Combining **Dual-Readout** Crystals and Fibers in a **Hybrid Calorimeter** for the IDEA Experiment

Marco Lucchini

INFN & University of Milano-Bicocca

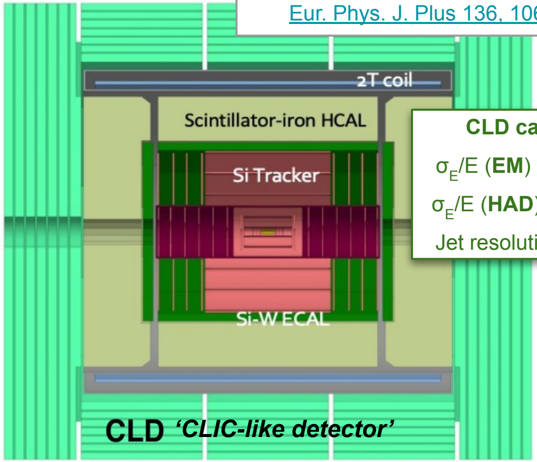
*On behalf of the **IDEA calorimeter group***

Current baseline detector concepts for future e^+e^- colliders

M.Aleksa et al., *Calorimetry at FCC-ee*, Eur. Phys. J. Plus 136, 1066 (2021)

Two main baseline concepts for general purpose detectors at future e^+e^- colliders (have been around since a while):

- **CLD**: Sampling calorimeters with silicon / plastic scintillators active elements interleaved with tungsten / steel
  - Exploiting high granularity for particle flow algorithms (combining tracker and calorimeter exploiting topological information)
- **IDEA**: Sampling calorimeters with ~2 m long scintillating (plastic) and cherenkov fibers inside absorber groove
  - Exploiting the dual-readout approach (correct for EM fluctuations in hadronic shower developments)

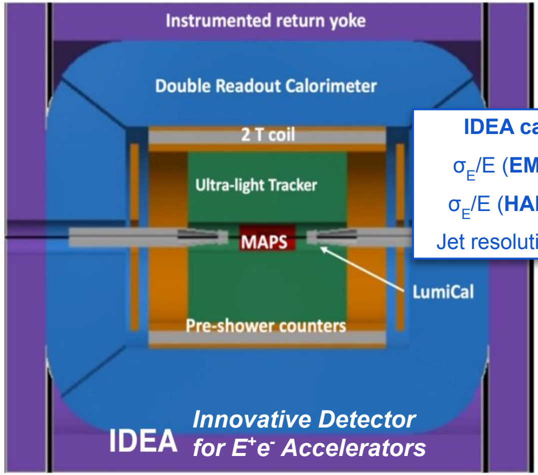


CLD calorimeter

σ_E/E (**EM**) ~15-17%/$\sqrt{E}$

σ_E/E (**HAD**) ~45-50%/$\sqrt{E}$

Jet resolution ~ 30%/$\sqrt{E}$



IDEA calorimeter

σ_E/E (**EM**) ~11%/$\sqrt{E}$

σ_E/E (**HAD**) ~30%/$\sqrt{E}$

Jet resolution ~ 30%/$\sqrt{E}$

Current baseline detector concepts for future e^+e^- colliders

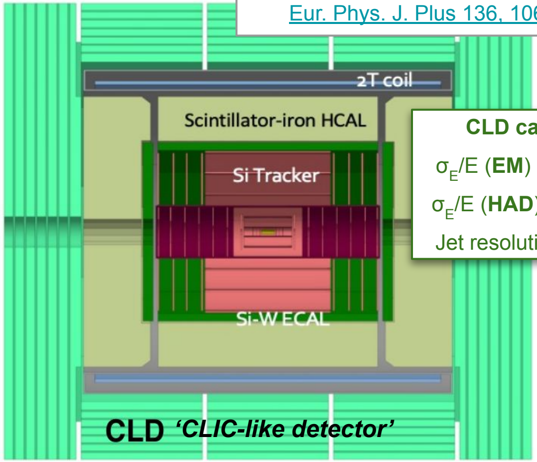
M.Aleksa et al., *Calorimetry at FCC-ee*, [Eur. Phys. J. Plus 136, 1066 (2021)](https://doi.org/)

Two main baseline concepts for general purpose detectors at future e^+e^- colliders (have been around since a while):

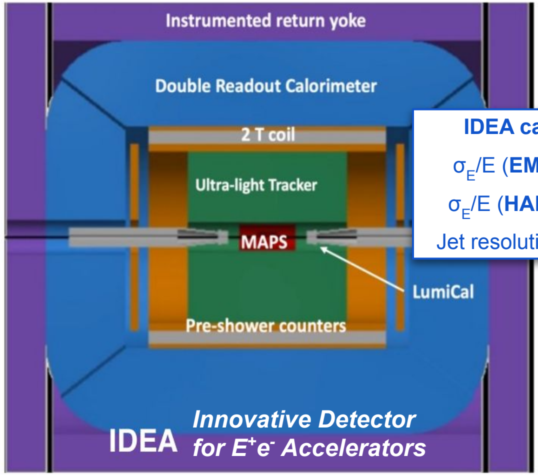
- **CLD**: Sampling calorimeters with silicon / plastic scintillators active elements interleaved with tungsten / steel
    - Exploiting high granularity for particle flow algorithms (combining tracker and calorimeter exploiting topological information)

- **IDEA**: Sampling calorimeters with ~2 m long scintillating (plastic) and cherenkov fibers inside absorber groove
    - Exploiting the dual-readout approach (correct for EM fluctuations in hadronic shower developments)

- **EM energy resolution is far from that of state-of-the-art homogeneous crystal calorimeters (1-3%/√E)**



CLD calorimeter
σ_E/E (**EM**) ~15-17%/√E
σ_E/E (**HAD**) ~45-50%/√E
Jet resolution ~ 30%/√E



IDEA calorimeter
σ_E/E (**EM**) ~11%/√E
σ_E/E (**HAD**) ~30%/√E
Jet resolution ~ 30%/√E

Potential for high EM energy resolution

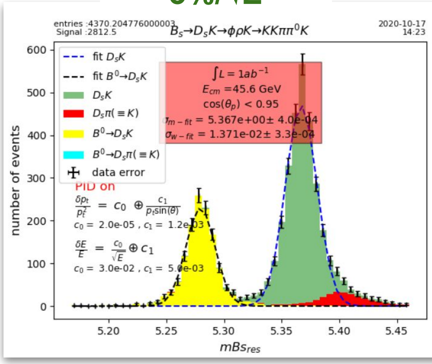
A calorimeter with **3%/√E** EM energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders

Potential for high EM energy resolution

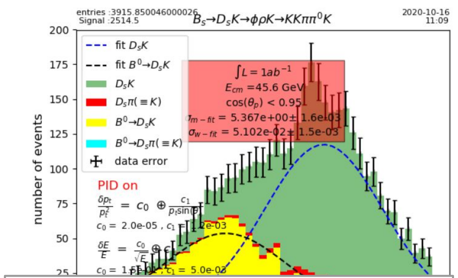
A calorimeter with **3%/√E** EM energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at e^+e^- colliders

- **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)

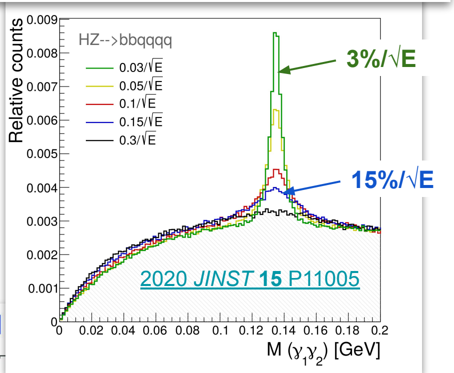
3%/√E



15%/√E

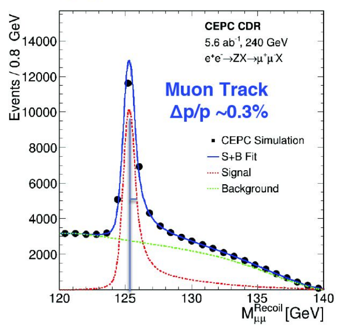


R.Aleksan et al., *Study of CP violation in $B^\pm$ decays to D0(D0)K$^\pm$ at FCCee*, arXiv:2107.05311

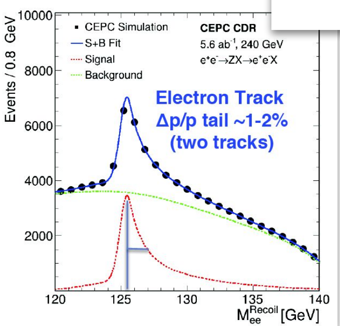


2020 *JINST* **15** P11005

▸ Z→μ⁺μ⁻ Recoil



▸ Z→e⁺e⁻ Recoil



Example from CEPC CDR

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

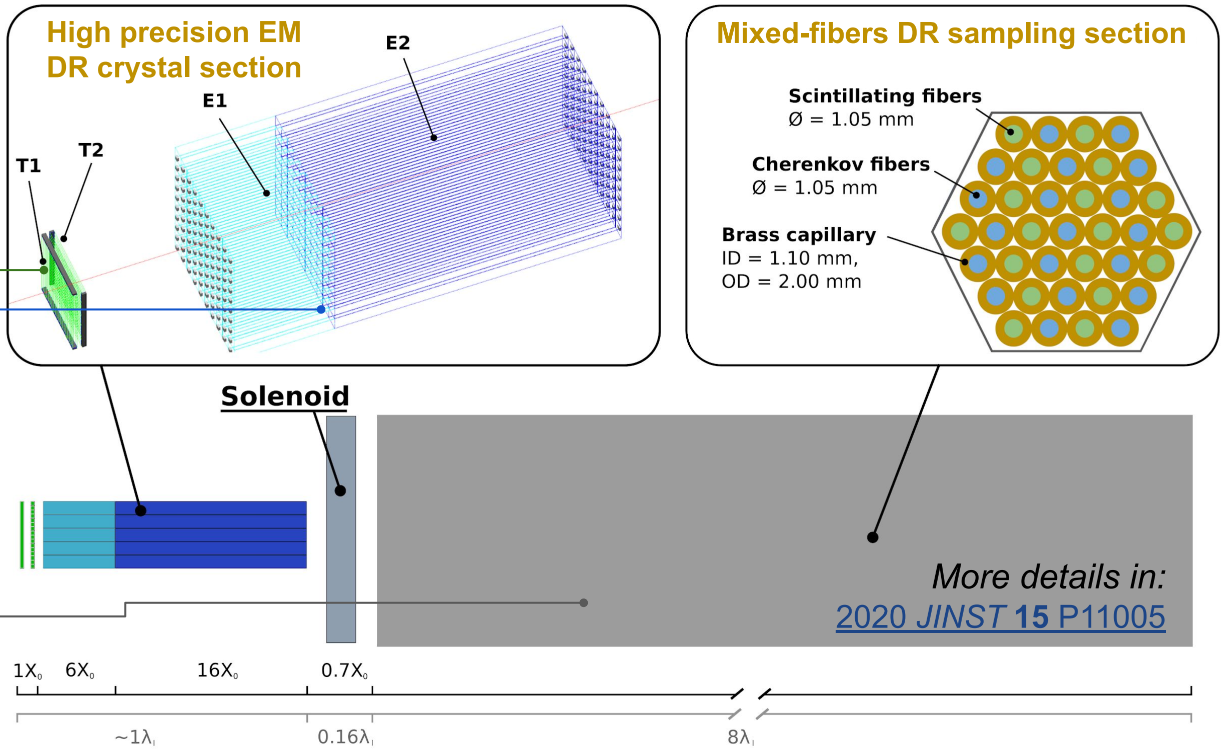
- **Excellent energy resolution to photons and neutral hadrons**
  (~3%/√E and ~30%/√E respectively)
- **Separate readout of scintillation and Cherenkov light**
  (to exploit dual-readout technique for hadron resolution and linearity)
- **Longitudinal and transverse segmentation**
  (to provide more handles for 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

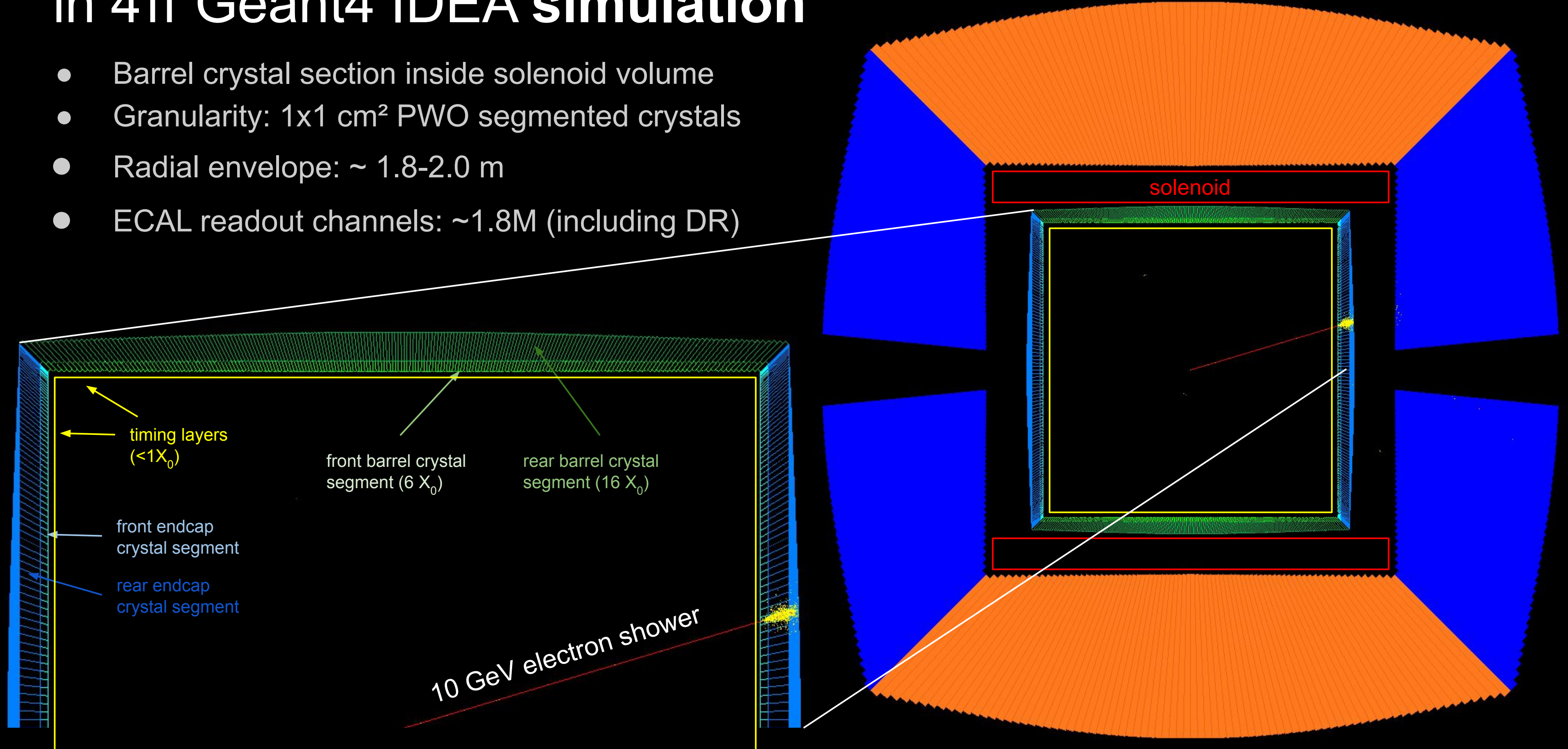
- **Transverse and longitudinal segmentation** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

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

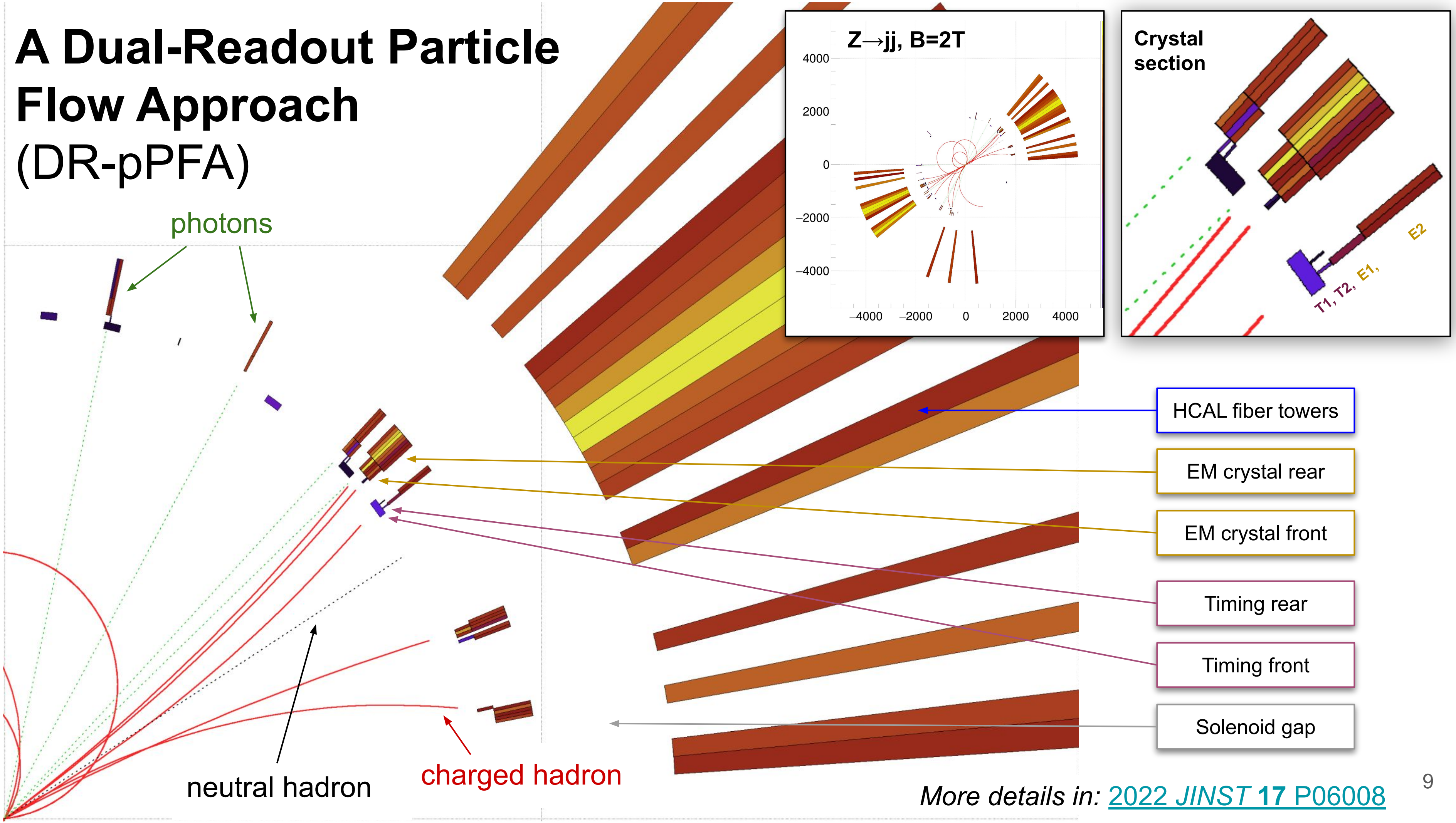


Integration of crystal EM calorimeter in 4π Geant4 IDEA **simulation**

- Barrel crystal section inside solenoid volume
- Granularity: 1x1 cm² PWO segmented crystals
- Radial envelope: ~ 1.8-2.0 m
- ECAL readout channels: ~1.8M (including DR)



A Dual-Readout Particle Flow Approach
(DR-pPFA)



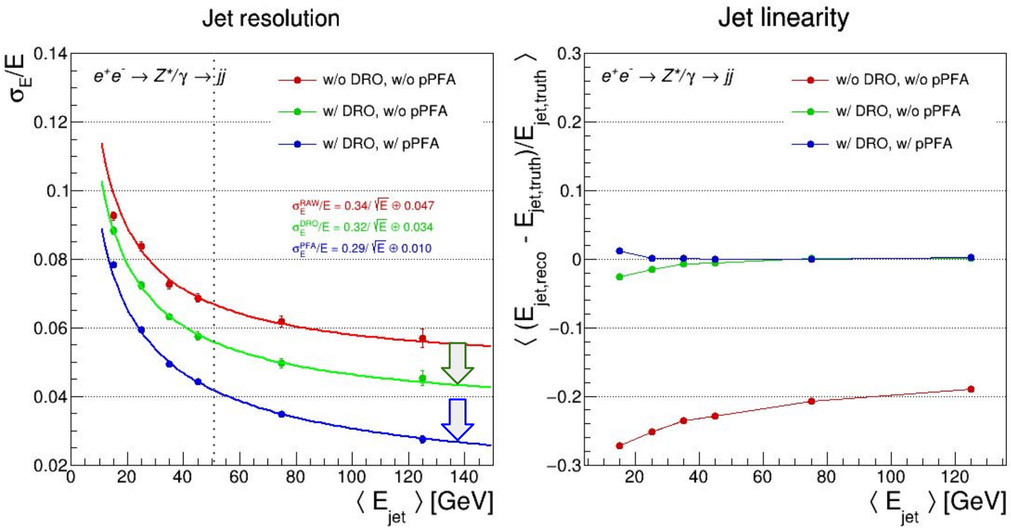
More details in: [2022 *JINST* **17** P06008]

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

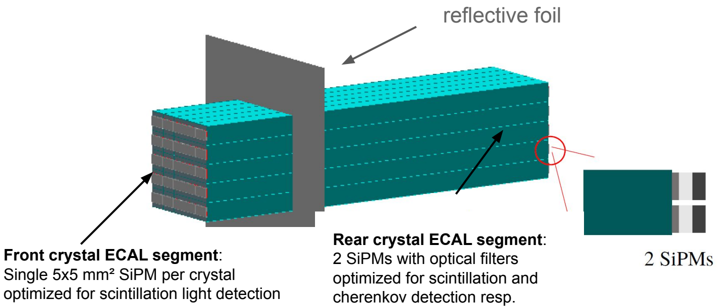


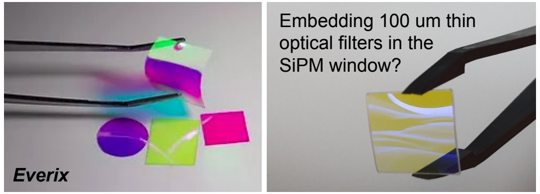
Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

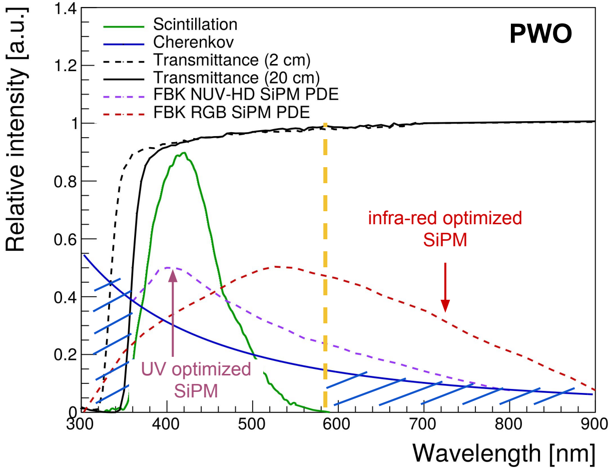
Ongoing R&D activities on the EM crystal section

- **Key R&D challenges**:
  - Crystal **readout with SiPMs**
    → challenging dynamic range and photon sensitivity
  - Multi-signal readout challenges:
    - Reasonable scintillation and cherenkov light yields
    - **Good separation of scintillation and cherenkov signals**
      → e.g. based on wavelength (thin filters)
  - Main crystal candidates are PWO, BGO, BSO because of their high Cherenkov yield and density

- Interest and efforts are ramping up within the IDEA calorimeter group and the CalVision project in the US

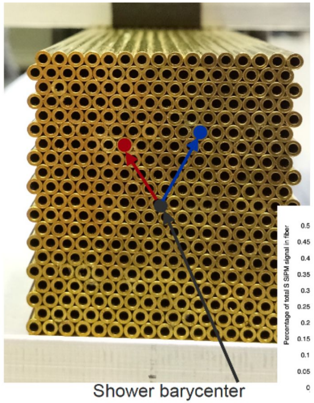


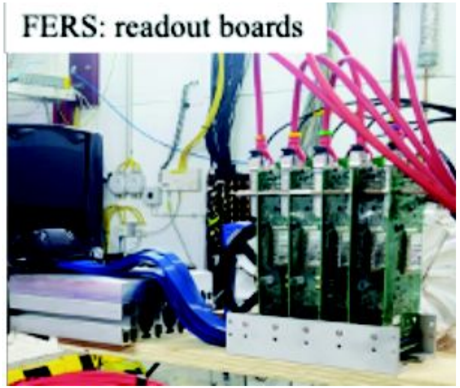




Test beam results from fiber calorimeter prototype

- **EM-size prototype** (10x10x100 cm^3) put on beam in 2021
- Basic calorimeter unit: one **brass capillary** tube of 2 mm external diameter hosting a fiber of 1 mm diameter
- Scaling up to hadron shower size ongoing (See I.Vivarelli @ ECFA Desy Workshop)





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 international collaborative efforts** to address **R&D challenges** and development of simulation tools to optimize a cost-effective calorimeter design