Dual-Readout Crystal Calorimetry for future e^+e^- colliders

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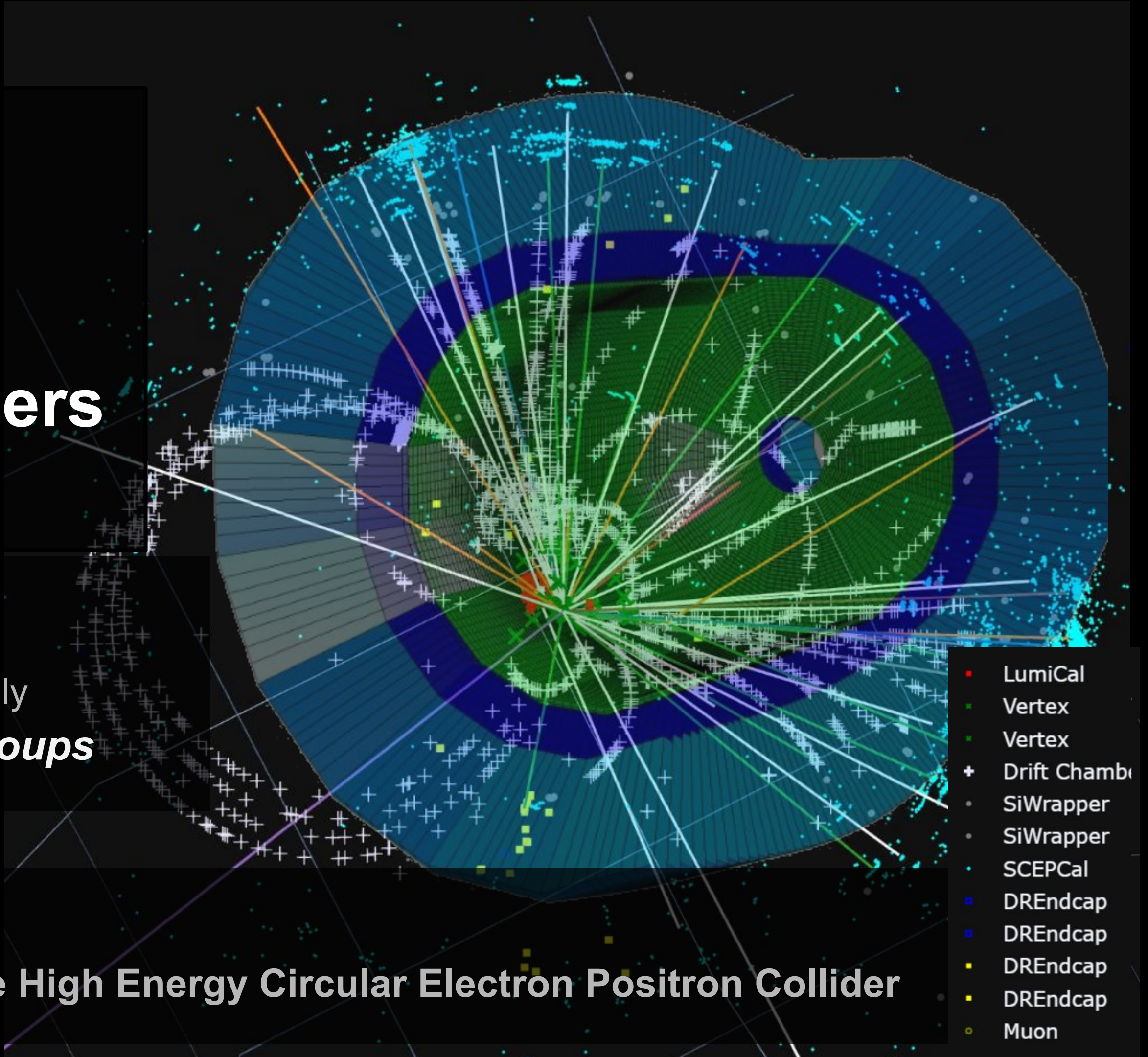


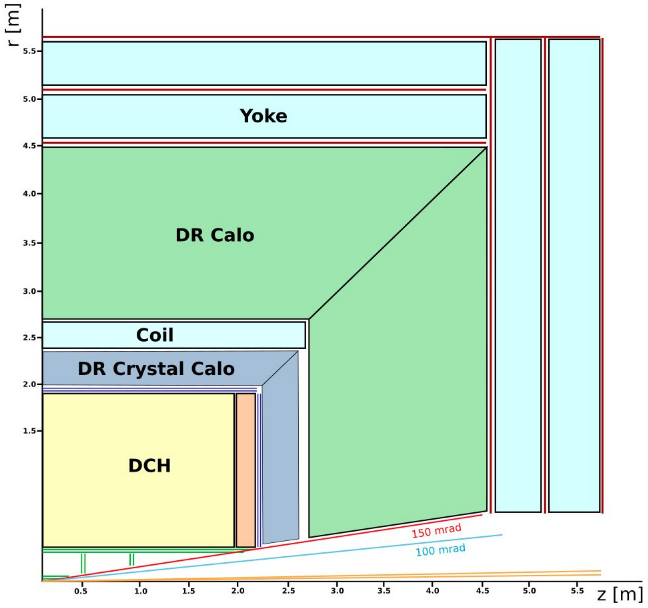
Guangzhou, November 6-10, 2025
2025 International Workshop on the High Energy Circular Electron Positron Collider

Hybrid dual-readout calorimetry in the IDEA detector

- Evaluate the potential and the feasibility of integrating a **cost-effective homogeneous dual-readout segmented** crystal **EM** calorimeter in the IDEA detector

- First studies and concept descriptions in:
  - Conceptual design: 2020 *JINST* **15** P11005
  - Jet performance: 2022 *JINST* **17** P06008
  - New IDEA baseline: arXiv:2502.21223v1

- Activity at 360 degrees:
  - Simulation studies (from standalone to full sim)
  - R&D on technology and proof-of-principle
  - Prototyping of a calorimetric module



Hybrid dual-readout calorimetry
in the IDEA detector

- Evaluate the potential and the feasi **homogeneous dual-readout segn** IDEA detector

See tomorrow's talk from R.Ferrari for details on the Fiber (Hadronic) section of the DR Calorimeter

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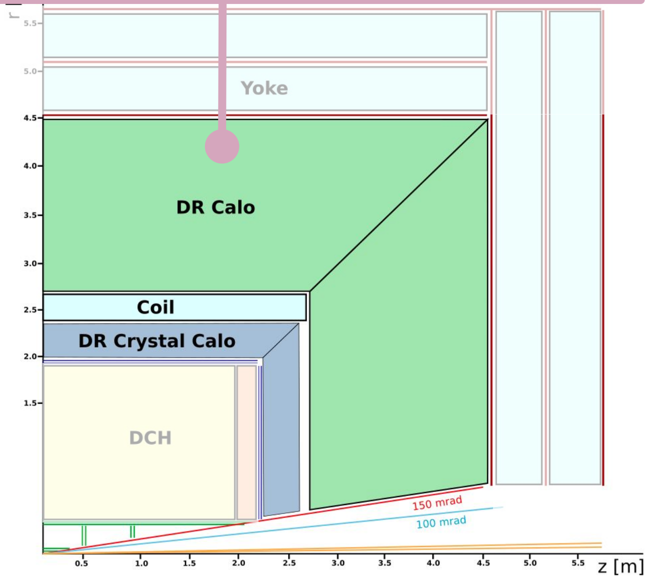
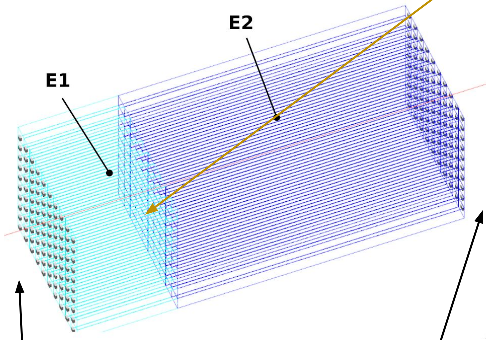


Conceptual layout

Optimize energy resolution:
no dead material at
shower maximum

Contained number of channels
Transverse granularity: 1x1-1.5x1.5 cm²
Longitudinal segmentation: 2 layers
Total channel count ~2M



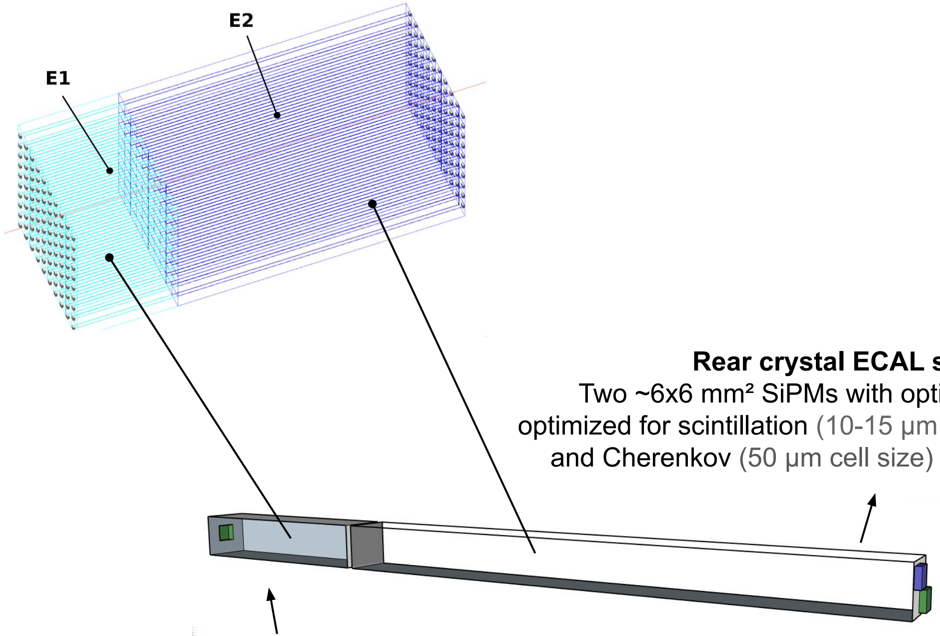
Simplify integration aspects:
SiPM+electronics readout,
cooling and services only at
front and rear sides

Conceptual layout

<u>Dual-readout implementation</u>

Cost-effective SiPM readout

Optical filters for separation of Cherenkov and scintillation signal from the same active elements

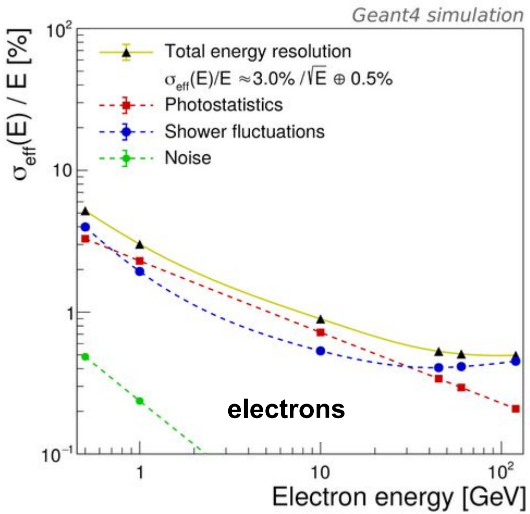


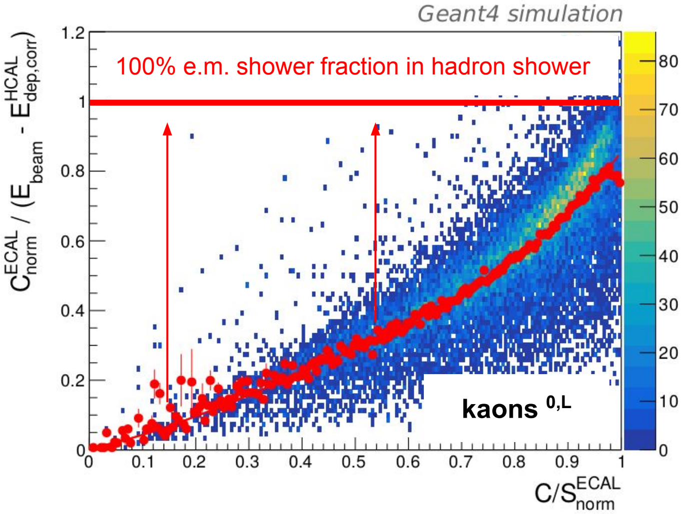
Rear crystal ECAL segment:
Two ~6x6 mm² SiPMs with optical filters optimized for scintillation (10-15 μm cell size) and Cherenkov (50 μm cell size) detection

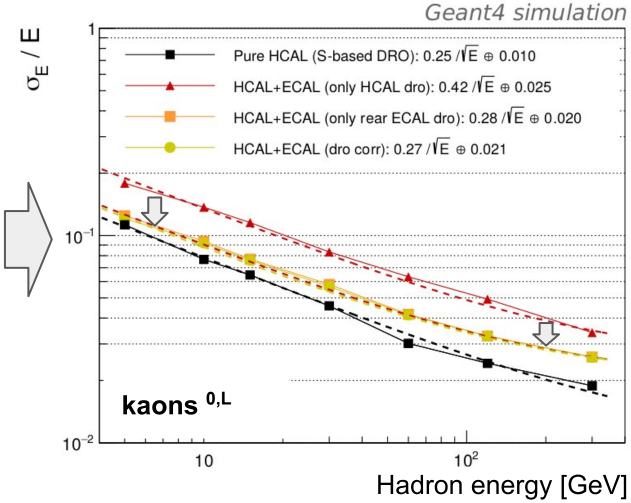
Front crystal ECAL segment:
Single ~6x6 mm² SiPM per crystal optimized for scintillation light detection (10-15 μm cell size)

Energy resolution - simulation

- Electromagnetic energy resolution better than 3%/√E⊕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 ~30%/√E⊕2%



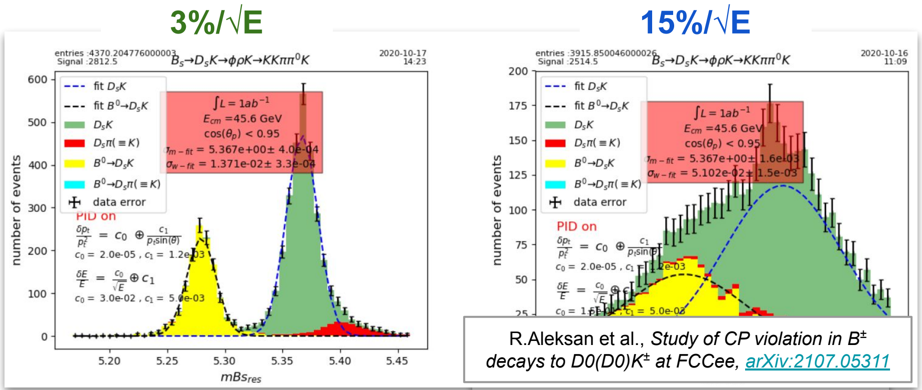




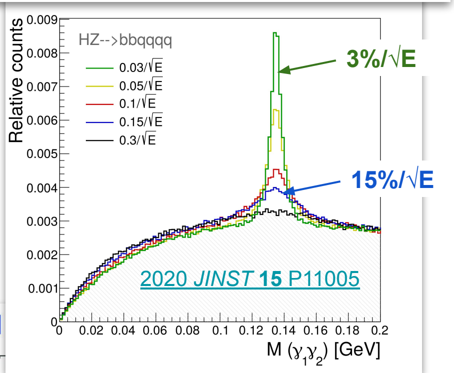
High EM energy resolution potential at e^+e^- Higgs factories

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

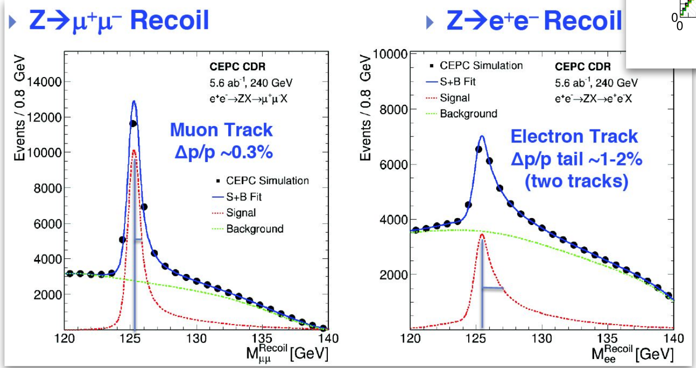
- **CP violation studies** with B_s decay to final states with low energy photons
- **Clustering of π^0's photons** to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)



R.Aleksan et al., *Study of CP violation in $B^\pm$ decays to D0(D0)$K^\pm$ at FCCee*, arXiv:2107.05311



2020 *JINST* **15** P11005

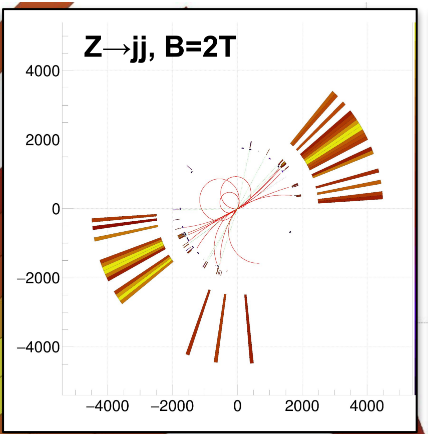


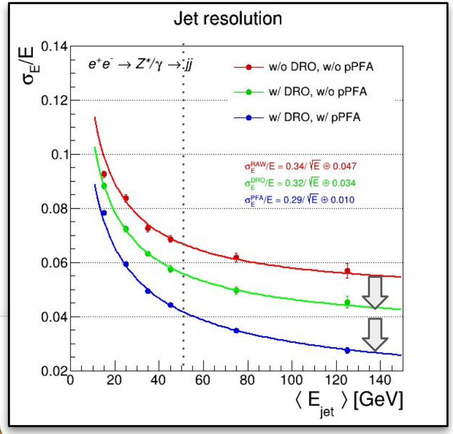
Example from CEPC CDR

Jet reconstruction

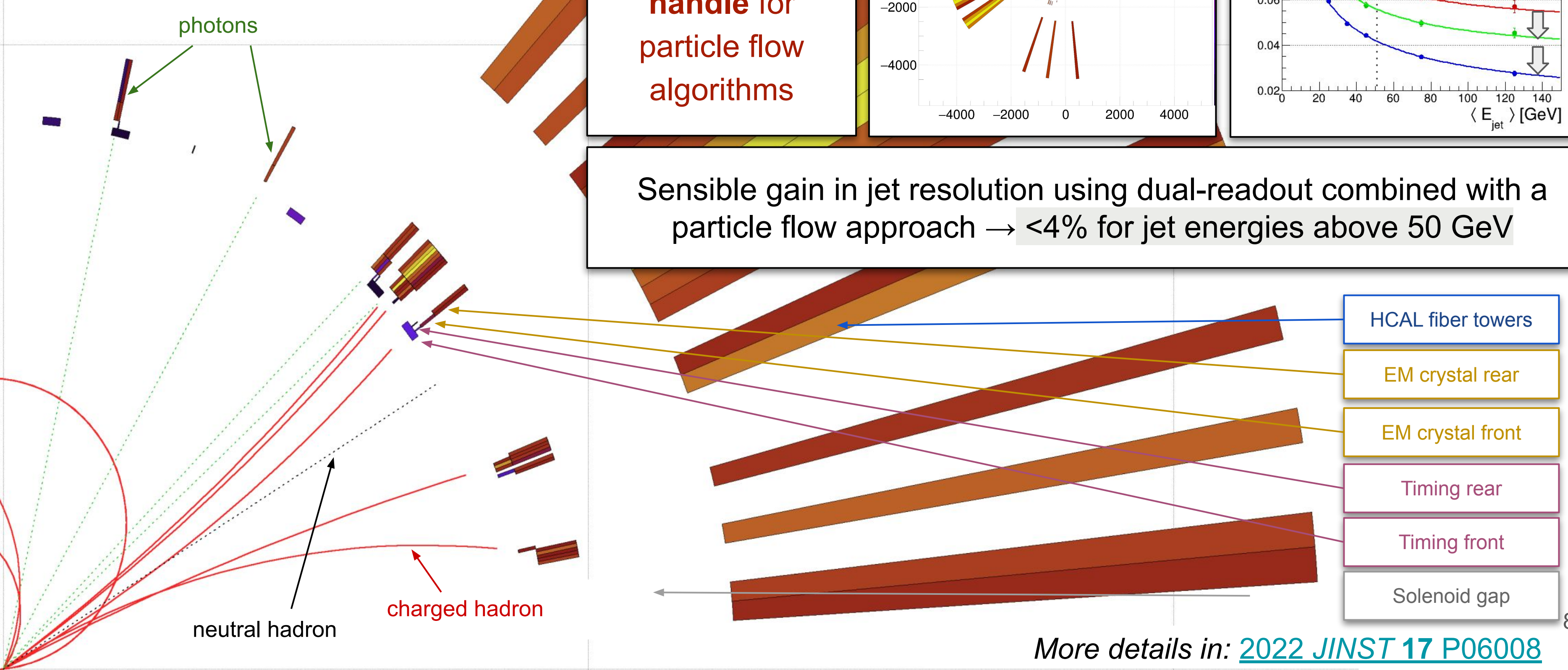
with a dual-readout particle flow algorithm

Longitudinal segmentation provides a **powerful handle** for particle flow algorithms





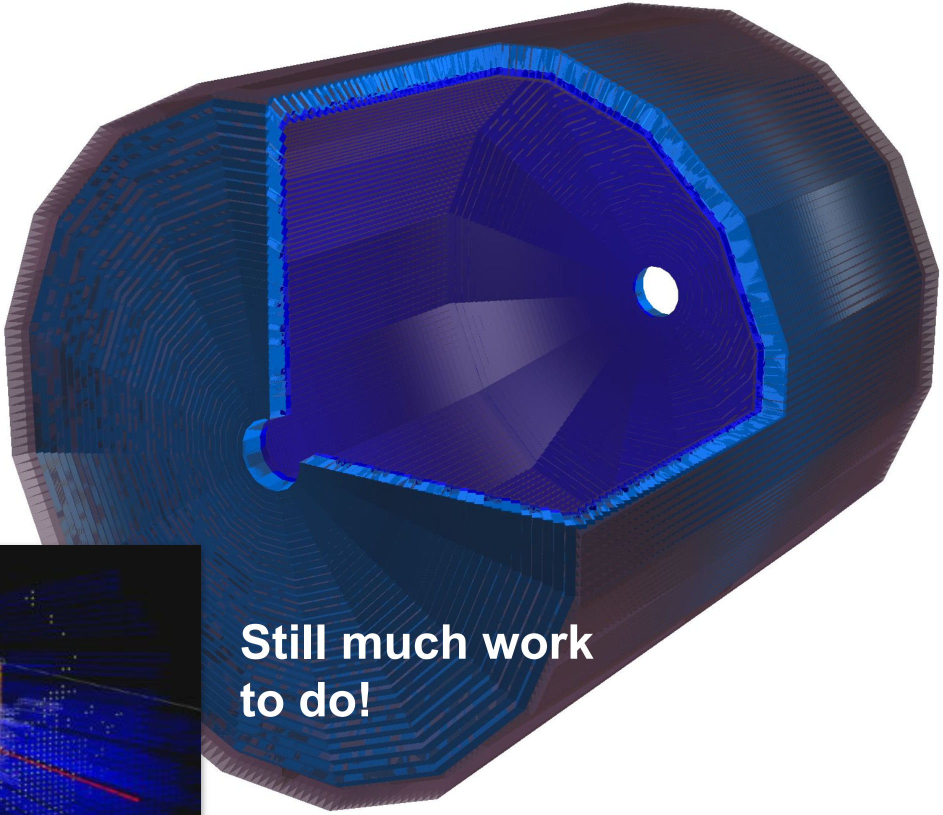
Sensible gain in jet resolution using dual-readout combined with a particle flow approach → <4% for jet energies above 50 GeV

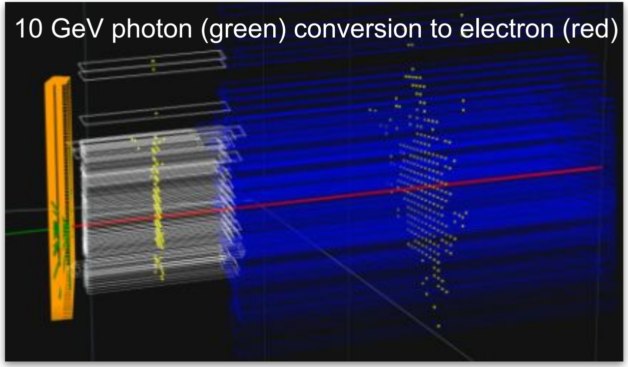


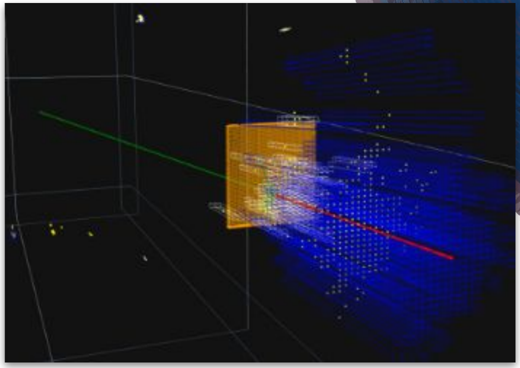
More details in: [2022 *JINST* **17** P06008]

Implementation in **key4hep** gearing up

- Great progress in developing a fully differentiable detector geometry and simulation in key4hep (github)
    - SiPMs and digitized readout implemented
    - ML angular resolution and e/gamma regression studies underway
    - Integration with IDEA detector underway
    - Generated proper digis in key4hep and realistic TB module geometry




10 GeV photon (green) conversion to electron (red)

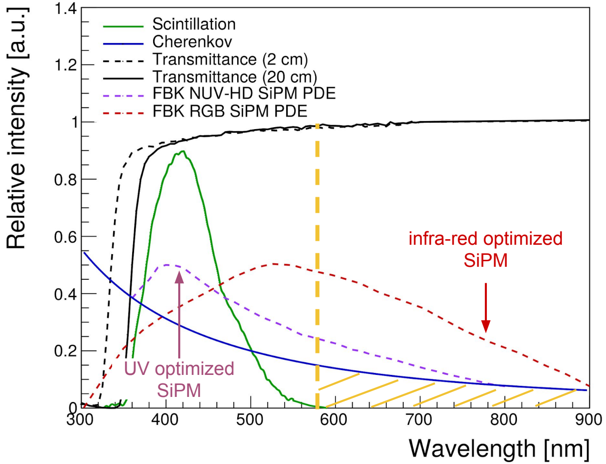


See W.Chung at CALOR2024

Dual strategy for *dual*-readout implementation

PWO (λ-based)

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



BG(S)O (λ+t-based)

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

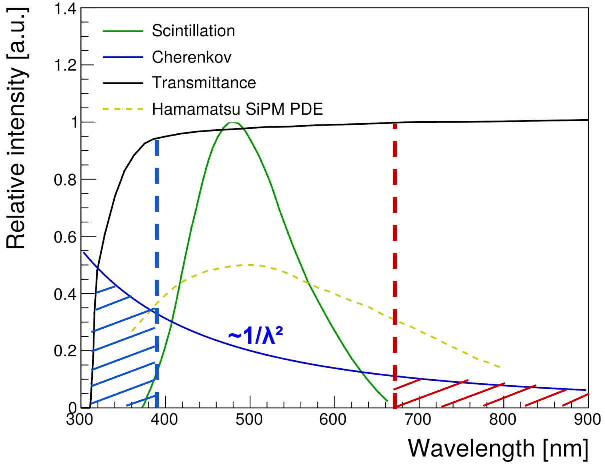


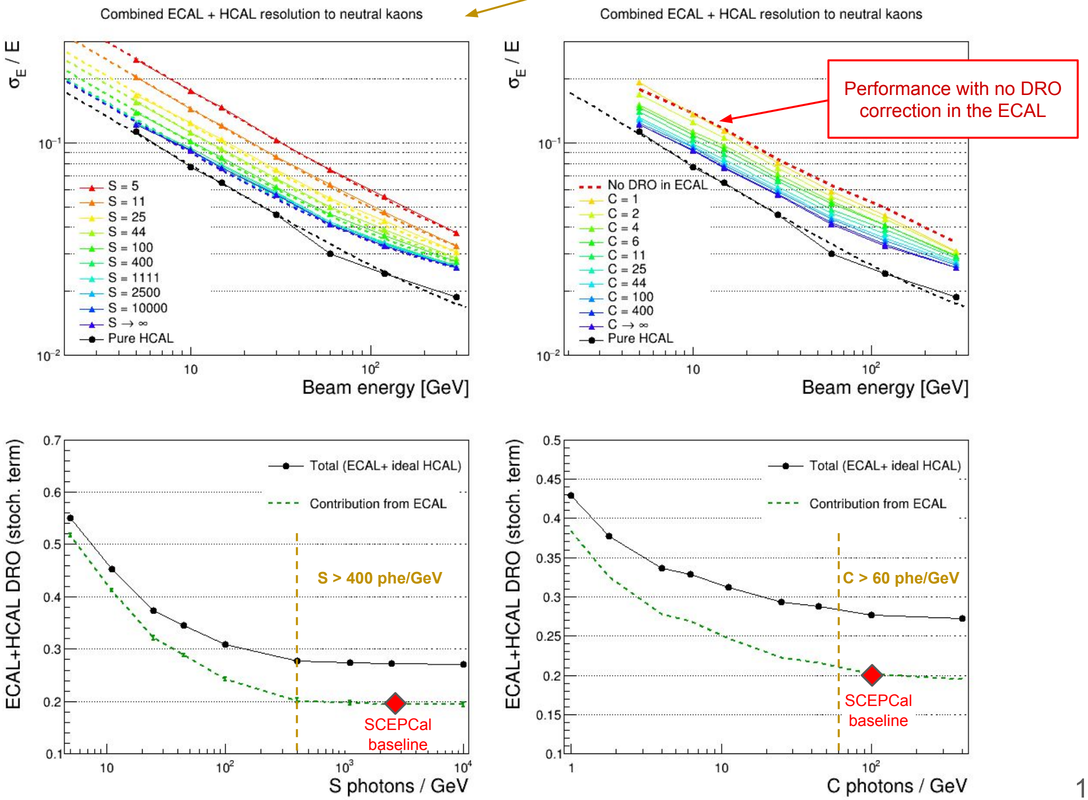
Photo-statistic requirements for S and C

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

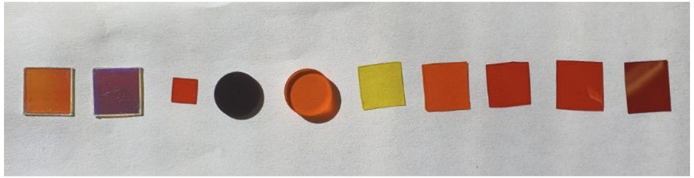
- **Baseline layout choices** (granularity and SiPM size) to **provide sufficient light collection efficiency** in Geant4
  - Need experimental validation with lab and beam tests

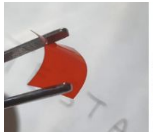


R&D and prototyping with PWO

Laboratory measurements - **optical filter** selection

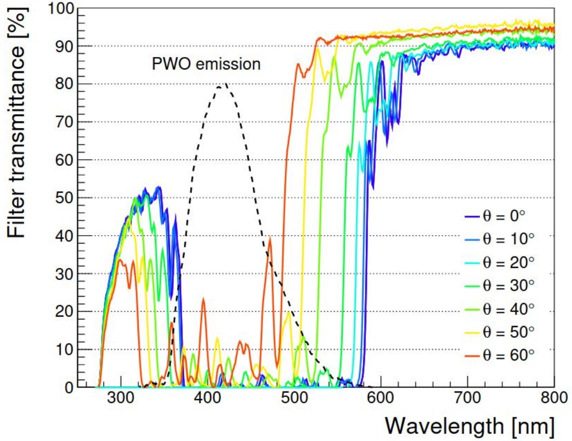
- Focus on **thin filters** (~100 µm) **for optimal integration with SiPMs**
- Interference filters discarded due to the angular dependence of their transmittance curve
- Identified a few ~100 um thick filters which let pass **less than 1% of PWO scintillation light** (K24, K25)



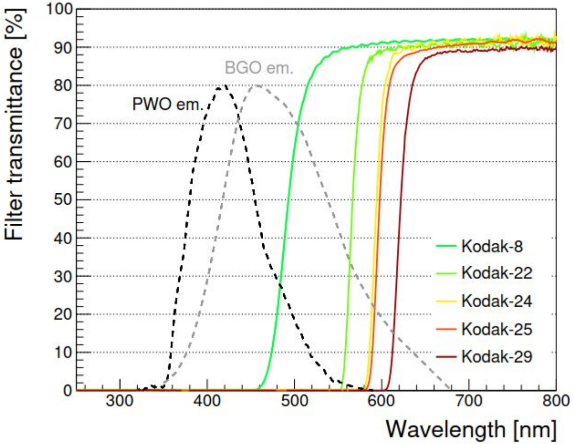


$$\frac{LO_{filter}}{LO} = \frac{\int_{300\ nm}^{800\ nm} EM(\lambda)\cdot T(\lambda)\cdot PDE(\lambda)d\lambda}{\int_{300\ nm}^{800\ nm} EM(\lambda)\cdot PDE(\lambda)d\lambda}$$

Everix interference filter (λ>580 nm)



Kodak absorptive filters



Photon transmittance at normal incidence angle

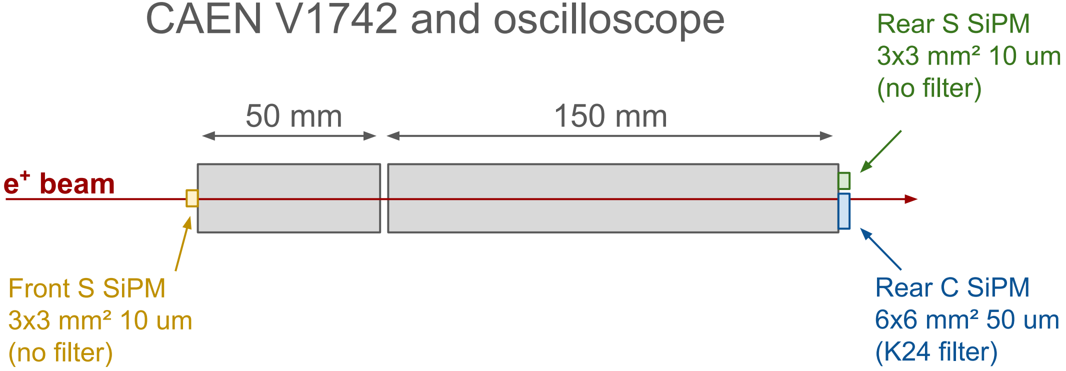
Filter label	BGO/BSO	PWO	
Hoya-U330	8.8%	26.8%	
Hoya-O56	12.8%	0.3%	
Kodak-8	40.7%	7.9%	
Kodak-22	11.2%	0.1%	
Kodak-24	6.2%	<0.1%	
Kodak-25	5.5%	<0.1%	
Kodak-29	2.7%	<0.1%	
Eve-Abs-580	8.1%	<0.1%	
Eve-Int-580	7.0%	1.4%	→8.0%*
Eve-Int-650	1.1%	2.5%	→15.0%*

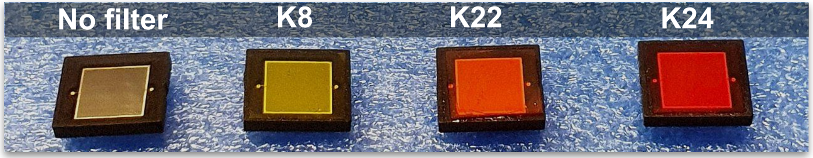
*when considering angular distribution of scintillation photons

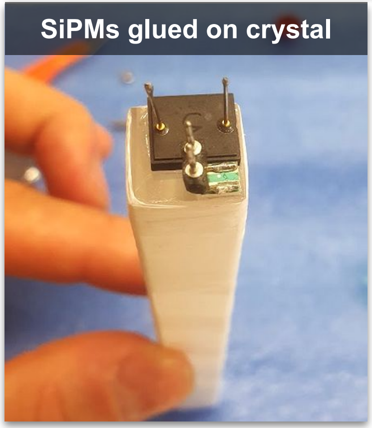
Test beam setup and goals

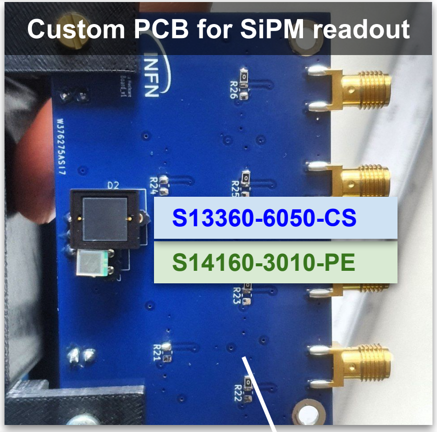
CERN H6, July 2024

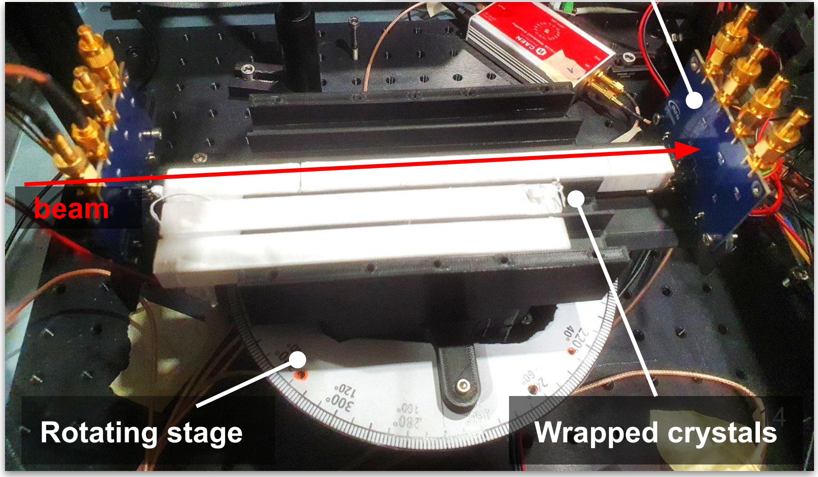
- Focus on single crystal test (PWO and BGO) to assess photon yields for both scintillation and cherenkov light
- Rotating stage to study angular dependence of the Cherenkov signal
- SiPM readout using transimpedance amplifiers on custom PCB + waveform digitized with CAEN V1742 and oscilloscope











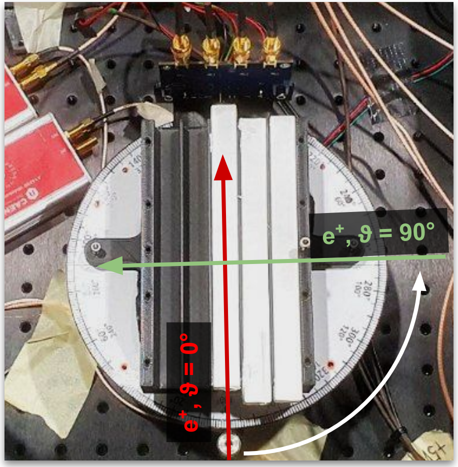
Test beam results - **C angular dependence in PWO**

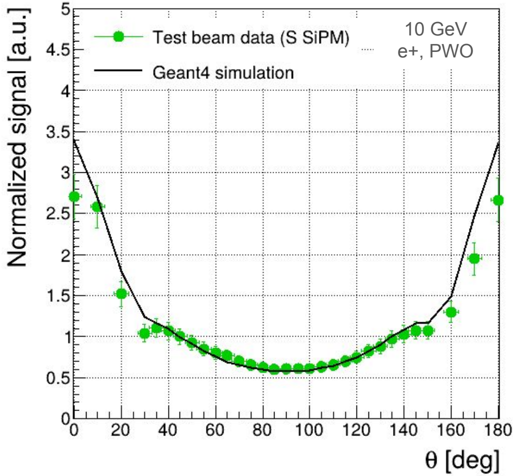
Rotation of crystal axis with respect to beam direction in the range 0-180°

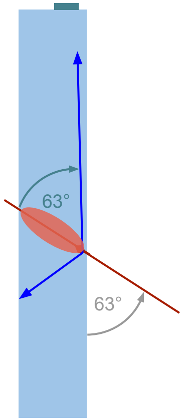
Factor 6 variation of energy deposited in crystal reasonably reproduced by Geant4

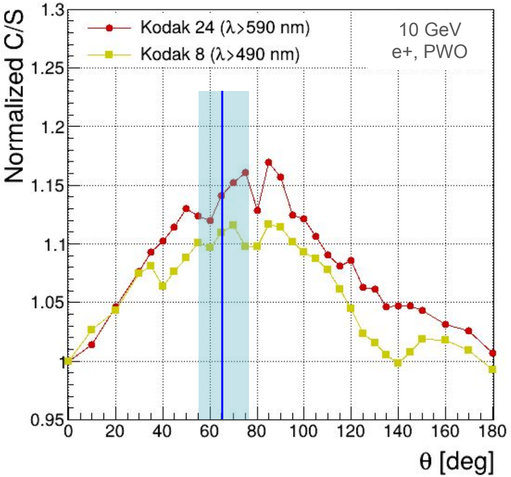
Calculation of S/C event-by-event shows

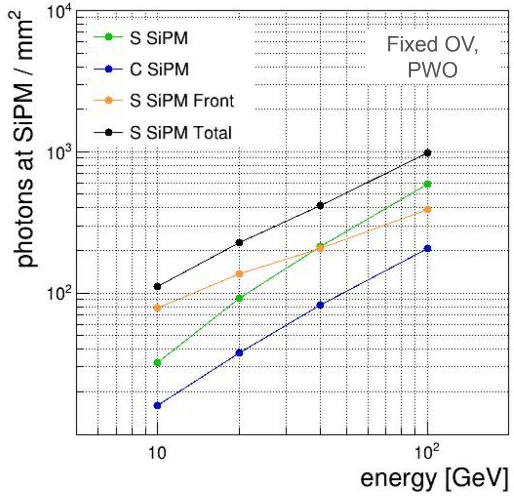
- Maximum of C-signal in correspondence of Cherenkov emission angle in PWO
- Variation less pronounced when S contamination is larger (Kodak 8 filter vs Kodak 24)
- Only few percent variation for a few deg around 0°

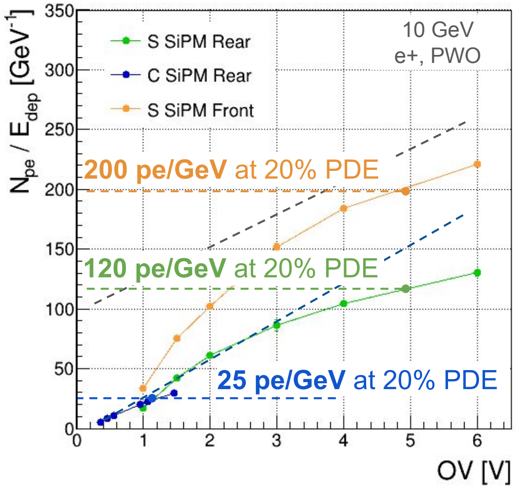












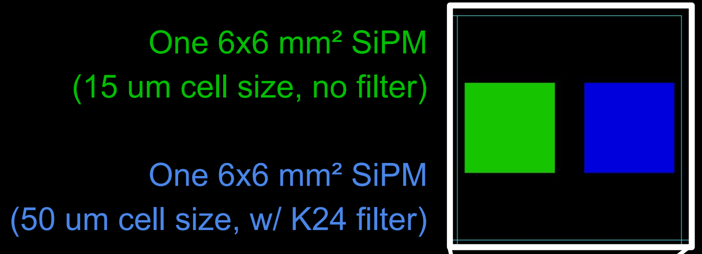
Test beam results - **light yields in PWO**

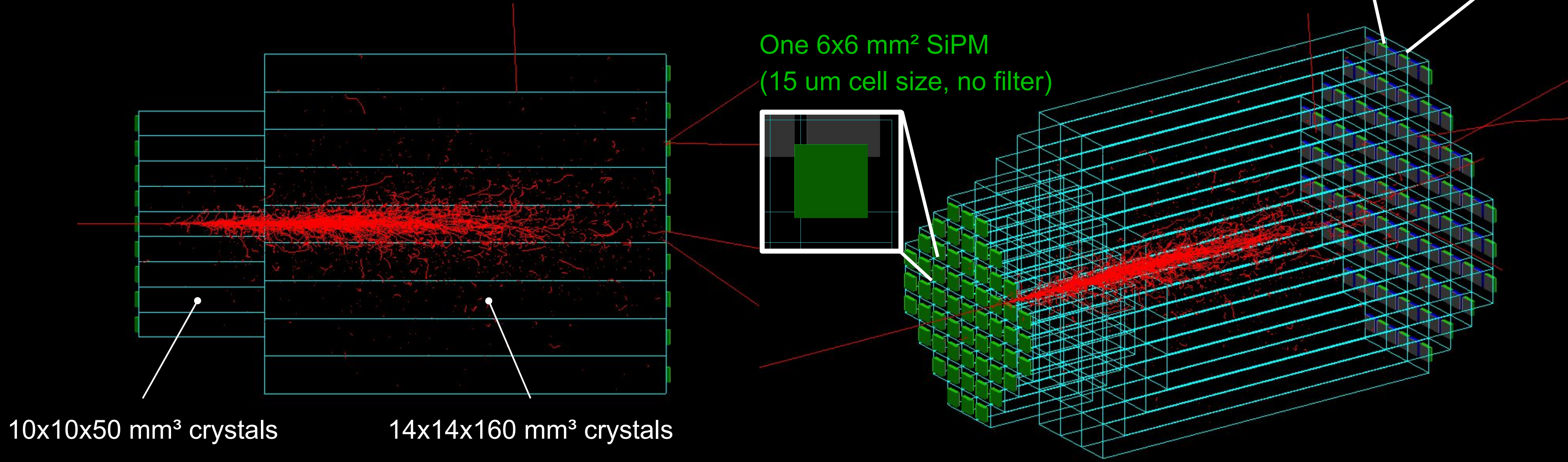
- Fraction of shower energy in front crystal decreases as expected due to shower maximum depth change
- Calibrated sum of front and rear scintillation signals and Cherenkov signal grow linearly with deposited energy

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

Prototype design

- Plan to assemble a 9x9 PWO matrix
  - 10x10x50 mm³ front crystals, 14x14x160 mm³ rear crystals
  - 6x6 mm² SiPMs (15 and 50 um, for S and C, resp.)
  - Electronics with FERS-5200 (Citiroc1A)
  - Mechanical design to enable the exchange of the central 3x3 core with BSO crystals and waveform digitization readout

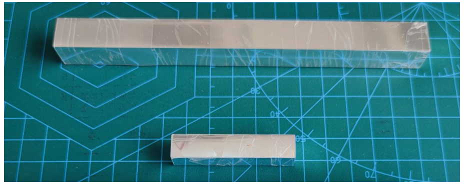




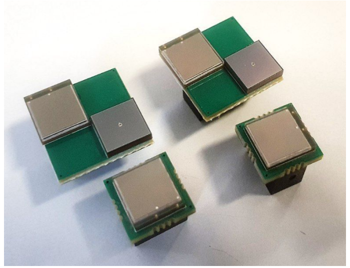
Prototype components under procurement

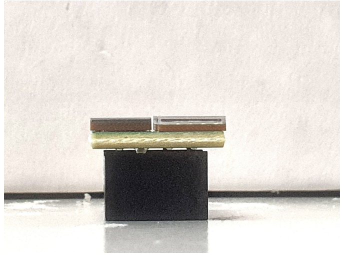
- All components in hand except crystals (issue with export license)

Crystals and SiPMs

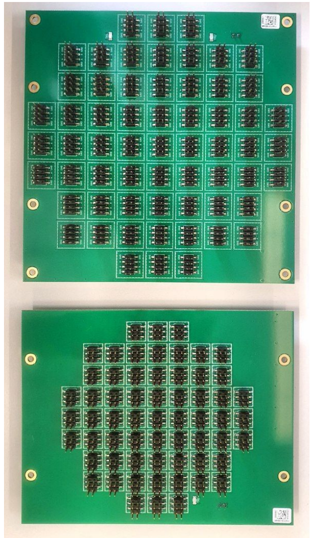


SiPM PCBs

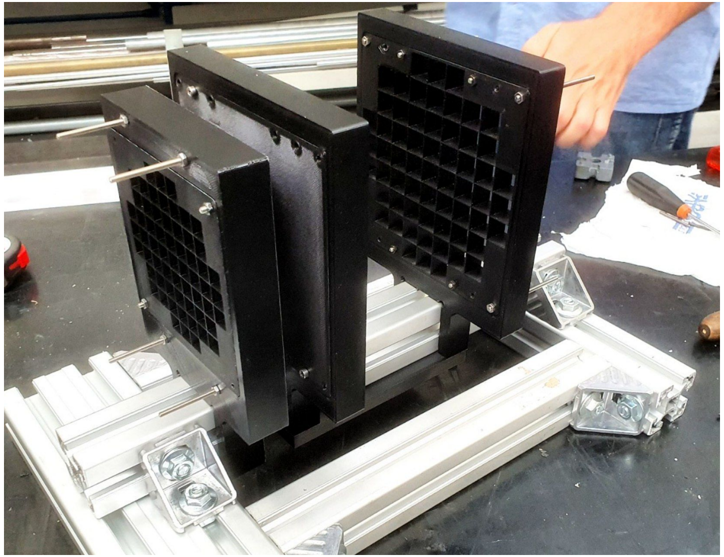




Concentrator PCBs

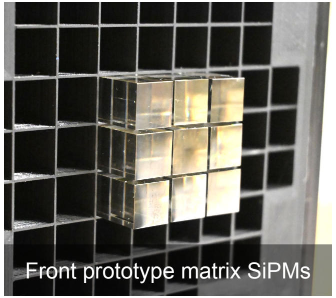


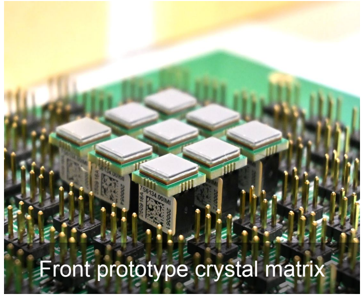
3D-printed alveolar structure

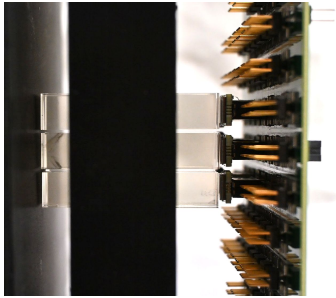


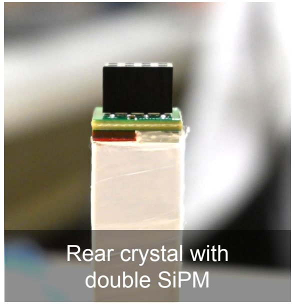
Pictures from recent **test beam** (Sept-Oct 2025)

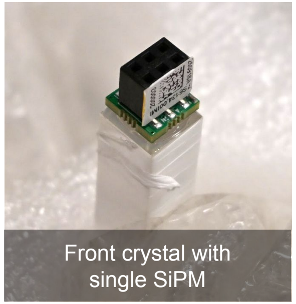
- A test with only few crystals mounted but full prototype mechanics, electronics and readout chain performed at the SPS H6 in Sept-Oct 2025

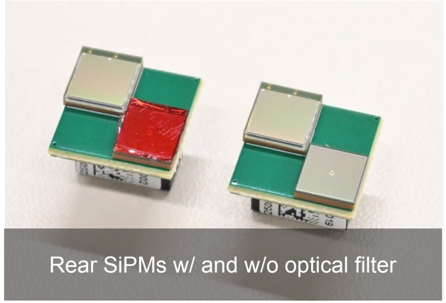

Front prototype matrix SiPMs

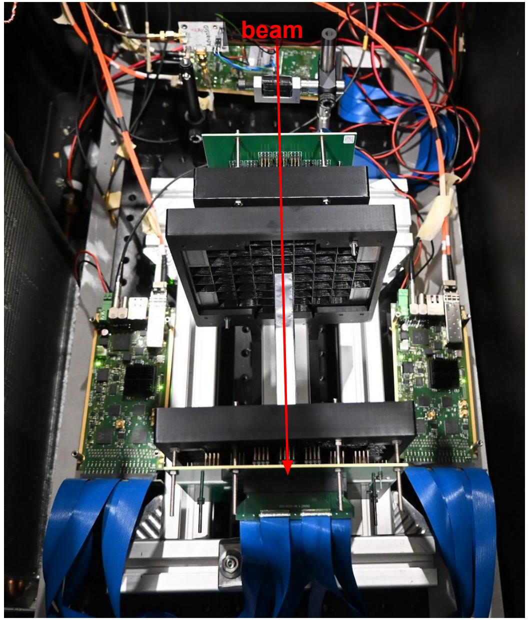

Front prototype crystal matrix




Rear crystal with double SiPM


Front crystal with single SiPM

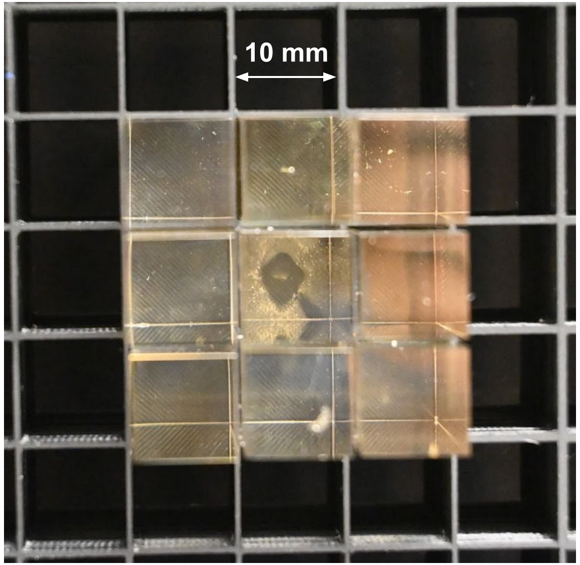

Rear SiPMs w/ and w/o optical filter



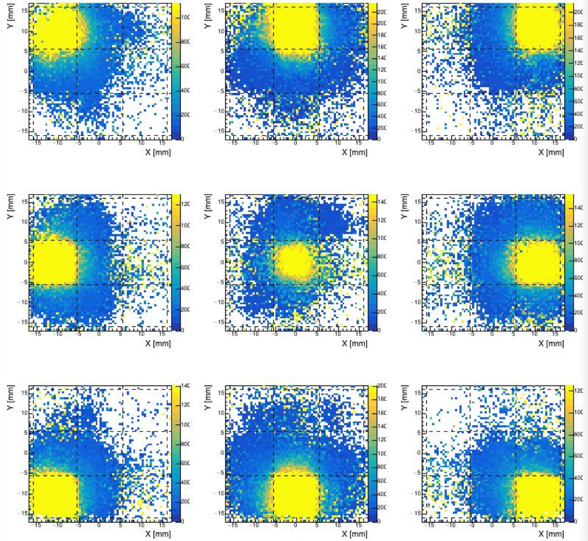
First glance at test beam data

- Ongoing analysis on first data taken with
  - New SiPMs → improved PDE and better light collection efficiency
  - FERS 5200 electronics and EUDAQ framework

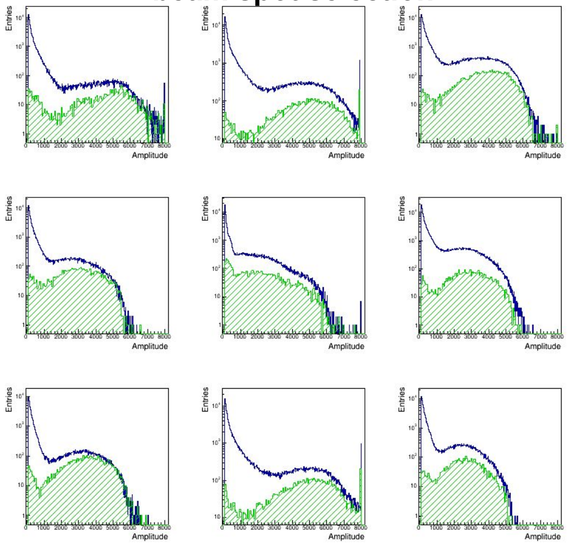
Picture of front matrix crystals



Measured signal from 40 GeV positron shower vs beam impact point



Measured signal w/ and w/o 3x3 mm² beam spot selection



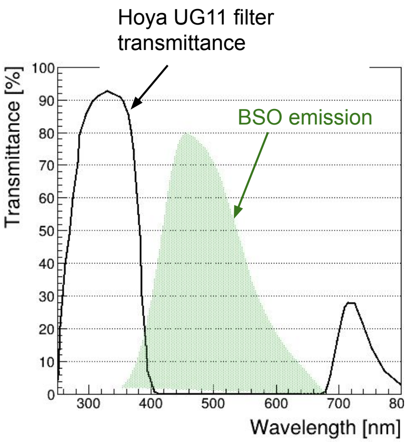
R&D and prototyping with BGO/BSO

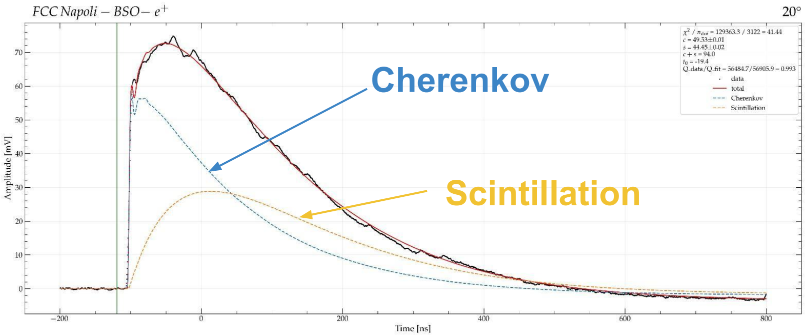
Test beam results - **C angular dependence in BSO**

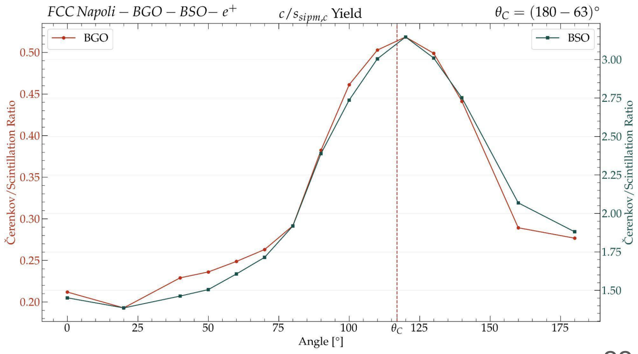
BSO crystal coupled to SiPM with **UG11 optical filter** (<1% of S light passing through)

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

Angular dependence of C/S peaks as expected around cherenkov cone emission angle (~63°)



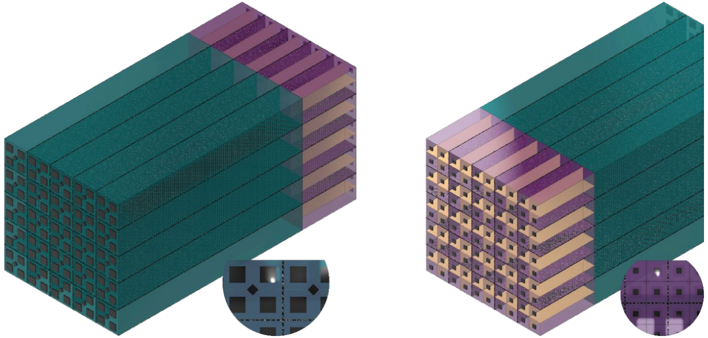


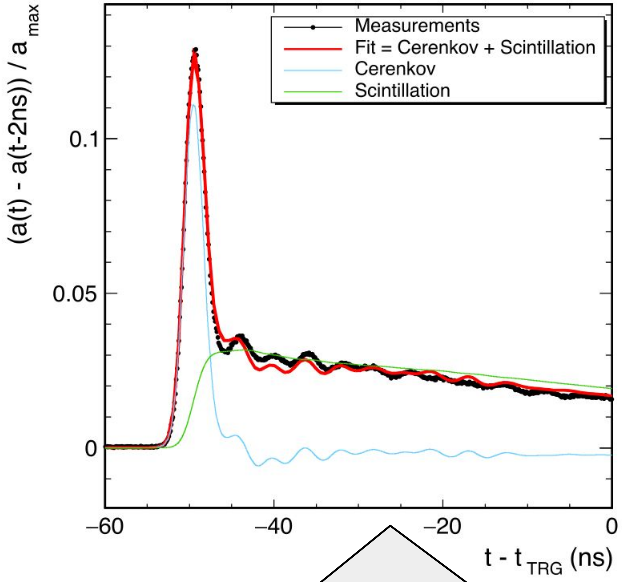


BGO prototype geometry

Development of a second full containment prototype made of BGO crystals ongoing lead by Calvision

- 10x10 front array, 1 SiPM/crystal
  - Readout with FERS CITIROC
  - Finalizing choice of small cell SiPMs now
- 5x5 rear array, 4 SiPM/crystal, UG330 filters
  - Readout with DRS or other >=2GS/s digitizer
  - Use waveform analysis to separate S/C
  - Using Broadcom 6mmx6mm SiPMS





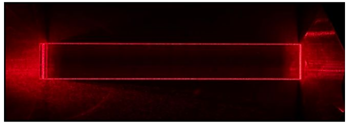
Decomposition of S / C in BGO waveform after SDL filter

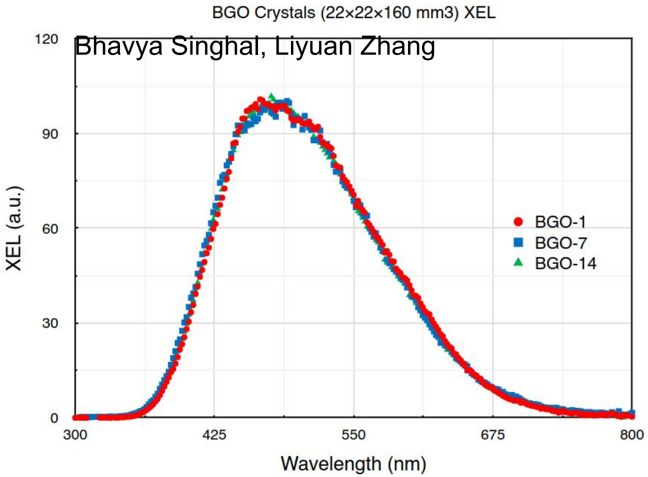
- > 150 Č PE/GeV (4x 6mx6mm SiPMs)
- expect ~2x greater yield w/ optimal light coupling

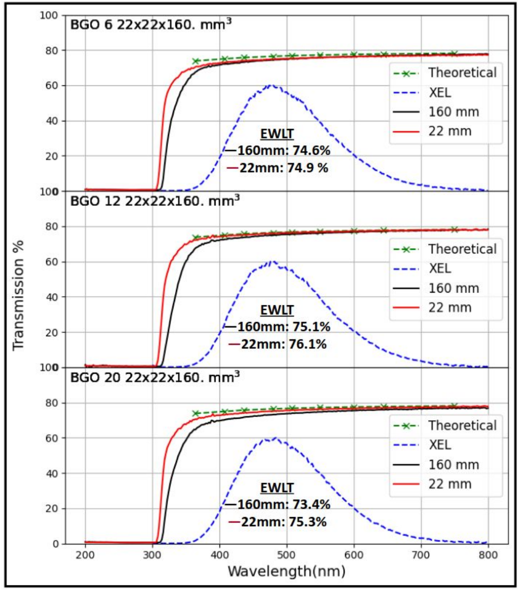
First 20 large BGO crystals

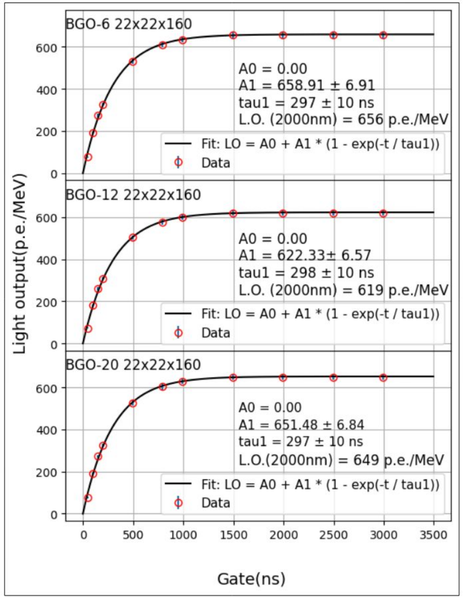
- **BGO crystals** (22×22×160 mm^3) for rear segment under test at Caltech
- Initial checks and uniformity look good
- Waiting for delivery for front crystals and some rear crystals due to export issues

Shanghai SICCASS High Technology Corporation









Summary and outolook

- **A broad R&D program to optimize dual-readout** in scintillating crystals using optical filters and SiPM is **progressing well** thanks to successful beam test campaigns in 2024/2025
  - Will continue, in parallel with prototype construction

- **Construction of two full containment prototypes is close to completion**
  - Plan to be tested on beam in Q2-Q3 2026
  - Following step: a combined test beam with fiber dual-readout (DRCAL) calorimeter

- **Good progress on full simulation implemented in key4hep:** working on reconstruction and validation before moving to higher level physics studies

acknowledgments

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NextGenerationEU

Ministero dell'Università e della Ricerca

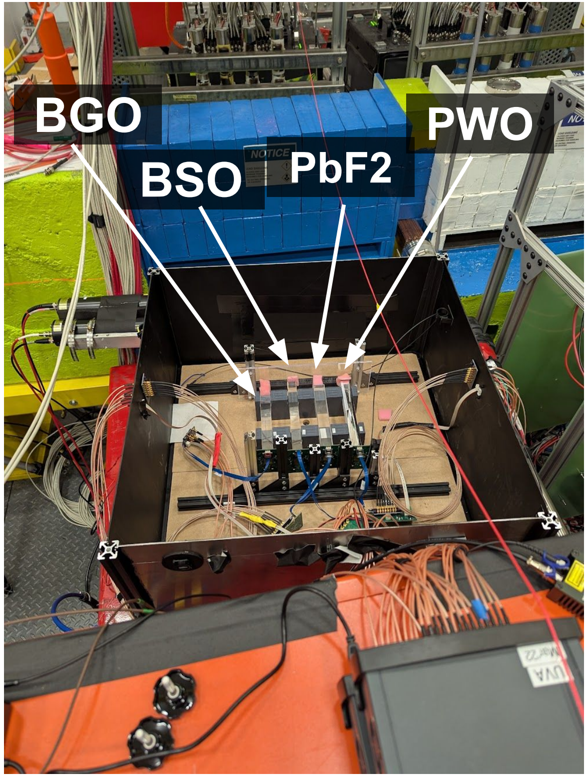
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

Additional material

A broad collaboration

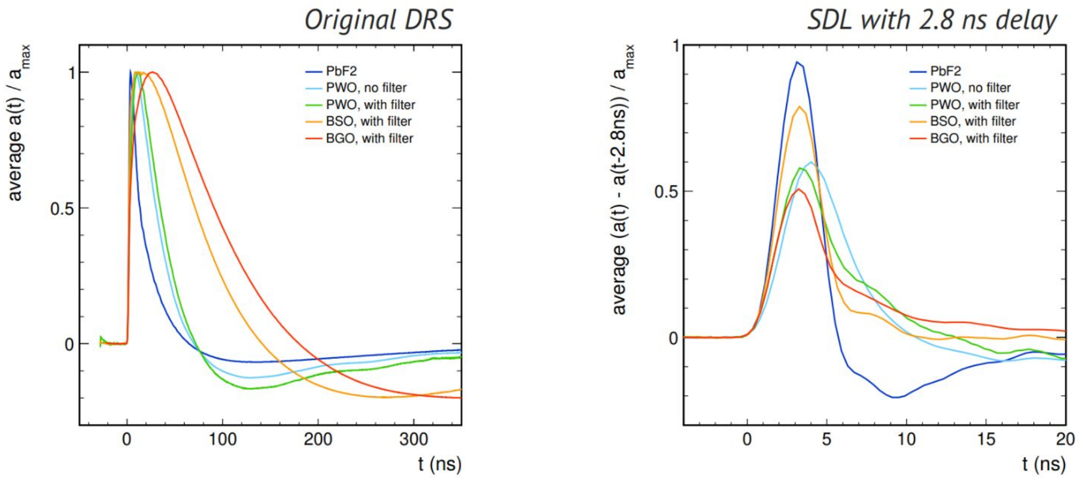
- Interest and efforts growing since 2023
  - **INFN**:
    - INFN groups: Milano-Bicocca, Napoli, Perugia
    - Coordination within the RD_FCC italian collaboration and national grants (PRIN 2022 MAXICC)
  - **CALViSION**:
    - A DOE funded project bringing together several US institutions
    - Maryland, Princeton, UVa, Caltech, FNAL, ANL, SLAC*, Michigan, Catholic University of America*, Brandeis*, Stonybrook*, Rutgers*, TTU. MIT, Baylor*, Purdue, Caltech
  - CERN (Switzerland) with the support of European widening project TWISMA (GA 101078960)
  - IN2P3-IP2I (France)

Jefferson Laboratory test beam (2025)

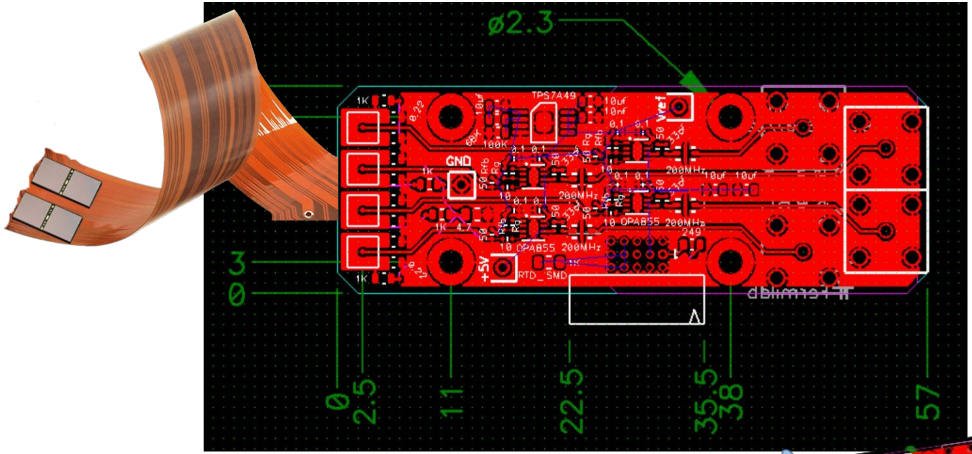


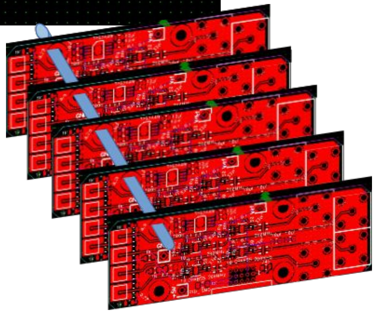
Recent opportunity to take electron data with a faster electronics version of the 2024 DESY TB amps

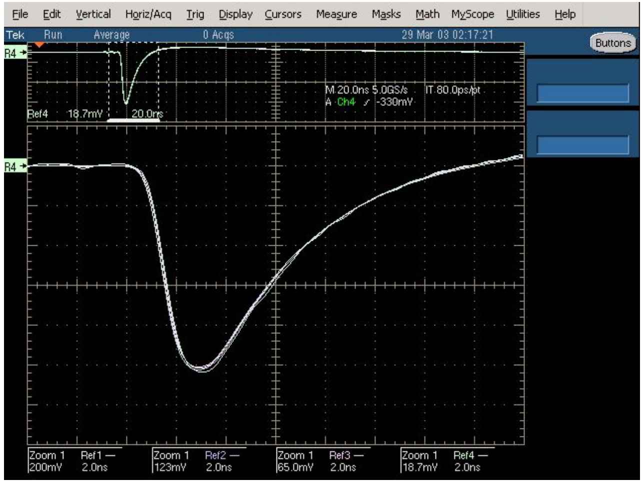
- Compare S/C separation w/ and w/o SDL filter and versus sampling rates (analysis in progress)



Electronics for rear module (Sergey Los, FNAL)







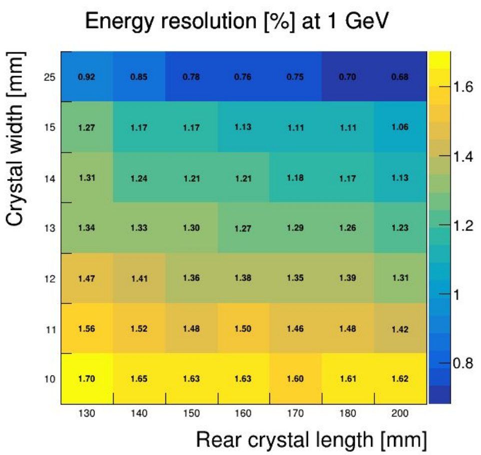
Rear amplifiers

- 4 channels/board
- Based on OPA 855
- O(ns) rise time
- Flex circuit to connect to crystals
- One board fits in "shadow" of one crystal

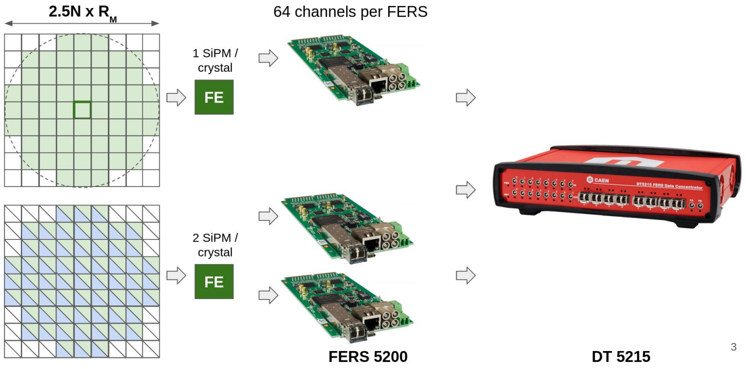
Front flex circuits and adapter for FERS to be designed next

PWO-based prototype

- Layout optimization (crystal dimensions) ongoing
- Procurement of FERS-5200 + DT5215 CAEN electronics for readout completed, purchase of crystals and SiPMs in early 2025
- Design of mechanical support and front-end about to start
- Plan to use DAQ/readout system common to HIDRA (fiber dual-readout calorimeter) prototype for optimal integration



Prototype readout schematics



Geant4 simulation of prototype