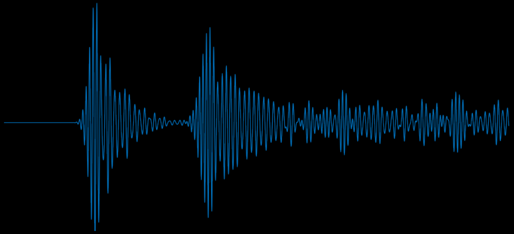
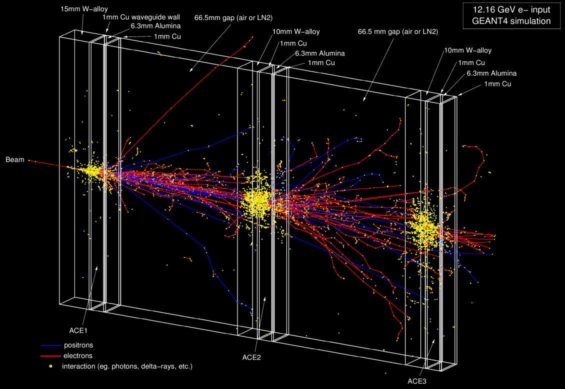


5D Picosecond Timing Layers for Future Calorimeters

Updates from the
Askaryan Calorimeter Experiment (ACE)



Remy Prechelt[1]
for the ACE Collaboration

P. W. Gorham[1], J. Bynes[1], B. Fox[1], C. Hast[2], B. Hill[1], K. Jobe[2],
C. Miki[1], M. Olmedo[1], R. Prechelt[1], B. Rotter[1], D. P. Saltzberg[3],
S. A. Wissel[4], G. S. Varner[1], S. Zekioglu[3]

[1]Univ. of Hawai'i at Manoa (UHM)
[2]SLAC National Accelerator Laboratory (SLAC),
[3]Univ. of California, Los Angeles (UCLA),
[4]Penn. State University (PSU)

INTRODUCTION

ACE

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

1. Picosecond to sub-picosecond timing of high-energy showers.
2. Sub-millimeter to millimeter spatial resolution in all three coordinates.
3. Calorimetric energy measurement.

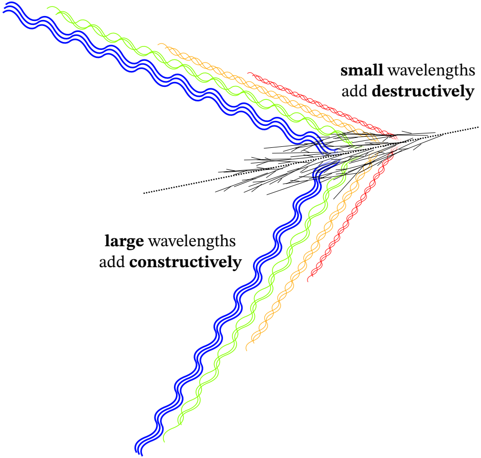
while simultaneously being mostly commercial-off-the-shelf (COTS), relatively low-cost, and *extremely rad-hard*, capable of withstanding FCC radiation fluences in the forward region. In this presentation, we show:

1. Brief review of the results of the T-530 beam tests at SLAC.
2. New simulations on deploying ACE layers at FCC and EIC relevant energies.

ASKARYAN EFFECT

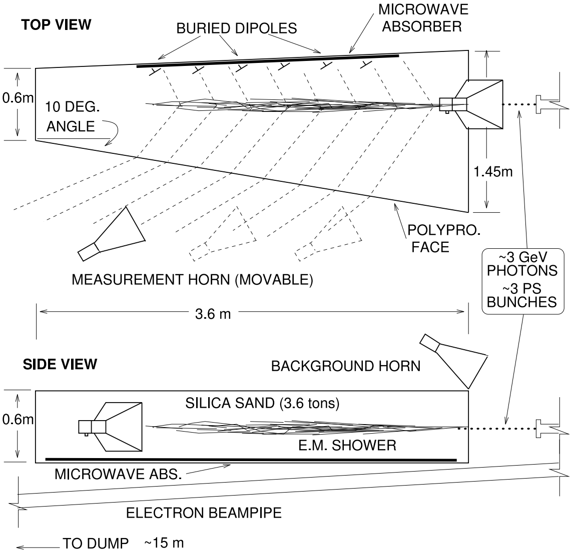
ASKARYAN EMISSION

- 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/ $Q \sim N_{\text{excess}} e \sim 0.2 N_{\text{shower}} e$
- The Cherenkov emission from all the particles in the shower is adding *constructively*; for typical media, this *coherence* extends up to >10 GHz.
- This is coherent microwave Cherenkov!



EXPERIMENTAL VALIDATION OF THE ASKARYAN EFFECT

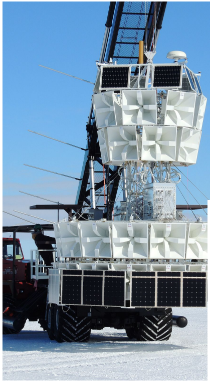
First theorized by G. Askaryan in 1962, and first detected in 2001 by Gorham & Saltzberg [1], Askaryan radiation since been directly measured in ice [2], salt [3], air [4], and alumina [5] up to $E \sim 3 \times 10^{19}$ eV with both e^- and γ using SLAC's ESA (T460, T464, T486, T530).

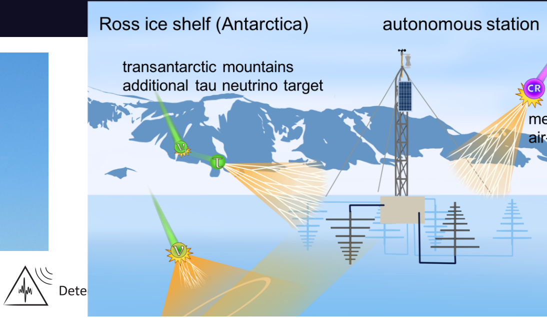


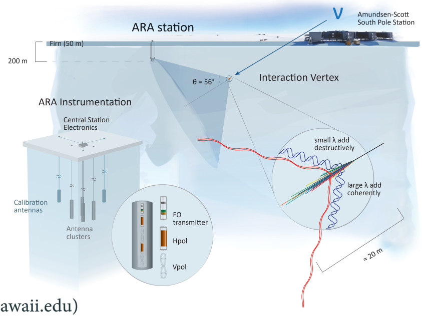
USE IN UHE NEUTRINO EXPERIMENTS

Askaryan emission is the primary method for detecting UHE neutrinos ($E_\nu > 10^{18}$ eV) via radio-Cherenkov (Askaryan) from neutrino-induced showers in the Antarctic ice with ARA [6], ARIANNA [7], and ANITA [8].

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



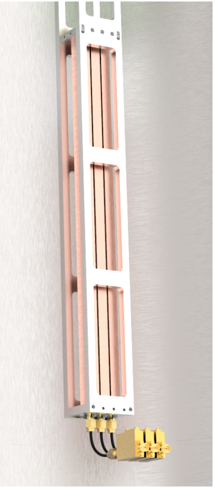


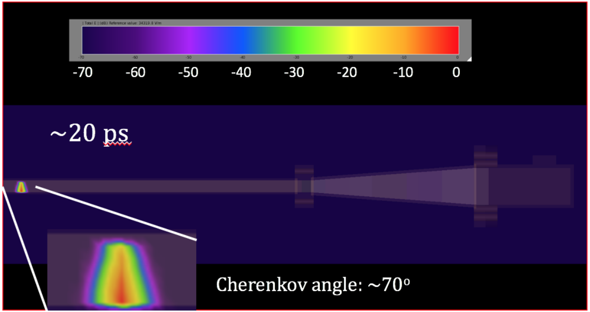


T-530: ASKARYAN CALORIMETER EXPERIMENT

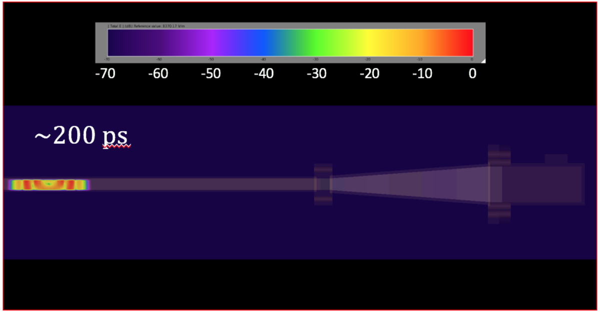
ASKARYAN CHERENKOV ELEMENTS

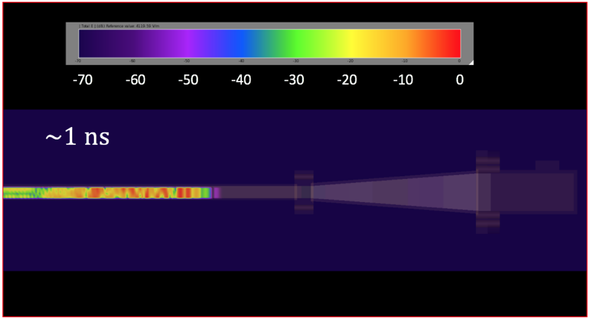
- We use standard WR51 (12.6mm x 6.3mm) copper waveguides loaded with alumina bars (Al_2O_3).
- Askaryan (microwave Cherenkov) from a shower moving through the waveguide is coupled into the TE_{10} mode (5-8 GHz) and propagates to each end.
- We amplify the ns-scale pulse with low-noise amplifiers (LNAs)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

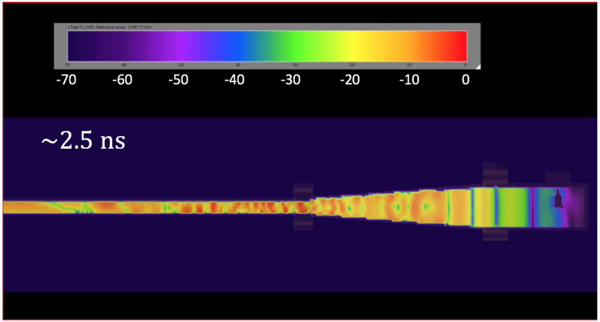




Cherenkov angle: ~70º





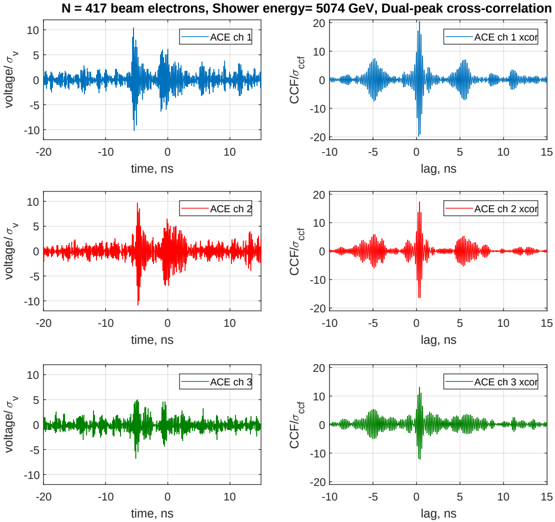


ENERGY THRESHOLD AND RESOLUTION

- In radio & microwave, thermal noise a major challenge -> all EM modes are "pre-loaded" with thermal photons. *The threshold of ACE elements is strongly driven by temperature; best performance is achieved in cryo* but is not essential for all use cases.
- 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.
- For our ACEv3 prototype in LN2/LHe, the single-element (waveguide) energy threshold was 90 ± 18 GeV but this scales as $1/\sqrt{N} \implies 51 \pm 11$ GeV for a 3-waveguide (2.5 cm $= 0.7\ X_0$) layer.

EXTRACTING TIMING INFORMATION

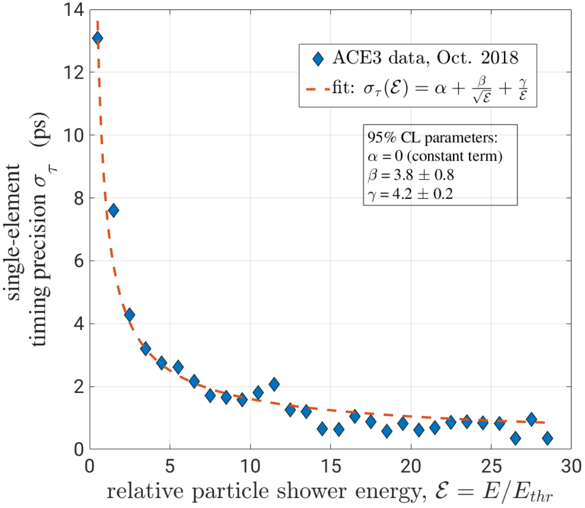
- This is not a traditional photon counter - ACE elements record the full time-domain electric field as the shower transits the waveguide.
- Cross-correlating separate ACE elements, or individual elements with the waveguide impulse response, gives an exceptional time of arrival measurement for the shower front.
- The high-bandwidth (>4 GHz) and high center frequency (6 GHz) compared to other HEP technologies both contribute to the exceptional timing precision.



R. Prechelt (prechelt@hawaii.edu)

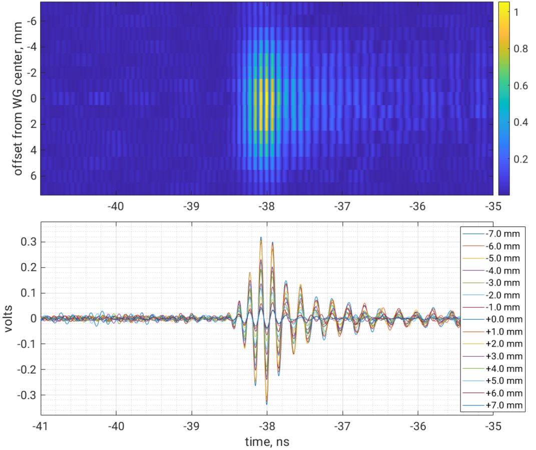
TIMING RESOLUTION

- For our ACEv3 prototypes, we measured $\sim$ 1.2 ps *per-element* timing resolution for showers significantly above threshold.
- The timing resolution scales with $1/\sqrt{N}$ so the 3-waveguide (2.5 cm $= 0.7\ X_0$) layer in ACEv3 achieved better than 3 ps resolution for showers with total energy ~50 GeV.



SPATIAL RESOLUTION

- 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, $\Delta y \sim 300\ \mu\text{m}$ at 90 GeV. This improves to $100\ \mu\text{m}$ 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.

5D Askaryan Calorimeters for Future Colliders

SIGNIFICANT IMPROVEMENTS SINCE ACEV3

- Since our last beam test in 2018, ACE prototypes have improved by ~2x (i.e. lower energy threshold) and are still likely to improve over the next few years.
- Recently started several more years of DoE funding to further develop the ACE concept with additional beamtests expected next year.

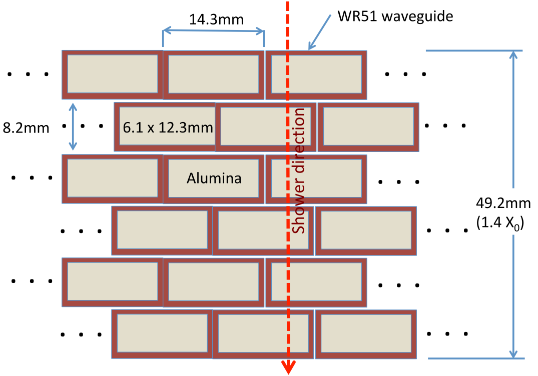
An ACE Timing/Calorimeter Layer

- Our baseline ACE timing layer is nominally 3-6 waveguides thick but can be tuned to fit the needs of an experiment.
- Total thickness is ~50 mm = 1.4 X_0 (few % of FCC-hh baseline ECal depth)
- Using our latest waveguide design in LN_2 with LHe cold-taps for the LNAs , a single Askaryan timing layer would provide:

$$E_{\mathrm{thr}} \sim 20\ \mathrm{GeV}$$

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

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



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

For showers with total energy above ~ 20 GeV, these are 5D detectors!

… BUT THIS IS CUSTOMIZABLE!

ACE elements are dominated by *thermal noise*, not a *"cutoff"* in any particular physics process, so performance scales $\sim \frac{1}{\sqrt{N}}$ over the entire usable energy range.

Thicker ACE Layers

- For example, a 20 cm thick layer of ACE elements can provide single picosecond timing for all showers with total energy above 10 GeV.
- For *far forward* or *off-momentum* particles that you might otherwise send to a beam dump (i.e. ACE's contribution to total grammage is irrelevant), ACE layers could be as thick as needed to achieve energy thresholds down to a ~GeV.

Waveguide sizes and geometries can also be adjusted to meet specific performance & cost requirements for a given experiment.

WHAT MIGHT THIS LOOK LIKE FOR A FUTURE COLLIDER?

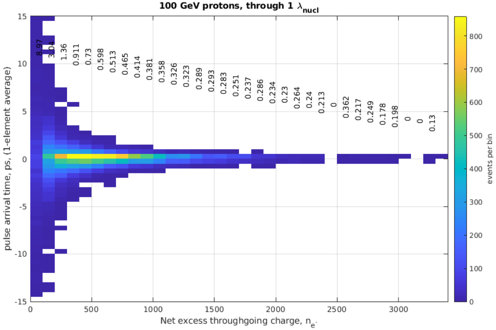
- Due to their high threshold and relatively coarse energy resolution, ACE layers are not practical as a *standalone calorimeter* technology for most *standard* applications.
- However, at a future high CoM colliders (i.e. FCC-ee/hh) many showers will be above threshold ($\mathcal{O}(20\text{ GeV})$) in the barrel/forward region.
- Several *Askaryan timing 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.
- ACE elements could also be used as standalone detectors in the *far-forward regions* at the EIC, especially in regions where other detectors may struggle with radiation fluence.

FAR-FORWARD PHYSICS AT THE EIC

Due to our energy threshold, ACE is not extremely competitive *in the barrel* at the EIC.

However, a single ACE layer located in the *far-forward* or *off-momentum* detector points at the EIC could provide $\lesssim 3ps$ timing and $\sim 10\ \mu$rad angular reconstruction for almost far-forward protons for *diffractive studies* or *far-forward* physics (assuming an accurate enough clock!)

ACE can also potentially reconstruct or precision measurement of the *collision location*; >order of magnitude better than current proposals.

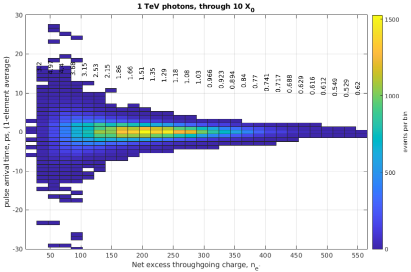


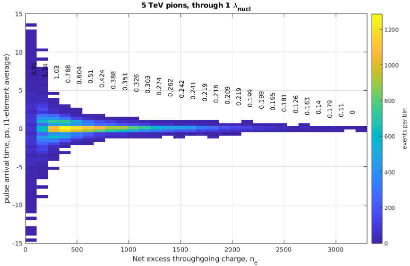
Open Question: What physics does this precision timing or far forward detector enable?

FCC-HH/FCC-EE

At the FCC-hh, ACE can *be competitive* in the barrel and forward detectors when placed inside an existing calorimeter technology.

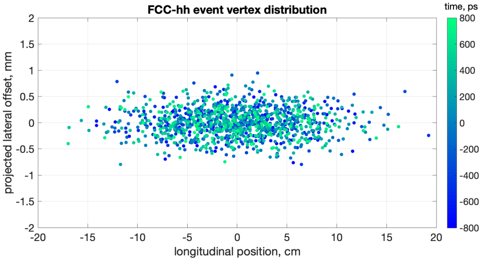
- $\sigma_t \lesssim 1\ ps$ for almost all FCC-like 1 TeV photons with a 5 cm-thick barrel detector located in the ECal. For the best events, $\sigma_t \lesssim 300$ fs (assuming a perfect accelerator clock).
- For this configuration, these timing constraints provide a position measurement along the long waveguide axis to $\sim 150\mu m$ as well as an excellent angular measurement.
- ACE should perform even better in the forward region and simulations are under way!

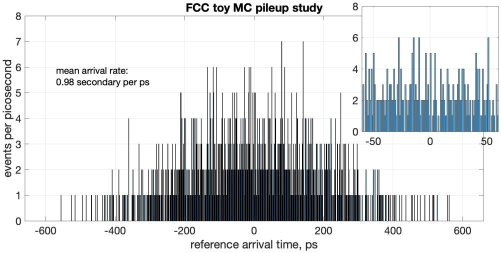

1 TeV photons, through 10 X_0


5 TeV pions, through 1 λ_{nucl}

PILEUP REDUCTION (PRELIM.)

- 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 be provided.





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 with our existing simulations.
- Does sub-picosecond timing, and extreme η-resolution, on some fraction of ECal/HCal events significantly enhance particular searches for new physics?
- We are also working with other collaborators on how to define and distribute extremely high-precision clocks to allow timing resolutions of this accuracy to be useful!
- …and anything else!

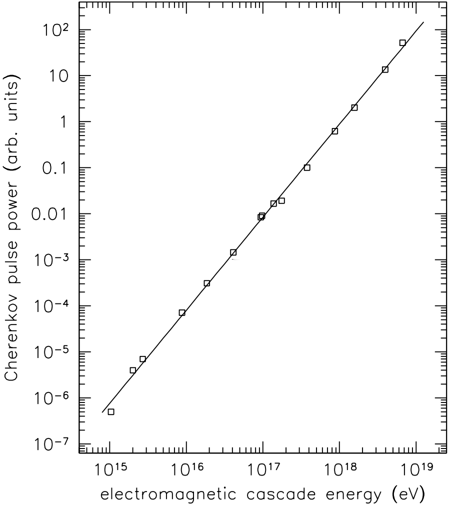
Feel free to email me (`prechelt@hawaii.edu`) or send me a Zoom link; I'll gladly chat about the possibilities of ACE (we are excited about exploring this other groups).

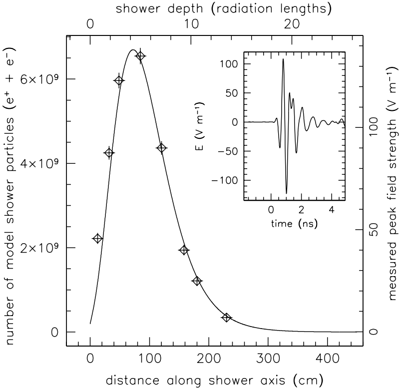
BACKUP

ASKARYAN CALORIMETRY

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

Validated across >8 orders of magnitude in shower energy - *extreme dynamic range.*





The field tracks the shower evolution and produces an extremely broadband (impulsive) signal [9, 10].

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).
- $\gtrsim 10,000$ 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!

SIGNIFICANT IMPROVEMENTS TO ACE ELEMENTS

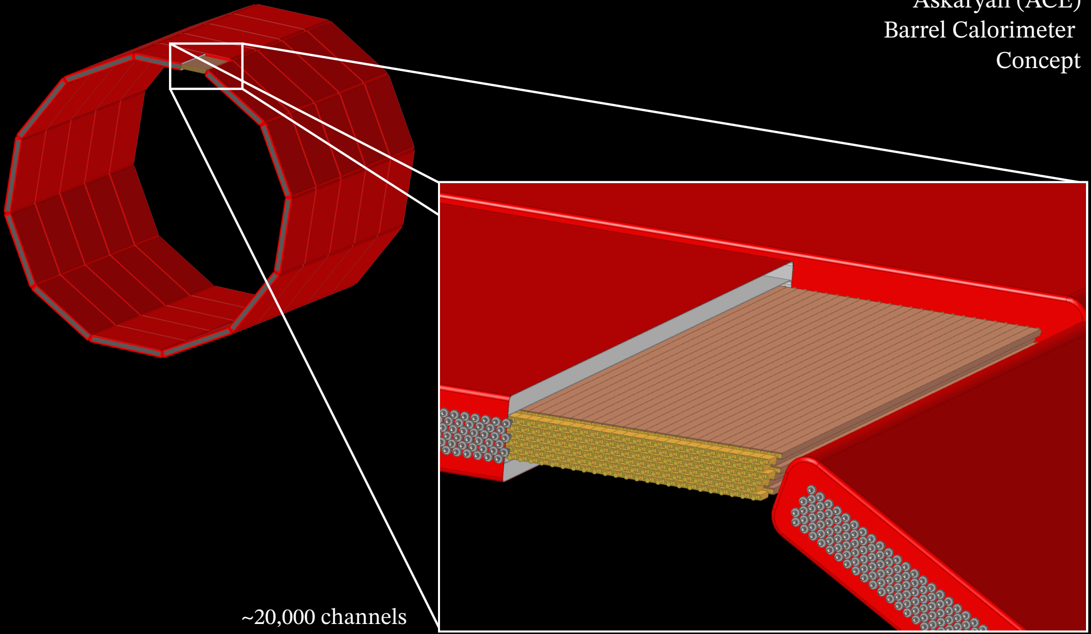
Since the ACEv3 beamtests in 2018, we have undergone an intense period of R&D on improving the individual ACE waveguides. Since then, we have designed:

1. New double-stacked waveguide design with waveguide couplers to lower the energy threshold by ~2x.
2. A completely new waveguide-coax coupler with double the bandwidth of existing designs; a ~30% improvement in timing and energy threshold.
3. Improved LNAs with ~40% lower noise figure (← not included in this presentation)

These improvements have been demonstrated in the lab as well as in our electromagnetic simulations and potentially make ACE suitable for other experiments outside of the FCC.

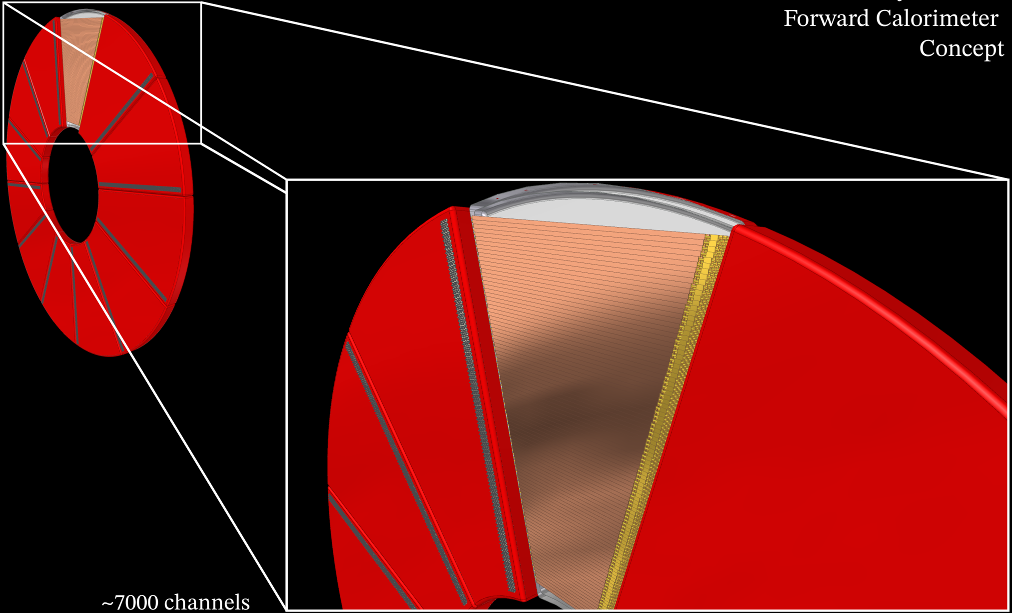
We have recently started several more years of DOE funding (including more beam tests in the future).

Askaryan (ACE) Barrel Calorimeter Concept



~20,000 channels

Askaryan (ACE)
Forward Calorimeter
Concept



~7000 channels

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