Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

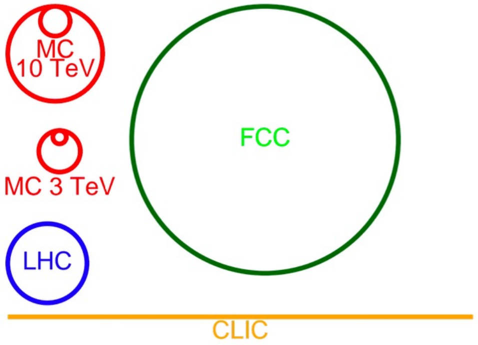
RD_MUCOL @ LNF

International MUON Collider Collaboration

- A muon collider can provide leptonic collisions at multi-TeV center-of-mass energies in a compact circular machine:
  - all collision energy is available to the hard-scattering process;
  - energy and momentum of the colliding particles are precisely known;
  - final states are in general “cleaner” w.r.t. hadronic machines.

A muon collider combines precision physics and high discovery potential.

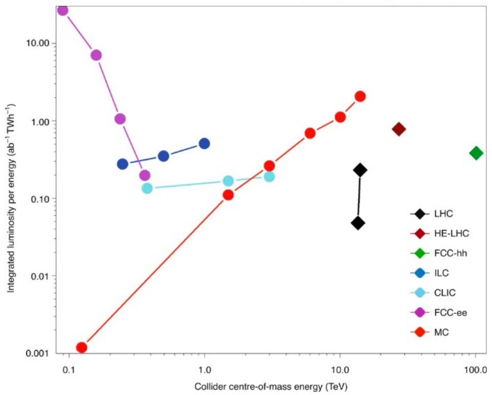
footprints for different high-energy facilities



- Muon colliders are compact: cost effective and possibly more sustainable.

annual integrated luminosity per consumed electric power as a function of the center-of-mass energy

K.R Long et al., Nat. Phys. 17, 289 (2021)



- Muon colliders are power-efficient at high collision energies.

Personale Ricercatori: 10 (2.4 FTE) Tecnologi: 2 (0.6 FTE)	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**

20 September 2023, LNF_gr1

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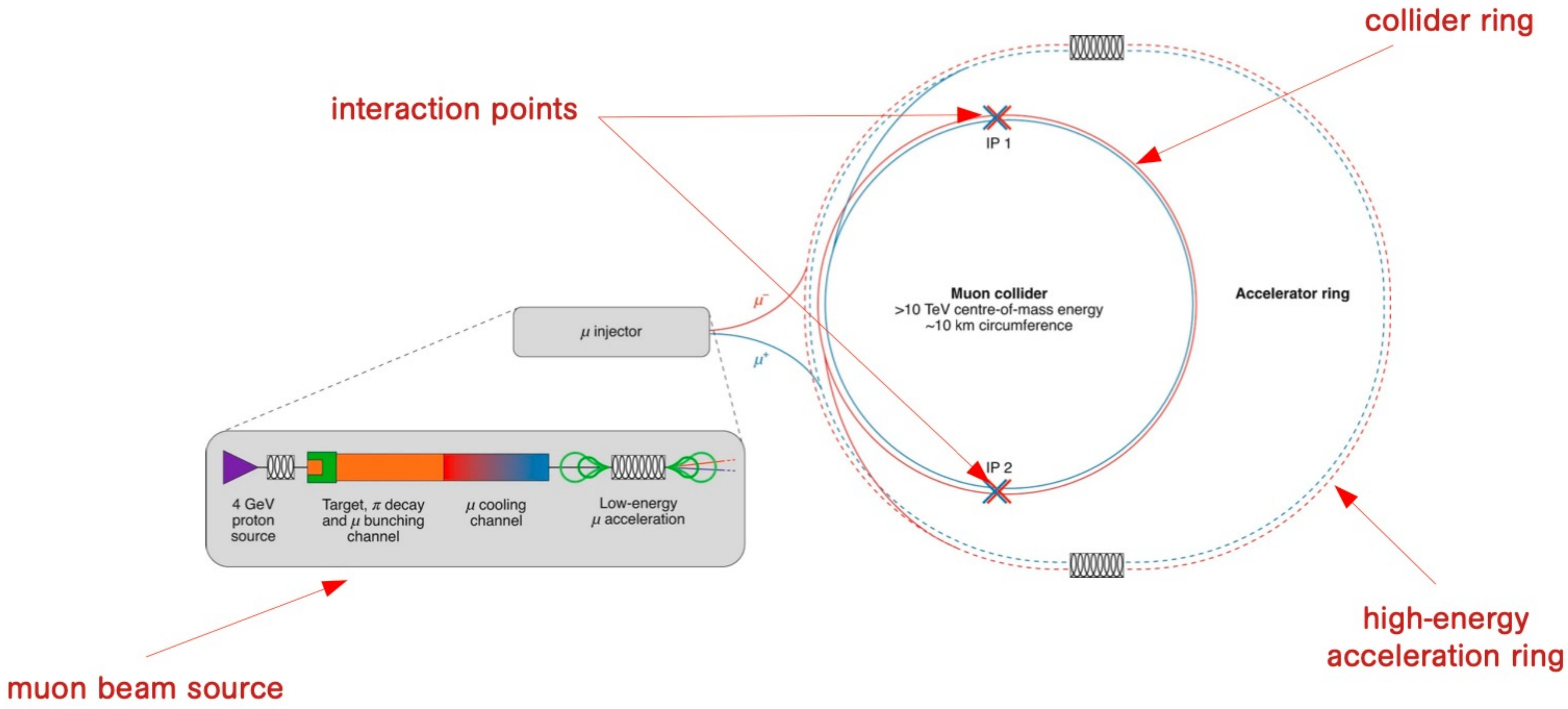

Design fully driven by the muon lifetime.

20 September 2023, LNF_gr1

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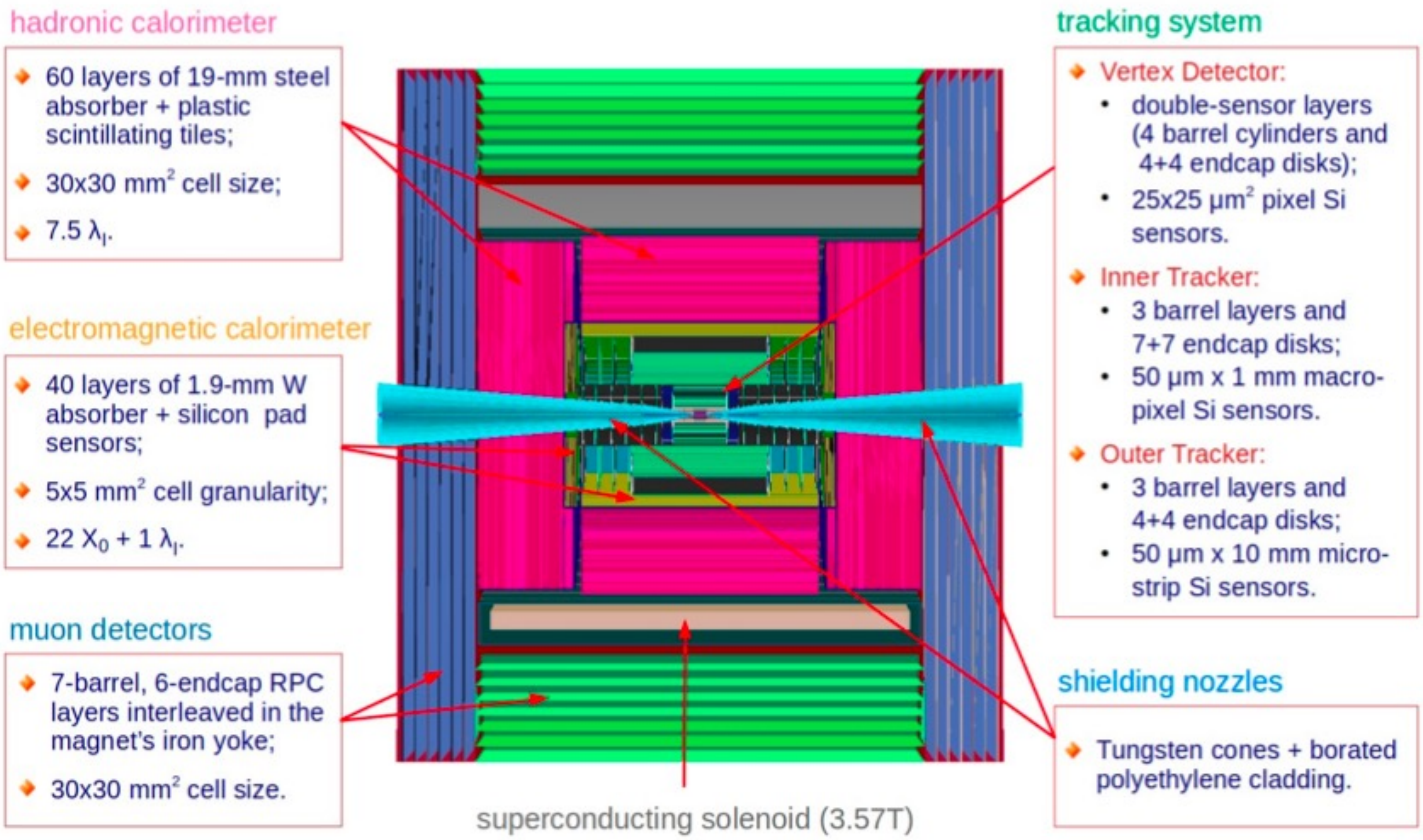
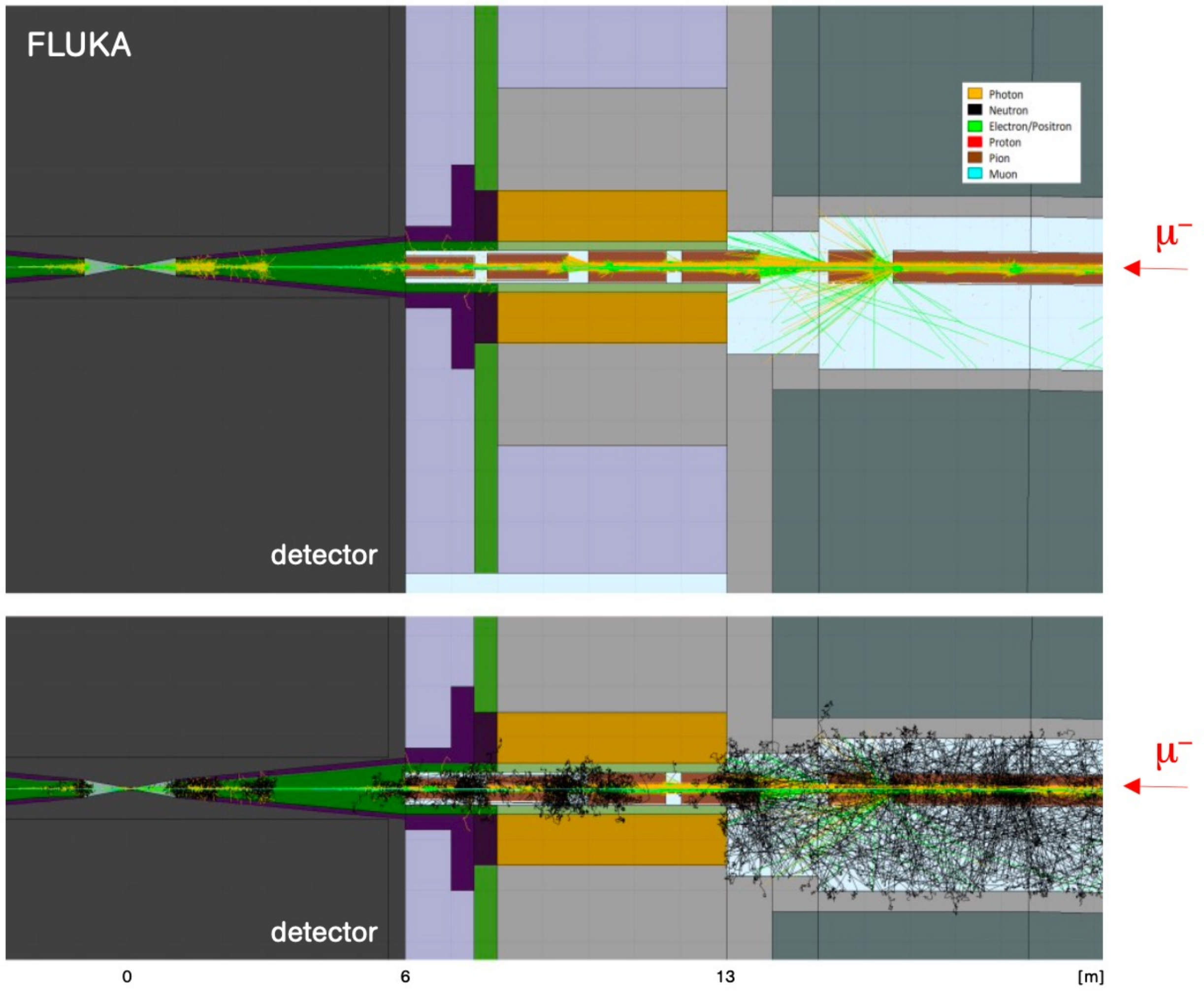
International MUON Collider Collaboration



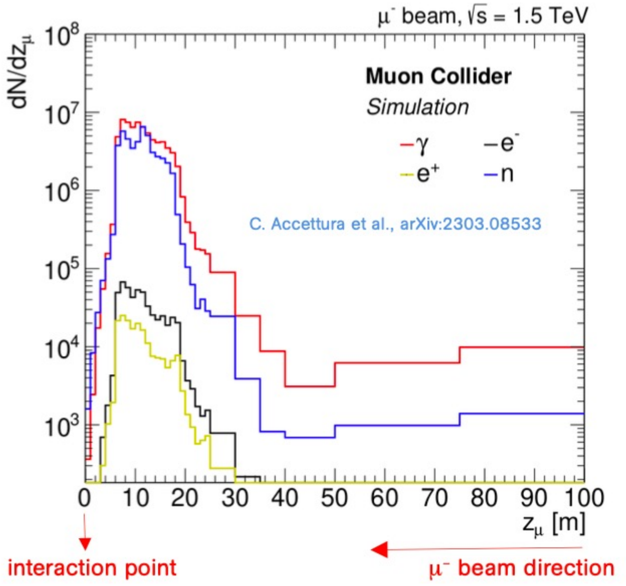
The detector model for 3-TeV studies is based on CLIC's detector concept + the MDI and vertex detector designed by the US Muon Accelerator Program.

20 September 2023, LNF_gr1

F. Collamati et al., 2021 JINST 15 P11009



- The primary source of machine background arises from the interaction of the decay products of the muons in the beams with the machine components (beam-induced background, BIB):
  - at each bunch crossing, high levels of photons, neutrons, and electrons/positrons enter the detector.



decay position of muons contributing to the background in the detector

R&D status for an innovative crystal calorimeter for the future Muon Collider

C. Cantone, S. Ceravolo, E. Di Meco, E. Diociaiuti, D. Paesani, I. Sarra – LNF INFN

F. Colao – ENEA Frascati

A. Saputi – INFN Sezione di Ferrara

D. Tagnani – INFN Sezione di Roma Tre

L. Sestini – INFN Padova

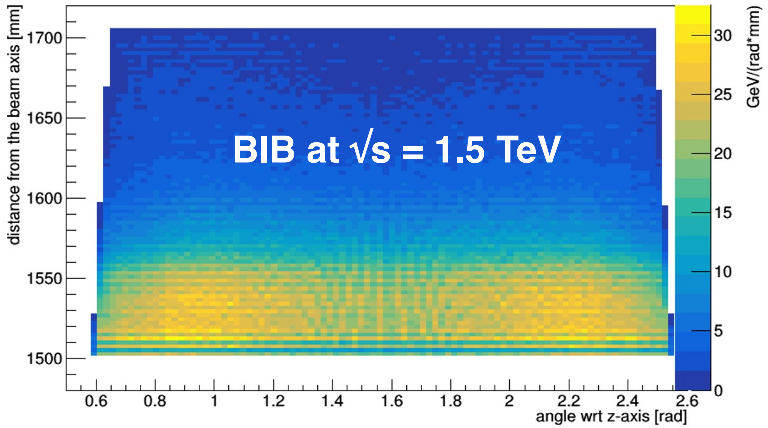
M. Moulson – Hike

S. Martellotti– Hike

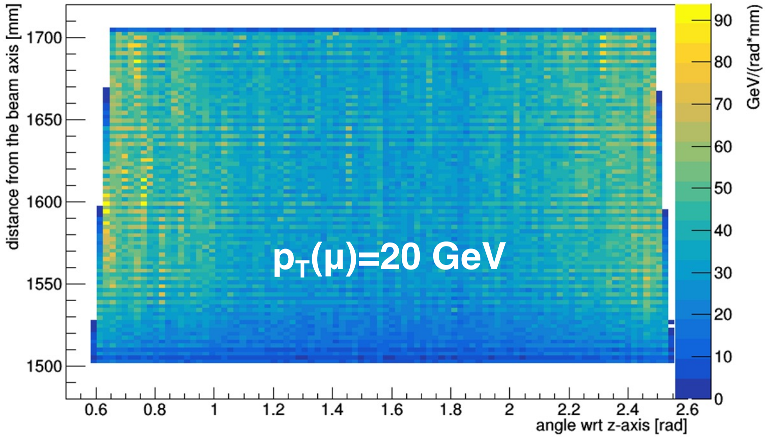
20 September 2023, LNF_gr1

Beam Induced Background

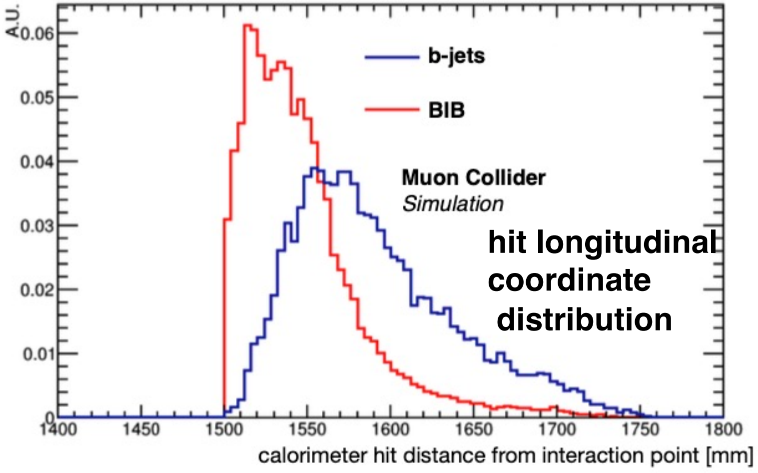
Energy released in ECAL barrel by one BIB bunch crossing

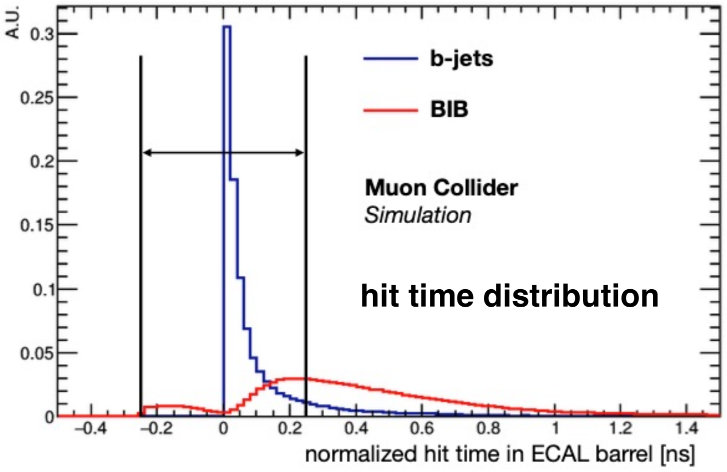


Energy released in ECAL barrel by uniformly distributed prompt muons in the (θ,ϕ) space



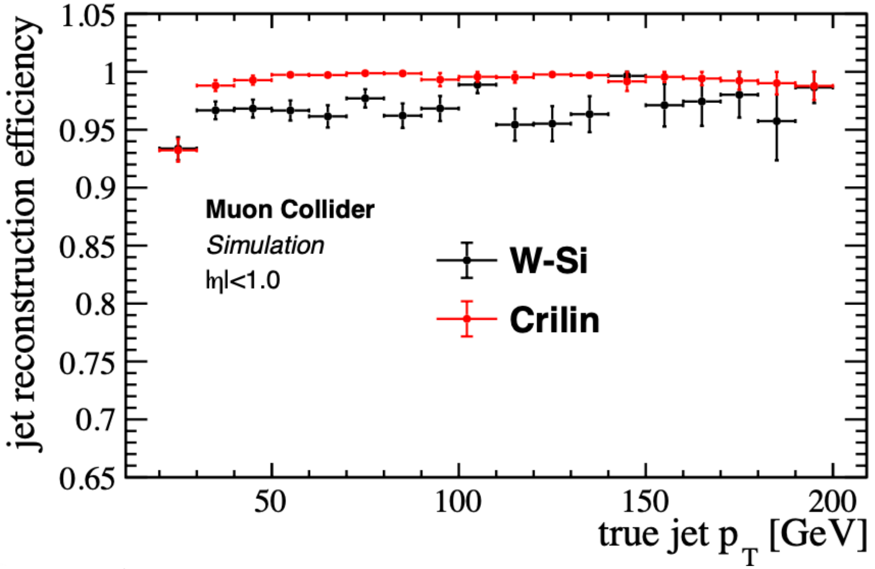
- Expected BIB on the ECAL barrel ~300 γ/cm^2/events with E~1.7 MeV.
- BIB can be subtracted using information from energy releases in the ECAL.
- The BIB produces most of the hits in the first layers of the calorimeter while i.e. muons produce a constant density of hits after the first calorimeter layers.
- Since the BIB hits are out-of-time wrt the bunch crossing, a **measurement of the hit time performed cell-by-cell** can be used to **remove most of the BIB.**

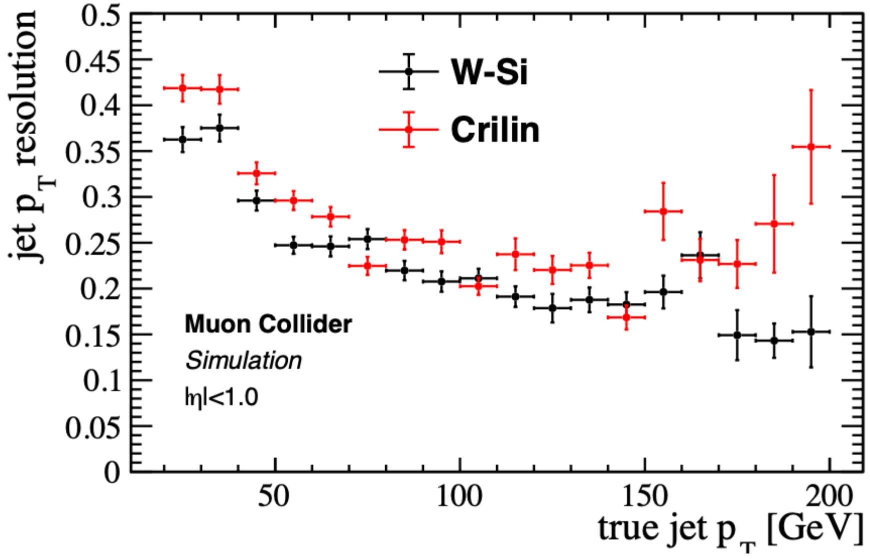




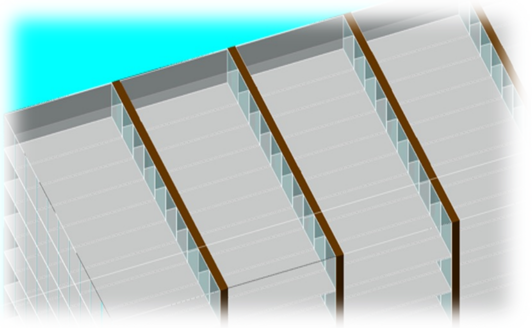
The Crilin calorimeter

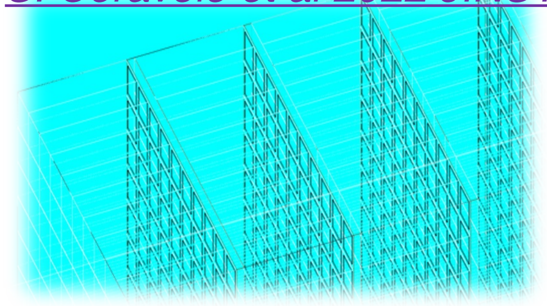
- The goal is to build a crystals calorimeter, fast, relative cheap, and with high granularity (both transversal and longitudinal) optimized for muon collider.
- Our proposed design, **Crilin**, is a **semi-homogeneous** electromagnetic calorimeter made of **Lead Fluoride Crystals** (PbF_2) matrices where each crystal is readout by 2 series of 2 UV-extended surface mount **SiPMs.**
- **It represents a valid and cheaper alternative to the W-Si Muon Collider ECAL**.





S. Ceravolo et al 2022 JINST **17** P09033



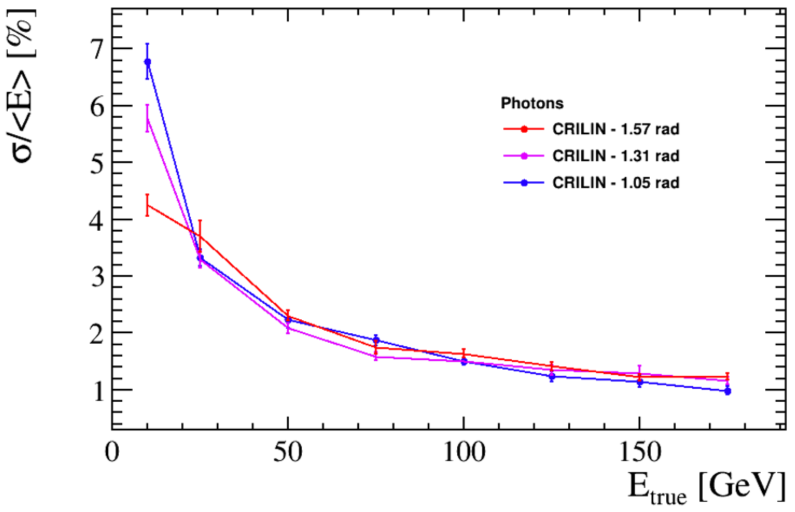


Performances with photons

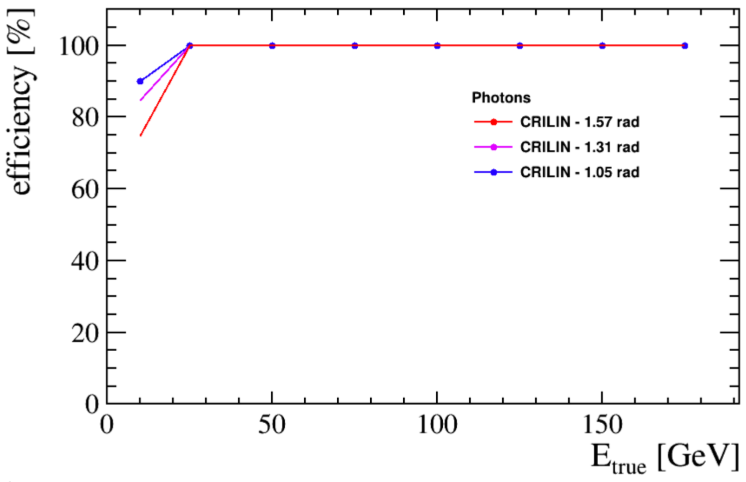
The ECAL barrel with Crilin technology has been implemented in the Muon Collider simulation framework

- 5 layers of 45 mm length, 10 X 10 mm^2 cell area. Dodecahedra geometry → 21.5 X_0
- In each cell: 40 mm PbF_2 + 3 mm SiPM + 1 mm electronics + 1 mm air

- Crilin is particularly suited for the BIB 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



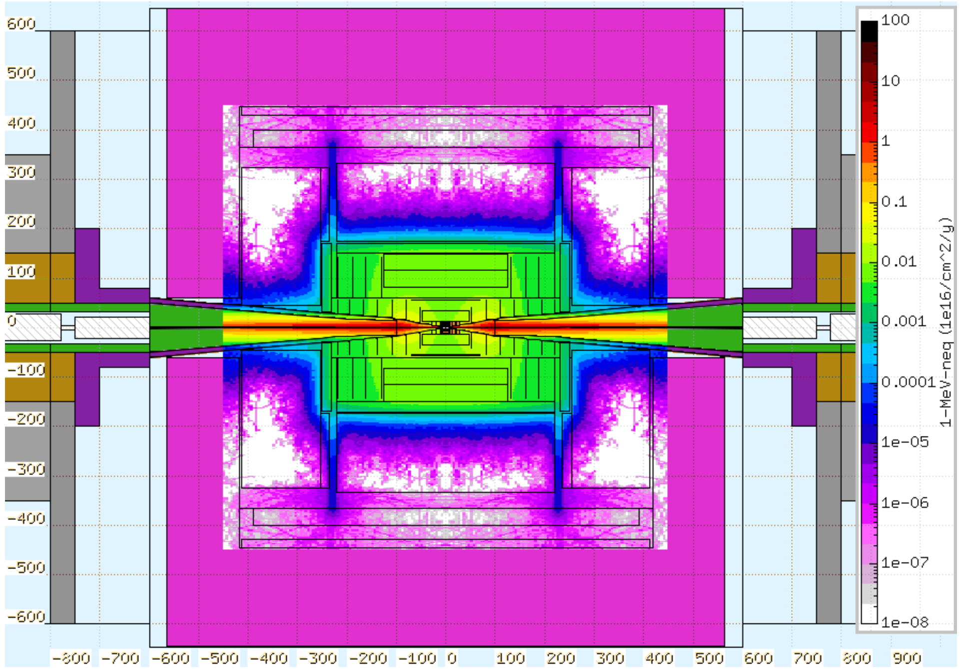
$\frac{\sigma}{E} \simeq \frac{14\%}{\sqrt{E}}$ for theta = 1.57

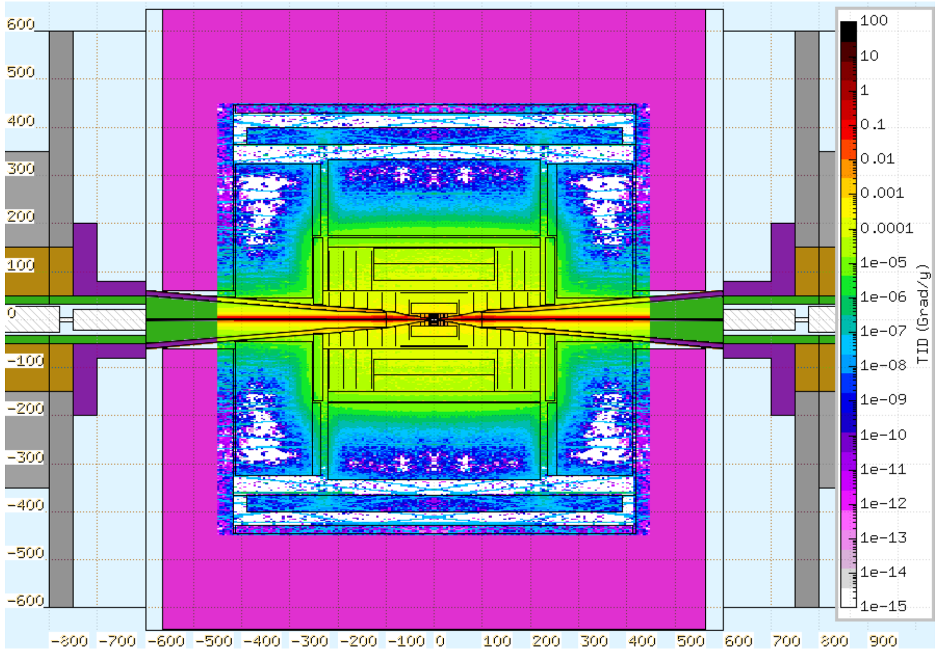


$N^{fake}_{CRILIN} \simeq 0$ number of fake clusters per event

Radiation enviroment

FLUKA simulation for the BIB at $\sqrt{s}$=1.5 TeV

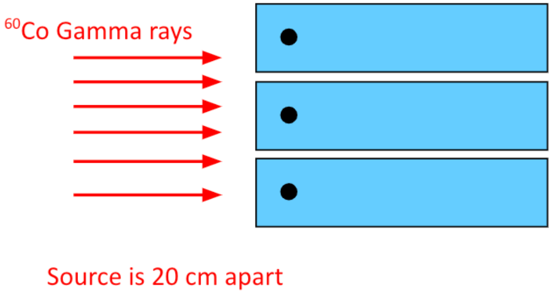


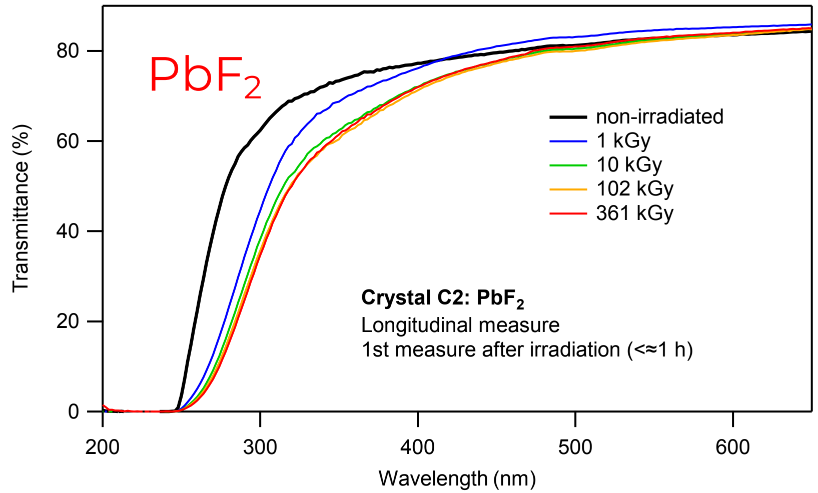


- **Neutron fluence** $\sim 10^{14}$ n_{1MeVeq}/cm^2**year** on ECAL.
- **TID ~ 1 Mrad/year** on ECAL.

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)

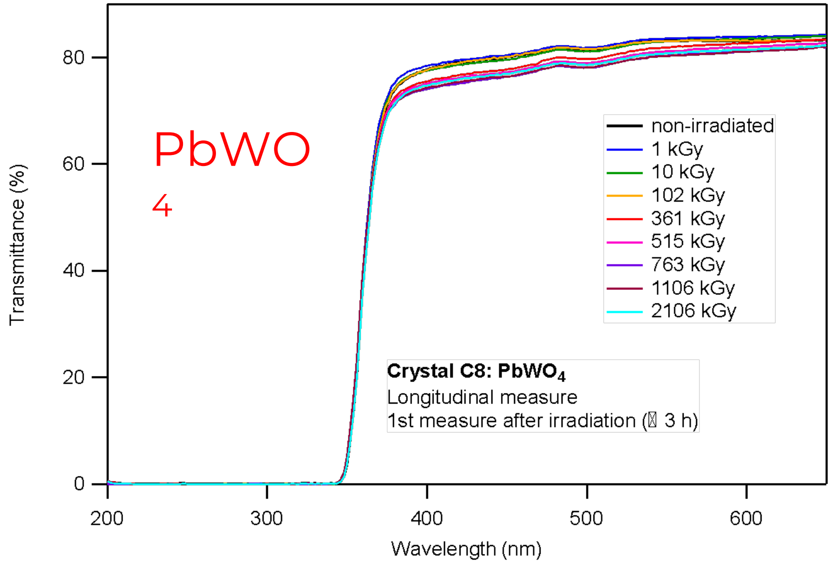




- For PbF_2:
  - **after a TID > 35 Mrad no significant decrease** in transmittance observed.
  - Transmittance after neutro irradiation showed no deterioration
- For $PbWO_4$-UF:
  - **after a TID > 200 Mrad no significant decrease** in transmittance observed.

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



SiPMs radiation hardness

Neutrons irradiation: 14 MeV neutrons with a total fluence of 10^{14} n/cm^2 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;

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

15 μm pixel-size

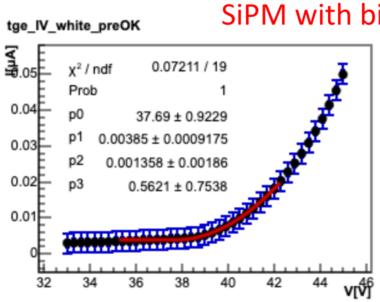
T [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	75.29 ± 0.01	12.56 ± 0.01	30.45 ± 0.01	46.76 ± 0.01
-5 ± 1	75.81 ± 0.01	14.89 ± 0.01	32.12 ± 0.01	46.77 ± 0.01
0 ± 1	76.27 ± 0.01	17.38 ± 0.01	33.93 ± 0.01	47.47 ± 0.01

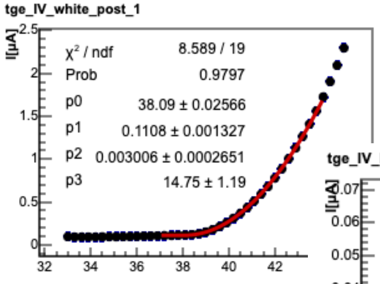
10 μm pixel-size

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

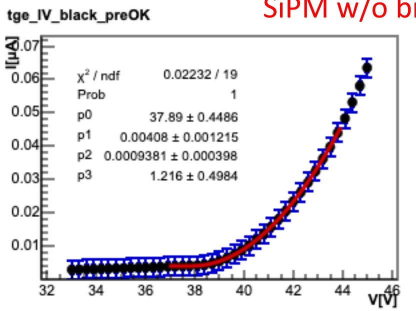
1 Mrad dose

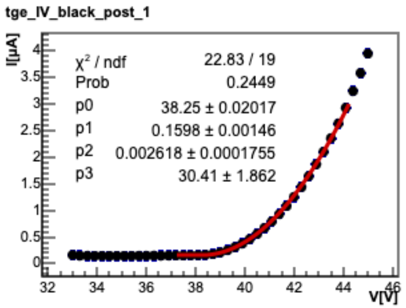
SiPM with bias





SiPM w/o bias





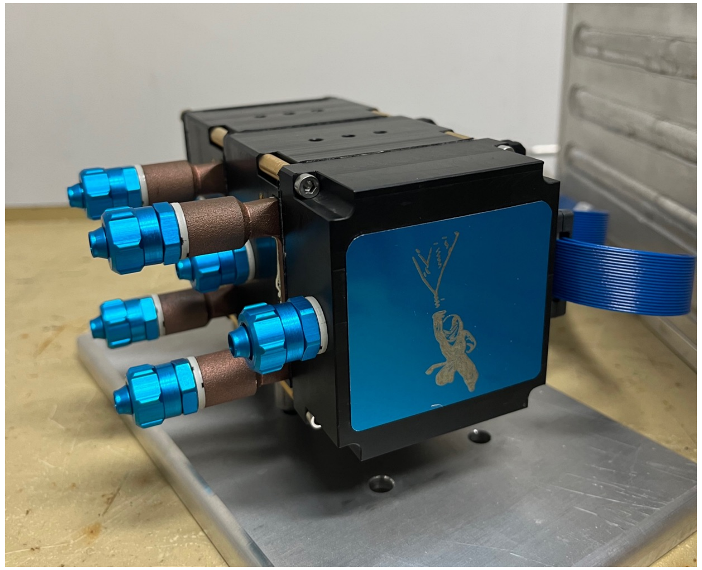
R&D status

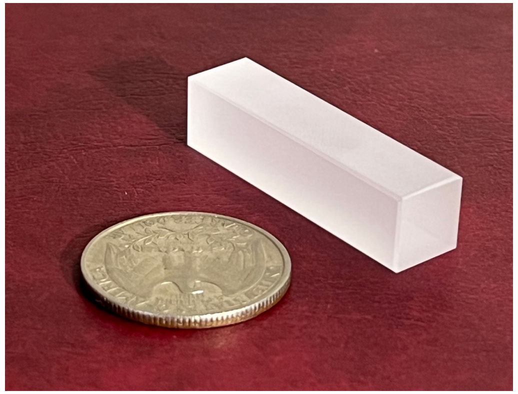
Prototype versions
- Proto-0 (2 crystals → 4 channels)
- Proto-1 (3x3 crystals x 2 layers → 36 channels)

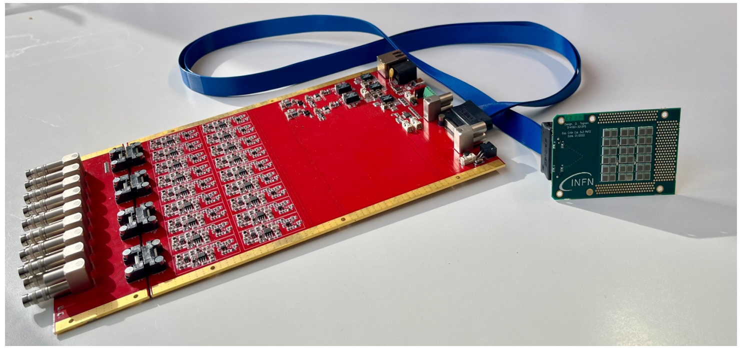
Front-end electronics
- Design completed
- Production and QC completed

Radiation hardness campaigns

Test beam campaigns
- Proto-0 at CERN H2 (August 2022)
- Proto-1 at LNF-BTF (July 2023) and CERN (August 2023)



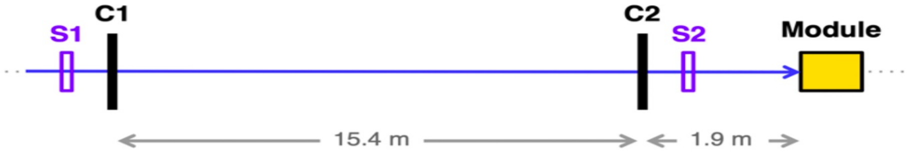


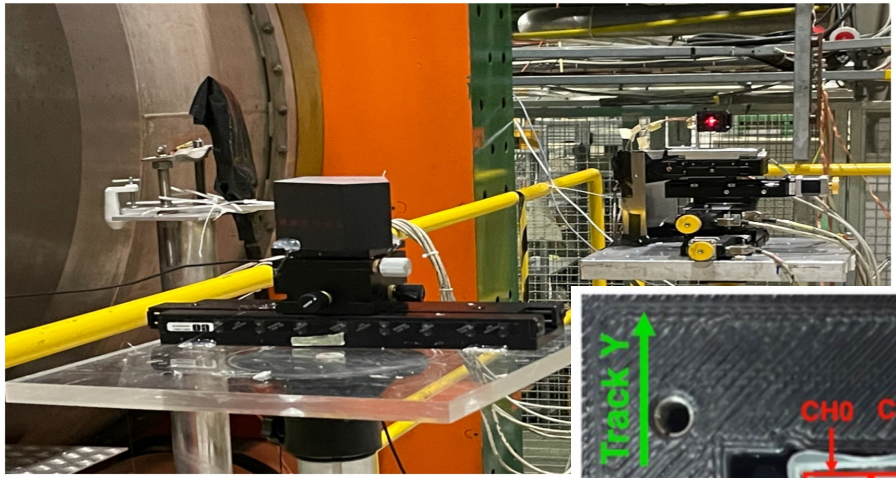


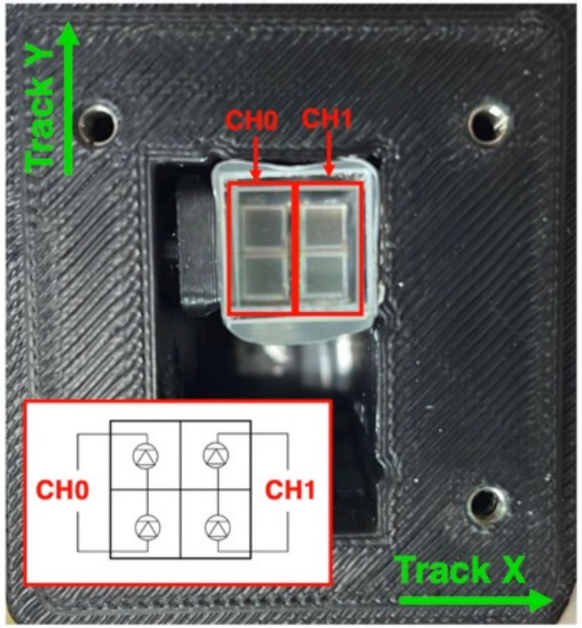
Proto-0: Single crystal beam test

Beam test on Proto-0 in a single crystal configuration in fall 2022:

- $10 \times 10 \times 40$ mm^3 single crystal → 2 options: **PbF_2** (4.3 X_0) **$PbWO_4$-UF** (4.5 X_0).
- Four 3x3 mm^2, 10 μm pixel size SiPMs for two independent readout channels (SiPM pairs connected in series).
- Mylar wrapping - No optical grease.







Aim:

- Validate CRILIN new readout electronics and readout scheme.
- Study systematics of light collection in small crystals with high *n*.
- Measure time resolution achievable with different crystal choices.

Results

Two different orientation were tested → **FRONT** and **BACK:**

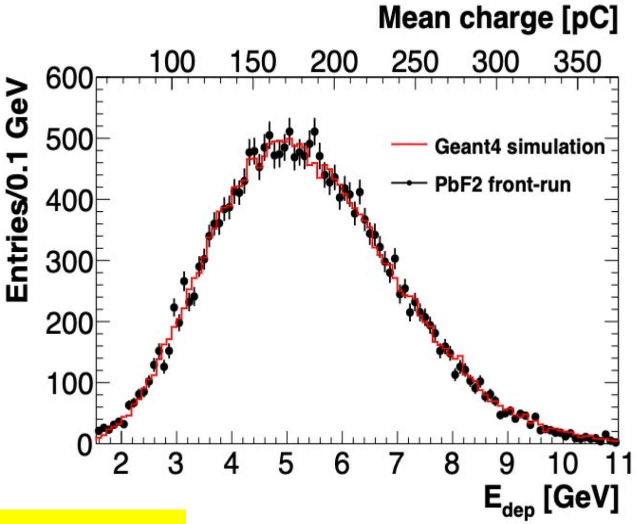
- The BACK run time resolution is better, even after correction, for both crystals.
- PbF_2 outperforms $PbWO_4$-UF despite its higher light output (purely Cherenkov)
- **PbF_2** → σ_{MT} < 25 ps worst-case for E_{dep} > 3 GeV
- **$PbWO_4$-UF** → σ_{MT} < 45 ps worst-case for E_{dep} > 3 GeV

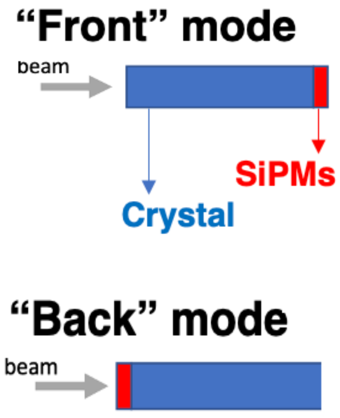
PbF_2

	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

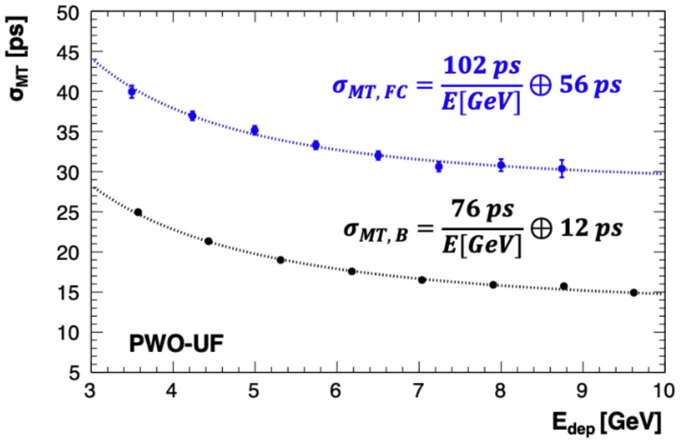
	back-run	front-run
E_{dep} MPV [GeV]	6.39 ± 0.01	6.88 ± 0.01
E_{dep} sigma [GeV]	1.83 ± 0.01	1.99 ± 0.01
pC/GeV	~66.7	~76.9
NPE/MeV	~0.58	~0.67

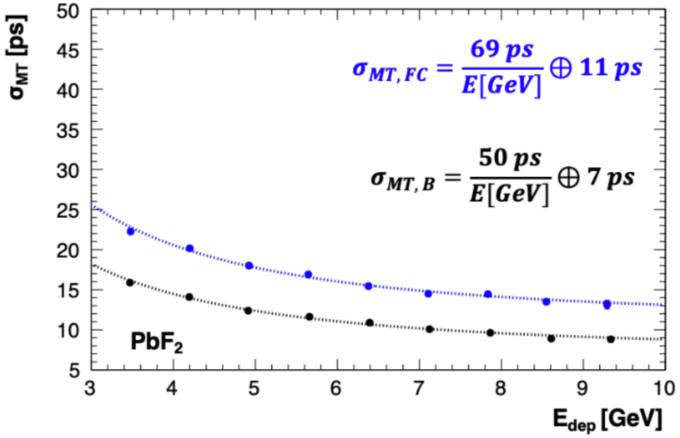




Proto-0

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





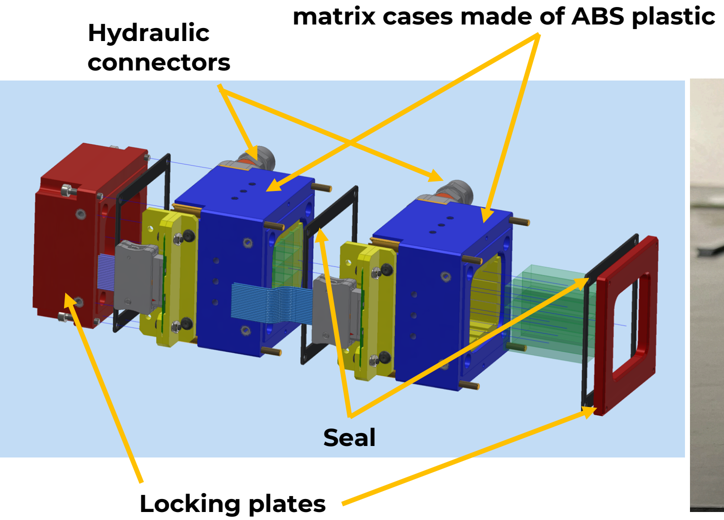
Proto-1

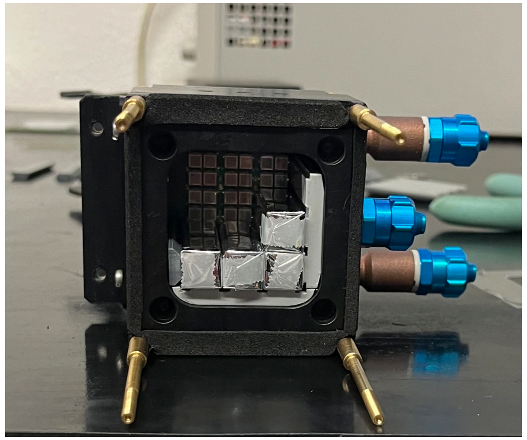
Two stackable and interchangeable submodules assembled by bolting, each composed **of 3x3 crystals+36 SiPMs** (2 channels per crystal)

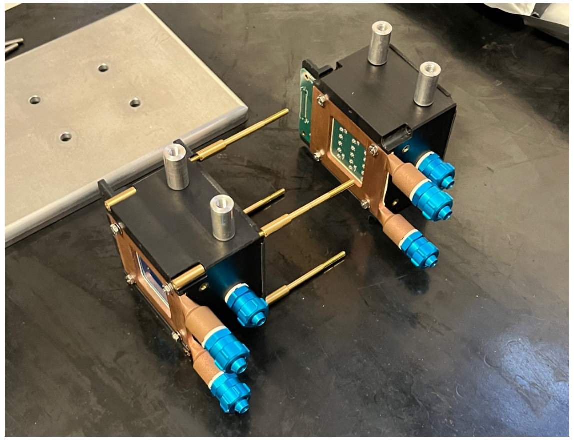
- light-tight case which also embeds the front-end electronic boards and the heat exchanger needed to cool down the SiPMs.

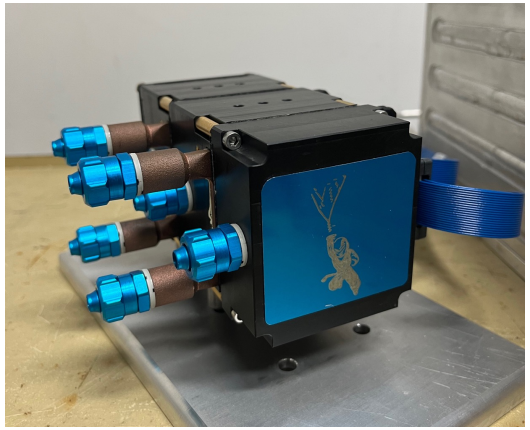
Cooling system:

- Total heat load estimated: **350 mW per crystal** (two readout channels)
- Cold plate heat **exchanger** made of copper mounted over the electronic board.
- **Glycol based water solution** passing through the deep drilled channels.









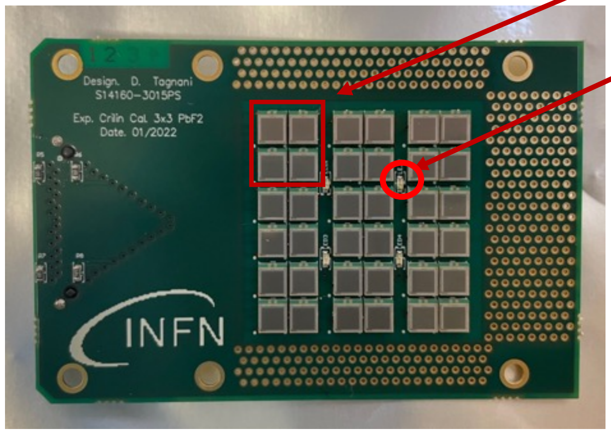
Proto-1: Electronics

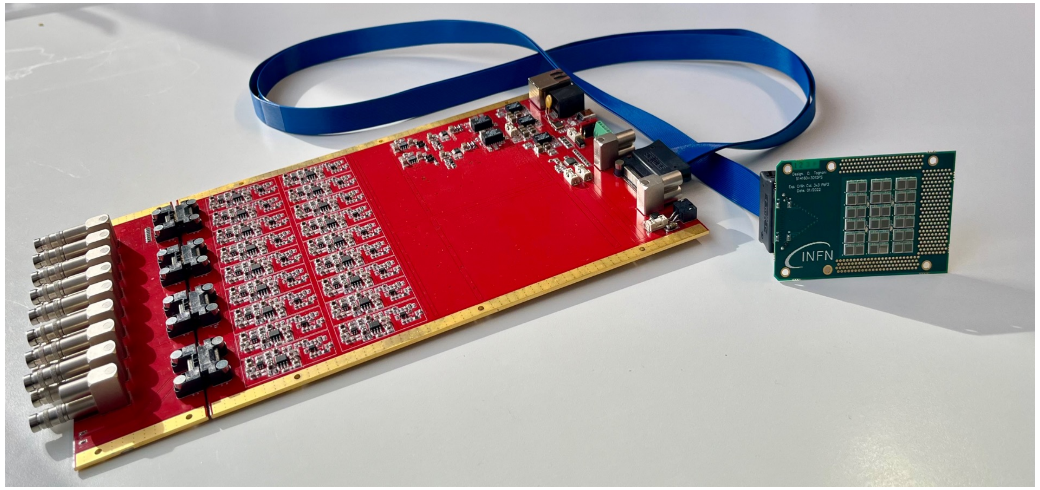
The **SiPMs board** is made of:

- **36 10 μm Hamamatsu SiPMs** →each crystal has **two separate readout channels connected in series**.
- Four SMD blue LEDs nested between the photosensor packages.

The **Mezzanine Board** for 18 readout channels:

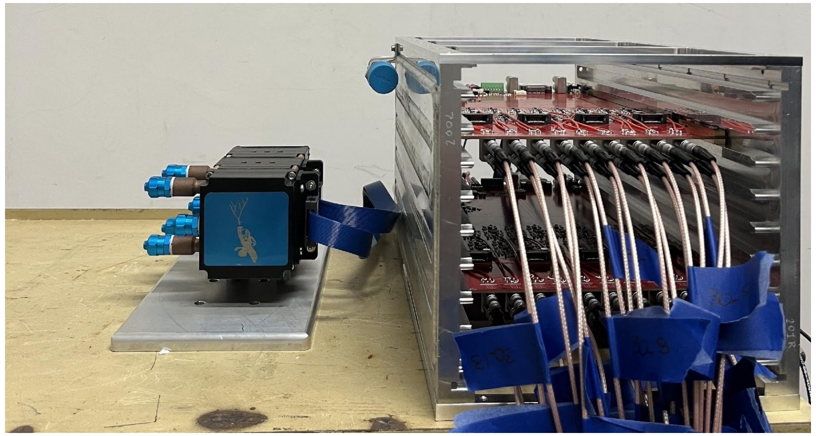
1. Pole-zero compensator and high speed non-inverting stages;
2. 12-bit DACs controlling HV linear regulators for SiPMs biasing.
3. 12-bit ADC channels;
4. Cortex M4 LPC407x Processors.

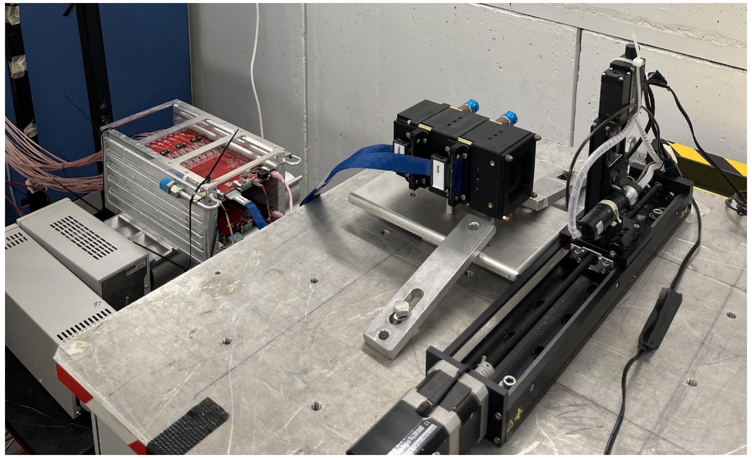




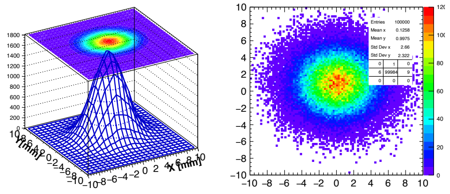
Test Beam @ BTF

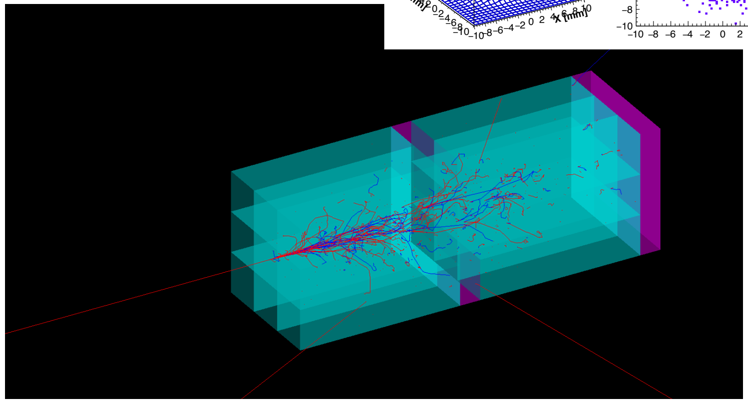
e^- 450 MeV @BTF, July 2023

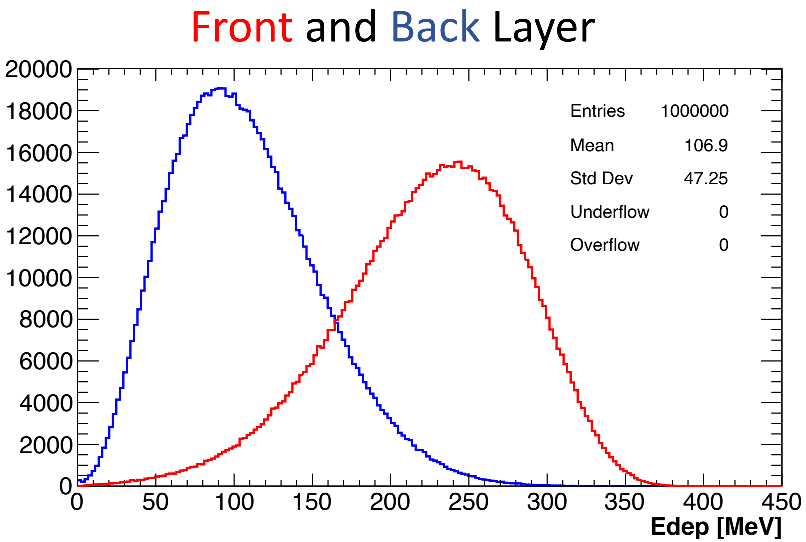


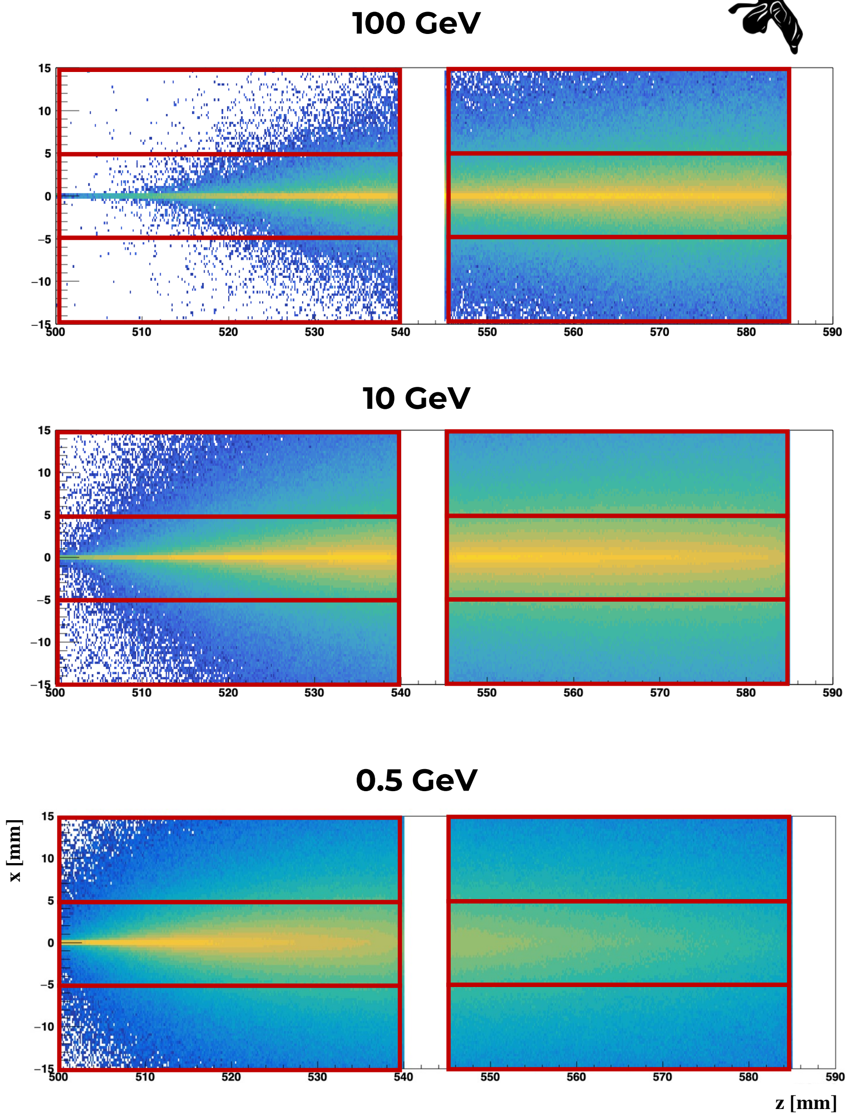


Monte Carlo





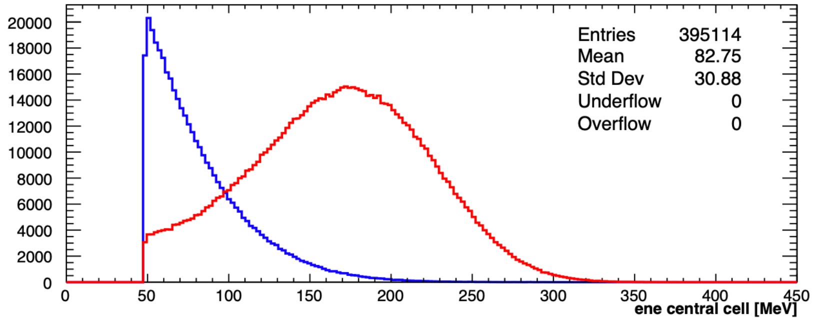




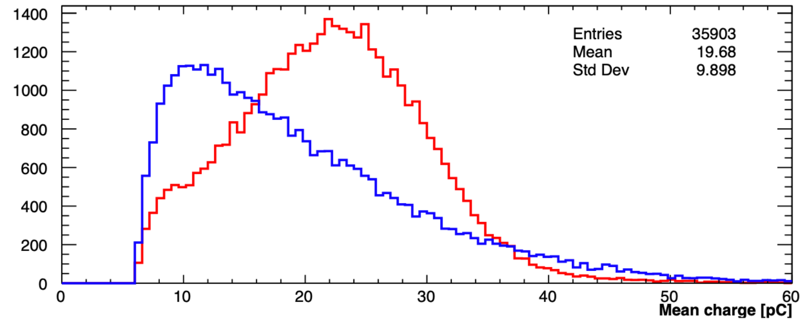
Test Beam @ BTF: Result

Threshold a 6 pC → 50 MeV

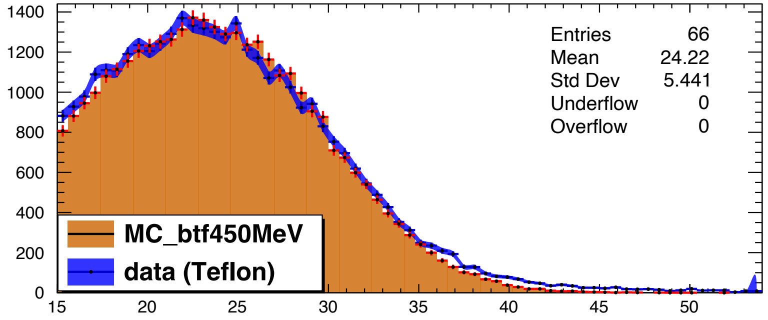
MC

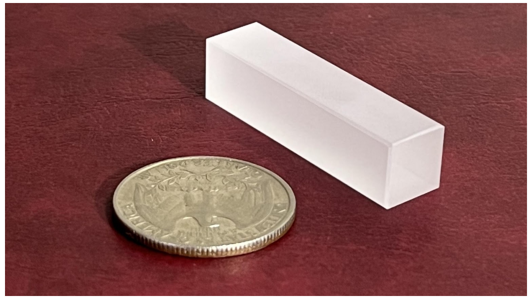


DATA

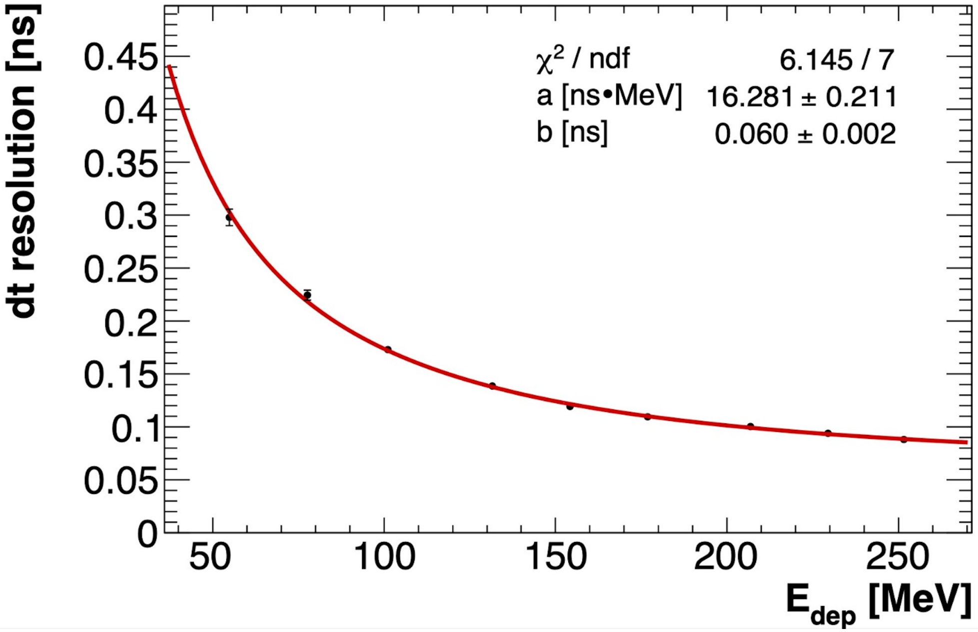


Equalization data-MC



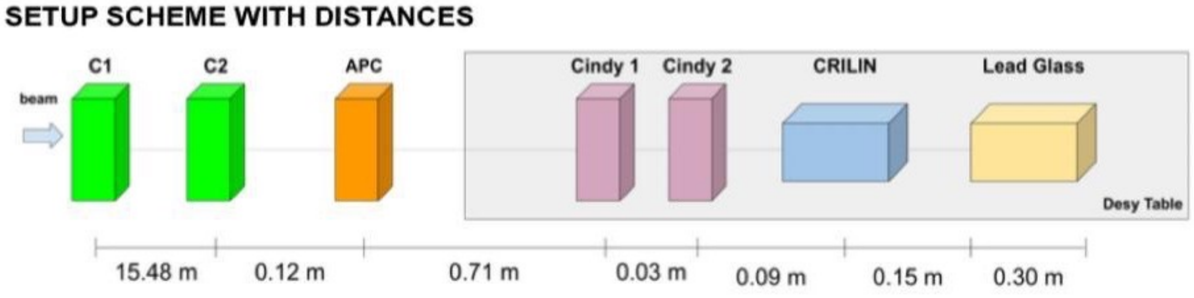


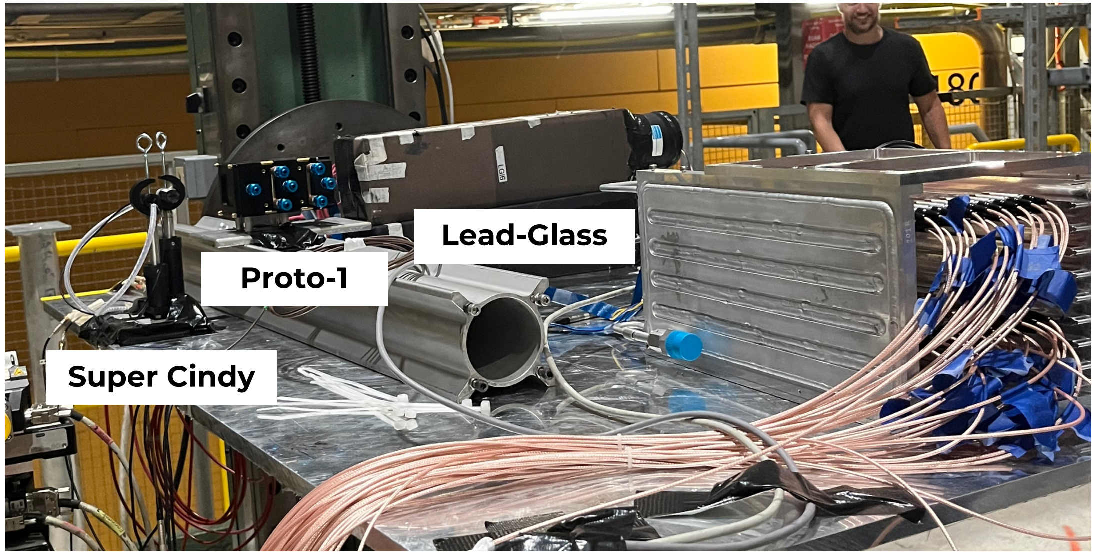
~ 0.13 pC/MeV response (Teflon)
~ 0.32 PE/MeV @ Vop +2 (Teflon)
~ 0.25 PE/MEV @ Vop +2 (Mylar)

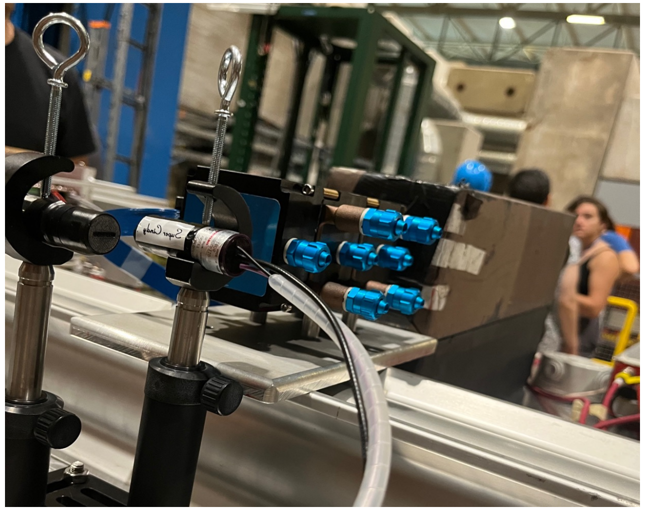


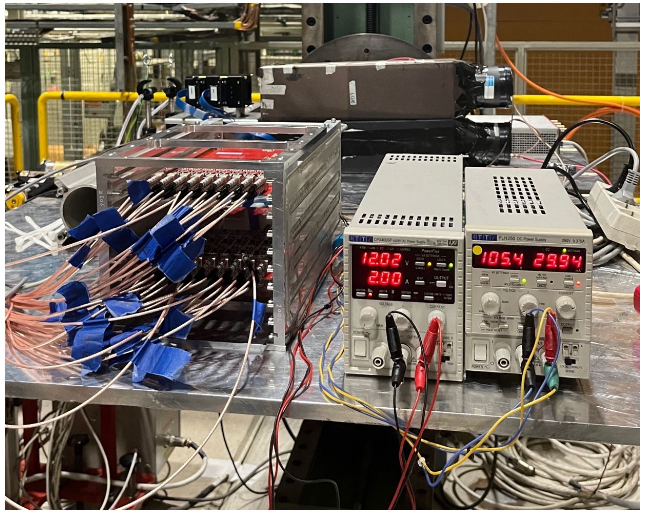
Test Beam @ CERN

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



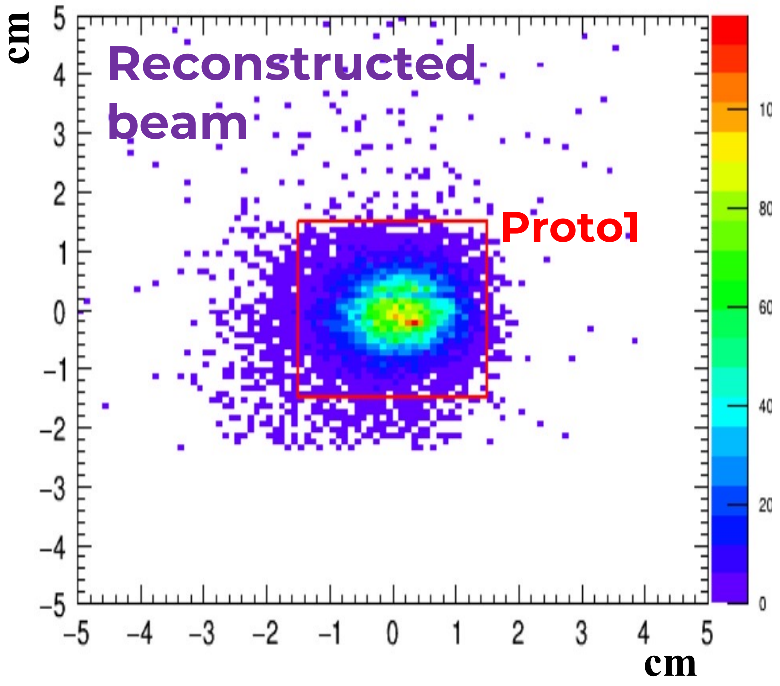




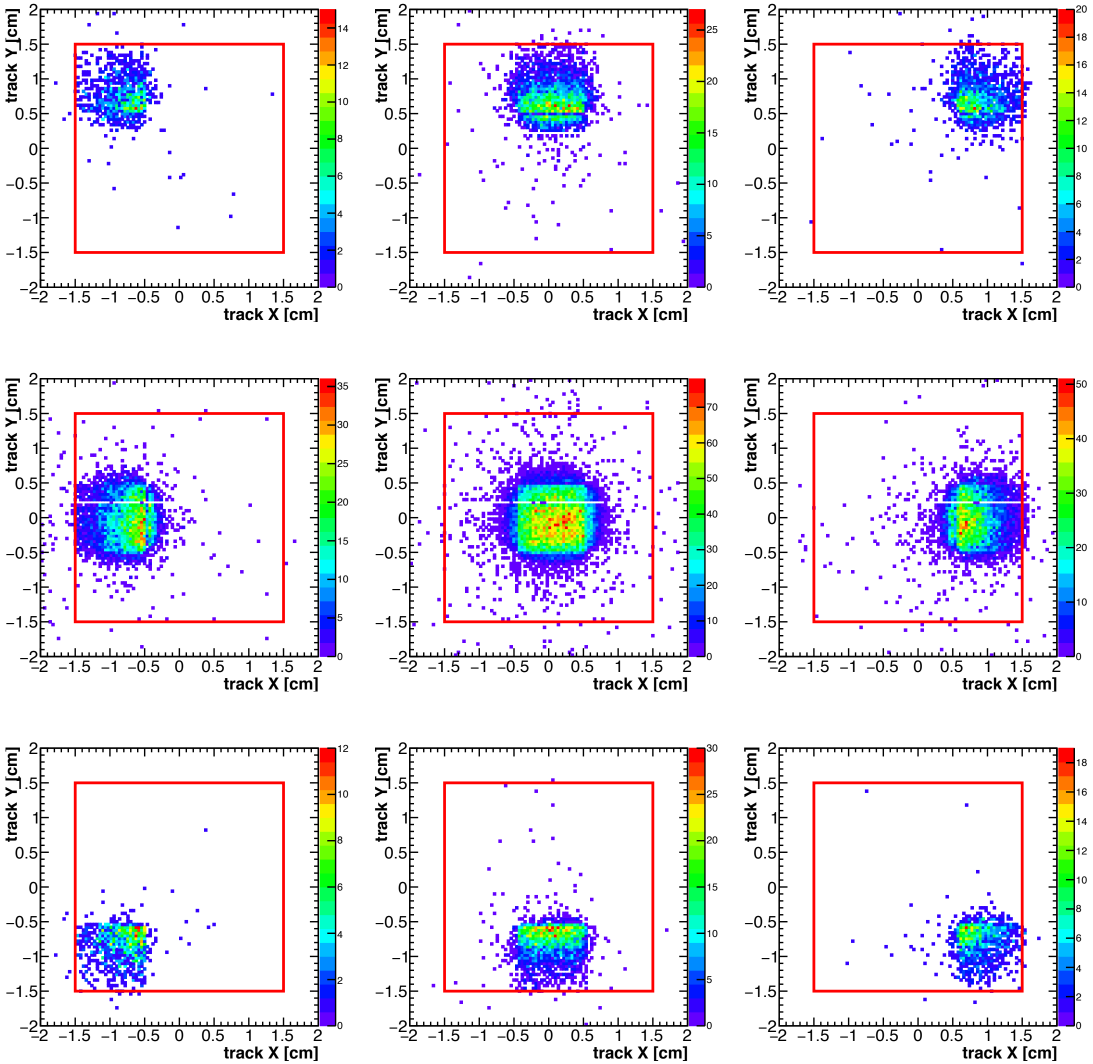


- Beam reconstructed with 2 silicium strip telescopes
- Data acquisition with 2 CAEN V1742 (32 ch each) modified @ 2 Vpp
- 5 Gs/s sampling rate

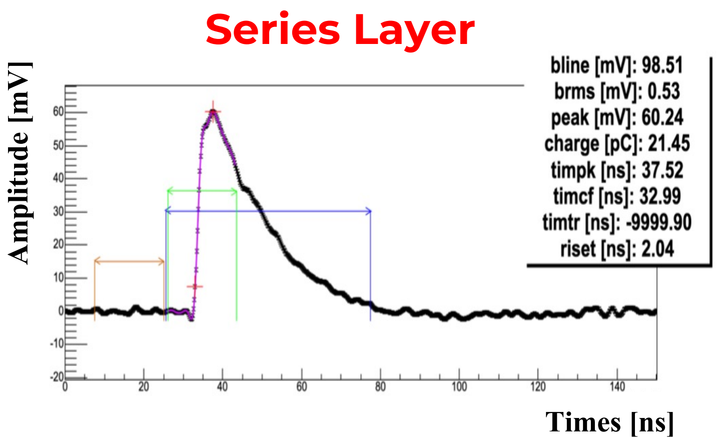
Test Beam @ CERN – 2 –

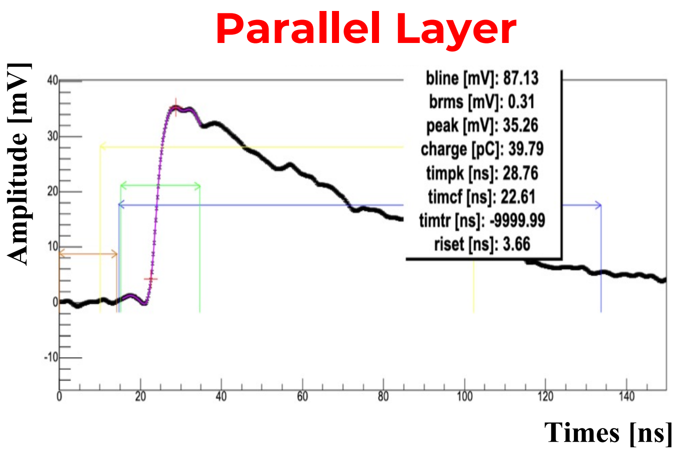


Reconstructed beam on 1st layer crystals



Test Beam @ CERN – 3 –

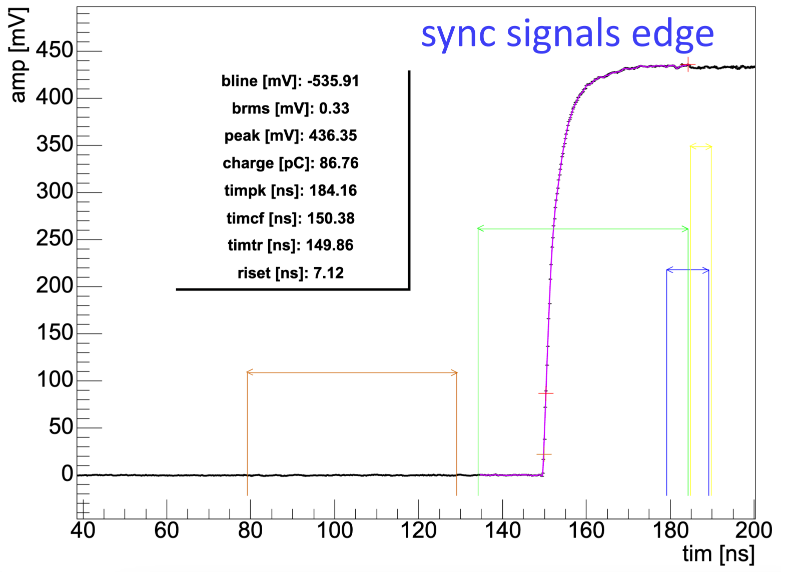




- Low pass filtering (Bessel 2nd order) cutoff_parallel ~ 2 * cutoff_series
- Cut-off frequency based on two parameters: baseline RMS and risetime (10-90%)
- Wave quality flag based on baseline RMS, peak, and risetime to discard bad waves
- Processing cuts: peak > 2 mV

Sync pulses reconstruction:

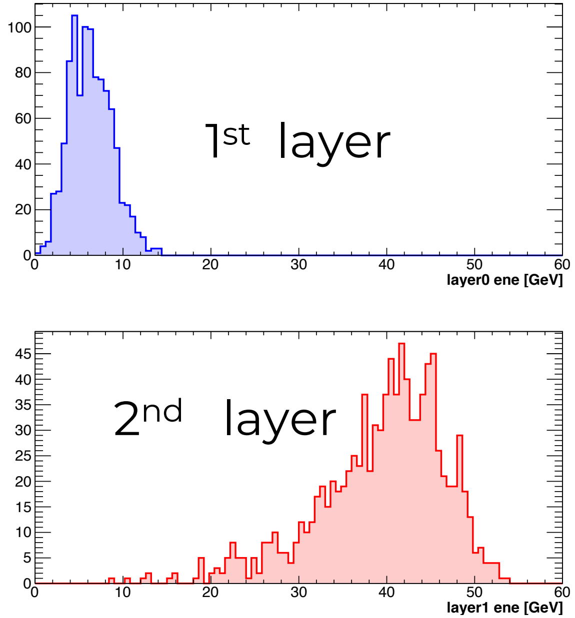
- O(10 ps) ch-to-ch in the same chip
- O(30 ps) board-to-board jitter



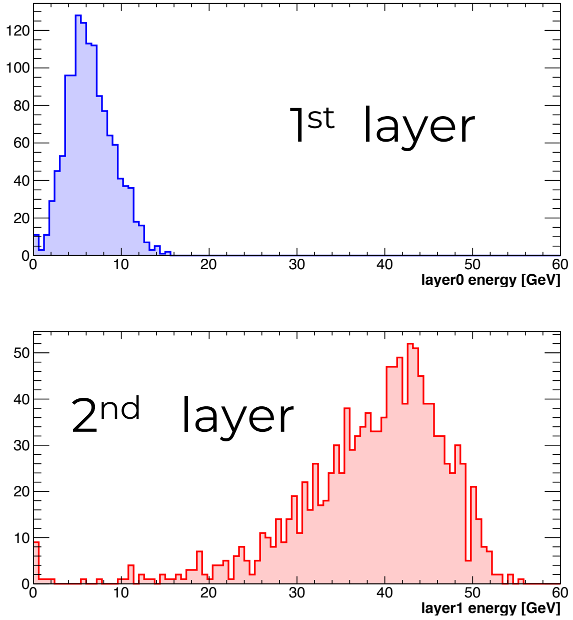
Test Beam @ CERN: Result

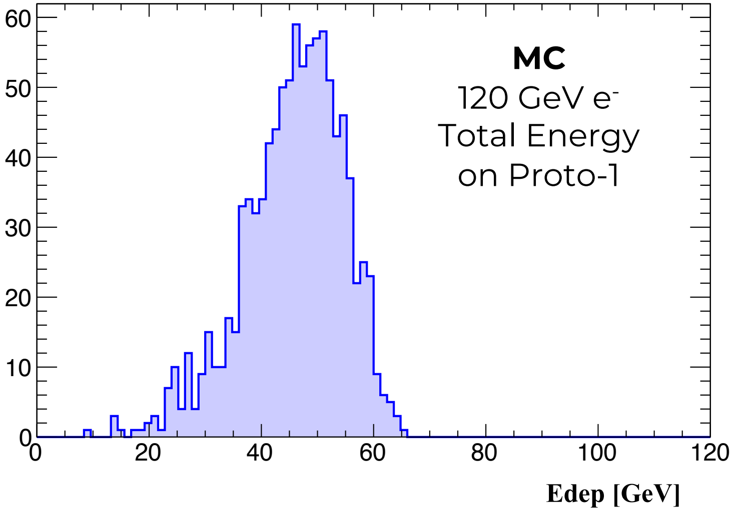
Excellent agreement between data e MC

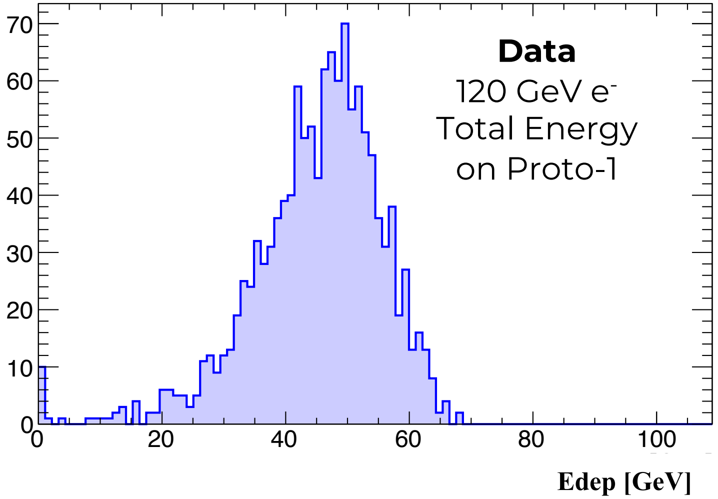
MC
120 GeV e⁻



DATA
120 GeV e⁻

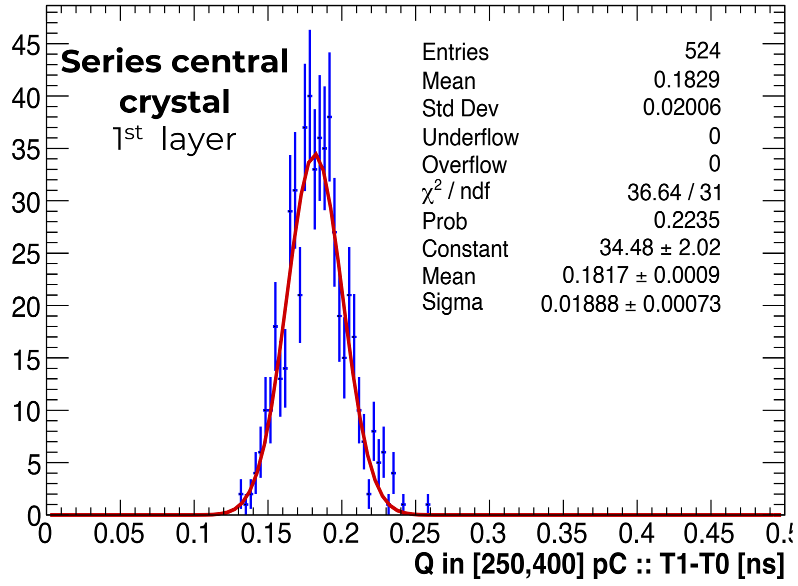


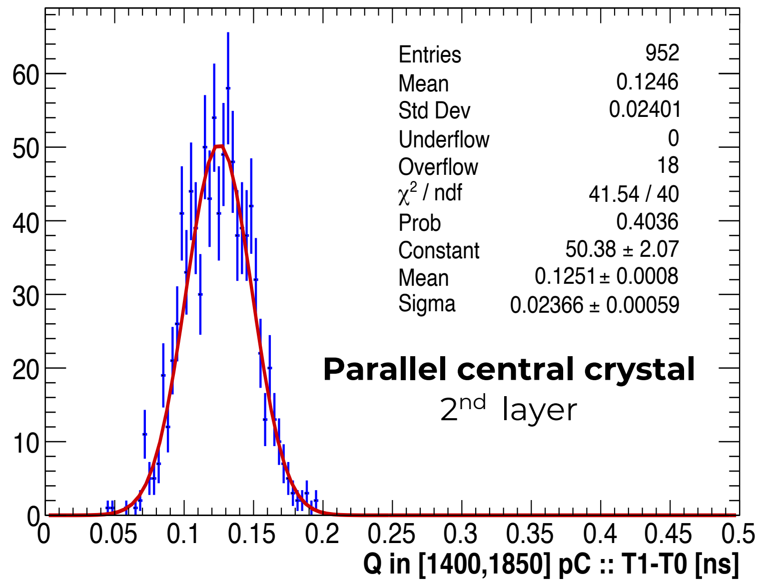




Test Beam @ CERN: Timing

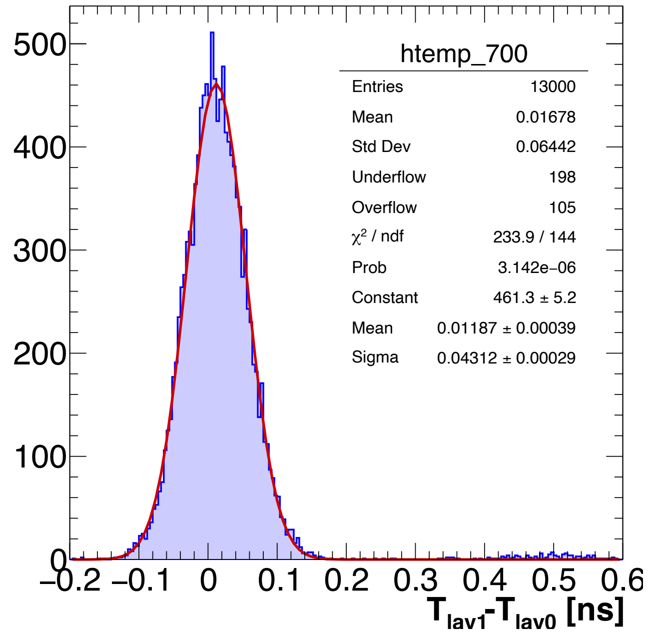
- Time Resolution @ 120 GeV is of **O(20 ps)** both in the series and in the parallel layers using the time SiPMs difference of the central crystals
- Studies on using the layer mean time are ongoing





TLAYER1 – TLAYER0

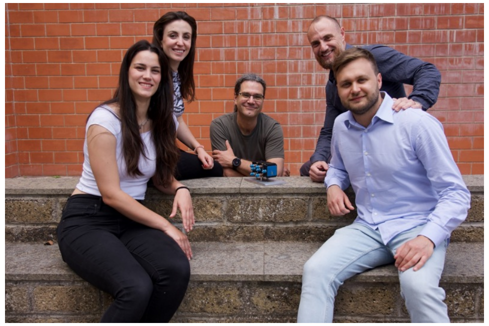
σ_{DT} = 40 ps dominated by syncronisation jitter O(32ps)

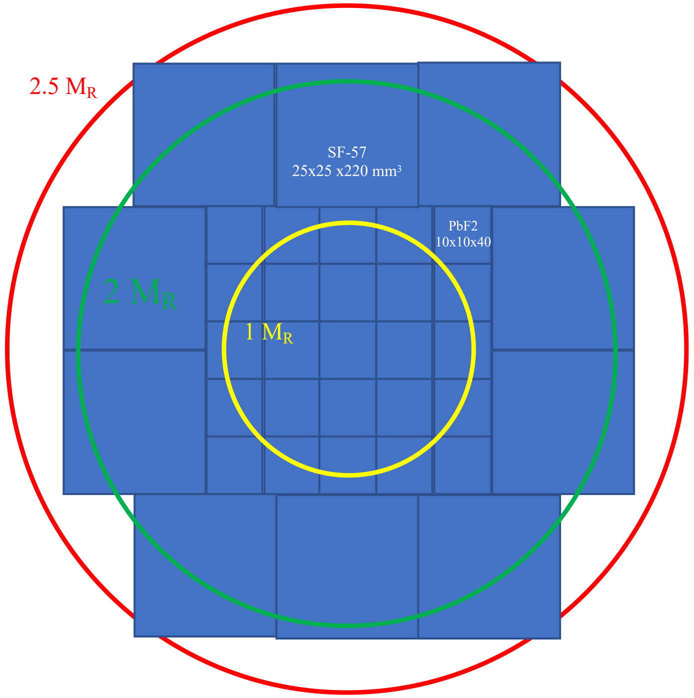


Next steps (2024 - 2025)

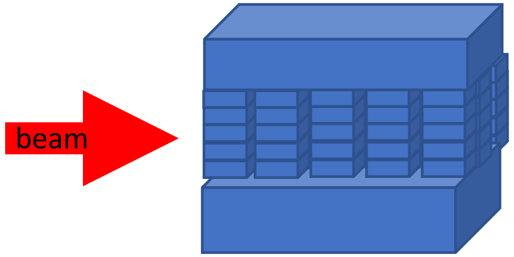
- 120 kEur has been assigned to develop a 5x5x 4layers Crilin prototype
  - 16 X_0 and 1 M_R

- Submitted a DRD project to achieved and 21 X_0 and 2,5 M_R coverage
  - lateral leakage recovery matrix of lead glass (cheap) crystals
  - extra layer in z → 5x5x 5layers Crilin





Transverse view

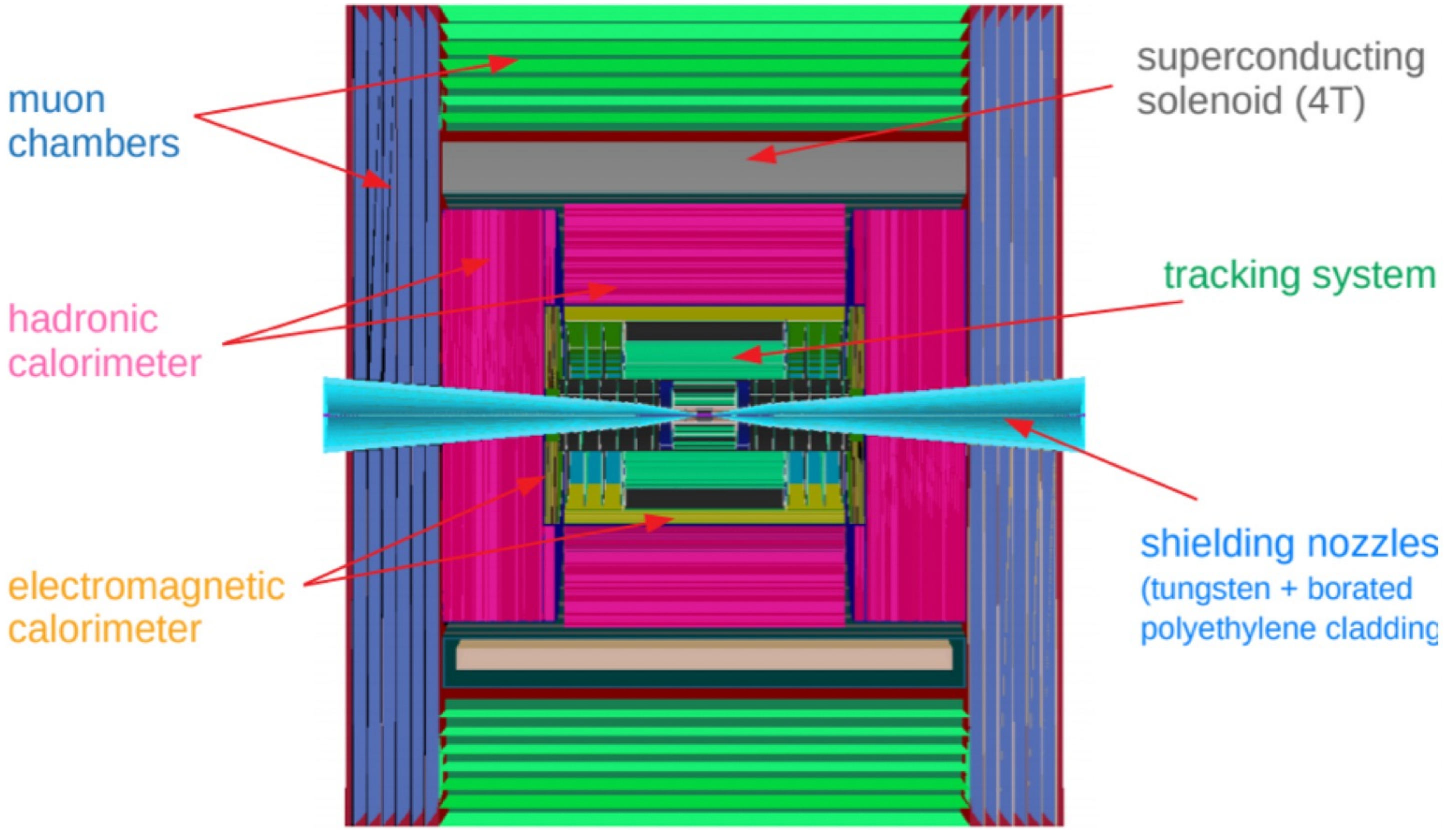


Backup slides

- The International Muon Collider Collaboration is focusing on developing two muon collider concepts:
  - a 10 TeV collider with an integrated luminosity target of 10 ab^{-1}/IP in 5 years of operation;
  - a possible intermediate stage at 3 TeV with an integrated luminosity target of 1 ab^{-1}/IP in 5 years of operation.
- Initial parameters are based on studies by the US Muon Accelerator Program (MAP).

Parameter	Unit	3 TeV	10 TeV
L	10^{34} $cm^{-2}s^{-1}$	2	20
N	10^{12}	2.2	1.8
f_r	Hz	5	5
P_{beam}	MW	5.3	14
C	km	4.5	10
<B>	T	7	10.5
ε_L	MeV m	7.5	7.5
σ_E / E	%	0.1	0.1
σ_z	mm	5	1.5
β*	mm	5	1.5
ε	µm	25	25
$\sigma_{x,y}$	µm	3	0.9

Muon Collider

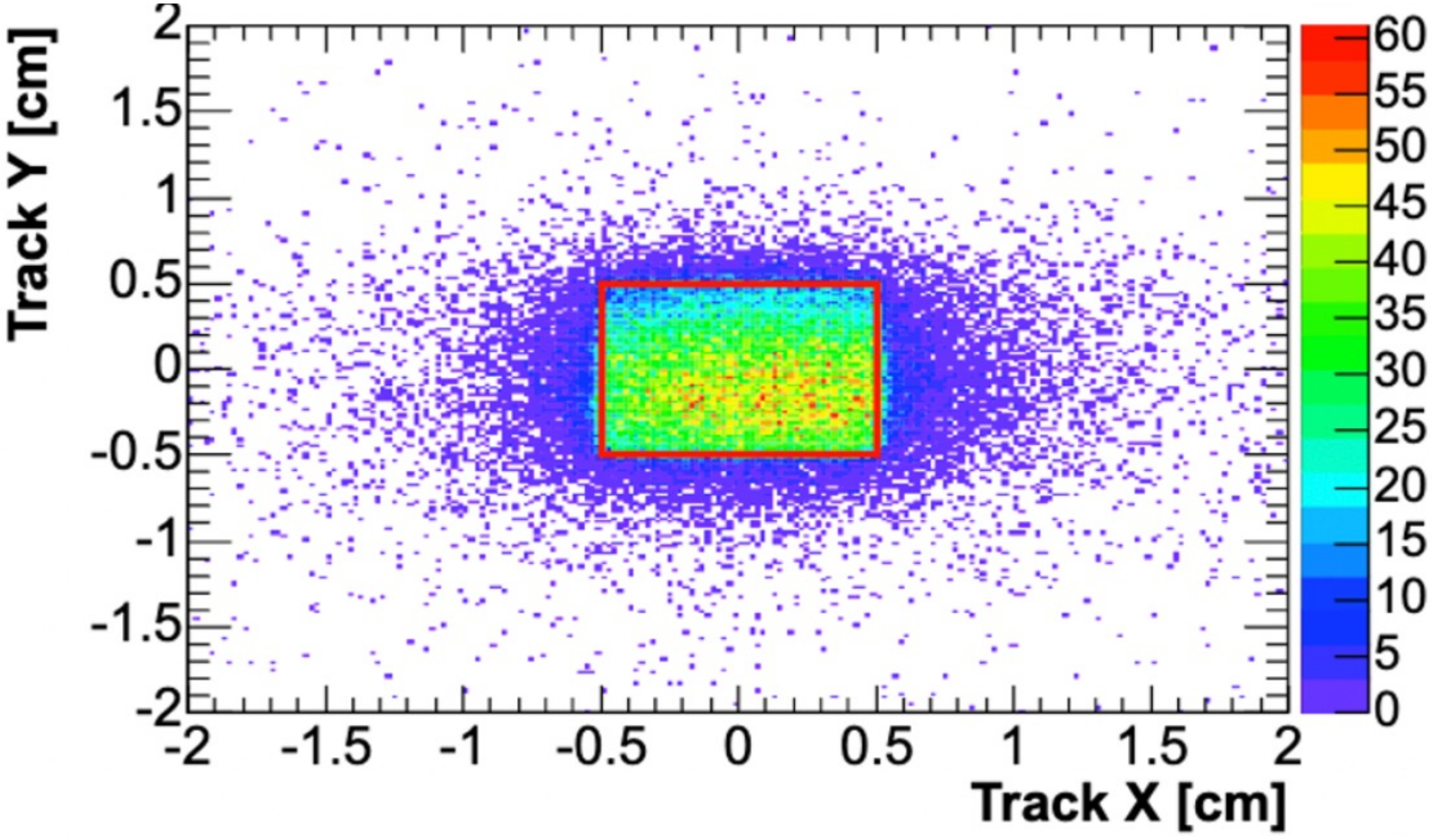


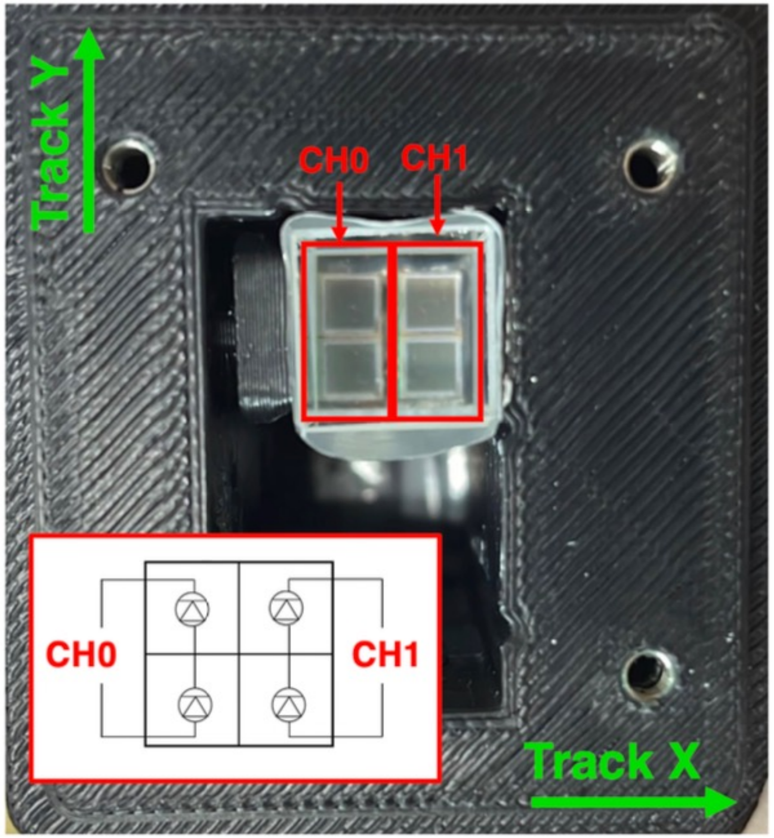
Main issues: BIB and radiation damage
Optimized detector interface:

- Based on CLIC detector, with modification for BIB suppression.

- Dedicated shielding (nozzle) to protect magnets/detector near interaction region.

Tracking and coordinates





- Extrapolation of tracks to the upstream crystal face
- Geometrical 1×1 cm^2 fiducial volume

- Proto-0 assembly
- PbF2 crystal and SiPM matrix are visible
- SiPM series wiring scheme (in red)

Energy scale

Edep

- Geant4 simulation of beam test in both configurations
- Energy scale from MC fit using resampled beam positions from tracking systems

Optical and digitisation

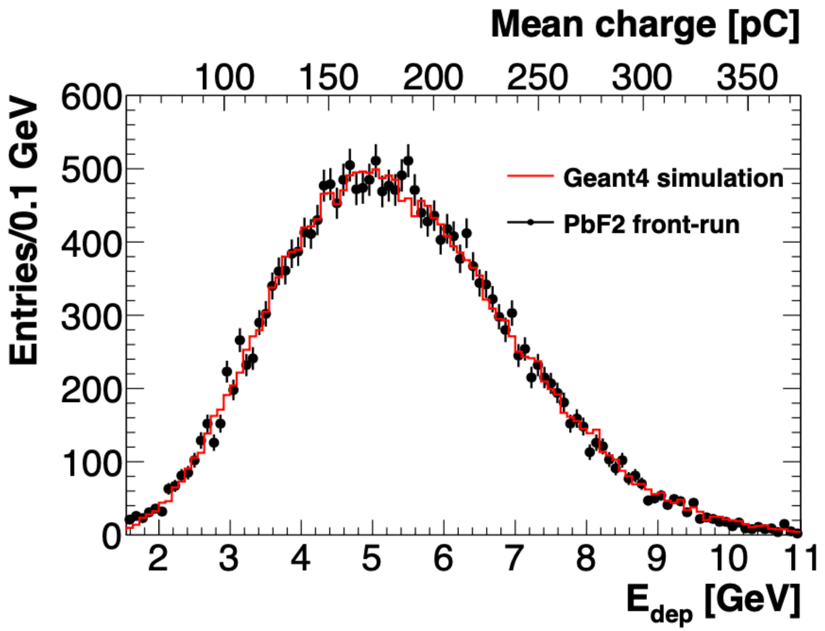
- Optical transport simulation of Cherenkov light also implemented for PbF2 (next slides)
- Wrapping and SiPM optical surfaces implementation
- WF digitisation using single PE SiPM response and optical photons arrival times

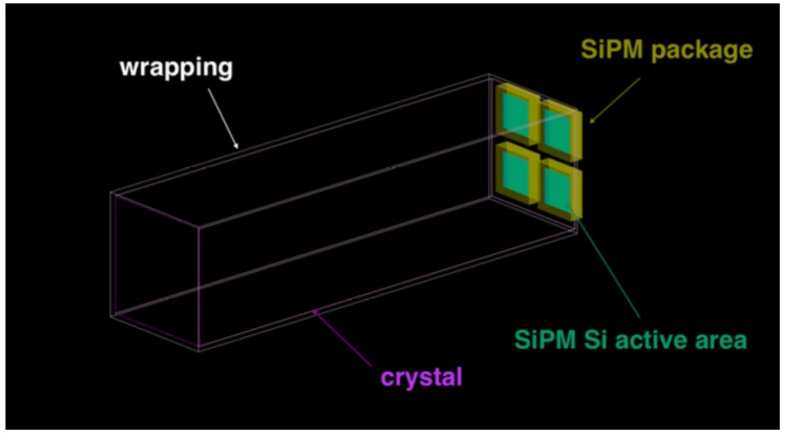
PbF_2

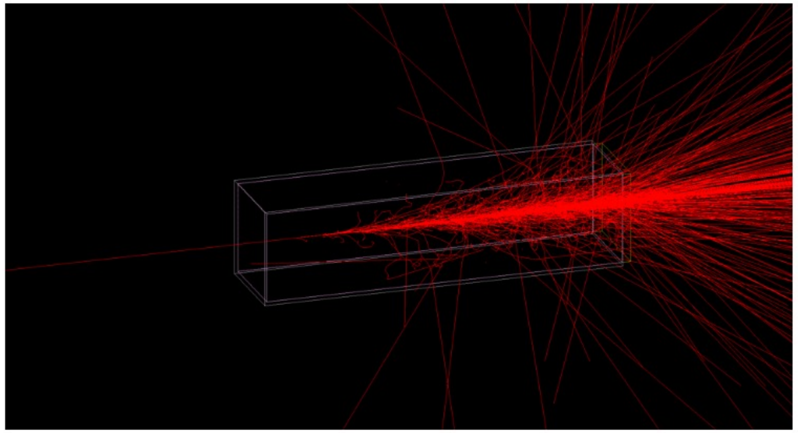
	back-run	front-run
E_{dep} MPV [GeV]	4.26 ± 0.01	4.81 ± 0.03
E_{dep} sigma [GeV]	1.35± 0.01	1.46 ± 0.02
pC/MeV	~29.3	~35.6
NPE/MeV	~0.30	~0.30

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	~0.11	~0.13

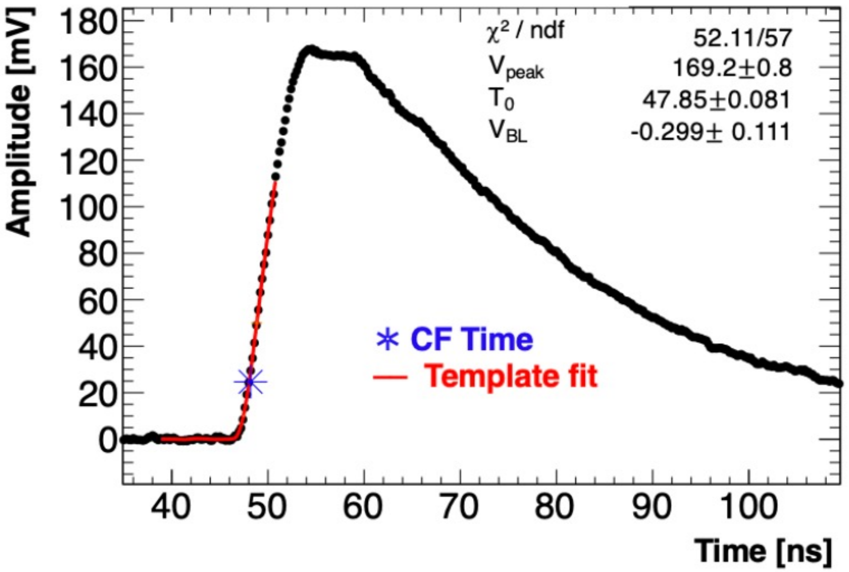


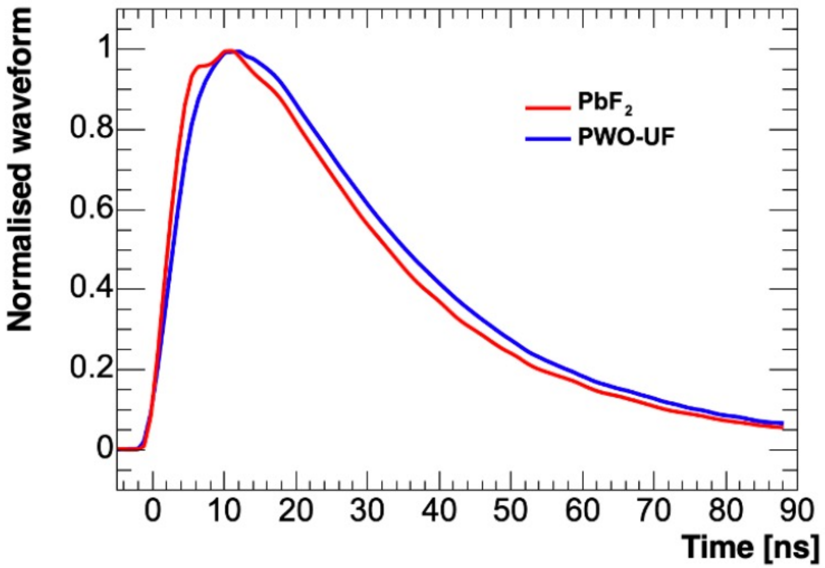




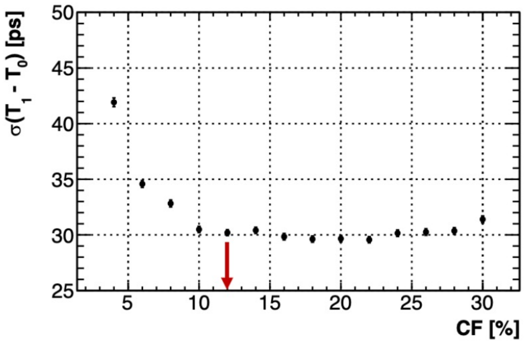
Waveform recontruction

- Template fit for WF reconstruction
- Timing extraction using CF method

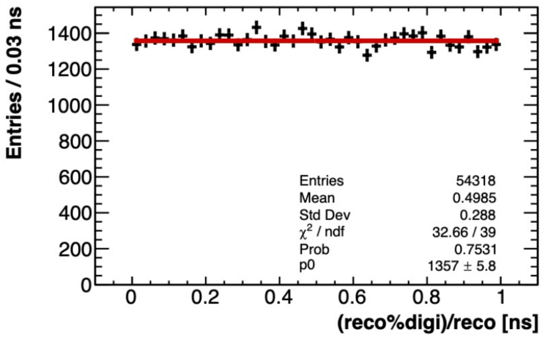




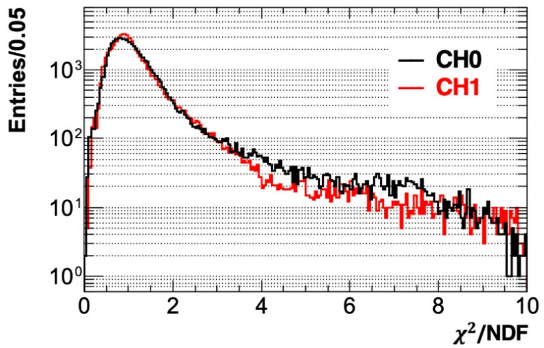
CF optim



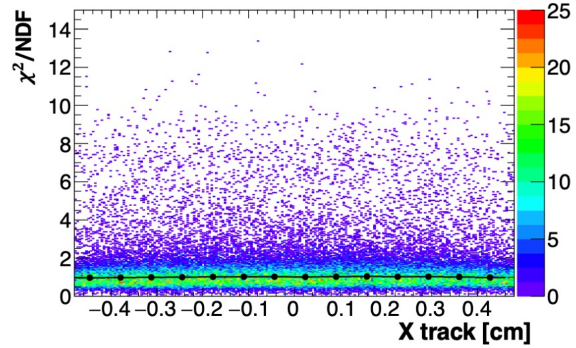
bias check



fit chi2s



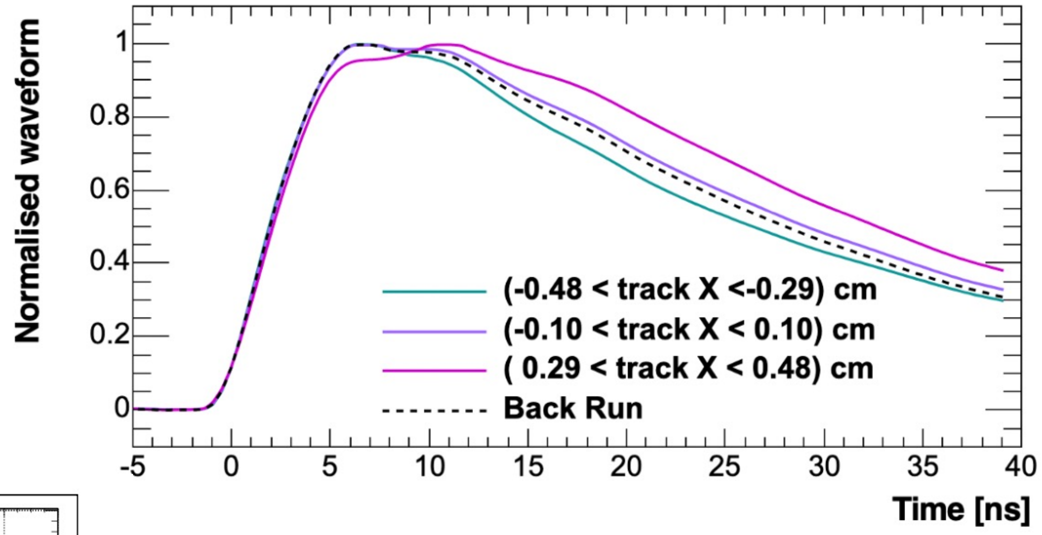
chi2:pos

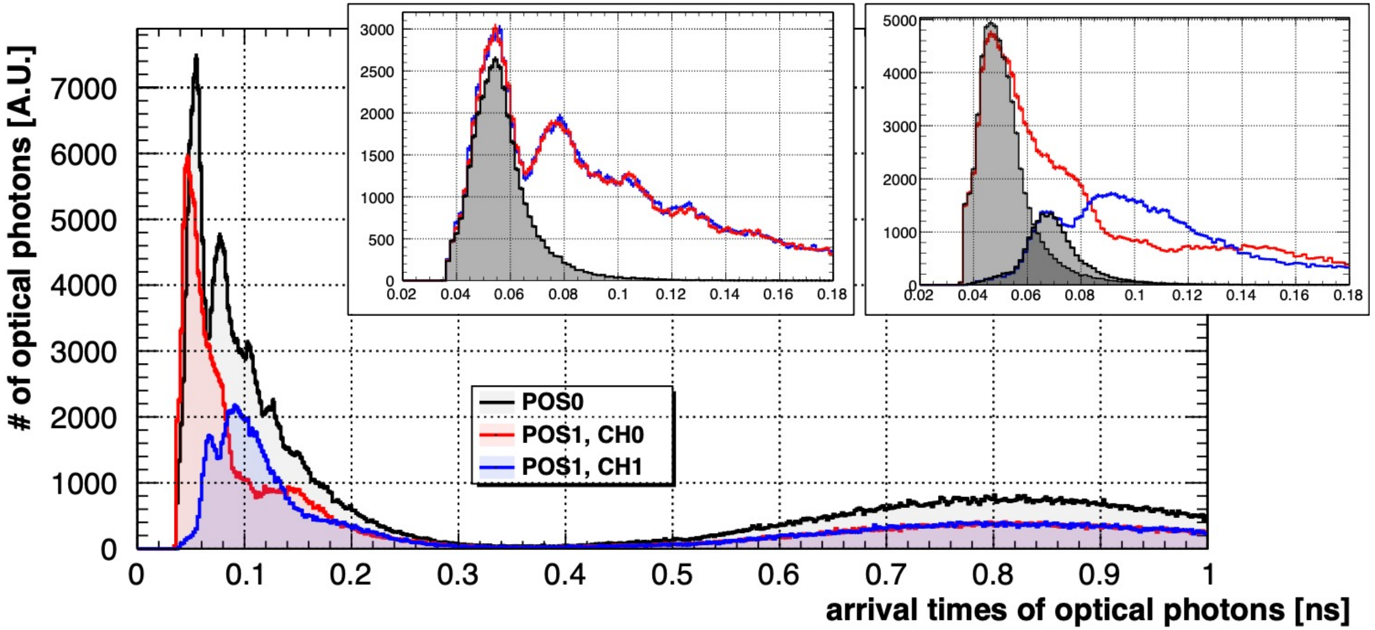


Positional effects: waveshapes

Effects on waveforms (data)

- Pulse shape modification as a function of impact position selected with different fiducial cuts
- Green → particle incident directly on SiPM pair giving signal
- Magenta → particle incident on opposite SiPM pair
- Purple → particle incident between SiPM pairs
- Dashed line → signal shape for back runs



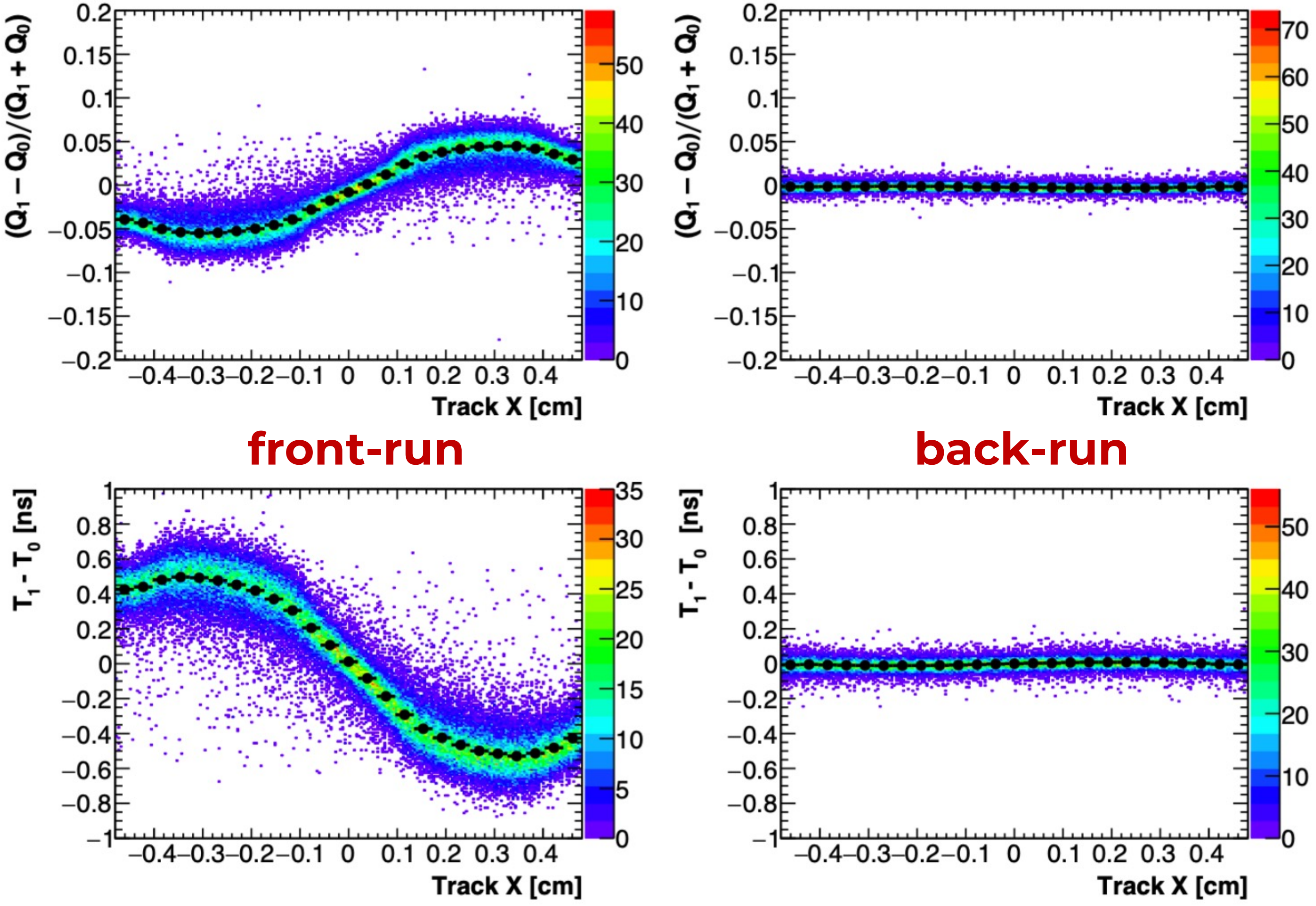


Optical simulation

- Simulated time distributions for optical photons arrival on the photosensors, for two beam positions
- POS0: centred beam the crystal
- POS1: 3 mm beam offset (towards CH0)
- shaded areas → contributions due to light reaching the photosensors directly (i.e., with zero or one reflections)

Positional effects: charge and timing

PbF2 DATA



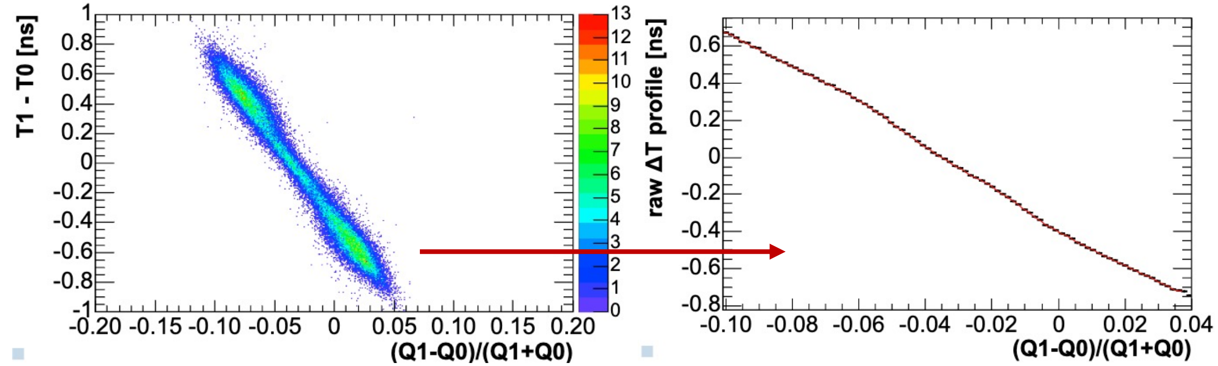
- +/- 10 % maximum imbalance in light collection
- anticorrelated effect on timing (T1-T0)

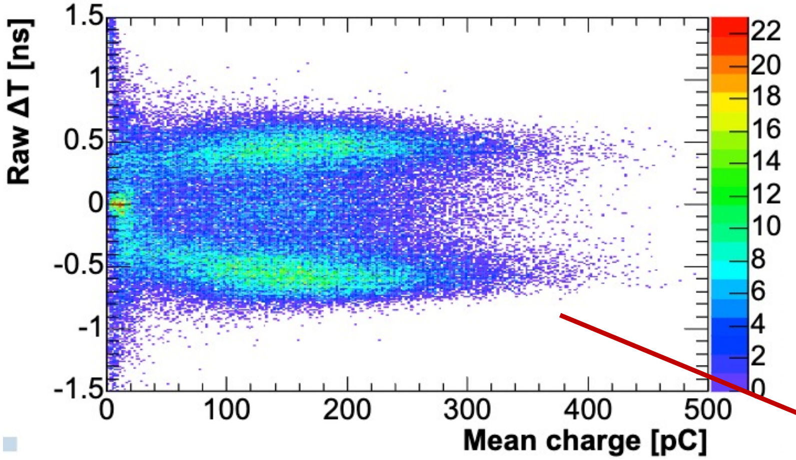
- No significant effects for back-runs
- Similar effects for PbWO4-UF

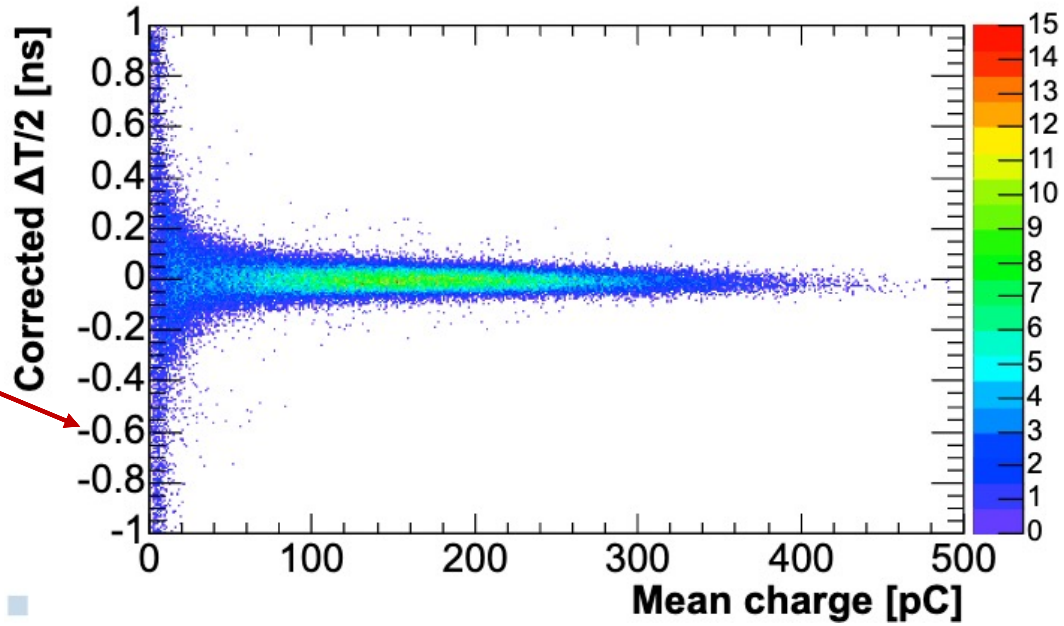
- Light propagated indirectly is more strongly attenuated due to the longer total path length traversed and the multiple reflections
- earlier arrival times for photons arriving directly

Correction process

- The front mode shows a peculiar distribution both in time time difference and charge sharing:
  - ➢ the relationship between this two quantities can be used as correction function
  - ➢ Negligible effect in back runs

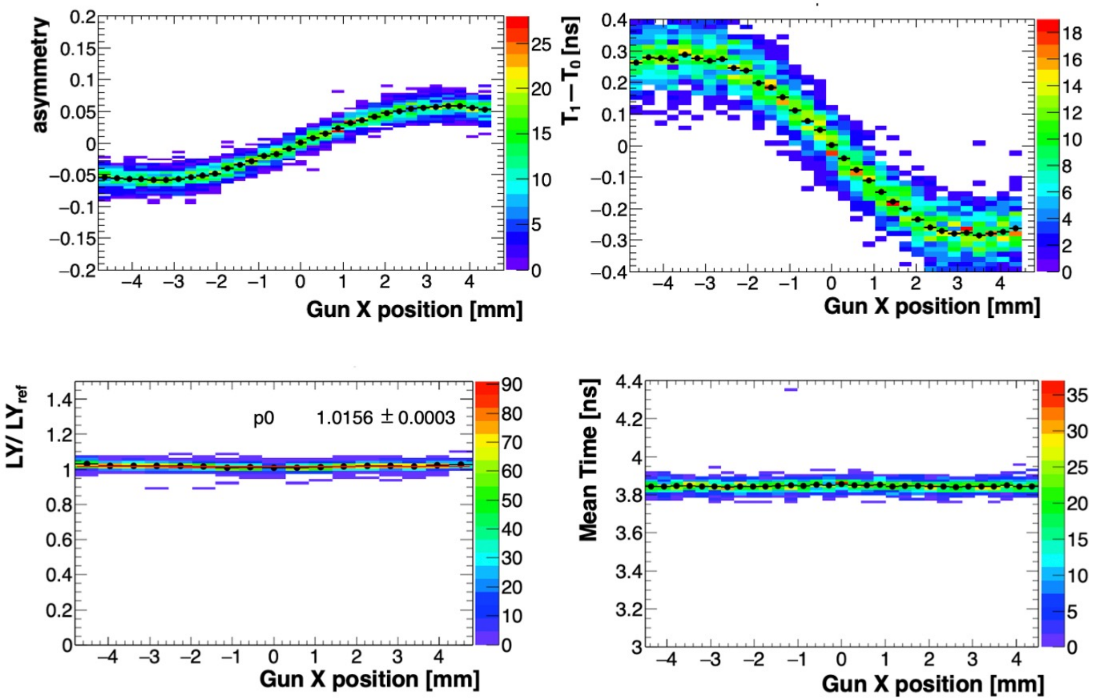


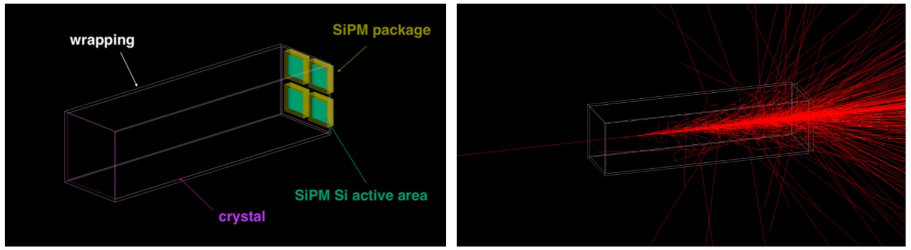


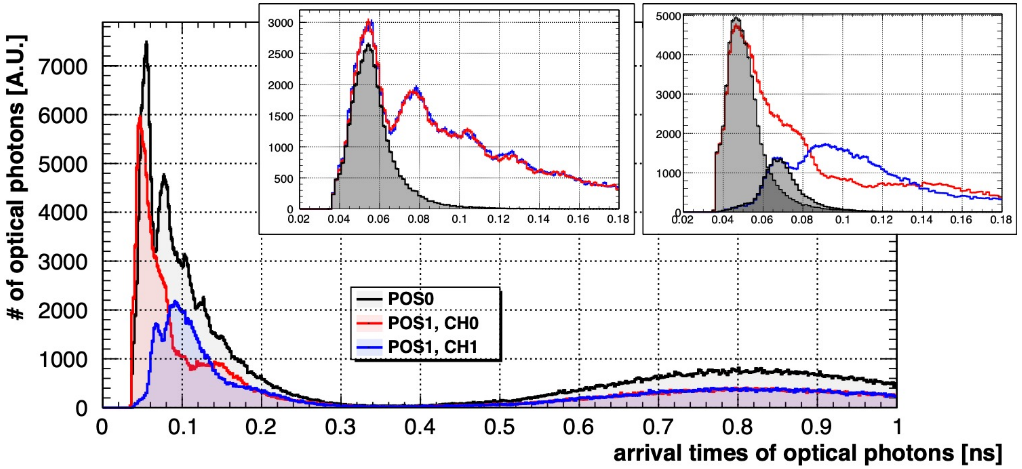


MC validation: optical simulation

- Simulated time distributions for optical photons arrival on the photosensors, for two beam positions
- POS0: centred beam the crystal
- POS1: 3 mm beam offset (towards CH0)
- shaded areas → contributions due to light reaching the photosensors directly (i.e., with zero or one reflections)







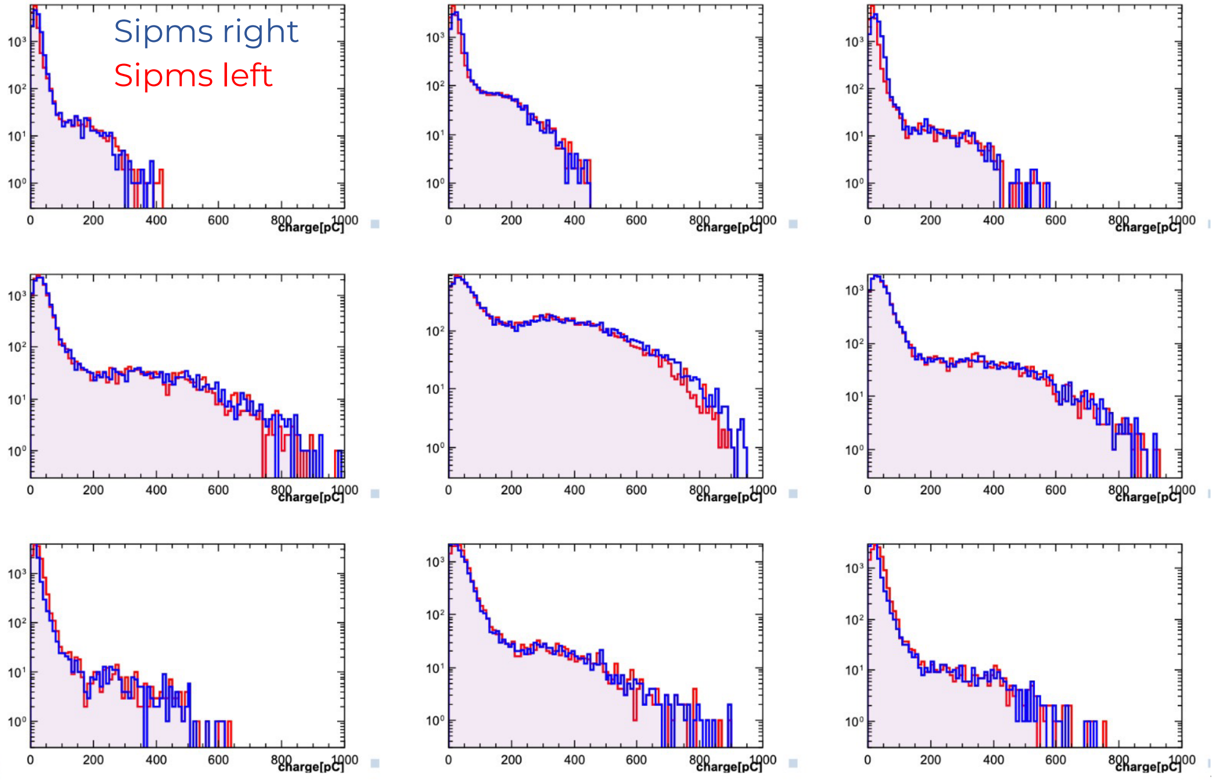
- Confirmation of the positional effects
- Charge asymmetry matched within 20 %
- Smaller timing offsets in simulation wrt data
- mean-time and mean-energy information are always well behaved

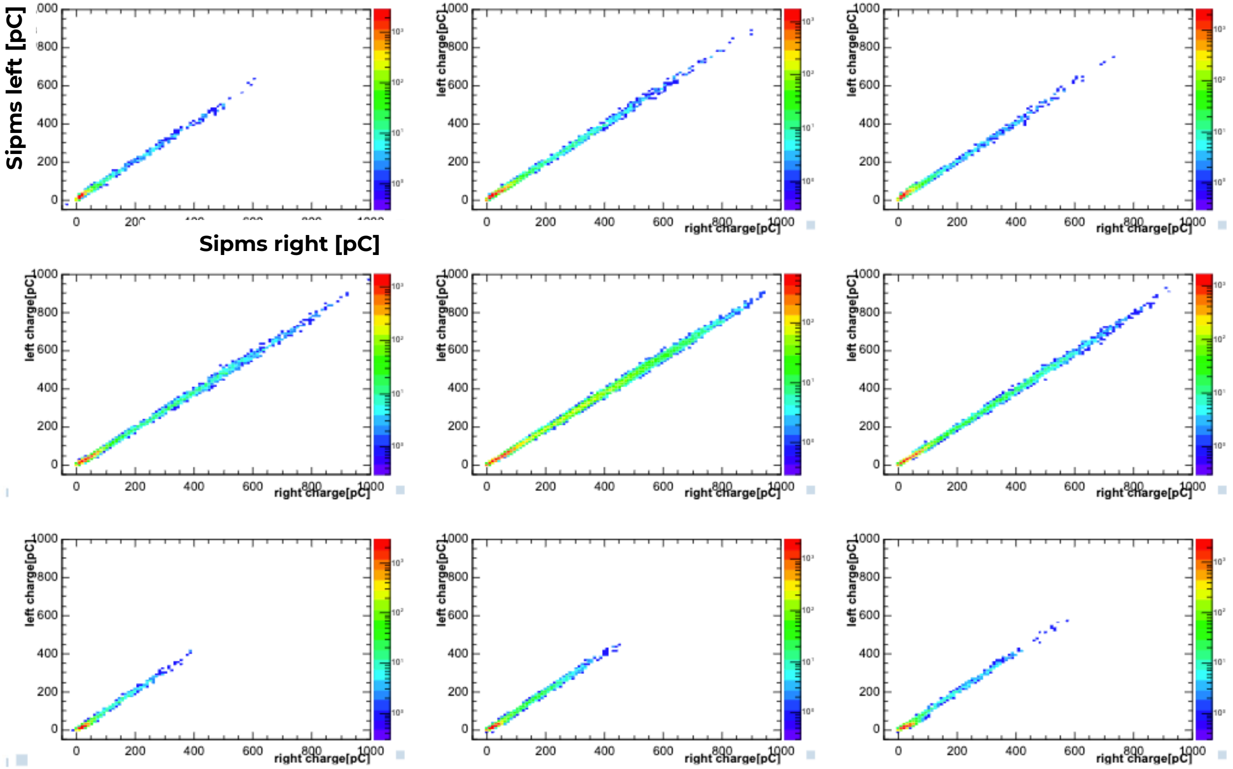
Test Beam @ CERN – Proto-1 –

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 + 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