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Venezia

Highlights from CERN Test Beam for the IDEA dual readout ECAL

Marcello Campajola

INFN and University of Napoli 'Federico II'
email: macampajola@na.infn.it

Università degli Studi di Napoli Federico II

INFN Napoli

IDEA calorimeter

Two calorimeter sections:

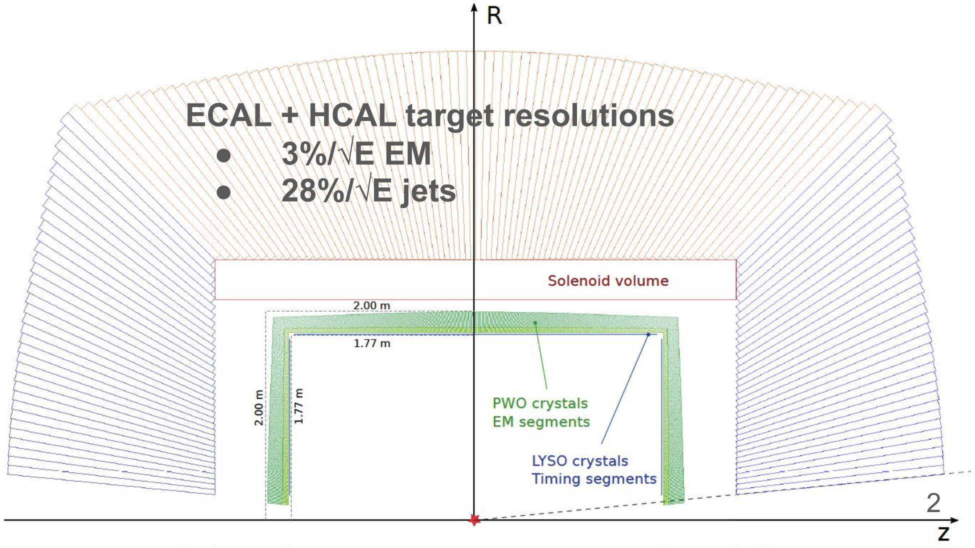
- a dual-readout fiber hadronic calorimeter (HCAL)
- **a homogeneous dual-readout crystal EM calorimeter (ECAL)** → **now in the IDEA baseline**
  - improve event reconstruction
  - expand landscape of possible physics studies, i.e. flavour physics

ECAL requirements:

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

ECAL + HCAL target resolutions

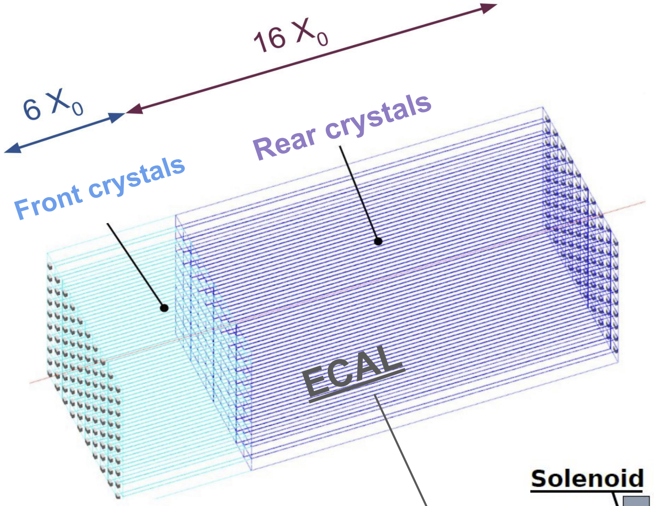
- **3%/√E EM**
- **28%/√E jets**



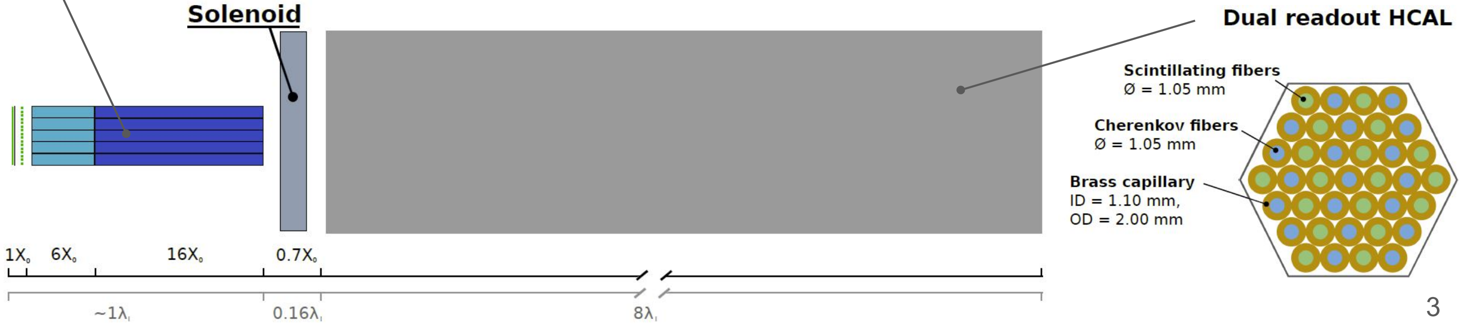
First studies and concept descriptions in:

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

ECAL key design features



- **Crystals w/ high density** (short X_0, small RM)
  - $PbWO_4$, BGO and BSO are good candidates
  - Two layers (e.g. 6+16X_0)
  - Fine granularity: O(cm^2) cross section
- **SiPM readout**:
  - 1 channel for the front crystal
  - 2 channels for the rear crystal (optimized for DR)



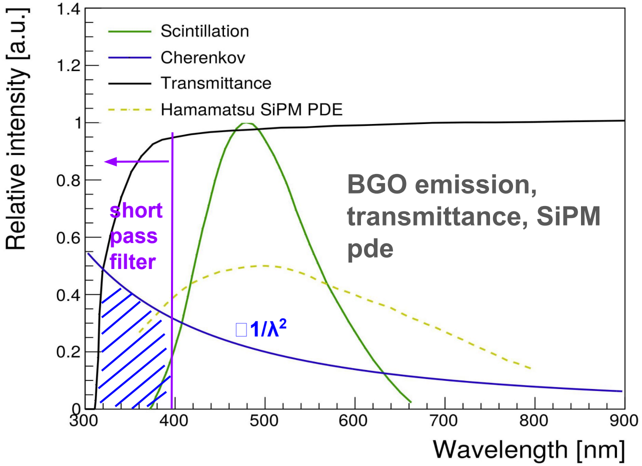
Dual readout strategy

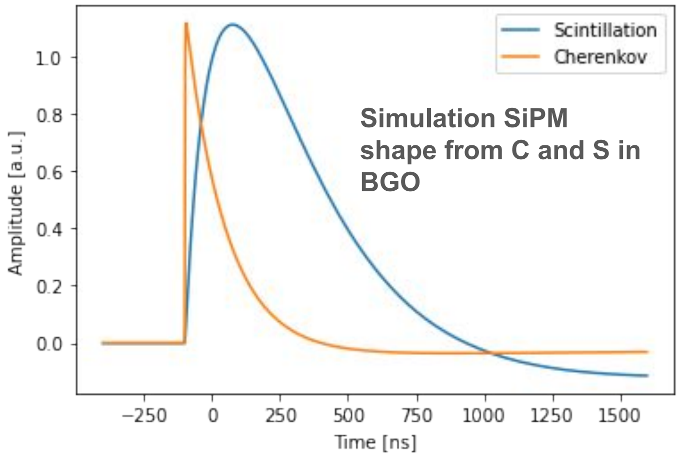
Cherenkov (C) and Scintillation (S) light detection and separation very challenging in homogeneous materials

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





Dual readout strategy

Crystal transparency where Cerenkov light is most intense (near UV) is poor. So feasibility of 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

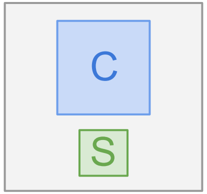
Rear crystal ECAL segment

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)

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Groups and activities

Activity at 360 degrees:

- Simulation studies (from standalone to full sim)
- R&D on technology and proof-of-principle
  - Identification of optimal crystal, filters and SiPM
  - Proof-of-concept with lab measurements and TB
- Prototyping of a calorimetric module

Participating groups:

- INFN (Milano-Bicocca, Napoli, Perugia)
- CERN and IN2P3-IP2I
- CALVISION

This talk will focus on R&D activities coordinated by INFN groups related to DR in a crystal ECAL

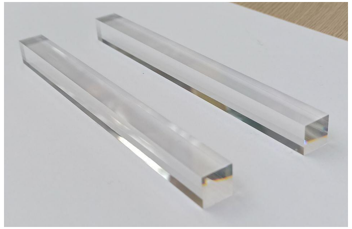
Project goals are also part of the DRD6 collaboration WP3 task 3.1.2

R&D activities

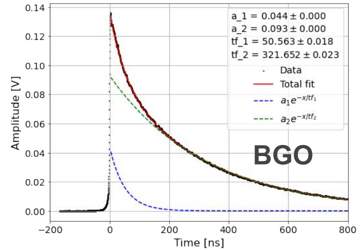
First activities **focus on understanding photon collection in with various technological choices (crystals, filters, SiPMs, FE)**

- 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

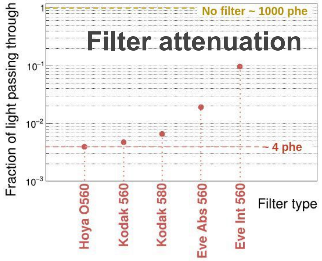
SICCAS Crystals



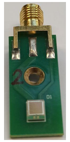
Time constant characterization

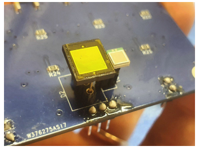


Schott UG11 UVA

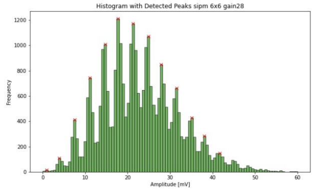


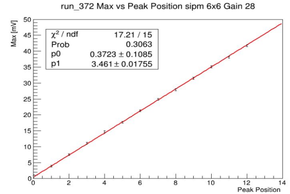
Hamamatsu SiPM:
S13360 / 14160-6050
S14160-3010-PE

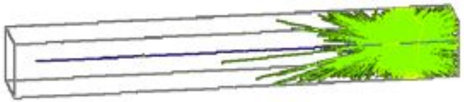




SiPM amplitude calibration

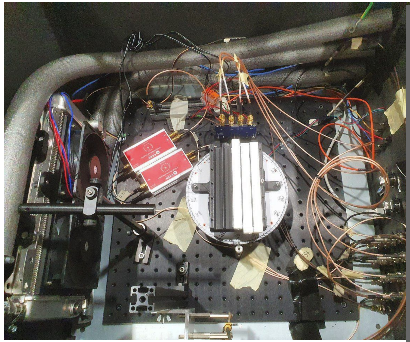






CERN TB

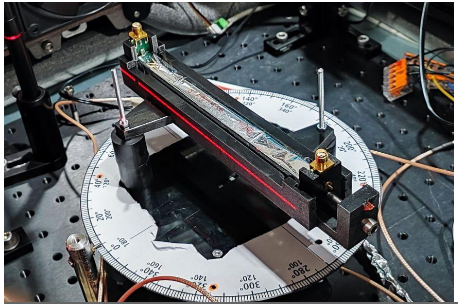
In July 2024 a **Test beam at CERN SPS H6** beam line prepared and coordinated by **MIB** and **Napoli** and with participation from **Perugia, US** and **CERN**

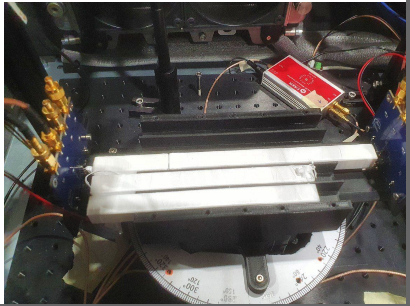


The focus was demonstrating/quantifying Cherenkov photon collection

- tests with electrons (10-100 GeV), muons, hadrons
- tested a variety of filters and crystals

TB crew



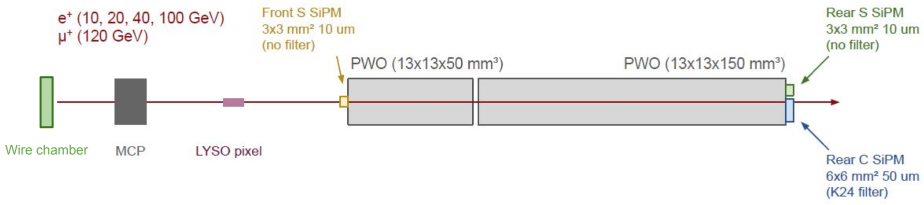


TB setup

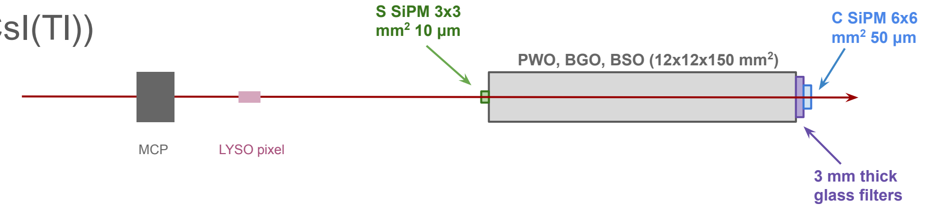
CERN TB

Two setup configurations:

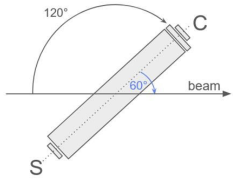
A. **Two layer crystal module**
   - Focus on PWO, several red filter tested
   - Wire chamber for tracking
   - DRS digitization



B. **One crystal w front/back readout**
   - Several crystal tested (BGO, BSO, PWO, CsI(TI))
   - UV filter for BGO/BSO, red filter for PWO
   - High bandwidth preamp
   - Larger range digitization w oscilloscope for pulse shape analysis



- Rotating stage for C/S study as a function of crystal-beam angle
- MCP and LYSO for timing studies



CERN TB data and analyses

Plenty of useful data to make technological choices for the prototype construction

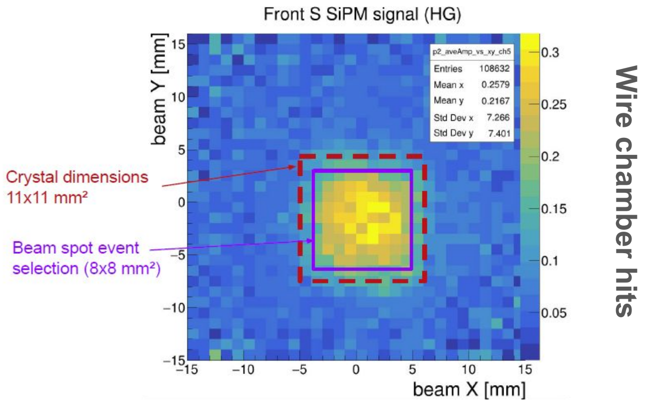
Analyses in progress:

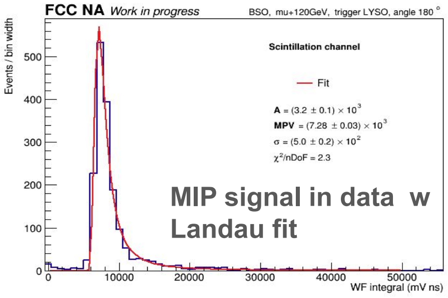
- C/S separation with filters and pulse shape analysis
- module energy linearity
- SiPM dynamic range

First results from runs with MIPs

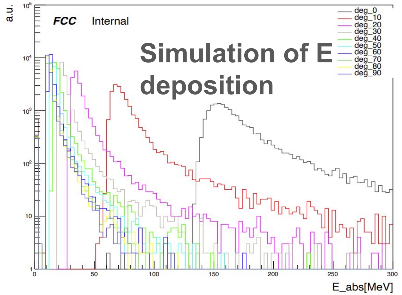
- Setup alignment
- Crystal uniformity
- Energy calibrations

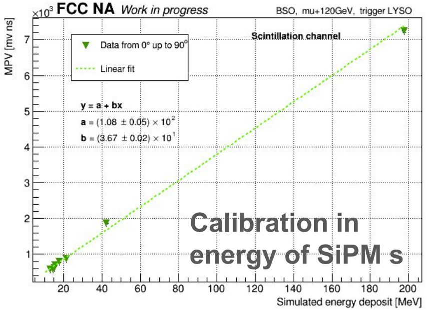
MIPs on setup A





MIPs on setup B

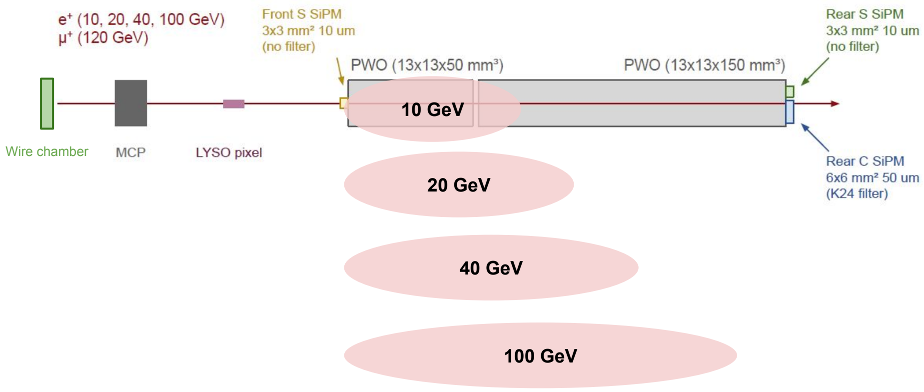




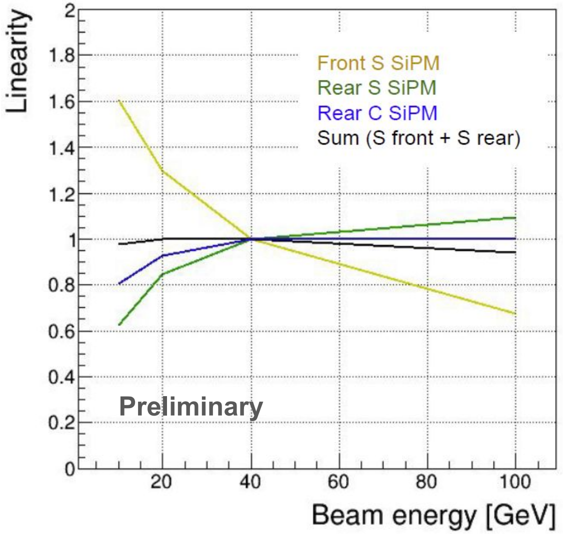
Preliminary results from CERN TB

Energy scan to study linearity with electron runs with setup A (PWO)

- Signal of front and rear scintillation SiPMs change as shower energy increases and shower maximum moves towards the rear crystal



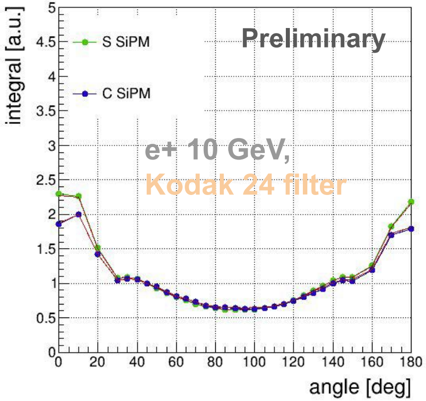
- **Combination of front and rear SiPMs yields reasonable linearity**

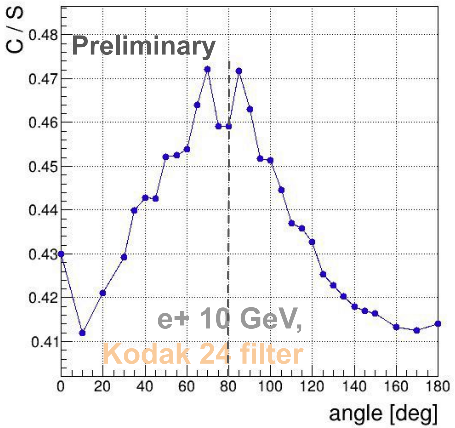


Preliminary results from CERN TB

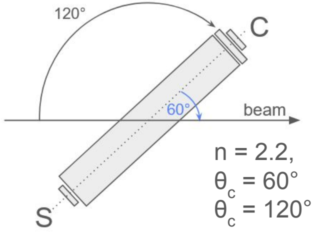
Angular scan in PWO with setup A & B to study C/S variations

- **C/S ratio peaking** at the C emission angle in both the setups

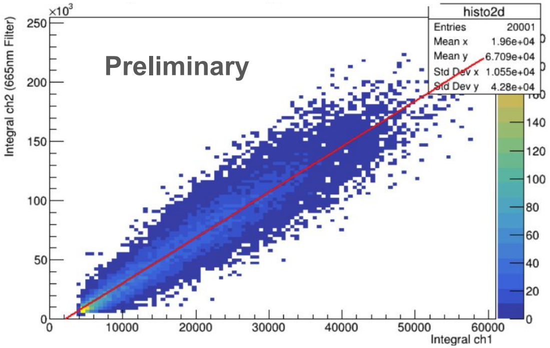


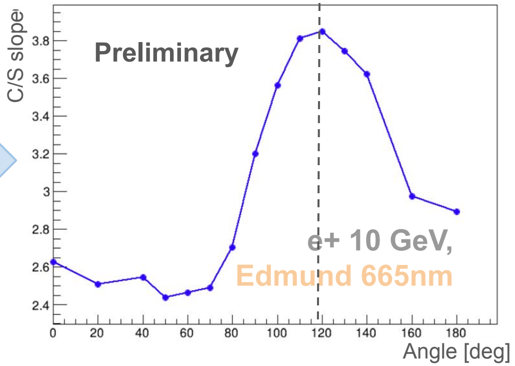


e+ on setup A



n = 2.2,
θ_c = 60° (setup A)
θ_c = 120° (setup B)



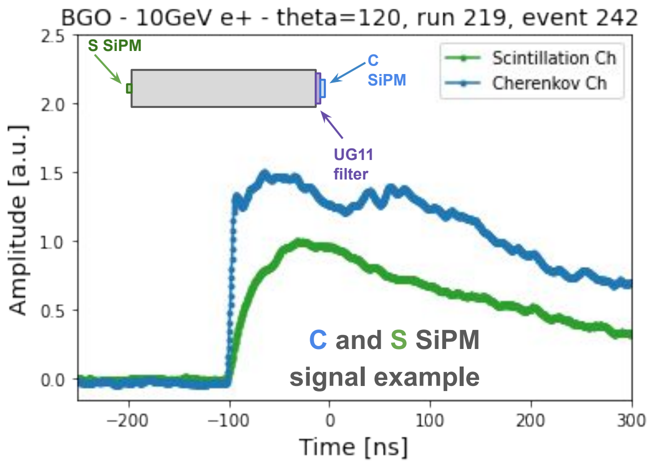


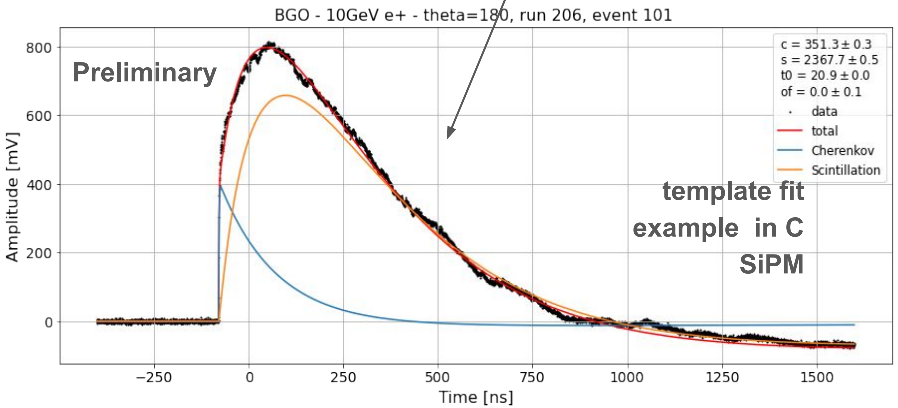
e+ on setup B

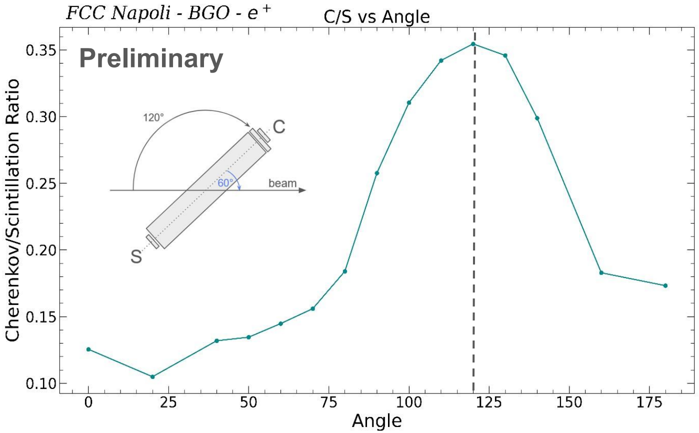
Preliminary results from CERN TB

Pulse shape analysis studies with BGO (setup B):

- **Different pulse shapes in SiPMs w and w/o filter**
  - C contribution on the rise time clearly observable
- Nice discrimination of **C** vs **S** phe with a template* fit on the C SiPM





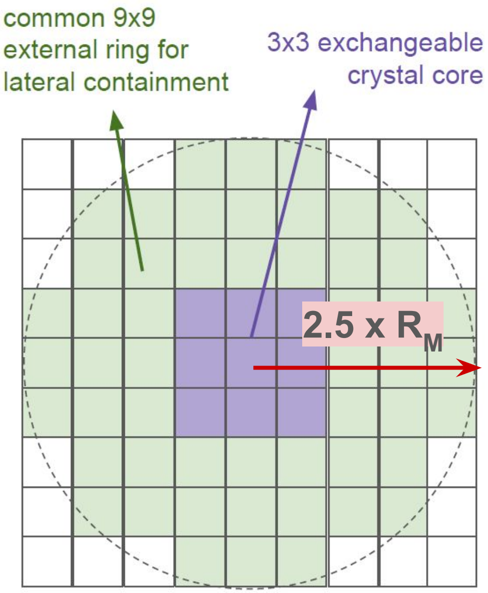


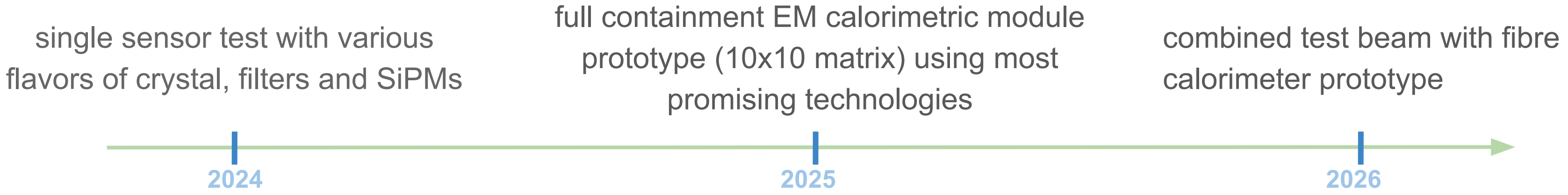
*templates from SiPM+electronic single phe shape convolution with arrival time distributions

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*)
  - **team of analyst working 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.

*similar/complementary R&D activities and plans also from US (see in the backup)





Acknowledgments

Great thanks to the CERN TB crew:

M.Lucchini, A.Benaglia	(INFN MIB)
L. Borriello, C. Di Fraia, L. Favilla, G. Gaudino, S. Perna M. Campajola, M. Francesconi	(INFN NA)
S.Moneta	(INFN PG)
L.Roux, J.Delenne	(CERN)
G.Cummings, J.Zhu, L.Guan	(FNAL, Michigan)

and people behind the scene working on the setup simulation:

D. Boccanfuso, F. Cirotto, A. D’Avanzo (INFN NA)

Backup

Dual readout ECAL: overview

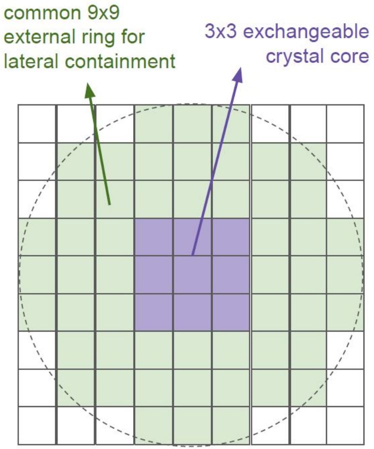
Table 1. Comparison of some of the key crystal properties for HEP applications. From left to right: crystal name, density, interaction length, radiation length, Molière radius, light yield relative to that of $PbWO_4$, scintillation decay time, photon time density and estimated cost for mass production.

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	7.1
BGO	7.1	22.7	1.12	2.23	70	300	0.23	7.8
BSO	6.8	23.4	1.15	2.33	14	100	0.14	7.8
CsI	4.5	39.3	1.86	3.57	550	1220	0.45	8.0

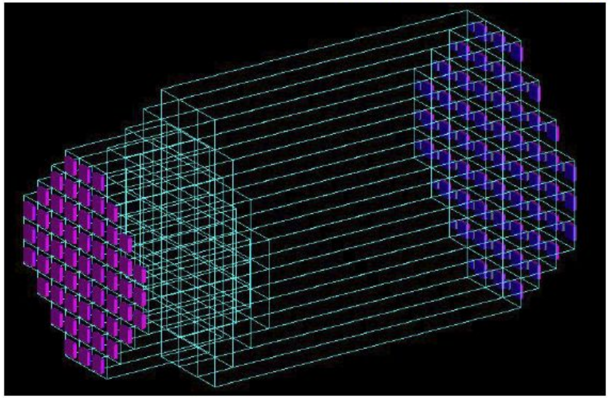
Towards a multi-channel prototype

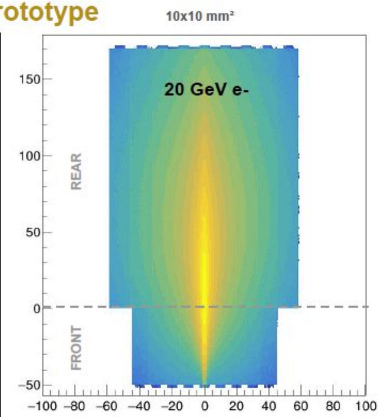
Coordinated/supported/funded by **MAXICC/INFN**

- 2024 lab and beam test results will inform the choice of a baseline technology to **build a full containment EM calorimeter prototype.**
    - Modular design to test complementary technology (e.g. PWO and BSO)
- Plan for a **test of the prototype on beam at CERN in the second half of 2025**
    - 2-week test beam slot requested at SPS (H6) for late September 2025



Geant4 simulation of prototype

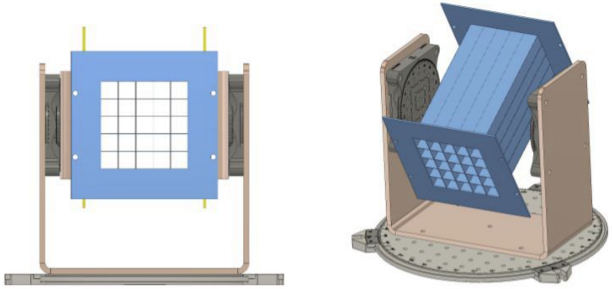


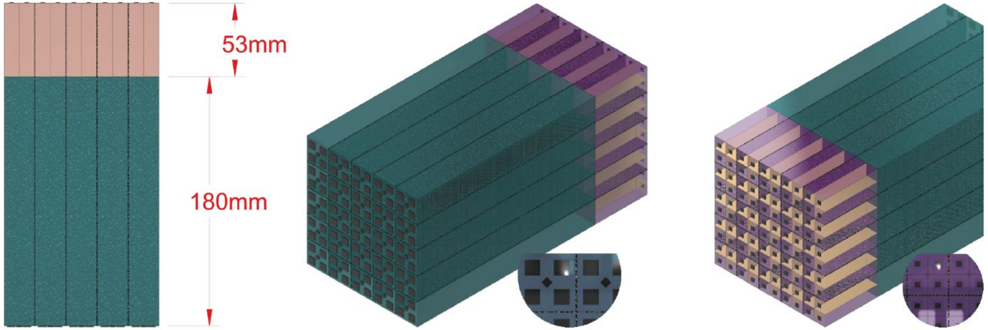


Towards a multi-channel prototype

Coordinated/supported/funded by **CALVSION**

- **Complementary plan for a full containment EM calorimeter prototype**
  - matrix with BGO
  - $22X_0$ deep, $5X_0$ x $5X_0$ lateral with $1X_0$ and ¼X_0 lateral granularity
- Crystal purchase in progress - expected to arrive and complete testing in spring
- Studies to improve electronics (e.g. linearity) over next 6-8 months





more in [Marco L. & Bob H. slides](#) at *DRD6 collaboration meeting*

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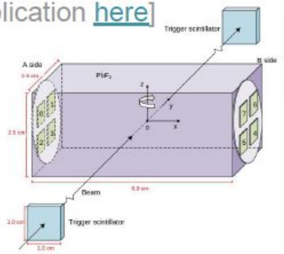
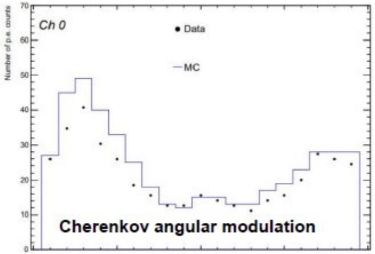
Analysis and submission of 2023 test beam work

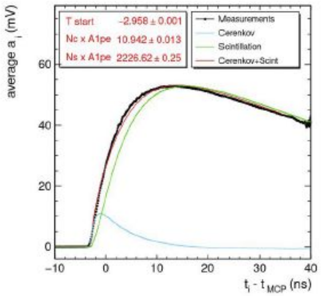
Concentrated on tests of optical photon modeling

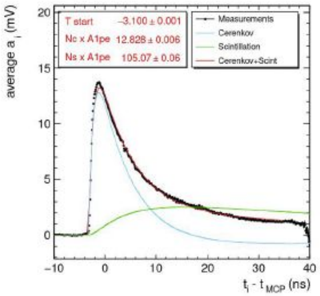
- Study modeling of light collection in of PbF2 (pure Cherenkov radiator) [recent publication [here](#)]

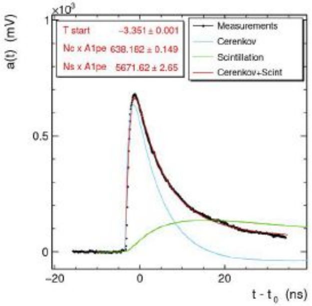


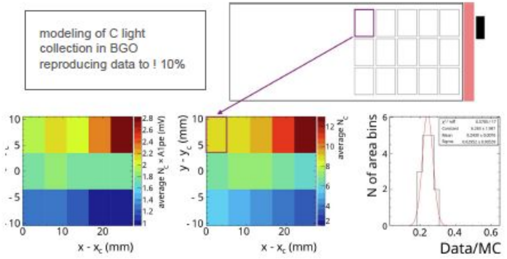


- Initial tests of S/C light light collection and modeling in BGO [recent publication [here](#)]





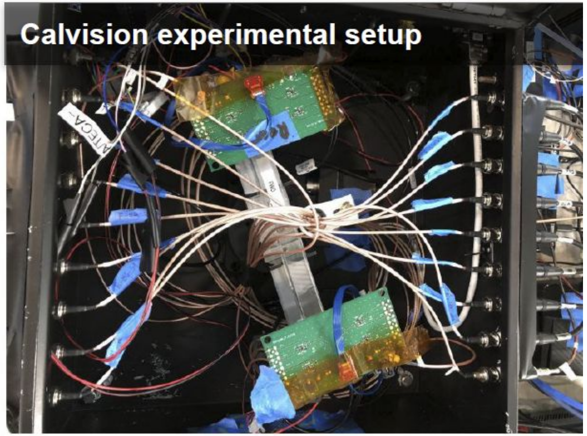


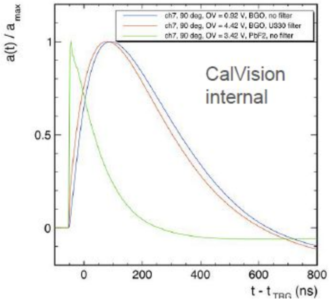


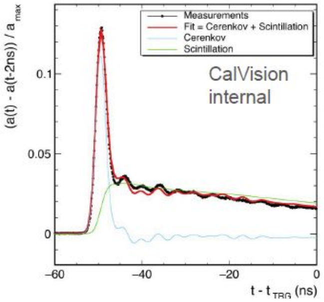
from [Marco L. & Bob H. slides](#) at
DRD6 collaboration meeting

Test beam at DESY (April 2024)

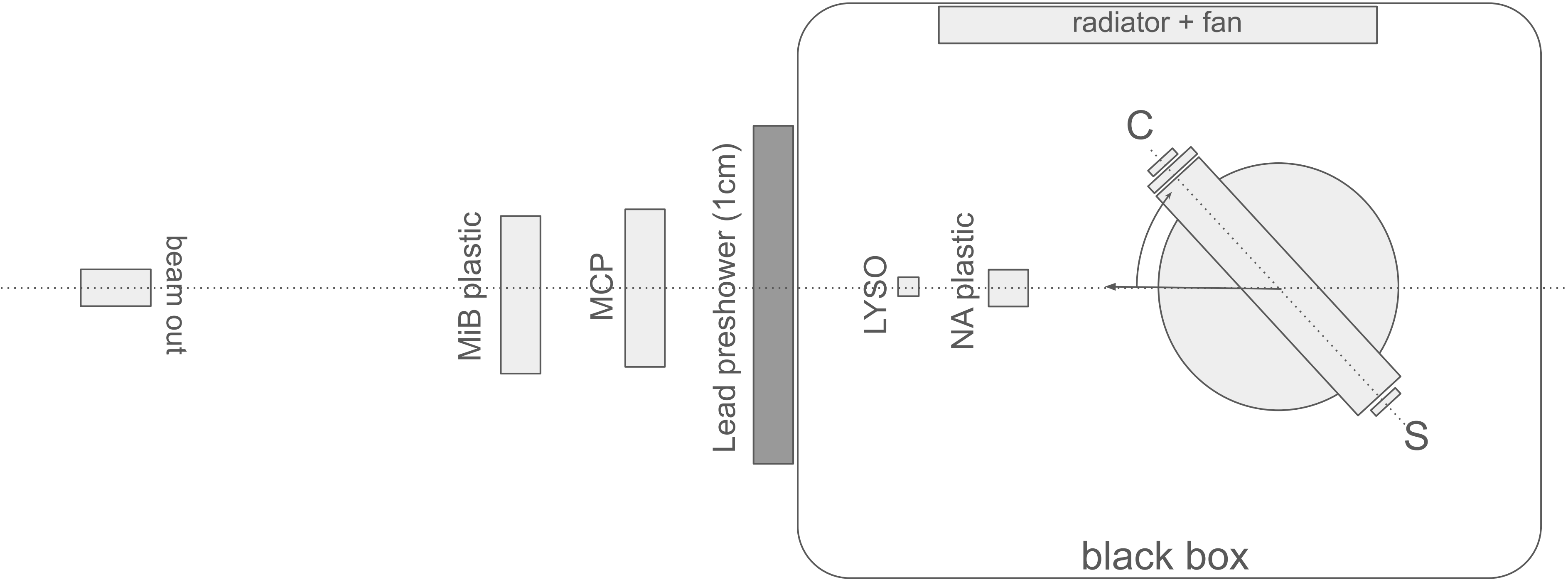
- Focus on large crystals with improved SiPM readout and better optical coupling
  - Repeating study on PbF2 and BGO with better SiPMs and testing more crystal flavors (PWO, heavy glasses, ...)
  - Test of different filters using silicon cookies as optical interface, Broadcom SiPMs



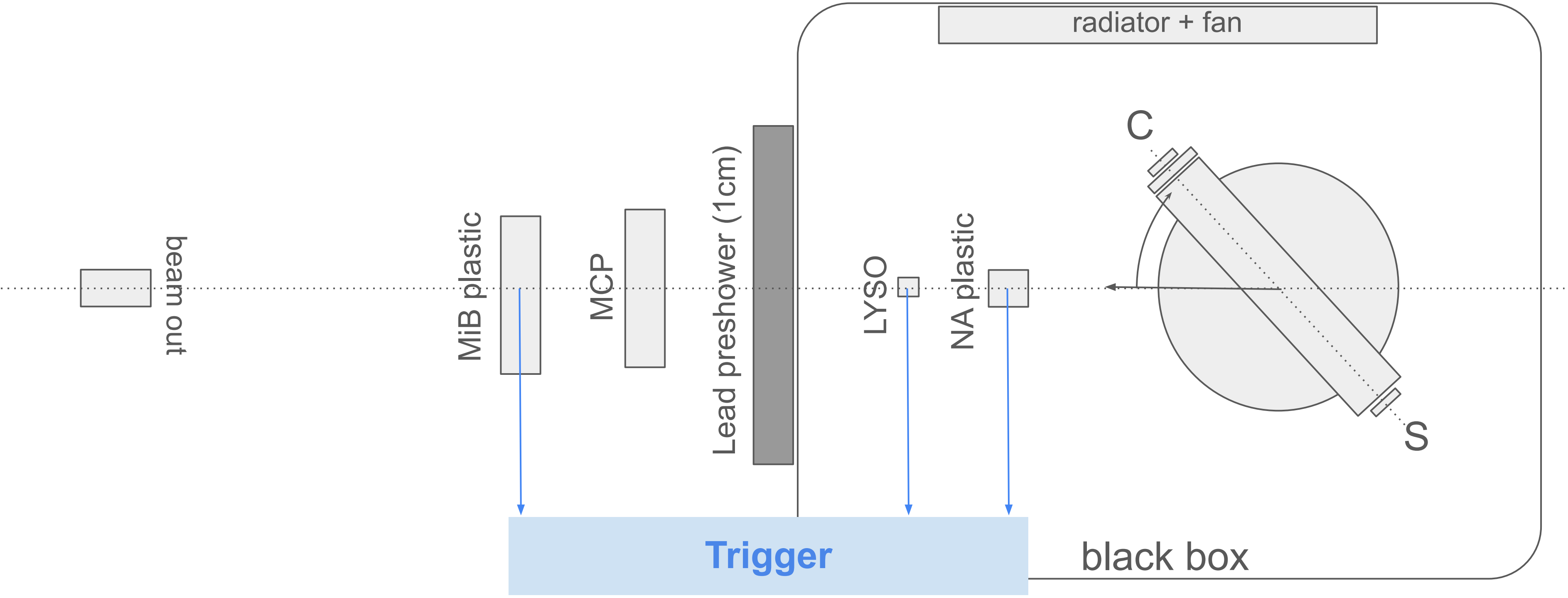




Setup schematic

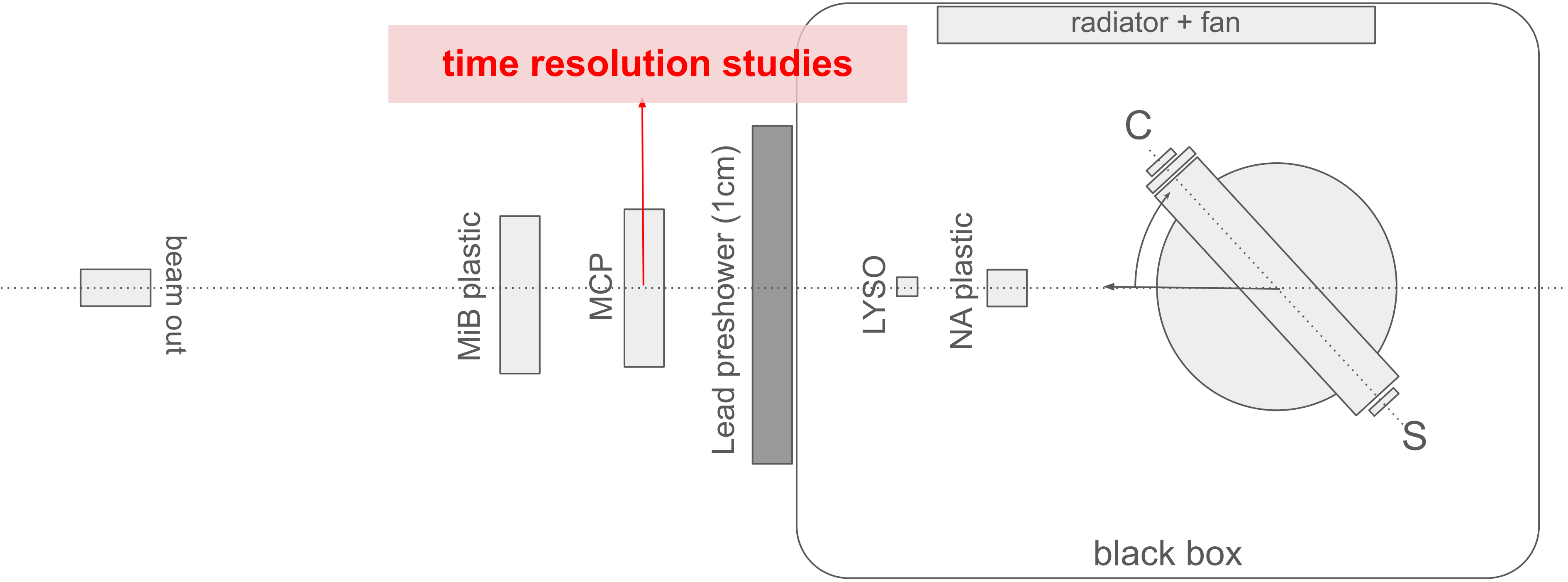


Setup schematic



Marcello Campajola - INFN Napoli and UNINA

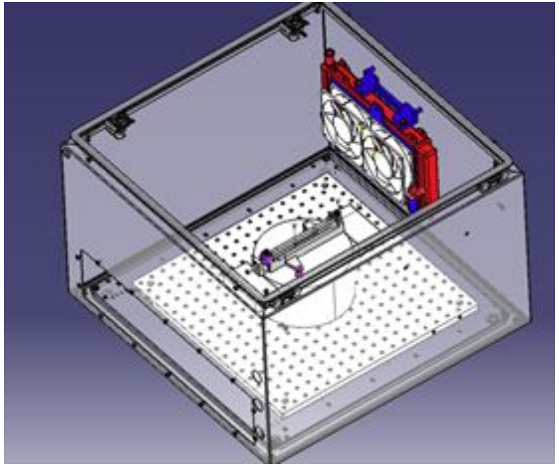
Setup schematic

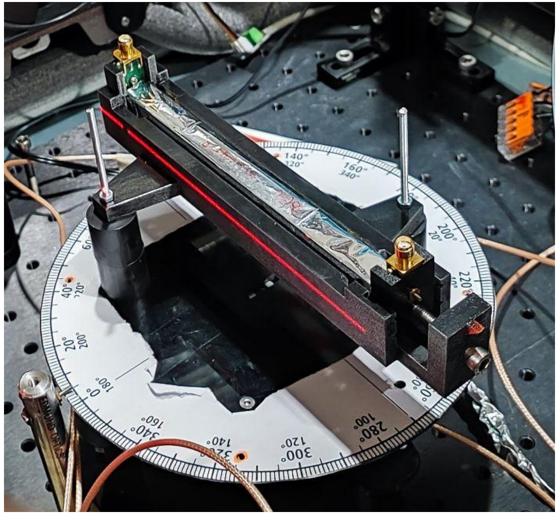


Setup mechanics

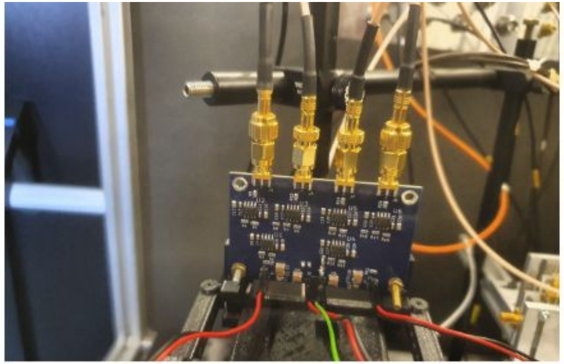
- Stainless steel box (1.5mm thickness) 40 x 60 x 60 cm3;
- Internal nitrile insulation (2 mm);
- Thorlabs perforated aluminum bench 45x45 cm2;
- Homemade rotator from: top diameter 15 cm;
- 3D printed crystal and sipm holder;
- Flange with feedthrough connectors;

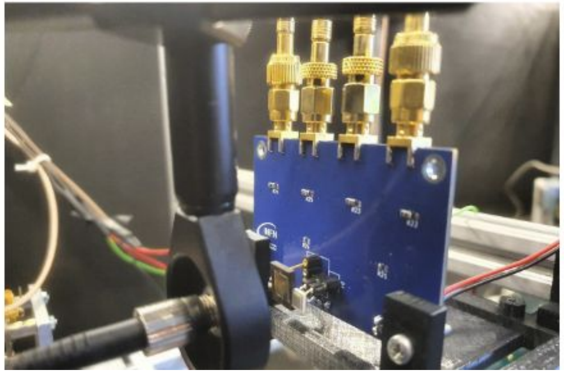
- Box temperature conditioning with internal radiator with fans connected to an external LAUDA chiller;
- Internal temperature sensor + PID software feedback to the chiller for temperature stabilization;
    - □ stable operations at 23° C

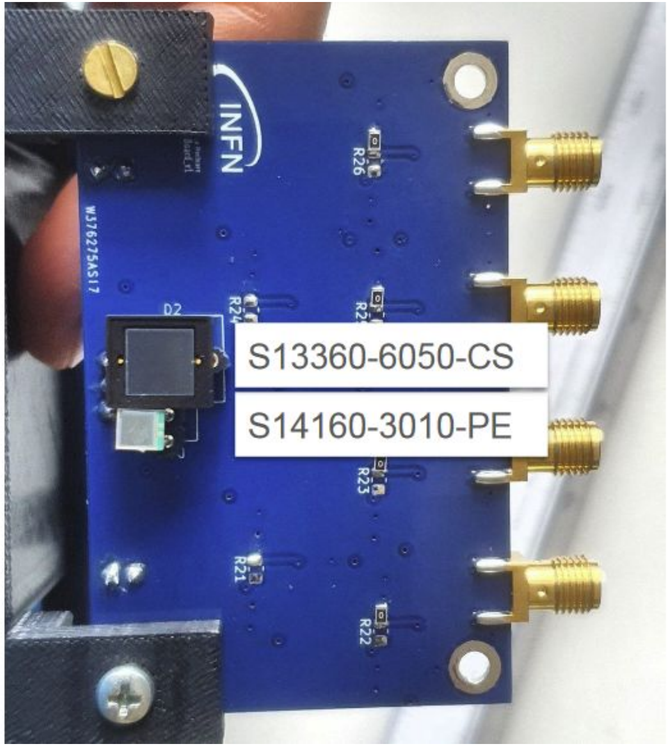




SiPM front end (setup A)



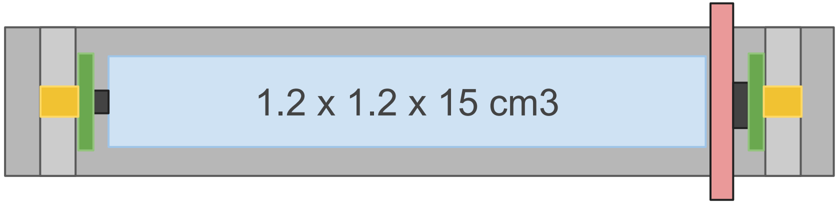




Crystals, Filters and SiPM (setup B)

Absorptive colored glass filter (SCHOTT) on the Cherenkov side

- **long pass:** OG550, RG-610, RG-665, RG-715 + KODAK thin film 580 nm → PWO
- **short pass:** UG11 → BGO, BSO, CsI



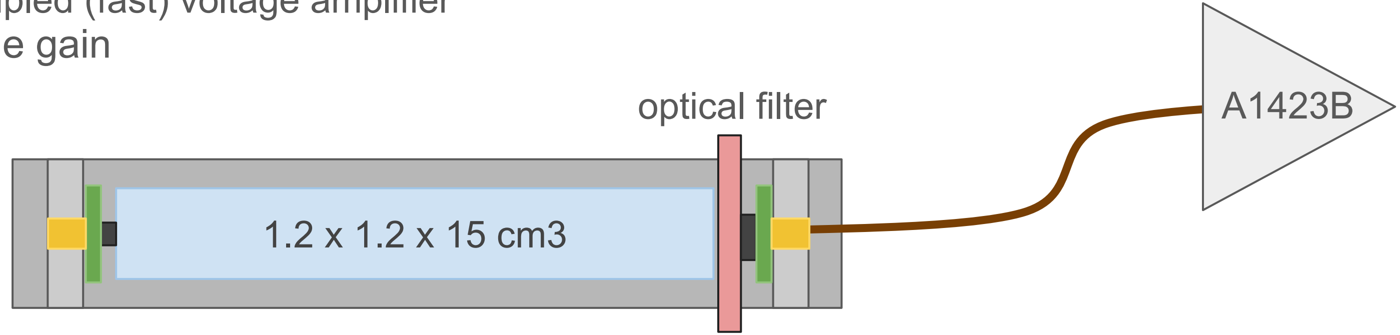
Scintillation side
SiPM 3x3 mm2
HPK S14160-3010

Cherenkov side
SiPM 6x6 mm2
HPK S14160-6050

SiPM front end (Setup B)

2x CAEN A1423B Wide band (1.5 GHz) preamplifier

- AC coupled (fast) voltage amplifier
- Variable gain

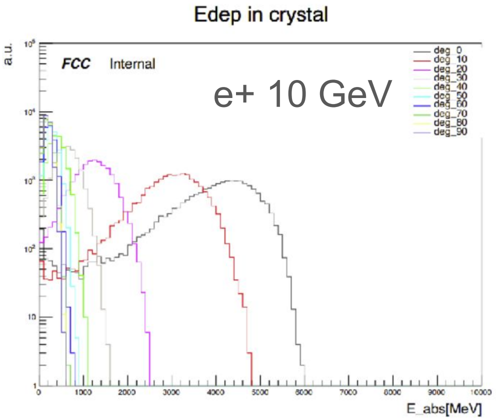


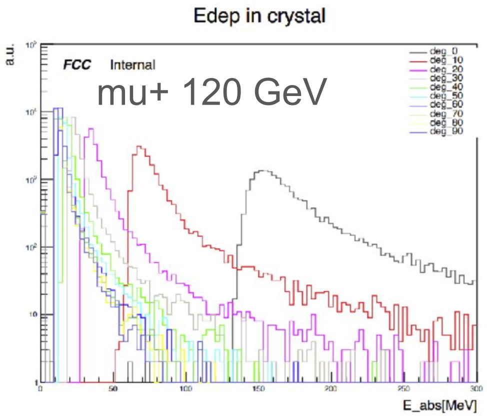
Scintillation side
SiPM 3x3 mm2
HPK S14160-3010

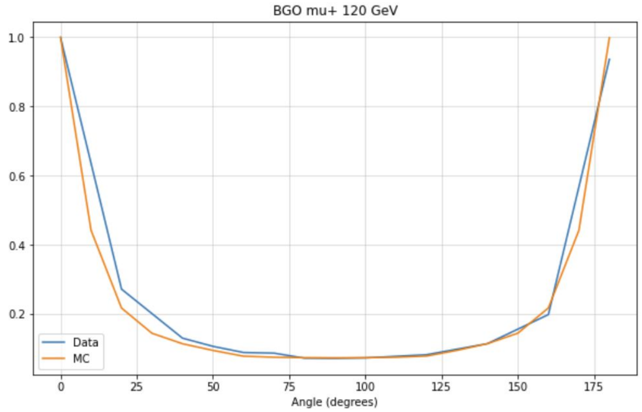
Cherenkov side
SiPM 6x6 mm2
HPK S14160-6050

Simulation

- **Recent effort from NA to work on Geant4 simulation of TB setup B**
- Useful in this data analysis and for the prototyping of the full containment module







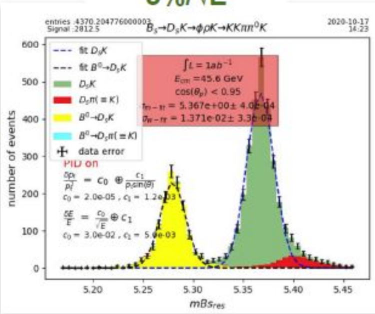
from [Marco L. slides](#) at *IDEA Study Group meeting*

High EM energy resolution potential at e+e- Higgs factories

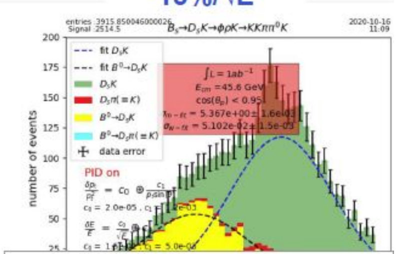
A calorimeter with **3%/√E EM** energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders

- **CP violation studies** with B_s decay to final states with low energy photons
- **Clustering of π^0's photons** to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)

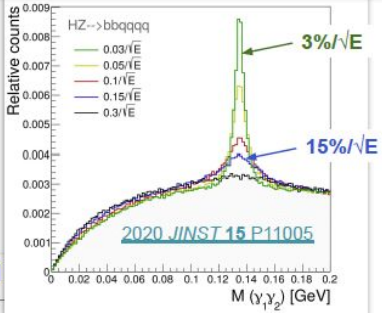
3%/√E

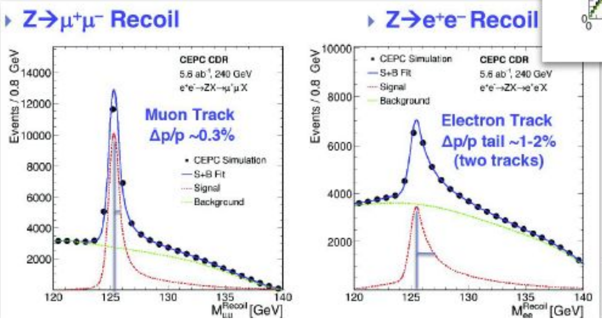


15%/√E



R.Aleksan et al., *Study of CP violation in B± decays to D0(D0)K± at FCCee*, [arXiv:2107.05311](#)





Example from [CEPC CDR](#)

3

The **dual-readout method** in a hybrid calorimeter

Including a **dual-readout** in the crystal EM calorimeter section enables the use of DR method in a hybrid calorimeter configuration

1. Evaluate the χ-factor for the crystal and fiber section
2. Apply the DRO correction on the energy deposits in the crystal and fiber segment independently
3. Sum up the corrected energy from both segments

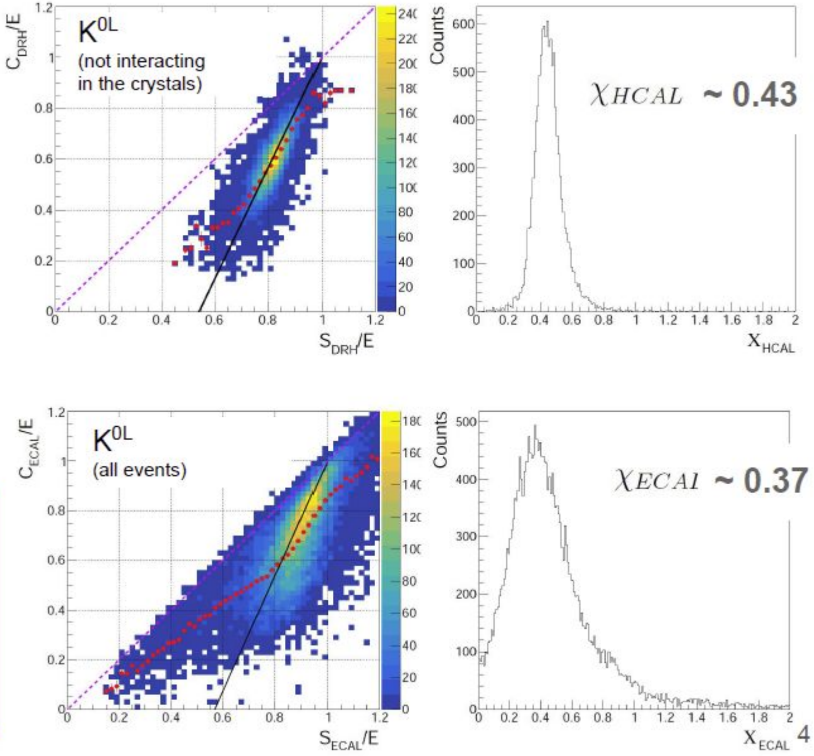
$$\chi_{HCAL} = \frac{1-(h/e)_s^{HCAL}}{1-(h/e)_c^{HCAL}}$$

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

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

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

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

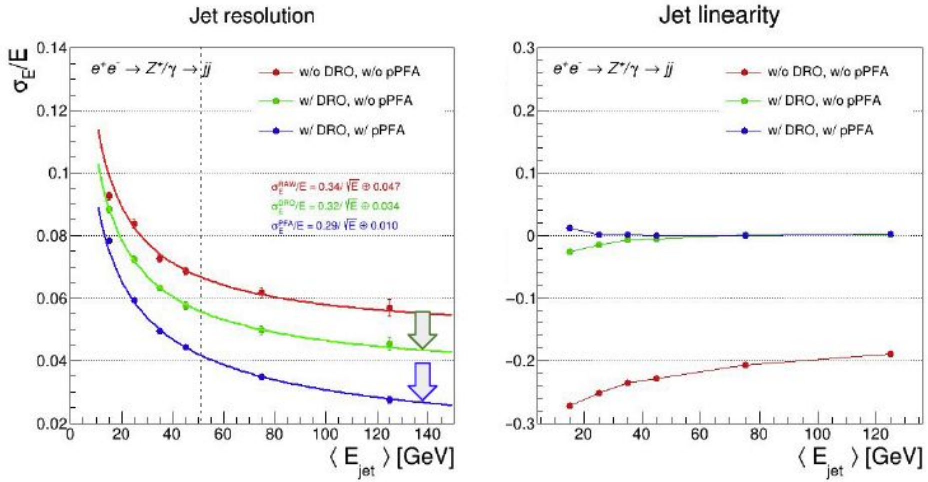


Jet resolution: with and without DR-pPFA

More details in:
2022 *JINST* **17** P06008

Jet energy resolution and linearity as a function of jet energy in off-shell $e^+e^- \to Z^* \to jj$ events (at different center-of-mass energies):

- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA

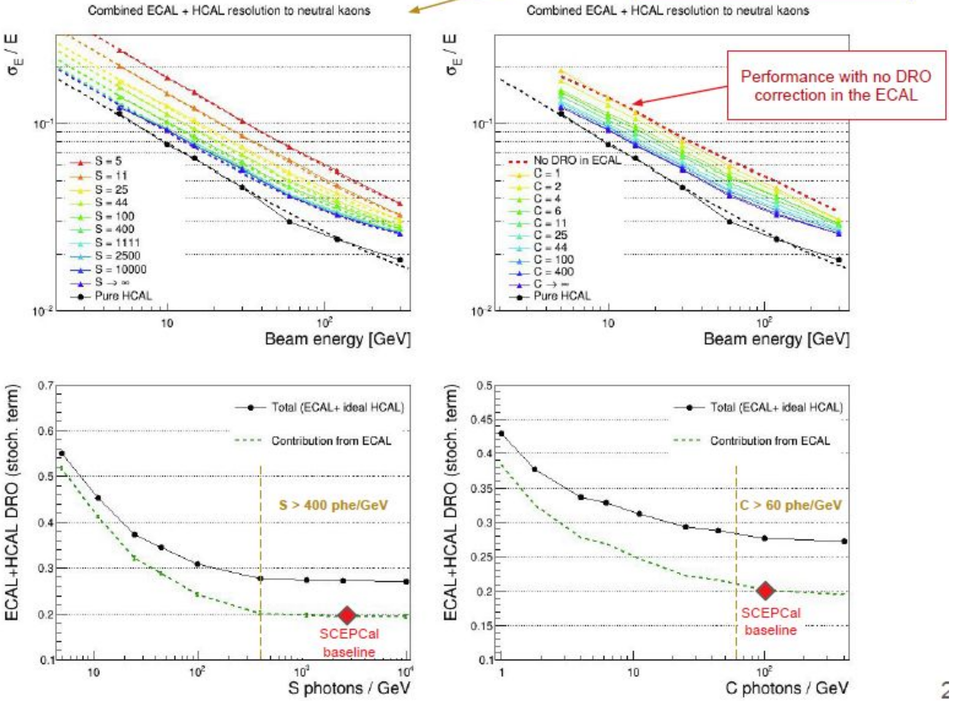


Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

Photo-statistic requirements for S and C

Smearing according to Poisson statistics

- A poor S (scintillation signal) impacts the hadron (and EM) resolution stochastic terms:
  - S > 400 phe/GeV
- A poor C (Cherenkov signal) impacts the C/S and thus the precision of the event-by-event DRO correction
  - C > 60 phe/GeV
- **Baseline layout choices** (granularity and SiPM size) to **provide sufficient light collection efficiency** in Geant4
  - Need experimental validation with lab and beam tests



Dual readout ECAL: overview

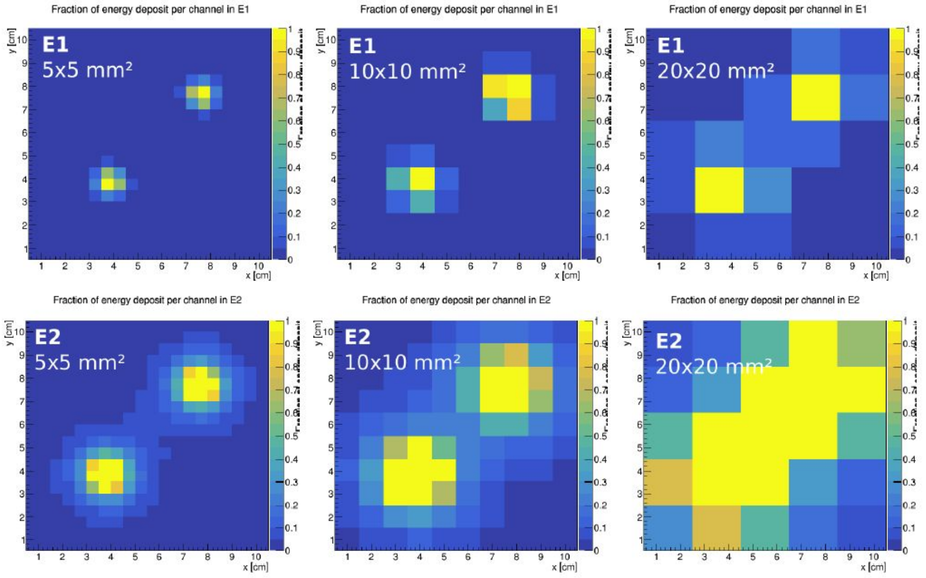


Figure 14. Transverse separation of two photons emitted with an angle of about 3 degrees, in the front and rear layer of the crystal ECAL (with PbWO crystals), for different scenarios of transverse segmentation ($5 \times 5\,\mathrm{mm}^2$, $10 \times 10\,\mathrm{mm}^2$, $20 \times 20\,\mathrm{mm}^2$).

Dual readout ECAL: overview

arXiv:2203.04312v2

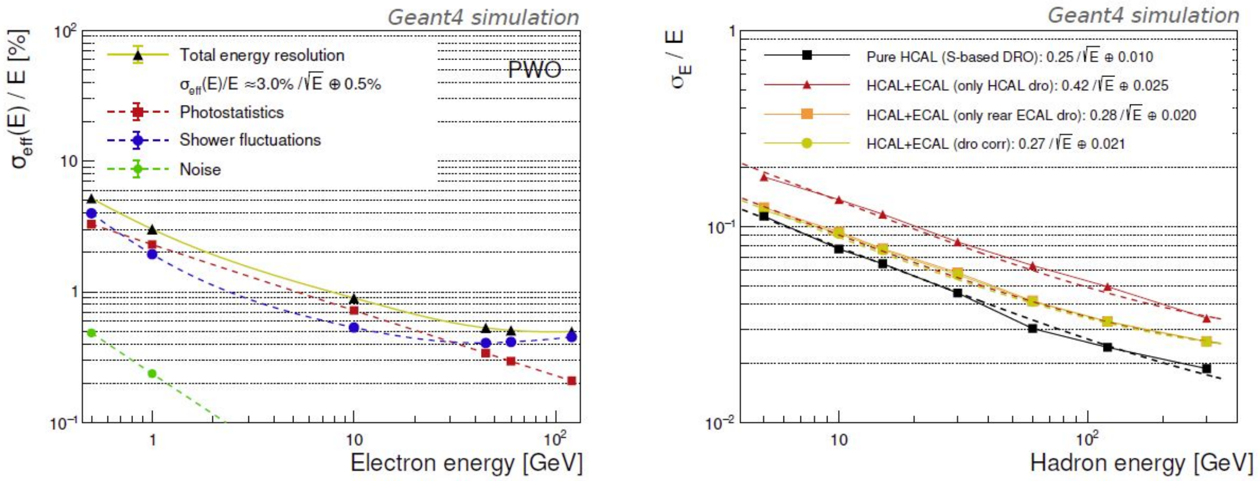
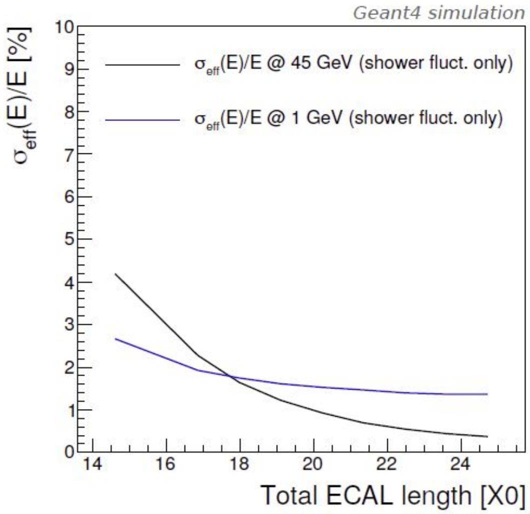


Figure 15: Simulated resolutions for a combined dual-readout crystal ECAL and a dual-readout spaghetti HCAL from Ref. [5], for a pure dual-readout spaghetti, for that with a conventional crystal EM, and that with a dual-readout crystal EM calorimeter. Note that the energies of particles produced at electron-positron Higgs factories are mostly below 20 GeV, and so this is the most relevant part of the hadronic resolution. The average energy of a charged pion is 3 GeV [5]. On average, 13% of the jet energy is from neutral hadrons [5]. Shown are EM (left) and hadronic (right) resolutions.

Dual readout ECAL: overview

arXiv:2203.04312v2



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