Dual-Readout Calorimetry

Letter of Intent

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Abstract

The design of present HEP calorimetry systems is largely driven by issues of rad-hardness and pile-up rejection and by the presence of large-dynamic-range signals. As a consequence, hadron calorimeters have modest low-energy performance, dominated by stochastic terms ranging from $\sim 45\%/\sqrt{E}$ to $\sim 80\%/\sqrt{E}$. All the above experimental conditions are absent at leptonic Higgs factories [1–4] so that detectors with unprecedented precision, resolution and reliability can be successfully exploited to reconstruct very clean events of energies O(100 GeV). The 20-year-long $R\&D$ program on Dual-Readout Calorimetry (DR, DRC) of the DREAM/RD52 collaboration [5–12] shows that, through the parallel, independent readout of scintillation (S) and Čerenkov (C) light, the fluctuations in the electromagnetic (em) fraction of hadronic showers can be canceled and a $\sim 30\%/\sqrt{E}$ hadronic resolution is achievable, together with excellent particle-ID capability and em energy resolutions. All exceed the (rather modest) minimal requirements in the existing detector requirement documents [1–4]. The em resolution could be improved to state-of-the-art performance by exploiting DR in a crystal em calorimeter [5,13]. However, much work remains to design an optimized DRC system and assess its impact on the physics program at future Higgs factories. In this LoI, we review open issues on state-of-the-art DRC and its optimization in association with a full-detector design, as a result of the ongoing work for the IDEA [2,3,14] proposal for a CEPC/FCCee detector. We invite others in the HEP community (in particular in the US) to join us in this work.

Advantages of Precision, High Resolution Calorimeters

The challenges of the lepton collider program are largely set by the nature of the datasets, measurements therein, and new physics observables. The number of acquired ZH events is expected to exceed 10^6 with additional statistics collected at the Z peak around 10^{12}, 5(6) orders of magnitude higher than LEP(SLC). To optimally benefit from these large datasets, the intrinsic measurement resolutions and event-to-event information have to be substantially increased.

Roughly 2/3 of all HZ events will have 4 or more jets, all made of particles with an average energy of $\sim 2-3$ GeV. The DRC fiber-sampling approach brings the stochastic term down below $30\%/\sqrt{E}$ through a high sampling frequency and the integration of the shower over its longitudinal development. The latter, in addition, leads to a less-noisy information.

The DR information, with the same level of granularity of the LHC detectors, further improves the measurement by removing the systematic non-linearity stemming from the e/h response. In the crystal em calorimetry option, already proposed in the 4th Concept LoI [15,16], the DR performance for hadronic showers is maintained at the exceptional level of the fiber-sampling calorimeter, while also providing $3\%/\sqrt{E}$ photon resolution with multiple longitudinal segments, at nearly 100% sampling fraction and optimized for particle separation and particle identification. The fast, intrinsic timing capabilities of DRC makes it well-suited for beating down out-of-time backgrounds, as expected at muon colliders, and enhancing particle identification through the time-of-flight/arrival of MIPs and neutrals, needed for heavy flavor physics.

The path of detector and simulation studies is outlined below. The highest impact innovations in HEP came from pushing the detectors and analysis in unison to achieve the challenges of new collider frontiers. The DRC will be the first major advance in measurement resolution over all previous collider-detector calorimetry systems and will provide an excellent training ground for future talents in experimental physics.

Detector $R\&D$

The advancements in solid-state light sensors such as SiPMs have opened the way for highly granular fiber-sampling detectors with the capability to resolve the shower angular position at the mrad level or even better. Readout ASICs providing timing with ~100 ps precision may allow to reconstruct the longitudinal shower position with ~ 5 cm precision but the large number and density of channels call for an innovative readout architecture for efficient information extraction. Both charge-integrator and waveform-sampling ASICs are available on the market and candidates for first performance studies have been identified. Digital SiPMs (dSiPMs) may allow to greatly simplify the readout architecture but the technology is still far from maturity. An $R\&D$ program is under discussion.

Robust and reliable methods for the mechanical construction and assembly have to be identified. The gluing of capillary tubes looks very promising and is being exploited for the construction of a $1\ m$ long, $10\times 10\ cm^2$ module. Scaling up to $\sim 60\times 60\ cm^2$ will be the next step. Projective-geometry solutions will be studied in a Korean-funded $R\&D$ program.

About fibers, a suitable choice of core material, numerical aperture and properly tuned filtering, should allow to obtain yields of $100-400$ p.e./GeV, with an acceptable attenuation length. Qualification of fibers, optical coupling and light sensors will be part of the workplan.

Crystal calorimeters are not limited by sampling fluctuations and can provide em energy resolutions at the level of $3\%/\sqrt{E}$, allowing efficient reconstruction of π^0's and particle assignments to jets [13]. The identification of Higgs bosons via missing mass in ZH events is one of the key programs at future lepton colliders. The high em resolution together with bremsstrahlung recovery will bring the quality of electron-decay channel results at the same level of the muon channel. In addition, precise em resolution could benefit flavor physics and lepton universality studies.

Past detectors with crystal em sections, such as the CMS detector, have poor hadronic resolution due to coarse segmentation and large difference in response to em and hadronic particles. Cheaper photodetectors can alleviate the former, DR techniques the latter. While DR in principle works for crystals, in the past, the limitations due to sensor costs and performance, allowed to distinguish S and C photons via timing and optical properties only. The S light yield had to be reduced to the same level of the C yield, severely degrading the em resolution. Recent studies [13] show, however, that using SiPMs allows three readouts per tower in a highly segmented calorimeter, with two depth segments, at a reasonable cost, putting within reach the potential of both state-of-the-art electromagnetic and hadronic calorimetry. Thin precision-timing layers added to the front could allow a formidable particle identification system for flavor physics and reduction of machine backgrounds.

Simulation, performance and data analysis

Previous and ongoing physics and performance studies have been performed with a dedicated Geant4 simulation and custom code. One major development will consist in implementing the dual-readout calorimeter concept in a common software called Key4Hep [17]. Apart from understanding the ultimate resolution for all physics objects and evaluating the final performance on the physics programme, open issues include:

- Design an ad-hoc PFA algorithm and assess its potential physics gains.
- Develop a detailed, detector-specific, brem-recovery algorithm.
- Understand the efficacy of the timing layer for reducing machine background at muon colliders.
- Exploit innovative deep-learning algorithms for coping with complex final states.
- Study how to further increase the Čerenkov light yield at an affordable cost.
- Last but not least: validate the simulation predictions with test-beam data.

Invitation to collaborate

We invite others in the HEP community (and in particular in the US) to join us in the development of this exciting detector, so that its great potential for enabling the physics programs of future lepton colliders could be assessed as part of the Snowmass process.

Main contacts:

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