Test beam of a cell prototype for a dual readout-calorimeter proposal at the Future Circular Collider FCC-ee

Lucrezia Borriello
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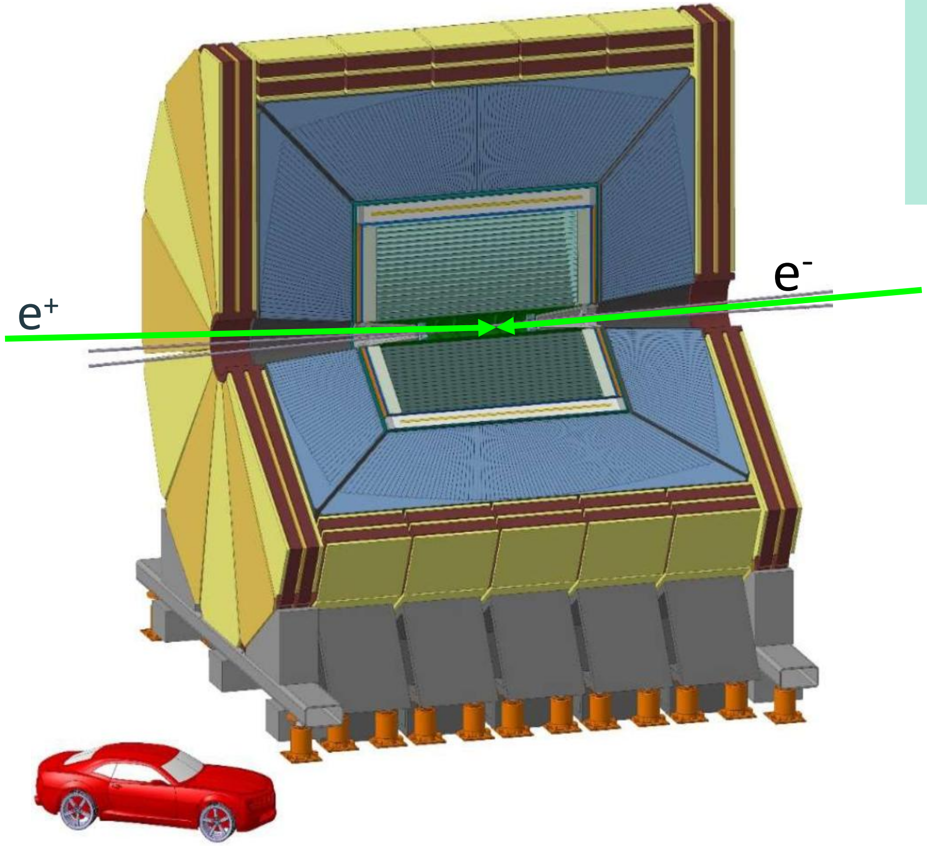
On Behalf of RD_FCC NA Group

IDEA Detector (Innovative Detector for Electron-positron Accelerators)

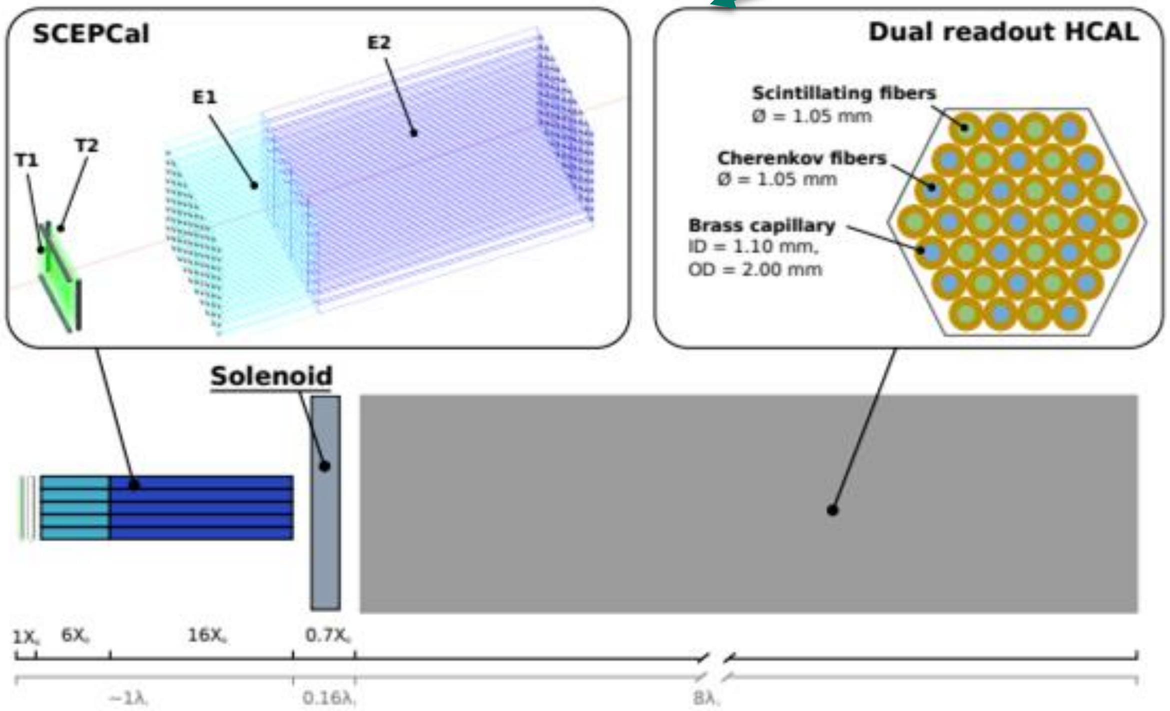
Project for a hermetic detector for FCC-ee:



IDEA detector concept:

- vertex detector
- drift chamber
- preshower detector
- **dual-readout calorimeter**
- muon system
- magnet systems

- scintillating crystal for detection of EM showers
- ultrathin-bore solenoid
- hadron calorimeter based on scintillating and quartz fibers



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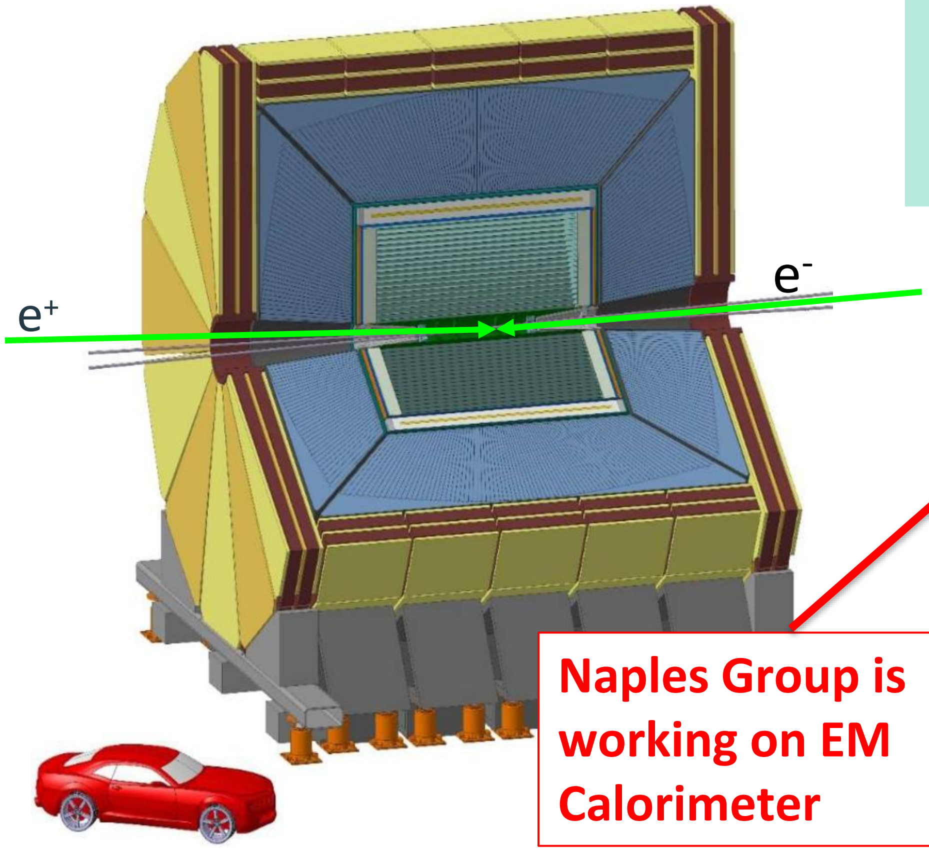

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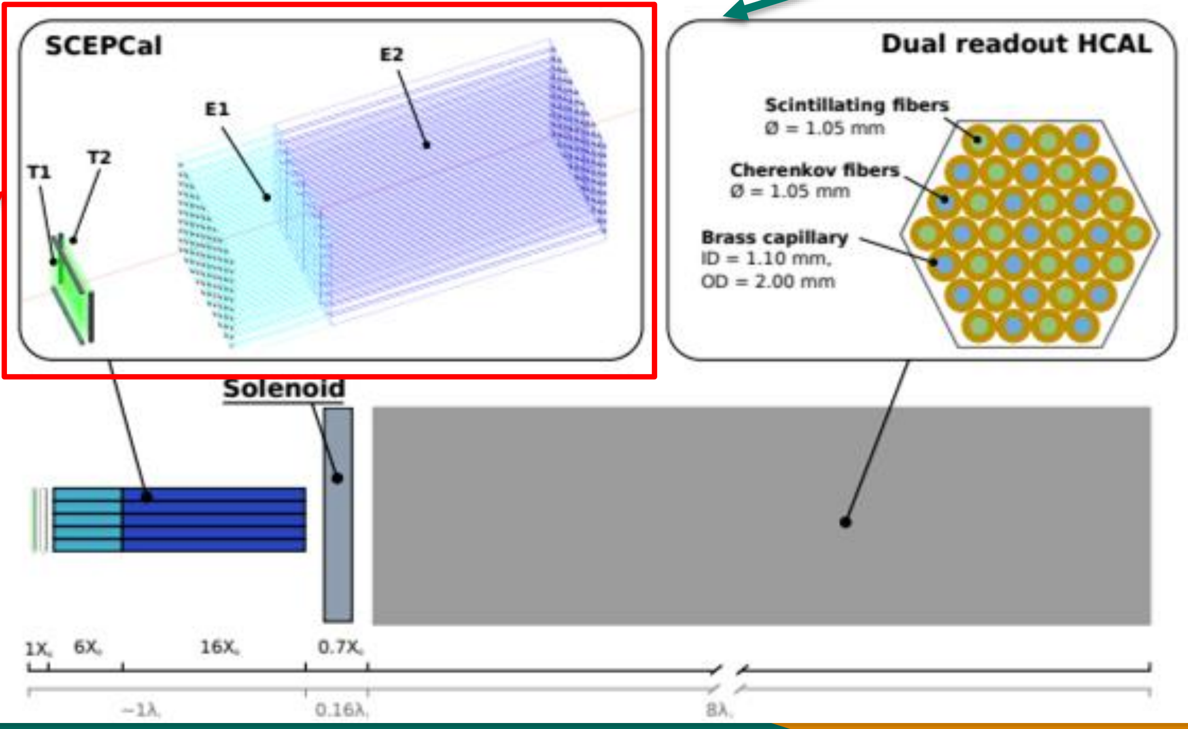


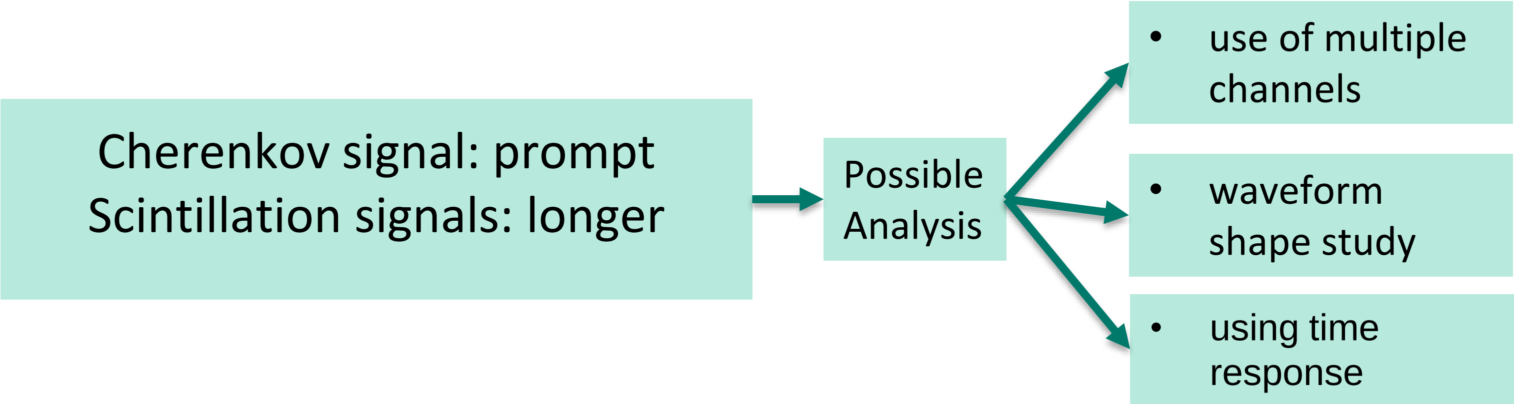
Naples Group is working on EM Calorimeter

Dual-readout calorimetry technique:

- **Contemporary measurement of Scintillation and Cherenkov light:**
  - analysis event-by-event of the electromagnetic component of hadronic showers

Strategy for Dual Readout with Crystals

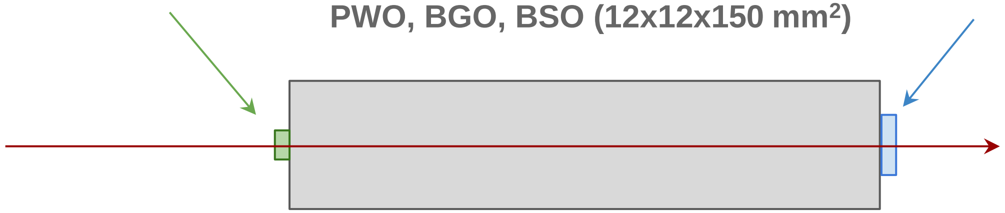
- Our goal: discriminating the Cherenkov signal from the Scintillation signal inside different crystal samples:



	time	spectrum
Cherenkov	fast	$1/\lambda^2$
Scintillation	slow	peaked

Setup for Dual Readout with Crystals:

Basic Setup:



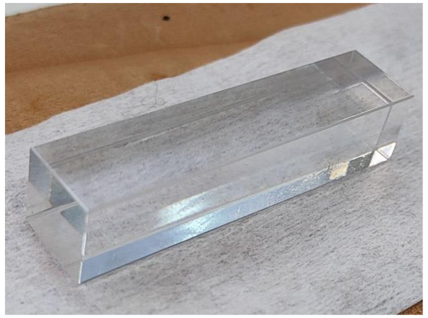
3×3 mm² SiPM: used to collect scintillation light, featuring a 10 µm SPAD pitch to avoid saturating the SiPM microcells

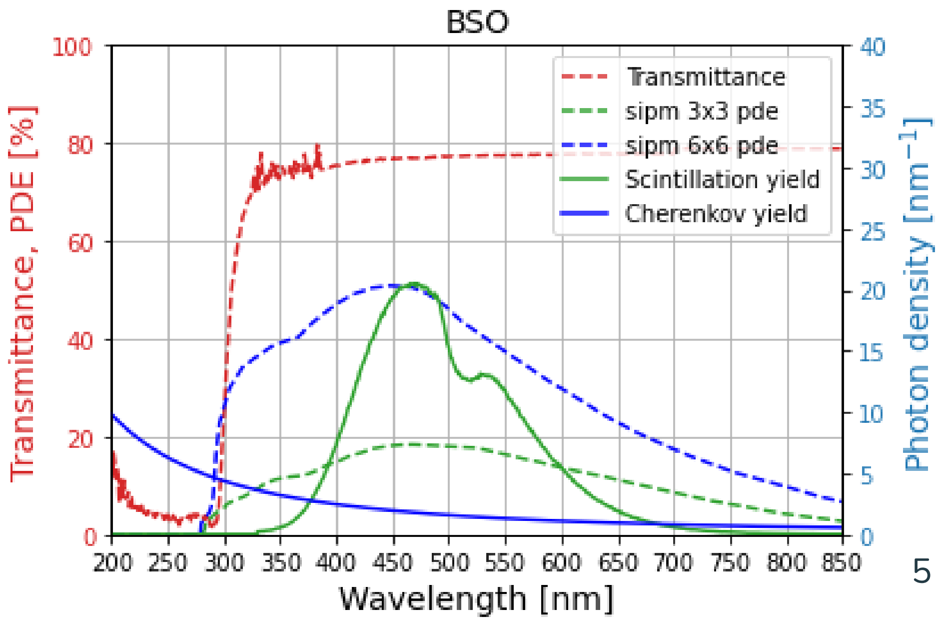
6×6 mm² SiPM employed for Cherenkov light collection, featuring a 50 µm SPAD pitch and enhanced geometrical acceptance to maximize photon collection efficiency.

Crystals under consideration:

Dimensions: 15x1.2x1.2 cm^3

Characteristics of the crystals			
	BGO	BSO	PWO
Radiation Length [cm]	1.12	1.15	0.92
Density [g/cm³]	7.13	6.8	8.28
Refractive Index %	2.15	2.68	2.16
Light Yield [photons/MeV]	7500	1500	190



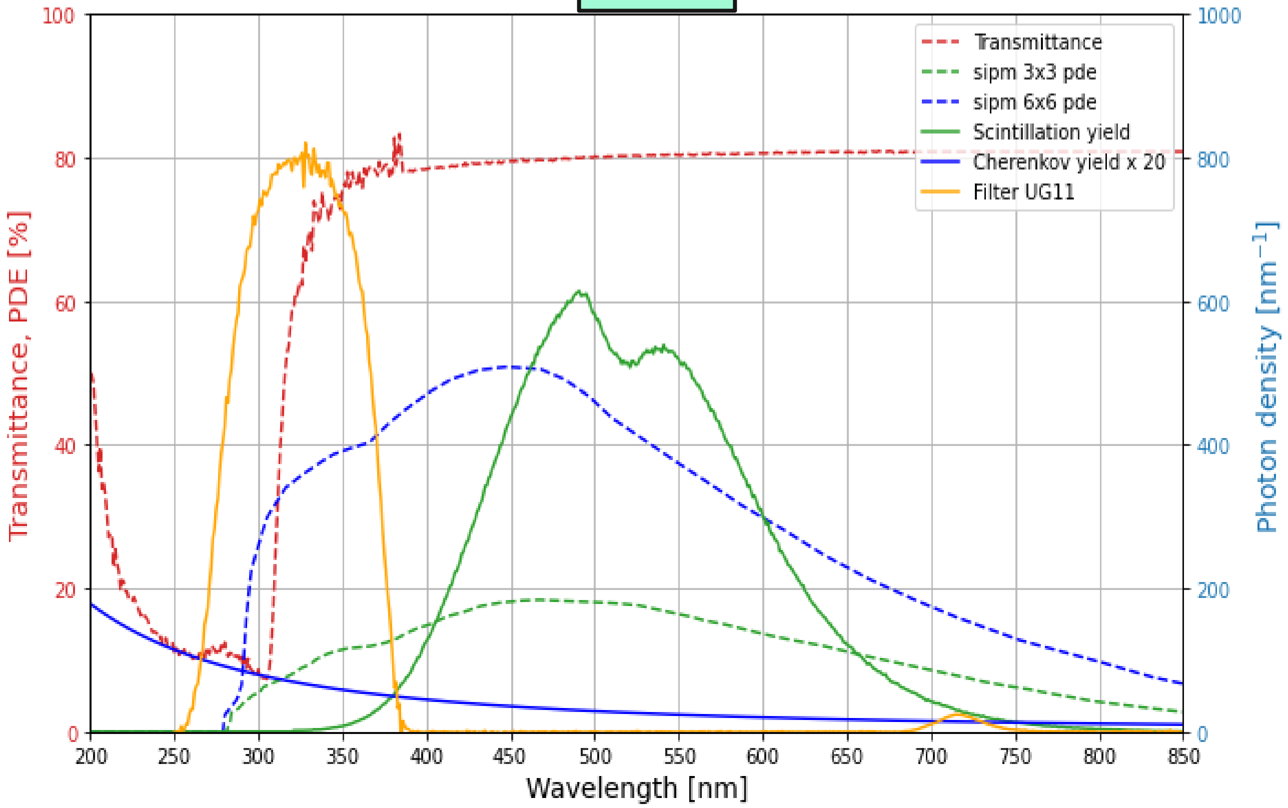


Strategy for extracting the Cherenkov signal

Ratio of the expected number of photons for Scintillation and Cherenkov effect for a MIP is of the order of :

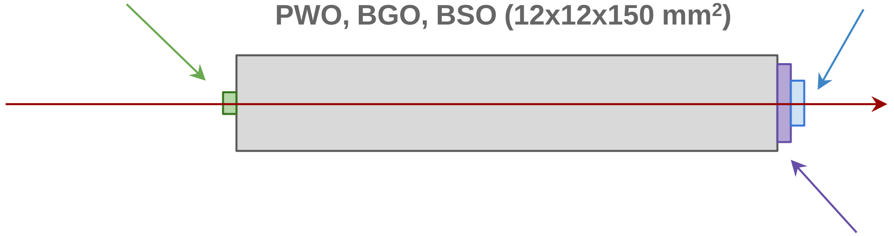
$$\frac{\text{Number of Scintillation photons}}{\text{Number of Cherenkov photons}} \cong 100$$

BGO



Need a strategy to reduce this ratio

Use optical filters to select the specific region of the light spectrum and favor the Cherenkov signal



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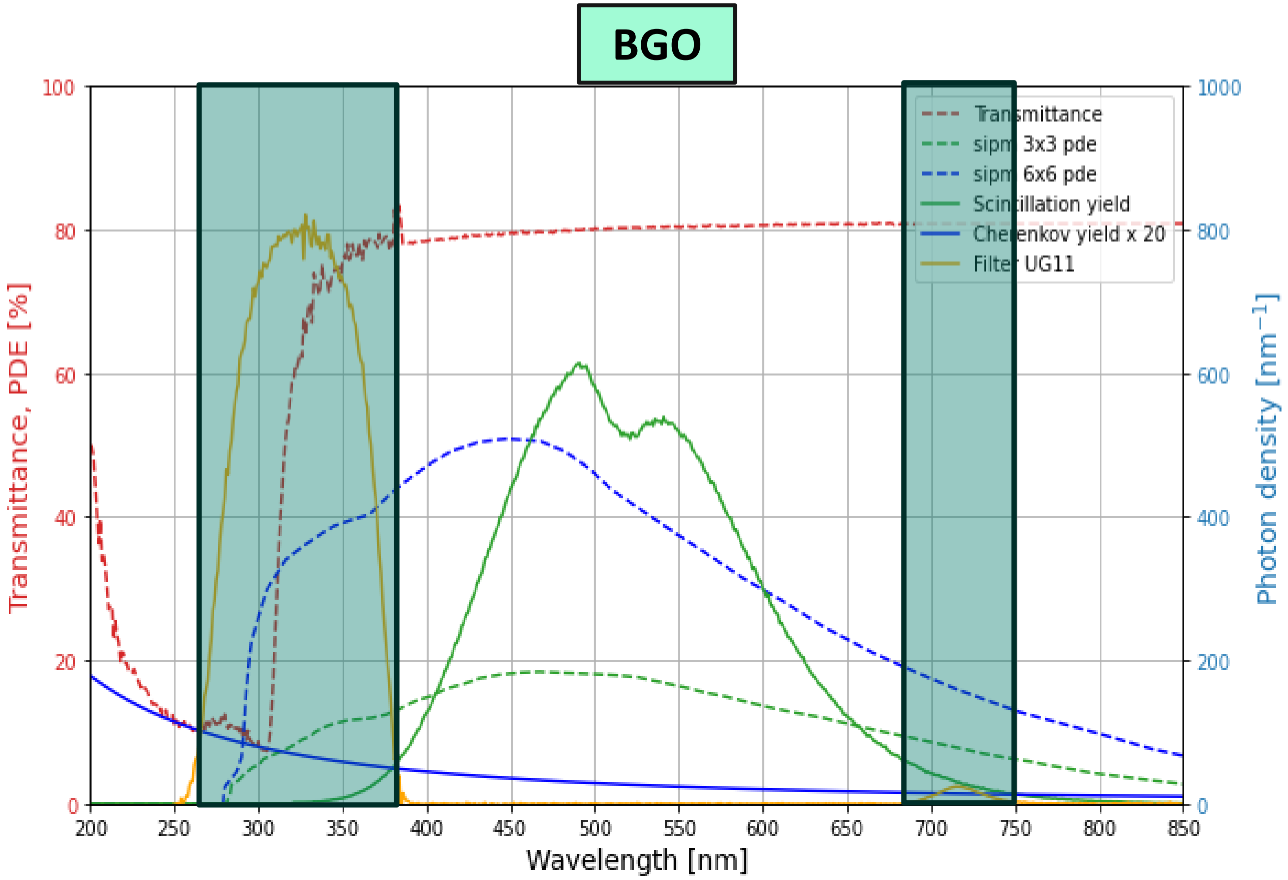

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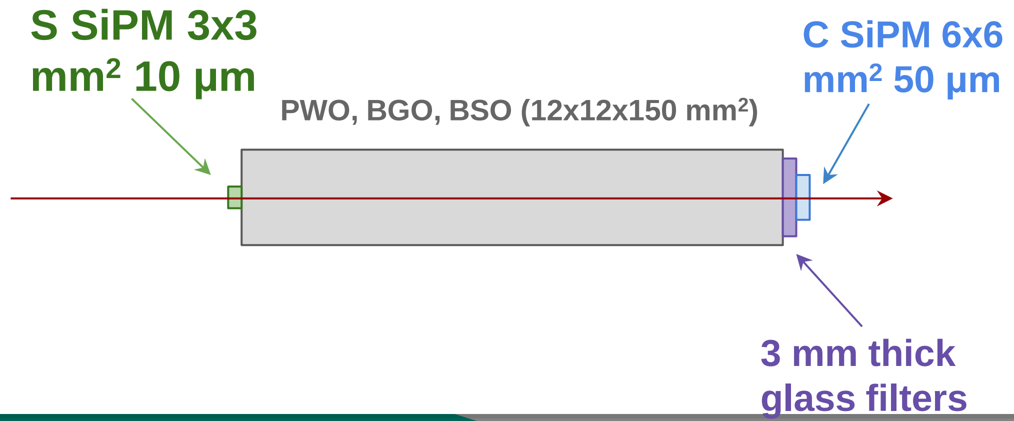

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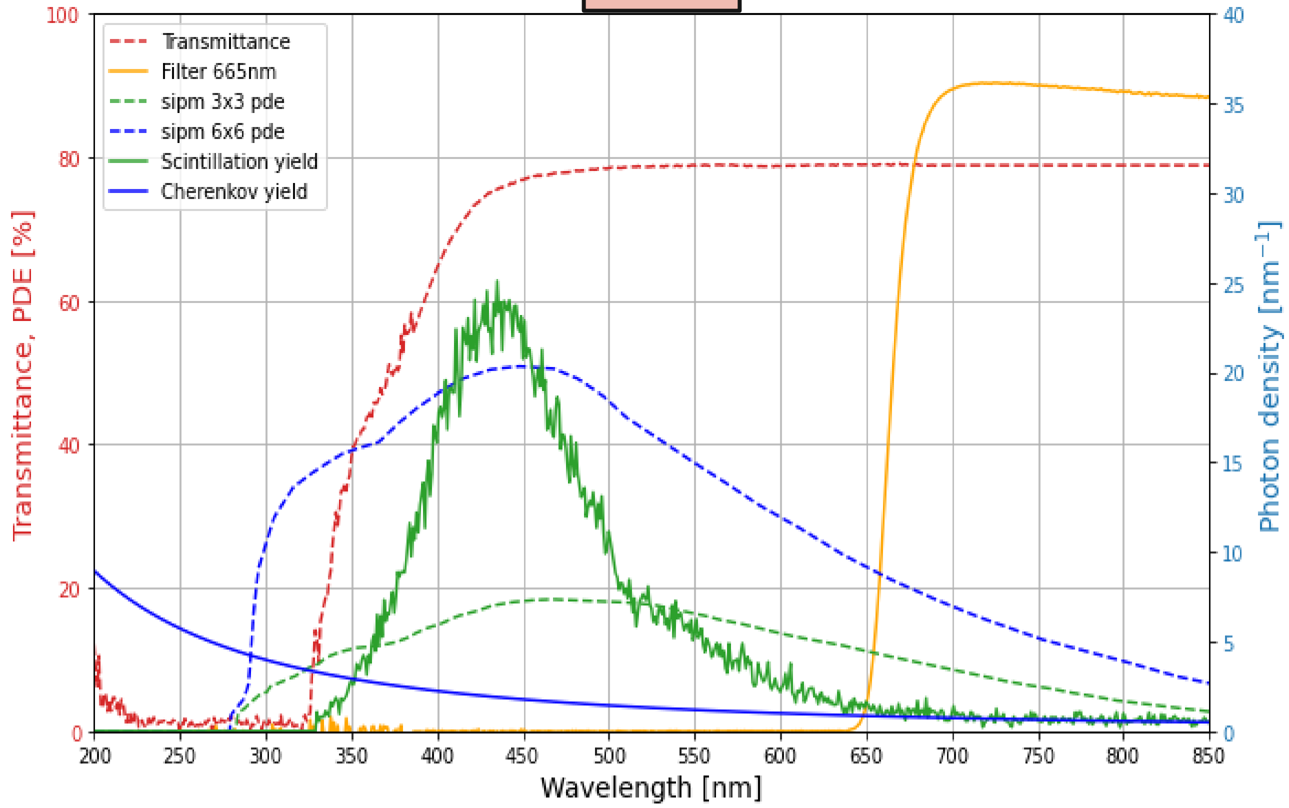
PWO



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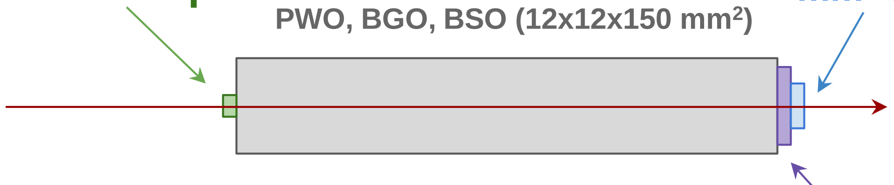
Use optical filters to select the specific region of the light spectrum and favor the Cherenkov signal

S SiPM 3x3 mm² 10 µm

C SiPM 6x6 mm² 50 µm



3 mm thick glass filters

Strategy for extracting the Cherenkov signal

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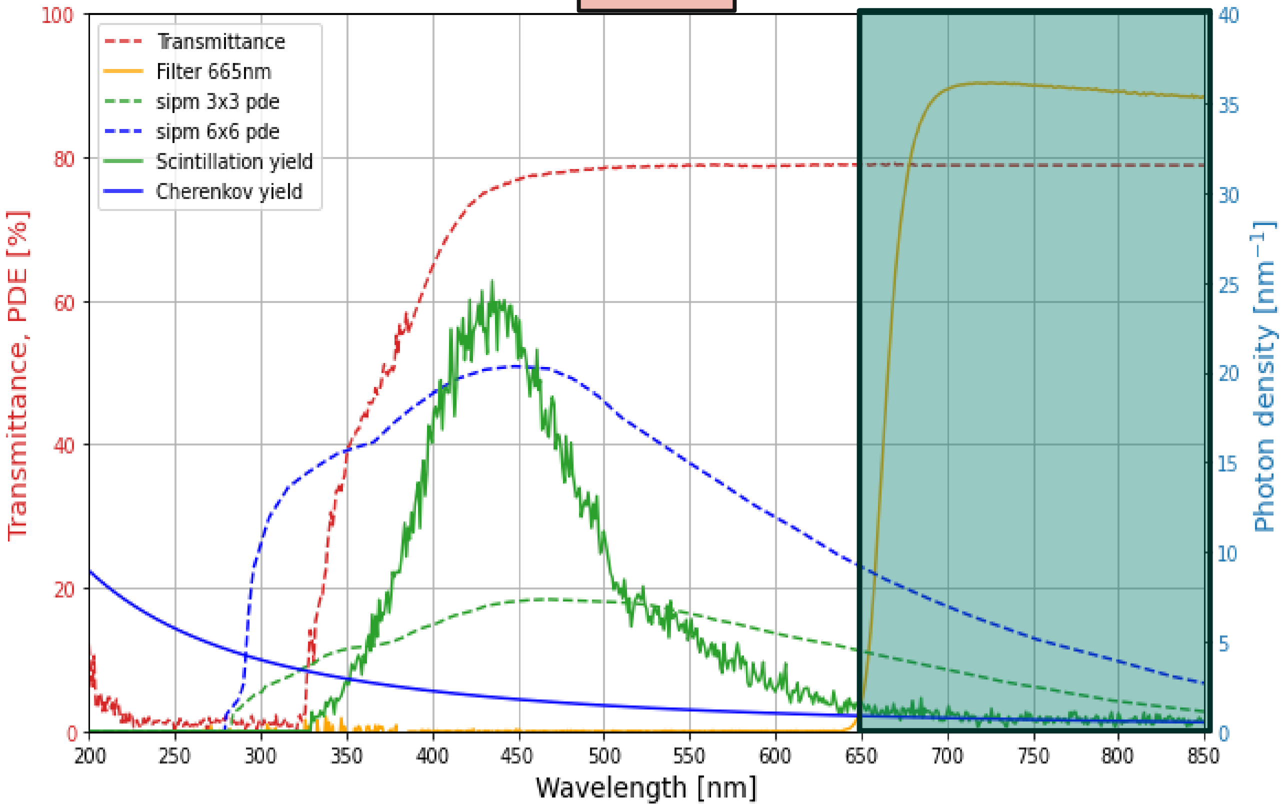

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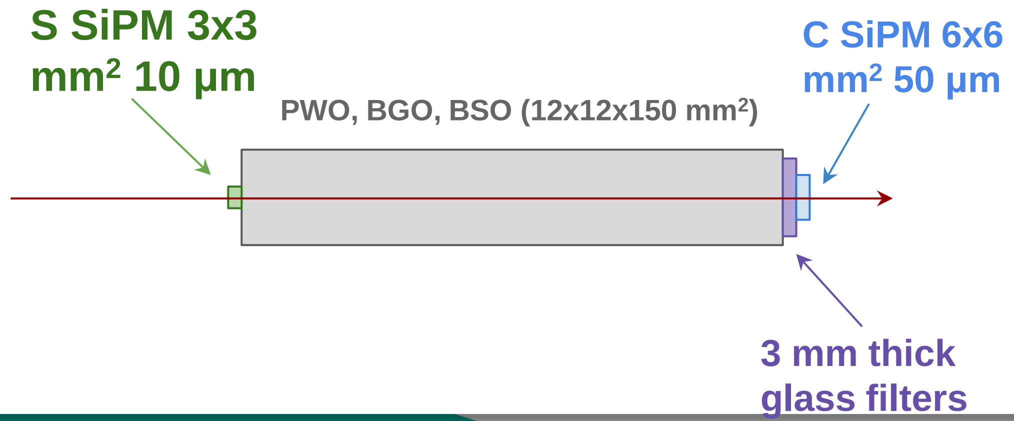
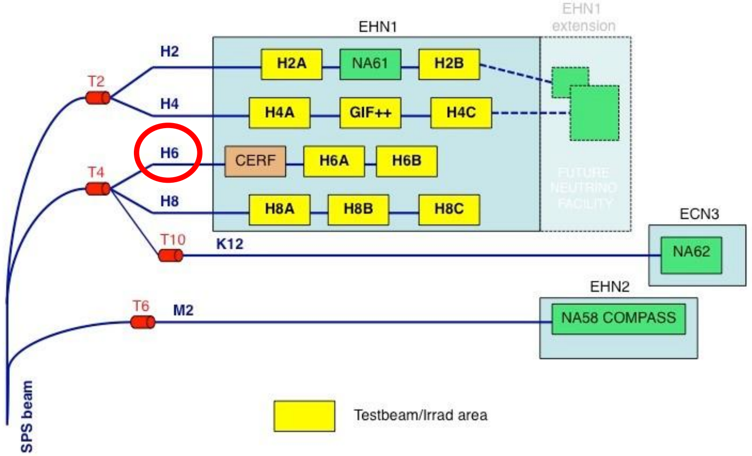


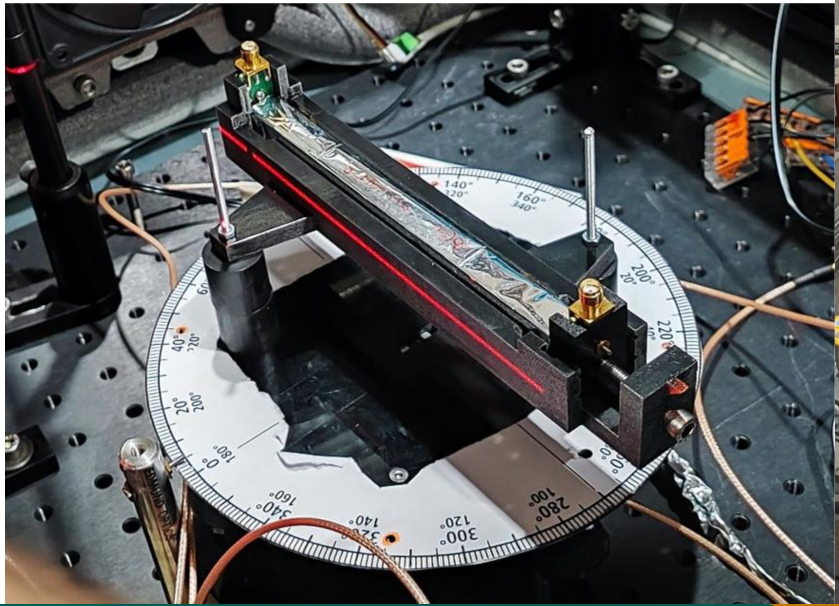
Test Beam at CERN NA site

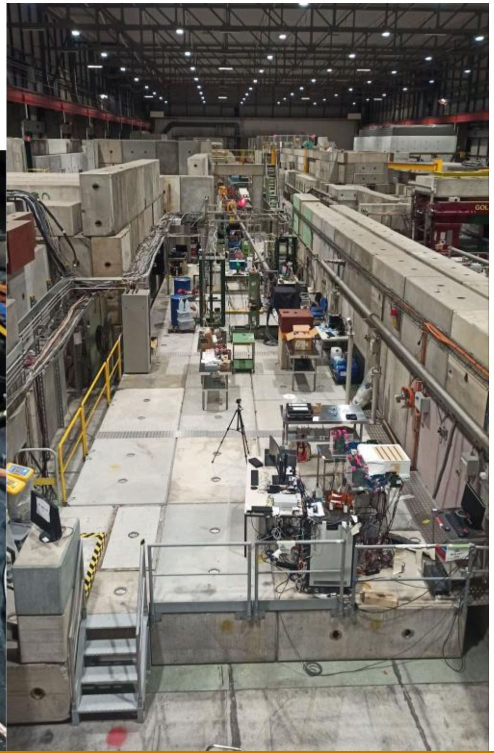
- From 17-24 July 2024 we carried out a beam test **at CERN SPS H6** beam line prepared and **coordinated by MIB and Napoli** and with participation from Perugia, US.



The primary goal was to demonstrate and quantify the collection of Cherenkov photons

- tests with **positrons** (10-100 GeV), **mu+ 120 GeV**
- we have performed several runs at different angles





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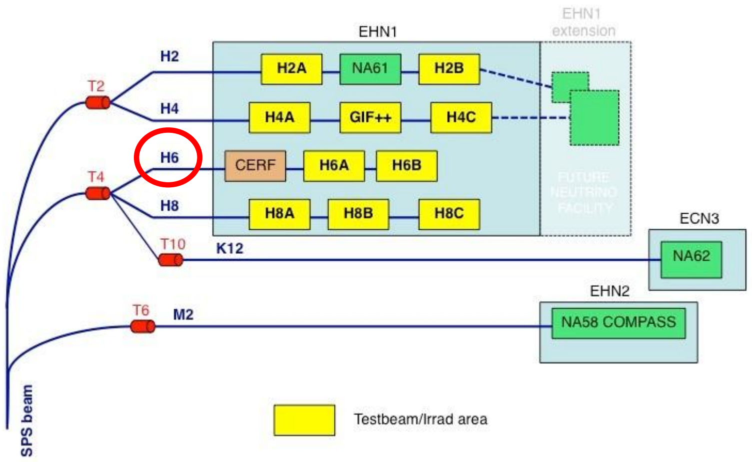
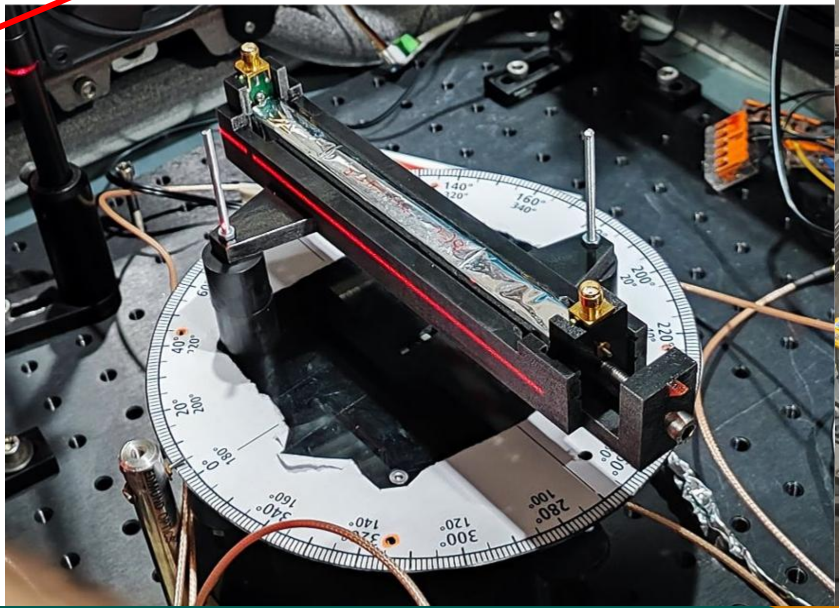
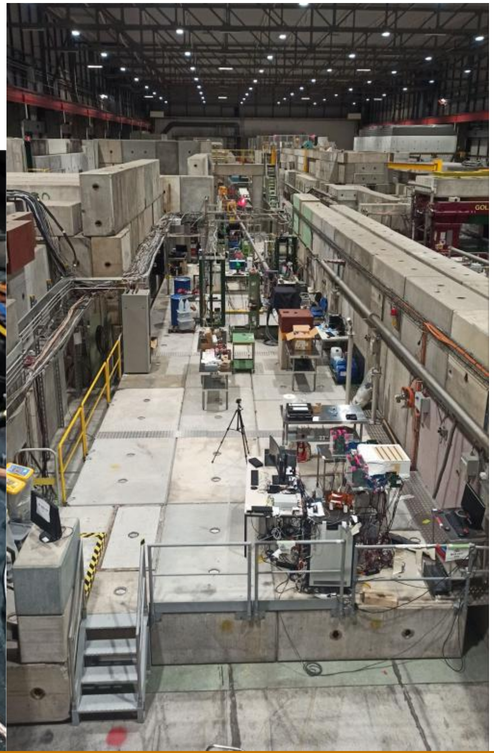


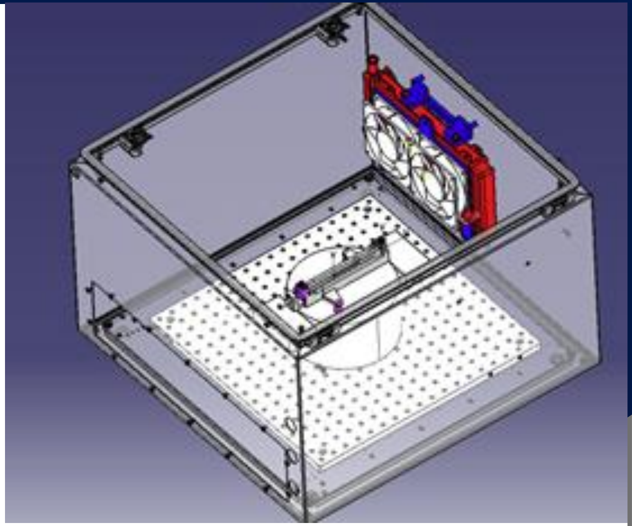
Here I am!

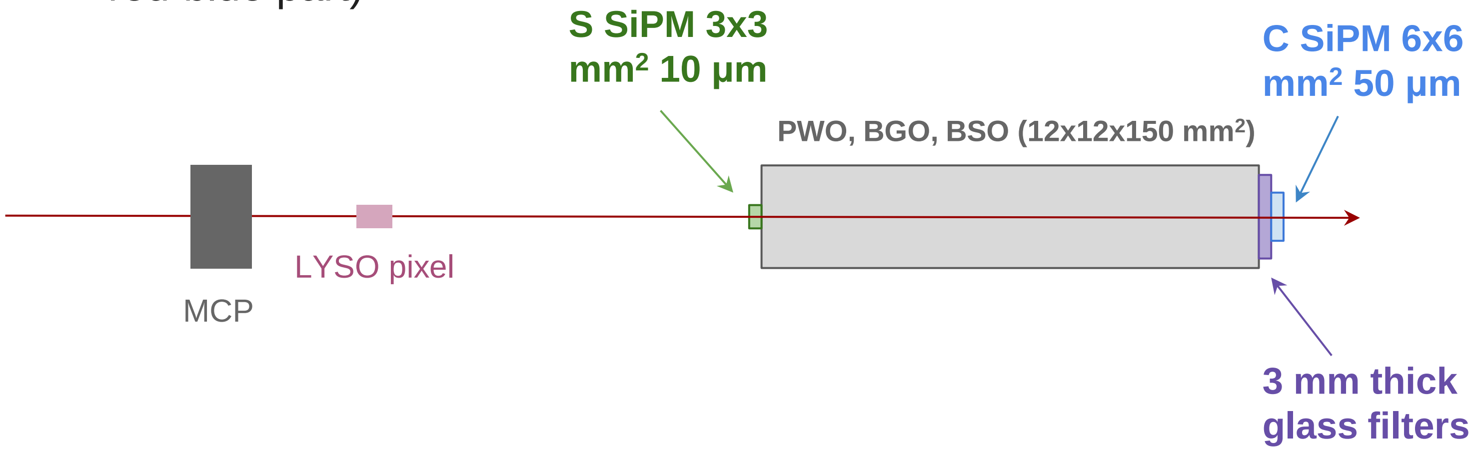


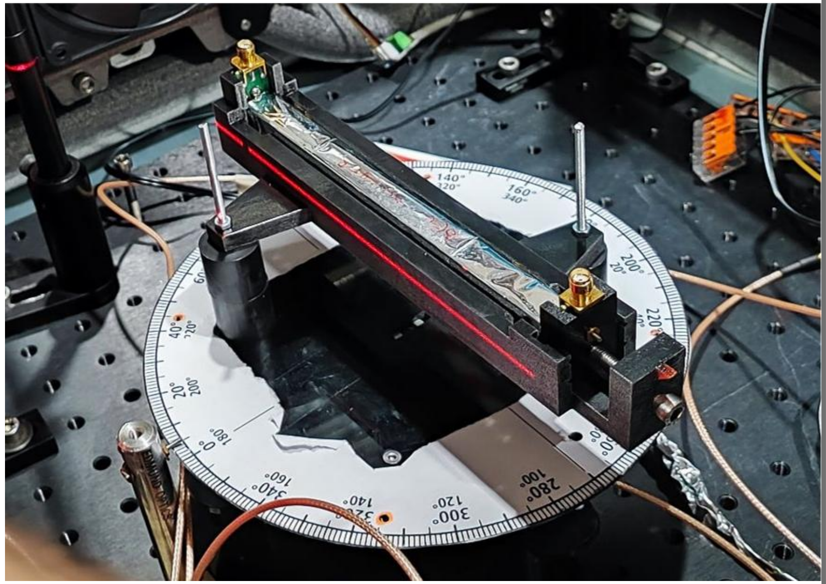


CERN Test Beam Setup

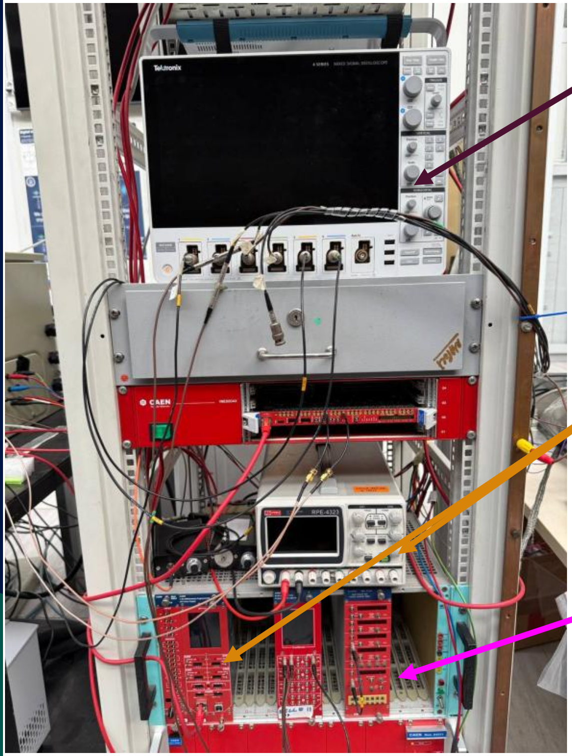
- Tested a variety of filters and crystals (BGO, BSO, PWO) of size 15x1,2x1,2 cm^3 , all possible candidates to be part of the calorimeter
- High bandwidth preamps CAEN serie A1423B:
  -Gain range from +18dB to +54dB
- Digitization with oscilloscope Tektronix Oscilloscope MSO46B for pulse shape analysis:
  - 1,5 GHz Bandwidth
  - 6 Analog channels
- Rotating stage for C/S study as a function of crystal-beam angle
- Dark box with temperature conditioning (see figure on the right the red-blue part)







Setup Components

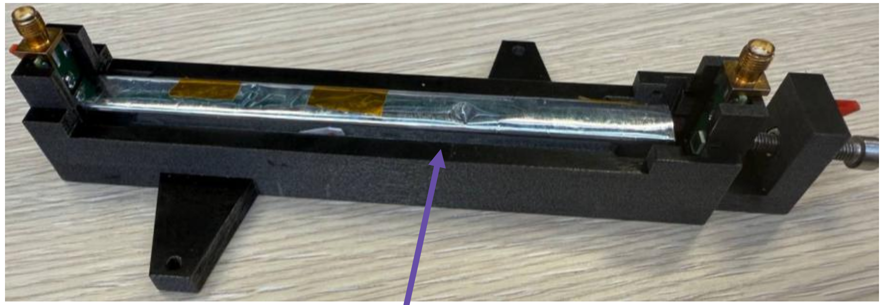


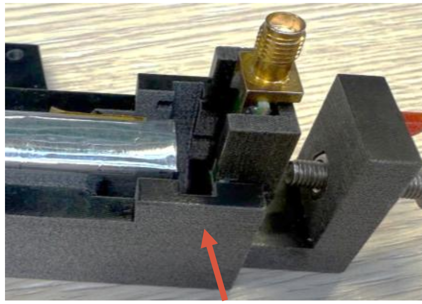
Oscilloscope

Power supplies

NIM modules: Trigger Generation

CAEN Preamplifier



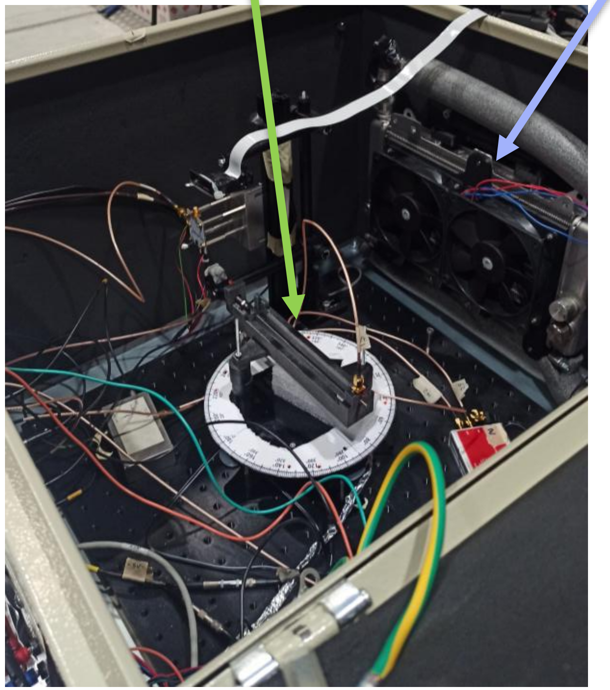


Wrapping Photoreflective

Cavity hosting the filter

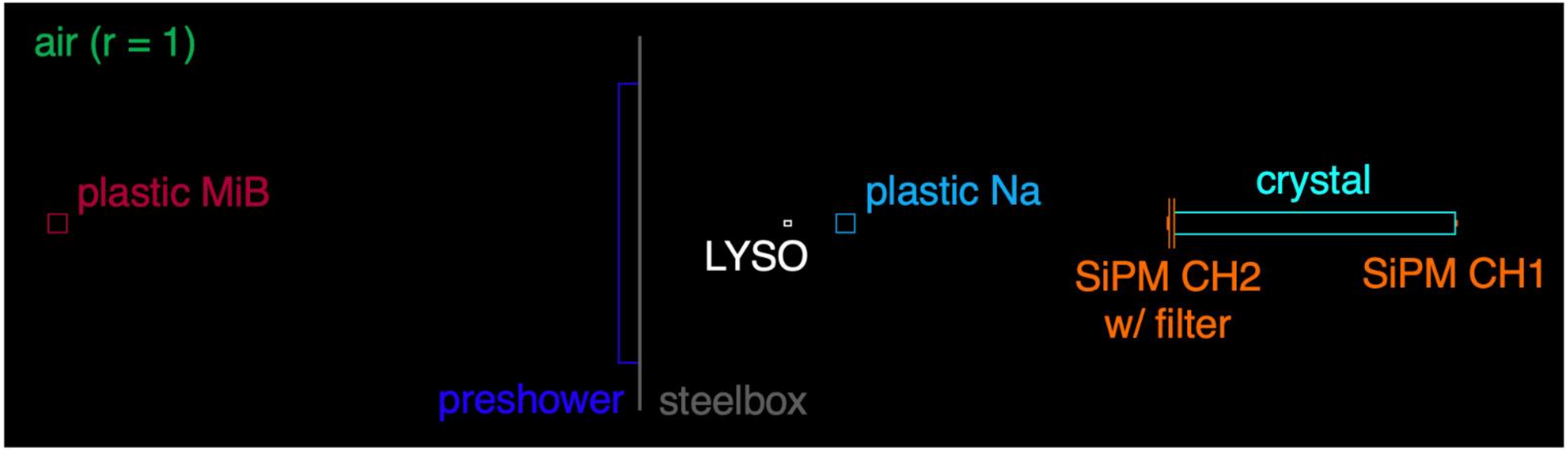
Rotating stage

cooling

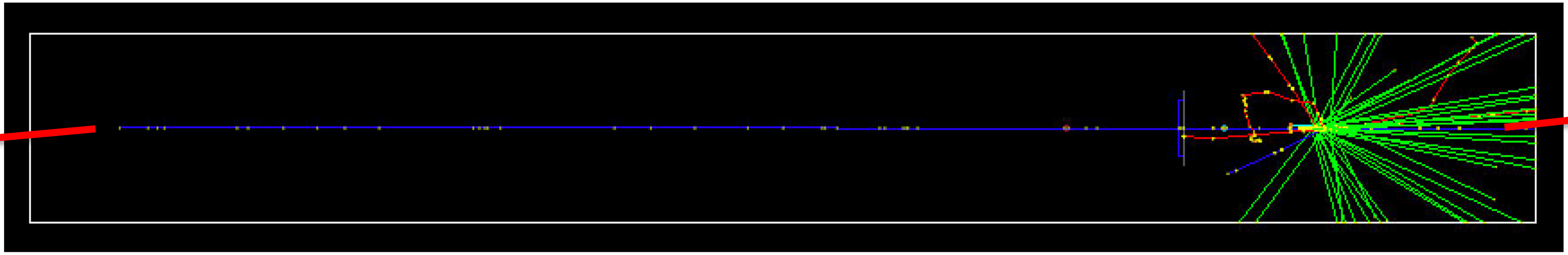


Box

Test beam setup simulation

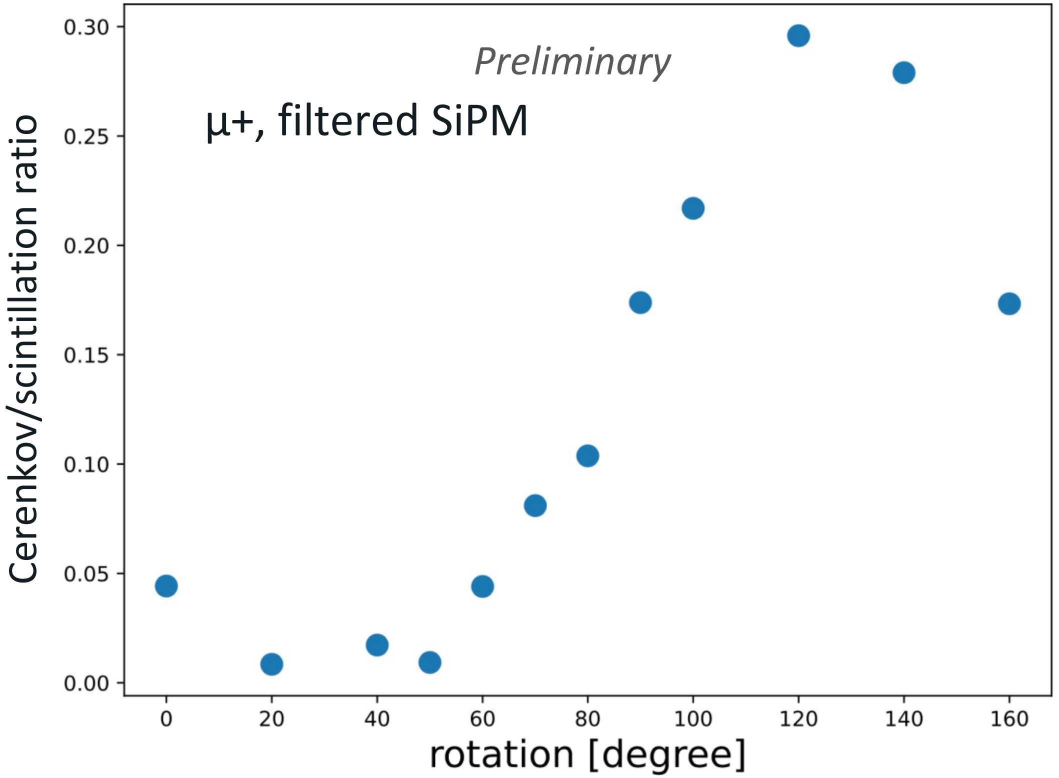


beam source (μ+ and e+)

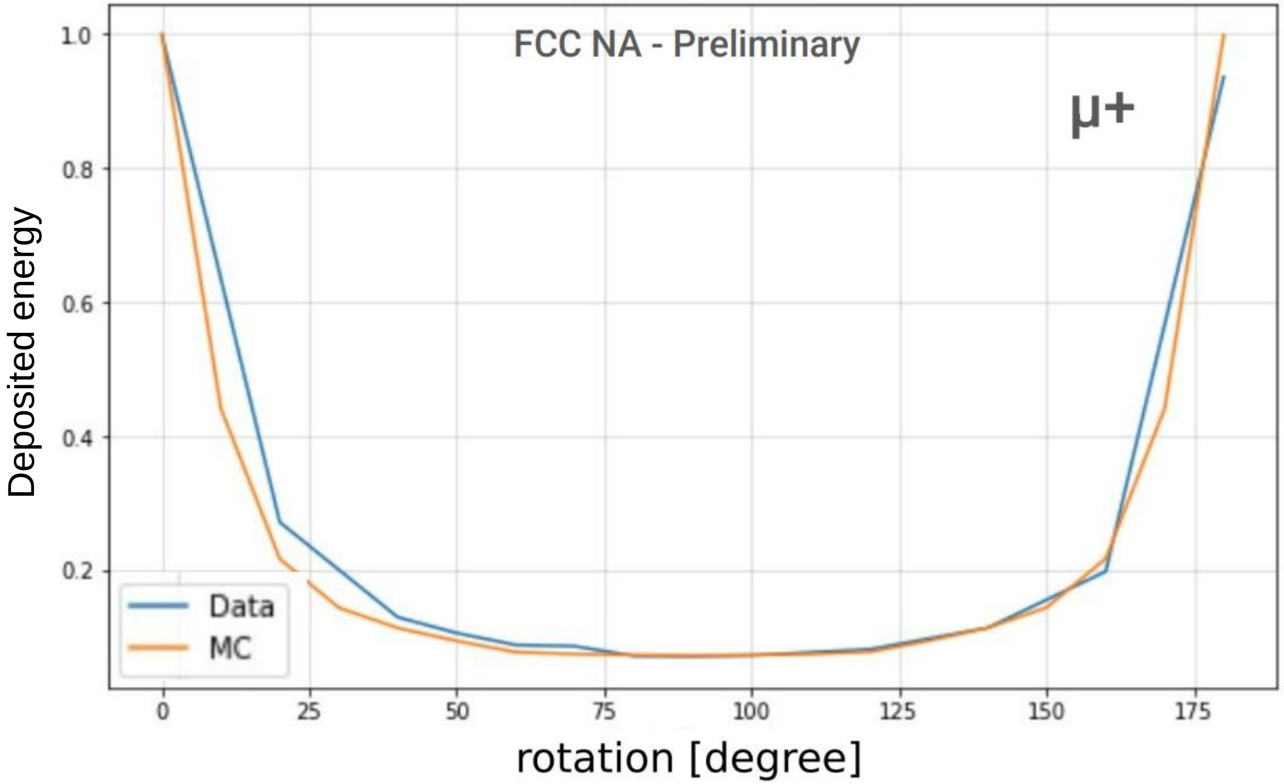


crystal center (**BGO**, PWO, BSO)

Data vs simulation: c/s ratio, deposited energy



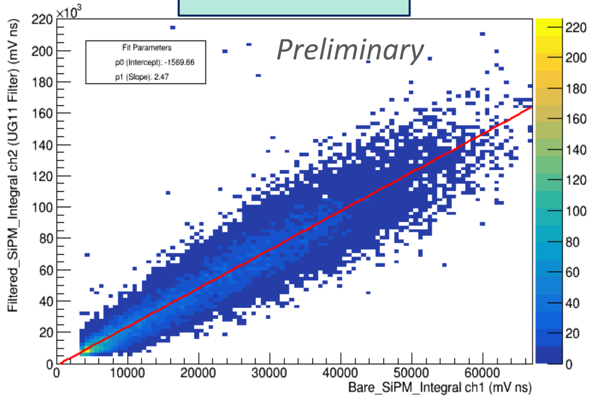
Cherenkov/scintillation ratio obtained from simulations with BGO and a muon beam. A distinct peak is observed at the expected Cherenkov angle.



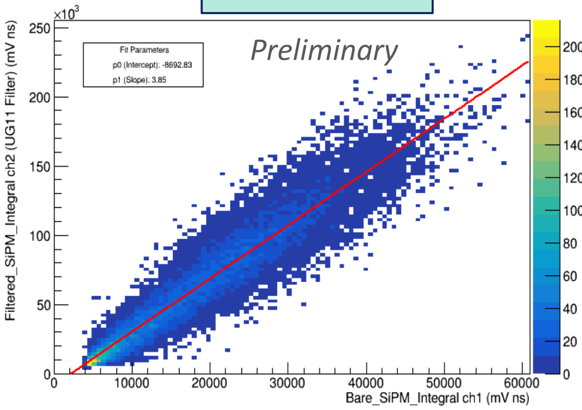
Comparison of deposited energy in simulation and integrated waveforms from data. Normalized with respect to 0°

Study of Charge Ratio Variation in angular scan

PWO $\theta = 60°$

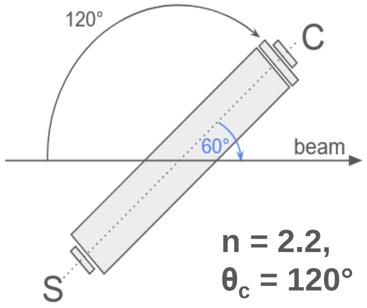


PWO $\theta = 120°$



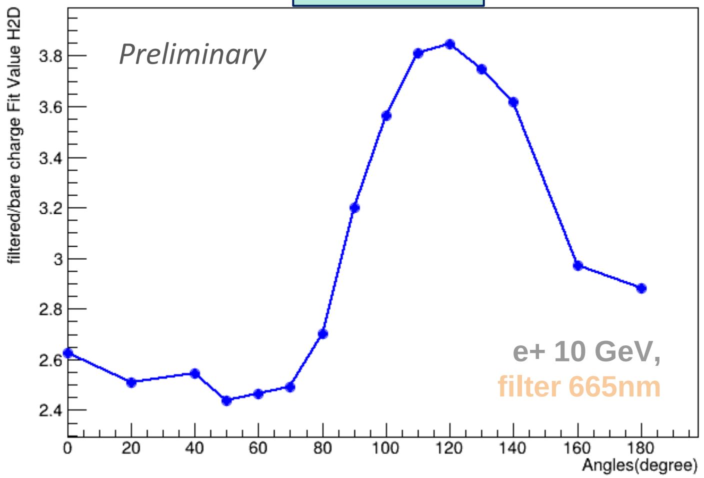
- Charge ratio peaking at the C emission angle
  - smoking gun of cherenkov detection!

- We studied the 2D histogram of the charge of filtered SiPM (dominated by cherenkov) vs the charge of bare SiPM (dominated by scintillation).

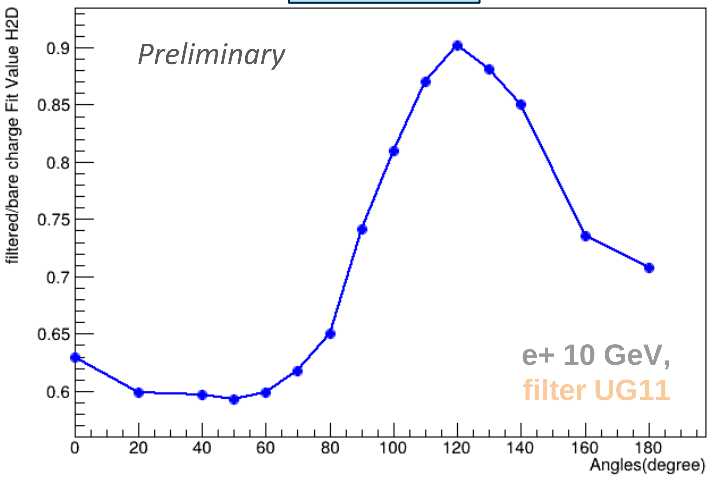


- Then we performed a linear fit: if there were only scintillation the slope would always be equal depending on the angle.
- Iterated for each crystals for every run of the angular scan

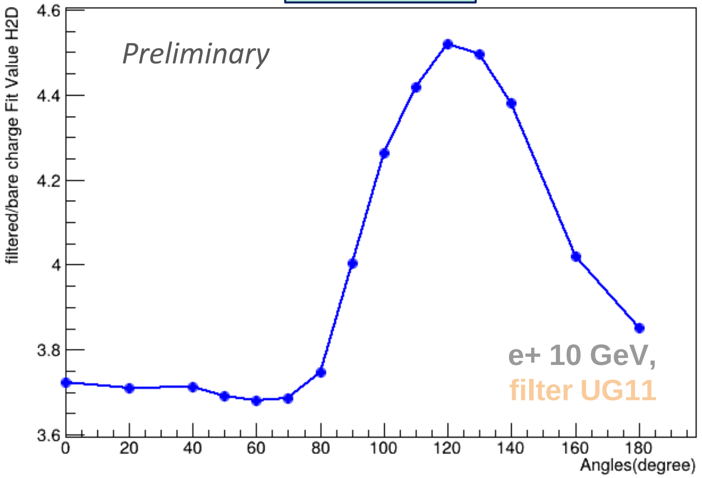
PWO



BSO



BGO



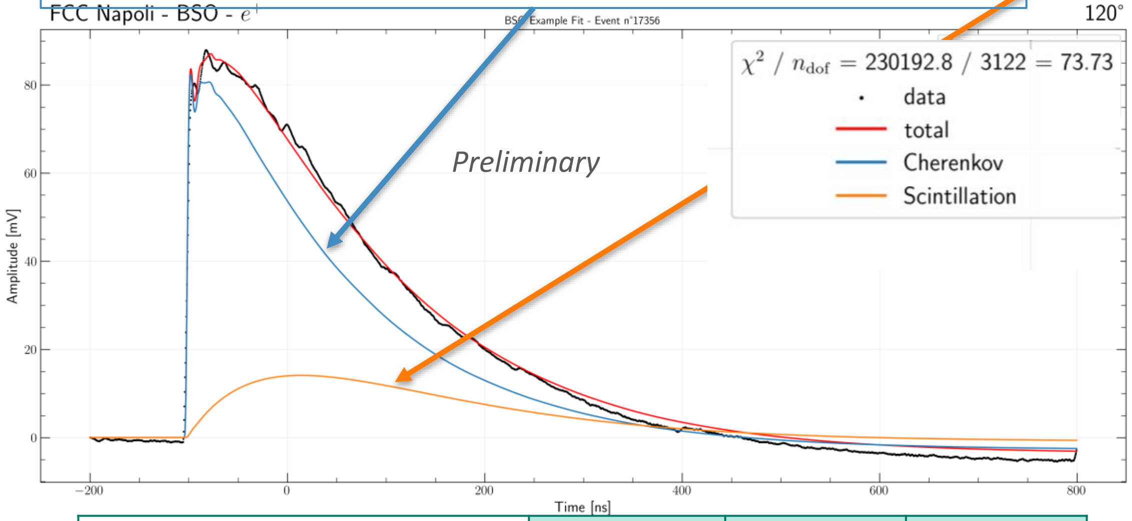
Cherenkov component extraction Strategy

- We analyzed the shape of the filtered SiPM waveform by exploiting the timing characteristics of the Cherenkov and scintillation components. A dedicated template fitting approach is applied to disentangle and quantify both contributions.

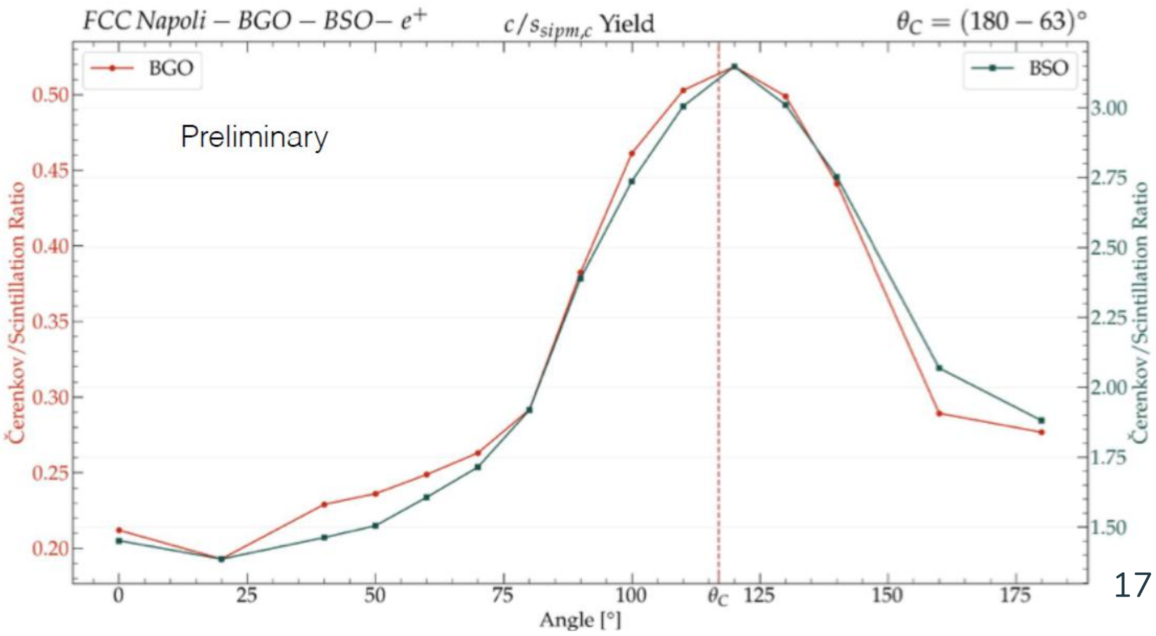
Template fitting technique:

- The Cherenkov template is obtained from dedicated laser calibration data using a Hamamatsu laser, providing the single-photon response (SPR).

- The Scintillation template is generated by convolving the SPR with a double-exponential decay function representing the scintillation time profile of the crystal.



	BGO	BSO	PWO
Pulse shaping analysis	✓	✓	✗



Conclusions

In this test beam, we were able to test different types of crystals and filters in various configurations.
Initial studies with 2D histograms confirmed the ability to observe an effect that could serve as a smoking gun for Cherenkov signal detection. Identified the correlation between the Charge ratio of the two SiPMs and the emission angle.

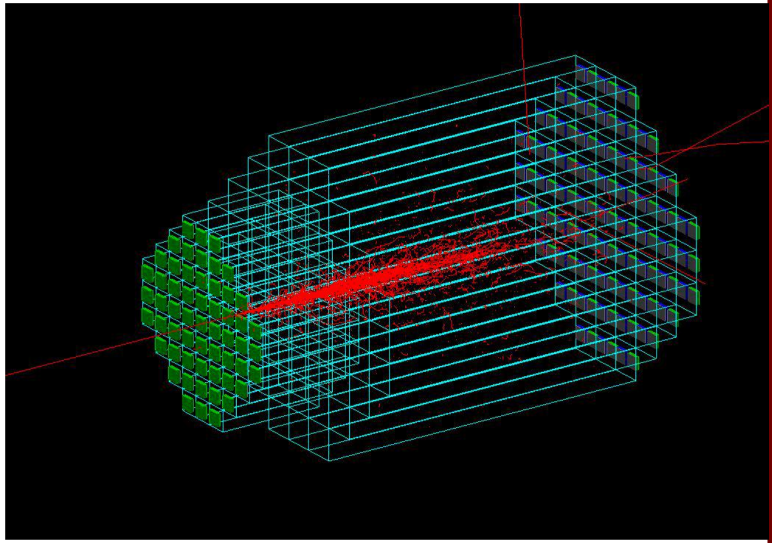
Work so Far

- We are performing a fit on the single waveform in order to derive the scintillation and cherenkov components.
- In addition, we are working on the simulation with GEANT4 to compare with the data taken at the test beam.

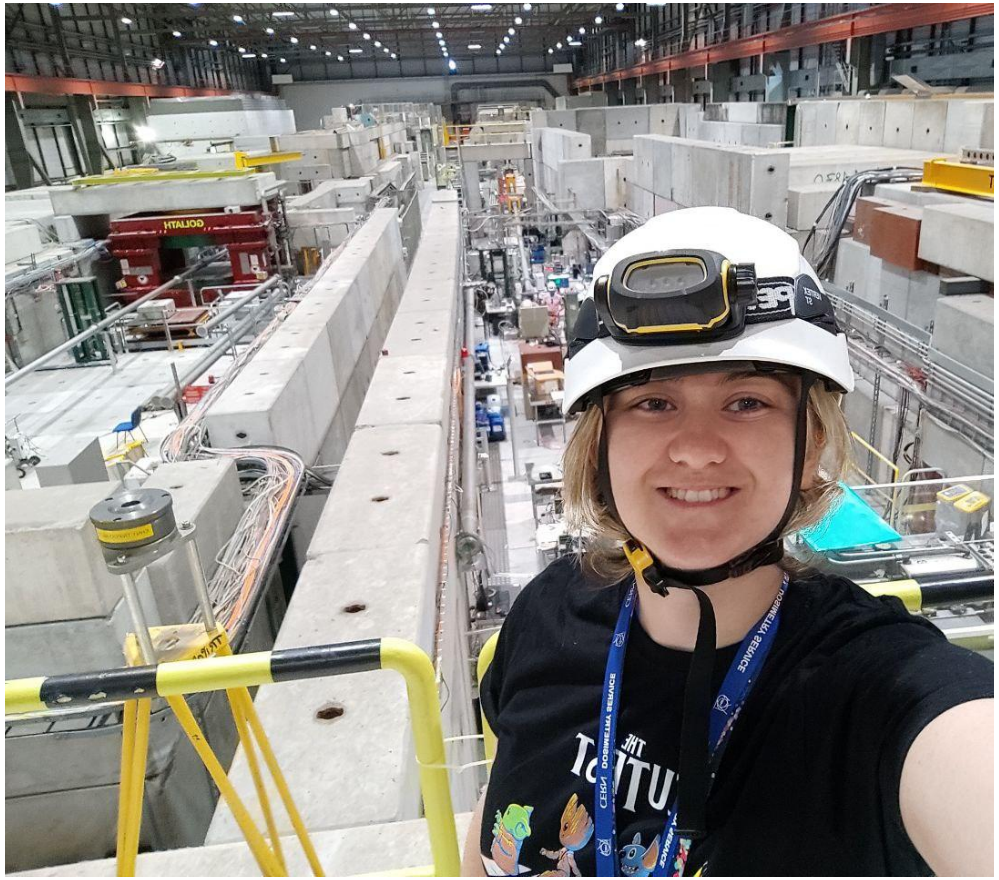
Future Work: large prototype

- Additionally, we have a slot at CERN to perform the next test beam, planned with a larger setup, at the end of September 2025.
- Goals: longitudinal part with short (6X0) and long (16X0) crystals
- Transverse shower containment (2.5RM)
- Dual readout in the back for C/S separation

To prepare for this, we are focusing on the implementation and optimization of our setup



THANK YOU FOR YOUR ATTENTION



Contacts:
- lucrezia.borriello@cern.ch
- lucrezia.borriello@na.infn.it

Backup Slides

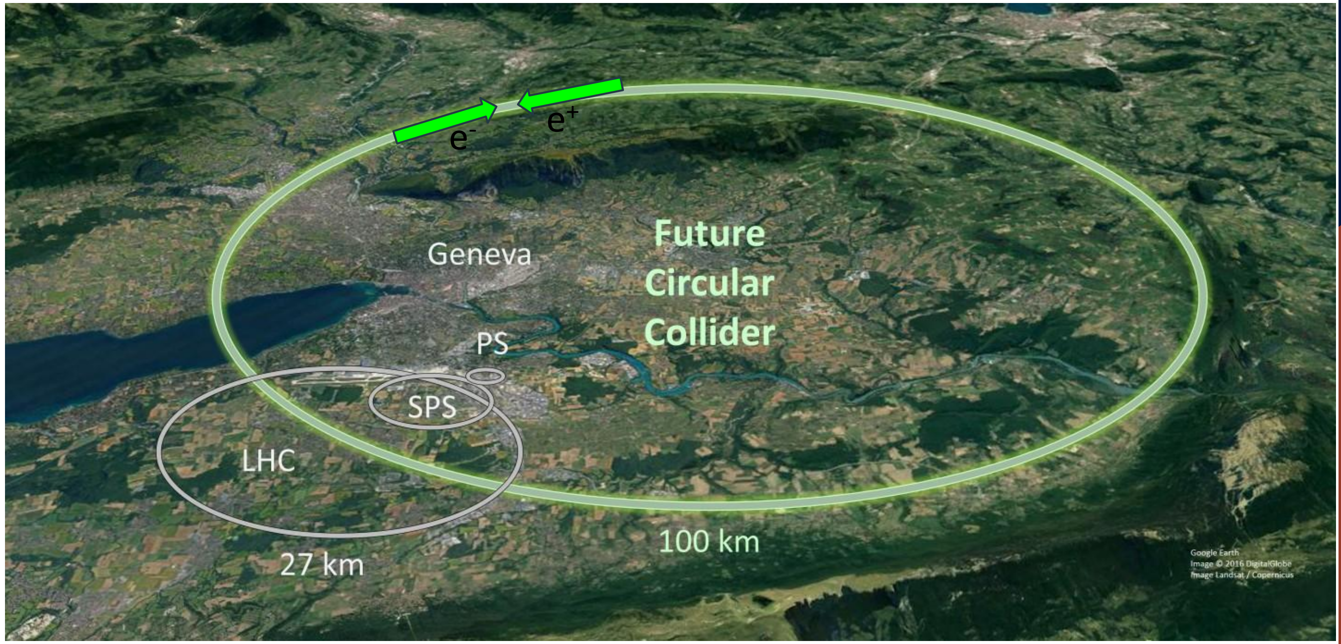
References:

- *IDEA Detector Poster(Innovative Detector for Electron-positron Accelerators) designed for future accelerators e^+e^- , L. Borriello, https://agenda.infn.it/event/38127/timetable/?view=standard#117-il-rivelatore-idea-propost*
- *FCC-ee: The Lepton Collider : Future Circular Collider Conceptual Design Report Volume 2*, A. Abada et al. (The FCC Collaboration), Eur.Phys.J.ST 228 (2019) 2, 261-623
- *The IDEA detector concept for FCC-ee*, G. Gaudio, PoS ICHEP2022 337
- *Dual-readout calorimetry*, Sehwook Lee et al., Rev. Mod. Phys. 90, 025002
- *Combining Dual-Readout Crystals and Fibers in a Hybrid Calorimeter for the IDEA Experiment*, M. Lucchini et al. (The IDEA proto Collaboration), PoS EPS-HEP2021 (2022) 850

FUTURE CIRCULAR COLLIDER (FCC) EXPERIMENT

Examines scenarios for three different types of particle collisions:

- **FCC-ee: Electron-positron collisions**;
- FCC-hh: Hadronic collisions, protons or ions;
- FCC-he: Proton electron collisions.



Goals:

- Uniquely map the properties of the Higgs boson and the Z and W bosons;
- Study of physics beyond the Standard Model

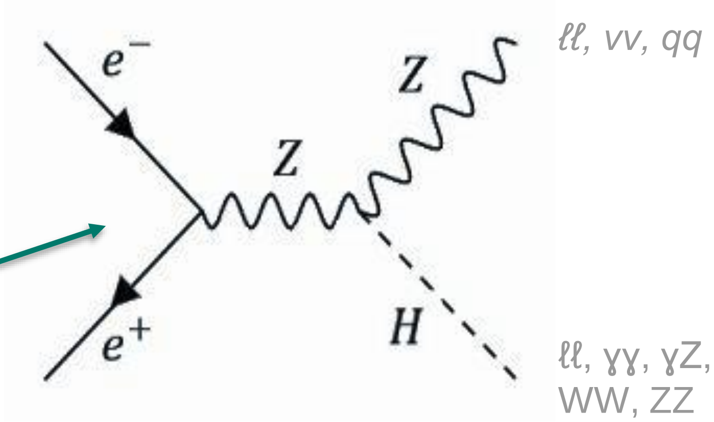
Characteristics:

- Circumference: 91 km
- Energies: up to 365 GeV for FCC-ee and up to 100 TeV for FCC-hh

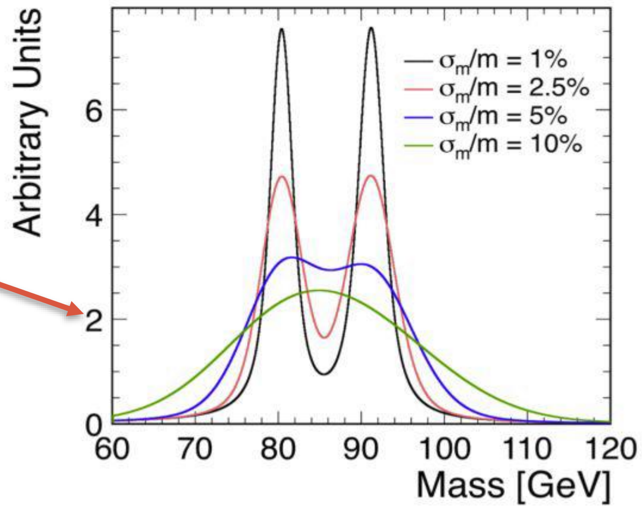
Targets for Calorimeter Performance

Jet energy resolution represents a fundamental benchmark for evaluating the performance of detectors at e^+e^- colliders.

- At √s ≈ 250 GeV, **Higgs bosons** are predominantly produced via the **Higgsstrahlung** process.
  - Roughly **97% of Standard Model Higgsstrahlung events** result in final states containing jets.



- To effectively separate jets originating from **W and Z bosons**, a calorimeter resolution of approximately **30%/√E** (i.e., **3–4% at 90 GeV**) is required.



Challenging for conventional calorimeters

● Typical hadronic calorimeter resolution: ≳ 50%/√E (e.g., ATLAS)

Targets for Calorimeter Performance

EM energy resolution is just as crucial!

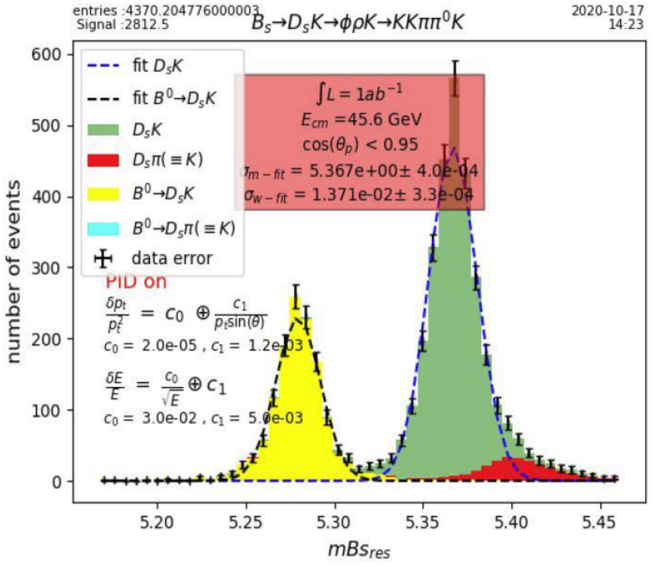
A resolution of 3%/√E for electromagnetic energy can significantly enhance event reconstruction and broaden the physics reach. → For example:

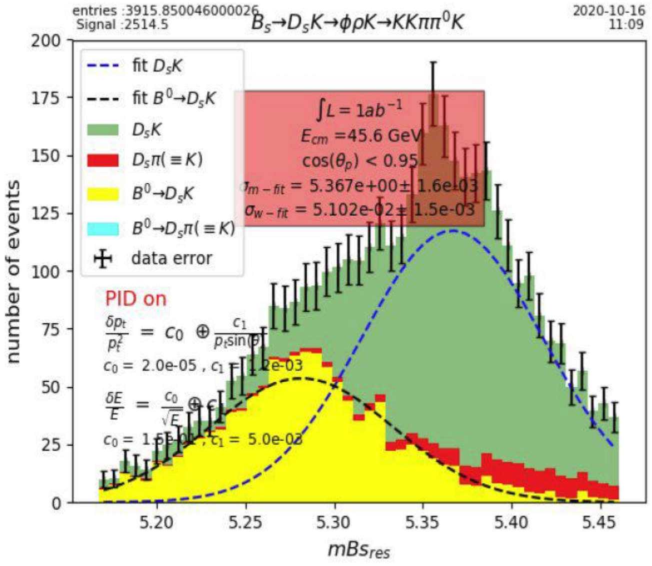
- Accurate reconstruction of final states with low-energy photons (e.g., π^0)
- Enhanced jet clustering performance
- Mitigation of bremsstrahlung effects in electron measurements

$$\frac{\delta E}{E} = 3\%/\sqrt{E}$$

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

$$\frac{\delta E}{E} = 15\%/\sqrt{E}$$





Best current performance: 1–2%/√E with homogeneous crystal calorimeters

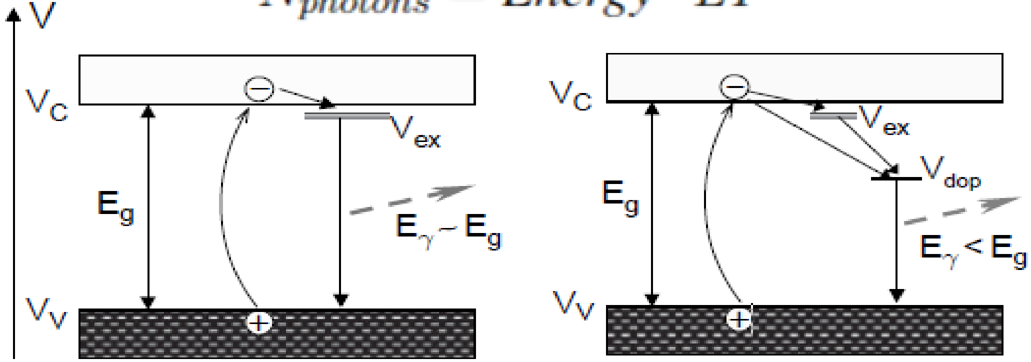
Dual-readout calorimetry technique:

- **Contemporary measurement of Scintillation and Cherenkov light:**
  - analysis <u>event-by-event</u> of the electromagnetic component of hadronic showers

Scintillation:
Charged particles deposit energy into the material, exciting electrons which then release absorbed energy in the form of light (photons).

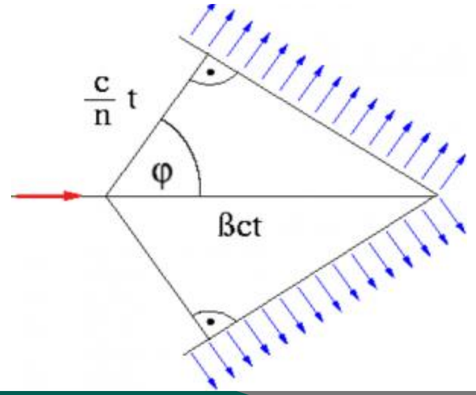
$$Energy = l\rho \frac{dE}{dx}$$

$$N_{photons} = Energy \cdot LY$$



Cherenkov effect:
Light emitted when a charged particle exceeds the speed of light in a medium.
The number of Cherenkov photons emitted per unit path length with wavelengths between λ_1 and λ_2:

$$\frac{dN}{dx} = 2\pi\alpha z^2 \sin^2\theta_C \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$



Strategy and Setup for Dual Readout with Crystals

- Our goal: discriminating the Cherenkov signal from the Scintillation signals inside different crystal samples:

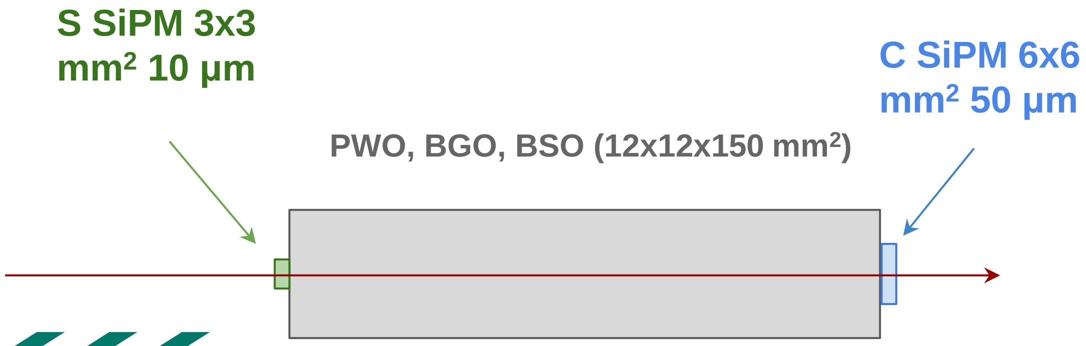
Cherenkov signal: prompt
Scintillation signals: longer

→ Possible Analysis →

- use of multiple channels
- waveform shape study
- using time response

	time	spectrum
Cherenkov	fast	$1/\lambda^2$
Scintillation	slow	peaked

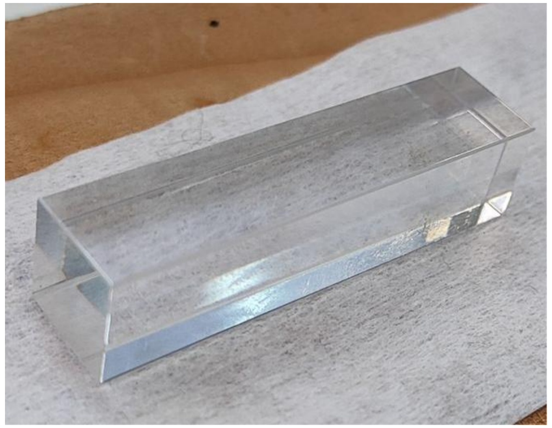
Basic Setup:



3×3 mm² SiPM: used to collect scintillation light, featuring a 10 μm SPAD pitch to avoid saturating the SiPM microcells

6×6 mm² SiPM employed for Cherenkov light collection, featuring a 50 μm SPAD pitch and enhanced geometrical acceptance to maximize photon collection efficiency.

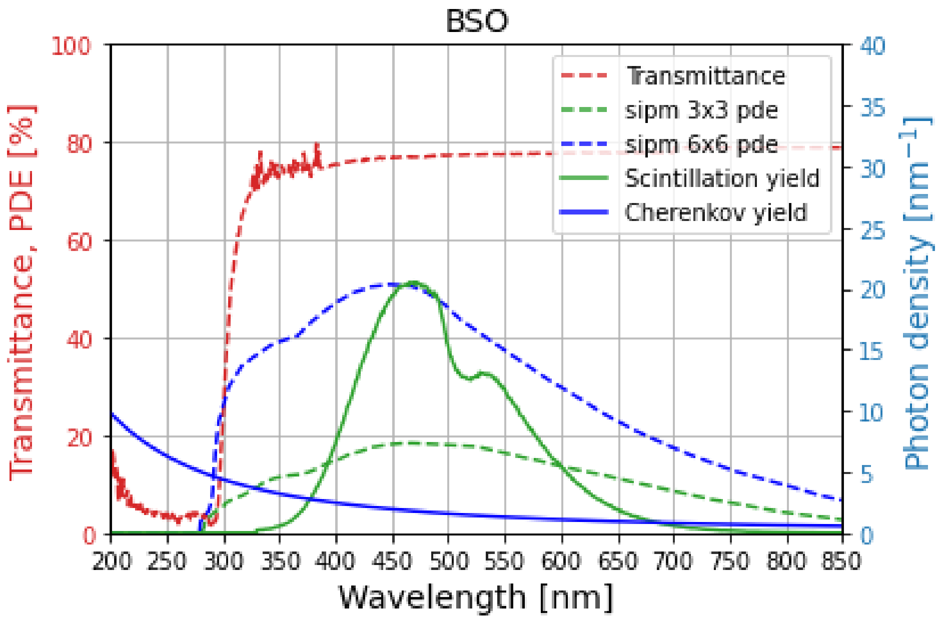
Crystals under consideration

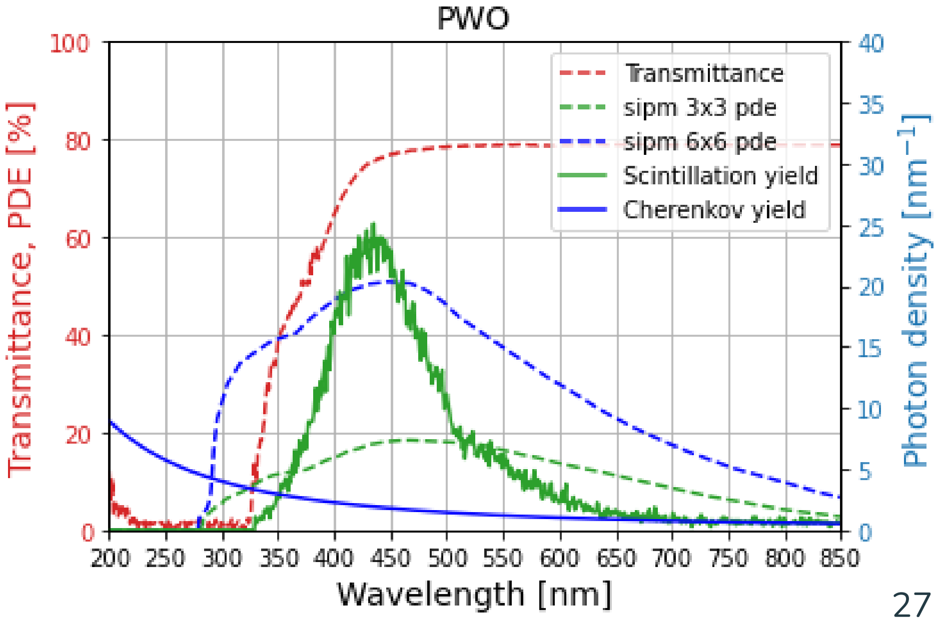


Dimensions: 15x1.2x1.2 cm^3

The light emitted by the crystals is detected using two Silicon Photomultipliers (SiPM) with efficiency shown in the figures

Characteristics of the crystals			
	BGO	BSO	PWO
Radiation Length [cm]	1.12	1.15	0.92
Density [g/cm^3]	7.13	6.8	8.28
Refractive Index %	2.15	2.68	2.16
Light Yield [photons/MeV]	7500	1500	190





Large prototype: longitudinal and Transverse

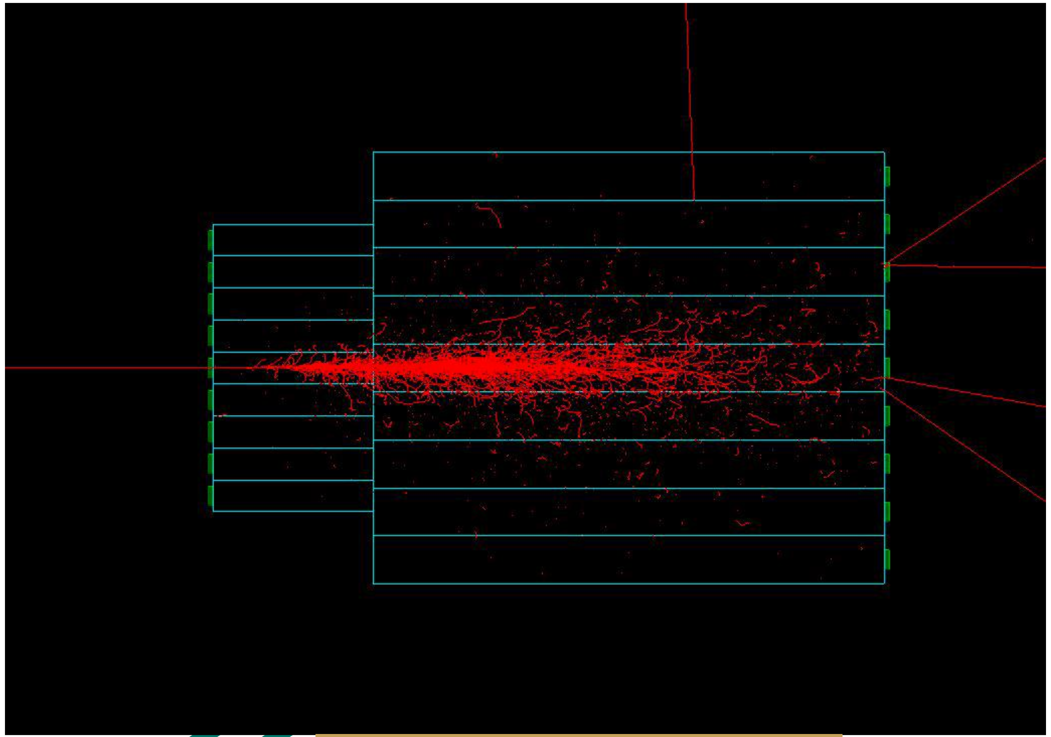
Plan for a 9x9 PWO matrix with exchangeable 3x3 central section for BGO/BSO tests

10 mm x 10 mm x $6X_0$ in front and 14 mm x 14 mm x 16 X_0 in back with Double readout

FERS 5200 readout for PWO crystals, waveform digitisation for BGO/BSO module

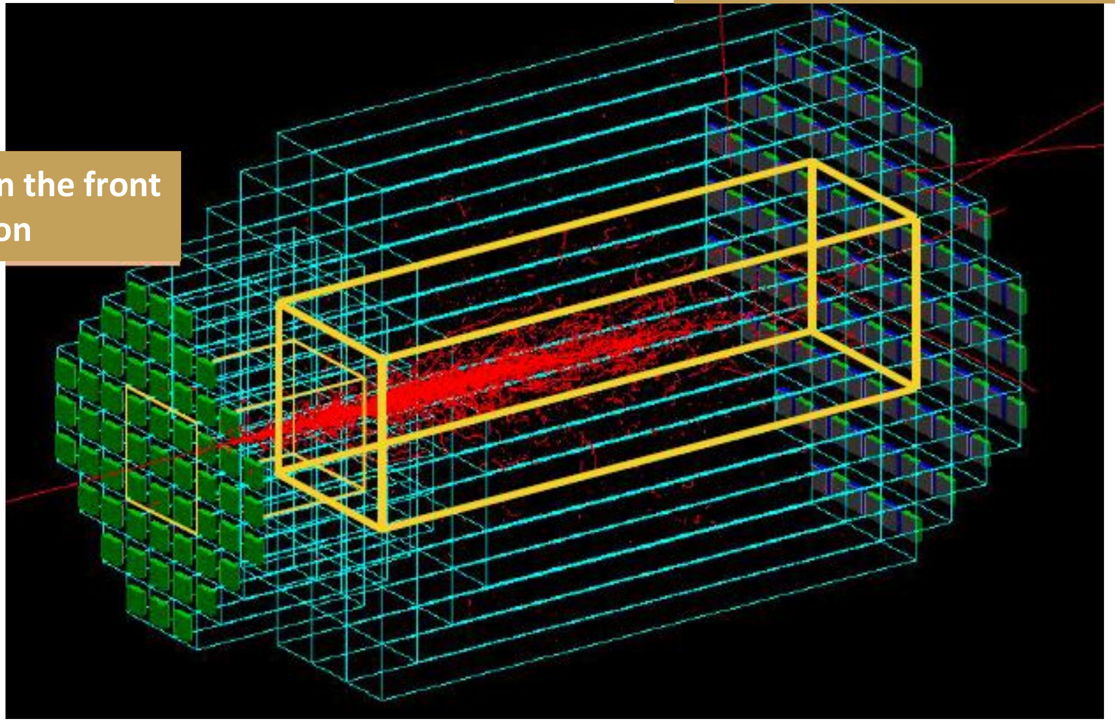
Goal: Test actual calorimeter performances and validate DR effect on resolution

To be tested on beam in September



Shower containment: 2.5 *RM*

Single SiPM in the front for scintillation



Double readout in the back (w optical filters)

Dual-Readout algebra

$$S = E \times [\ f_{em} + s \times (1 - f_{em})\ ]$$

$$C = E \times [\ f_{em} + c \times (1 - f_{em})\ ]$$

f_{em} = electromagnetic shower fraction

$s = (h/e)_S$, $c = (h/e)_C$: detector-specific constants

by solving the system, both E and f_{em} can be reconstructed

E measured at em energy scale

Dual-Readout formulae

$$E = \frac{S - \chi \cdot C}{1 - \chi}$$

measurable event by event, if χ known

$$1 - f_{em} = \frac{1}{1 - \left(\frac{h}{e}\right)_C} \cdot \frac{S - C}{S - \chi \cdot C}$$

measurable if χ known

(1-f_{em}) can be reconstructed within (unknown) constant factor (>) O(1)

$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C} = \frac{E - S}{E - C}$$

$$if \ \left(\frac{h}{e}\right)_S > \left(\frac{h}{e}\right)_C \Rightarrow \chi < 1$$

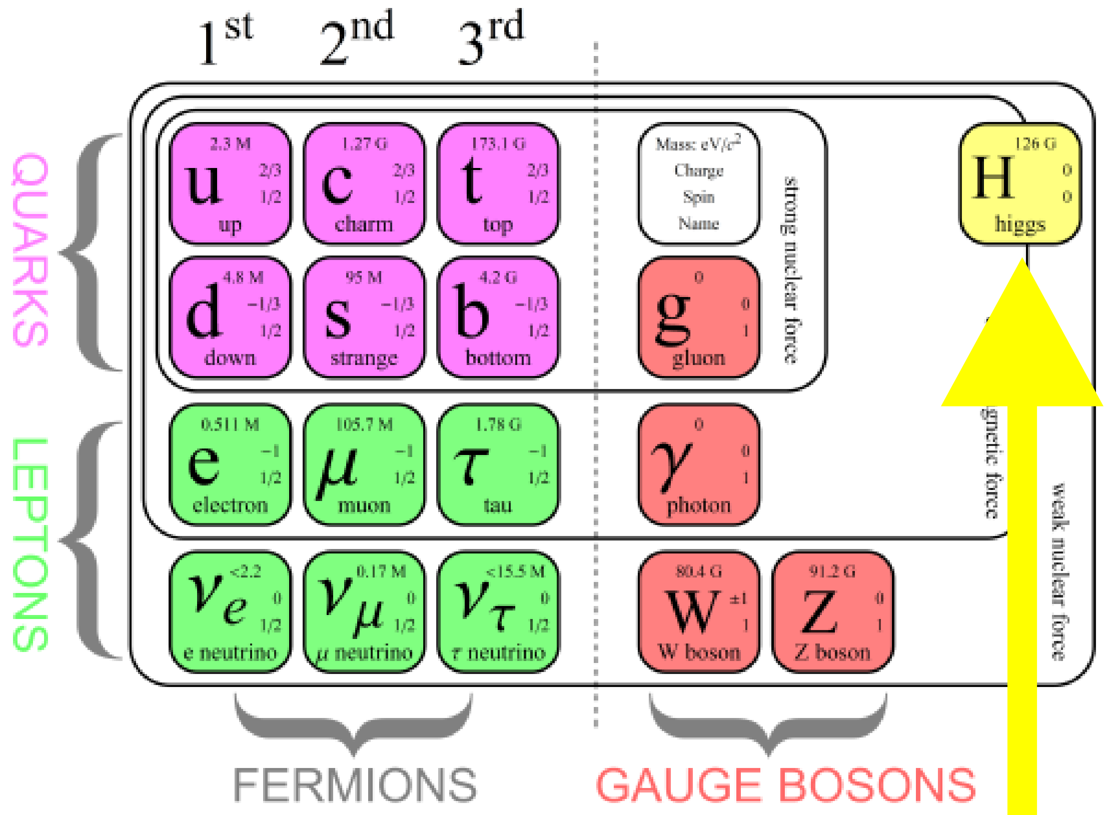
χ measurable if E known → **χ can be extracted from testbeam data**

Where are We?

Standard Model

Describes:

- Quantum Electrodynamics (QED)
- Quantum Chromodynamics (QCD)
- Electroweak theory
- Higgs Mechanism



Open Questions:

- Dark Matter and Dark Energy
- Gravity
- Barionic asymmetry
- Numerous free parameters

Hardware Side

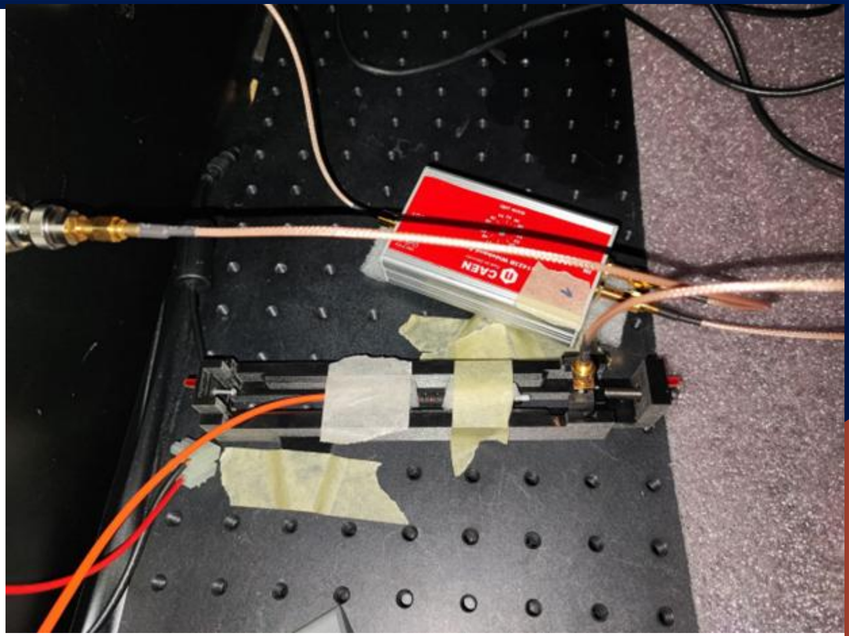
I calibrate the Silicon Photomultiplier (SiPM) that we used at the test beam, they are of different sizes and 'using a preamplifier that allows us to have various gains.

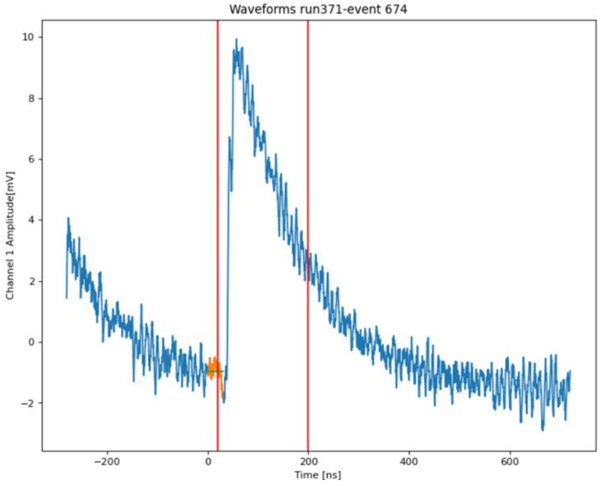
Measurement:

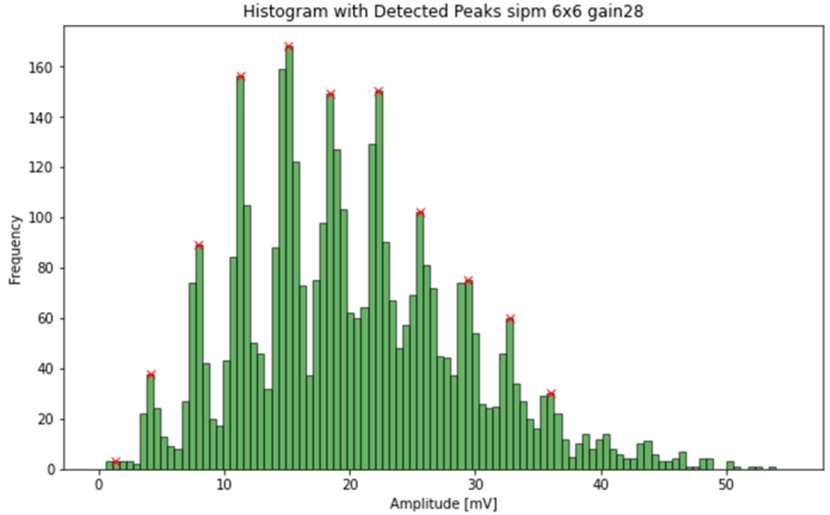
•Use a led drive that with a fiber brings light to our sipm, then we acquire our signal with the oscilloscope.

•We study the waveforms of our signals and apply some cuts so that we have selections that allow us to have a good definition of the peaks

•Estimate the peaks of single photons and then make the fit on the points

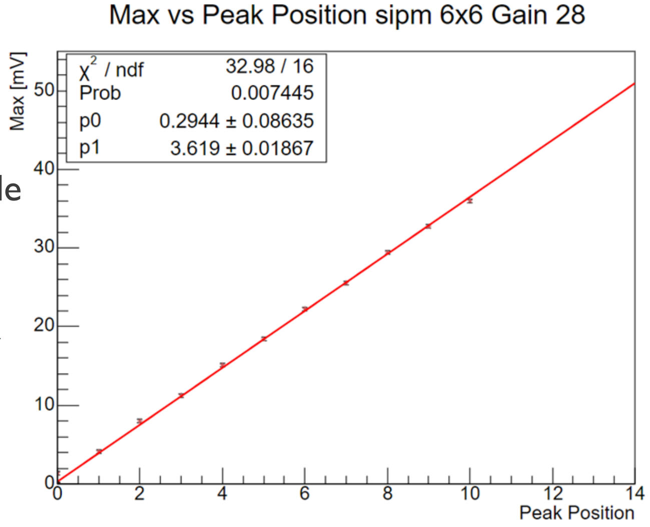




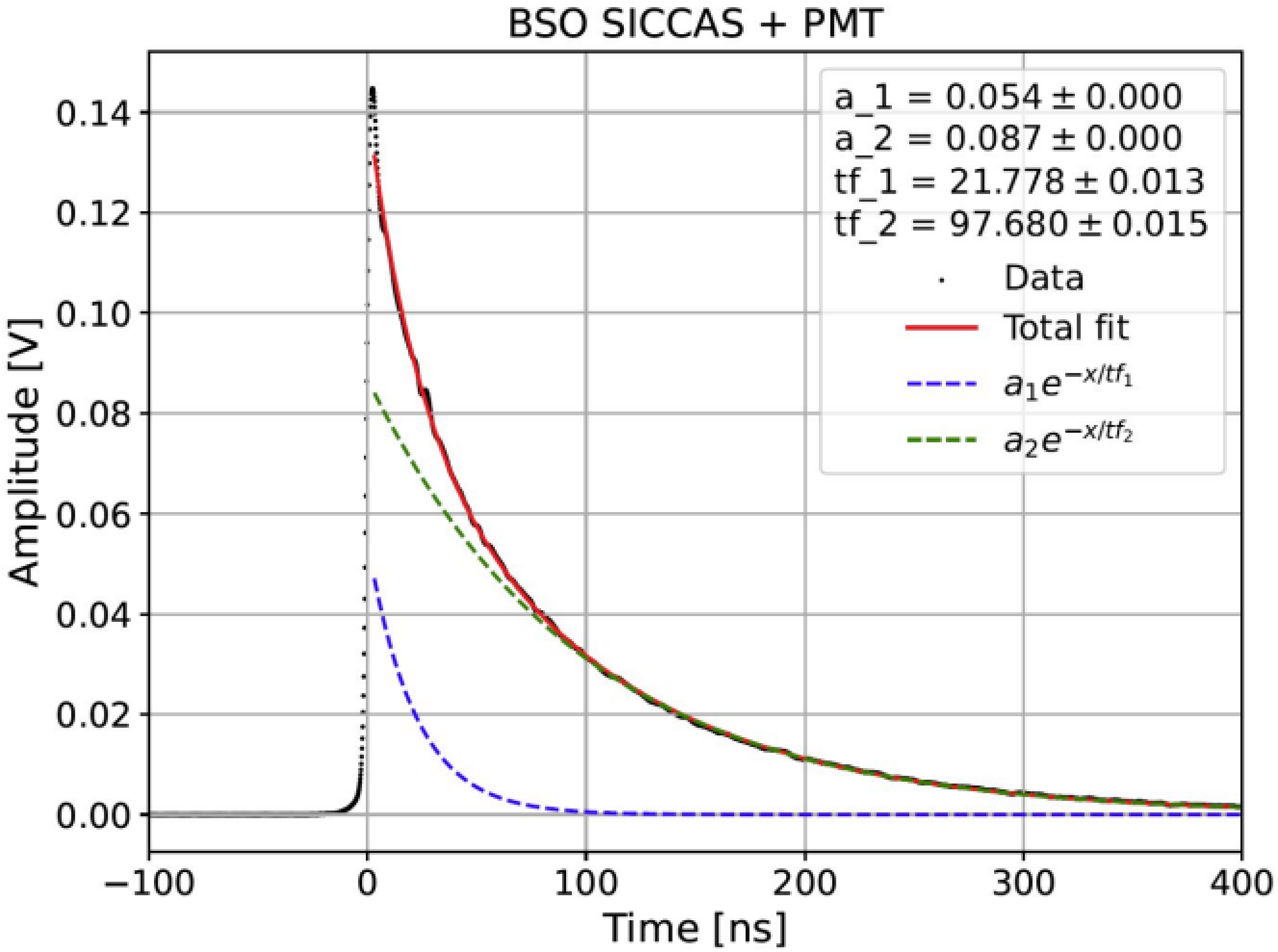


From the fit of the amplitude we get:

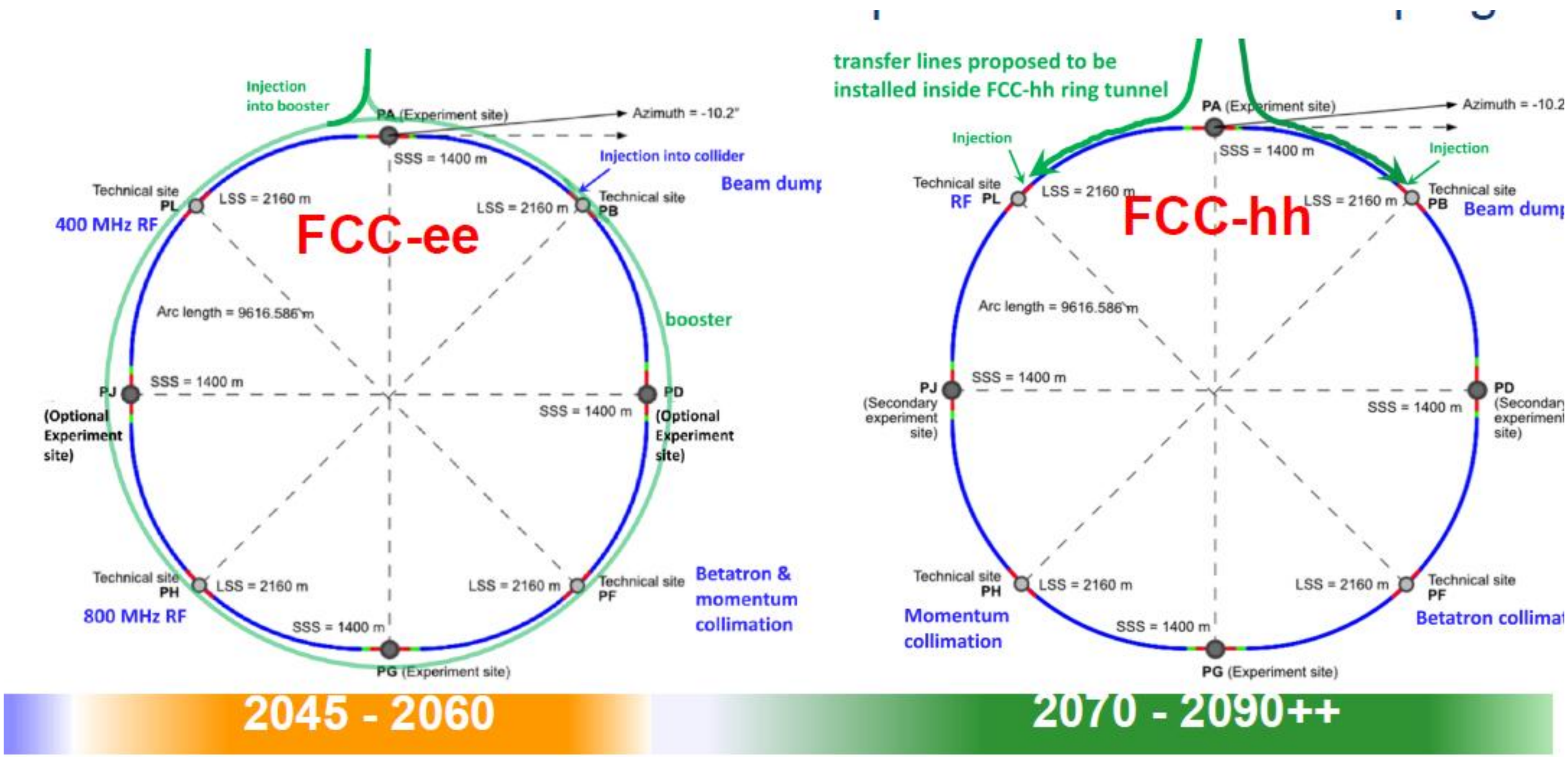
A=p_0+p_1 n_pe



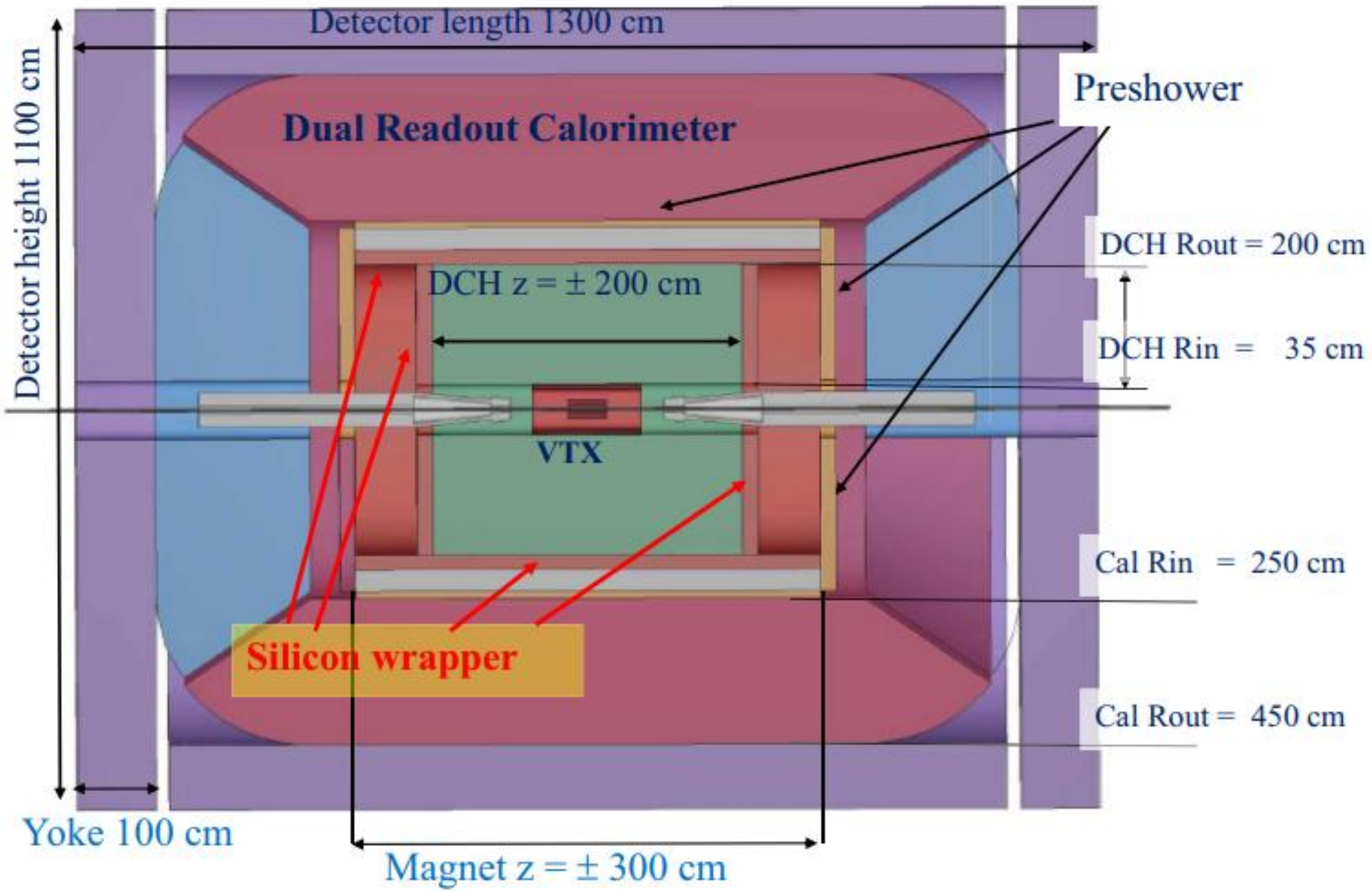
Time of fall for BSO



Proposed time for the experiment FCC



Internal structure of the idea detector



IDEA detector design with additional layer of homogeneous material

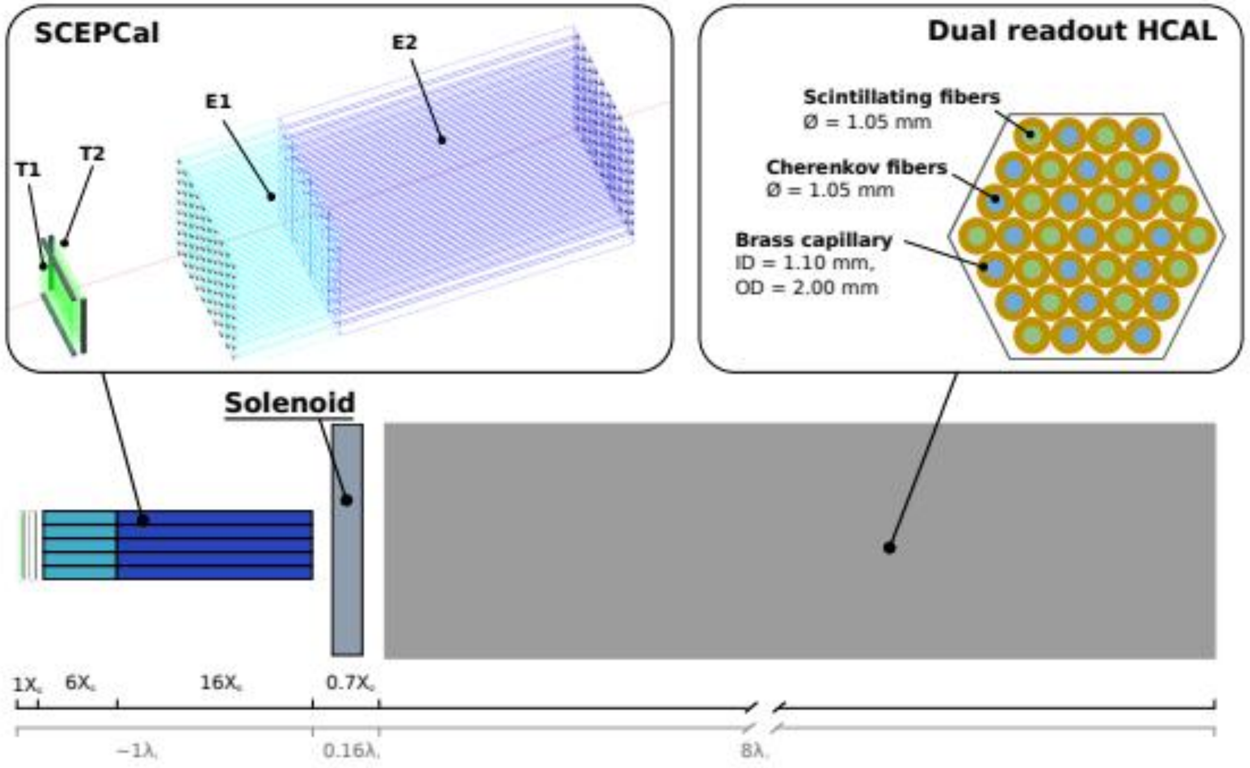


Figure 12. Overview of a hybrid segmented calorimeter layout featuring 4 front segments which exploit scintillating crystals for detection of EM showers followed by an ultrathin-bore solenoid and a hadron calorimeter based on scintillating and quartz fibers.

IDEA detector design with additional layer of homogeneous material

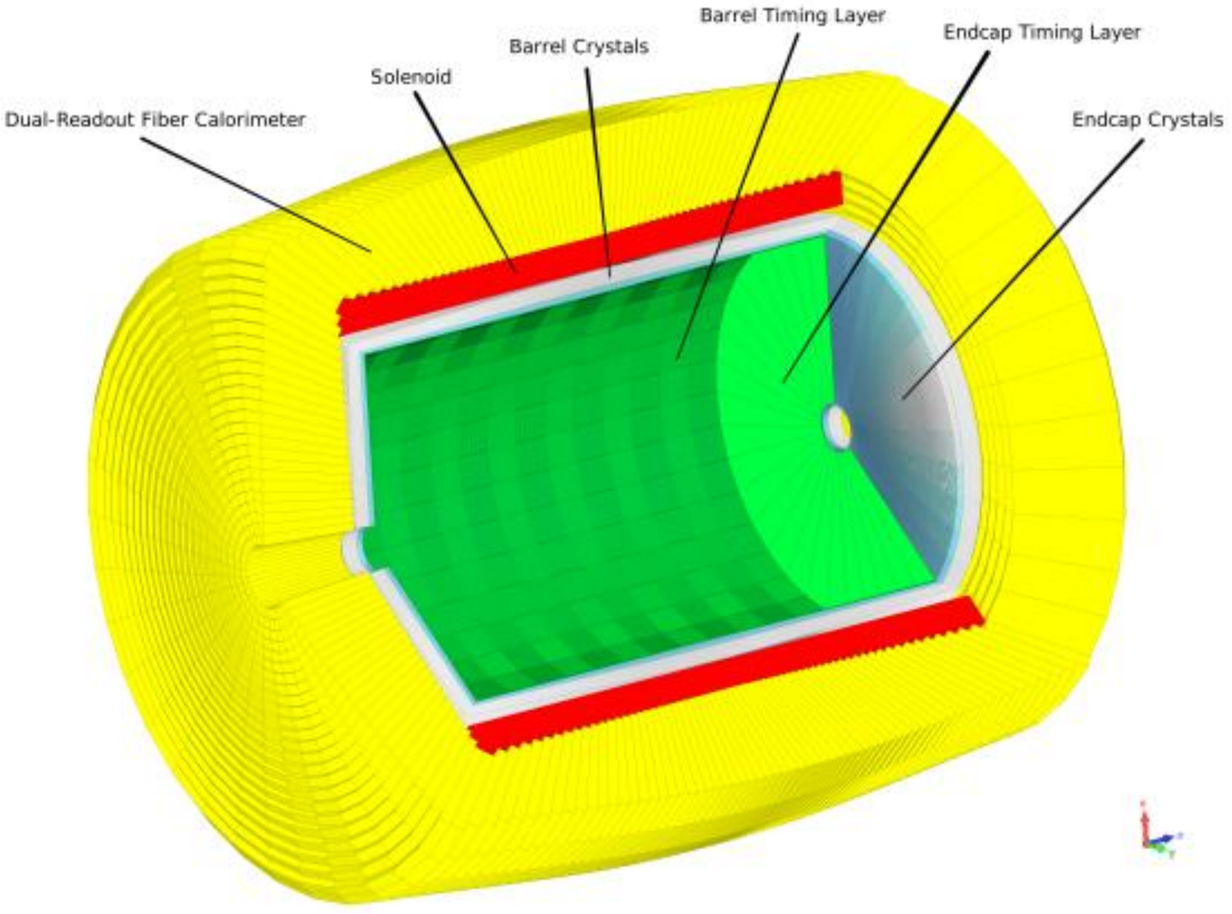
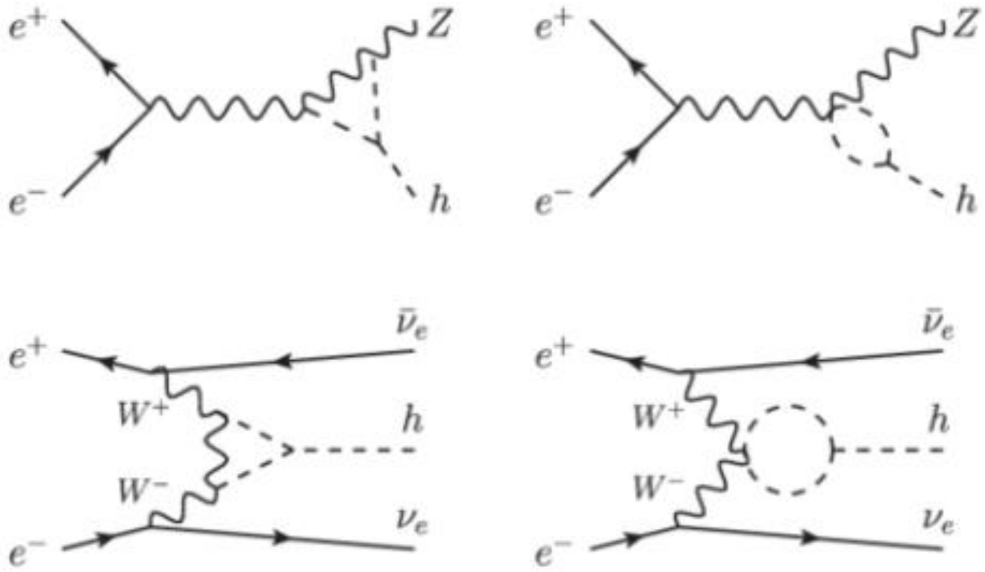
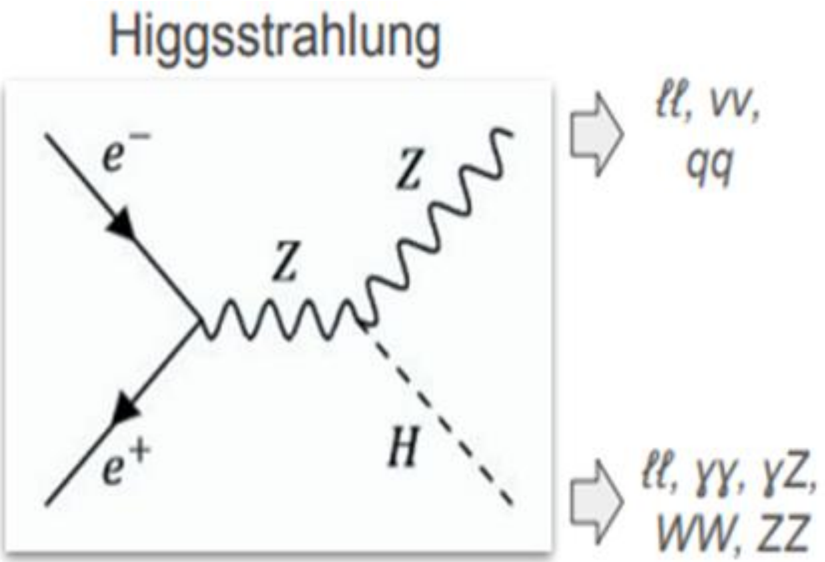


Figure 13. Implementation of the hybrid calorimeter system described in Figure 12 in a 4π detector geometry. The layers of the detector from the inner one to the outer one are: crystal timing layers T1 and T2 (green), crystal ECAL layers E1 (light blue) and E2 (white), solenoid (red), dual-readout fiber calorimeter (yellow).

The Higgs boson



with the substantial luminosity delivered at 240 and 365 GeV, the FCC-ee exhibits a unique sensitivity to the trilinear coupling by measuring its energy-dependent effects on individual Higgs observables at the quantum level, such as the HZ and the $\bar{\nu}\nu H$ production cross-sections



SiPM 6x6

Structure

Typ. no.	Number of channels (ch)	Effective photosensitive area/channel (mm²)	Pixel pitch (µm)	Number of pixels/channel	Package	Window	Window refractive index	Geometrical fill factor (%)
S14160-3050HS	1	3.0 × 3.0	50	3531	Surface mount type	Silicone	1.57	74
S14160-4050HS		4.0 × 4.0		6331				
S14160-6050HS		6.0 × 6.0		14331				
S14161-3050HS-04	16 (4 × 4)	3.0 × 3.0		3531				
S14161-3050HS-08	64 (8 × 8)	3.0 × 3.0		3531				
S14161-4050HS-06	36 (6 × 6)	4.0 × 4.0		6331				
S14161-6050HS-04	16 (4 × 4)	6.0 × 6.0		14331				

Electrical and optical characteristics (Typ. Ta=25 °C, Vover=2.7 V, unless otherwise noted)

Parameter		Symbol	S14160/S14161 -3050HS-04, -08	S14160/S14161 -4050HS-06	S14160/S14161 -6050HS-04	unit
Spectral response range		λ	270 to 900			nm
Peak sensitivity wavelength		λp	450			nm
Photon detection efficiency at λp*3		PDE	50			%
Breakdown voltage		V_{BR}	38			V
Recommended operating voltage*4		Vop	V_{BR} + 2.7			V
Vop variation between channels in one product*5	Typ.	-	0.1			V
	Max.		0.2			
Dark current	Typ.	I_D	0.6	1.1	2.5	µA
	Max.		1.8	3.3	7.5	
Crosstalk probability		-	7			%
Terminal capacitance		Ct	500	900	2000	pF
Gain		M	2.5×10^6			-
Temperature coefficient of recommended reverse voltage		ΔTVop	34			mV/°C

*3: Photon detection efficiency does not include crosstalk and afterpulses.
*4: Refer to the data attached for each product.
*5: The parameter is for the S14161 series (multichannel type)

SiPM 3x3

Structure

Type no.	Photosensitive area (mm)	Pixel pitch (μm)	Number of pixels	Fill factor (%)	Package	Window material	Window refractive index
S14160-1310PS	1.3 × 1.3		16663				
S14160-3010PS	3 × 3	10	89984	31			
S14160-6010PS NEW	6 × 6		359011		Ceramic	Silicone resin	1.57
S14160-1315PS	1.3 × 1.3		7284				
S14160-3015PS	3 × 3	15	39984	49			
S14160-6015PS NEW	6 × 6		159565				

Electrical and optical characteristics (Typ. Ta=25 °C, V_R=Vop, unless otherwise noted)

Type no.	Spectral response range λ (nm)	Peak sensitivity wavelength λp (nm)	Photon detection wavelength at λp*3 PDE (%)	Breakdown voltage V_{BR} (V)	Recommended operating voltage*4 Vop (V)	Vop variation within a reel (V)
S14160-1310PS						
S14160-3010PS			18		V_{BR} + 5	
S14160-6010PS NEW	290 to 900	460		38 ± 3		±0.1
S14160-1315PS						
S14160-3015PS			32		V_{BR} + 4	
S14160-6015PS NEW						

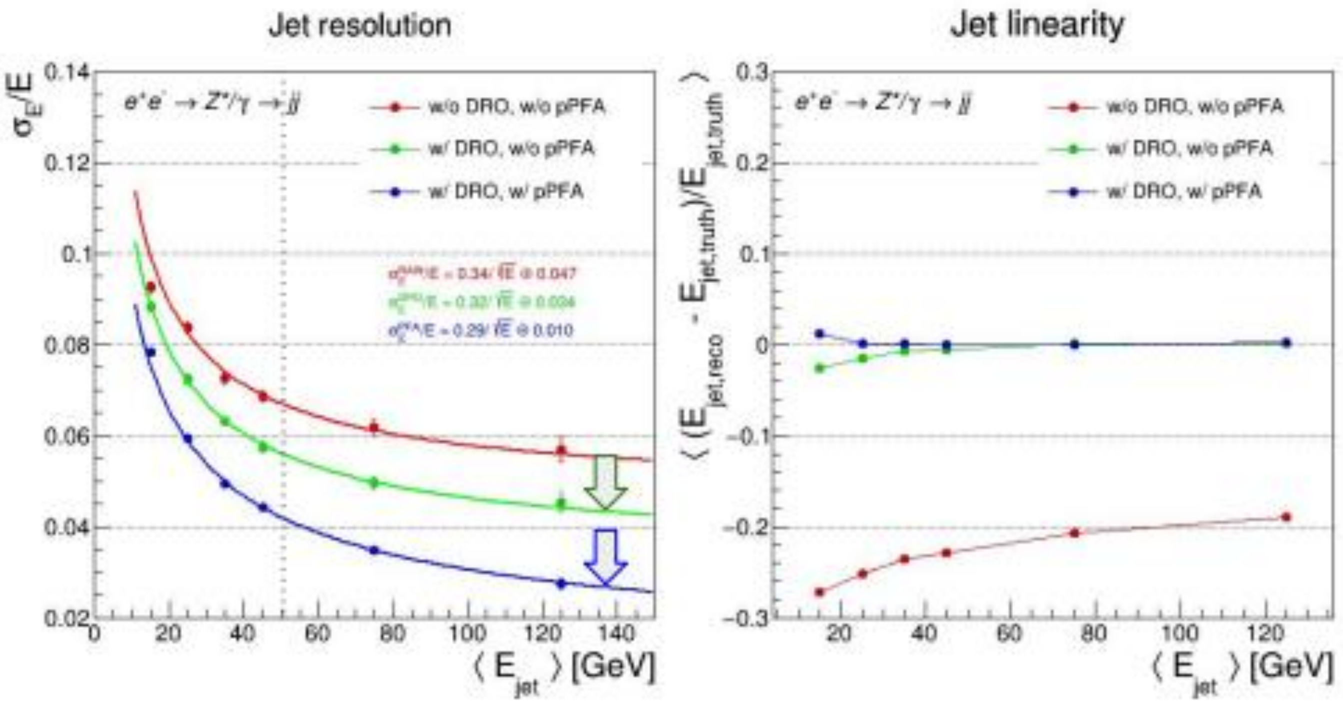
Type no.	Dark count rate*5 DCR typ. (kcps)	Dark count rate*5 DCR max. (kcps)	Direct crosstalk probability Pct (%)	Terminal capacitance at Vop*6 Ct (pF)	Gain M	Temperature coefficient of Vop ΔTVop (mV/°C)
S14160-1310PS	120	360		100		
S14160-3010PS	700	2100		530	1.8×10^5	
S14160-6010PS NEW	3000	10000	<1	2200		34
S14160-1315PS	120	360		100		
S14160-3015PS	700	2100		530	3.6×10^5	
S14160-6015PS NEW	3000	10000		2200		

*3: Photon detection efficiency does not include crosstalk and afterpulse.
*4: Refer to the data attached for each product.
*5: Threshold=0.5 p.e.
*6: f=100 kHz

Jet resolution: with and without DR-pPFA

Jet energy resolution and linearity as a function of jet energy in off-shell $e^+e^- \rightarrow Z^* \rightarrow jj$ 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

slide Marco Lucchini Seminar on Calorimetry at Future Colliders 25th May 2023

Specifications on Preamplifier CAEN serie A1423B

Characteristics:

Packaging	Shielded Box Dimensions (WxHxD connector excluded): 55 x 25 x 95 mm3 (without connectors) Weight: 134 g
Gain range	From +18 dB to +54 dB Step: 2 dB for 18-36 dB range, 3 dB for 36-54 dB range Selectable via 16 position Rotary Switch
Polarity	Positive or negative input signals
Bandwidth	- 1.5 GHz (-3dB)
Noise Figure	7 dB @ 1 GHz
INPUT IN(*)	Detector input (AC decoupled) Input impedance: 50 Ω (SWR < 1.5:1), SMA 142-0711-811 Johnson connector. (*)Safety and Operation requirements: The input circuit includes a protection network to prevent damage to the input circuit from transient generated in the IN/HV network (up to ± 500 V). Anyway care must be taken in the use of A1423B with high voltage detectors.
INPUT (HV)	HV BIAS input / Detector bias voltage Range: ±750V SMA 142-0711-811 Johnson connector.
OUTPUT (OUT)	Amplifier Out (AC decoupled) Dynamics: ±1 V (2V absolute) Output impedance: 50 Ω (SWR < 1.5:1) SMA 142-0711-811 Johnson connector
Power Requirements	• External power supply (included); • Consumption: +12 V 250 mA (typical) The module is powered by an external AC-DC stabilized power supply provided with the amplifier and included in the delivered kit. Note: Using a different power supply source, like battery or linear type, it is recommended to provide +12V and, at least, 500 mA. The power jack is a 2.1mm type, a suitable cable is the RS 656-3816 type (or similar).