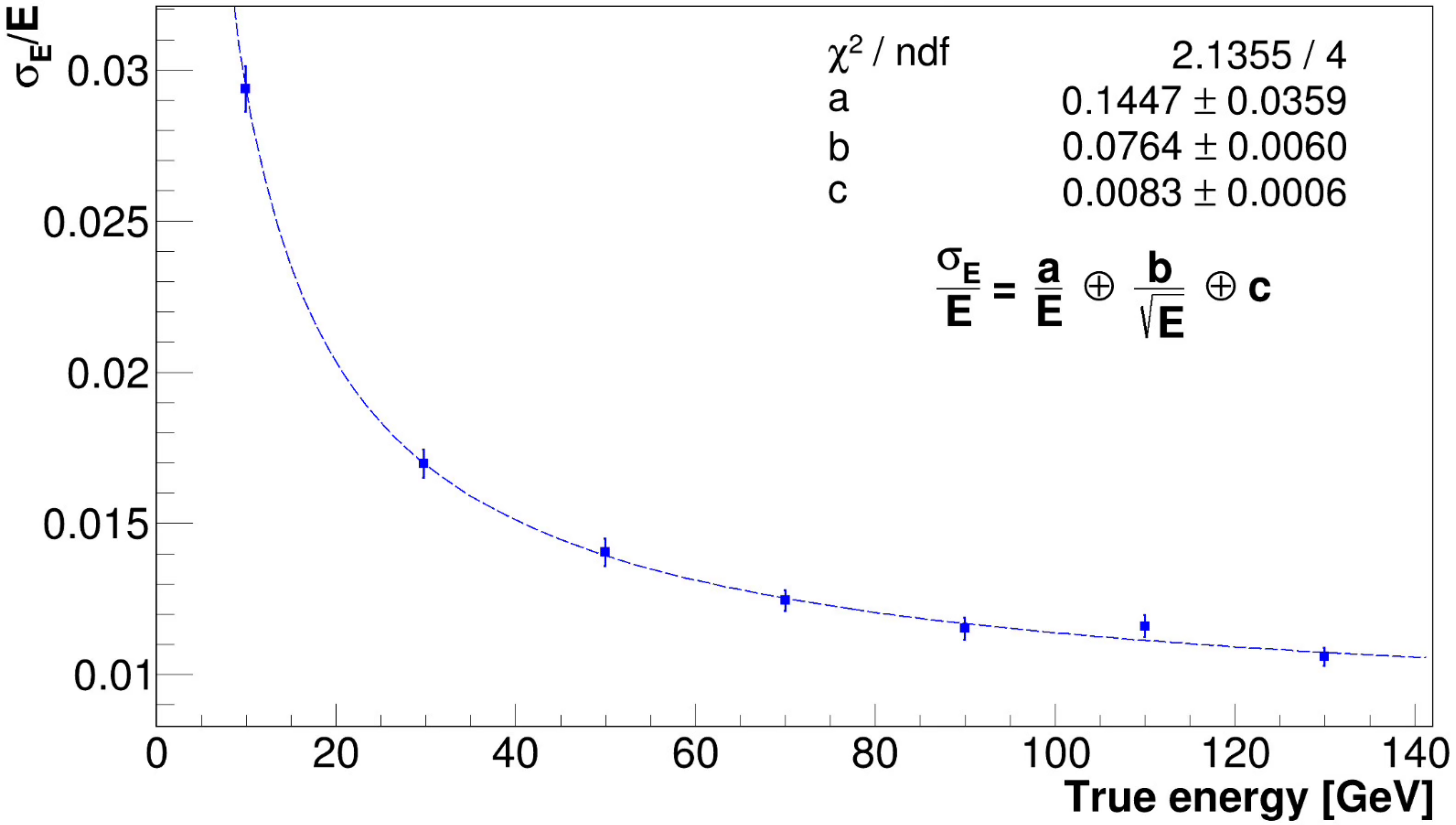
New 7x7 CRILIN module: simulation results

- Some specifics:
  - 0.2 pe/MeV per crystal
  - 10 MeV Gaussian noise (to mimic electronic noise)
  - 30 MeV threshold per crystal



Simulation results on linearity and energy resolution confirm expectations!





Conclusion and next steps

A lot of interesting results in the past months:

- PbF_2 ($PbWO_4$-UF) robust to >35(200) Mrad and SiPMs validated up to 10^{14} n_{1MeV}/cm^2 displacement-damage eq. fluence
- Time resolution < 40 ps for single crystals for E>1 GeV deposited energy

For 2025:

- 2 TB campaigns to test different FEE and beam monitoring

For the future (2026):

- New 7x7(crystals)x5(layers) module under construction, ready by the end of the year
- Calibration at LNF BTF in December 2025
- Next year's TB campaigns (March 2026) to test final module

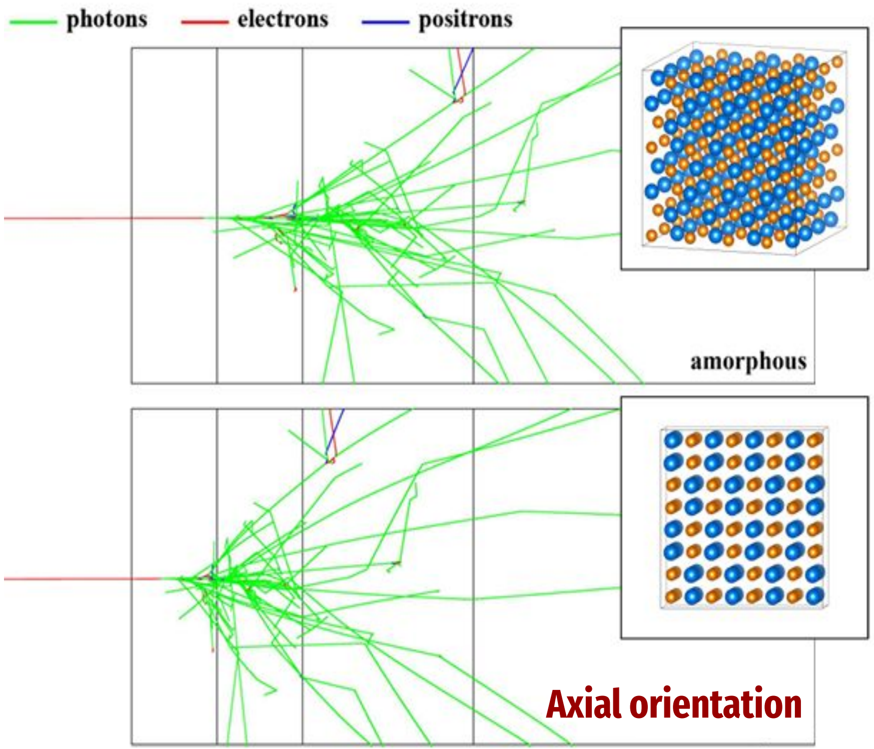
The OREO (ORiEnted calOrimeter) project

Alessia Selmi
aselmi@uninsubria.it
On behalf of the OREO collaboration

DRD6 collaboration meeting
WP3 Parallel Session
Subtask 3.1.4
Oct. 30-Nov 1, 2024

MiB - Ferrara
LNL - LNF

Orienting an electromagnetic calorimeter!



(not an actual G4 event – for visualisation only)

Acceleration of the electromagnetic shower development [1][2][3]

Reduction of the effective radiation length X_0, whereas λ_{int} (hadronic) is unaffected

Improved γ/hadron discrimination [4]

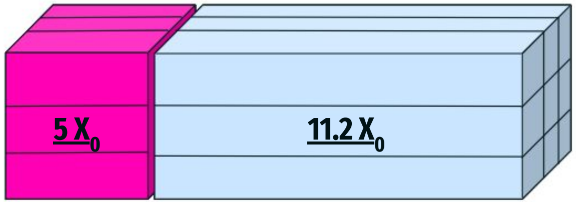
2024

OREO - ORiEnted calOrimeter

Deliverables and milestones

R&D financed by INFN CSN5
Included in H2020AidaInnova
WP8 task 3.1

CSN5 Ricerca Tecnologica



3x3 matrix of **oriented $PbWO_4$ Ultra Fast** readout by SiPMs with:

- An oriented layer of 5 X_0
- A non oriented layer of 11.2 X_0

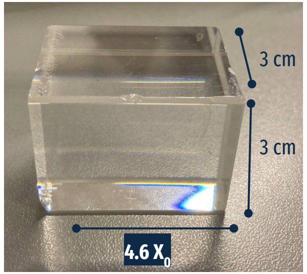
D1 → Two layer PWO-UF prototype fully assembled

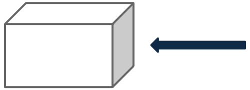
M1 → First experimental tests at CERN PS&SPS and data analysis

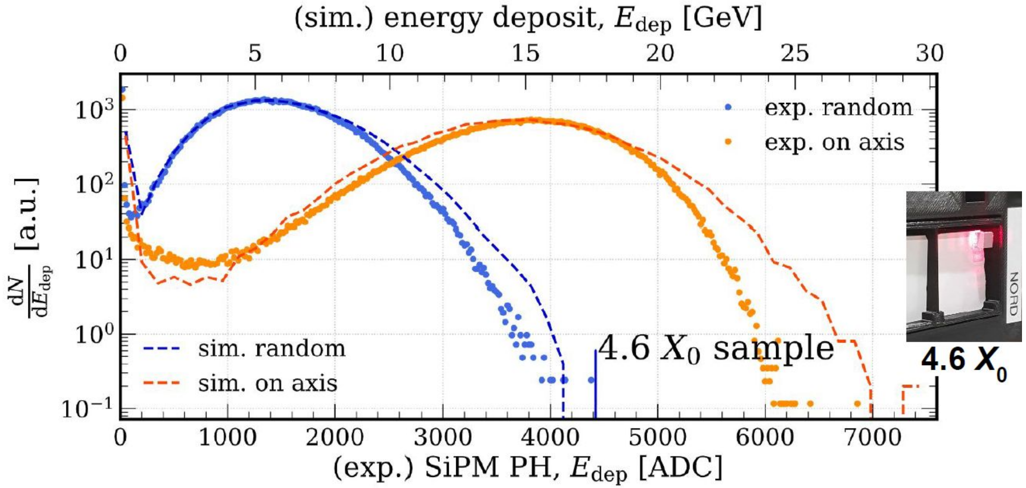
2022

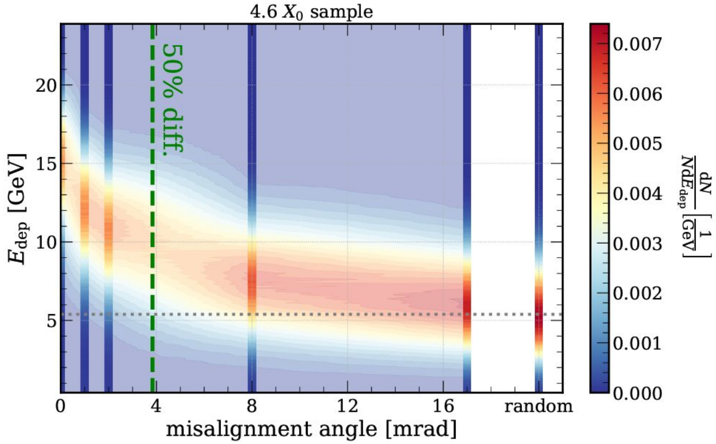
Where we were...

Experimental investigation in **thin** oriented $PbWO_4$ @ CERN SPS [5]



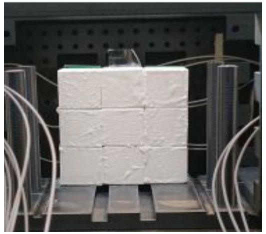






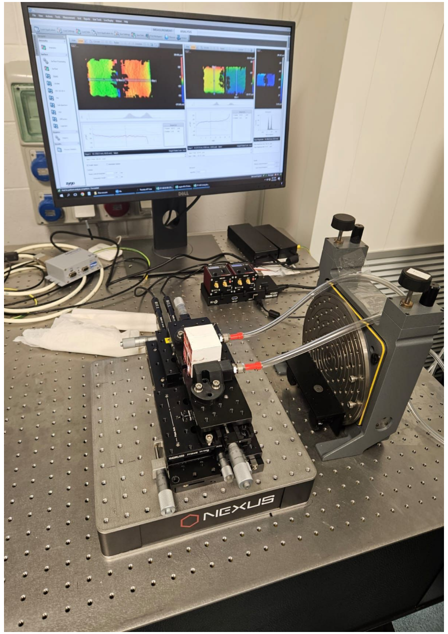
2024

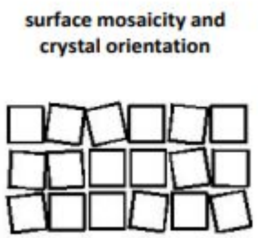
DRD6- OREO first prototype

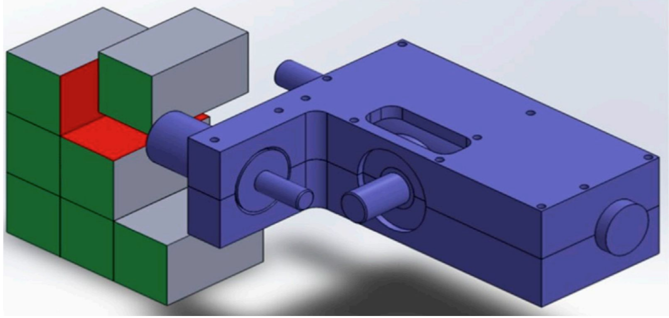


D1 --> Two layer PWO-UF prototype fully assembled

Construction of the OREO prototype: crystal characterization [6]







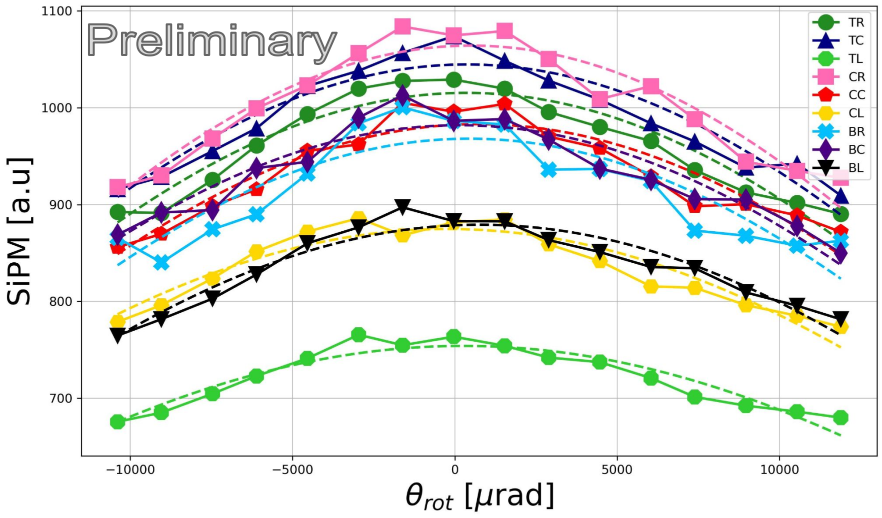
Gluing procedure:

- preliminary lattice characterisation with laser
- autocollimator and HRXRD
- on roto-translational adjusters → real-time corrections of relative miscut
- Fizeau interferometer for real-time check

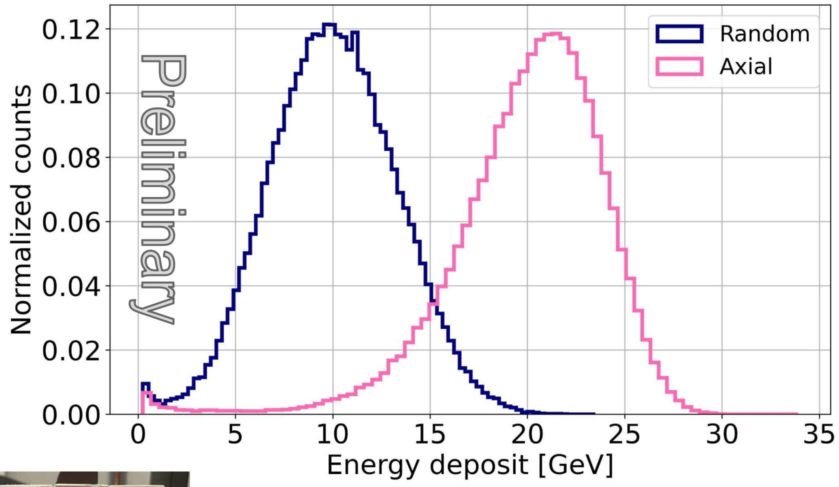
M1

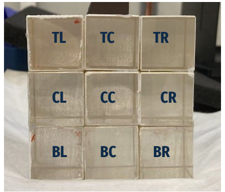
First experimental tests at CERN PS&SPS and data analysis

6 GeV electrons @ T9 PS



120 GeV electrons @ H4 SPS





The crystals are well inter-aligned!

2025 - Deliverables and Milestones

CSN5
Ricerca
Tecnologica

INFN

D2 → Characterization and preparation of PWO-UF crystals with smaller transverse size to study the transverse shower development

M2 → Report on MC simulation of the first prototype in Geant4

M3 → First report of beamtest results data analysis

European Commission

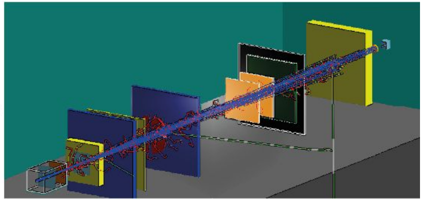
Marie Skłodowska-Curie Actions Individual Global Fellowships
GA 101032975

Trillion

Steering and radiation effects in oriented crystals and their applications implementation into Geant4
https://www.fe.infn.it/trillion/

Coordinators:
G.Paternò, A.Sytov

I.N.F.N GEANT



2026 - Deliverables and Milestones

D3 → Final MC package in Geant4

M4 → Final report of beamtest results data analysis

M5 → Implementation of the OREO technology in realistic experimental scenarios - in synergy with other DRD6 groups

Ongoing collaborations:

- Task 3.1.3 CRILIN for joint testbeam
- Task 3.4.1 ScintCal with UNIVPM team for photoelastic characterization of PWO crystals