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

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Crystal calorimetry has a long history of pushing the frontier of high energy resolution measurements for electromagnetic particles. Recent technological developments in the fields of crystal manufacturing and photo-detector developments (SiPMs) have opened new perspectives on how a segmented crystal calorimeter with dual-readout capabilities can be exploited for particle detectors at future collider experiments. In particular, a cost-effective integration of such a crystal calorimeter with the fiber-based calorimeter of the IDEA detector could achieve an energy resolution of $3\%/\sqrt{E}$ for electromagnetic particles and $26\%/\sqrt{E}$ for neutral and charged hadrons. In this contribution we provide a first demonstration of how the development of a new dedicated particle flow algorithm that exploits the dual-readout information (DR-PFA) from such a calorimeter can achieve an excellent energy resolution of 4% for 50 GeV jets and 3% for 100 GeV jets. Such a resolution is comparable to that of the highest performing PFA calorimeters and enables an efficient separation of the W and Z boson dijet invariant mass, a key requirement for detectors at future e^+e^- colliders.

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1. Introduction

Among the highest priorities in the future of particle accelerators is the construction of an e^+e^- collider such as CEPC, FCC-ee or ILC for detailed studies of the Higgs boson properties and exploration of new physics beyond the Standard Model. In this context, the design of innovative detectors that can maximally exploit the collider potential by accurately measuring all particles originating from the collision is crucial and the design of the calorimeter system is a key aspect. One of the main performance benchmarks for such a calorimeter is its capability to measure jets with good energy and angular resolution to reconstruct events with Z, W or H boson decaying in hadronic modes. Historically, two main strategies have been pursued in the design of the calorimeter, one exploiting a highly granular Si-W sampling calorimeter and exploiting particle flow algorithms [6, 7] and a second one exploiting the simultaneous readout of scintillation and Cerenkov signals to correct for fluctuations in the electromagnetic fraction, f_{em}, of hadron showers using the dual-readout method [1].

In this contribution we explore the potential of combining the two methods using a dual-readout hybrid calorimeter system consisting of a homogeneous crystal electromagnetic section with transverse and longitudinal segmentation followed by a sampling calorimeter section made of scintillating and Cerenkov fibers embedded in a brass absorber as in the baseline IDEA calorimeter [2, 3]. The addition of a crystal section, with respect to the IDEA baseline design, provides an excellent time and energy resolution for photons and electrons (at the level of 20 ps and $3\%/\sqrt{E}$ resp.) and a powerful tool for particle identification based on the 4-layer longitudinal segmentation [5]. The segmented crystal section, instrumented with dual-readout capabilities, also facilitates the development of a dedicated particle flow algorithm which enhances the jet energy resolution combining charge particle measurements from the tracking system while maintaining an excellent energy resolution for neutral hadrons ($25-30\%/\sqrt{E}$).

2. Description of the calorimeter simulation

The detector simulation includes a homogeneous crystal calorimeter section ($1.77 < R < 2.00$ m) followed by a fiber-brass sampling calorimeter ($2.50 < R < 4.50$ m). In the barrel region a 50 cm thick ultra-light solenoid (about $0.7X_0$) is located between the two calorimeter segments. A picture of the simulated geometry is shown in Fig. 1. In the crystal section, a thin ($< 1X_0$) and granular grid ($\sim 3\times 3$ mm^2) of LYSO:Ce crystals for timing measurements à la CMS MTD [4] is followed by two layers of PWO crystals of 6 and 16 X_0, respectively, as described in [5]. The PWO crystals have a projective geometry with a cross-section of about 1 cm^2 and could be read out with a pair of 5×5 mm^2 Silicon Photomultipliers (SiPMs) and dedicated optical filters for simultaneous detection of the scintillation (S) and Cerenkov (C) signals. Preliminary ray-tracing simulations [5] indicate that a yield of 2000 phe/GeV and 100 phe/GeV could be achieved for the S and C signals, respectively, and such values are used in the following to apply a Poissonian smearing on the reconstructed energy signals. An equal amount of polystyrene-based scintillator and clear plastic fibers (PMMA), placed in a chess-board like geometry with a 1.5 mm pitch, and embedded in a brass structure is used for the sampling section of the calorimeter. The fiber diameter is 1 mm thick so that each fiber is separated from the closest ones by 0.5 mm of absorber material. The fibers are arranged in projective readout towers with transverse front section of about 5×5 cm^2 for the present study while a much finer transverse granularity (down to single fiber level) could be implemented in reality and will be matter of future studies. The S and C signals from the fibers account for both Birks' saturation law and photostatistics effects (assuming light yields of 400 and 100 phe/GeV, respectively).

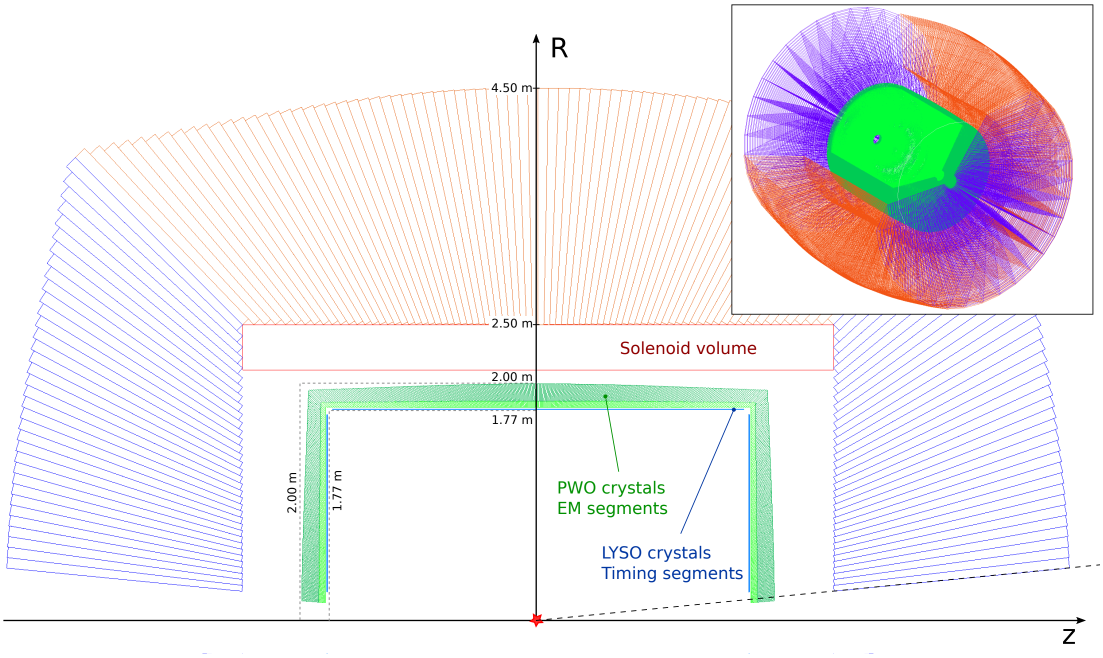

Figure 1: Side view of a single slice of the segmented dual-readout crystal calorimeter (green) inside the IDEA solenoid (red) and fiber calorimeter towers (blue and orange for endcap and barrel, respectively). A 3D broken view of the calorimeter is shown in the inset of the figure.

3. Dual-Readout Particle Flow Algorithm (DR-PFA)

The calorimeter presented above features single particle performance with excellent energy resolution for both electromagnetic and hadronic showers as discussed in [5]. The high granularity in the crystal section also offers a good tool for particle identification based on shower shapes in the transverse and longitudinal directions. In the present contribution we focus on the performance of such a hybrid dual-readout calorimeter system for reconstruction of dijet events. In particular, a dedicated algorithm has been developed to improve the calorimeter energy resolution of the jets by exploiting the high precision measurement of charged hadron momenta as it could be provided by a tracking system. This particular calorimeter system has a coarser longitudinal segmentation (5 layers) with respect to typical Si-W calorimeters designed for PFA (40+ layers) and thus standard algorithms [6, 7] cannot be applied. On the other hand, the higher energy resolution for photons (8-10 times better) and neutral hadrons (2-3 times better), as well as the linear response of the calorimeter to all hadrons provided by the dual-readout method, represent powerful handles to compensate for the poorer topological information on the showers.

Such a *Dual-Readout Particle Flow Algorithm* (DR-PFA) has been tested over a set of samples consisting of off-shell Z boson production decaying to a pair of jets ($e^+e^- \rightarrow Z/\gamma^* \rightarrow jj$) with center-of-mass energy, E_{CM}, varying from 30 to 250 GeV. Events containing muons or neutrinos in their final states have been discarded. The two jets in the event are produced back-to-back and equally share the energy of the event so that each jet has an energy of about $E_{CM}/2$. The samples are generated with the Pythia8 Monte Carlo (MC) generator and processed through the full Geant4 detector geometry described in the previous section. For illustrative purposes, an event display of a jet from a Z boson decay is shown in Fig. 2. The displayed trajectories of particles are calculated analytically for a 2T magnetic field using the MC truth information of the particle momenta at vertex. Each colored volume corresponds to a hit in the detector readout cells with the color scale being proportional to the amount of energy deposited in that cell. Each hit contains the information on the position of the cell (θ, ϕ) and its energy (both scintillation and Cerenkov signals) as well as the information on the longitudinal layer (e.g. crystal segments vs fiber tower).

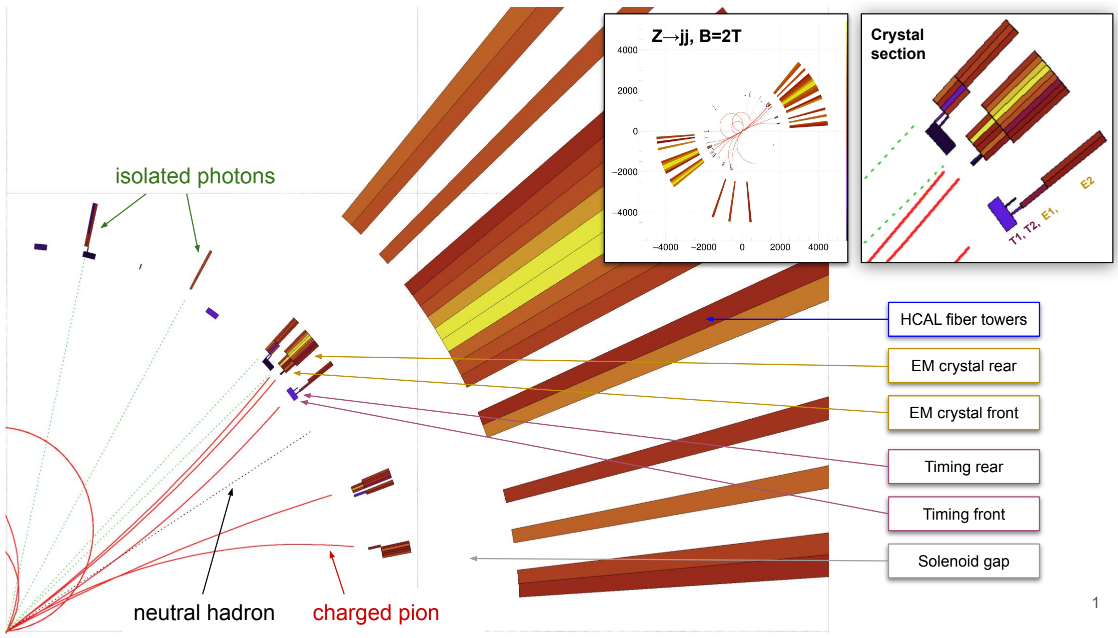

Figure 2: Event display of a jet from a $Z \rightarrow jj$ event at center-of-mass energy of 90 GeV, with a 2T magnetic field. The Monte Carlo tracks of charged pions are shown as red lines, neutral hadrons are represented as dashed black lines while photons (mainly from π^0 decays) are shown as green dashed lines. From inner to outer radius, the 2 layers of the LYSO crystal timing section, the 2 layers of the PWO crystal electromagnetic section, the solenoid gap and the readout towers of the fiber sampling hadron calorimeter are shown.

The DR-PFA algorithm consists of the following steps:

1. *Photon ID*: Identification of calorimeter hits in the crystal section belonging to photons and removal of such hits from the hit collection. The identification considers all crystal hits within a distance $\Delta R = \sqrt{\Delta\theta^2 + \Delta\phi^2}$, smaller than 0.01 from the four momentum vector of a photon as provided by the Monte Carlo truth (an MC independent algorithm is being developed as discussed in Sec. 5).

2. *Charged Track-Hit matching*: Association of calorimeter hits to charged tracks exploiting the dual-readout corrected response of the hybrid calorimeter. For each charged track, the available calorimeter hits are sorted by their distance, ΔR, from the track. Hits within a maximum cut-off distance (ΔR_{max}) are associated to a certain track as long as the addition of a new hit does not bring the total (dual-readout corrected) clustered energy closer to the track momentum. If the energy of clustered hits is within $\pm 0.75\sigma_E$ from the corresponding track momentum the matching is considered successful and the clustered hits are replaced with the track momentum (where σ_E is the expected calorimeter resolution to a single hadron of the corresponding energy, E, i.e. $26\%/\sqrt{E} \cdot E$). Otherwise the charged track is ignored and the calorimeter hits remain.

3. *Jet clustering*: A clustering of successfully matched charged tracks and unmatched calorimeter hits into jets is performed using the Durham anti-kt clustering algorithm (and requiring two jets in the event).

4. *Dual-readout correction of neutral hits*: For each jet a dual-readout correction is applied on the fraction of energy originating from unmatched hits (ideally corresponding to the neutral hadron component).

It should be noted that the dual-readout correction is used twice in the above algorithm: initially by correcting the clustered energy to improve the track-hit matching stage and later to correct for the unmatched calorimeter hits that should belong to neutral hadrons. As no MC truth information is used for the separation of the neutral and charged hadron hits, the present algorithm is subject to the usual *confusion term* which limits the performance of typical PF algorithms. This is due to the fact that hits belonging to a neutral hadron can be mistakenly associated to a charged hadron track as the hadron showers often overlap in the calorimeter volume.

4. Jet reconstruction

The performance of the algorithm has been evaluated as a function of the jet energy and compared with the case where the jet are reconstructed using only the calorimeter hit information, directly fed to the jet clustering algorithm with and without the dual-readout correction. The results are shown in Fig. 3. As expected the dual-readout correction restores the linearity of the calorimeter within $\pm 1\%$ and improves the energy resolution for 50 GeV jets from about 6.5% to 5.5%. The use of the DR-PFA algorithm further enhances the energy resolution by a similar amount achieving a 4% resolution at 50 GeV and 3% for 100 GeV jets.

5. Summary and outlook

While the dual-readout particle flow algorithm (DR-PFA) presented in this contribution is at its early stage of development it already demonstrates the potential of a hybrid calorimeter with segmented dual-readout crystals in front of the IDEA fiber-based sampling calorimeter for jet reconstruction. Using the DR-PF algorithm the jet energy resolution improves with respect to a calorimeter-only reconstruction from 5.5% to 4% at 50 GeV achieving a competitive performance

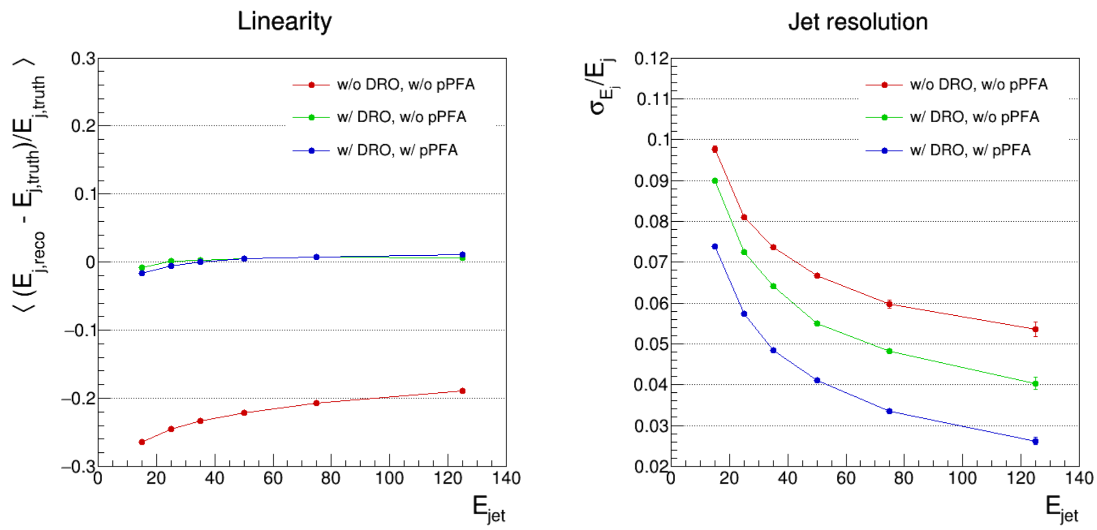

Figure 3: Jet energy linearity (left) and resolution (right) as a function of the jet energy. The calorimeter-only performance with (green) and without (red) dual-readout information is compared to the performance achieved using the DR-PFA algorithm (blue).

that meets the demanding requirement for future e^+e^- colliders to enable an efficient separation of the Z and W boson invariant mass.

Work is ongoing to further improve the robustness and performance of the algorithm. In particular, to develop a photon identification algorithm independent of MC information and that purely uses the shower shapes to identify hits from photons or electron showers. An additional step to clean up the collection of unmatched hits from residual hits of charged hadrons before the jet clustering is also being studied by developing a 'neutral seed' based algorithm. Furthermore, the excellent energy resolution for electromagnetic showers also opens the possibility to cluster photons into the corresponding π^0's, thus reducing the angular spread of particles belonging to a given jet.

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