Segmented Crystal ECAL with Dual-Readout

Marco Lucchini
for the IDEA calorimeter and Calvision groups

International Workshop on The High Energy Circular Electron Positron Collider

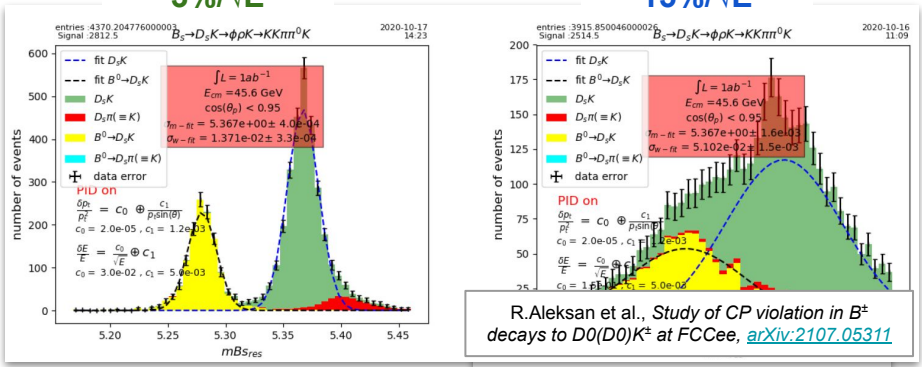
Oct. 23 - 27, 2023, Nanjing, China

Potential for high EM energy Resolution at Higgs factories

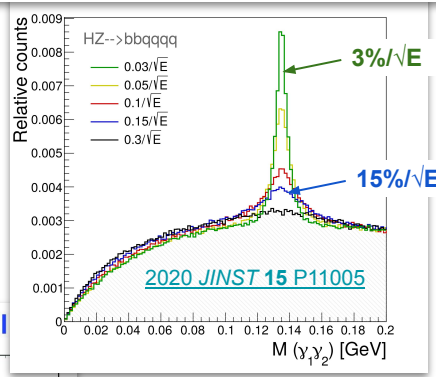
A calorimeter with **3%/√E** EM energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders

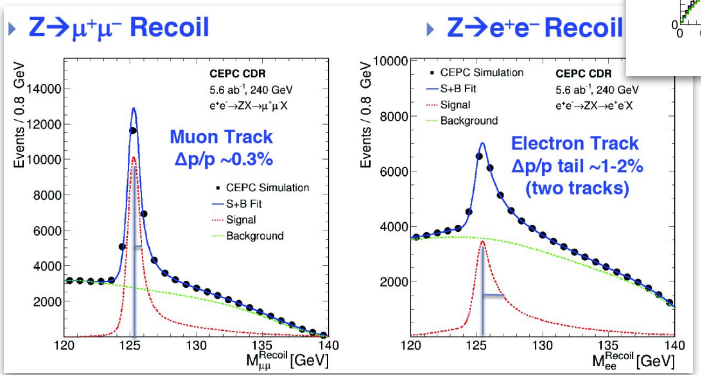
- **CP violation studies** with B_s decay to final states with low energy photons
- **Clustering of π^0's photons** to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)

3%/√E **15%/√E**



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





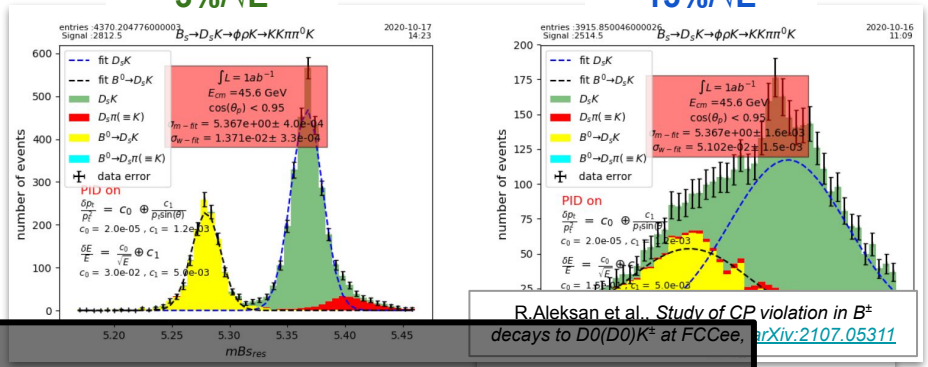
Example from CEPC CDR

Potential for high EM energy Resolution at Higgs factories

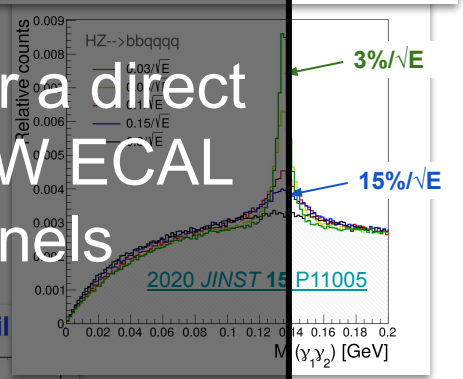
A calorimeter with **3%/√E** EM energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders.

- **CP** [illegible] with B_s decays to final states with low energy photons
- **Clustering of π⁰'s** [illegible] to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)

3%/√E **15%/√E**

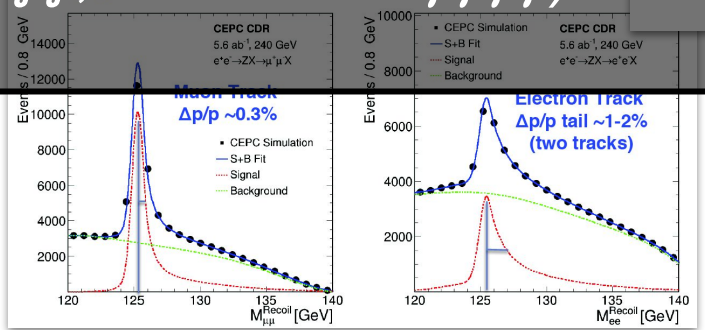


R.Aleksan et al., *Study of CP violation in B± decays to D0(D0)K± at FCCee*, arXiv:2107.05311



See Zhiyu Zhao's talk in previous session for a direct comparison between a crystal ECAL and SiW ECAL performance on some benchmark channels

($H \to gg, H \to \gamma\gamma, B^0_{recoil} \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$)



Example from CEPC CDR

Technological progress in the fields of crystals and photodetectors has **enabled** the design of **a cost-effective and highly performant calorimeter**

Excellent energy resolution to photons and neutral hadrons
(~3%/√E and ~30%/√E respectively)

Separate readout of scintillation and Cherenkov light
(to exploit dual-readout technique for hadron resolution and linearity)

Longitudinal and transverse segmentation
(to provide more handles for PID and particle flow algorithms)

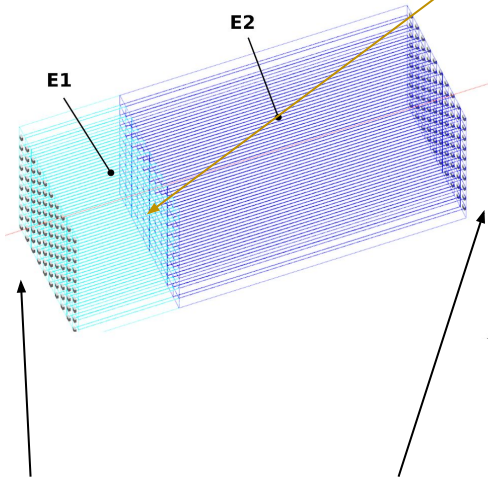
Energy resolution at the level of 4-3% for 50-100 GeV jets

Precise time tagging for both MIPs and EM showers
(time resolution better than 30 ps)

"Maximum information" calorimetry
(**6D**: x,y,z,t,E,C/S)

Conceptual layout

Optimize energy resolution:
no dead material at
shower maximum

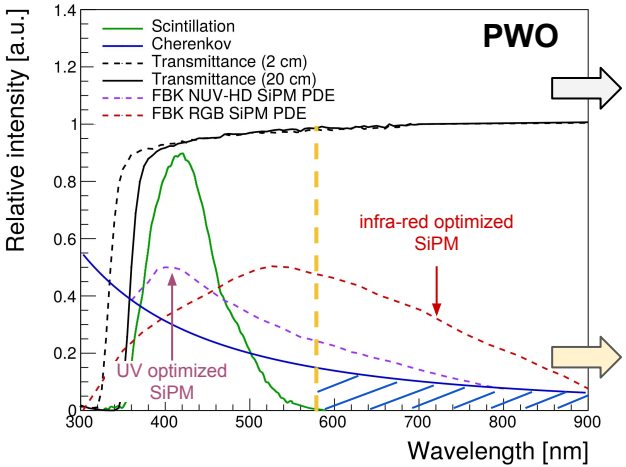


Contained number of channels
Transverse granularity: 1x1-1.5x1.5 cm²
Longitudinal segmentation: 2 layers
Total channel count <1800k

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

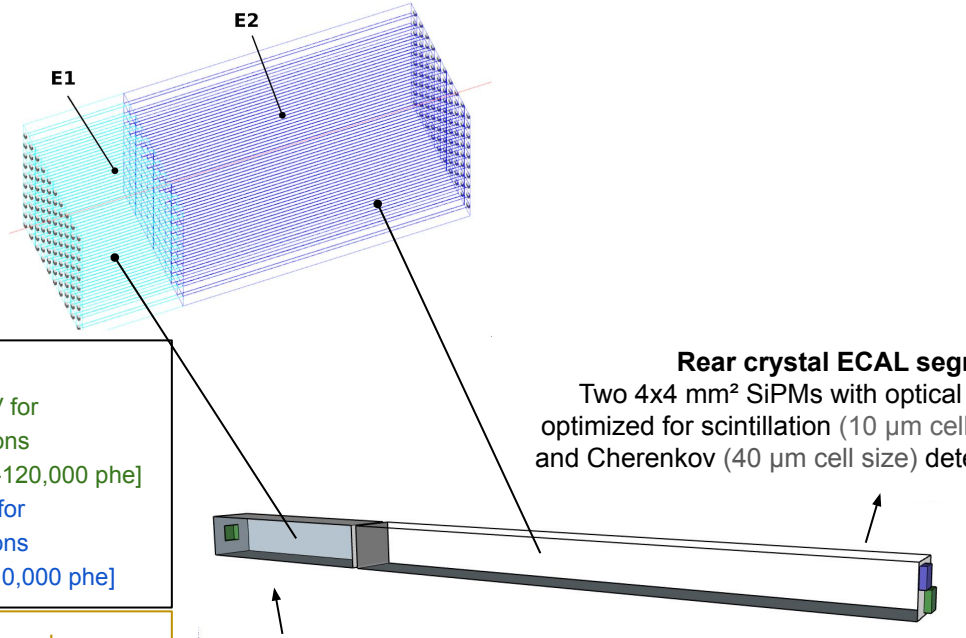
Conceptual layout

Dual-readout implementation
Cost-effective SiPM readout
Optical filters for separation of Cherenkov and scintillation signal from the same active elements



Estimated:
- >2000 phe/GeV for scintillation photons [dyn. range: 100-120,000 phe]
- >100 phe/GeV for Cherenkov photons [dyn. range: 10-10,000 phe]

Cherenkov photons above scintillation peak are much less affected by elf-absorption

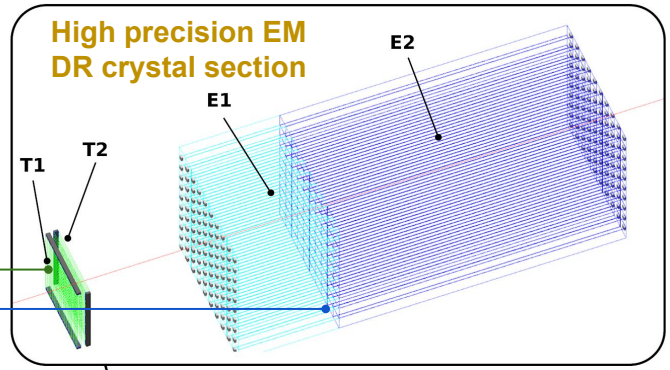


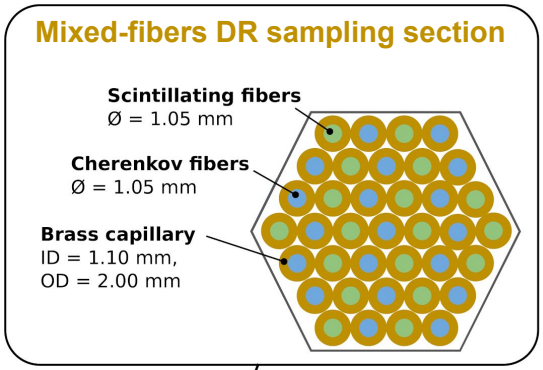
Rear crystal ECAL segment:
Two 4x4 mm² SiPMs with optical filters optimized for scintillation (10 μm cell size) and Cherenkov (40 μm cell size) detection

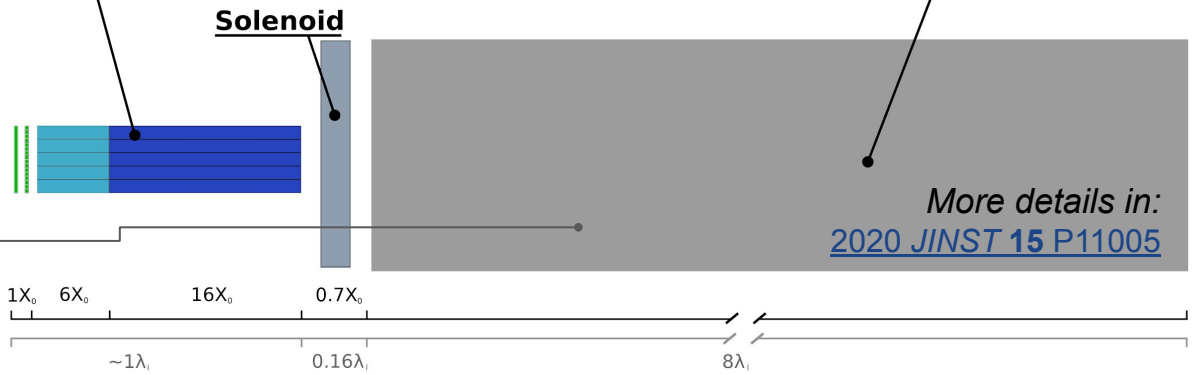
Front crystal ECAL segment:
Single 5x5 mm² SiPM per crystal optimized for scintillation light detection (10 μm cell size)

Conceptual layout: maximum information calorimetry

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~$0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries



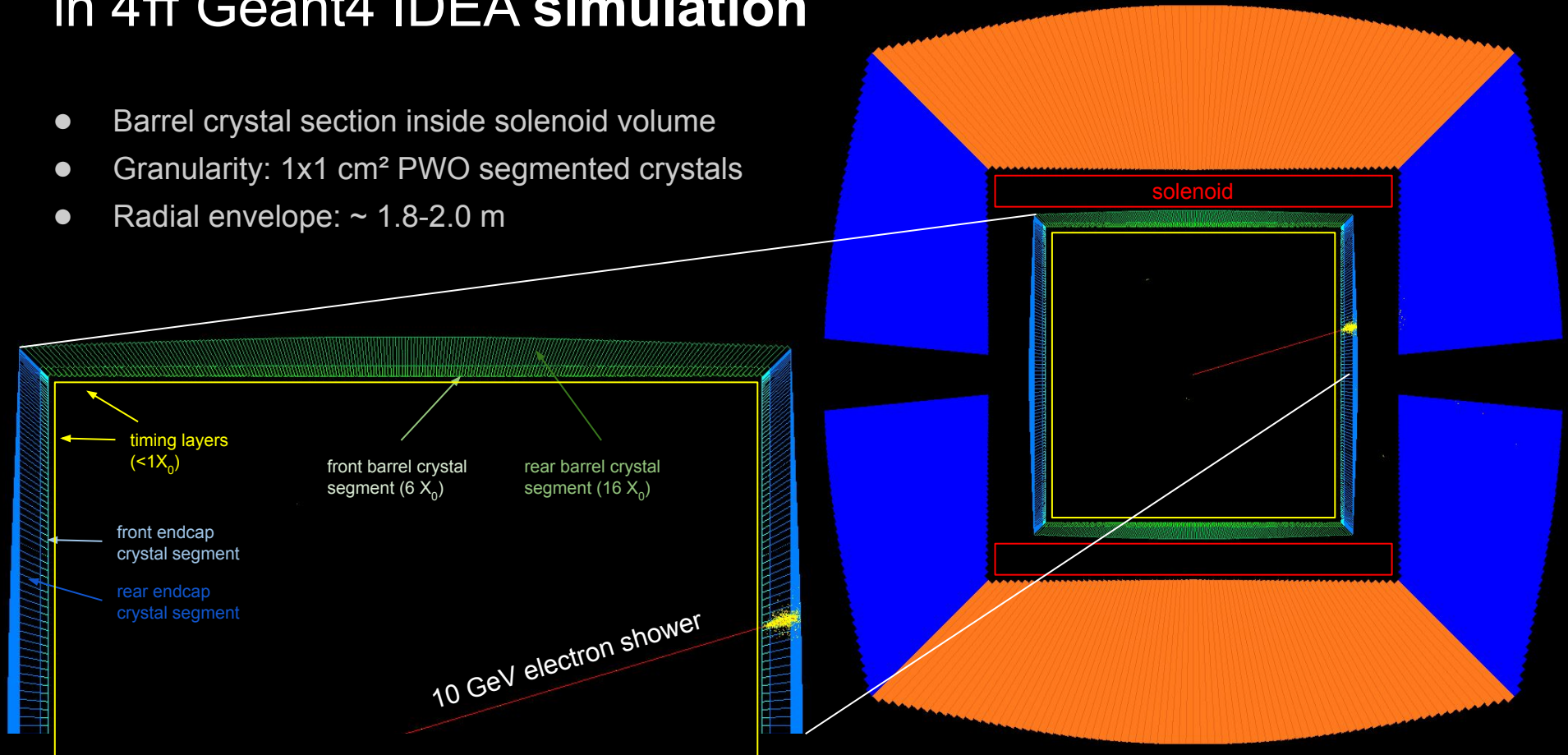




More details in:
2020 *JINST* **15** P11005

Integration of crystal EM calorimeter in 4π Geant4 IDEA **simulation**

- Barrel crystal section inside solenoid volume
- Granularity: 1x1 cm² PWO segmented crystals
- Radial envelope: ~ 1.8-2.0 m

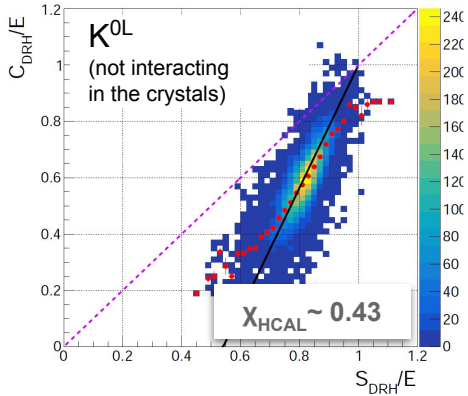


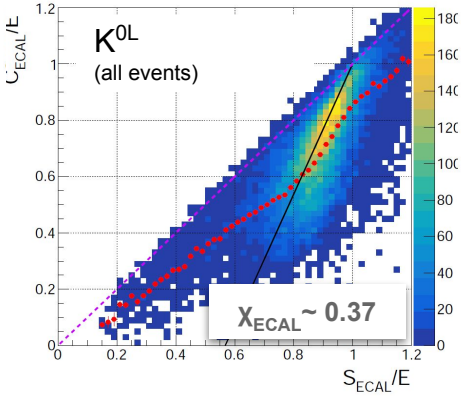
The **dual-readout method** in a hybrid calorimeter

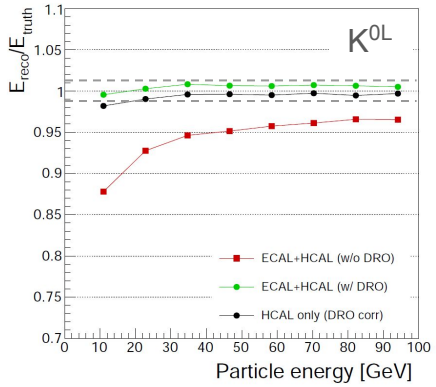
- Apply the DR correction on the energy deposits in the crystal and fiber segments first and then sum up the corrected energy from both segments

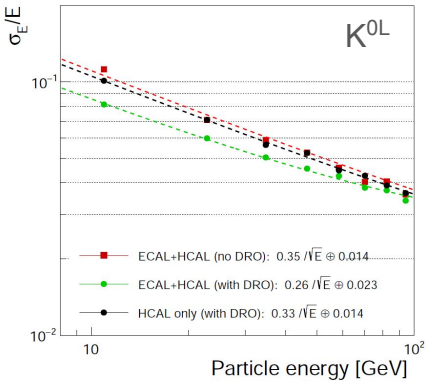
$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}}$$
$$E_{total} = E_{HCAL} + E_{ECAL}$$

- **Dual-readout method confirms its applicability in a hybrid calorimeter**
  - Response linearity to hadrons restored within ±1%
  - Hadron energy resolution comparable to that of the fiber-only IDEA calorimeter



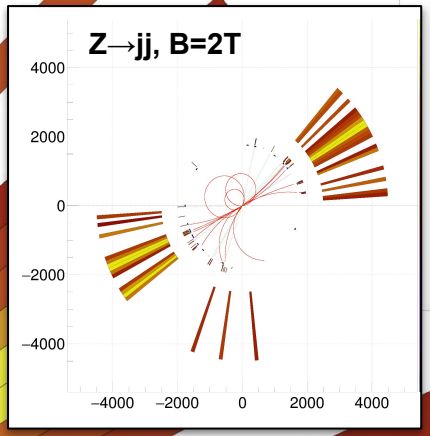


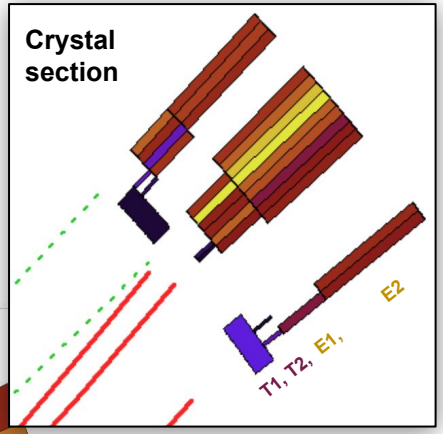




A Dual-Readout ‘prototype’ Particle Flow Algorithm (DR-pPFA)

- Full calorimeter simulation in Geant4
- Tracker MC truth momentum smeared





photons

HCAL fiber towers

EM crystal rear

EM crystal front

Timing rear

Timing front

Solenoid gap

neutral hadron

charged hadron

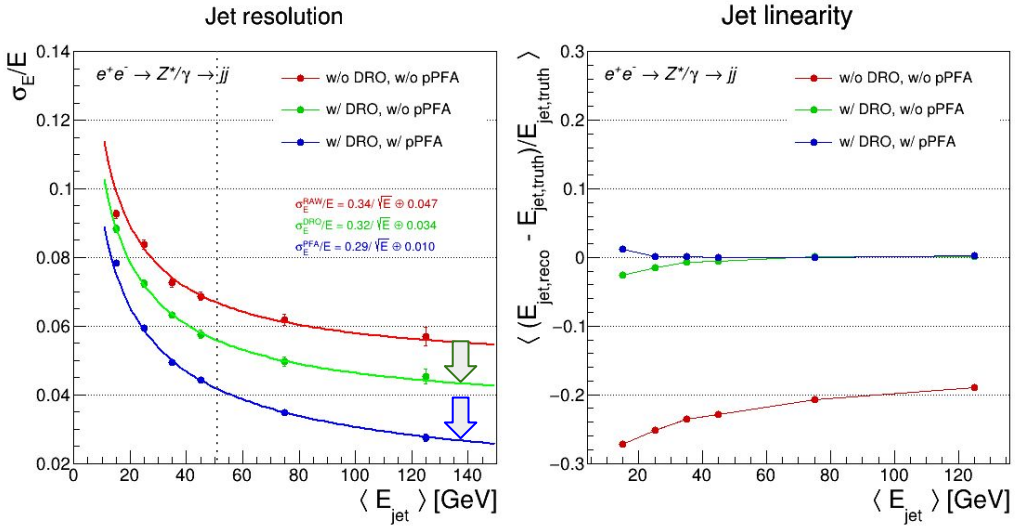
More details in: [2022 *JINST* **17** P06008]

Jet resolution: with and without DR-pPFA

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

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

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



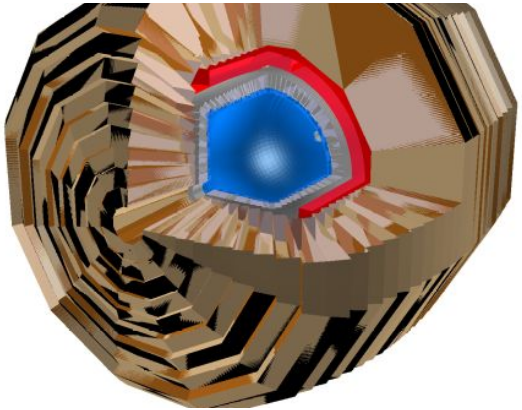
Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

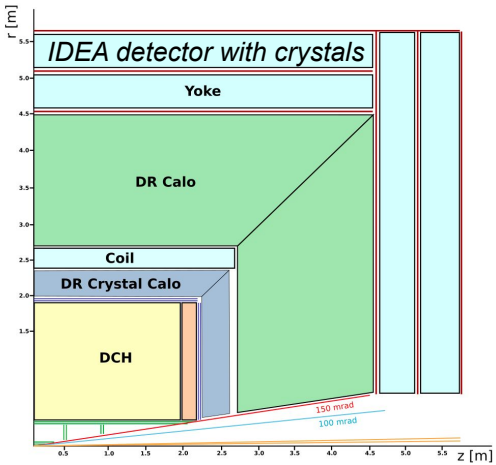
Transitioning to the key4hep toolkit

- Crystal calorimeter geometry implemented in **DD4HEP**
- Working on validation of simulation and first reconstruction studies using **edm4hep** data format
- Near/long term goals:
  - Reproduce a subset of Geant4 standalone results
  - Optimization of crystal granularity against low level particle reconstruction benchmarks (e.g. separation of photons from π^0's)
  - Complete integration with other IDEA sub-detectors
  - Explore different options for solenoid location
  - Continue development of dedicated particle flow reconstruction algorithm optimized for dual-readout information

W.Chung

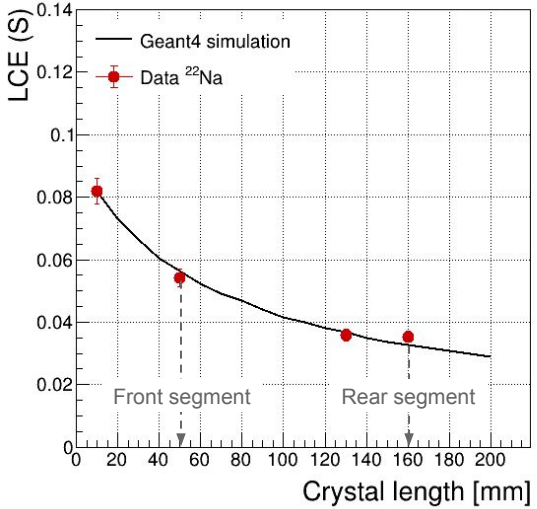
IDEA + SCEPCal (detector element sizes exaggerated for visibility)

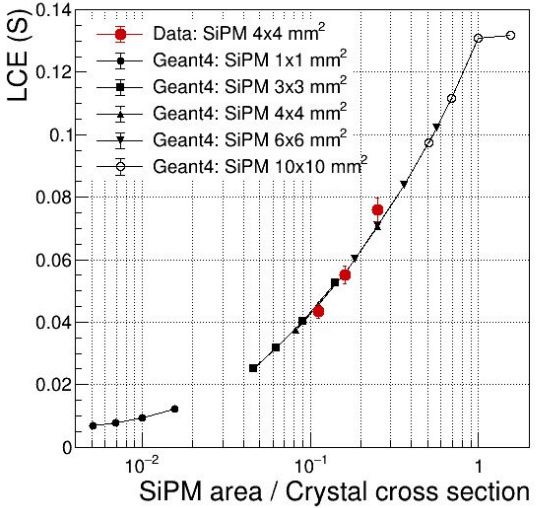


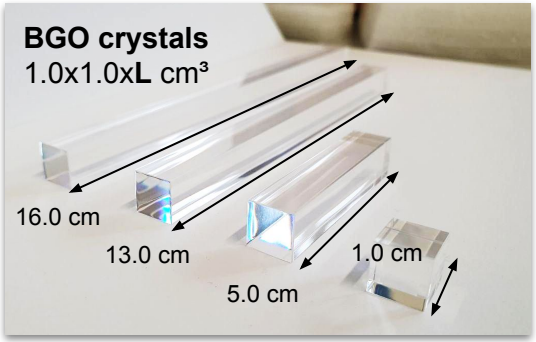


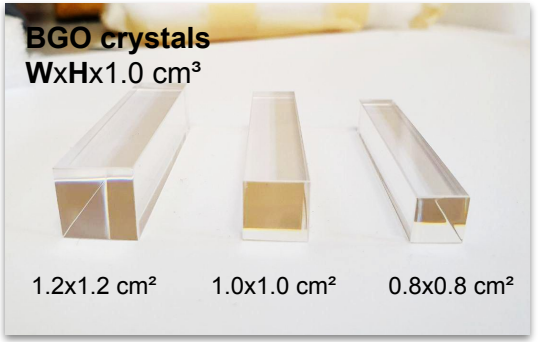
Light output measurements

- Ongoing laboratory measurements to validate simulation
  - Good agreement between data and Geant4 ray tracing
- Studying light collection efficiency as a function of:
  - Crystal length (e.g. front vs rear segment)
  - SiPM active area wrt crystal cross section



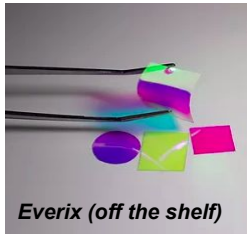


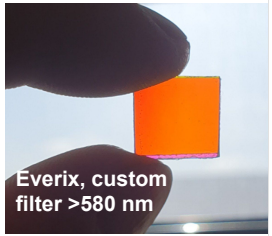


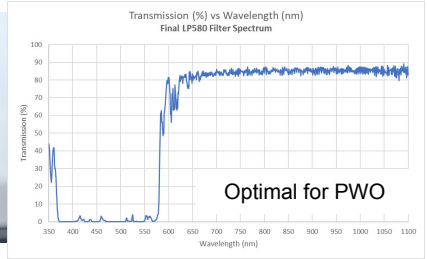


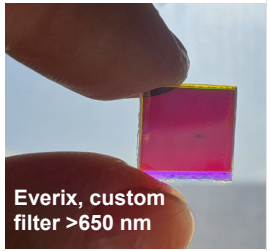
R&D on optical filters

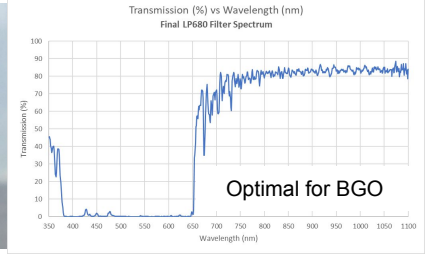
- Exploring both absorption and interference optical filters
- Interference filters
  - Custom development ongoing with *Everix*
  - Possibly very thin O(200) um → possibility to embed into SiPM protective window
  - Transition edge shifts with incidence angle (impact with scintillation light to be assessed)
- Absorption filters
  - Off-the-shelf product
  - Typically thicker O(2) mm
  - Insensitive to incidence angle

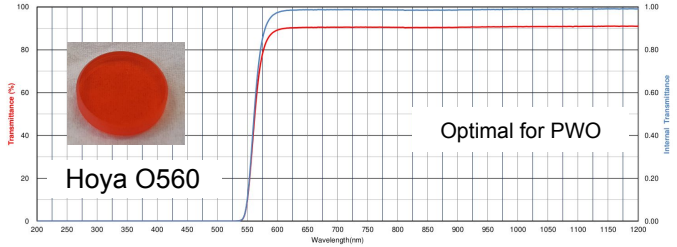


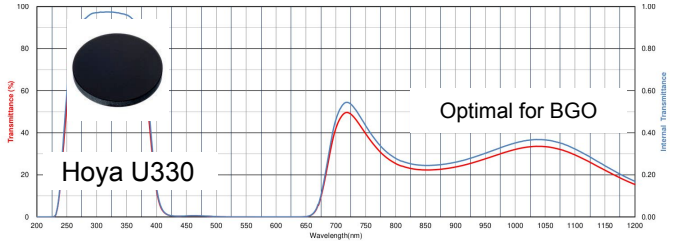






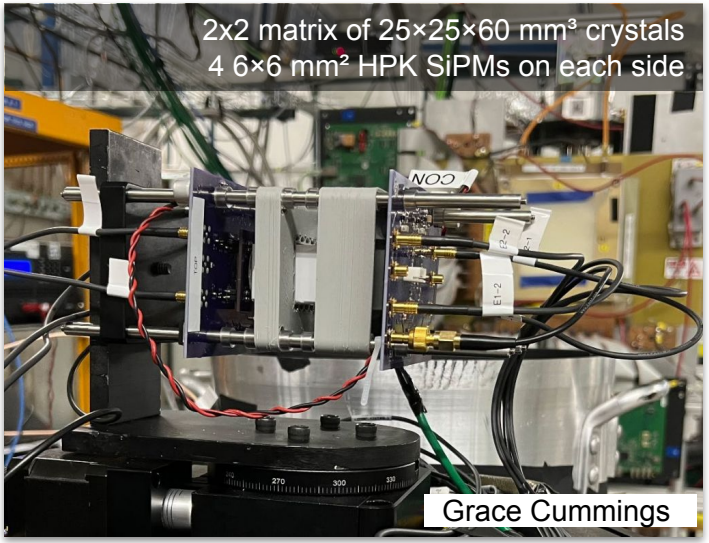


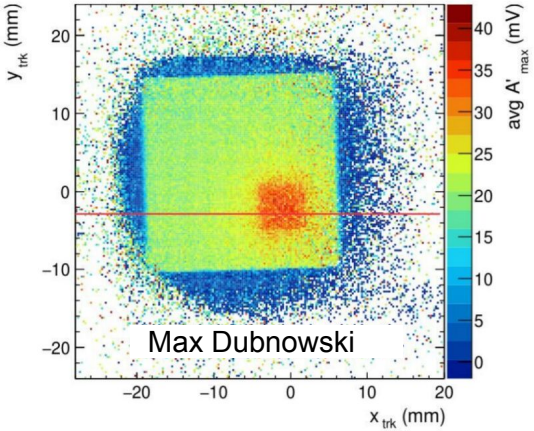




First beam tests at FNAL in 2023 (Calvision, US)

- First single crystal tests on beam at FNAL
  - PbF2, PWO at different angles
  - PWO with U330 filter on rear side
  - BGO with R660 filter on rear side
- Study sensor response with 120 GeV pions (~MIPs)
- Data analysis and comparison with Geant4 simulation ongoing





Summary

- EM energy resolution at the 1-3%/√E level can **expand the physics potential of e^+e^- collider experiments** providing enhanced sensitivity to low energy photons

- A **dual-readout hybrid calorimeter** (homogeneous crystals + fibers in brass tubes) **can meet the requirements of EM, HAD and jet energy resolution** (through the development of dedicated dual-readout particle flow algorithms)

- **Growing national and international efforts** (INFN MiB&Napoli, Calvision in US, Lab27 at CERN) to address **R&D challenges** and development of simulation tools to optimize a cost-effective calorimeter design in the context of the ECFA strategic Detector R&D roadmap→ forming DRD6 collaboration