Dual readout calorimetry for the IDEA detector concept

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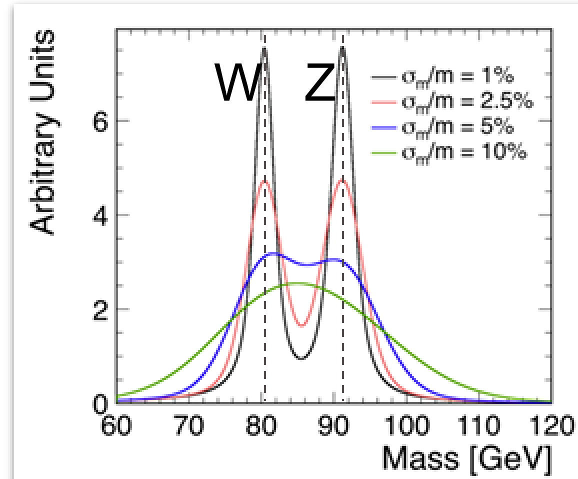
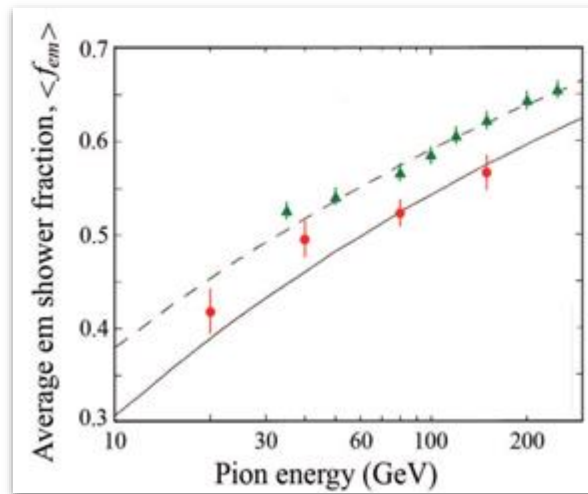
**Special thanks to M. Lucchini for kindly sharing some of this material*

Jet energy resolution is a key requirement for future e+e- colliders

- The next generation of leptonic colliders requires a jet energy resolution of ~30%/√E (~3-4% @90 GeV) to distinguish jets from W or Z bosons
- Limiting factors for jet energy resolution:
  - The fraction of electromagnetic (fem) shower increases with energy and fluctuates event-by-event
  - Calorimeters typically respond differently to the EM and had component
- Two historical approaches to address this challenge
  - Particle Flow
  - Dual readout
- IDEA is pursuing the hybrid dual-readout method with a possible exploitation of PF algorithm
  - Crystal dual readout (EM-section): ~ 3%/√E
  - Fibre sampling dual readout (Hadronic-section) ~30%/√E

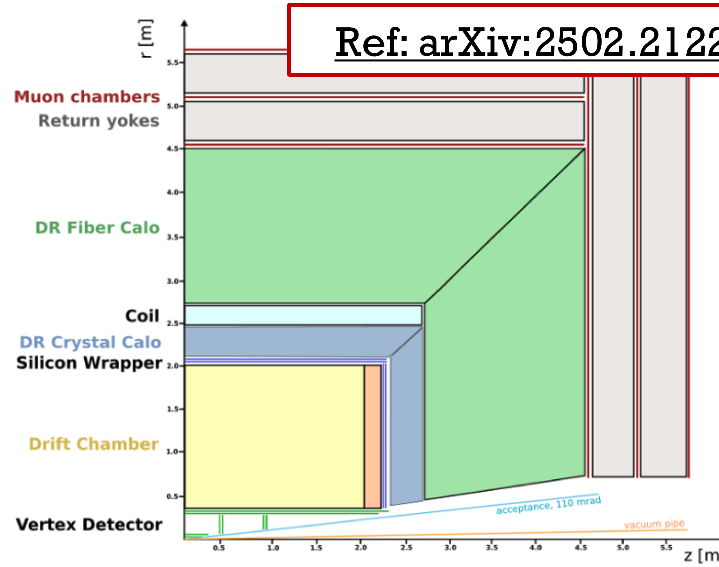




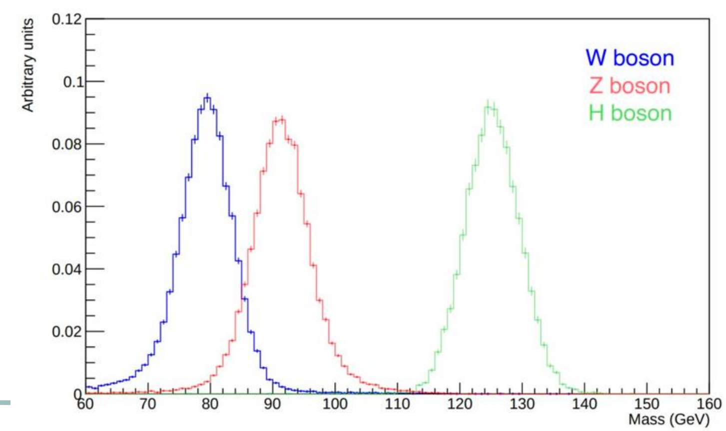
IDEA: detector concept

- Beam pipe: R ≈ 1.0 cm
- Highly transparent tracking
  - Si pixel vertex detector (monolithic technology)
  - Drift Chamber
  - Si wrappers (timing option under discussion)
- Dual-readout crystal ecal: ≈ 22 X_0
  - ~ 3%/√E EM energy resolution
- Thin superconducting solenoid: 3 T
- Dual-readout calorimetry 2 m / 7 λ_{int}
  - ~ 30%/√E energy resolution
- Muon chambers
  - μ-RWELL in return yoke

Ref: arXiv:2502.21223

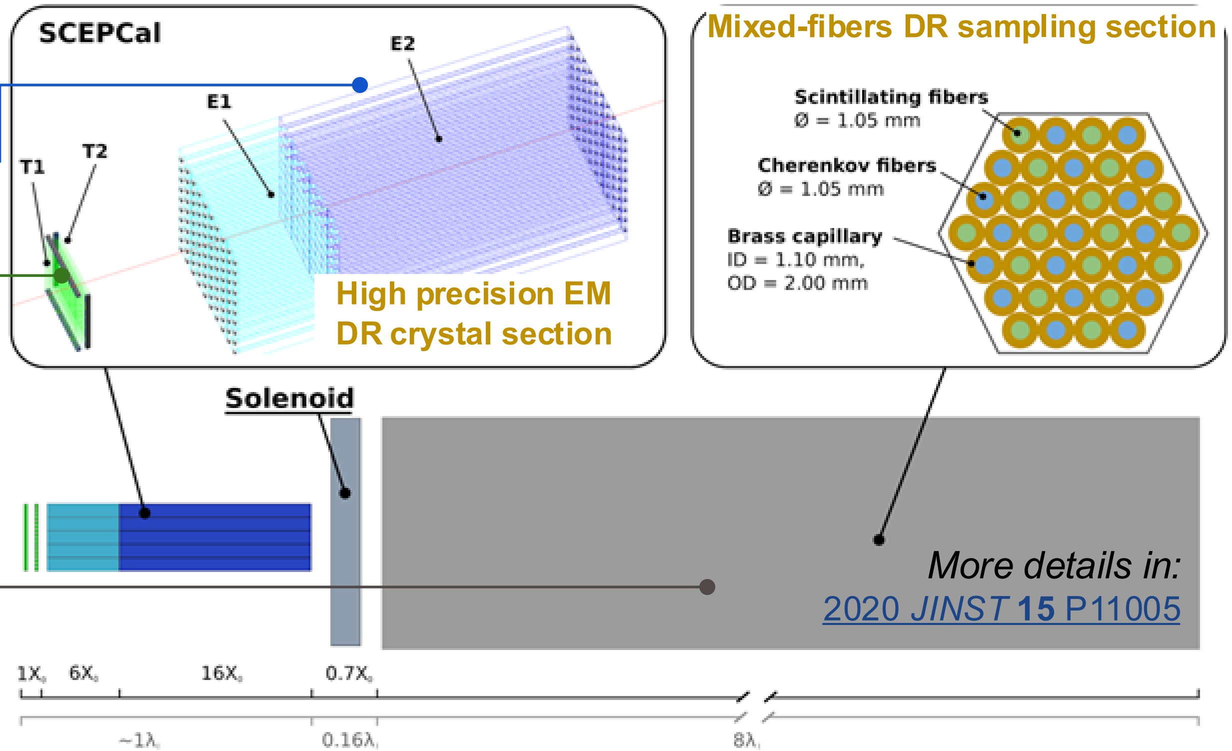


Target jet-jet mass resolution $\frac{\sigma}{E} = \frac{30\ \%}{\sqrt{E}}$



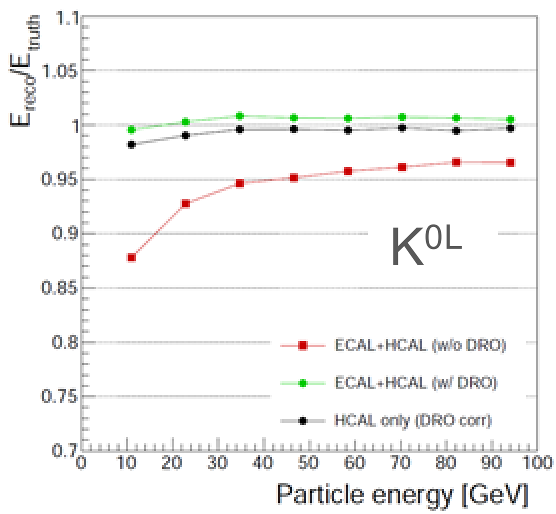
Hybrid Dual readout: conceptual layout

- Timing layers — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~1X0)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- ECAL layers — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~6X0)
  - Rear segment (~16X0)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- Ultra-thin IDEA solenoid
  - ~0.7X0
- HCAL layer — $\sigma^{HAD}_E/E \sim 30\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibres (for Cherenkov signal) inserted inside capillaries

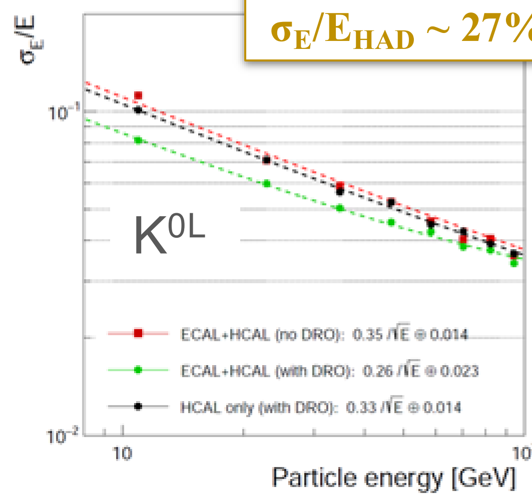


The dual-readout method in a hybrid calorimeter

- Evaluate the χ-factor for the crystal and fibre section
- Apply the dual readout correction on the energy deposits in the crystal and fibre section independently
- Sum up the corrected energy from both sections



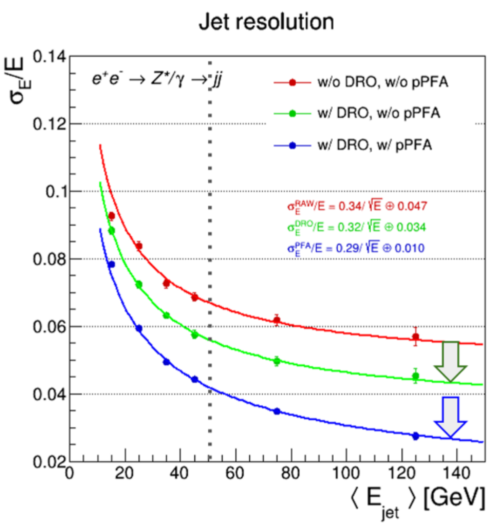
$\sigma_E/E_{HAD} \sim 27\%/\sqrt{E} \oplus 2\%$

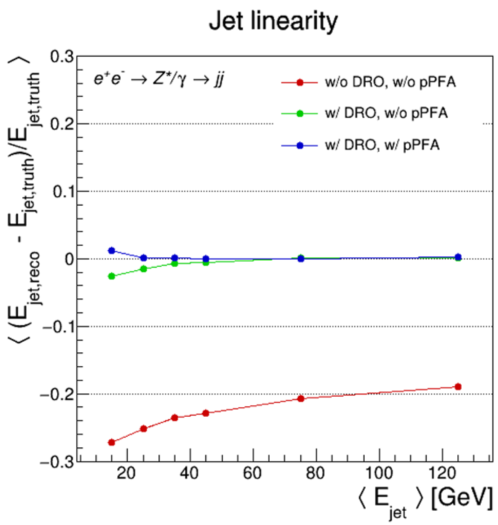


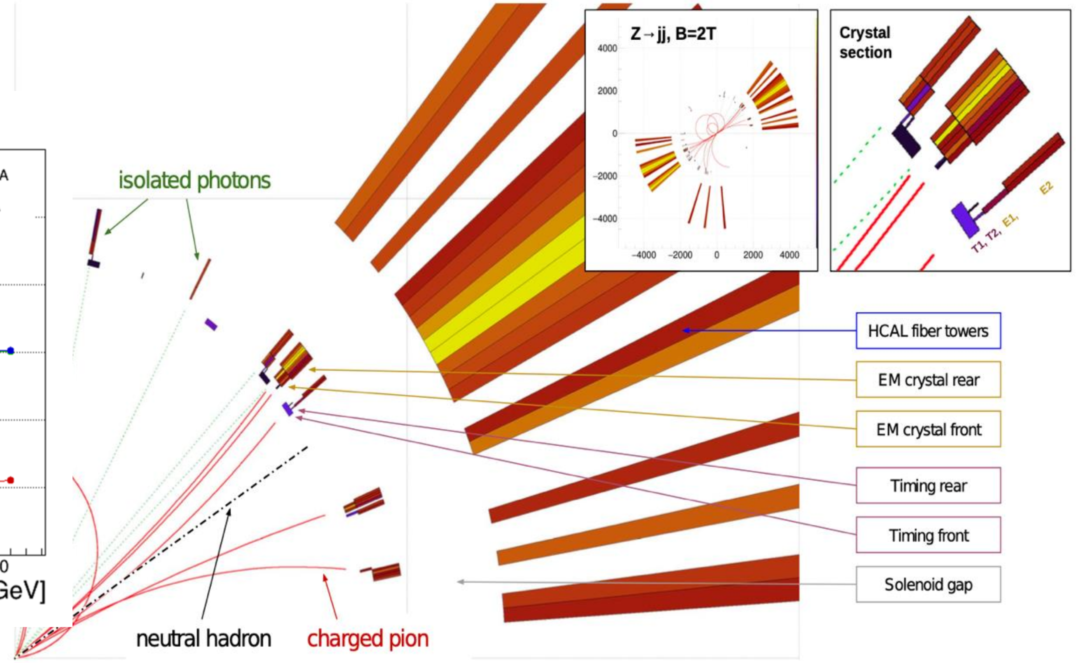
- G4 simulation confirm the Dual-readout applicability to a hybrid system
  - Response linearity to hadrons restored within ±1%
  - Hadron energy resolution comparable to that of the fiber-only IDEA calorimeter

Jet resolution: with and without DR-pPFA

Particle Flow Algorithm combined to dual-readout method was studied with G4 simulation







Sensible improvement observed in jet resolution → 3-4% for jet energies above 50 GeV

Crystal calorimeter R&D (EM section)

- Early-stage R&D: efforts ramping up mostly in 2023 thanks to national funds
  - Identify best crystal from the calorimetric point of view

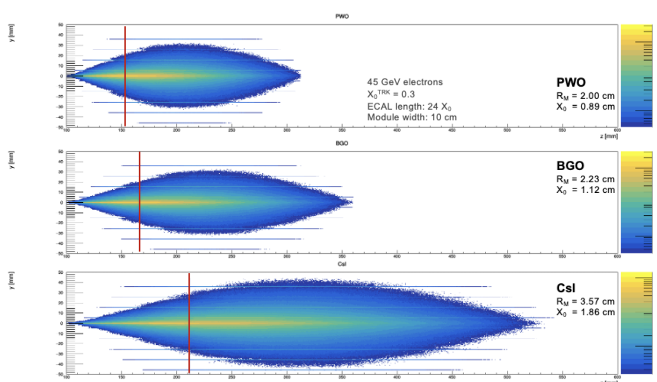
- **PWO**: the most compact, the fastest
- BGO/BSO: parameters tunable by adjusting the Si-fraction
- CsI: the less compact, the slowest, the brightest

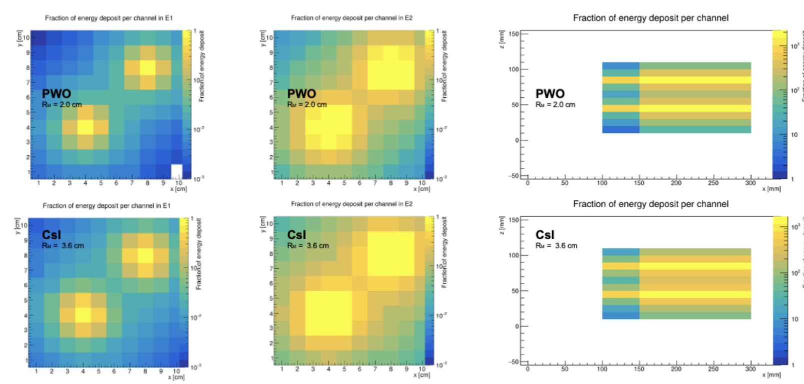
better for PFA

better stochastic term

The most interesting

Crystal	Density g/cm³	λ_I cm	X_0 cm	R_M cm	Refractive index, n	Relative LY @ RT	Decay time ns	Photon density (LY / τ_D) ph/ns	dLY/dT (% / °C)	Cost (10 m³) Est. \$/cm³	Cost*X_0 Est. \$/cm²
PWO	8.3	20.9	0.89	2.00	2.2	1	10	0.10	-2.5	8	7.1
BGO	7.1	22.7	1.12	2.23	2.15	70	300	0.23	-0.9	7	7.8
BSO	6.8	23.4	1.15	2.33	2.15	14	100	0.14	--	6.8	7.8
CsI	4.5	39.3	1.86	3.57	1.96	550	1220	0.45	+0.4	4.3	8.0

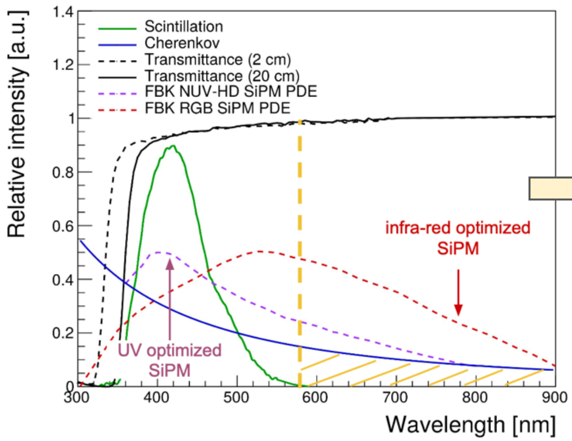




Crystal calorimeter R&D (EM section)

- Early-stage R&D: efforts ramping up mostly in 2023 thanks to national funds
  - Optimise the Dual-readout method

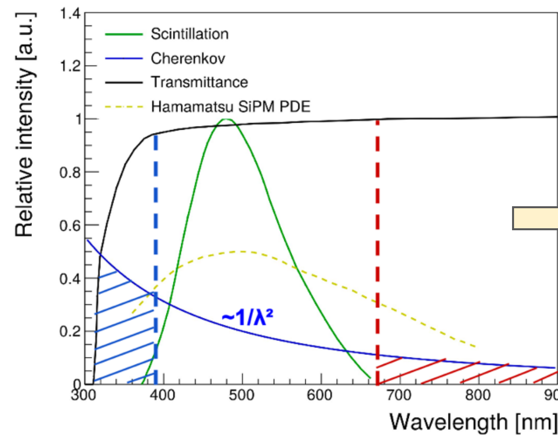
PWO (λ - based)



Low light yield at 420 nm → Easy to filter out scintillation light with a dedicated SiPM+optical filter (C photons with λ>580 nm)

Fast decay time (~10 ns) → hard to separate S and C using pulse shape

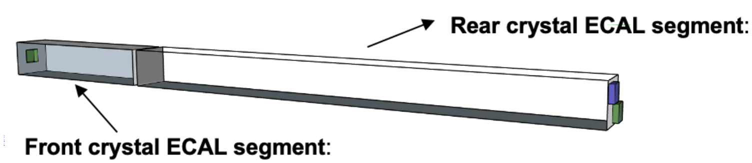
BGO / BSO (λ+t - based)

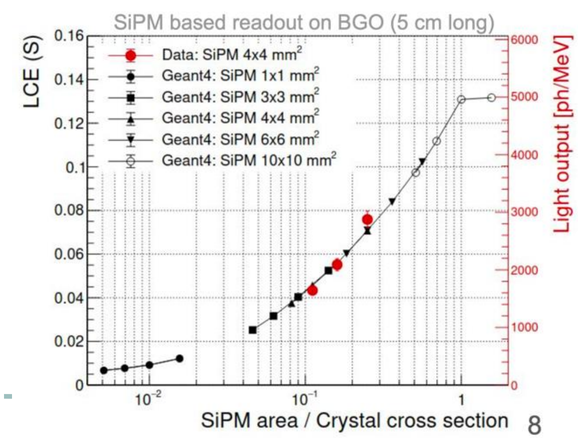


Higher light yield (10-30x PWO) at 480 nm → harder to filter out scintillation photons

Slow decay time (~100-300 ns) → can separate S/C by using a single SiPM (impact on the readout electronics to be considered)

Simultaneous readout of scintillation and Cherenkov light from the rear segment





Scintillating light output measured in the laboratory

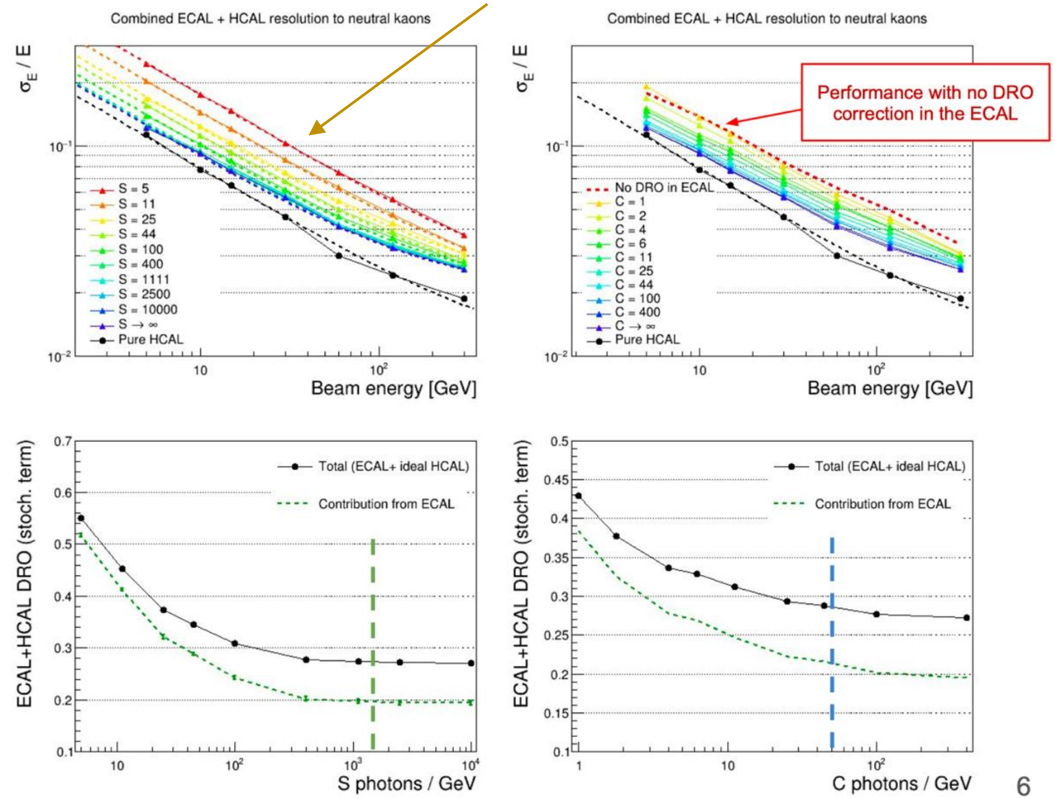
[M. Lucchini @ VCI2025]

Crystal calorimeter R&D (EM section)

- Early-stage R&D: efforts ramping up mostly in 2023 thanks to national funds
  - Photo-statistic requirements for S and C
  - SiPM selection

Smearing according to Poisson statistics

Simulation



- S > 1600 phe/GeV required for EM resolution better than 3%/√E
- C > 50 phe/GeV to reach target hadronic resolution using DR method
- SiPMs with enough dynamic range
- Experimental validation is needed

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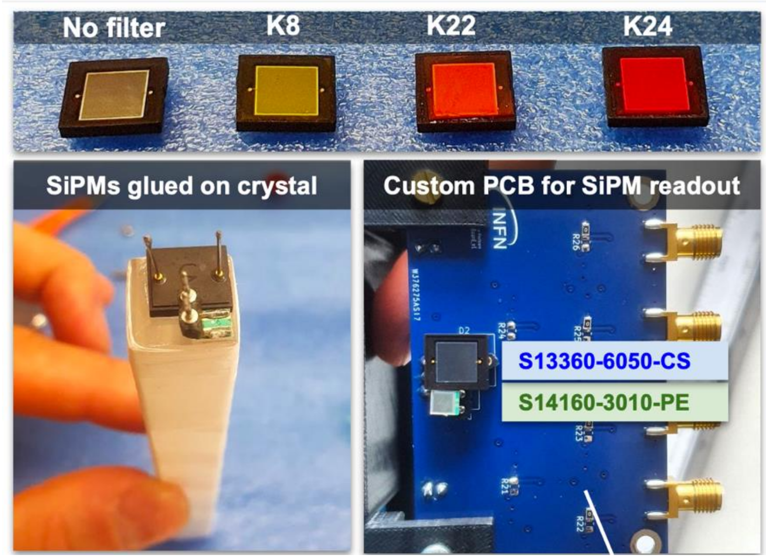
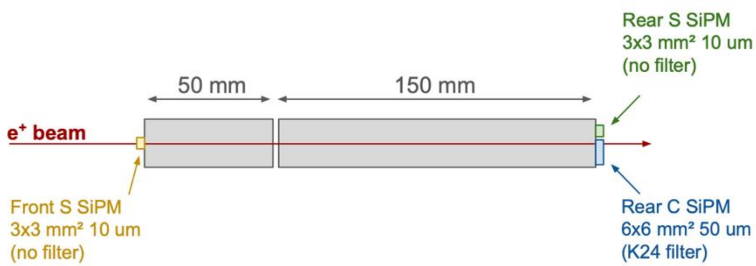
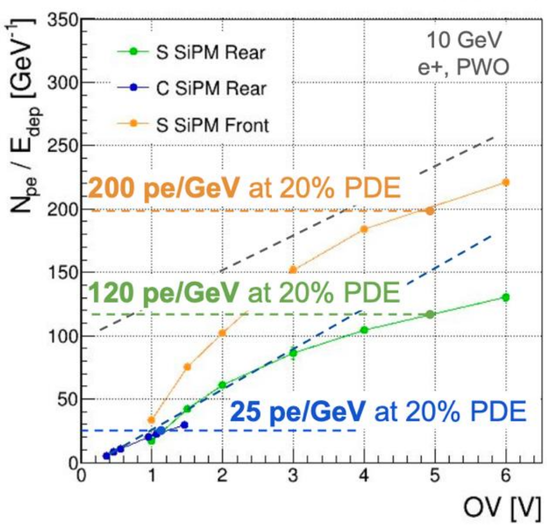
TB results (CERN H6, 2024)

- Test using a single crystal (PWO and BGO) to study the photon yield for Scintillation and Cherenkov light
- Rotating stage to study angular dependence of the Cherenkov signal



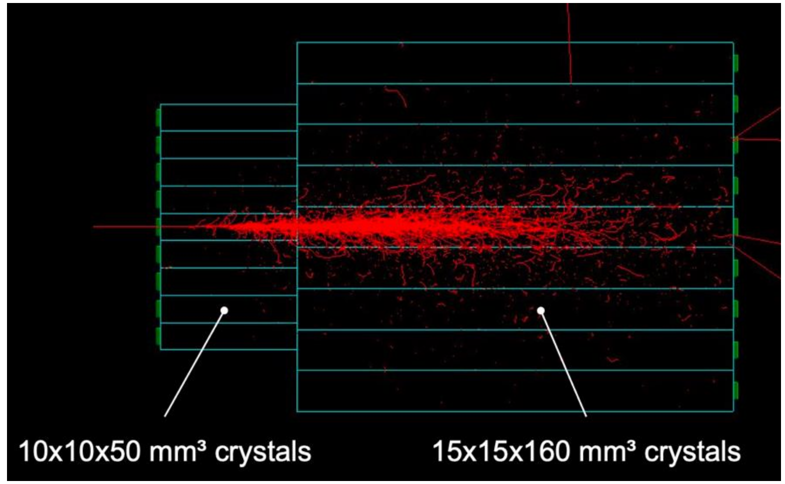


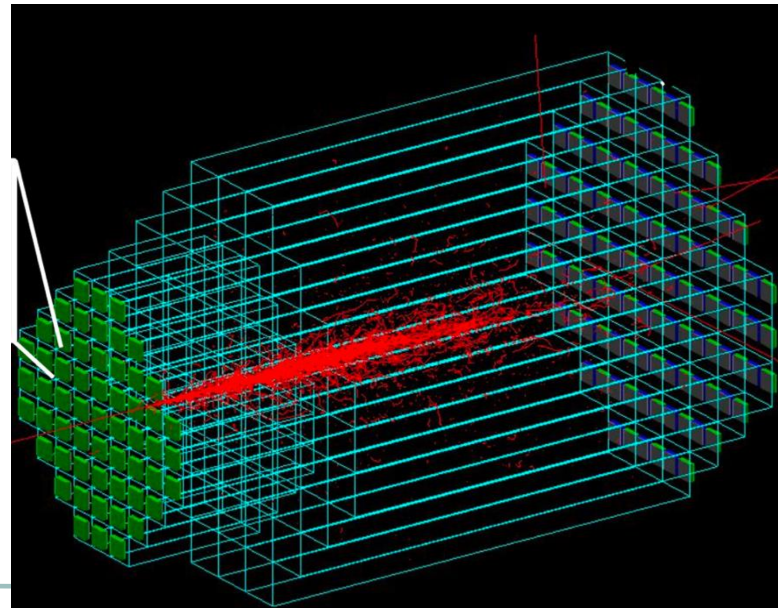


- Number of photoelectrons detected can be used to define SiPM/filter specifications:
  - Scintillation: ~36 pe/GeV/mm² at 20% PDE
    - → need 6x6 mm² SiPM and 40% PDE to reach target
  - Cherenkov: ~0.7 pe/GeV/mm² at 20% PDE
    - → need 6x6 mm² SiPM and 40 PDE to reach target
  - Contamination from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

Larger prototype under construction for the next TB

- Plan to assemble a 9x9 PWO matrix
- Front crystal equipped with Single 6x6 mm^2 SiPM (15 μm cell size, no filter)
- Rear crystal equipped with two 6x6 mm^2 SiPM
  - 15 μm cell size, no filter (Scintillating light)
  - 50 μm cell size, K24 filter (Cherenkov light)
- Possibility to exchange central 3x3 core with BG(S)O
- Baseline readout: FERS 5200 + A5202 (Citiroc1A)
- Possibility to apply pulse shape analysis with BG(S)O is on the table



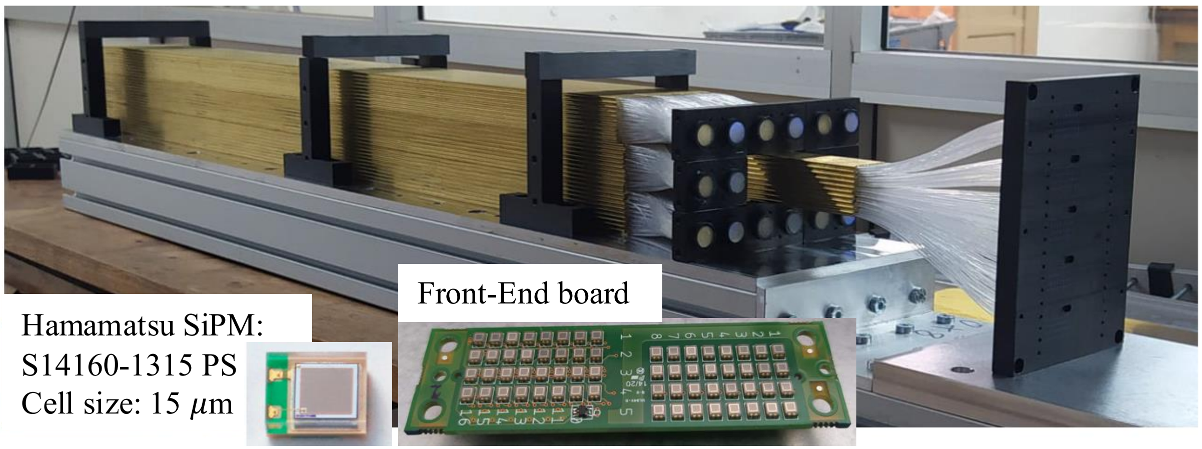


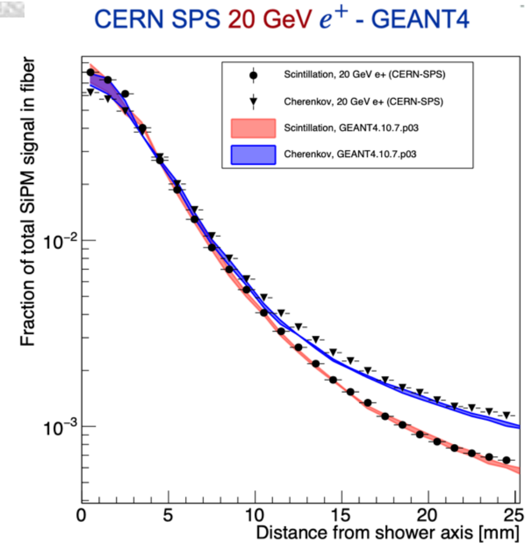
Fiber calorimeter R&D (hadronic section)

- More advanced R&D program: few national grants to support these activities (Italy, Korea, US)
- Different teams are assembling / reusing hadronic-sized prototypes to exploit:
  - Different absorber materials and integration techniques
  - Different light sensors (SiPM / MC-PMT)
  - Readout strategies (light intensity + timing / wave form / dSiPM)
- Three demonstrators are on the table for this year TB qualification

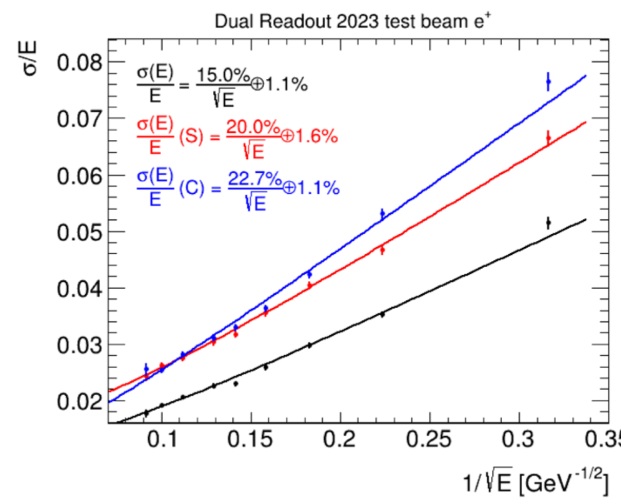
A short overview is available here. In the next slides, I will focus on the R&D studies within the HiDRa project

EM-sized prototype qualified on Beam in 2021 and 2023





- A small prototype was tested on beam in 2021 and 2023 (@DESY and @CERN) with electrons ranging from 1 to 120 GeV
- The prototype was made of brass capillary tubes (2 mm outer diameter) each hosting a fibre of 1 mm diameter: (10x10x100 cm^3)
- It was organized in 9 towers, each containing 16x20 capillaries with alternating scintillating and clear fibres
- The central tower was equipped with SiPMs while the surrounding towers were connected to PMTs (costs saving reason)

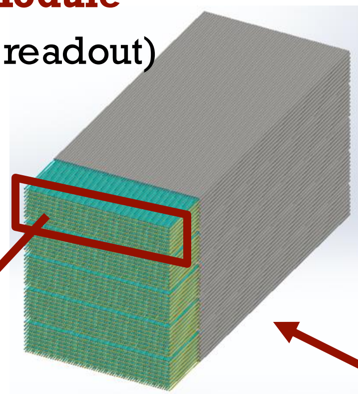


TB2021: *JINST* **18** P09021 (2023)
TB2023: arXiv:2503.15616

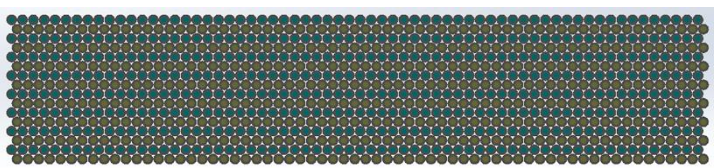
Hadronic-sized demonstrator is under construction

The Low Granular Module

5 Mini-modules (PMT readout)
~ 13 x 13 x 250 cm^3



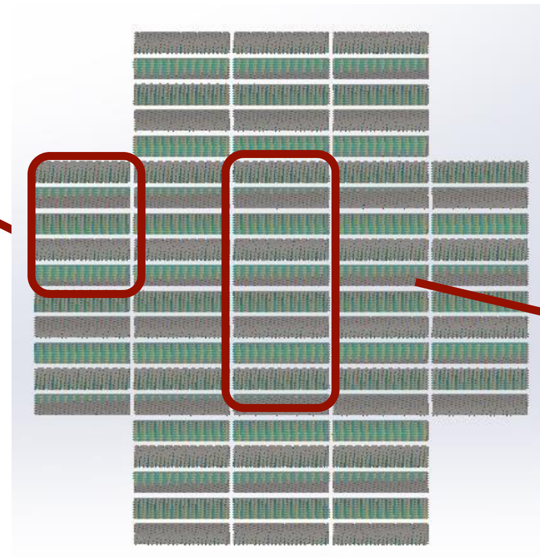
The mini-module



64 x 16 stainless steel capillaries: 2 mm outer diameter and 2.5 m long.
Scintillating and clear fibres (alternated in rows) to apply the dual-readout method

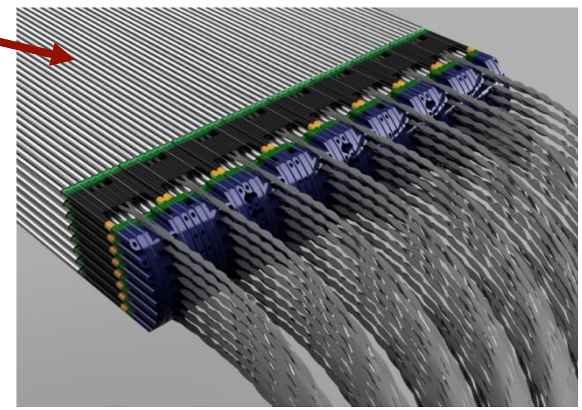
The HiDRa prototype

Designed to be scalable and large enough to measure hadronic performances



The High Granular Module

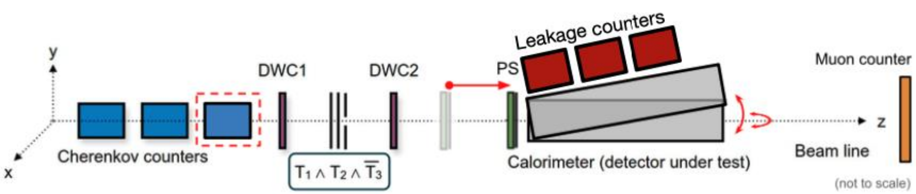
Two central modules read out with 10k SiPMs (one per fibre)

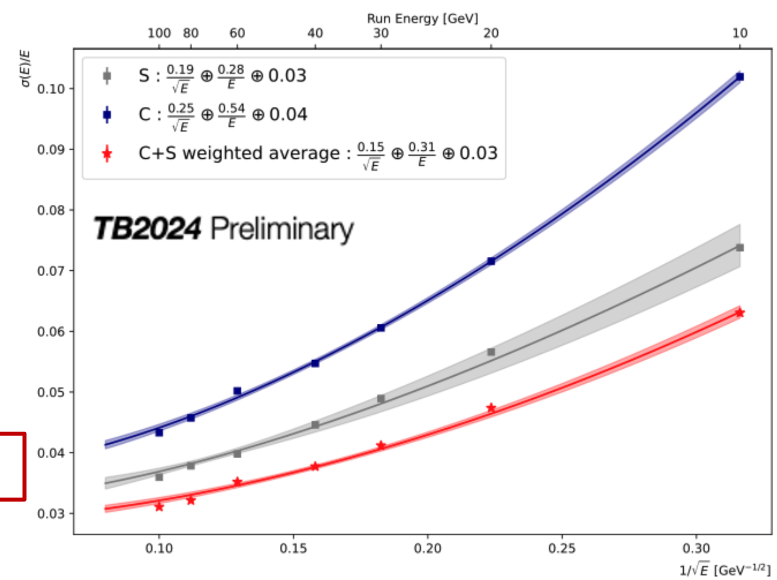


Challenging integration requiring precise assembly procedure and compact components (i.e. SiPMs, services and mechanical support) to fit in the back of the calorimeter

A part of the hadronic-sized calorimeter tested on beam in 2024

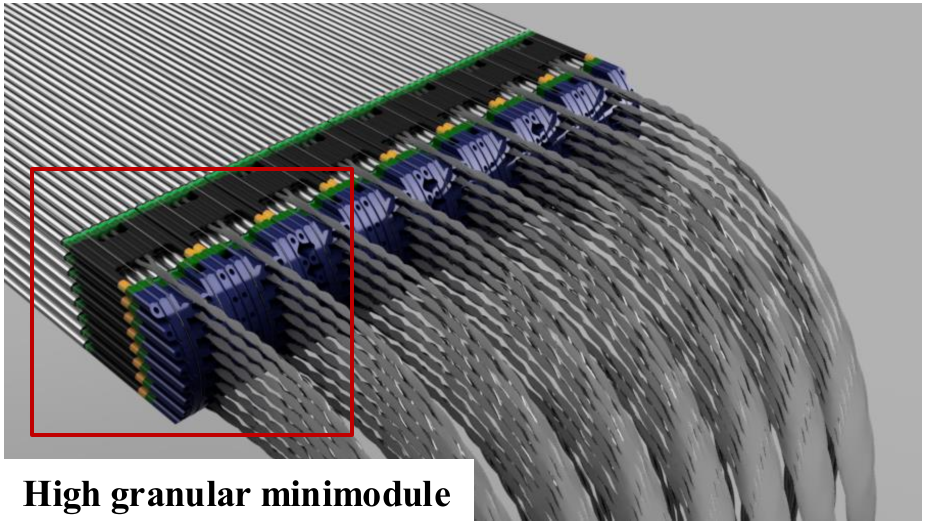
- Low Granular modules qualification on beam:
  - 36 HiDRa minimodules, 3 columns x 12 rows: ≈ 39 X 39 x 250 cm^3
  - Nominal angle of 2.5° (x and y axis) with the beam
  - PMT-readout only

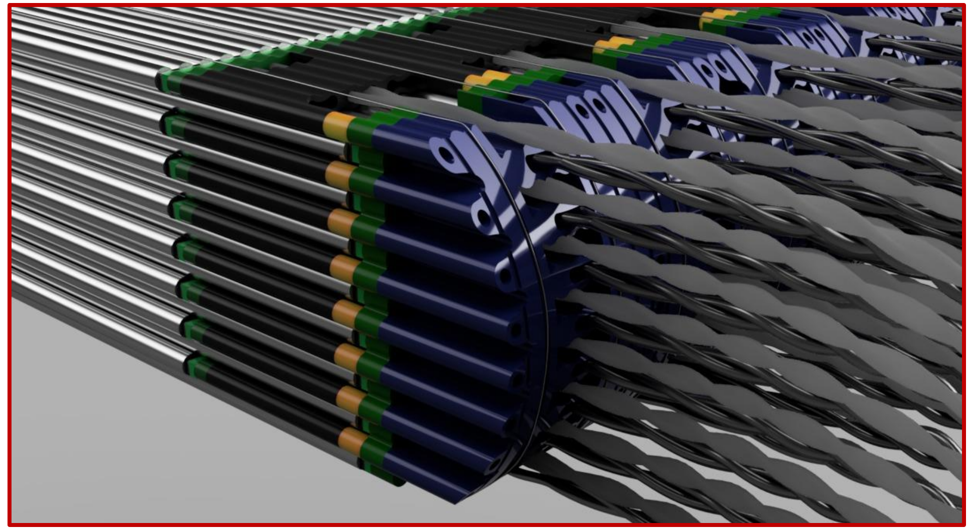


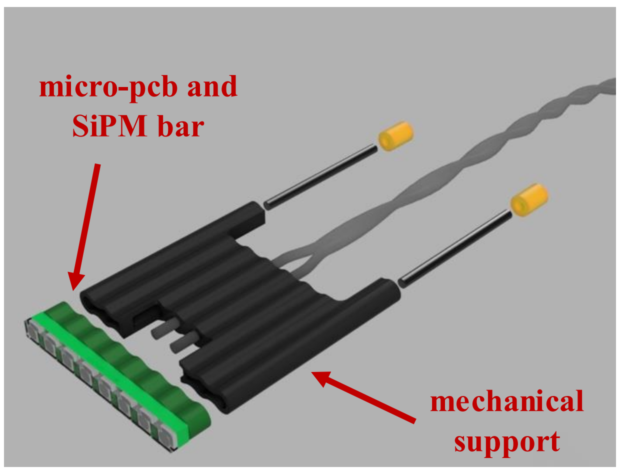


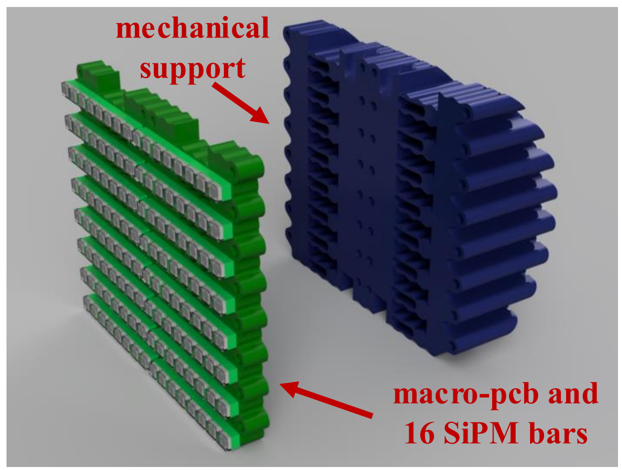
L. Nasella @ VCI2025

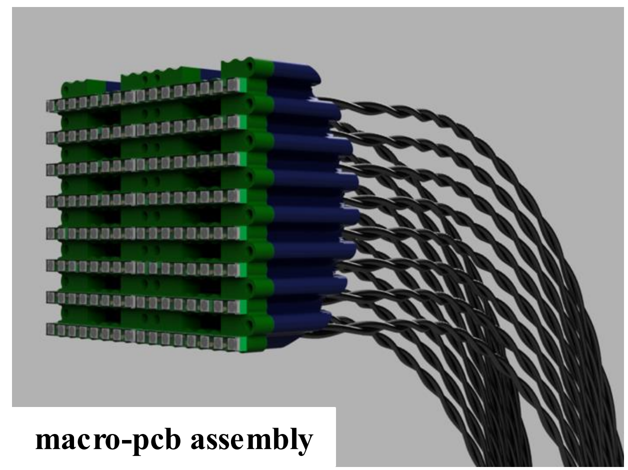
HG module assembly is progressing





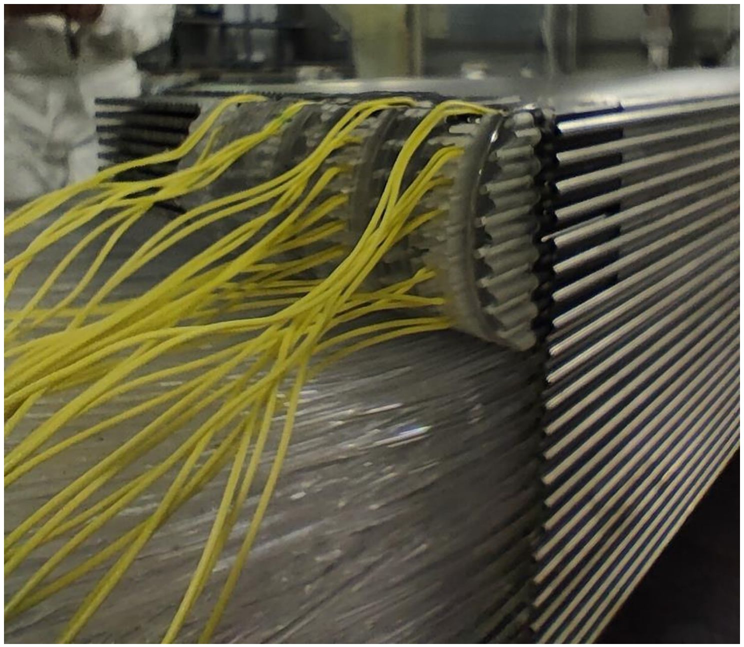




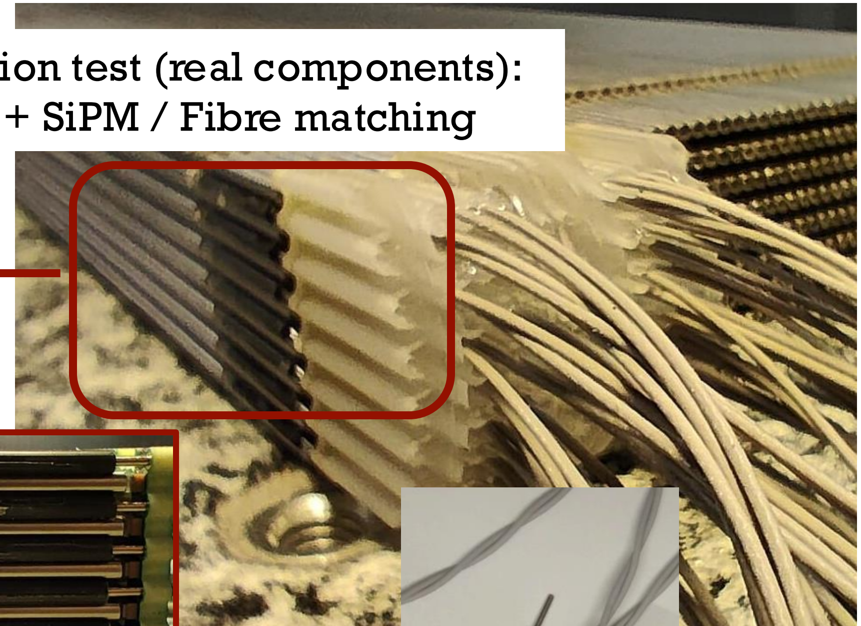


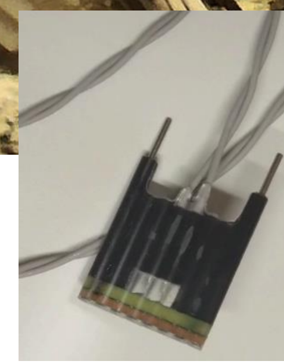
HG module assembly is progressing

1st integration test (dummy components): mechanical integration with LG modules



2nd integration test (real components): integration + SiPM / Fibre matching



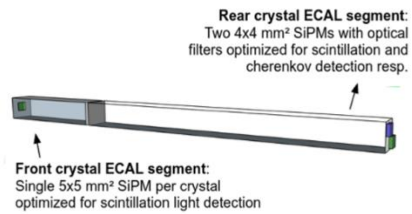


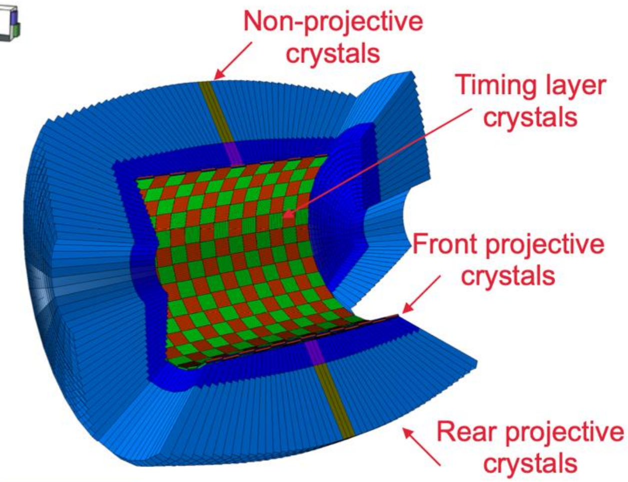
Almost 90% of the Low Granular modules are ready for the TB.
The production of High Granular modules, just started, is progressing well

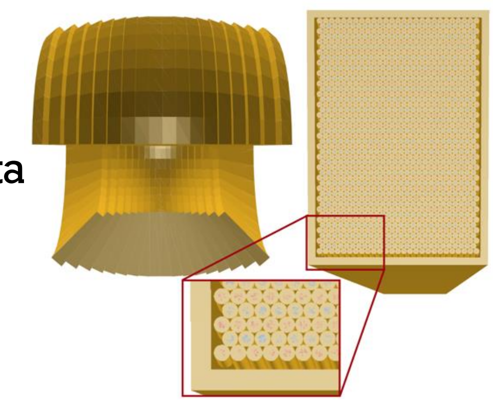
HiDRa will be qualified on beam at CERN SPS in September

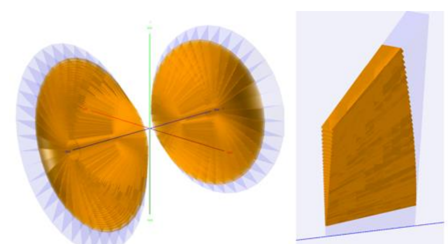
IDEA full simulation

- A full G4 simulation, describing the IDEA subdetectors is ready
- The geometry with the hybrid dual readout calorimeter has been recently included
  - Dual-readout crystals @IDEA_o2
    - Projective homogeneous (PWO) crystal calorimeter
    - Dual-readout capability ensured by two SiPMs instrumented on the rear section
    - Timing layer placed in front, based on LYSO crystals
  - Tubes-based dual-readout calo @IDEA_o2
    - Based on the new construction technique housing optical-fibres into capillary-tubes
- Performances tuned with recent test beam data
- Next to come: digitization and reconstruction









[L. Pezzotti @ 8th FCC Workshop]

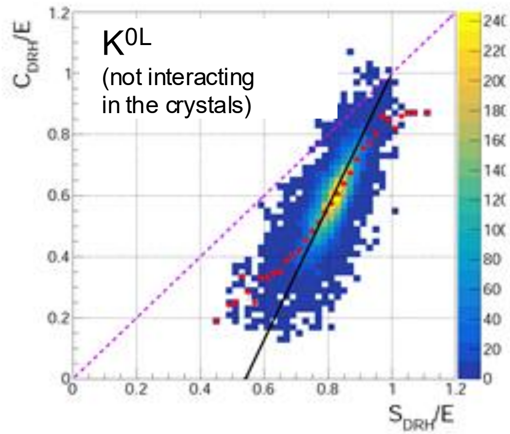
In summary

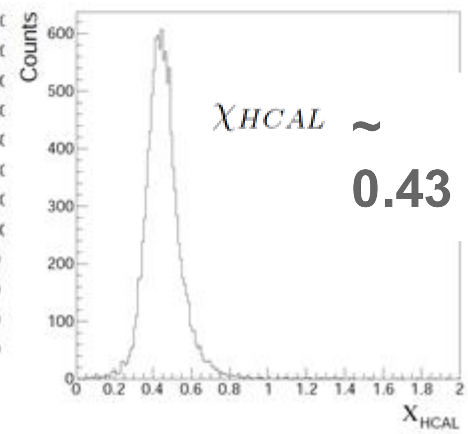
- The DRCal R&D is moving in several directions (i.e. detector design/optimization, integration and readout system)
- The hybrid dual readout calorimeter has been recently included in the IDEA G4 simulation
  - The detector response is regularly updated with results form the latest TB
  - It's a good time to use this powerful tool to update the detector performances
- Synergies and joint efforts are growing, hopefully we will have a combined test beam in the coming years

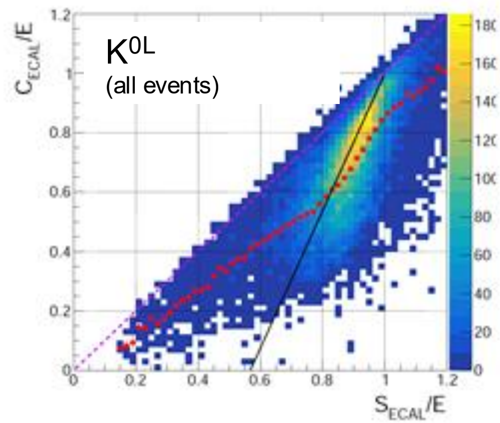
Backup

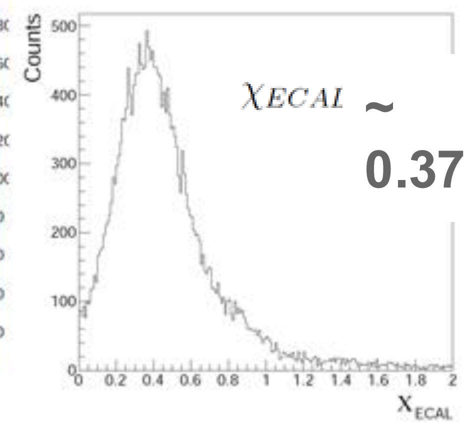
The dual-readout method in a hybrid calorimeter

- Evaluate the χ-factor for the crystal and fibre section
- Apply the dual readout correction on the energy deposits in the crystal and fibre section independently
- Sum up the corrected energy from both sections









$$\chi_{HCAL} = \frac{1-(h/e)_s^{HCAL}}{1-(h/e)_c^{HCAL}}$$

$$\chi_{ECAL} = \frac{1-(h/e)_s^{ECAL}}{1-(h/e)_c^{ECAL}}$$

$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1-\chi_{HCAL}}$$

$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1-\chi_{ECAL}}$$

$$E_{total} = E_{HCAL} + E_{ECAL}$$

Digital SiPM Platform for High Energy Physics

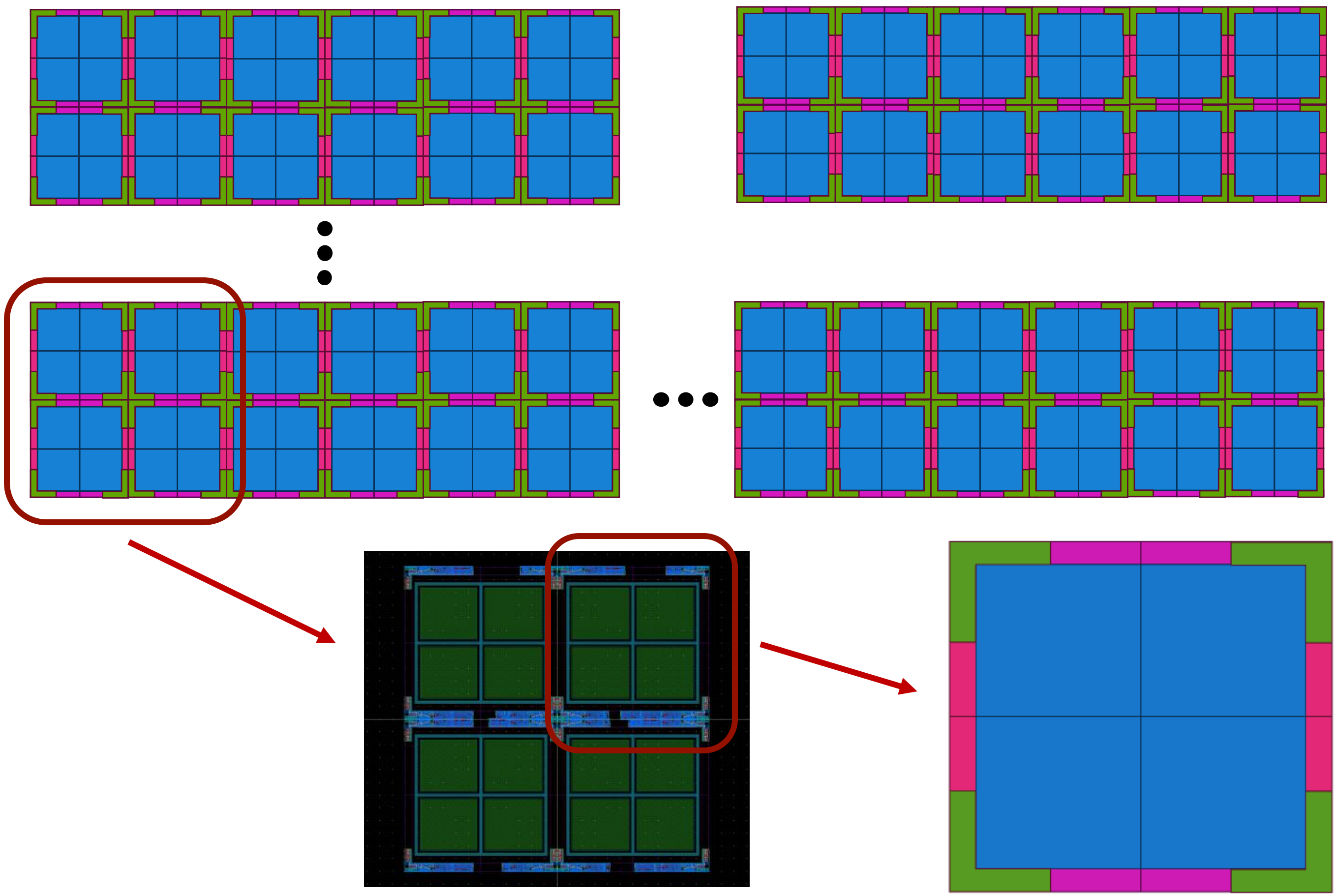
- ASPIDES is a two-year project funded by INFN (2025), coordinated by L. Ratti (INFN-PV)
- Goal: development of monolithic SiPMs in CMOS technology detectors with embedded functionalities (dSiPM)
  - Photon counting with wide dynamic range ($\approx 30\mu m$ pitch)
  - Fully digital output
  - ToA and ToT with resolution better than 100 ps
  - Threshold adjustment capabilities for noise rejection
  - Possibility to enable/disable individual micro-cells and global signal to enable/disable the array
- Study of radiation damage and operation at cryogenic temperatures
- Modelling of new SPAD devices with improved performance in radiation environment and at cryogenic temperatures
- Submission planned for Q4 2025 (LFoundry 110 nm, 6 metal layers)

ASPIDES

L. Ratti @ DRD4 WP1 meeting

Design is on-going

16 x 16 array, made of elementary clusters of 2x2 cells

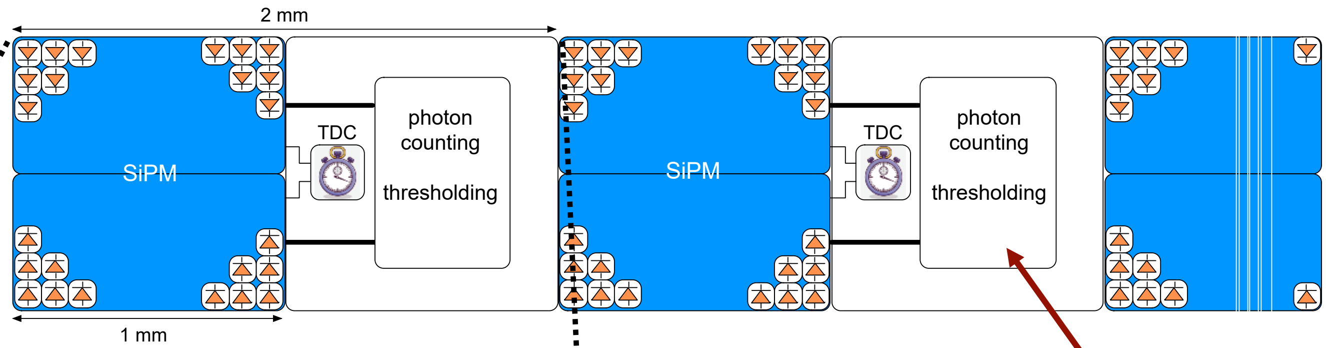


Basic building macro for the matrix

- Front-end
- SPAD active region
- Routing region
- Counter and NAND tree

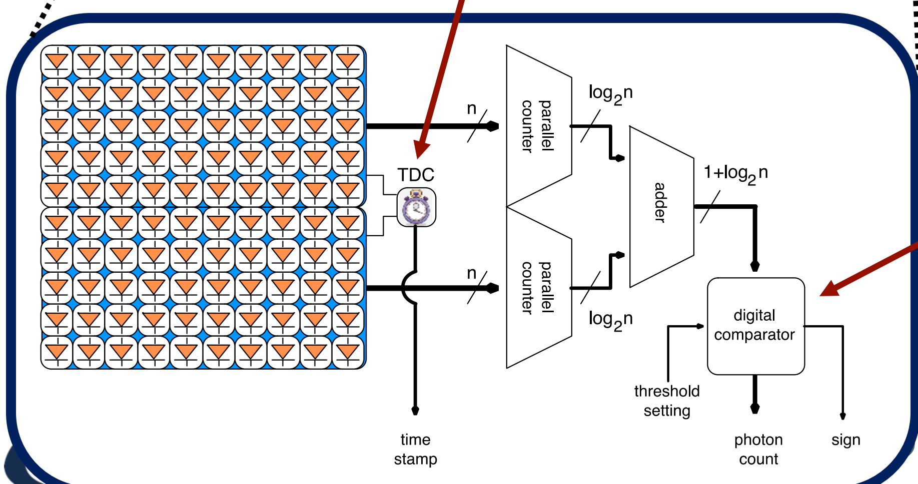
Demonstrator for DR calorimetry

1 Module = 8 dSiPMs 1x1 mm^2, interspaced by 2 mm



TDC close to the signal source: possibility to set a threshold on triggering signal

Electronics placed in the inter-SiPM region, taking advantage of the HiDRa geometry



Threshold: virtually any value can be set

L. Ratti @ DRD4 WP1 meeting