Challenges and detector concepts for future collider calorimetry

R. Gargiulo – LNF Seminar – 1st April 2026

INFN Istituto Nazionale di Fisica Nucleare Sezione di Roma

Outline of this talk

- Physics case for calorimeters at future colliders
  - Focus on electron-positron Higgs factories
- Approaches for improved jet energy resolution
  - Calorimeters R&Ds addressing this challenge
- Optimizing ECALs for e/photon & jet energy resolution
  - Dual readout crystal calorimetry
  - CRILIN calorimeter: concept and highlights

Calorimetry at future colliders

- **Higgs boson studies** (e^+e^-):
  - Excellent jet energy resolution
    - *New requirement for large colliders*
    - *≈90% of decays contains jets…*

- **Heavy flavour** (e^+e^-):
  - Excellent energy resolution for final states with π^0 or photons
  - High granularity for π^0/γ separation
  - **Timing** for ID of soft neutral particles?

- **Muon collider**:
  - Beam-induced backgrounds rejection
    - High transverse granularity
    - Longitudinal segmentation (ECAL also)
    - Excellent timing
  - Good jet energy resolution (HH → 4b)

- **FCC-hh**:
  - Granularity and excellent timing (pile-up rejection)
  - Good photons and jet energy resolution (HH →bbγγ)

Very low radiation levels… …High radiation levels

Time

Near future: FCC-ee

- Preferred option from CERN (viability under study)
  - New large tunnel required

- Z → WW → ZH → [tt ?] stages in center-of-mass energy

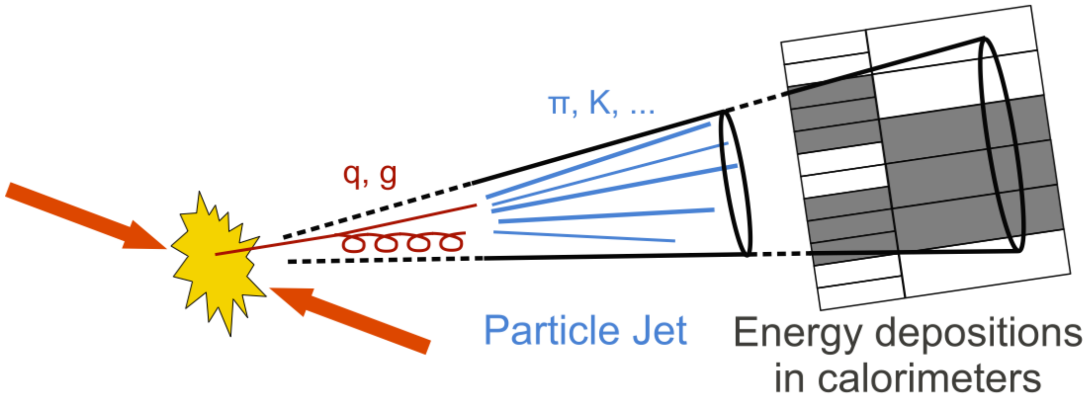
- Broad flavour physics program (Z stage)
- Very precise electroweak and single Higgs measurements

- No pileup, low radiation levels in the calorimeters

- Feasibility report: arxiv:2505.00272

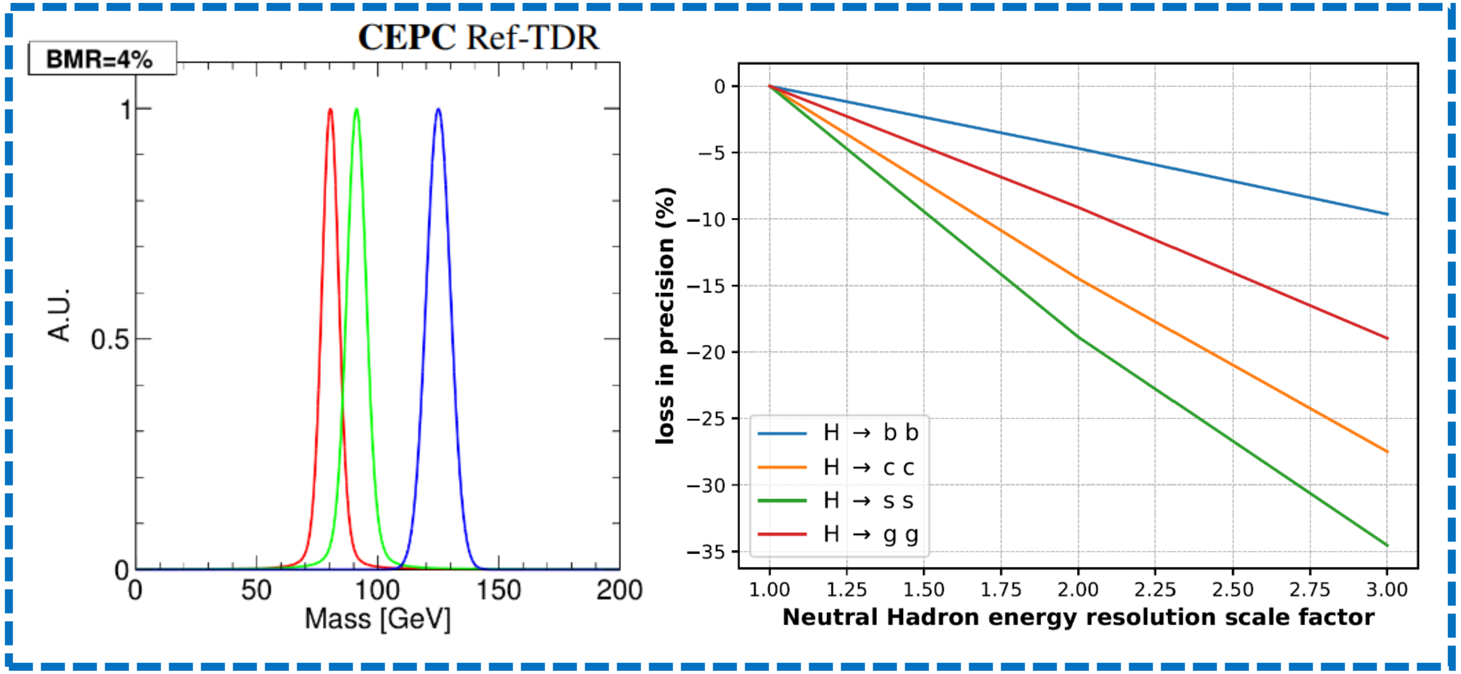
What is new for calorimeters vs. LHC?

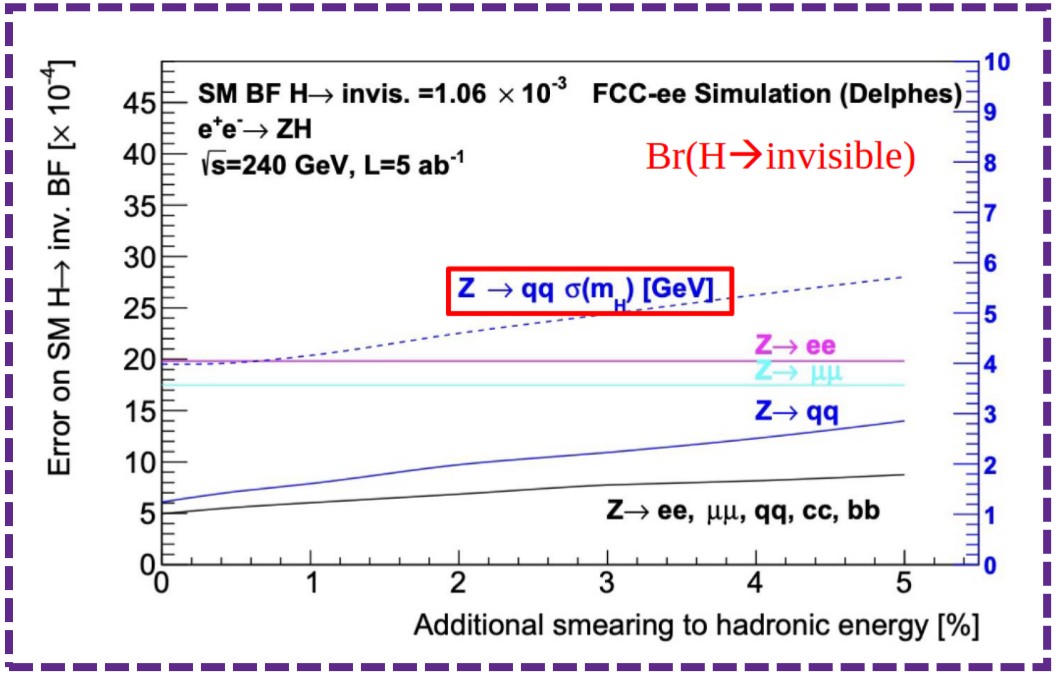
- High granularity (already explored at HL-LHC, for instance CMS HGCAL)
- O(30 ps) timing (for instance CMS ECAL phase-2)
- Excellent jet energy resolution (for Higgs factories)→ "new" requirement
  → *Going more in detail on the motivations*



Jet energy resolution at Higgs factories: motivations

- Traditionally required for Z/W dijets separation (from Higgs decays)
  - With recent simulations, found out that more than JER there are issues with jet matching in H→ZZ* (see backup)
- Important tested physics cases for excellent jet energy resolution (JER):
  - H → dijets (bb, cc, gg) BR measurements, to reject bkg from Z→qq
    - Requires boson mass resolution (BMR) close to 4%, equivalent to JER ~ $30\%/\sqrt{E} \oplus 4\%$
  - H → invisible, measuring dijet recoil mass (Z→qq)

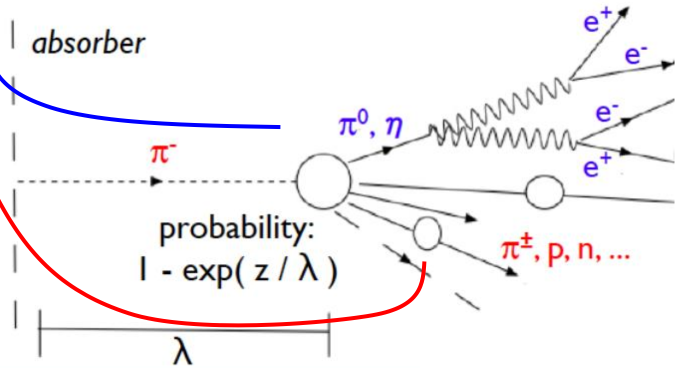




Jet resolution important → why so difficult?

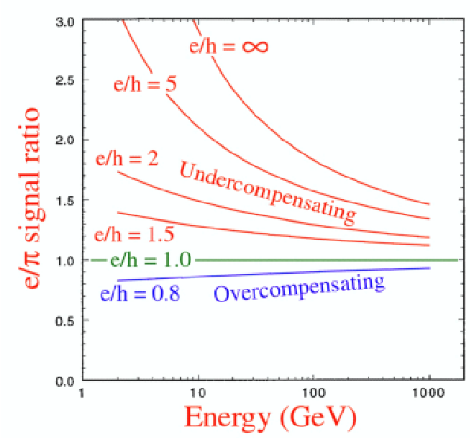
Hadron showers features → (non)-compensation

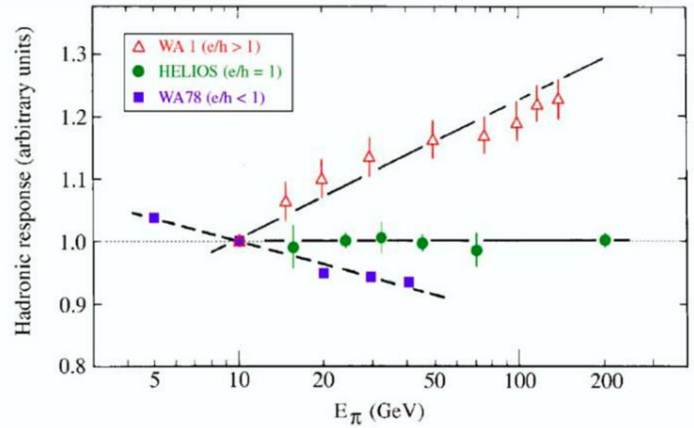
- Electromagnetic energy deposit → electromagnetic shower from π^0 production
- Hadronic en. deposit → ionization + neutrons ~~+ invisible energy (nucl. binding, delayed processes)~~
  - *Protons from neutrons absorption and nuclear fragments kin. energy partially recovered via ionization*
- Electromagnetic fraction (f_{EM}) changing event by event (π^0 content) and increasing with energy

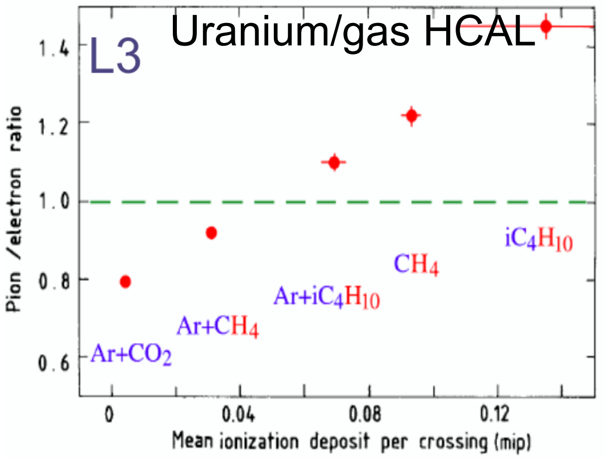


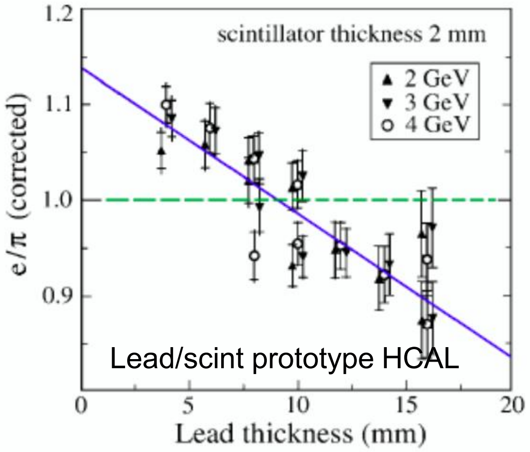
- If electromagnetic response (e) is *different* from hadronic response (h):
  - *huge fluctuations*
  - *non-linearity*

- **Compensation** (e/h = 1) can be achieved with **materials/sampling fractions tuning** (see plots)
  - Requires **sampling** calorimeters
  - Demonstrated by SpaghettiCal (lead+fibers) & SPAKEBAB (tuned Shashlik) R&Ds
  - Not easy and spoiling ECAL resolution due to sampling





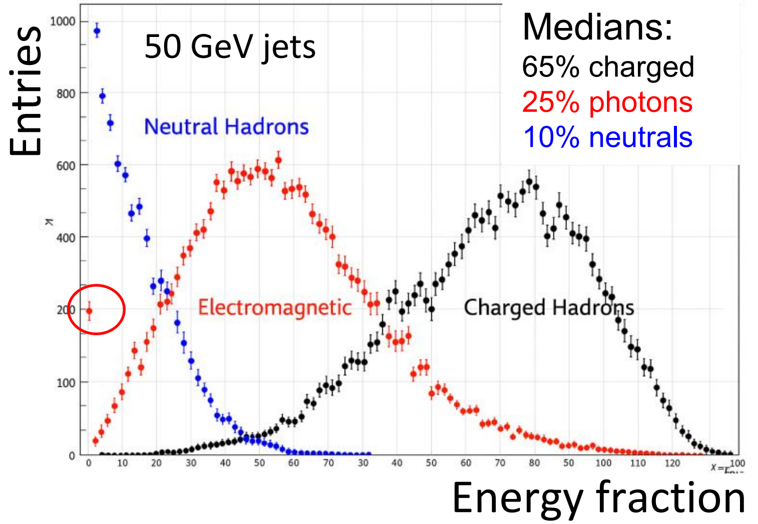


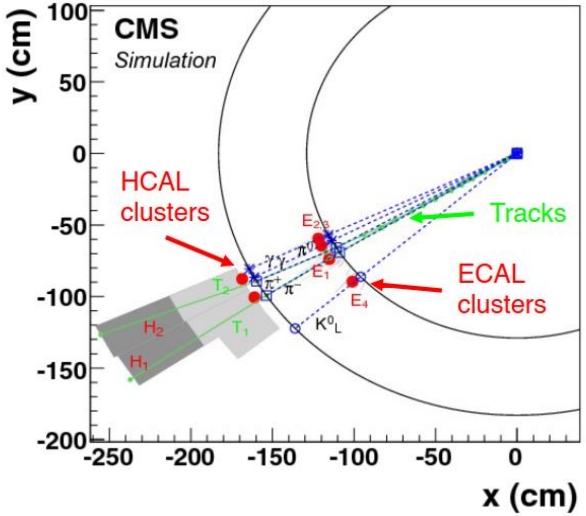


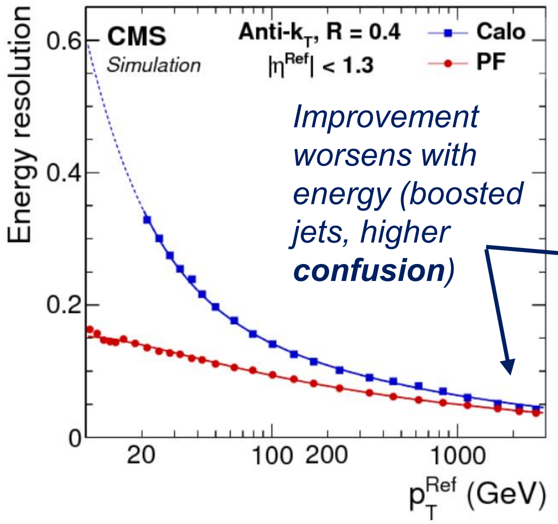
Modern complementary approaches

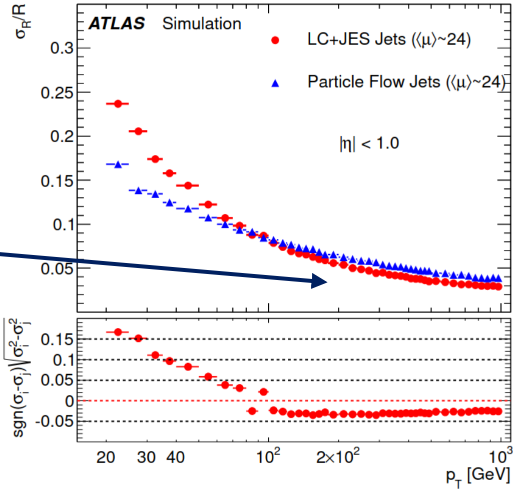
- **Offline compensation**: mainly dual-readout technique, separate scintillation/Cherenkov photons in HCAL (+ECAL possibly)
  - In-situ event-by-event measurement of electromagnetic fraction → 30%/ $\sqrt{E}$ resolutions expected for single hadrons

- **Particle flow** (already in use at LHC, with somewhat limited improvements)
  - Separating the 3 components from jets in calorimeters energy sum
  - Subtracting **charged hadrons** (65%) and **photons** (25%) energy so that only **neutral hadrons** (10%) are effectively measured by HCAL
    - up to a factor 3 ($\sqrt{10}$) improvement (photo-statistics scaling)
  - In reality: improvement < 3 due to noise in HCAL (low energy n. hadrons) + "**confusion**" in subtracting charged hadrons energy (high-energy)









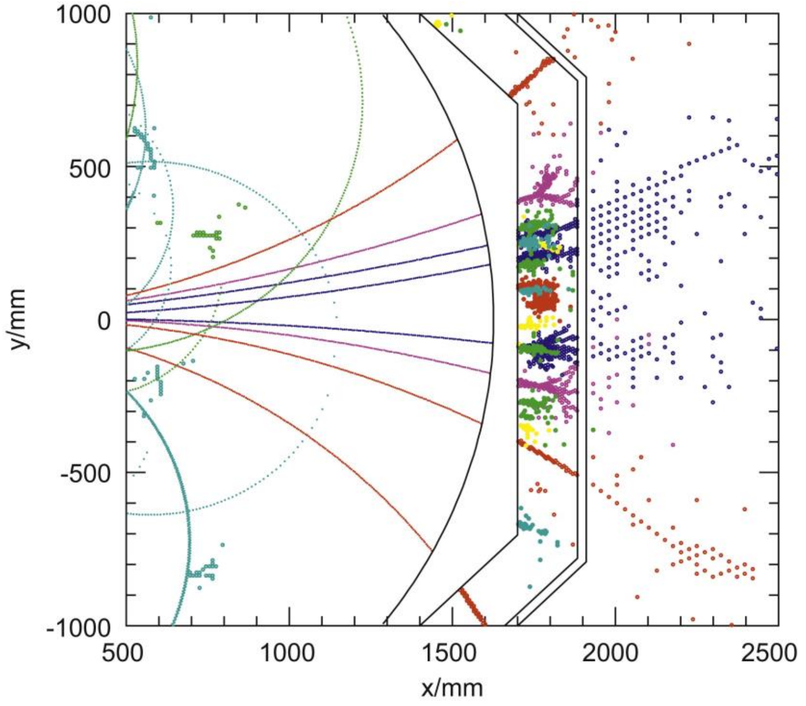
- **«Confusion»** term at LHC due to **low granularity**
  - Part of it from **large material budget** in the trackers

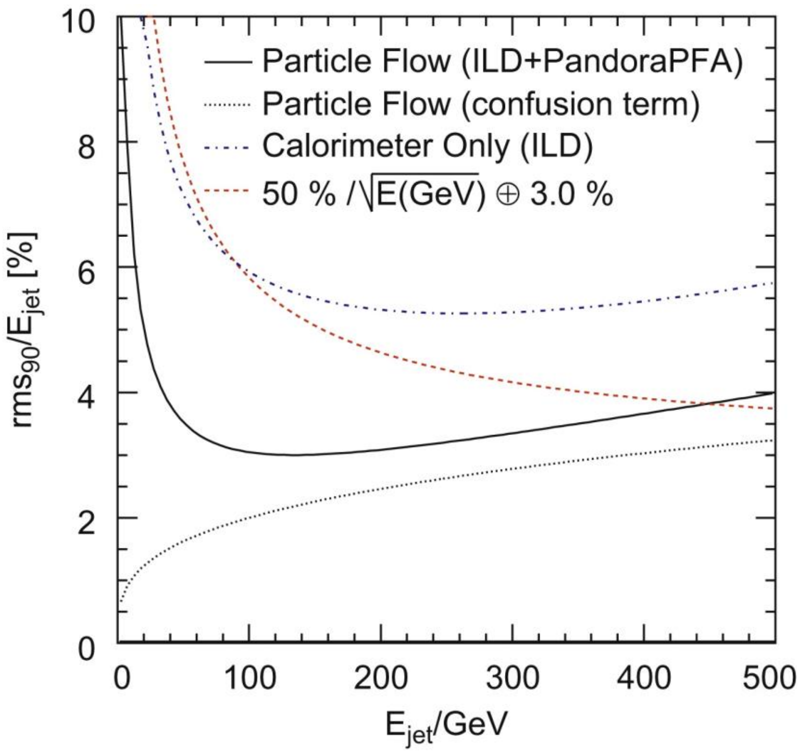
- Part of the jet resolution is due to pileup (LHC)

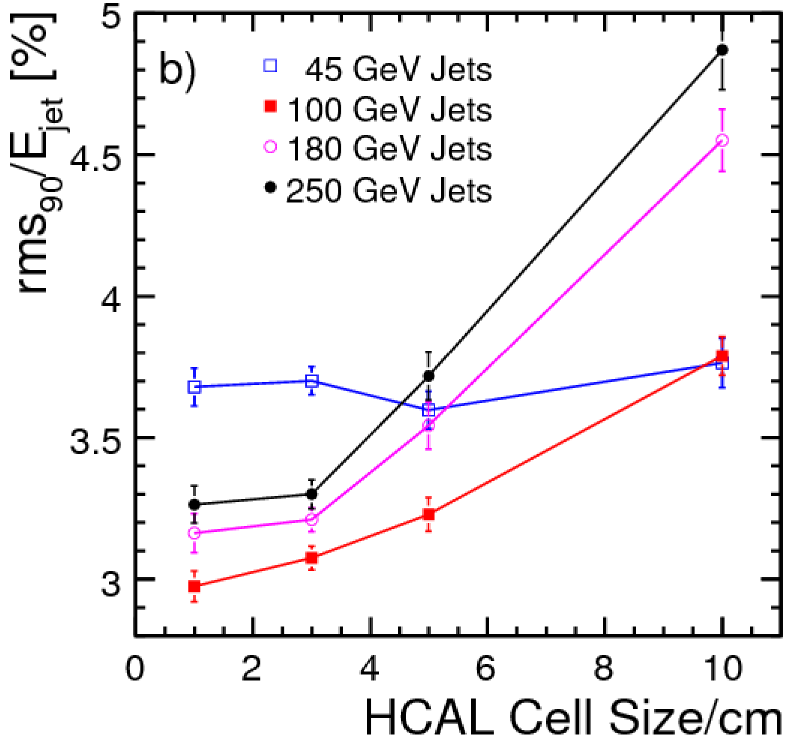
Particle flow with dedicated detectors

- **To achieve full potential of particle flow:**
  - thin tracker + granularity ~ 1 cm^2 in ECAL&HCAL + longitudinally segmented calorimeters
  - **See for instance studies with ILD detector + PandoraPFA algorithm (improves also at high energy)**

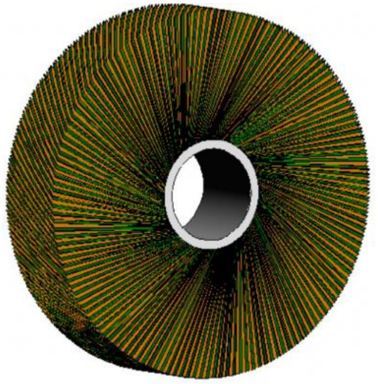
- **See (next slides) ALLEGRO, the calorimeter of one of the detector concepts for FCC-ee**



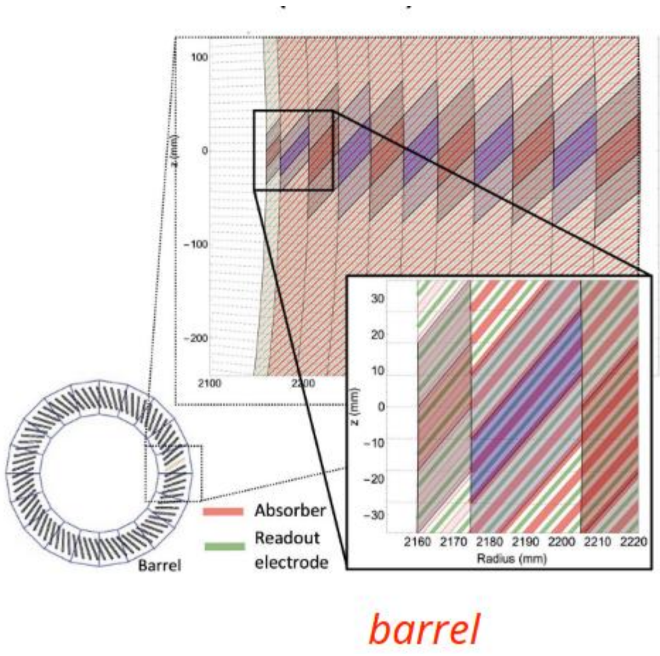


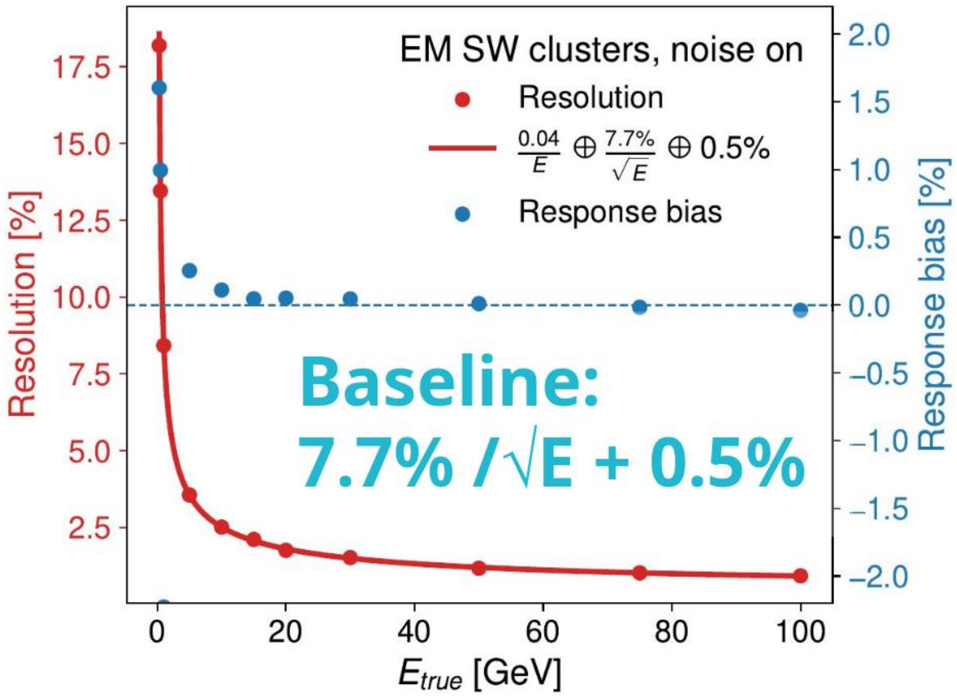


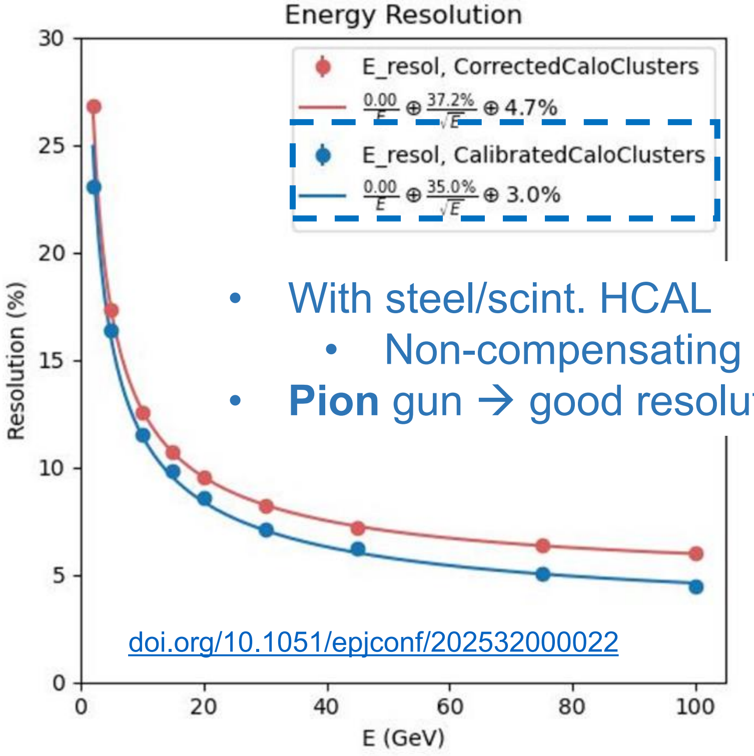
ALLEGRO calorimeter



- Sampling EM calorimeter (lead + liquid argon) “à la ATLAS” for Higgs factories
  - One of key features of “ALLEGRO" detector concept for FCC-ee (allegro.web.cern.ch/)
- Highly granular calorimeter with absorber planes inclined in r-phi (barrel) / turbine-like structure (endcap)
- Readout by segmented PCB planes alternated to Pb absorbers, gaps in between filled with Lar
- Good EM and single hadron resolutions thanks to granularity → what about jets?





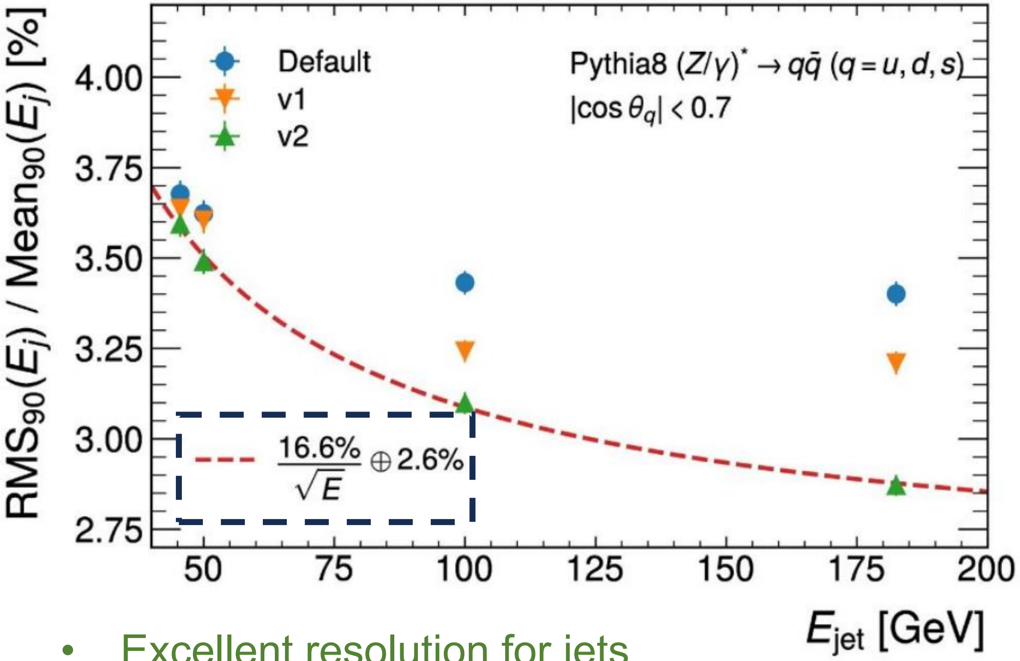


- With steel/scint. HCAL
  - Non-compensating
- **Pion** gun → good resolution

doi.org/10.1051/epjconf/202532000022

Jets in ALLEGRO

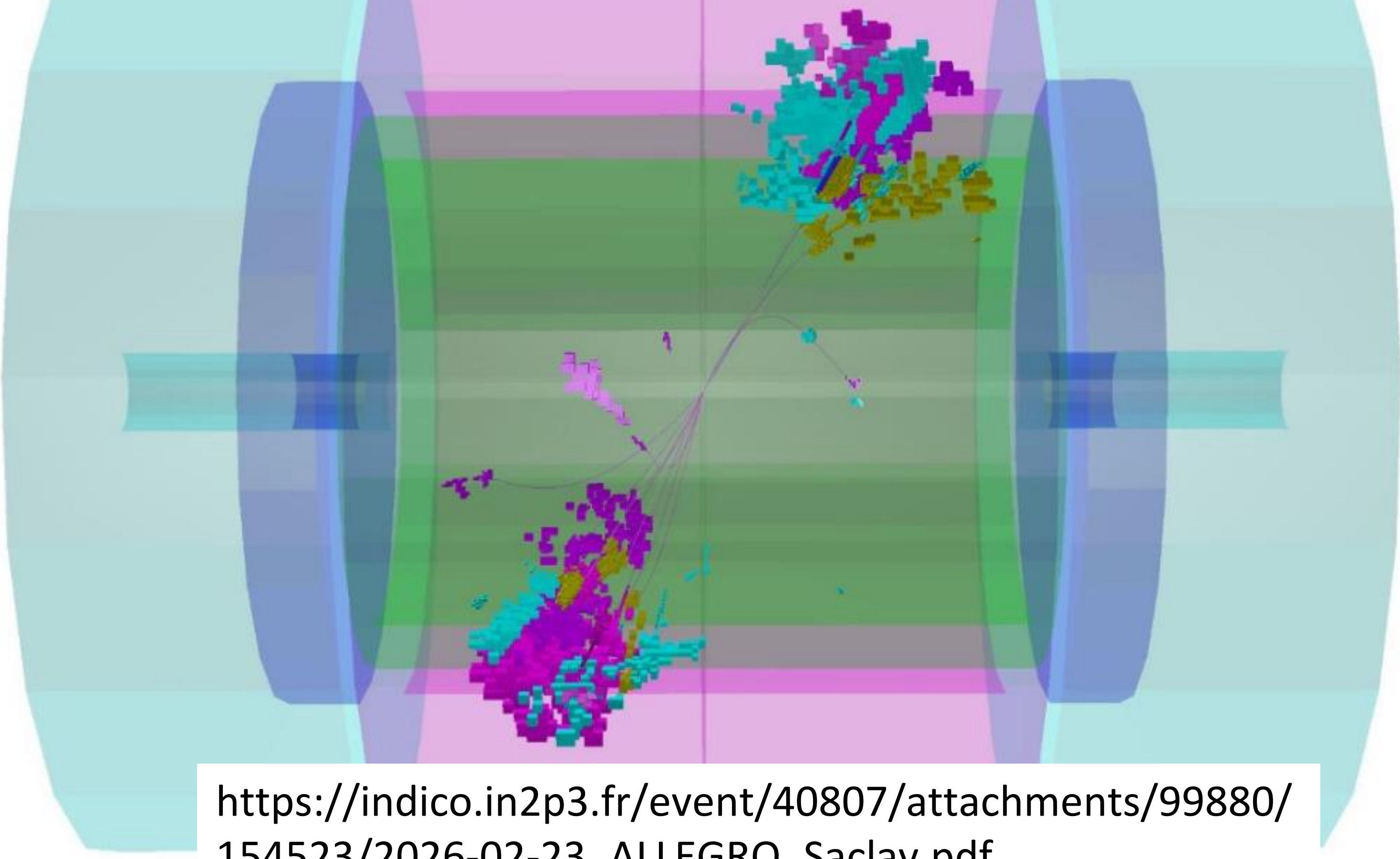
Charged hadron associated hits
Neutral hadron associated hits
Photon associated hits



- Excellent resolution for jets
- thanks to Graph Neural Network particle Flow

- **100 GeV event display**

Boosted jets, but no overlap



https://indico.in2p3.fr/event/40807/attachments/99880/154523/2026-02-23_ALLEGRO_Saclay.pdf

Beyond particle flow: *dual readout*

- Reaching superior single hadron energy resolution by **compensating offline, despite e/h different from 1**
  - Measuring Cherenkov (C) light, only related to fast charged particles, mainly (not only) electromagnetic deposits
  - Measuring **separately** scintillation (S) light (electromagnetic + ionization from slow protons and nuclear fragments)

- Energy reconstruction in terms of e/h → fluctuates together with f_{EM}:

$$\frac{E_{\text{meas}}}{E} = f_{\text{em}} + \frac{1}{e/h}, (1 - f_{\text{em}})$$

- Dual signal response (scintillation vs Cherenkov) - h_S, h_C (S/C hadron responses) are constant:

$$S = E[f_{\text{em}} + (1 - f_{\text{em}})h_S], \quad C = E[f_{\text{em}} + (1 - f_{\text{em}})h_C]$$

- Inverting the equations → Event-by-event EM fraction extraction:

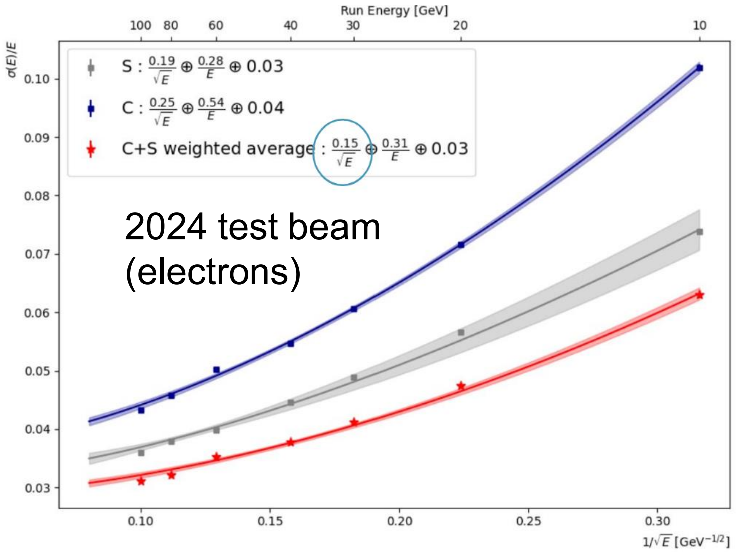
$$f_{\text{em}} = \frac{C h_S - h_C S}{(1 - h_C)S - (1 - h_S)C}$$

- Corrected energy → removes f_{EM} fluctuation by measuring it event-by-event → **offline compensation**:

$$E = \frac{S(1 - h_C) - C(1 - h_S)}{h_S - h_C}$$

HiDRa

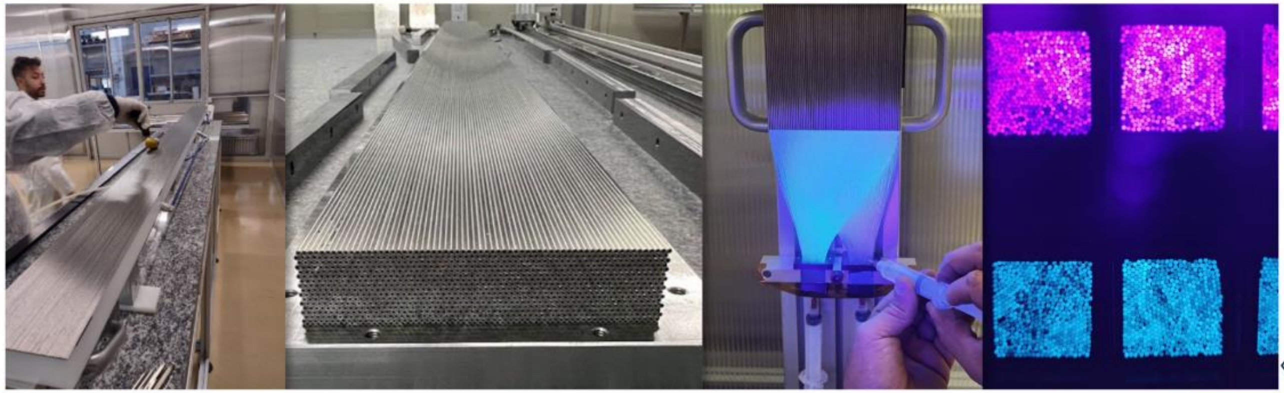
- Dual readout ECAL+HCAL based on steel tubes + S/C fibers
  - …or HCAL only, if placed after a different ECAL
- Limited resolution (15% stoch term) on photons and electrons
- Simulated performances close to 30% stoch. term on pions
  - Very small constant terms



Capillary tubes gluing process

Scintillating and Cherenkov fibers are collected separately

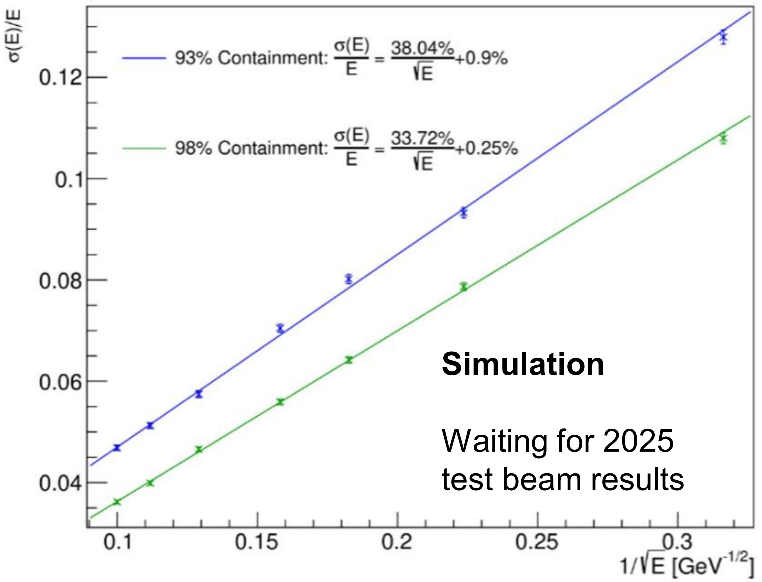
Assembly at INFN Pavia



Module ready for fiber insertion

Scintillating and Cherenkov fiber batches prepared for PMT integration

Pion resolution in [10, 100] GeV Range



Jets/hadrons → clear case

What about ECALs?

Not only energy resolution for ECALs...

Technological progress in the field of scintillators and photodetectors has **enabled** the design of **a cost-effective and highly performant calorimeter**

- **Longitudinal and transverse segmentation**
  (to provide more handles for PID and particle flow algorithms)
- **Separate readout of scintillation and Cherenkov light**
  (to exploit dual-readout technique for hadron resolution and linearity)
- **Precise time tagging for both MIPs and EM showers**
  (time resolution better than 30 ps)
- **Energy resolution at the level of 4-3% for 50-100 GeV jets**
- **All of this... Together with (next slide):**
  Excellent energy resolution to photons and neutral hadrons
  (~3%/√E and ~30%/√E respectively)

- 5D calorimetry
- (3D + E + t)

- **Remarks:**
- Detailed later → not compulsory
- Physics case not yet fully demonstrated

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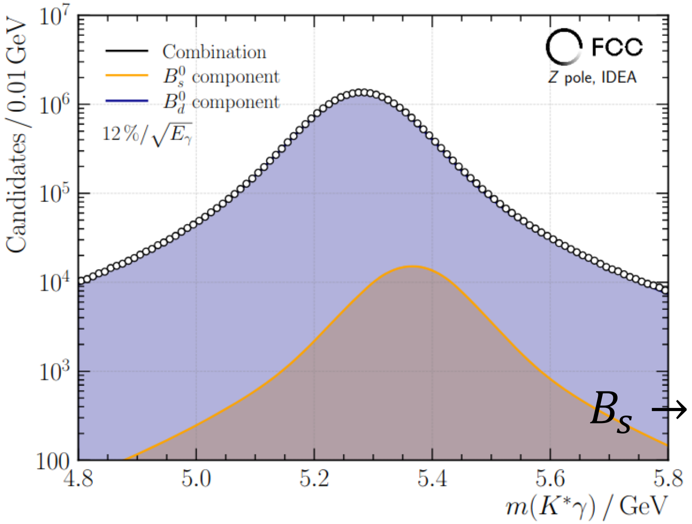
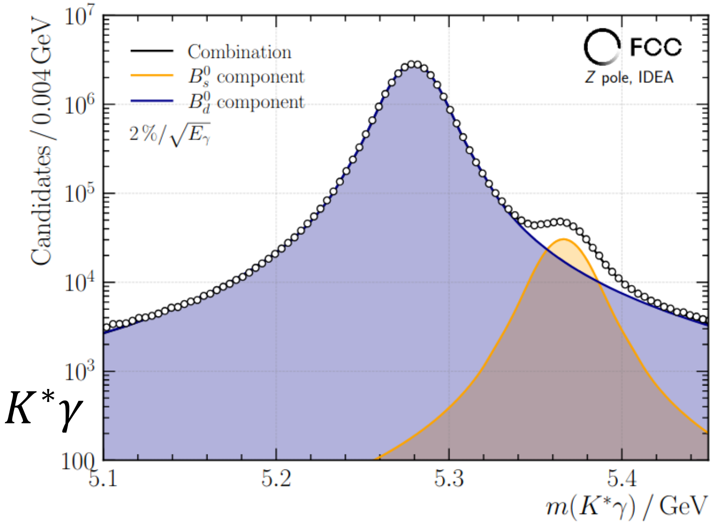
ECAL energy resolution at FCC-ee

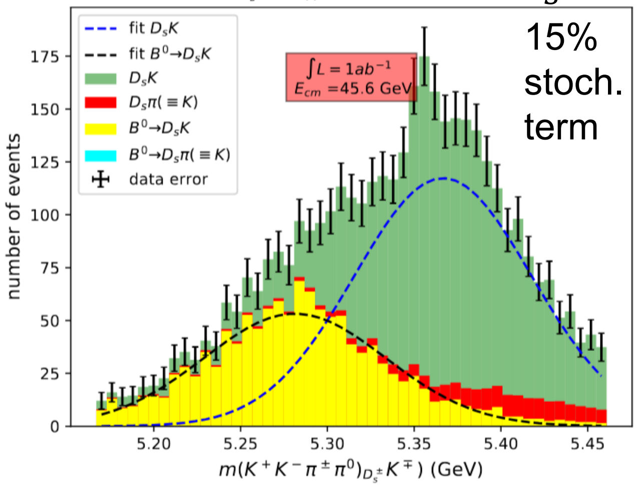
- As usual: Higgs→two photons, low statistics at FCC-ee (1/2M Higgs produced), so needs excellent resolution (not flagship channel though)
- *New: Z/ν_e coupling with $e^+e^- \to \nu_e\bar{\nu}_e\gamma$ (monophoton topology), needs excellent photon resolution*
- *Flavour with states containing photons and neutral pions - below: $B_s \to K^*\gamma, B_s \to D_s K(D_s \to \varphi\rho)$*
- New physics: ALPs/dark photons in e⁺e⁻ or 2/3 photons
- No requirements, but «best possible»
  - *Homogeneous calorimeters!*

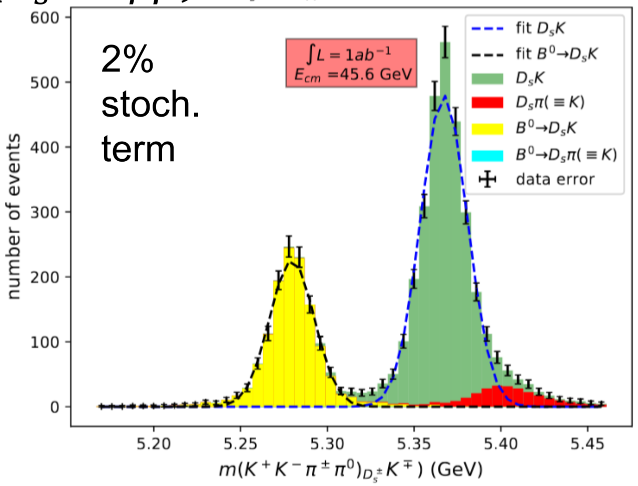




$B_s \to K^*\gamma$

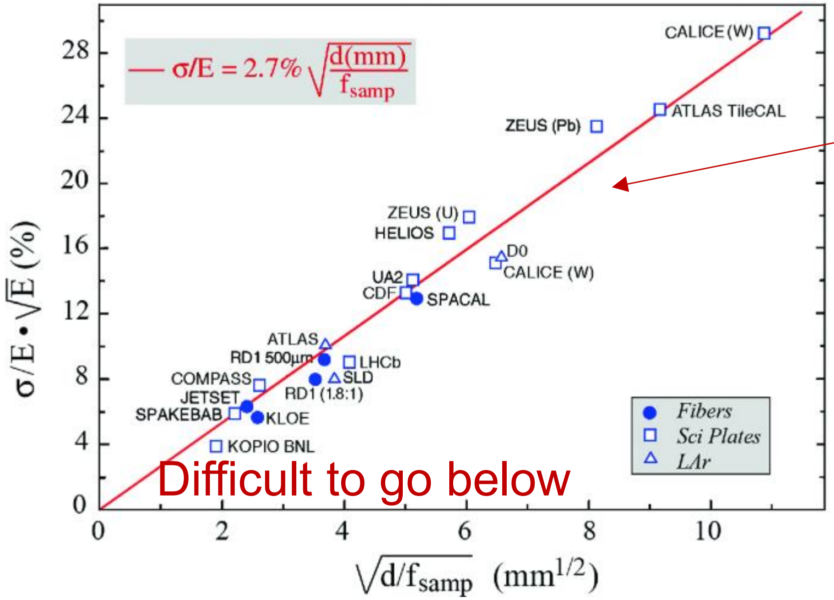
$B_s \to D_s K(D_s \to \varphi\rho)$



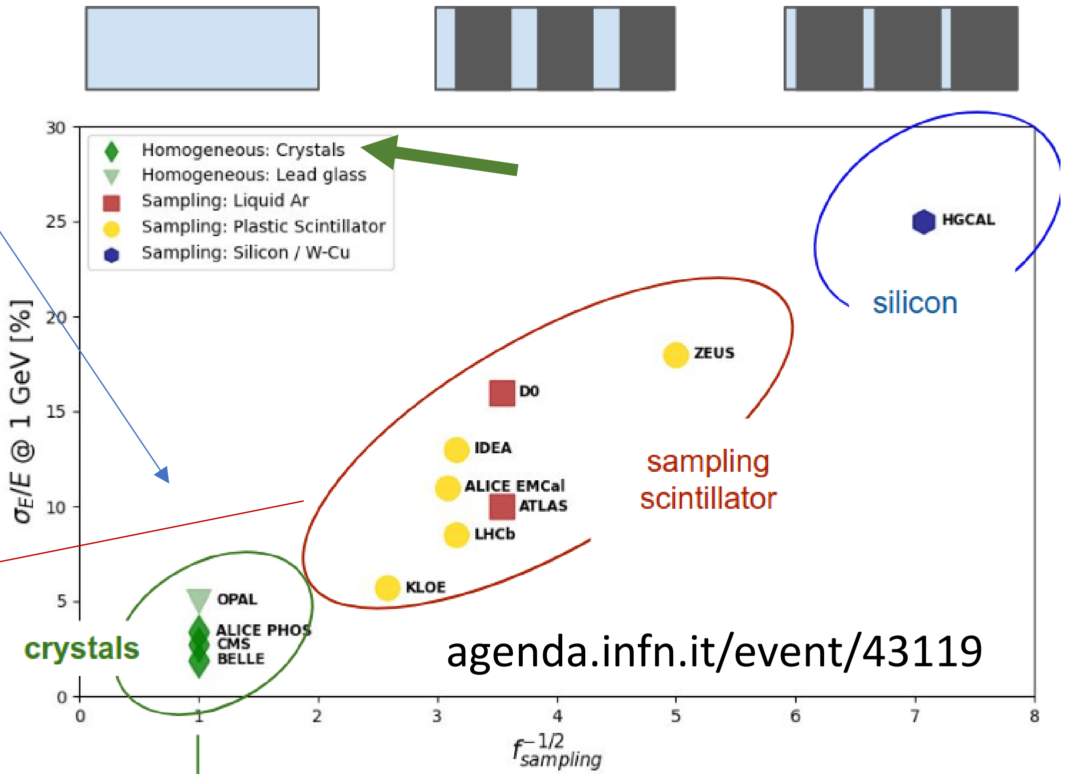


Homogeneous calorimetry

- Homogeneous calorimeters → no sampling fluctuations
  - Only way to get a 1-3%/√(E) energy resolution for photons (and thus π^0)
- Best example at colliders: **CMS crystal ECAL** ($PbWO_4$)
- FCC-ee sets **no stringent requirements on radiation tolerance and pileup for calorimeters**
  - New opportunity
  - **Allows focusing on best possible resolution**
  - **Crystals!**



A sample of existing and future calorimeters



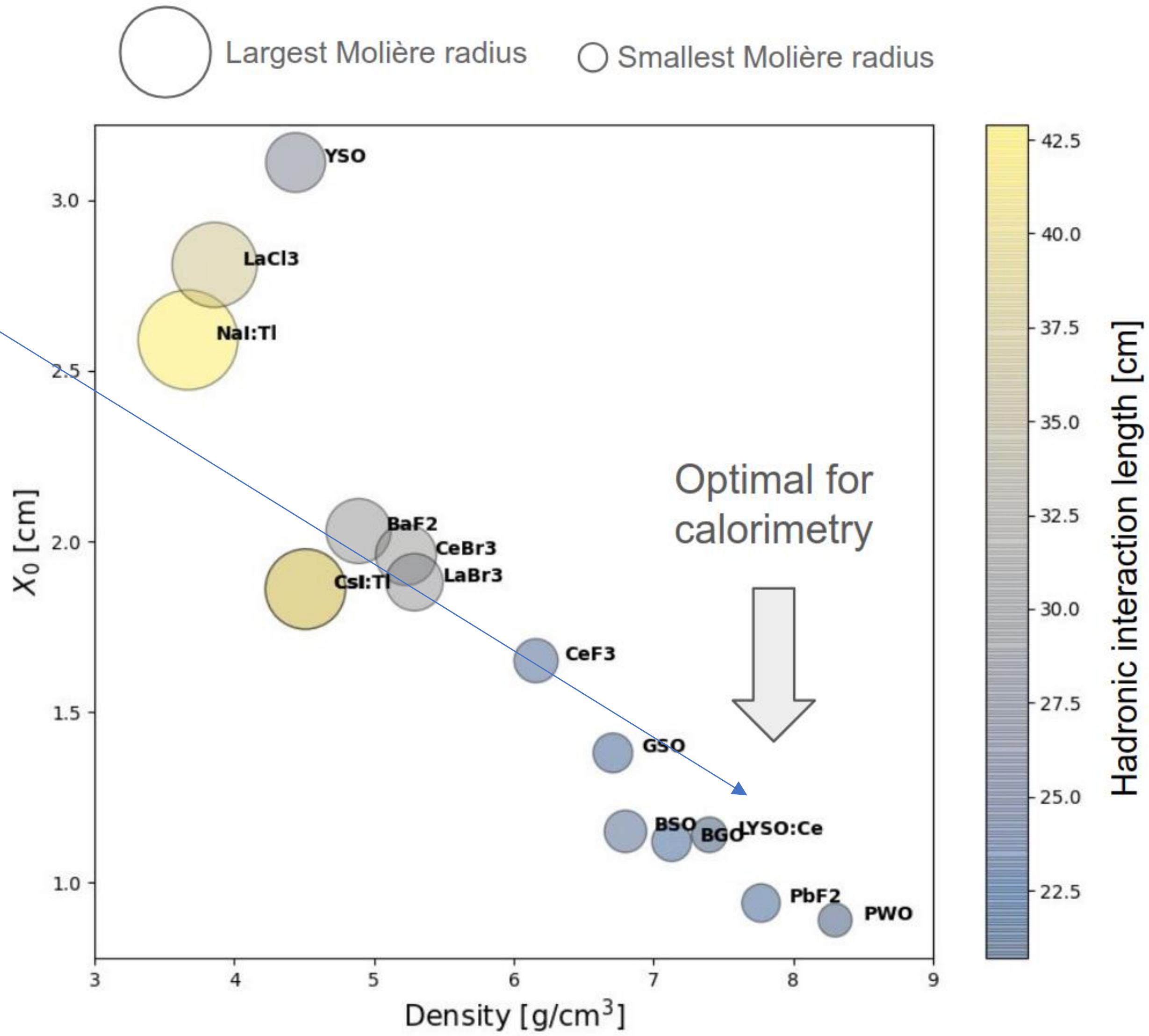
The entire EM shower is sampled, large light signals are produced

Crystals for future calorimeters

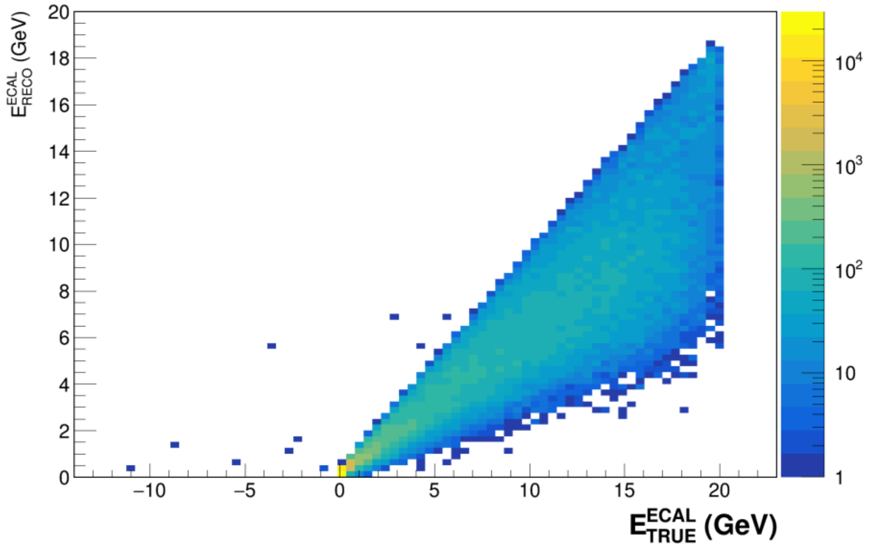
- Crystals suitable for collider calorimeters:
  - Compact as much as possible
  - < 1us decay time (at LHC, much better...)
  - Not too expensive (large volumes)

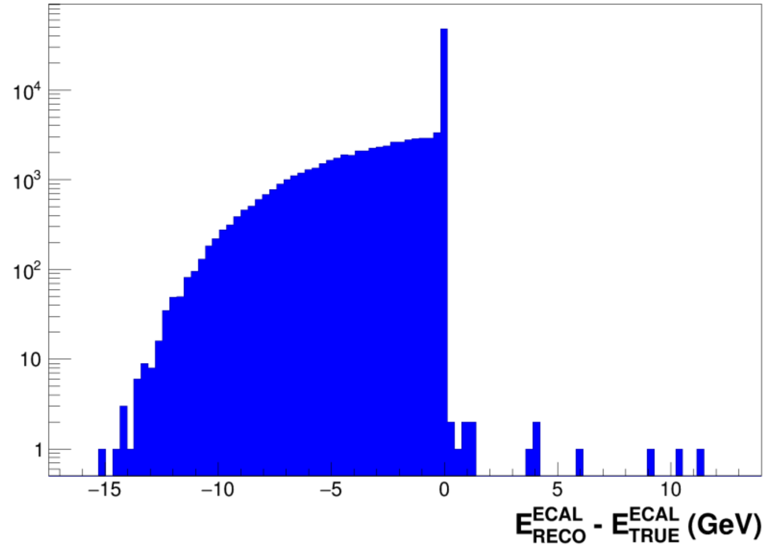
- Compact enough crystals:
  - LYSO (40 ns decay time, very expensive…)
  - BGO (300 ns decay time, lighter than others)
  - $PbWO_4$ (20 ns decay time, same cost as BGO)
  - PbF_2 (less expensive than PbWo4)
    - pure Cherenkov, no scintillation

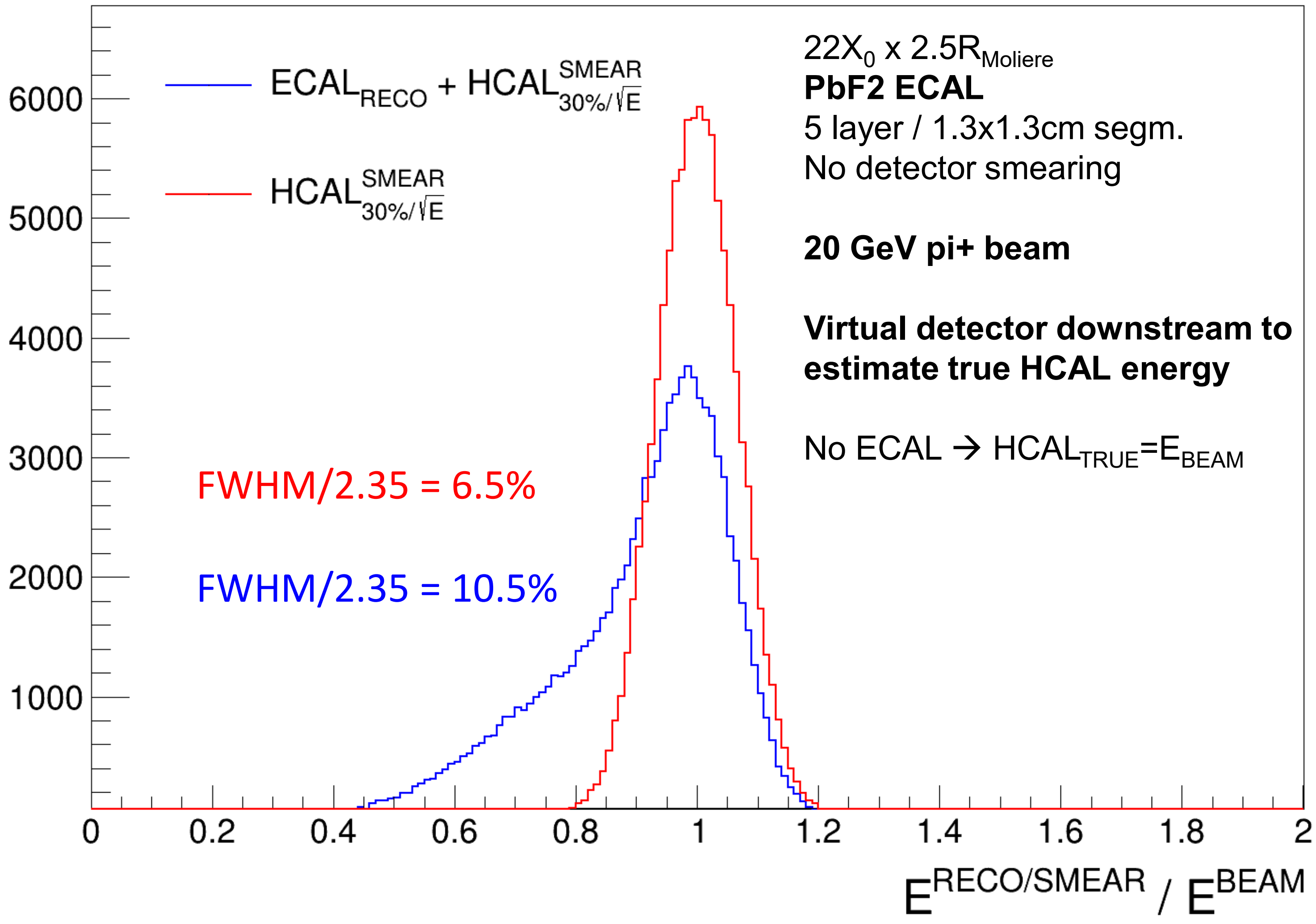
- Crystals → excellent solution for energy resolution
  - Cons:
    - Cost
    - Impact on hadron resolution
      - For CMS, ECAL non-compensation affects heavily single hadron resolution
      - Design choice, H->yy over jet res.



ECAL(PbF_2) + parametric HCAL simulation







$22X_0$ x $2.5R_{Moliere}$
PbF2 ECAL
5 layer / 1.3x1.3cm segm.
No detector smearing

20 GeV pi+ beam

Virtual detector downstream to estimate true HCAL energy

No ECAL → $HCAL_{TRUE}=E_{BEAM}$

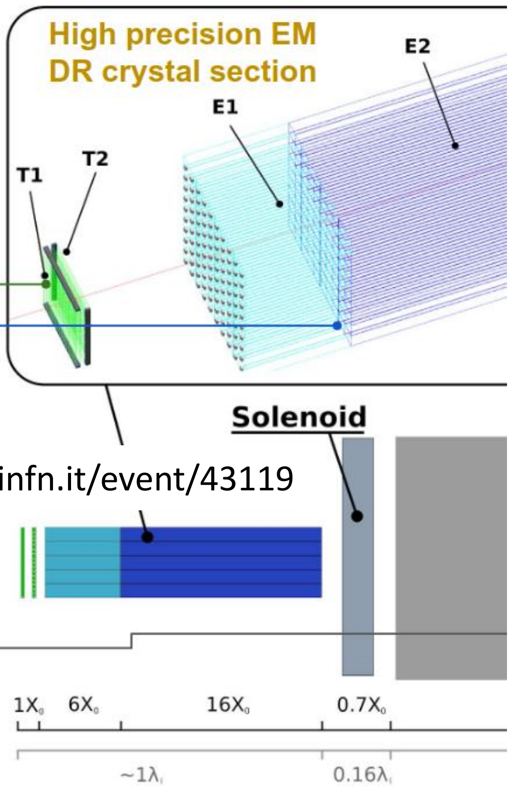
How to decrease ECAL impact?

Dual readout (again) / other roads

Dual readout ECAL with crystals

- One solution to decrease ECAL impact on hadrons is apply **dual readout** also in ECAL
  - Put forward first in 2009 by RD52 Collaboration (optical filters for Mo-doped PbWO4 crystals) (Akchurin et al., 2009a)
- Recently: homogeneous ECAL (**MAXICC project**) using optical filters in PbWO4 or waveform shape in BGO

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~$0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries



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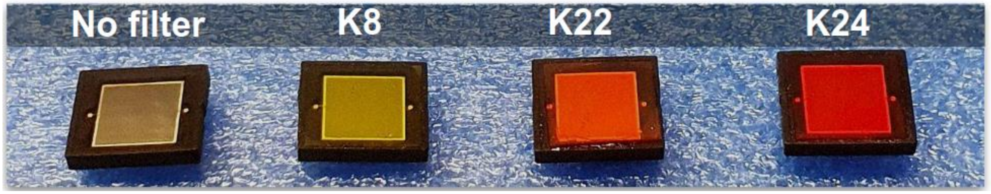

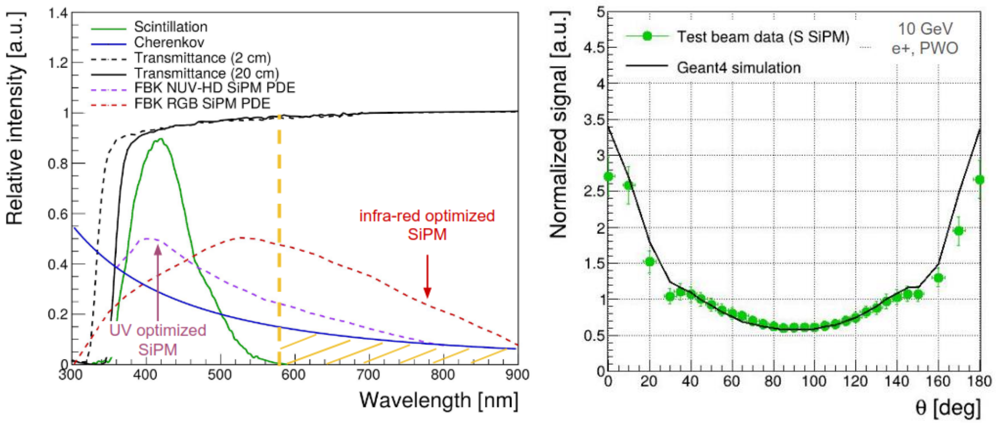

Targeting also BGO crystals (slower), to use waveform shape to separate S/C *(see backup)*

Requirements in terms of light yield

- Impact of ECAL on hadrons studied with neutral kaons
  - Not corrected with particle flow (neutral)

- A poor S (scintillation signal) impacts photostat. terms:
  - S > 1600 phe/GeV to get 3% stoch. term
- A poor C (Cherenkov signal) impacts the C/S and spoils precision of event-by-event dual readout correction
  - C > 60 phe/GeV
- Need experimental validation with lab and **beam tests** (next slide)
  - S > 1600 phe/GeV requires careful SiPM choice to avoid saturation
  - C > 60 phe/GeV is difficult but feasible

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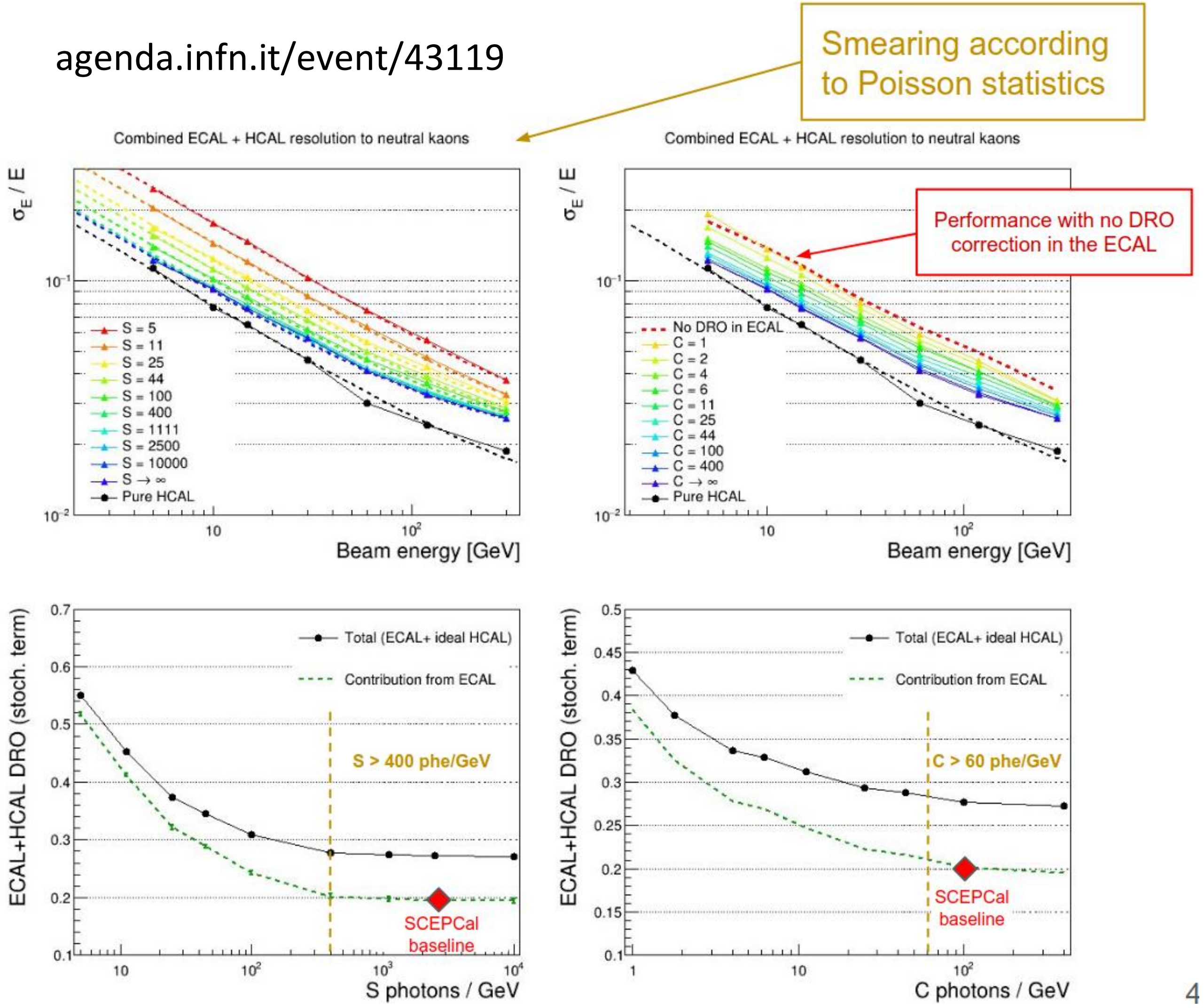
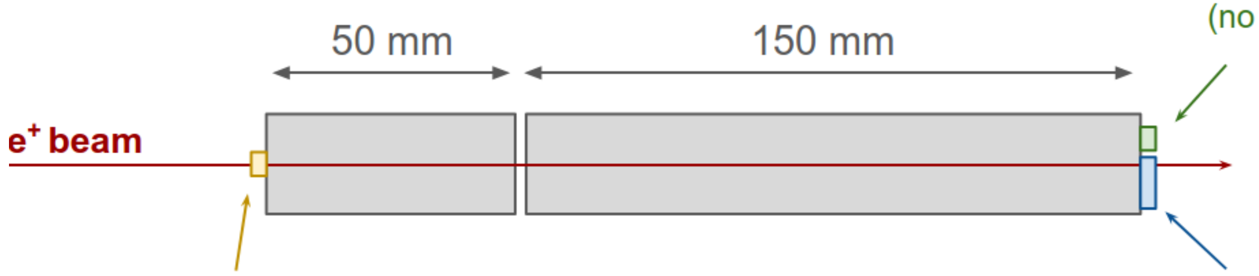


2024 test beam and prospects ($PbWO_4$)

No showstopper found!

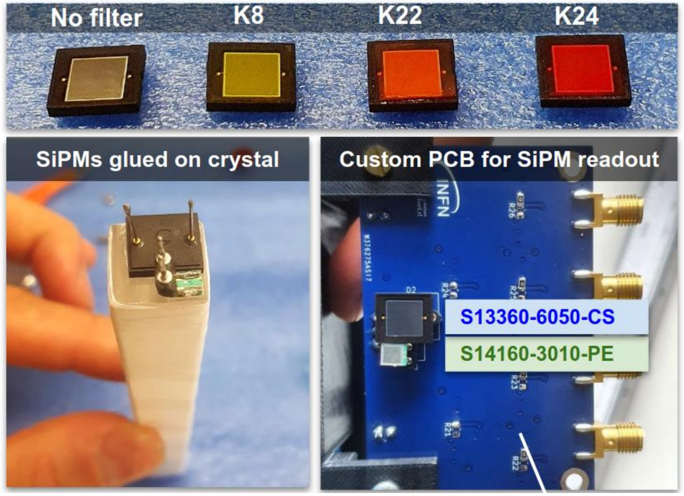


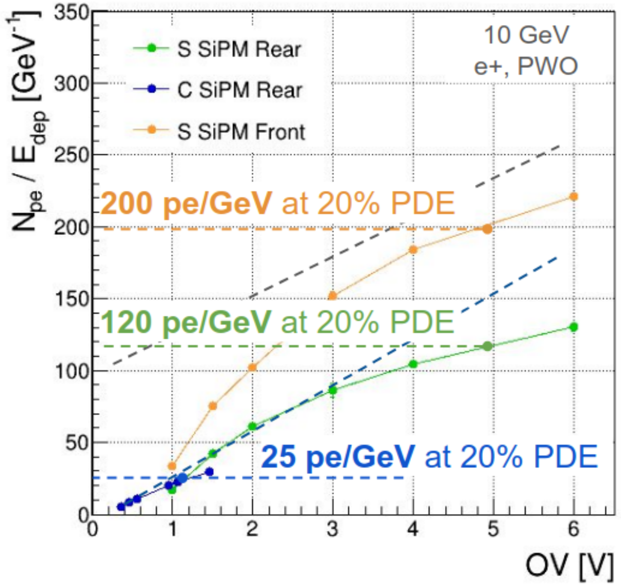
Front **S** SiPM
3x3 mm² 10 µm
(no filter)

Front and rear S SiPM responses proportional
Avoids SiPMs saturation (as would be with just 1 S SiPM)

Rear **S** SiPM
3x3 mm² 10 µm
(no filter)

Rear **C** SiPM
6x6 mm² 50 µm
(K24 filter)





- Number of photoelectrons detected can be used to define SiPM/filter specifications:
  - Scintillation: ~36 pe/GeV/mm² at 20% PDE
    - → need 6x6 mm² SiPM and 40% PDE to reach target (1600pe/GeV)
  - Cherenkov: ~0.7 pe/GeV/mm² at 20% PDE
    - → need 6x6 mm² SiPM and 40 PDE to reach target (60pe/GeV)
  - Contamination from S photons to C-signal <10%
    - → specification satisfied

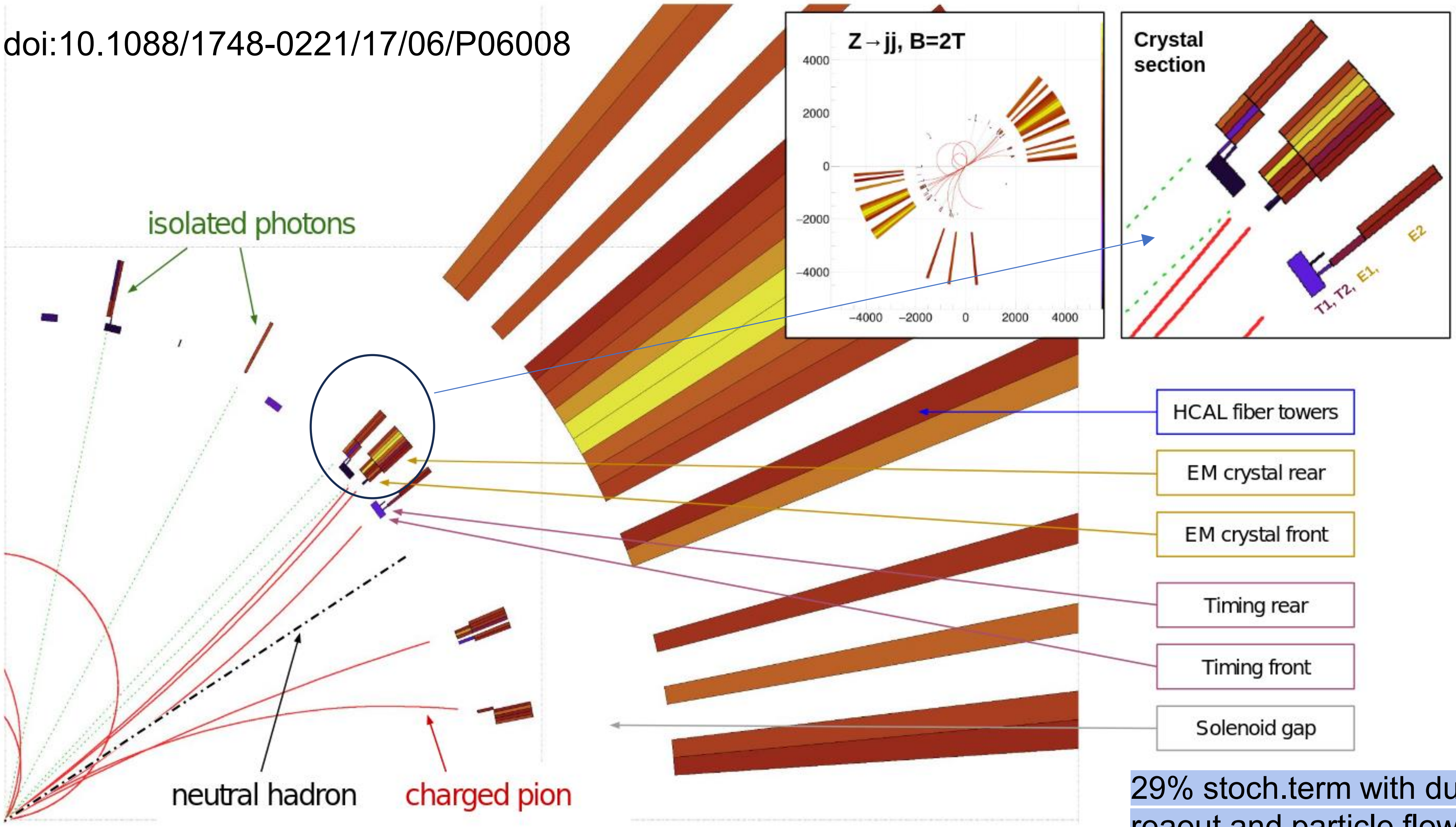
agenda.infn.it/event/45778/contributions/259798/

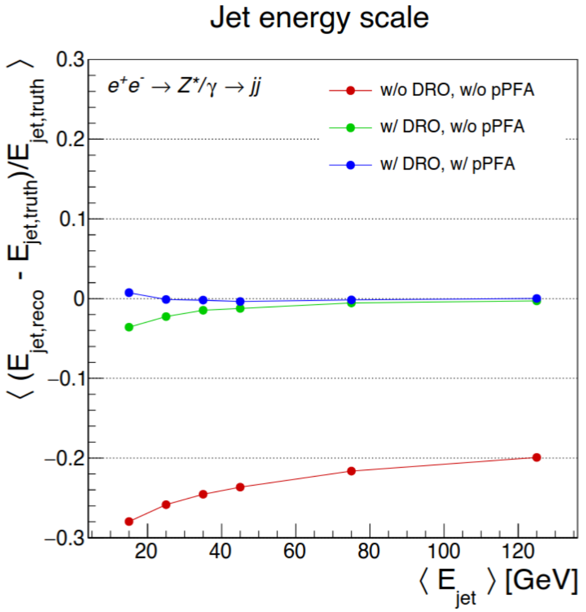
Dual readout ? OK

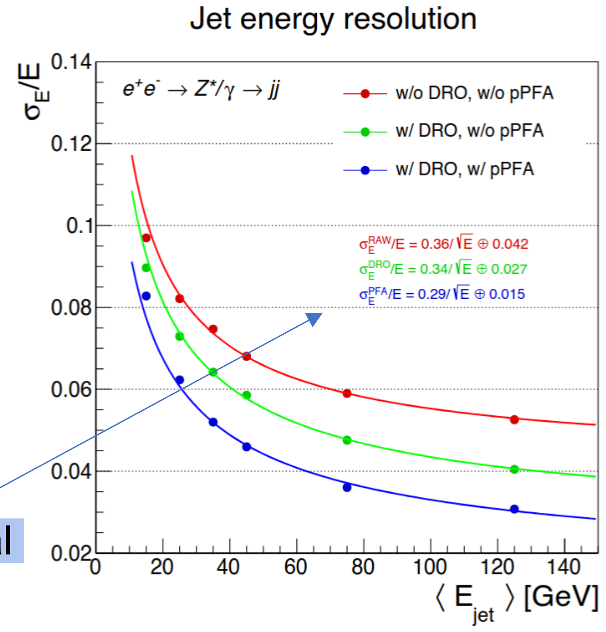
Combination with particle flow?

Dual readout + particle flow

doi:10.1088/1748-0221/17/06/P06008







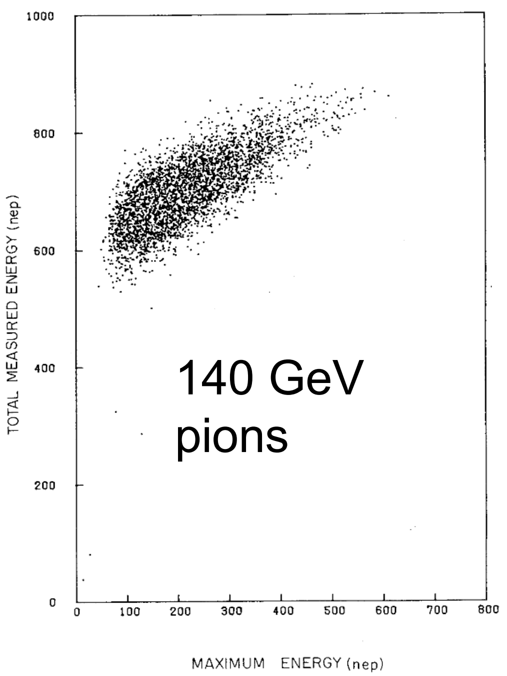
29% stoch.term with dual reaout and particle flow

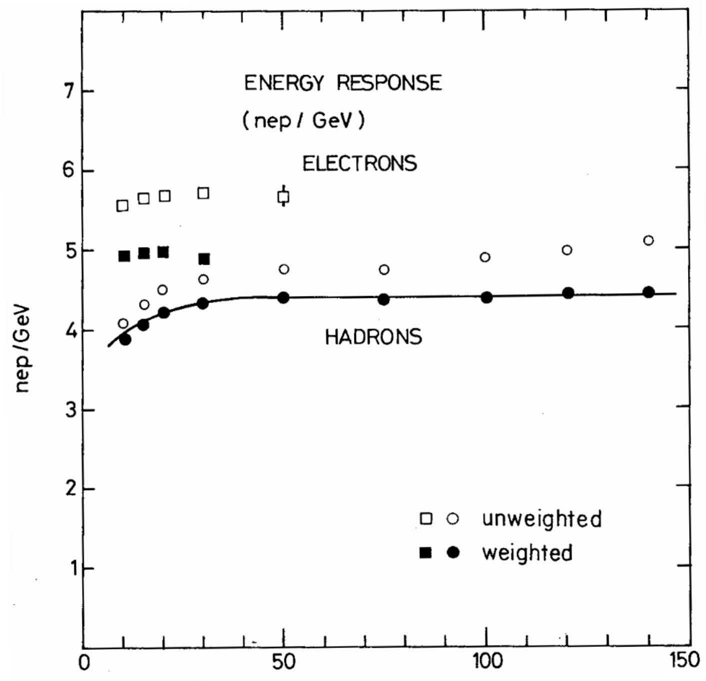
Dual readout ? OK

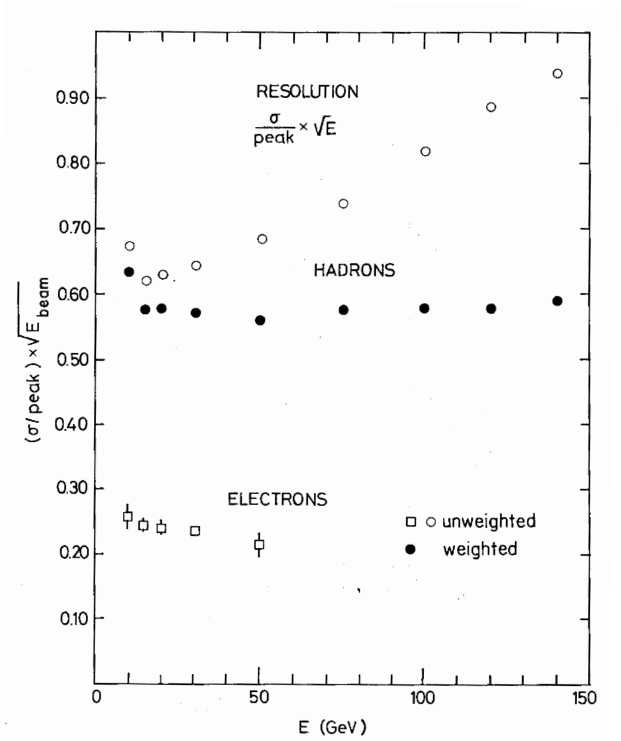
Complex technology - any other way?

Beyond dual readout for offline compensation

- Dual readout ultimately relies on estimating f_{EM} event-by-event
- This fraction can be also estimated in other ways, for example geometrically
- The electromagnetic part of the hadron shower is more narrow → they can be separated geometrically
- Pioneered by WA1 collaboration in *Nucl.Instrum.Meth.* 180 (1981) 429
- WA1 weighted events based on maximum energy in one layer (proxy for shower size)
  - Improvements in linearity and resolution



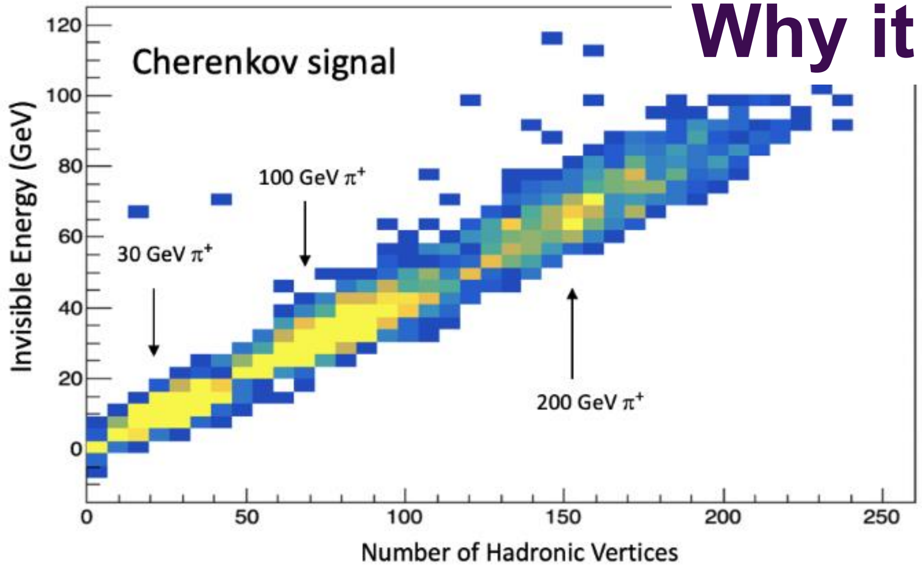




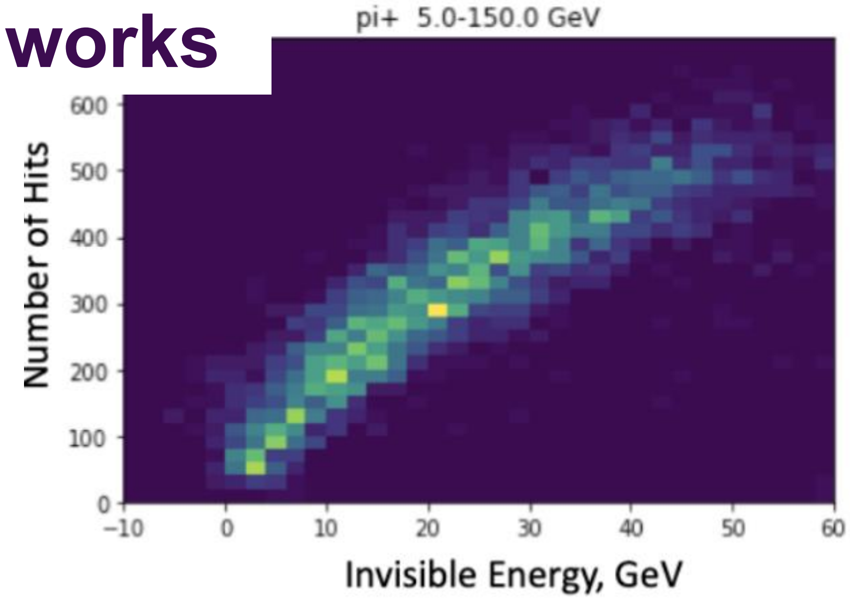
See next slide for modern attempts!

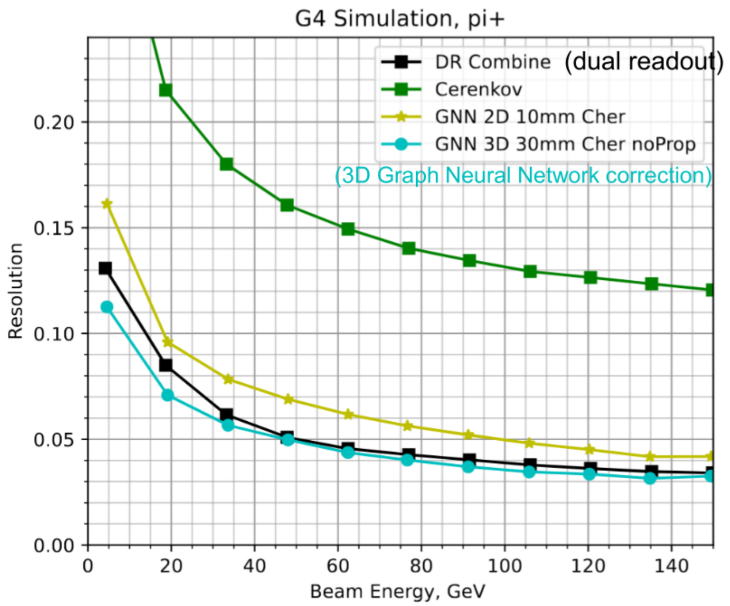
Adding longitudinal segmentation

- 2022 paper: “The (Un)reasonable Effectiveness of Neural Network in Cherenkov Calorimetry”
  doi.org/10.3390/instruments6040043 (CALOR 2022)
- Hadronic calorimeter with copper absorber + optical fibers (2D 1x1cm2 or 3D 3x3x3 cm3 readout)
- Using the cluster shape to correct the loss of energy in nuclear breakup and reactions
- Trained Graph Neural Network (GNN) to predict true energy (offline compensation)
- Competitive with dual readout! → *This could be tried in an ECAL like CRILIN (developed at LNF)*



Why it works





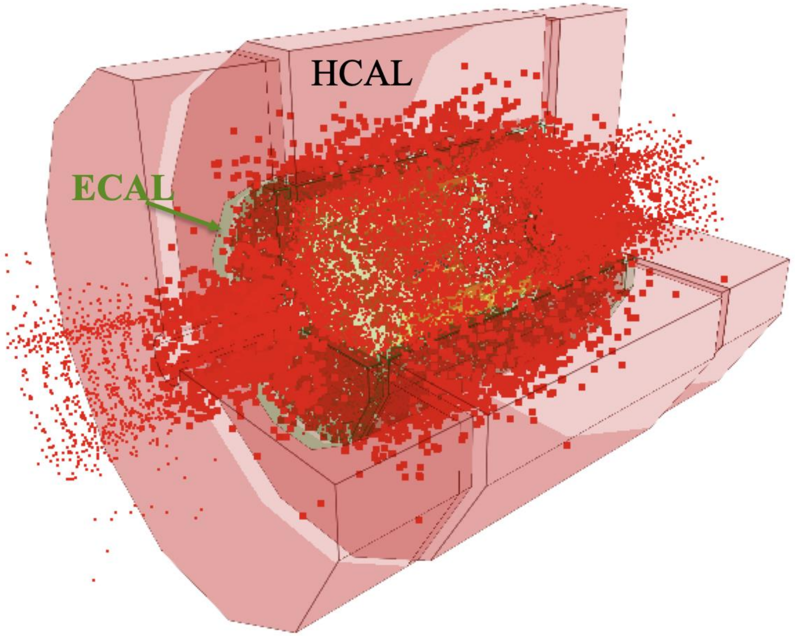
The CRILIN calorimeter story

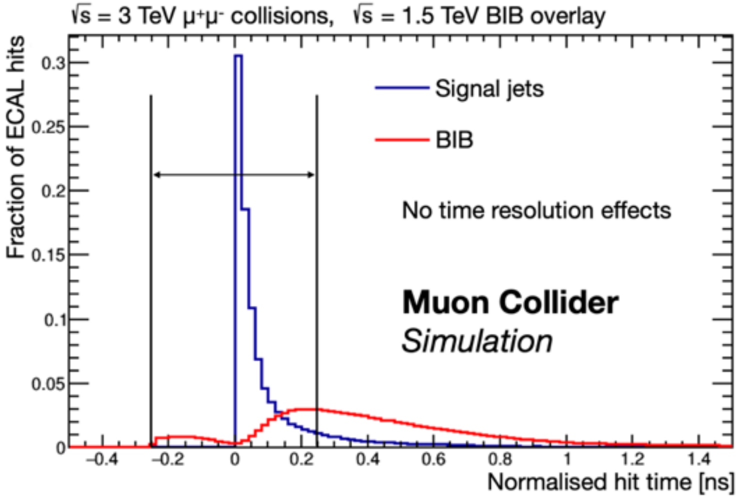
CRILIN as a muon collider ECAL

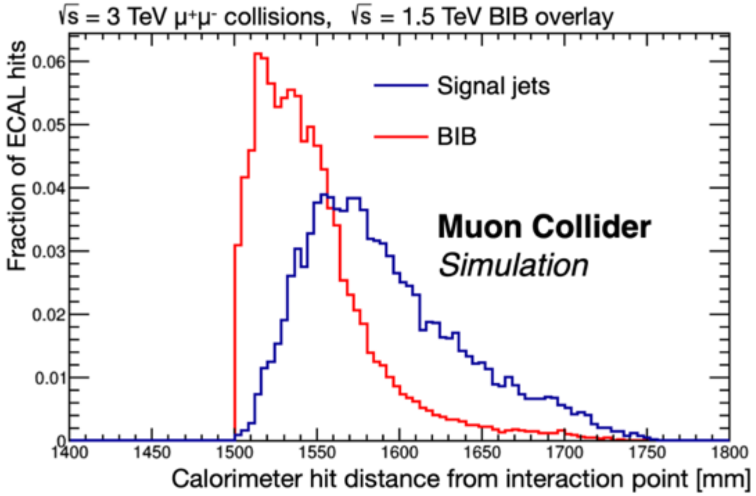
Beam-induced background (BIB):

- Flux of 300 particles per cm^2 through ECAL per bunch-crossing
  - Mainly O(1) MeV photons (96%) and neutrons (4%)
  - **Time of arrival delayed w.r.t. physics signals**
  - Different **hit profile** in R w.r.t. signal (low photon energy)
  - **Total Ionising Dose**: ~1 kGy/year
  - **Neutron fluence**: 10^{14} $n_{1MeVneq}/cm^2$ / year

BIB hits in the calorimeters







a MC ECAL must have:

- σ_t ~ 80 ps
- longitudinal segmentation
- transverse granularity
- radiation resistance
- σ_E /E~ 10%/√E (physics cases)

The Crilin calorimeter *concept*

- **Semi-homogeneous** ECAL made of **crystal matrices** readout by **SiPMs** (minimal interspacing)

Key characteristics:

Excellent timing: (<100 ps) for BIB rejection rate capability and 5D calorimetry

Longitudinal segmentation: for BIB rejection, particle flow & hadronic deposits discrimination

Transverse granularity: handling high-occupancy & particle flow

Crystal/readout choice:

High-density crystals: fulfil space constraints

Radiation hardness: proper crystals and photosensors (small pixels SiPMs)

Fast response: pure *Cherenkov* radiators / scintillating crystals with short decay time

→ PbF_2, $PbWO_4$-UF, …

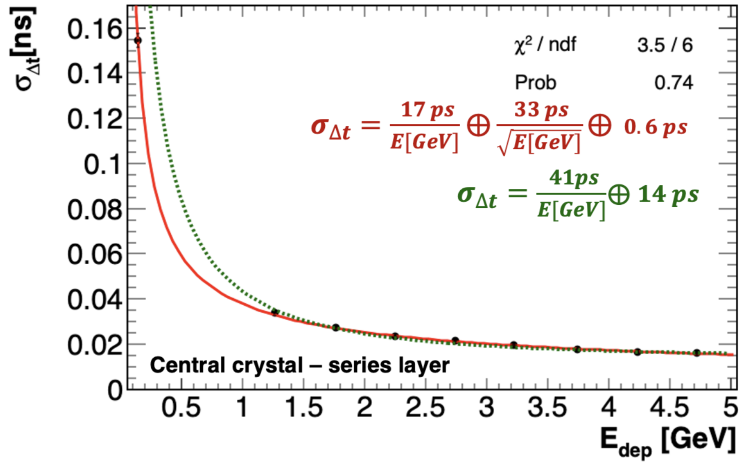
Unique features:

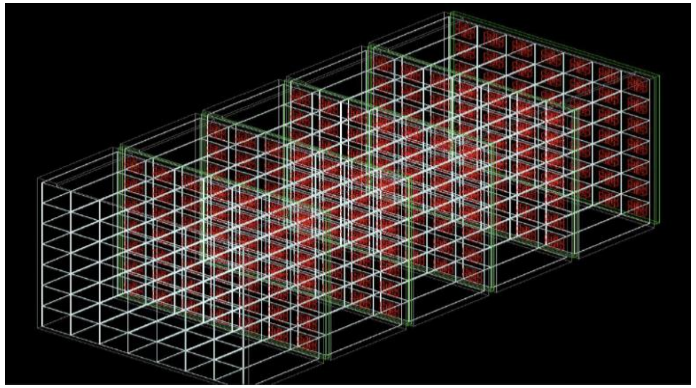
Semi-homogeneous: high resolution + longitudinal segmentation (sampling-like)

Flexibility: possibility to optimize #layers and design each layer independently

Compactness, despite high granularity and longitudinal segmentation (semi-homogen.)

"CRystal calorimeter wIth Longitudinal INformation"





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

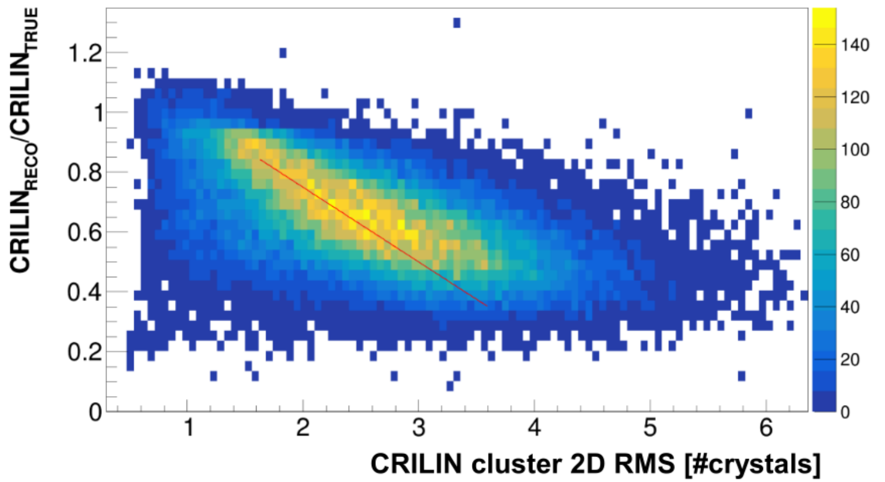
Born for the Muon Collider

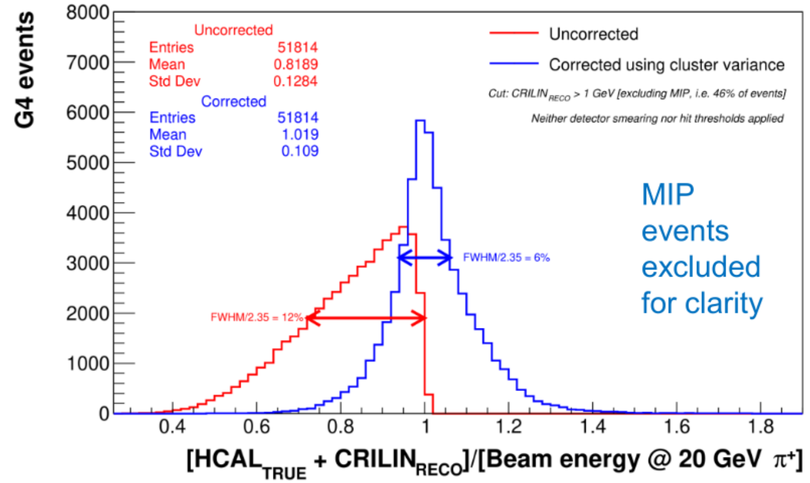
Now baseline of proof-of-concept detector

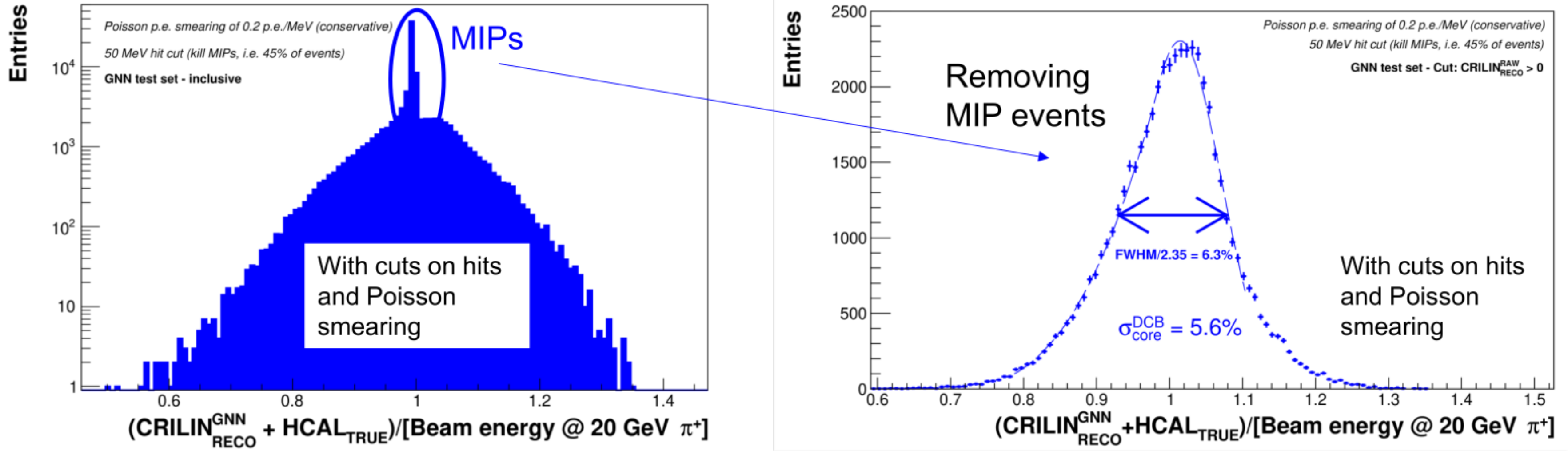
Suitable for ~any future collider!

Testing GNN offline-compensation

- Trying to achieve offline compensation with no dual readout with 20 GeV pions
  - Preliminary check → using Geant4 deposited energy → no Cherenkov isolation
- Before GNN training, looking at correlation between cluster 2D RMS and energy response
  - Correcting using the RMS shows 2x improvement in the resolution
- **Trained a GNN** using reconstructed (with Geant4 + smearing) vs true energy (with virtual detector upstream)



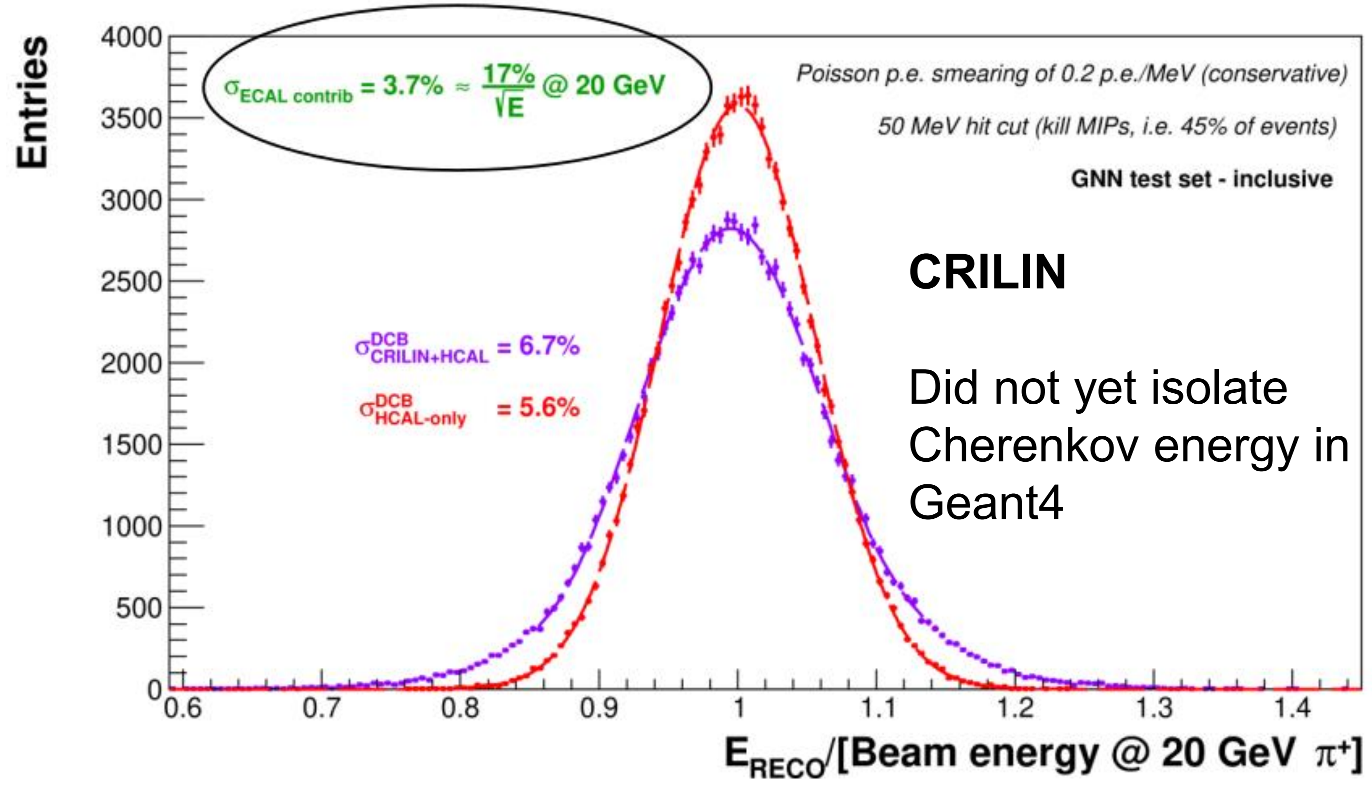


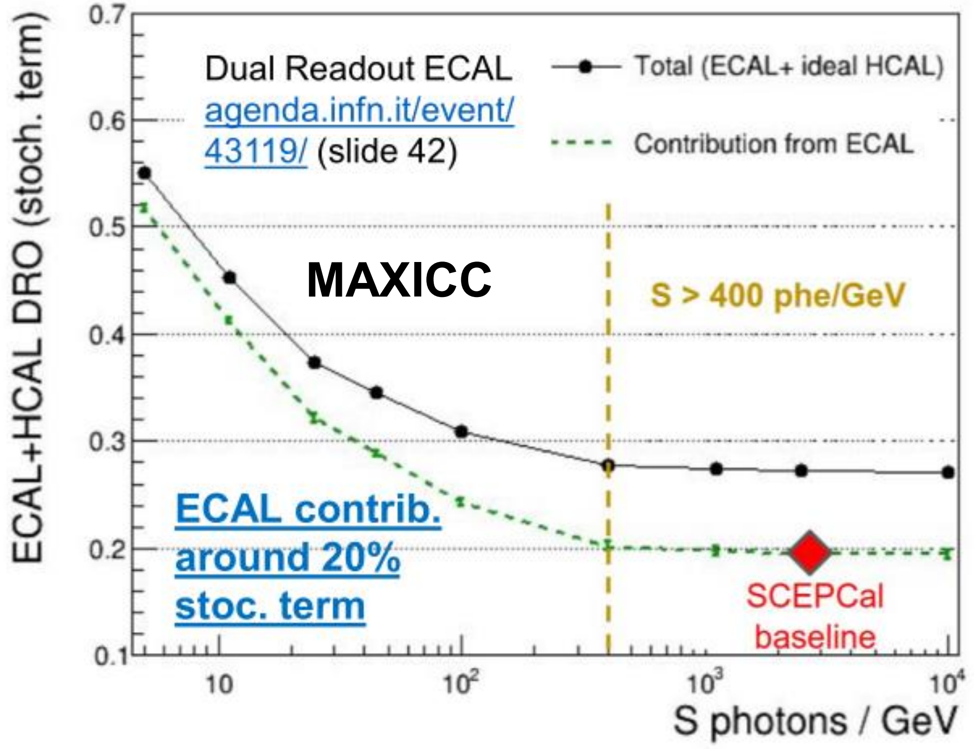


GNN offline-compensation vs. dual readout

- Looking at the ECAL contribution in the resolution for single hadrons
- For preliminary CRILIN studies: 25% stochastic term for parametric smearing of HCAL energy

- **Similar ECAL contributions in CRILIN and MAXICC**





Towards the real detector

Prototype versions

- Proto-0 (2 crystals → 4 channels)
- Proto-1 (3x3 crystals x 2 layers) → 36 chs
- Proto-2 (same) → 18 chs (1/SiPM), new electronics and mechanics

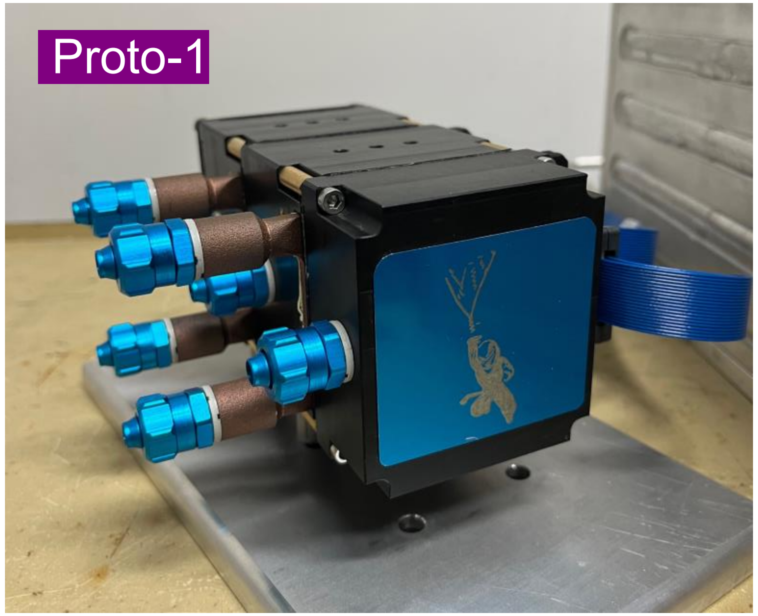
Radiation hardness campaigns

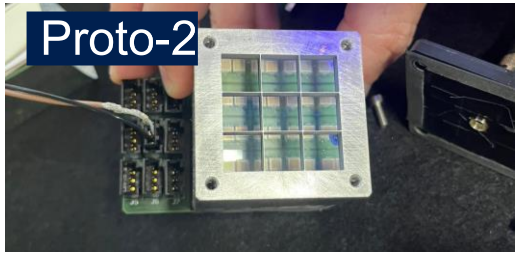
- Calliope @ ENEA Casaccia (TID)
- FNG @ ENEA Frascati (Neutrons)

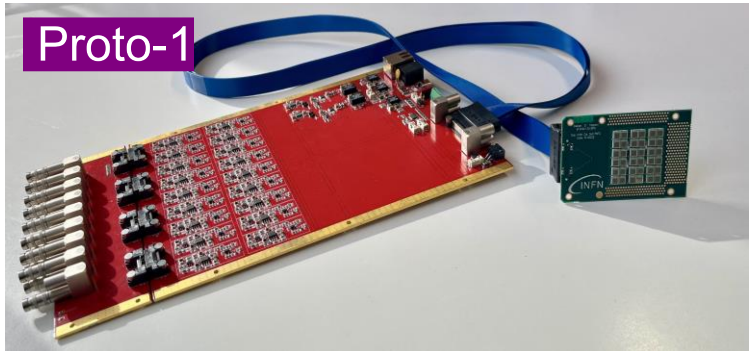
Beam test campaigns

- Proto-0 at CERN H2 (August 2022) ***Front. Phys. 11:1223183***
- Proto-1 at CERN (August 2023)
  - ***Timing + light yield***
- Proto-1 at LNF-BTF (July 2023-April 2024) ***doi:10.1109/TNS.2024.3364771***
- **Proto-2 at CERN (September 2025)**
  - **Data/MC shower profile 1-2-3 layers**

Proto-*: PbF_2 + 10 um SiPMs (Hamamatsu S14160-3010PS)



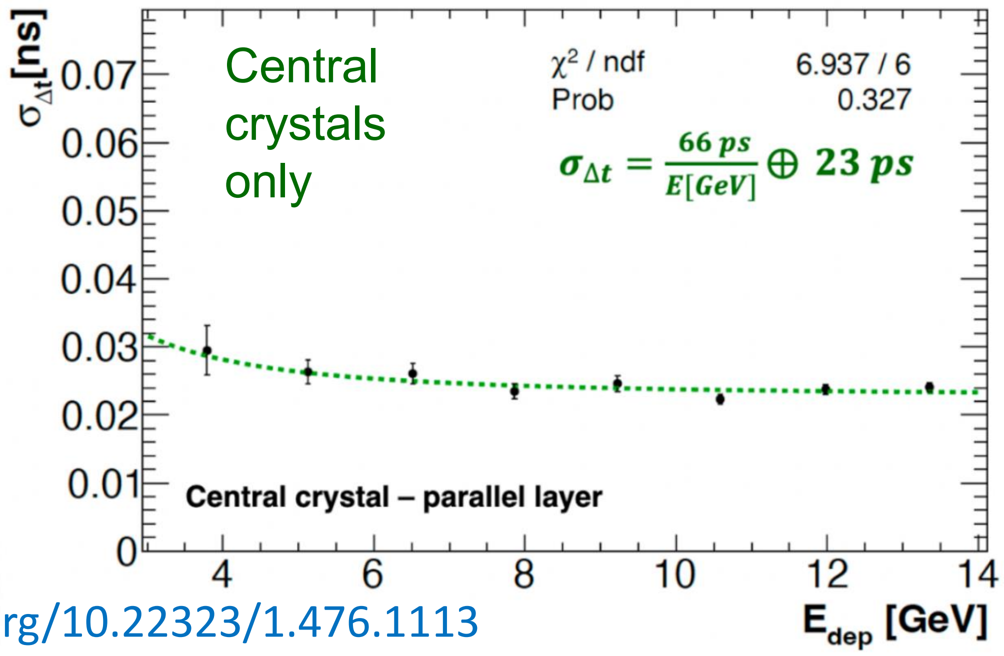




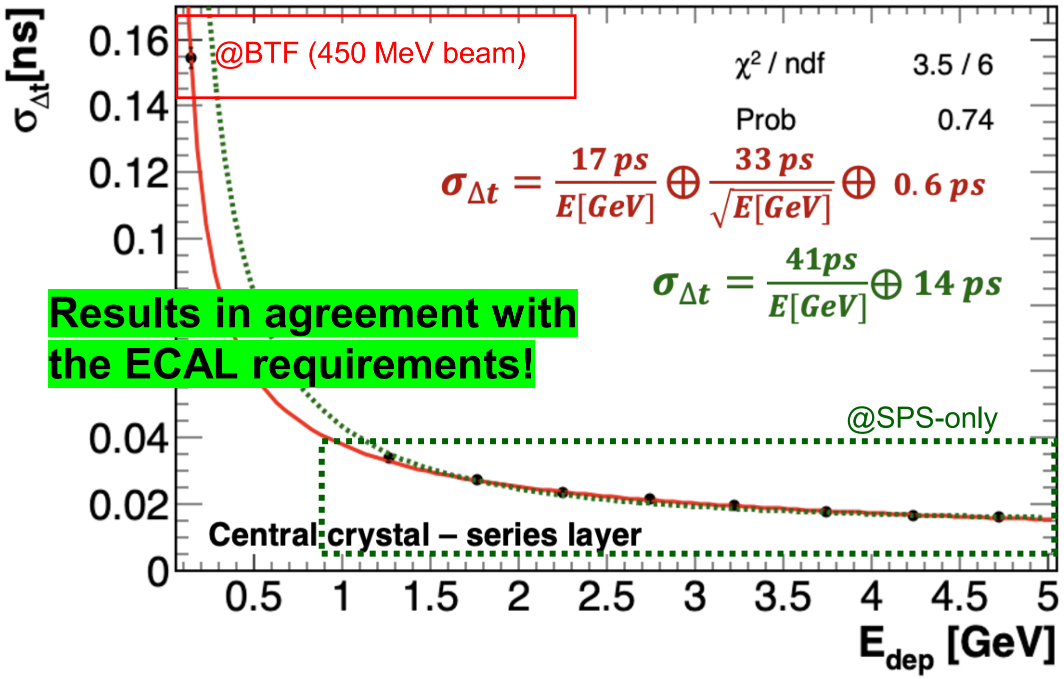
… waiting for full containment module

Proto-1 beam test @ CERN: Timing

- Time resolution: **O(20 ps), measured** with time differences between SiPMs on central crystals
  - 2 chs / crystal for Proto-1
- Excellent time resolution (45 ps) also with time differences between the 2 layers
  - *Time resolution dominated by the 2 CAEN boards sync jitter O(32ps/board)*



doi.org/10.22323/1.476.1113



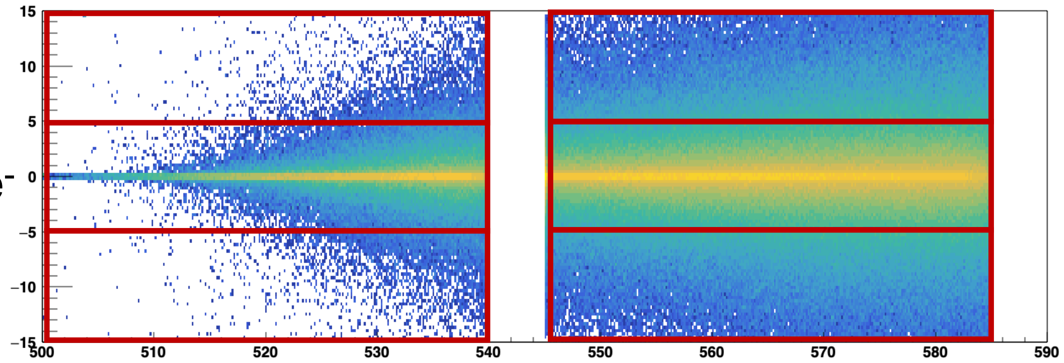
- Excellent time resolution at O(2) GeV energy deposits (first layer)
  - To be compared with (for instance) O(30) ps of CMS ECAL phase-2 at O(100) GeV
- Thanks to fast SiPM + electronics, short crystals and pure Cherenchov response

Proto-1 beam test @ CERN: data/MC

- **40-150 GeV electron beam (SPS-H2)**
- 2 crystal layers (**8.5 X_0**) -> no energy reco
- Energy deposit vs. MC -> Light yield

Energy reco possible with new larger prototype, now under construction

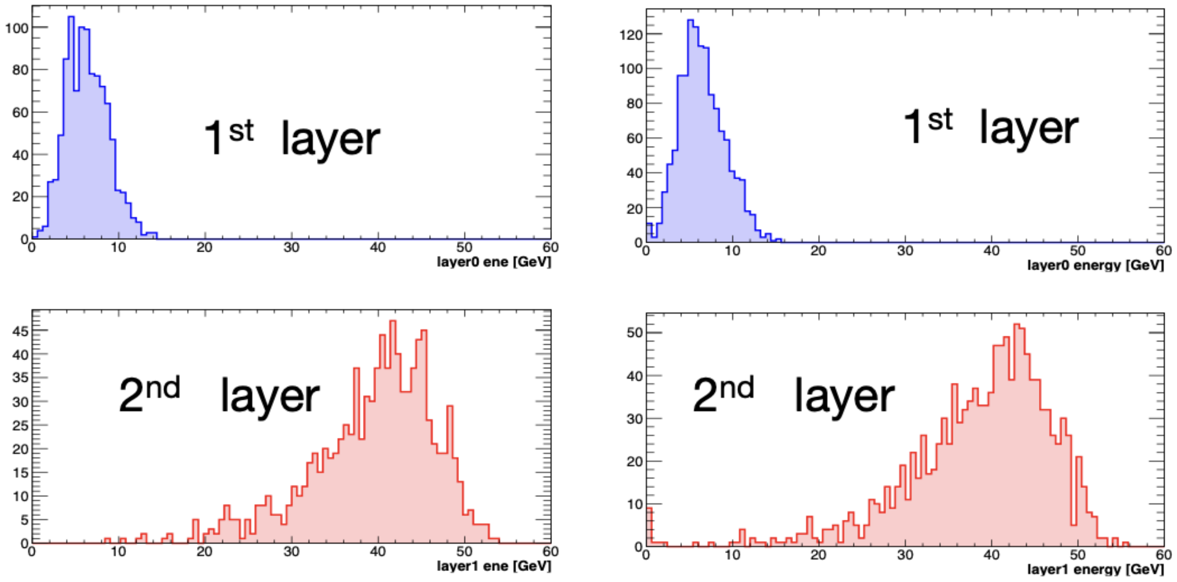
MC
120 GeV e^-

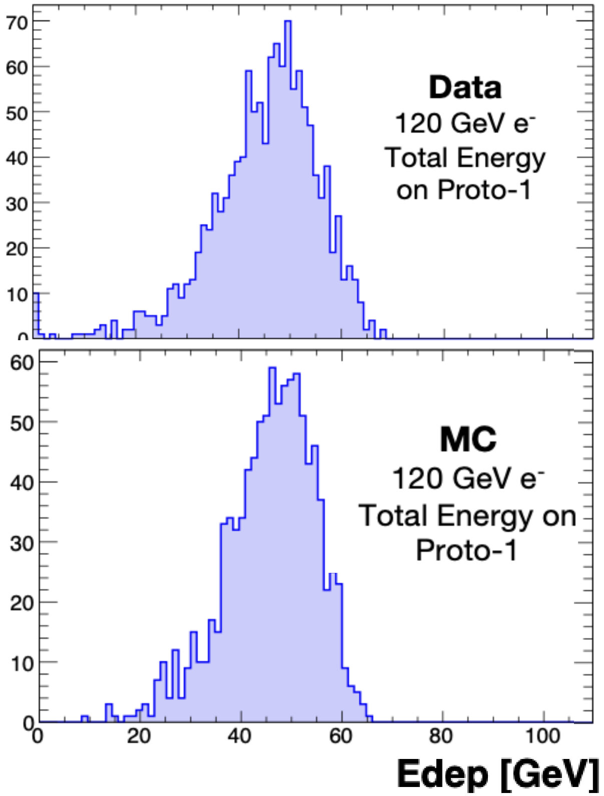


- Good agreement between **MC and data**
- Validation of the **simulation model**
- Evaluation of the light yield: 0.3 p.e. / MeV

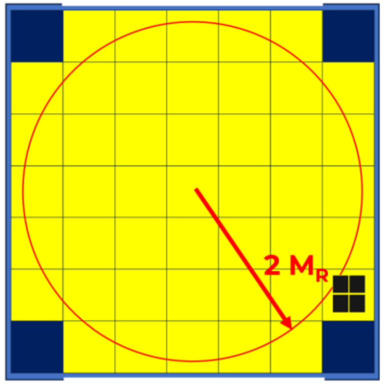
MC
120 GeV e^-

DATA
120 GeV e^-



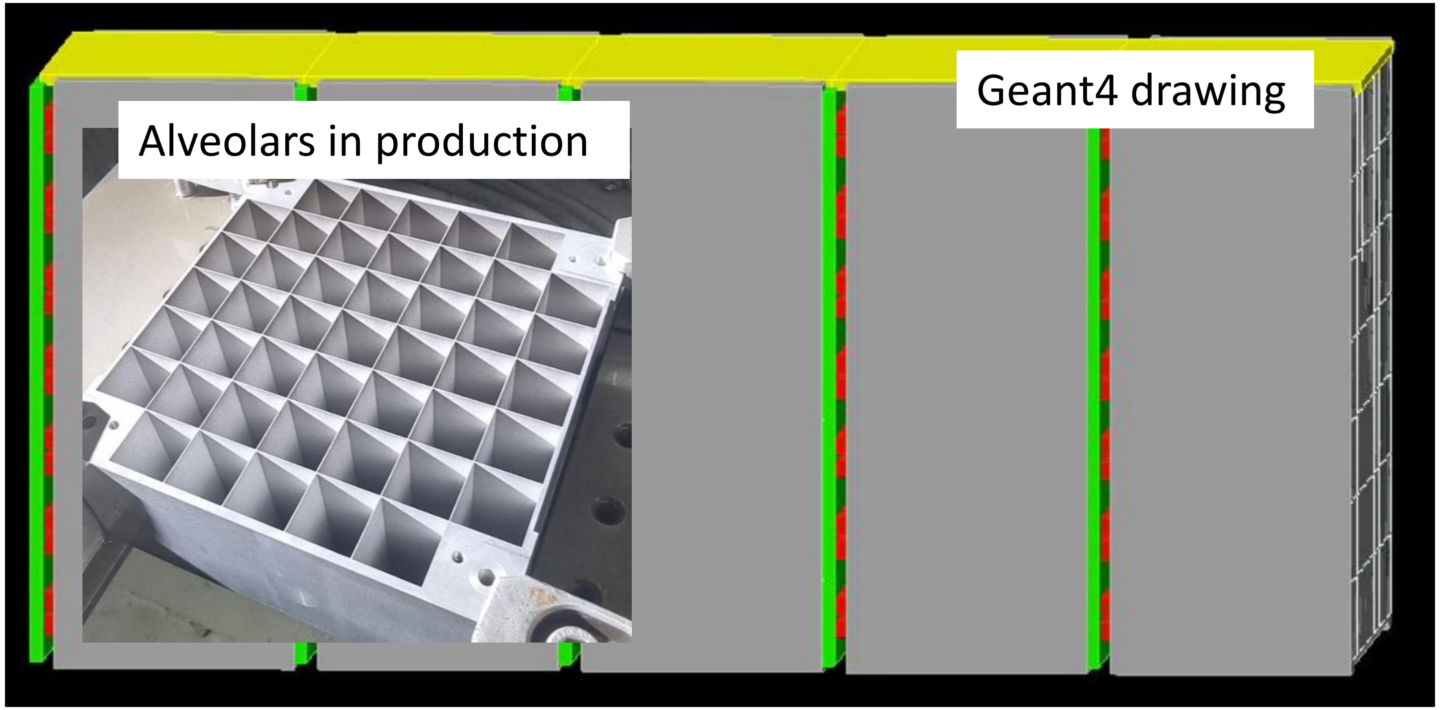


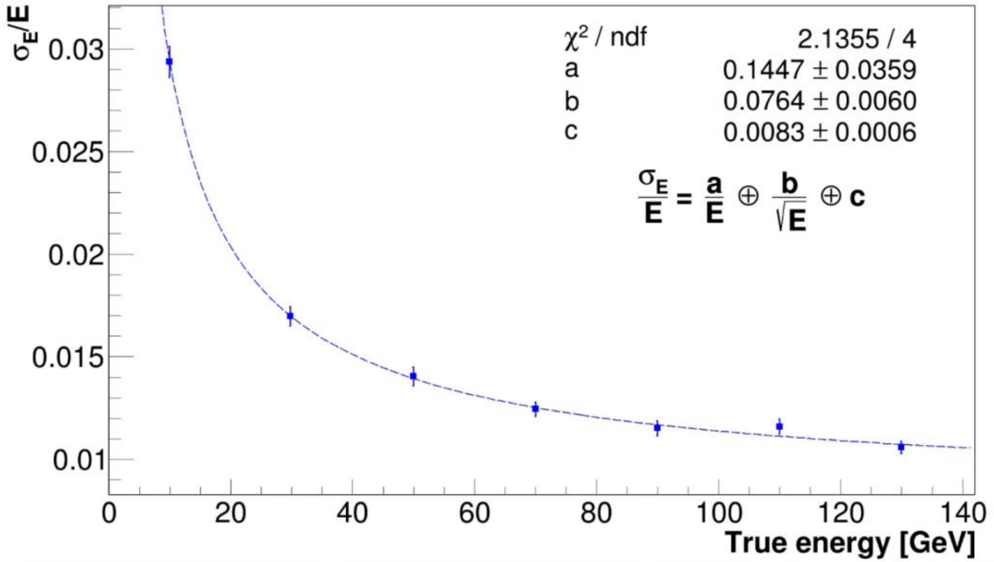
New 7x7 full-containment module



FINAL PROTOTYPE: **5 layers, 7x7 crystals, ~ 250 channels**

- slightly wider crystals (PbF_2 1.3x1.3 cm^2 with 0.1mm tolerance)
- **Aluminum alveolar matrix support**
  - → max 200μm inter-crystal thickness
  - *→ max 2mm external envelope thickness*
  - → max 5mm between layers





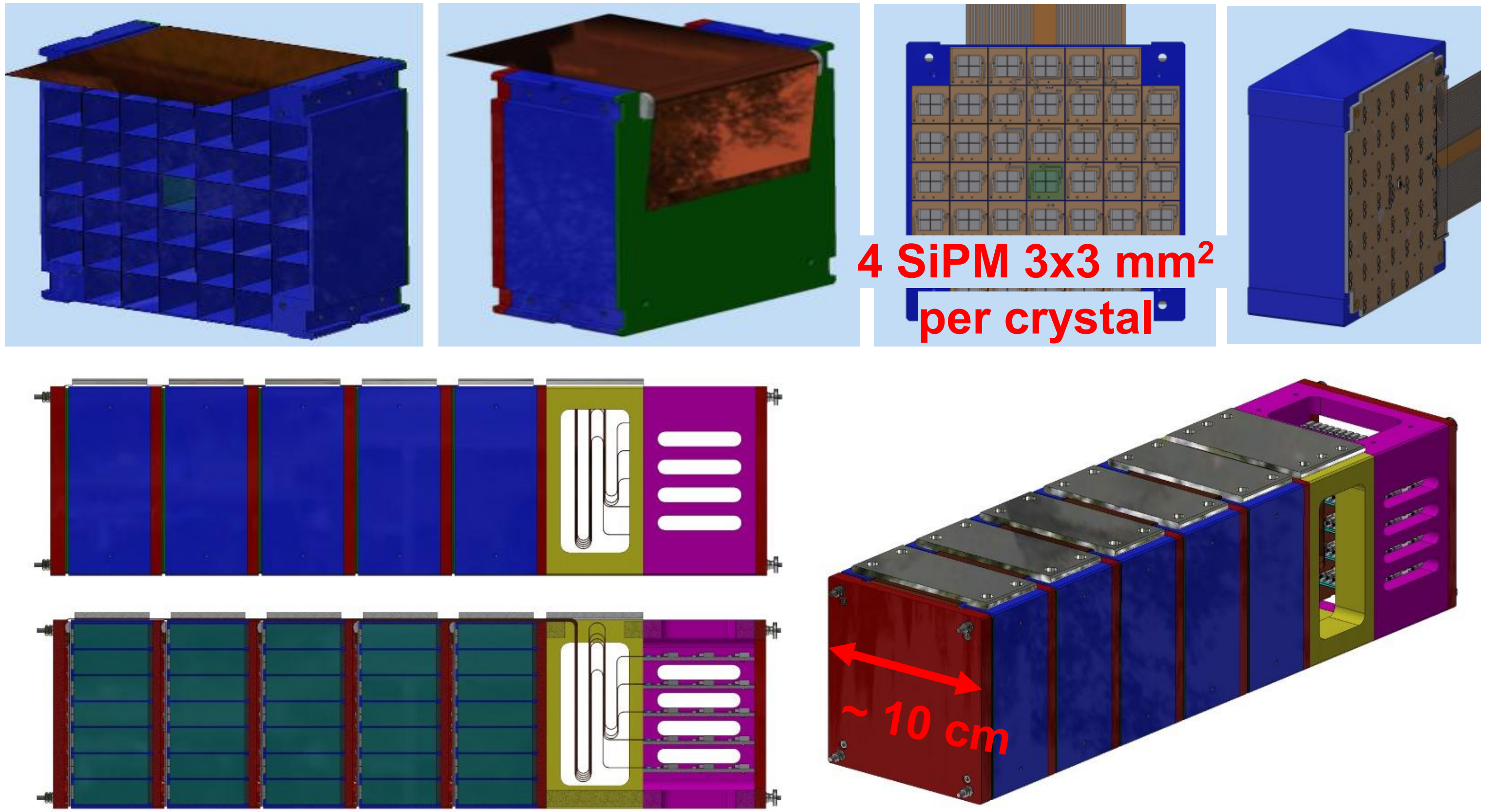
Simulation: Energy Resolution ~ 7.6%/√E

- 0.2 P.E./MeV per crystal (CONSERVATIVE)
- Gaussian noise σ = 10 MeV
- 30 MeV energy threshold per crystal

Upgrades w.r.t. prototypes

Improved readout/mechanics:
- Kapton strip for SiPM connection
- New custom FEE
- CAEN V1742 digitizer
- 2mm ext. envelope -> stackable

- ***Assembly designed to be:***
  - ***experiment-ready***
  - ***radiation-hard***



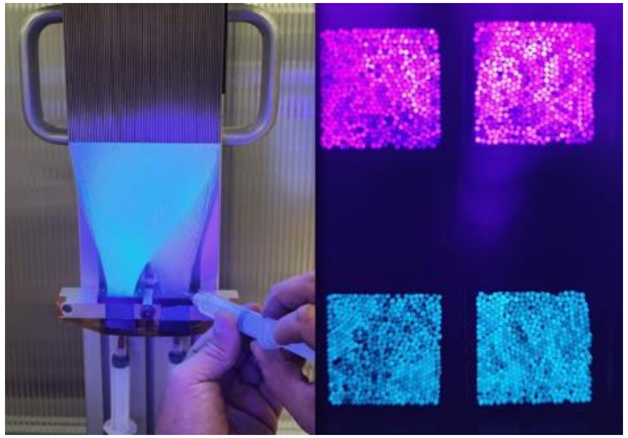
Test Beam @ CERN SPS (energy resolution) → May/June 2026

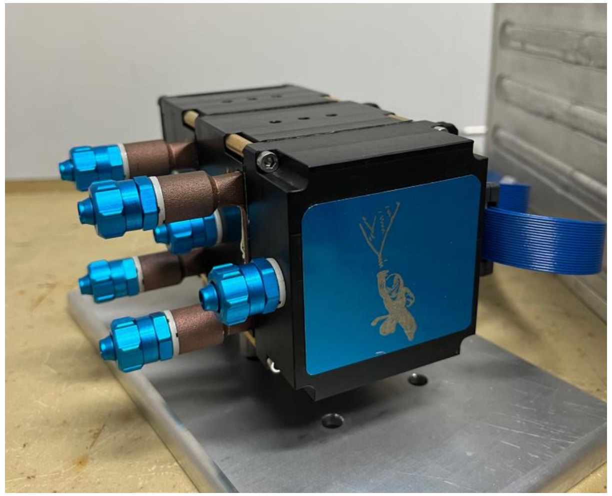
CRILIN points for an Higgs factory ECAL

- Crystals material changeable without breaking CRILIN semi-homogeneous philosophy!
  - But PbF_2 is the less expensive suitable crystal ...
- Already with lead fluoride CRILIN may reach >0.6 p.e./MeV [0.3 p.e. MeV now]
  - → 4% stoch. term → can work as a very precise electromagnetic calorimeter
- CRILIN is already optimized for particle flow → 1.3 cm cell size / 5 layers
  - Fine longitudinal segmentation very important (see ALLEGRO performances...)
- Offline compensation (à la dual readout) doable thanks to fine long. segm.
  - See 2022 paper on Cherenkov HCAL shown before + ALLEGRO performances...
- 20 ps timing at small energy deposits could be important for flavour (at Z)
  - It can also reduce the confusion term in particle flow (showers clustered in time)
  - If needed (?) add MIP timing layer with scintillator (same mechanics and electonics)
- Cherenkov hadron showers are smaller in eta/phi w.r.t. scintillating materials
  - Decrease of the confusion term in particle flow

Summary

- Future colliders impose **stringent calorimetry requirements**:
  - high granularity, precision timing and excellent jet/photon energy resolution
- **Jet energy resolution (JER)** is critical for Higgs physics but limited by hadronic shower fluctuations
- Two main *complementary* strategies for JER:
  - **Particle flow** (granular detectors), “subtracting” charged hadrons using tracker and photons with ECAL
  - **Offline compensation** (dual readout or alternatives) to mitigate fluctuations
- **Homogeneous crystal ECALs** enable excellent resolution (~3%/√E)
- Combined with segmentation and timing, support particle flow and dual readout
- **CRILIN concept (developed at LNF)**: semi-homogeneous, fast-timing with Cherenkov crystals, tuned for Muon Collider, allows optimization for FCC-ee





Backup slides

Costs of crystals

www.pi.infn.it/~bedeschi/RD_FCC/IDEA_costing/FCC_MidTerm_IDEA_Calo_CostEstimate_V2.pdf

Crystal	ρ [g/cm^3]	λ_I [cm]	X_0 [cm]	R_M [cm]	LY/LY$_0$ [a.u.]	τ_D [ns]	Photon density [photons/ns]	Est. cost [€/cm^2/X_0]
$PbWO_4$	8.3	20.9	0.89	2.00	1	10	0.10	6.8
BGO	7.1	22.7	1.12	2.23	70	300	0.23	6.7
BSO	6.8	23.4	1.15	2.33	14	100	0.14	8.1
CsI	4.5	39.3	1.86	3.57	550	1220	0.45	7.4
PbF_2	7.8	22.4	0.94	2.18	–	–	–	5.6

PRELIMINARY ESTIMATES

- PbF_2 «prototype» cost is around 17 \$/cm^2/X_0
- For large productions it may go lower than 5.6 \$/cm^2/X_0

agenda.infn.it/event/23861/#14-rd-calorimetro

Timing at FCC-ee (tracker)

https://indico.mitp.uni-mainz.de/event/403/contributions/5530/attachments/3965/5193/The%20experimental%20challenge%20for%20flavour%20physics%20at%20the%20FCC-ee_Armin%20Ilg.pdf

hep-ex > arXiv:2511.17447

- Kaon ID for flavour tagging (s jets contain more kaons) and flavour physics
- γ/neutral hadron separation for particle flow reconstruction
- Background suppression in flavour physics (e.g $B_s^0 \to D_s K$ from $B_s^0 \to D_s \pi$)

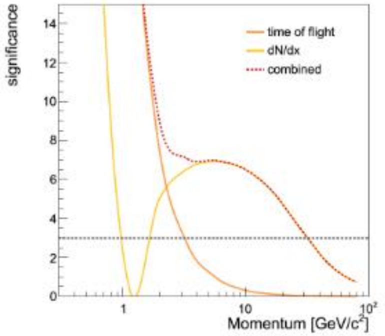
Drift chamber as tracker

- dE/dx and/or cluster counting (dN/dx)

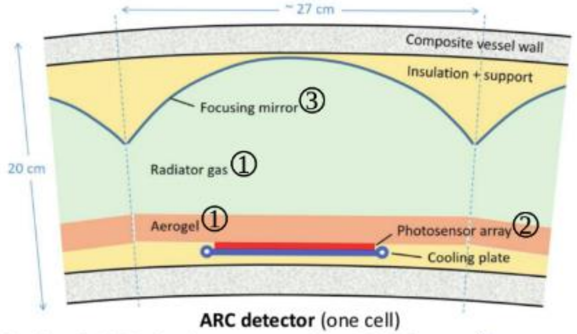
Timing measurement for time-of-flight

- $O(30)$ ps to get PID at low momenta (LGADs, MAPS, etc.). $O(100)\text{m}^2$ of sensors needed

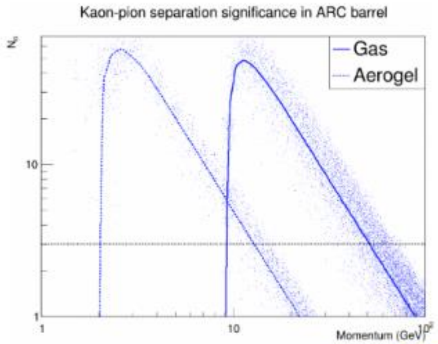
Ring imaging Cherenkov (RICH) detectors



Kaon-pion separation using drift chamber and TOF (F. Bedeschi [6])



Cell of ARC detector for FCC-ee (R. Forty)



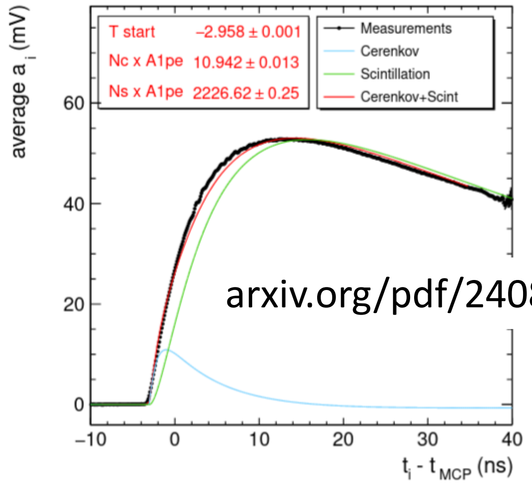
Kaon-pion seperation in ARC (M. Tat)

Timing in the tracker needed,
OR
pixel + MIP timing layer + photon timing with ECAL

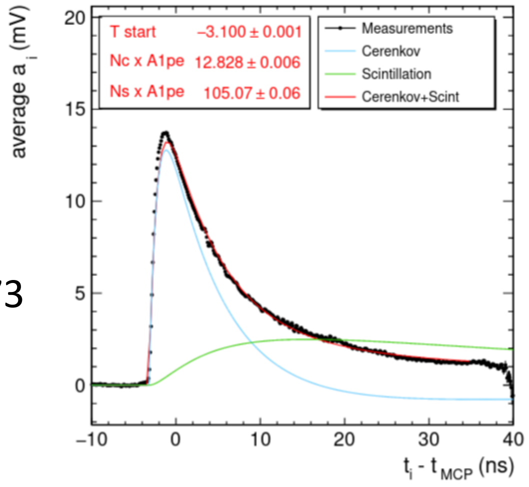
MAXICC with filters+pulse shapes (BGO)

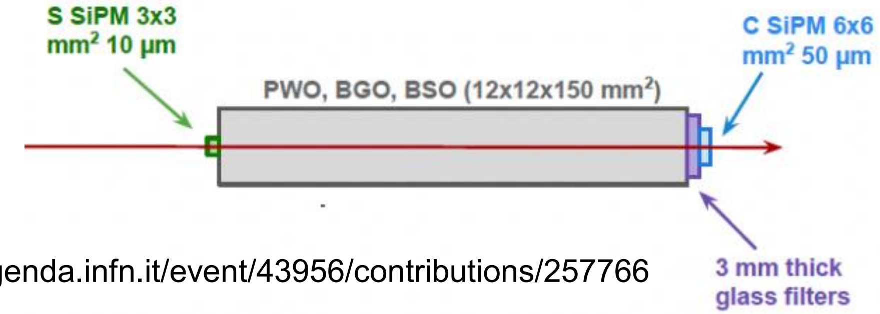
- BGO scintillates in the green and is slower
  - Easier to separate S/C
  - Less compact than $PbWO_4$
- Building upon old pioneering work by Wigmans et al.
  - doi.org/10.1103/RevModPhys.90.025002

- Using filters + waveforms shape to separate Cherenkov
- Approach validated by changing the crystals/angle beam to tag the Cherenkov

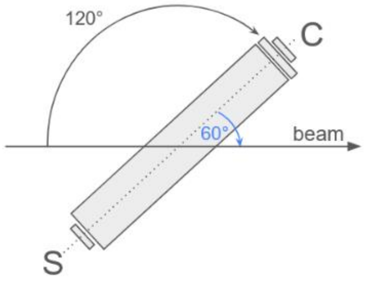


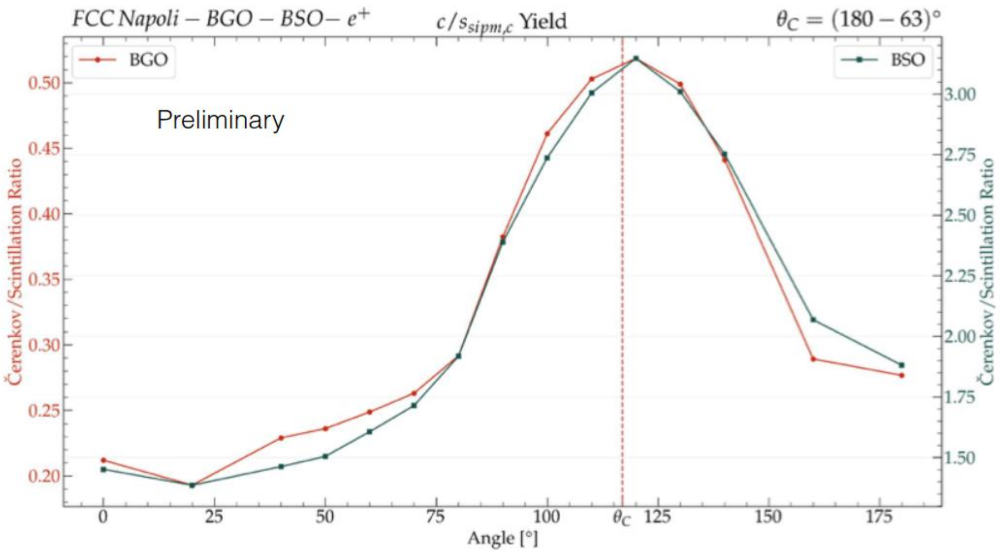
arxiv.org/pdf/2408.11973





agenda.infn.it/event/43956/contributions/257766

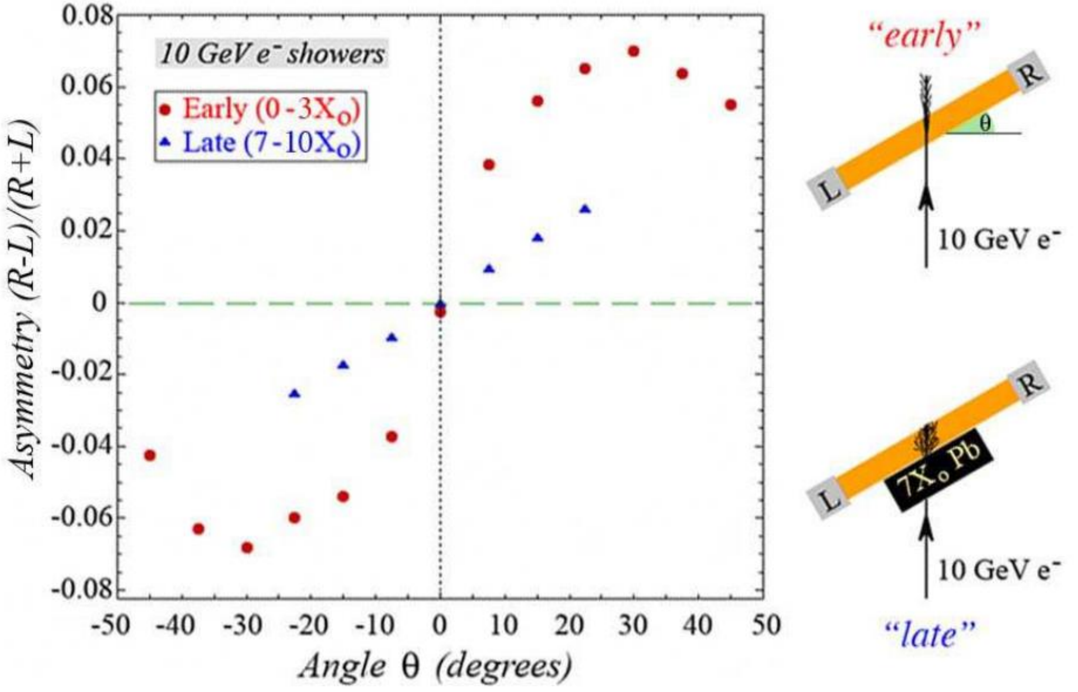


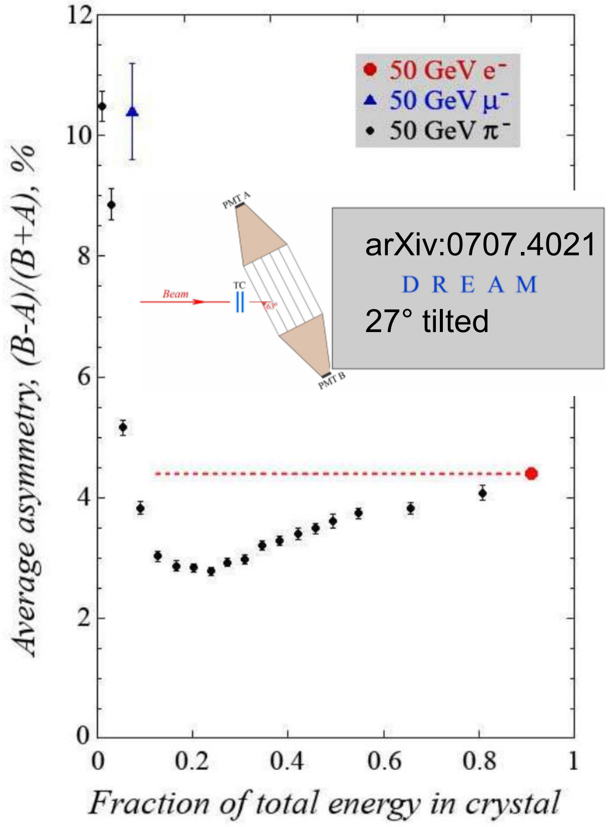


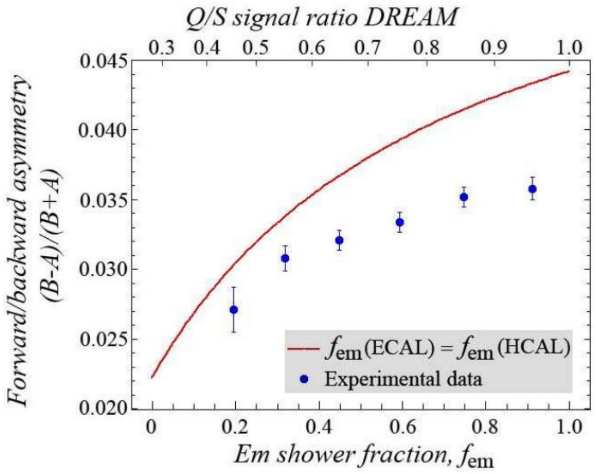
Notch filters (BGO green light emission suppressed)

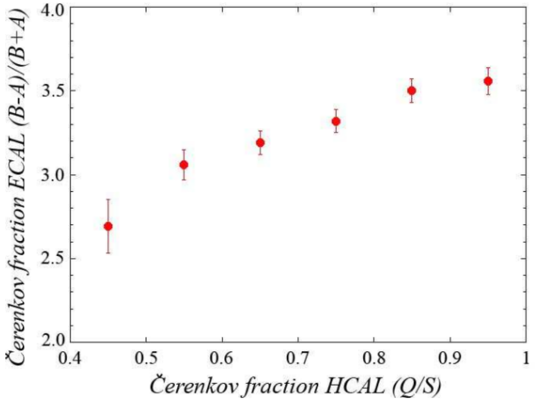
Other ideas: forward-backward asymmetry

- Due to Cherenkov forward emission, Cherenkov light is preferentially collected in forward photosensors → Allows dual readout
- Tests done many years ago → pointing to an ECAL with tilted $PbWO_4$ crystals









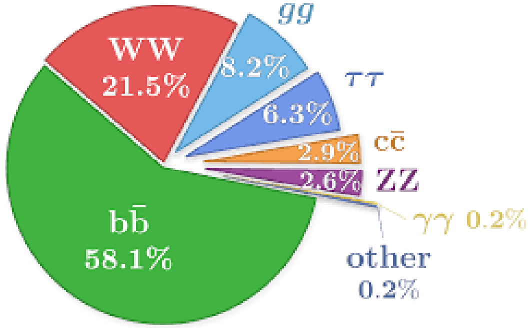
CRILIN light yield increase

- Numbers here just to show the potential improvements
- Assessment requires real optimization and tests
- Constraints on crystals sizes not taken into account
- Energy deposited in the different layers not taken into account → possibly CRILIN can even use 50um pixel SiPMs

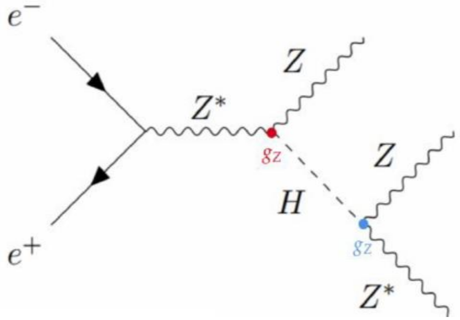
Factor	Before (10 µm, 4×3×3 mm^2)	After / optimized (15 µm, 2×2 SiPM array)	Single-SiPM crystal (15 µm)		
SiPM PDE	18 %	25 %	25 %		
SiPM format & tiling (active area)	4×3×3 mm^2 → 36 mm^2	2×2 × 6×6 mm^2 → 12×12 mm^2	1 × 6×6 mm^2 → 6×6 mm^2		
Crystal area	10×10 mm^2	≥16×16 mm^2 (matches array + packaging)	≥8×8 mm^2 (matches single SiPM + packaging)		
Coverage fraction (active / crystal)	36 %	56 %	56 %		
Microcells per SiPM	3×3 mm^2, 10 µm → 14–40k	6×6 mm^2, 15 µm → 160k	6×6 mm^2, 15 µm → 160k		
Light yield (p.e./MeV)	0.3	0.65	0.65		
Photostatistics term	5.8 % / √E	~4 % / √E	~4 % / √E		
Saturation @100 GeV deposit	low → fine	16.25 k p.e./SiPM → 10 % occupancy → fully linear	65 k p.e./SiPM → 40 % occupancy → still linear		

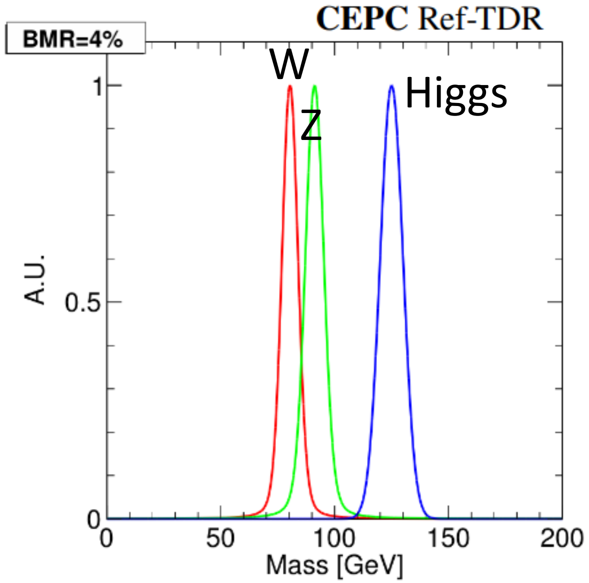
Traditional motivation: Z vs. W dijets separation

- Need to extract Γ_H from total ***XS(e^+e^- → ZH)*** and ***BR(H→ZZ*)*** measurements (Same ZH coupling)
- One of best channels (in theory): e^+e^- → ZH(→ZZ*) → Z(→2l) H→[Z(→2q) Z*(→2q)]
  - Needs fully hadronic H→ZZ*/WW* separation using dijet mass for H→WW* rejection
    - Traditional reason to require excellent jet energy resolution (JER) in e^+e^- → ZH
  - Actually, in recent simulations, issues w/ matching of soft jets from virtual Z → independent on JER
- In "mixed" channel (2l+2ν+2q) good results despite JER
- Z(→2q) Z(→2q) Z*(→2l) channel not yet studied



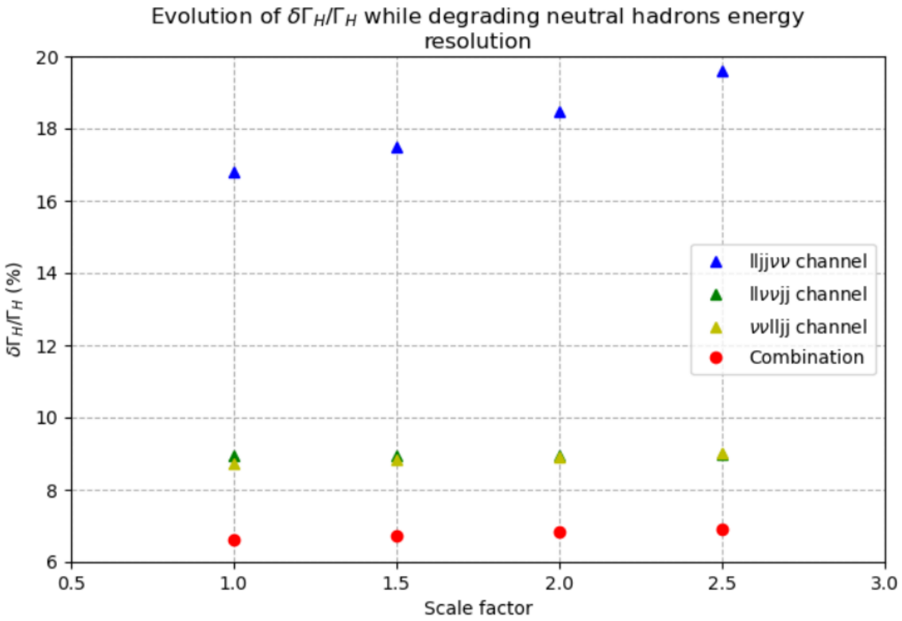
ZZZ^* decay type	Number of events for L = 5 ab^{-1}
Fully hadronic	~ 9000
Fully leptonic	~ 8
Mixed channels	~ 1500
2 leptons, 4 jets	~ 2600
2 jets, 4 leptons	~ 250





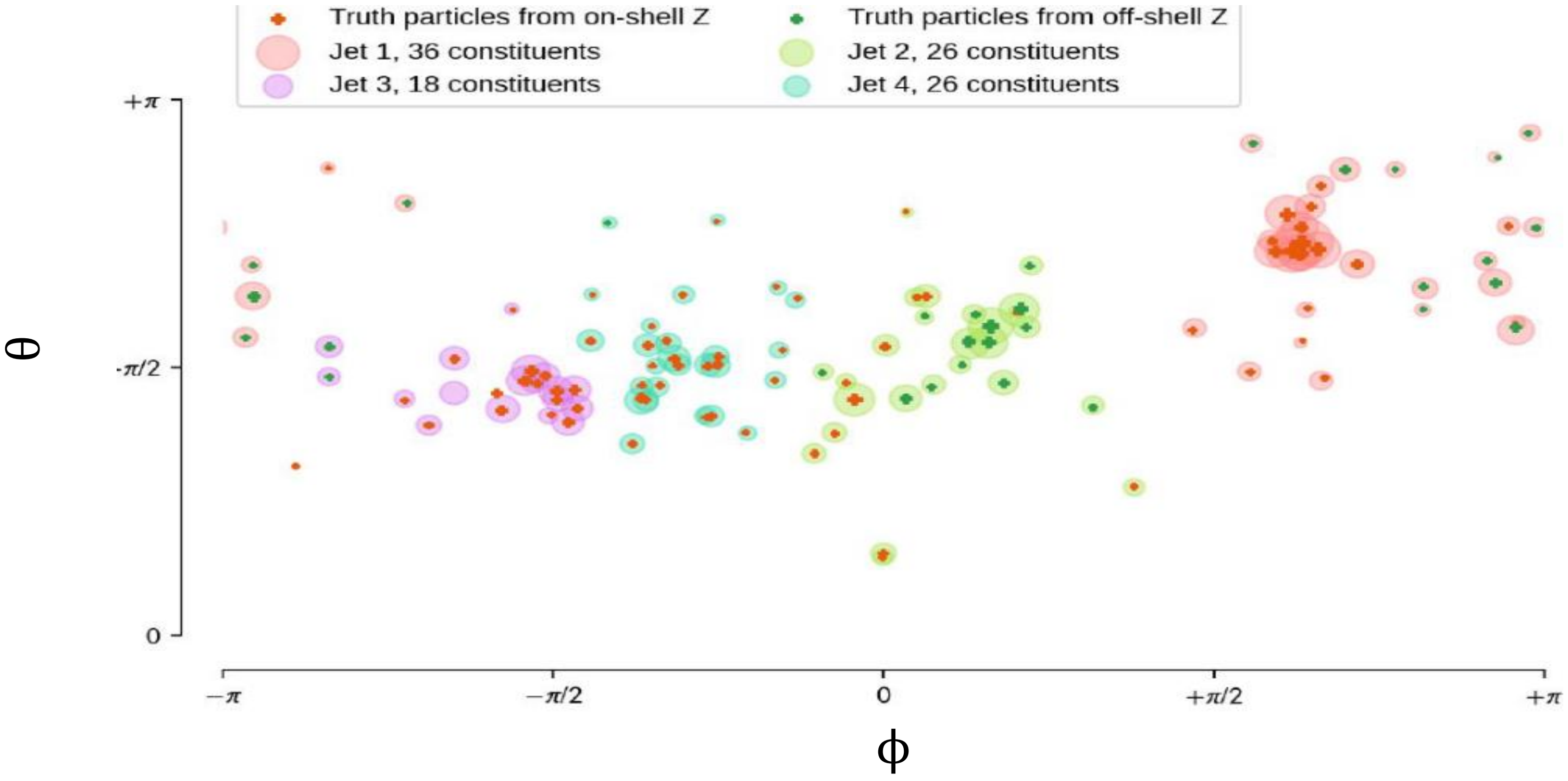
Jet matching issues beyond JER

Moving to mixed channel



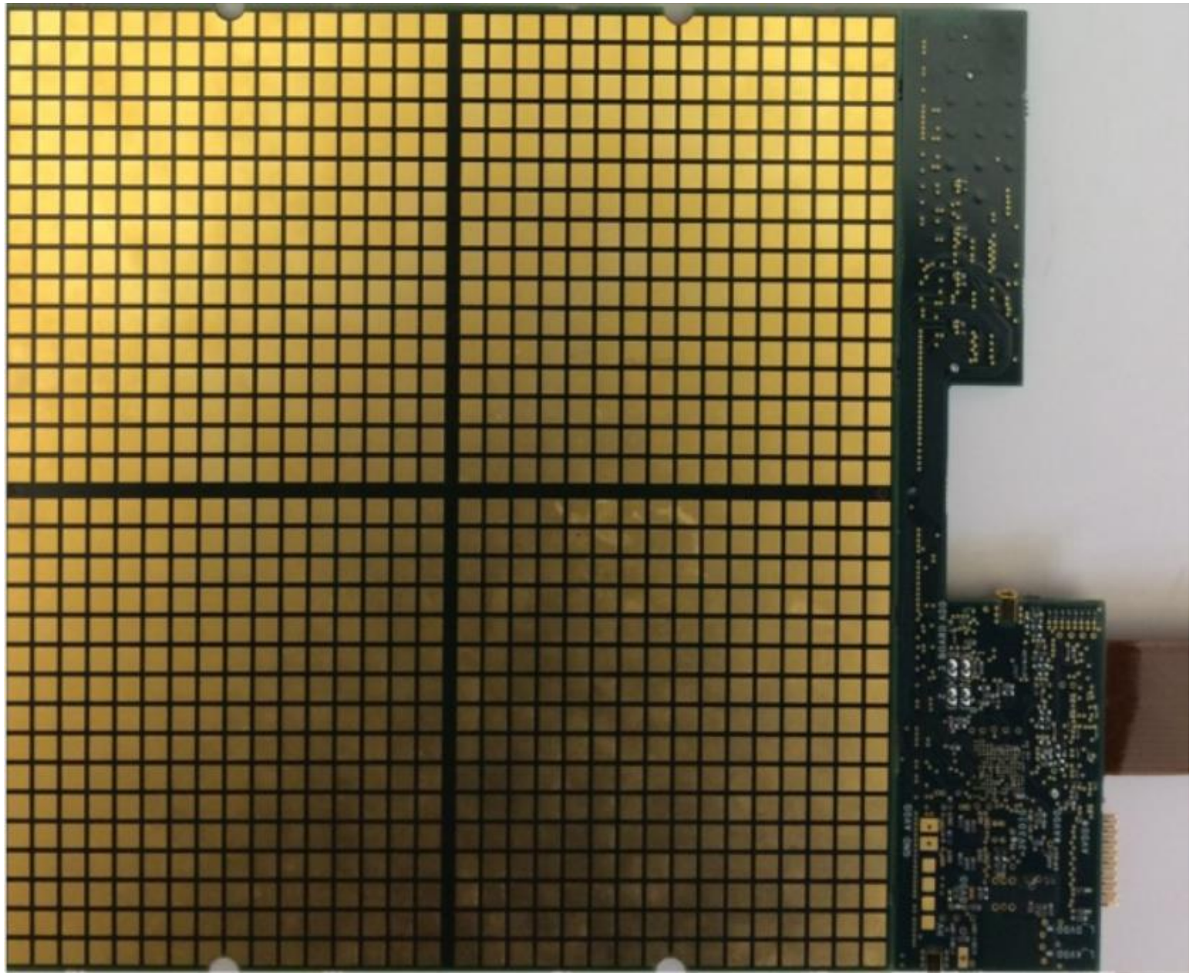
indico.cern.ch/event/1307378/contributions/5721488 & 10.17181/4wxpk-1zy78

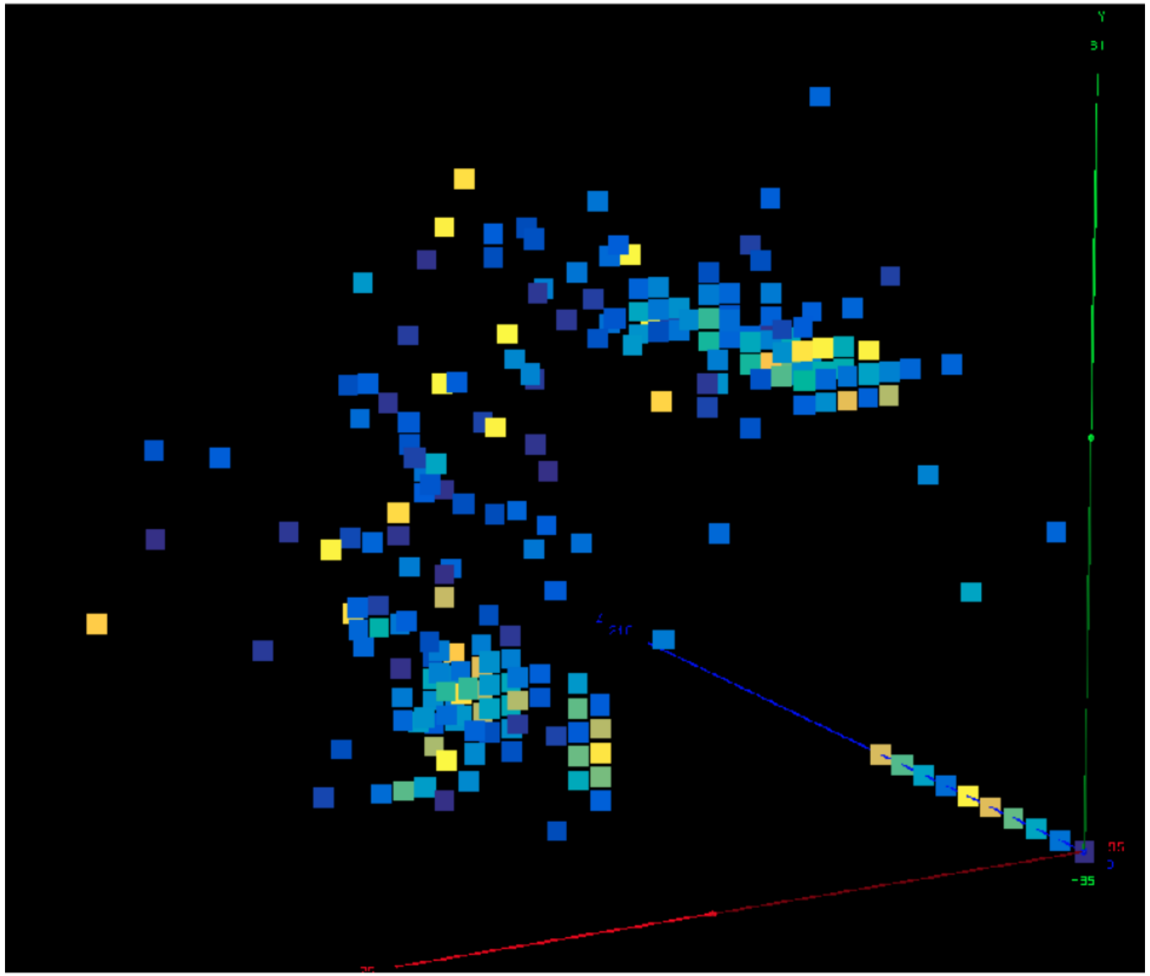
Jet matching (ZH with 4 jets)



SiW calorimeter

- Main feature: 5x5mm sampling with O(40) layers and tungsten absorbers → extreme particle flow





The Muon Collider project

- The **Muon Collider** represents a promising **future collider project**, designed to collide beams of muons (μ^-) and antimuons (μ^+) in a circular geometry at **multi-TeV center-of-mass energies**.

- Advantage of using muons is that, as **elementary particles** with **mass ~200 that of electrons**, allows to reach:

  - Elevate center of mass energies

  - High luminosity values

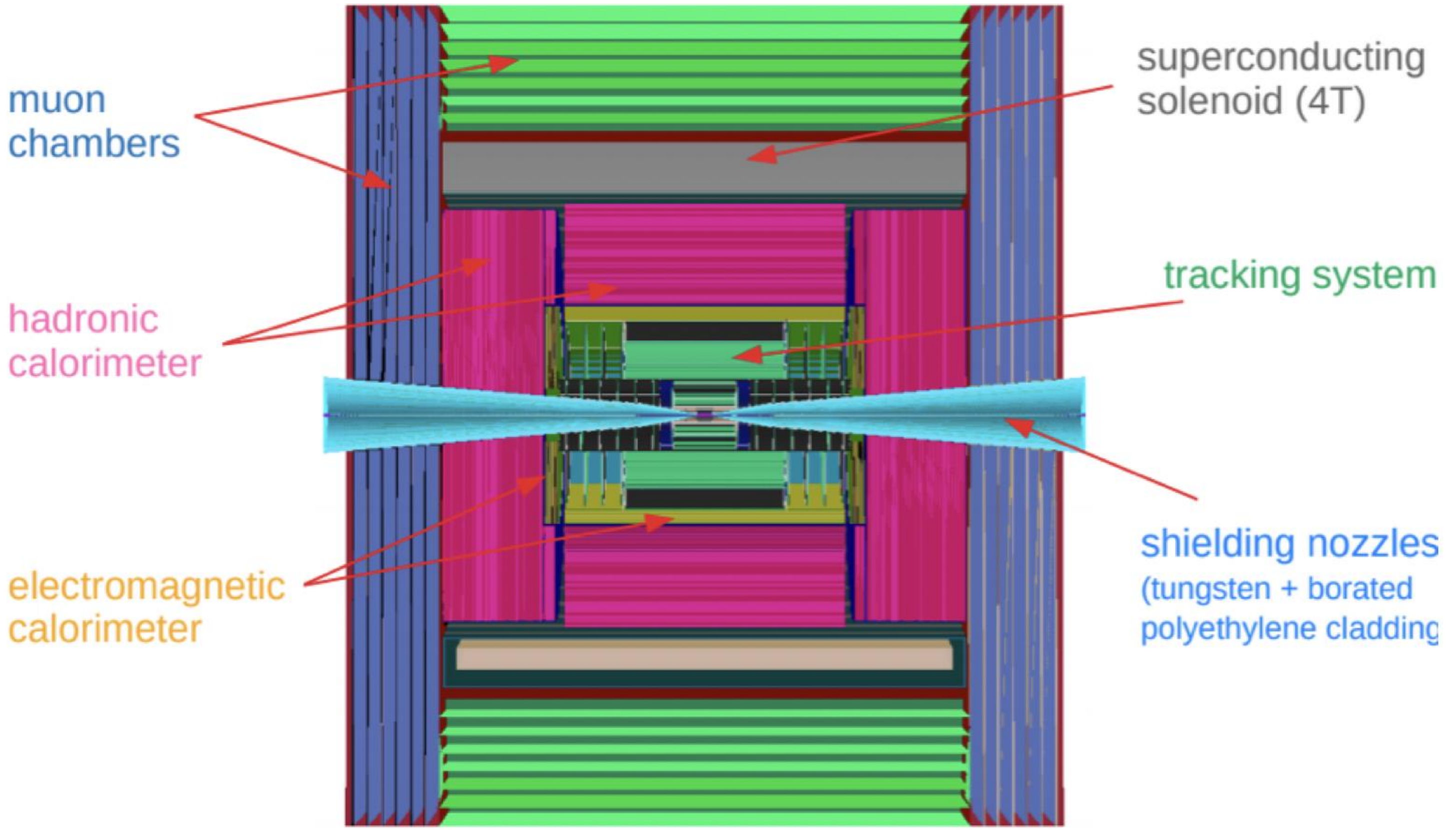
  - Clean collisions

https://arxiv.org/pdf/2303.08533

✓ These characteristics allows to combine:

Direct search on new physics	Precision measurements
E.g. the dark sector	ideal tool for Higgs boson studies

Muon Collider



Main issues: BIB and radiation damage
Optimized detector interface:

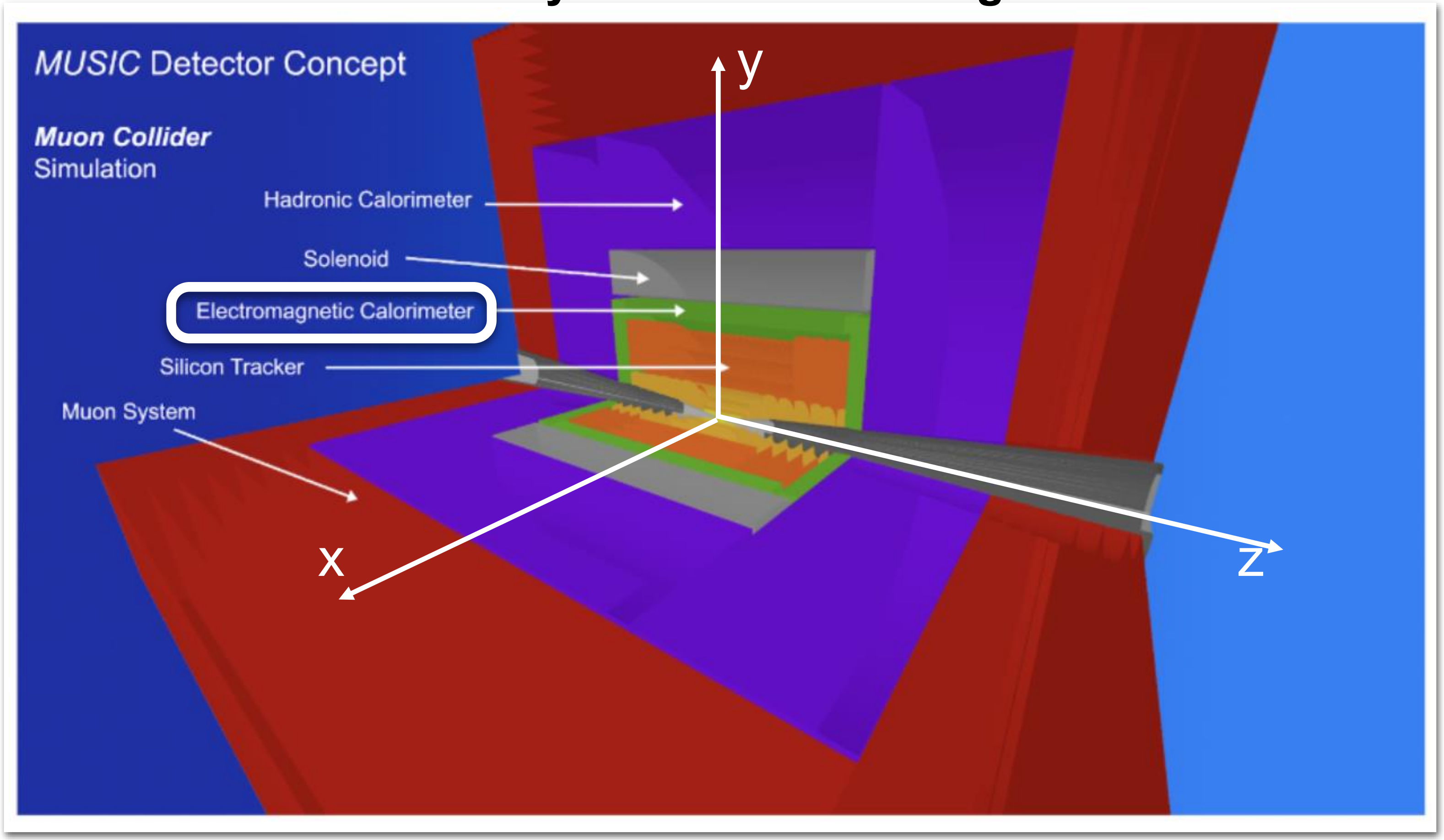
- Based on CLIC detector, with modification for BIB suppression.
- Dedicated shielding (nozzle) to protect magnets/detector near interaction region.

The MUSIC detector layout

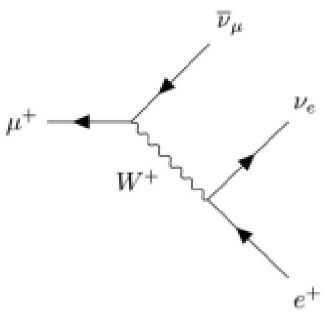
- The detector follows a classical **cylindrical shape** and **hermetic geometry** typical for a multi-purpose detectors for symmetric collisions.

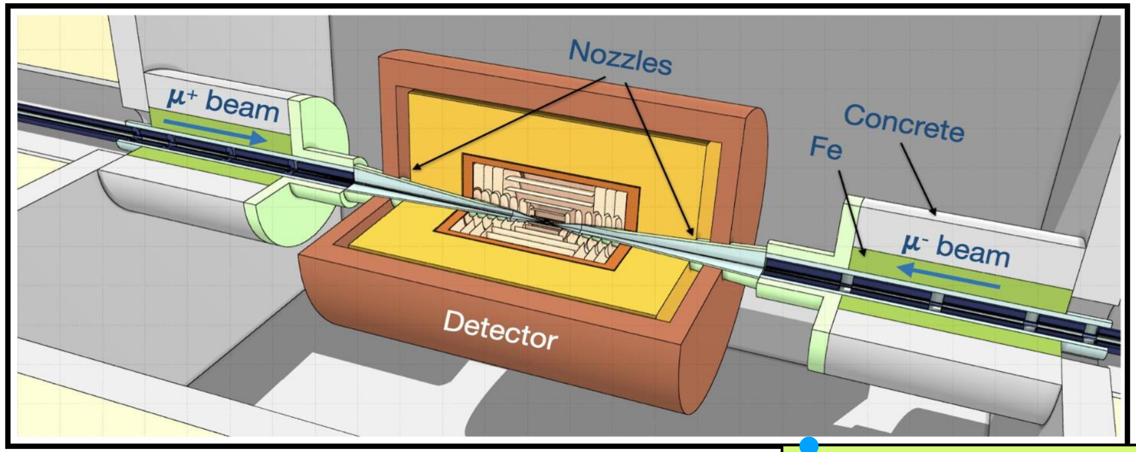
- **Electromagnetic calorimeter** placed in between the **Silicon Tracking system** and the **5 T superconductive solenoid**.

MUSIC: MUon System for Interesting Collisions

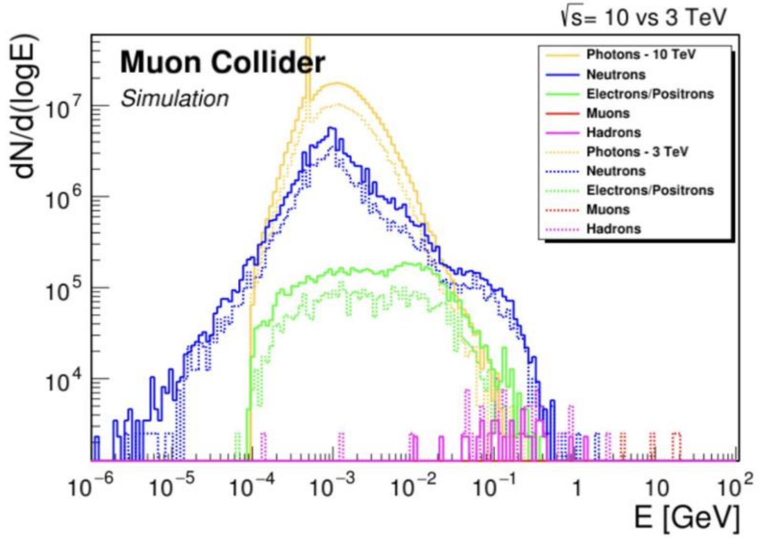


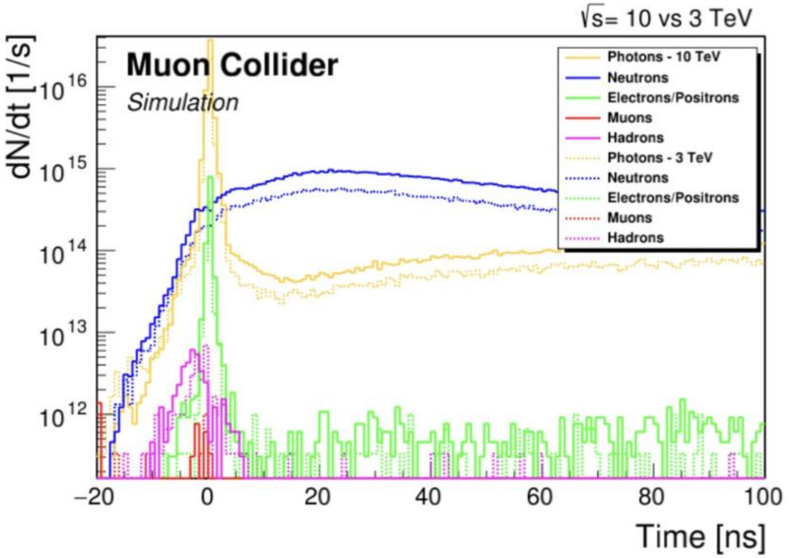
The machine background from muon decays





https://arxiv.org/abs/2311.03280





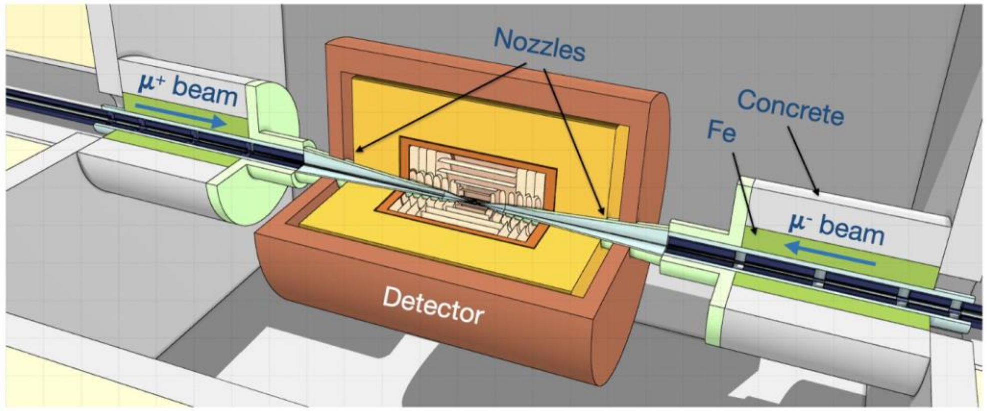
- The **decay of muons** in flight along the accelerator ring produces high-momentum secondary particles, which interact with the machine's materials, and generate an **intense flux of tertiary particles** →**Beam-Induced Background** (BIB)
- Pair of Tungsten conical-shape absorber (nozzles) in the forward region on the detector.
- Residual component characterized by: **low energy** and **broad arrival time distributions**.

For √s=10 TeV, the **incoherent pair production process** is an important source of high-energy background particles in time with the signal.

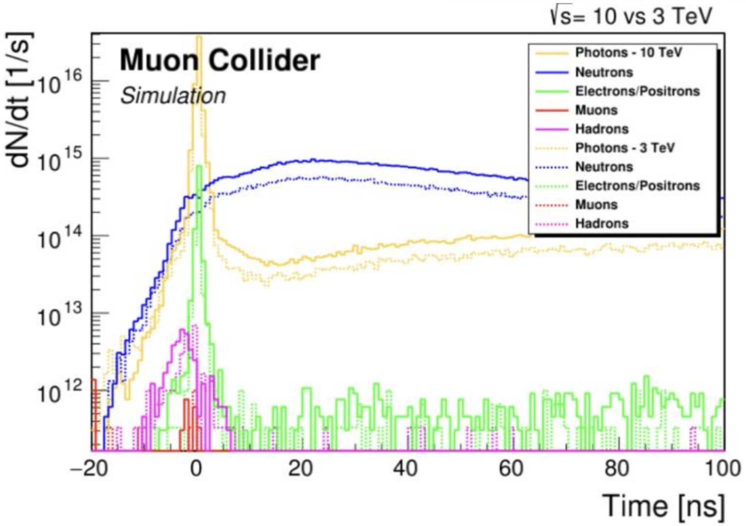
Beam Induced Background

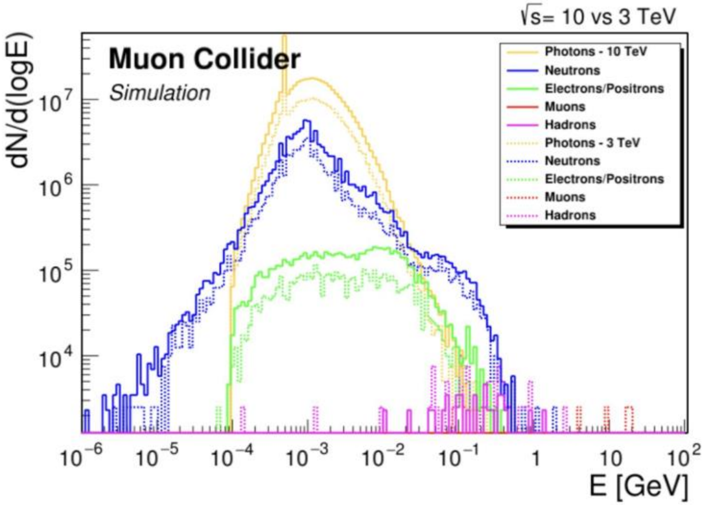
The decay of muons in flight along the accelerator ring produces high-momentum secondary particles, which interact with the machine's materials, and generate an **intense flux of tertiary particles** entering the detector region→ Beam-Induced Background (BIB)

- MDI optimized to reduce this contribution throughout a pair of Tungsten conical-shape absorber (**nozzles**) in the forward region on the detector.
- **Residual component** characterized by **low energy and broad arrival time distributions.**



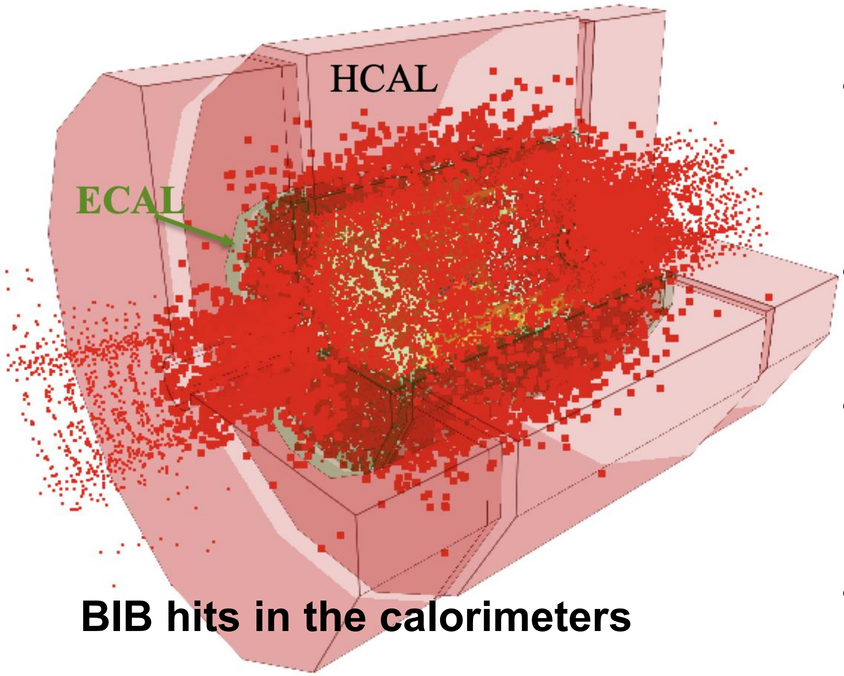
- For $\sqrt{s}$=10 TeV, also the **incoherent pair production** process is an important source of high-energy background particles in time with the signal.





Beam Induced Background

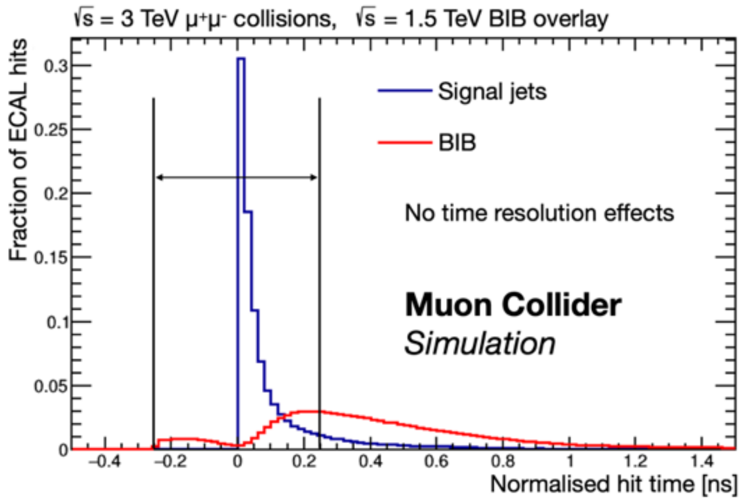
- **The beam-induced background (BIB)** poses the main challenge for the detector development at the Muon Collider
- Produced by muons decay in the beams, and subsequent interactions with the machine
- The BIB produces a flux of 300 particles per cm^2 through the ECAL surface
- 96% photons and 4% neutrons, average photon energy 1.7 MeV

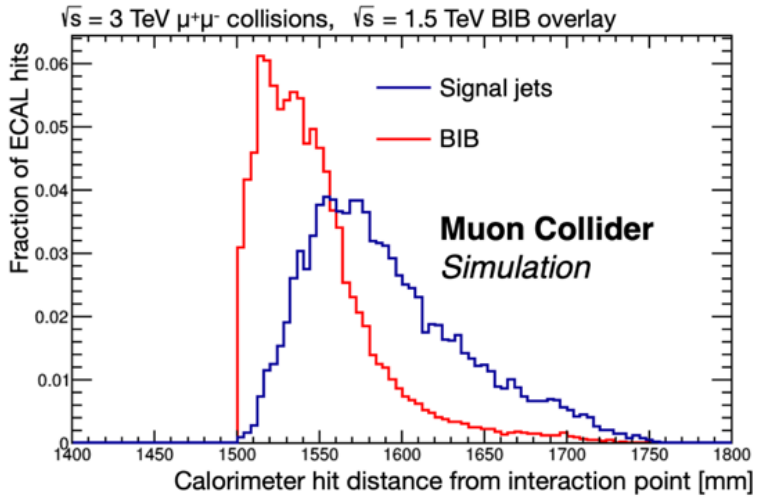


BIB hits in the calorimeters

Key features:

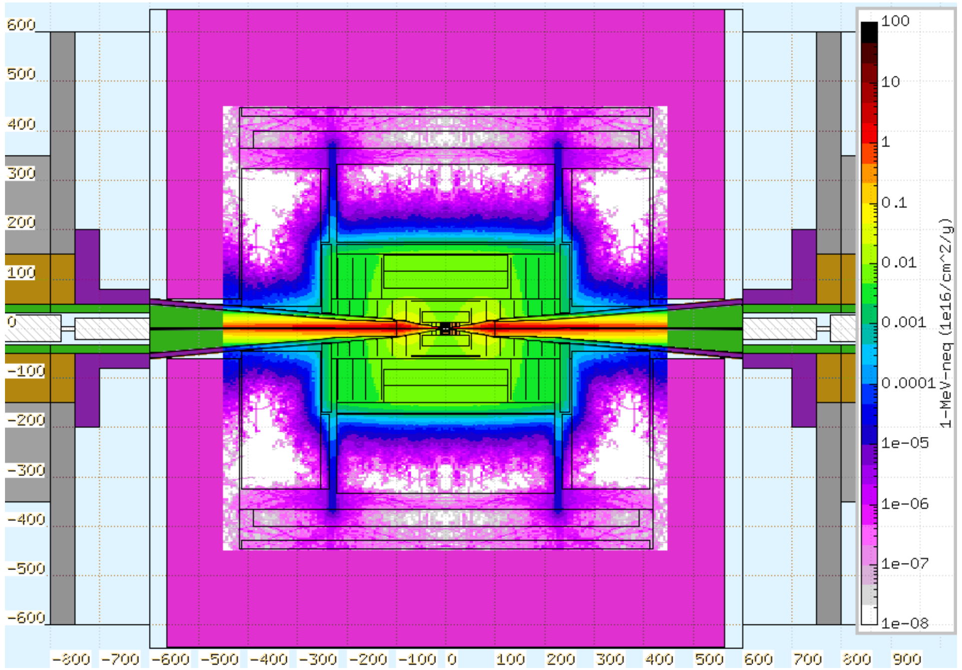
- **Timing**: BIB hits are out-of-time, a resolution in the order of 100 ps is needed
- **Longitudinal segmentation**: different profile for signal and BIB
- **Granularity**: helps in separating BIB particles from signal, avoiding overlaps in the same cell
- **Energy resolution:** target $\frac{\Delta E}{E} \simeq \frac{10\%}{\sqrt{E[\mathrm{GeV}]}}$

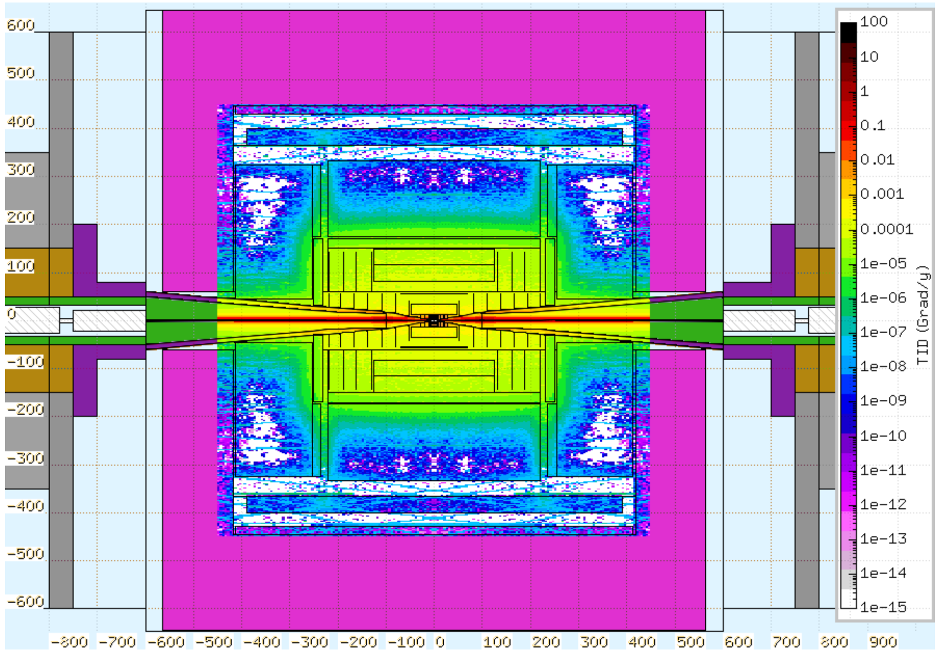




Radiation enviroment

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



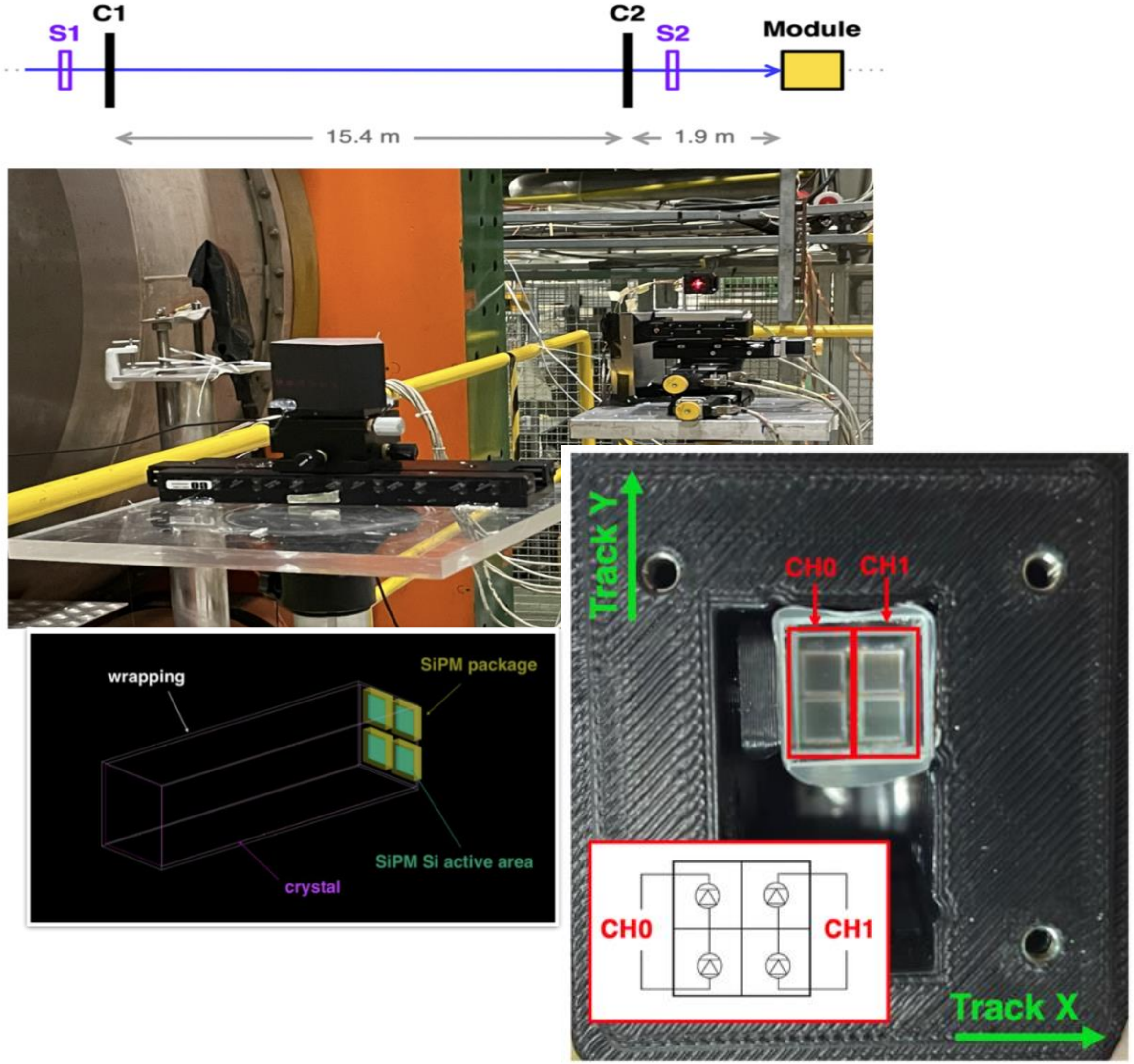


- **Neutron fluence** $\sim 10^{14}$$n_{1MeVeq}/cm^2$**year** on ECAL.
- **TID** $\sim$ **1 kGy/year** on ECAL.

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.



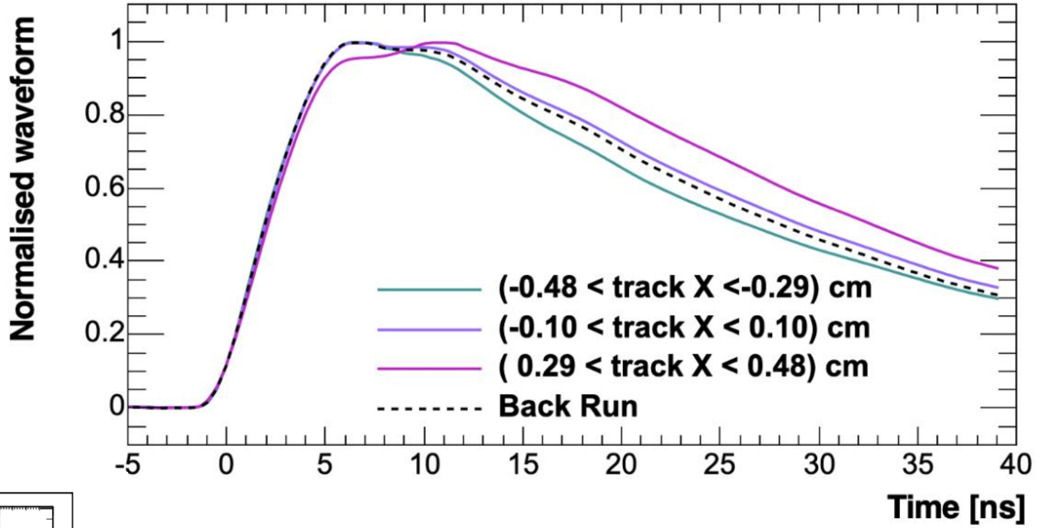
Aim:

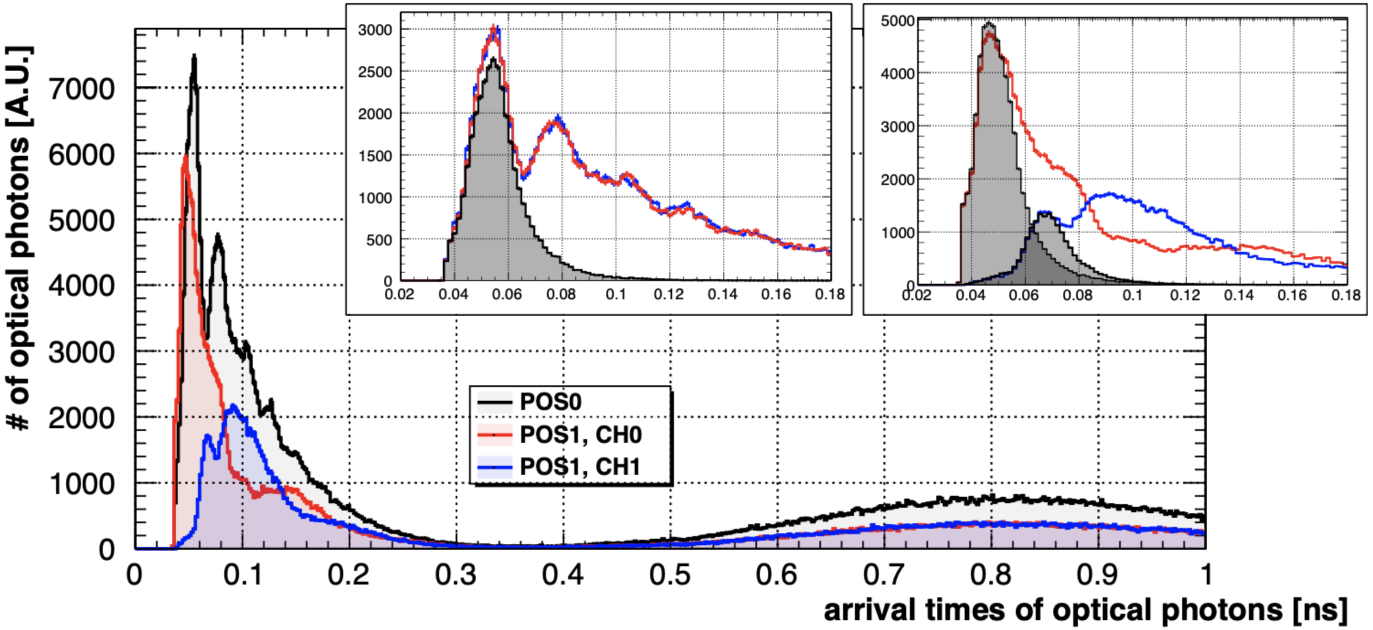
- Validate CRILIN new readout electronics and readout scheme.
- Study systematics of light collection in small crystals with high *n*.
- Measure time resolution achievable with different crystal choices.

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



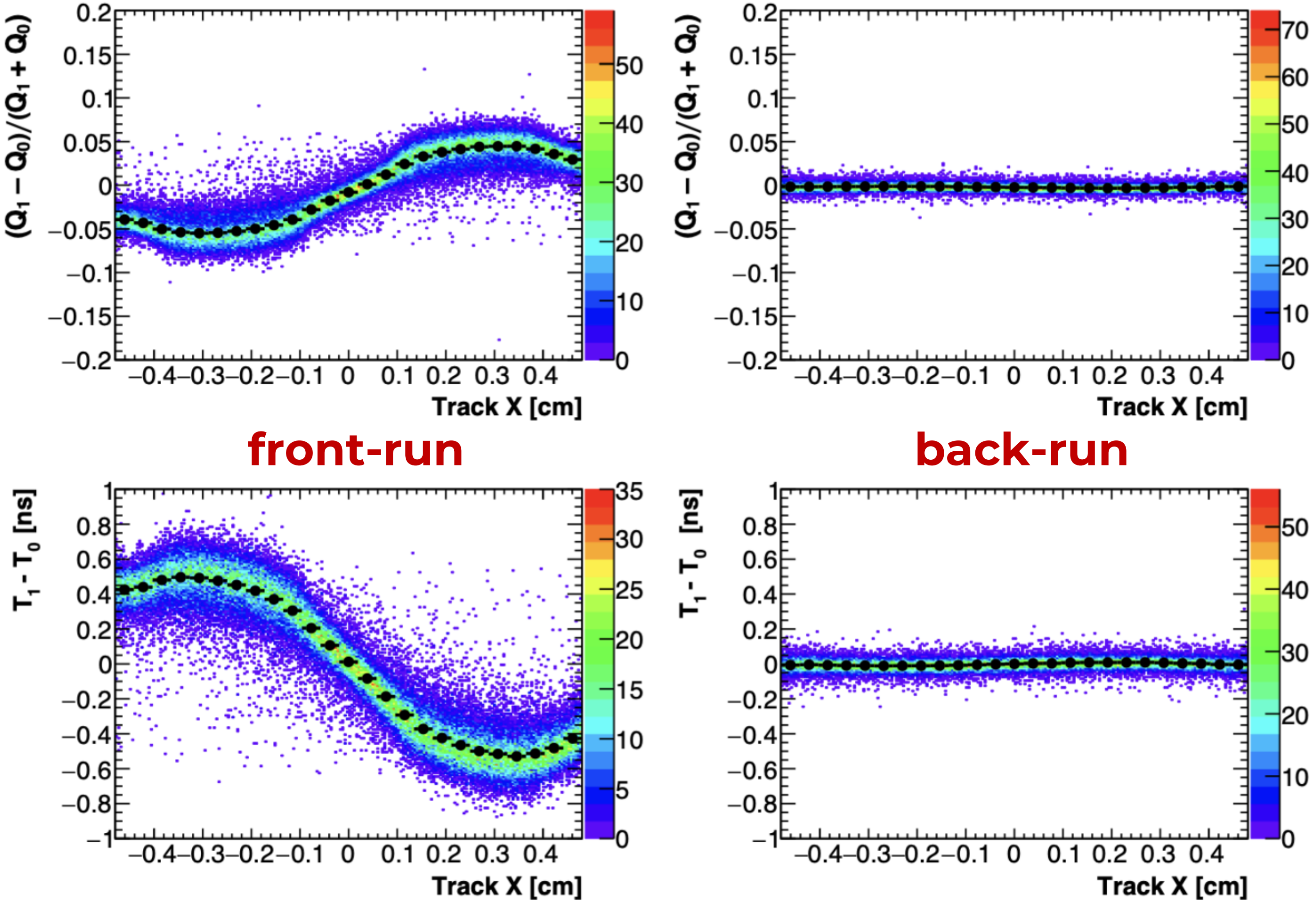


Optical simulation

- 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



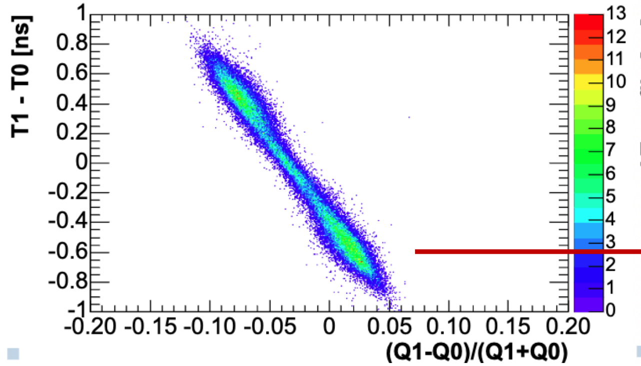
- +/- 10 % maximum imbalance in light collection
- anticorrelated effect on timing (T1-T0)

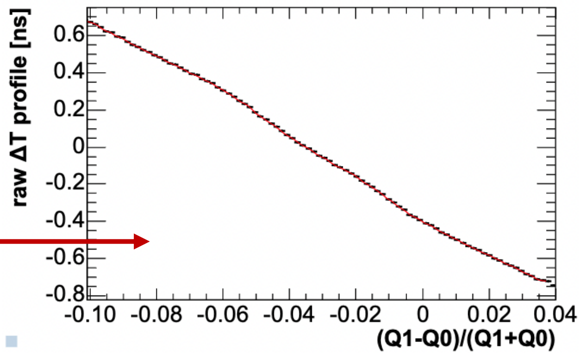
- No significant effects for back-runs
- Similar effects for PbWO4-UF

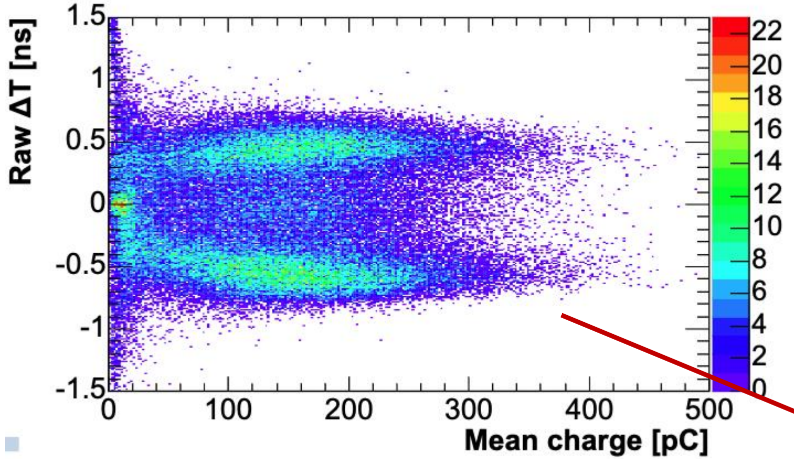
- Light propagated indirectly is more strongly attenuated due to the longer total path length traversed and the multiple reflections
- earlier arrival times for photons arriving directly

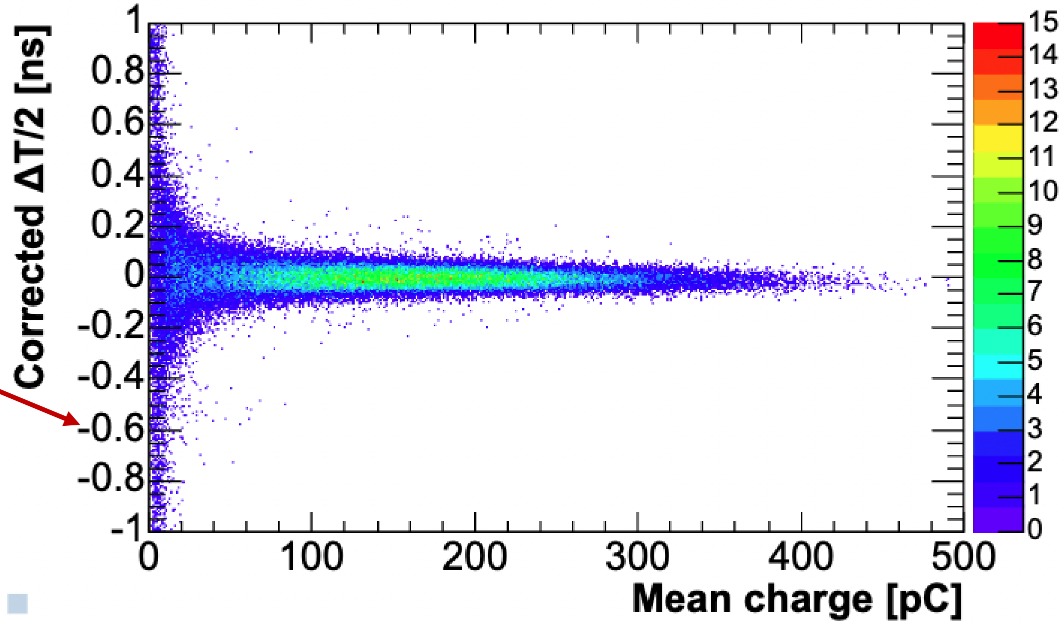
Correction process

- 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



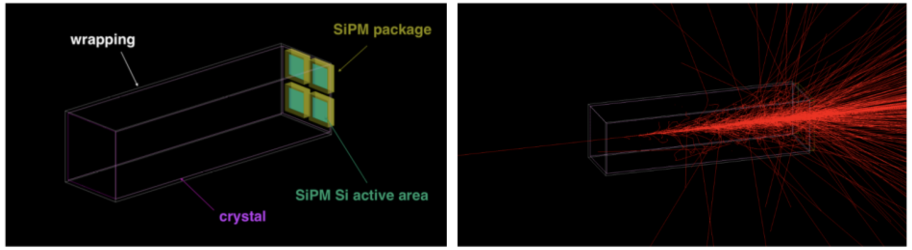


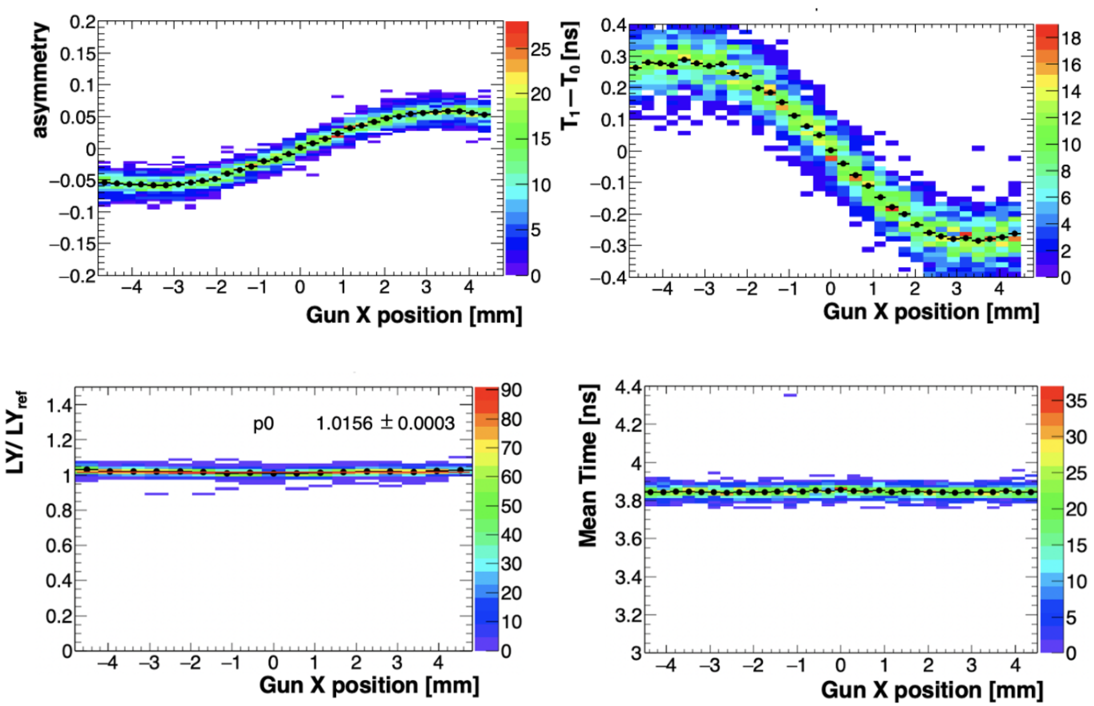


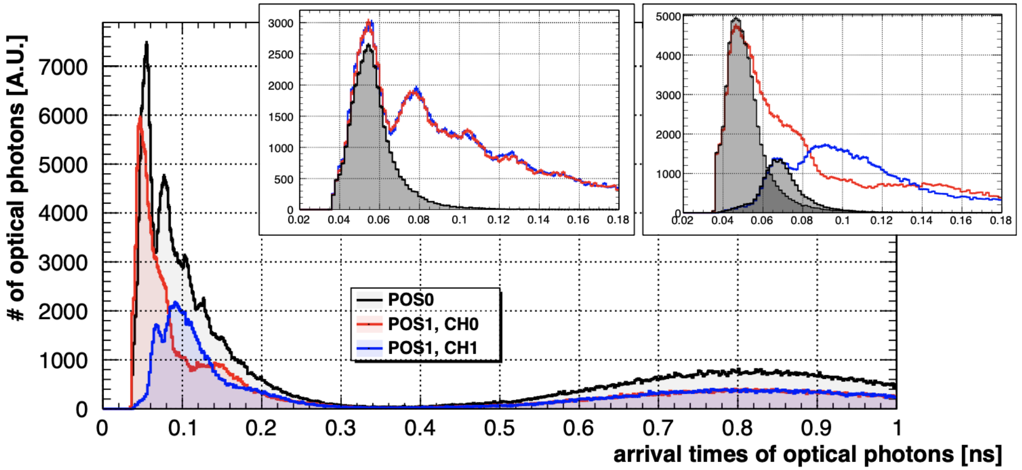


MC validation: optical simulation

- 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

Results

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

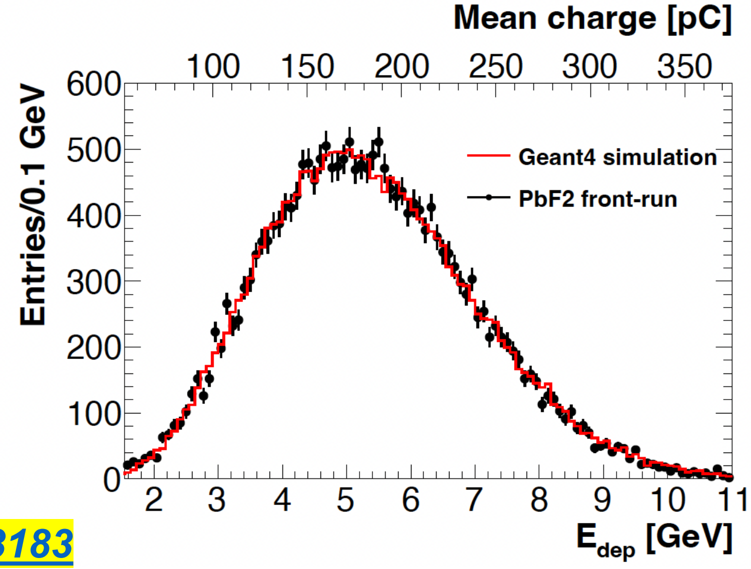
- The BACK run time resolution is better, even after correction, for both crystals.
- PbF_2 outperforms $PbWO_4$-UF despite its higher light output (purely Cherenkov)
- **PbF_2** → σ_{MT} < 25 ps worst-case for E_{dep} > 3 GeV
- **$PbWO_4$-UF** → σ_{MT} < 45 ps worst-case for E_{dep} > 3 GeV

PbF_2

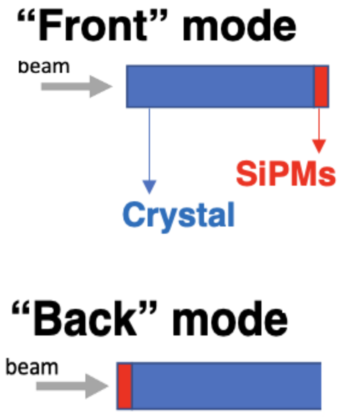
	back-run	front-run
E_{dep} MPV [GeV]	4.26 ± 0.01	4.81 ± 0.03
E_{dep} sigma [GeV]	1.35 ± 0.01	1.46 ± 0.02
pC/GeV	~29.3	~35.6
NPE/MeV	~0.30	~0.30

PWO-UF

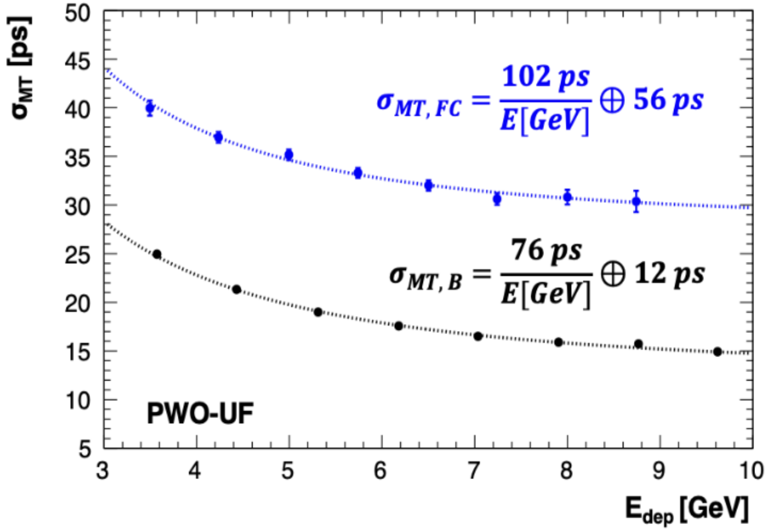
	back-run	front-run
E_{dep} MPV [GeV]	6.39 ± 0.01	6.88 ± 0.01
E_{dep} sigma [GeV]	1.83 ± 0.01	1.99 ± 0.01
pC/GeV	~66.7	~76.9
NPE/MeV	~0.11	~0.13

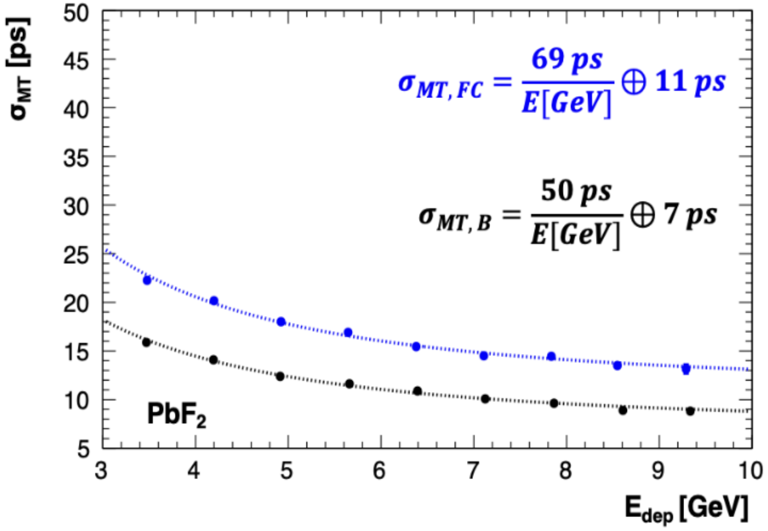


C. Cantone et al. 2023 Front. Phys. 11:1223183



Proto-0

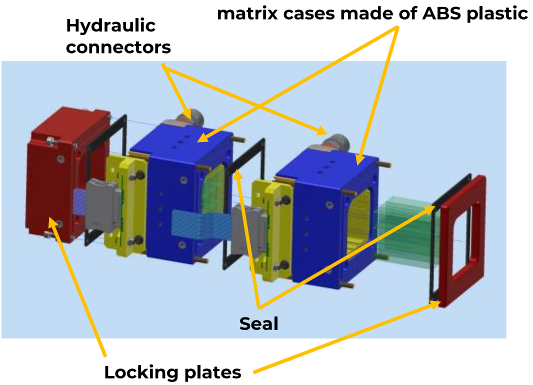


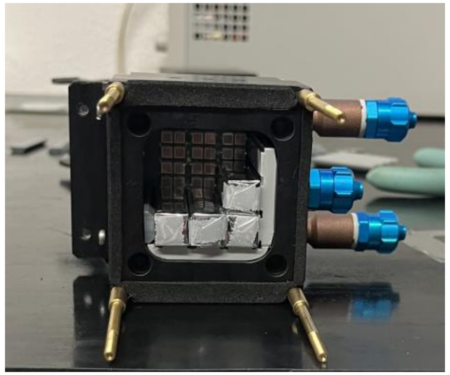


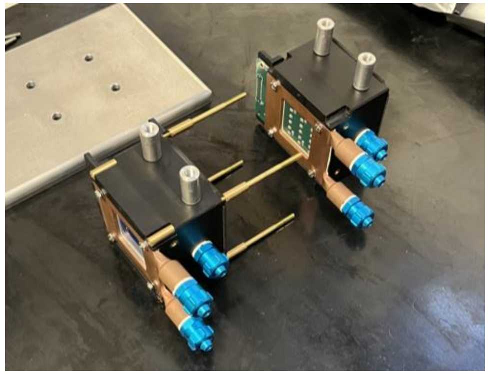
Proto-1: Mechanics and Electronics

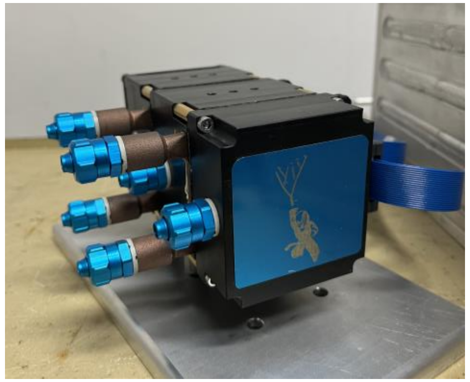
Mechanics:

- 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.



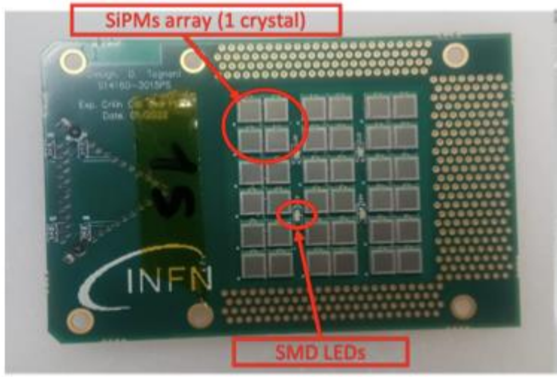


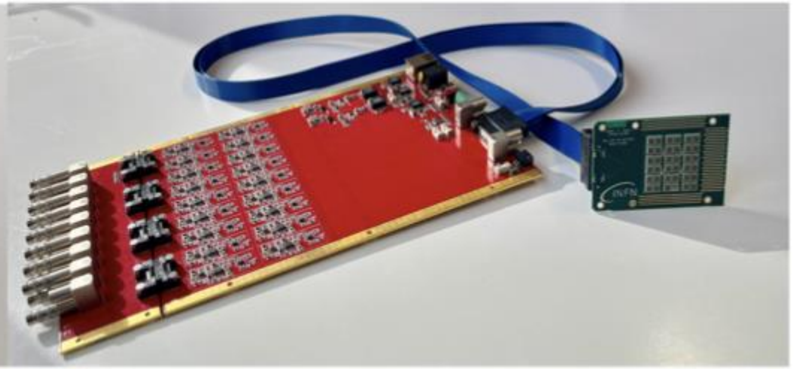




Electronics:

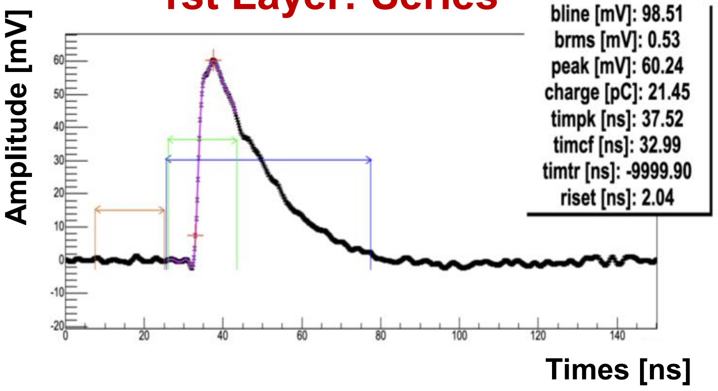
- **SiPMs board:** custom SiPM array board 36x10 μm Hamamatsu SMD SiPMs
- **Mezzanine board:** 18x readout channels → amplification, shaping and individual bias regulation, slow control routines



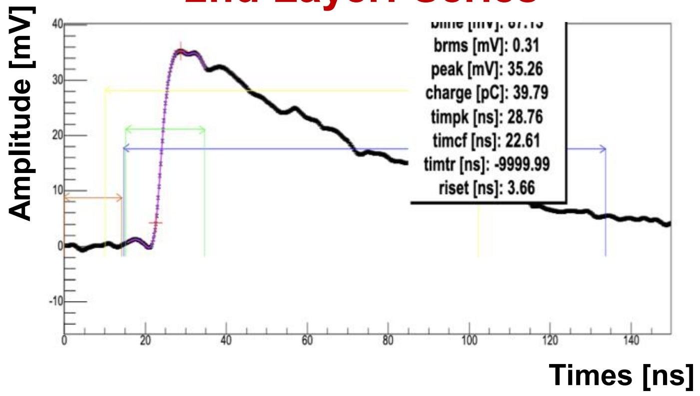


Proto-1 beam test @ CERN

1st Layer: Series



2nd Layer: Series

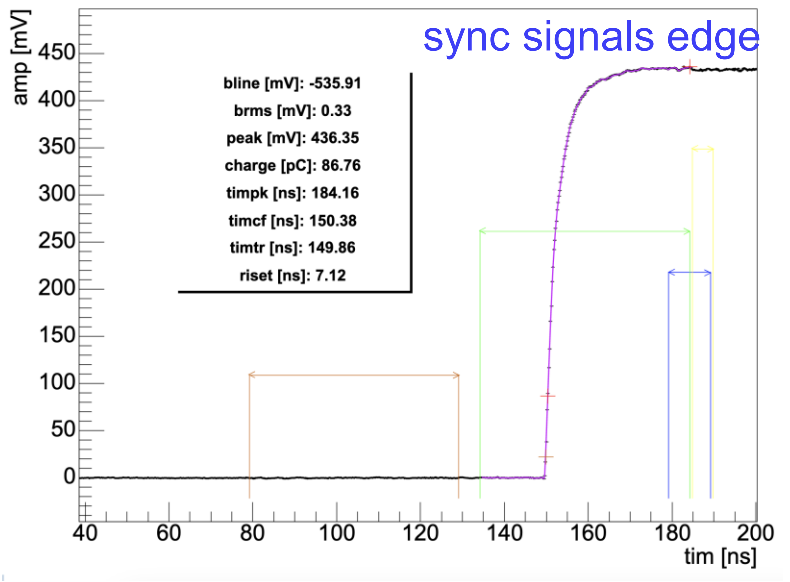


- **Two different connection in the two layers:** series and parallel
- **Low pass filtering** (Bessel 2nd order) cutoff_parallel ~ 2 * cutoff_series.
- Cut-off frequency based on two parameters: baseline RMS and risetime (10-90%)
- Wave quality flag based on baseline RMS, peak, and risetime to discard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

Sync pulses reconstruction:

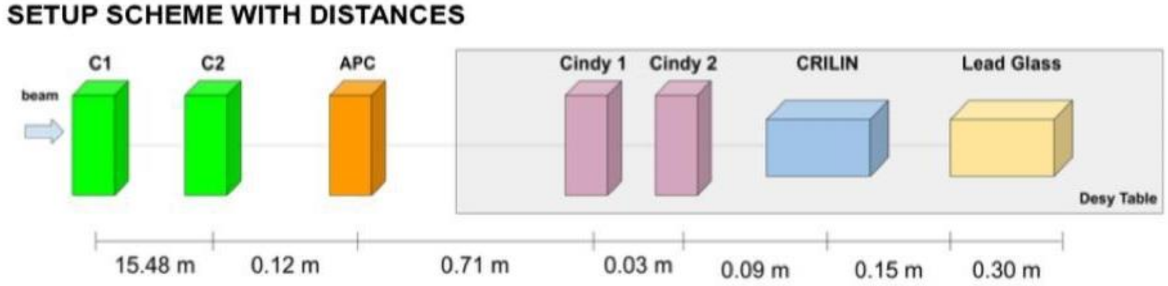
- O(10 ps) ch-to-ch in the same chip

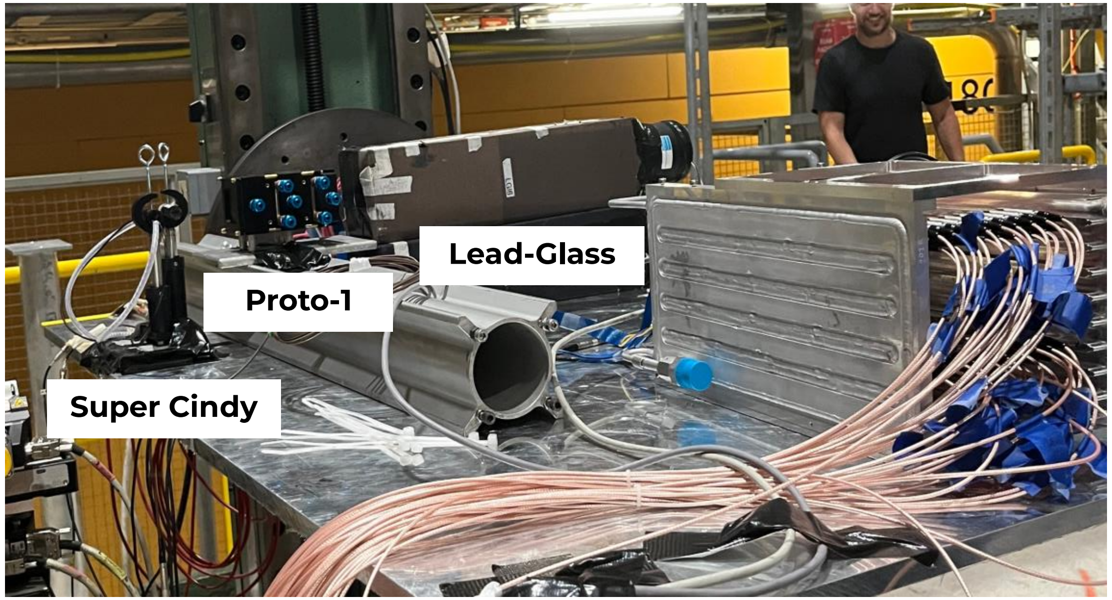
- O(30 ps) board-to-board jitter

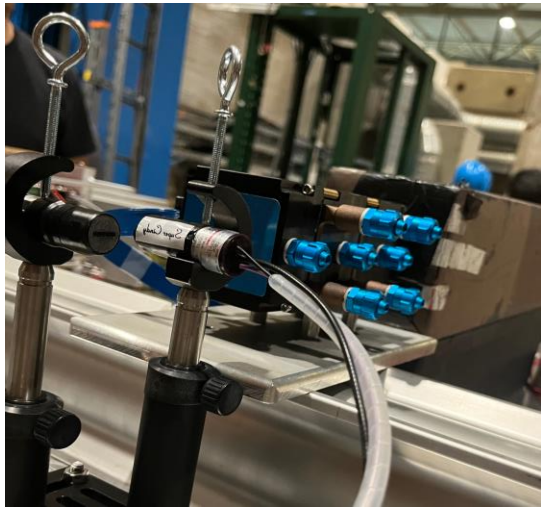


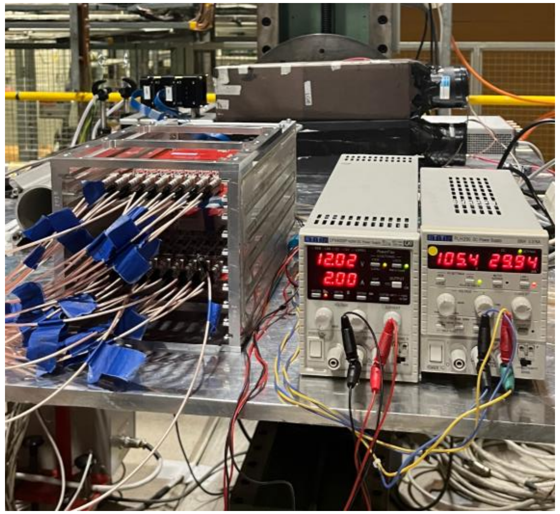
Proto-1 beam test @ CERN: setup

H2-SPS-CERN, August 2023









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

Radiation hardness of PbF2 and PWO-UF

- Expected ECAL barrel ionizing radiation dose: 1 kGy/year (100 krad)
- Expected ECAL barrel neutron fluence: 10^{14} $n_{1MeVneq}/cm^2$ / year

Preliminary conclusions:

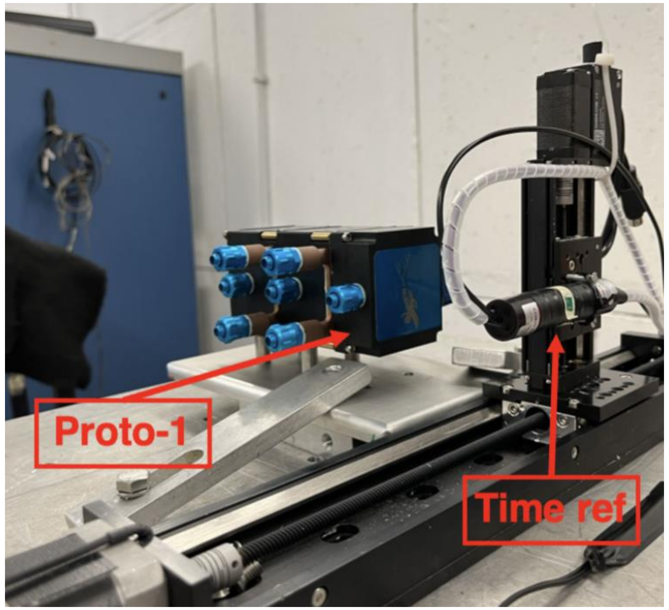
- PbF2 shows increased transmission threshold at low wavelength already at 10-100 kGy
- PWO-UF shows no shift in low-wavelength threshold and only ~2% loss of blue-green transparency even at 2 MGy!

- **Czochralski-grown** PWO (Crytur) is of high quality. Literature suggests that **Bridgeman-grown** PbF2 (SICCAS) may have inferior radiation hardness, requiring separate validation.

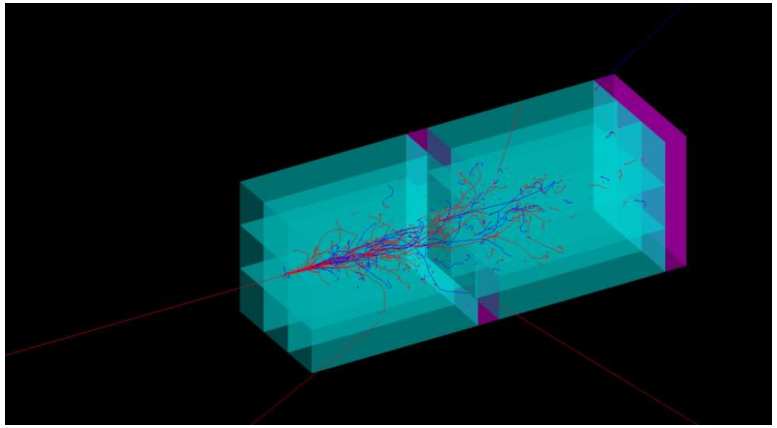
Light Yield (LY) loss evaluation @ BTF

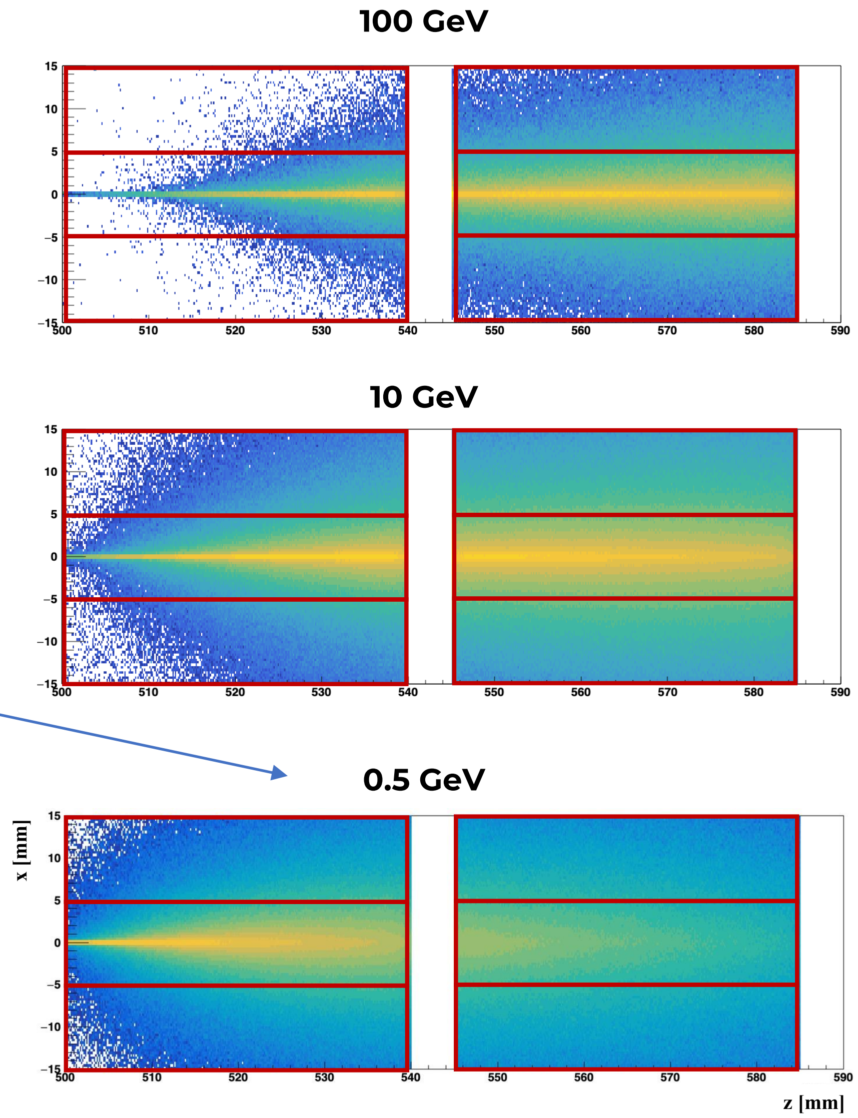
BTF, April 2024

- Study of the LY loss of 1 layer of Proto-1 after TID irradiation
- Beam: 450 MeV electrons with average multiplicity set to 1
- Beam centered on all 9 crystals (one at the time)



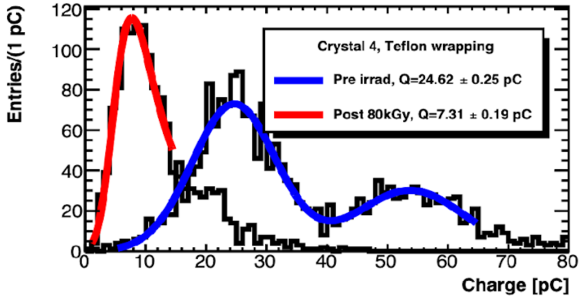
Monte Carlo

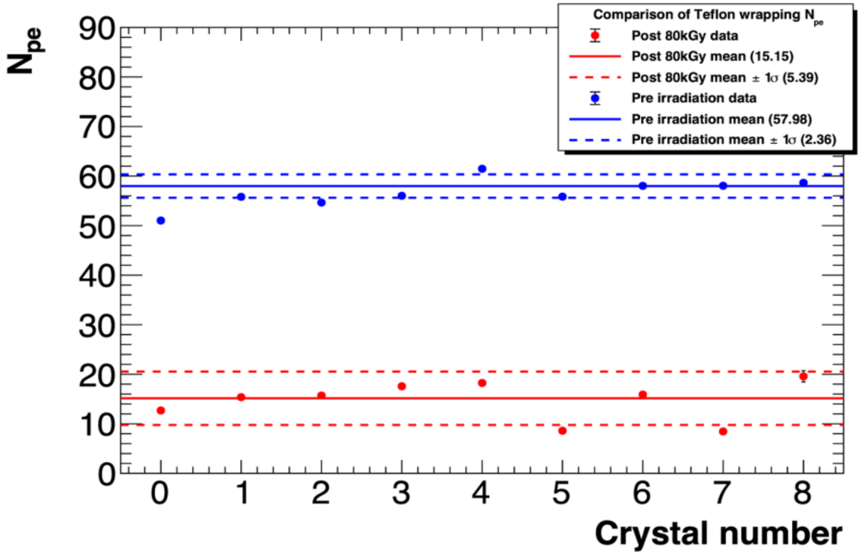


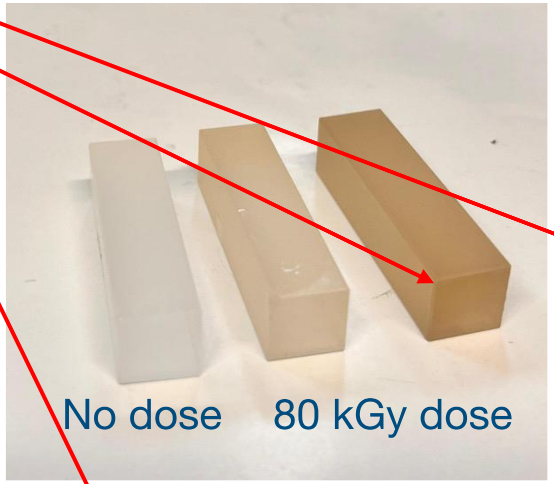


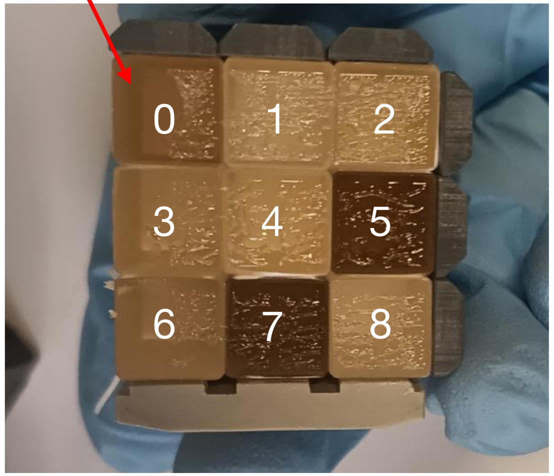
LY loss @ BTF: Teflon wrapping

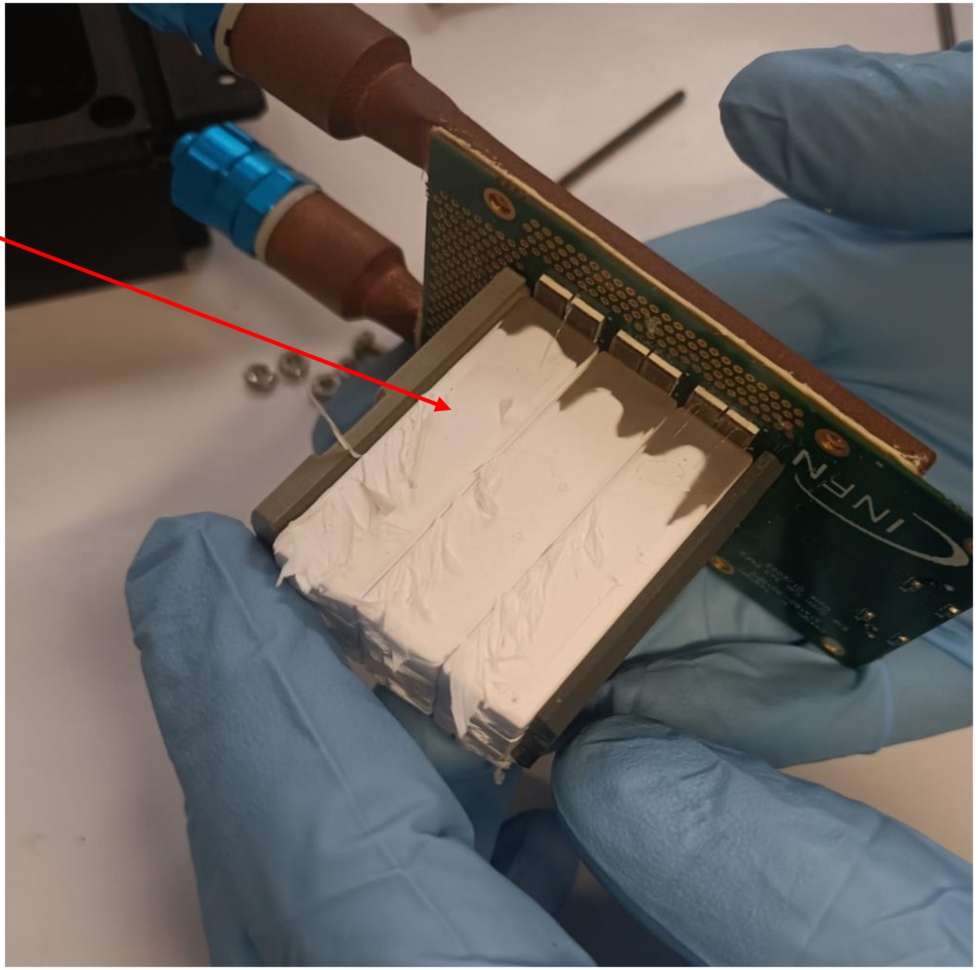
After 80 kGy (8 Mrad) irradiation
- Teflon was damaged and brittle
- Crystals show loss of transparency
- Huge variability between crystals









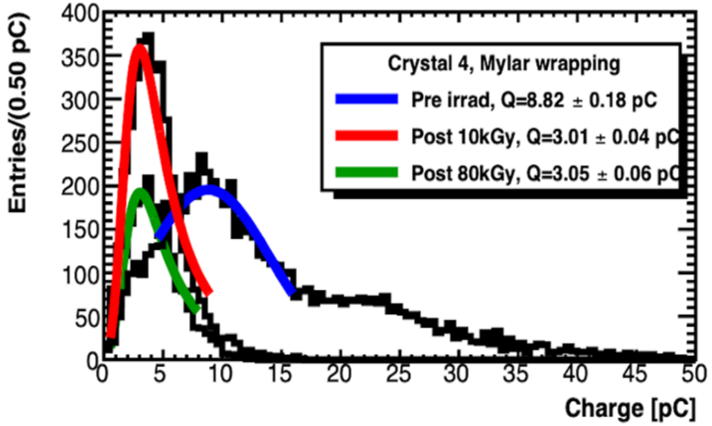


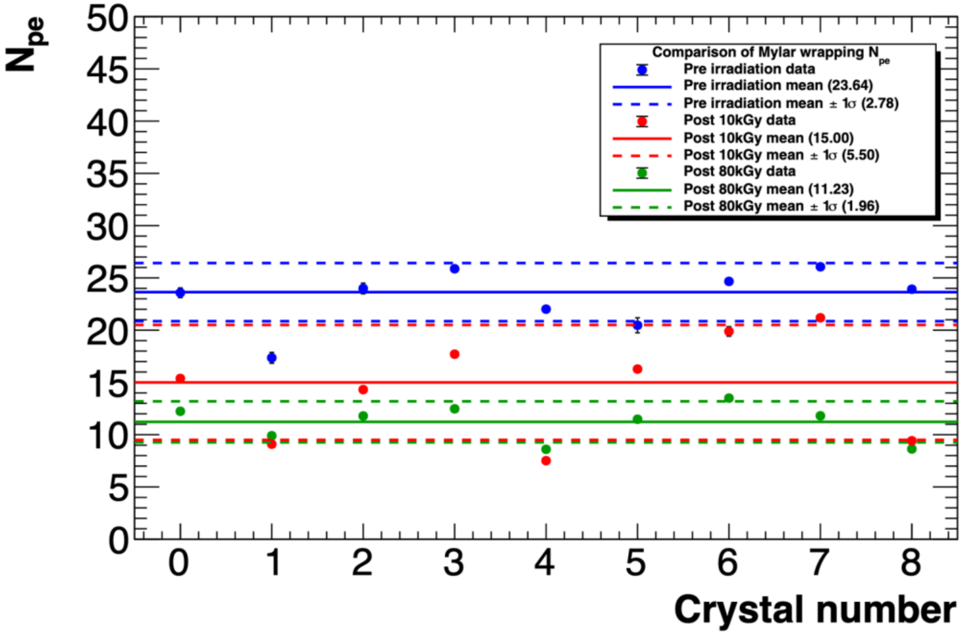
Beam test @ BTF: Mylar wrapping

- Test repeated with a Mylar wrapping
- Same SiPMs / new crystals
- *No annealing effect after 48h and 60h*

- *SiPMs PDE loss and window degrading not yet tested*
- *New test scheduled for January with laser monitoring (SiPM only + Crystal&SiPM)*

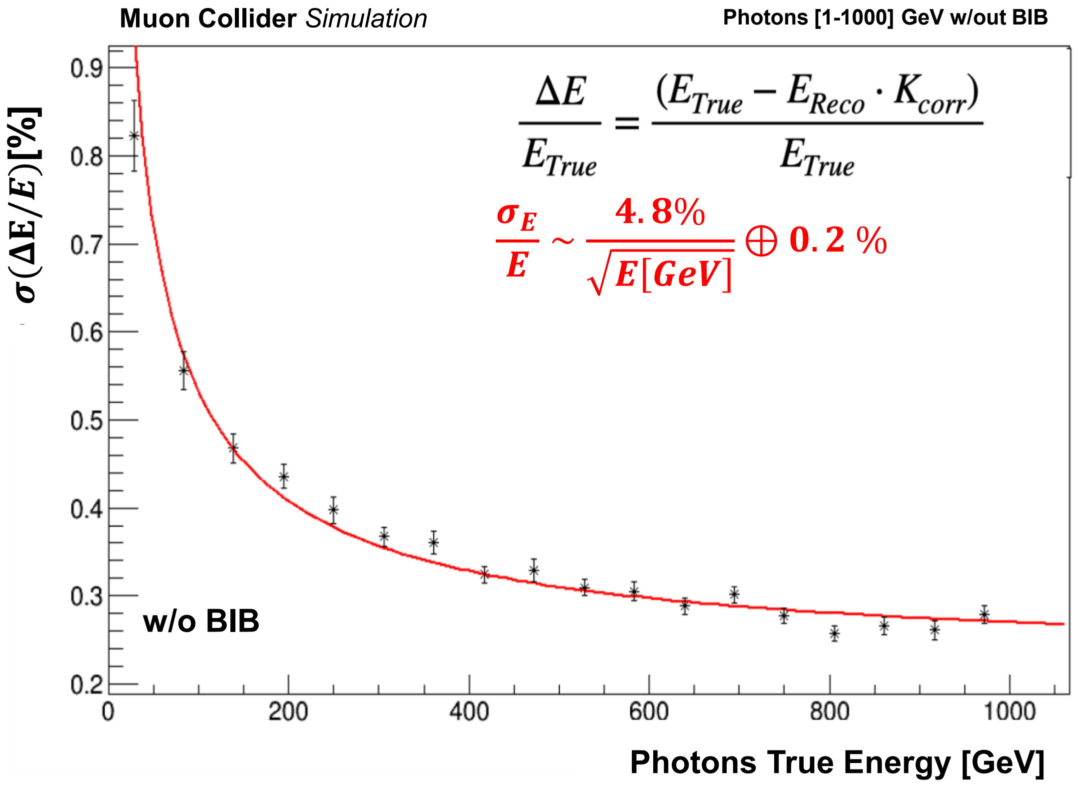
Charge distribution of PbF_2 pre, after 10 kGy and after 80 kGy irradiation

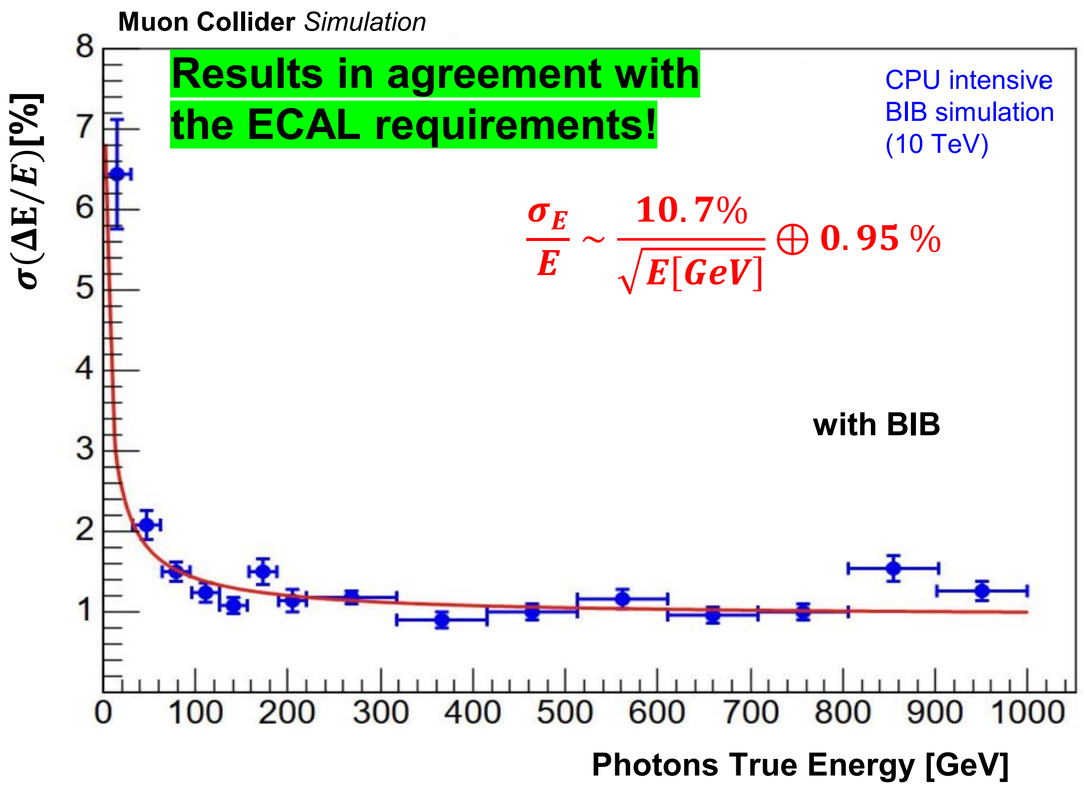




Simulated performances

- ECAL barrel with Crilin technology implemented in the Muon Collider simulation framework
  - 6 layers with 45 mm length, 10x10 mm^2 cell area → **25 X_0**
  - **In each cell:** 40 mm PbF_2 + 3 mm SiPM + 1 mm electronics + 1 mm air
  - Light yield and time resolution taken from test beams



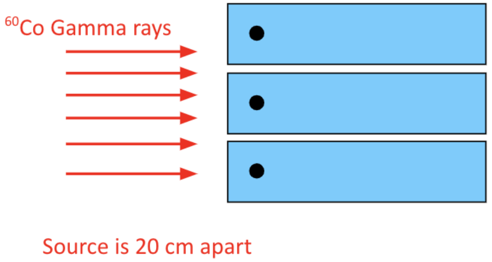


Crystals radiation hardness

Neutron fluence: ~$10^{14} n_{1MeVeq}/cm^2$ year on ECAL + **TID (total ion. Dose): ~ 1 kGy/ year** on ECAL

Both PbF_2 and $PbWO_4$-UF crystals (1x1x4 cm^3) irradiated with:

- TID (up to 2 MGy @ Calliope, Enea Casaccia)
- Neutrons (up to 10^{13} n/cm^2 @ FNG, Enea Frascati – 14 MeV fast neutrons)

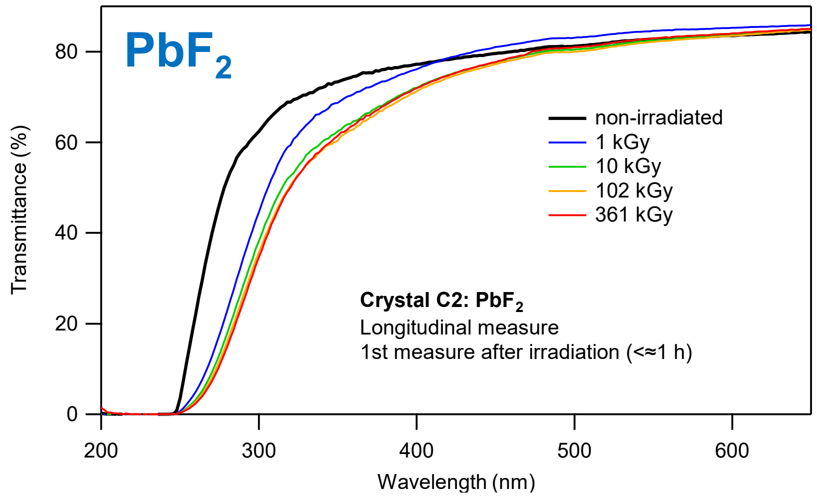


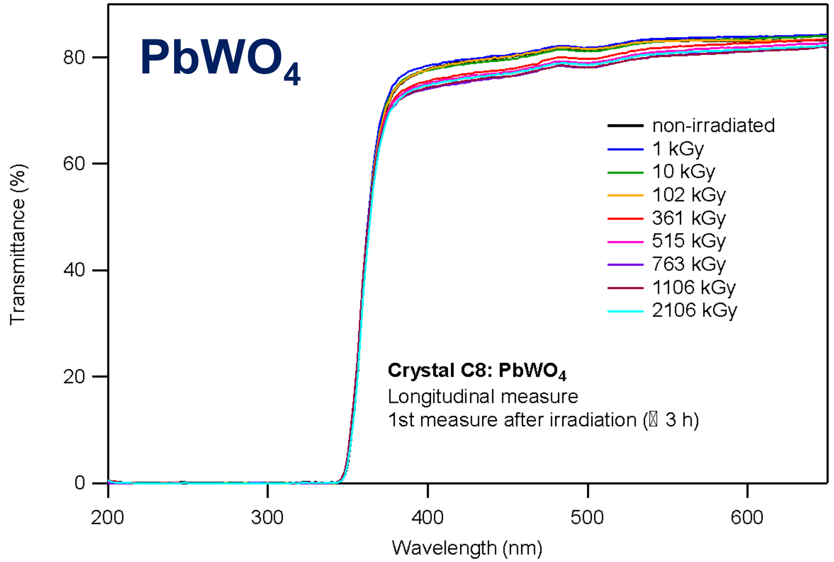
- **For PbF_2:**
  - after 350 kGy TID: *no problematic decrease* in transmittance
  - No deterioration with neutrons

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 2 MGy TID: no problematic decrease in transmittance

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





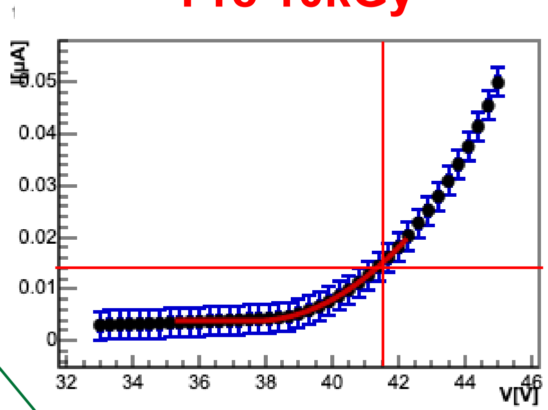
SiPMs radiation hardness

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

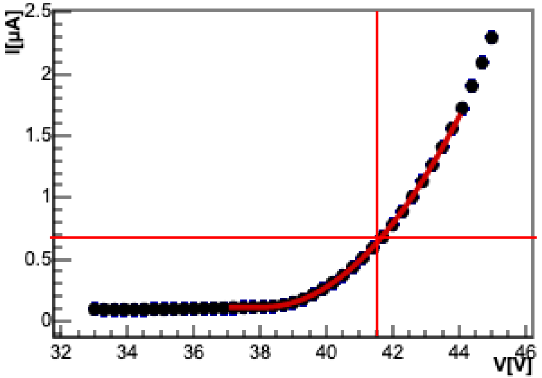
- **10 kGy** TID on single SiPMs
- **Neutrons irradiation:**
  - 10^{14} n/cm² at 14 MeV for 80h on a series of 2 SiPMs (10 and 15 μm pixel-size)
- Extrapolating from I-V curves at 3 different temperatures:
  - Breakdown voltages (V_{br})
  - Currents at the operational voltage ($V_{op} = V_{br}$+4V)

For the expected radiation level, **the best SiPMs choice are the 10 μm ones** for their lower dark current (dominated by neutron damage)

Pre 10kGy



Post 10kGy



Dark current @ V_{op} (~41.5V) goes from 14 nA to 600 nA

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

Towards the real detector: Proto-2

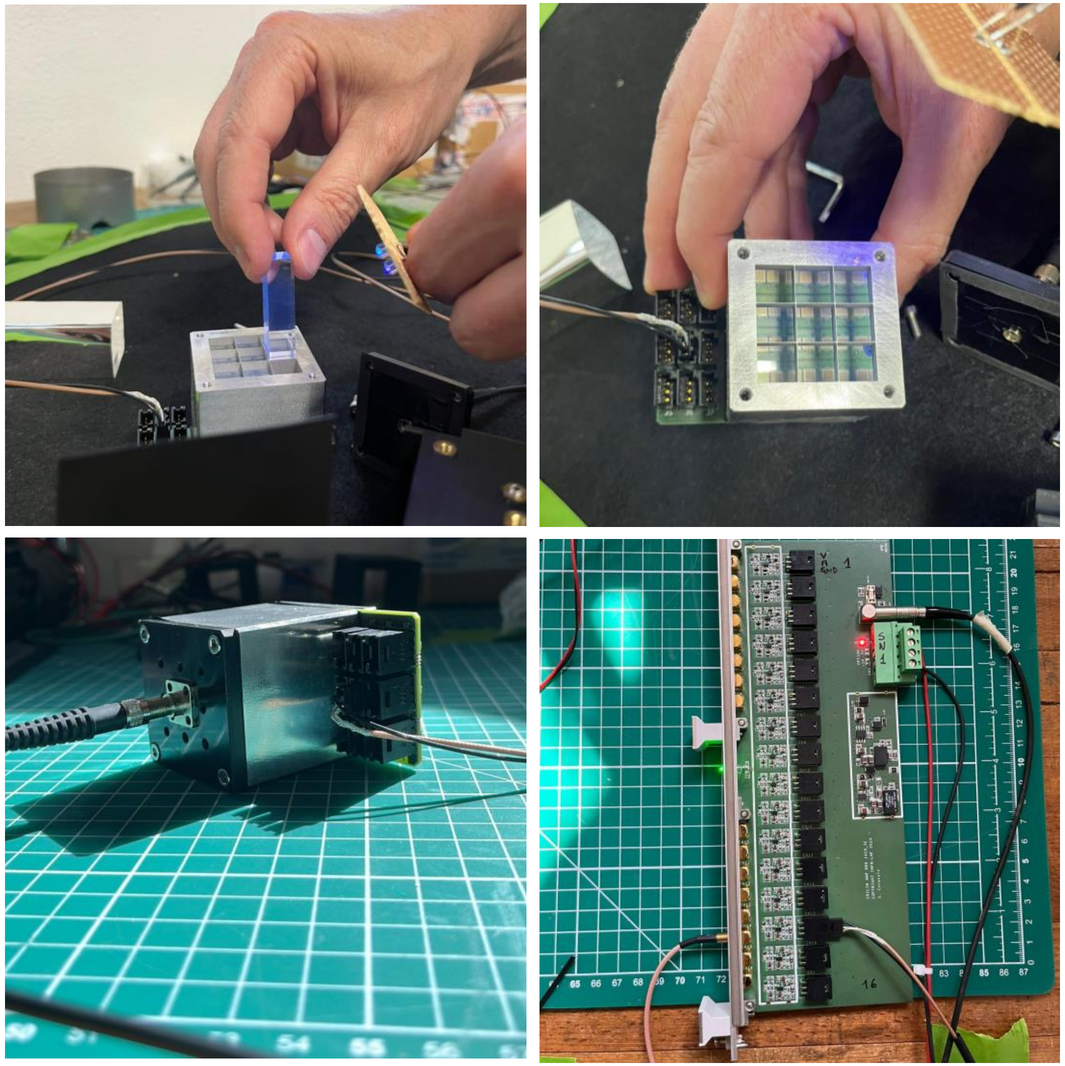
Prototype versions
- Proto-2 (3x3 crystals x 1 layers)

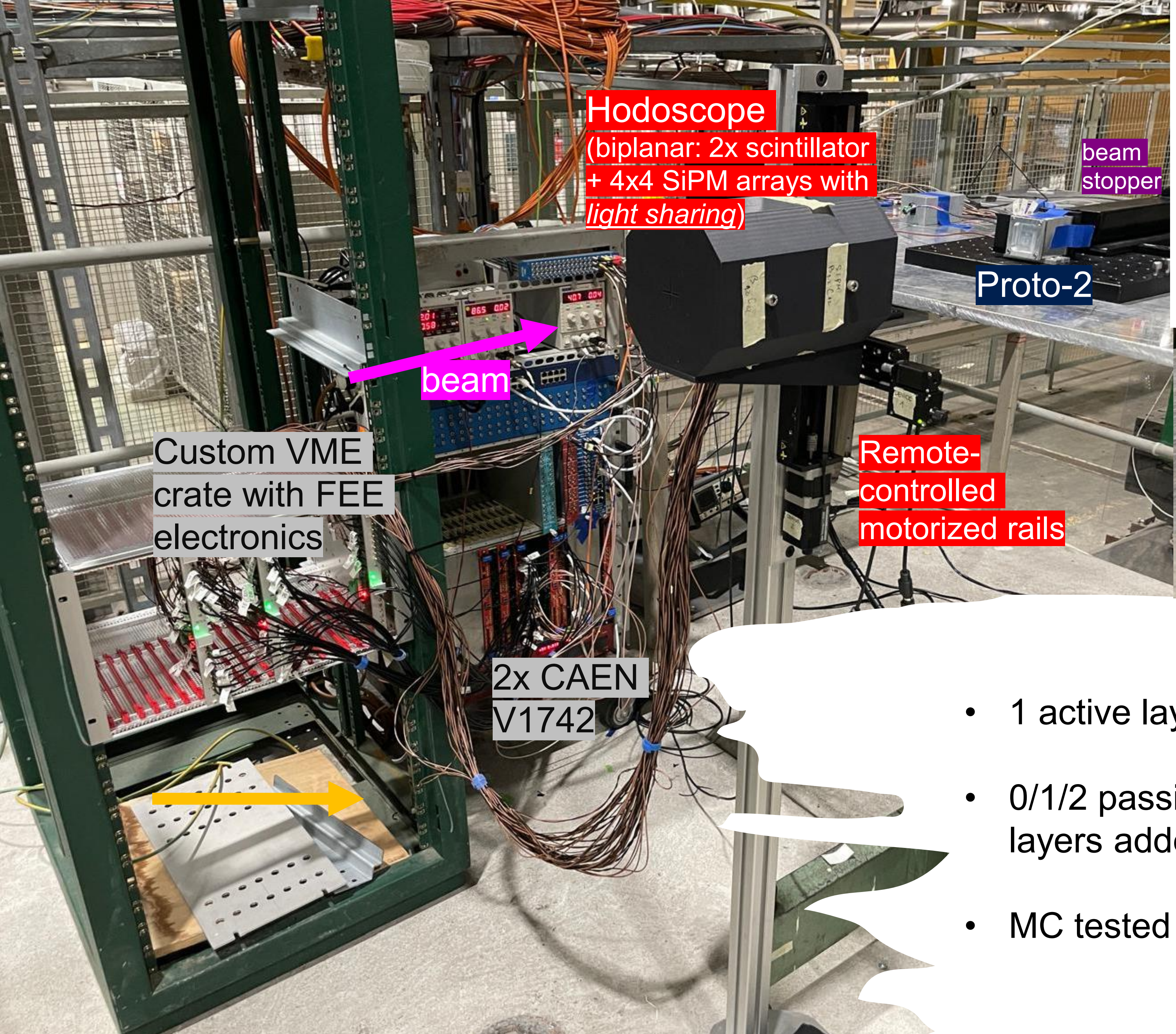
Mechanics
- New aluminum 3x3 alveolar matrix with 150 um septa

Front-end electronics
- Upgraded electronics (faster)

Lab tests
- Cosmics with LYSO crystals

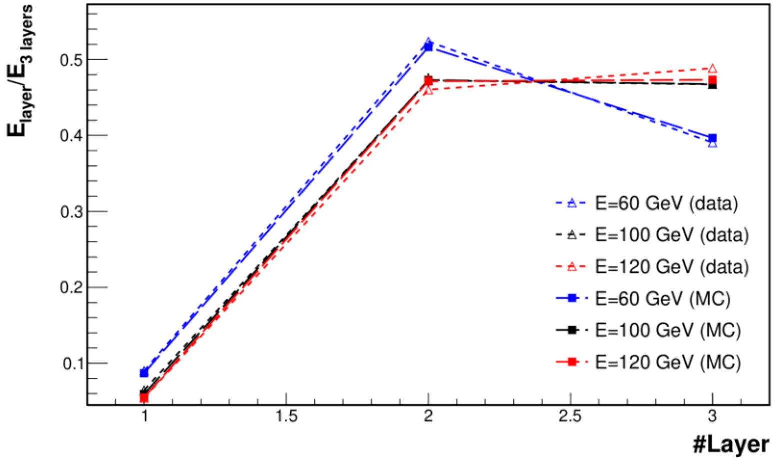
Beam test campaigns
- Proto-2 at CERN H2 (September 2025)





September 2025 @ SPS-H2

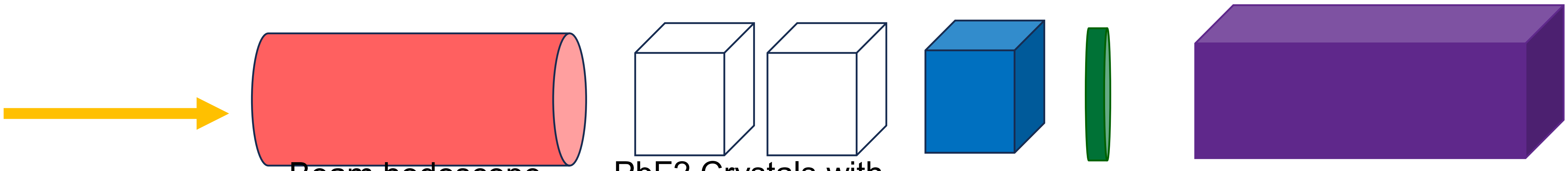
- 1 active layer
- 0/1/2 passive layers added
- MC tested



Test Beam @ CERN SPS 2025

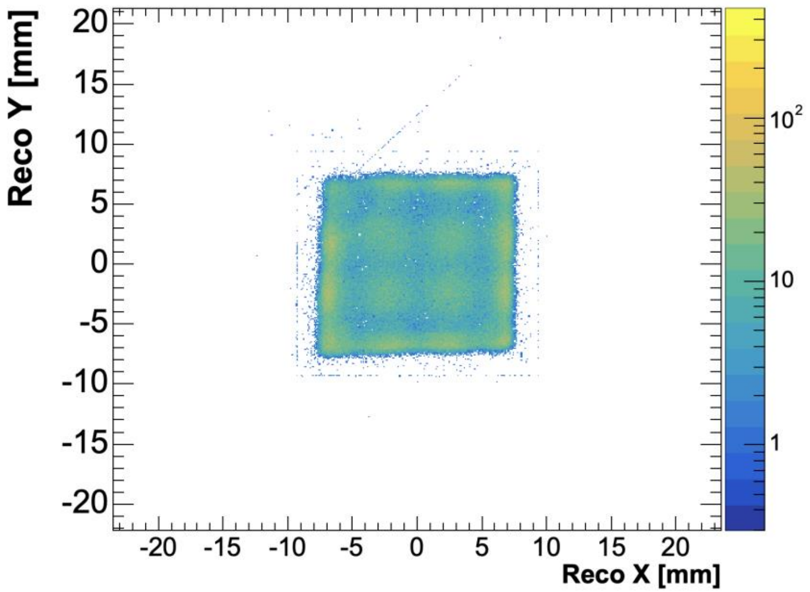
- Measured the response of layers 1, 2, and 3 by adding passive layers at different beam energies (60, 100, and 140 GeV)

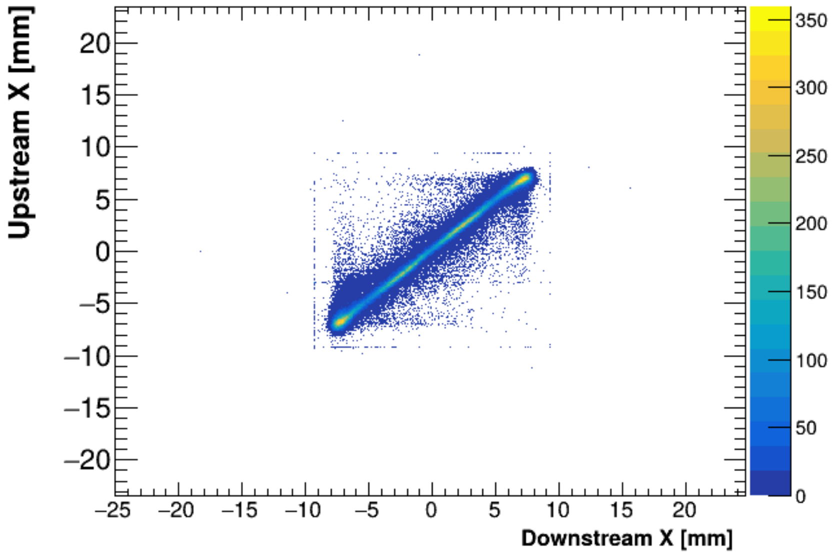
- Tested a new beam hodoscope (scintillator+SiPMs with light sharing)
  - Achieved a spatial resolution of about 150 μm in x and y

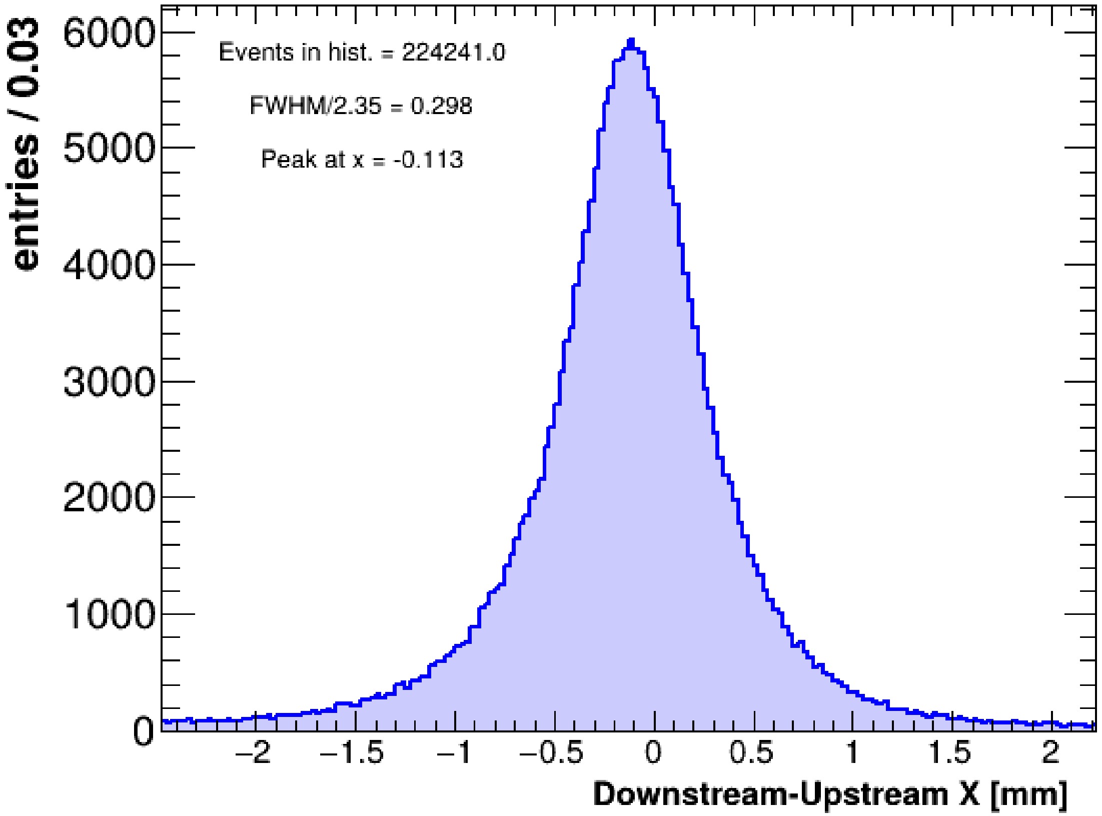


Proto-2: test beam highlights

PRELIMINARY







Beam profile with hodoscope (X, Y) + **resolution** and **correlation** between **2 layers**