Calorimeter R&D

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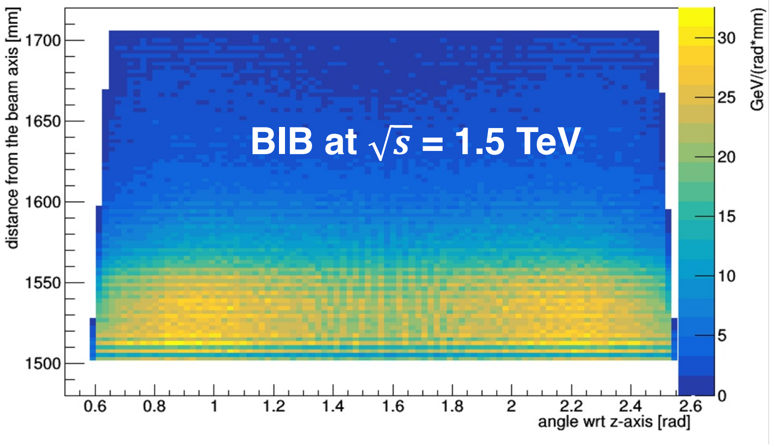
IMCC and MuCol annual meeting - 12-15 March 2024, CERN

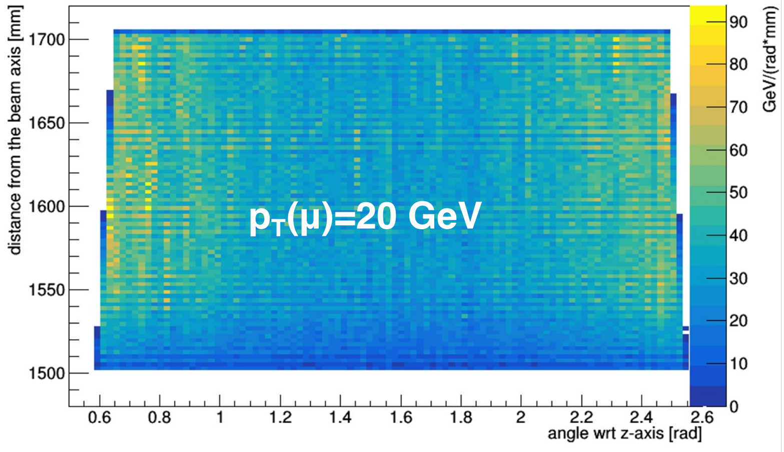
ECAL R&D

Beam Induced Background in ECAL

Energy released in ECAL barrel by one BIB bunch crossing



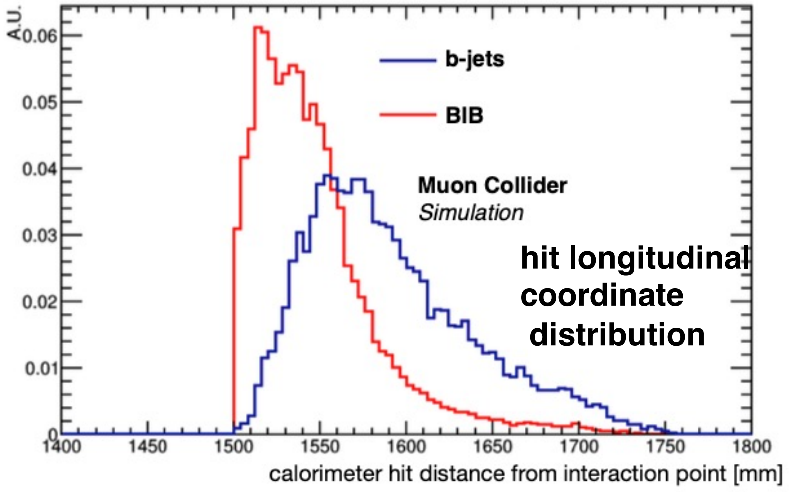
Energy released in ECAL barrel by uniformly distributed prompt muons in the (θ,ϕ) space

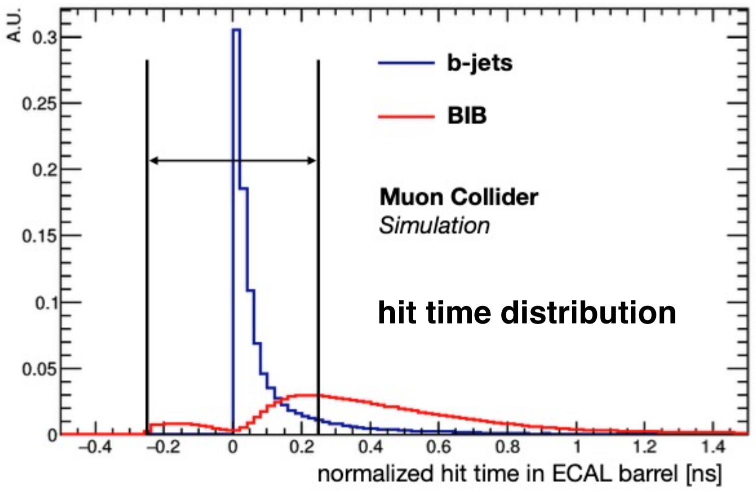


- Expected BIB on the ECAL barrel **~300 γ/cm^2 /event** with E~1.7 MeV.
- BIB can be handled using information from energy releases in the ECAL.

Key features:

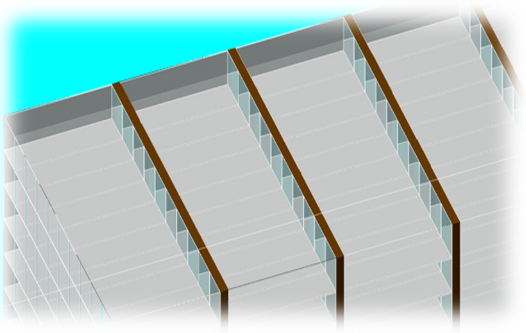
- **Timing**: BIB hits are out-of-time a resolution in the order of **100 ps is needed**
- **Longitudinal segmentation**: different profile for signal and BIB
- **Granularity**: in order to avoid BIB overlap in the same cell
- **Energy resolution:** target → $\frac{\Delta E}{E} = \frac{10\%}{\sqrt{E[GeV]}}$

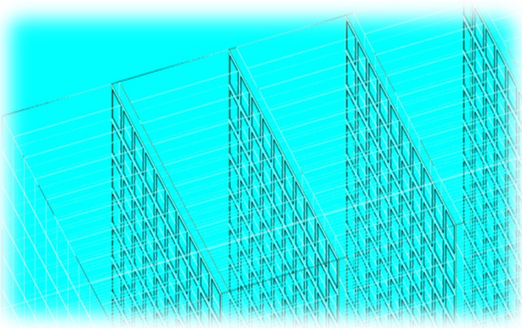


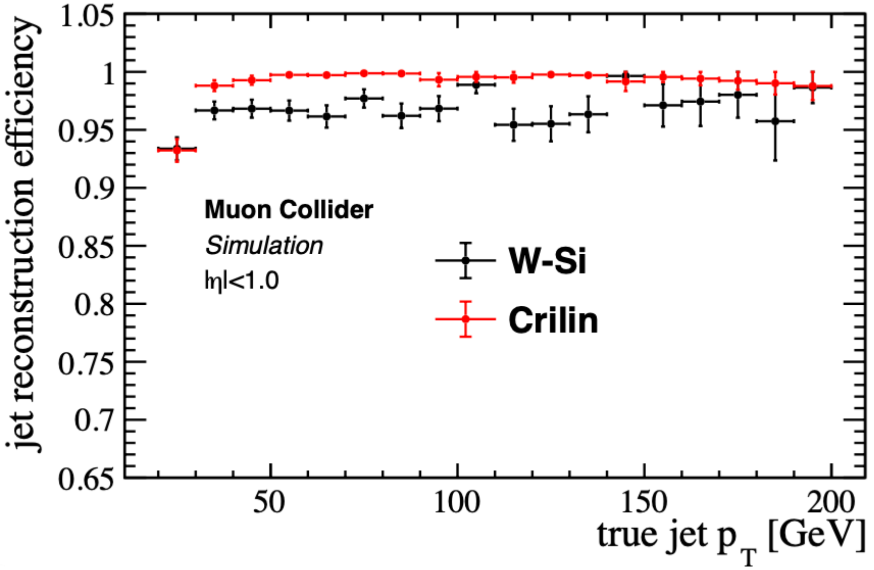


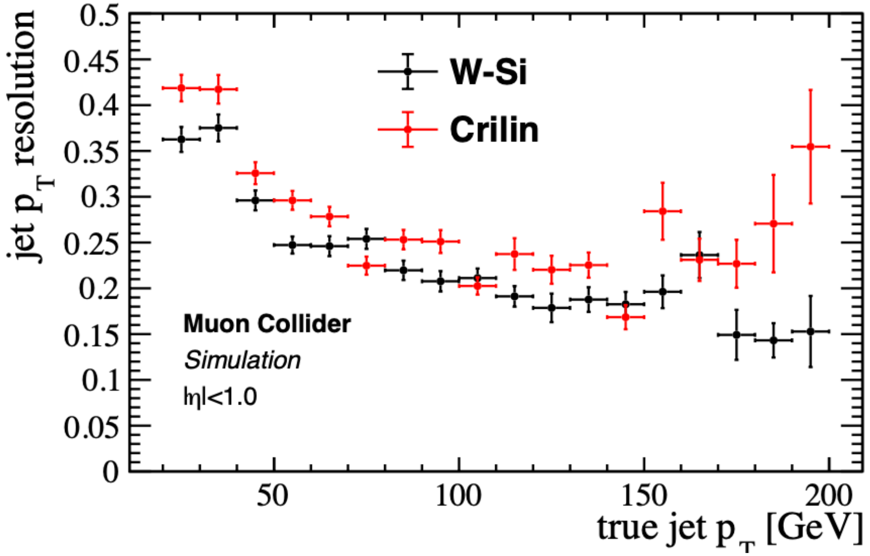
The Crilin calorimeter

- The goal is to build a crystals calorimeter that is fast, relatively cheap, with high granularity (both transversal and longitudinal), and radiation hard → optimized for muon collider characteristics.
- **Crilin** is a **semi-homogeneous** electromagnetic calorimeter made of **Lead Fluoride Crystals** (PbF_2) matrices where each crystal is readout by 2 series of 2 UV-extended surface mount **SiPMs.** *S. Ceravolo et al 2022 JINST **17** P09033*
- Two prototype versions built and tested up to now: Proto-0 and Proto-1.
- The final layout (3 TeV configuration) will consist of 5 layers of crystal matrices (22 X_0)



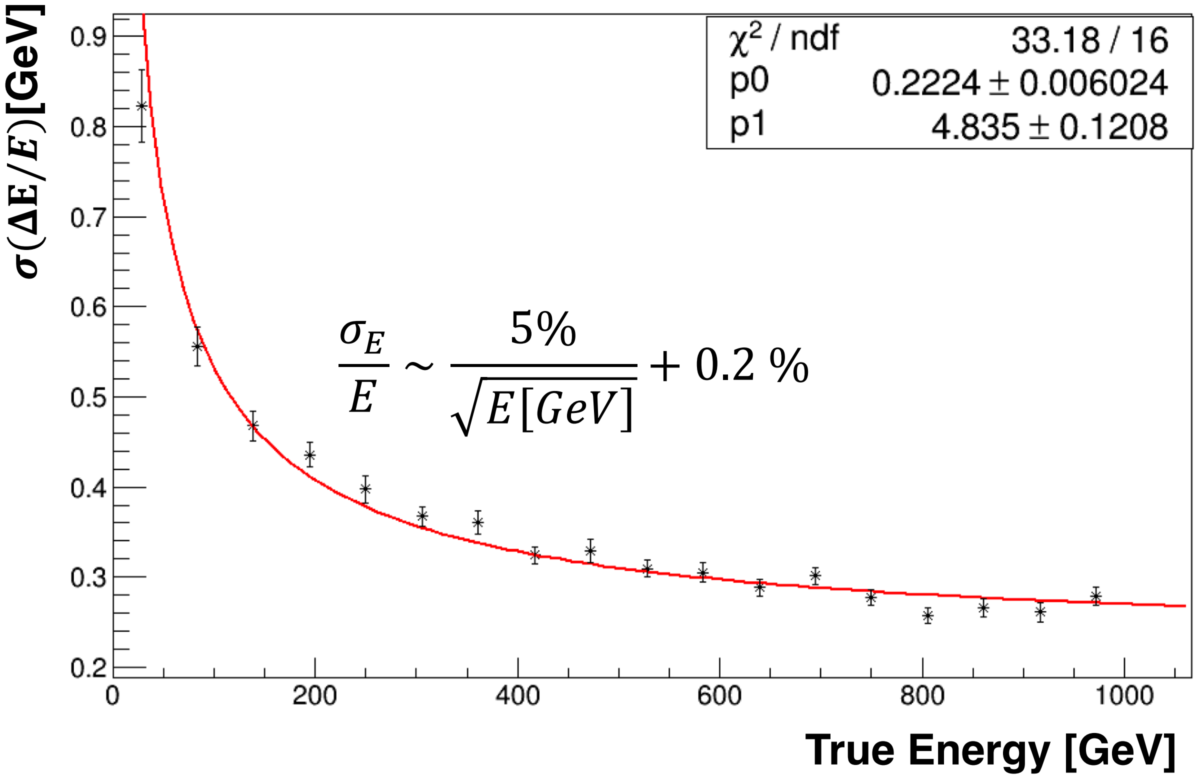




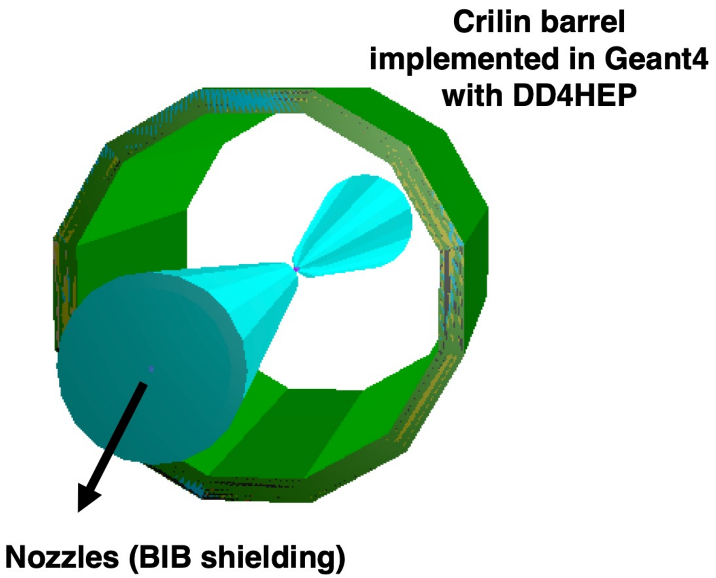


Simulation in the MC-framework

- Crilin layout was implemented in the official Muon Collider simulation framework
- It is necessary to have a good performance on the measurement of photon/electron energy **from GeV to TeV scale**
- BIB contribution is not kept into account for now (work in progress)



$$\frac{\sigma_E}{E} \sim \frac{5\%}{\sqrt{E[GeV]}} + 0.2\ \%$$



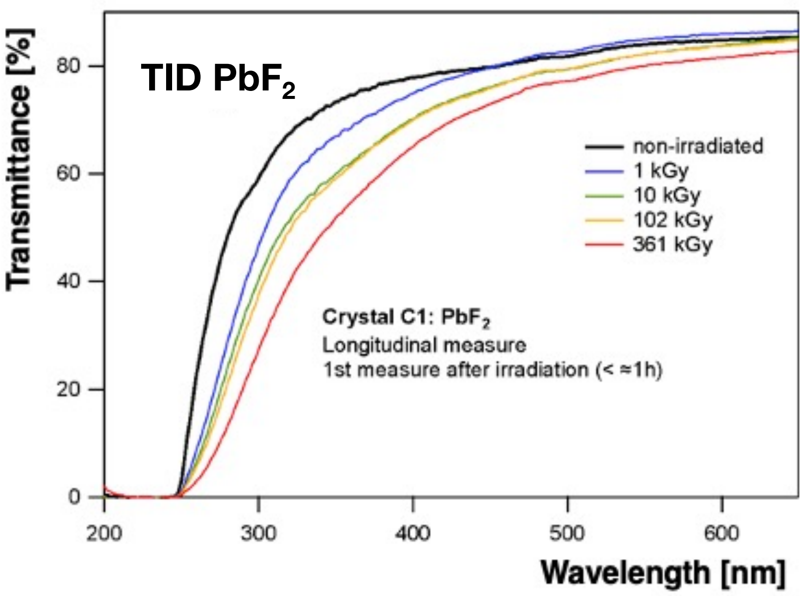
Photon energy resolution in the central barrel region 70°< θ <110°

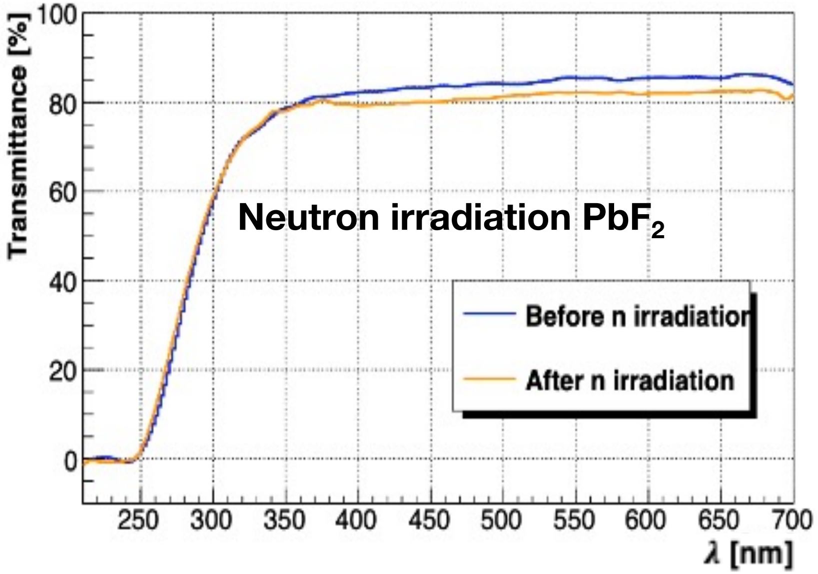
See C. Giraldin's talk, indico

Radiation hardness tests

Neutron fluence: $\sim 10^{14} n_{1MeVeq}/cm^2$ **year** on ECAL **TID:** $\sim$ **10 kGy/ year** on ECAL.

- **Cristals:** PbF_2 checked for TID (up to **1 MGy** @ Calliope, Enea Casaccia) and 14 MeV neutrons from ENEA-FNG, up to **10^{13} n/cm²**)
  - ➢ No significant loss in transmittance up to 350 kGy.
  - ➢ Good alternative (stable up to 2 MGy) is PWO-UF.
- **SiPMs:** 10 and 15 μm px-size SiPMs irradiated at ENEA-FNG up to $10^{14} n_{1MeVeq}/cm^2$
  - ➢ 10 μm px-size have a more manageable dark current increase





10 μm pixel-size SiPMs

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	1.84 ± 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

R&D status

Prototype versions

- Proto-0 (2 crystals → 4 channels)
- Proto-1 (3x3 crystals x 2 layers → 36 channels)

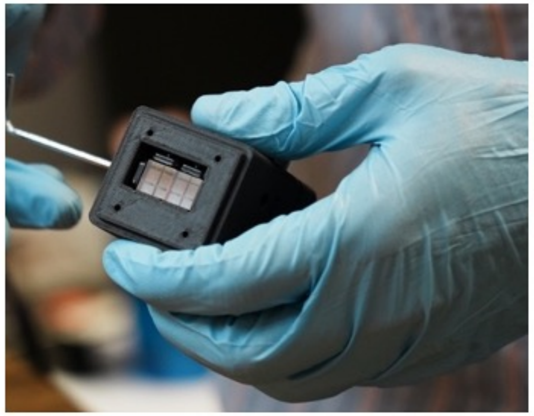
Front-end electronics

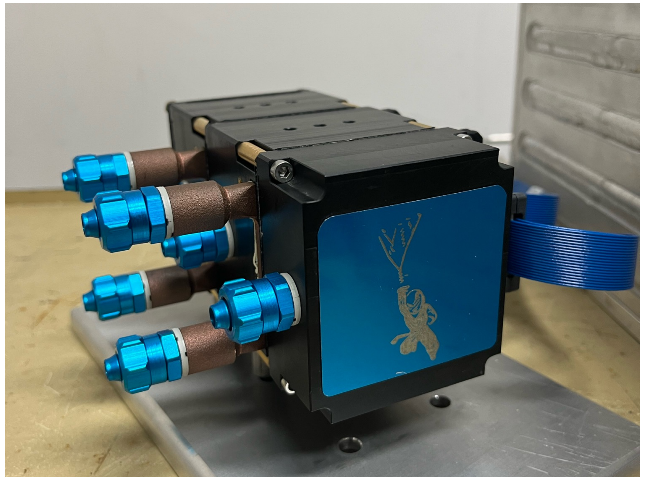
- Design completed
- Production and QC completed

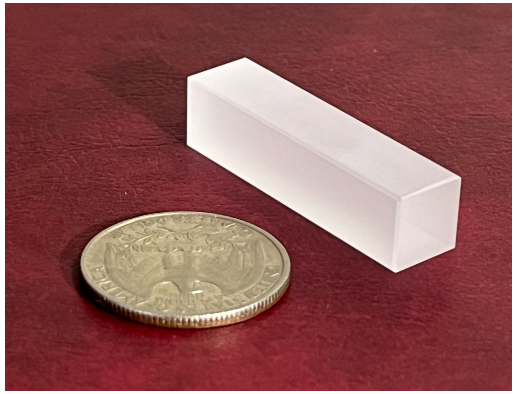
Radiation hardness campaigns

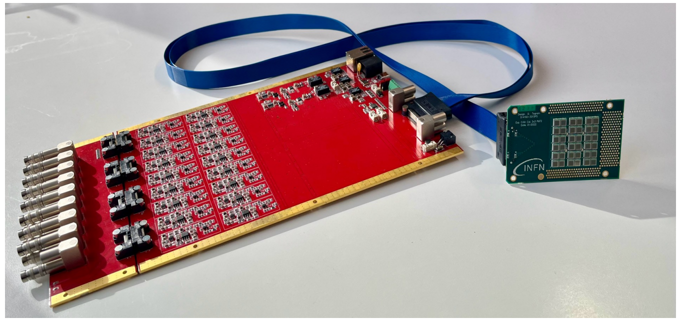
Test beam campaigns

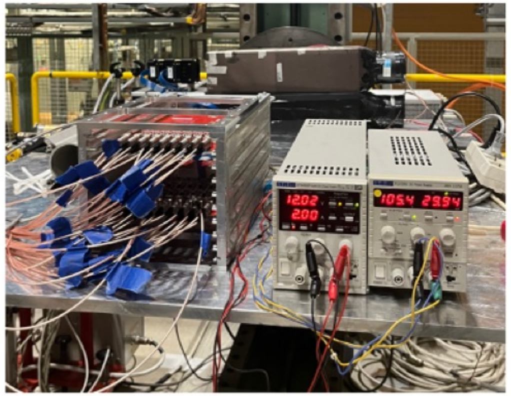
- Proto-0 at CERN H2 → C. Cantone et al. 2023 Front. Phys. 11:1223183
- Proto-1:
  - LNF-BTF (July 2023)
  - CERN-SPS-H2 (August 2023)











Proto-1: LY and timing @ 450 MeV

Aim:

- Test CRILIN performances at low energies
- Study different wrappings and configurations, Teflon and Mylar.
- First raw estimation of the energy resolution

Light Yield results:

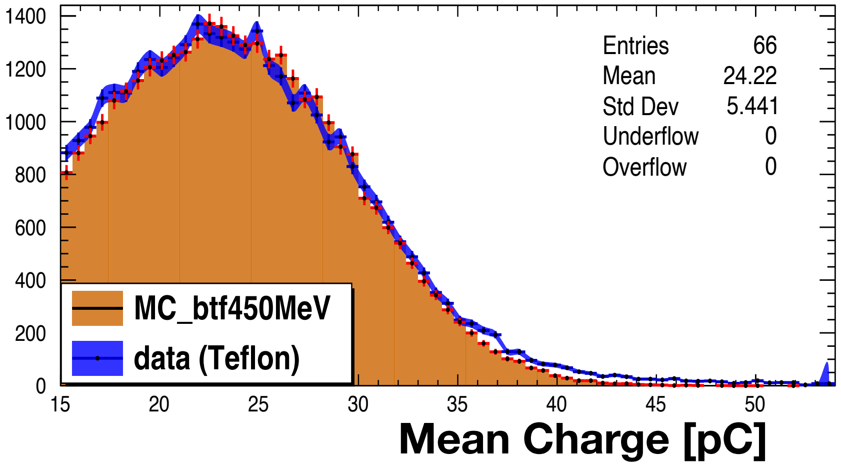
- ~ 0.32 PE/MeV @ V_{op} +2V→ Teflon
- ~ 0.25 PE/MEV @ V_{op} +2V→ Mylar

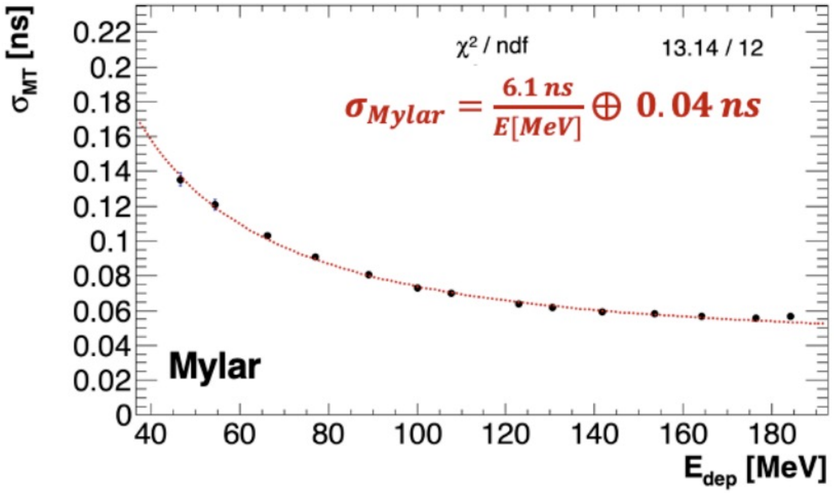
Beam: 450 MeV electrons in single particle mode

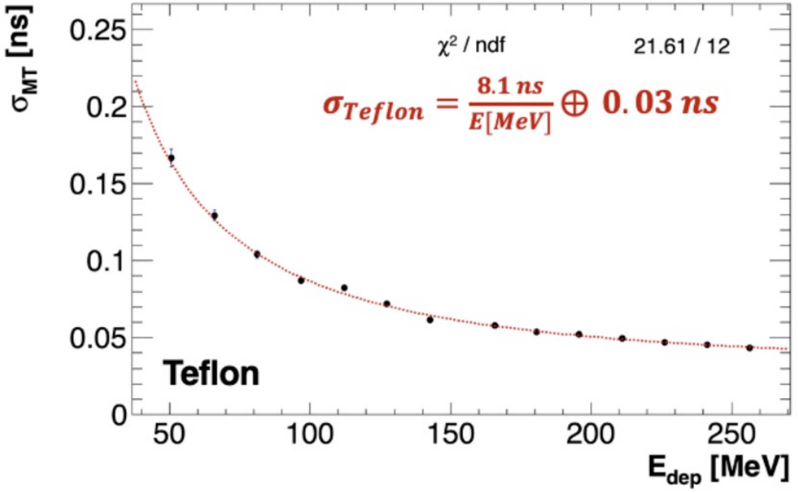
Timing results:

- Two wrappings compared → **Teflon outperforms Mylar**, higher amount of charge collected.
- Results are encouraging if we consider the very low light output

C. Cantone et al. 2024 doi:10.1109/TNS.2024.3364771

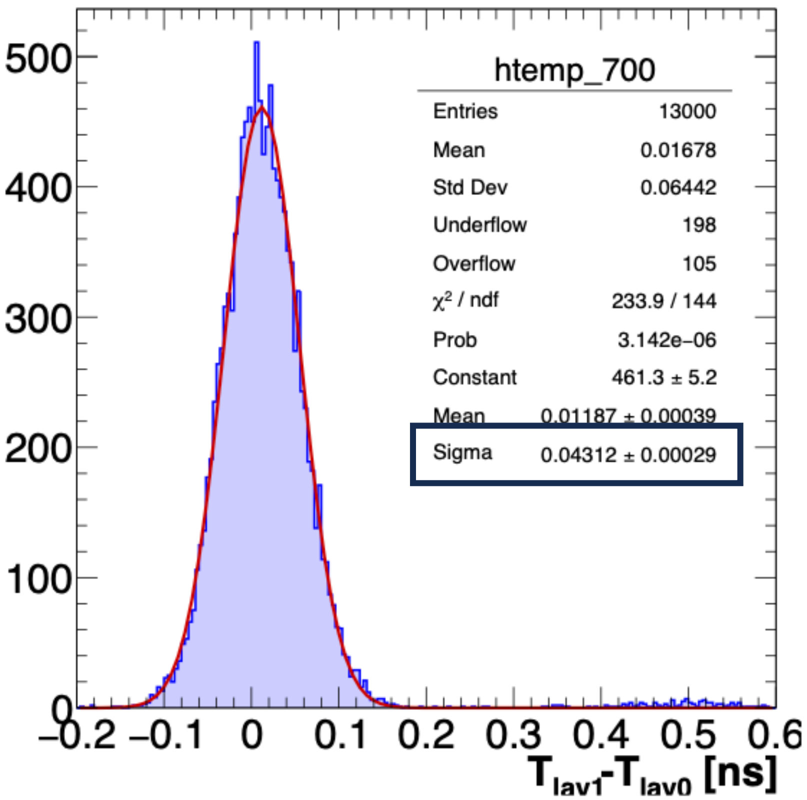


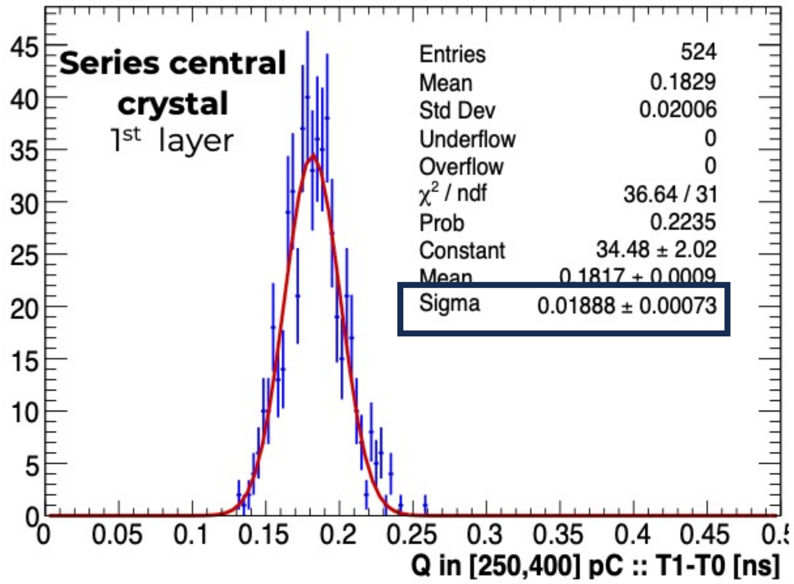


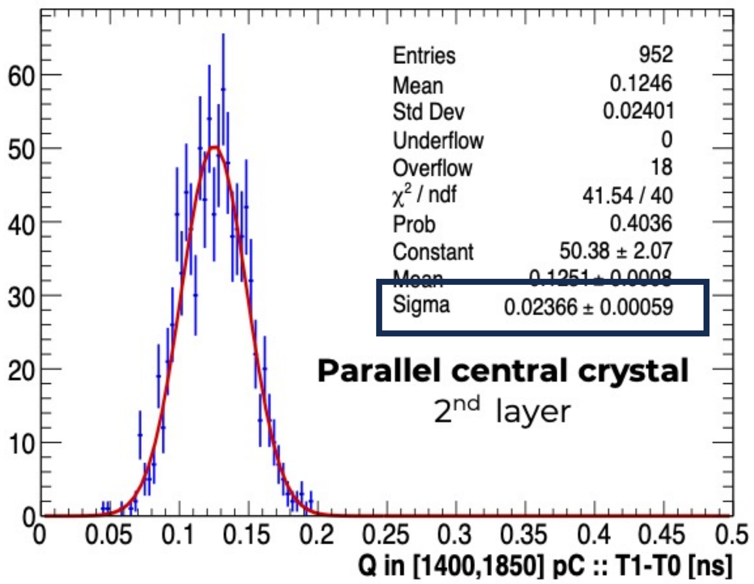


Proto-1: Timing @ 120 GeV

- CERN SPS-H2→ energy scan with electrons from 40 GeV to 150 GeV
- **Aim:** evaluation of energy and time resolution
- Time Resolution @ 120 GeV is of **O(20 ps)** both for both layers using the two channels time difference for the central crystals
- Studies on using the layer mean time are still ongoing
- For TLAYER1 – TLAYER0 **σ(ΔT) ~ 40 ps** mainly dominated by synchronisation jitter estimated to be O(32ps)



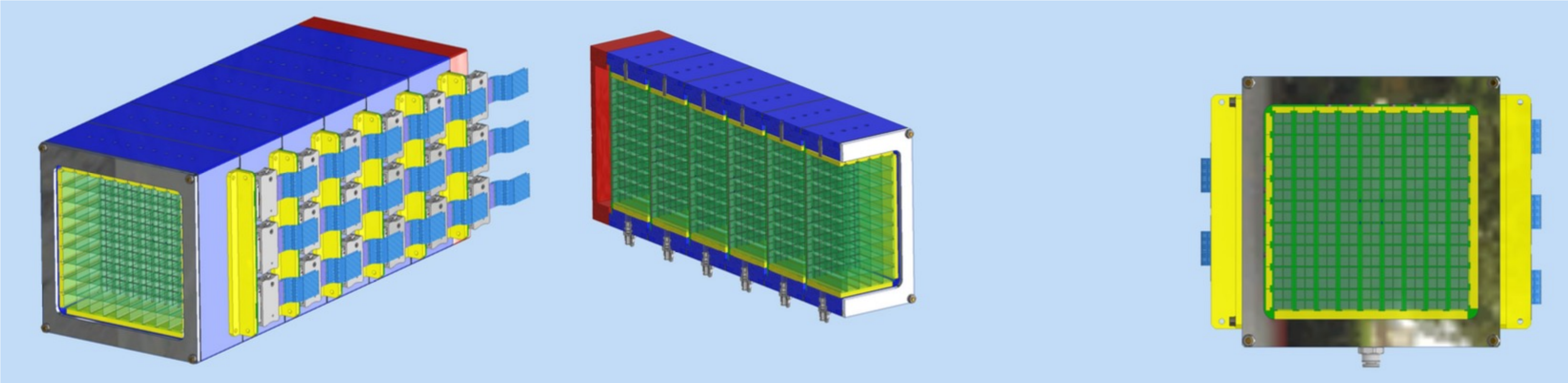




Analysis still on going

Next steps on ECAL side

- Test beam @ BTF of LNF with e- to measure the light yield loss in terms of photoelectrons detected by the SiPMs after 10 Mrad of irradiation from March 25, 2024.
- 2024 – 2025:
  We submitted and won a PRIN proposal for a 210 kEUR grant for the project CALORHINO: an innovative radiation-hard calorimeter proposal for a future Muon Collider Experiment →120 kEur has been assigned to develop a 5x5 x4(layers) Crilin prototype: 1 MR – 16.8 X0
- DRD6-WP3 from 2025:
  Expanding upon the PRIN prototype to a 9x9 x4(layers) configuration, with a target of 2 M_R – 21 X_0.



HCAL R&D

HCAL requirements

BIB in hadron calorimeter:

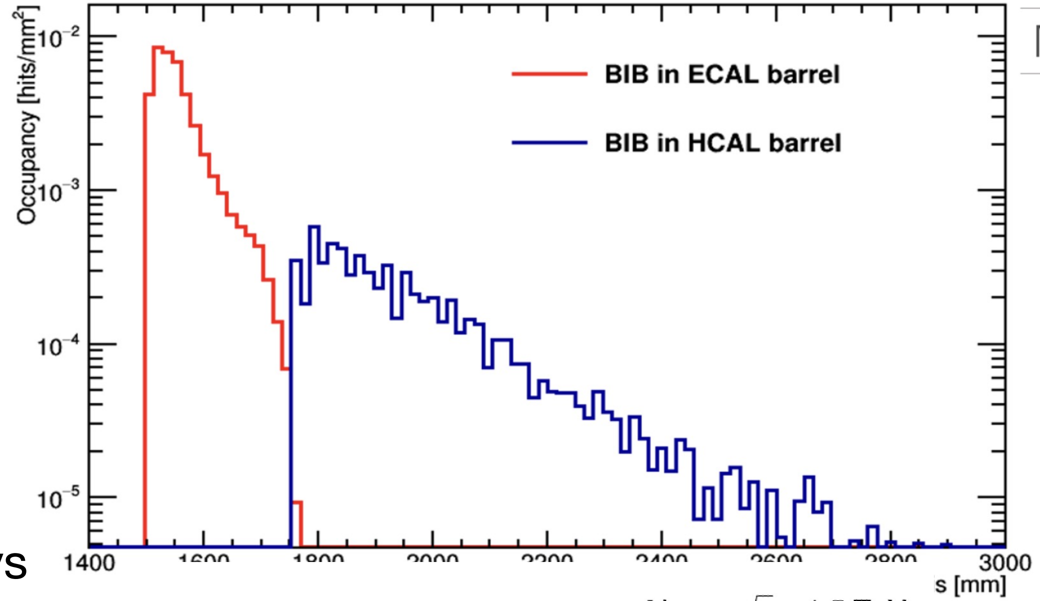
- Mostly photons (96%) and neutrons (4%)
- Large asynchronous component
- Occupancy: 0.06 hits / cm^2

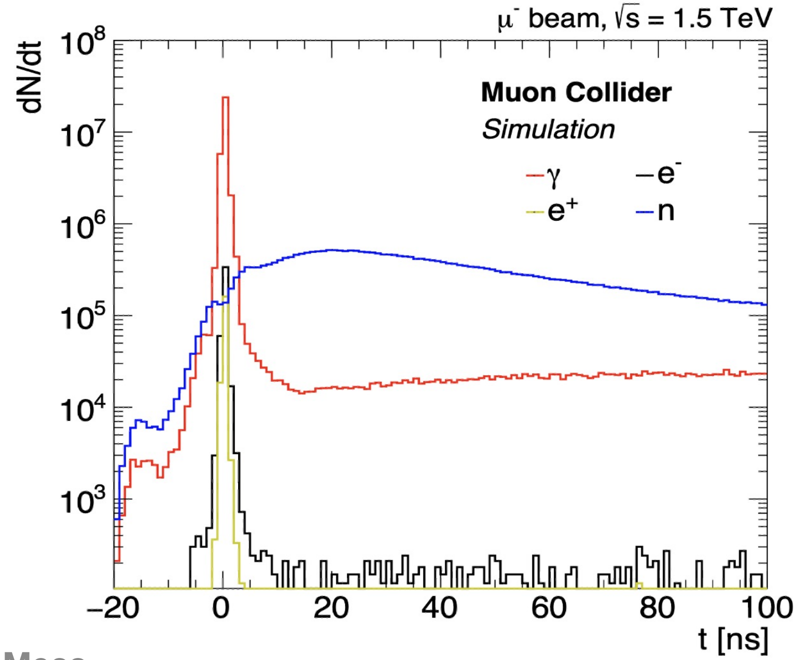
Goals:

- 3-4 % jet energy resolution for hadronic Z decays
- How: particle flow reconstruction
    - $\frac{10\%}{\sqrt{E[GeV]}}$ for ECAL
    - $\frac{30\%}{\sqrt{E[GeV]}}$ **for HCAL**

Detector requirements:

- High granularity (< 3cm^2)
- Single layer timing 100 ps - few ns





HCAL readout with MPGD

Proposal: micro-pattern gaseous detectors as readout layers for a sampling hadronic calorimeter

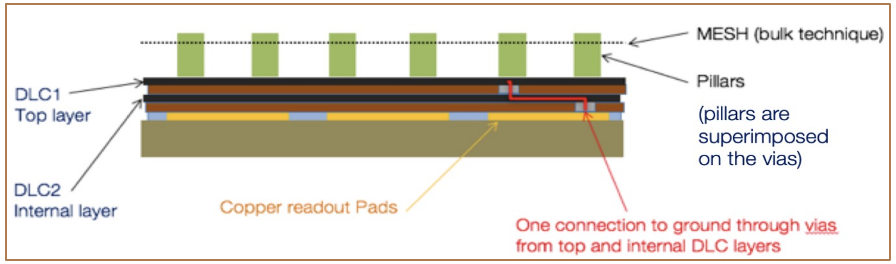
MPGD features:

- **cost-effectiveness** for large area instrumentation
- radiation hardness up to several **C/cm²**
- **discharge rate** not impeding operations
- rate capability **O(MHz/cm²)**
- space resolution **O (100 *μ*m)**, allowing high granularity
- time resolution with MIPs **few ns**

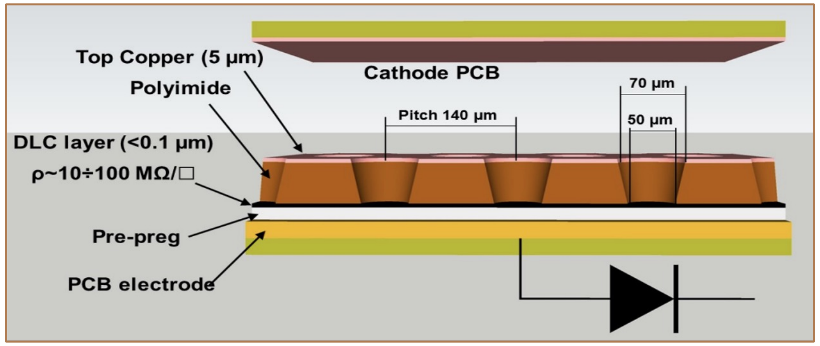
Plan: systematically comparing two MPGD technologies for hadronic calorimetry: *μ*-RWELL and resistive MIcroMegas

See A. Pellecchia's talk, indico

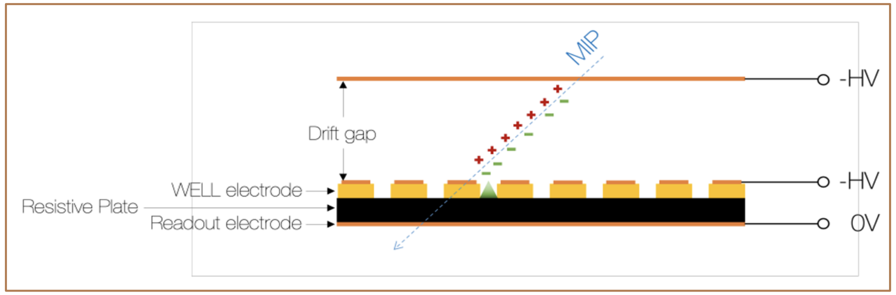
Micromegas (MM)



*μ*RWELL



RPWELL



MPGD-HCAL simulations

Two ongoing simulation activities:

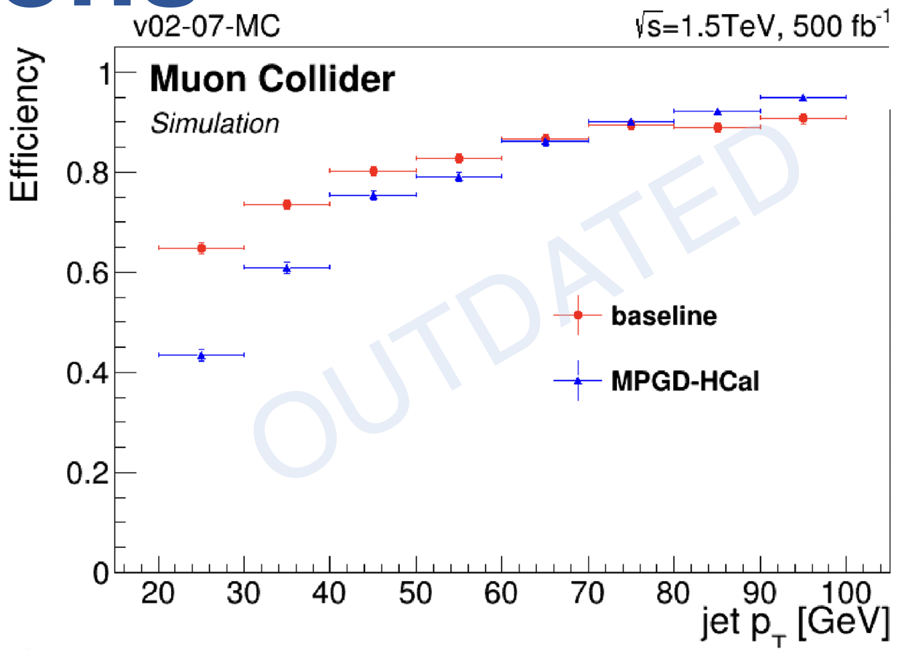
Simulation in Muon collider framework: an MPGD-HCAL **geometry** has been **implemented** in the Muon collider software.

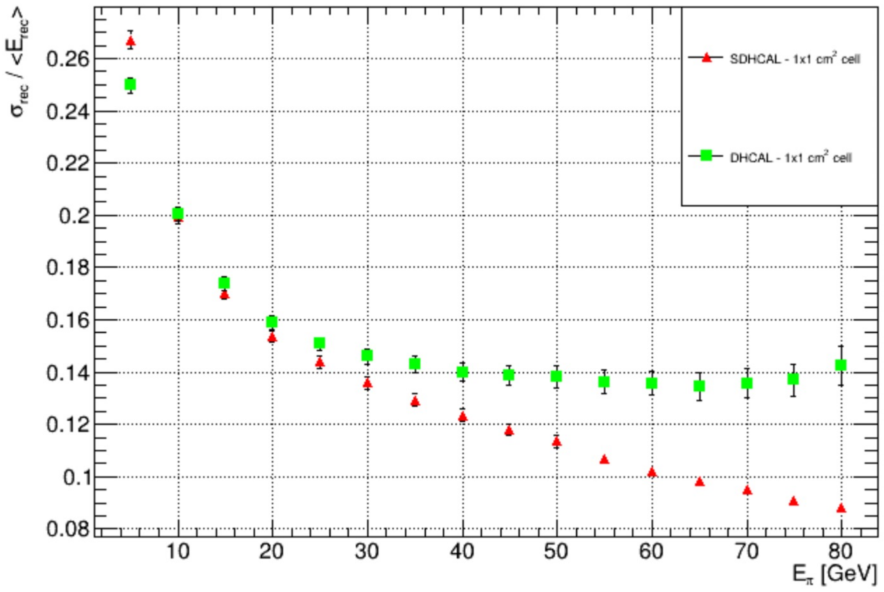
Efficiency and resolution of MPGD calorimeter is comparable with baseline, but **bugs** causing worse efficiency and energy resolution are being investigated. Ongoing **debugging**

Standalone Geant4 simulation for shower containment calculation

- Longitudinal containment in 10 λ, transversal in 3 λ

Main result: Semi-digital calorimeter energy resolution down to 8% for a 80 GeV pion





MPGD-HCAL hardware R&D

Prototypes of resistive MPGDs produced and tested within **RD51 common project:**

- 7 μ-RWELL, 4 MicroMegas, 1 RPWELL

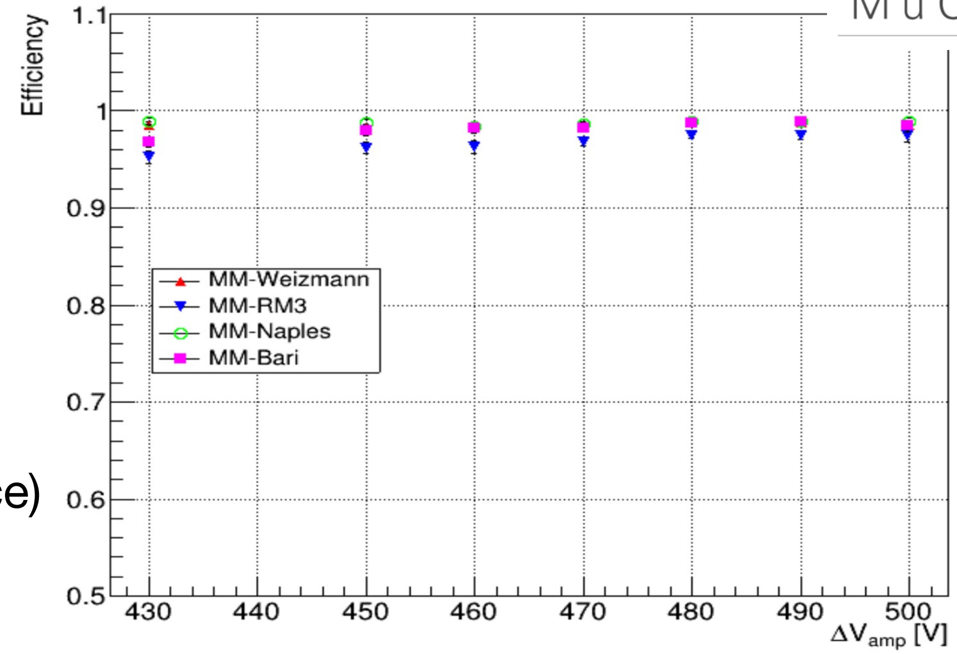
Goal: comparing the three technologies first with MIPs, then in calorimetry

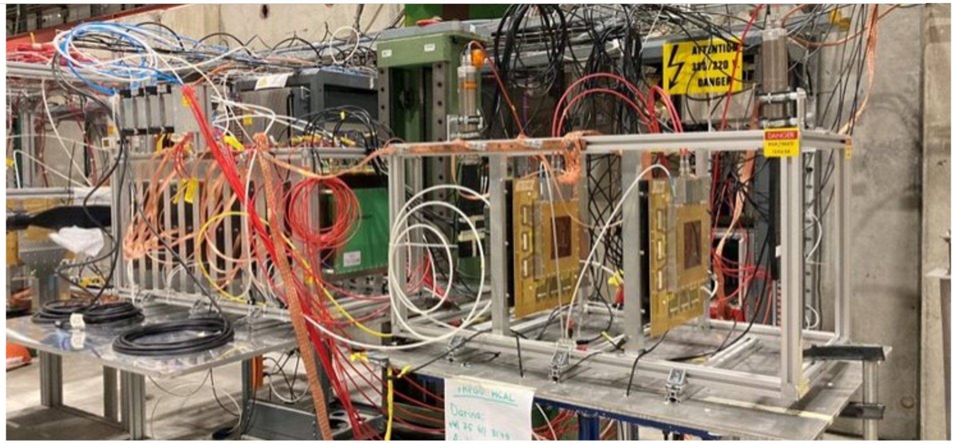
Performed **two test beams**:

- SPS with high-energy muons in July 2023 (MPGD performance)
- PS with low-energy pions in Aug-Sept 2023 (calorimeter performance)

Results:

- Good detector intrinsic performance (space resolution, efficiency)
- Various response uniformity for different technologies, under investigation
- High probability of cross-talk between pads due to readout vias routing

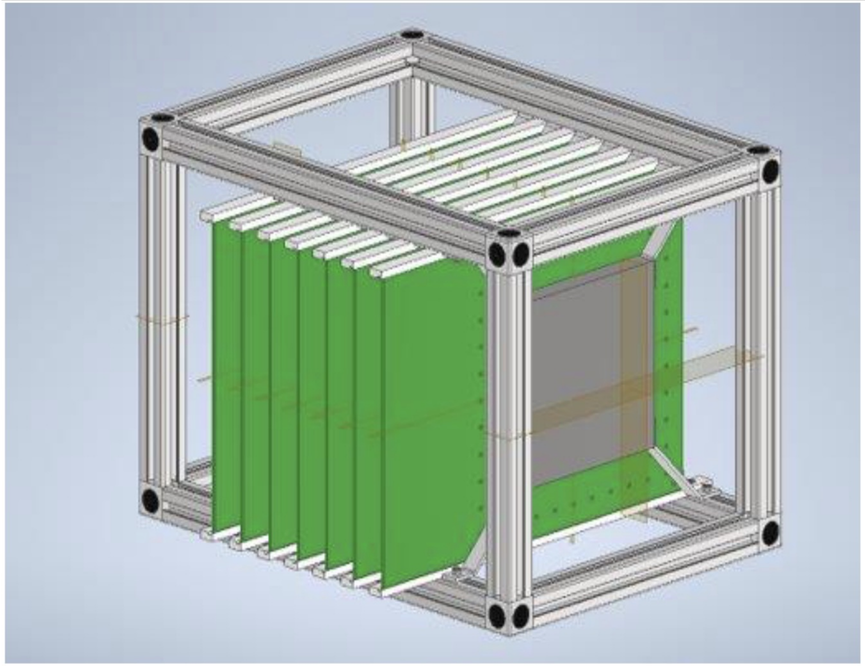




Test beam setup at SPS, Size: 20x20 cm², 1x1 cm² pads

Next steps on HCAL

- Consolidating results with present prototypes in two test beams in 2024
- Beginning integration with more modern readout electronics
- **New prototypes:**
  - 4 **large detectors** (50×50 cm^2) to be built in 2024
  - Design **optimization** to exclude cross-talk and simplify manufacturing
  - Redesign of modular mechanics
  - Started **common project with Crilin** (ECAL): expected common test beam in 2025

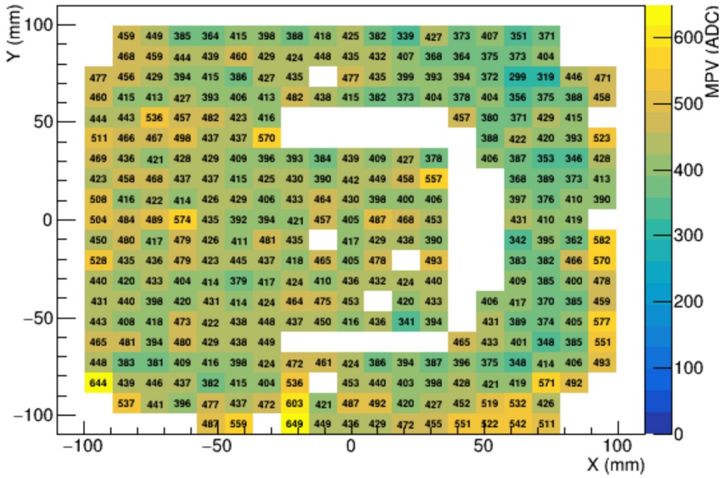


Backup slides

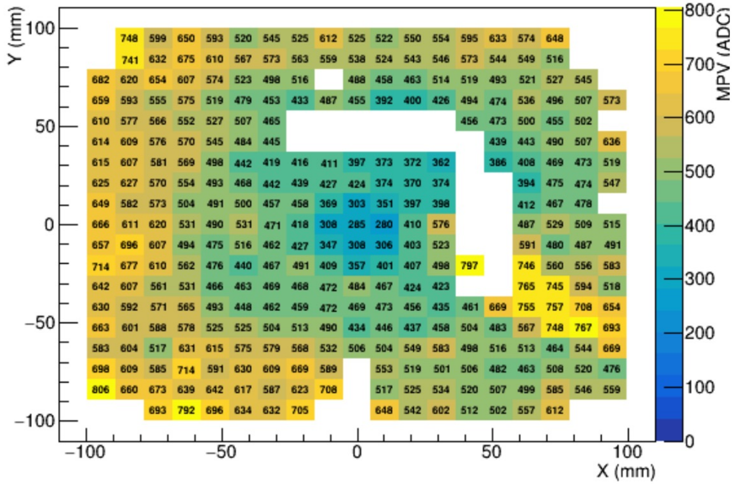
Backup plots

Various response uniformity for different technologies, under investigation

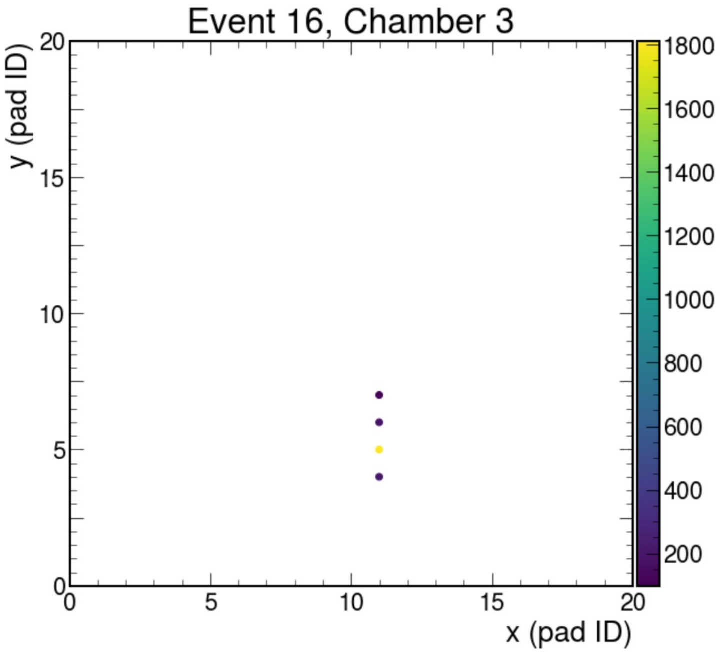
Charge map of muon hits in a MicroMegas

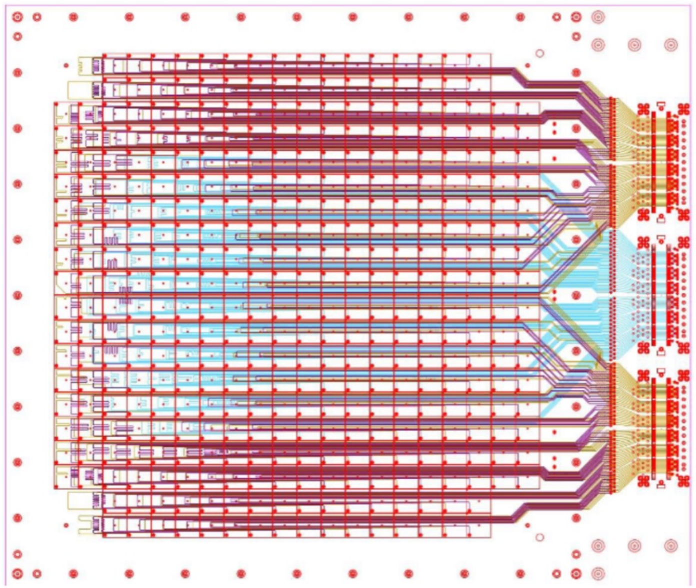


Charge of muon hits in a µ-RWELL



High probability of cross-talk between pads due to readout vias routing



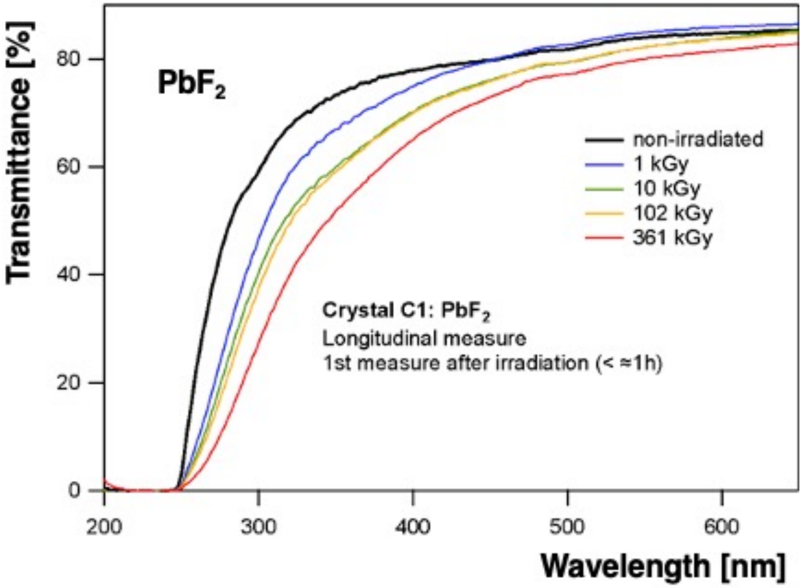


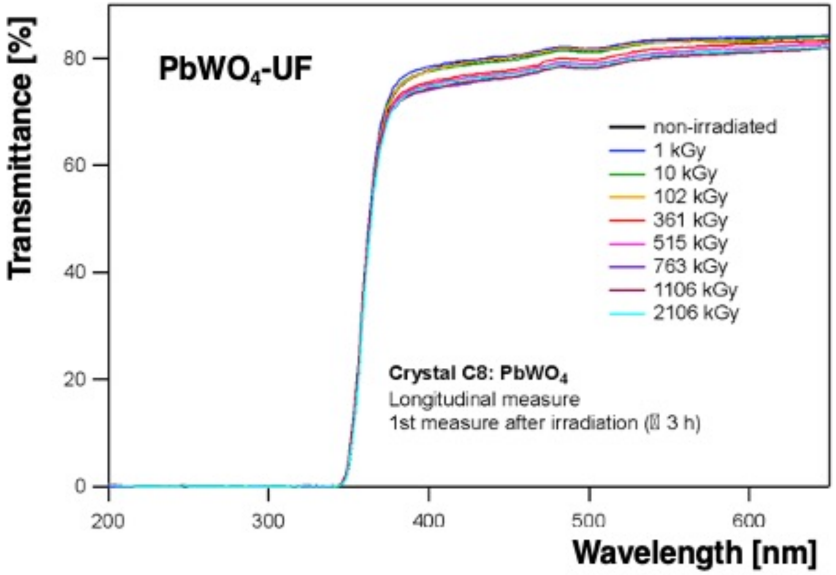
Radiation hardness: Crystals

Neutron fluence:~10^{14} n_{1MeVeq}/**cm² year** on ECAL **TID** ~ **100 krad/year** on ECAL.

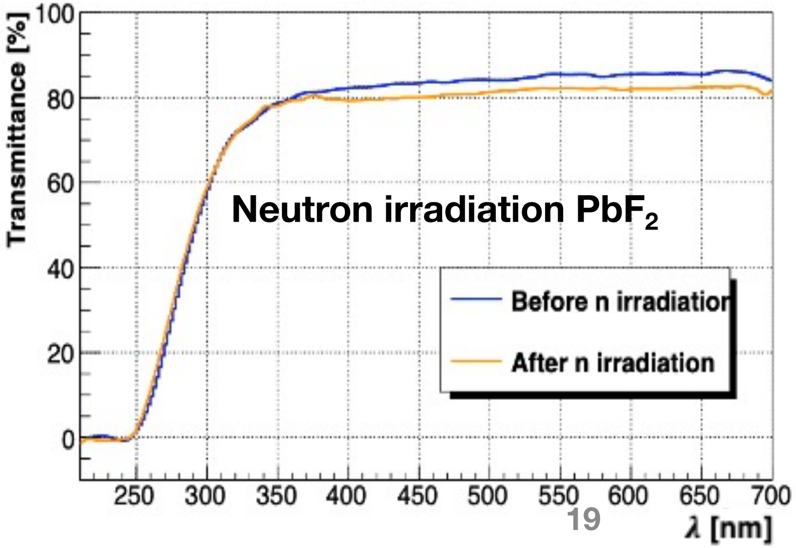
Radiation hardness of two PbF_2 and $PbWO_4$-UF crystals (10x10x40 mm³) checked for TID (up to **1 MGy** @ Calliope, Enea Casaccia) and neutrons (14 MeV neutrons from Frascati Neutron Generator, Enea Frascati, up to **10^{13} n/cm²**)

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





Crystal	PbF_2	PWO-UF
Density [g/cm³]	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



Radiation hardness: SiPMs

Neutrons irradiation:
14 MeV neutrons with a total fluence of 10^{14} n/cm² (@FNG) for 80 hours on a series of two SiPMs (10 and 15 μm pixel-size). Extrapolated from I-V curves at 3 different temperatures:

- Currents at different operational voltages.
- Breakdown voltages;

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	12.56 ± 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

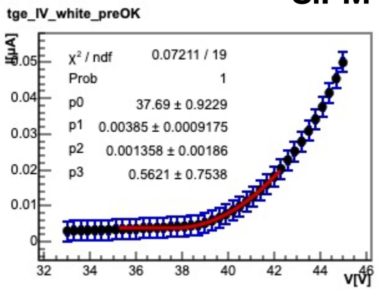
10 μm pixel-size

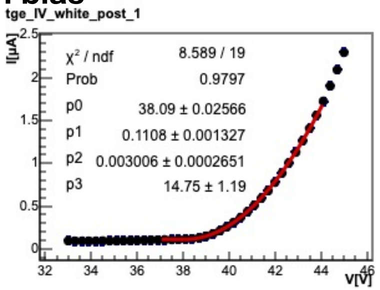
T [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	76.76 ± 0.01	1.84 ± 0.01	6.82 ± 0.01	29.91 ± 0.01
-5 ± 1	77.23 ± 0.01	2.53 ± 0.01	9.66 ± 0.01	37.51 ± 0.01
0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

For the expected radiation level, **the best SiPMs choice are the 10 μm one** for its minor dark current contribution.

TID:
no significant amount of dark current up to 10 kGy (@Calliope).

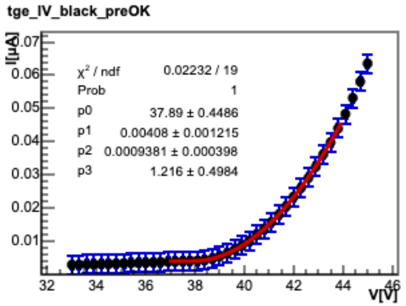
SiPM with bias

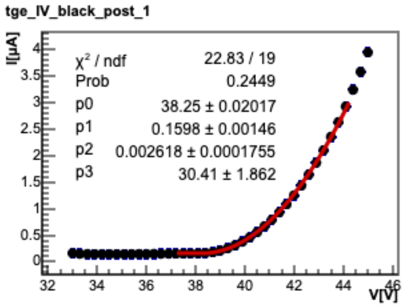




10 kGy dose

SiPM w/o bias

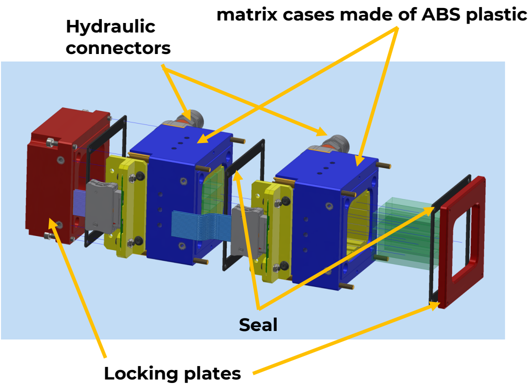


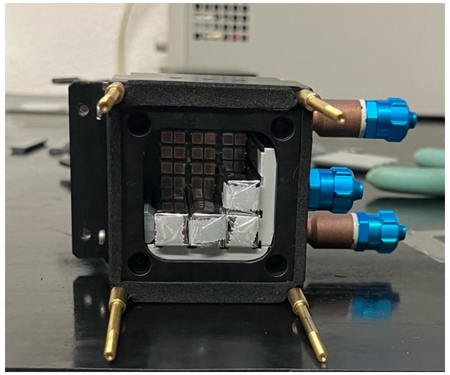


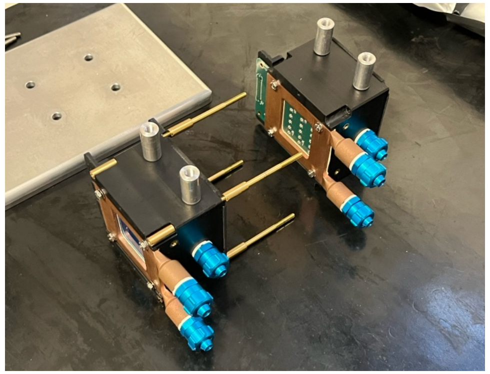
Proto-1: Mechanics and Electronics

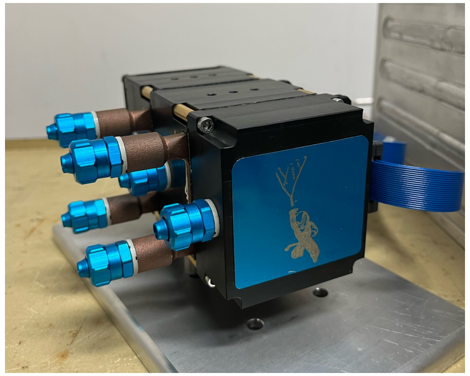
Mechanics:

- Two stackable and interchangeable submodules assembled by bolting, each composed of 3x3 crystals+36 SiPMs (2 channel per crystal)
- light-tight case which also embeds the front-end electronic boards and the heat exchanger needed to cool down the SiPMs.



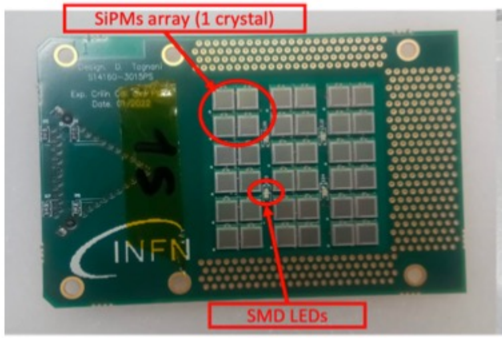


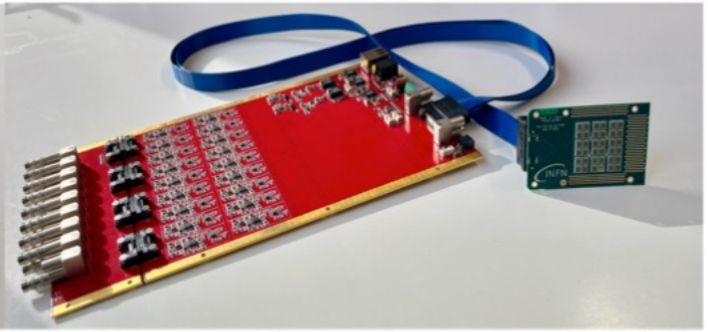




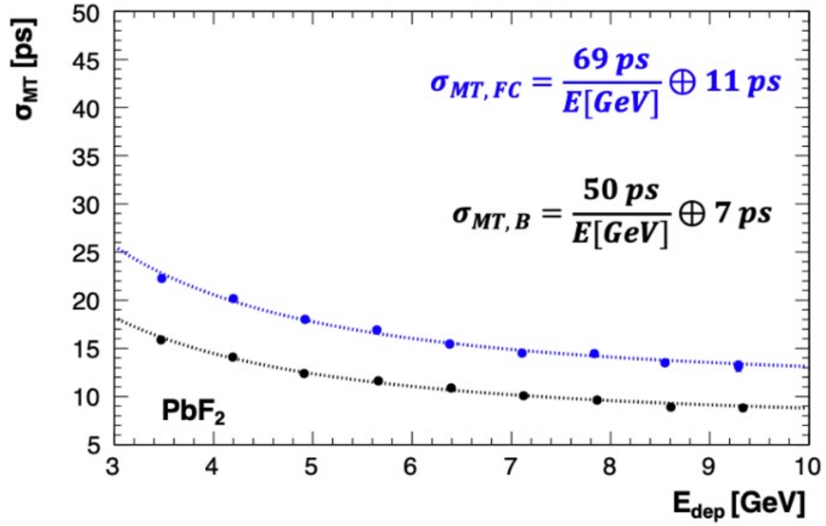
Electronics:

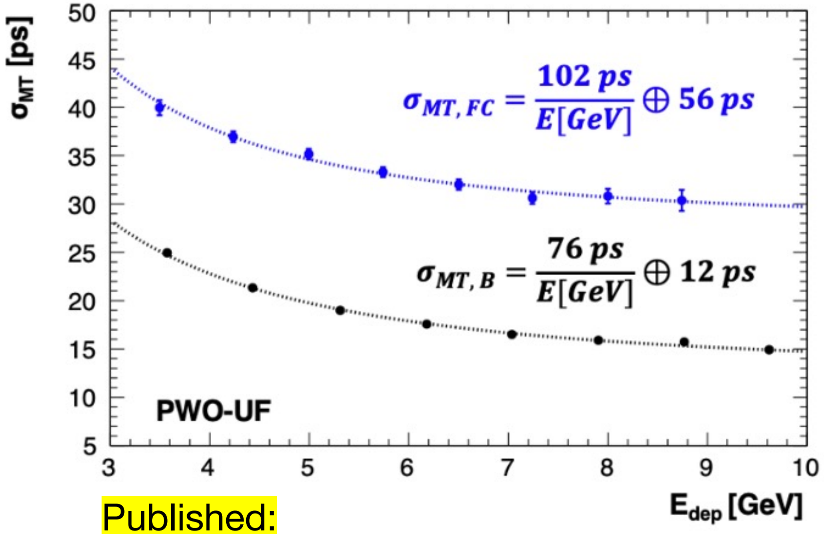
- **SiPMs board:** custom SiPM array board 36x10 μm Hamamatsu SMD SiPMs
- **Mezzanine board:** 18x readout channels → amplification, shaping and individual bias regulation, slow control routines



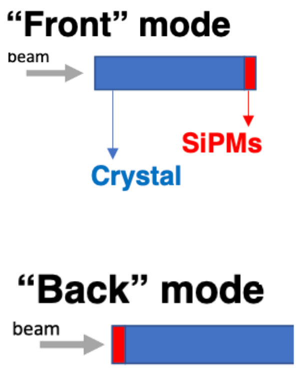


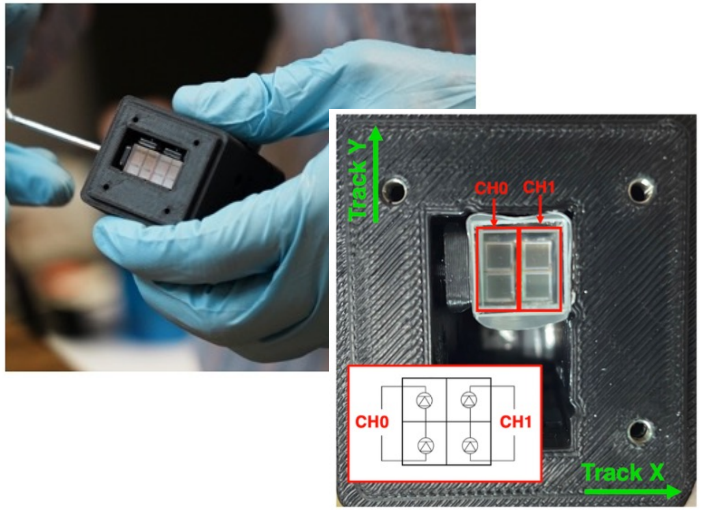
Test beam campaigns: Proto-0





- CERN SPS-H2→ 120 GeV e^- beam on a single crystal prototype
- Cherenkov systematics in the light propagation→ **FRONT** and **BACK** orientation tried
- The **BACK** run time resolution is better for both crystals.
- PbF_2 outperforms $PbWO_4$-UF despite its higher light output (purely Cherenkov)
- **PbF_2** → σ_{MT} < 25 ps worst-case for E_{dep} > 3 GeV
- **$PbWO_4$-UF** → σ_{MT} < 45 ps worst-case for E_{dep} > 3 GeV





PbF_2	back-run	front-run
E_{dep} MPV [GeV]	4.26 ± 0.01	4.81 ± 0.03
E_{dep} sigma [GeV]	1.35± 0.01	1.46 ± 0.02
pC/MeV	~29.3	~35.6
NPE/MeV	~0.26	~0.30

PWO-UF	back-run	front-run
E_{dep} MPV [GeV]	6.39 ± 0.01	6.88 ± 0.01
E_{dep} sigma [GeV]	1.83 ± 0.01	1.99 ± 0.01
pC/MeV	~66.7	~76.9
NPE/MeV	~0.58	~0.67

Published:
Frontiers in Physics, https://doi.org/10.3389/fphy.2023.1223183

Test beam campaigns: Proto-1 BTF

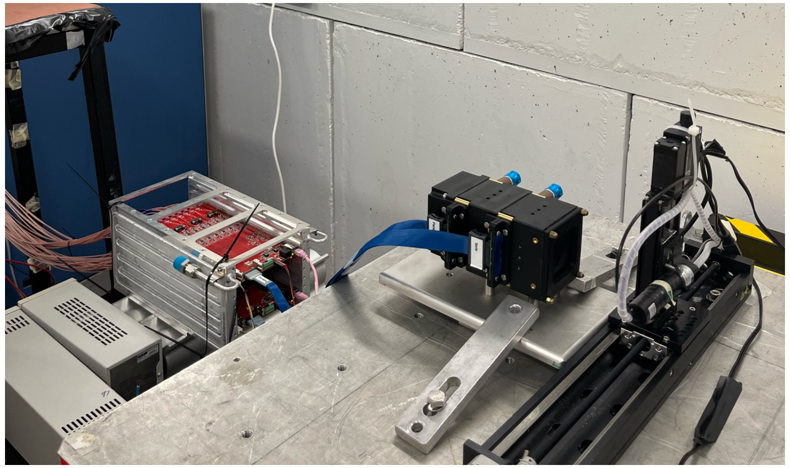
Aim:

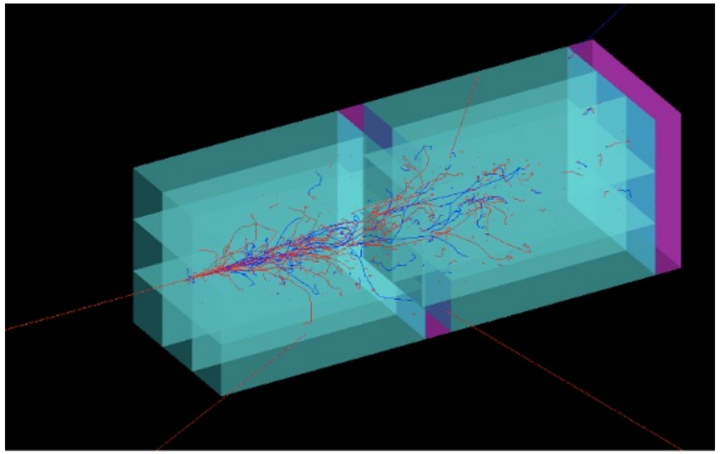
- Test CRILIN performances at low energies
- Study different wrappings and configurations
- First raw estimation of the energy resolution

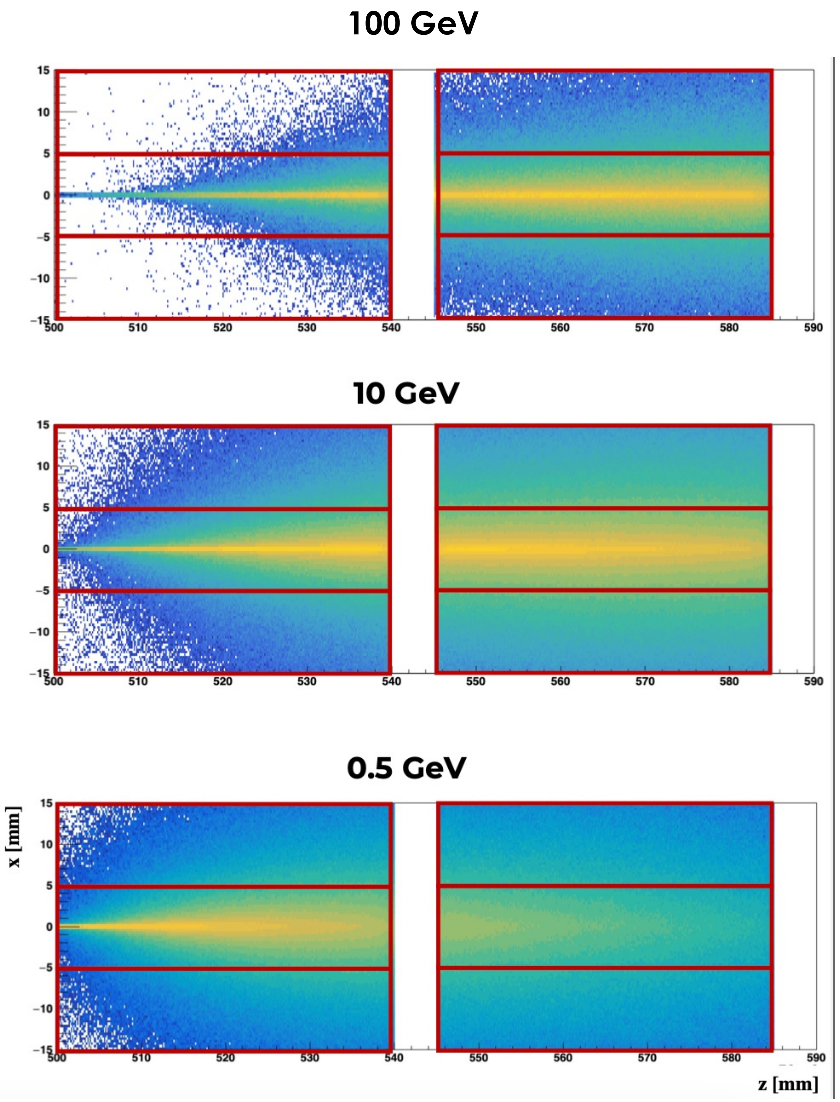
Beam: 450 MeV electrons in single particle mode

Proto-1:

- PbF_2 crystals → wrappings: Mylar and Teflon
- Readout: 10 µm pixel-size SiPMs, one layer with series connection, the other with parallel connection

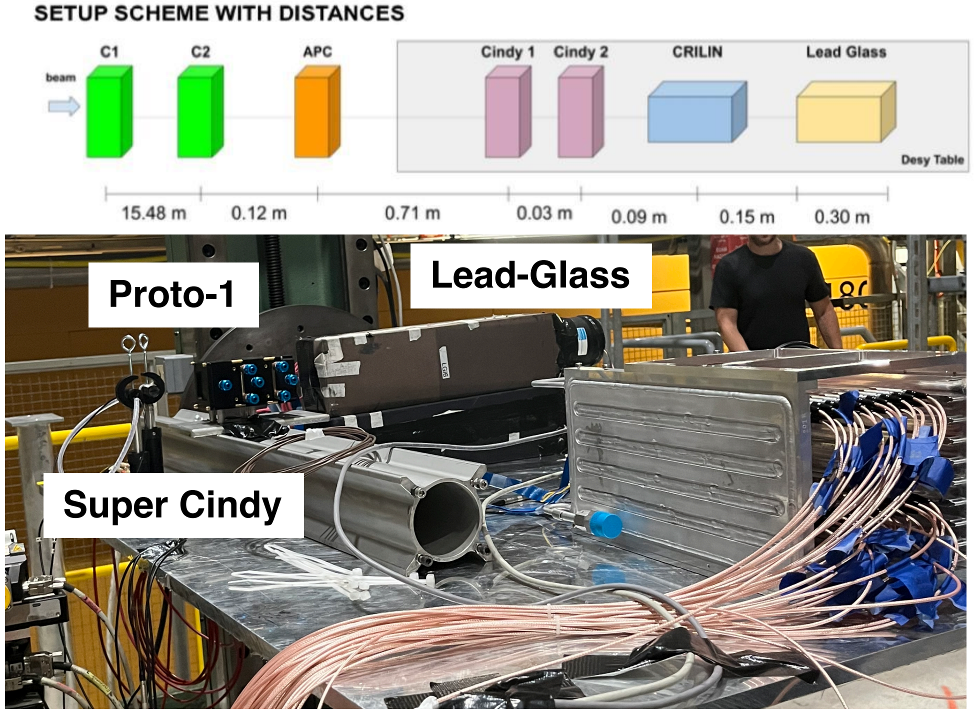


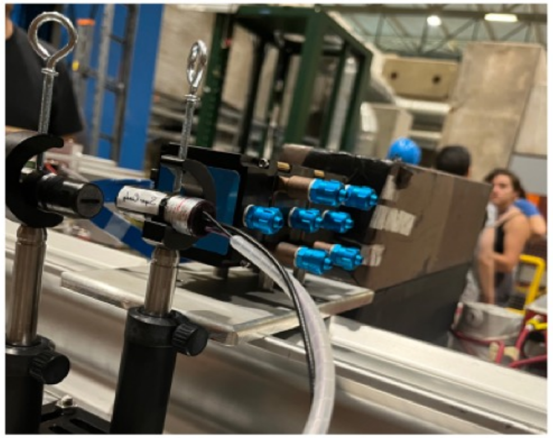


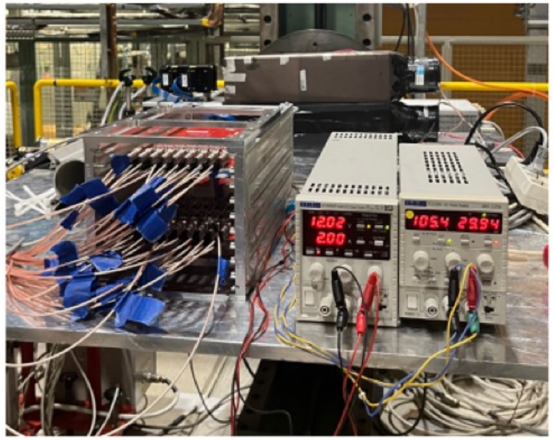


Test beam campaigns: Proto-1 H2

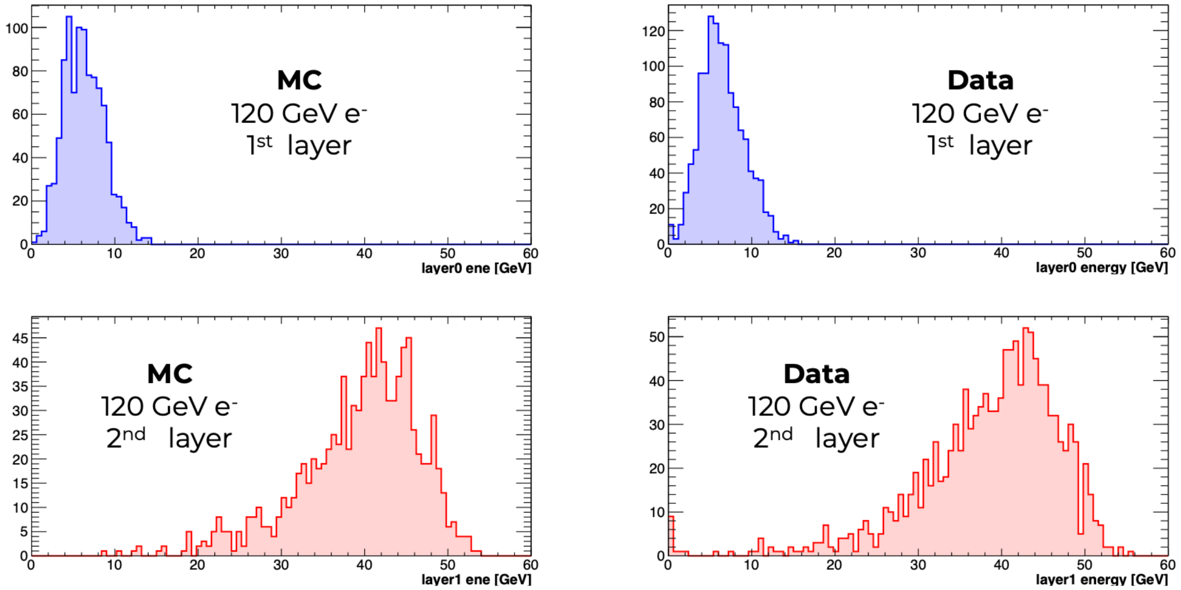
- CERN SPS-H2→ energy scan with electrons from 40 GeV to 150 GeV
- Aim: evaluation of energy and time resolution
- Beam reconstructed with 2 silicon strip telescopes
- Data acquisition with 2 CAEN V1742 (32 ch each) modified @ 2 Vpp
- 5 Gs/s sampling rate







Data-MC agreement



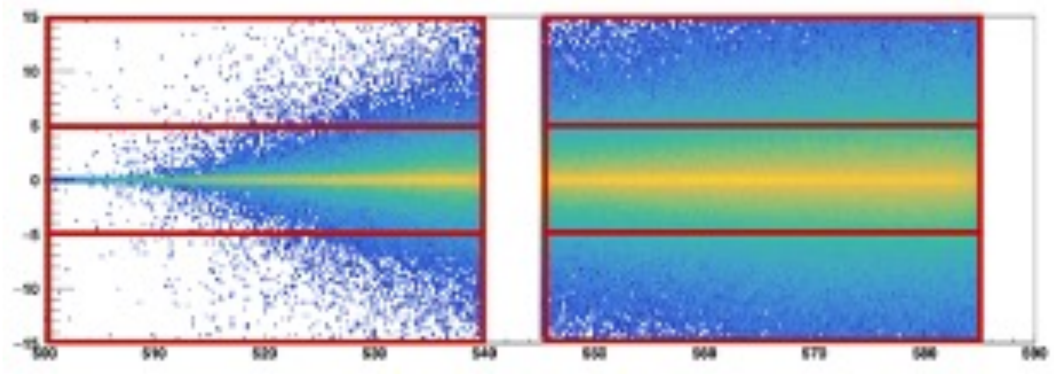
Geant-4 simulation of the prototype with a 120 e^- beam

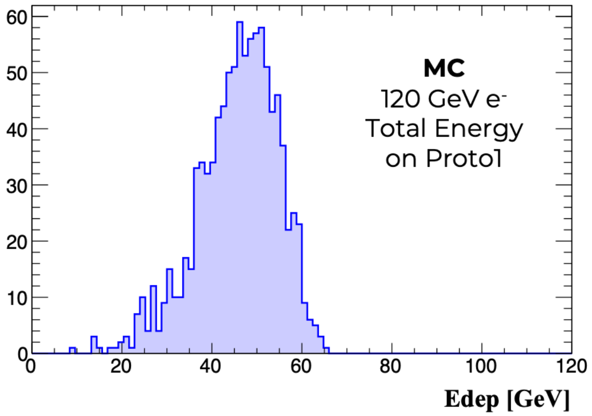
Energy deposit simulated:

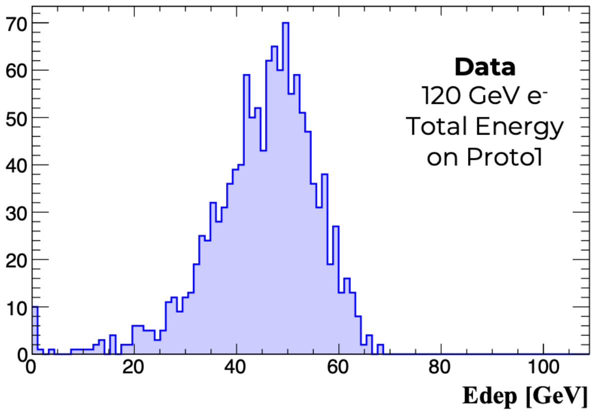
- in the two layers
- In the whole prototype

Excellent agreement between data and MC for all configurations

120 GeV

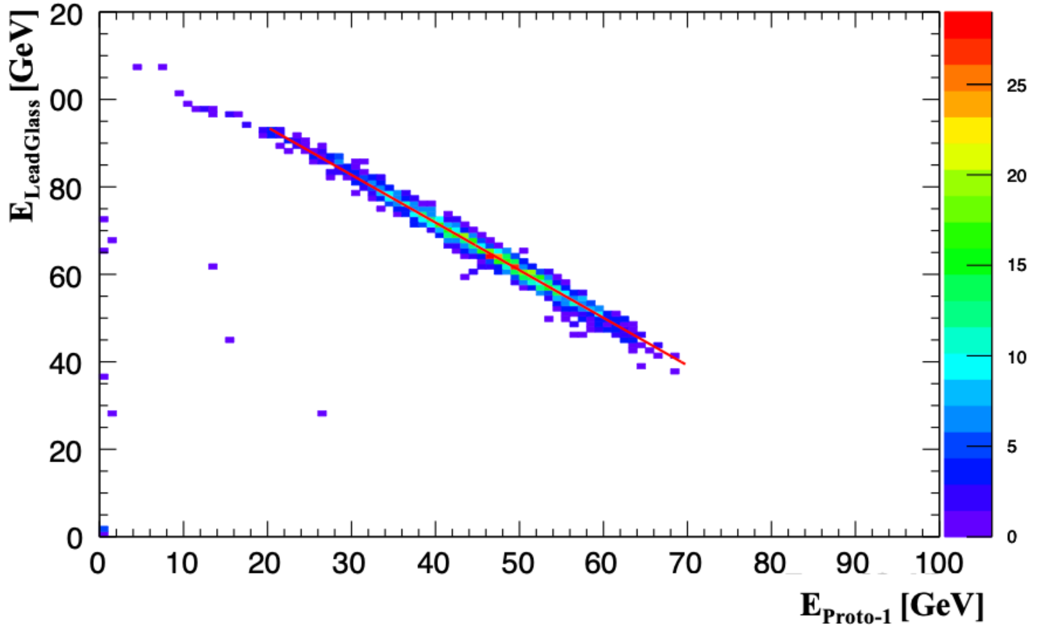


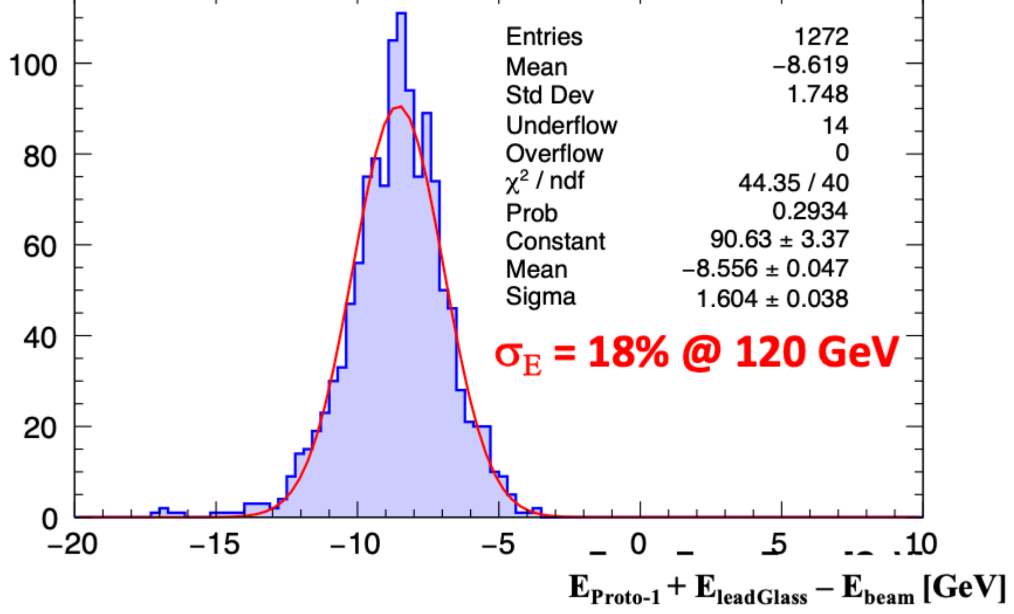


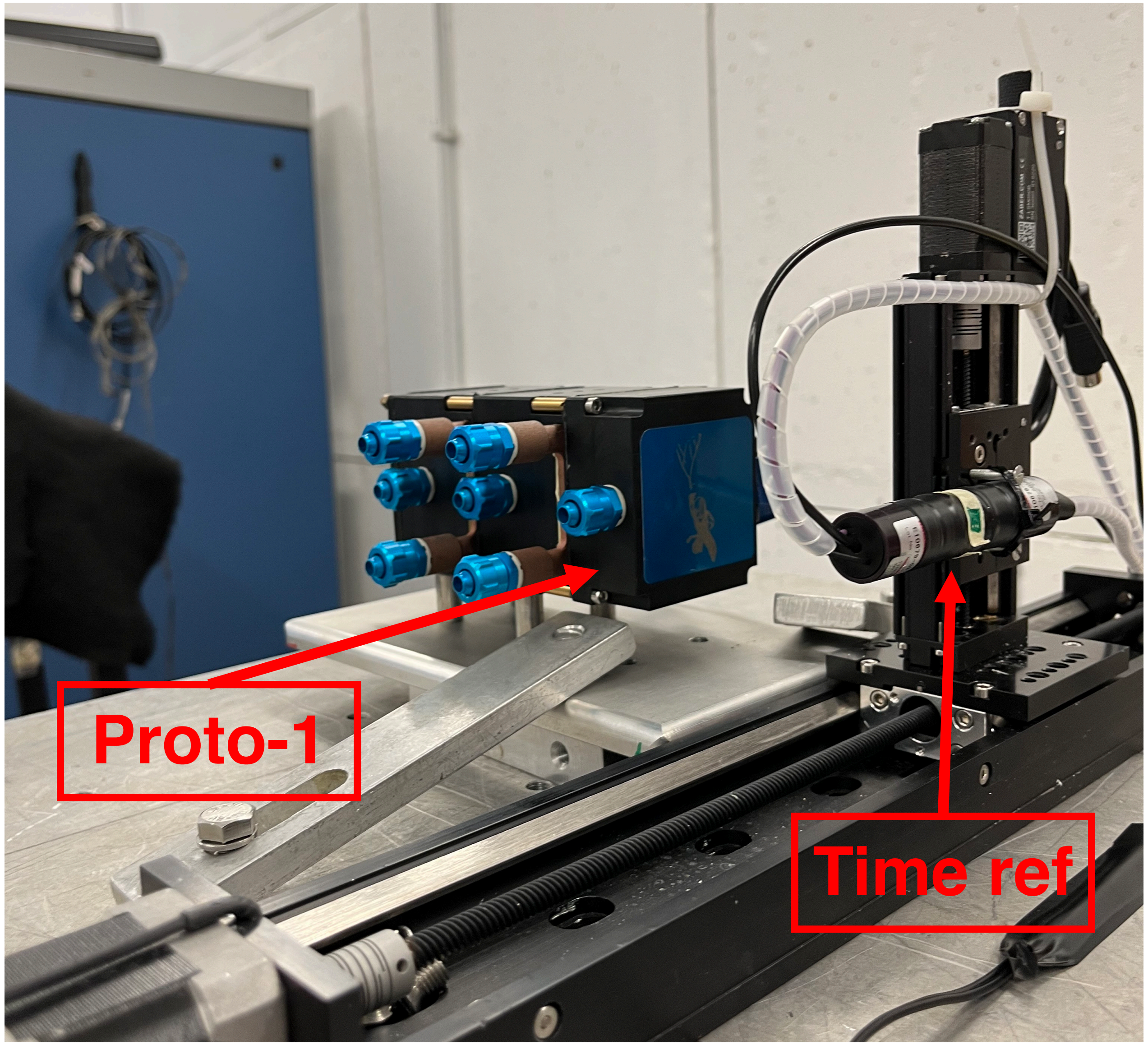


Proto-1 + Lead Glass

Energy resolution is dominated by leakage:
- A 24 X_0, ~2 M_R, lead glass crystal + PMT is used as tail catcher to recover the longitudinal leakage
- The energy resolution @ 120 GeV including the leadglass contribution→ Proto-1 apport is negligible, this is a good indication for the future large-scale prototypes.






Proto-1
Time ref