Highlights from the Test Beam for IDEA's electromagnetic calorimeter at CERN

Riunione Gruppo 1-16/01/2025 - Napoli

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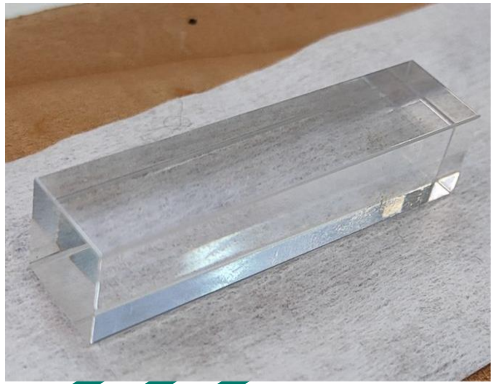
Dual Readout with Crystals

- Include in the IDEA detector design an additional layer of homogeneous material for the Calorimeter that allows to improve the energy resolution

IDEA calorimeter baseline
Cherenkov and Scintillation fiber based
σ_E/E (EM) ~13%/√E
σ_E/E (HAD) ~31%/√E

Calorimeter homogeneous medium=crystal
σ_E/E (EM) ~3%/√E
σ_E/E (HAD) ~30%/√E

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



Cherenkov signal: prompt
Scintillation signals: longer

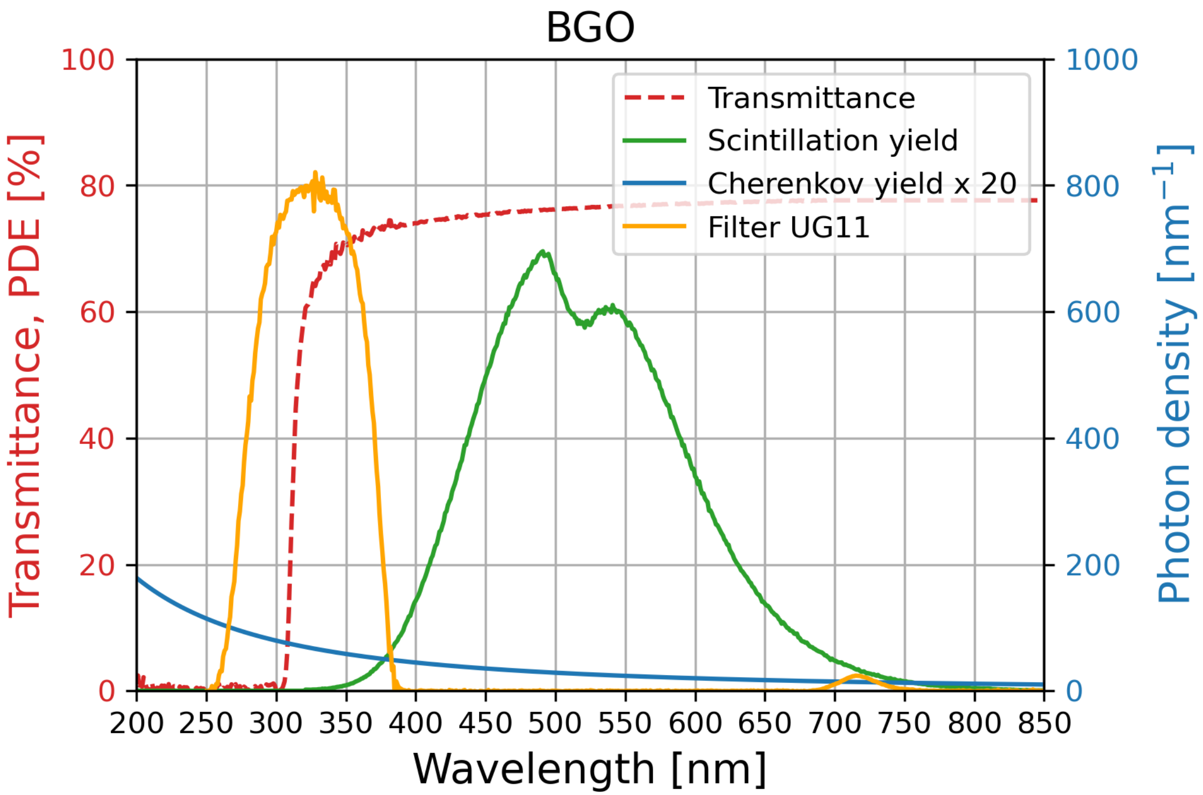
	time	spectrum
Cherenkov	fast	$1/\lambda^2$
Scintillation	slow	peaked

Study of Crystal features

The source employed for the first study of investigating Cherenkov and Scintillation light is cosmic rays → Secondary cosmic rays, mainly μ

We calculated the expected number of photons for scintillation and Cherenkov effect and the ratio is of the order of :

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



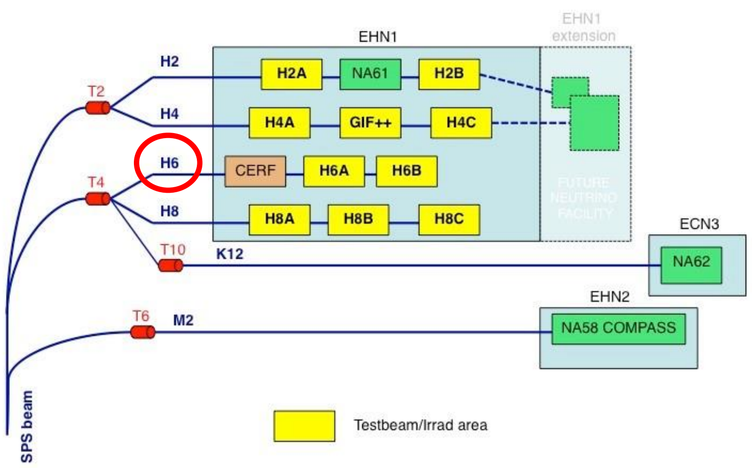
We need a strategy to reduce this ratio

↓

We use optical filters that allow us to select the specific region of the light spectrum and favor the Cherenkov signal

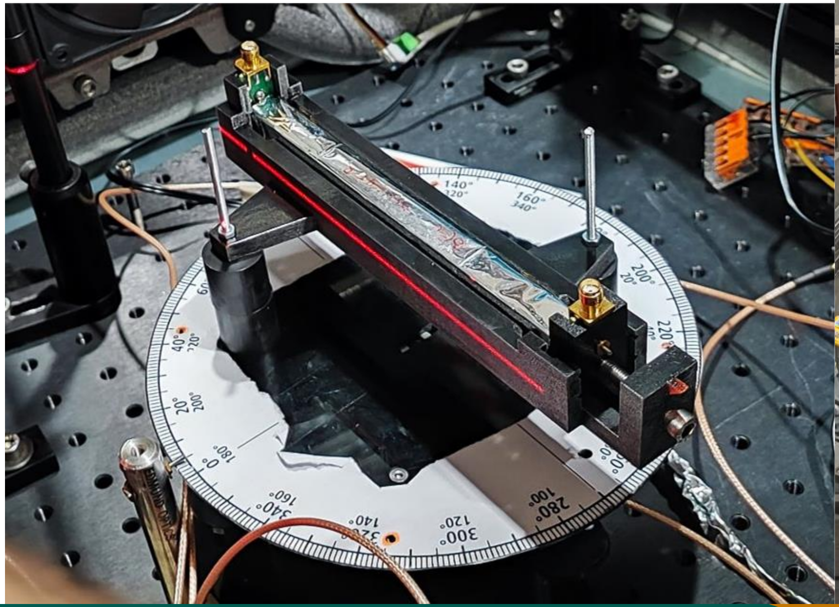
Test Beam at CERN NA site

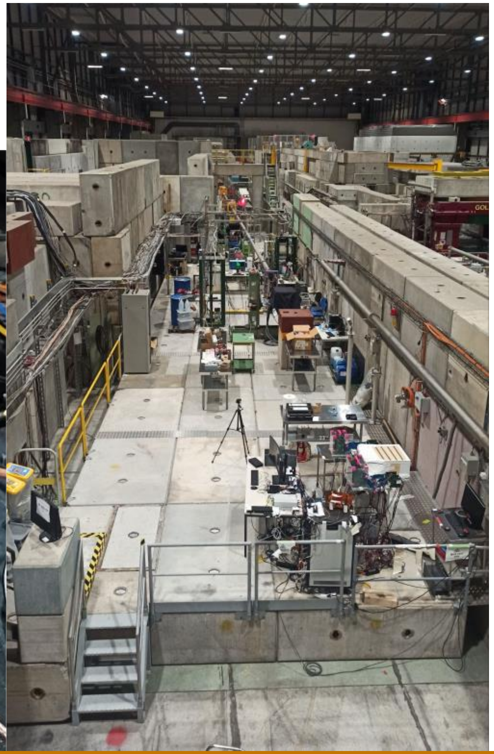
- From 17-24 July 2024 we carried out a beam test **at CERN SPS H6** beam line prepared and **coordinated by MIB and Napoli** and with participation from Perugia, US.



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

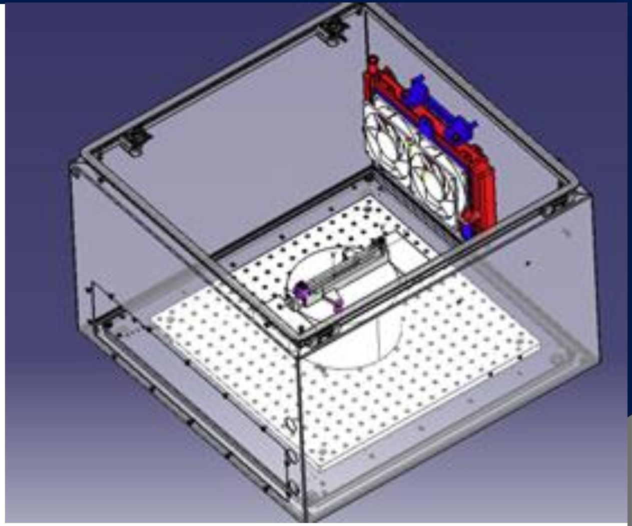
- tests with **positrons** (10-100 GeV), **mu+ 120 GeV**
- we have performed 126 runs where each run has from 5000 to 40000 events

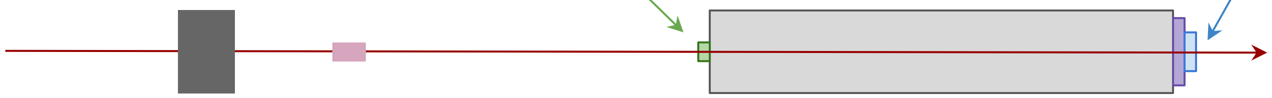


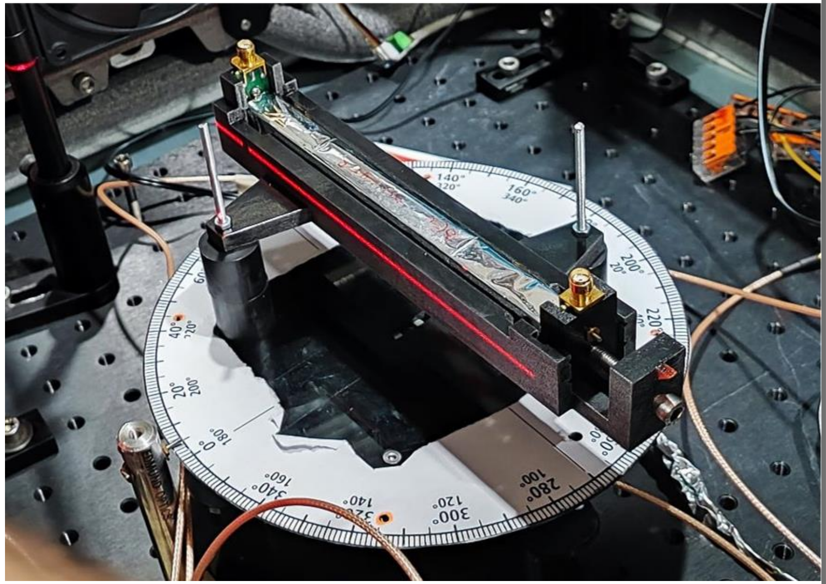


CERN Test Beam Setup

- 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
- and digitization with oscilloscope Tektronix Oscilloscope MSO66B 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-blu part)





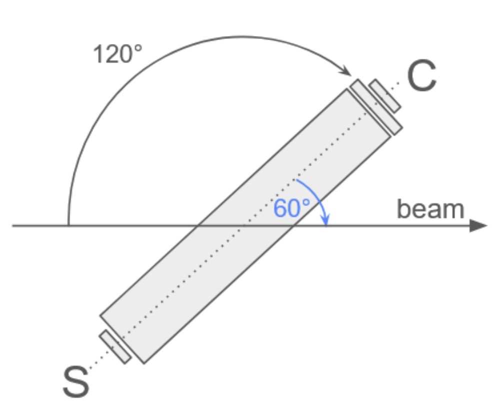


Setup fully developed in Naples and completed at CERN

Study of C/S Variation in angular scan with PWO

- We studied the 2D histogram of the integrals of channel with the filter dominated by contribution cherenkov on the integral of channel without filter dominated by scintillation.

- Then we performed a linear fit, since if there were only scintillation the slope would always be equal depending on the angle. I have done this for all the runs of the angular scan



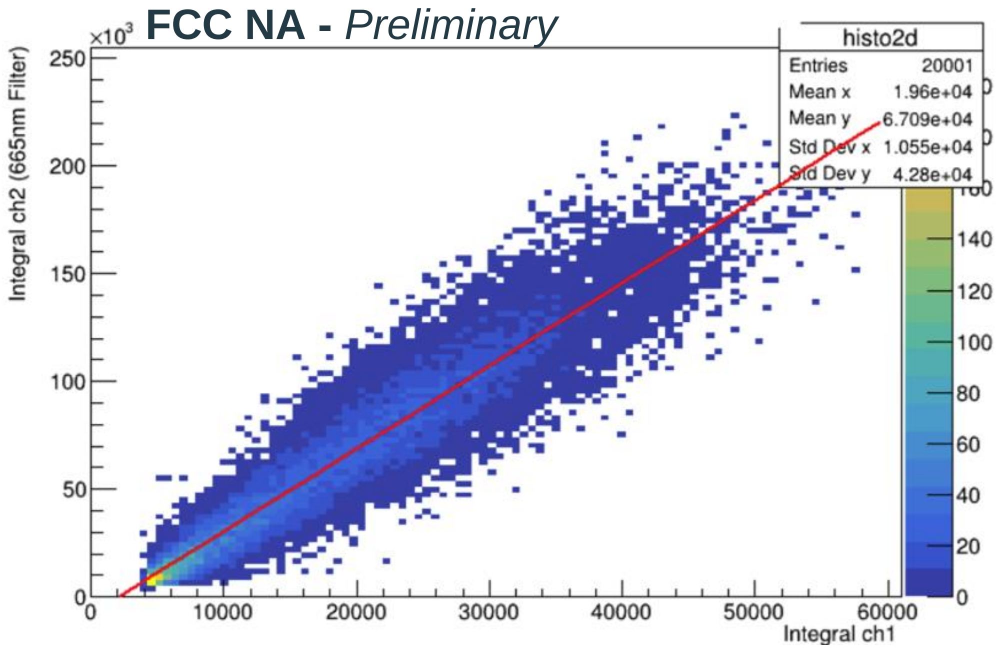
The Cherenkov angle increases until it reaches a maximum for β = 1:

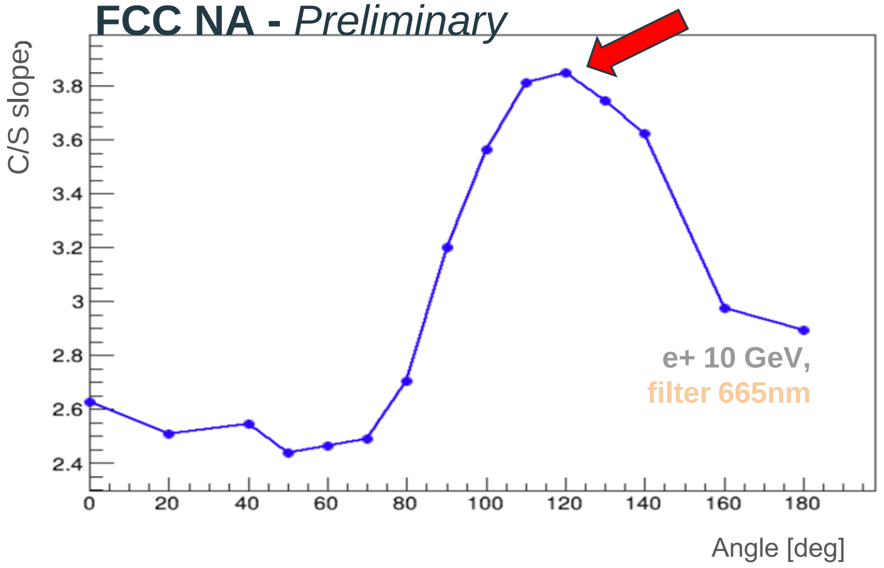
$$\theta_C^{max} = \arccos\frac{1}{n}$$

$$n = 2{,}2$$

$$\theta_C^{max} = 120°$$

- **C/S ratio peaking at 120° the C emission angle**
  -smoking gun of cherenkov detection!





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 Cherenkov/Scintillation ratio and the emission angle.

Work in Progress

- We are investigating various ways to perform a fit on the single waveform in order to derive the scintillation and cherenkov components.
- We are carrying out SiPM calibration measurements to have a single-photon shape.
- In addition, we are working on the simulation to compare with the data taken at the test beam, see Antonio's presentation.

Future Work

- We are currently working on writing an article summarizing the results of this beam test.
- Additionally, We have submitted a request to book a time slot at CERN to perform the next test beam, planned with a larger setup, at the end of September 2025.
- To prepare for this, we are focusing on the implementation and optimization of our setup

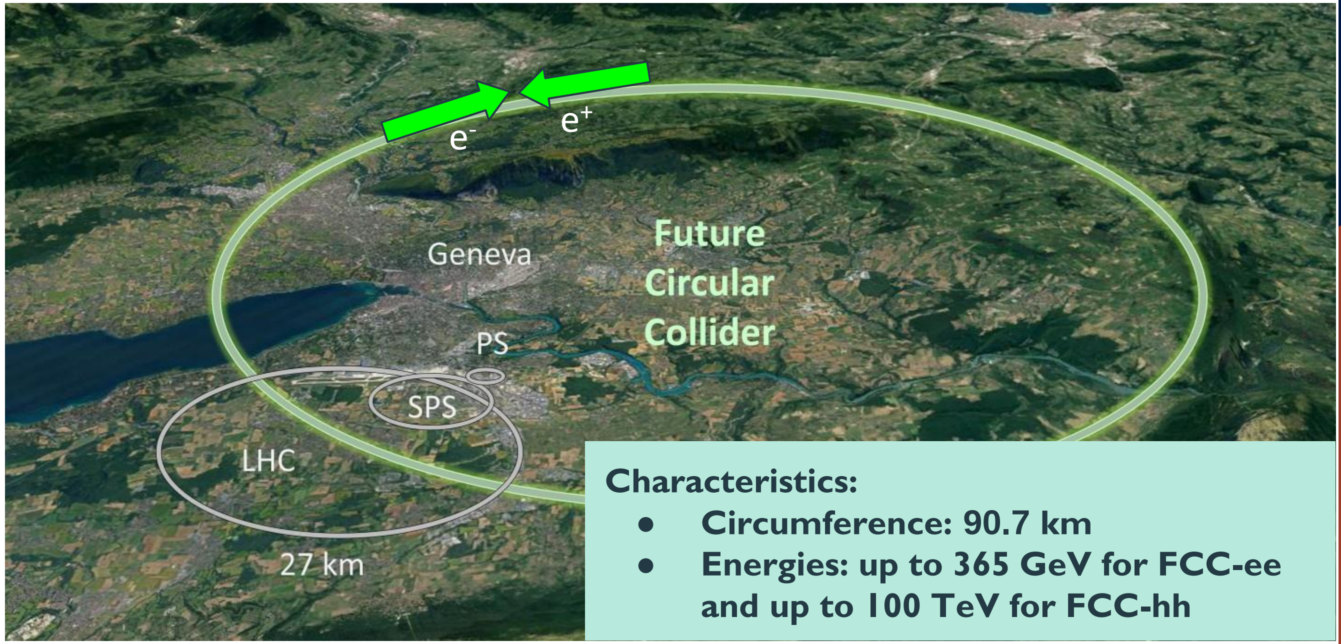
THANK YOU FOR YOUR ATTENTION

Backup Slides

FUTURE CIRCULAR COLLIDER (FCC) EXPERIMENT

Examines scenarios for three different types of particle collisions:

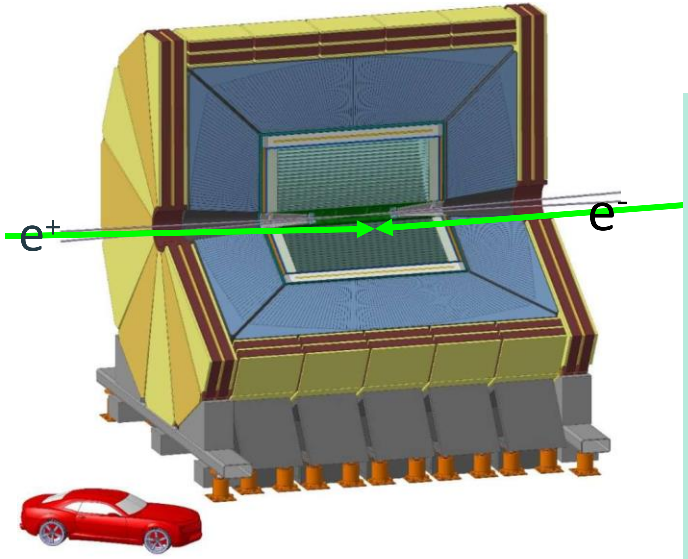
- FCC-ee: Electron-positron collisions;
- FCC-hh: Hadronic collisions, protons or ions will collide;
- FCC-he: Proton electron collisions.



Characteristics:

- **Circumference: 90.7 km**
- **Energies: up to 365 GeV for FCC-ee and up to 100 TeV for FCC-hh**

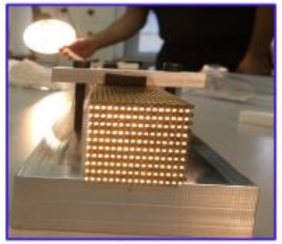
IDEA Detector



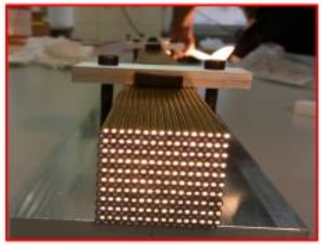
IDEA detector concept:

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

A **Calorimeter** allows to **measure the particle energy** lost in the medium



scintillating fibres



Cherenkov fibres

Study of Crystal features

The source employed for the first study of investigating Cherenkov and Scintillation light is cosmic rays → Secondary cosmic rays, mainly μ

Below 200 GeV, muon energy losses are mainly due to ionization and the dE/dx is roughly $2\frac{MeV}{g}cm^2$

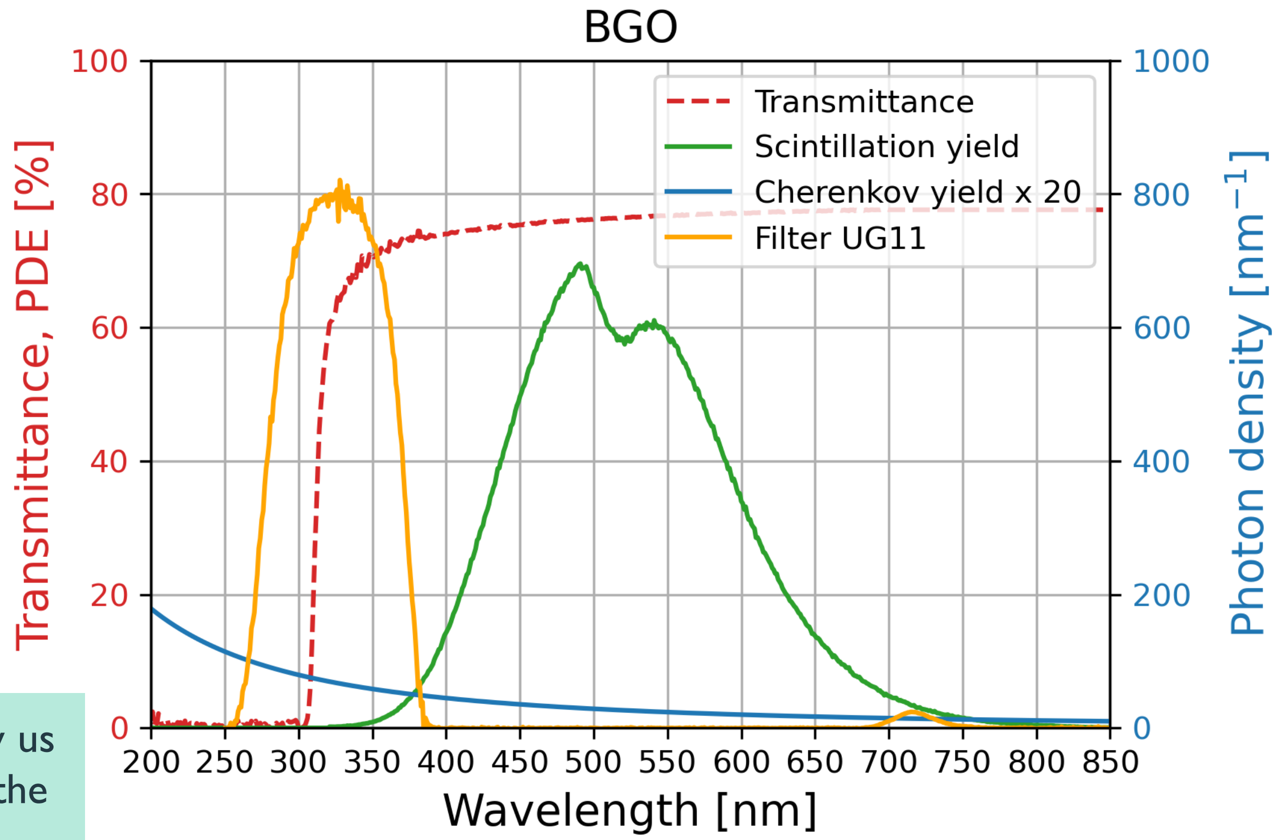
We calculated the expected number of photons for the two effects:

Scintillation
$$Energy = l\rho\frac{dE}{dx}$$
$$N_{photons} = Energy \cdot LY$$

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

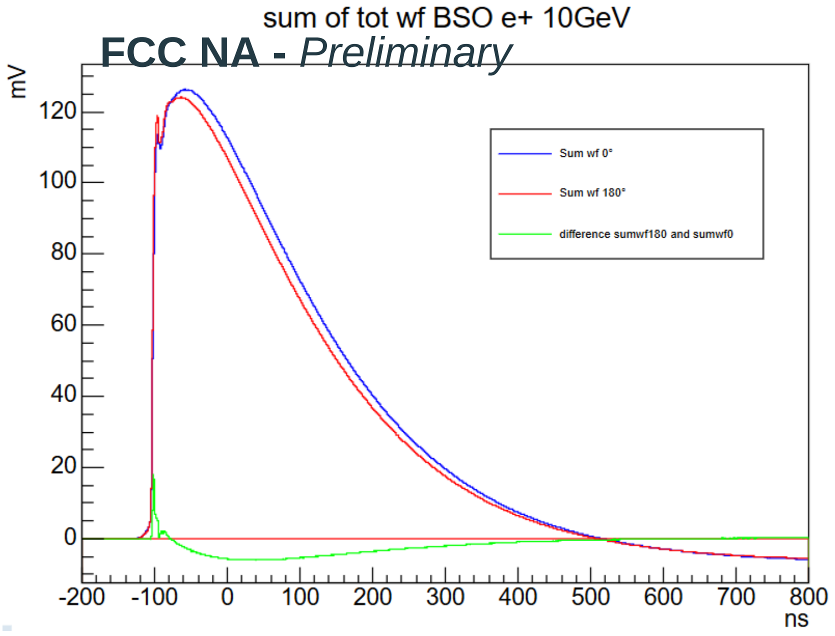
Number of Scintillation photons:
- BGO~1121

Number of Cherenkov photons:
- BGO~13



We need a strategy to reduce this ratio → We use optical filters that allow us to select the specific region of the light spectrum and favor the Cherenkov signal

Signal extraction Strategy



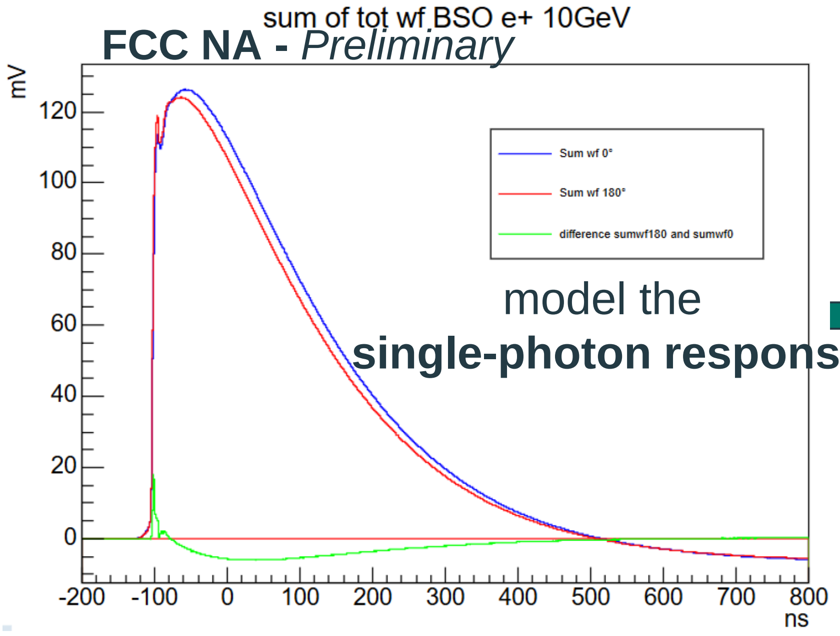
In figure: sum of all waveforms at 0° and 180°:
→ proxy of what the "average" response looks like

→ We want to model the shape as function of the **single photon shape** and characteristic scintillation time, with C photons considered prompt.

→ Once that is done **we fit the waveform and extract C and S components**

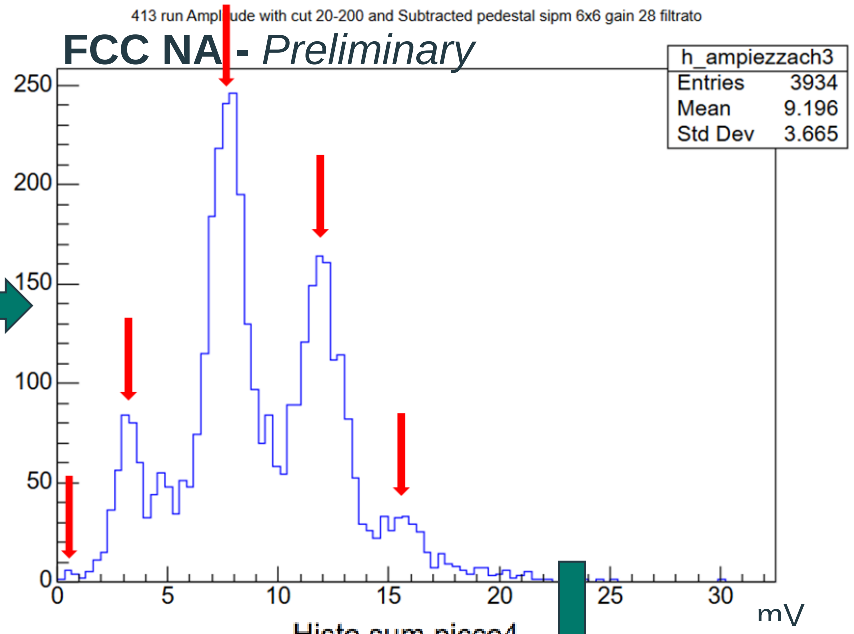
→ We need to model the **single-photon response**!

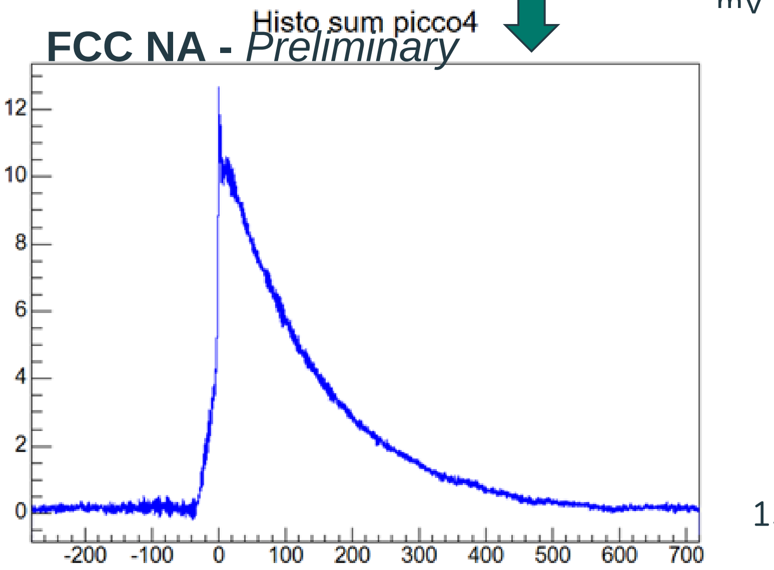
Signal extraction Strategy

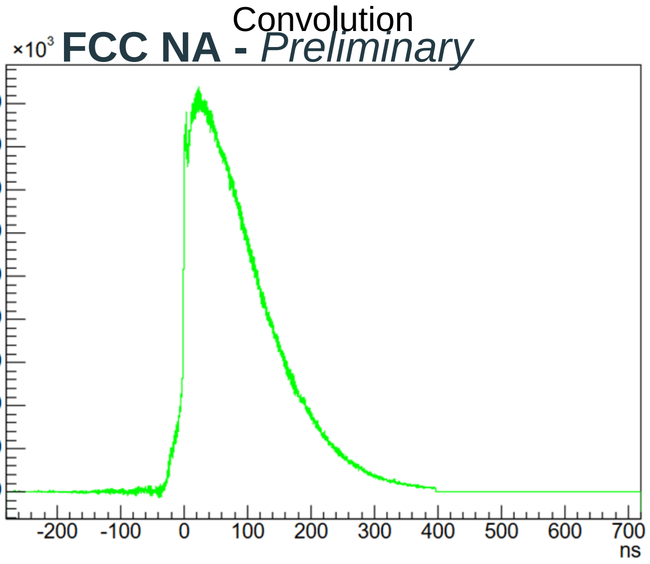


model the
single-photon response

“Dark” measurement:
I have studied the amplitudes of the wf,there is the presence of 5 distinct peaks. Then what I did was to study the wf corresponding to these 5 peaks and I made the average wf for each peak

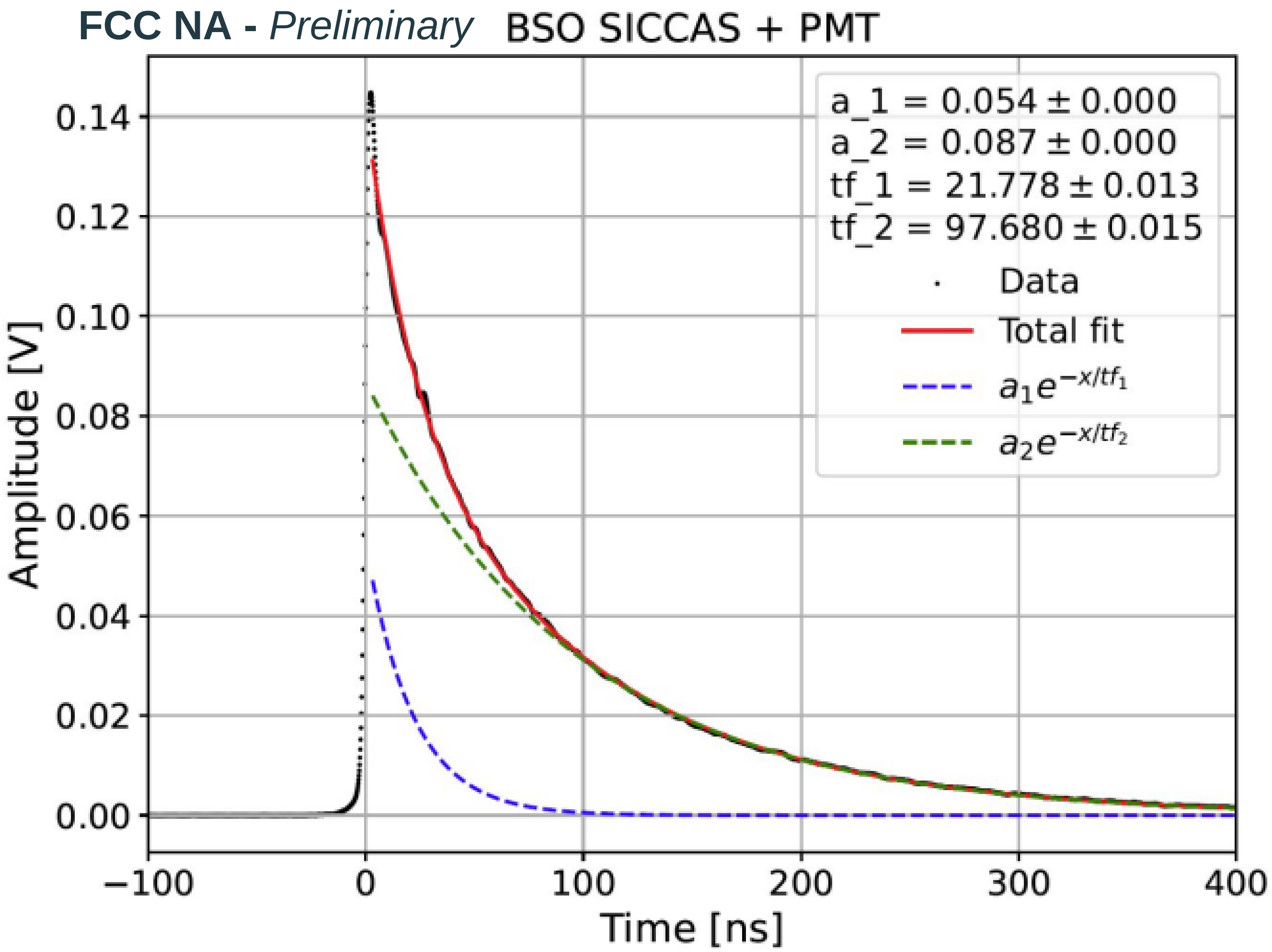




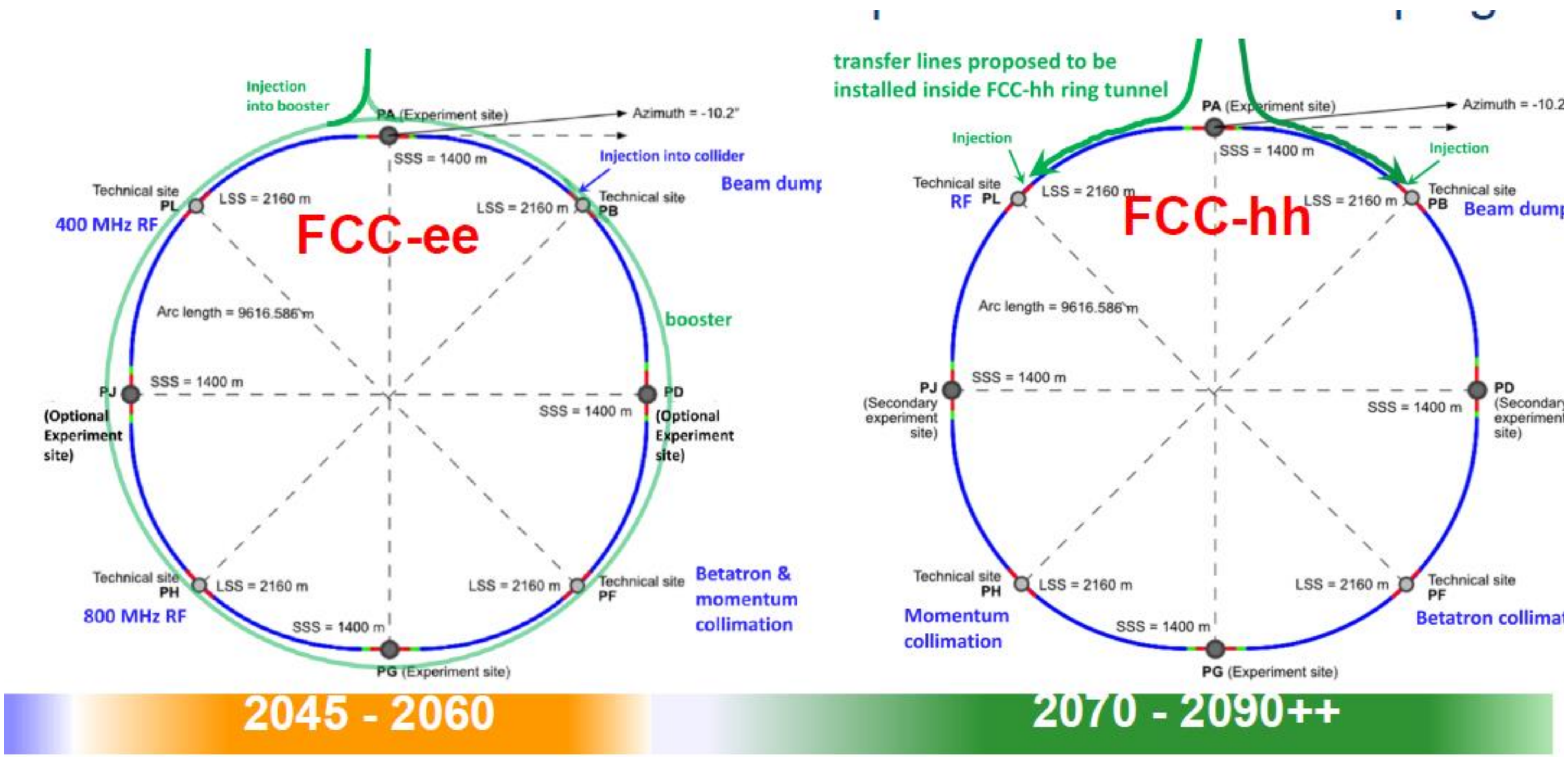


I used for the convolution the shape of the average wf for peak 4 of the dark measurements + an exponential that represent time of fall of BSO

Time of fall for BSO



Proposed time for the experiment FCC

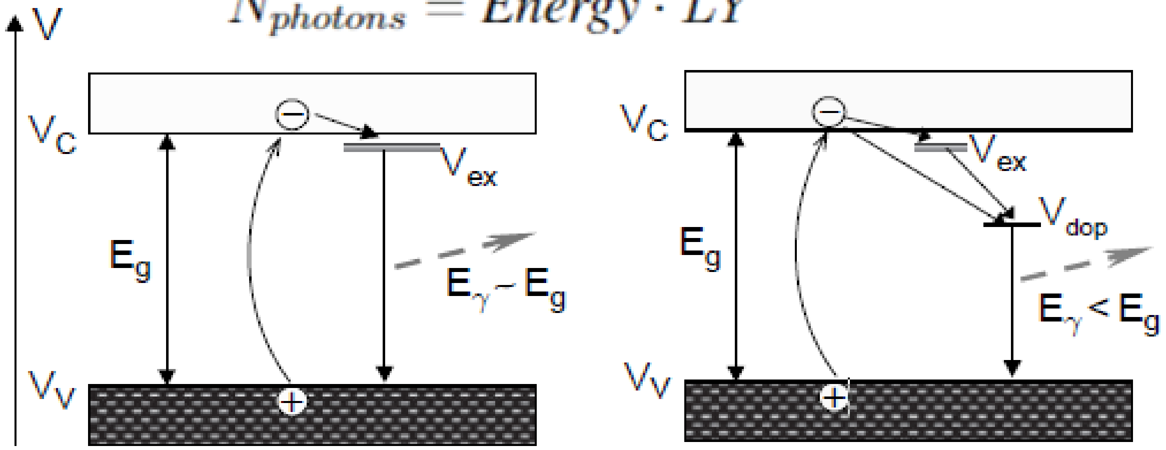


Scintillation and Cherenkov effect

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

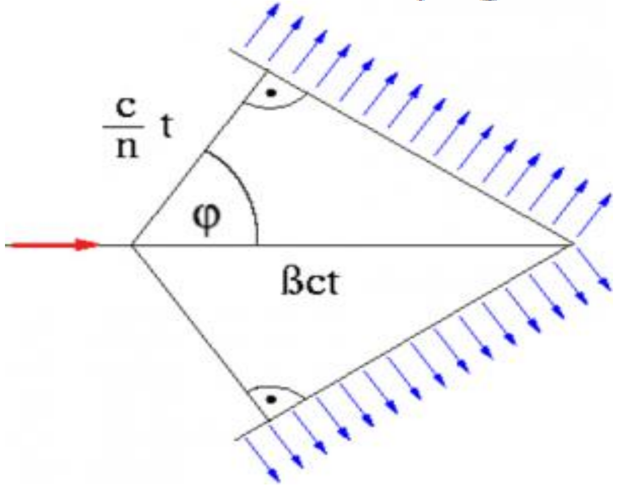
$$Energy = l\rho\frac{dE}{dx}$$

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



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

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



Dual-readout calorimetry: Contemporary study of scintillation and Cherenkov that allows for event-by-event analysis of the electromagnetic component

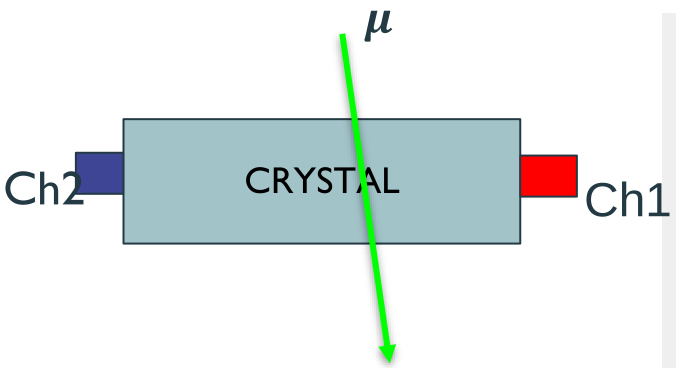
Study of Crystals with Cosmic Rays

The source employed for investigating Cherenkov and Scintillation light is cosmic rays → Secondary cosmic rays, mainly μ

Scintillation
$$Energy = l\rho\frac{dE}{dx}$$
$$N_{photons} = Energy \cdot LY$$

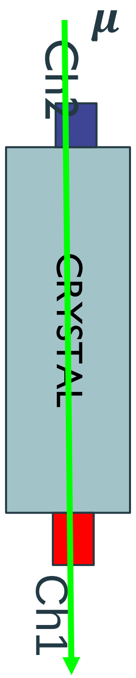
Cherenkov
$$\frac{dN}{dx} = 2\pi\alpha z^2 \sin^2\theta_C\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

Rate=1.4 $cm^{-2}\,min^{-1}$



Number of Scintillation photons:
- BGO~1121
- PWO~31

Number of Cherenkov photons:
- BGO~13
- PWO~12



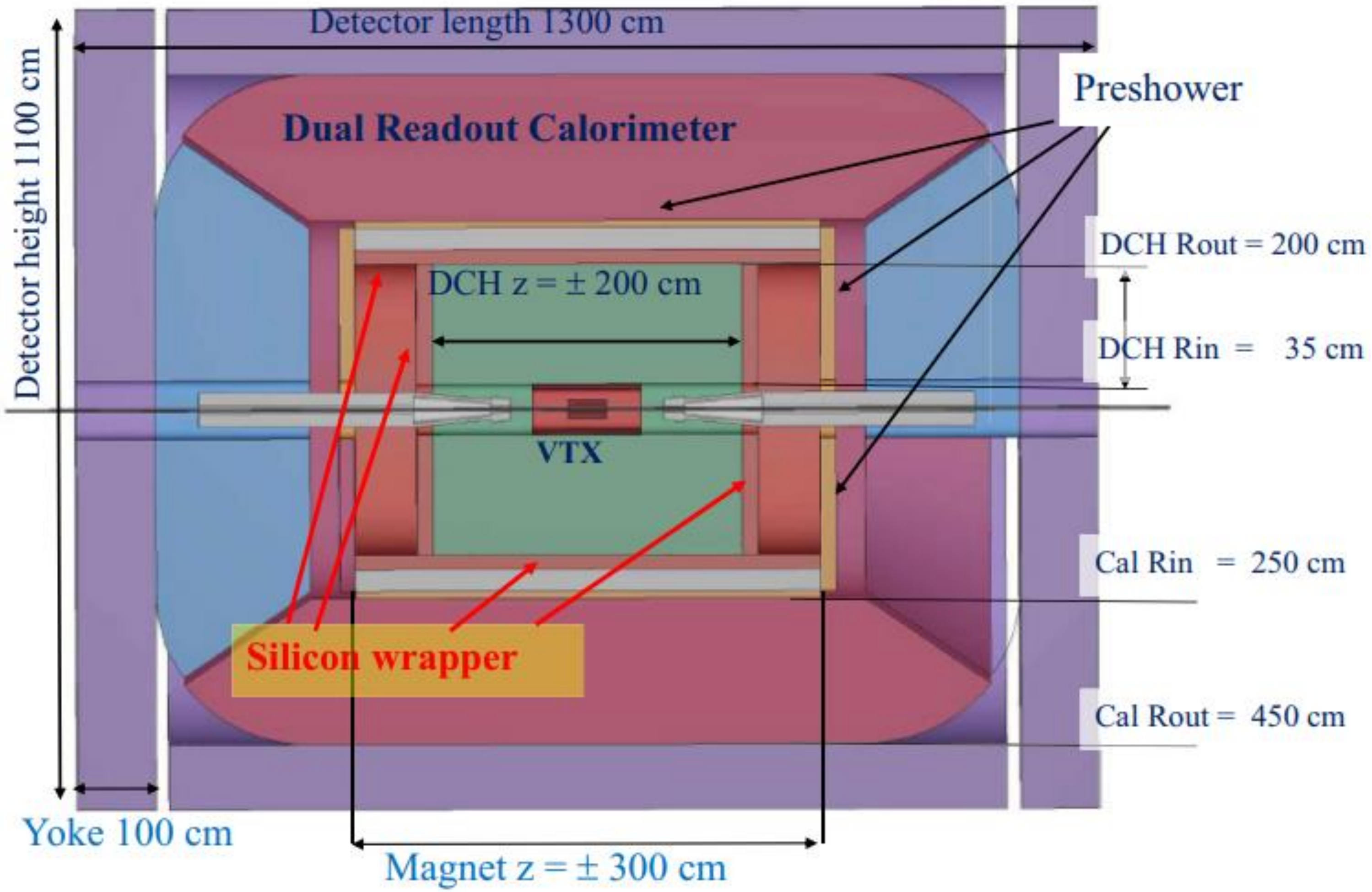
Number of Scintillation photons:
- BGO~4671
- PWO~128

Number of Cherenkov photons:
- BGO~53
- PWO~51

We need to reduce this ratio and we need a strategy

We use optical filters that allow us to select the specific region of the light spectrum and favor the Cherenkov signal

Internal structure of the idea detector



IDEA detector design with additional layer of homogeneous material

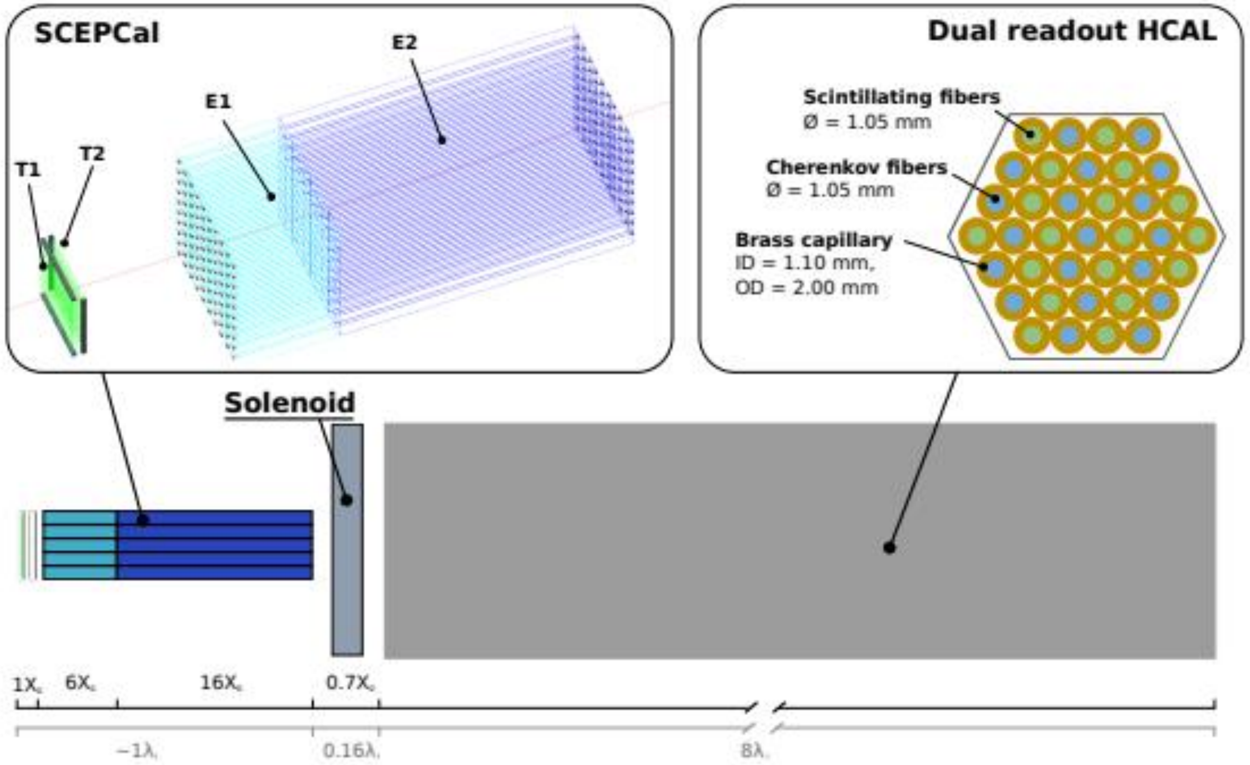


Figure 12. Overview of a hybrid segmented calorimeter layout featuring 4 front segments which exploit scintillating crystals for detection of EM showers followed by an ultrathin-bore solenoid and a hadron calorimeter based on scintillating and quartz fibers.

IDEA detector design with additional layer of homogeneous material

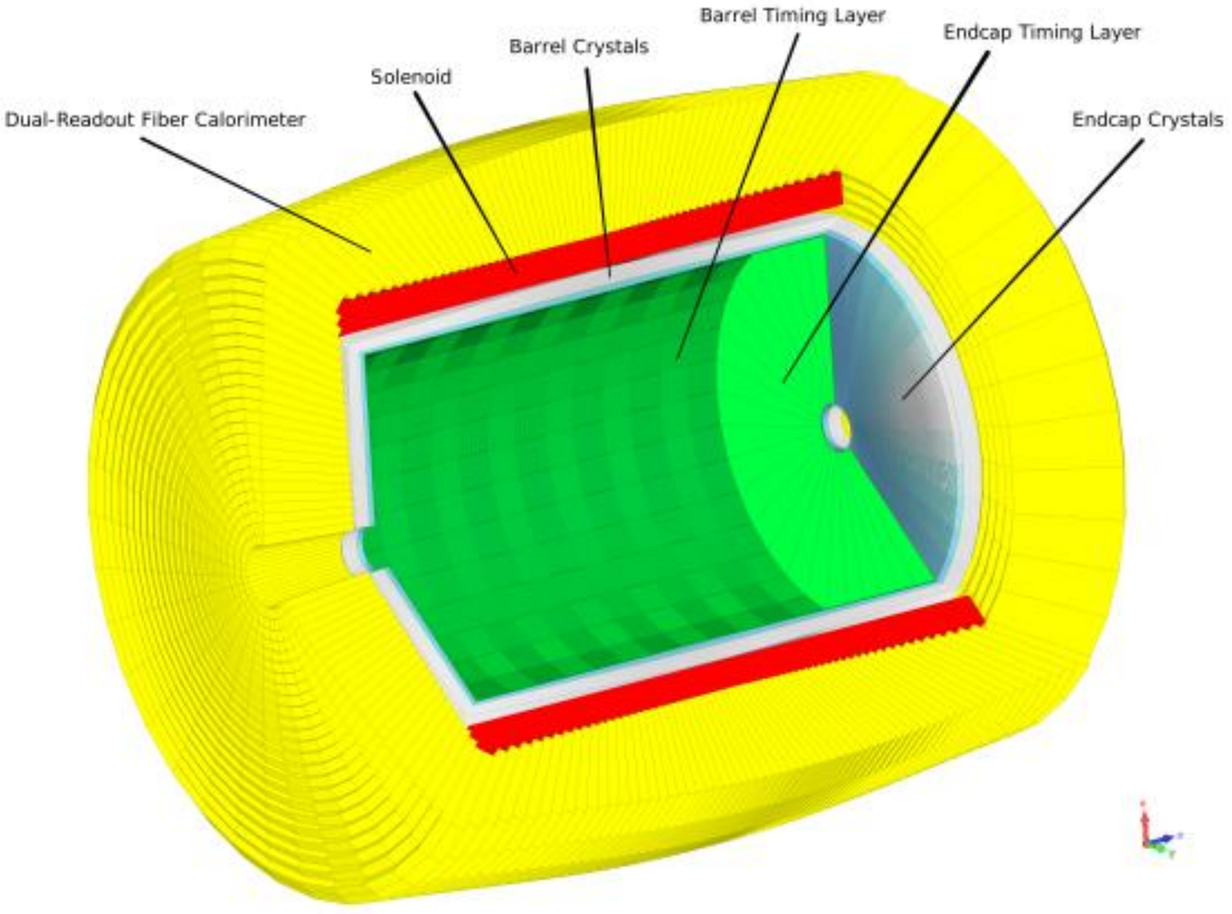
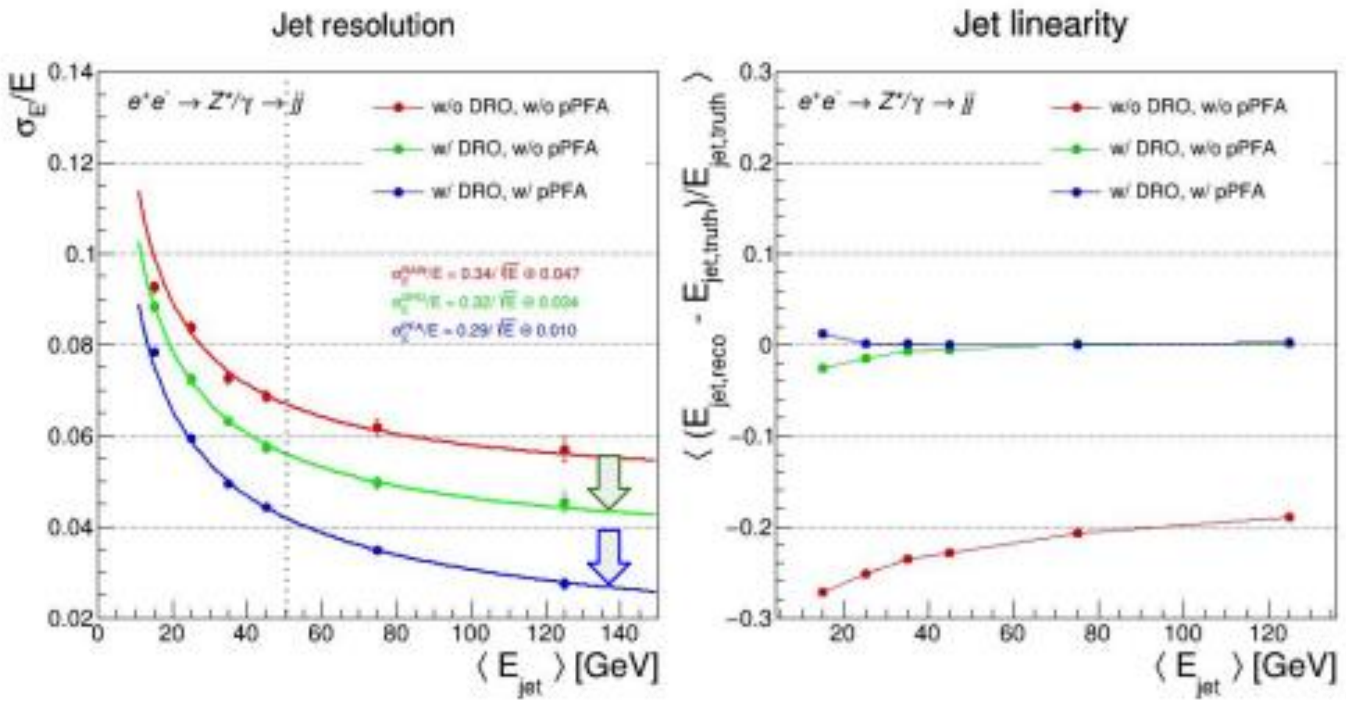


Figure 13. Implementation of the hybrid calorimeter system described in Figure 12 in a 4π detector geometry. The layers of the detector from the inner one to the outer one are: crystal timing layers T1 and T2 (green), crystal ECAL layers E1 (light blue) and E2 (white), solenoid (red), dual-readout fiber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

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