Snowmass 2021 Letter of Interest:
Calorimetric Picosecond Timing Planes for Future 100 TeV-scale Collider Detectors

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Future colliders with center-of-mass energies in the tens to even a hundred TeV are now under detailed study [1, 2]. Among the most pressing design issues is the need for new methods to address the daunting levels of pileup in detectors near the collision region. Equally challenging are the high levels of ionizing radiation near the beam, leading to more and more rapid degradation of detector elements as luminosity grows. One of the most promising ways to make progress on the former issue is to improve the detector timing precision down from the nanosecond to the picosecond level. And in the case of the latter issue, extreme radiation environments will require use of materials with intrinsic radiation hardness.

The Future Circular Collider Conceptual Design Report Volume 2 (FCC-hh [1]) emphasizes the importance of timing in resolving the enormous issue of pileup of verticies in the luminous region of the interactions. Because of the finite duration of bunch crossings in the collision region, events may share the same vertex but a different time, or occur at the same time, at different vertices.

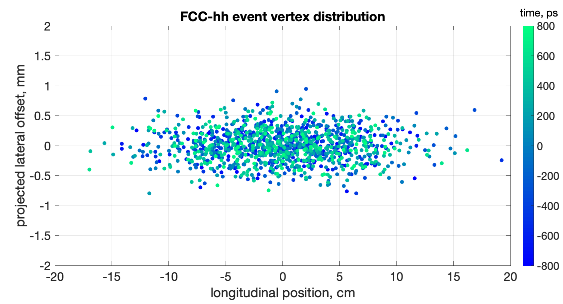

FIG. 1: *Temporal and spatial distribution of vertices in a simulated FCC-hh proton-proton collision event at 100 TeV.*

While the nominal level of pileup of ~ 1000 for a simulated FCC-hh event (Fig. 1) can be mitigated at some level by timing precisions of ~ 25 ps, a timing resolution of 5 ps per track is necessary to reduce effective pileup to ≤ 1 at large rapidity. It is evident that for future colliders at even higher collision energies, fully commensurate four-dimensional fits to vertex positions will become critical to optimizing performance of these systems. The large number of vertices in Fig. 1 also illustrates the high level of radiation tolerance required to provide adequate detector longevity. This is certainly true in the low-rapidity region, but it becomes a dominant issue for forward detectors, where the problen

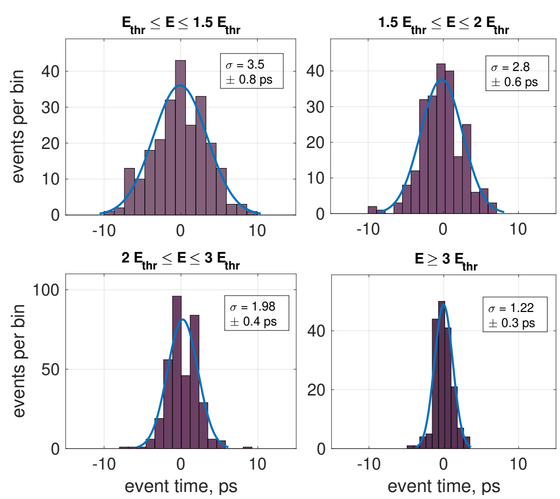

FIG. 2: *Single-ACE-element timing distributions for events during the first T-530 beam test, for several ranges of shower energy relative to the design-dependent threshold energy, around 1500 GeV in this effort, but later reduced to several hundred GeV.*

Significant effort is now underway to improve the timing of current collider detector technologies, and timing resolutions of 15-30 ps with silicon-based detectors have been demonstrated in some cases [3–6]. Traditional vertexing of collider events has been primarily three-dimensional, with the event time generally known to no better than 100 ps, equivalent to 30 mm of spatial precision, far worse than the sub-millimeter precision of spatial trackers. An ideal detector would not only provide high precision in spatial dimensions, but also in time and energy as well, and such detectors have been described as *5D* (five-dimensional) detectors, providing (x, y, z, t, E) with a single detector. This versatility in a single instrument will be of limited value, however, unless it is combined with a corresponding radiation hardness.

Within the last five years we have introduced a novel methodology, based on the Askaryan effect – coherent radio-to-microwave Cherenkov emission from the negative charge excess in a high-energy electromagnetic cascade [7, 11]. We denote the detector elements as Askaryan Cherenkov Elements (ACE). They are based on calorimetric sampling of electromagnetic or hadronic cascades, timing the moment of transit of the shower through each element. Their geometry yields spatial constraints as well, marking them as true 5D detector elements. The detectors do not detect single particles directly, but are sensitive to particle-induced showers, which create strong, back-to-back coherent microwave impulses within a 6×12 mm dielectric-loaded waveguide [12]. These impulses are then amplified and read-out at either end of the meter-long waveguide. Because the bandwidth of these elements far exceeds that of normal photonics detectors, cross-correlation of the received signals, combined with signal-averaging over a small array of such elements yields a picosecond time-of-arrival, and an estimate of transiting shower energy and location within the waveguide. In addition, the time difference for the two ends yields a sub-mm longitudinal centroid for the shower transit location through the waveguide array. Finally, fitting of the differential amplitude responses in the array yields a transverse position to several mm or better.

In a series of beam tests at SLAC, denoted T-530, we have experimentally demonstrated timing precision of $\lesssim 3$ picoseconds on electron showers, as shown in Fig. 2 for one of the ACE beam tests [8]. The observed timing precision is shown as a function of detector energy threshold, a design-dependent parameter. While our early experiments were limited to thresholds of O(1000 GeV), we have now verified that $E_{thr} \simeq 200$ GeV is achievable with current technology, using a timing plane thickness of several cm and combination of a modest number of elements. Even with these improvements, E_{thr} is significantly higher than typical photonics instrumentation, due to the fact that the method relies on showering of the primary particle, whether photon, lepton, or hadron. However, in the forward direction, for pseudorapidity $\eta \geq 3$, the corresponding transverse momentum threshold is $p_T \leq 20$ GeV, at which a large fraction of vertices will be detected. Future development could push E_{thr} to 100 GeV or below if necessary, using improvements in cryogenic low-noise amplifiers to reduce the thermal noise [19]. Clearly, advances in GHz analog-to-digital samplers must also go hand-in-hand with these efforts; such devices are already in development within our collaboration [18].

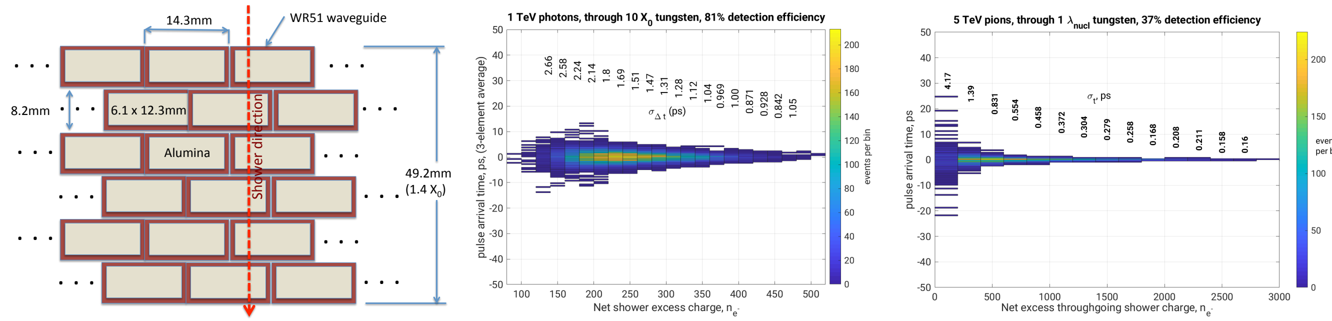

FIG. 3: *Left: Cross section of a segment of a proposed ACE timing plane 6 elements thick, about 1.4 X_0 in column density. Center: Timing distributions for 1 TeV photons centered on 3 of 6 elements, showering through 10 radiation lengths of tungsten, as a function of the excess charge in the shower, which is a proxy for the shower depth or upstream energy deposited. Right: similar timing distribution for 5 TeV pion showers after 1 nuclear interaction length.*

Fig. 3 shows a scaling of our observed timing distributions to an FCC-like collider detector. We simulate 1 TeV photon and 5 TeV pion showers using a hybrid GEANT4 + RF/microwave simulation based on the experimental results [9, 10], through the 5 cm thick, 1.4 X_0, timing layer shown at the left, with the shower centered on 3 of the 6 elements (which differs from the track shown). The shower energy is indicated by excess electronic charge in the cascade. For the photons, showers are detectable above 200 GeV, and extend up to 1 TeV, with overall detection efficiency over 80%. Similarly for the pion through 1 nuclear interaction length, the detector turns on at a few hundred GeV shower energy, and showers extend up to the pion energy. The lower $\sim 40\%$ detection efficiency is due to more deeply interacting pions for which the showers develop late. In both cases, the timing precision for most events is of order 1 ps, but exceptional pion events can approach 100 fs resolution

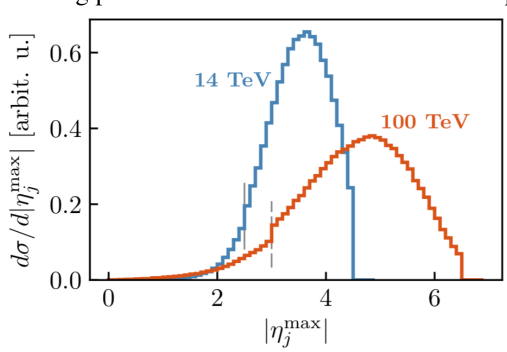

FIG. 4: *Example of pseudorapidity distributions of the most forward jet for Higgs vector boson fusion process at the FCC-hh compared to the LHC [17].*

The FCC and other future colliders at the 100 TeV COM-scale will feature many events with collision products with energies in the tens of TeV, requiring extreme dynamic range and linearity, two features that we believe are hallmarks of our approach. In addition, our primary detector elements – dielectric-loaded waveguides – are constructed simply of copper and solid Al_2O_3, among the most radiation tolerant materials known [13–15]. The ACE methodology does have a relatively high turn-on energy, of order 100-200 GeV depending on the configuration. This will limit its utility for low p_T events in a detector barrel region, but at higher rapidity, even low-p_T jets will have high total energy, which will lead to efficient detection of jets even with a 100-200 GeV total energy threshold. The extreme dynamic range of the detector elements will allow them to be used at the highest energies without saturation or compromise to linearity.

Our methodology will provide a radiation-hard complement to other detector systems with high precision at low p_T, with particular strength in the forward direction. While ACE elements have limited applications for current high energy colliders due to the relatively high turn-on energy, this will be substantially mitigated for future colliders where the collision phase space favors more interactions with products with higher rapidity, and thus higher true energy, for a given transverse momentum p_T. An example of this trend is shown in Fig. 4, where simulations of the distribution of pseudorapidity for jets from Higgs vector boson fusion show a strong bias toward the forward direction at the FCC compared to the LHC [17]. In this case, although not shown here, the peak of leading jet transverse momentum p_T increases from about 60 GeV to ~ 100 GeV, well above our detection threshold for $|\eta| \geq 3$.

The challenges facing physicists on the instrumentation frontier as we look forward to 100 TeV colliders are extreme in almost every parameter imaginable: radiation tolerance, pileup confusion, dynamic range, and the shift of physics to the forward direction, where spatio-temporal resolution will be most critical. We urge our Snowmass 2021 colleagues to consider and promote the importance of developing multiple complementary detector technologies well in advance of the advent of future collider construction.

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