Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

International MUON Collider Collaboration

Calorimetro e.m. simulazione e misure su prototipo CRILIN

Ivano Sarra - LNF
on behalf of e.m. calorimeter group

Meeting con i referee di RD_MUCOL - 4/9/2023

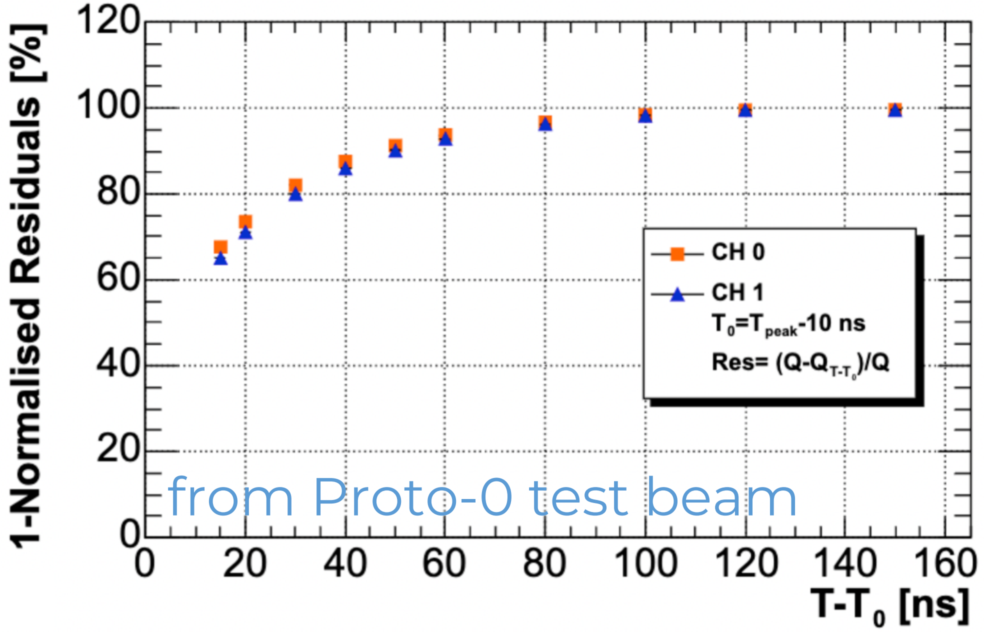
Simulation

- The ECAL barrel with Crilin technology has been implemented in the Muon Collider simulation framework
- As for the other detectors, the implementation is done with the DD4HEP interface to Geant4
- **It is longer than previous studies**: from 40 mm length cell to 45 mm, to increase the number of $\mathbf{X_0}$ (from 18.8 to **21.5**)
- 5 layers of 45 mm length, 10 X 10 mm^2 cell area. Dodecahedra geometry
- In each cell: 40 mm PbF_2 + 3 mm SiPM + 1 mm electronics + 1 mm air

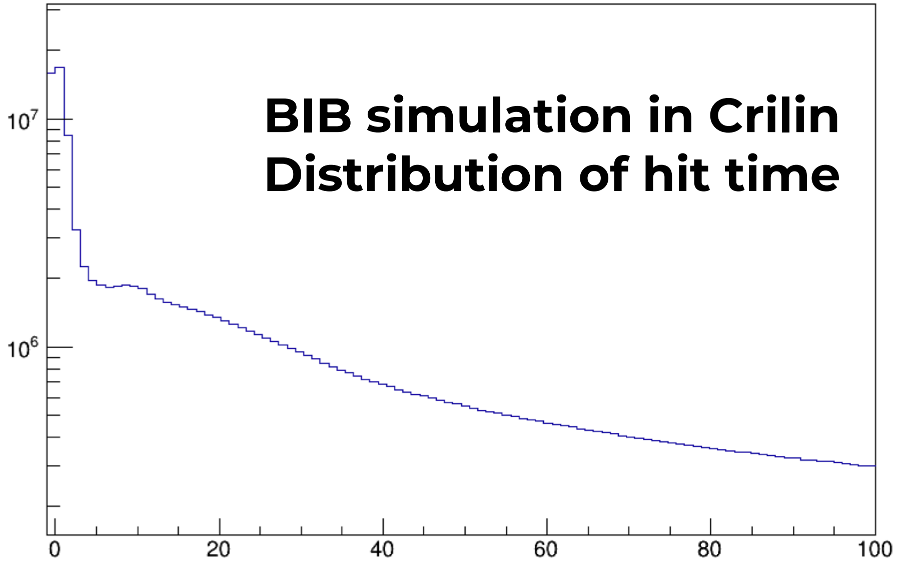
Integration Time

- The integration time has two main effects:

The fraction of signal charge collected



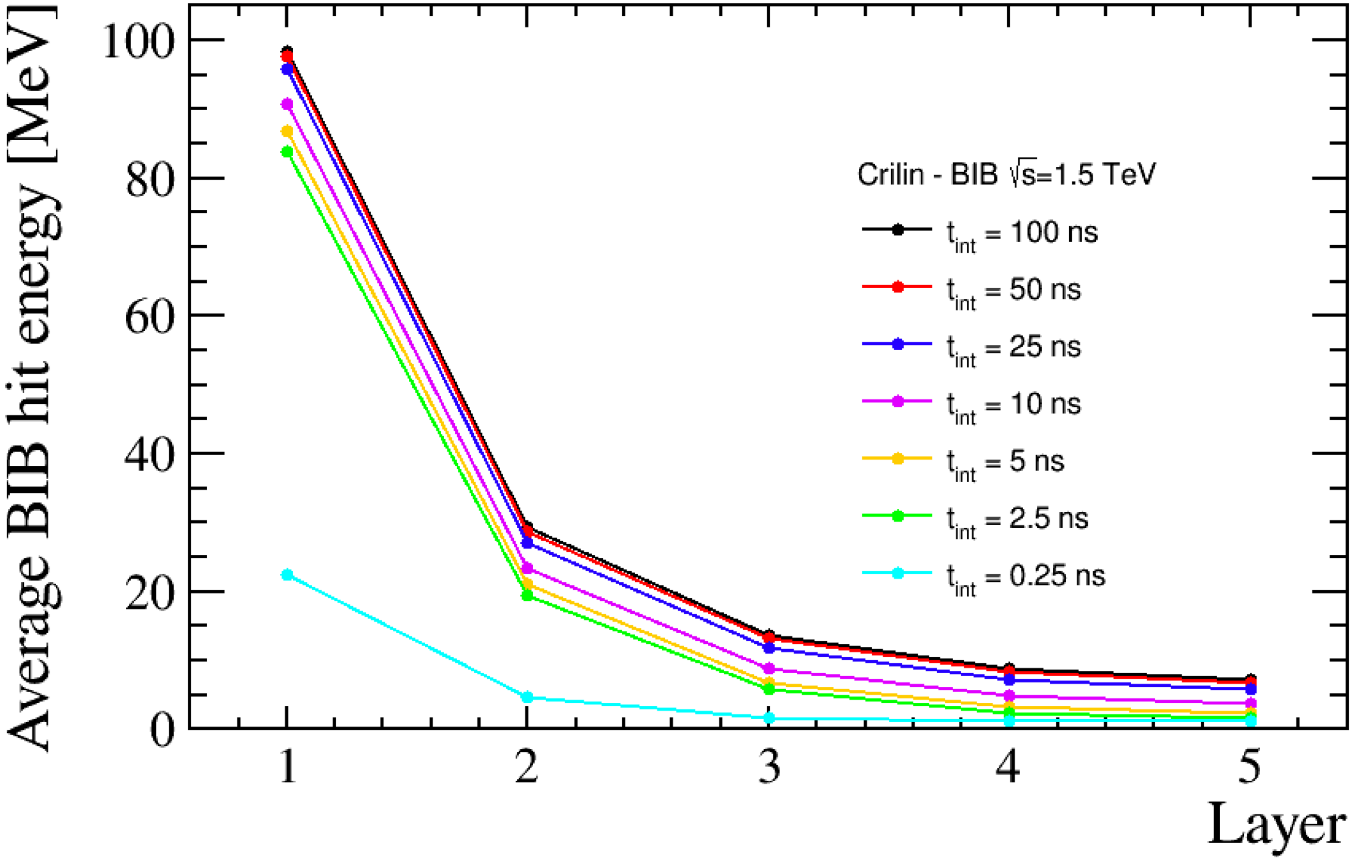
The amount of integrated BIB energy



Lorenzo has implemented these two effects in DDCaloDigi processor (for Crilin)

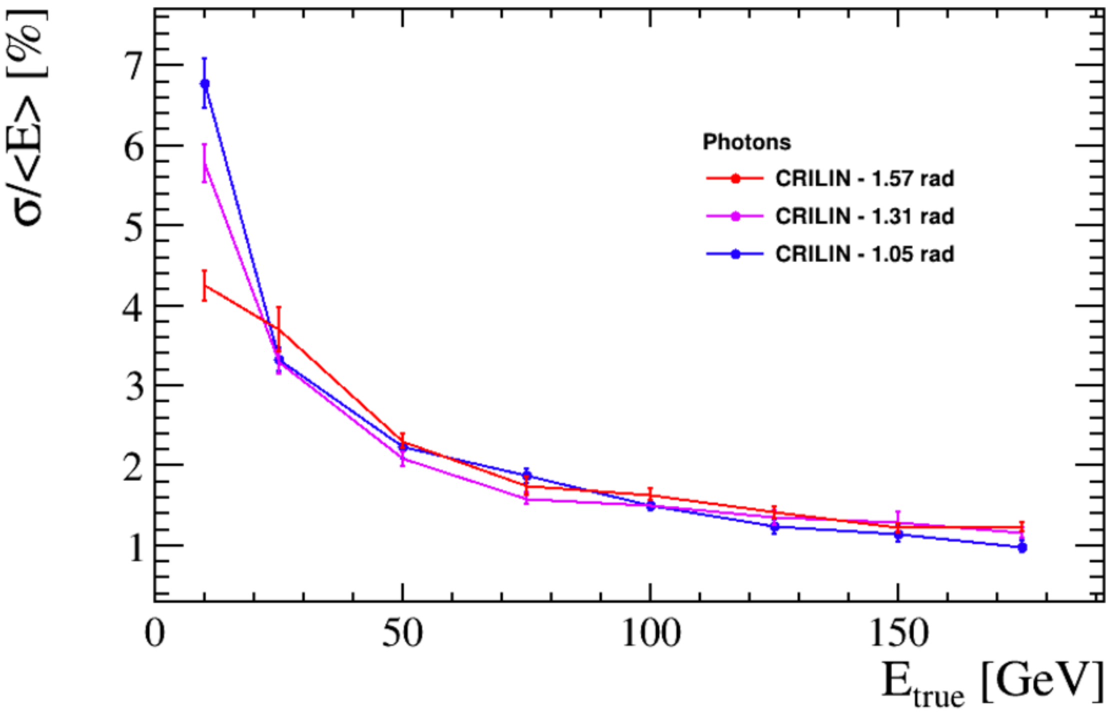
- Proto-1 electronics is faster → reduced decay time of ~10 ns
- **Cherenkov light creates a visible BIB threshold to ~0.6 MeV deposit energies → this effect must be introduced in the simulation, natural BIB mitigation is expected**

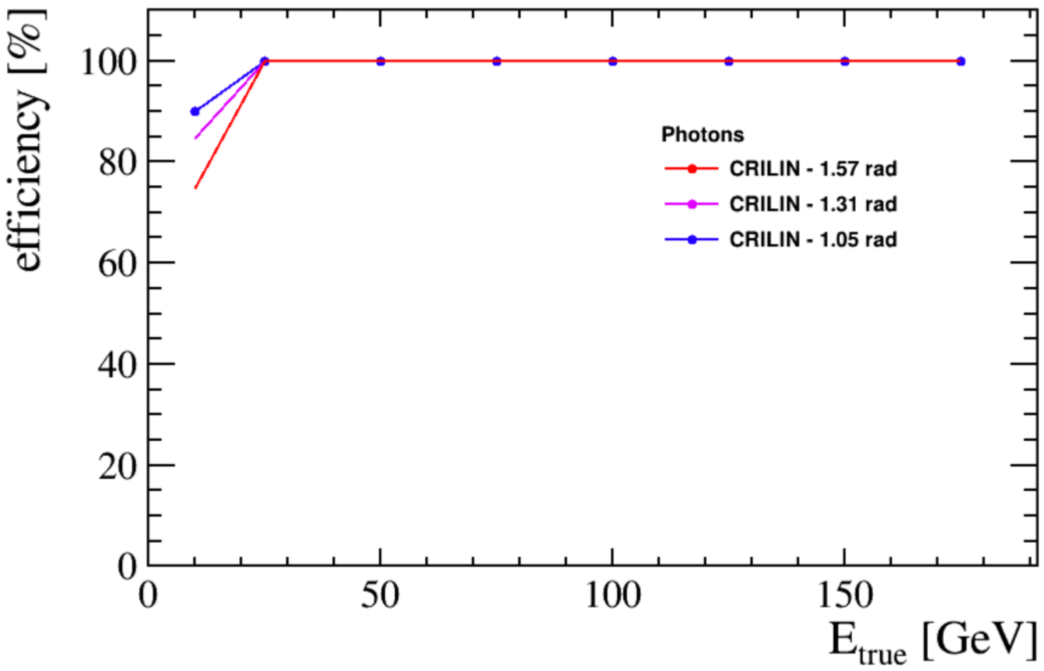
Integration Time -2-



Following: results with integration time = 25 ns

Crilin performances

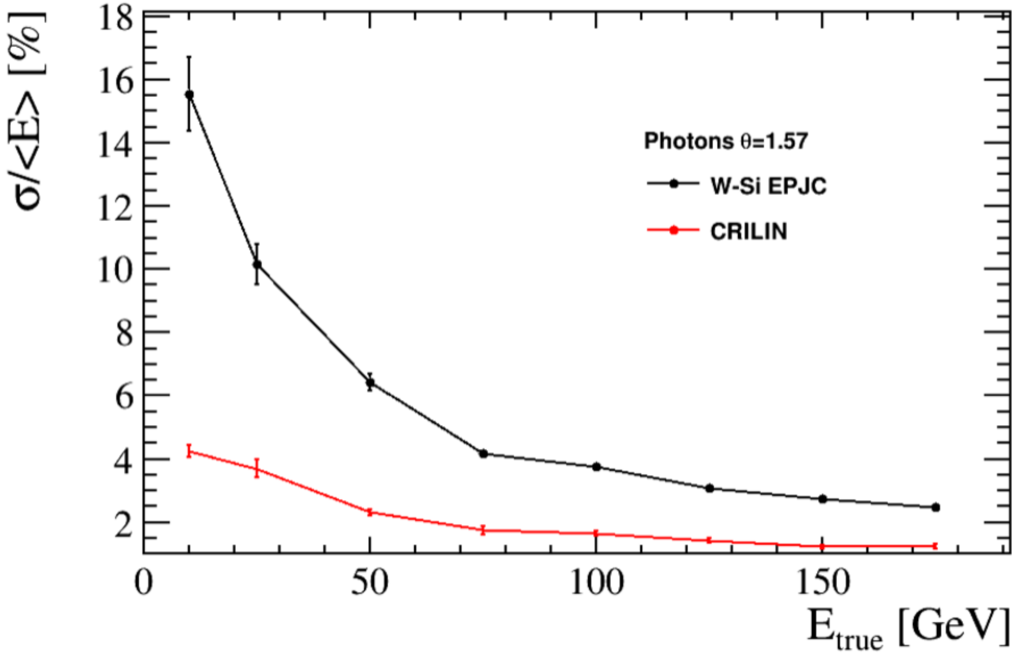


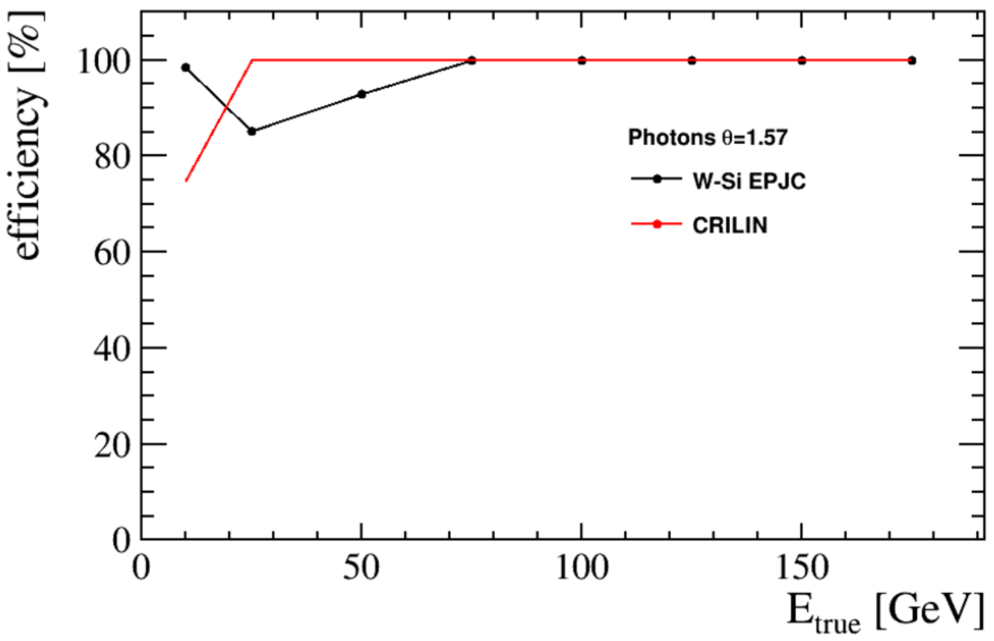


$\frac{\sigma}{E} \simeq \frac{14\%}{\sqrt{E}}$ for theta = 1.57

$N_{CRILIN}^{fake} \simeq 0$ number of fake clusters per event

Crilin performances -2-





$N^{fake}_{CRILIN} \simeq 0$

$N^{fake}_{W-Si} \simeq 60$

W-Si: 40 layers, 2 MeV threshold in each cell

- This plots don't demonstrate that Crilin is better than W-Si: the message is that **with a proper reconstruction strategy we can mitigate the impact of the BIB, and obtain the target performance**
- A more dedicated reconstruction strategy could be studied also with the W-Si

Crilin performances -3-

- However Crilin is particularly suited for this mitigation strategy: having thicker layers, the BIB energy is integrated in large volumes, reducing the statistical fluctuations of the average energy

- Moreover Crilin has just 5 layers wrt to 40 layers of the W-Si calorimeter, less readout channels and it costs a factor 10 less

- **The same strategy is being applied to the jet reconstruction**: different energy range than >10 GeV photons

- Prospects: test Crilin as Endcap ECAL

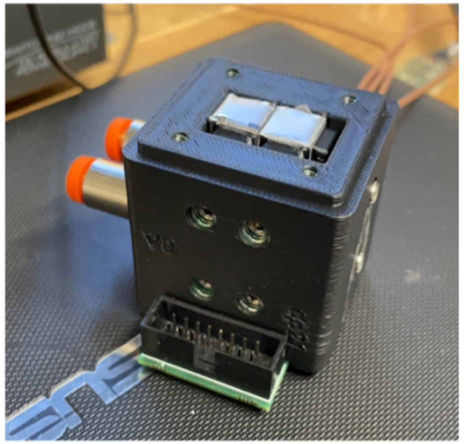
R&D status

Prototype versions
1. Proto-0 (2 crystals + 4 channels)
2. Proto-1 (3x3 crystals + 36 channels) x2 layers

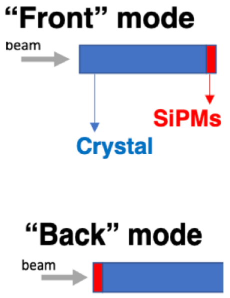
*2022 JINST **17** P09033*

Test Beam @SPS CERN, August 2022

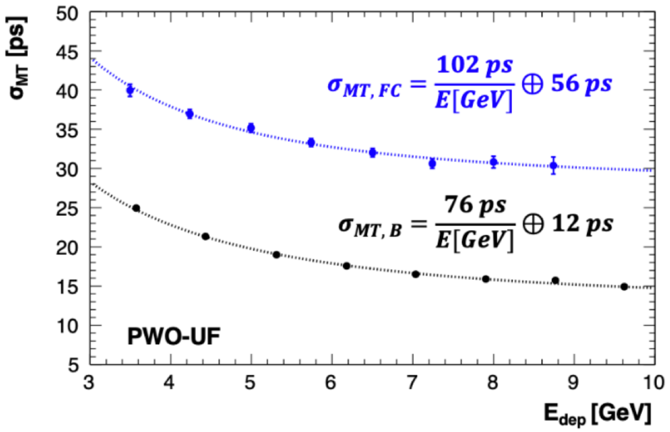
- The BACK run time resolution is better, even after correction, for both crystals.
- PbF_2 outperforms $PbWO_4$-UF despite its higher light output (purely Cherenkov)
- **PbF_2 →** σ_{MT} < 25 ps worst-case for E_{dep} > 3 GeV
- **$PbWO_4$-UF →** σ_{MT} < 45 ps worst-case for E_{dep} > 3 GeV

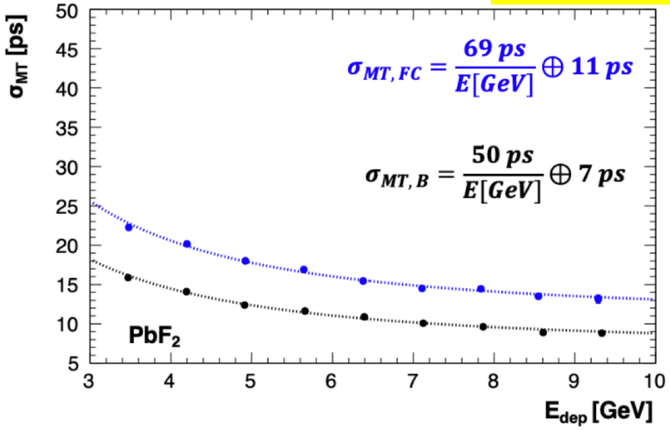


Proto-0



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



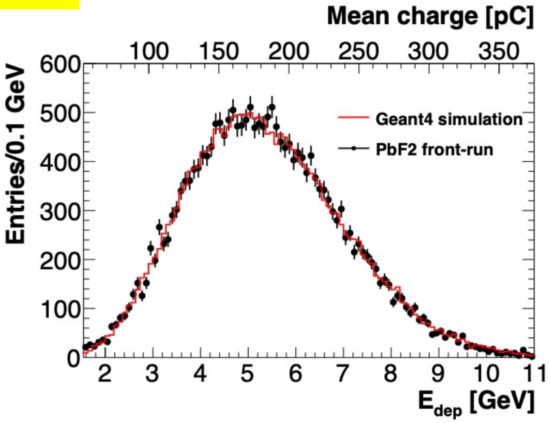


PbF_2

	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/GeV	~29.3	~35.6
NPE/MeV	~0.26	~0.30

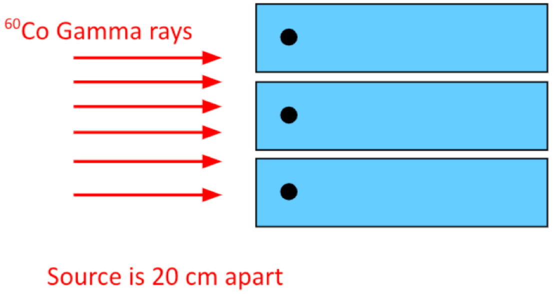
PWO-UF

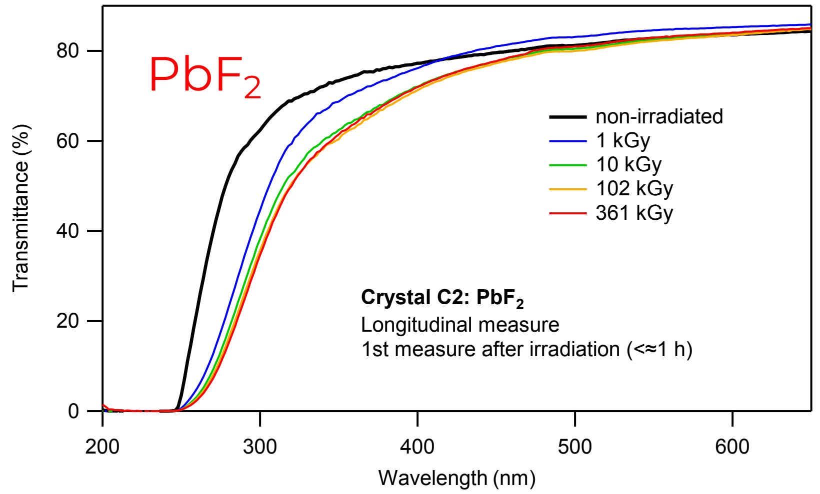
	back-run	front-run
E_{dep} MPV [GeV]	6.39 ± 0.01	6.88 ± 0.01
E_{dep} sigma [GeV]	1.83 ± 0.01	1.99 ± 0.01
pC/GeV	~66.7	~76.9
NPE/MeV	~0.58	~0.67



Crystal radiation hardness

Radiation hardness of two PbF_2 and $PbWO_4$-UF crystals (10x10x40 mm^3) checked for TID (up to 100 Mrad @ Calliope, Enea Casaccia) and neutrons (14 MeV neutrons from Frascati Neutron Generator, Enea Frascati, up to 10^{13} n/cm^2)

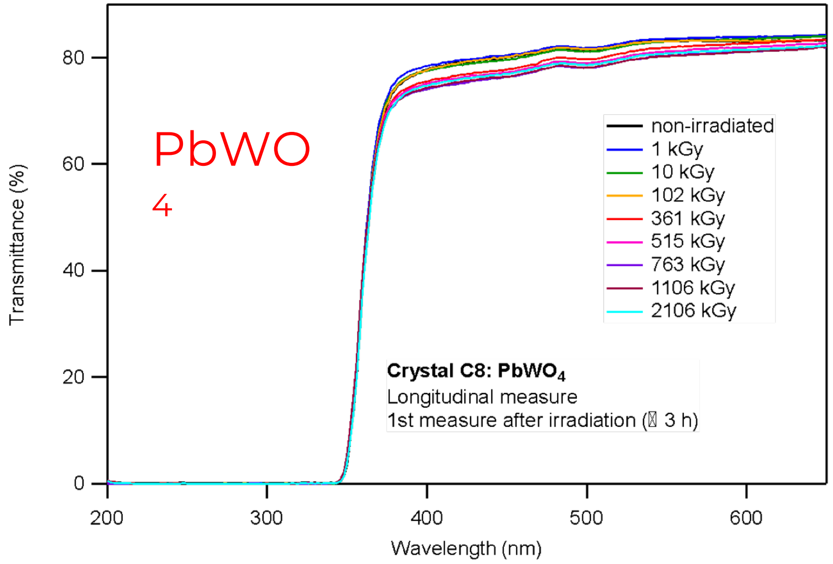




- For PbF_2:
  - **after a TID > 35 Mrad no significant decrease** in transmittance observed.
  - Transmittance after neutro irradiation showed no deterioration

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

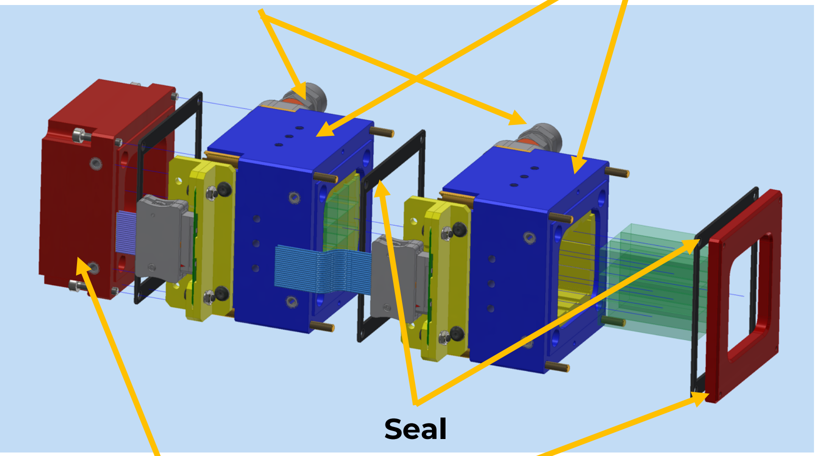


- For $PbWO_4$-UF:
  - **after a TID > 200 Mrad no significant decrease** in transmittance observed.

Proto-1 → Mechanics

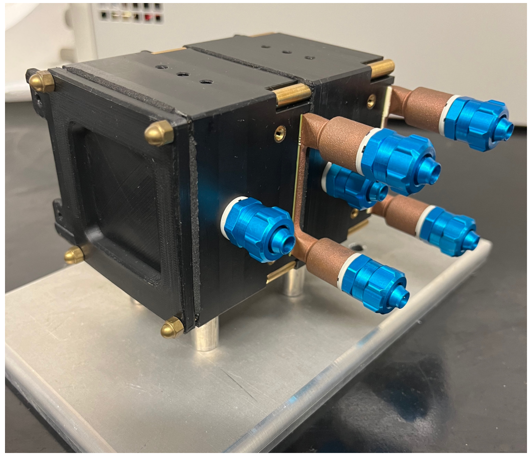
Hydraulic connectors

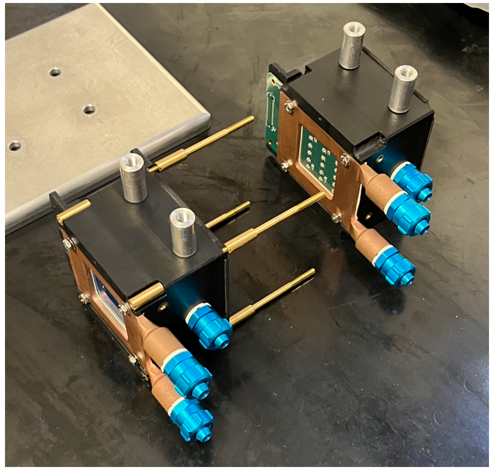
matrix cases made of ABS plastic



Locking plates

- **350 mW / crystal** thermal load
- Additively manufactured micro-channel heat exchanger for liquid coolant circulation



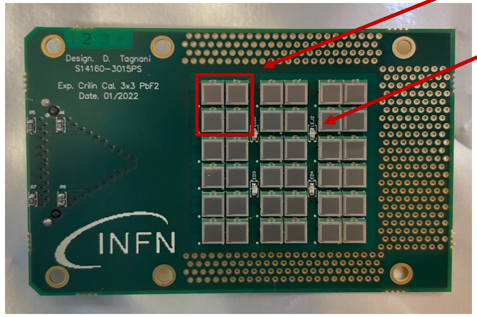


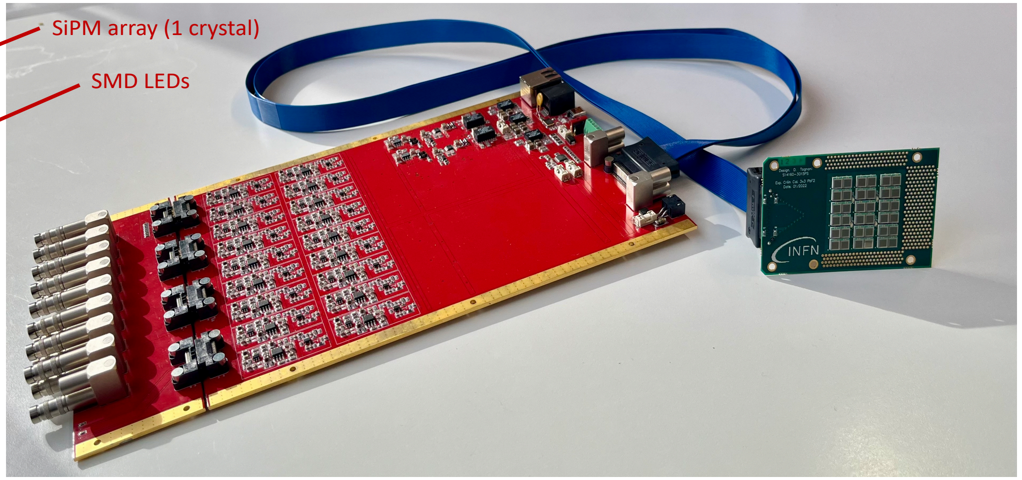
Proto-1 → Electronics

- Design completed
- Production and QC completed

SiPM board
Custom SiPM array board
36x **10 μm Hamamatsu SMD SiPMs**

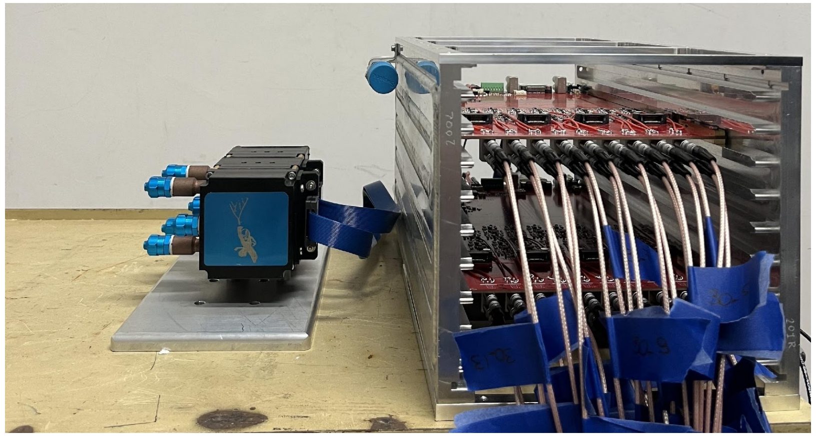
FEE/controller board
18x readout channels
Amplification, shaping and individual bias regulation
Slow control (temperature, bias and current monitors)

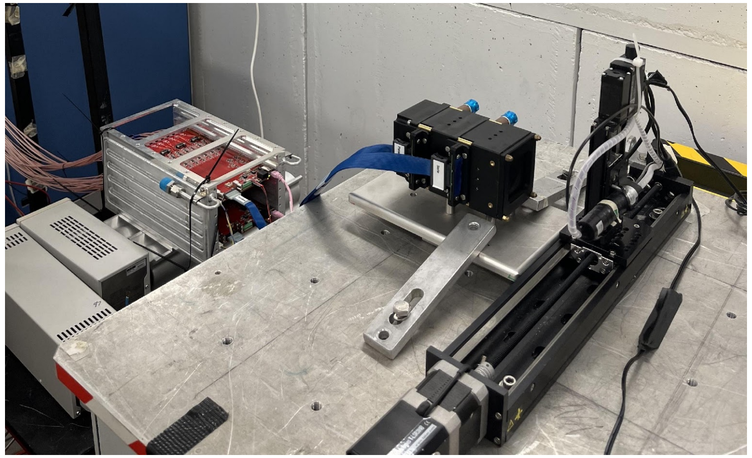




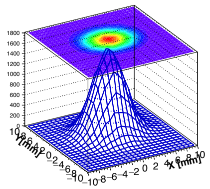
Test Beam @ BTF

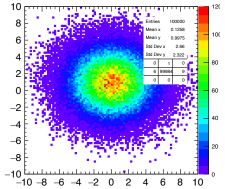
e⁻ 450 MeV @BTF, July 2023

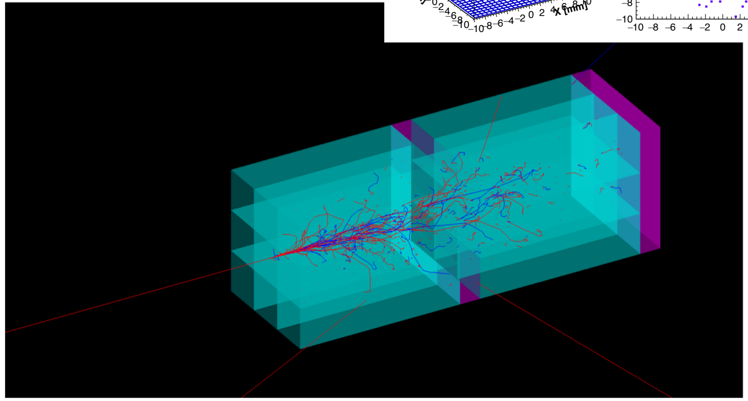




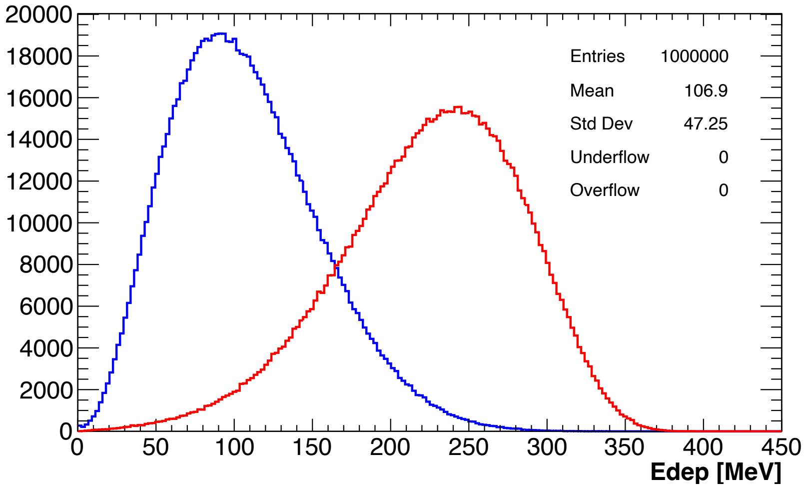
Monte Carlo

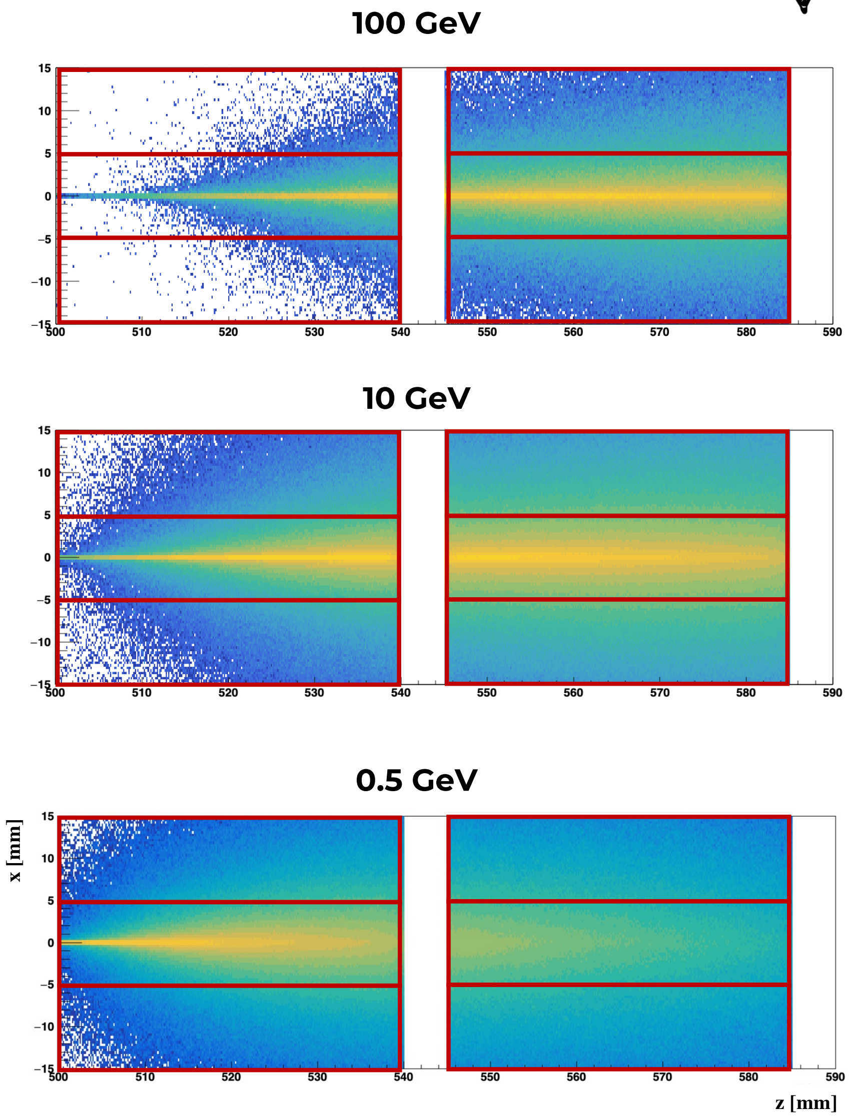






Front and Back Layer

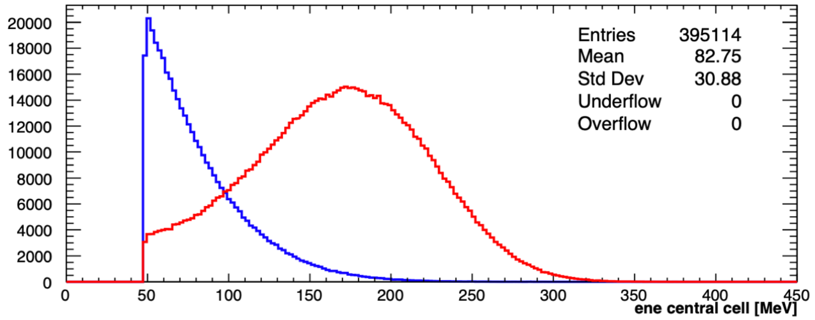




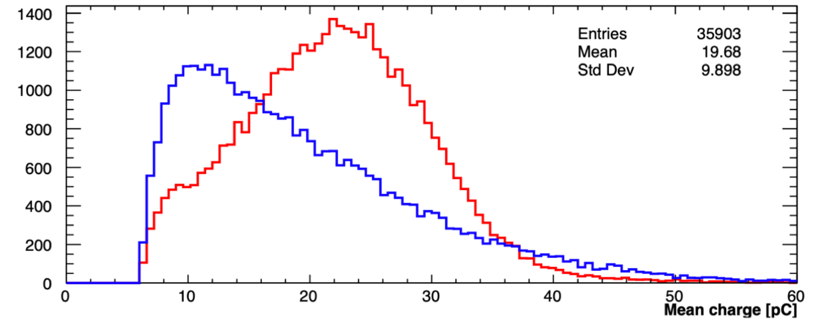
Test Beam @ BTF -result-

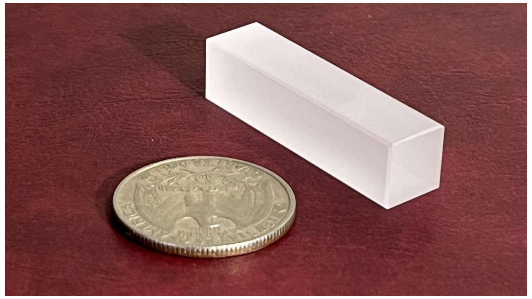
Threshold a 6 pC → 50 MeV

MC

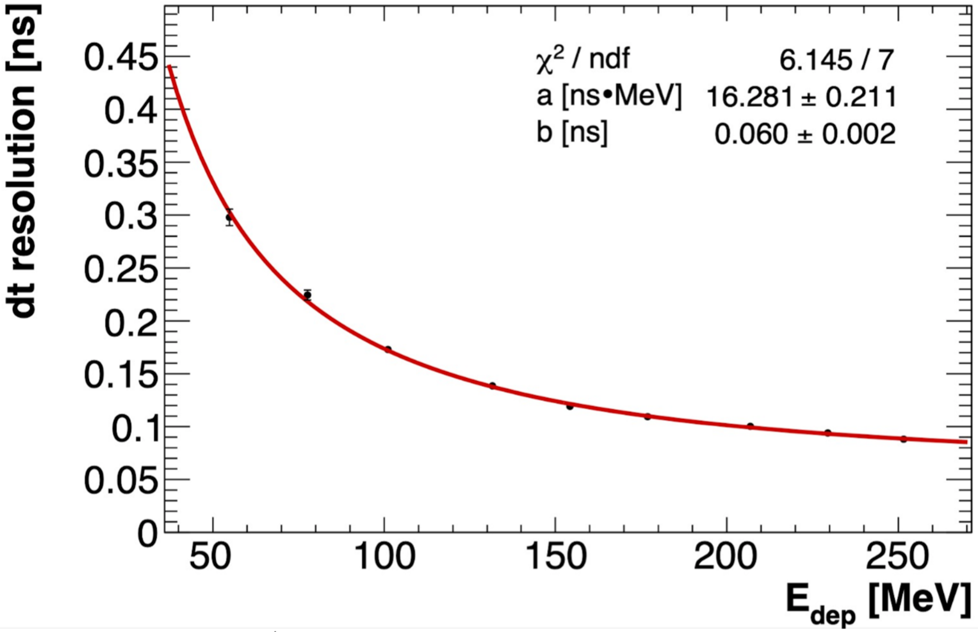


DATA

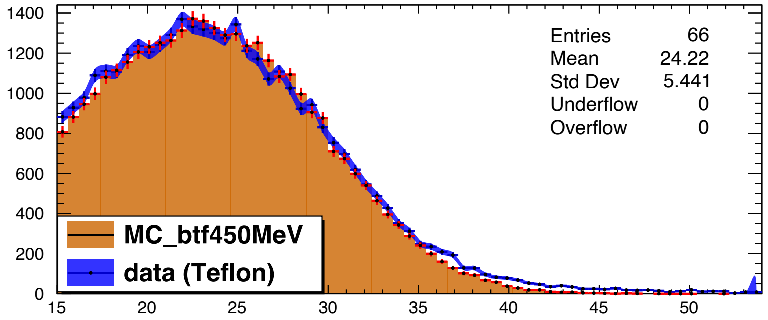




~ 0.13 pC/MeV response (Teflon)
~ 0.32 PE/MeV @ Vop +2 (Teflon)
~ 0.25 PE/MEV @ Vop +2 (Mylar)



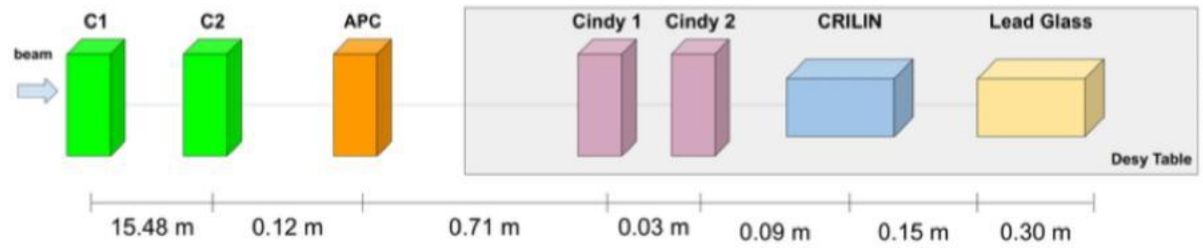
Equalization data-MC

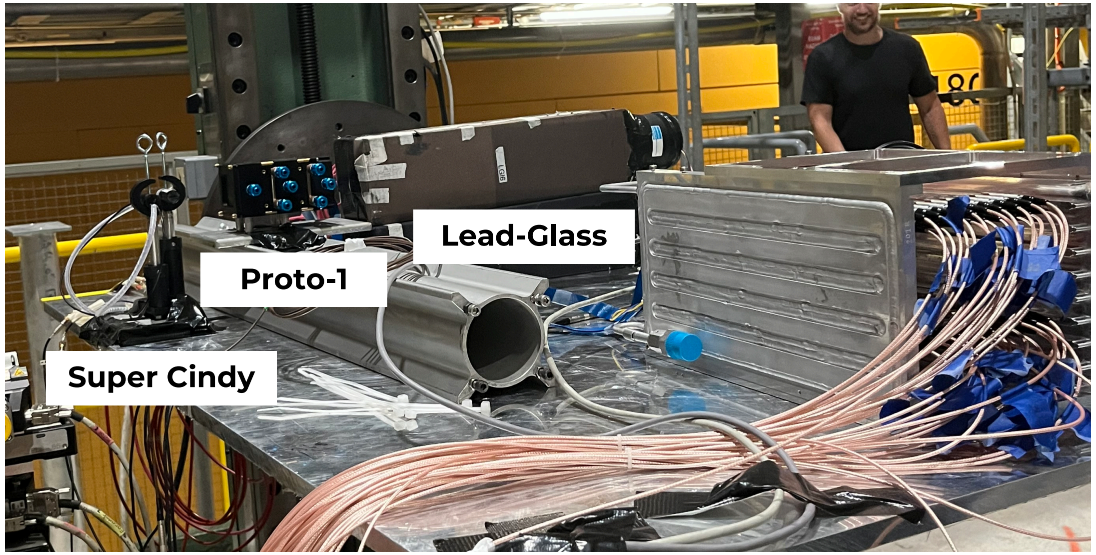


Test Beam @ CERN

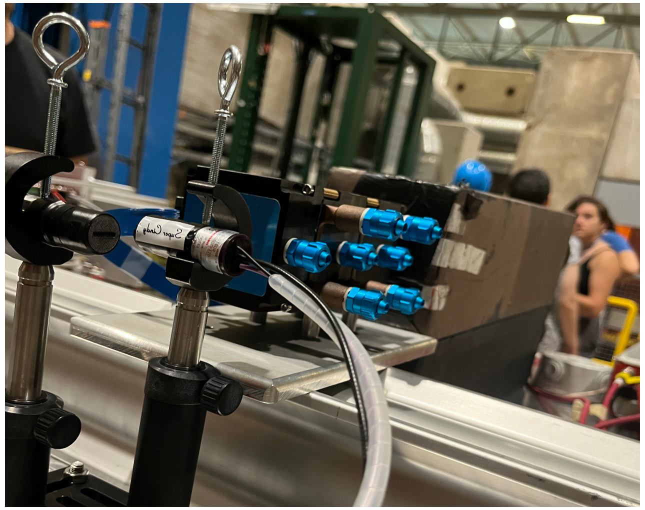
e^- 40 – 60 – 100 – 120 – 150 GeV
@CERN, August 2023

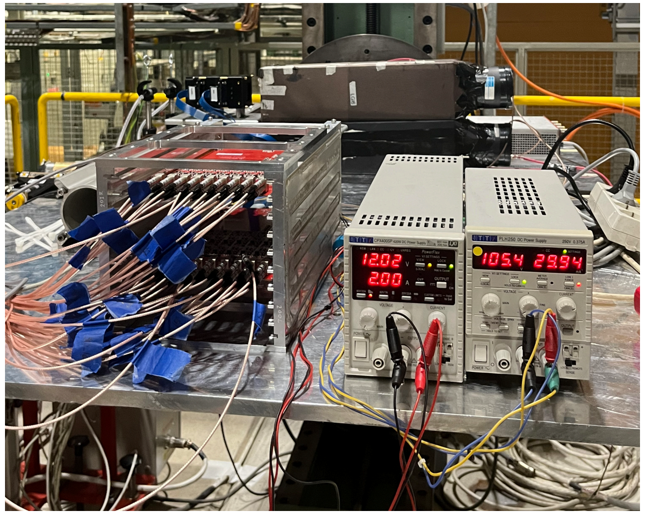
SETUP SCHEME WITH DISTANCES





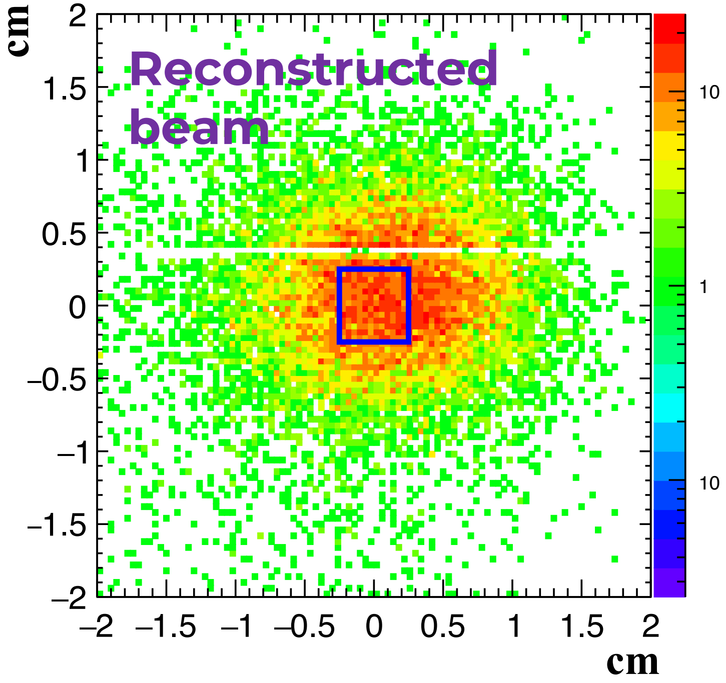
- Beam reconstructed with 2 silicium strip telescopes
- Data acquisition with 2 CAEN V1742 (32 ch each) modified @ 2 Vpp
- 5 Gs/s sampling rate

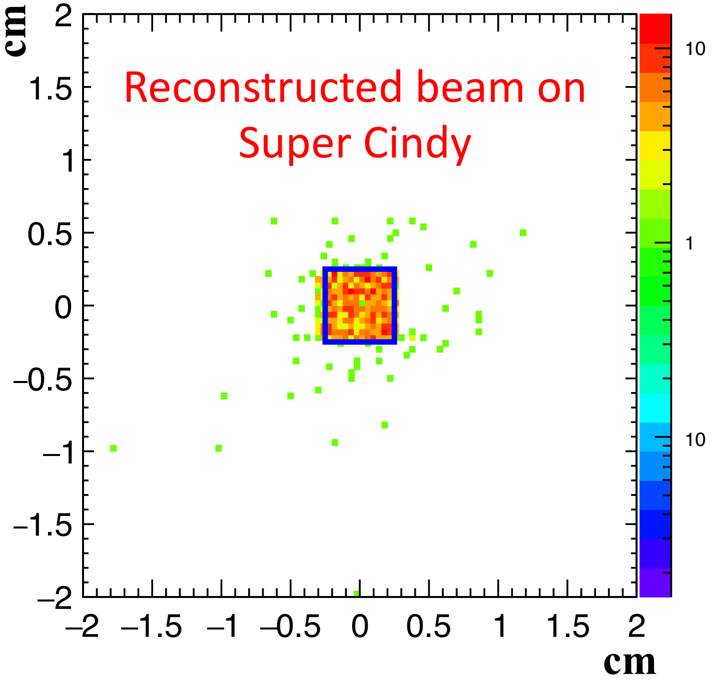


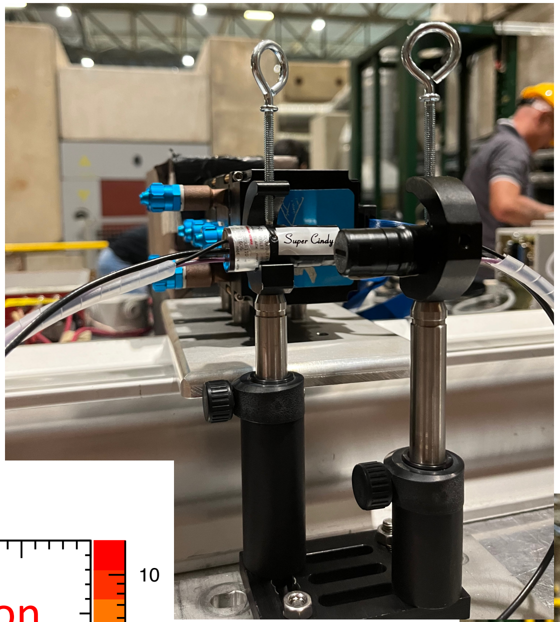


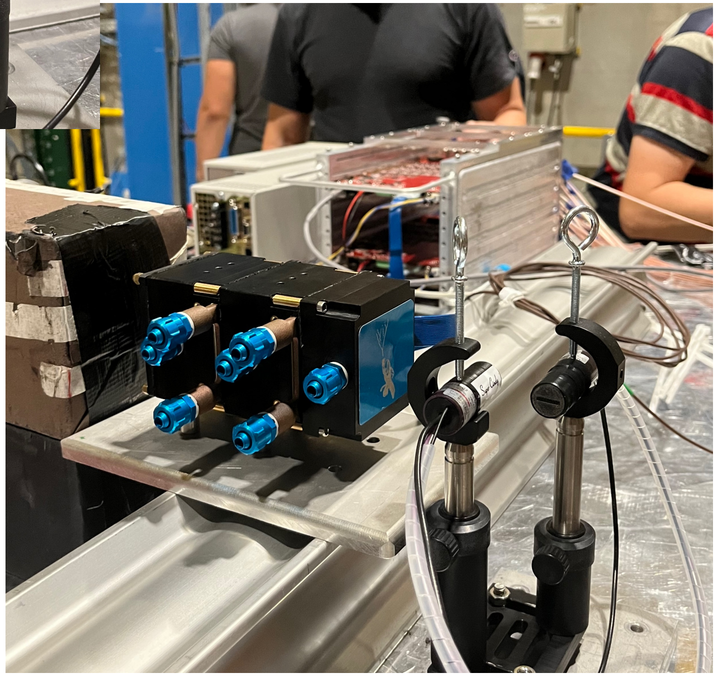
Test Beam @ CERN – Super Cindy –

- 2 fast PMT 9880U
- 2 x 5x5x7 mm³ BC408 scintillators
- Optical alignment

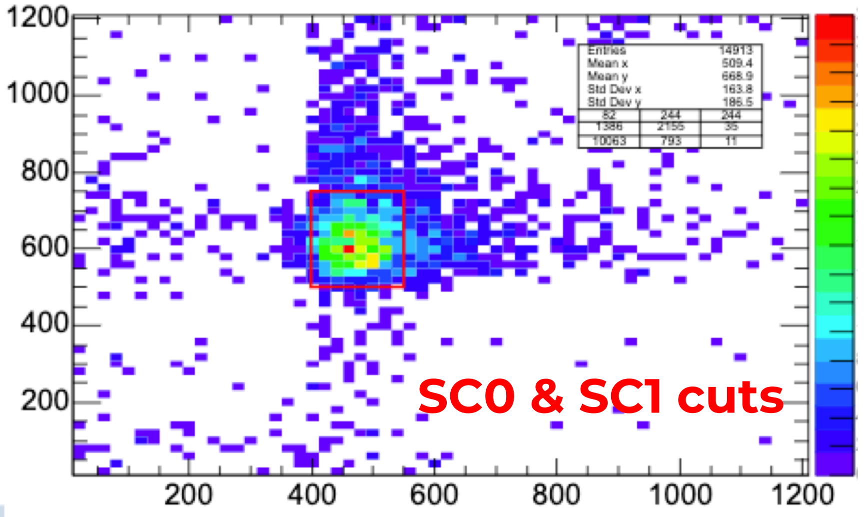


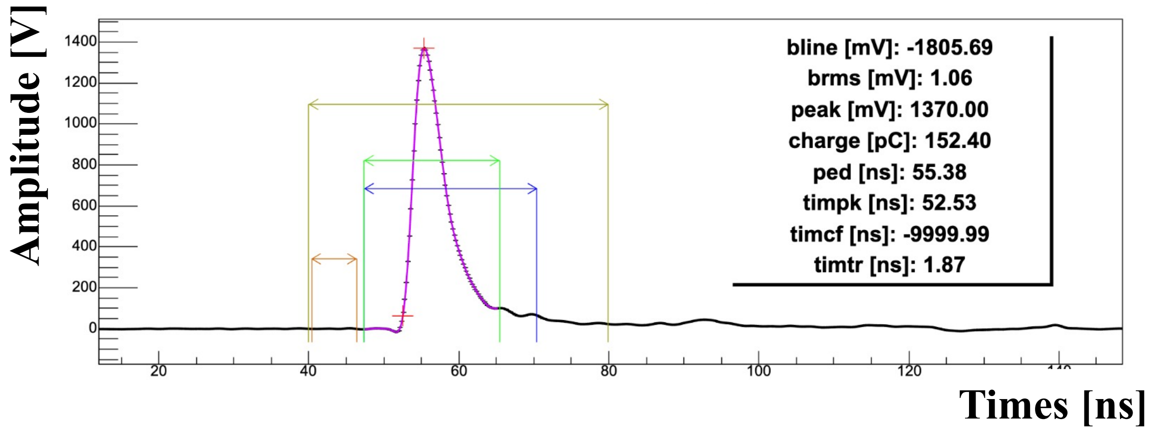




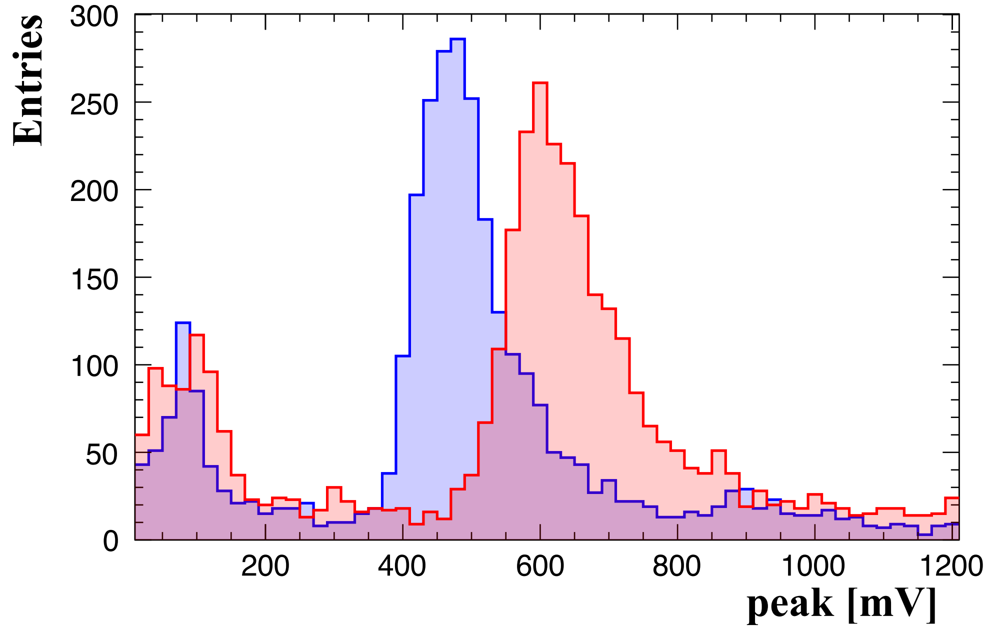


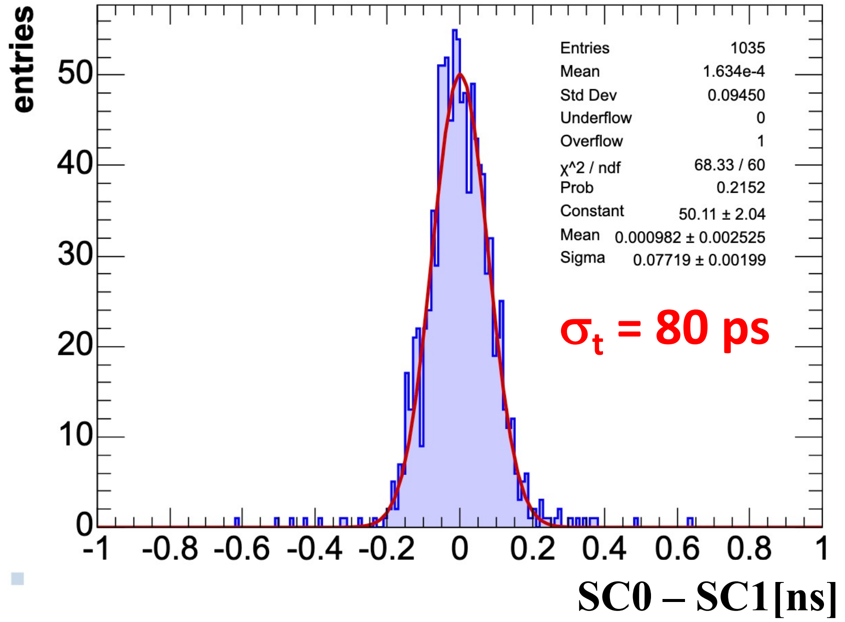
Test Beam @ CERN – Super Cindy –



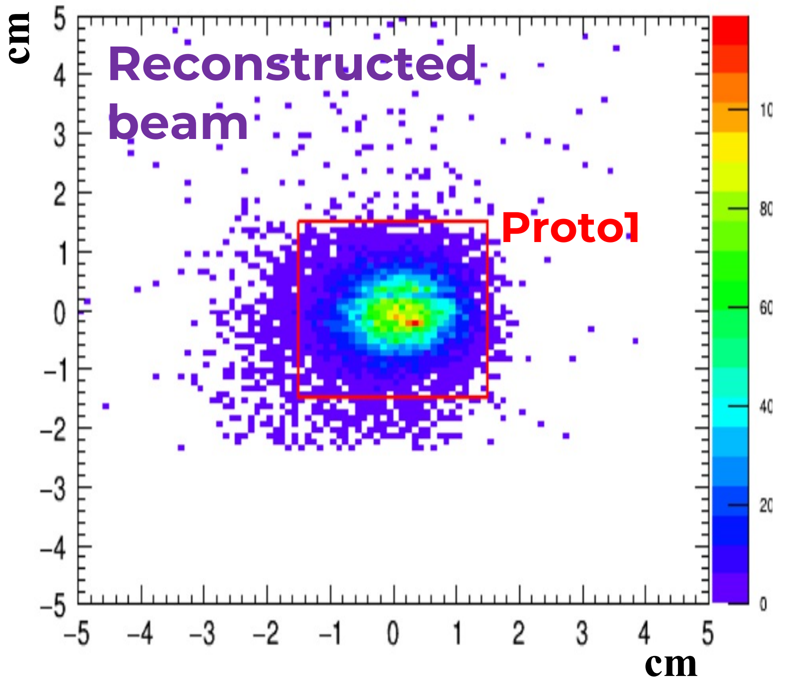


Super Cindy mean time resolution O(40 ps)!!!

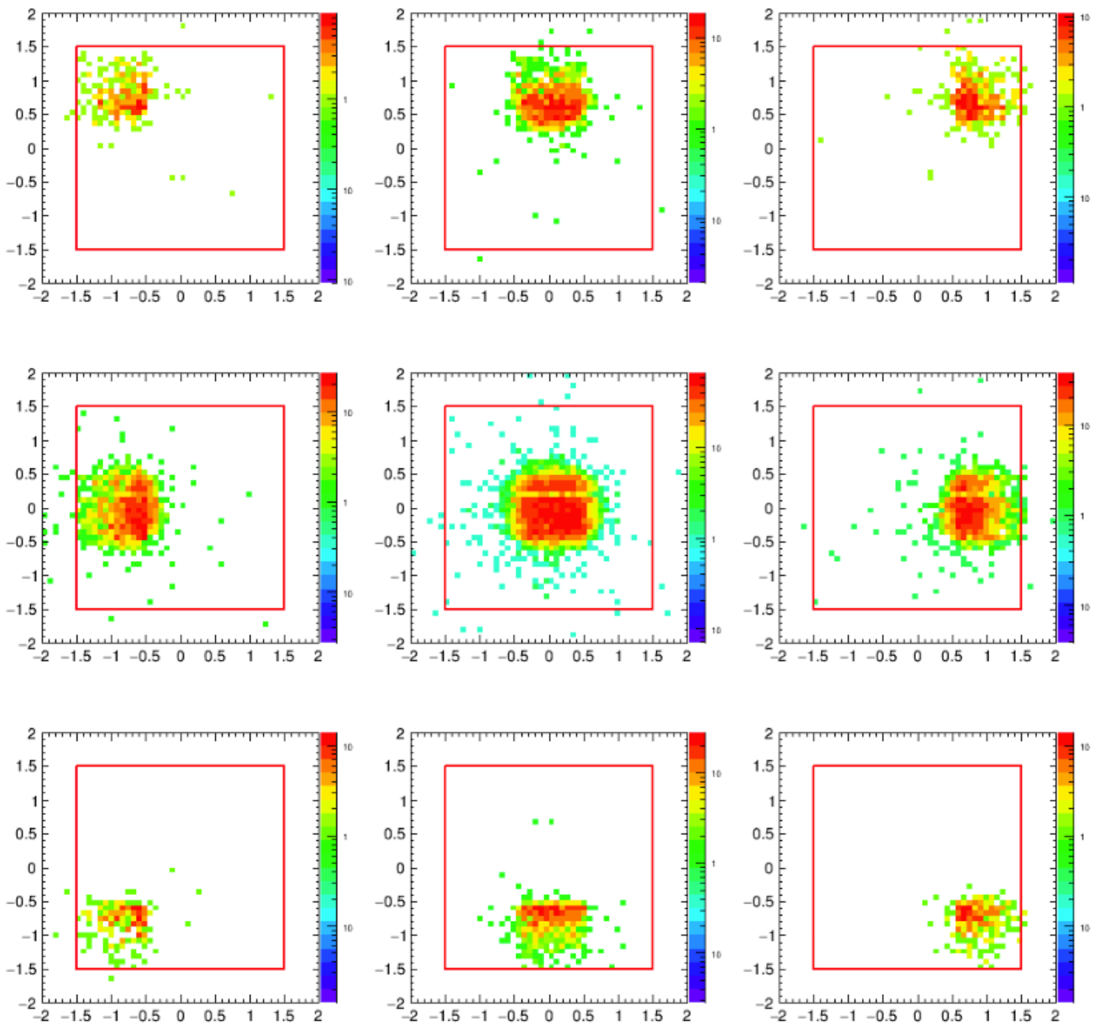




Test Beam @ CERN – Proto-1 –



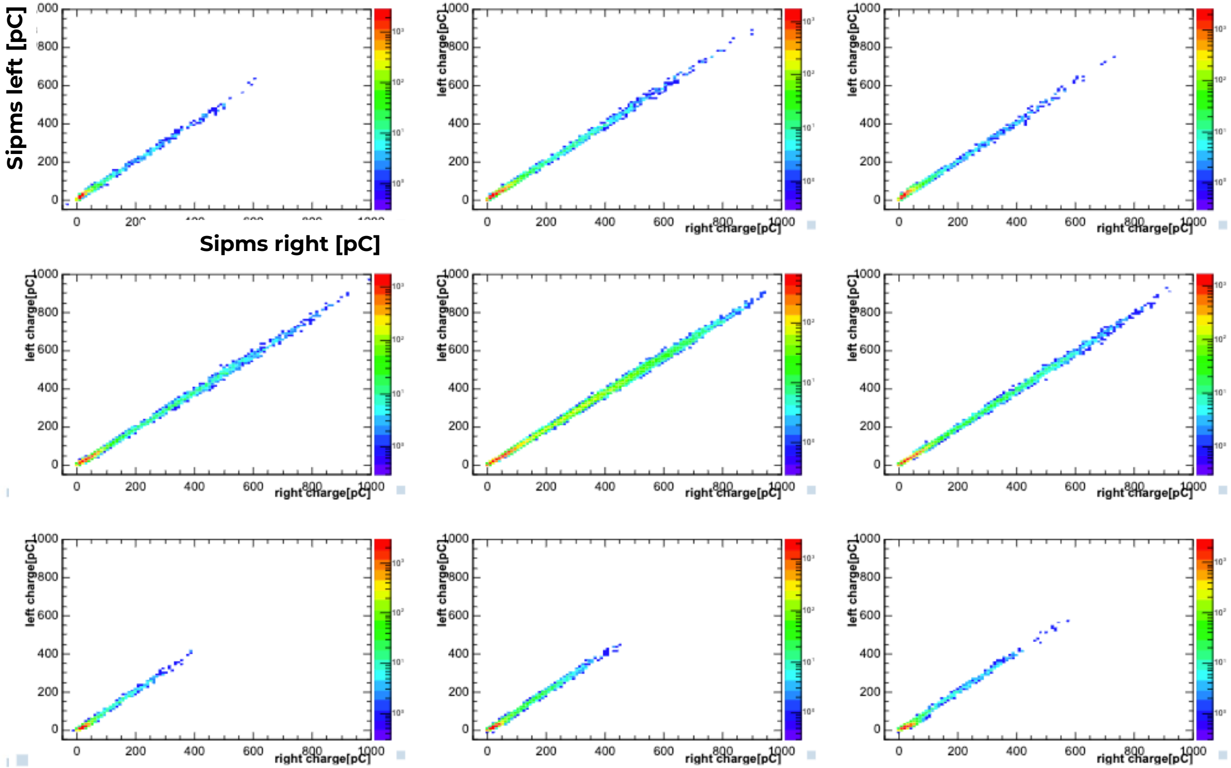
Reconstructed beam on 1st layer crystals



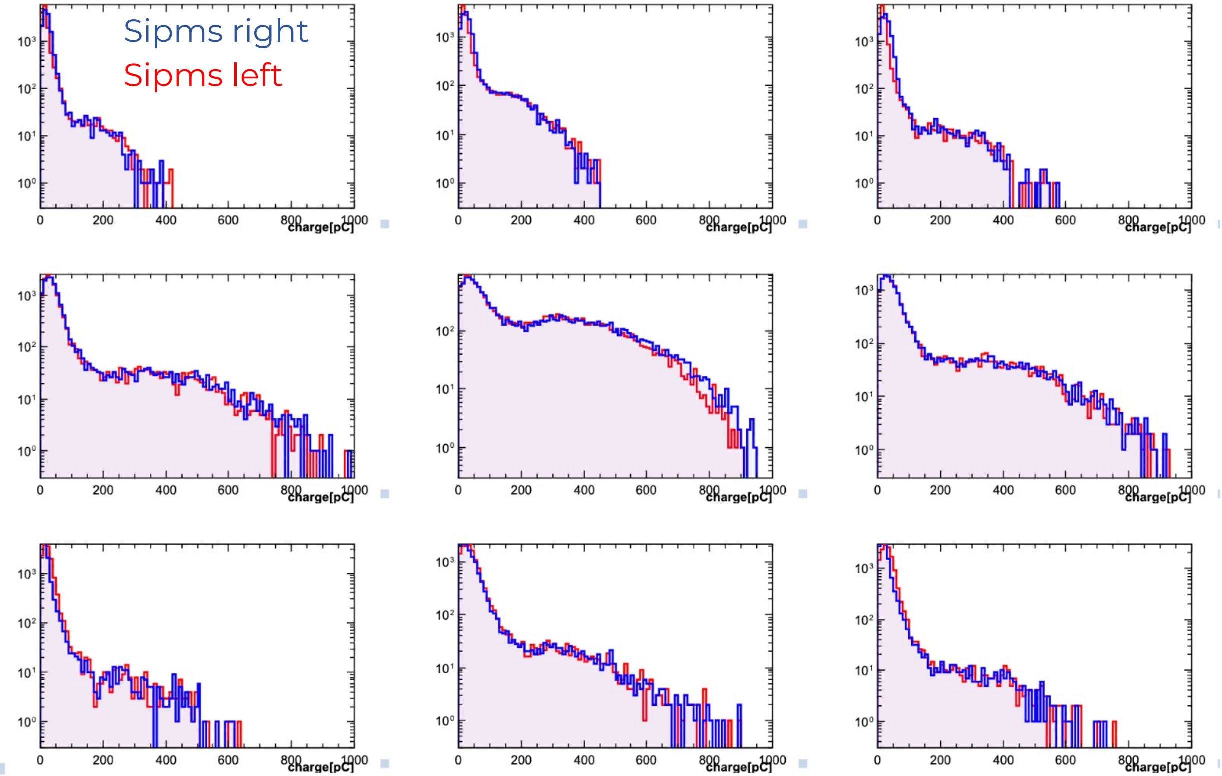
Test Beam @ CERN – Proto-1 –

Excellent channels equalization:

- Same SiPMs production lot
- Cherenkov light and good production quality



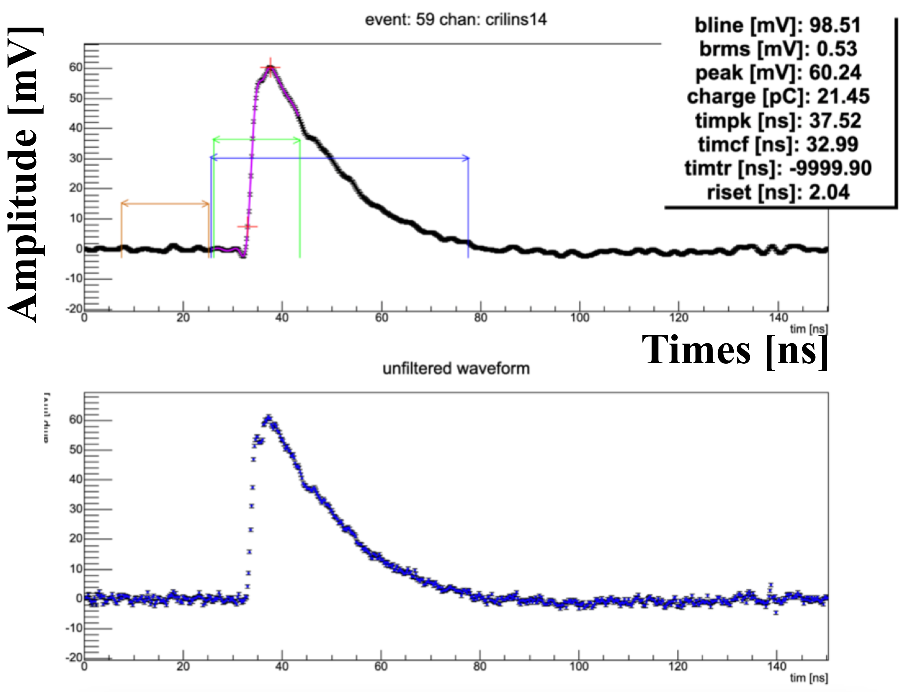
120 GeV: crystals charges on 1st layer



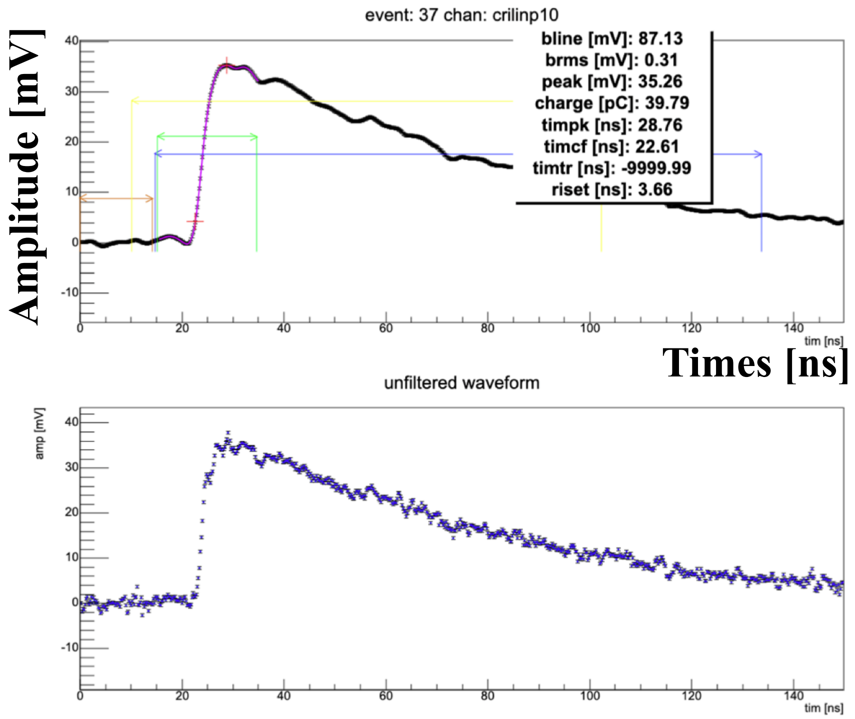
Test Beam @ CERN – Proto-1 –

- Low pass filtering (Bessel 2nd order) cutoff_parallel ~ 2 * cutoff_series
- Cut-off frequency based on two parameters: baseline RMS and risetime (10-90%)
- Wave quality flag based on baseline RMS, peak, and risetime to discard bad waves
- Processing cuts: peak > 2 mV

Series Layer

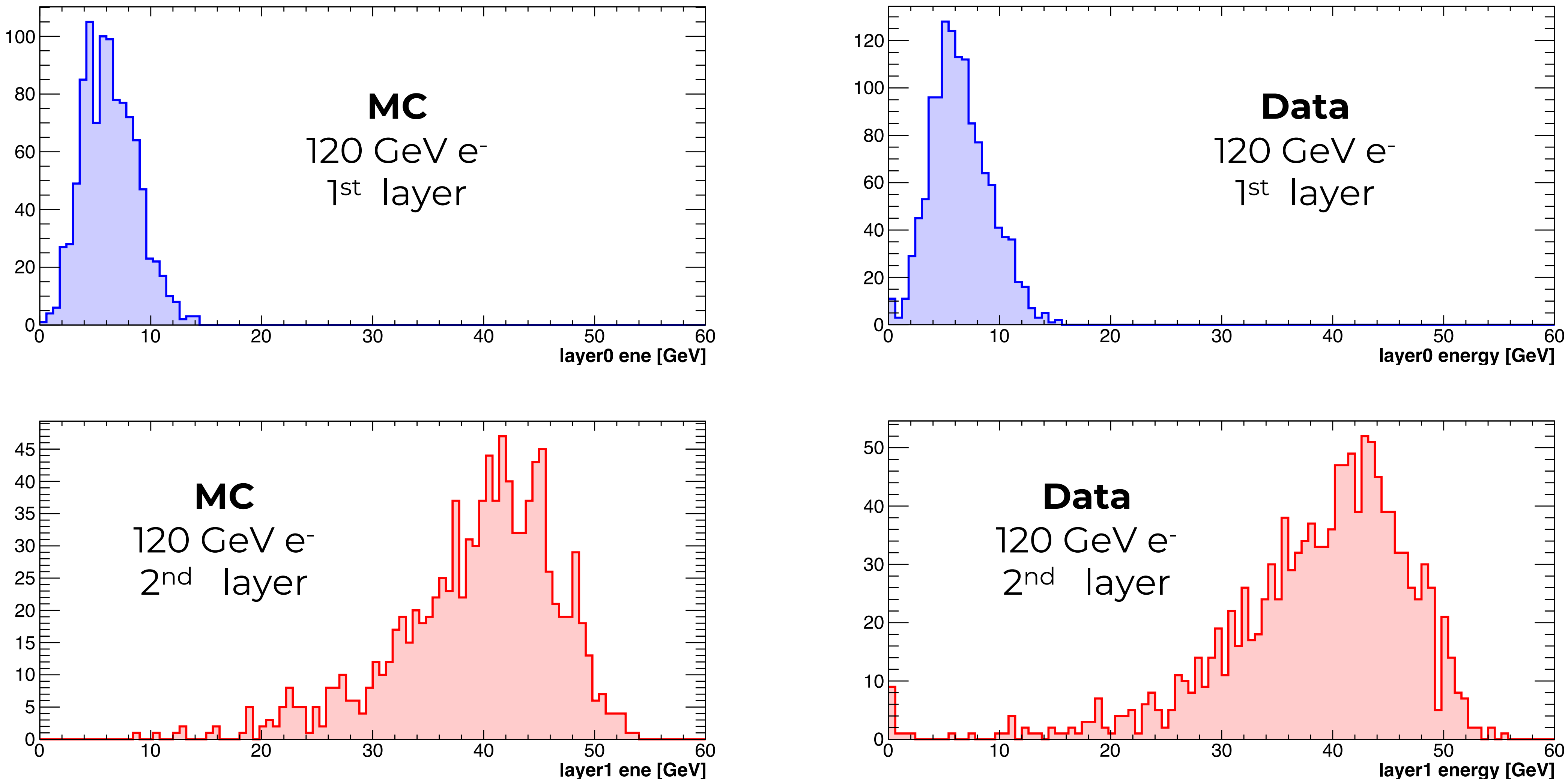


Parallel Layer



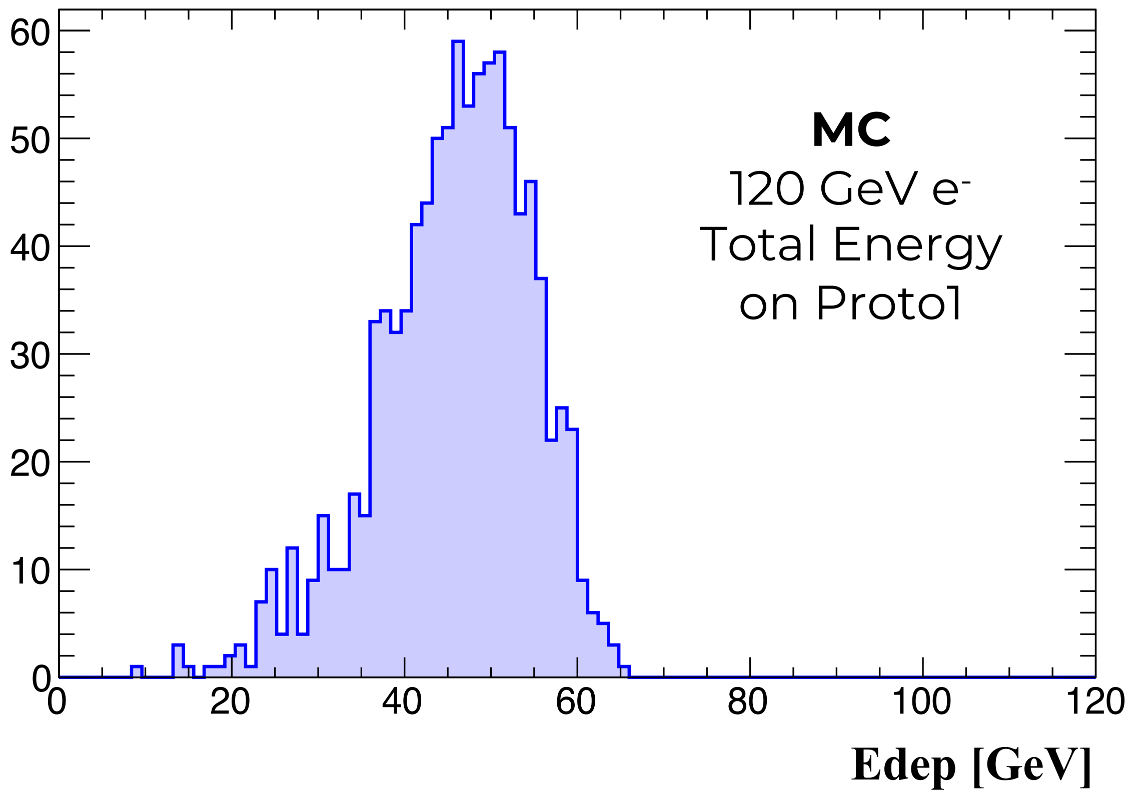
Test Beam @ CERN – result –

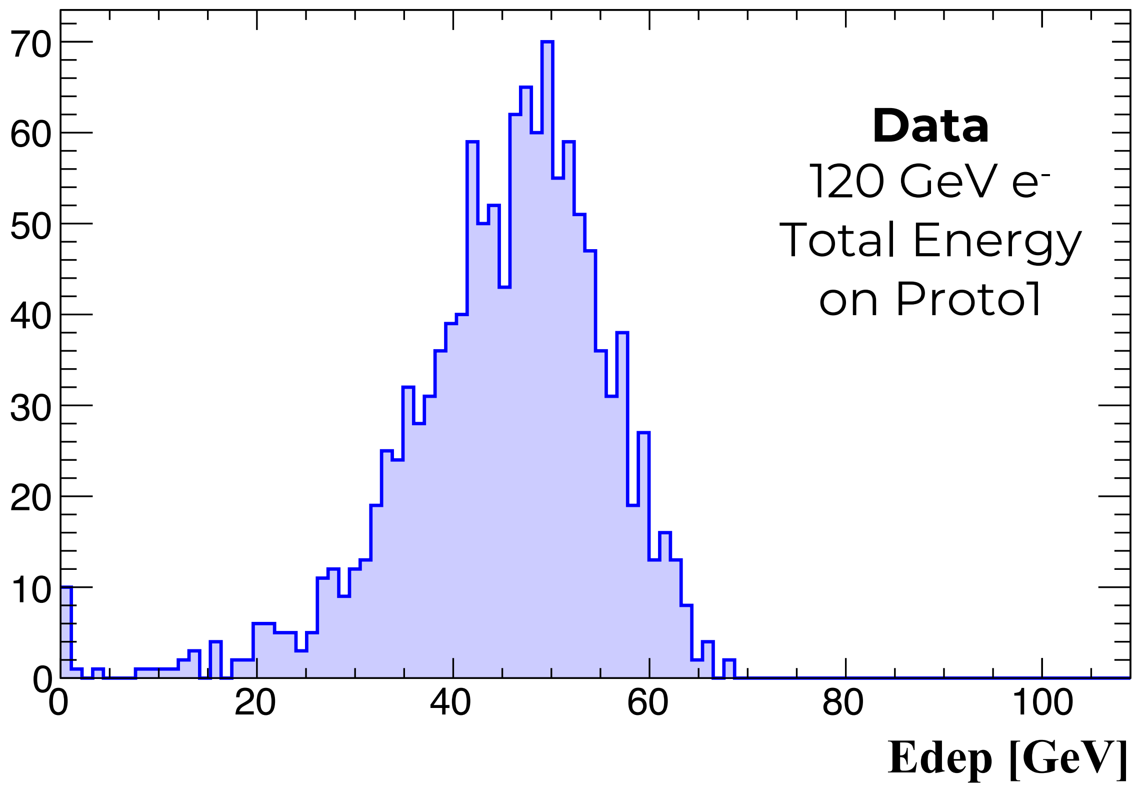
Excellent agreement between data e MC



Test Beam @ CERN – result –

Excellent agreement between data e MC

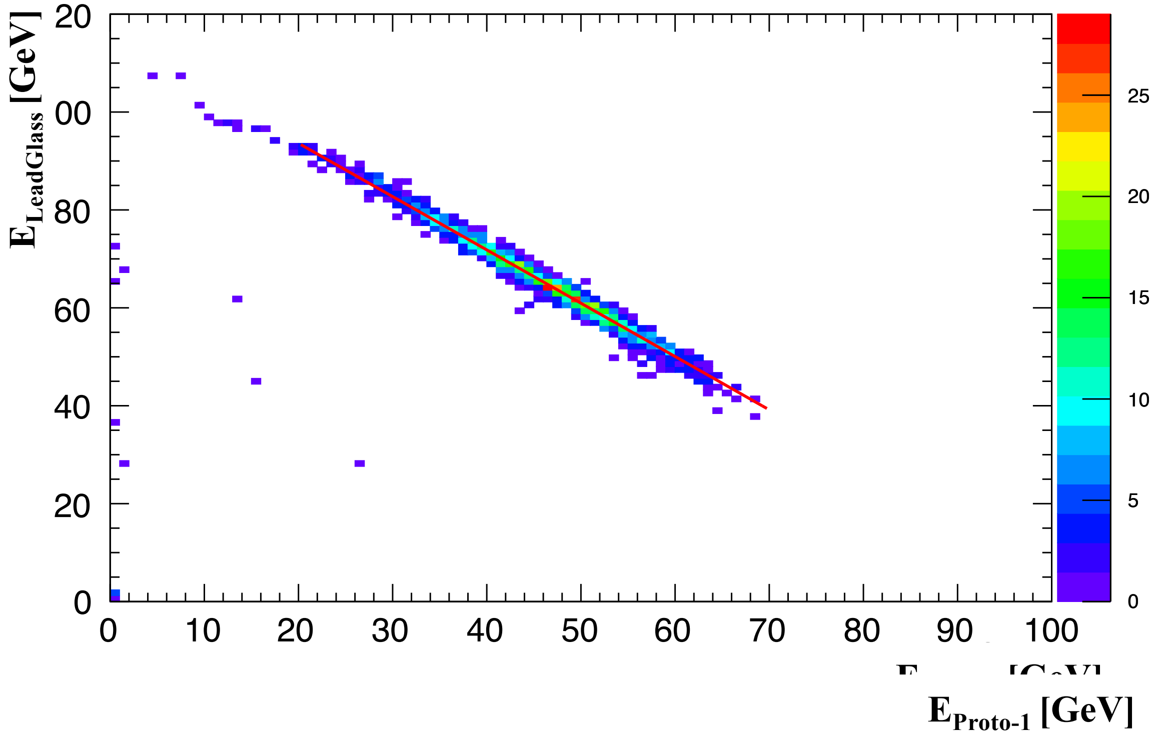


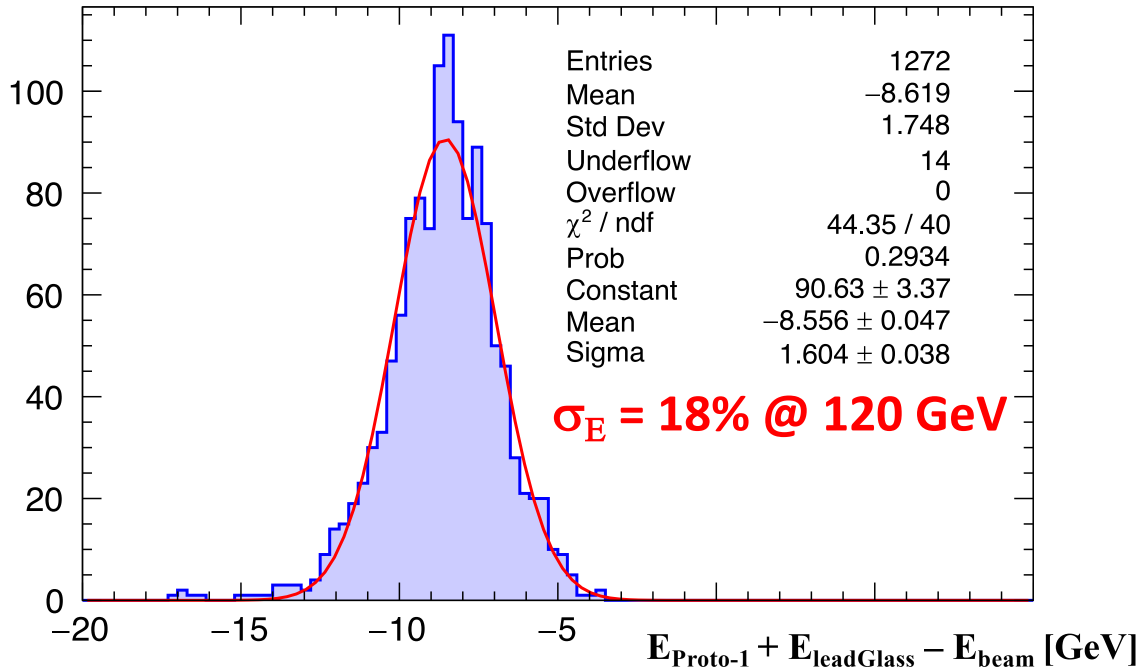


Test Beam @ CERN
– Proto-1 + Lead Glass –

Energy resolution is dominated by leakage

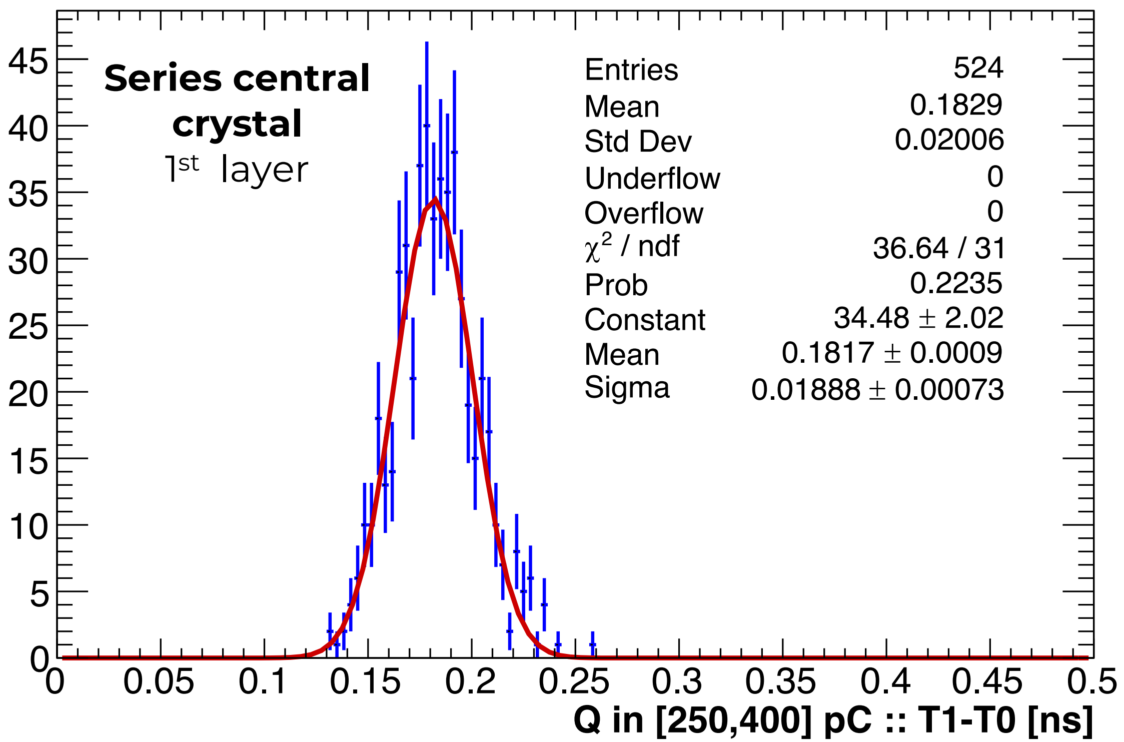
- ➢ Used 24 X_0, ~2 M_R, lead glass crystal + PMT to recover the longitudinal leakage
- ➢ We obtained about the lead glass measured energy resolution @ 120 GeV → Proto-1 apport is negligible → good indication for the future large-scale prototypes

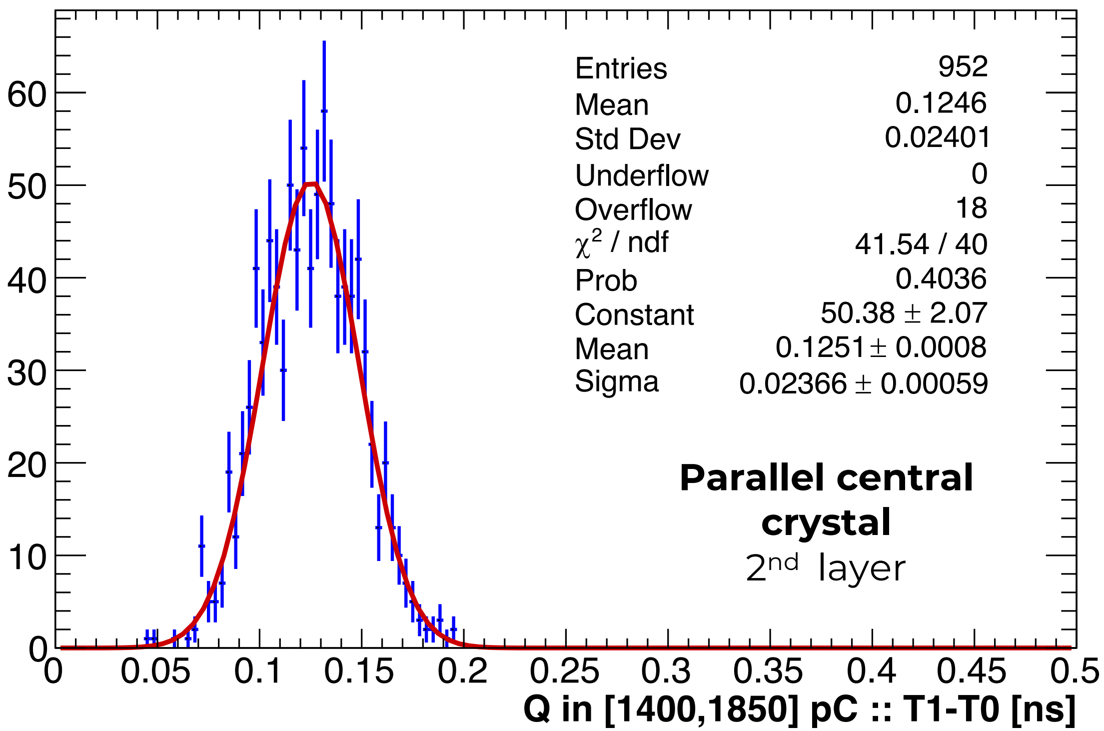




Test Beam @ CERN – timing –

- Time Resolution @ 120 GeV is of **O(20 ps)** both in the series and in the parallel layers using the time SiPMs difference of the central crystals
- Studies on using the layer mean time are ongoing





International MUON Collider Collaboration

Next steps (2024 - 2025)

Personale	FTE
C. Cantone	0.2
A. Cemmi (Enea Casaccia)	0.25
F. Colao (Enea Frascati)	0.2
E. Diociaiuti	0.1
I. Di Sarcina	0.25
P. Gianotti	0.2
F. Happacher	0.1
R. Li Voti	0.3
I. Sarra (RL)	0.4
J. Scifo (Enea Casaccia)	0.25
R. Soleti (DIPC, Spagna)	0.5
A. Verna (Enea Casaccia)	0.25
Tot.	**3.0**

- **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.**
- **Submitted a DRD project to achieved a 3 M_R coverage**
- **Sharp increase in the number of people and FTE already in 2024 + A. Saputi [Sez. di Ferrara] and D. Tagnani [Sez. di Roma3] (mechanics and electronics engineers)**

PRIN + INFN

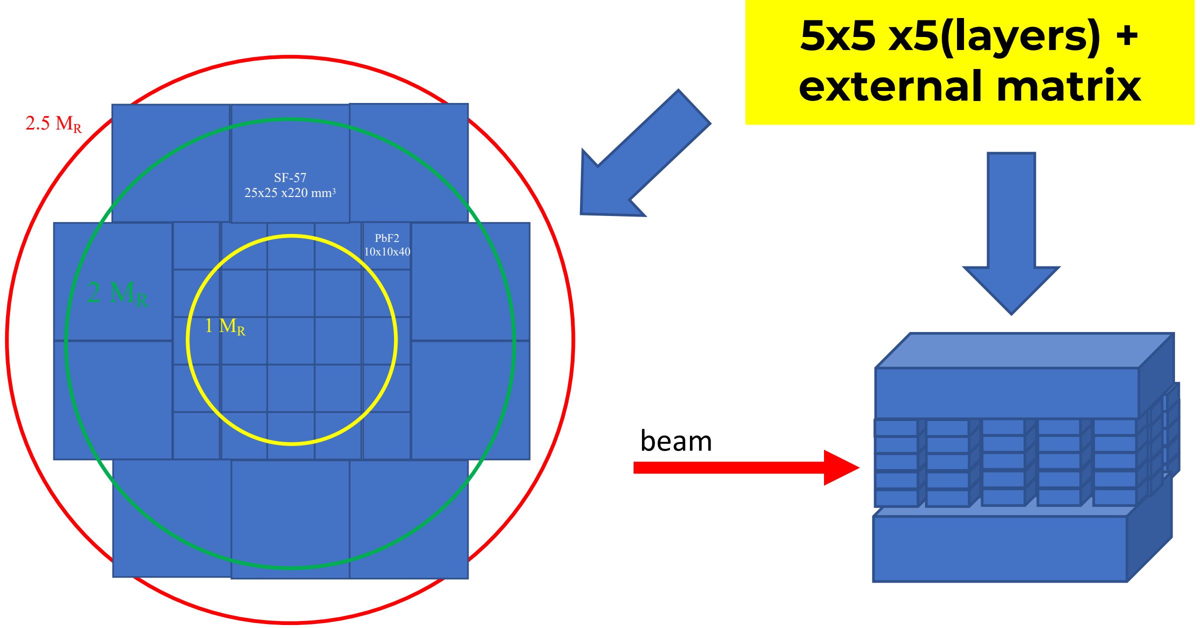
- ❖ Dei richiesti 138 keur sono stati assegnati 120k-2.5k(overhead INFN) = 117.5 keur
- o Recupero dei 20 keur: singola lettura per canale: 200 → 100 chs
  (7->4 digitizers, 450->300 SiPMs, 14->8 boards)
  [ho però sbagliato il costo dei digitizer 7 keur/each->12 keur/each]

➢ Richieste INFN 2024 – 2025 per:

- matrice di recupero leakage per copertura 2 R_M → **Richieste 2024 ~ 34keuro (sinergica a DRD6)**
- 5^o layer per arrivare a 20 X_0 → **Richieste 2025 ~ 25 keuro (in gran parte sinergica a DRD6)**

Detailed cost breakdown ECAL

ITEM	kEUR	QUANTITY	TOTAL	BUDGET POST
PbF2 crystals	0.1	110	11.00	B (general expenses)
SiPMs	0.03	450	13.50	B (general expenses)
Samtec Micro Cables (ERCD-040-40.00-TEU-TED-1-D) + Boards connectors	0.25	14	3.50	E (Consumables)
Custom Electronics Boards (BIAS + Readout) - 18 CH each HV: 0-100V, Gain: x4 or x8 selectable, web interface	2.25	14	31.5	E (Consumables)
CAEN V1742 digitizer	7	*12* 7	49	E (Consumables)
Mechanics: modules envelope	1.5	4	6	E (Consumables)
Cooling system x SiPMs: micro channels cooling layers and pipes	5	4	20	E (Consumables)
SiPMs for PET	0.06	10	0.6	B (general expenses)
Crystals for PET	0.06	5	0.3	B (general expenses)
Project Travel Costs for Meetings			3	E (Consumables)
TOTAL			**138.40**	



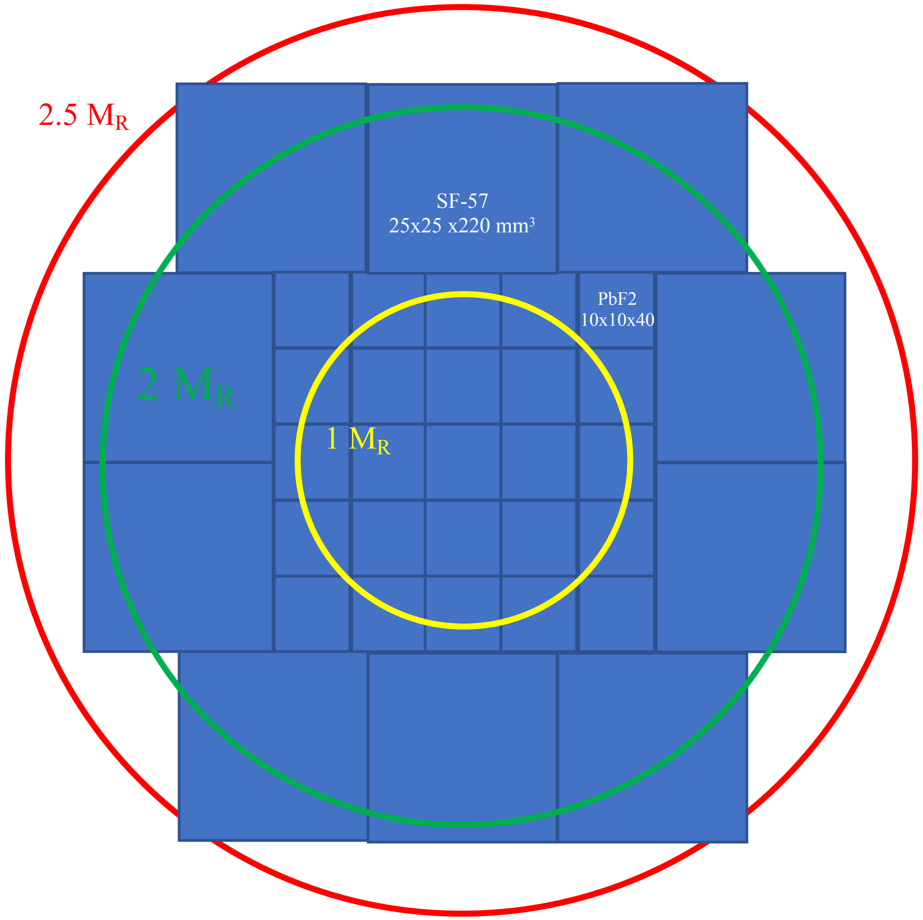
PRIN + INFN

Le richieste sono sinergiche al progetto presentato al DRD6 task3:

Richieste – matrice di recupero	kEur
Taglio e rilavorazione cristalli SF-57 Na62	8.5
10 PMT+partitori	10
Realizzazione Meccanica Matrice di recupero	2.5
power supply per i PMT --> CAEN R8033	13 (inventario)
Tot.	**34**

Richieste – 5x5 x5 layer	kEur
Programmatore ARM ULINKPro	2.5
Metabolismo 3fte	5
Tot.	**7.5**

Missioni	kEur
Irraggiamento a Casaccia e FNG Proto-1	5.5 (SJ)
Responsabilità Sarra: Detector Coordinator per il calorimetro	3
Metabolismo 3fte	4
Test beam Crilin prototipi (pre-shower, SiPM irraggiati)	10 (SJ)
Tot.	**7 + 15.5 (SJ)**



DRD6 task3

M. Casarsa[1], A. Ferrari[2], N. Pastrone[3], I. Sarra[4], L. Sestini[5], S. R. Soleti[6]

1) INFN - Sezione di Trieste, via A. Valerio 2, 34127 Trieste, Italy
2) Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany
3) INFN - Sezione di Torino, via P. Giuria, 10125 Torino, Italy
4) INFN - Laboratori Nazionali di Frascati, via Enrico Fermi, 54, 00044 Frascati RM, Italy
5) INFN - Sezione di Padova, via F. Marzolo 8, 35131 Padova, Italy
6) Donostia International Physics Center, Manuel Lardizabal Ibilbidea, 4, 20018 Donostia, Gipuzkoa, Spain

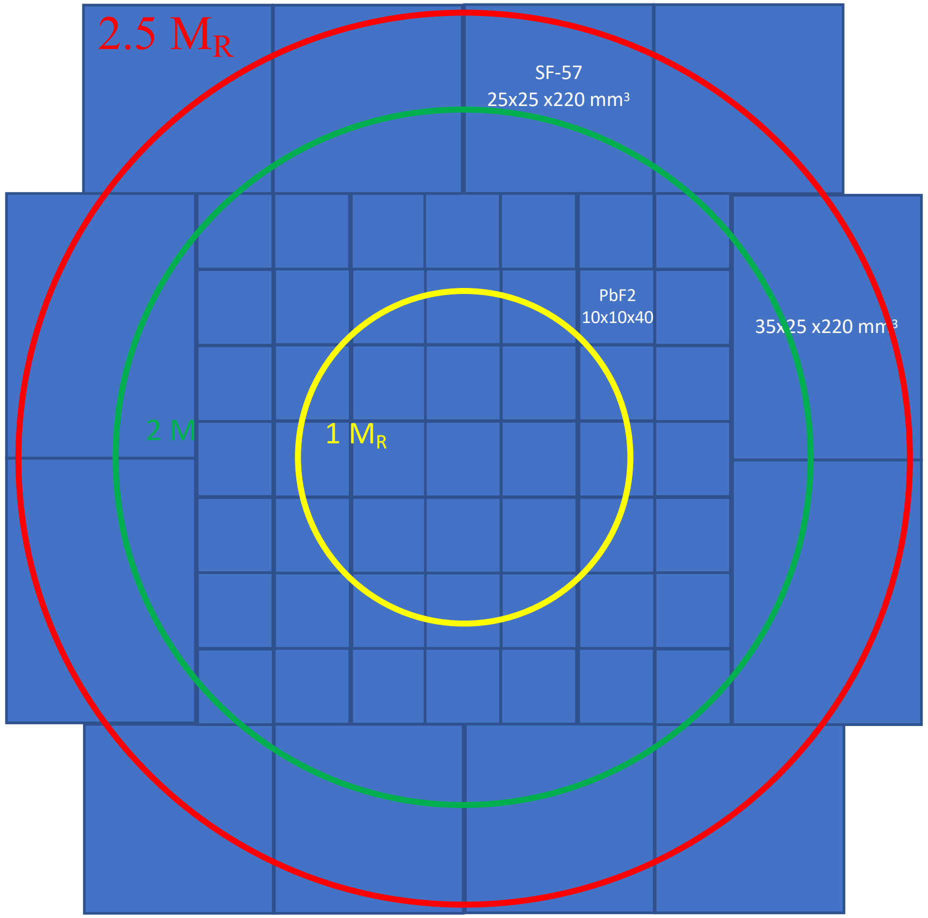
Development and test of an innovative semi-homogeneous calorimeter for a future Muon Collider

March 29, 2023

- **6 instituti (4 dell'INFN) → 7.2 fte @ 2024**
- **Proiezione @ 2025 – 2026 – 2027 → 9.5 fte**

$2\ M_R = 3.5/\mathbf{2.2} + 1.1/\mathbf{2.6}$

$2.5\ M_R = 3.5/\mathbf{2.2} + 2.4/\mathbf{2.6}$



DRD6 task3 – costo Progetto -

$2\ M_R = 3.5/\mathbf{2.2} + 1.1/\mathbf{2.6}$
$2.5\ M_R = 3.5/\mathbf{2.2} + 2.4/\mathbf{2.6}$

Totale necessario per la realizzazione del progetto 230 keur

Proposed "materials" funding to be requested 1) LNF 2) Padova 3) Torino 4) Trieste 5) HZDR 6) DIPC	Institute 1: 75 kEUR for remaining SiPMs, Electronics, and Mechanics development and production Institute 2: 75 kEUR for DAQ Institute 3: 30 kEUR for remaining Crystals Institute 4: 7.5 kEUR for Simulation Environment Institute 5: 17.5 kEUR for Simulation, Shielding and Test Facilities Institute 6: 25 kEUR for a automatic SiPMs calibration station