INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

International
MUON Collider
Collaboration

Muon Collider's detectors R&D

E. Di Meco on behalf of the RD_Mucol group

Riunione CSN1 LNF: European Strategy- October 18 2024

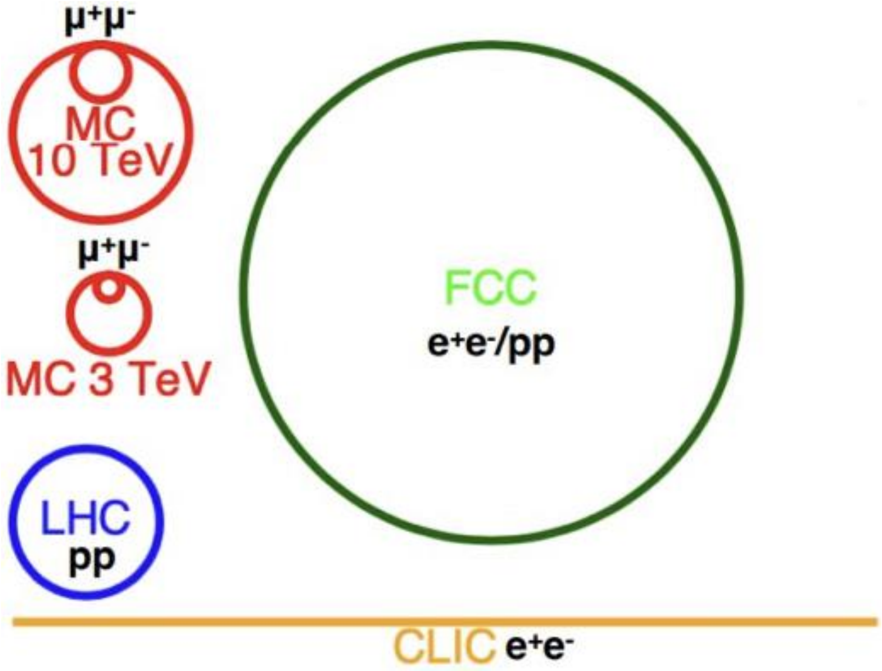
A Muon Collider

International MUON Collider Collaboration

A Muon Collider is being considered as an option for a next generation facility; studies for 3 and 10 TeV designs are being carried out showing several advantages but also technological challenges.

Muon Collider pros:

- **m_μ>>m_e** hence negligible synchrotron radiation
- **Point-like particle**: all energy is available for the collision
- perfect for direct search of heavy states
- **broad physics reach**: SM precision tests, BSM direct and indirect search, lepton flavour universality tests



Muon Collider cons:

- **τ_0= 2.2μs :** very fast cooling and fast-ramping magnet system needed
- μ decay + interaction with machine: **beam-induced background (BIB)**, partially shielded by nozzles
- **Intensive neutrino flux**

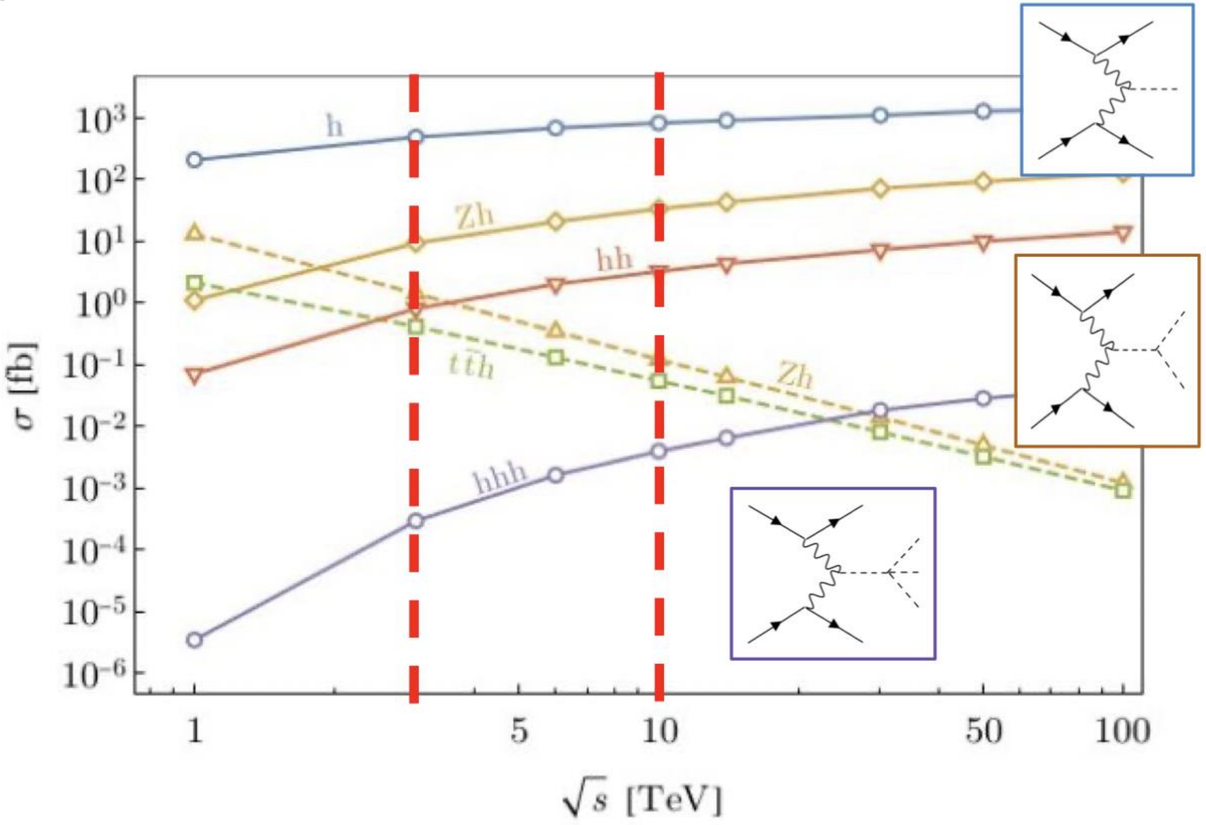
Higgs Physics @ Muon Collider

The last ESPPU identified Higgs Physics as the main physics target at future colliders:

- Measure Higgs couplings to fermions and bosons at ~O(1%) level
- Measure Higgs potential with multi-higgs processes

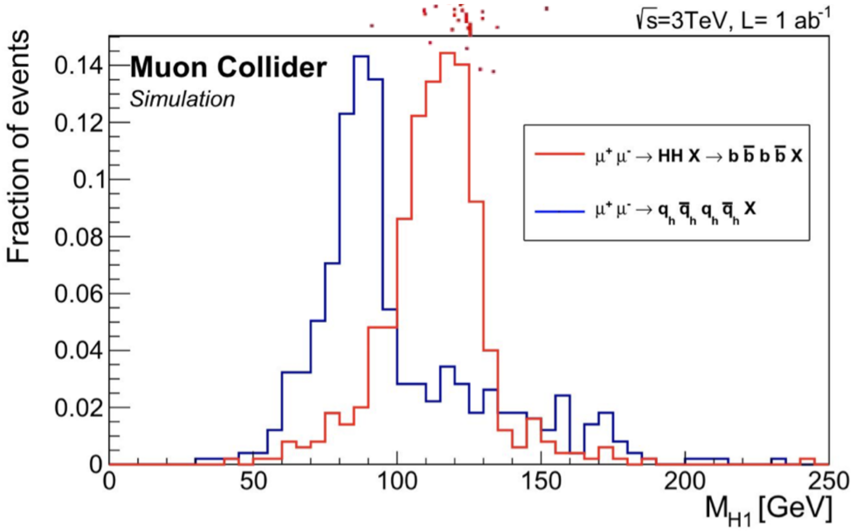
The **Muon Collider** is by all means **a Higgs factory**

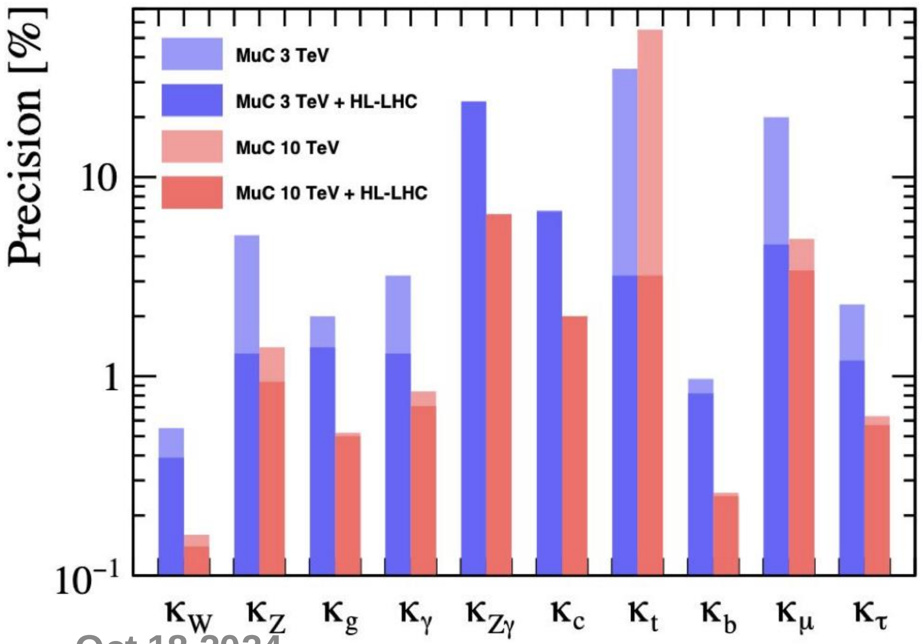
Energy	Luminosity	number of Higgs
3 TeV	1 ab^{-1}	5×10^5
10 TeV	10 ab^{-1}	9.5×10^6
14 TeV	20 ab^{-1}	2.2×10^7
30 TeV	90 ab^{-1}	1.2×10^9



Coupling precisions and Di-Higgs

- **Coupling measurements** simulated with full and parametric simulations → results are consistent and very close to the phenomenological studies (optimization still in progress)
- **Di-Higgs** production is particularly sensitive to **trilinear Higgs self-coupling λ_3 (only the HH→bbbb** channel has been considered for now)
- Extrapolation to higher energies and luminosities → **Muon Collider provides most precise results**
- Possibility to access **Higgs quartic self-coupling** λ_4 (only pheno study for now), expectations: **$\delta\lambda_4$= 50% at E_{com}= 14 TeV with 20 ab^{-1}**





The Muon Collider is **definitely competitive** in the landscape of future colliders

Experiment	Luminosity	COM Energy	$\delta\lambda_3$
CLIC	5 ab^{-1}	3 TeV	-7%,+11%
ILC	8 ab^{-1}	1 TeV	10%
FCC-hh	30 ab^{-1}	100 TeV	3%
Muon Collider	**2 ab^{-1}**	**3 TeV**	**15%**
Muon Collider	**10 ab^{-1}**	**10 TeV**	**3.5%**
Muon Collider	**20 ab^{-1}**	**14 TeV**	**2.5%**
Muon Collider	**90 ab^{-1}**	**30 TeV**	**1%**

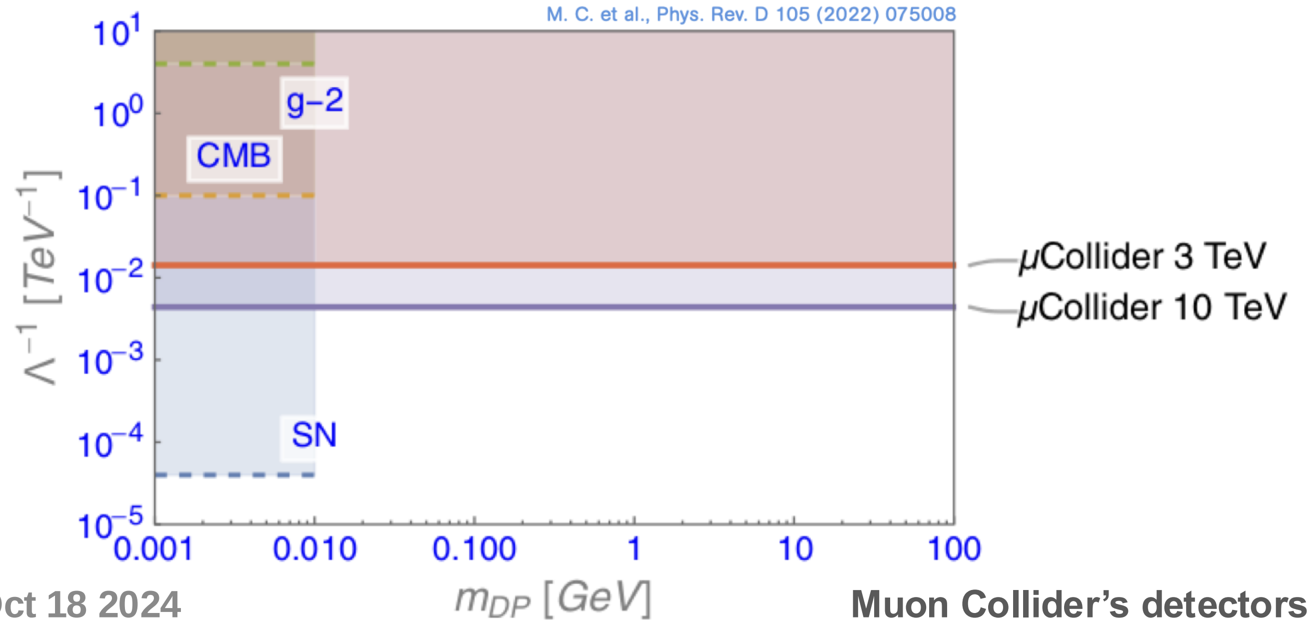
BSM @ Muon Collider

Higgs boson couplings represent a guaranteed result, but the muon collider physics program is much broader.

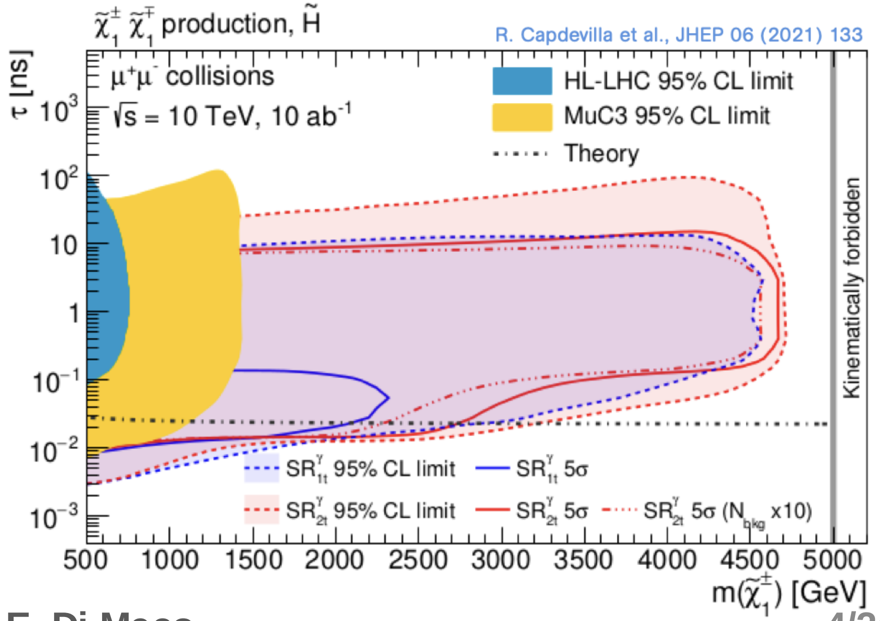
- Search for a **dark photon** (DP) or an **ALP** produced in association with a photon at √s = 3 TeV (1 ab-1) and √s = 10 TeV (10 ab-1) in events with a **single monochromatic photon**.

- Search for **wino and higgsino dark matter** at √s = 3 TeV (1 ab-1) and √s = 10 TeV (10 ab-1) with the **disappearing track signature**.

95% CL limits on DP effective coupling to muons

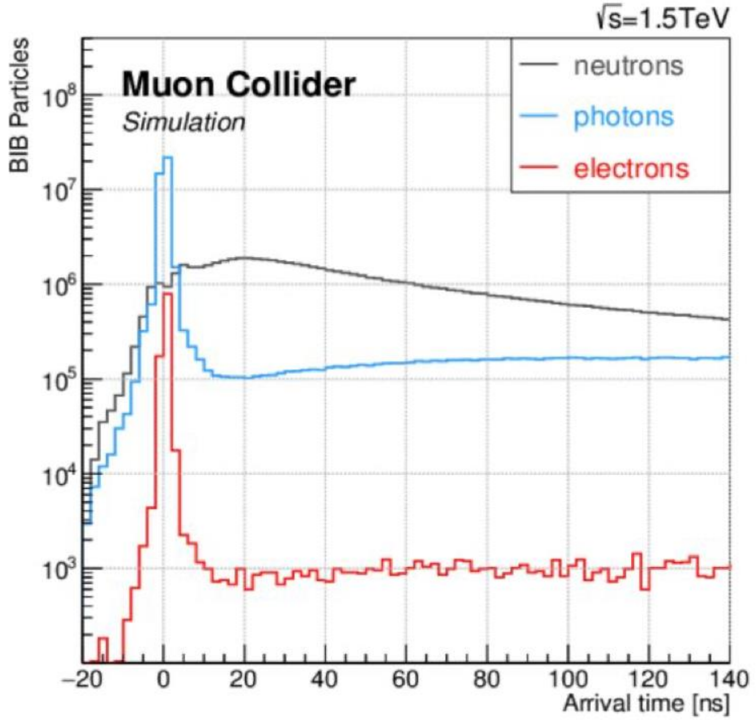


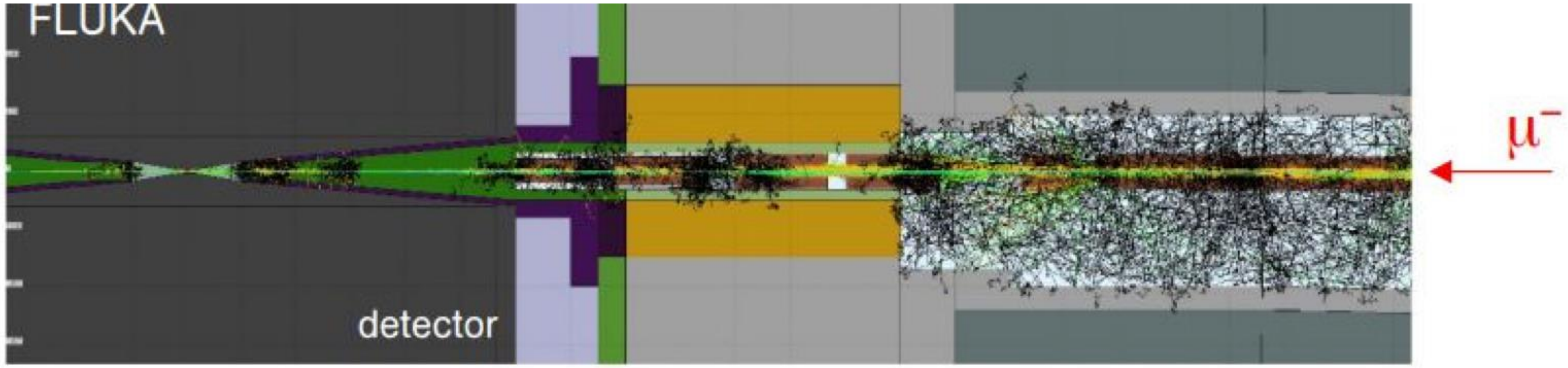
expected sensitivity as a function of chargino m and τ



Beam Induced Background

- Muons decay → decay products interact with machine**: intense fluxes of particles reach the detector**:
  - high multiplicity of particles in the tracker (mainly in first layers)
  - diffuse background in calorimeters
- Innovative techniques and optimised algorithms are fundamental to mitigate the impact of BIB
- **Tungsten nozzles** mitigate radiation coming to the detector
- BIB is off-time wrt bunch crossing, algorithms and detectors tailored to exploit these features
- Still working on the MDI optimization for 10 TeV





Machine Detector Interface – 10 TeV

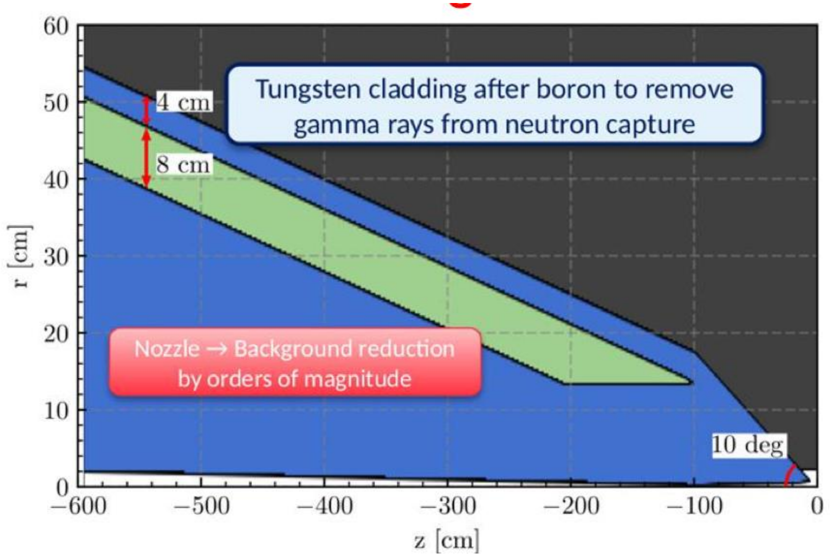
New design needed for the 10 TeV MDI:

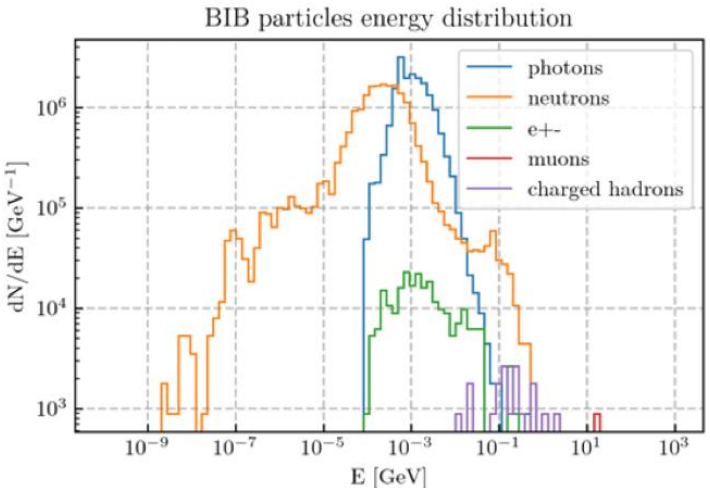
- Different nozzle design wrt previous studies
- @ 10 TeV: **significant background from incoherent e⁺e⁻** pairs produced @ bunch crossing:
  - High energy e+/e- in the detector in time wrt bunch crossing
  - Confined to the inner regions thanks to the solenoidal B Field→ vertex detector and inner tracker layers

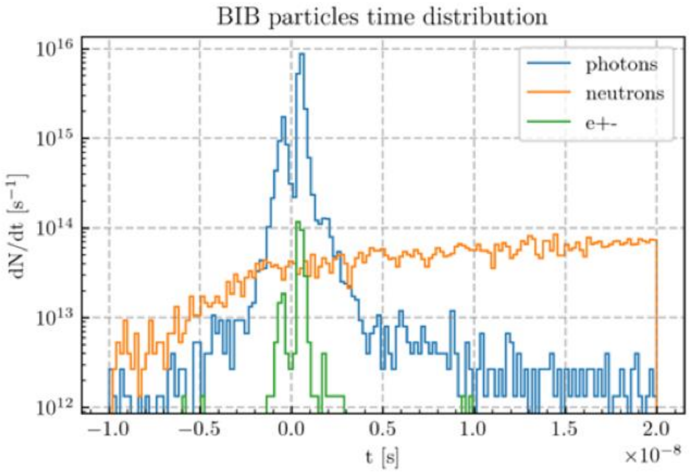
MAP's 1.5 TeV nozzle | new 10 TeV nozzle

Collider energy	1.5 TeV	3 TeV	10 TeV (v 0.8)	10 TeV (EU24*)
Photons	7.1E+07	9.6E+07	1.6E+08	9.9E+07
Neutron	4.7E+07	5.8E+07	1.4E+08	1.1E+08
e+/e-	7.1E+05	9.3E+05	8.9E+05	1.2E+06
Ch. hadrons	1.7E+04	2.0E+04	5.2E+04	4.2E+04
Muons	3.1E+03	3.3E+03	3.3E+03	9.6E+03

10 TeV	BIB	e⁺e⁻ pairs
Photons	9.9E+07	4.0E+06
Neutron	1.1E+08	1.3E+05
e+/e-	1.2E+06	2.1E+05

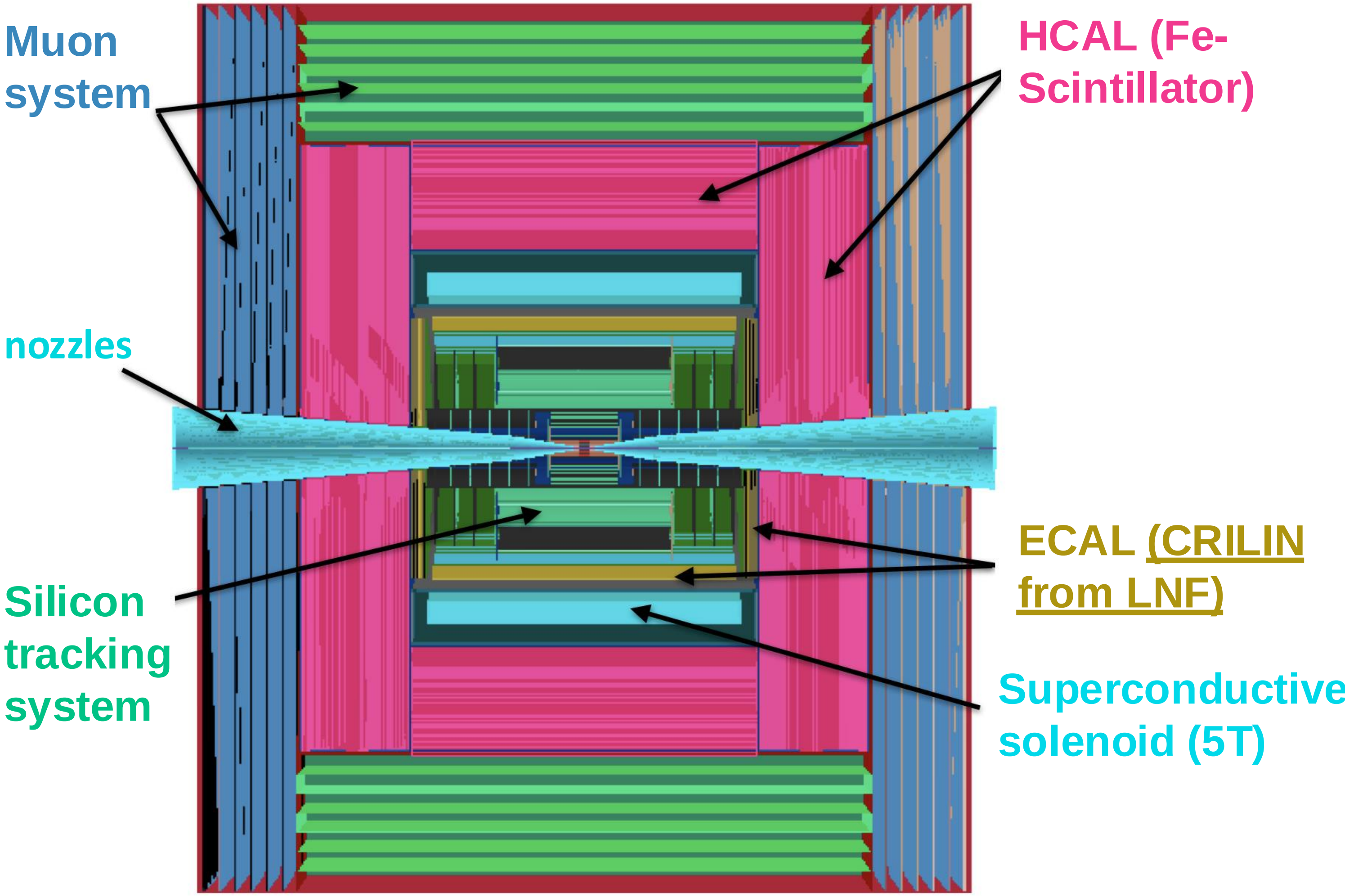






New detector concept: MUSIC detector

- **Main physics requirements→** ability to reconstruct:
  - boosted low-pT physics objects from Standard Model processes;
  - central energetic physics objects from decays of possible new massive states;
  - less conventional experimental signatures: disappearing tracks, displaced leptons, displaced photons or jets, ...
  - multipurpose
- **Constraints from the machine design**: final focusing quadrupoles at ±6 m from the interaction point
- **Machine background conditions**: the high levels of BIB will impose the technological choices, reconstructed algorithms ad the detector design

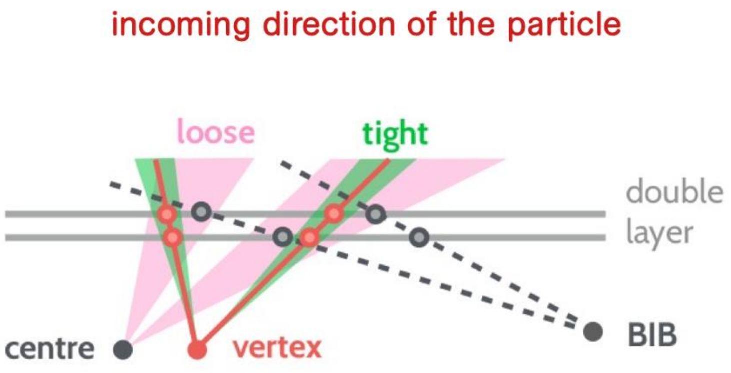


Tracker requirements

- In the tracking system, the BIB produces a huge amount of spurious hits (most from very low-p electrons looping inside)

Key features of the tracking system to deal with the BIB:

- **high granularity;**
- **precise timing;**
- **directional information;**
- characteristics of the detector response (pulse shape and pixel cluster size).



Vertex detector:

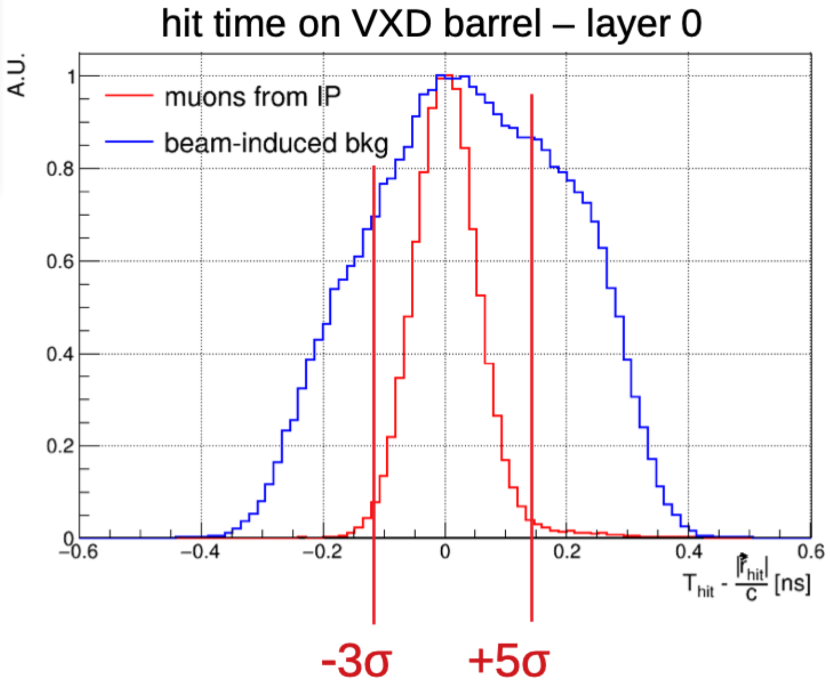
- Silicon pixels 25 x 25 μm^2
- Spatial resolution 5μm x 5 μm
- Time resolution 30 ps

Inner and outer tracker:

- macropixel 50 μm x 1 mm.
- Spatial resolution 7μm x 90 μm.
- Time resolution 60 ps.

Ongoing R&D:

Silicon LGAD sensors for 4D tracking up to very high fluence

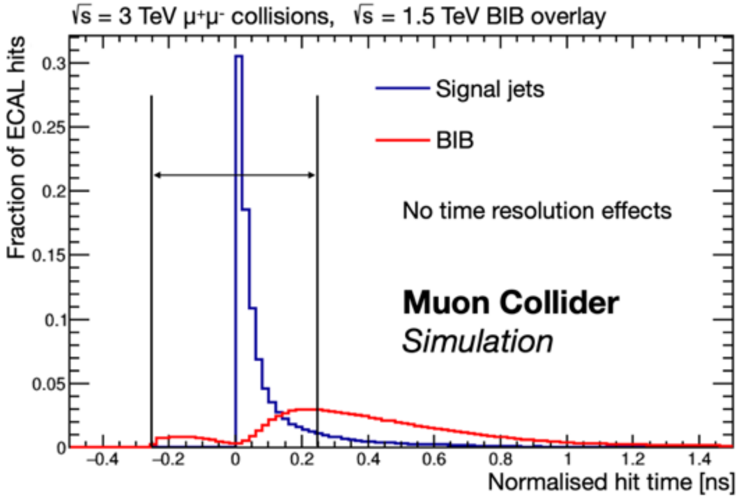


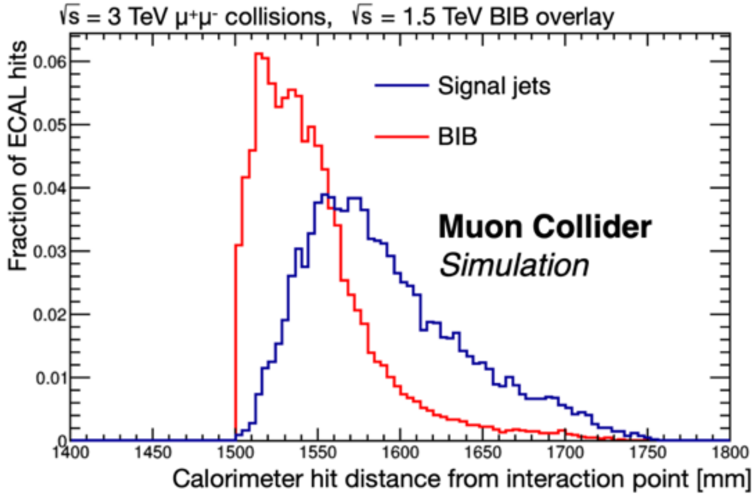
Higher hit occupancies than at HL-LHC detectors are expected, but **the crossing rate** at the muon collider is **~30-70 kHz vs 40 MHz at LHC**.

ECAL requirements

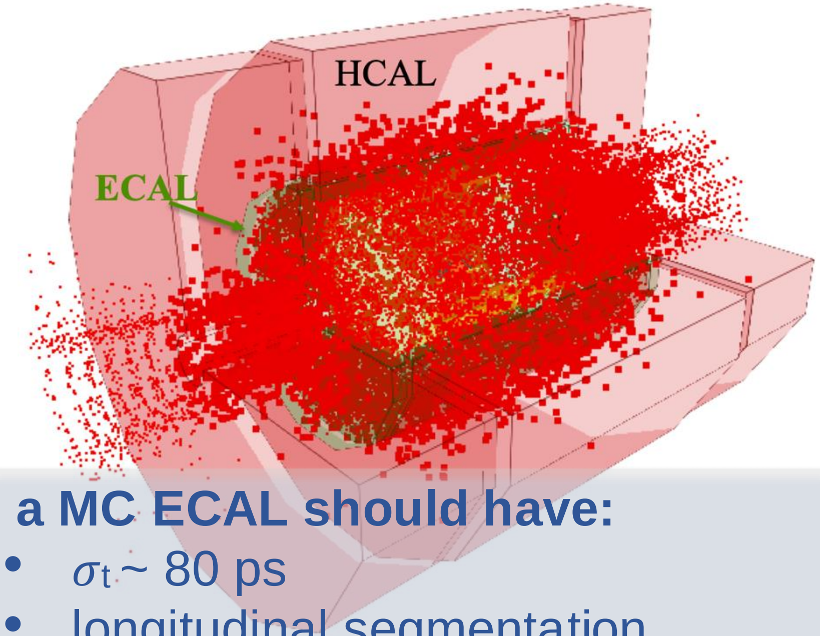
BIB in the ECAL region (after nozzles and tracking system):

- Flux of 300 particles per cm^2 through the ECAL surface mainly γ (96%) and n (4%), average photon energy 1.7 MeV
- **Time of arrival flatter** throughout the bunch crossing → can exclude most of BIB with an acquisition window of ~240 ps
- Different **hit longitudinal profile** wrt signal
- **Total Ionising Dose**: ~1 kGy/year
- **Neutron fluence**: 10^{14} $n_{1MeVneq}/cm^2$ / year





BIB hits in the calorimeters



a MC ECAL should have:

- σ_t ~ 80 ps
- longitudinal segmentation
- fine granularity to distinguish BIB and signal
- radiation resistance
- σ_E/E ~ 10%/√E

→ The W-Si sampling calorimeter (CALICE-like) initially considered as the primary candidate, now CRILIN is the baseline choice.

Magnet

Key aspect: **position of the magnet**. Need to keep under control:

- Momentum resolution of tracks (especially at low)
- Good energy resolution for photons ($\frac{10\%}{\sqrt{E[GeV]}}$) and jets (~10%)

MUSIC solution:

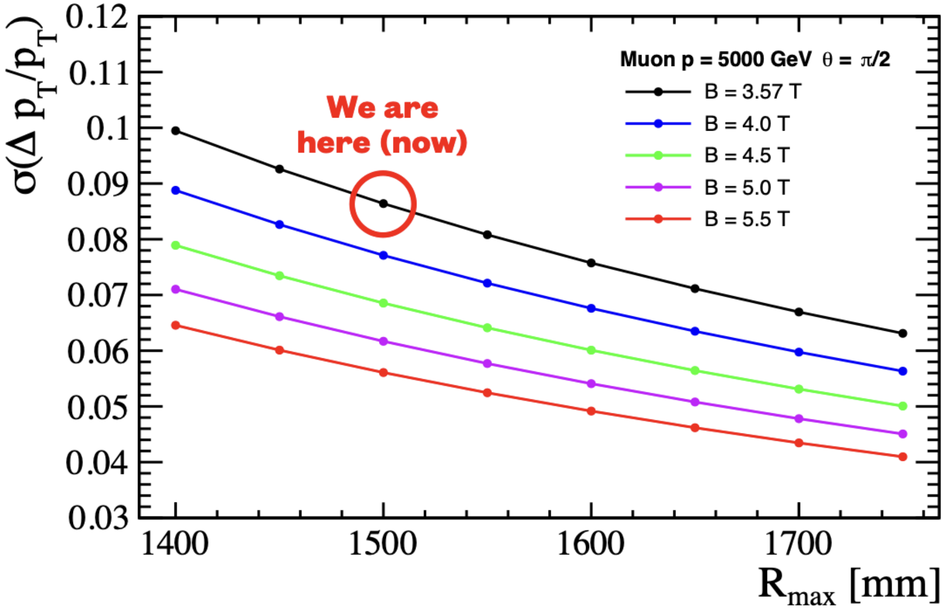
- place the solenoid between the calorimeters
- close the B field with the iron in HCAL

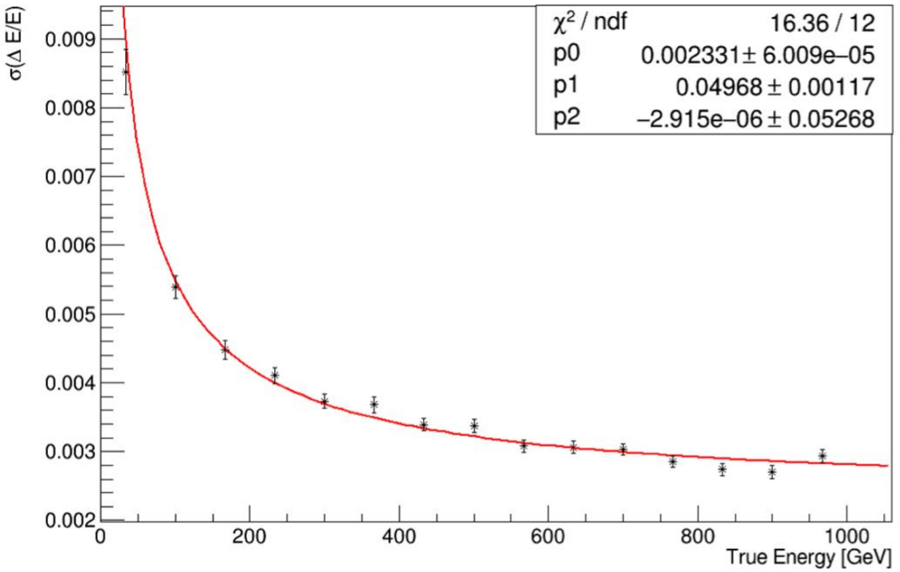
Magnet thickness:

Given by: $t_{coil}/X_0 = (R/\sigma_h X_0)(B^2/2\mu_0)$

t_{coil} thickness of the coil
R radius of the coil
B the magnetic field
σ_h hoop stress of the coil

E	B	R	t(coil)
3 TeV	3.57 T	3821 mm	344 mm
10 TeV	**4 T**	**2393 mm**	**270 mm**
10 TeV	**5 T**	**2393 mm**	**423 mm**





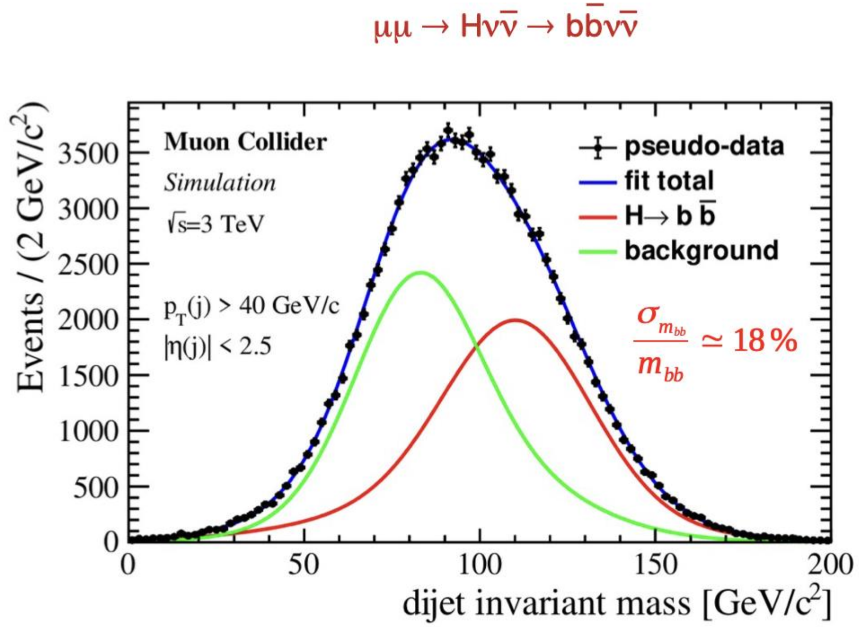
HCAL requirements

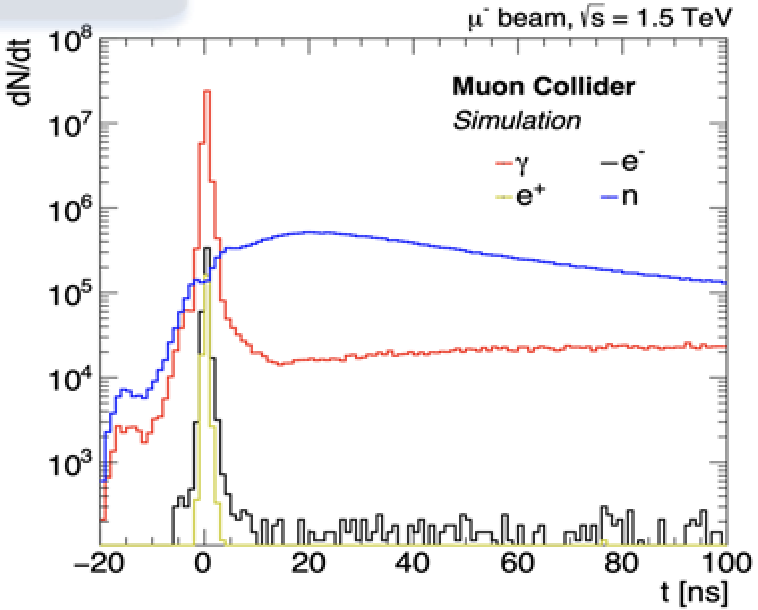
BIB in hadronic calorimeter:

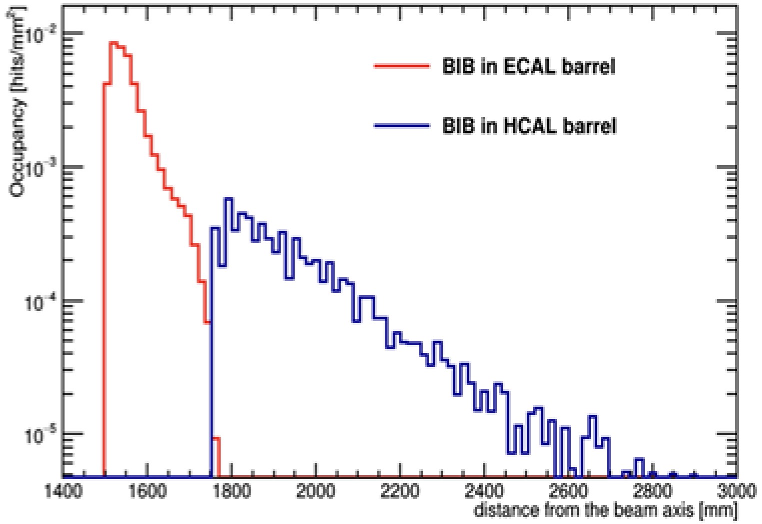
- Mostly photons (96%) and neutrons (4%)
- Large asynchronous component
- Occupancy: 0.06 hits / cm^2 ~10 times lower than ECAL

Detector requirements:

- 3-4 % jet energy resolution for hadronic Z decays
- particle flow reconstruction
- $\frac{30\%}{\sqrt{E[GeV]}}$ **for HCAL**
- High granularity (< $3cm^2$)
- Single layer timing 100 ps - few ns







Ongoing R&D:

- HCAL based on Micro-Pattern Gaseous Detectors
- FIS-2 project from LNF: CRILIN and innovative hadronic calorimeter→ MITICO (MultI TeV Colliders CalOrimeter)

Muon system requirements

In the muon system, significant BIB effects only in the endcap regions close to the beamline:

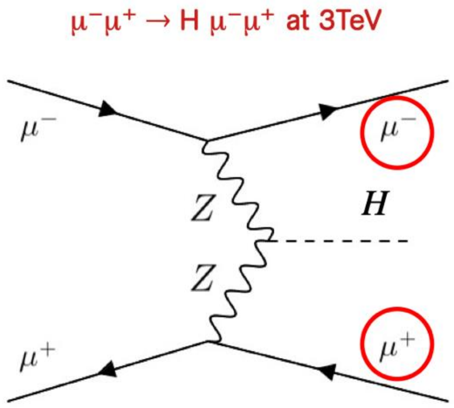
- required **good spatial resolution and possibly sub-ns time resolution**

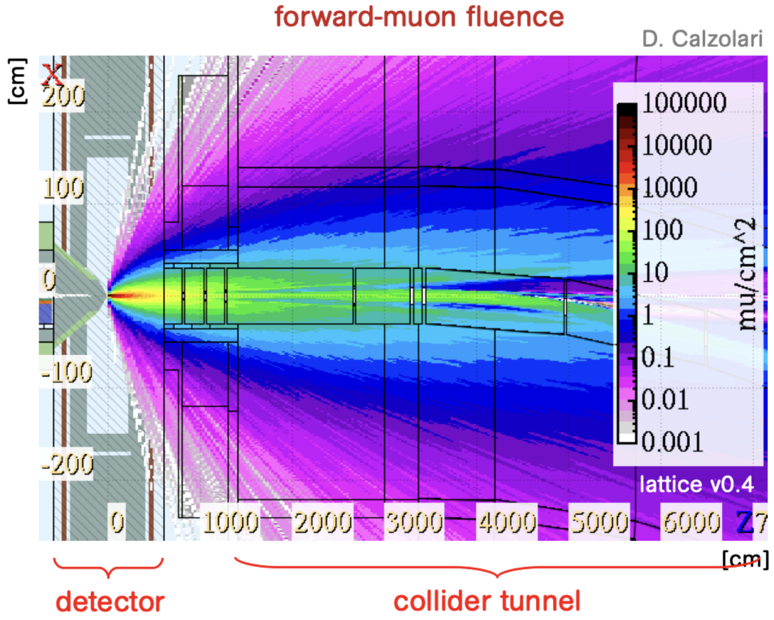
Under investigation the possibility of detecting the forward-scattered muons associated with the ZZ-fusion production process:

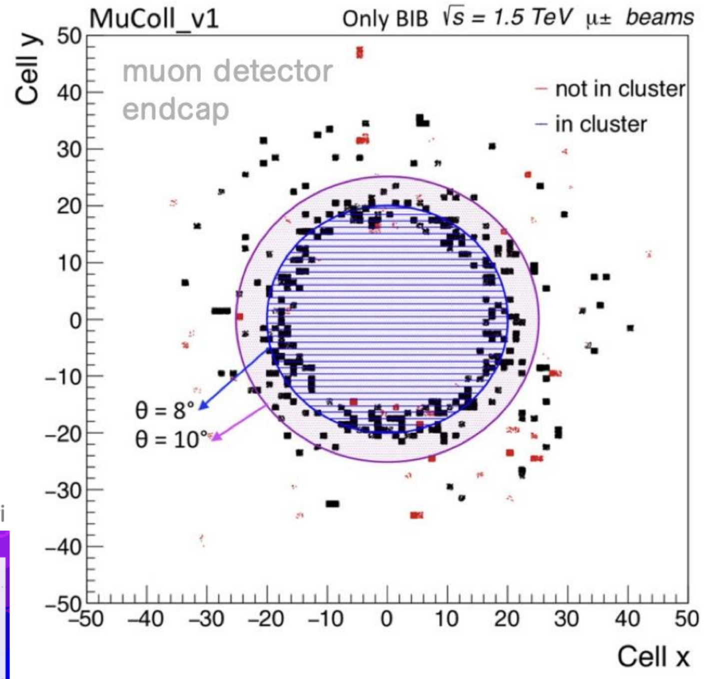
- exploit the specific ZZ-fusion signature;
- possibly help with the measurement.

Ongoing R&D:

Muon detector based on PicoSec Micromegas:







The Crilin calorimeter

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

Key Features:

Excellent timing: (<100 ps) to reject the BIB out- of-time hits and for good pileup capability.

Longitudinal segmentation: allows to recognize fake showers from the BIB.

Fine granularity: reduced hit density in a single cell and distinguish the BIB hits from the signal.

Good resistance to radiation: good reliability during the experiment

Crystal choice:

High-density crystal: selected to balance the need for increased layer numbers with space constraints

Speed response: Cherenkov/fast crystals, ensuring accurate and timely particle detection

→ **PbF2, $PbWO_4$-UF, LYSO…**

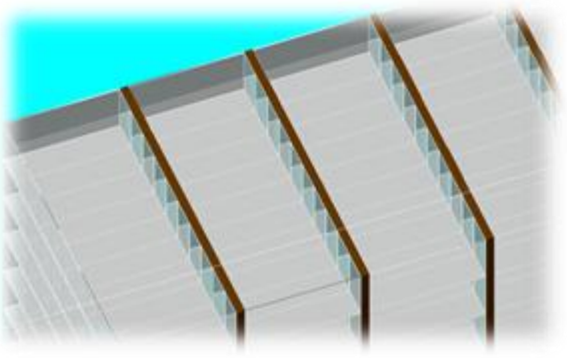
*S. Ceravolo et al 2022 JINST **17** P09033*

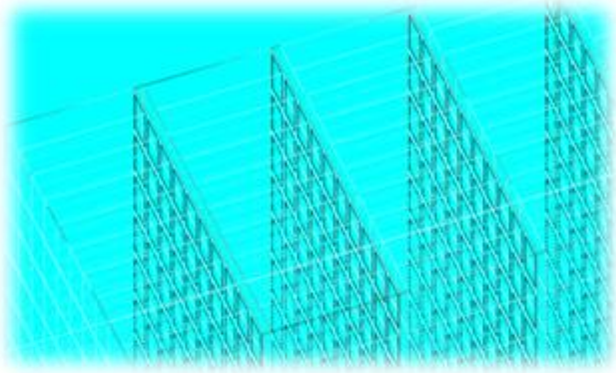
Differentiation:

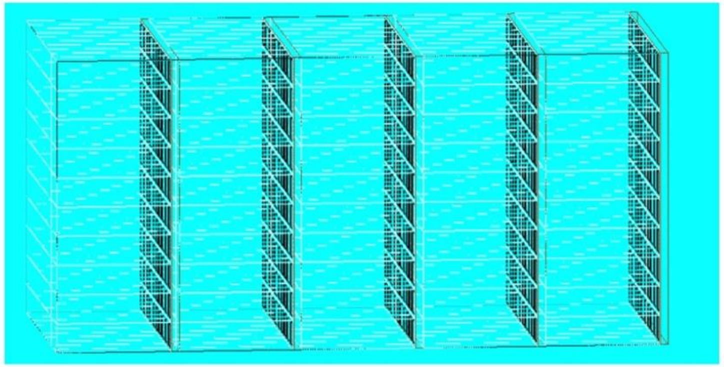
Semi-homogeneous : strategically between homogeneous and sampling calorimeters → able to exploit the strengths of both kinds

Flexibility: able to modulate energy deposition for each cell and adjust crystal size for tailored solutions

Compactness: Unlike segmented or high granularity calorimeters CRILIN can optimize energy detection while staying compact



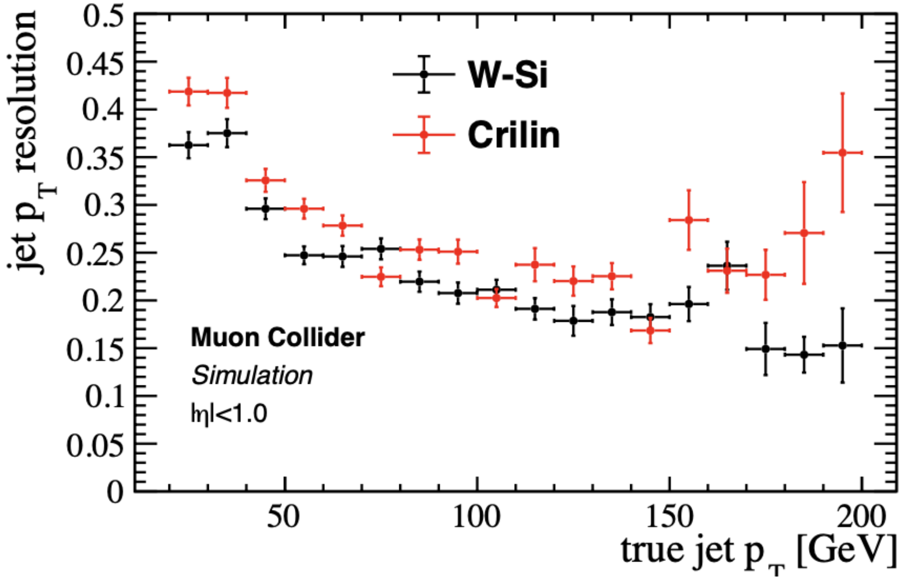


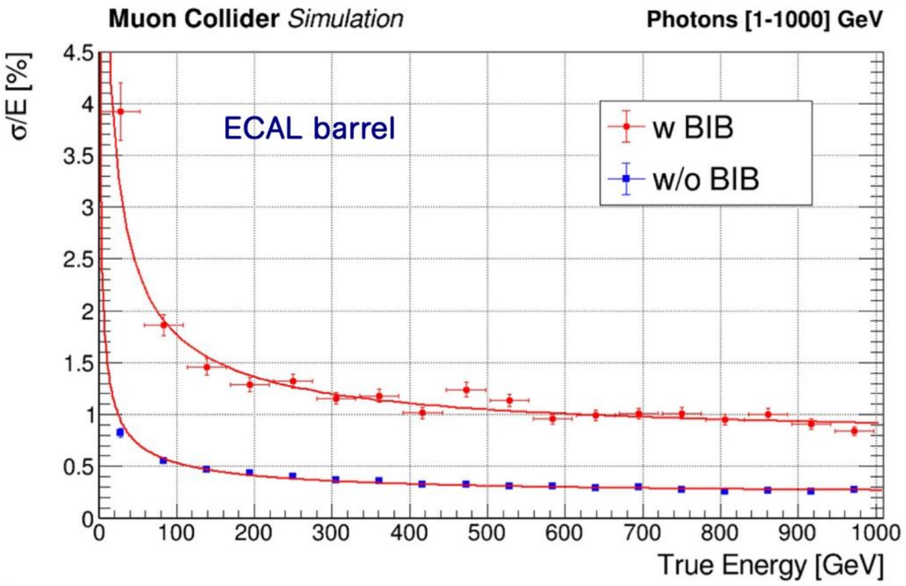


Simulated performances

- 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 → **21.5 X_0**
    - ➢ **In each cell:** 40 mm PbF_2 + 3 mm SiPM + 1 mm electronics + 1 mm air

- Design optimized for BIB mitigation: having thicker layers, the BIB energy is integrated in large volumes → reduced statistical fluctuations of the average energy
- 5 layers wrt to 40 layers of the W-Si calorimeter → **factor 10 less in cost (6 vs 64 Mchannels)**





w/out BIB

$$\frac{\sigma_E}{E} \sim \frac{4\%}{\sqrt{E[GeV]}} \oplus 0.2\ \%$$

w/ BIB

$$\frac{\sigma_E}{E} \sim \frac{15\%}{\sqrt{E[GeV]}} \oplus 0.8\ \%$$

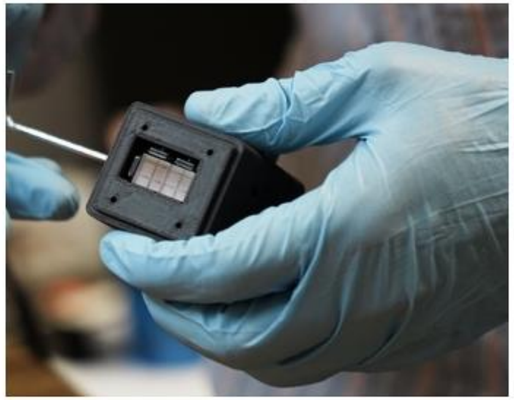
R&D status

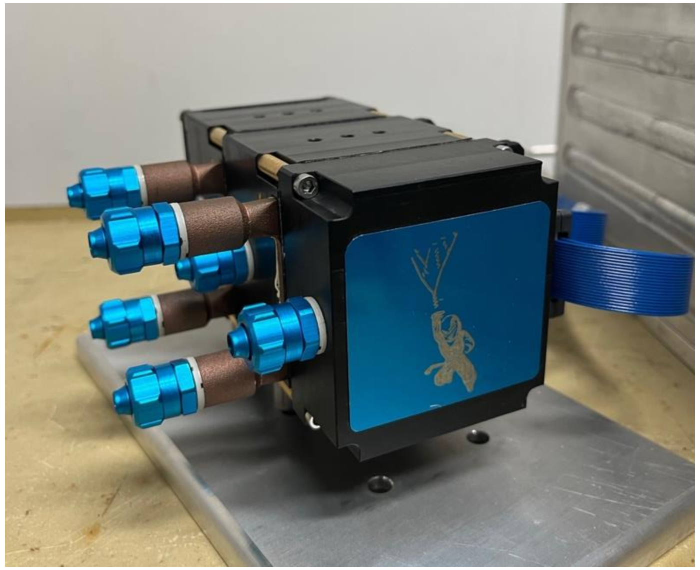
Prototype versions
- Proto-0 (2 crystals → 4 channels)
- Proto-1 (3x3 crystals x 2 layers → 36 channels)

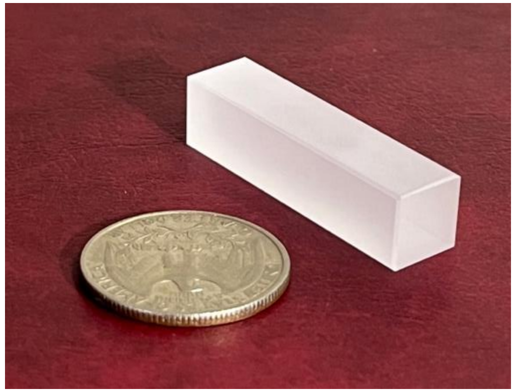
Front-end electronics
- Design completed
- Production and QC completed

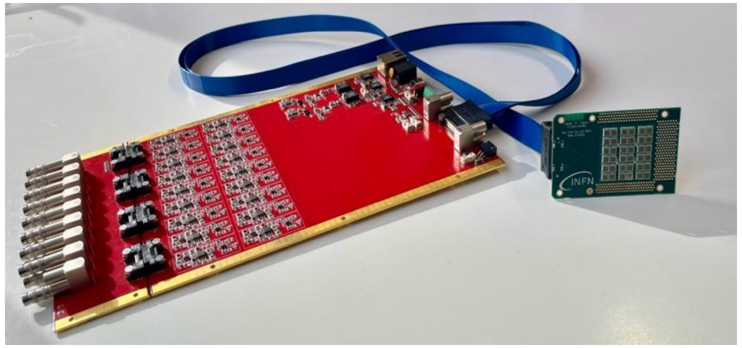
Radiation hardness campaigns

Beam test campaigns
- Proto-0 at CERN H2 (August 2022) [C. Cantone et al. 2023 Front. Phys. 11:1223183]
- Proto-1 at LNF-BTF (July 2023-April 2024) [C. Cantone et al. 2024 doi:10.1109/TNS.2024.3364771]
- Proto-1 at and CERN (August 2023)





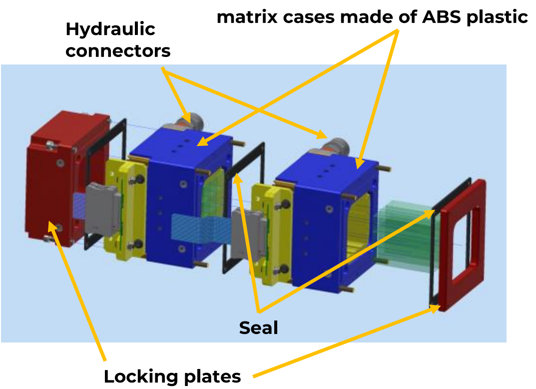


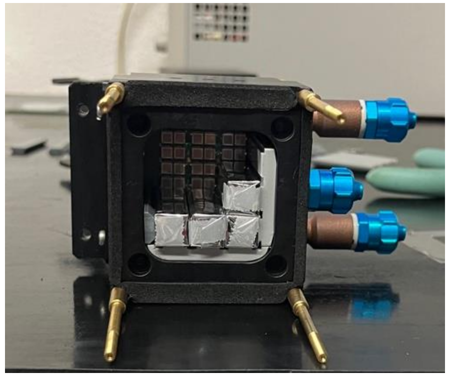


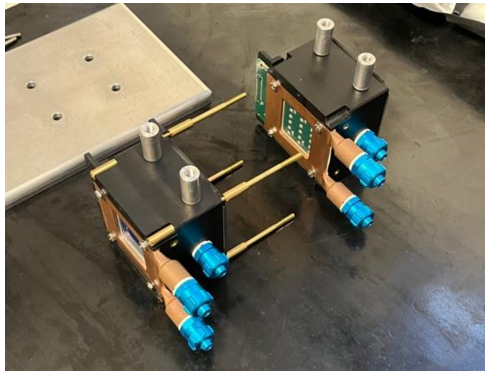
Proto-1: Mechanics and Electronics

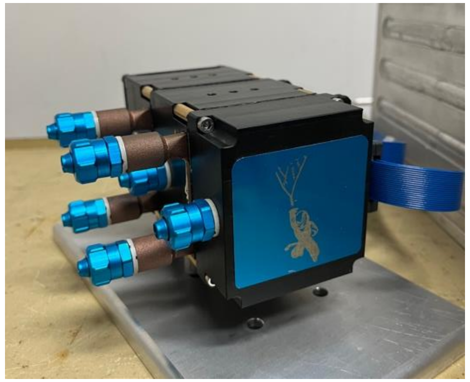
Mechanics:

- 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.



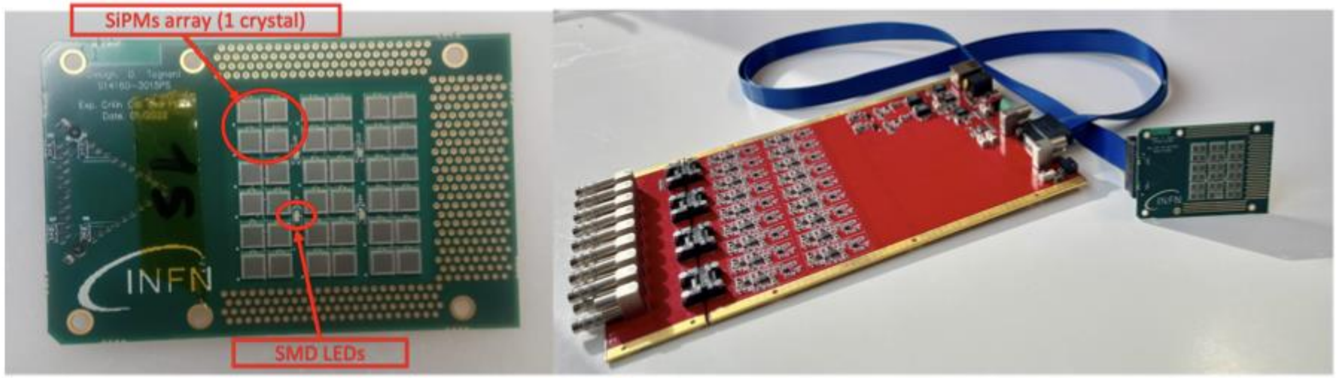






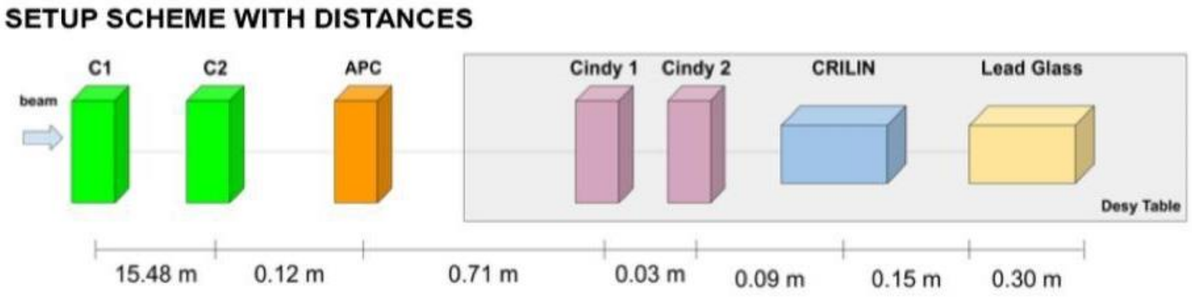
Electronics:

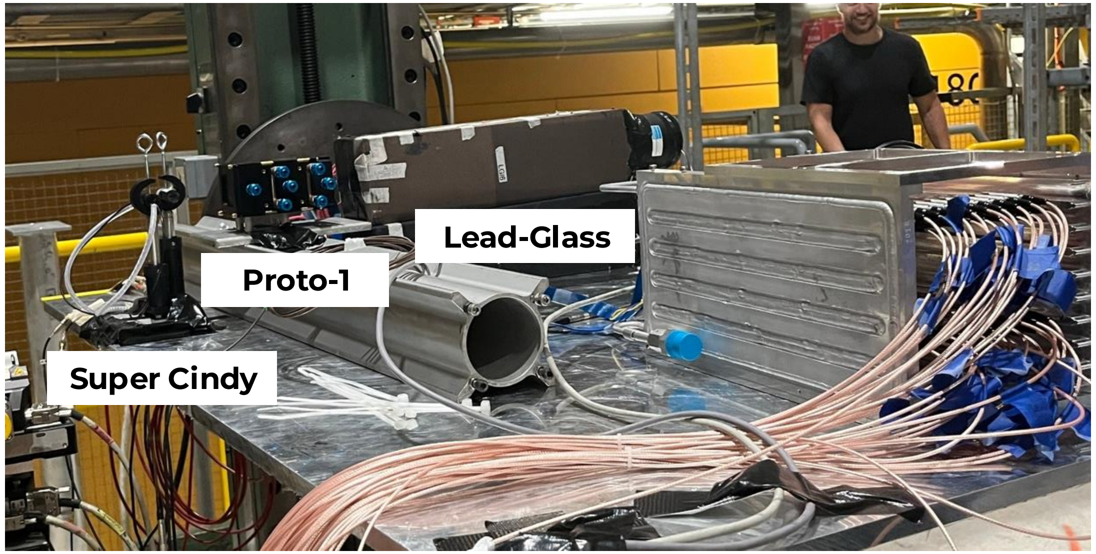
- **SiPMs board:** custom SiPM array board 36x10 μm Hamamatsu SMD SiPMs
- **Mezzanine board:** 18x readout channels → amplification, shaping and individual bias regulation, slow control routines



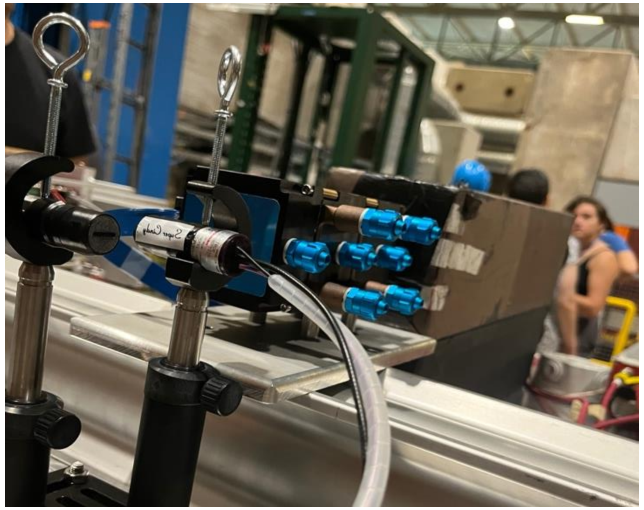
Beam test @ CERN

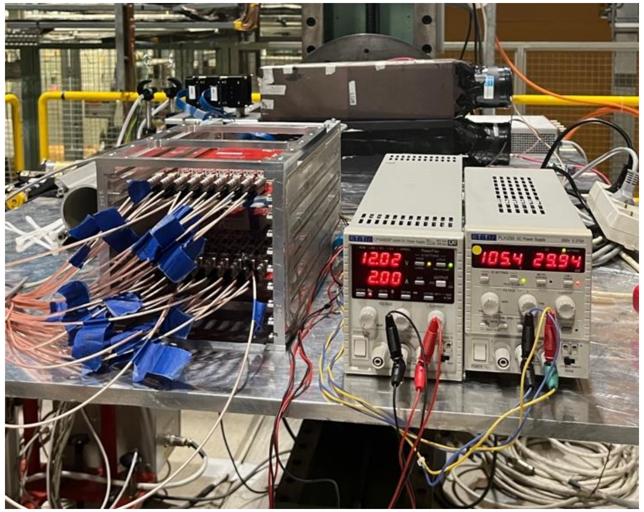
H2-SPS-CERN, August 2023





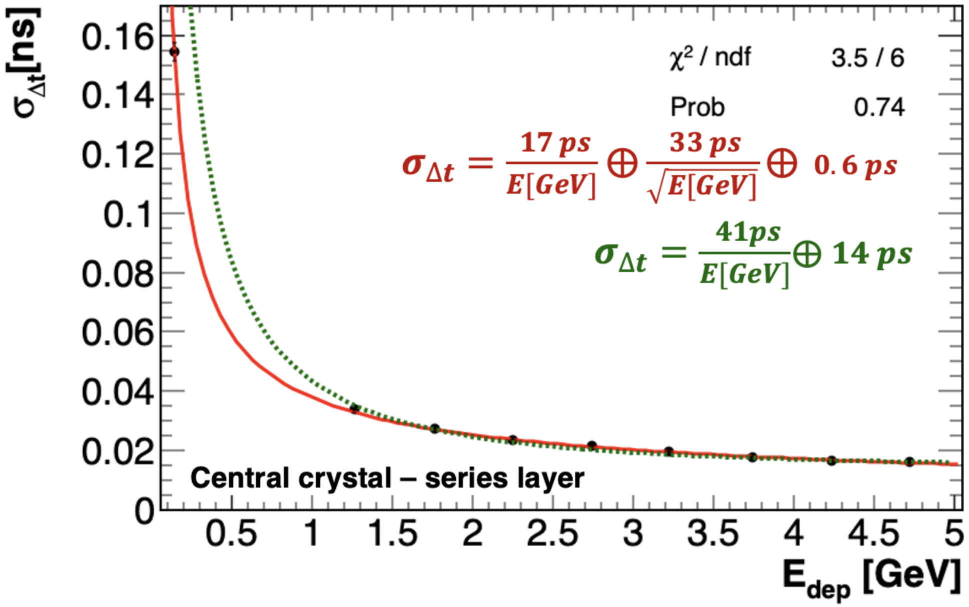
- Electron beam from 40 GeV up to 150 GeV
- Beam reconstructed with 2 silicon strip telescopes
- Data acquisition with 2 CAEN V1742 (32 ch each) modified @ 2 Vpp
- 5 Gs/s sampling rate

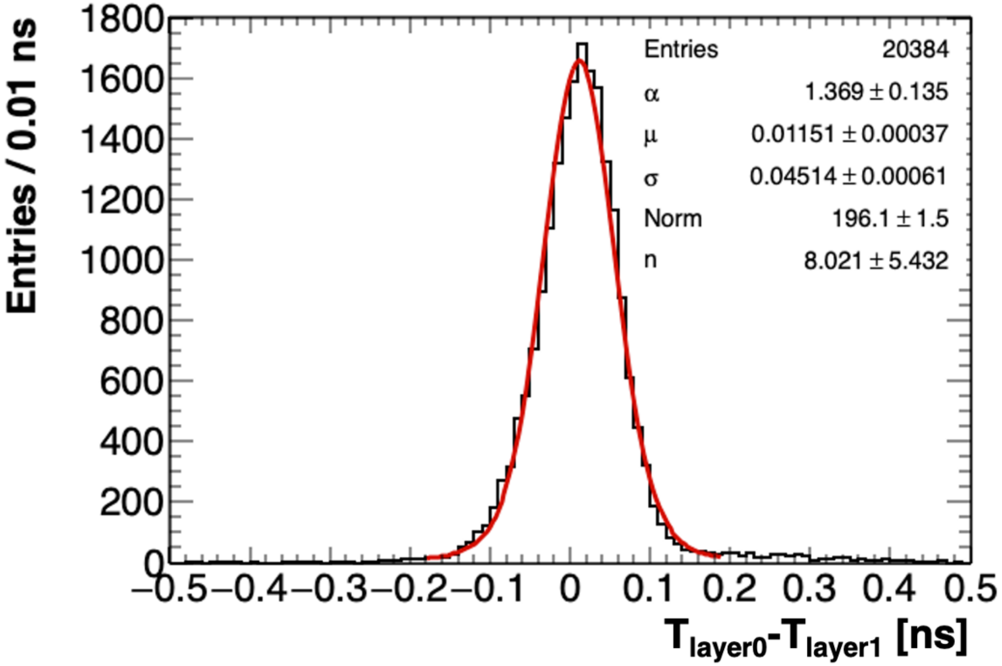


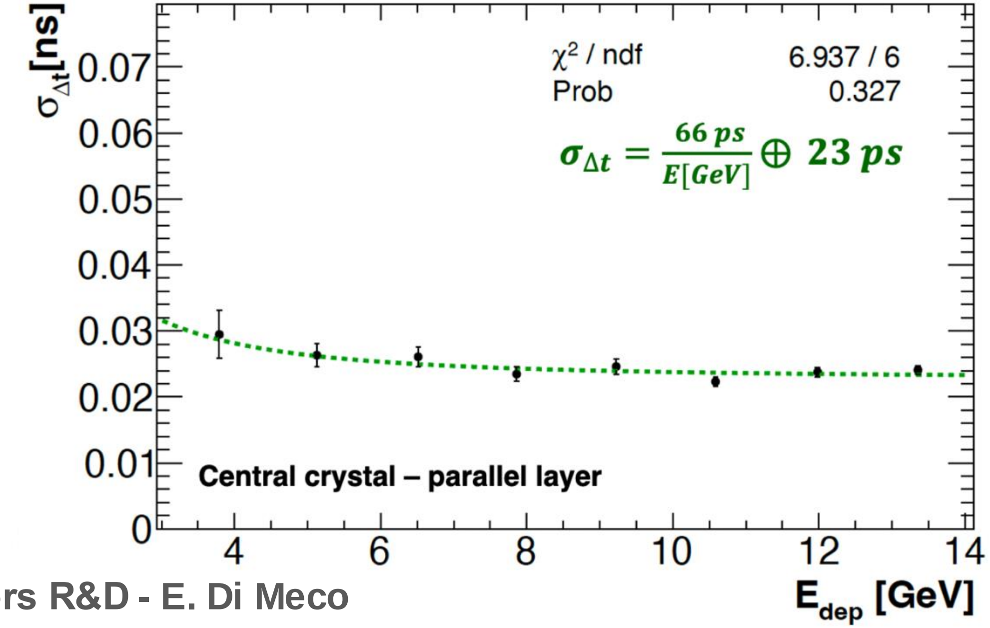


Timing performances @ SPS-H2

- Time Resolution of **O(20 ps)** both in the series and in the parallel layers using the SiPMs time difference of the central crystals
- Excellent results using most energetic crystal of different layers. **Time resolution dominated by the 2 boards synchronisation jitter** O(32ps)



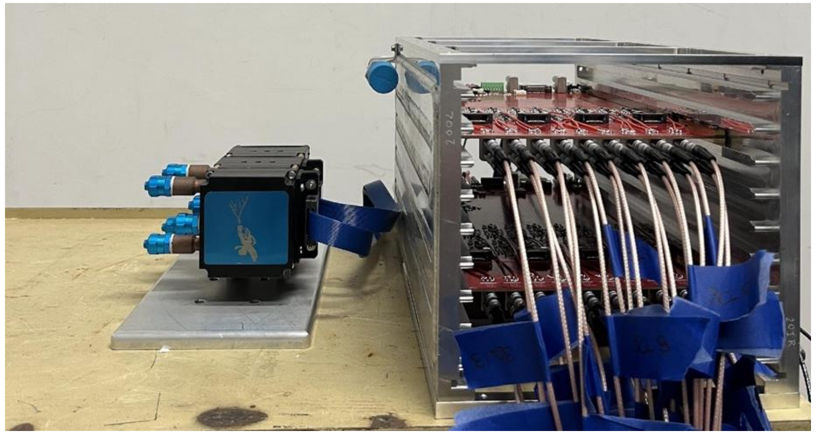


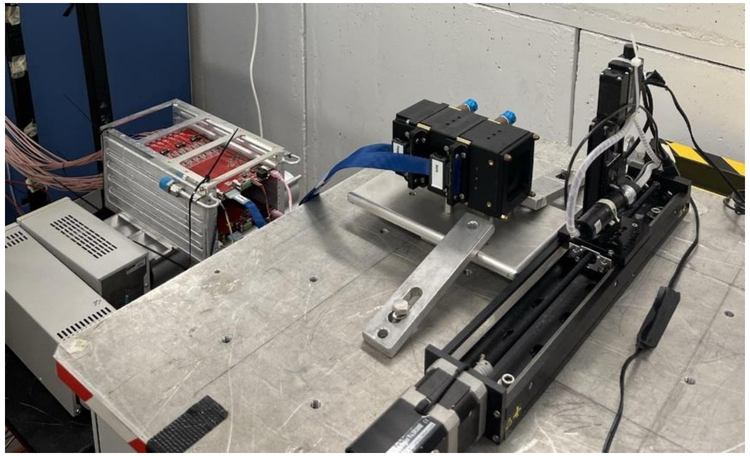


Beam test @ BTF

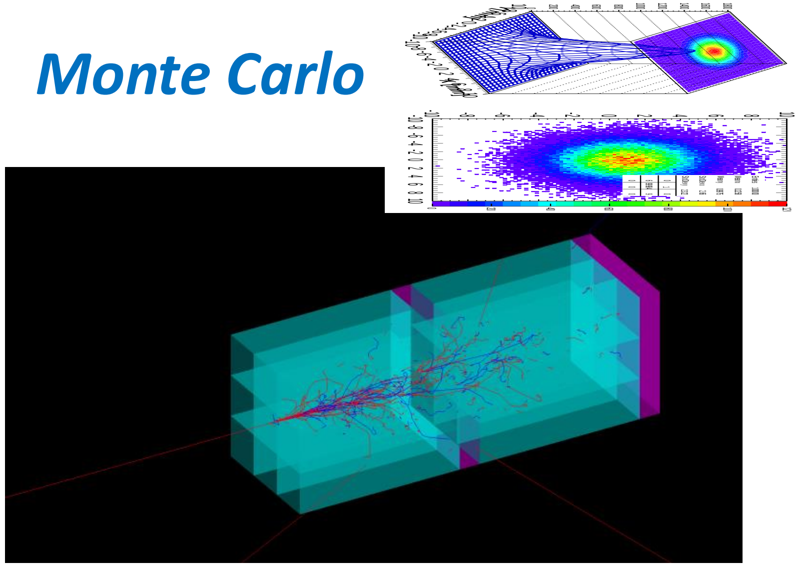
BTF, April 2024

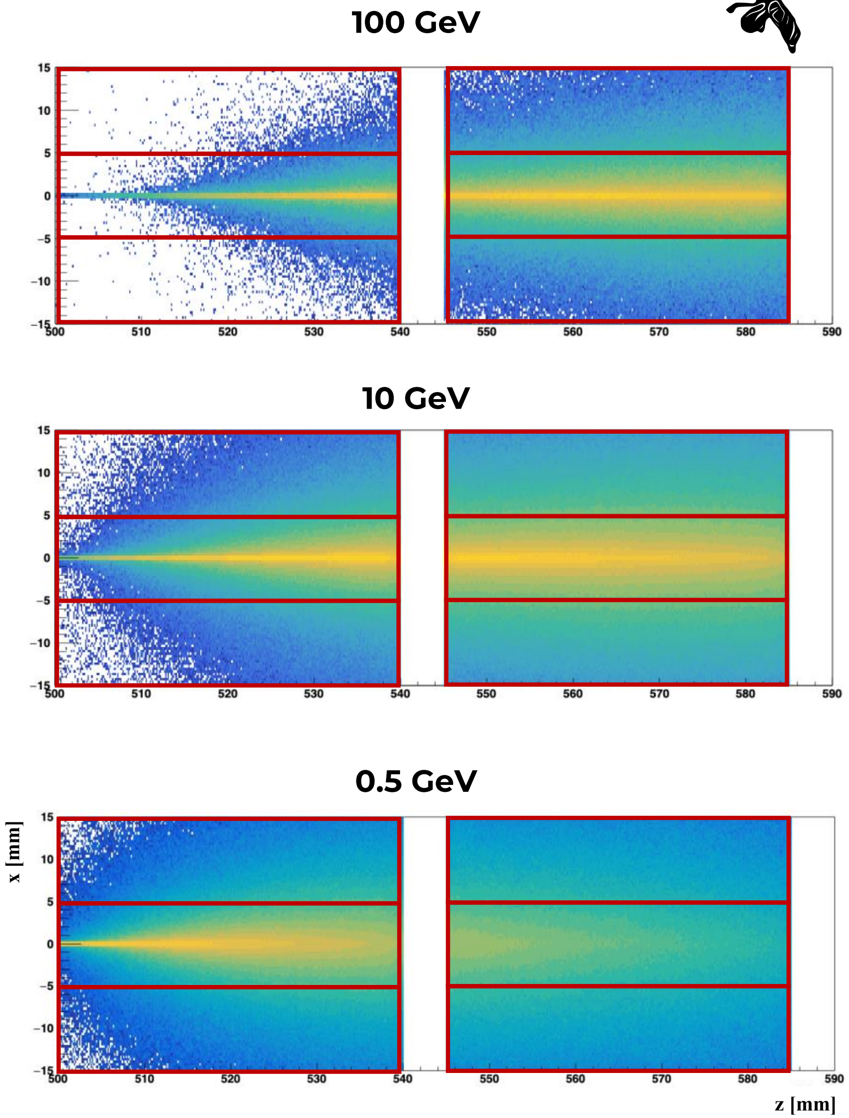
- Study of the LY loss of one layer of Proto-1 after Gamma ray irradiation
- Beam: 450 MeV electrons with multiplicity 1
- Beam centered on a different crystal at each run





Monte Carlo



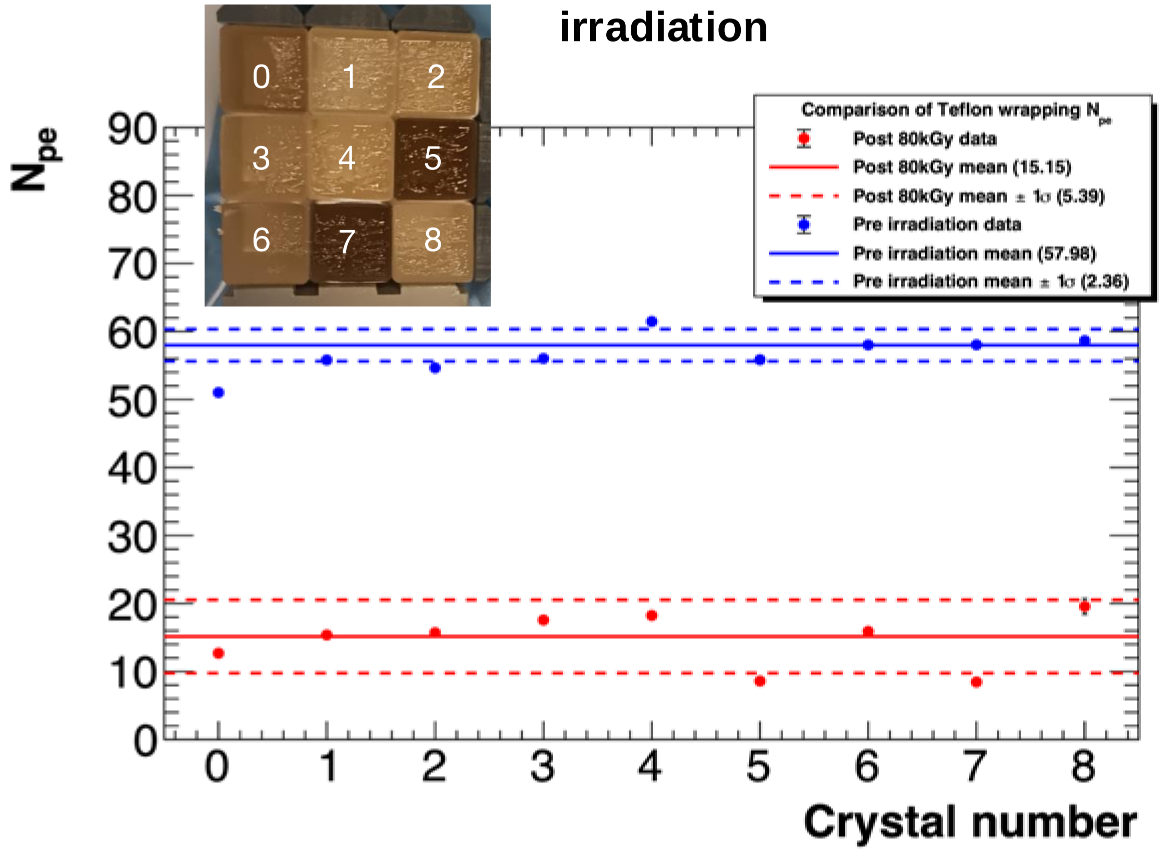


Beam test @ BTF: crystals

- Crystals tested with two different wrapping, Teflon and Mylar, up to 80 kGy
- LY loss evaluated through variation in charge and number of photo-electrons

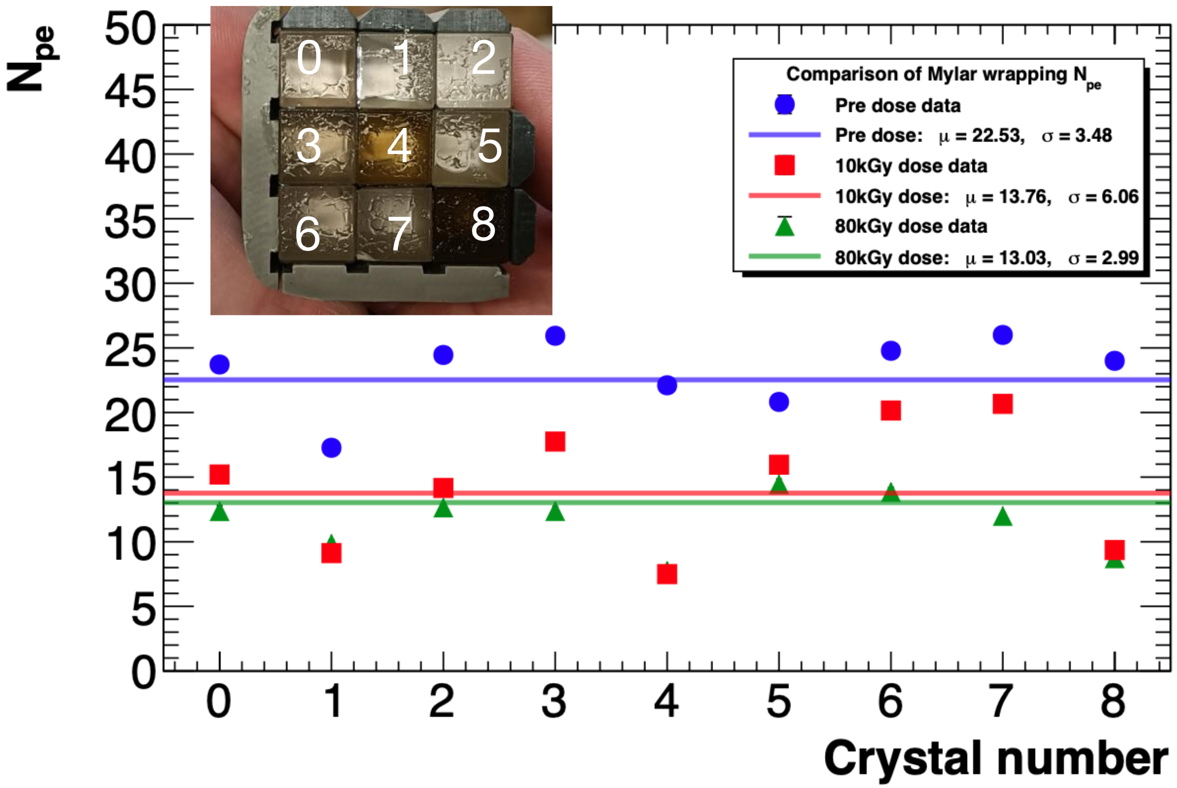
Telfon wrapping

Npe values of PbF_2 pre and post 80 kGy irradiation



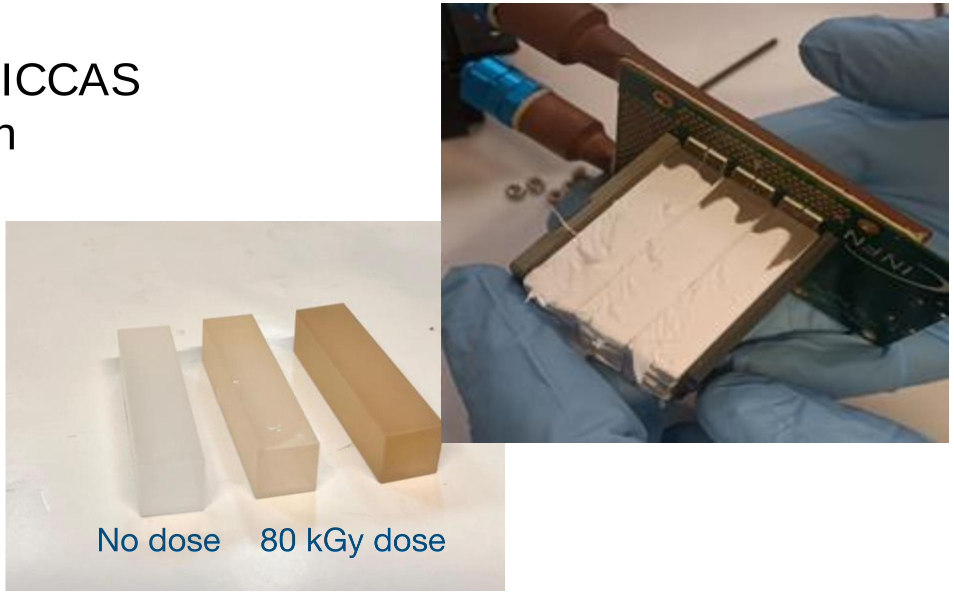
Mylar wrapping

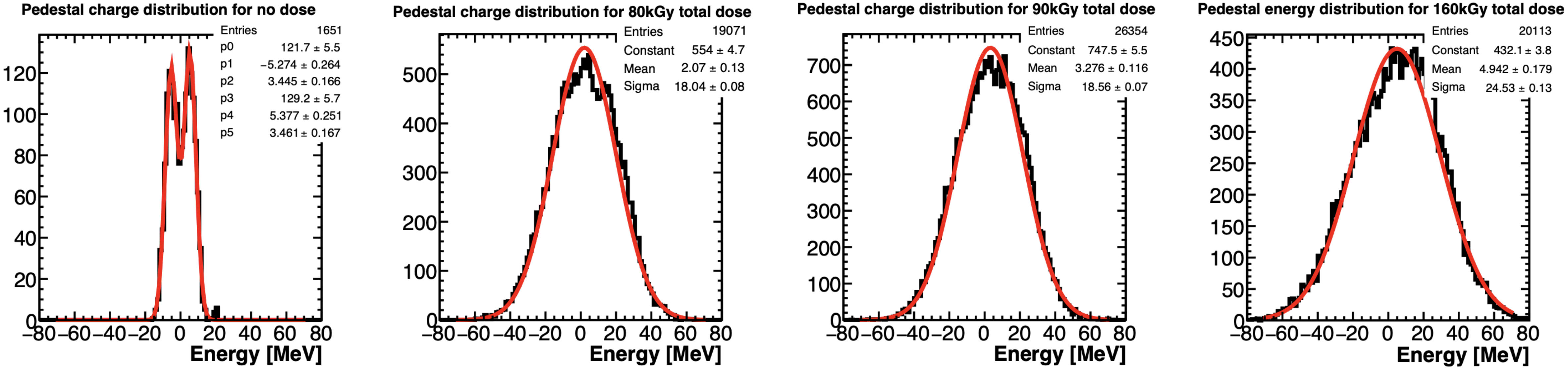
Npe values of PbF_2 pre, after 10 kGy and after 80 kGy irradiation



Beam test @ BTF: considerations

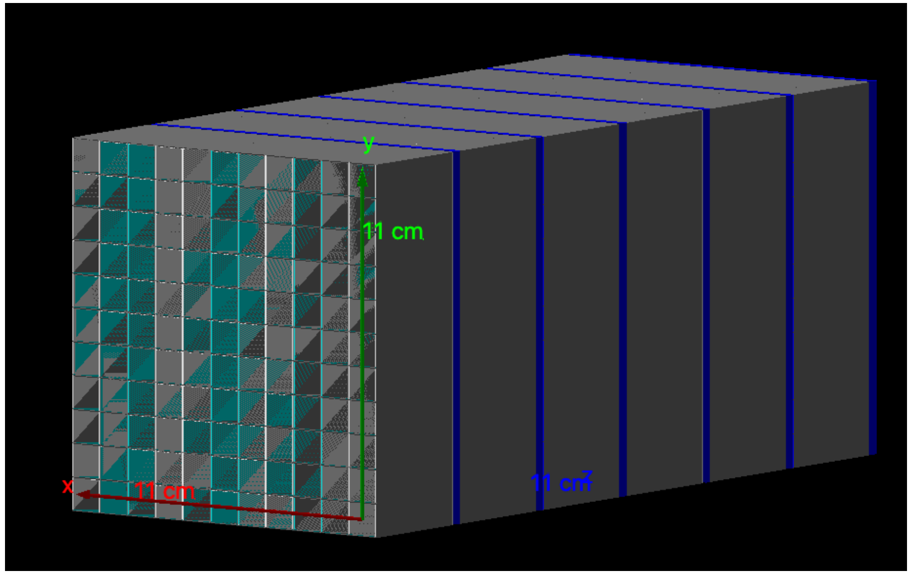
- Considerable variability in crystals' response to radiation, despite SICCAS claiming use of high-purity (>99.9%) PbF_2 powder for crystal growth
- Crystals evident loss of transparency
- Transparency loss was uniform length-wise in the crystals
- Teflon was damaged and brittle
- SiPM dark counts increases significantly with the absorbed dose
- New tests planned to evaluate SiPMs PDE loss and optical grease degradation

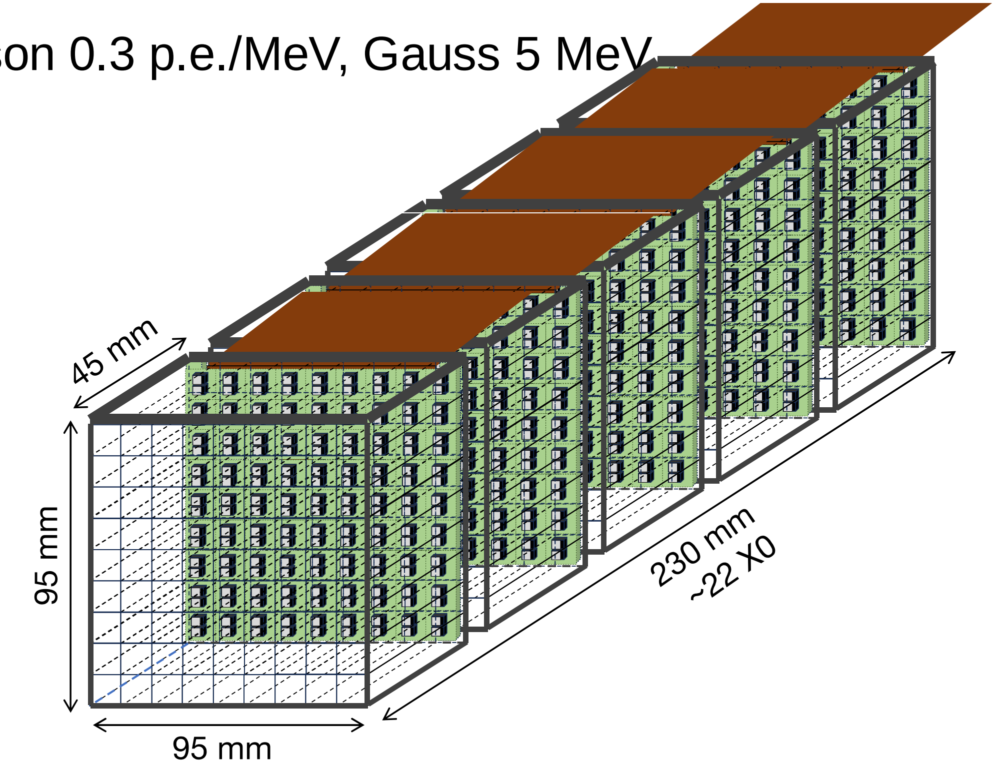




Geant4 simulation of the new prototype

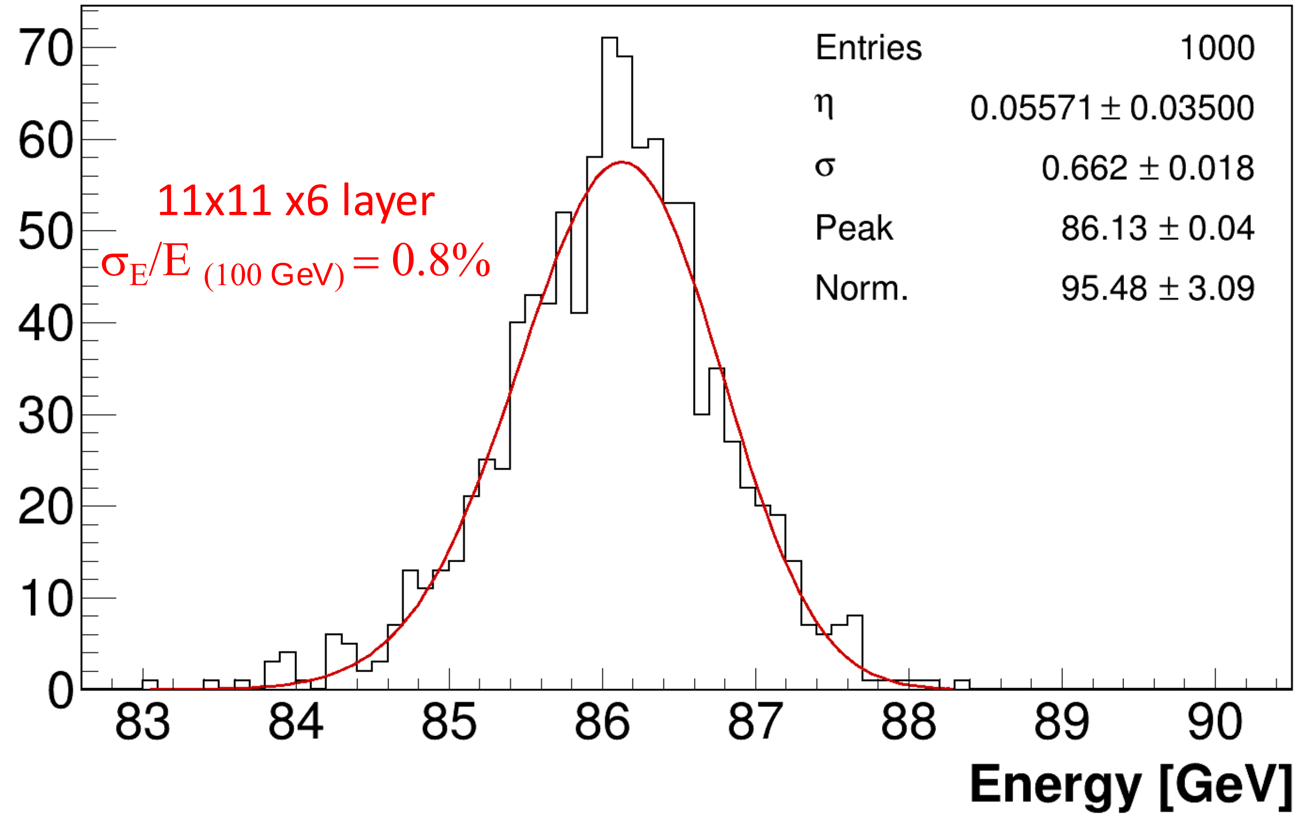
- Initial proposal **11x11 x6 layer** (crystals 10x10x40 mm^2 each) → **2.5 R_M – 26 X_0**
- Crystals wrapped in 150 um Mylar foils and placed a 150 um aluminum honeycomb
- 2 SiPMs 3x3 mm^2 per cystal, 2 mm thick, per layer
- 2 mm thck PcB, per layer
- Photostatistics and noise measured during beam tests : Poisson 0.3 p.e./MeV, Gauss 5 MeV

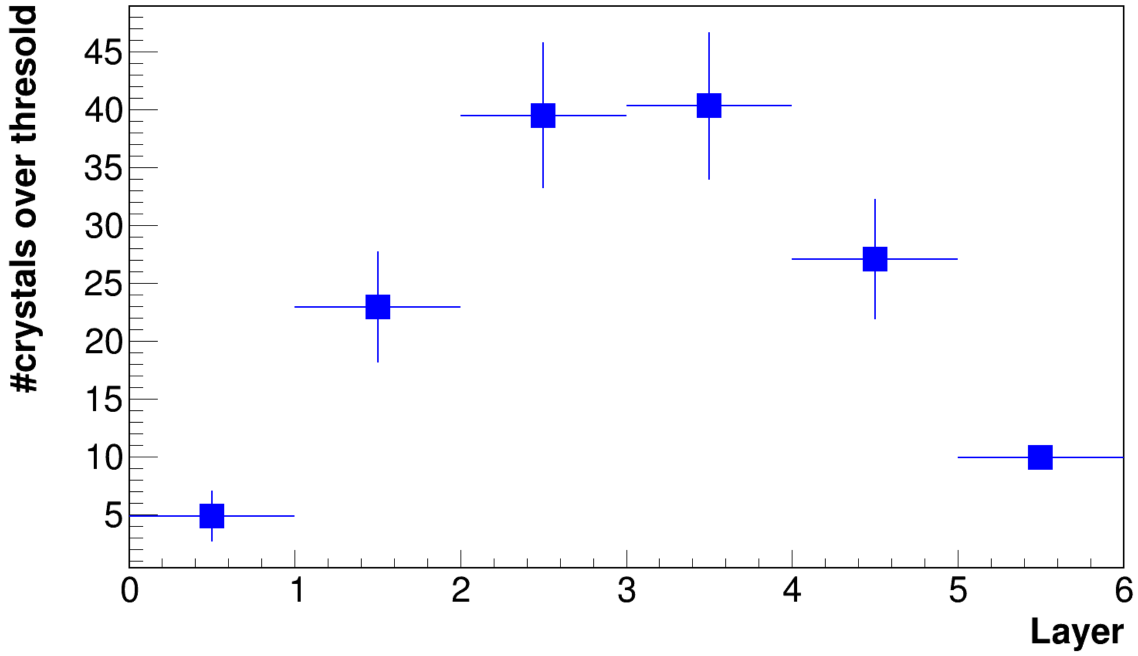




Number of crystals optimization

- By setting a threshold similar to that expected for the Muon Collider (i.e. 40 MeV) per crystal, we optimized the number of crystals, with the goal of minimizing the energy resolution loss → optimization performed for an electron beam with 100 GeV of energy.

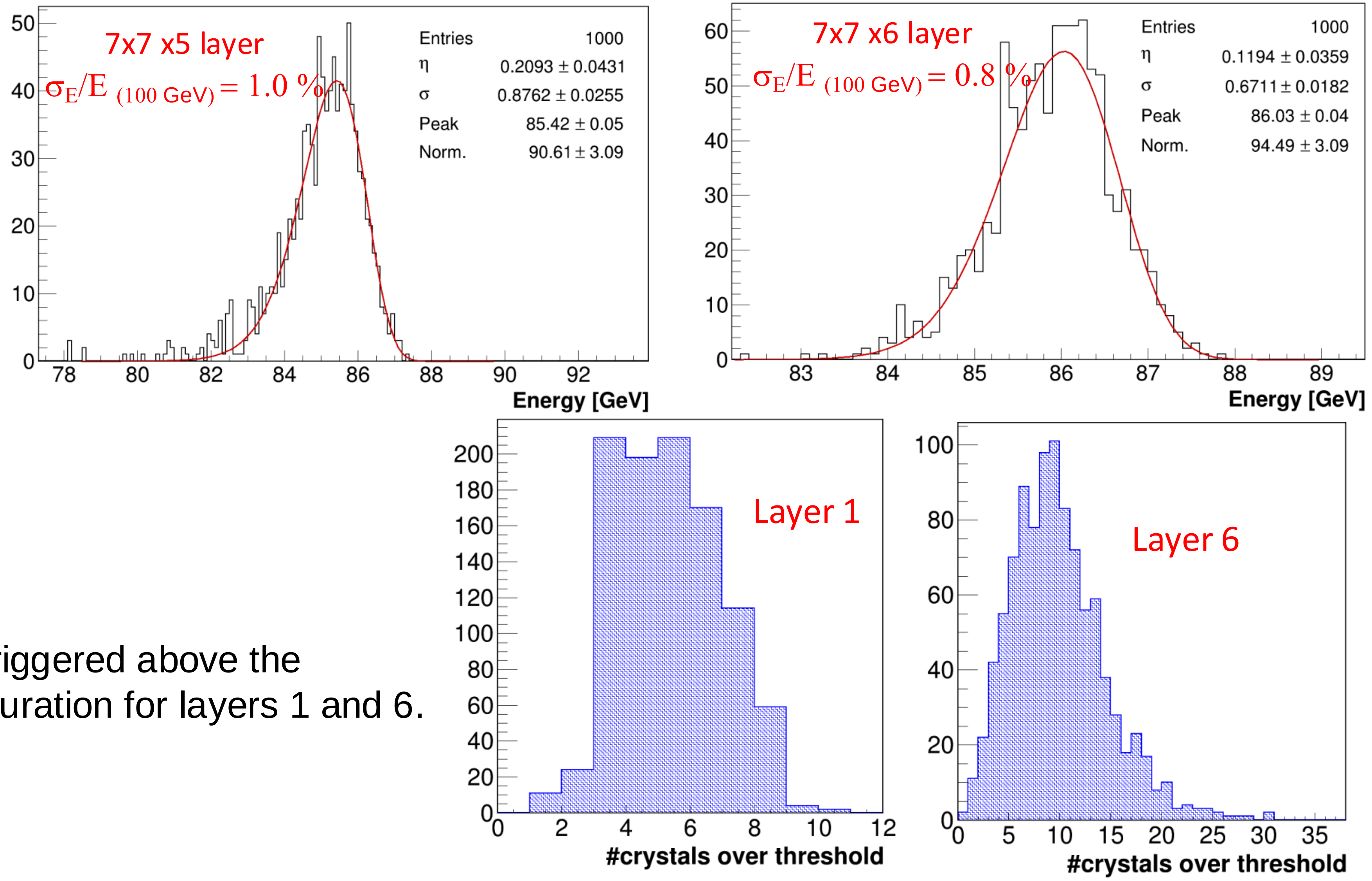




Number of layers optimization

The average number of crystals triggered above the threshold leads to a 7x7 configuration for layers 2, 3, 4, and 5

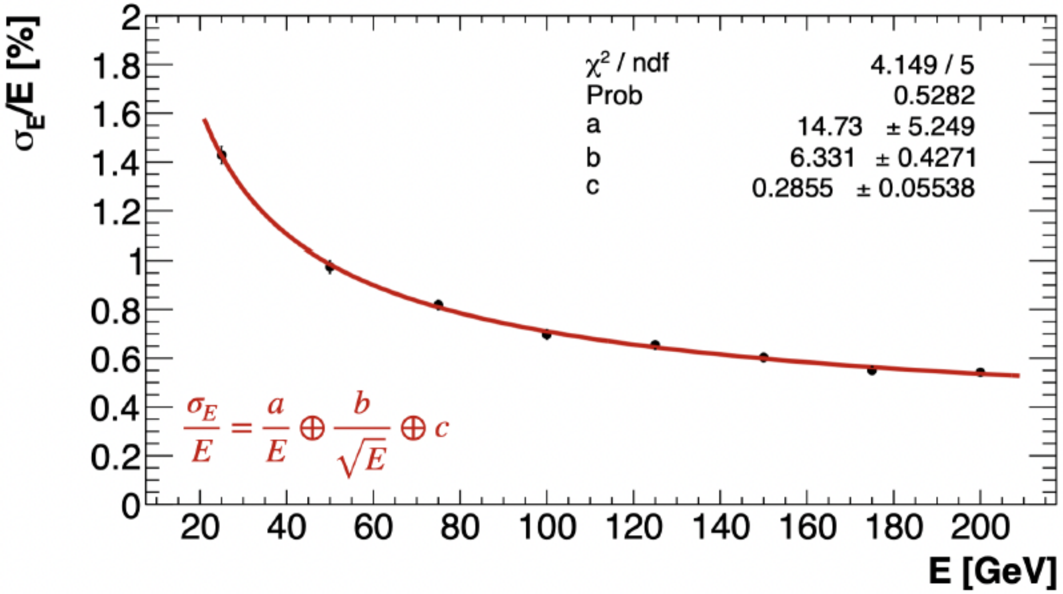
The sixth layer is crucial for maximizing energy resolution→ longitudinal leakage creates a much larger energy fluctuation compared to lateral leakage (for the same amount of leakage).

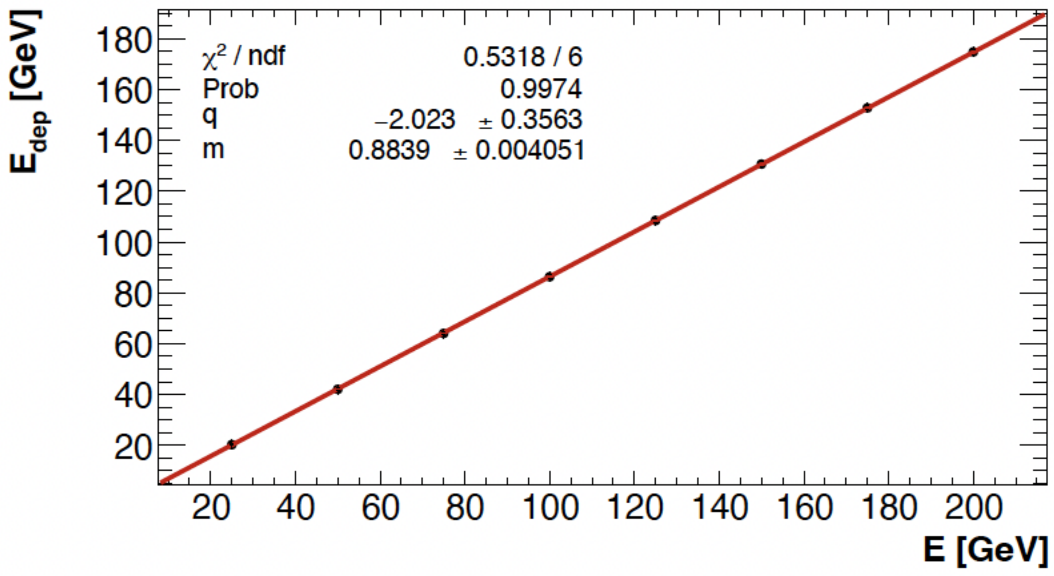


The average number of crystals triggered above the threshold leads us to a 5x5 configuration for layers 1 and 6.

Energy resolution and linearity

- Energy Resolution and Linearity as a function of E for the reduced matrix:
- 7x7 in layers 2, 3, 4, and 5, and 5x5 in layers 1 and 6 → ~250 crystals in total.
- $\sigma_E/E \sim 6\%/\sqrt{E}$ satisfies the Muon Collider requirements!
- stochastic term comparable to the one expected from photo-statistics (5.8%)





Conclusions

- A Muon Collider is a valid and challenging opportunity as next collider
- Many studies are yet to be improved but the physics program stands really strong, wide and competitive
- The effects of beam-induced background in the detector have been thoroughly studied with a detailed detector simulation and mitigation measures are in place to keep them under control.
- Full-simulation studies at 3 TeV are concluded and now 10 TeV studies are close to be finalized.
- The full-simulation studies point the way for the detector R&D (some R&D’s already well advanced).
- The goals for the European Strategy update are a detector concept for 10 TeV collisions and the muon collider reach for representative physics cases.

Backup slides

Muon Collider parameters

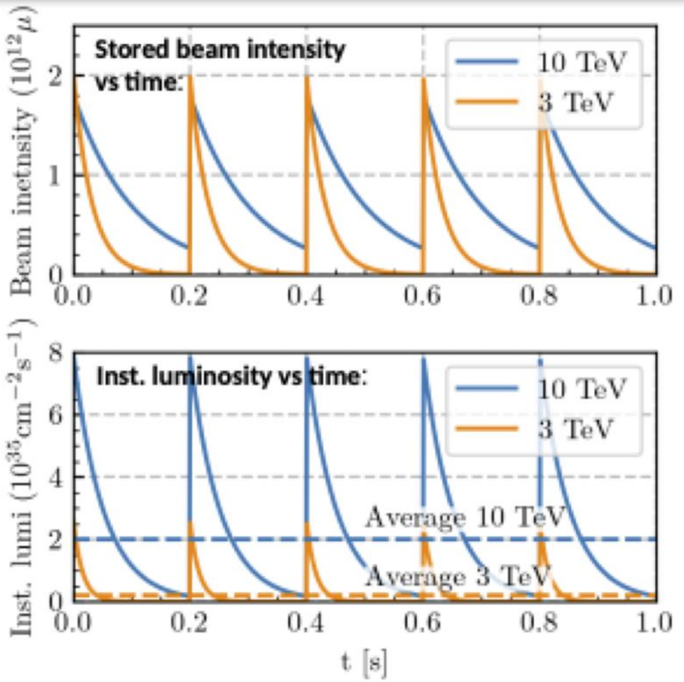
International MUON Collider Collaboration

Example as discussion basis numbers will change

	=3 TeV	=10 TeV
Beam parameters		
Muon energy	1.5 TeV	5 TeV
Bunches/beam	1	
Bunch intensity (at injection)	2.2×10^{12}	1.8×10^{12}
Norm. transverse emittance	25 µm	
Repetition rate (inj. rate)	5 Hz	
Collider ring specs		
Circumference	4.5 km	10 km
Revolution time	15.0 µs	33.4 µs
Luminosity		
Target integrated luminosity	1 ab^{-1}	10 ab^{-1}
Average instantaneous luminosity (5/10 yrs of op.)	$2 \times 10^{34}\ cm^{-2}s^{-1}$ / $1 \times 10^{34}\ cm^{-2}s^{-1}$	$1 \times 10^{35}\ cm^{-2}s^{-1}$ / $2 \times 10^{35}\ cm^{-2}s^{-1}$

$\tau = 2.2\times10^{-6}$ s

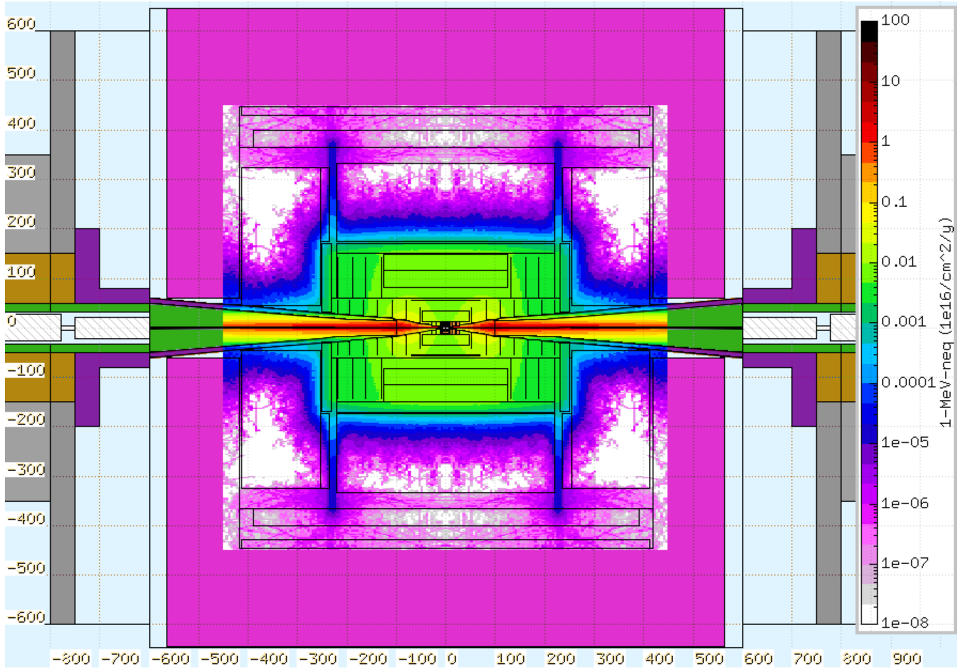
Muon decay	=3 TeV	=10 TeV
Mean muon lifetime in lab system ($\gamma\tau$)	0.031 s	0.104 s
Luminosity lifetime	1039 turns	1558 turns

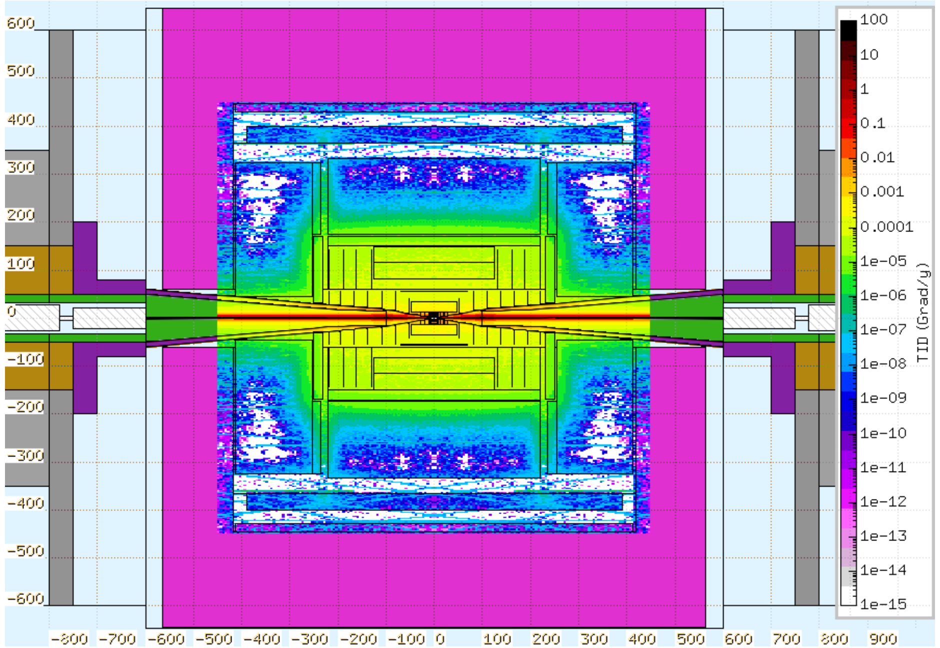


See also parameter doc: https://cernbox.cern.ch/s/NraNbczzBSXctQ9

Radiation enviroment

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



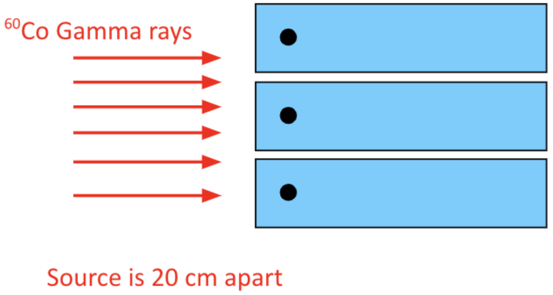


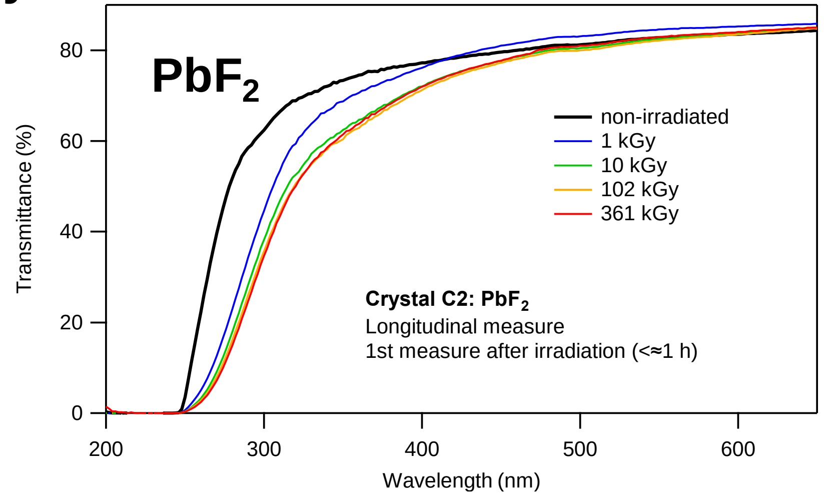
- **Neutron fluence** $\sim \mathbf{10^{14}} \mathrm{n}_{1MeVeq}/\boldsymbol{cm^2}$**year** on ECAL.
- **TID ~ 1 kGy/year** on ECAL.

Crystal radiation hardness

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

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)



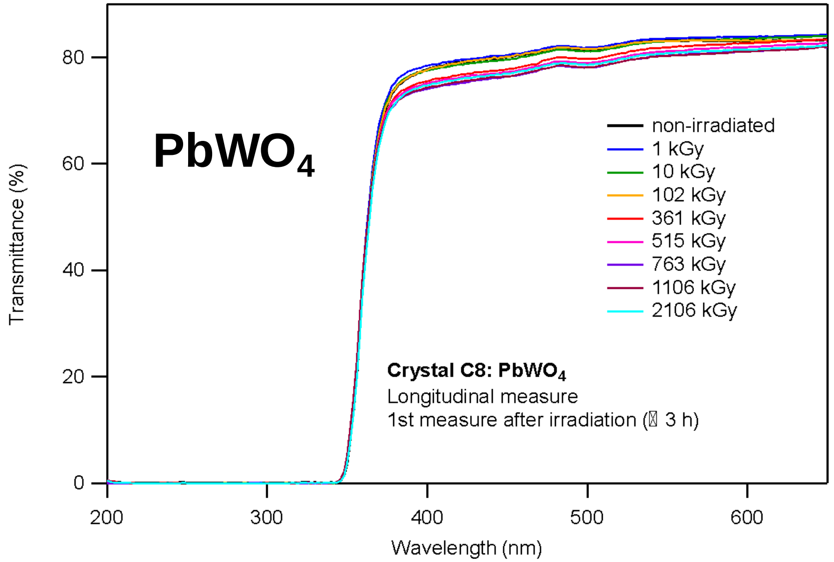


- **For PbF_2:**
  - ➢ **after a TID > 350 kGy no significant decrease** in transmittance observed.
  - ➢ Transmittance after neutron irradiation showed no deterioration

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

- **For $PbWO_4$-UF:**
  - ➢ **after a TID > 2 MGy no significant decrease** in transmittance observed.

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



SiPMs radiation hardness

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

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;

15 μm pixel-size

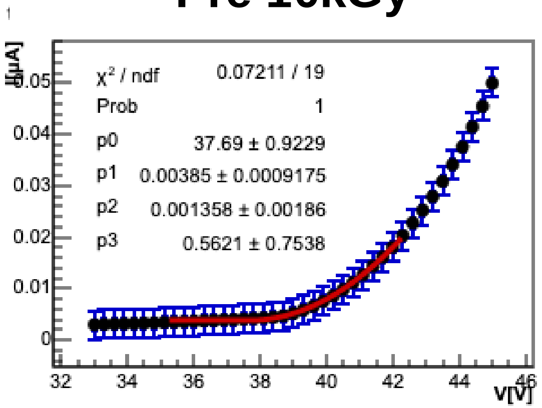
T [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	75.29 ± 0.01	12.56 ± 0.01	30.45 ± 0.01	46.76 ± 0.01
-5 ± 1	75.81 ± 0.01	14.89 ± 0.01	32.12 ± 0.01	46.77 ± 0.01
0 ± 1	76.27 ± 0.01	17.38 ± 0.01	33.93 ± 0.01	47.47 ± 0.01

10 μm pixel-size

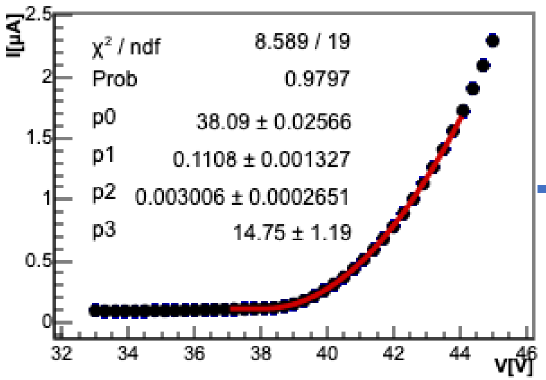
T [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	76.76 ± 0.01	1.84 ± 0.01	6.82 ± 0.01	29.91 ± 0.01
-5 ± 1	77.23 ± 0.01	2.53 ± 0.01	9.66 ± 0.01	37.51 ± 0.01
0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

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

Pre 10kGy



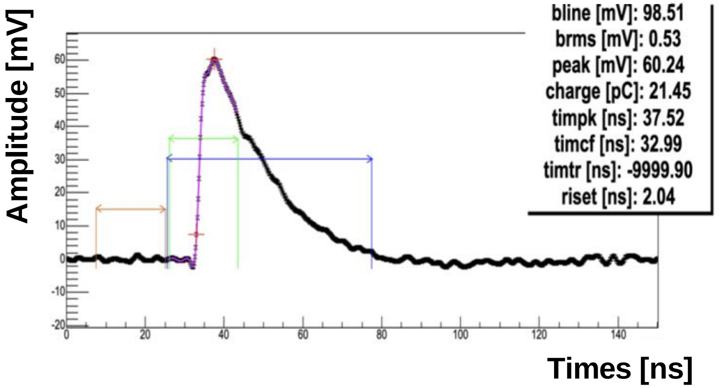
Post 10kGy



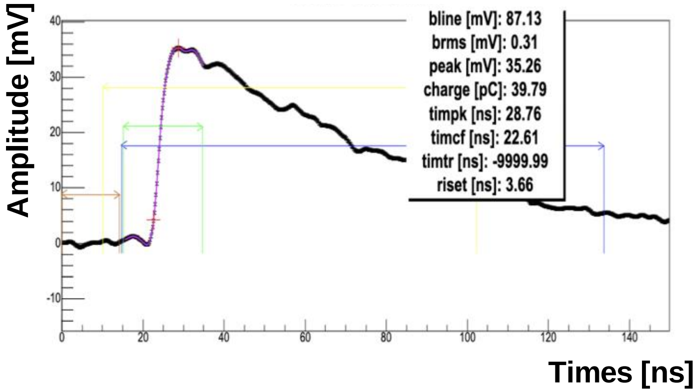
Dark current @ Vop goes from 12 nA to 600 nA

Beam test @ CERN: Configuration

1st layer: SiPMs series

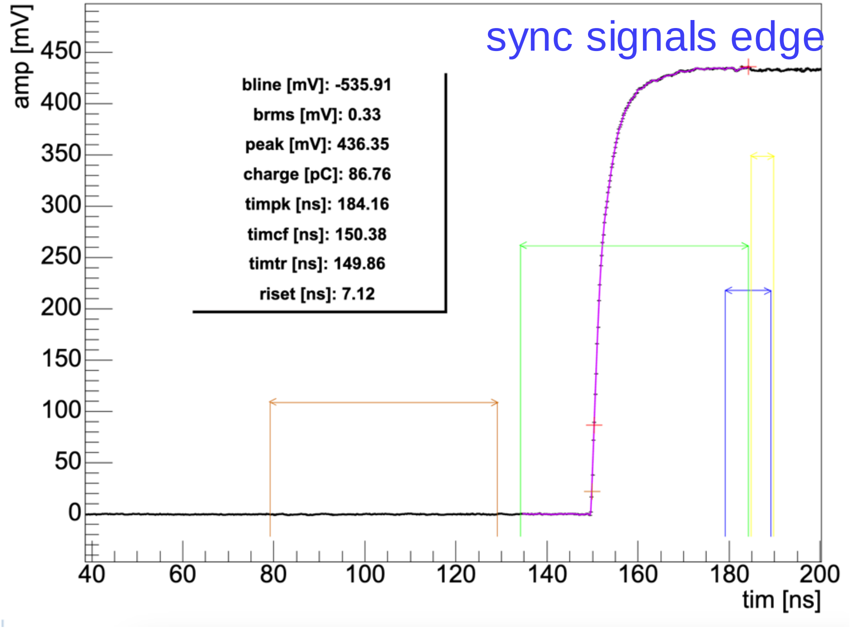


2nd layer: SiPMs parallel



Syncronisation pulses reconstruction:

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

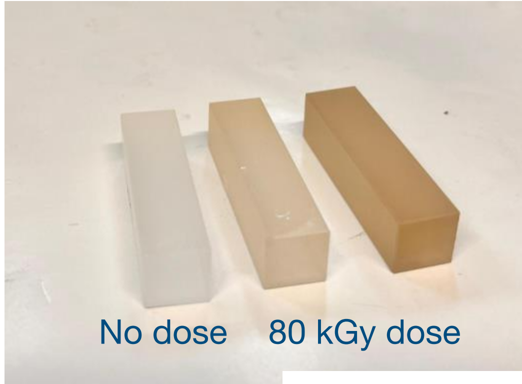


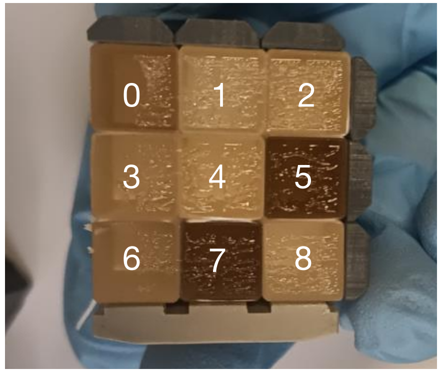
- **Two different connection in the two layers:** series and parallel
- **Low pass filtering** (Bessel 2nd order) cutoff_parallel ~ 2* cutoff_series.
- Cut-off frequency based on two parameters: baseline RMS and risetime (10-90%)
- Wave quality flag based on baseline RMS, peak, and risetime to discard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

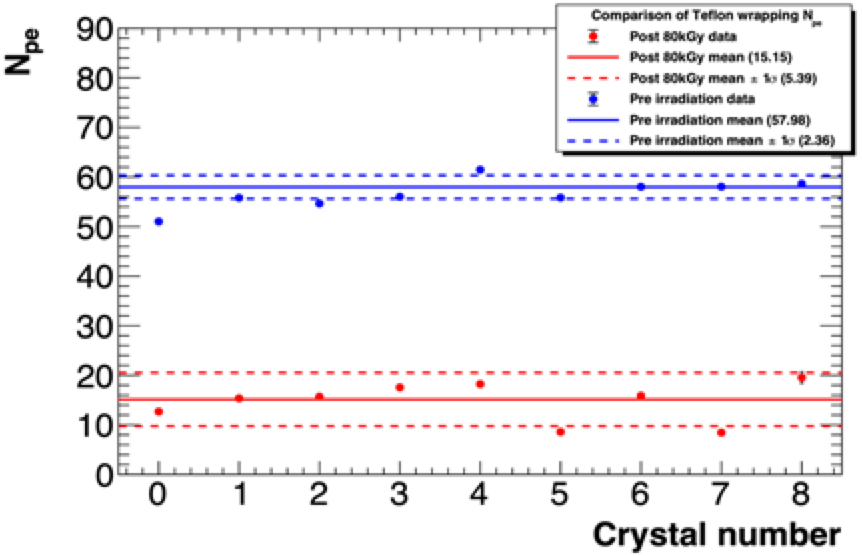
Beam test @ BTF: Teflon wrapping

After 80 kGy (8 Mrad) irradiation

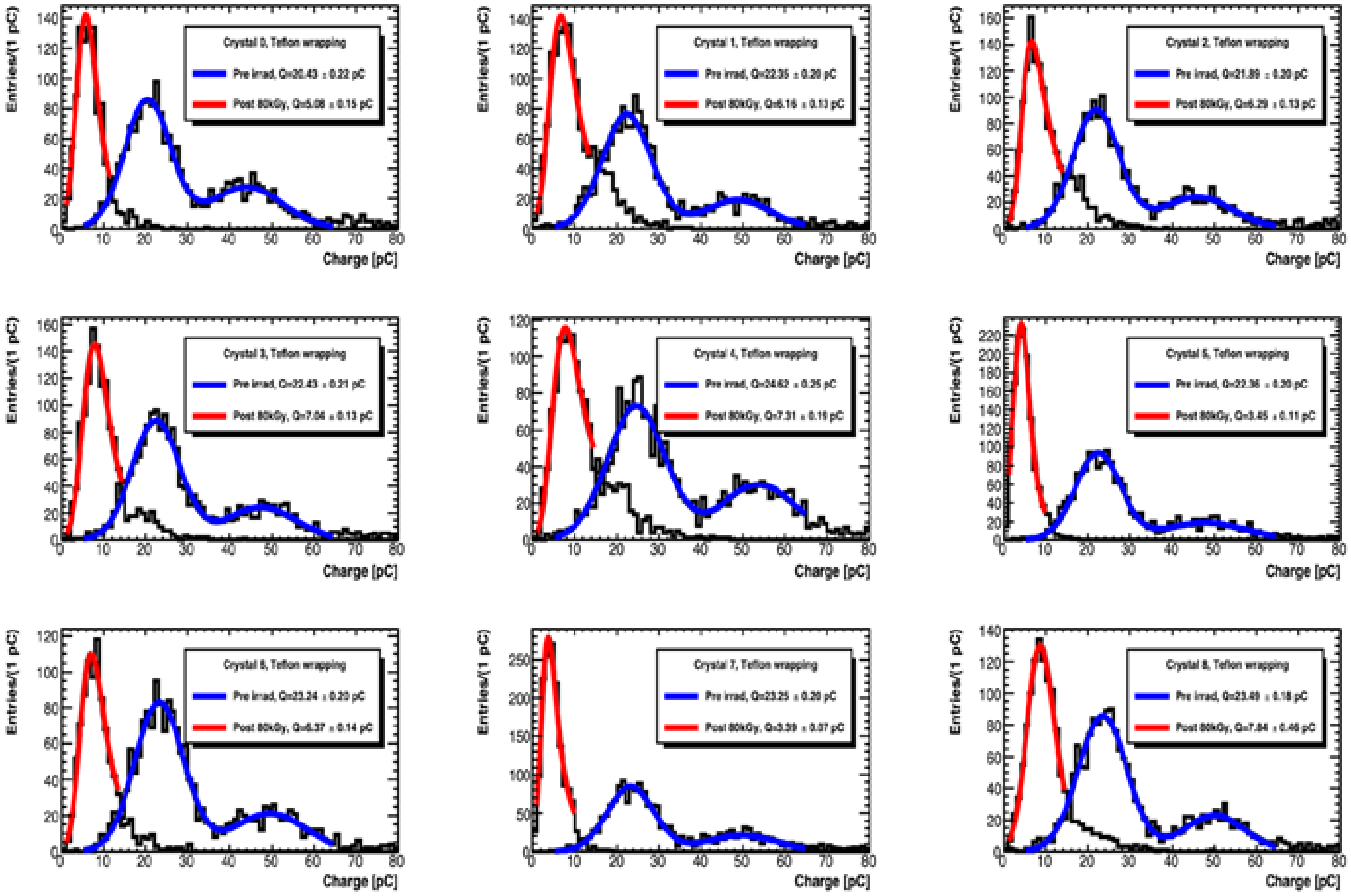
- Teflon was damaged and brittle
- Crystals evident loss of transparency





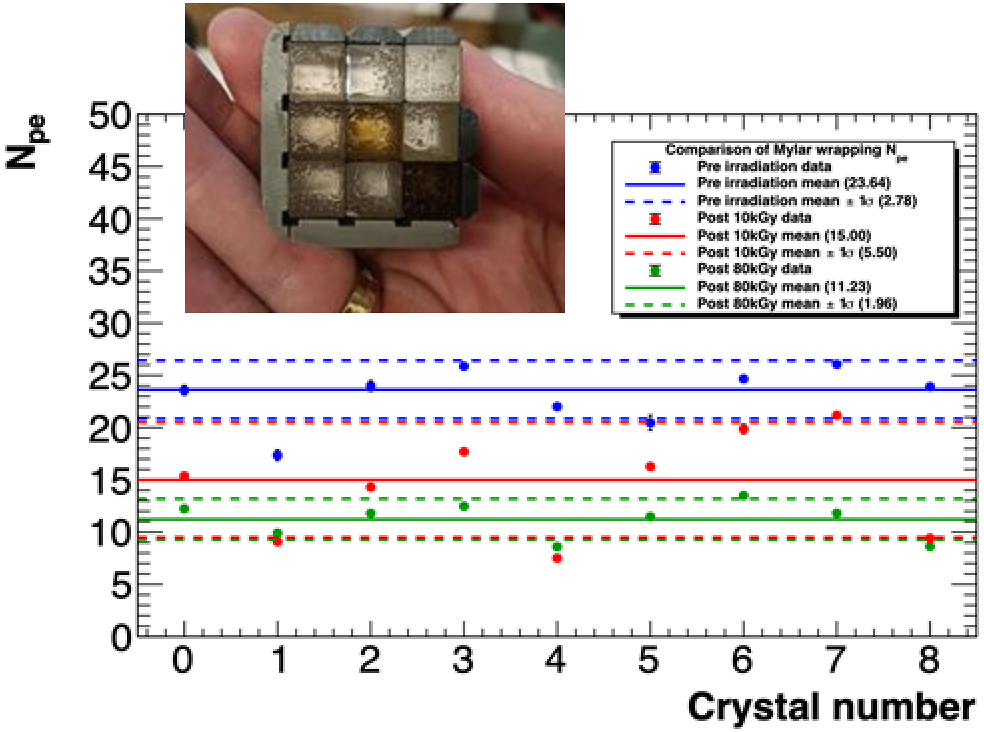


Charge distribution of PbF_2 pre and post irradiation



Beam test @ BTF: Mylar wrapping

- Test repeated with a Mylar wrapping
- **No annealing after 48h and 60h observed**
- New test planned to evaluate SiPMs PDE loss and optical grease degradation



Charge distribution of PbF_2 pre, after 10 kGy and after 80 kGy irradiation