Askaryan Radio Array (ARA): Status and Performance

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INTRODUCTION

GZK Process and Sources

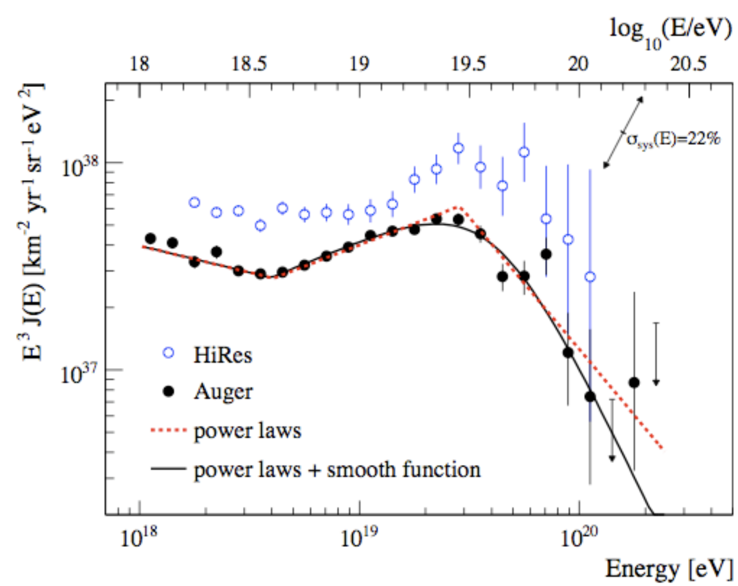
- Greisen-Zatsepin-Kuzmin (GZK): Cosmic rays with E > $10^{19.5}$ eV interact with cosmic microwave background (CMB) photons
- Process produces neutrinos, some at ultrahigh energies (UHE)
- Neutrinos are not subject to these successive interactions and happily continue on.
- UHE neutrinos could also be produced at a source location
  - If observed, will trace back to source

$$\mathbf{p} + \gamma_{\rm CMB} \rightarrow \mathbf{\Delta}^* \rightarrow \mathbf{n} + \pi^+$$

$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^- + \bar{\nu}_{\mathbf{e}}$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow \mathbf{e}^+ \bar{\nu}_\mu \nu_{\mathbf{e}}$$



Large Volume Detectors

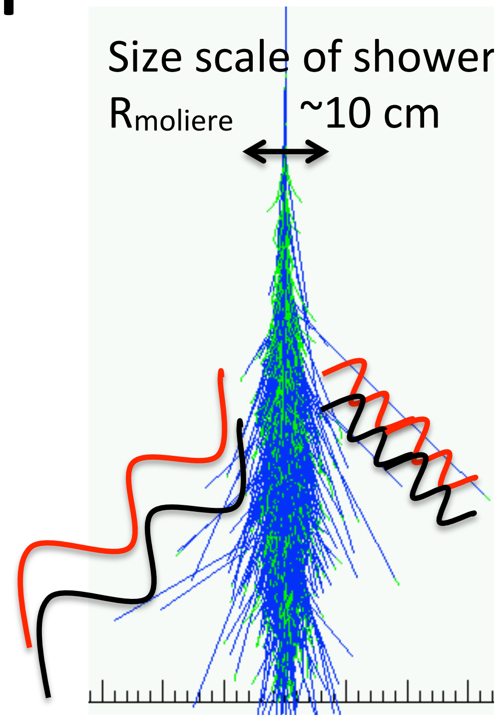
- Consider GZK models, Antarctic ice, earth shadowing, neutrino cross sections
  - Less than 1/km^3/year/energy decade

$$F \propto \frac{1}{At\Omega}$$

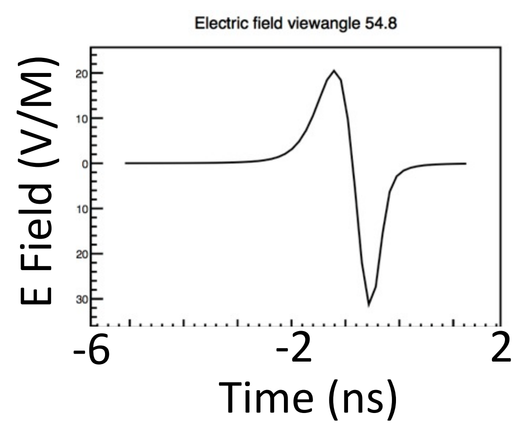
- Synoptic – balloons
  - Large target volume - O(10^6 km^3); short flight time 30-40 days
  - More limited viewing angles → less solid angle
  - Must be reconstructed after flight and "landing"
  - Good as a "discovery" instrument for highest energies (>10^{20} eV)
- *In situ* arrays
  - Long operation time (years); smaller observable volume - O(100 km^3)
  - Larger solid angle for observable signals
  - Environmental problems *in situ* – measure and model environment, ice
  - But better able to obtain more information about event - direction, pol., etc.
  - Good as an observatory – long term stability, reaches lower energy (10^{17} eV)

Detection technique

- How to get large-scale detection -
  - Brute force: make 100 IceCubes
  - Use a different approach – radio Cherenkov technique
- Coherent Cherenkov signal from net "current," instead of from individual tracks
  - A ~20% charge asymmetry develops in the shower (positrons annihilated, electrons not)
  - If $\lambda \gg R_{Moliere}$ (radial size scale) → Coherent Emission
  - Hypothesized by Gurgen Askaryan, 1962
  - Effect observed in ice, water, salt
  - Impulsive bipolar signal
- Long (~1 km) attenuation lengths in 0.1-1 GHz → large observable volume

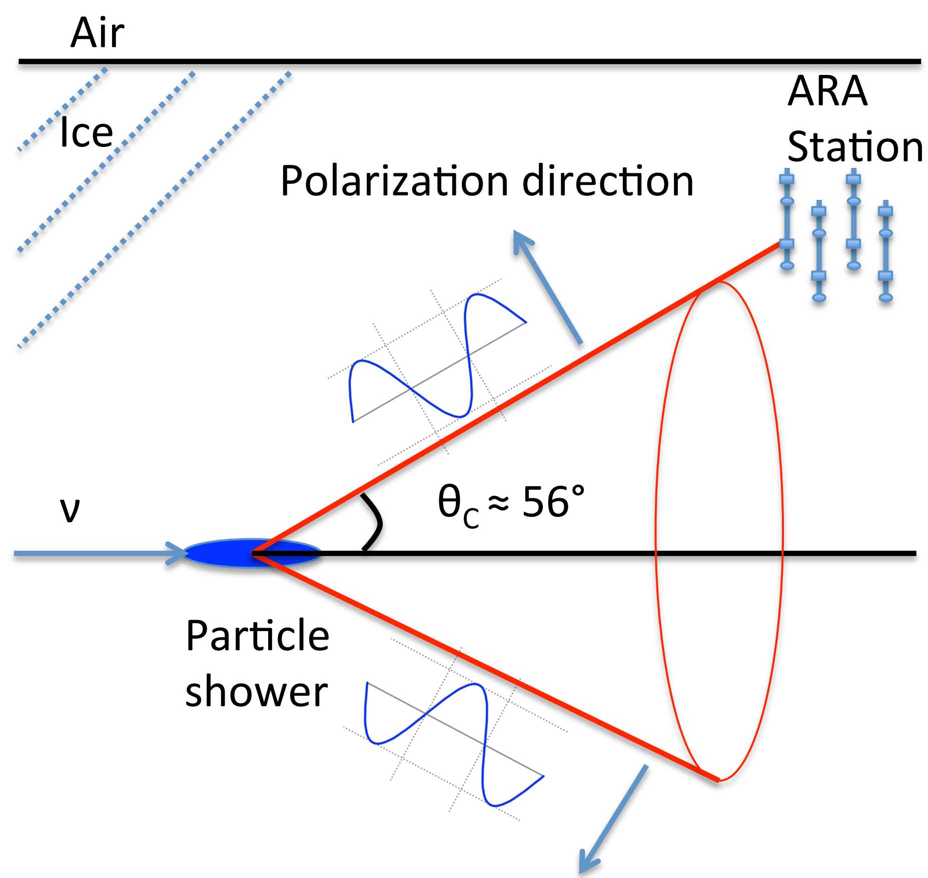


Particle shower



Detector Concept

- Place antennas in ice to observe the radio signals
- Delays in arrival times used for reconstruction
- 3-D array design for each station
  - Varying baseline directions – not localized to 1 plane
  - Good reconstruction in arrival direction from surrounding ice volume
- Observation angle determines the coherence of the signal and thus frequency content



EXPERIMENT AND DETECTOR

ARA Collaboration

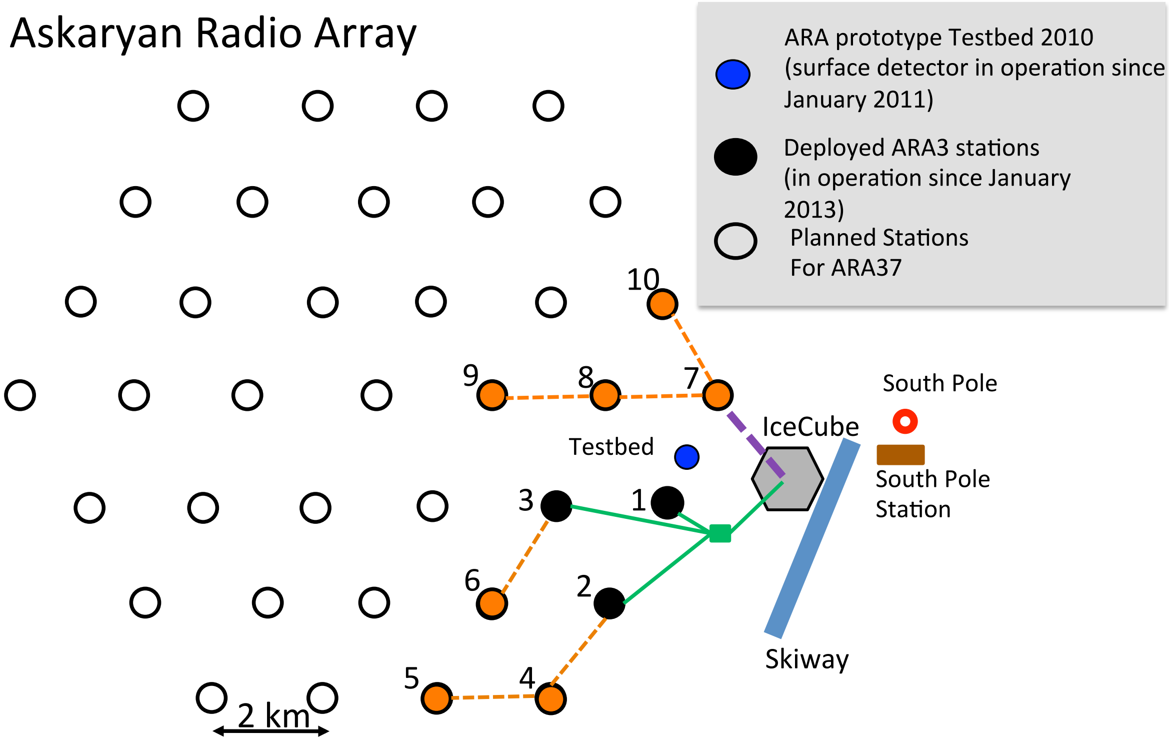
USA:

- Ohio State University
- University of Delaware
- University of Kansas
- University of Maryland
- University of Nebraska
- University of Wisconsin – Madison

UK: University College London
Belgium: Université Libre de Bruxelles
Japan: Chiba University
Taiwan: National Taiwan University
Israel: Weizmann Institute of Science
Germany: University of Bonn
Australia: University of Adelaide

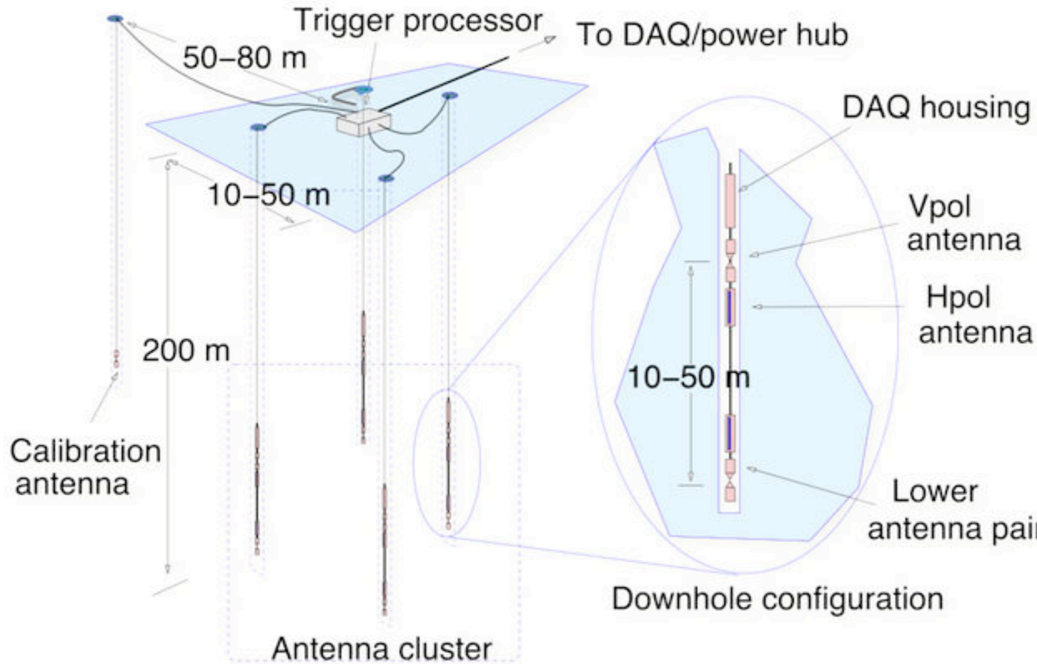
- International collaboration with 12 institutions
- ~50 authors

ARA layout



- Currently installed: 3 design stations + 1 shallow prototype Testbed
  - Installation dates: Testbed 2010-2011 @ 30 m depth;
  - A1 2011-2012 @ 100m depth; A2 and A3 2012-2013 @ 200 m depth
- Next installation phase: 7 more stations for ARA10
- Total planned – 37 stations viewing ~ 100 km^2 of surface area

Station Design



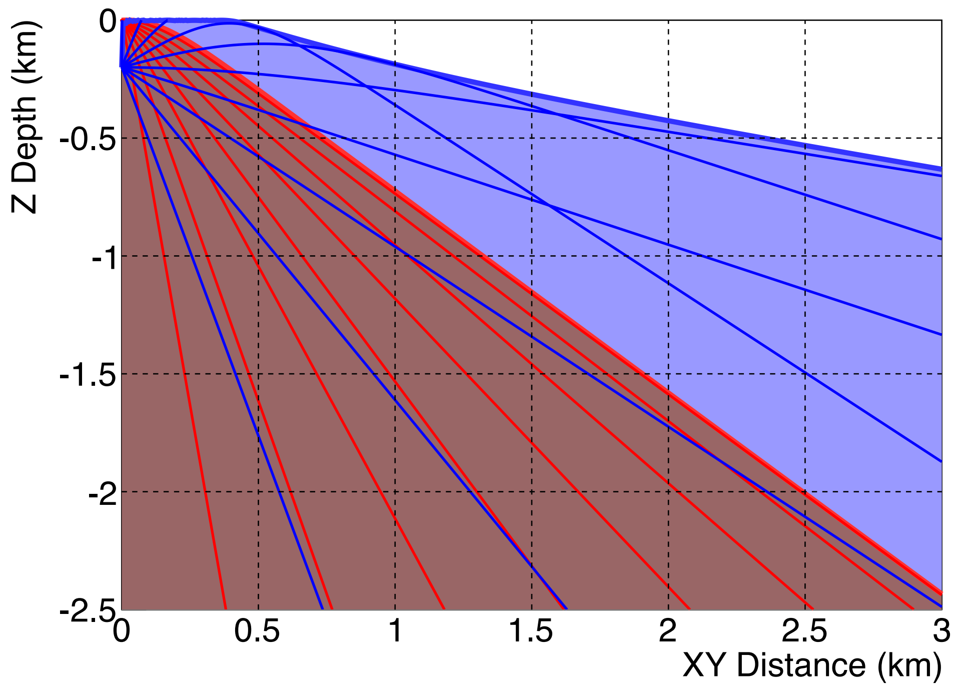
Hpol quad-slotted cylinder antenna

Vpol bicone antenna

- 4 strings with 4 antennas each
  - 2 pairs (upper and lower) of 1 Vpol and 1Hpol antenna
- 2 Calibration pulser antennas @ receiver antenna depth
- 4 fat dipole antennas at surface for cosmic ray identification
- Deployed 200m deep in ice – minimize effect of firn layer

- Bandwidth: 150-850 MHz
- Azimuthal symmetry, dipole at low frequencies

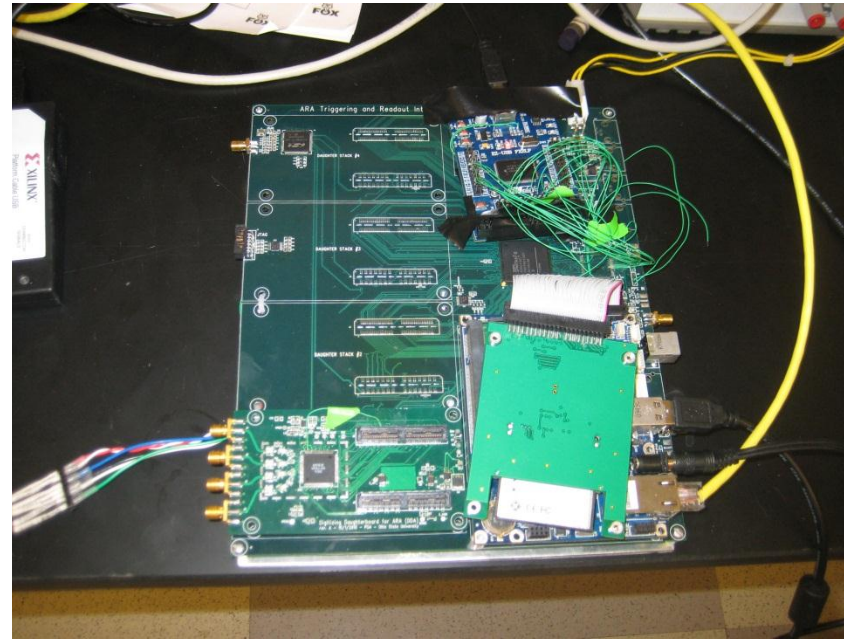
Importance of Deep Deployment



- Firn – layer of compacted snow
  - Quickly changing index of refraction (~1.35 → ~1.78 within top ~150 m of ice)
  - Causes curvature in paths of rays in ice
  - Limits viewable volume and observable neutrino incident angles
  - 30 m → 200 m depth: increases effective volume by factor of ~3.2
- Cost-benefit analysis
  - Ice closer to surface is colder, longer attenuation length
  - Drill to lower depths to gain effective volume vs money and time to drill further

Electronics

- 3.2 Gigasamples/sec rate
- Trigger –
  - Tunnel diode acts as a power integrator over few ns time scale
  - Requires 3 excursions of tunnel diode output above threshold within 110 ns in antennas of same polarization (3/8)
  - Threshold automatically adjusted to maintain steady global trigger rate
- 12-bit digitization
- 400 ns output waveform



- Notch filter at 450 MHz removes communications signals
- LNA for each antenna improves received signal strength above background

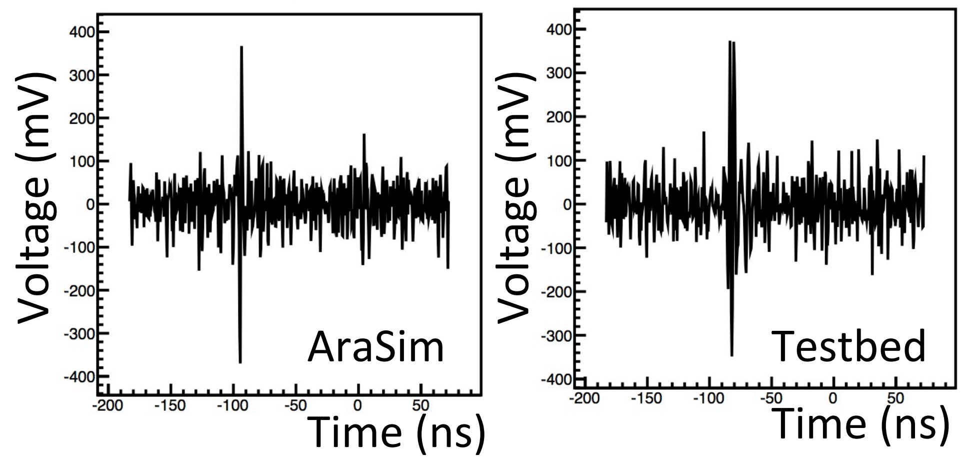
See talk by Thomas Meures in afternoon for further developments

ANALYSIS STATUS

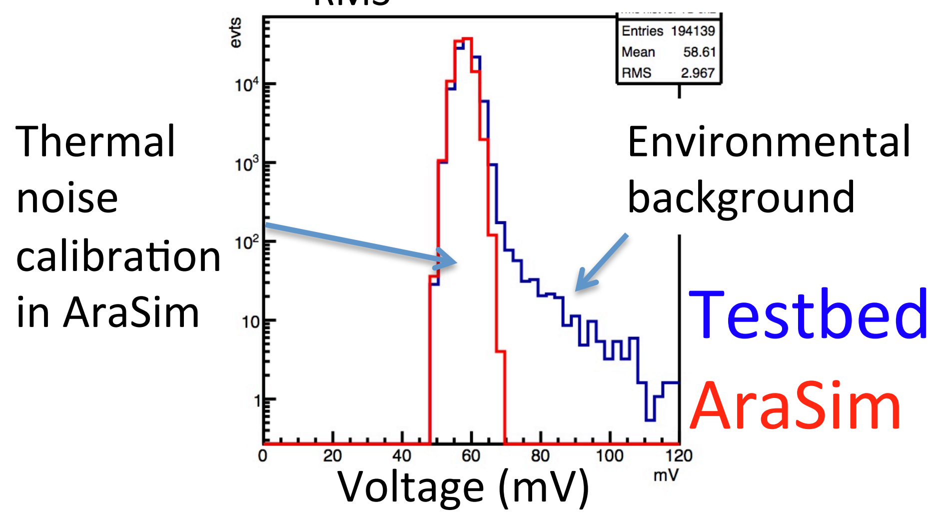
AraSim

- Official collaboration Monte Carlo simulation package for assessing sensitivity and general use
- Writes simulated events in data format for direct comparison
- Simulates full trigger and signal chain for neutrino events detected by ARA stations
- Uses parameterized shower signal
- Takes into account
  - Index of refraction model
  - Calibrated noise simulation
  - Antenna and electronics responses
  - Trigger model

Calibration pulser event waveforms

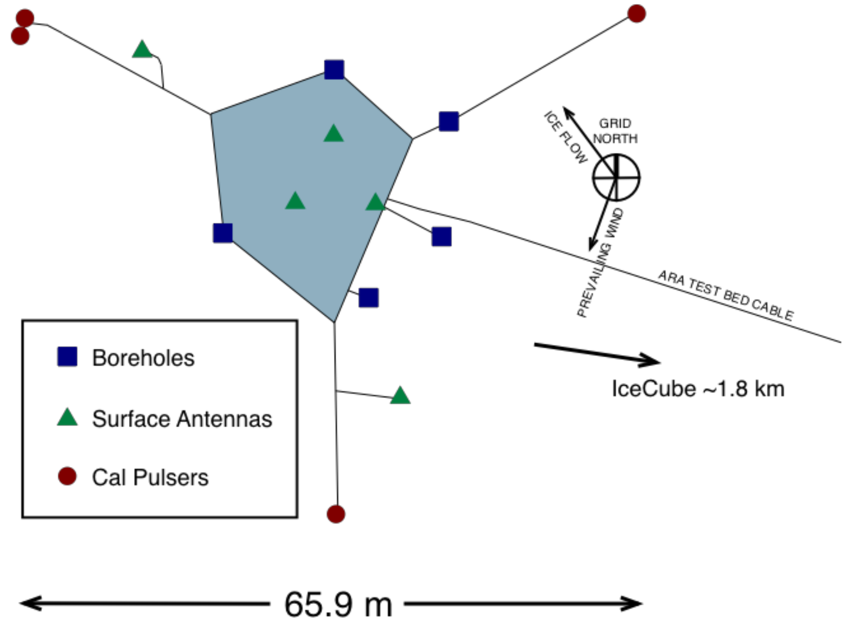


V_{RMS} Distribution

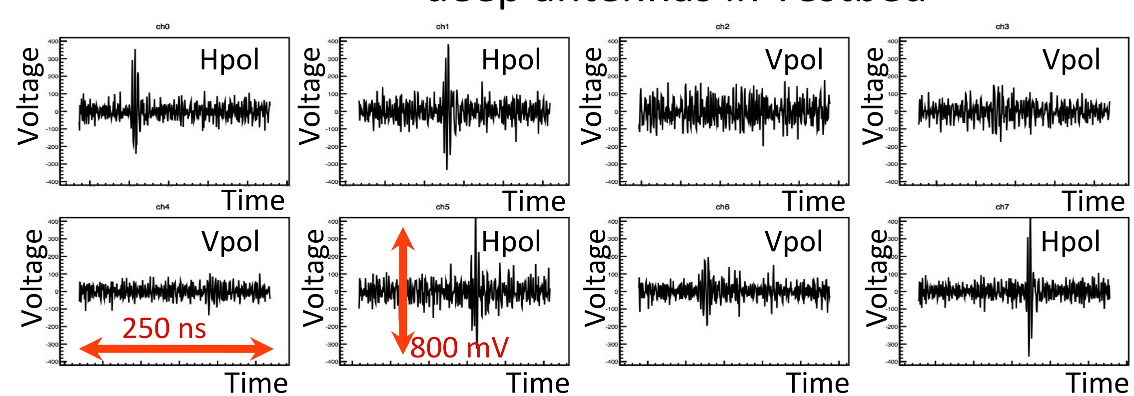


Testbed Analysis

- Total 16 antennas, 8 borehole antennas at 150 MHz to 850 MHz
- Maximum depth of antennas ~ 30 m
- 3 sets of calibration pulsers
  - Each set has a Vpol and an Hpol pulser
- First ARA neutrino searches carried out with Testbed station data



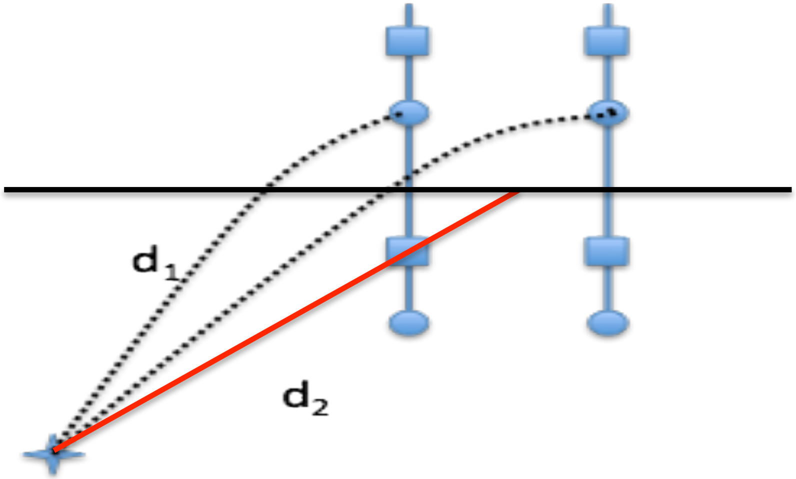
Calibration pulser event waveform from 8 deep antennas in Testbed

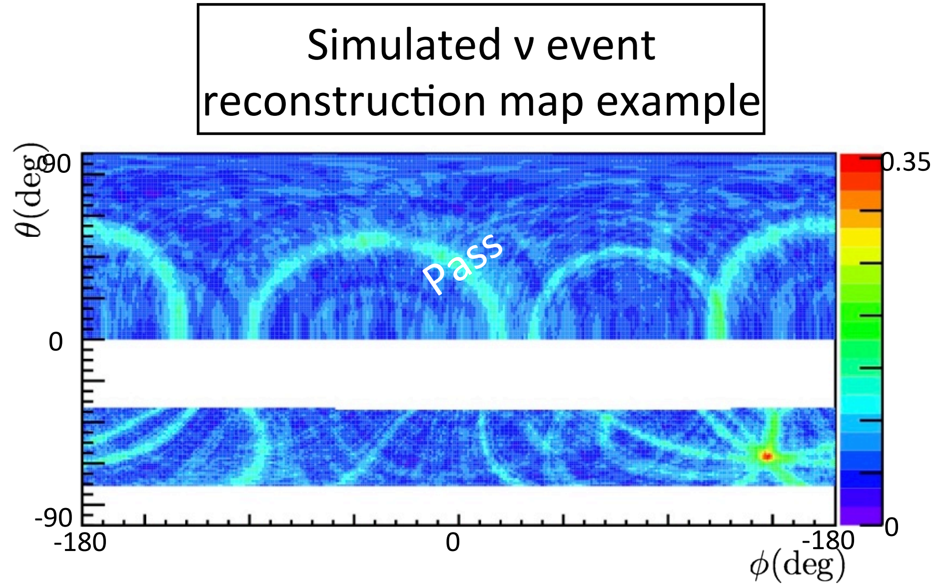


ARA – Testbed Neutrino Analysis

- Standard ARA blinding protocol – examine 10% of data to characterize backgrounds and tune cuts
  - Thermal Noise
  - Continuous wave (CW)
  - Anthropogenic impulsive background
- 3 analyses – ~330 million events
- OSU Cut-based Analysis –stage 1: Feb-Jun 2012; stage 2: Jan 2011-Dec 2012
  - Interferometric reconstruction from ray-traced cross-correlation map
  - Optimized cuts for background rejection and signal retention
- UCL Cut-based Analysis – Jan 2011 - Dec 2012
  - Uses least-squares fit to a source location
  - Examines the coherently summed waveform for power
- KU Template-Based Analysis – only Mar-Aug 2011
  - Hit times from voltage above threshold, impulsiveness and quality cuts
  - Hit pattern forms a "template"; reject repeated templates

OSU analysis - Reconstruction Quality Cut

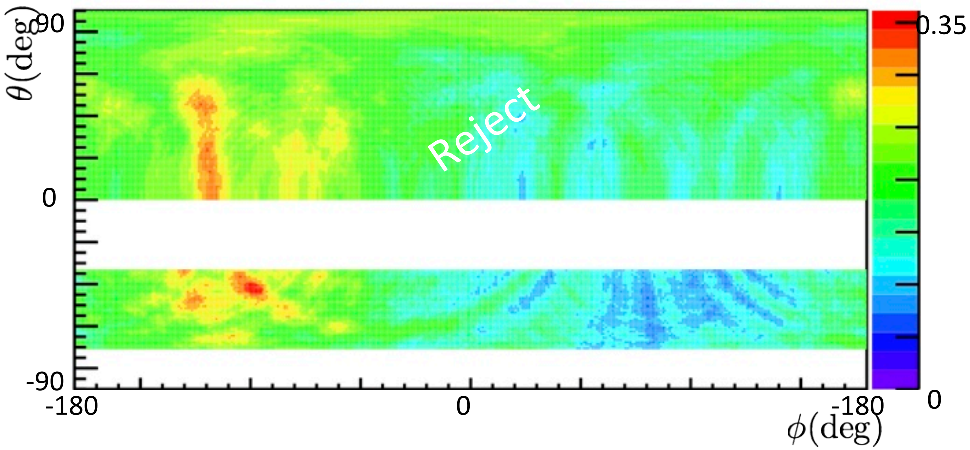




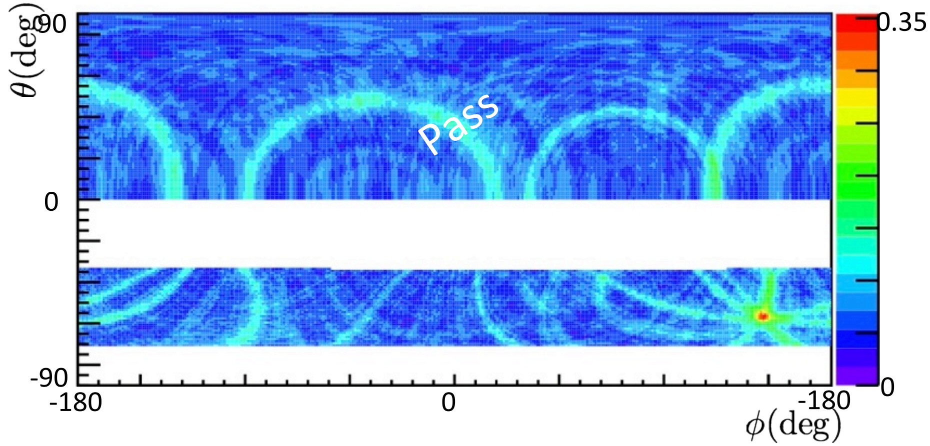
- Reconstruction based on timing from ray-tracing – use 30 m and 3 km maps in Hpol and Vpol
- Requires at least one reconstruction map to be of good quality
  - 1 deg^2 < Area of 85% contour surrounding the peak < 50 deg^2
  - Total 85% contour peak area < 1.5 x Area of 85% contour surrounding the peak
- Depending on the polarizations which pass the cut, the event is separated into Vpol and/or Hpol channels
- Rejects ~95% of noise-dominated events after initial quality cuts

OSU analysis - Reconstruction Quality Cut

Known background event reconstruction map example



Simulated ν event reconstruction map example



- Reconstruction based on timing from ray-tracing – use 30 m and 3 km maps in Hpol and Vpol
- Requires at least one reconstruction map to be of good quality
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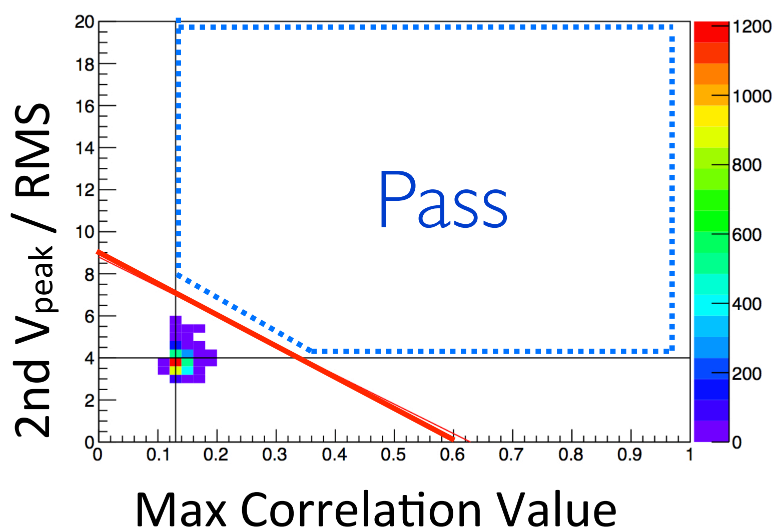
  - Total 85% contour peak area < 1.5 x Area of 85% contour surrounding the peak
- Depending on the polarizations which pass the cut, the event is separated into Vpol and/or Hpol channels
- Rejects ~95% of noise-dominated events after initial quality cuts

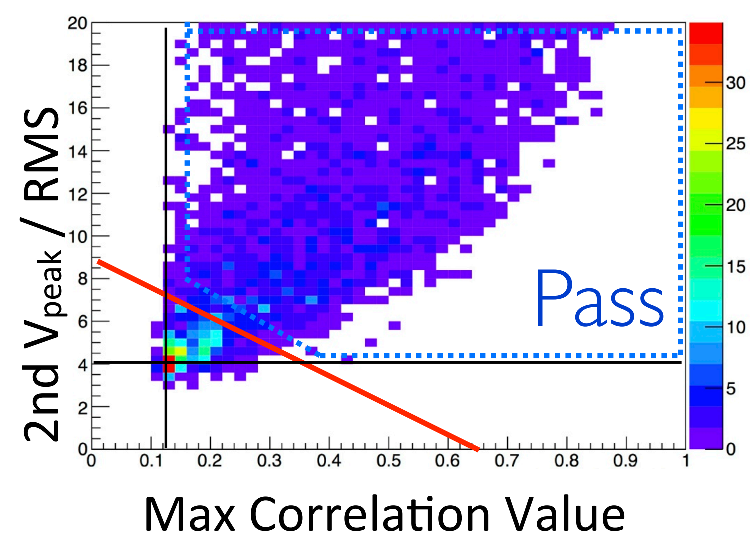
2nd V_{peak} / Correlation Cut

- Other cuts : Data Quality cut, Down cut, CW cut, Delta delay cut, Gradient cut, Geometry cuts (clustering, South Pole, Calibration Pulser), periods of known increased activity at South Pole
- Expect a correlation between V_{peak}/RMS from waveform and correlation value from reconstruction map for an impulsive event
- After removing known background events with other cuts, use this relation to get background estimation
- We optimized the cut for best limit on maximal Kotera *et al*. model
- As a last cut, this rejects 22% of Kotera neutrino flux

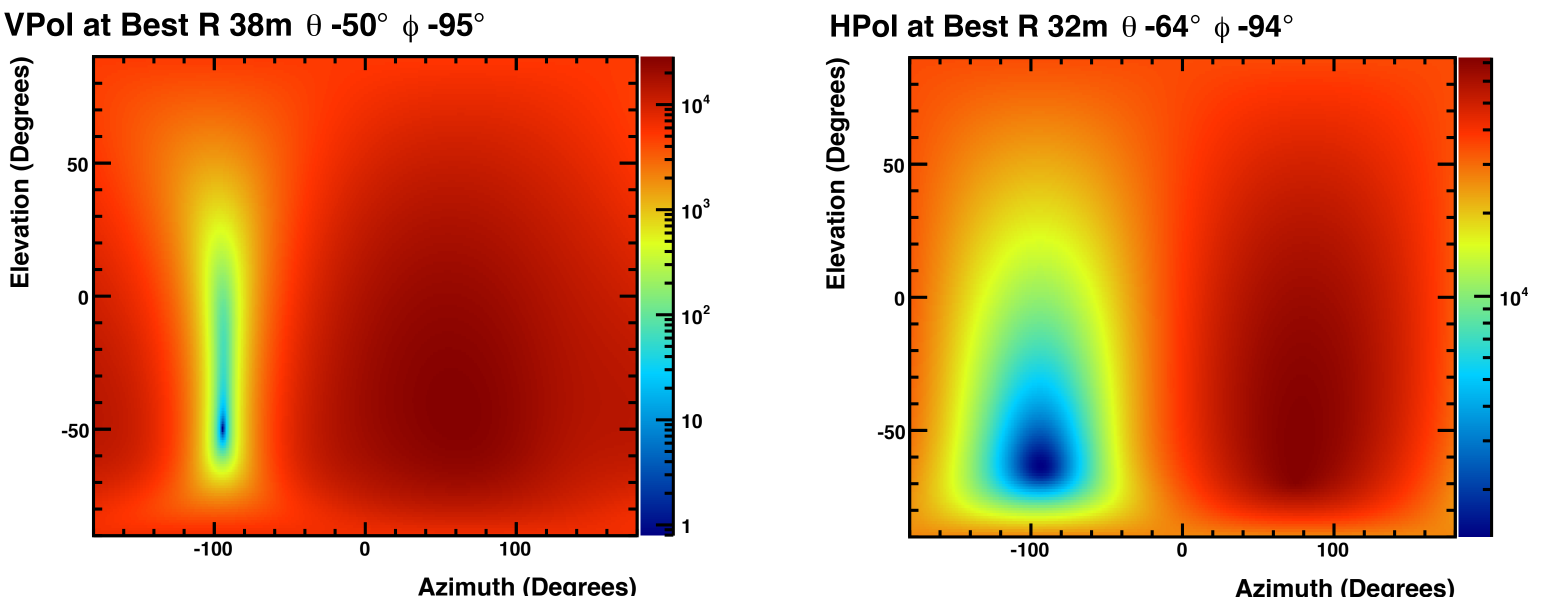
Testbed 10% data set after cuts applied



Simulated 10^{18}eV ν set with cuts applied

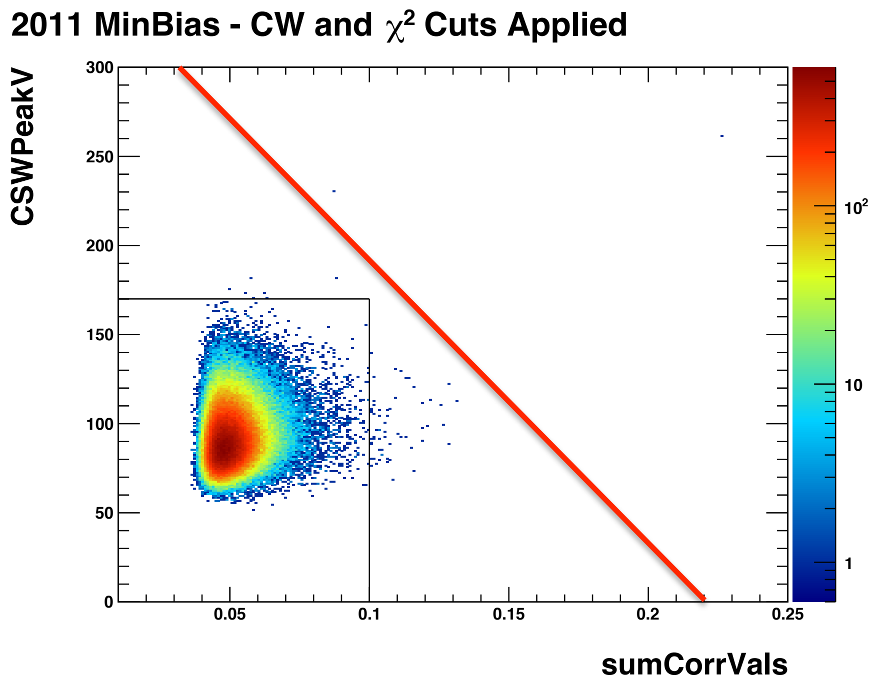


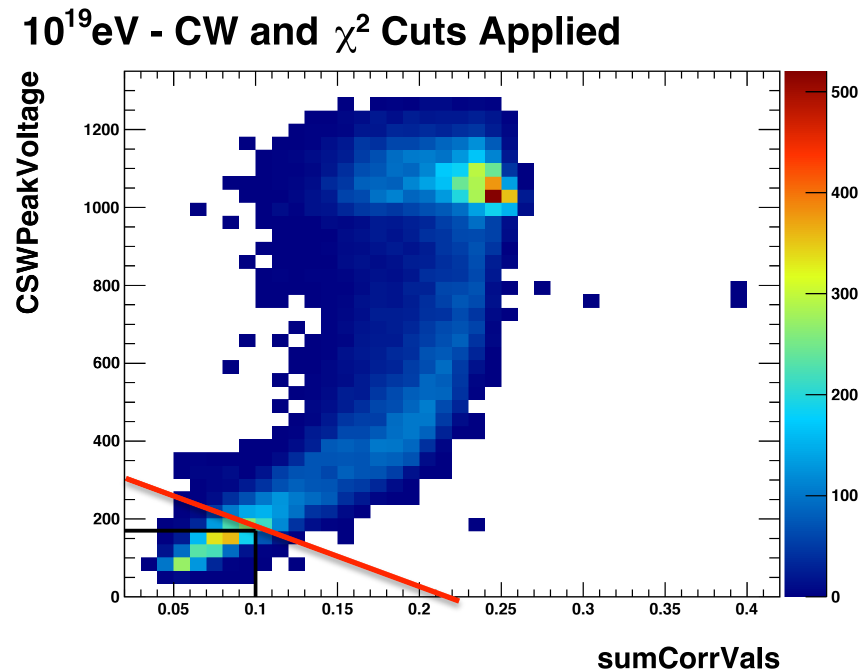
UCL Analysis Reconstruction



- Obtain coherently summed waveform (CSW):
  - Iteratively find the best correlation between a waveform and the CSW; obtains set of delays with best correlation
- Compare delays used to make the CSW to delays expected from putative source positions: minimize $\chi^2 = \Sigma(T_{expected} - T_{observed})^2$
- Cut events with $\chi^2 > 2$.
- Also cut events with excess CW power

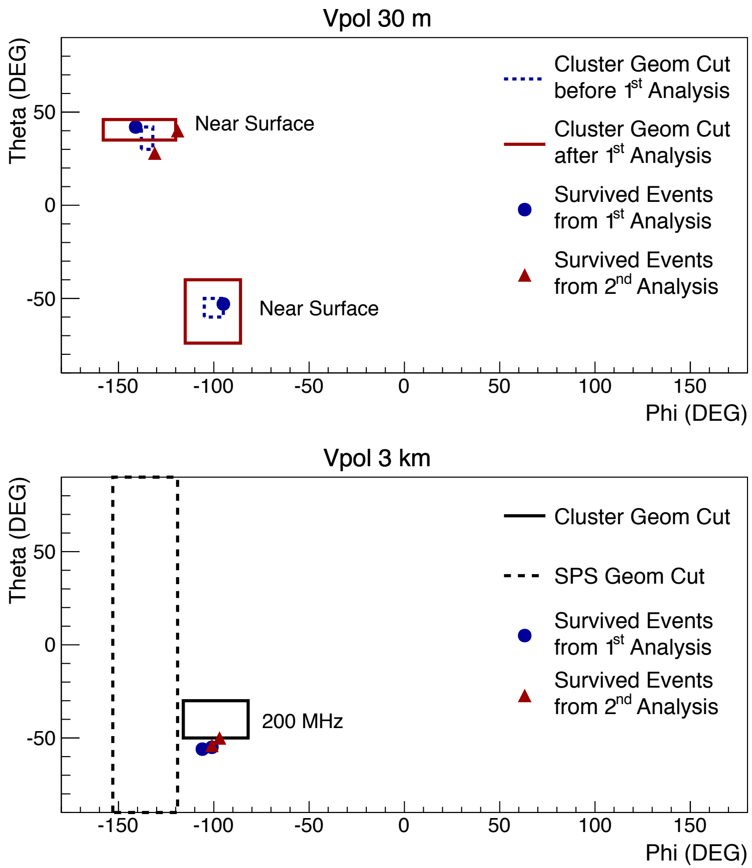
UCL - "Powherence" Cut

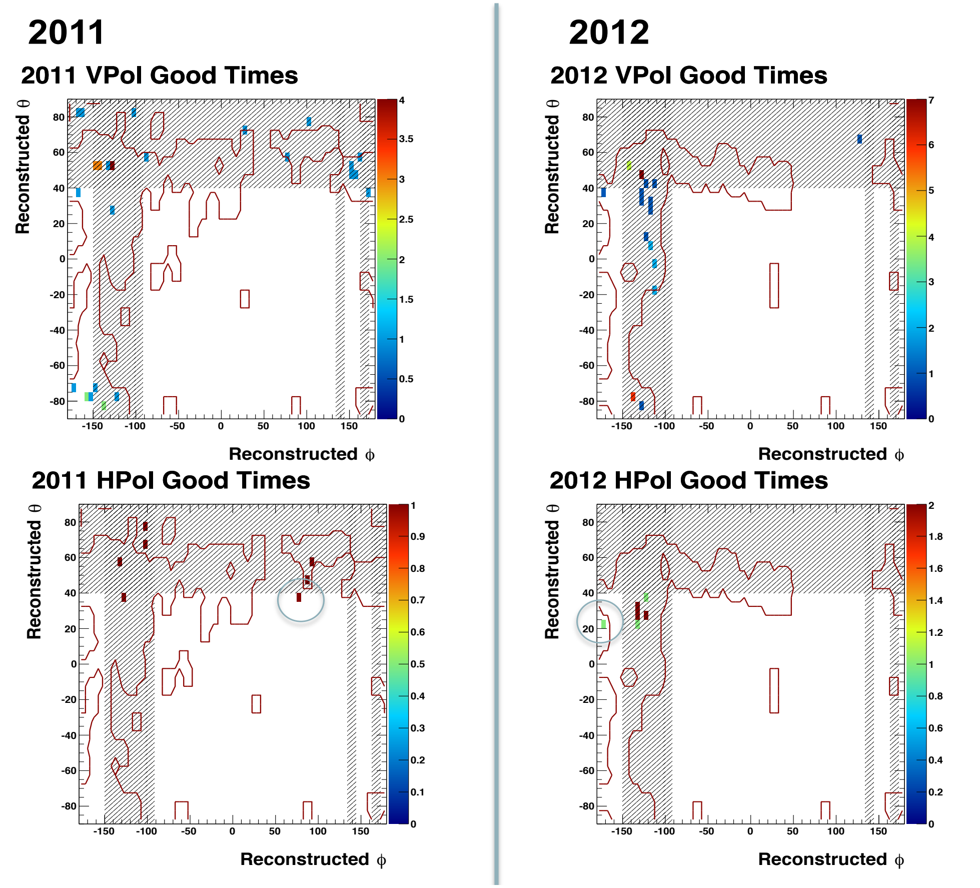




- Linear combination of:
  - peak power of the CSW
  - sum of the maximum correlation values of antennas with the CSW of the remaining antennas
- Expect impulsive events to separate out from noise, CW

Clustering - OSU, UCL



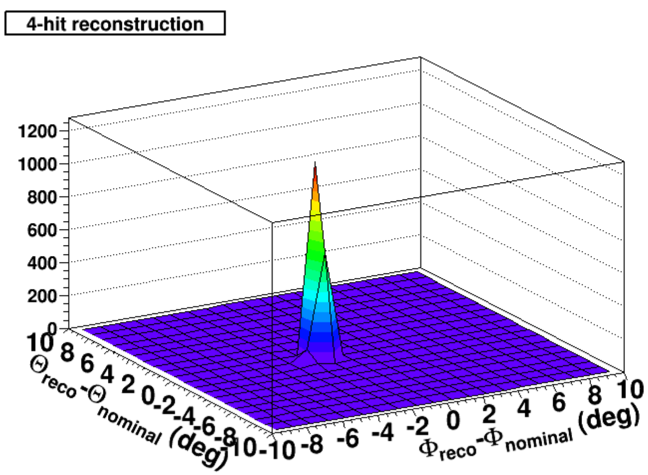


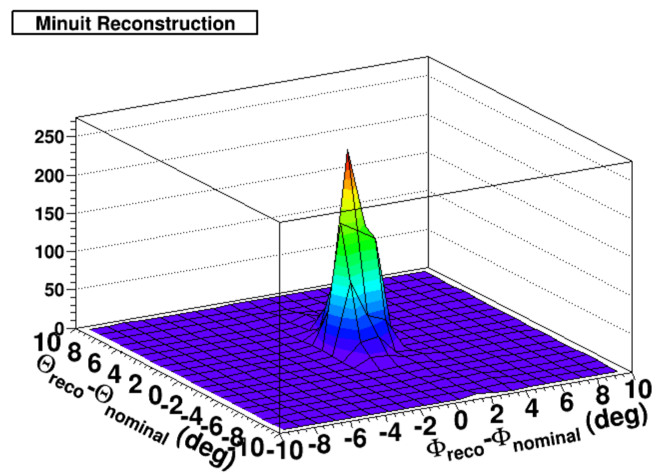
- Both analyses reject events reconstruction to a location where an excess of events can be found
- Also reject South Pole phi range and require reconstruction in the ice

KU Analysis – Template-based

Initial Requirements:
CW filter
4 antennas have peaks in excess of 6X RMS
Minimum waveform power requirement
well-reconstructed single source vertex
non-pulser reconstruction location

- Template matching: take remaining events and find the cross correlation between the events
  - If events have high CC, they are alike and are thus rejected



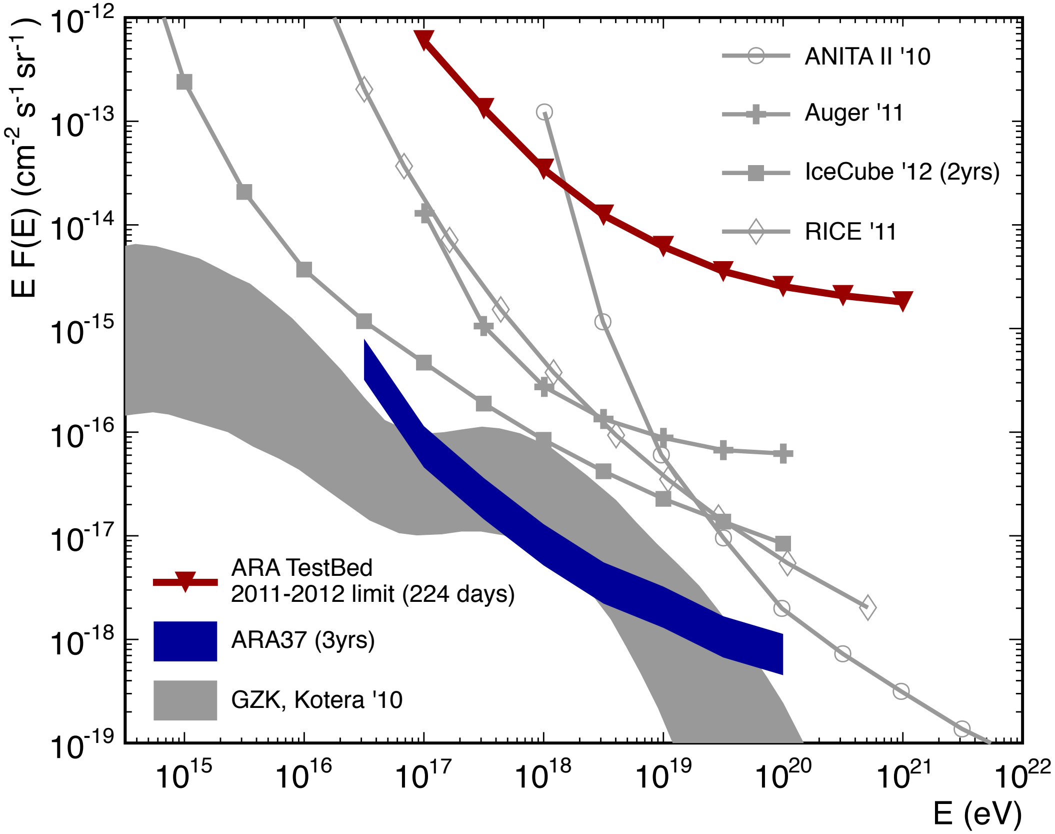


Analysis Results

- OSU analysis
  - Stage 1: 3 events passed cuts
    - Known background event types, adjusted the gradient and clustering geometric cuts to better match those types
  - Stage 2: 2 events passed cuts
    - Also known backgrounds, slightly expanded clustering geometry cuts to reject the events (5% change in rejected area)
- UCL analysis: 1 event passed cuts
  - CW event with two carrier frequencies, non-impulsive
- KU analysis: 1 event passed cuts
  - Consistent with calibration pulser event, misidentified by template matching
- No neutrino candidates

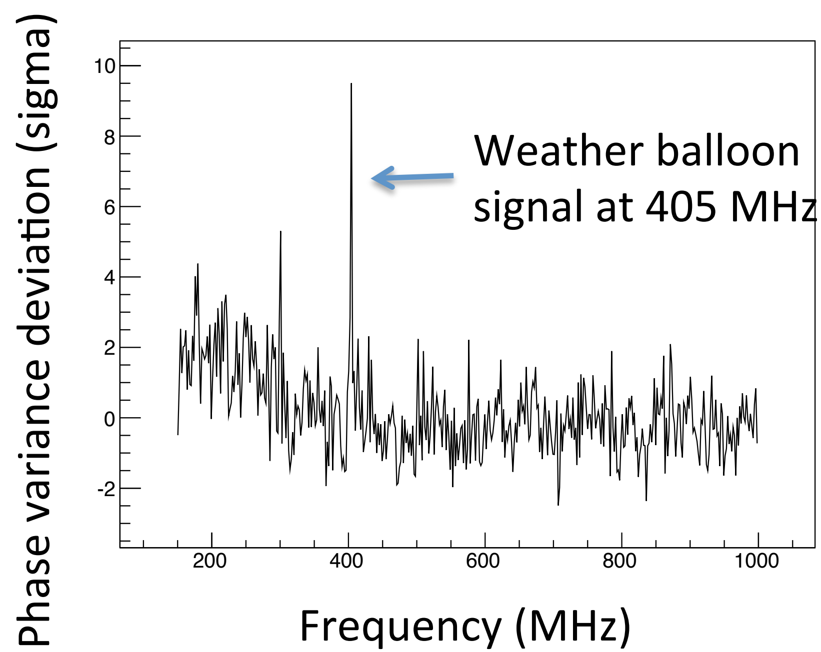
Sensitivity

- First limits from ARA Testbed found (see arXiv:1404.5285)
- Limits comparable for the two 2011-2012 analyses
- Projected sensitivity of expanded array extends to GZK flux models



Future Improvements

- Reconstruction methods
  - Account for index of refraction and reflection
  - Reconstruction quality parameters
- Better identification of anthropogenic signals from South Pole
  - Improve livetime and event selection during active season
- Improved CW removal
  - Developing phase variance technique for filter instead of cutting outright
- Improved trigger
  - require causal time sequence with respect to known geometry



Summary

- ARA is continuing to be built
  - Drilling and installation planned for this season
- End-to-end calibration using TA LINAC planned
  - See talk by Keiichi Murase in the second session
- First limits from Testbed analysis
  - arXiv:1404.5285, to be submitted to Astrophysical Journal
- Further stations will see marked improvement in sensitivity
  - Deeper station, more antennas
  - Improved (2nd generation) analysis techniques
  - See talk by Thomas Meures in the second session

Backup Slides

Passed Events Table from 2011-2012 TestBed Data

	Total	Quality Cut	Reco. Qual
Events	~330,000,000	157,019,347	3,265,047

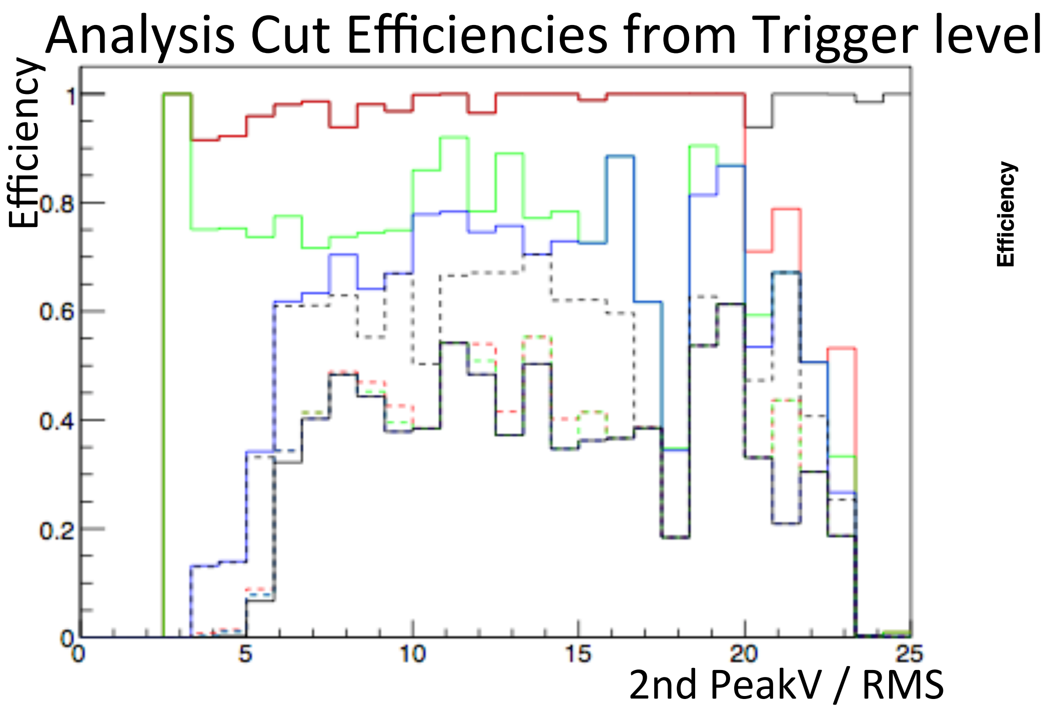
Vpol channel

	Pass Events
Reco.Qual Vpol	1,839,348
NoisyTime	1,354,670
Geom Cuts	1,122,083
Gradient Cut	1,120,713
Delta Delay	178,796
CW	177,944
Down	16,894
Rcut	0

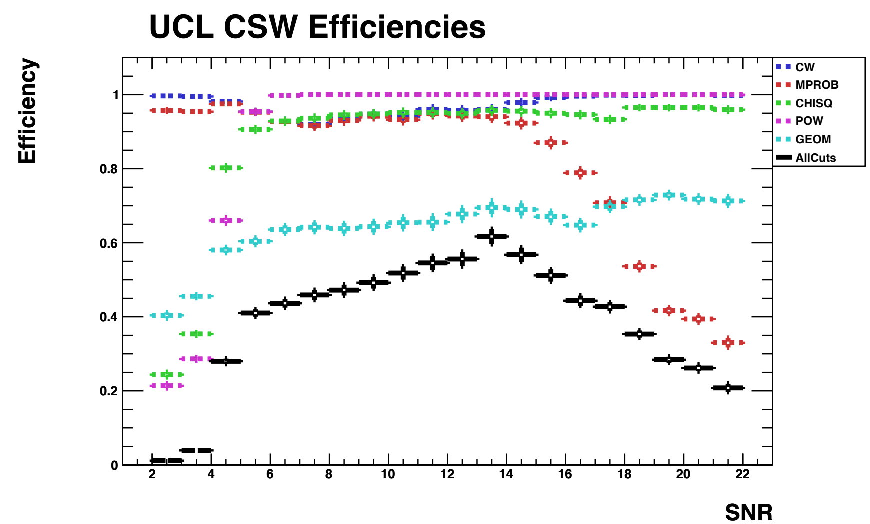
Hpol channel

	Pass Events
Reco.Qual Hpol	1,443,303
NoisyTime	1,095,497
Geom Cuts	904,099
Gradient Cut	903,036
Delta Delay	145,196
CW	142,581
Down	19,394
Rcut	0

Cut Efficiencies

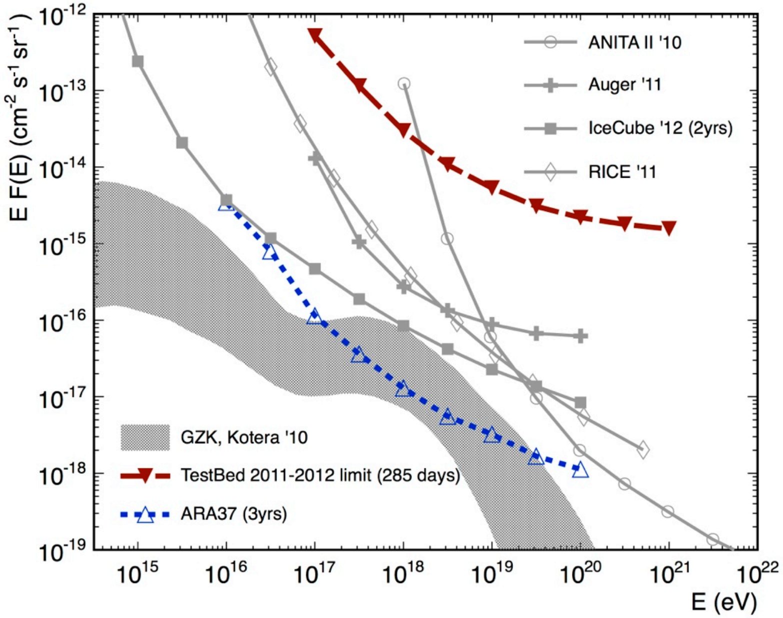


OSU



UCL

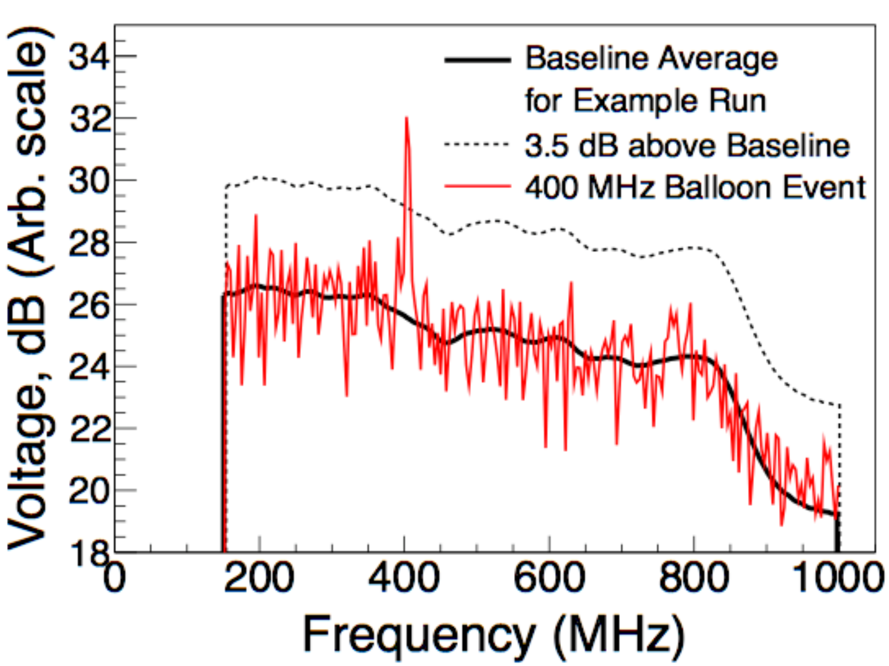
Neutrino Limit from 2011-2012 Testbed Data

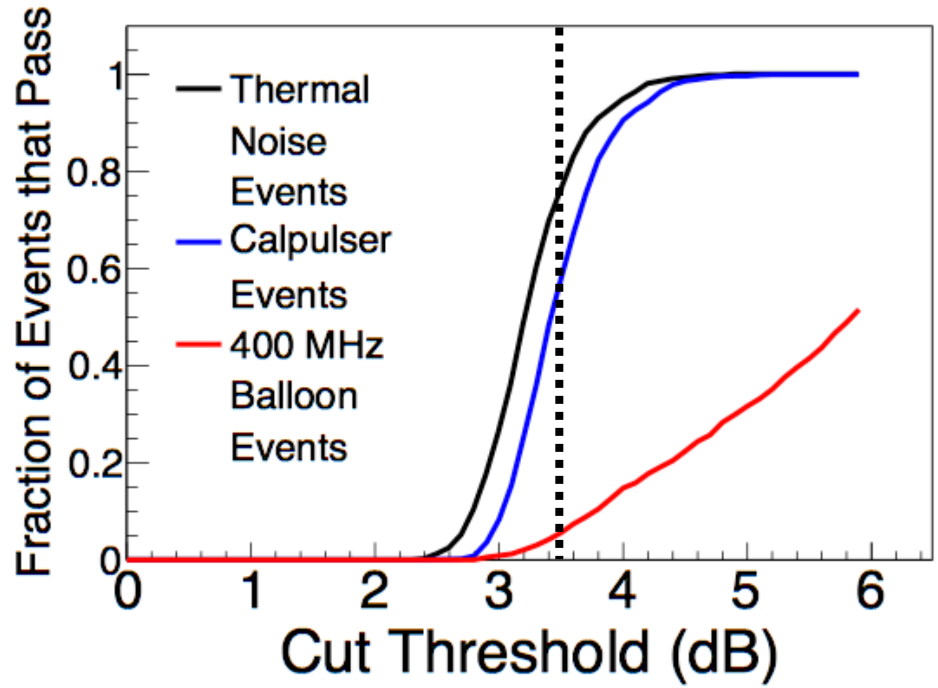


	Effective Area at 10^{19} eV [km^{2}sr]	Accumulative Factor from Testbed Analysis
Testbed Analysis	7.37E-04	1
Testbed Trigger	4.08E-03	6
ARA one station Trigger	1.70E-02	23
ARA two stations Trigger	2.98E-02	40
ARA 37 Trigger	4.04E-01	550

- After finalizing all the cuts, we looked at remaining 90% of data
- ~ 0.06 expected thermal background events and ~ 0.02 neutrino events from 1.5 years of Kotera flux from TestBed
- Analysis cut efficiency on Kotera model ~ 40% for V_{peak}/RMS from 7 to 20
- From first 2012 4 months analysis, we had 3 survived events and from 2011-2012 analysis, we had 2 survived events (total livetime ~ 285 days)
- Both survived events are anthropogenic backgrounds (rejected by modifying geometric cuts)
- Zero neutrino candidate event

Rejecting CW Background





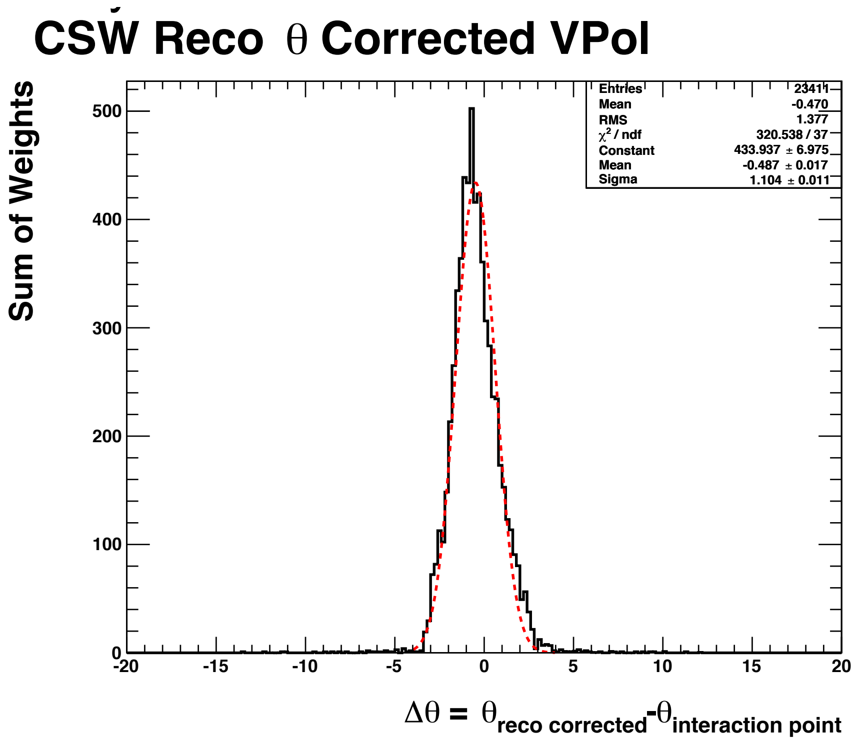
- Design cut based on ANITA experience
- Make average spectrum for each run (1 run = 18000 evts ~ 30 minutes)
- Reject events whose Fourier transformed voltage waveform exceeds 3.5 dB baseline anywhere in frequency space
- Will optimize the cut using AraSim and 10% not blinded testbed data

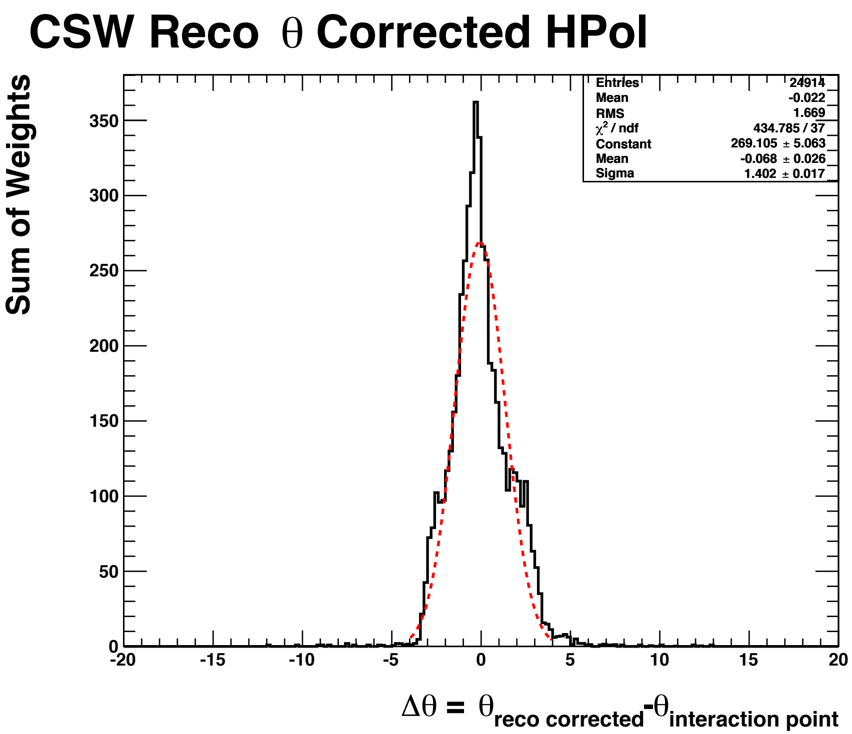
Event Cut Table (OSU)

Total	3.3E8					
Cut	Number passing (either polarization)					
Event Qual.	1.6E8					
Recon. Qual.	3.3E6					
	VPol			HPol		
		Rejected			Rejected	
	In sequence	as last cut	as first cut	In sequence	as last cut	as first cut
Recon. Qual.	1.8E6			1.4E6		
SP Active Period	1.4E6	125	4.9E5	1.1E6	13	3.5E5
Deadtime < 0.9	1.4E6	0	3.2E4	1.1E6	0	9.2E3
Saturation	1.4E6	0	1.4E4	1.1E6	0	618
Geometric, except SP	1.3E6	7	9.9E4	1.0E6	0	4.6E4
SP Geometric	1.1E6	0	2.9E5	9.0E5	1	2.0E5
Gradient	1.1E6	0	1.4E4	9.0E5	0	4.6E3
Delay Difference	1.8E5	0	1.5E6	1.5E5	0	1.2E6
CW	1.8E5	0	1.3E4	1.4E5	1	3.4E4
Down	1.7E4	15	1.6E6	1.9E4	1	1.2E6
V_{peak}/Corr	**0**	1.7E4	1.8E6	**0**	1.9E4	1.4E6

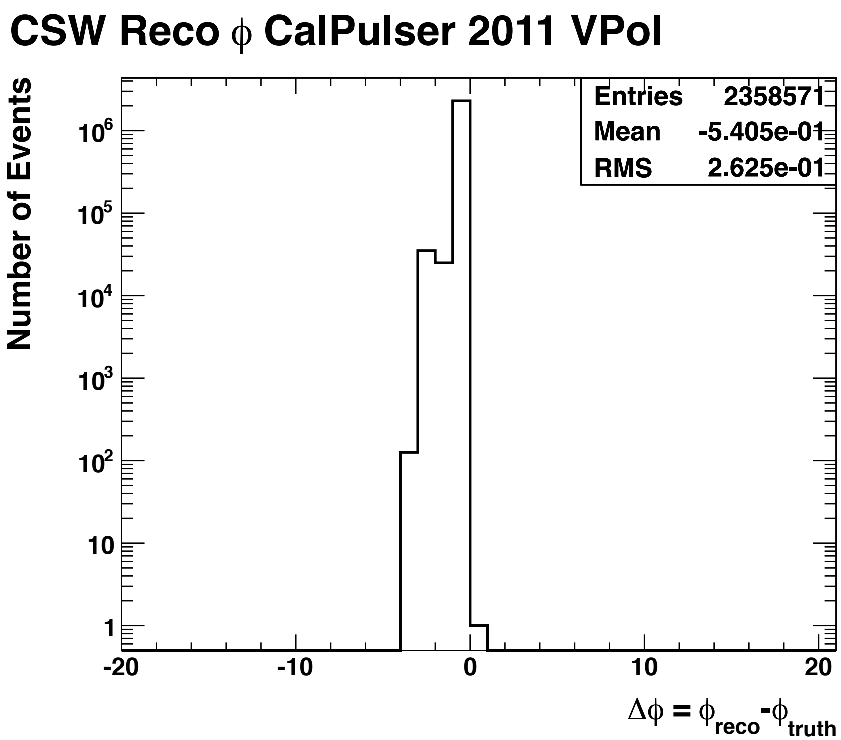
Table 2: This table summarizes the number of events passing each cut in the Interferometric Map Analysis, in Phase 2 (2011-2012, excluding Feb.-June 2012). We list how many events each cut rejects as a last cut, and how many are rejected by each cut if it is the first cut. After the Event Quality and Reconstruction Quality Cuts are applied, VPol

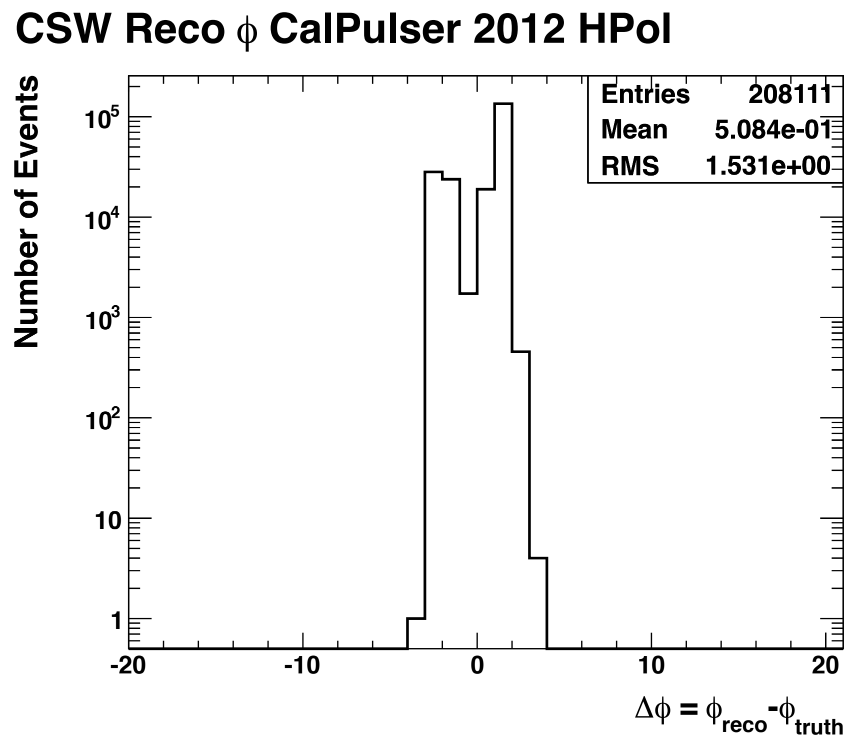
Reconstruction Error - Simulation





Reconstruction - Calpulser





Reconstruction - Calpulser