

# 'Maximum Information' Crystal Calorimetry for future Higgs factories

Vienna Conference on Instrumentation, 17 - 21 February 2025

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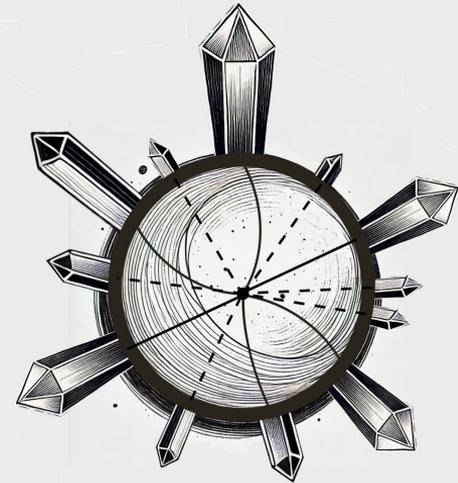
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# Context

- A **future  $e^+e^-$  circular collider** broadly recognized as the best strategy to continue the exploration of the Higgs boson at higher precision and search for hints of new physics  
[see M.Dams at VCI2025]
- A key performance benchmark for future detector concepts is **jet energy resolution**
  - Most final states from Higgs decays with 2, 4 or 6 jets
  - Resolution of **4-5% at 50 GeV** required to discriminate W vs Z boson hadronic decays
- **Electromagnetic energy resolution ( $\sim 3\%/\sqrt{E}$ )** required to maximally exploit the physics potential of the collider
  - e.g. flavor physics and ALPs studies with low energy photons in final state
- A **hybrid dual-readout calorimeter** that can meet these requirements is being studied:
  - A sampling fiber-based dual-readout hadronic section [see L.Nasella at VCI2025]
  - A segmented high precision homogeneous crystal electromagnetic section [this talk!]

# Hybrid dual-readout calorimeter conceptual layout

‘Maximum Information’, aka 6D crystal calorimetry approach (x, y, z, E, t, C/S)

## Timing layer

$$\sigma_t \sim 20 \text{ ps}$$

- LYSO:Ce crystal grid ( $\sim 1X_0$ )
- 3x3x60 mm<sup>3</sup> active cell
- SiPM readout

## ECAL layers

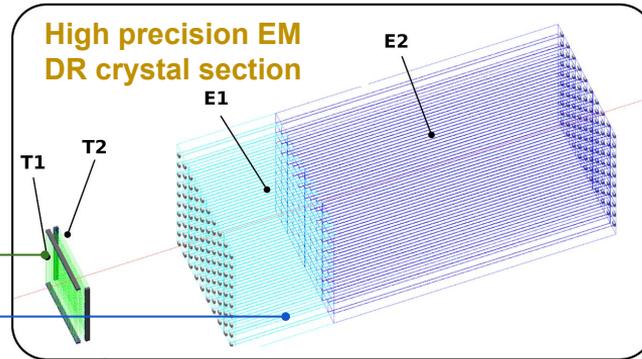
$$\sigma_E^{EM}/E \sim 3\%/\sqrt{E}$$

- Quasi-projective PWO crystals
- 10x10x200 mm<sup>3</sup> tower size
- Front segment ( $\sim 6X_0$ )
- Rear segment ( $\sim 16X_0$ )
- SiPM readout

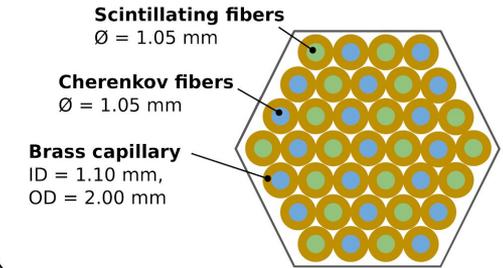
## HCAL layer

$$\sigma_E^{HAD}/E \sim 30\%/\sqrt{E}$$

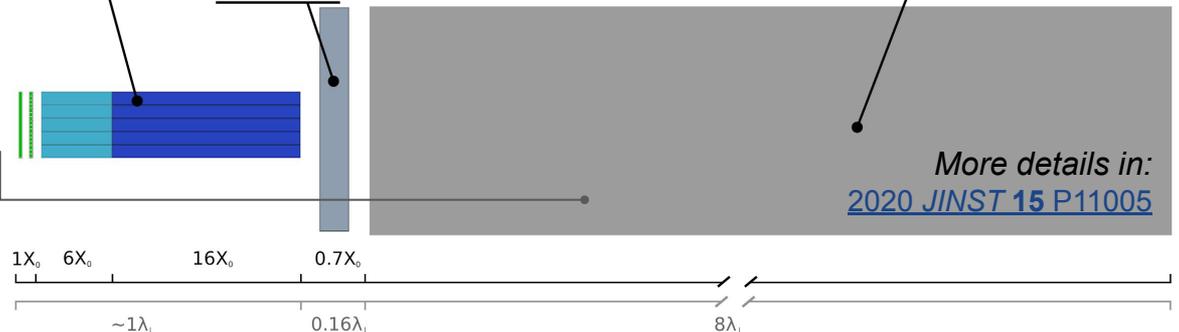
- Scintillating (S) and “clear” PMMA (C) fibers inserted inside brass capillaries
- SiPM readout



## Mixed-fibers DR sampling section



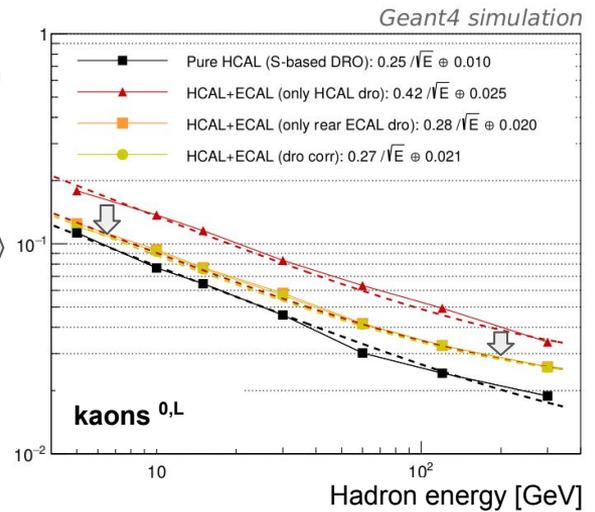
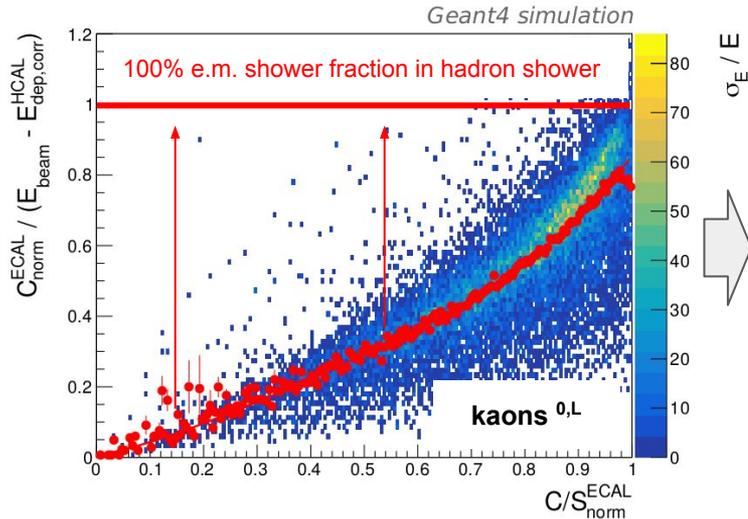
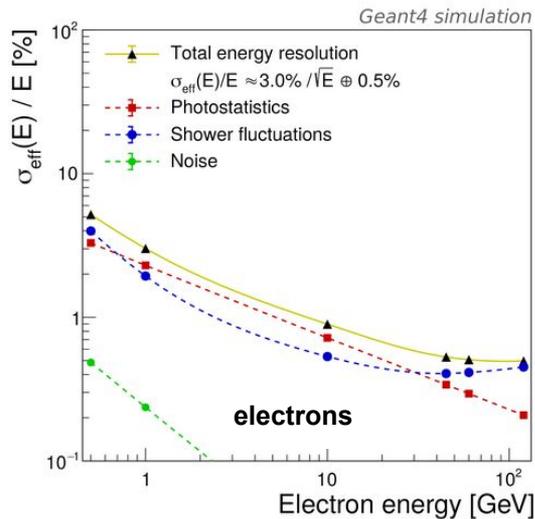
## Solenoid



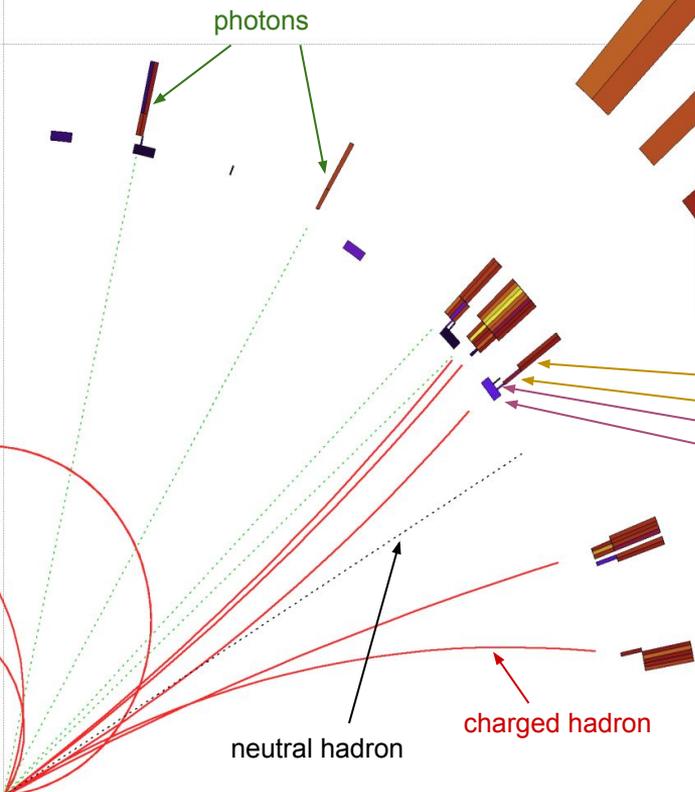
More details in:  
[2020 JINST 15 P11005](https://arxiv.org/abs/2002.08715)

# Energy resolution - simulation

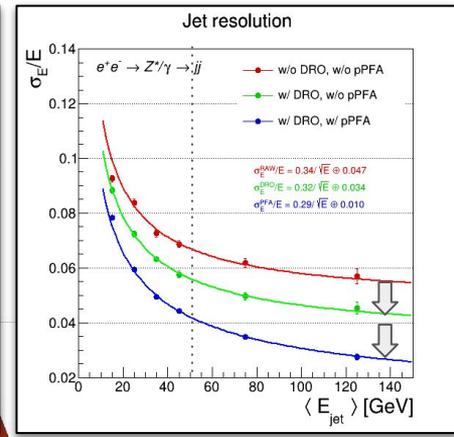
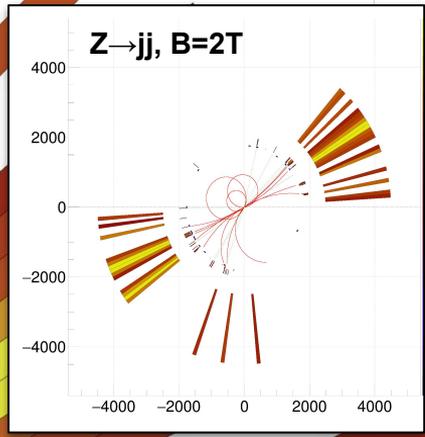
- Electromagnetic energy resolution better than  $3\%/\sqrt{E} \oplus 1\%$  with homogenous crystals
- Simultaneous detection of scintillation and cherenkov signal to maintain applicability of the dual-readout method in a hybrid calorimeter concept
  - Correct event-by-event the fluctuations of e.m. shower fraction in both calorimeter segments
  - Restore linear response to hadronic showers and achieve energy resolution of  $\sim 30\%/\sqrt{E} \oplus 2\%$



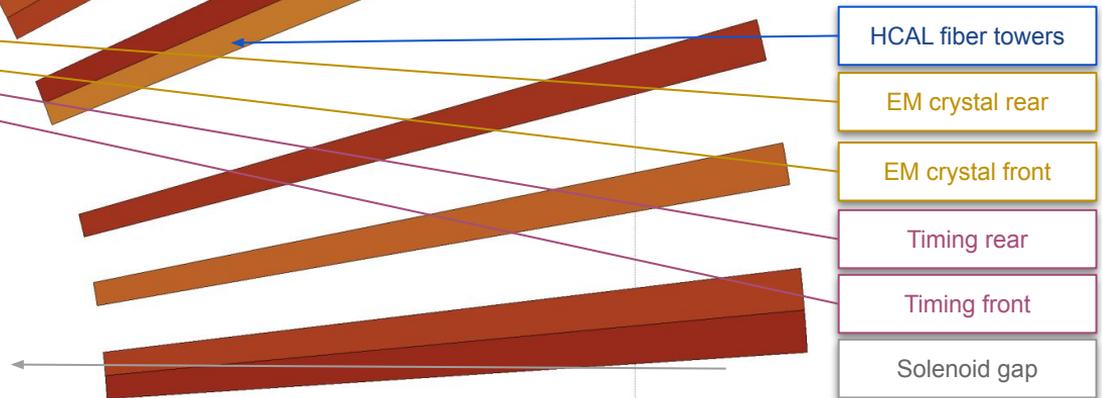
# Jet reconstruction with a dual-readout particle flow algorithm



Longitudinal segmentation provides a powerful handle for particle flow algorithms



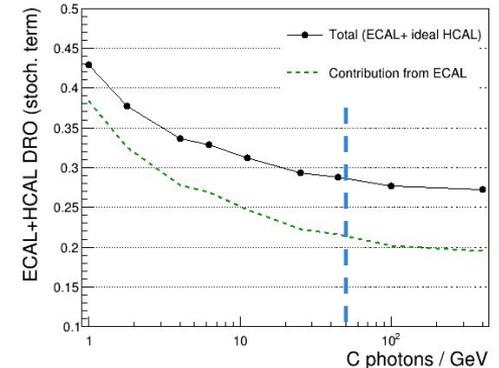
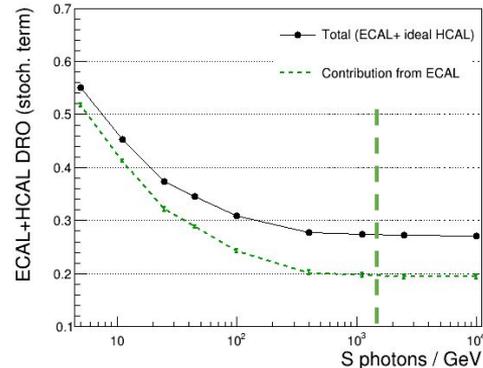
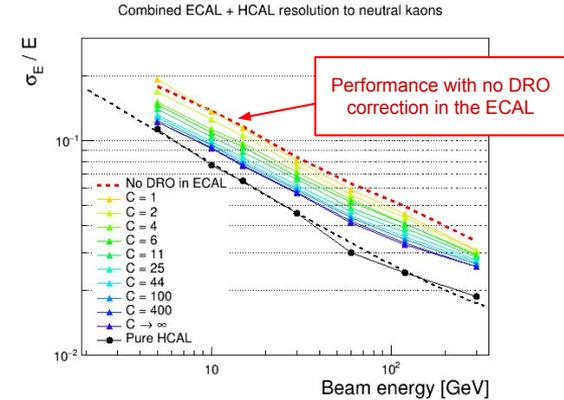
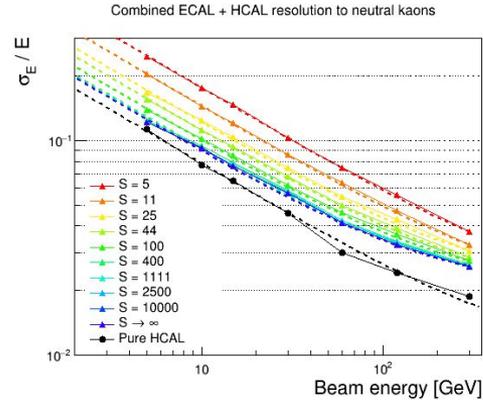
Sensible gain in jet resolution using dual-readout combined with a particle flow approach  $\rightarrow$  <4% for jet energies above 50 GeV



More details in: [2022 JINST 17 P06008](#)

# Light yields requirements for S and C

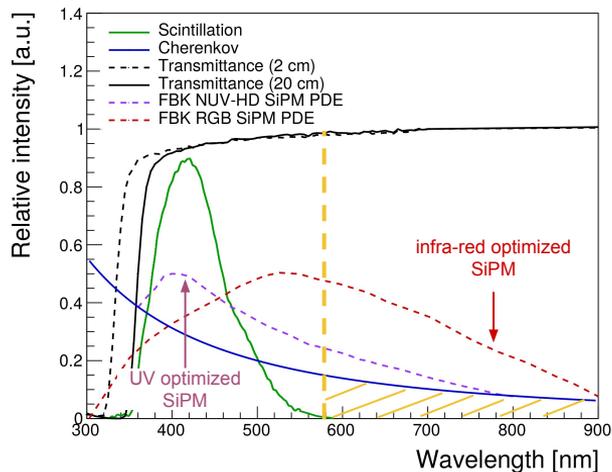
- Impact of photostatistics on energy resolution studied with simulation
- Required scintillation light yield for e.m. resolution  $< 3\%/\sqrt{E}$ 
  - **$S > 1600$  phe/GeV**
- Required Cherenkov light yield for dual-readout method to reach target hadronic resolution
  - **$C > 50$  phe/GeV**
- **Baseline layout choices must provide sufficient light yields**
  - Need experimental validation



# Strategies for dual-readout implementation

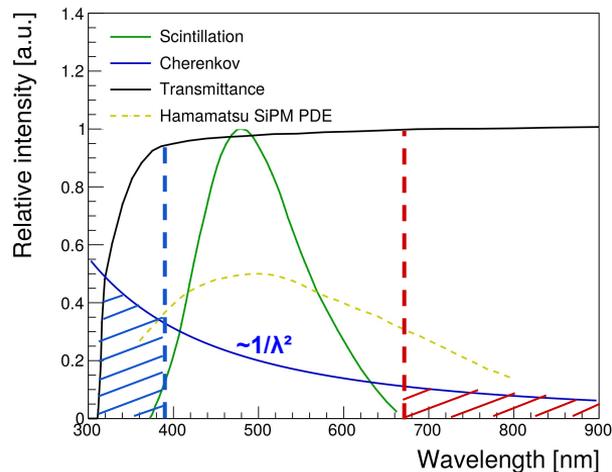
## PWO ( $\lambda$ -based)

- Highest refractive index, lowest  $R_M$  and  $X_0$
- Low light yield at 420 nm  $\rightarrow$  easier to filter out scintillation light with a dedicated SiPM+optical filter and detect C photons at  $\lambda > 580$  nm
- Fast decay time ( $\sim 10$  ns)  $\rightarrow$  hard to separate S and C using pulse shape



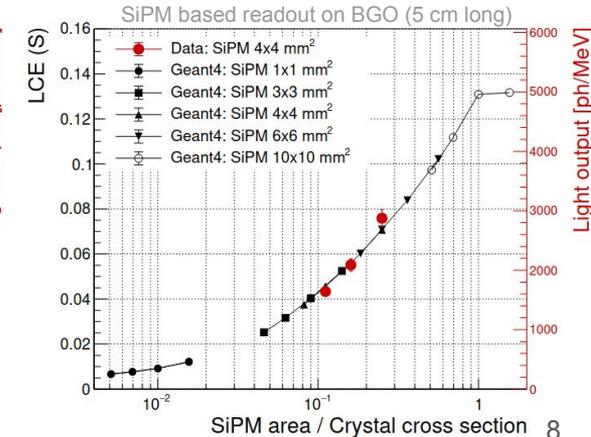
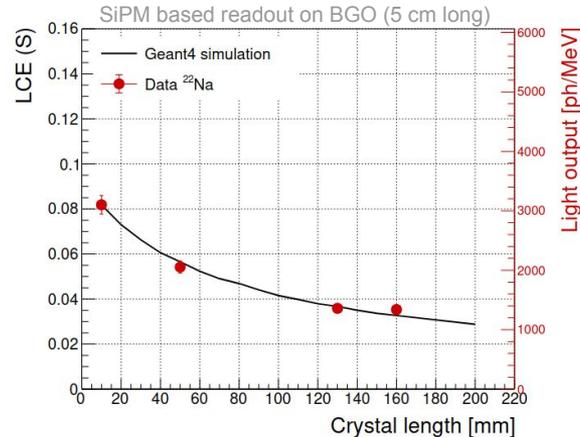
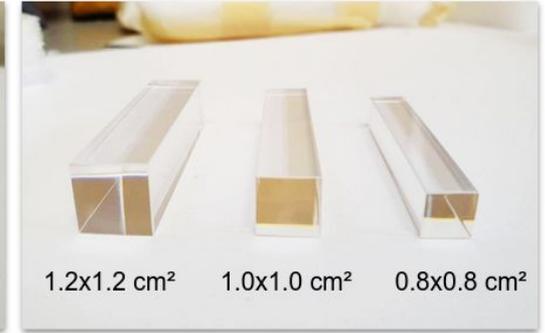
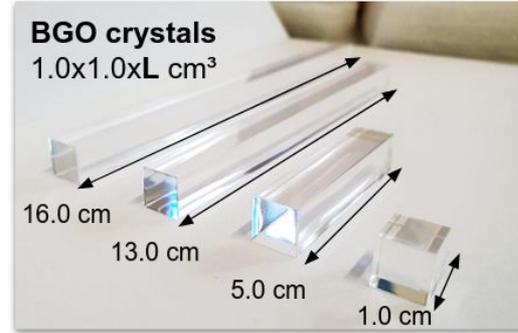
## BG(S)O ( $\lambda+t$ -based)

- Higher light yield (10-30x PWO) at 480 nm  $\rightarrow$  excellent photostatistics  $\rightarrow$  harder to filter out scintillation photons  $\rightarrow$  narrower band for infrared C photon detection ( $\lambda > 680$  nm)
- Wider transparency band for 'UV Cherenkov' ( $\lambda \in [320, 380]$  nm)
- Slow decay time ( $\sim 100-300$  ns)  $\rightarrow$  can separate S/C with timing



# Laboratory measurements - scintillation light output

- Light output measured using teflon wrapped crystals, optical grease and Cs-137 source
  - **Absolute scintillation yields:**  
 BGO / BSO / PWO  
 5000 / 1000 / <100 ph/MeV  
 (with full crystal end face readout)
  - **LO vs crystal length:**  
 1.6x higher light yield in front crystal (5 cm) than in rear one (15 cm)
  - **LO vs SiPM size:**  
 confirmed approximate scaling as fraction of crystal surface covered

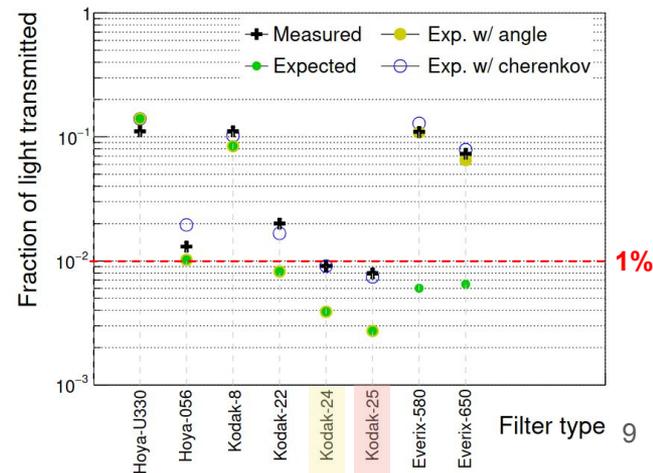
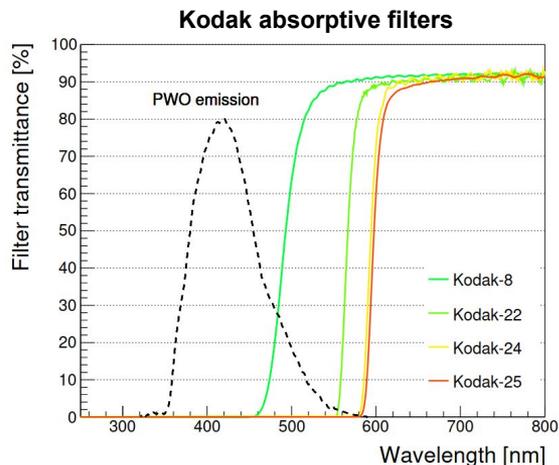
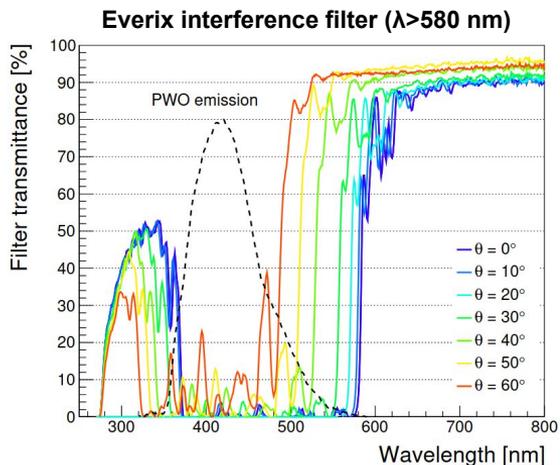


# Laboratory measurements - optical filter choice

- Focus on **thin filters** (~100 μm) for optimal integration
- Interference filters discarded due to angular dependence
- Identified a few ~100 μm thick filters which let pass **less than 1% of PWO scintillation light** (K24, K25)
- Measurements with source agree with model predictions based on crystal and filter optical properties

| Filter label | Manufacturer | Thickness | Cut-off range            | Type         |
|--------------|--------------|-----------|--------------------------|--------------|
| Hoya-U330    | Hoya         | 1.00 mm   | $400 < \lambda < 680$ nm | Absorptive   |
| Hoya-O56     | Hoya         | 2.50 mm   | $\lambda < 560$ nm       | Absorptive   |
| Kodak-8      | Kodak        | 0.10 mm   | $\lambda < 490$ nm       | Absorptive   |
| Kodak-22     | Kodak        | 0.10 mm   | $\lambda < 565$ nm       | Absorptive   |
| Kodak-24     | Kodak        | 0.10 mm   | $\lambda < 590$ nm       | Absorptive   |
| Kodak-25     | Kodak        | 0.10 mm   | $\lambda < 595$ nm       | Absorptive   |
| Eve-Abs-580  | Everix       | 0.26 mm   | $\lambda < 580$ nm       | Absorptive   |
| Eve-Int-560  | Everix       | 0.26 mm   | $370 < \lambda < 580$ nm | Interference |
| Eve-Int-650  | Everix       | 0.26 mm   | $370 < \lambda < 650$ nm | Interference |

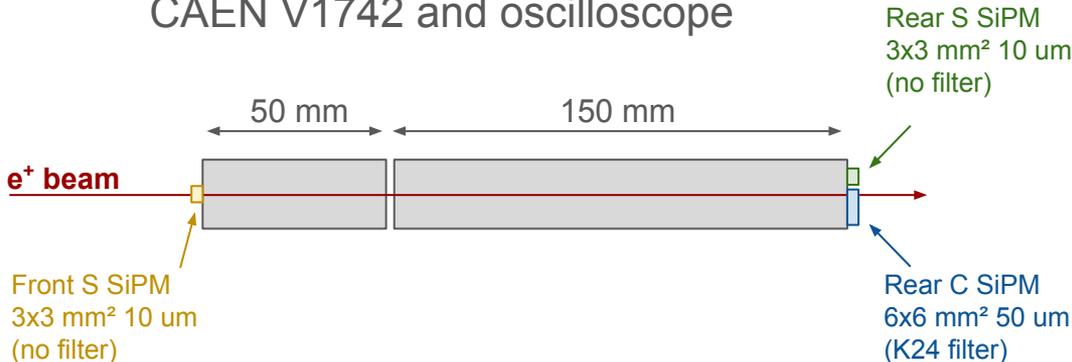
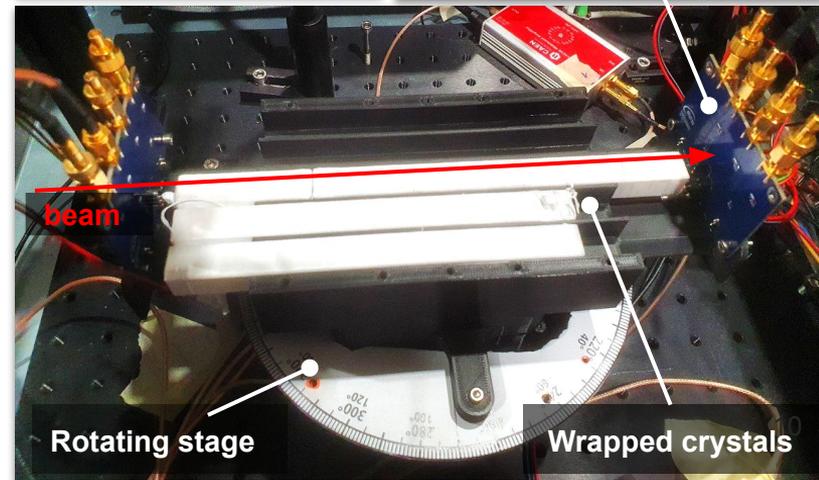
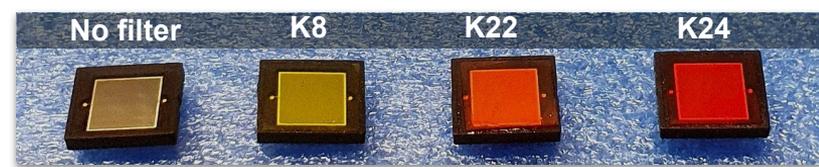
$$\frac{LO_{\text{filter}}}{LO} = \frac{\int_{300 \text{ nm}}^{800 \text{ nm}} EM(\lambda) \cdot T(\lambda) \cdot \text{PDE}(\lambda) d\lambda}{\int_{300 \text{ nm}}^{800 \text{ nm}} EM(\lambda) \cdot \text{PDE}(\lambda) d\lambda}$$



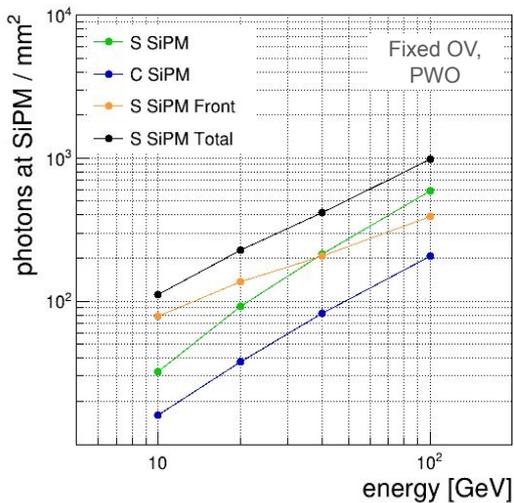
# Test beam setup and goals

## CERN H6, 2024

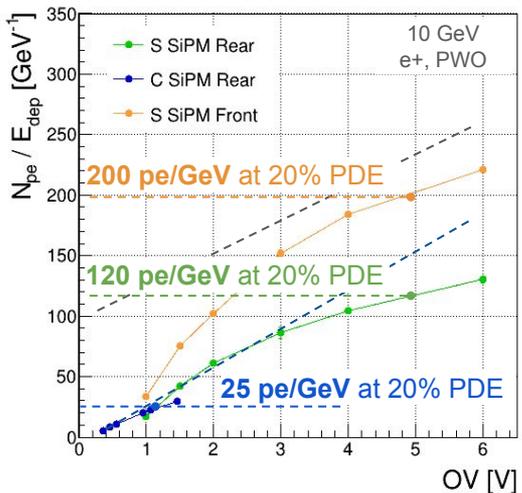
- Focus on single crystal test (PWO and BGO) to assess photon yields for both scintillation and cherenkov light
- Rotating stage to study angular dependence of the Cherenkov signal
- SiPM readout using transimpedance amplifiers on custom PCB + waveform digitized with CAEN V1742 and oscilloscope



# Test beam results - light yields in PWO



- Fraction of shower energy in front crystal decreases as expected due to shower maximum depth change
- Calibrated sum of front and rear scintillation signals and **Cherenkov signal** grow linearly with deposited energy



- Number of photoelectrons detected can be used to define SiPM/filter specifications:
  - Scintillation:  $\sim 36 \text{ pe/GeV/mm}^2$  at 20% PDE
    - $\rightarrow$  need  $6 \times 6 \text{ mm}^2$  SiPM and 40% PDE to reach target
  - Cherenkov:  $\sim 0.7 \text{ pe/GeV/mm}^2$  at 20% PDE
    - $\rightarrow$  need  $6 \times 6 \text{ mm}^2$  SiPM and 40 PDE to reach target
  - Contamination from S photons to C-signal  $< 10\%$ 
    - $\rightarrow$  specification satisfied

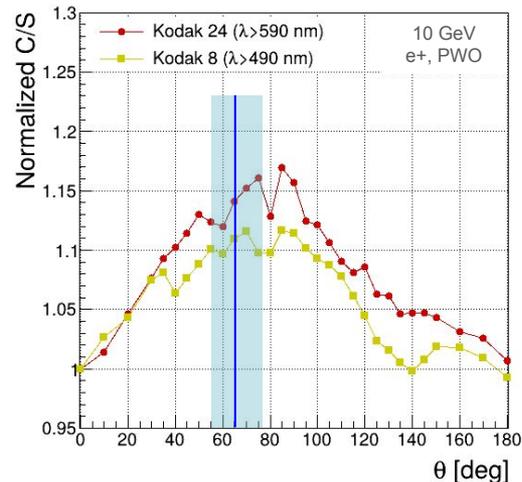
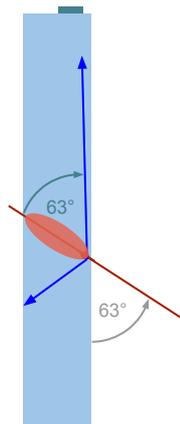
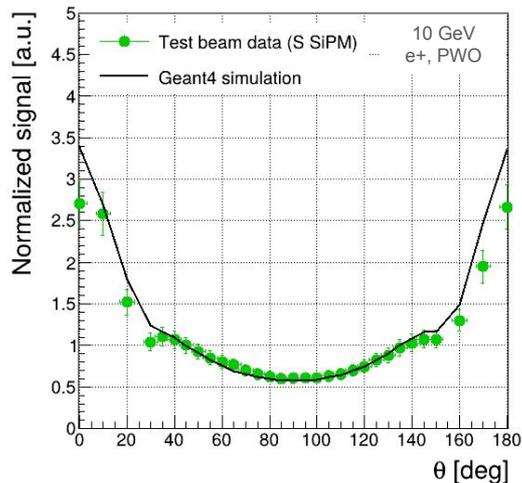
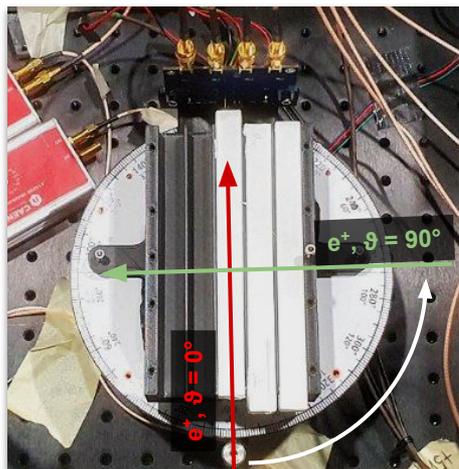
# Test beam results - C angular dependence in PWO

Rotation of crystal axis with respect to beam direction in the range 0-180°

Factor 6 variation of energy deposited in crystal reasonably reproduced by Geant4

Calculation of S/C event-by-event shows

- Maximum of C-signal in correspondence of Cherenkov emission angle in PWO
- Variation less pronounced when S contamination is larger (Kodak 8 filter vs Kodak 24)
- Only few percent variation for a few deg around 0°

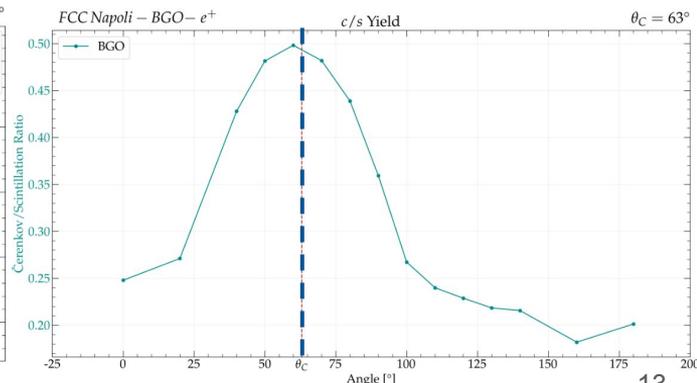
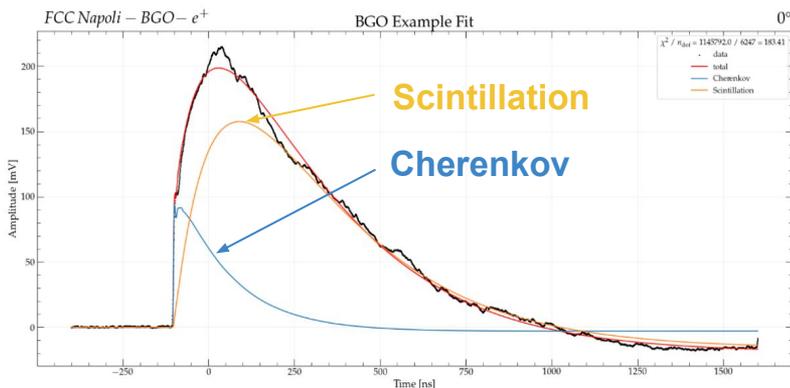
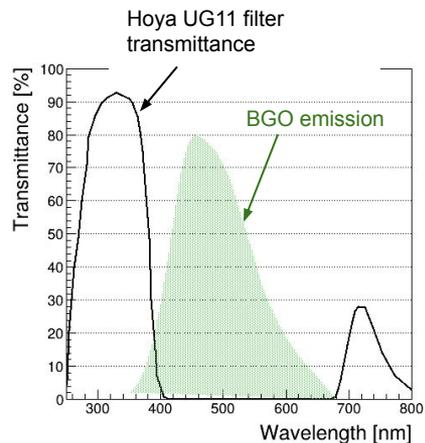


# Test beam results - C angular dependence in BGO

BGO crystal coupled to SiPM with U330 optical filter (<1% of S light passing through)

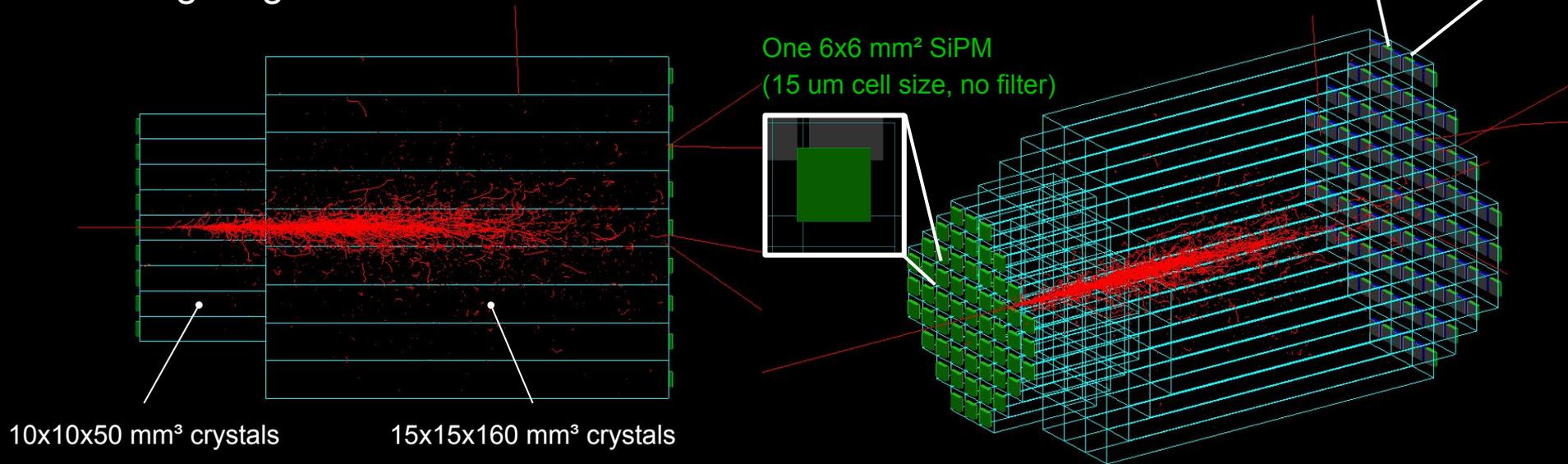
Template pulse shape fitting of SiPM+filter signal in BGO yields a good estimate of the cherenkov signal

Angular dependence of C/S peaks as expected around cherenkov cone emission angle ( $\sim 63^\circ$ )



# Ongoing prototype construction

- Plan to assemble a 9x9 PWO matrix
  - Procurement of crystals and SiPMs ongoing
  - Testing of electronics started (FERS 5200, Citiroc1A)
  - Possibility to exchange central 3x3 core with BG(S)O crystals and waveform digitization
- Targeting test on beam in Fall 2025



# Summary

- A **highly performant dual-readout hybrid calorimeter** system meeting future  $e^+e^-$  colliders requirements is being studied within an international coordinated effort by various groups (CalVision, MAXICC, DRD6 and IDEA study group)
- **Simulation performance studies show promising results:**
  - **Excellent EM, HAD and jet resolution** by combining the DRO information from different calorimeter segments (homogeneous crystals & sampling fibers) with **particle flow algorithm**
- **Progress in R&D to identify optimal crystal, filter and SiPM configuration** through lab and beam tests in 2024 → light yield requirements within reach
- Two baseline implementation strategies (PWO and BGO-based) will be pursued with the construction of **full containment prototypes** to be tested **in Fall 2025**

# acknowledgments



Finanziato  
dall'Unione europea  
NextGenerationEU



Ministero  
dell'Università  
e della Ricerca



**Italiadomani**  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA