Snowmass2021 - Letter of Interest

[Dual Readout Compensated Calorimetry with Tile Sensors]

Instrumentation Frontier Topical Groups: (check all that apply □/■)

□ (IF1) Quantum Sensors
• (IF2) Photon Detectors
□ (IF3) Solid State Detectors and Tracking
□ (IF4) Trigger and DAQ
□ (IF5) Micro Pattern Gas Detectors (MPGDs)
• (IF6) Calorimetry
□ (IF7) Electronics/ASICs
□ (IF8) Noble Elements
• (IF9) Cross Cutting and Systems Integration

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Abstract: We discuss techniques and materials to develop optimize the energy resolution in the long-term performance of calorimeters as required by the challenging environment of future colliders and high intensity experiments. We extend the Dual Readout compensation by using 2 tile types, one sensitive to to e-m showers, such as quartz Cerenkov tiles, and another such as scintillator tiles, sensitive to low energy particles such as neutrons, nuclear fragments. Many advantages over fiber calorimeters are discussed.

Dual-Readout Compensated Calorimetry with Tile Sensors Yasar

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ABSTRACT: We discuss techniques and materials to develop optimize the energy resolution in the long-term performance of calorimeters as required by the challenging environment of future colliders and high intensity experiments. We extend the Dual Readout compensation by using 2 tile types, one sensitive to to e-m showers, such as quartz Cerenkov tiles, and another such as scintillator tiles, sensitive to low energy particles such as neutrons, nuclear fragments. Many advantages over fiber calorimeters are discussed.

A goal for hadron and jet calorimetry is a resolution scaling better than $\sigma_E/\sqrt{E} < 20\%/\sqrt{E}$, with a 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 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. Dual Readout Calorimetry measures scintillation light and Cerenkov light on the same hadron shower to correct the jet energy – a form of "compensation" for hadron and jet energy measurements. Dual Readout with parallel scintillator fibers and quartz fibers shows promise for future experiment.

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

We extend parallel fiber dual readout calorimetry first to Dual Tile Readout, more applicable to many future experimental requirements in many Frontier areas (Energy, Intensity, Cosmic), 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 study designs of prototype tile dual calorimeters using Fe, Cu, Cerenkov tiles(Quartz, UVT lucite, Teflon AF, water, and aerogel tiles) and scintillator tiles(Plastic and novel rad-hard hydrogenous tiles), including an integral Cerenkov-compensated e-m front end using Pb and W tiles.

These MC studies are easily extended to other tile types appropriate for dual readout and able to extend to multiple readout with 3 or more types of tile radiation sensors with different responses and/or higher contrast signals to showers. These 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. These may improve dual readout and may lead to even more improvements to compensation by extending to triple or more readout. Of special interest is application of dual or multiple readout to high granularity particle/energy flow carlorimeters, not possible with parallel fibers, and discuss the potential to add such tiles to the CALICE calorimeters, upgrade calorimeters for ATLAS and CMS Phase and groups studying future machine(ee,pp,ep) detectors, b-physics experiments, tagged νe beams, and space-based calorimeters. By extending dual readout compensation to tiles with radiation resistance, good energy resolution calorimeters more resistant to high radiation damage (and tiles are more easily replaced than fibers) may result. Compensated calorimeters with higher rate/time resolution could result.

An example - a GEANT4 MC of a simple Dual Readout tile calorimeter consisting of 5mm thick each of quartz tiles, plastic scintillator tiles, and Cu absorber tiles. Two energies (50, 100 GeV) each of 1000 electrons (red dots) and of ~1000 pions (blue dots) [Figure 1a] were sent into the 50x50 cm area calorimeter, 12.2 L_{int} (3.5 m) deep. The number of photons between 325-650nm generated in the Cerenkov 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 p.e., consistent with present tile calorimeters with "sigma" tiles and WLS fiber readout. The collected convert/normalize the number of collected p.e. in Cerenkov light and in Scintillator light to the same energies $E_{Cerenkov}$ and $E_{Scintillator}$, and then plotted as a scatter plot of E_C vs E_S for each electron[Figure 1a]. After that normalizing of the energies, the electron-incident scatter plot E_c vs E_s (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 clearly better (narrower). Pions of 50, 100 GeV were then simulated. The resulting E_c vs E_s signals were normalized to energy using the electron normalization and scatter-plotted. The hadron points(blue) in the scatter plot lie mainly below the $E_c = E_s$ electron line(in blue), with a clear correlation between E_c vs E_s. A line was fitted to the correlated hadron scatter points (Green line as shown schematically only for 50 GeV), and the fitted slope R of that line is used to correct the energy. The angle **θ** between the line $E_C=E_S$ and the green line linear fit with slope R to the blue hadron scatter points is given by $\theta = \arctan(R) - \pi/4$, shown as an arc (Fig1a). 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 fitted slope R: $R=(1+\alpha)/\alpha$ or $\boldsymbol{\alpha} = 1/(1-R)$[1]. As the slope R gets steeper/larger, the correction linear term $\alpha(E_s-E_c)$ becomes more important as E_C falls faster than E_s. What this correction says is that when the Cerenkov energy E_c is the same as scintillation energy E_s, as is the average case with electrons or $\pi^{+/-}$ charge-exchange to π^o, then (E_s-E_c)~> 0 and no correction is needed to E_s, the 1st approximation to the energy. 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), with a proportionality constant $\alpha = 1/(1-R)$, in effect linearly projecting the scatter plot onto a histogram with an axis perpendicular to the fitted line. *The (mean, rms) = (100, 2.66) GeV [Fig. 1b] shows energy resolution promise that could enable W-> jet-jet separation especially with even higher sampling frequency (1/5-1/10 Xo) that is being performed.* 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 $E_c=E_s$.

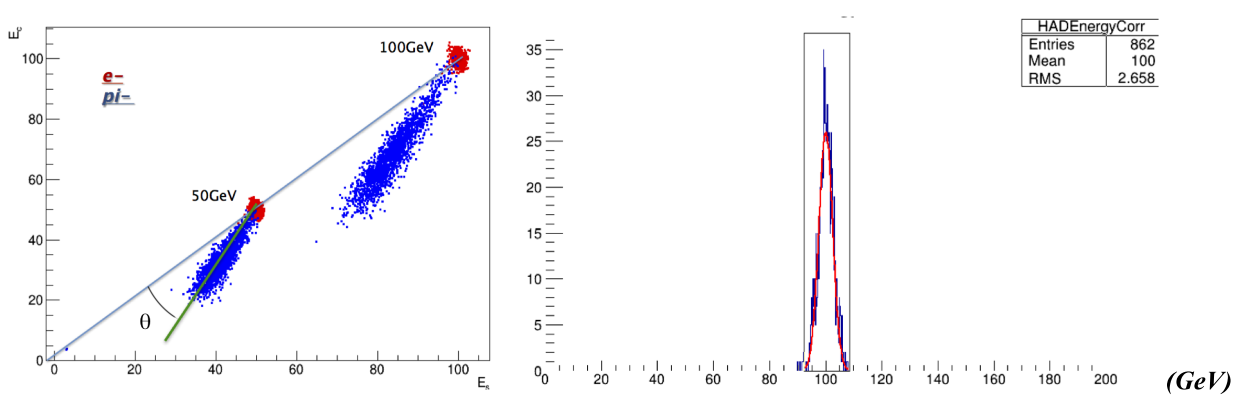

Fig. 1a (L): Tile Dual Readout GEANT4 MC: Scatter plot of $E_{Cerenkov}$ (E_C) vs $E_{Scintillator}$ (E_s) in a tile calorimeter consisting of tiles 0.5 cm thick each of quartz, plastic scintillator, and Cu absorber. Two energies (50, 100 GeV) each of electrons (red dot clusters on line $E_c=E_s$) and pions (blue dots) with a linear fit (green line shown). When the pion (E_s,E_c) points were projected onto an axis perpendicular to the linear fit, the resolution on hadrons is narrower and more Gaussian, shown for 100 GeV π in Fig2b.

Fig. 1b(R): Histogram of the 100 GeV π events at left vs Cerenkov corrected energy, in effect projected perpendicularly to the linear fit to the E_c vs E_s correlation. *The (mean, rms) = (100, 2.66) GeV shows promise for W-> jet-jet separation.* Finer sampling (0.2 X_o) improves this resolution.

[1] This analysis can be shown to be completely equivalent to S. Lee, M. Livan, R. Wigmans, Dual-Readout Calorimetry, arXiv:1712.05494 [physics.ins-det] AND to D.E. Groom, Degradation of resolution in a homogeneous dual-readout hadronic calorimeter (2012) http://lanl.arxiv.org/pdf/1210.2334.pdf