Object Reconstruction in Non-Pointing Geometry

C S Cowden 1
Texas Tech University, Department of Physics, Lubbock, Texas, USA
E-mail: christopher.cowden@ttu.edu

Abstract. The Combined Forward Calorimeter (CFC) option for the Phase II upgrades covers the endcap region (1.5 < |η| < 4) and its design calls for embedded clear and rad-hard scintillation fibers in an absorber matrix. The object construction using complementary features of Cherenkov and scintillating signals coupled with fast timing information results in some unique capabilities for high efficiency particle identification, precision energy measurement, background suppression and triggering. These topics along with possible pile-up mitigation techniques at the HL-LHC will be discussed in detail.

1. Introduction
The Combined Forward Calorimeter (CFC) was proposed as a replacement for the CMS endcap calorimeters for Phase II upgrades expected to operate in the HL-LHC. The CFC would replace both hadronic and electromagnetic calorimeters into a combined system. This device collects signals in two types of fibers: (1) a scintillating Cerium doped quartz fiber and (2) a clear un-doped quartz fiber. The Cherenkov signal (Q) produced in the un-doped quartz and the dE/dX sensitivity in the scintillator (S) provide the tools needed to remove fluctuations from the electromagnetic fraction on an event-by-event basis using the dual readout technique [1, 2, 3, 4].

It would also be desirable to extend the current CMS end-cap coverage to be consistent with the proposed tracker coverage. Therefore, the CFC proposal is to cover the range 1.5 < |η| < 4 in order to avoid a transition in calorimeter systems at η = 3.5 to the HF detector which is currently in place. This design is described in more detail in another contribution in these proceedings [5].

The following discussion assumes a configuration in which all towers and fibers run parallel to the beam. Fibers are placed 2 mm apart alternating between quartz and scintillating. The calorimeter segments are 2 cm² in the transverse plane, and this segmentation is constant throughout the depth of the calorimeter. A depth segmentation is obtained by digitizing the quartz channel with a 5 GHz sampler.

2. Particle Identification
Some conservative assumptions regarding the capabilities of processing timing information in the level 1 (L1) trigger decision were made. Particle identification performance is based on the...
assumption that the L1 trigger level digitizes signals at 40 MHz. The longitudinal segmentation based on time slicing is included later in the offline particle identification.

Based on the transverse shower shape and $Q/S$ (quartz and scintillator, respectively) ratio, a reasonable $e/\gamma$ background rejection can be achieved. Figure 1 and Figure 2 show distributions of these variables at $\eta = 1.5$ and $\eta = 2.0$, respectively, both with and without in-time pileup. The transverse shower shape is defined here as the ratio of energy in a $7 \times 2 (\eta \times \phi)$ cluster of towers to a $10 \times 42$ cluster of towers $- \frac{E(7 \times 2)}{E(10 \times 42)}$.

$Q/S$ provides a measure of the electromagnetic fraction ($f_{em}$) since $f_{em}$ only depends upon $Q/S$ and the detector compensation ($e/h$). A ratio near 1 indicates the shower has a large $f_{em}$ fraction.

Figure 1. Distributions of variables used in particle identification with and without in-time pileup at $\eta = 1.5$. 
The amount of pileup present in clusters increases at higher pseudo-rapidities. However, transverse shower shapes remain a good observable for background rejection. Some improvements to the front-end electronics have been suggested which could introduce some timing aspects into the L1 decision. For example, a TDC or 80 MHz digitization rate could provide a coarse depth segmentation to help identify hadrons.

Figure 3 shows a study comparing electron/pion separation in the non-pointing geometry to a quasi-pointing geometry. Although the cluster sizes and shapes were not fully optimized, the two options show similar performance.
Figure 3. Charged pion rejection rates with the online algorithm are compared for a signal (electron) identification efficiency of 80% with and without in-time pileup, at various rapidities. Also shown is the same rejection rate comparison in a quasi-pointing geometry.

The offline particle identification employs the timing information obtained by the 5 GHz digitizer on the \( Q \) channel to discriminate between hadronic and electromagnetic showers. Figure 4 shows this discriminating power at various pseudo-rapidities for a fixed signal (electron) efficiency of 95%. In this case, the charged pion rejection is \( \sim 99\% \).

Figure 4. Charged pion rejection rates with the offline algorithm are compared for a signal (electron) identification efficiency of 95% at various rapidities without in-time pileup.

3. Timing Features

The position of a shower in \( \eta - \phi \) space is determined to first order by the location of the shower at the face of the detector. In this approximation, showers which develop deeper are incorrectly found at a smaller \( \eta \). These showers contribute to a small tail in the \( E_T \) resolution resulting from this incorrect position. This tail can be corrected by taking the time into account. Figure 5 shows the anti-correlation of time to \( E_T / E \). Also shown is the \( E_T / E \) resolution before and after the time correction to \( E_T \).
As has been stated previously, with a fast digitizer, it is possible to slice pulses in the time domain to provide a measure of longitudinal segmentation. Figure 6 shows that both in and out of the presence of $E[n] = 140$ vertices, showers originating from pions arrive before showers originating from electrons. Since hadronic showers typically penetrate the absorber deeper than do electromagnetic showers, the time of arrival of signal at the back of the detector is earlier for hadrons. The correlation of deeper position and earlier times results from particles traveling faster than the speed of light in the fiber.

Figure 6. Shower profiles are compared between electron and pion showers in the case of pure signal, or in the presence of $E[n] = 140$ minimum bias vertices. A coarse depth segmentation is implied by the vertical line.

The intrinsic time resolution of this geometry has a dependence upon the angle made by the incoming particle. In the high $\eta$ region, where this angle is more shallow, the time resolution is broadest and, conversely, the intrinsic resolution is best at lower $\eta$. Figure 7 shows the time resolution of electromagnetic showers as a function of $1/\sqrt{E}$ for three angles.
Signal photons populate various helical modes. These modes lead to a dispersion in the time of arrival for photons produced by a single charged particle. These modes can be characterized by the effective speed along the fiber axis or, alternatively, as the effective index of refraction, \( n_{\text{eff}} \). The distribution of \( n_{\text{eff}} \) is shown in Figure 8 for a pion shower.

![Figure 7](image-url)  
**Figure 7.** The EM time resolution as a function of \( 1/\sqrt{E} \) for three angles the incoming particle makes w.r.t to the fiber axis.

**Figure 8.** The effective index of refraction for pion induced showers.

4. Conclusions
The CFC would have a fine transverse segmentation for both EM and hadronic showers which help provide good object identification and background rejection in the HL-LHC environment. The inclusion of pulse shape analysis in offline reconstruction adds an interesting perspective on 3D energy reconstruction from a device that does not suffer from the inter-calibration issues of longitudinally segmented calorimeters.

5. References
[1] N. Akchurin et al., Nucl. Instr. and Meth. A 536 (2005) 29; Nucl. Instr. and Meth. A 548 (2005) 336; Nucl. Instr. and Meth. A 686 (2012) 125; Nucl. Instr. and Meth. A 735 (2014) 130.
[2] N. Akchurin et al., Nucl. Instr. and Meth. A 533 (2005) 305.
[3] N. Akchurin et al., Nucl. Instr. and Meth. A 537 (2005) 537; Nucl. Instr. and Meth. A 584 (2008) 304.
[4] N. Akchurin et al., Nucl. Instr. and Meth. A 735 (2014) 120.
[5] N. Akchurin, in these proceedings.