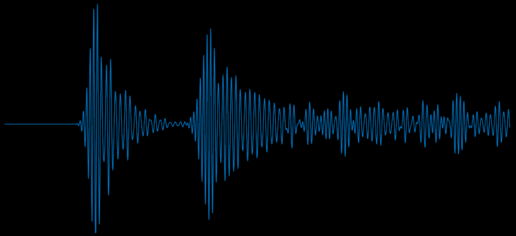

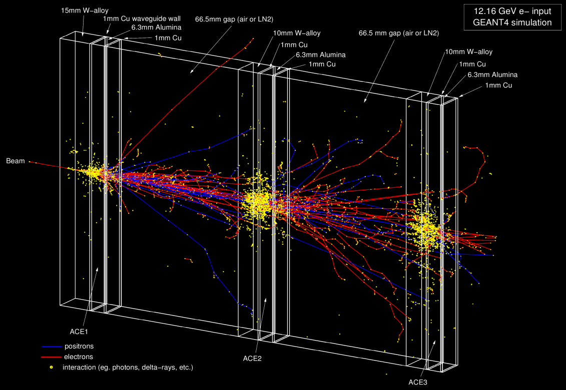

Askaryan (5D) Calorimeters

Picosecond Timing of High-Energy Showers using Coherent Microwave Cherenkov Emission

Results from the
Askaryan Calorimeter Experiment (ACE)

Remy Prechelt
for the ACE Collaboration

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Introduction

Picosecond timing, both in the tracker and calorimeter, is a major technical frontier for producing new physics at a future collider.

Precision timing technology must also be able to withstand extreme conditions!

Future Collider Conditions [1, 2]

- Pile-up (PU): $\simeq 1000$ 5-7x HL-LHC
- Radiation: $\gtrsim 10^{18}\ \mathrm{n_{eq}/cm^2}$ 100x HL-LHC
- Pseudorapidity: $|\eta| \lesssim 6$ $|\eta| < 3 - 4$ at HL-LHC
- Angular Resolution: 10 mrad separation between jets 0.1x HL-LHC

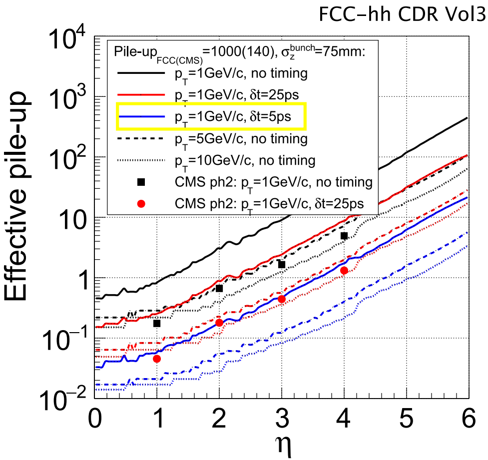
Priority Research Direction (PRD)
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification

TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of 0.5×0.5 cm^2, hadronic cells of 1×1 cm^2 TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps
TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) $\mathrm{n_{eq}/cm^2}$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps

PRDs and Technical Requirements (TR) from the 2020 HEP BRN.

Picosecond Timing

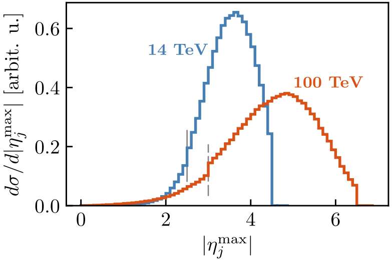
- Timing is an extremely powerful tool for resolving pileup.
- A 100 TeV pp requires 5 ps resolution for effective PU $\sim$ 1 for 1 GeV at $\eta = 4$.
- $\sim$ 1 ps for $PU \sim 1$ for 1 GeV at $\eta = 5$.



The effective pile-up reduction for various timing resolutions and momenta for the FCC-hh.

New Physics Moves Forward

- As CoM energy increases, many new physics signals shift into the forward region where radiation fluence will be maximal.
- Need to separate showers separate by $< \mathcal{O}(1^\circ)$ and reject backgrounds at the same time [3].
- Pushes calorimeter designs to very high-granularity [4].



Example psuedorapidity distributions for Higgs vector boson fusion at the FCC-hh compared to the LHC [5].

Angular Resolution

- 100 TeV pp requires $(\Delta\eta, \Delta\phi)$ of 0.01×0.01 for ECal, 0.025×0.025 for HCal
- Pushes calorimeter designs to high-granularity, 5×5 mm^2 for ECal, $1 - 3$ cm^2 for HCal => extremely high channel counts

As part of the Askaryan Calorimeter Experiment (ACE), we have developed and *beam-tested* a new 5D calorimeter technology utilizing coherent microwave Cherenkov (Askaryan) emission to provide:

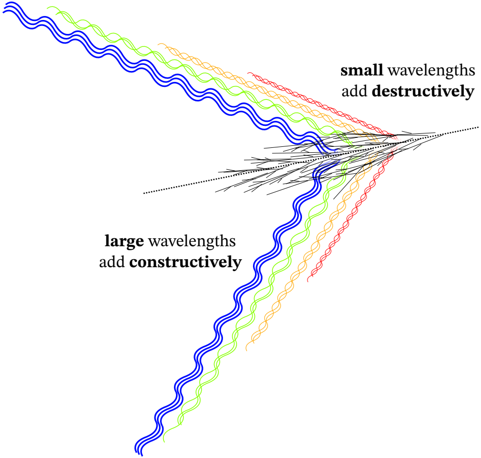
1. Picosecond timing of high-energy showers.
2. Calorimetry.
3. Sub-millimeter and millimeter spatial resolution.

while simultaneously being commercial-off-the-shelf (COTS), relatively low-cost, and *extremely rad-hard*.

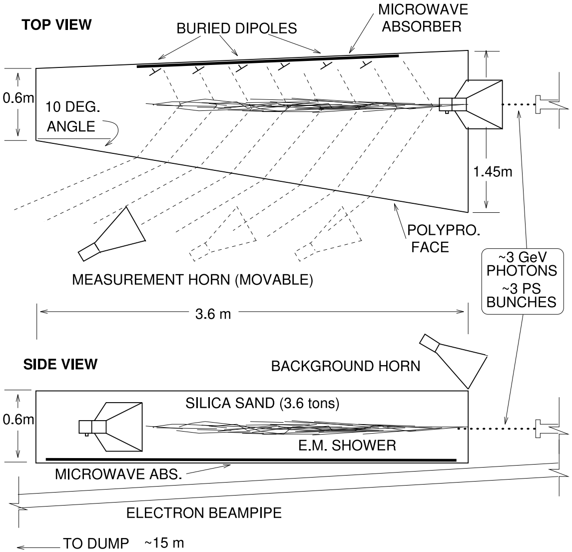
Overview

Askaryan Effect

- In dense media, EM showers develop a 10-20% compact negative charge excess on the shower front (e^- preferentially upscattered into shower, e^+ annihilated). *Typically mm-thick.*
- At wavelengths larger than the size of the charge excess, the Cherenkov from individual particles *cannot be resolved* and is observed as a single charge w/ $Q \sim N_{\text{excess}} e \sim 0.2 N_{\text{shower}} e$
- For typical media, this *coherence* extends up to >10 GHz - the emission from all the particles in the shower is adding *constructively*.
- This is coherent microwave Cherenkov!

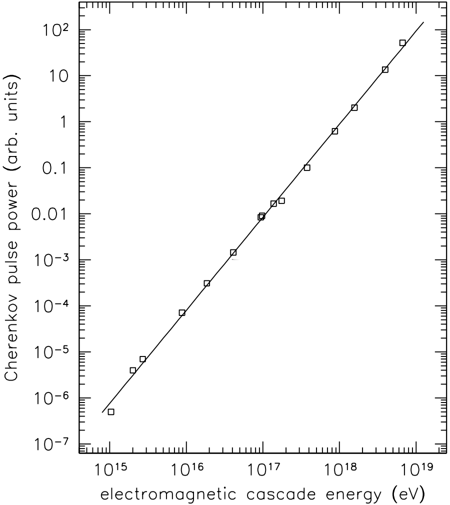


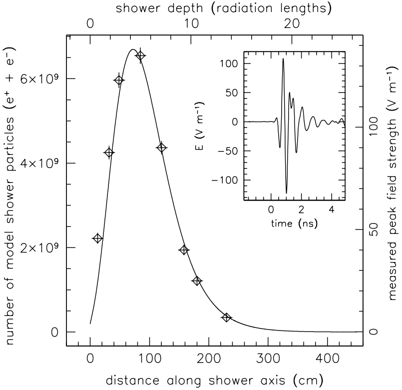
First theorized by G. Askaryan in 1962, and first detected in 2001 by Gorham & Saltzberg [6], Askaryan radiation since been directly measured in ice [7], salt [8], air [9], and alumina [10] up to $E \sim 3 \times 10^{19}$ eV with both e^- and γ using SLAC's ESA (T460, T464, T486, T530).



Askaryan emission is directly proportional to shower energy i.e. a calorimeter!

Validated across >8 orders of magnitude in energy with no observed saturation - *extreme dynamic range.*





The field tracks the shower evolution and produces an extremely broadband (impulsive) signal [11, 12].

Use in UHE Neutrino Experiments

Askaryan emission is the primary method for detecting UHE neutrinos ($E_\nu > 10^{19}$ eV) via radio-emission from neutrino-induced showers in the Antarctic ice with ARA [13], ARIANNA [14], and ANITA [15].

This allows these neutrino experiments to instrument up to $\sim$ 3M km^3.

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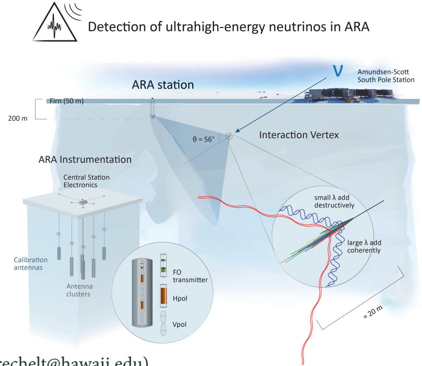

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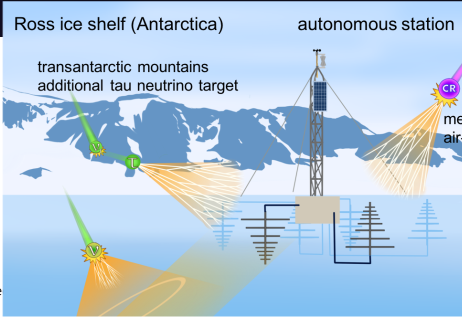
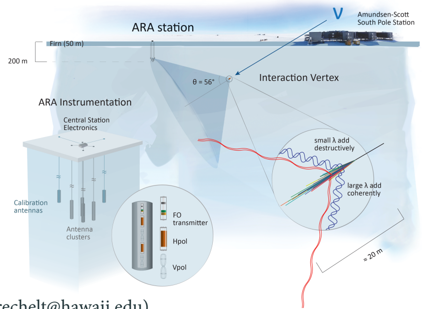
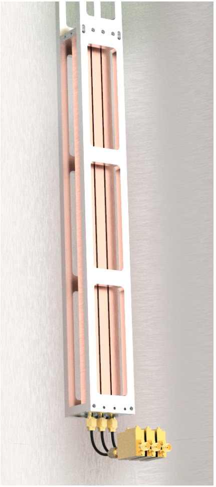




T-530: Askaryan Calorimeter Experiment

- We use standard WR51 (12.6mm x 6.3mm) copper waveguides loaded with alumina bars (Al_2O_3).
- Askaryan (microwave Cherenkov) from a shower moving through the waveguide is coupled into the TE_{10} mode (5-8 GHz) and propagates to each end.
- We amplify the ns-scale pulse with COTS low-noise amplifiers (LNAs) and sample with high-bandwidth digitizers.
- The measured waveform is a direct measurement of the shower energy via the coupled Askaryan emission and provides a precise time of arrival!
- Figure: Three ACEv3 elements in their test frame along with three COTS LNAs.



Alumina

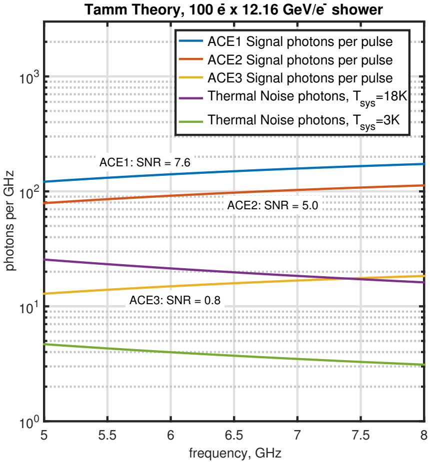
Alumina is a perfect material for this application:

- Extremely low loss dielectric ($\tan\delta \lesssim 3 \times 10^{-5}$ for commercial products).
- High microwave refractive index; n $\sim$ 3.15 => low threshold for Cherenkov production.
- Extremely rad-hard - has been tested up to $\sim 10^{25}$ n_{eq}/cm^2 and $>10^7$ Gy/s (for potential use in fusion reactors [16] - no *permanent* change in dielectric properties after irradiation under *FCC-hh forward calorimeter conditions*.
- Annual production > 120M tonnes with a diverse array of commercial uses - supply will not be an issue and keeps costs low.
- Very low thermal emissivity ($\epsilon \sim 0.02$) so not a significant contributor to thermal noise.

Only (available) material better than alumina is sapphire (which has cost and production complications).

Tamm Theory for Bounded Dielectrics

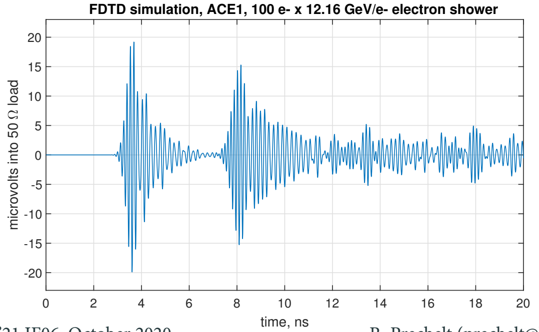
- Frank-Tamm theory for finite-track optical Cherenkov radiation can be used to analytically calculate the emitted power but must be modified for dielectrics bounded by conductors [10].
- … but ACE elements are true microwave devices =» geometric E&M (i.e. photon counting) not completely valid => requires full-wave solutions to Maxwell's equations!
- Despite that, Tamm signal strength estimates (Figure) agree well with experimental data - however, Tamm theory cannot reconstruct the time-domain behaviour of the waveforms.

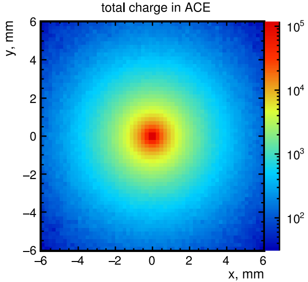


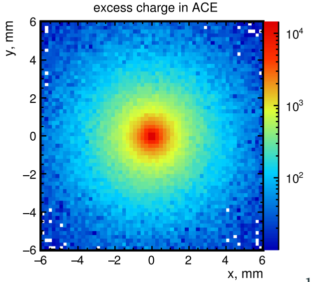
The photon spectrum of three consecutive ACE elements sampling an electron-induced shower compared to the thermal photon spectrum according to Tamm theory.

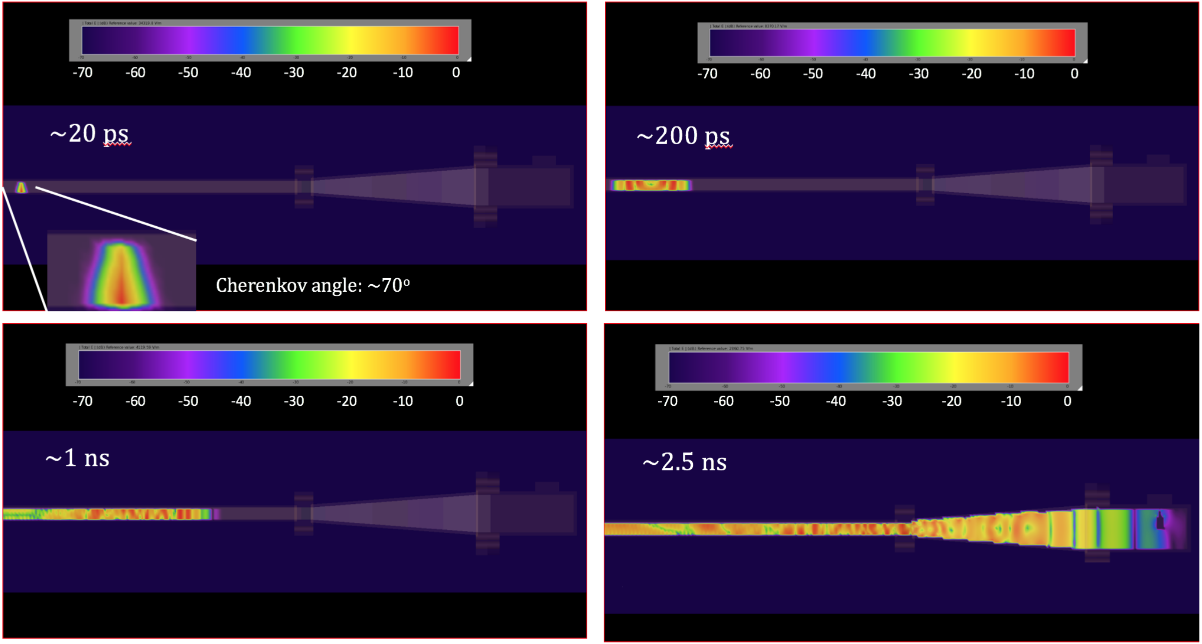
Custom Geant4 Electromagnetic Interface

- No available simulations tools - requires a combined simulation of the shower development (individual tracks) with time-domain relativistic E&M solvers such as finite-difference time-domain (FDTD) methods.
- We have built a Geant4-FDTD bridge to accurately simulate the response of ACE elements using commercial FDTD solvers.








-70 -60 -50 -40 -30 -20 -10 0
~20 ps
Cherenkov angle: ~70°
-70 -60 -50 -40 -30 -20 -10 0
~200 ps
-70 -60 -50 -40 -30 -20 -10 0
~1 ns
-70 -60 -50 -40 -30 -20 -10 0
~2.5 ns

Experimental Validation

To validate this concept, we have performed three extensive beam-tests at SLAC's ESTB A as part of the T-530 experiment:

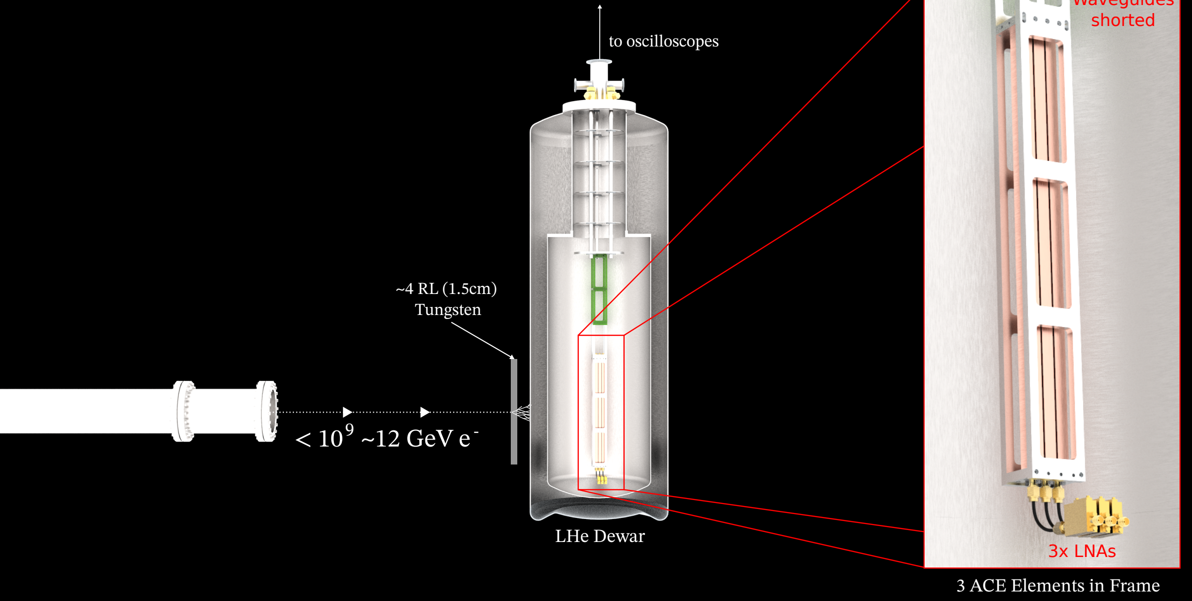
- ACEv1 (2015) [10]
  - First generation waveguide designed (COTS) w/ LN_2 cooling.
  - $\sim$20 K noise-figure (NF) cryo-LNAs and standard RF oscilloscopes.
  - First measurement of Askaryan effect in bounded dielectrics w/ detailed studies using a commercial calorimeter.
  - Achieved $\sim$ 3 ps timing resolution.
- ACEv2 (2016)
  - Second generation waveguide design to explore smaller form factors.
- ACEv3 (2018)
  - New third-generation waveguide design w/ timing studies in LHe.
  - $\sim$4 K NF cryo-LNAs.
  - Experimental focus on lowering energy threshold.
  - Achieved $\lesssim$ 1.2 ps timing resolution.

Thermal Noise -> Energy Threshold

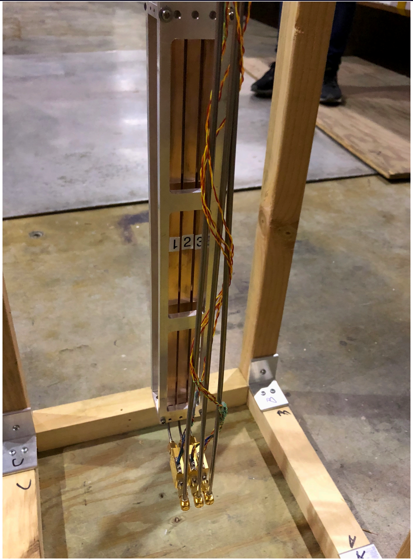
- In radio & microwave, thermal noise a major challenge -> all EM modes are “pre-loaded” with thermal photons.
- Due to the low emissivity of alumina, the primary contributor to the system temperature is the first-stage low-noise amplifier (LNA).
- The best COTS LNAs (today) achieve ~30 K of noise at room temperature, ~10 K in LN_2/LAr, and ~2 K in LHe.

To explore the full range of performance offered by the ACE concept, we performed our beam tests at room temperature, in LN_2, and in LHe.

ACEv3 (2018) Beam Test



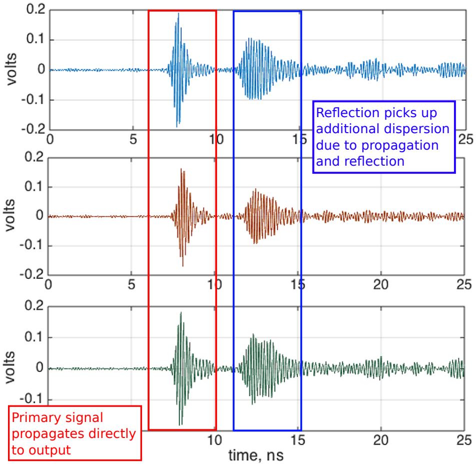
ACE3 Elements outside Dewar



ACE Waveforms

To reduce digitizer count, ACE elements in T-530 were shorted at one end - waveform is sum of primary and reflected Askaryan signals.

ACE elements could operate in this configuration to reduce cost and system complexity but with a higher risk of overlapping signals.



Energy Threshold ("Least-count Energy")

- The primary energy threshold is strongly determined by the noise temperature of the LNA (and $\beta \gtrsim 0.3$ required for Cherenkov production).
- We define the *least-count* energy, E_{thr}, as the shower energy required for a 5σ detection above thermal noise.
- For *a single* ACE waveguide, the measured least-count energy in T-530 was 200-400 GeV depending upon the cooling of the LNA.
- However, the least-count energy scales with the number of elements, $1/\sqrt{N_{det}}$; for N=6, (a reasonable number of elements for a single shower), this gives $E_{thr} \sim 80 - 160$ GeV.
- Any improvement in system temperature will directly translate into a lower least-count energy.

While this threshold makes Askaryan elements unsuitable for current energy scales, a future 100 TeV pp collider (like FCC-hh), will produce many showers with energies above ~ 100 GeV.

Energy Resolution

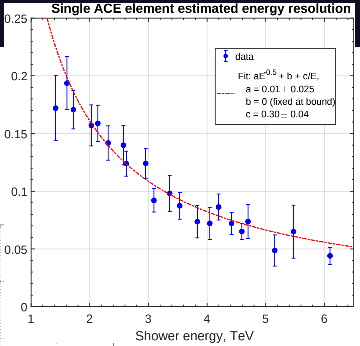
The energy resolution of ACE elements is also strongly limited by thermal noise - in T-530, resolution was dominated by the 1/E *electronics* term.

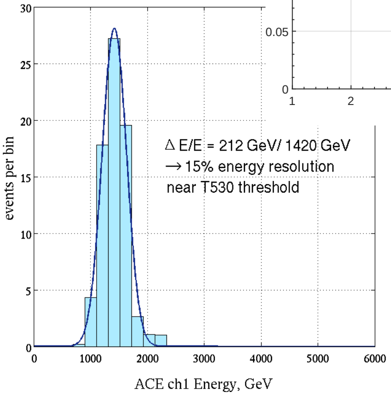
For a *single prototype* ACE waveguide in the T-530 configuration, we observed

$$\frac{\sigma_E}{E} \sim 23\% \left(\frac{200\text{ GeV}}{E}\right)\sqrt{\frac{1}{N_{\text{det}}}}$$

with a *constant* term consistent with 0 in all our beam-tests up to >6 TeV (limited by commercial calorimeter).

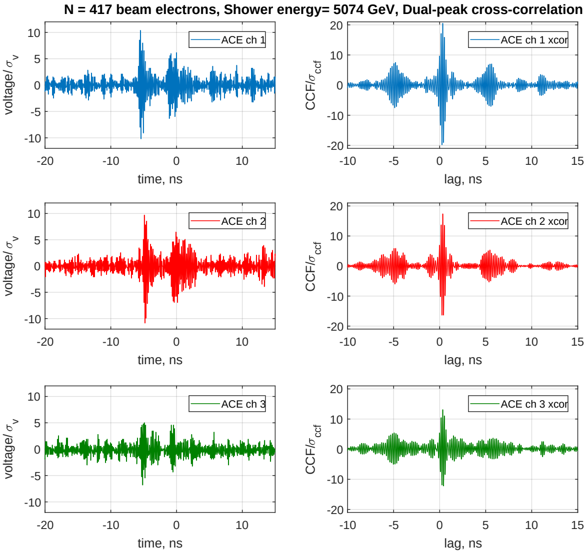
Stochastic term negligible in T-530 w/ ∼4 RL of tungsten for pre-shower.





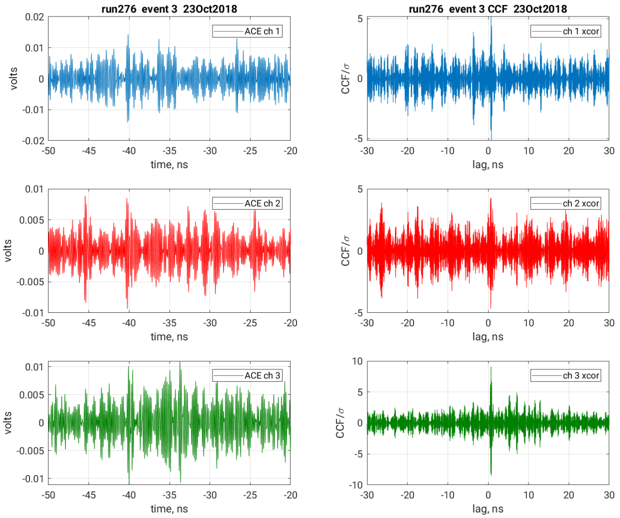
Extracting Timing Information

- This is not a traditional photon counter - ACE elements record the full time-domain electric field as the shower transits the waveguide.
- ACE measures the convolution of the shower w/ the waveguide impulse response (i.e. an LTI system).
- Cross-correlating separate ACE elements, or individual elements with the waveguide impulse response, gives an exceptional time of arrival measurement for the shower centroid.



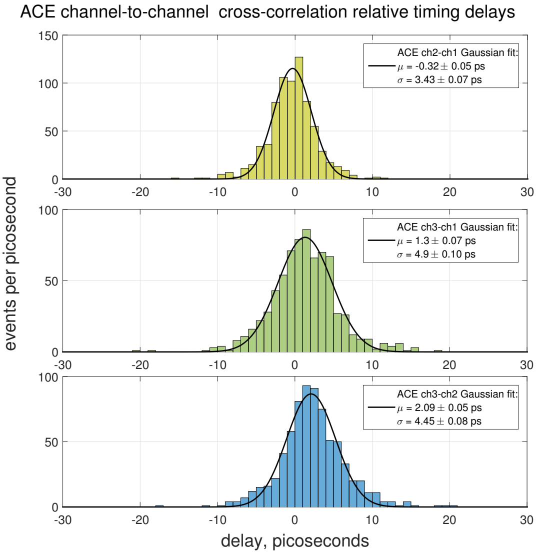
Extracting Timing Information

- Using a template, cross-correlation can extract accurate timing information even at low SNR.
- The high-bandwidth (4 GHz) and high center frequency (6 GHz) both contribute to the timing precision available from these elements.
- Figure: The extraction of the arrival time of a near-threshold shower in each of the three ACE elements in ACEv3 (2018) using a CCF template.



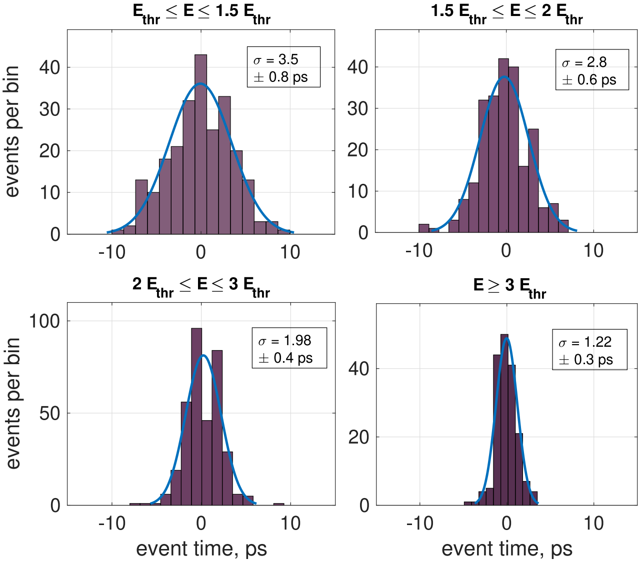
Timing Resolution

- ACEv1 tests (2015) achieved ~ 2 ps time resolution *per waveguide* using our first off-the-shelf prototypes.
- Figure: The width of the channel-to-channel delay distribution from these measurements is the convolution of the intrinsic timing resolution of each waveguide => includes a factor $\sim \sqrt{2}$ on *per-element* resolution.
- The figure also includes ~0.64 ps of oscilloscope *sampling jitter* => our first tests are approaching limits of high-bandwidth RF digitizers!

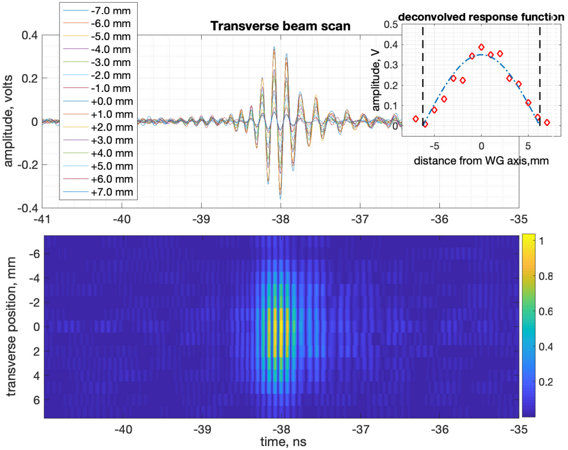


Timing Improves as Shower Energy Increases

- Timing resolution improves significantly as energy increases - *no evidence* of timing resolution *saturation* in experimental data up to energies well above FCC-hh.
- Figure: A single ACEv3 waveguide in T-530 achieved ~1.2 ps resolution by $3 \times E_{thr}$.
- *Best* digitizer technology (today) achieves 20-50 fs of sampling jitter - current fundamental limit on timing resolution for ACE elements.



- The relative timing of the waveforms at each end measures the location of the shower centroid along the long axis => position measurement much finer than the size of a waveguide.
- For a nominal 1 m long ACE waveguide, $\Delta y \sim 300\ \mu$m at 200 GeV. This improves to 100 μm for $E \gtrsim 3 \times E_{\text{thr}}$.
- With multiple elements, the transverse waveguide response gives a measurement smaller than the waveguide width $\Delta x \sim 3 - 5$ mm.



A transverse scan of an ACE element across the beam showing the expected TE_{10} response function.

Dynamic Range & Linearity => Multiple Shower Resolution

Dynamic Range

- ACE elements are streaming detectors w/ 100% duty cycle - no separate readout period/dead time.
- The dynamic range of ACE elements is limited only by the RF electronics (primarily, the LNA's IP3 & P1dB).
- >10,000 with current COTS electronics => will cover threshold to > 100 TeV without saturation.

Reconstructing Multiple Showers

- With high-dynamic range & high-linearity, ACE elements can reconstruct multiple simultaneous showers (as long as they transit the waveguide in different locations) => they act as calorimeter with much finer segmentation than their physical size => reduced channel count & cost!

T-530 Summary

With our *off-the-shelf* prototype elements, we have experimentally demonstrated as part of T-530:

1. 1-3 ps timing for showers with $E \gtrsim 200 - 400$ GeV *per waveguide*.
2. ~20% energy resolution for $E \sim 200 - 400$ GeV *per waveguide*.
3. $\Delta y \sim 100 - 300\ \mu$m, $\Delta x \sim 3 - 5$ mm at $E \sim 200 - 400$ GeV *per waveguide*.

… all of which improve strongly with E, N_{det}, and T_{sys}!

Large Parameter Space Available to Explore

There is still significant phase space to explore that could further improve ACE detector elements, including:

- Square waveguides support *two orthogonal polarizations* (more signals to cross-correlate) and lower intrinsic ohmic losses => automatic factor of $\sim$ 2x in threshold and energy, time, and position resolution.
- Alternative waveguide sizes can probe different parts of the Askaryan spectrum and could be optimized for specific detector implementations.
- Improved LNAs - LNAs with 50% lower noise temperature have already become commercially available since our 2018 beam test => direct improvement to ACE performance.
- Alternative digitizer designs and configurations to reduce RF system cost.

Recently started 3 more years of DoE funding to continue to develop this concept for an FCC-like collider. Much more to come from ACE!

5D Askaryan Calorimeters for Future Colliders

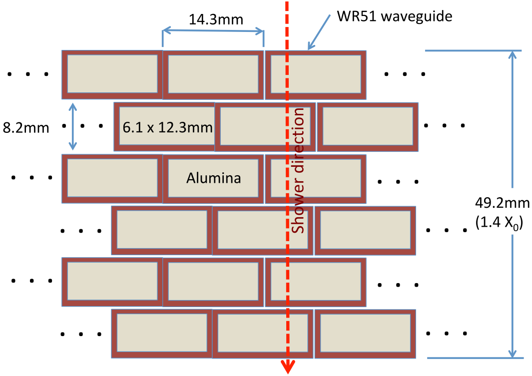
An ACE Timing/Calorimeter Layer

- A baseline Askaryan timing layer is nominally 3-6 waveguides deep with offsets between each layer.
- Total thickness is ~50 mm = 1.4 X_0 (few % of FCC-hh baseline ECal depth)
- Assuming the baseline performance of T-530, a single Askaryan layer would provide:

$$\frac{\sigma_E}{E} \sim 10\% \left(\frac{E_{\text{thr}}}{E}\right)$$

$$\sigma_t \sim 1.8 \text{ ps} \left(\frac{E_{\text{thr}}}{E}\right)$$

$$E_{\text{thr}} \sim 100 - 200 \text{ GeV}$$



$$\Delta x \sim 100\text{–}300\,\mu\text{m},\ \Delta y \sim 1\text{–}3\,\text{mm},\ \Delta z \sim 8\,\text{mm}$$

Above threshold, these are 5D detectors!

What might this look like for a future collider?

- Due to their high threshold, ACE elements are not practical for the HL-LHC and will never be a standalone calorimeter technology for a future collider.
- However, at a future high CoM energy colliders (i.e. HE-LHC, FCC-hh) or even contemporary heavy-ion colliders, many showers will be above threshold ($\mathcal{O}(100GeV)$).
- Several Askaryan *layers* could therefore be embedded inside another ECal or HCal technology (LAr, dual-readout, etc.) at several depths to provide exceptional timing and spatial measurement(s) as well as an additional energy measurement to be used in particle flow algorithms (PFA) and pile-up reduction.

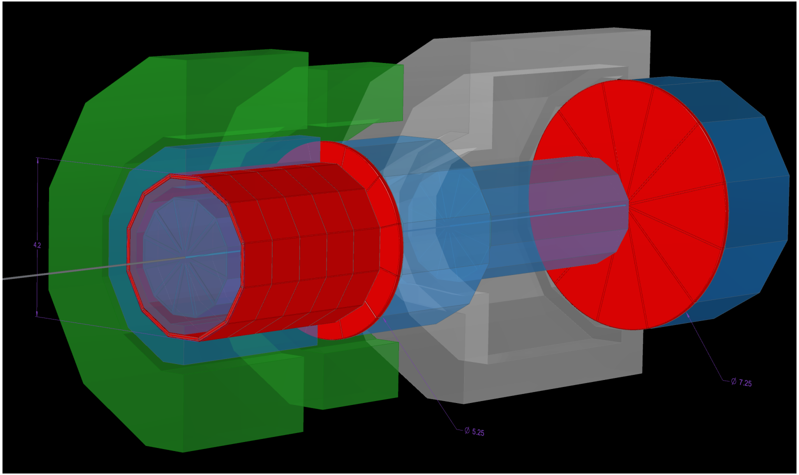
Fast Simulations =>

We have produced preliminary fast simulations for both barrel and forward calorimeter designs that incorporate a small number of Askaryan calorimeter layers using FCC-hh data from HepSim [17], and our combined Geant4-FDTD simulation tools.

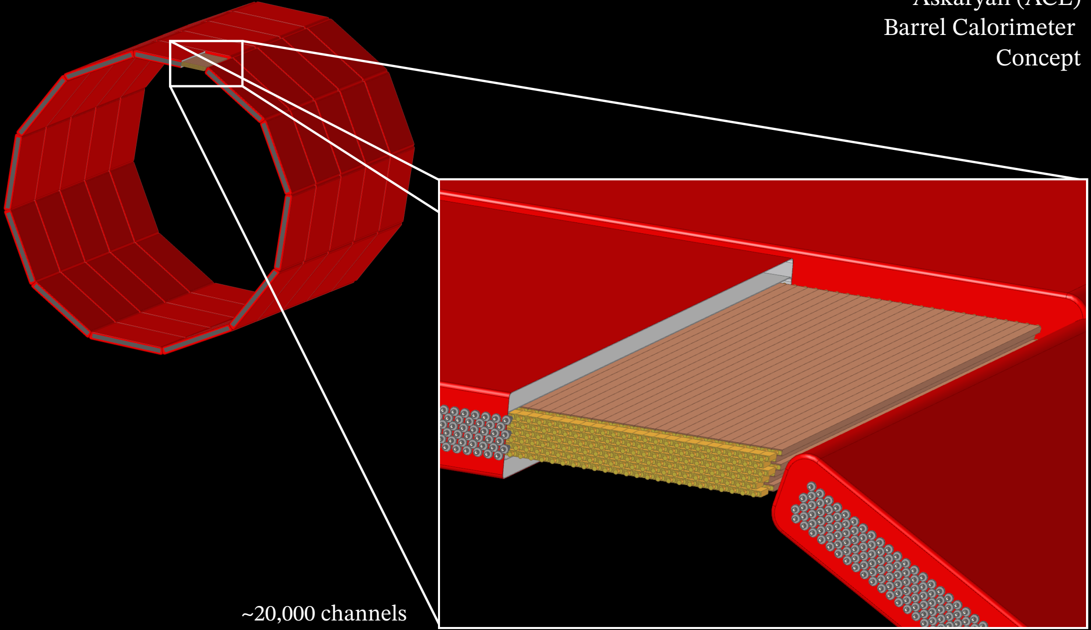
Calorimeter Concept

Askaryan detectors (shown in red) directly track the number of particles in a shower and are therefore most sensitive when near X_{max} in an ECal or HCal.

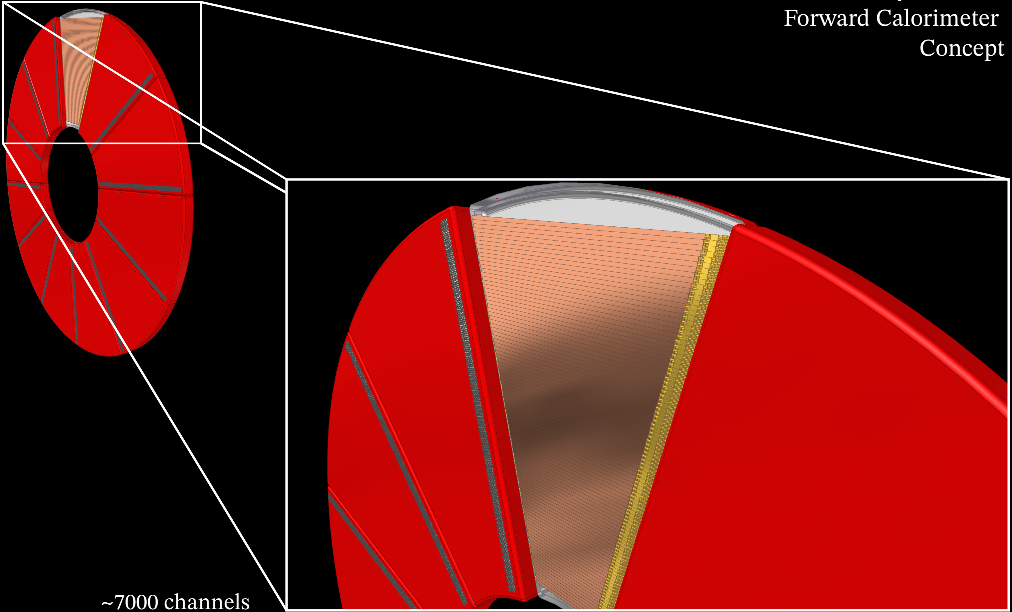
At 1.4 X_0, several layers could be placed inside an HCal (or an ECal) to significantly improve efficiency and performance without significantly altering shower development.



Askaryan (ACE)
Barrel Calorimeter
Concept



Askaryan (ACE)
Forward Calorimeter
Concept



~7000 channels

1 TeV Photons in ECal

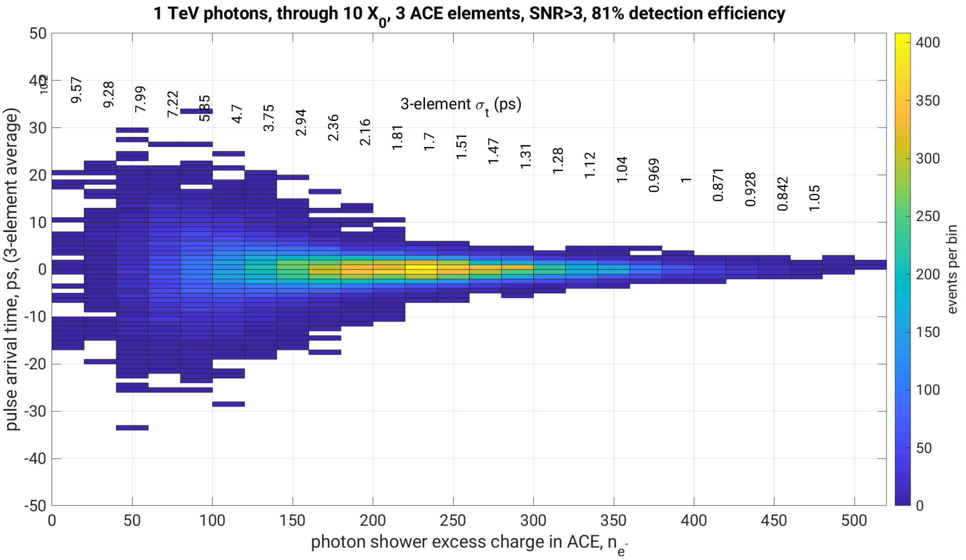


Figure: We assume a single *standalone* N=3 (N=6) Askaryan layer at 10 X_0 inside a barrel ECal:

Timing Measurement

- σ_t = 1.5 ps (1.1 ps) with 81% detection efficiency for 1 TeV photons events. For the best events, σ_t < 1 ps (700 fs).
- For this configuration, these timing constraints provide a position measurement along the long waveguide axis to $\sim$ 150μm.

Angular Measurement

- At 2m in the barrel region, polar angular resolution, $\Delta\theta \simeq 0.0043°$ => $\Delta\eta \simeq 7 \times 10^{-5}$. ~50-100x better η-resolution than FCC baseline designs if the vertex is otherwise known.
- The $\sim$ 3 mm transverse position resolution corresponds to $\Delta\phi \simeq 0.1°$.
- If the vertex is not known, a *standalone* Askaryan layer can provide strong sub-mm constraints on the vertex location.

5 TeV Pions in HCal

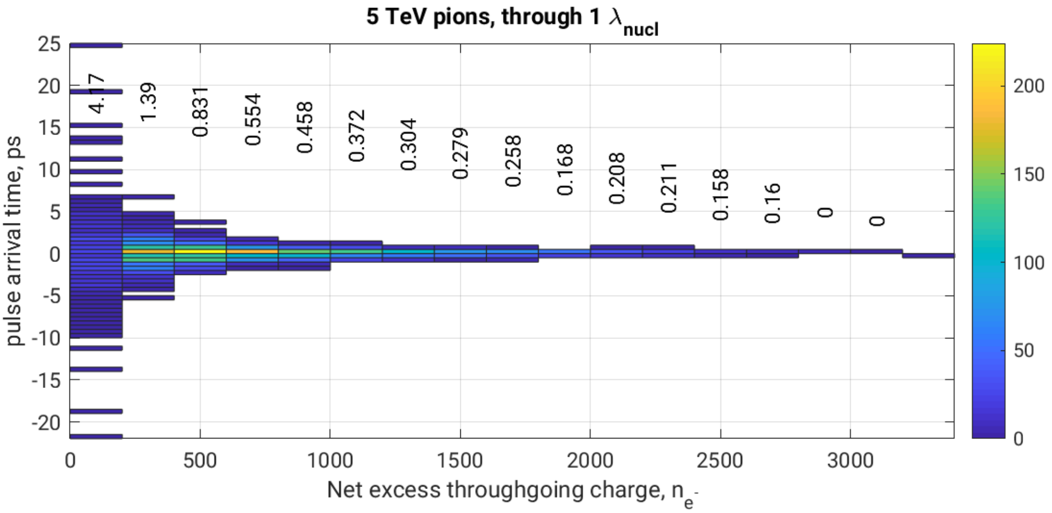


Figure: Timing resolution for N=3 Askaryan layer after 100 mm of tungsten (1 $\lambda_{nucl} \sim 40$ X_0).

Timing Measurement

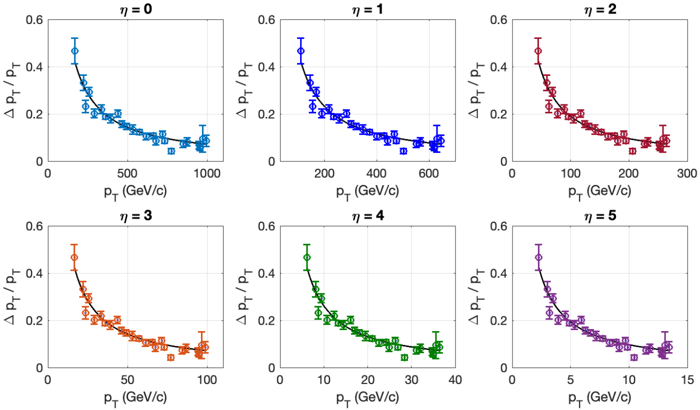
- Detection efficiency $\sim 37\%$ as many pion interactions do not produce prompt electromagnetic showers that transit through the layer.
- For those events that are detected, timing resolution < 1 ps for almost all events. For the best showers, resolution -> ~ 100 fs

Efficiency in the Forward Region

- At $\eta = 5$, a pion with $p_T = 60$ GeV will have a true energy of 5 TeV and will be much more common than in the barrel.
- Simulation results for a *single* Askaryan layer - multiple layers at various depths within a hadronic calorimeter will have higher efficiency.
- At 0.7-1.4 X_0, an Askaryan layer adds negligible absorption to the calorimeter.

Askrayan Timing Layers as 5D Detectors

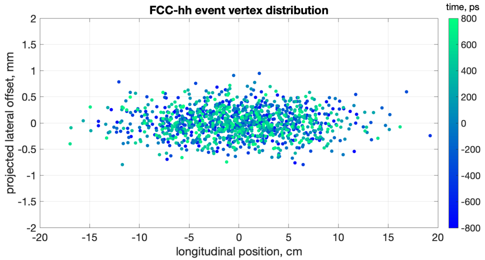
At high-η, where a particle with a given pT has increasingly larger true energy, ACE layers will be maximally sensitive and be true 5D calorimeters; by $\eta = 4$, a single Askaryan layer will provide ps and sub-ps timing as well as sub-mm tracking constraints for any electromagnetically showering particle pT $\gtrsim$ 10 GeV/c.

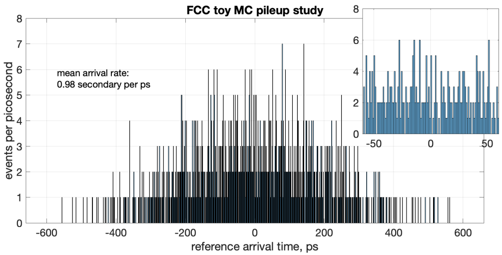


The pT resolution for a single ACEv1 element estimated from scaled test beam data for multiple values of the psuedorapidity, η - more recent designs have already improved on this performance.

Pileup Reduction

- We performed a preliminary simulation of FCC-hh pileup reduction using a *single Askaryan layer* in the barrel region - we assume each vertex produces an event that traverses an ACE element.
- With the resolution achieved by T-530, the mean rate per picosecond is $\mathcal{O}(1)$ - massively reducing pileup.
- This requires that the as-built detector geometry be known to sub-mm precision and a sub-ps zero-timing reference for the interaction point be provided.

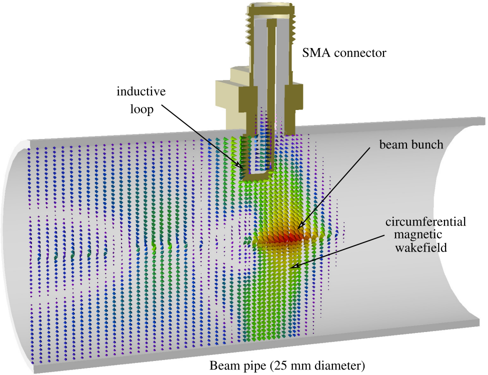


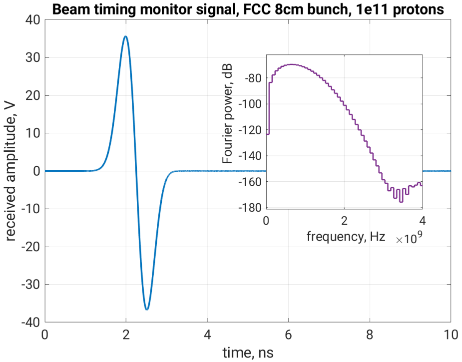


Beam Timing Probe (Prelim.)

Picosecond detectors require an extremely precise timing reference - typically sub-ps.

- Using the technology and simulations developed for ACE, we have started to develop a beam timing monitor capable of well below ps timing using magnetic wakefield sensors.
- Still very much a work in progress - more to come!





Cost & Economy of Scale (might remove)

- The waveguides & alumina are standard sizes and available off-the-shelf and low-cost and extremely durable - even custom sizes are cheap to produce at scale.
- RF instrumentation and measurement benefits from a vast economy of scale with a long technical heritage & global (still increasing) usage.
- Waveguides and alumina will not be a cost driver in the construction of Askaryan timing layers.

RF Digitizers Are Still Expensive

- The high-bandwidth RF digitizers that ACE needs to be maximally performant are still prohibitively expensive but are available today.
- Prices are coming down drastically due to economy of scale with roll-out of 5G and mmWave.
- Investment in HEP infrastructure to design, test, and manufacture custom digitizers to meet our jitter requirements is critical to further reduce the cost.

Future Work

Many tasks are on the roadmap for 2020-2023 to explore the ACE concept in more detail:

- Full system-level design of Askaryan timing layers for different FCC baseline detectors with detailed CAD engineering models.
- Full Geant4 & Delphes simulations with FCC baseline detectors using FCCSW for detailed simulation of performance including PFA and reconstruction.
- R&D into custom high-bandwidth RF digitizers and newly available commercial solutions to further refine our requirements.
- Sub-picosecond beam timing detector development with detailed electromagnetics simulation and hardware design.
- Another beam test in 2022-2023 to validate the performance of our next-generation Askaryan Calorimeter Elements.

Feedback Welcome!

Extremely interested in feedback/thoughts/ideas/collaboration from the community. In particular,

- How ACE could integrate and enhance performance of existing ECal/HCal designs? We are open to collaboration with calorimeter groups to study the performance of these combined calorimeters.
- Does sub-picosecond timing, and extreme η-resolution, on some fraction of ECal/HCal events significantly enhance particular searches for new physics?
- …and anything else!

Feel free to email us (`prechelt@hawaii.edu` and `gorham@phys.hawaii.edu`) or ping me on the Snowmass Slack, `@rprechelt`.

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