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Tile Multiple-Readout and Beyond for FCC

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Dual Readout Calorimetry measures scintillation light and Cherenkov light on the same hadron shower to correct the jet energy in order to compensate hadron and jet energy measurements. Dual Readout with parallel plastic scintillator and quartz fibers shows promise, but limitations exist including but not limited to radiation damage of the plastic scintillators and high costs. We present dual readout calorimetry with scintillator and Cherenkov tile readout and beyond to multiple tile readout, with superior energy resolution, and radiation resistant ionization sensors in the form of tiles (inorganic scintillators, Si, LArgon). Monte Carlo (MC) studies were used to design prototype tile dual calorimeters using Fe or Cu absorbers, Cherenkov and plastic scintillator tiles, including an integral Cherenkov-compensated electromagnetic frontend using Pb tiles. The MC studies are extended to other tile types appropriate for dual readout and extend to multiple readout with 3 or more types of tile radiation sensors – sensors with different responses and/or higher contrast to component signals to electromagnetic or hadron showers, neutrons and ions. Sensors include tiles with low refractive indices (aerogel, others), transition radiation "tiles", secondary emission tiles sensitive to ions and low energy protons, hydrogenous vs non-hydrogenous ionization-sensing tiles, and neutron sensing tiles. Multiple readout improves dual readout by extending to triple or more readout. Of special interest is application of tile dual or multiple tile readout to high granularity particle/energy flow calorimeters, not possible with parallel fibers.

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1. Introduction

A goal for hadron and jet calorimetry is a resolution scaling better than $\sigma_E/\sqrt{E} < 20~\%/\sqrt{E}$, with a specific goal of $\sigma_E/E < 3~\%$ at 50 GeV, in order to identify and separate W and Z decays to jet-jet with a 2.5 - 3σ confidence in the separation. The vector boson jet-jet decays have 5-6 times the rate of W, Z decays to leptons and greatly increase the ability to search for BSM (Beyond the Standard Model) physics. Future experiments would benefit from reconstructing/identifying W and Z bosons by jet-jet decays, especially the ability to separate W→jet-jet from Z→jet-jet decays. Reasonable separation requires a relative jet energy resolution of 3% at 100 GeV, with typical jet single particle energies 10 - 15 GeV. A 3% jet energy resolution from 50 - 500 GeV yields a 2.6 - 2.3σ W/Z separation [1].

Dual Readout with parallel scintillator fibers and quartz fibers shows promise for future experiments. However, the parallel fiber design has inherent limitations including the unavoidable constant terms from scintillating fiber light attenuation and radiation damage with depth, punch-through noise in the large fiber bundle readout, difficulty making fully projective towers over (θ,φ), streaming down the fiber holes, radiation damage to the plastic scintillator fibers with no convenient or cost-effective radiation resistant alternatives, no convenient longitudinal segmentation for tagging large longitudinal fluctuations nor a separate compensated high resolution electromagnetic front end for the photon component of incident jets and higher costs. At present, no parallel fiber dual readout prototype has an energy resolution that is predicted as possible with the general dual readout technique, $18\%/\sqrt{E}$, likely due in large part to the inherent limitations described above.

We have studied extending parallel fiber dual readout calorimetry first to Dual Tile Readout, more applicable to many future experiments, with superior energy resolution, and with the possibility of radiation resistant ionization sensors in the form of tiles (some inorganic scintillators, Si, LArgon). Monte Carlo (MC) studies are used to probe designs of prototype tile dual calorimeters using Fe, Cu, Cherenkov tiles (Quartz, UVT lucite, Teflon AF, water, and aerogel tiles) and scintillator tiles (plastic and novel radiation-hard hydrogenous tiles), including an integral Cherenkov-compensated electromagnetic front end using Pb and W tiles. We then discuss dual to multiple tile readout and beyond with a particular emphasis on possible future implementations. Of special interest is the application of dual or multiple readout to high granularity particle/energy flow calorimeters.

2. Dual Tile Readout MC Study

A Geant4 MC study of a simple Dual Readout tile calorimeter consisting of 5 mm thick quartz tiles, plastic scintillator tiles, and Cu absorber tiles was performed. Two energies, 50 and 100 GeV, each of 1000 electrons and of 1000 pions were sent into the 50 × 50 cm area, 12.2 interaction lengths (3.5 m) deep calorimeter and the results are shown in Fig. 1 (left). The number of photons between 325 – 650 nm generated in the Cherenkov tiles and in the scintillator (PPO-POPOP spectra) tiles were counted, and, in this toy model, 0.5% of the photons at random were assumed to be able to be collected and converted to photoelectrons, consistent with present tile calorimeters with "sigma" tiles and wavelength-shifting fiber readout. The collected scintillator photons were about 120 times more than the Cherenkov tile photons, but photostatistics are not the most limiting factors. The means of the histograms of the number of photoelectrons in the electron shower in quartz and scintillator tiles were used to convert/normalize the number of collected photoelectrons in Cherenkov light (E_C) and in Scintillator light (E_S) to the same energies and then plotted as a scatter plot. After the normalization, the electron-incident scatter plot (red points) lie along the green line shown as $E_C = E_S$. The tight clustering is evidence of good energy resolution for both electromagnetic signals, but with the scintillator resolution being clearly better (narrower).

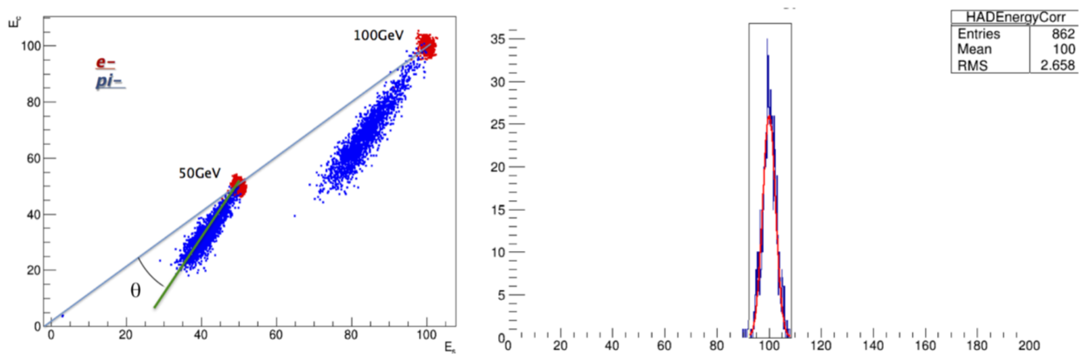

Figure 1. Left: Tile Dual Readout Geant4 MC: Scatter plot of Cherenkov (E_C) vs Scintillation (E_S) energy in the tile calorimeter described in the text. Right: Histogram of the reconstructed energy for 100 GeV pions.

The resulting E_C vs E_S signals from the simulation of pion events were normalized to energy using the electron normalization and scatter-plotted (blue points). The hadron points (blue) in the scatter plot lie mainly below the $E_C = E_S$ line, with a clear correlation between E_C vs E_S. Lines were fit to the blue points and these lines were used for corrections. If one projects the blue scatter points as a histogram onto an energy axis perpendicular to the fitted green linear correlation line, the energy distribution becomes quite Gaussian and narrower. The true energy E is given to first order by E_S , plus a correction term proportional to the difference (E_S - E_C) as $E = E_S + \alpha(E_S - E_C)$ where α is given by the slopes of the fits. As the slope gets steeper/larger, the correction linear term, $\alpha(E_S - E_C)$, becomes more important as E_C falls faster than E_S. When the Cherenkov energy E_C is the same as the scintillation energy E_S, as is the average case with electrons or pion charge-exchange to π^0, then $(E_S - E_C)> 0$ and no correction is needed to E_S. The difference (E_S - E_C) grows as the shower fluctuates more into nuclear/hadronic energies, and E_S must be increased by an amount proportional to (E_S - E_C). Figure 1 (right) shows the distribution of the reconstructed energy for 100 GeV pions. The (mean, rms) = (100, 2.66) is promising in terms of W→jet-jet separation especially with even higher sampling frequency (1/5-1/10 radiation lengths). We enhance this simple linear fit to the scatter plot for dual readout correction to include curvature with higher order fitted terms $\alpha_2(E_S - E_C)^2 + \alpha_3(E_S - E_C)^3$ +.., with energy dependent α's. There is a continuous mapping of the correlations in E_C vs E_S space to the line $E_C = E_S$.

3. Dual to Multiple Tile Readout

The potential performance of tile-like Dual Readout calorimeters can be enhanced with the utilization of not only plastic scintillator and transparent Cherenkov tiles with varied packing fractions and sampling, but also a large variety of other types of sensor tiles with different responses to neutrons, ion fragments, and electrons and photons. These sensors include more radiation-hard, hydrogenous, non-hydrogenous, neutron-sensitive-enhanced tiles, ion detector "tiles", ion- collecting liquids, TRD (Transition Radiation Detector) tiles, Secondary Emission, and others. Including a third or fourth sensor plane with different neutron (hydrogenous vs non-hydrogenous) or low energy sensitivity may enable more corrections for the lost nuclear energy. The possible options for further study include but are not limited to: a) Fused silica tiles ($n = 1.46$) in a hadron calorimeter with very fine sampling (0.3 – 3 mm); b) Lower index ($1.05 < n < 1.35$) radiation-hard tiles to achieve a high contrast ratio such as silica aerogels ($n = 1.05$ - 1.3) [2], polysiloxanes ($n = 1.35$, 100 MRad), Teflon AF ($n = 1.29$, 12 MRad), MgF_2 ($n = 1.37$); c) TRD such as straw tubes with a high β threshold tiles for detecting the electromagnetic component, interspersed with scintillator tile and absorbers; d) Bulk Liquids: for very large detectors such as long-baseline or cosmic neutrinos; e.g. liquid argon drifted ions and simultaneous Cherenkov light detection (the index is low enough that a good electromagnetic/hadronic contrast seems possible, and the scintillation light at 128 nm will not penetrate the light detector windows) and water "tiles" using $n = 1.29$ - 1.31 Teflon AF films; e) Drifted Ion detectors as "tiles" of Si, liquid argon or high pressure hydrogenous gas mixtures; f) secondary emission tiles such as large glass-based thin-film activated microchannel plates (MCPs) or metal foil "dynodes" that are directly sensitive to ionizing particles [3]; g) electromagnetic compartment with non-hydrogenous high light output scintillating tiles (LYSO, $PbWO_4$, ..), MgF_2, Teflon AF and silica aerogels.

4. Outlook

The existing MC framework will be extended to include three or more sensors in order to study the multidimensional correlations of sensors and develop algorithms to improve energy resolution beyond dual readout. At the first stage, non-hydrogenous scintillators, hydrogenous or other neutron sensitive scintillators, and two indices of Cherenkov tiles or the secondary emission tiles will be probed. The MC study will target combining the best properties of both tile multiple readout and particle flow.

References

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