CALORIMETERS

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Workshop on FCC-ee and Lepton Colliders

January 24, 2025

Overview: Calorimeters for Future Colliders

- **Scope of the Presentation**:
  - Focus on electromagnetic and hadronic calorimeters for **FCC-ee** and **Muon Collider**.
  - Cover the main challenges and needs for future collider experiments.

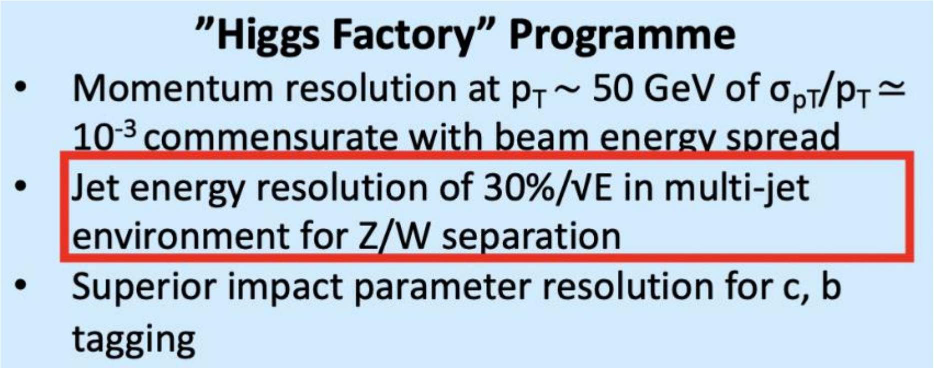
- **Common Features**:
  → **High Granularity**: Essential for detailed event reconstruction.
  → **High Time Resolution**: Critical for separating overlapping events and clustering.

- **Diverse Physics Cases**:
  → Different physics goals demand tailored technological solutions.
  → A variety of innovative approaches have been explored so far.

Calorimeters Requirements

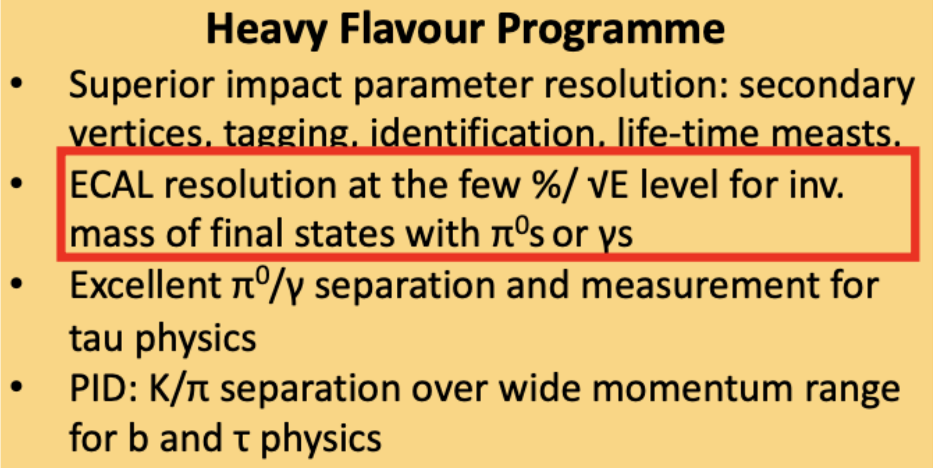
- In this talk, we will focus only on calorimetric requirements

→ General physics/detector requirements have been extensively covered in previous talks



"Higgs Factory" Programme

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of $30\%/\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few $\%/\sqrt{E}$ level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

- **Energy Resolution**
  - ECAL: better than **$10\%/\sqrt{E}$**
  - HCAL: better than **$55\%/\sqrt{E}$**

Common requirement for both FCC-ee and Muon Collider

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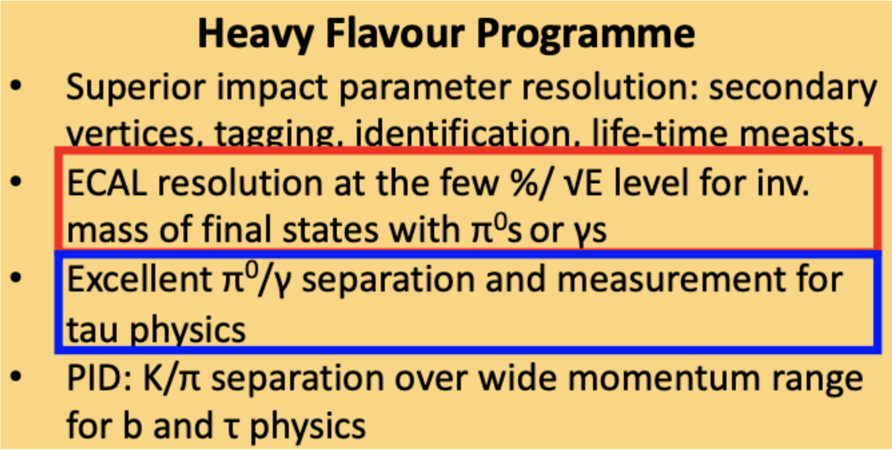

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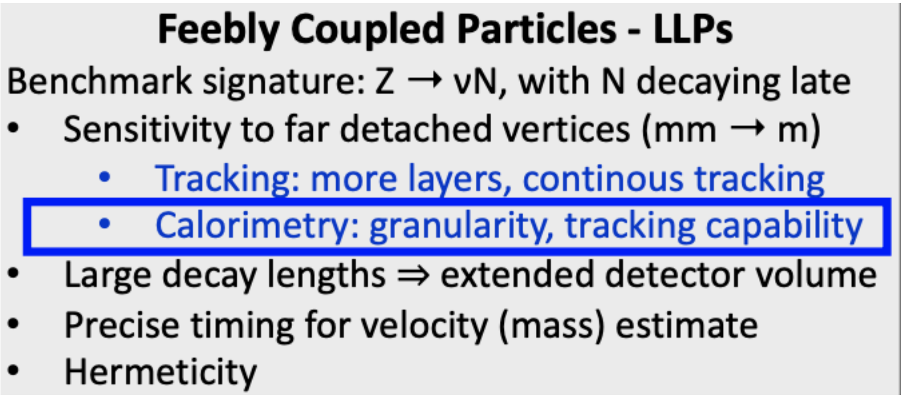

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

- **High granularity** is essential and indispensable in the new colliders:
  - → Surviving high rates and being able to cluster multi-events
  - → Jet reconstruction optimization based on Particle Flow Analysis (PFA)

Common requirement for both FCC-ee and Muon Collider

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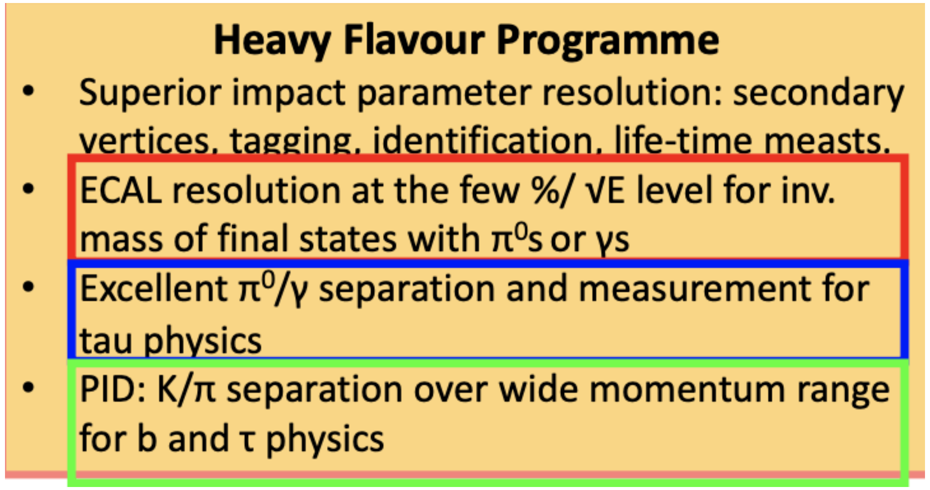

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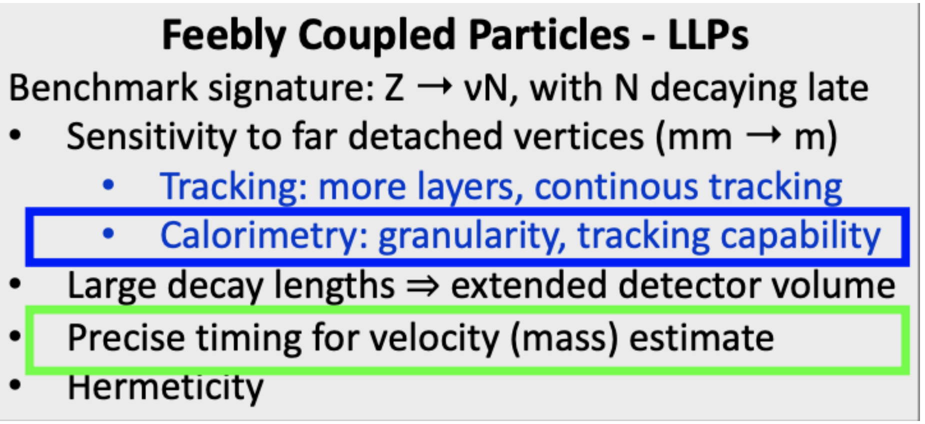

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- **Time Resolution:**

  →Surviving high rates and being able to cluster multi-events

  →potential for PID with TOF

  →supplemental info for PFA and hadronic energy reconstruction

  - ECAL: **O(50 ps)**
  - HCAL: **O(ns)**

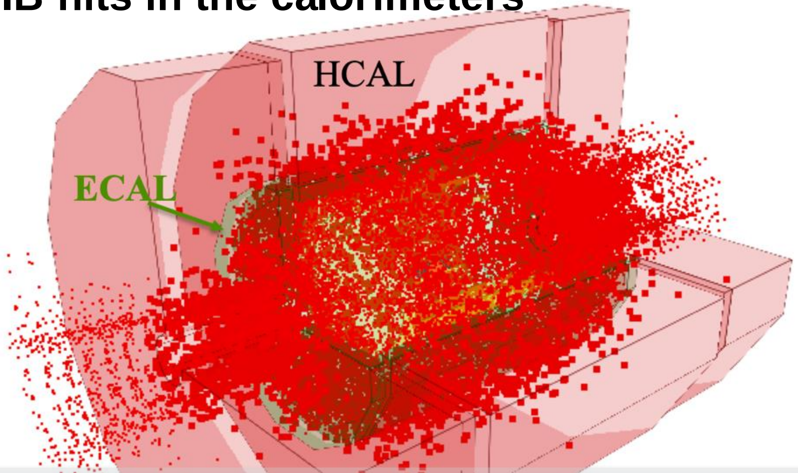
Common requirement for both FCC-ee and Muon Collider

Muon Collider: BIB and radiation hardness

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 **longitudinal profile** wrt signal
- **Total Ionising Dose**: ~1 kGy/year
- **Neutron fluence**: 10^{14} $n_{1MeVneq}$/cm^2 / year

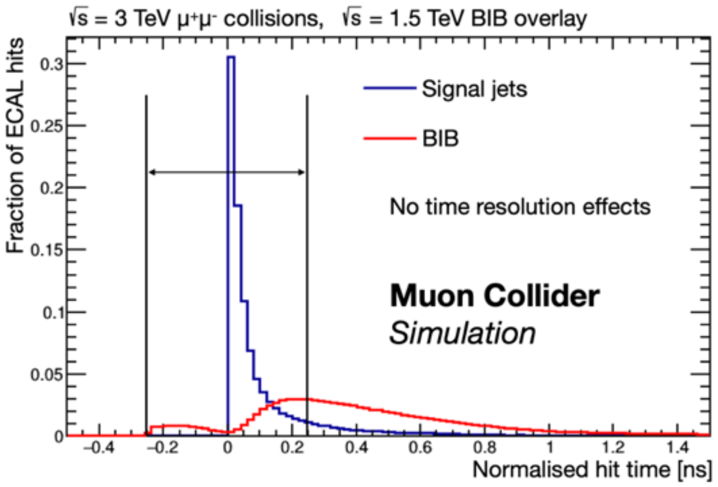
BIB hits in the calorimeters

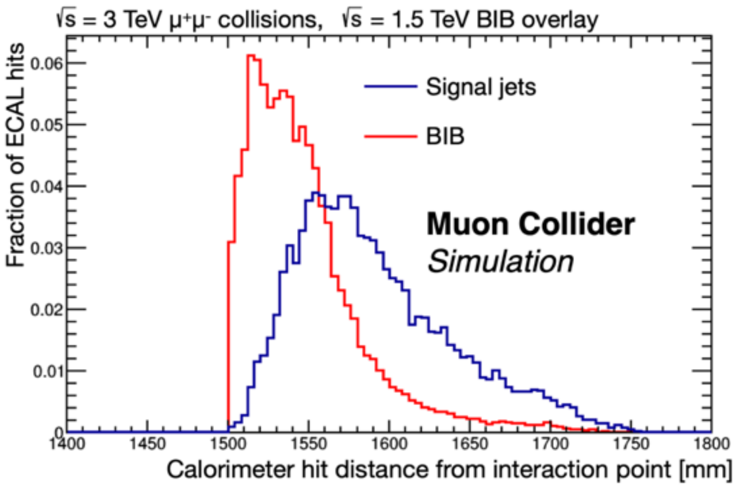


a MC ECAL should have:

- 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) stands out as a strong contender: initially considered as the primary candidate.





Muon Collider: BIB and radiation hardness

HCAL requirements

BIB in hadron calorimeter:

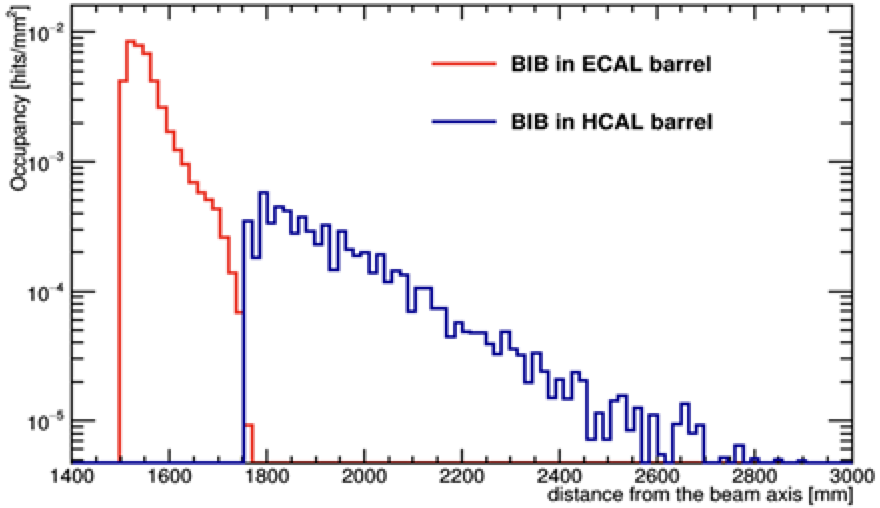
- Mostly photons (96%) and neutrons (4%)
- Large asynchronous component
- Occupancy: 0.06 hits / cm^2

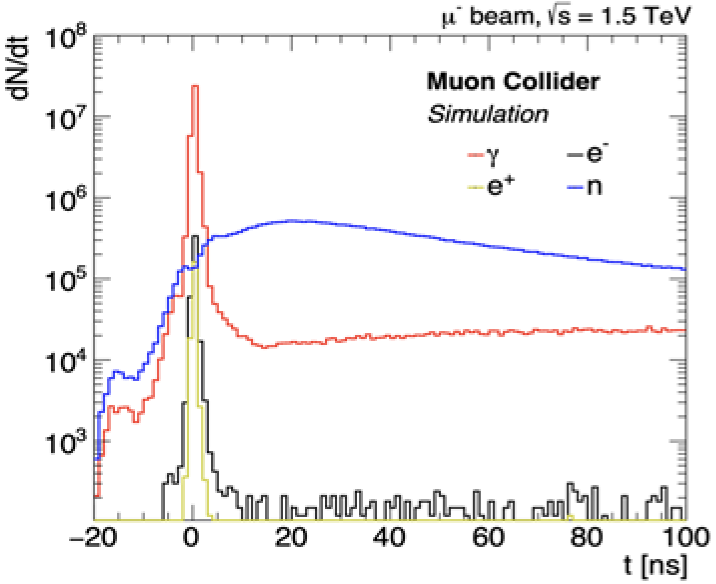
Goals:

- 3-4 % jet energy resolution for hadronic Z decays
- How: particle flow reconstruction
  - ○ $\frac{10\%}{\sqrt{E[GeV]}}$ for ECAL
  - ○ $\frac{55\%}{\sqrt{E[GeV]}}$ **for HCAL**

Detector requirements:

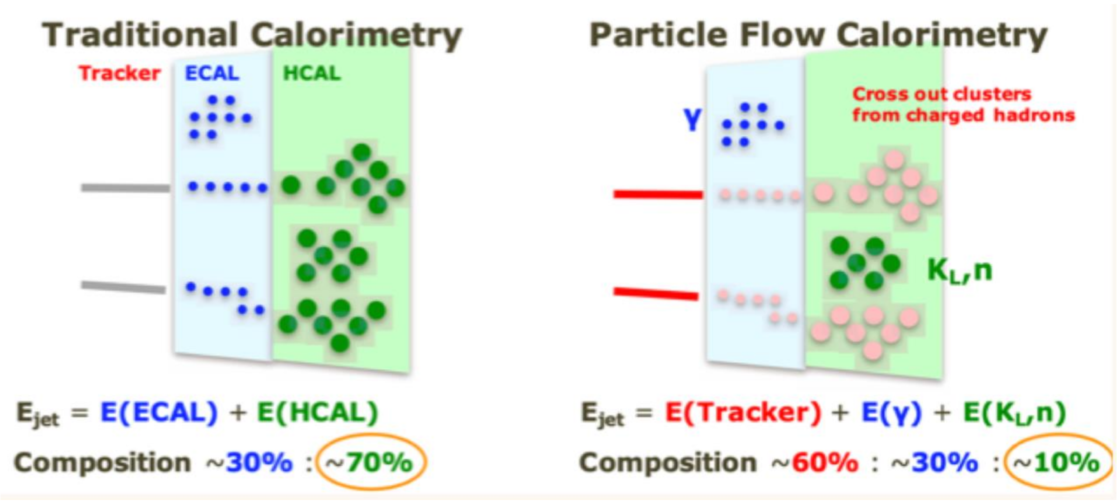
- High granularity (< $3cm^2$)
- Single layer timing 100 ps - few ns





Particle Flow Algorithm (PFA)

- ✓ Need high granular calorimeter
- ✓ Particle Flow (PFlow) objects built from tracks and (associated) clusters
- ✓ Energy from calorimeters used as little as possible
- ✓ Calorimeter needed for reconstruction of neutral components of shower
- ✓ Composition of jet:
  - charged hadrons 60%
  - photons 30%
  - neutral hadrons 10%



Uses granularity to separate **neutral** from **charged** contributions

Exploits the **tracking system** to measure with precision the energy/momentum of charged particles

PFA: some numbers -1-

Understanding the jet energy resolution needed

ee→ZH→ZVV **full hadronic**

Reconstruct Z in ee, μμ or $q\bar{q}$ and **H in 4 jets**.

- 10^6 ZH events yield ~ **74000 H→WW** and **9800 H→ZZ**.
- **To have 1% contamination** of ZZ by WW implies less than $98/74000=1.3\times10^{-3}$ fraction of W events reaching the Z mass.
  → 1.3×10^{-3} ~ **3σ**

$m_W = 80.4$ GeV

$m_Z = 91.2$ GeV

- $\sigma = \frac{m_z - mW}{3} = 3.6\ \text{GeV} \Rightarrow \frac{3.6\ GeV}{m_W}$ ~ **4.5% mass resolution on hadronic vector bosons.**
- Slightly better is needed to take into account both Z and W mass peak width.

PFA: some numbers -2-

Typical jet energy composition: 30% photons / 70% hadrons (60% charged / 10% neutral)

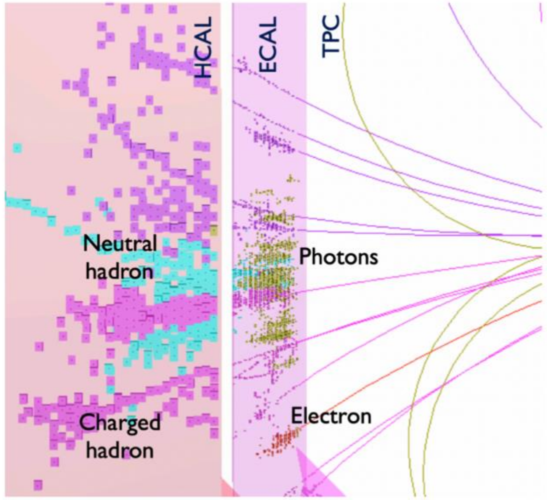
To get to the desired resolution, either

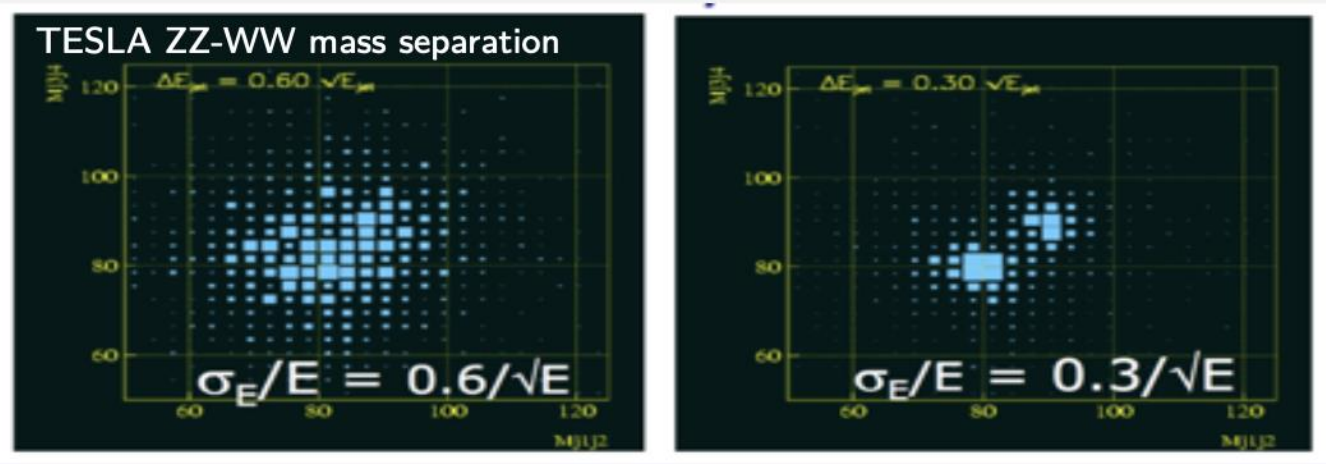
1) have both ECAL and HCAL with excellent EM and hadron energy resolution

→ e.g. 40 GeV jet, ECAL with 5%/√E and HCAL with 30%/√E => O(4%) (= 26%/sqrt(E))

2) use particle-flow algorithm (PFA) to leverage excellent momentum resolution from tracker for charged Hadron contribution

→ e.g. 40 GeV jet, x3(ECAL,)x2(HCAL) worse resolutions (ECAL ~ 15%/√E, HCAL ~ 60%/√E) => 3.5%





Reaching jet energy resolution

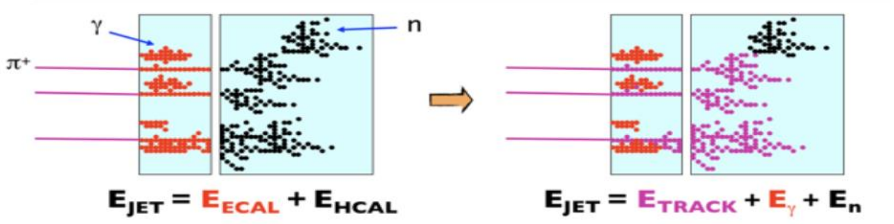
- Summarizing:

- jets resolution [50, 500] GeV better than ~ 3 − 4 % ~ 30%/√E (E in GeV)
- use optimal sub-detector for jet energy estimation.
- separate energy depositions from close-by particles.

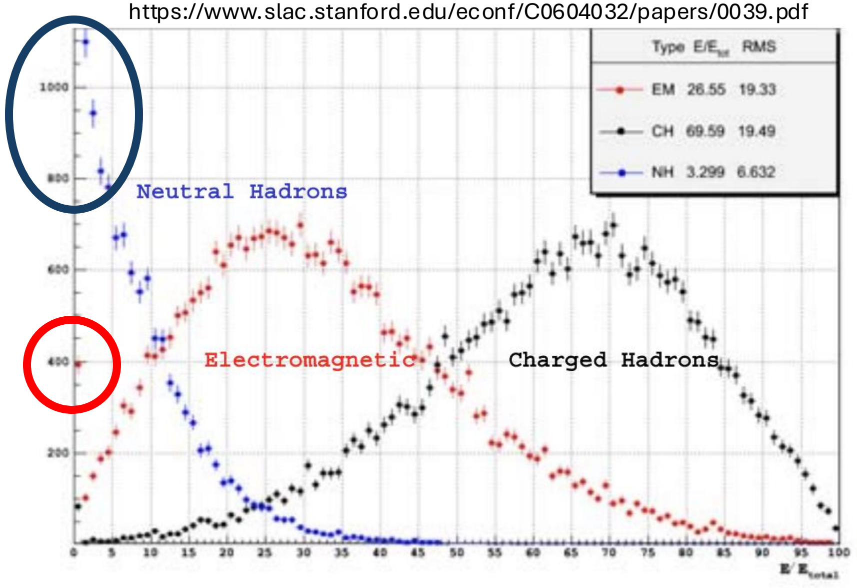
σ_{jet} = 30%/√E
needs $\sigma_{\gamma} \leqslant$ 15%/√E & $\sigma_{h0} \leqslant$ 55%/√E

- However, the situation is more complex:

analyzing the charged and neutral components of jets individually



https://www.slac.stanford.edu/econf/C0604032/papers/0039.pdf



Jet components in e^+e^- to ttbar 6 jets

Ecal ~ 1 λ_i

- Many low energy γ ⇒ badly resolved
- Many low energy h_0 ⇒ a high number of h_0 interact only in ECAL
- 2/3 of h0 start showering in ECAL.
- Photons from π^0 increase confusion between jets - could be addressed by π^0 reconstruction in PFA, requires excellent γ energy resolution (also desirable for heavy flavour physics)

→ Perfect E_{CAL} σγ = O(5%/√E) and should also be an HCAL

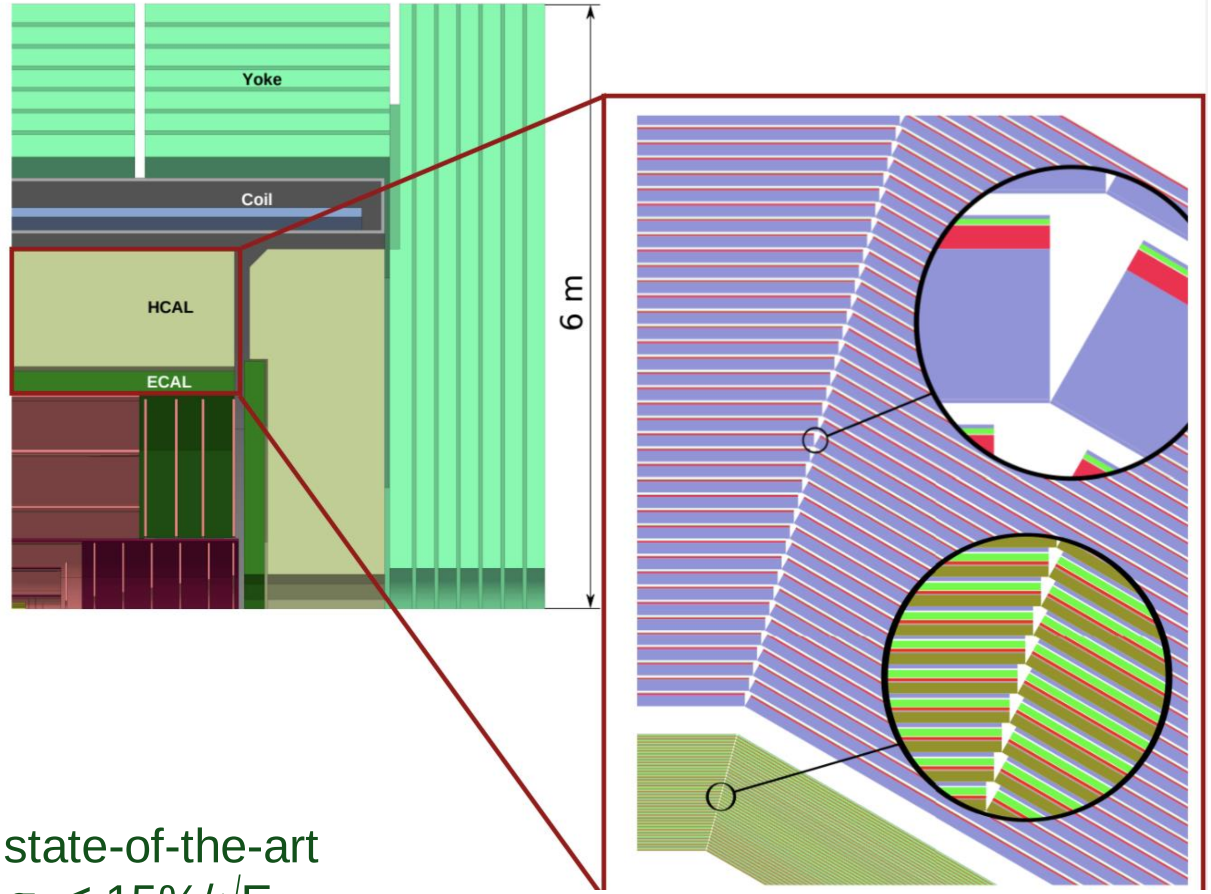
Calorimetry @ CLD

- ☐ **CLD: CLIC-like detector**

- ☐ Short, compact calorimeters fully inside the solenoid

- ☐ ECAL:
- 40 layers (22 X_0 deep) of 1.9 mm tungsten absorber, and 0.5-mm-thick silicon sensors with **5x5 mm^2 granularity**

- ☐ HCAL:
- 44 layers (5.5 (+1) λ_i) of 19 mm steel absorber, and 3-mm-thick scintillator tiles with **3x3 cm^2 granularity**



The SiW ECAL, with its O(100M channels), represents the state-of-the-art in high granularity, achieving a photon energy resolution of $\sigma_\gamma \leq 15\%/\sqrt{E}$

The combined ECAL+HCAL hadronic energy resolution is approximately **45%/√E**

Calorimetry @ ALLEGRO

- ❑ **A Lepton coLlider Experiment with Granular Read-Out**

- ❑ Highly-granular noble liquid ECal
  - ○ Pb/W+LAr (or denser W+LKr)

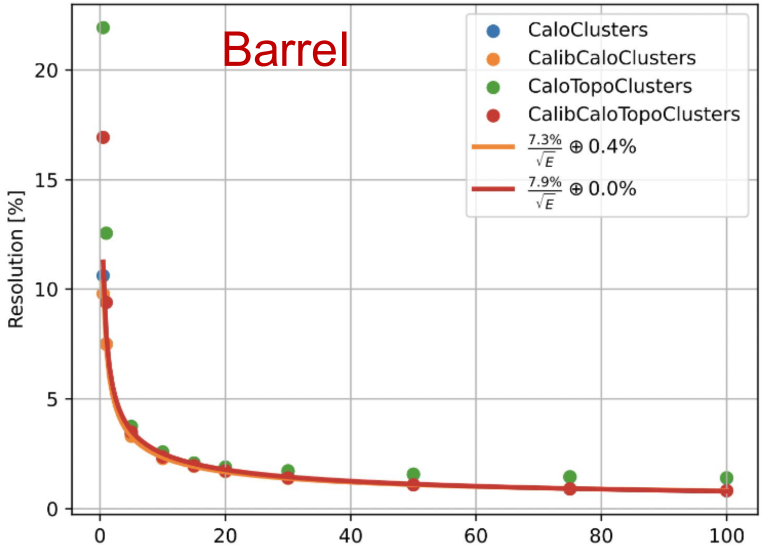
- ❑ TileCal-like or CALICE-like HCal
  - ○ TileCal: WS fibres+SiPMs at outer radius
  - ○ Calice: SiPMs directly on scintillators

Detector design optimization not finalized
Current focus on implementing all calorimeters in the full simulation

ALLEGRO: ECAL simulation

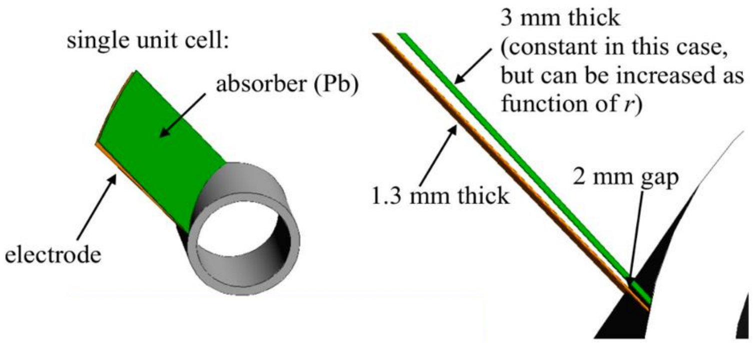
❑ Barrel simulation

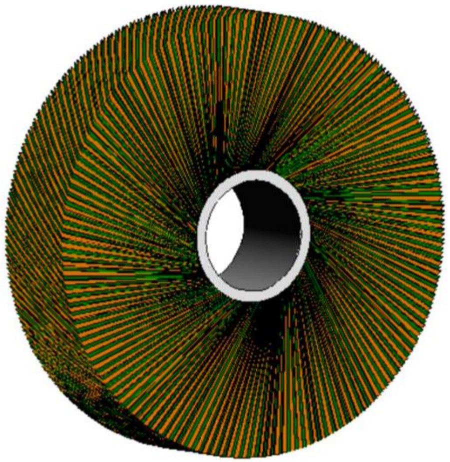
- EM resolution with a **stochastic term of 7-8%**
- Benchmark for geometry optimization: photon/π0 separation

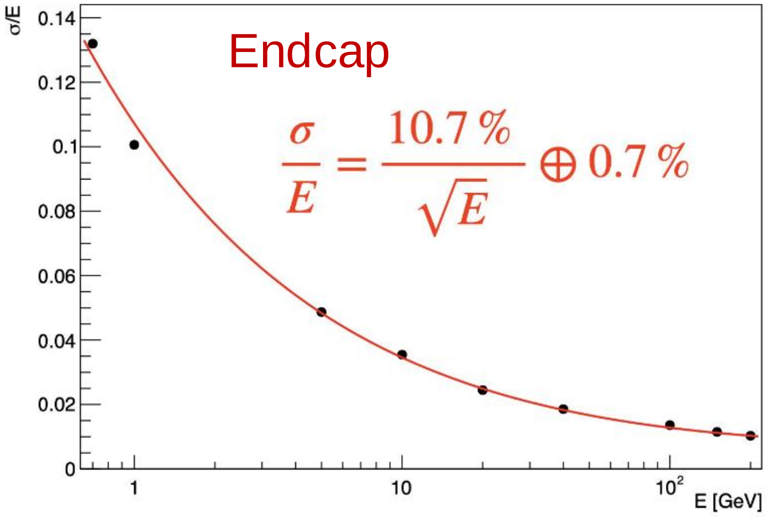


❑ Endcaps simulation

- Endcap design more complex than barrel
- “Turbine design” subdivided into a set of nested wheels
- Resolution similar to barrel







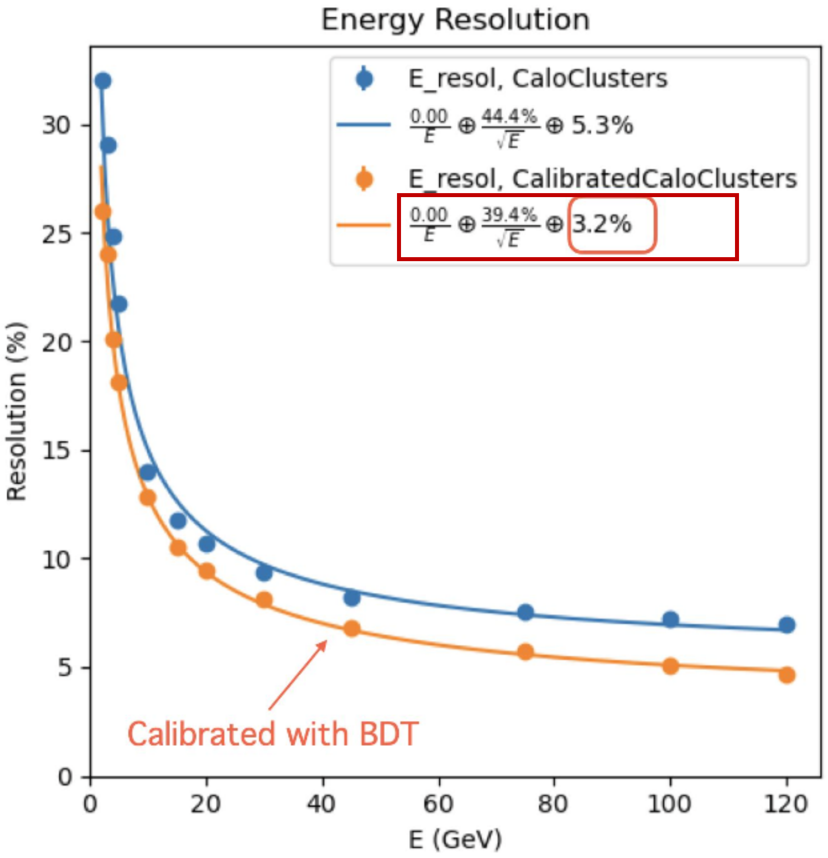
ALLEGRO: HCAL simulation

❑ Design

- 5 mm steel absorber plates alternating with 3 mm scintillator plates
- 140 cm deep (8-9 λ)
- Removed the Pb plates compared to FCC-hh design (**HCal acts as return yoke for the central solenoid**)

Implemented calibration of cluster energy, using boosted decision tree (BDT), compared to cell-based approximate calibration using 100 GeV π-

- Inputs: total cluster energy $E_{cluster}$ and energy per layer → $E_i/E_{cluster}$
- Regression target: $E_{true}/E_{cluster}$
- Constant term decreased from 5.3% to 3.2%, energy response $(E_{cluster}-E_{true})/E_{true}$ → within 1-2%

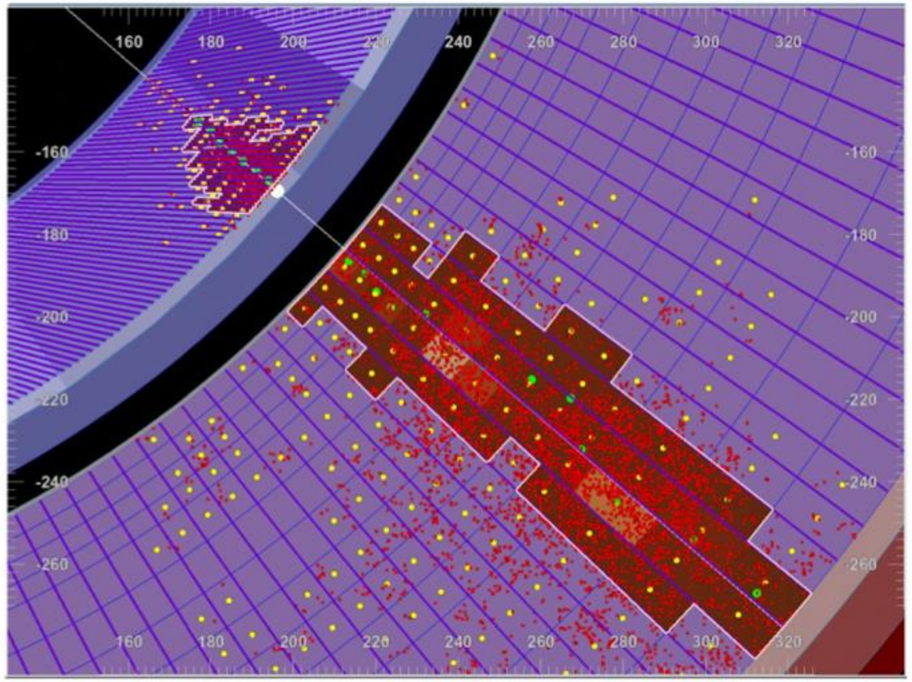


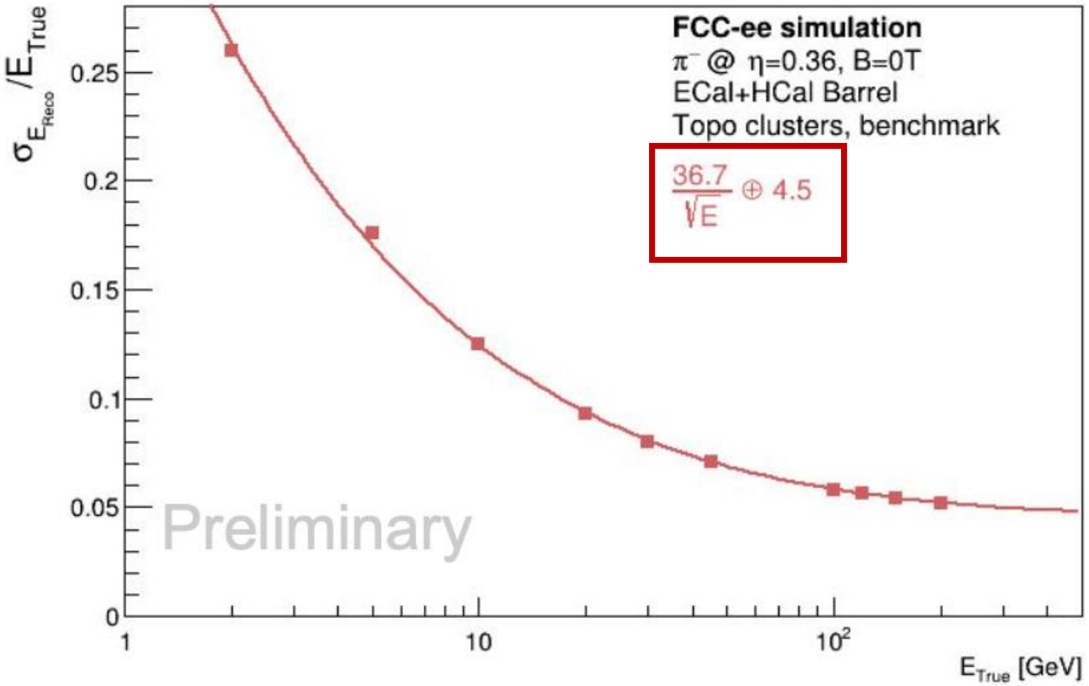
ALLEGRO: ECAL + HCAL simulation

❑ **Only Barrel**

- Topological clustering implemented in the barrel region
- Cluster energy calibration is done with a BDT (similar to HCal)

❑ Both, ECal and HCal communities plan to build a test-beam prototype(s) in coming years





Calorimetry @ IDEA

❑ **Novel dual-readout calorimeter design** using

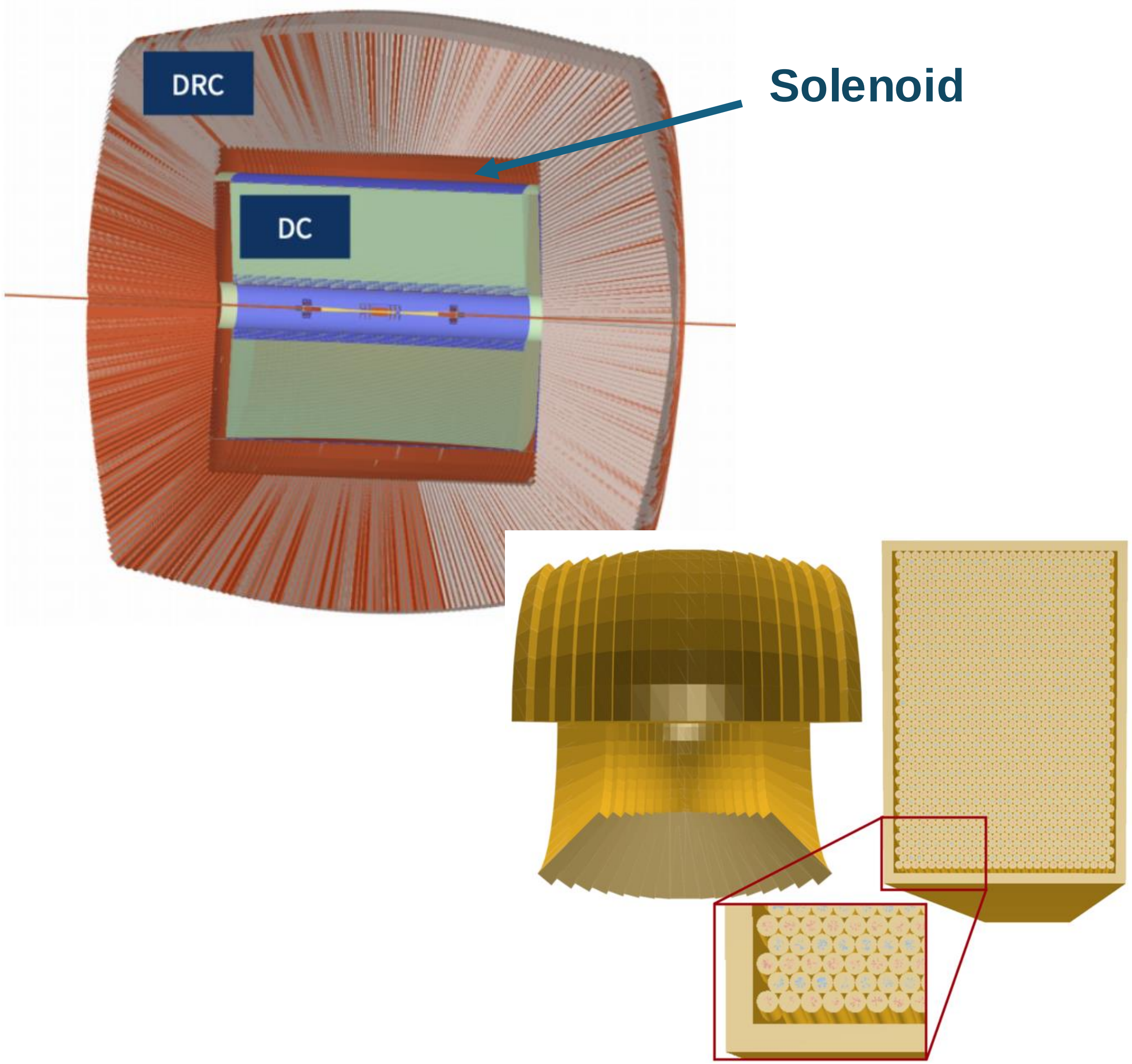
- a new construction technique for housing optical fibers (S and C) into brass capillary-tubes

✓ measure both electromagnetic & hadronic components with two different channels:

→ **excellent energy resolution for hadrons via event-by-event dual-readout correction**

✤ Projective geometry with a uniform sampling fraction

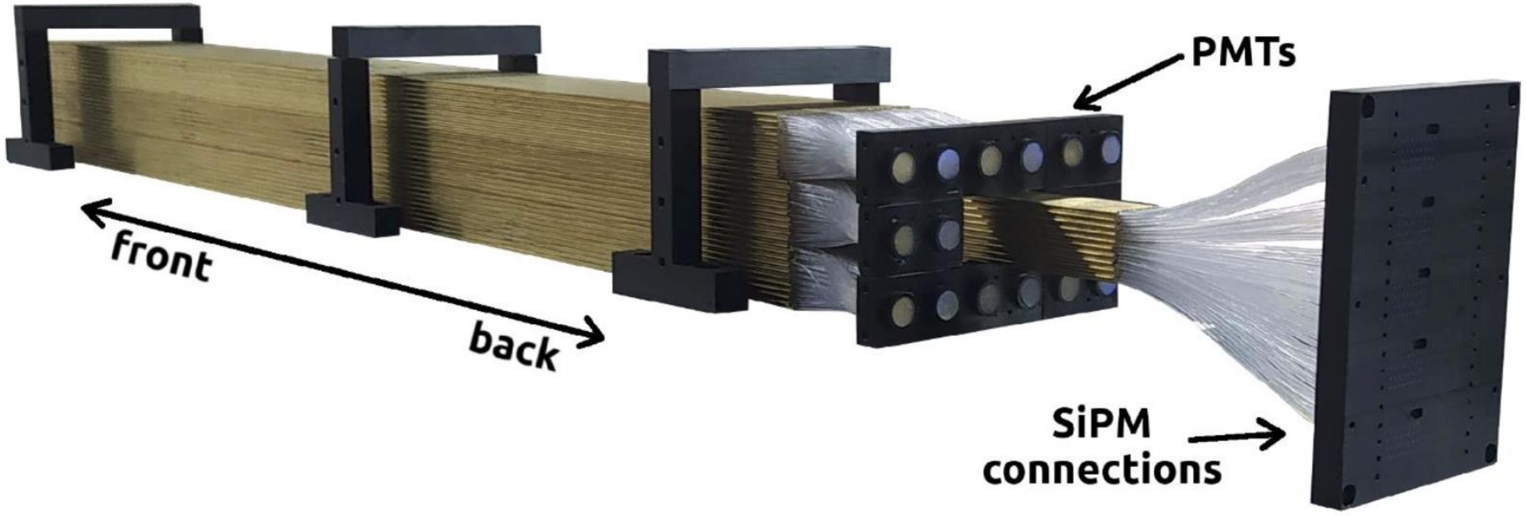
✤ Longitudinally unsegmented

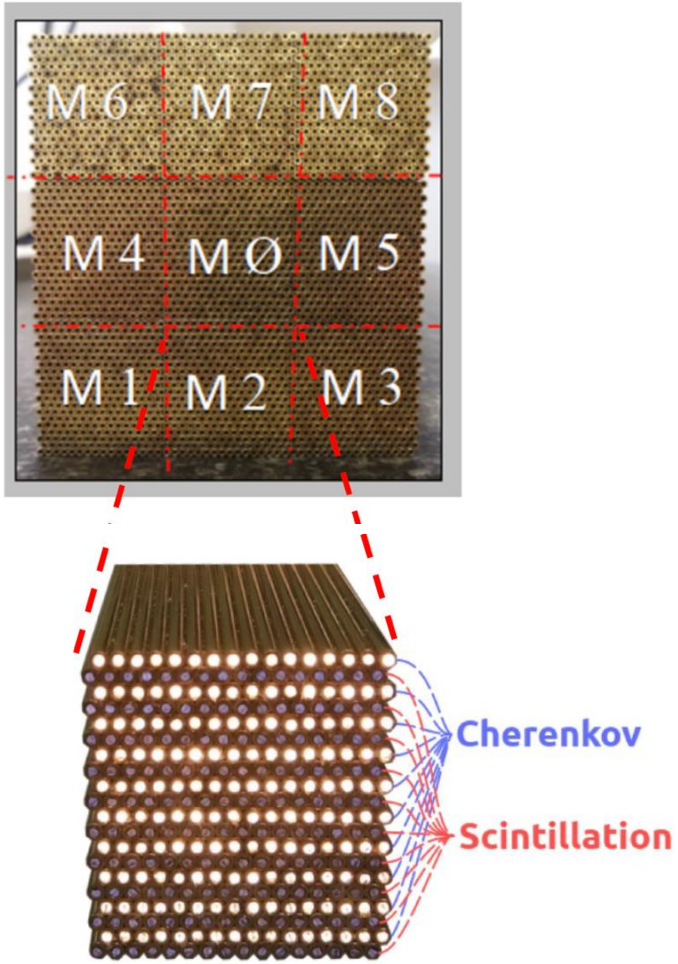


Test Beam Results – SPS CERN 2023 –

✓ A first prototype was tested at CERN and used to validate the em-shower simulation:

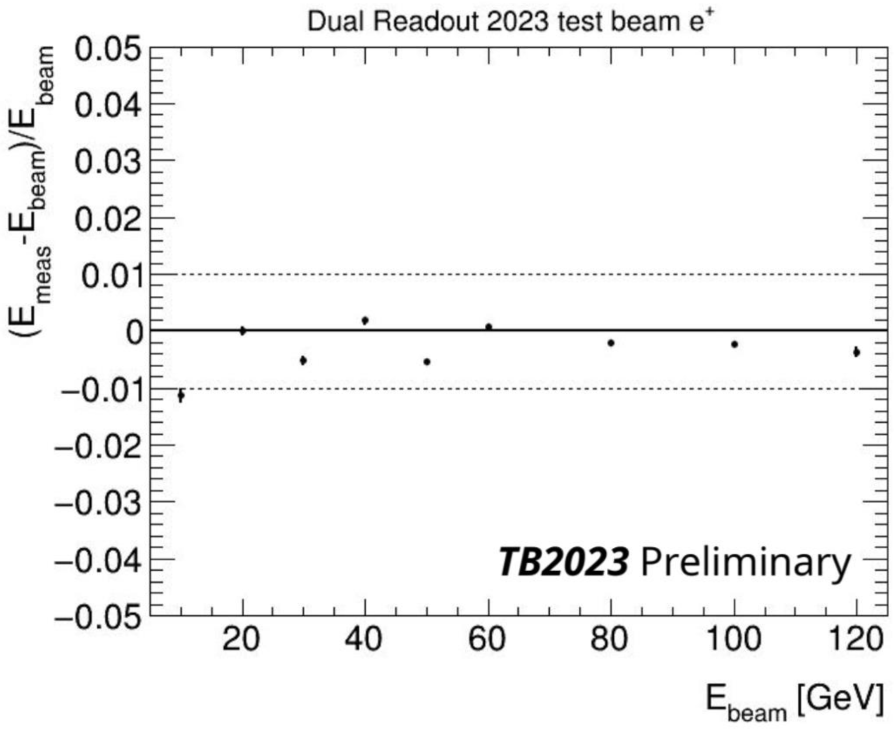
- 9 modules made of 16x20 brass capillaries → 10x10x100 cm^3 volume
- Tube inner diameter: 1.1 mm, outer diameter: 2 mm
- Alternating rows of scintillating and clear (→ Cherenkov) optical fibers

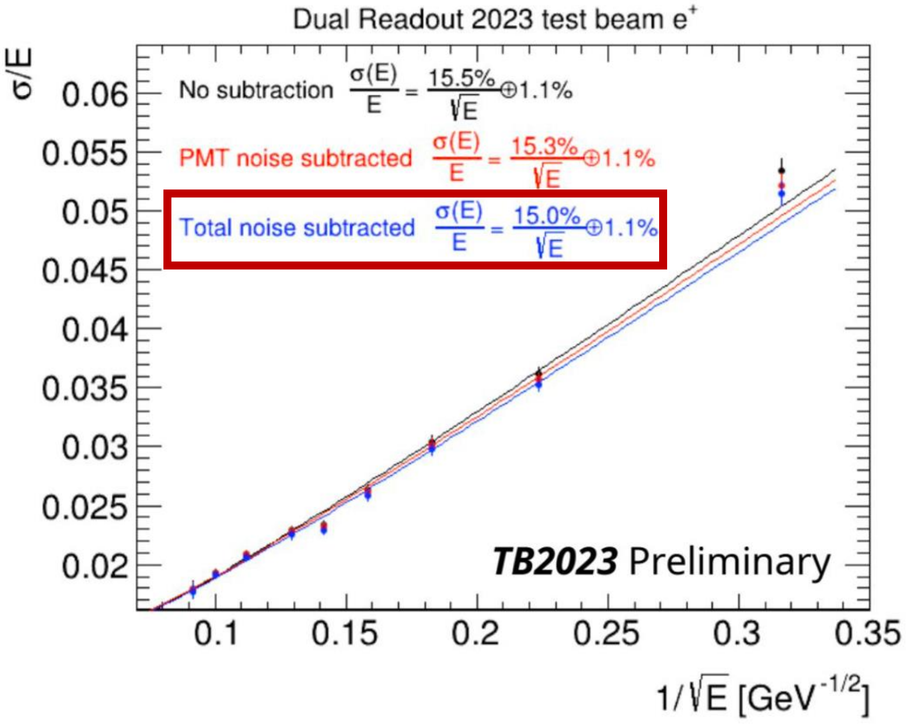




Test Beam Results – SPS CERN 2023 -

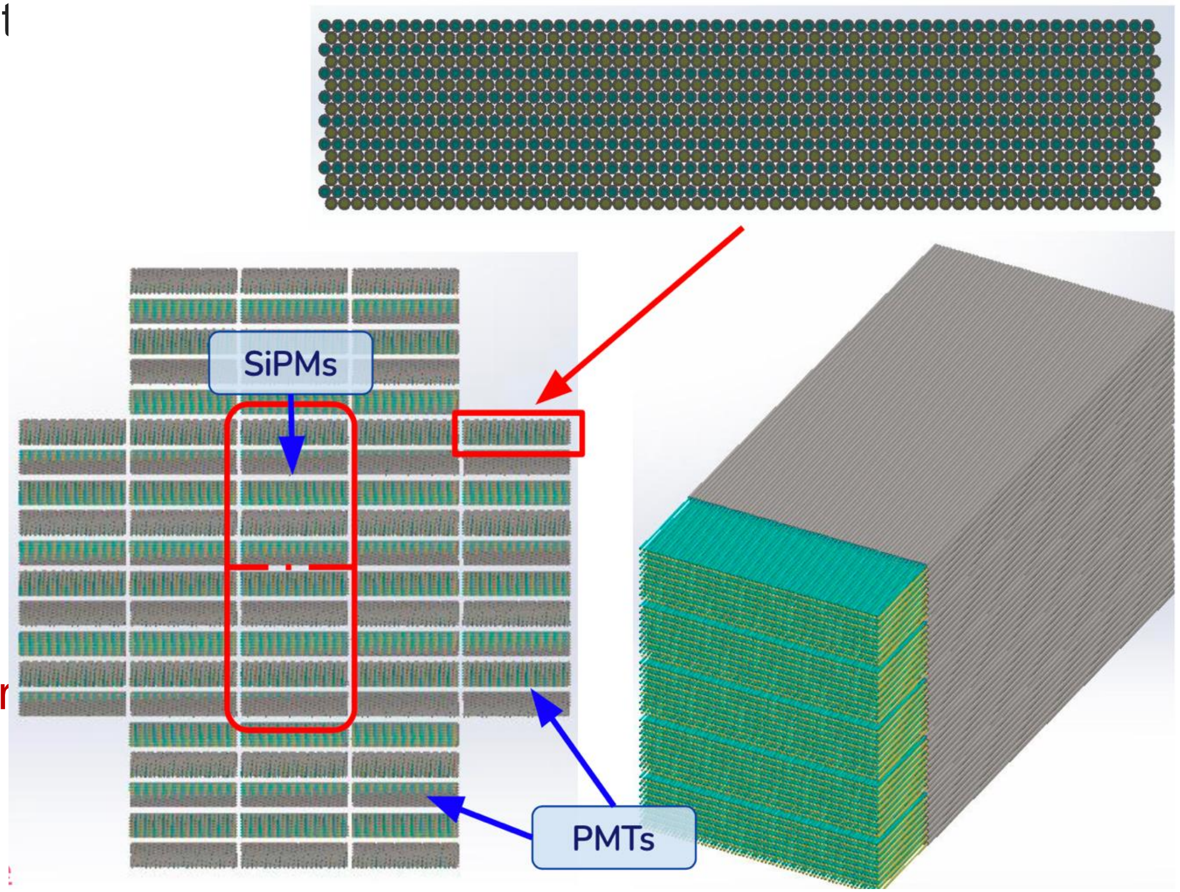
- ❑ Linear response within 1% in the whole [10, 120] GeV energy range, and **energy resolution close to the value predicted by the simulation**:
- ● Larger constant term compatible with beam energy spread suggested by SPS experts
- ● Detailed work on better understanding of noise produced by SiPMs ongoing





HiDRa prototype

- ✓ A new prototype, named Hidra, is being built and tested at CERN
- Size: 65 × 65 × 250 cm^3
  (almost) fully contained hadron showers
- 80 modules, each made of 16 x 64 steel capillaries
- Mixed SiPM and PMT readout
  → Cost/Performance optimization
  → Significant increase in DAQ complexity (10240 SiPMs)
- Each external module read out by two PMTs, one for S fibres and the other for C fibres (512 fibres each)
- Aiming to identify a scalable and cost-effective solution for dual-readout calorimeter building in preparation for the IDEA experiment proposal

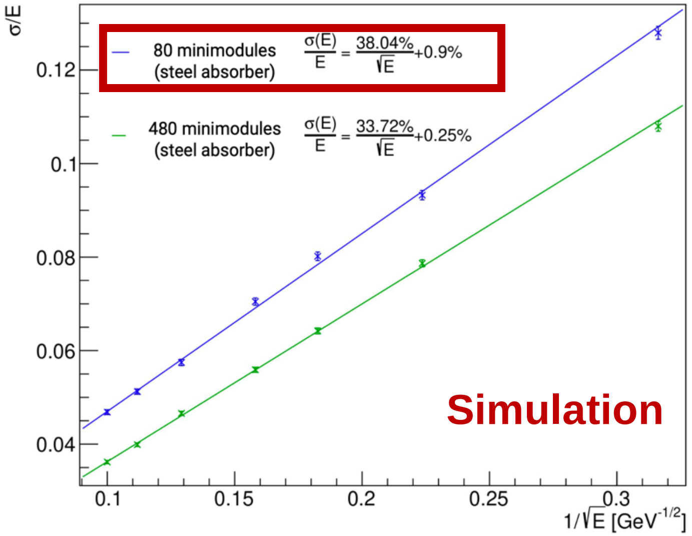


HiDRA first tests and simulation

- ✓ First characterization of the new prototype on beam at CERN at the end of August 2024
- Partially completed calorimeter with **36/80 modules**, using PMT-only readout
- 12 x 3 modules, ~ 38.4 x 33.9 x 250 cm^3 Containment for hadron showers: **~ 87% (estimated through Geant4 simulation)**
- Data analysis ongoing

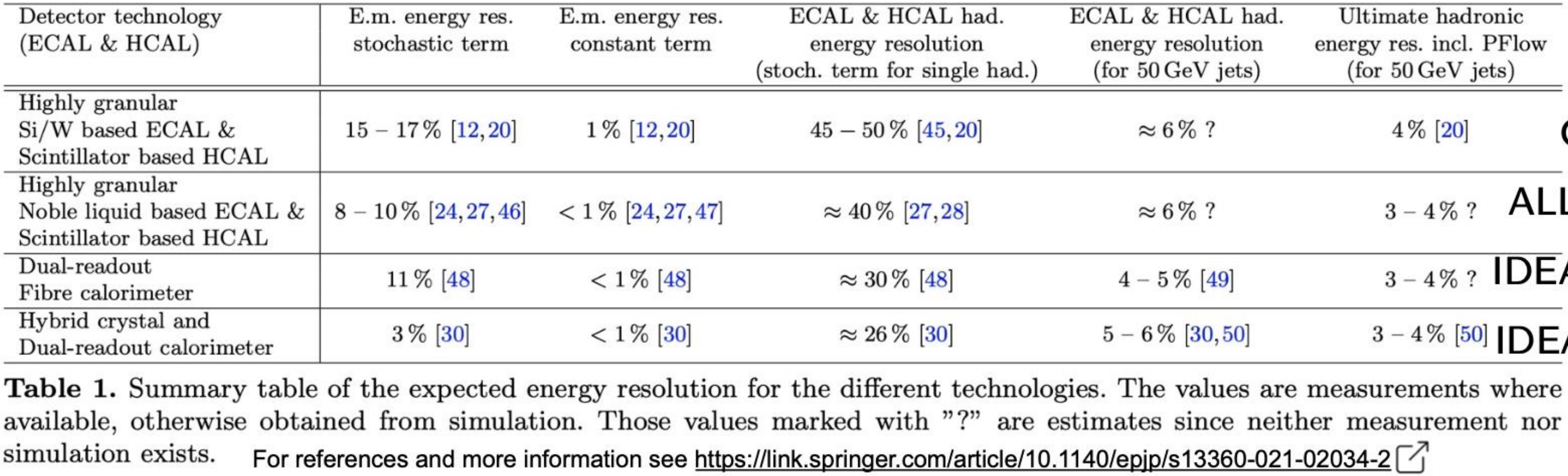
➢ Software-based activities ongoing in parallel, including Machine Learning techniques

Pion resolution in [10, 100] GeV Range



Simulation

Summary FCC-ee Calorimeters



Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)	
Highly granular Si/W based ECAL & Scintillator based HCAL	$15 - 17\,\%$ [12,20]	$1\,\%$ [12,20]	$45 - 50\,\%$ [45,20]	$\approx 6\,\%$?	$4\,\%$ [20]	CLD
Highly granular Noble liquid based ECAL & Scintillator based HCAL	$8 - 10\,\%$ [24,27,46]	$< 1\,\%$ [24,27,47]	$\approx 40\,\%$ [27,28]	$\approx 6\,\%$?	$3 - 4\,\%$?	ALLEGRO
Dual-readout Fibre calorimeter	$11\,\%$ [48]	$< 1\,\%$ [48]	$\approx 30\,\%$ [48]	$4 - 5\,\%$ [49]	$3 - 4\,\%$?	IDEA HCAL
Hybrid crystal and Dual-readout calorimeter	$3\,\%$ [30]	$< 1\,\%$ [30]	$\approx 26\,\%$ [30]	$5 - 6\,\%$ [30,50]	$3 - 4\,\%$ [50]	IDEA ECAL

Table 1. Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with ”?” are estimates since neither measurement nor simulation exists.

For references and more information see https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

Highlights of the most compelling ongoing R&D activities for calorimeters in the Muon Collider and FCC-ee

(only a selection is presented here due the time constraints)

R&D for new ECALs: CRILIN

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.

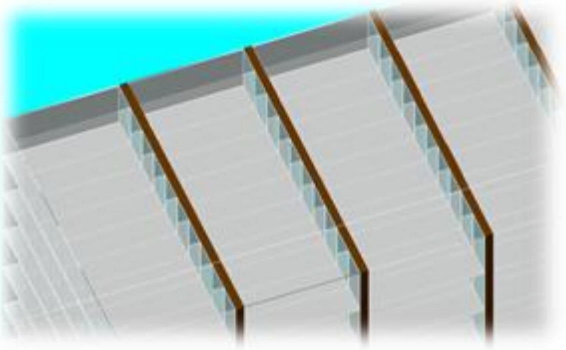
Key Features:

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



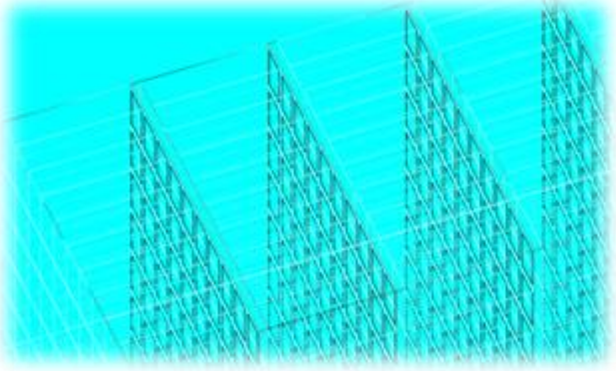
Crystal choice:

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*

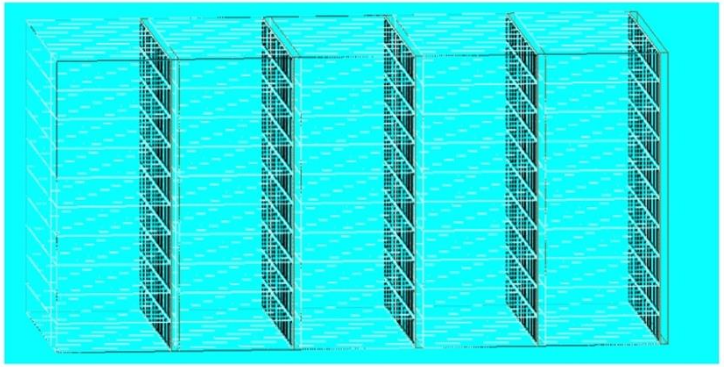


Differentiation:

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

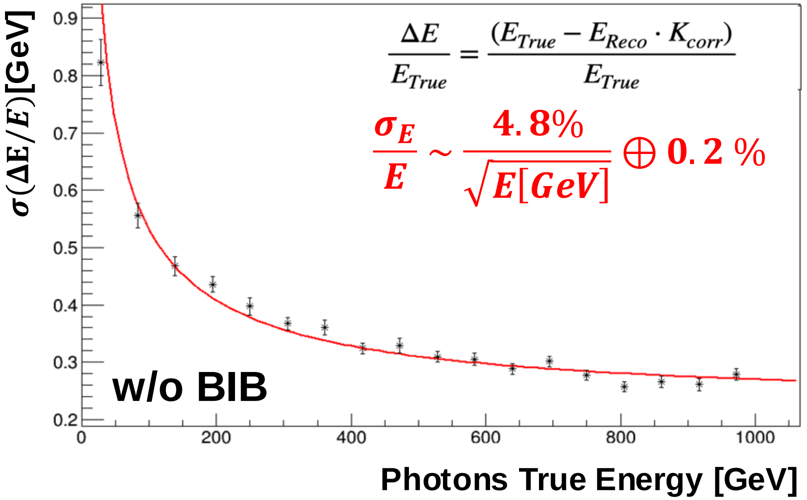


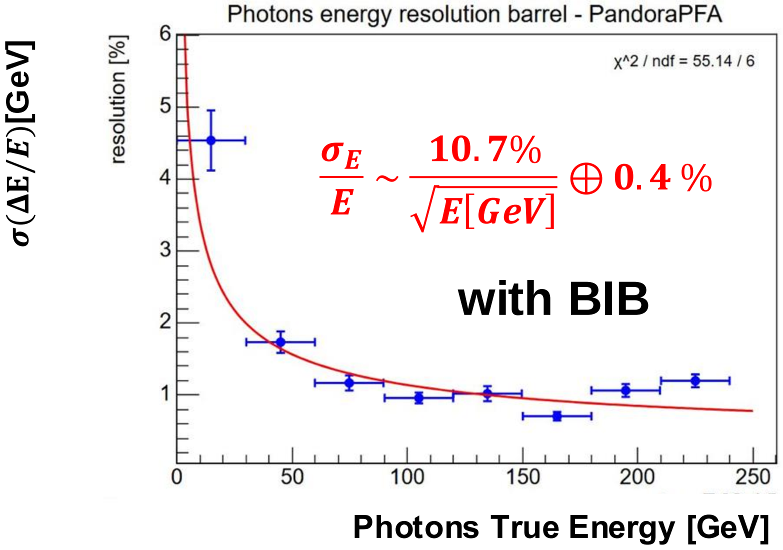
Simulated performances

- The ECAL barrel with Crilin technology has been implemented in the Muon Collider simulation framework
  - ➢ 6 layers of 45 mm length, 10 X 10 mm^2 cell area → **26 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 Mchs)**





R&D status

Prototype versions

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

Front-end electronics

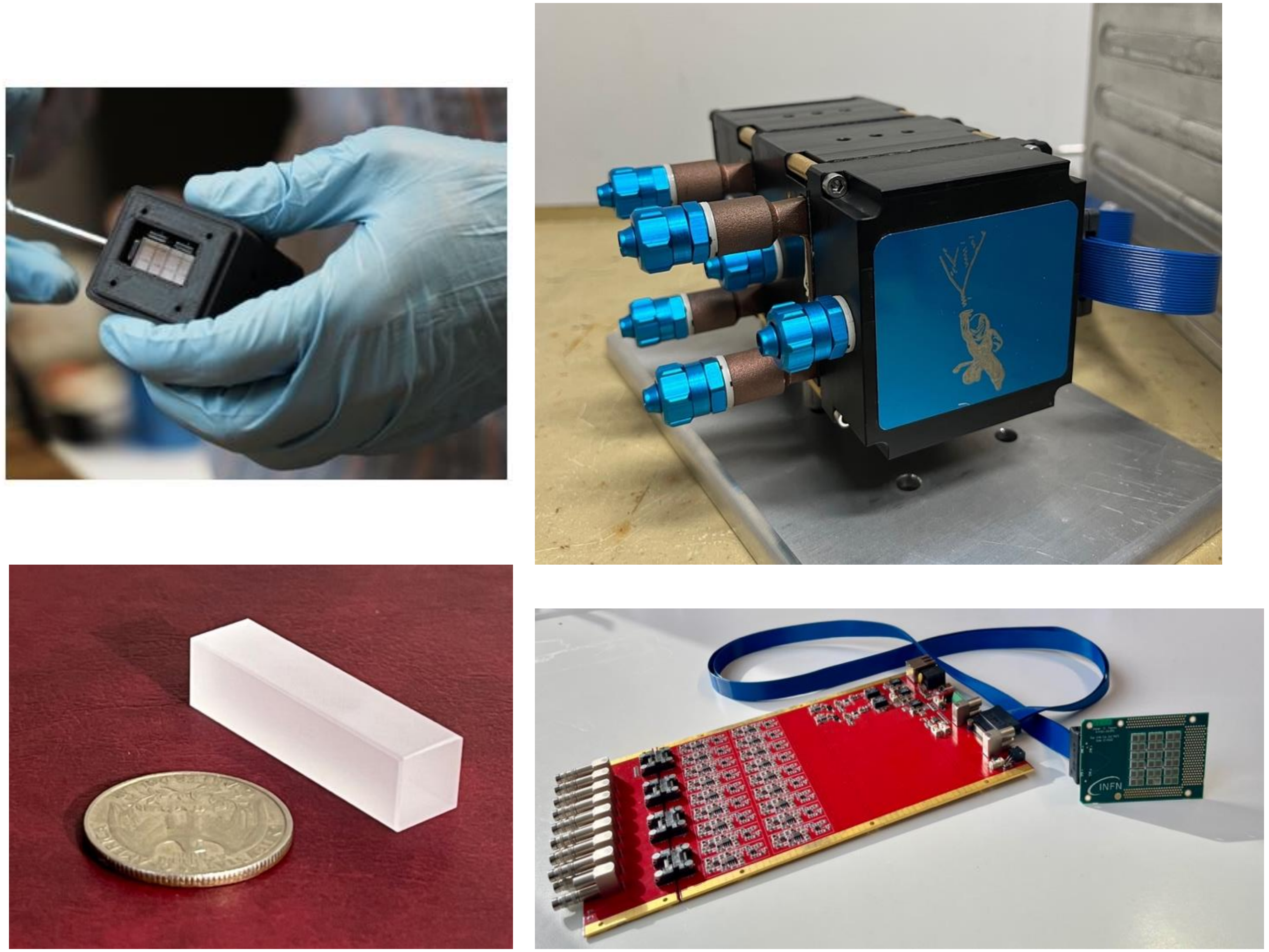
- Design completed
- Production and QC completed

Radiation hardness campaigns

- OK w/10um Hamamatsu SiPM – O(10^{14}) n_{1MeV}/cm^2
- OK w/PbF2 & PbWO-UF Crystals - O(10) Mrad

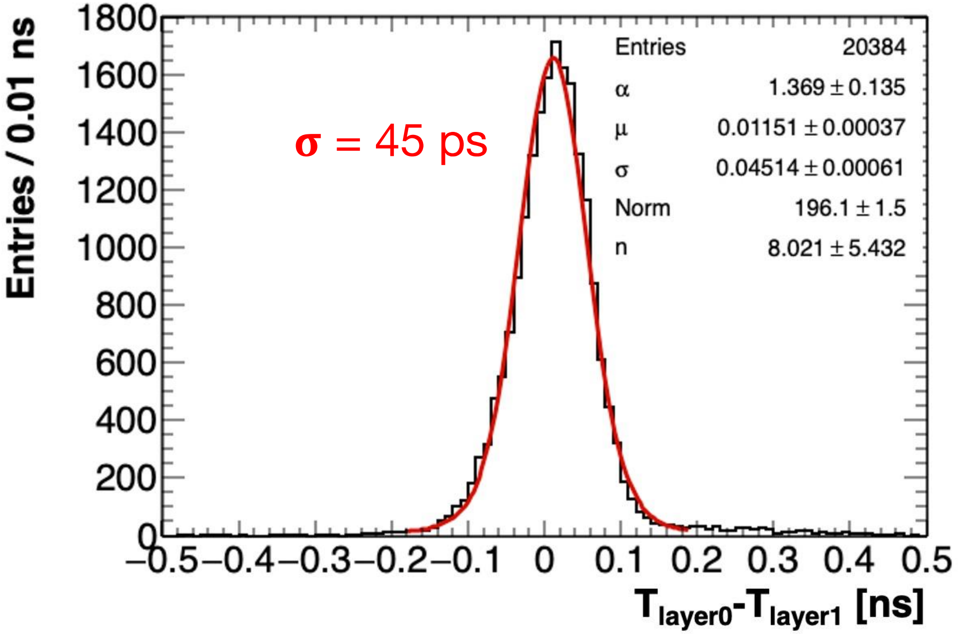
Beam test campaigns

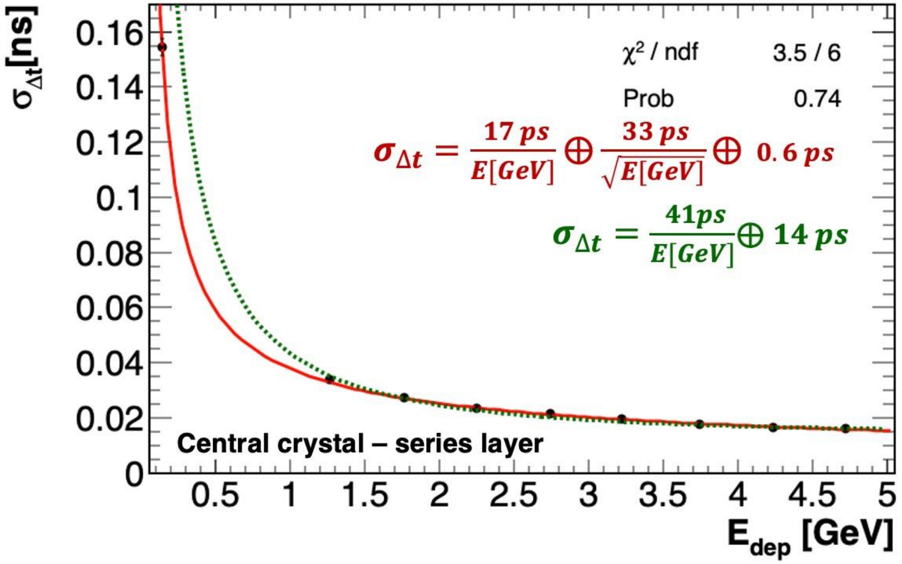
- Proto-0 at CERN H2 (August 2022)
  C. Cantone et al. 2023 Front. Phys. 11:1223183
- Proto-1 at LNF-BTF (July 2023-April 2024)
  C. Cantone et al. 2024: doi:10.1109/TNS.2024.3364771
- Proto-1 at CERN (August 2023)

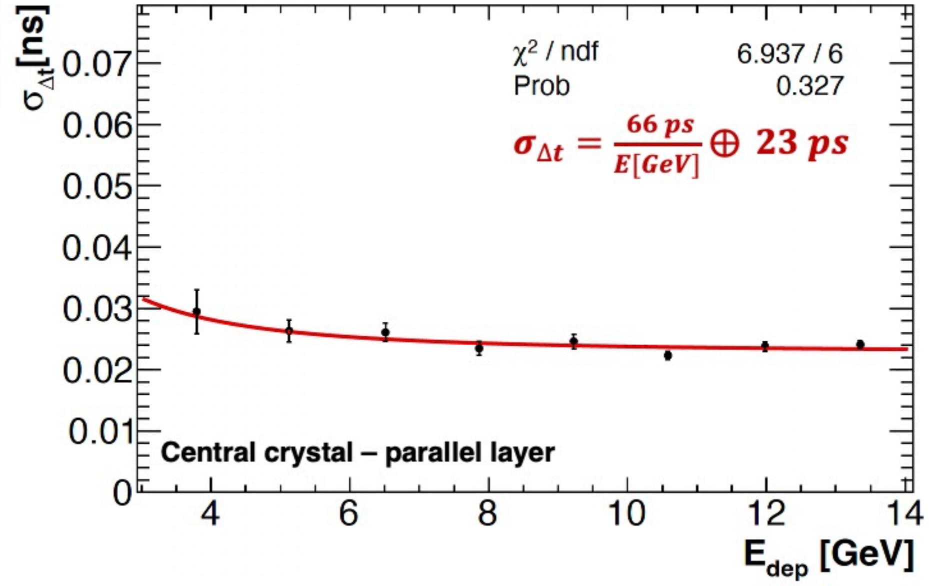


Beam test @ CERN: Timing

- Time Resolution is of **O(20 ps)** both in the series and in the parallel layers using the time SiPMs 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)

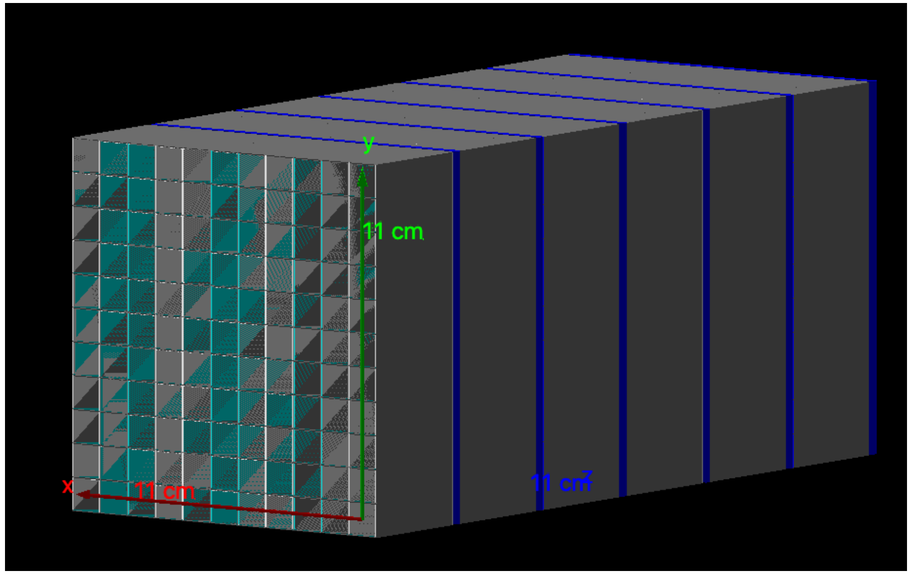


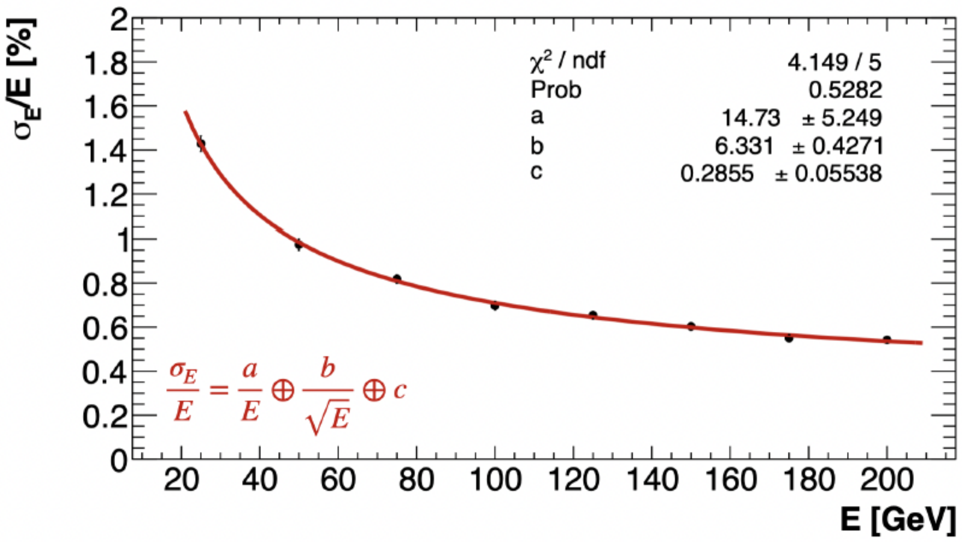




Large area prototype simulation and work plan

- Initial proposal **11x11x6 layer** (crystals 10x10x40 mm^2 each) → **2.5 R_M – 26 X_0**
- Crystals 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





- **σ_E/E ~ 6%/√E** satisfies the Muon Collider requirements
- stochastic term comparable to the one expected from photo-statistics (5.8%)
- **Test Beam at SPS Scheduled for Late 2025**

R&D for new ECALs: MAXICC

Two calorimeter sections:

- a dual-readout fiber hadronic calorimeter (HCAL)
- **a homogeneous dual-readout crystal EM calorimeter (ECAL)**
  - improve event reconstruction
  - expand the landscape of possible physics studies, i.e. flavour physics

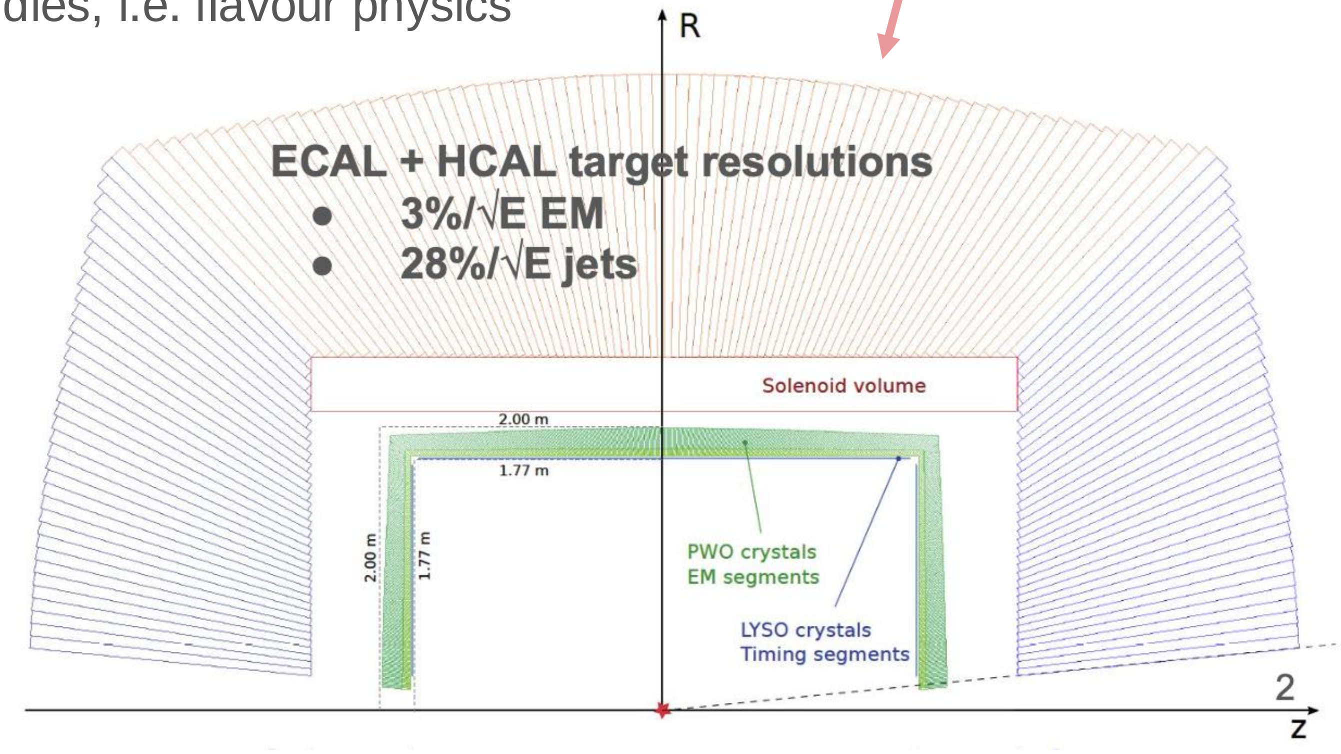
ECAL requirements:

- **3%/√E EM energy resolution**
- **dual-readout (DR)** capability for use in a hybrid calorimeter configuration
- **high granularity** for PFA

First studies and concept descriptions in:

- [2020 JINST 15 P11005]
- [2022 JINST 17 P06008]

Now in the IDEA baseline

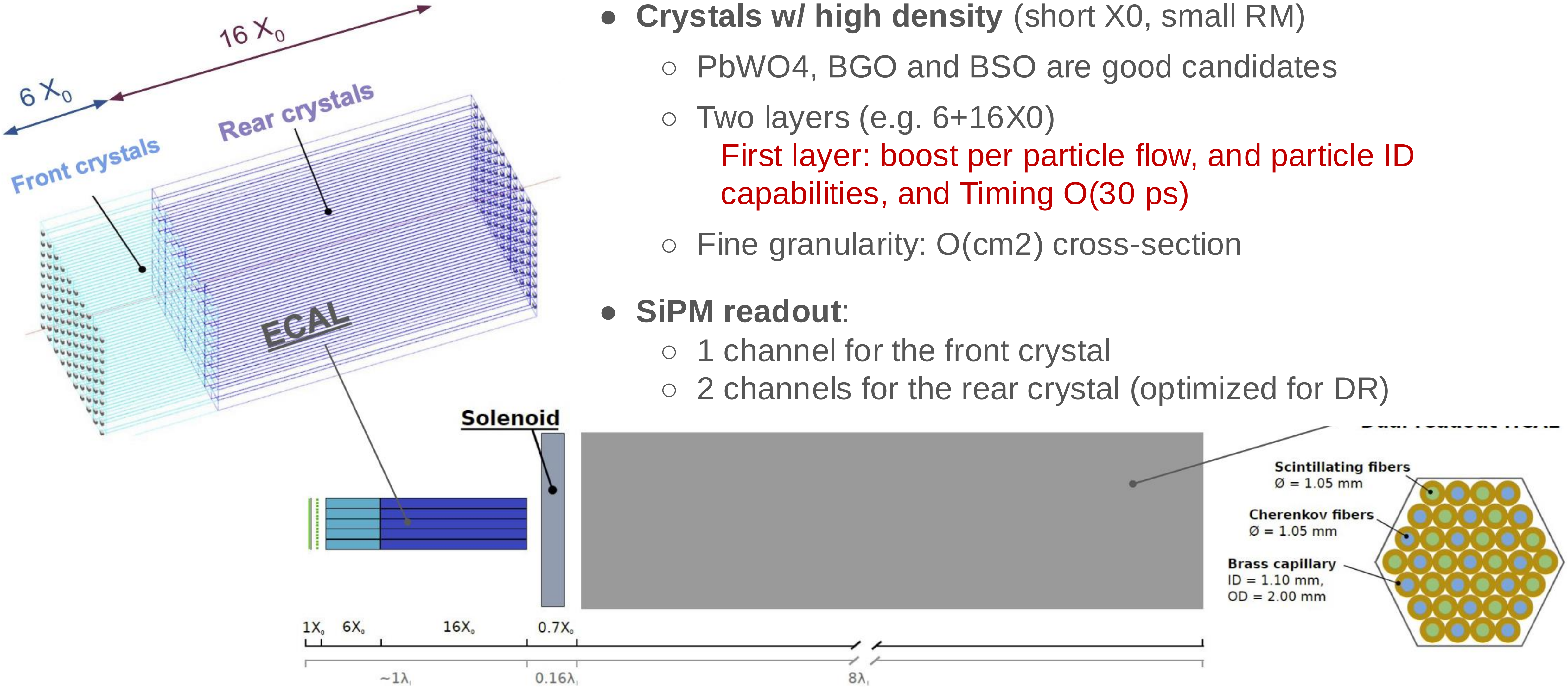


ECAL + HCAL target resolutions

- **3%/√E EM**
- **28%/√E jets**

ECAL key design features

- **Crystals w/ high density** (short X0, small RM)
    - PbWO4, BGO and BSO are good candidates
    - Two layers (e.g. 6+16X0)
      First layer: boost per particle flow, and particle ID capabilities, and Timing O(30 ps)
    - Fine granularity: O(cm2) cross-section
- **SiPM readout**:
    - 1 channel for the front crystal
    - 2 channels for the rear crystal (optimized for DR)



Dual readout strategy

Crystal transparency where Cerenkov light is most intense (near UV) is poor.
So the feasibility of the concept strongly depends on:

- **Adequate statistics of C photoelectrons** (> ~50 phe/GeV)
- **Reasonably large S photoelectrons** (> ~2000 phe/GeV)
- **Sufficient separation of C from S light**
  → Wavelength digitization for timing/pulse shape discriminators

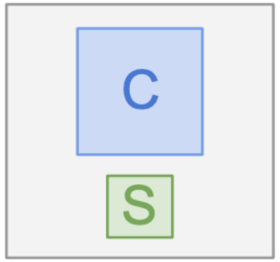
Rear crystal ECAL segment

two SiPMs optimized for S and C detection respectively

Front crystal ECAL segment:

one SiPMs optimized for S detection

Rear crystal segment face

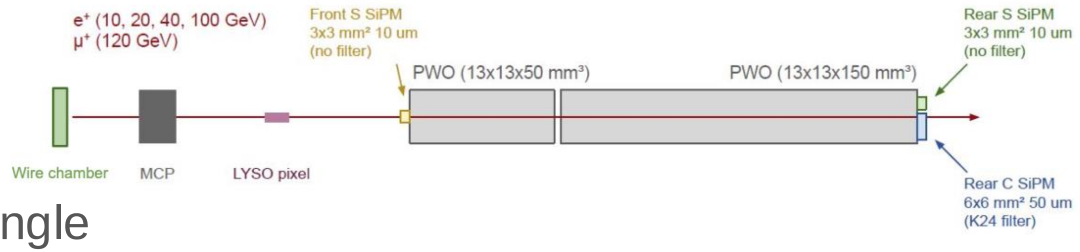


optical filter + 6x6 mm^2 SiPM with 50 μm cell size (large area and good pde)

3x3 mm^2 SiPM with 10 μm cell size (high dynamic range)

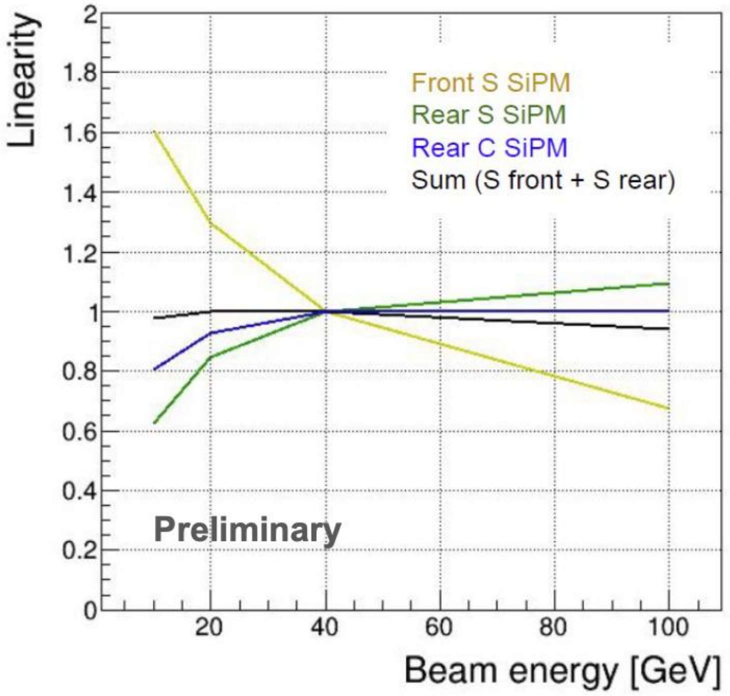
Preliminary results from CERN TB

- Focus on PWO, **several red filters tested**
- Wire chamber for tracking
- DRS digitization
- Rotating stage for C/S study as a function of crystal-beam angle



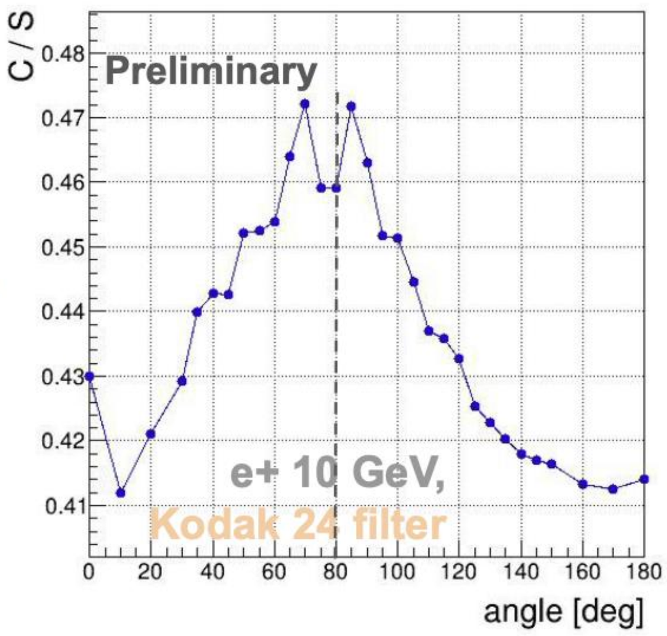
Energy scan to study linearity with electron runs

- ✓ **Combination of front and rear SiPMs yields reasonable linearity**

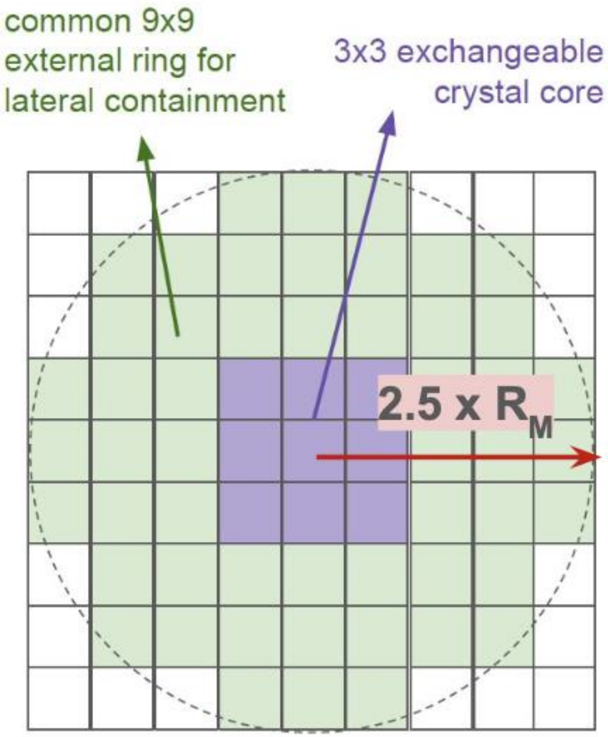


Angular scan with PbWO to study C/S variations With

- ✓ ±10° impact angle variation, C varies by ~5%, much smaller than the ~14% Poisson fluctuation of a 50 Phe Cherenkov signal at 1 GeV.



Summary and work plan



- R&D and proof-of-principle of a dual readout ECAL concept is ongoing
  - large efforts in 2023/24 with a series of beam tests on single crystal modules (@ CERN, DESY, FNAL)
  - **working on test beam data analysis and G4 simulation**
    - **first positive results**

- Plan is to achieve the demonstration of this calorimetric technique using a full-scale EM calorimeter prototype by the next 1-2 years.

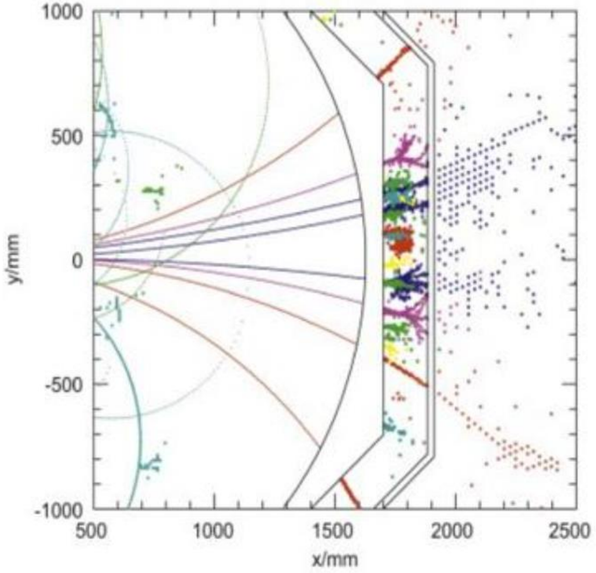
2024	2025	2026
single sensor test with various flavors of crystal, filters and SiPMs	full containment EM calorimetric module prototype (9 x 9 matrix) using most promising technologies	combined test beam with fibre calorimeter prototype

R&D for new HCALs

PFA: **Construction of individual particles and estimation of their energy/momentum in the most appropriate sub-detector**.

PFA requires the **different sub-detectors including calorimeters to be highly granular**.

PFA uses granularity to **separate neutral from charged** contributions and exploits the tracking system to measure with precision of the energy/momentum of charged particles.



Ejet.	$= E_{charged}$ +	$E\gamma$ +	Eh0
fraction	60%	30%	10%

- Charged tracks resolution $\Delta p/p \sim O(10^{-5})$
- Photon(s) energy resolution $\Delta E/E \sim 10\% / \sqrt{E}$
- Neutral hadrons energy resolution $\Delta E/E \sim 45\% / \sqrt{E}$

Two technologies were developed for hadronic calorimeters:

Analogue HCAL (AHCAL)

Semi Digital HCAL (SDHCAL) → stainless steel / iron /Pb + { Glass RPC / MPGD }

Semi-Digital HCAL: Readout and Advantages

Readout Approach

Combines **digital and analog principles**:

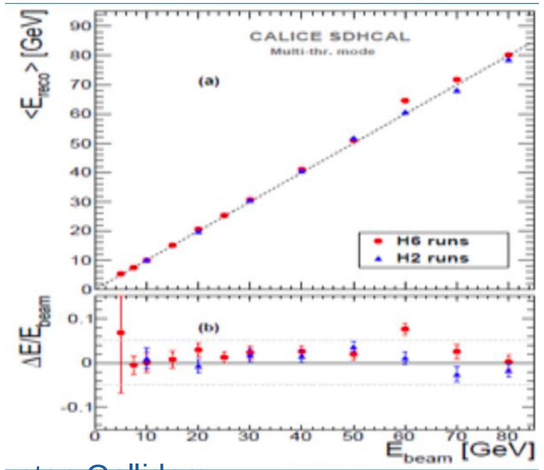
- **Multiple thresholds** classify signals by energy deposition (e.g., "low," "medium," "high").
- Enhances energy resolution with **simplified electronics** compared to analog systems.

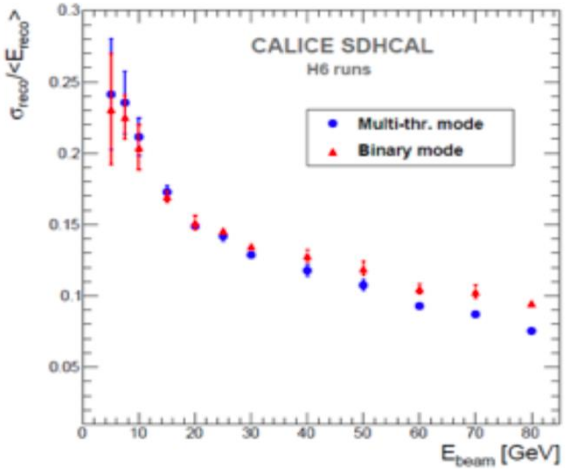
Advantages

- **High granularity** for precise particle tracking and jet reconstruction.
- Optimized for **Particle Flow Algorithm (PFA)** techniques.
- **Cost-effective** alternative with reliable energy and position reconstruction.

A technological prototype of 48 layers of 2 cm stainless steel interleaved with planes made of Glass RPC, successfully tested fulfilling all the ILD requirements:

➢ compactness
➢ self-supporting mechanical structure.
➢ Triggerless mode
➢ Power-pulsing mode



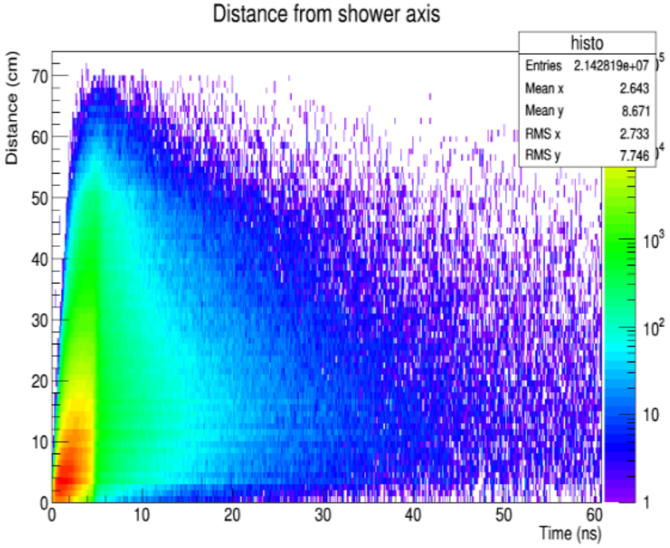


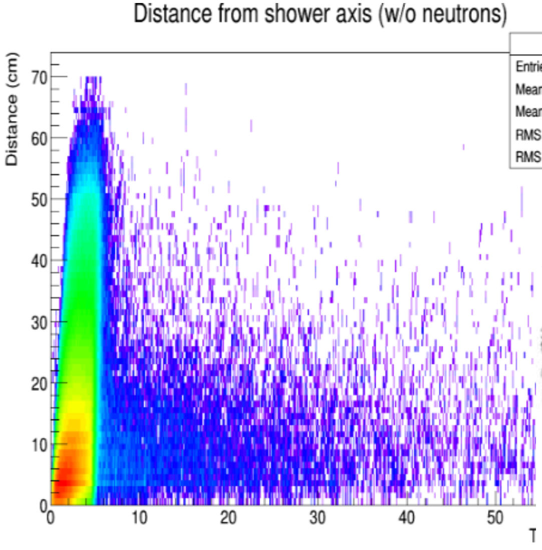
SDHCAL → T-SDHCAL

A powerful tool for PFA

- ➢ SDHCAL was first developed for ILC (Glass RPC): low rate and power pulsing
- ➢ SDHCAL needs to be adapted to cope with circular collider requirements
  - ❑ Continuous readout
  - ❑ Higher rate

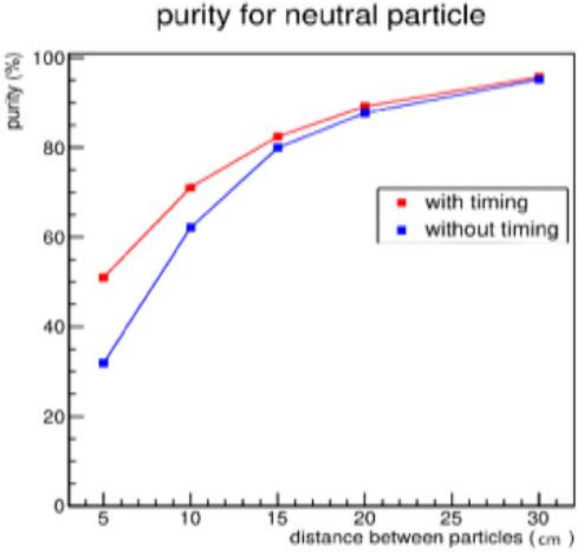
Time information could improve significantly hadronic shower separation at a lower distance

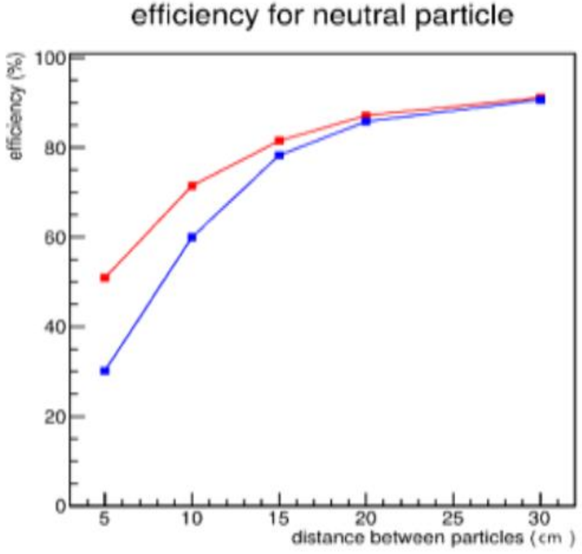




Contribution of delayed neutrons could be separated
→ better energy reconstruction
→ better close-by showers separation

include time information
improves close-by shower separation





SDHCAL-MPGD for the future Muon Collider

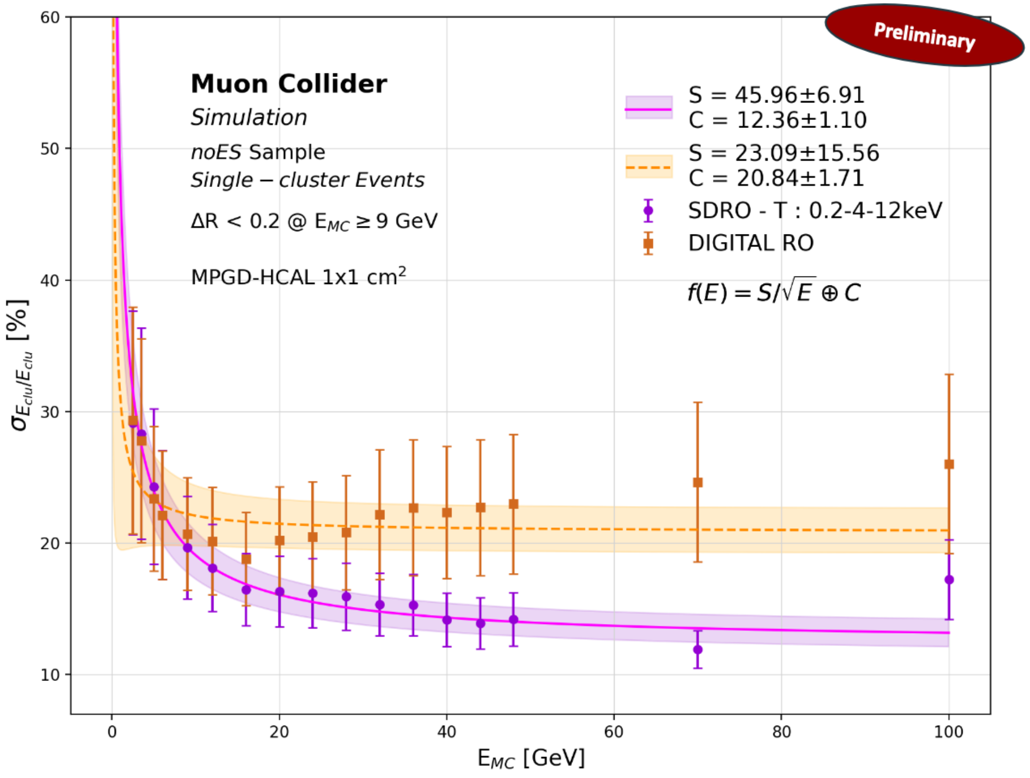
Proposal: Sampling HCAL with Micro-Pattern Gaseous Detectors (MPGD) readout

Features:

- ○ Cost-effective instrumentation of large area
- ○ Radiation hard
- ○ Rate capability of MHz/cm^2
- ○ Readout granularity at-will (≤1cm^2)
- ○ Small Pad multiplicity – *Spatial resolution few mm*
- ○ Argon-based gas mixtures – *Time resolution few ns*

Preliminary result of Simulation studies

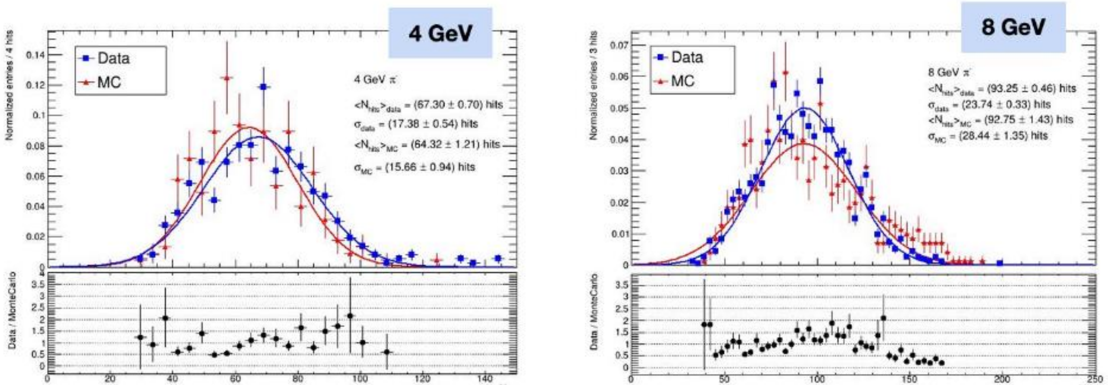
- Only pions not showering in ECAL
- Better performance of SDRO vs DRO
- For now: HCAL-only energy resolution **≤ 60%/√E** => OK
- Future: implement/correct PFA algorithm => Jet Energy Resolution
- Future: implement a more realistic calorimeter (cracks/dead area)



Test Beam and future plan

2023 Test-beam @PS:

- **1λ depth & 1λ diameter**
  - 8 MGDPs (4 uRwell, 3 MicroMegas, 1 RPWELL)
  - first 2 layers of 4 cm iron to enhance showers
  - 2 cm of iron for other layers
- **Pions energy: 2 - 11 GeV**



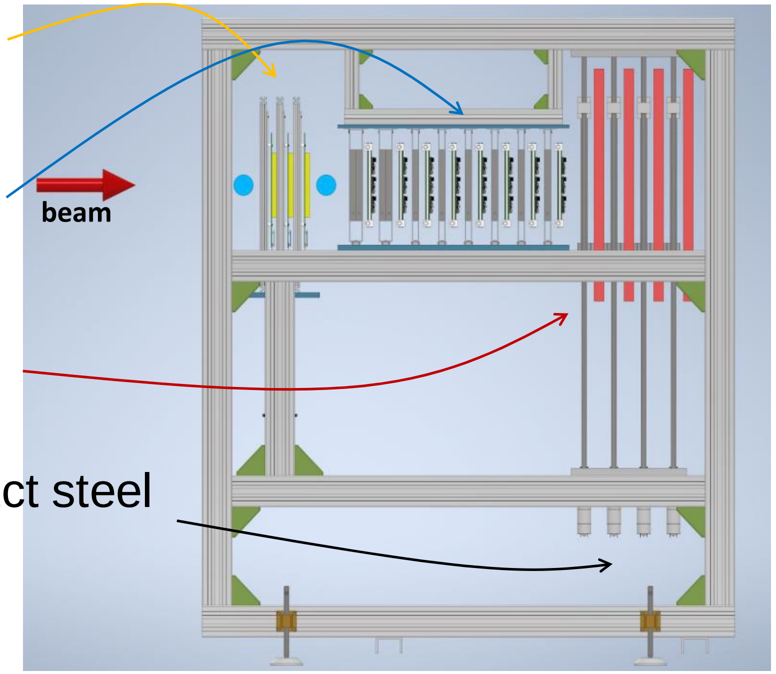
Good agreement in # hits in Testbeam vs GEANT4 MC

2025 Test beam

- 2 λ_i MPGD HCAL

2026 Test beam

❖ 26 X_0 CRILIN + 2 λ_i MPGD HCAL



- Triple-GEM tracker
  - Moveable to scan entire surface
- 1λ with 20x20cm^2
  - 8 dets, 8x2cm steel
- 1λ with 50x50cm^2
  - 4 dets, 4x4cm steel
- Allows to insert / extract steel absorbers

CONCLUSIONS → DRD6

- **Detector R&D (DRD) collaborations** being set-up to implement the **ECFA detector R&D Roadmap**

- **DRD6 is the right framework for the communities to work together**
  WP1 => highly granular sandwich calorimeters
  WP2 => noble-liquid calorimeters
  WP3 => optical calorimeters
  WP4 => electronics and DAQ

- Even if we continued to work on different technologies, we collaborate in activities transversal to the DRD (1-1 correspondence with DRD6 working groups)
  - Software (simulation, reconstruction, ML techniques)
  - Test beams
  - Electronics (frontend, backend/DAQ)

☐ Built the collaboration → **connect people from different groups, projects, institutes**
☐ Share experience → **progress faster and better**

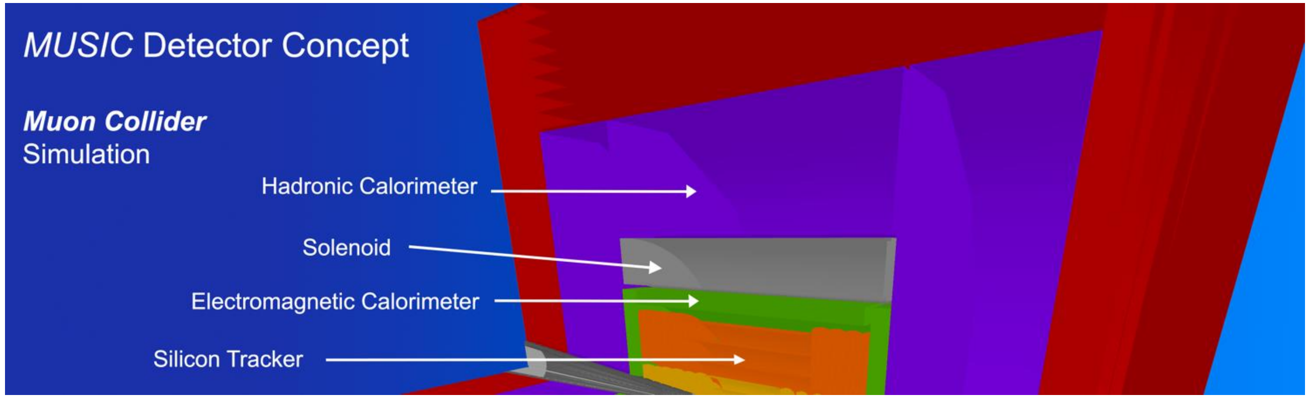
Thanks for your attention

A Music-like detector for FCC-ee

MUSIC detector developed for the Muon Collider, already exceeds FCC-ee requirements in:
- Rate capability.
- Radiation resistance.

- ❑ Tracking System
  - ➢ CLIC-like, same as for CLD system, remains applicable.

- ❑ CRILIN and HCAL-MPGD Integration
  - ➢ Strongly developed to support particle flow algorithms (PFA).



A Music-like detector for FCC-ee

- **CRILIN Electromagnetic Calorimeter:**
  - 5 layers enough for FCC-ee energies.
  - Dual-readout implementation possible - overall or only in external layers -.
  - Excellent spatial, temporal, and energy resolution.
  - 5D reconstruction of the event.

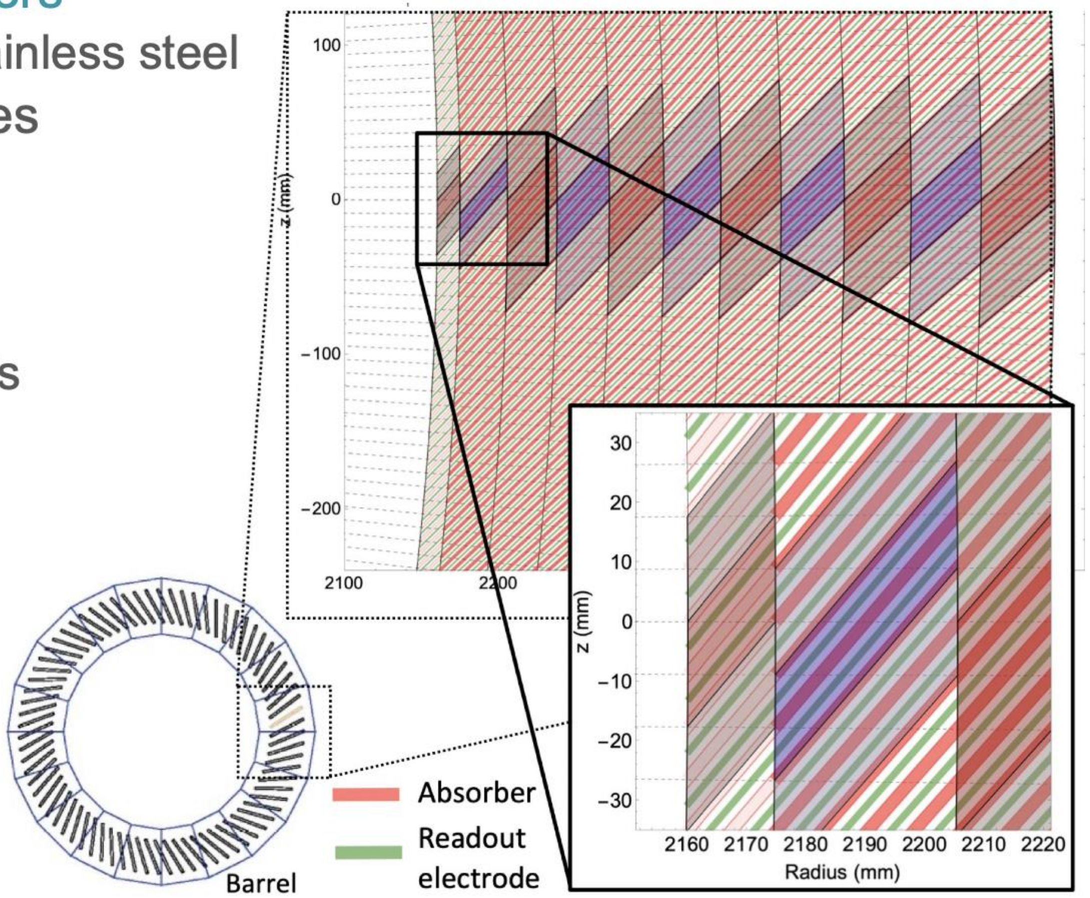
- **HCAL-MPGD Hadronic Calorimeter:**
  - Strongly developed to support particle flow algorithms (PFA).
  - Ensures hermeticity, even with low HCAL radiation lengths.

- **The passive-to-active material ratio can be increased in the last layers, allowing HCAL to serve as an efficient muon detector.**

Spares

ALLEGRO ECal barrel design

- **Baseline design** (exact parameters subject to further optimisation):
    - 1536 straight inclined (50.4°) 2 mm absorbers
        - 1.8 mm Pb, 0.1 mm glue and 0.1 mm stainless steel
    - Multi-layer PCBs used as readout electrodes
    - 1.2-2.4 mm LAr gaps
    - 40 cm deep (≈ 22 X_0)
    - Segmentation
        - $\Delta\theta$ ~ 10 (2.5) mrad for regular (strip) cells
        - $\Delta\phi$ ~ 8 mrad
    - 11 longitudinal compartments (in depth)



- **Possible options**
    - LKr or LAr active medium
    - W or Pb absorbers
    - Al or carbon fibre cryostat
    - Absorbers thicker at outer radius

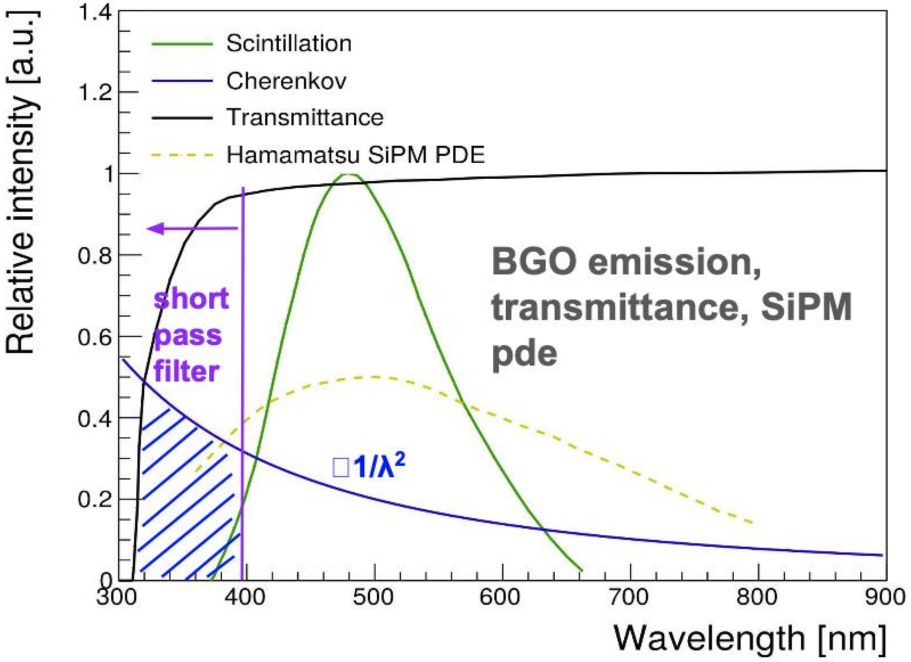
Dual readout strategy

Cherenkov (C) and Scintillation (S) light detection and separation very challenging in homogeneous materials

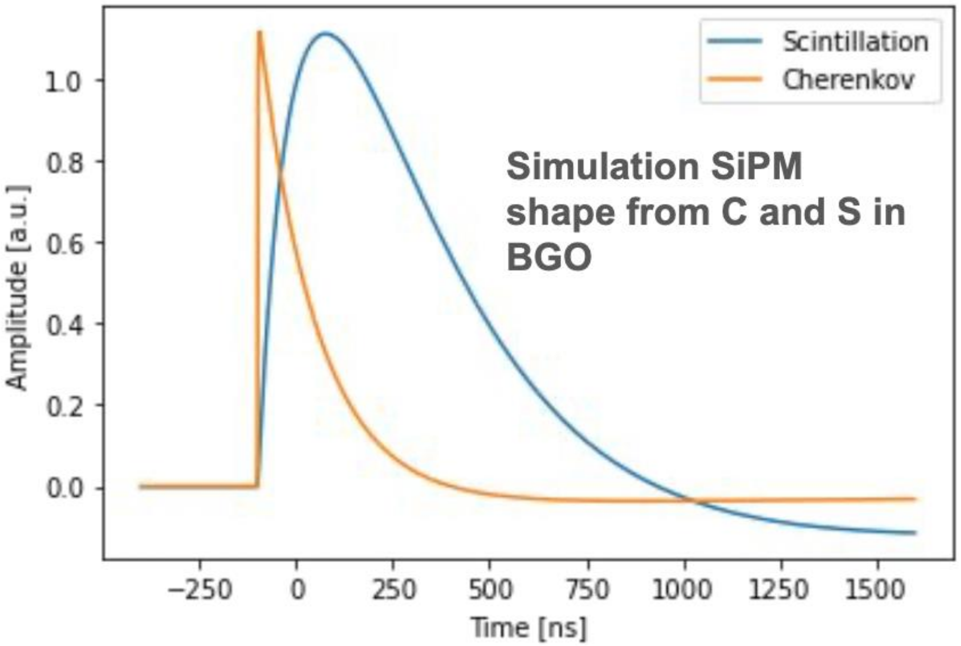
C vs S distinctive features:

- **C emission faster than S**
- **C emission spectrum broader than S**

→ C/S separation with filters and pulse shape analysis



BGO emission, transmittance, SiPM pde



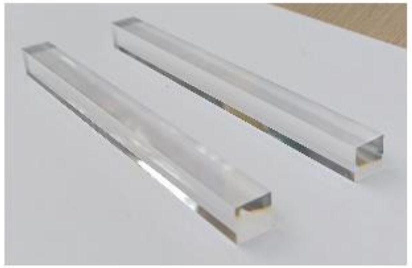
Simulation SiPM shape from C and S in BGO

R&D Activity

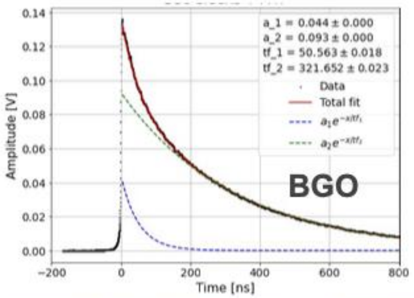
First activities **focus on understanding photon collection in with various technological choices (crystals, filters, SiPMs, FE)**

- Laboratory benches exploiting radioactive sources, excited photoluminescence and cosmic rays for single calorimetric cell
  - Characterization of:
    - Scintillating crystals (PWO, BGO, BSO, CsI)
    - Absorptive optical filters to isolate the Cherenkov light (Edmunds, Kodak)
    - SiPMs (Broadcom, Hamamatsu)
- Geant4 simulation with single crystal geometry

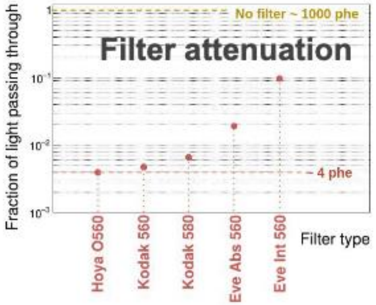
SICCAS Crystals



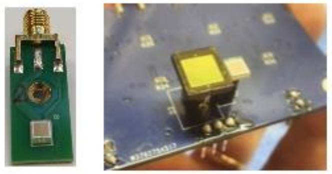
Time constant characterization



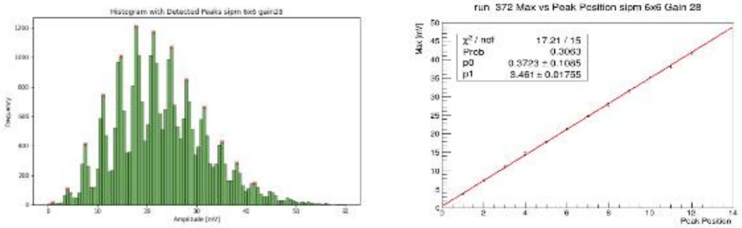
Schott UG11 UV



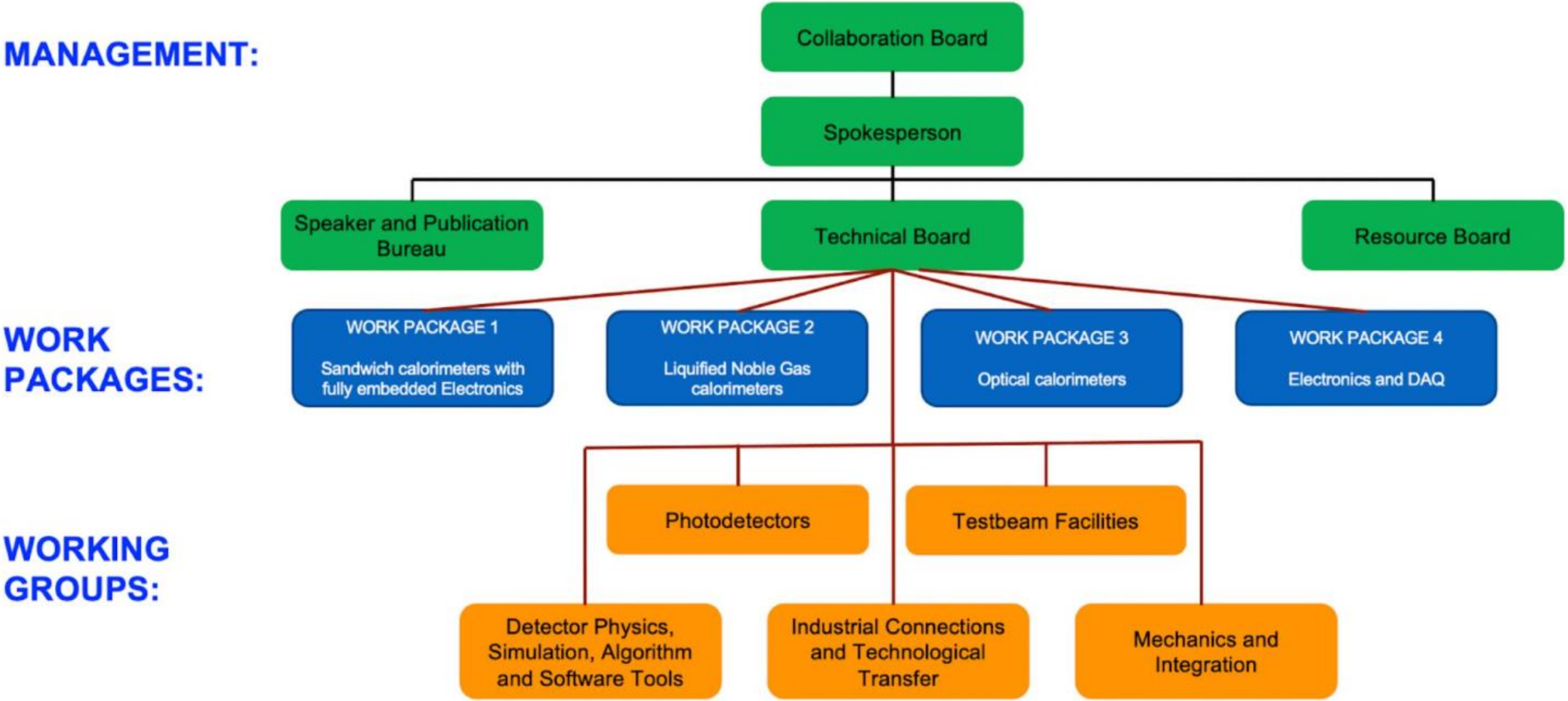
Hamamatsu SiPM:
S13360 / 14160-6050
S14160-3010-PE



SiPM amplitude calibration



DRD6 management organization



MANAGEMENT:

Collaboration Board

Spokesperson

Speaker and Publication Bureau

Technical Board

Resource Board

WORK PACKAGES:

WORK PACKAGE 1
Sandwich calorimeters with fully embedded Electronics

WORK PACKAGE 2
Liquified Noble Gas calorimeters

WORK PACKAGE 3
Optical calorimeters

WORK PACKAGE 4
Electronics and DAQ

WORKING GROUPS:

Photodetectors

Testbeam Facilities

Detector Physics, Simulation, Algorithm and Software Tools

Industrial Connections and Technological Transfer

Mechanics and Integration