First data analysis steps for the Askaryan Radio Array stations

Thomas Meures
for the ARA-collaboration

Outline

1. **Reminder: The ARA-detector:**
    - Method
    - Setup
    - Data acquisition
2. **Data analysis:**
    - Low level data filters
    - Reconstruction
    - CW treatment
3. **Example cuts and sensitivity**

The ARA-detection method

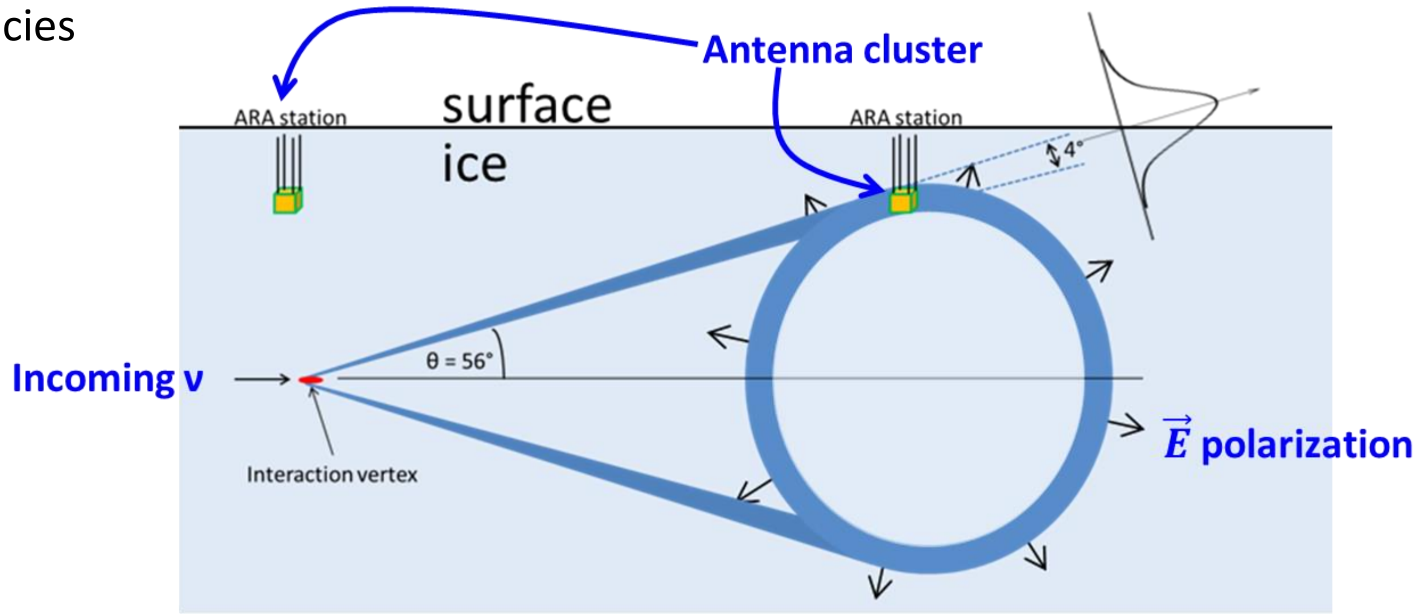
Detection via the Askaryan effect:

- Neutrinos produce particle cascades in the ice
- If the energy is high enough, a significant negative charge excess (~20%) is built up through:
  - Compton scattering, Delta-rays

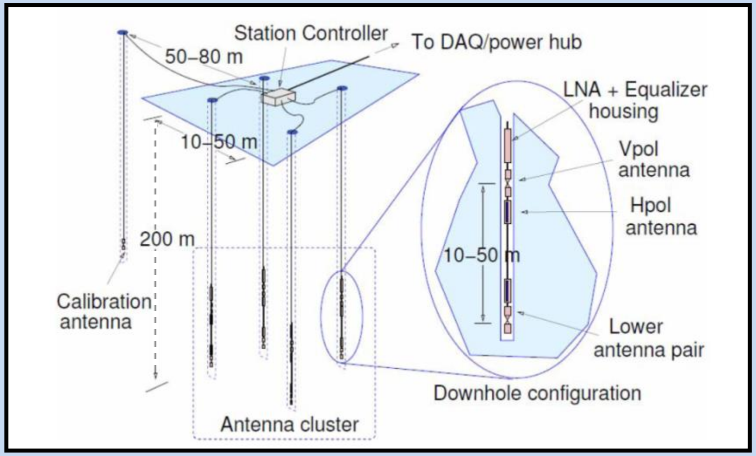
Coherent emission at radio frequencies

The ARA principle:

- Independent antenna clusters, to maximize the effective volume



The ARA-detector



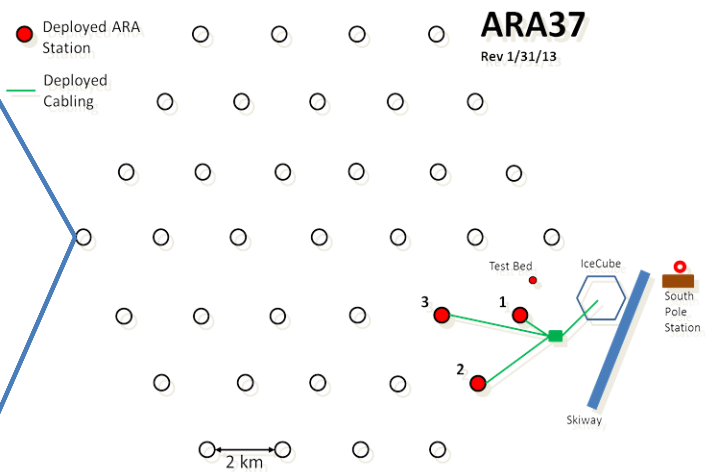
Each station:

- **Measurement system:**
  - 4 holes, 20 m spacing
  - 16 antennas, 150 MHz – 800 MHz
    (8 horizontally polarized., 8 vertically pol.)

- **Calibration system:**
  - 2 holes, ~40 m distant
  - 4 pulsing antennas (2 h-pol., 2 v-pol.)

Each station is an autonomous detector!

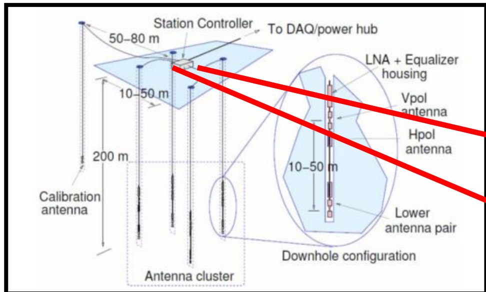
- 37 antenna stations planned
- 3 stations deployed at the current date (two currently operating)



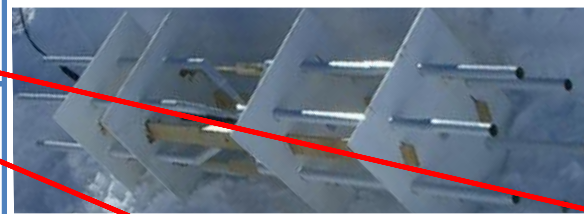
- Stations spaced by 2 km
  → **Maximizing effective volume by avoiding overlap**

- Antennas deployed in a depth of 200 m
  → **Minimizing the effect of "ray curvature" due to the changing index of refraction in the ice**

The ARA data acquisition



Surface antennas

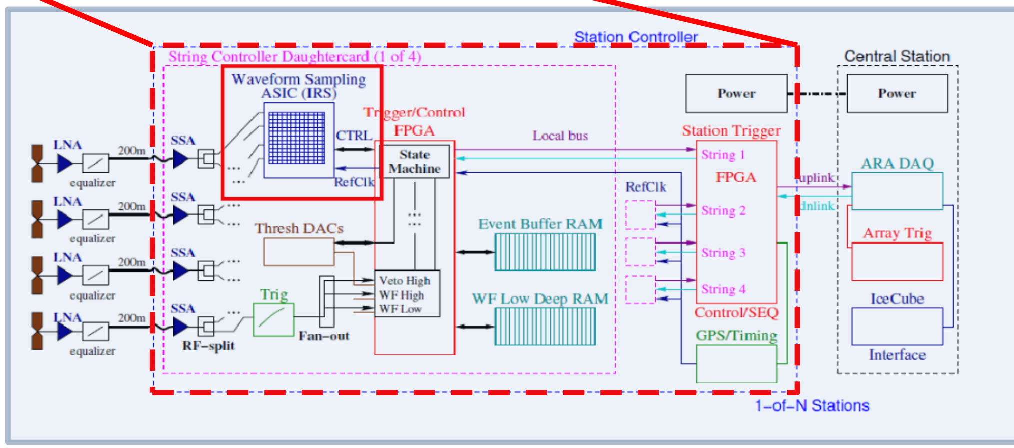


- Band + notch filter, to limit the LNA input to **"our"** signal
- **L**ow **N**oise **A**mplifier to enhance the signal for the data acquisition system
- RF over fiber link for loss-less transmission

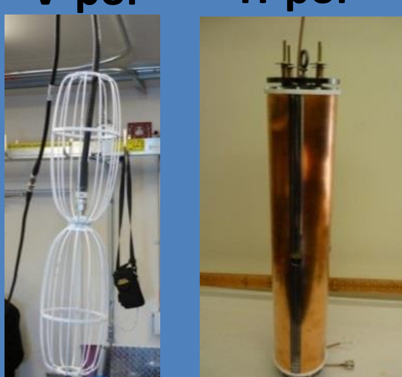
RF over fiber link

Low noise amplifier

Notch filter



V-pol **H-pol**



In-ice Antennas

Special features of the IRS2 digitizer:

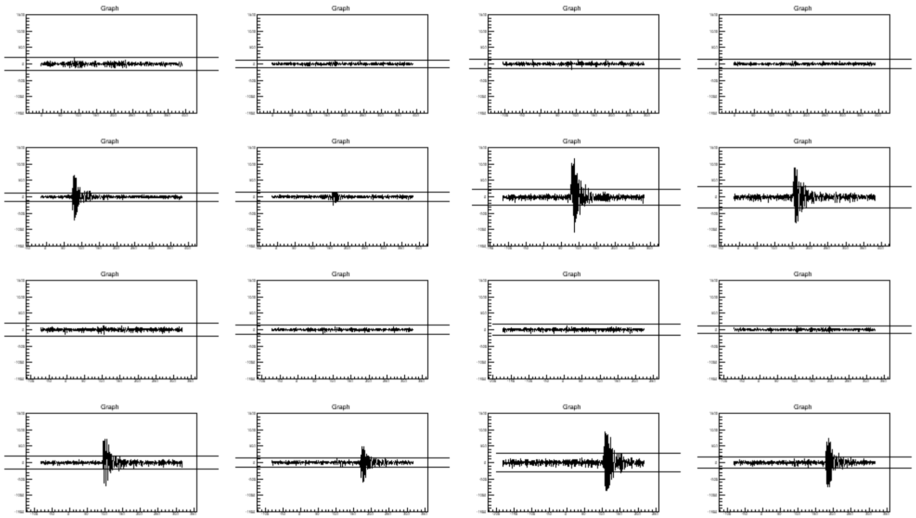
- High sampling speed up to 4 GHz
- Extra deep storage: 32k samples/channel = ~10µs
- Designed for low power consumption (using only low speed elements)

Low level filters

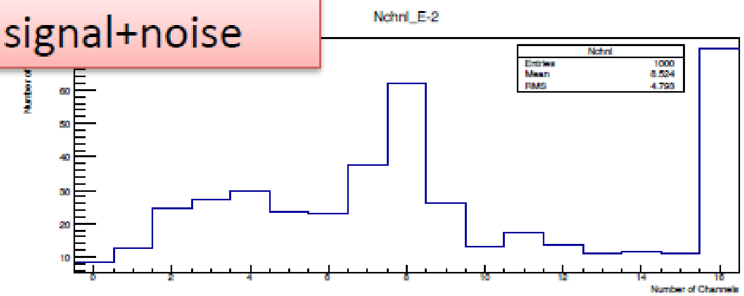
Low level data filters

Purpose: Filter data to be transferred north via satellite during the year, reduce thermal noise triggers to ~1%

1. **N-channel filter:**
   Sets threshold to recorded waveforms, count channels with voltage above threshold during event

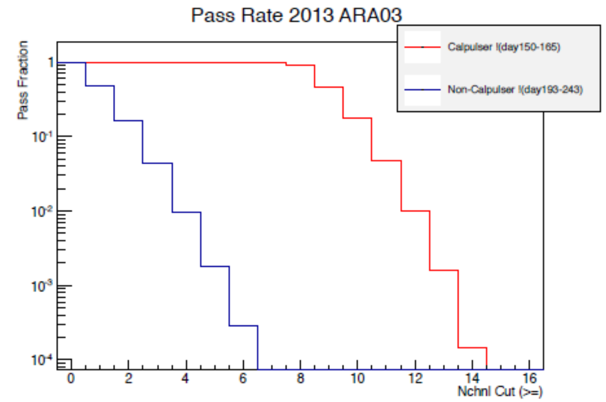


E^{-2} signal+noise



Passes about 83% simulated E^-2 neutrinos, while only 0.6% simulated thermal noise

Look at real data:



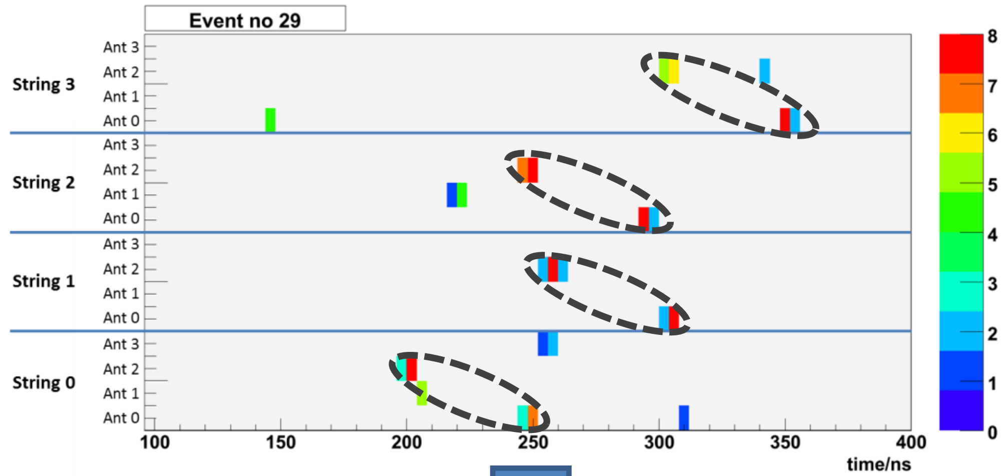
All calpulser events pass after cutting all noise

By Ming-Yuan Lu, UW

Low level data filters

2. Time-sequence algorithm:

- Record voltage above set threshold as antenna hit
- Calculate measure for the recorded hit pattern to be produced by plane wave-front



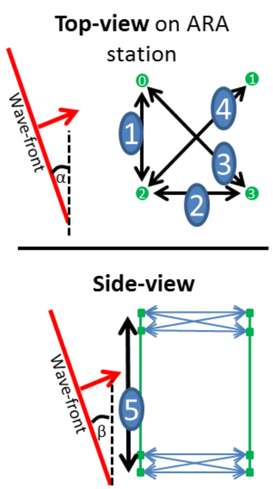
- Histogram time differences for all appearing antenna hit-pairs.

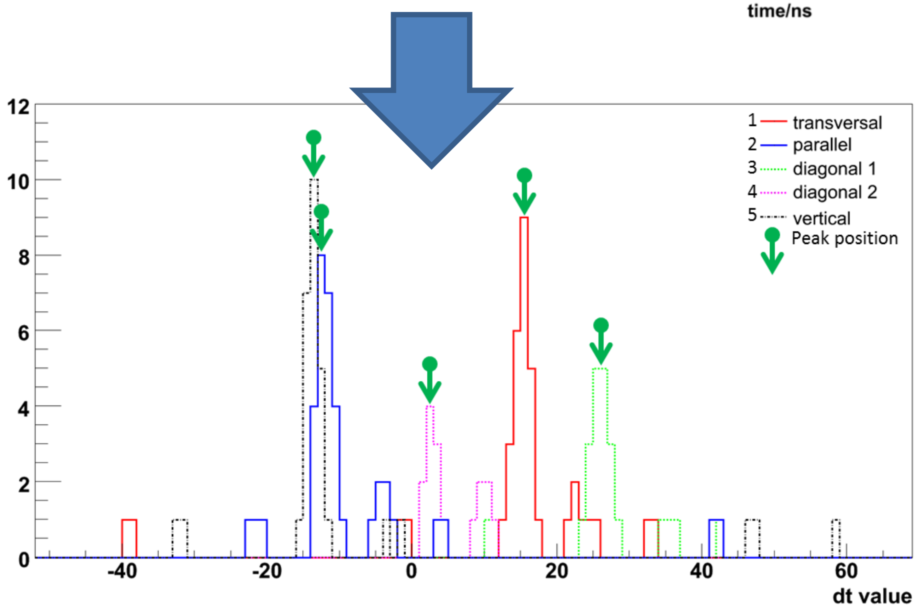
Expectation:

- Antenna pairs with same space relation show same time difference

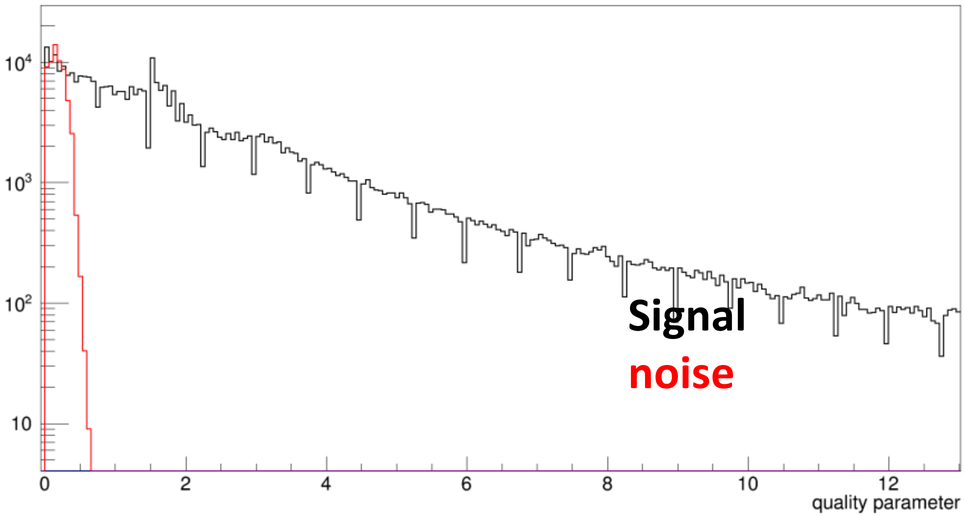
→ Accumulation at certain time difference for a signal event

→ **Sum maximal hit counts**

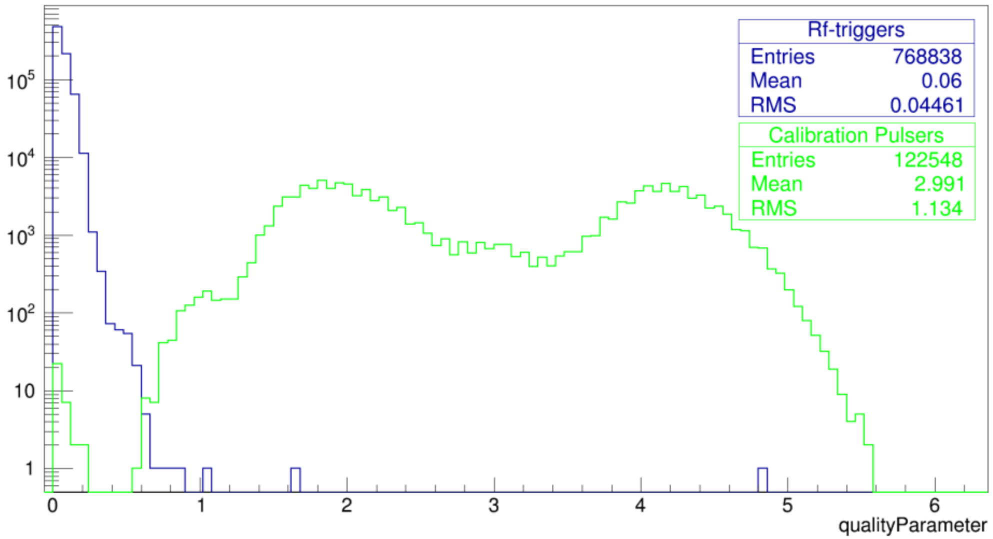




Low level data filters



Look at real data (ARA03):



Cutting noise to <0.4 %:

→ Remaining E-2 neutrinos: ~79 %

→ Remaining Calibration pulsers: ~all

ARA analysis approaches

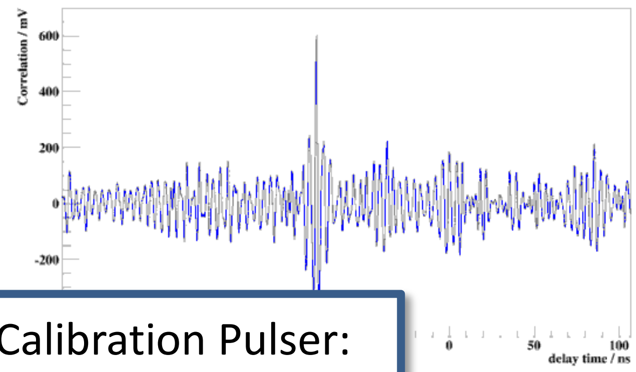
We need to distinguish neutrinos from:

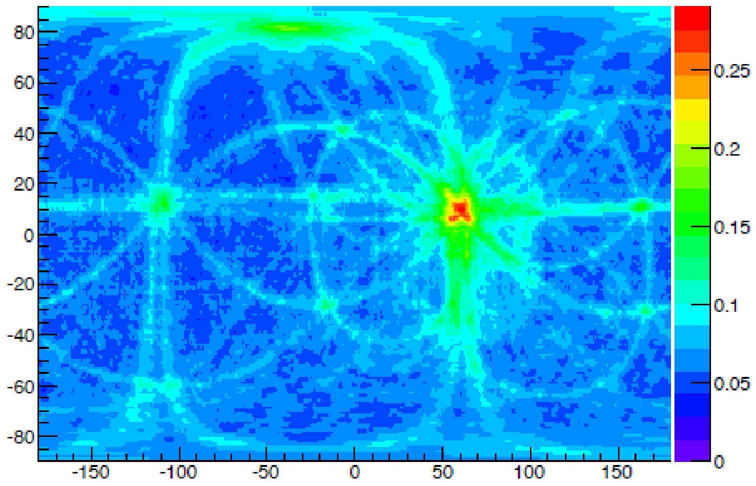
- Thermal noise
- Continuous wave sources (mostly radio communications)
- Man made impulsive events

Analysis 1

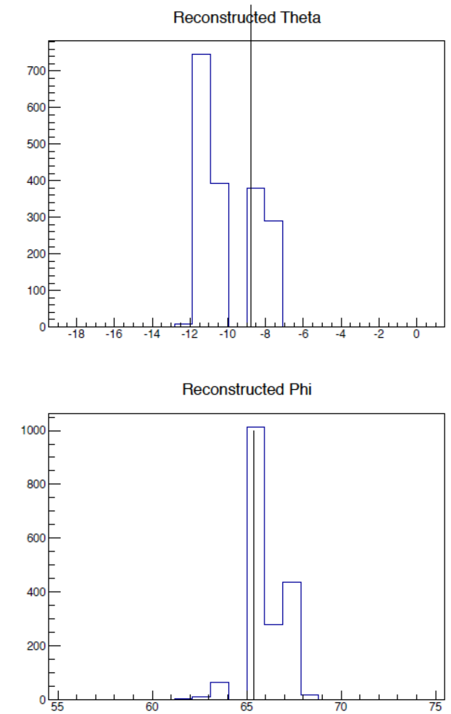
Event reconstruction through interferometric Maps (Eugene Hong, Carl Pfendner, OSU):

- Shift waveforms between antenna pairs according to expectations of a vertex position on the sky (distance is fixed).
- Calculate the sum of correlation for such a set of shifts
- Accounts for changing index of refraction through ray-tracing





ARA station: Calibration Pulser:



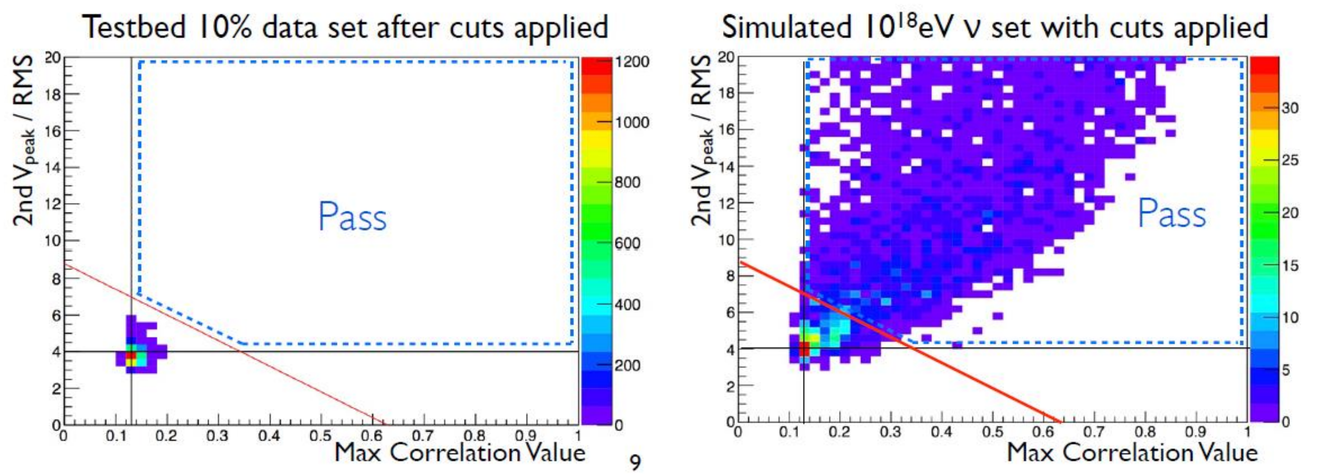
Precision to be determined

Analysis 1 Data cuts

CW: Need to identify, need to check influence

Currently investigated method from LOFAR:
Check for phase variance between antennas in consecutive events:
- CW: phase expected to be constant
- Noise, Single events: random variance of phase

A currently investigated approach:
Extend TestBed analysis to ARA-stations (use main cut):
- Check for 2^{nd} highest peak in all waveforms
- Plot this versus the maximum in interferometric map



By E. Hong, C. Pfendner

Analysis 2

Matrix Based event reconstruction (After Bancroft's method):

- Use arrival time differences from correlation **(precision ~100 ps)**
- Set up system of equations, linear for the vertex coordinates:

$$2x_{i,j}x_v + 2y_{i,j}y_v + 2z_{i,j}z_v = r_i^2 - r_j^2 - c^2\left(t_i^2 - t_j^2\right) + 2c^2 t_{i,j} t_v$$

- Solve linear system of equations:

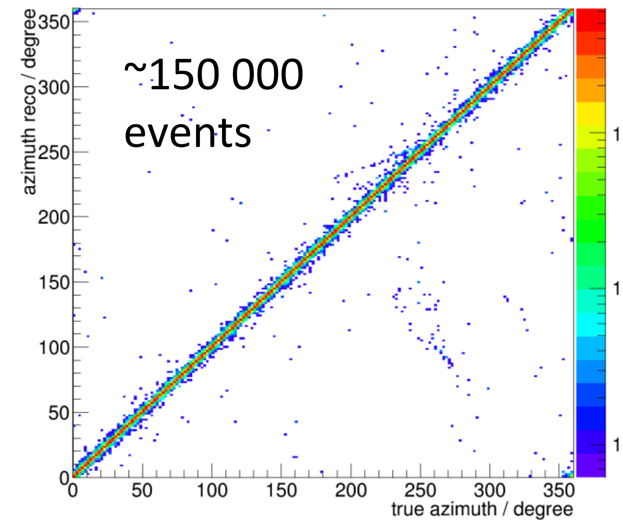
$$a * v = b$$

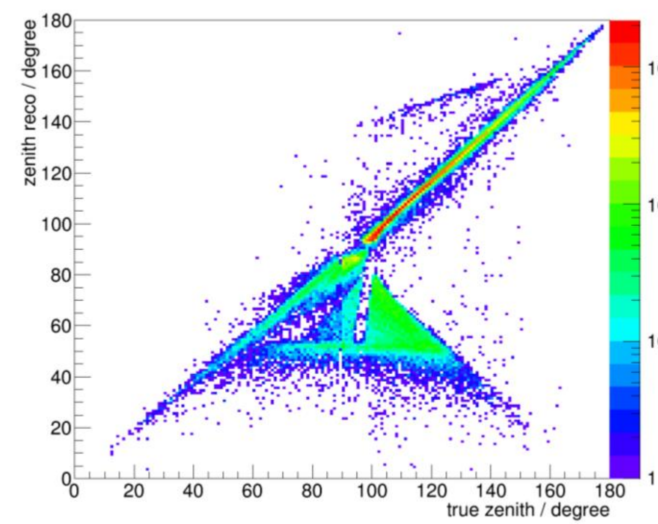
- Scan t_v to find minimal residual:

$$\text{res} = \left\| \frac{b}{|b|} - \frac{a * v}{|a * v|} \right\|^2$$

- **Some advantages:**
  Fast algorithm, not seed dependent

Simulated E^-2 neutrinos (res<0.01):





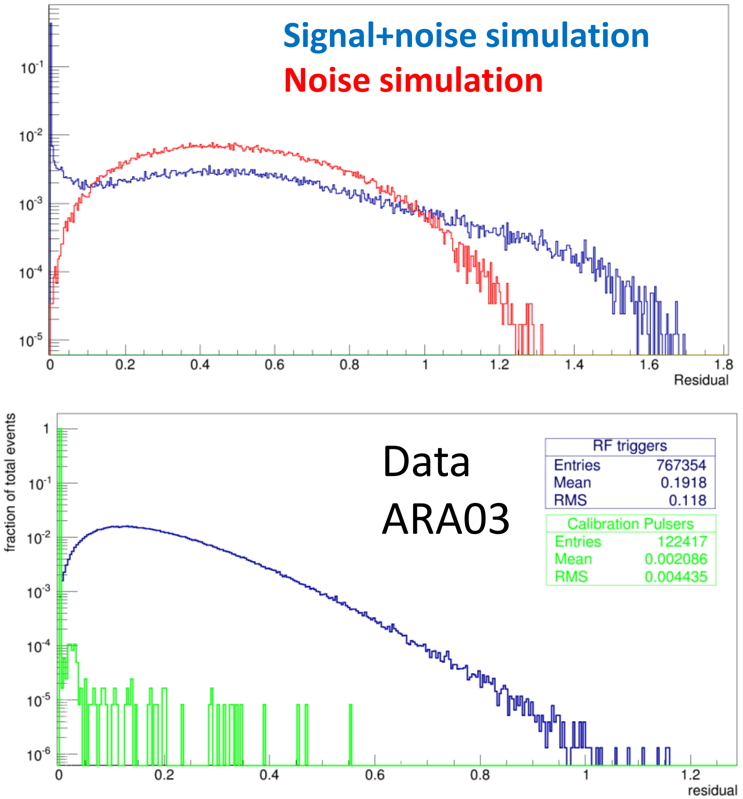
Analysis 2 Data cuts

looking at the real data

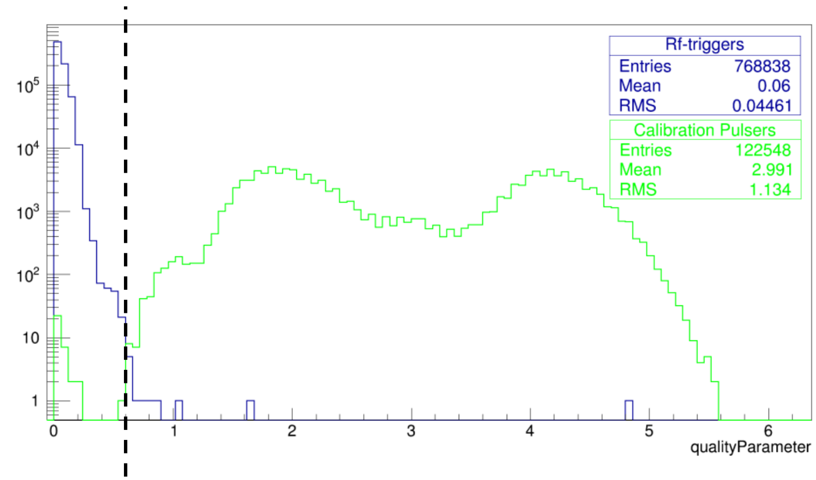
Signal – Noise separation:

- Event from above are not reconstructed downwards
- Good separation possibility through residual

Residual distribution



Time sequence parameter: ARA03



Test simple cut combination on available data subset:

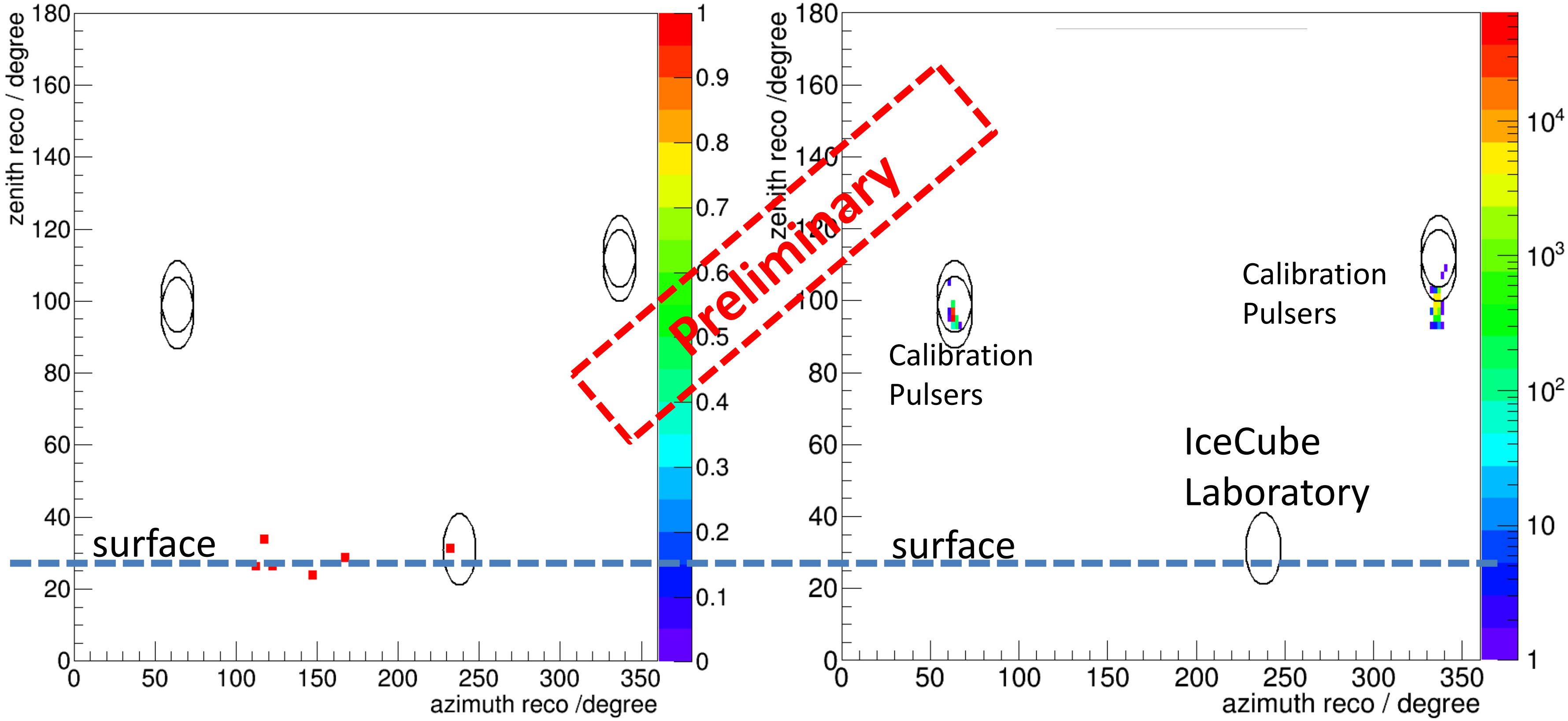
- Data sample: 0.5% of all recorded data

Require:

- Residual < 0.01
- Time sequence parameter > 0.6

Result ARA03 - "skymap"

looking at the real data



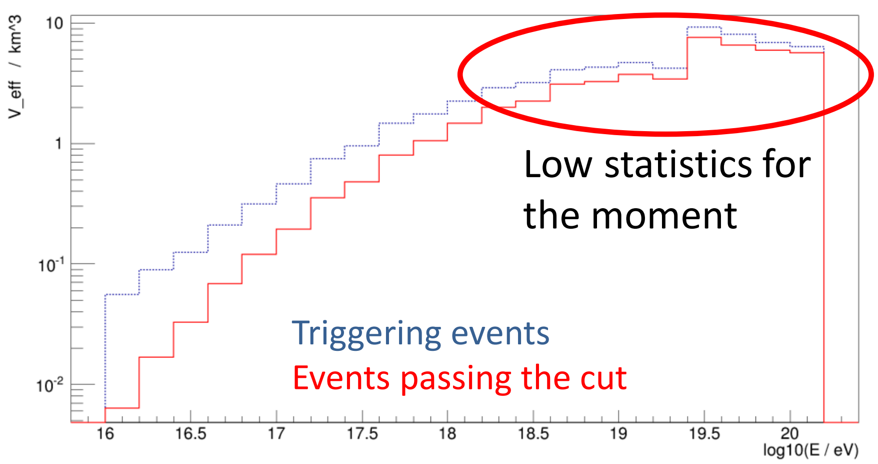
Type	Total	Surviving cuts	Percentage
RF triggers	767354	6	8E-4 %
Calibration	122417	121416	99 %

Simulation results

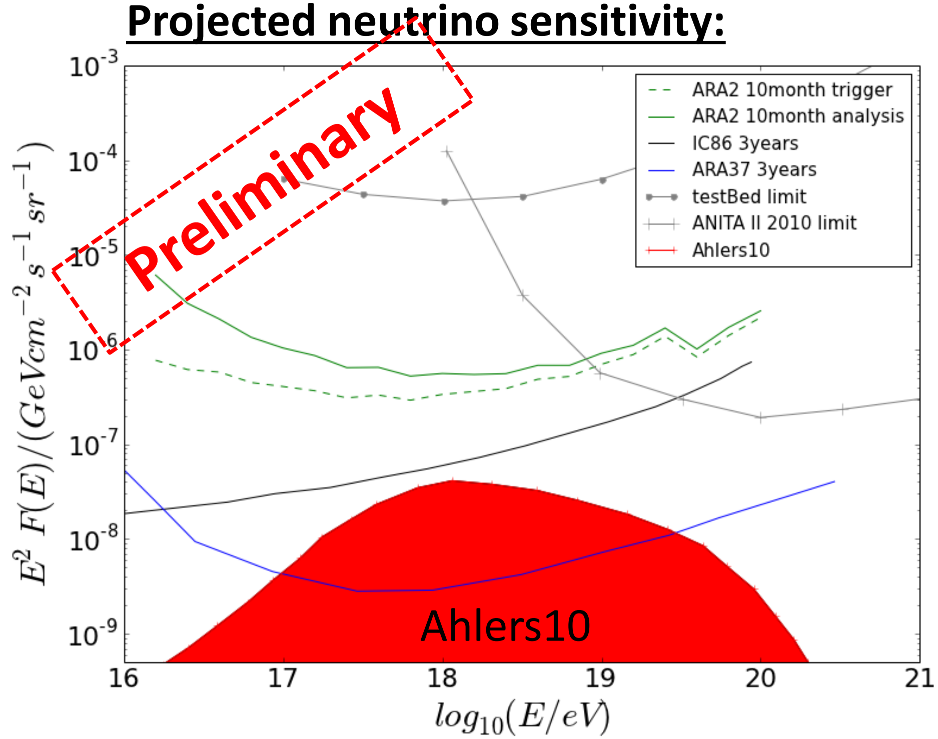
- The presented 2 cuts need:
  - more detailed treatment,
  - more intelligent combination,
  - More data to test on (only 0.5% so far)
- Assume same cuts and same results for 2 stations full data

…to get an idea of a possible neutrino sensitivity at analysis level

Effective volume of two ARA-stations:



Projected neutrino sensitivity:



Using Ahlers2010
→ Number of neutrinos:
ARA2(10month) analysis projection: ~0.4
Scale this to ARA37(3years): ~27
This is all very preliminary!

Summary

- Low level filters work well to reduce thermal noise to <0.5% while keeping more than 80 % of the signal
- Reconstructions are under way to be used as signal to noise discrimination and for determination of the incoming angle. **More reconstructions are available and tested!**
- A simple 2 cut combination could be sufficient for background rejection (CW influence still needs to be investigated)
- **Stay tuned for the full ARA2 data analysis coming up soon**

BACKUP

Event reconstruction

Currently tested on the ARA stations:

- TMinuit reconstruction
- Coherently summed wave maximization
- Interferometric maps
- Matrix based linear reconstruction
- Analytic Sphere Method

Event reconstruction

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- TMinuit reconstruction
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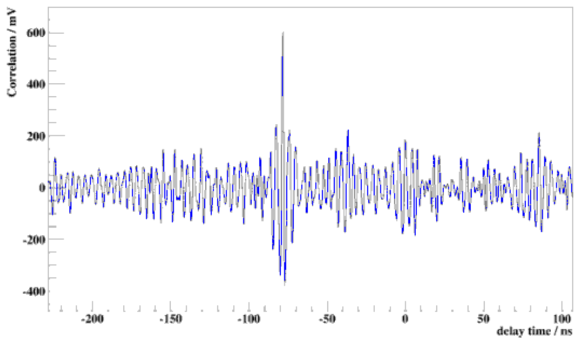
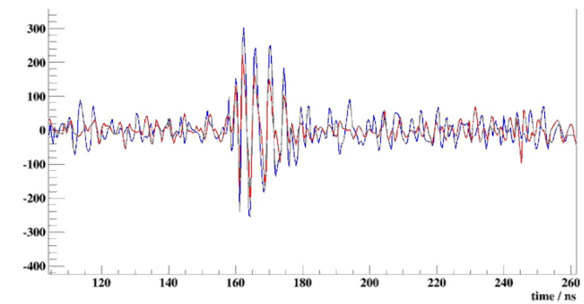
- Analytic Sphere Method

Uses threshold based hit-finder in the time domain waveforms

Use cross-correlation antenna pairs

- Arrival times are determined by searching for the maximum correlation of two waveforms:
- **Correlation:** $\frac{\sum[V_{1,i}*V_{2,i}]}{\sqrt{\sum V_{1,i}^2 * \sum V_{2,i}^2}}$

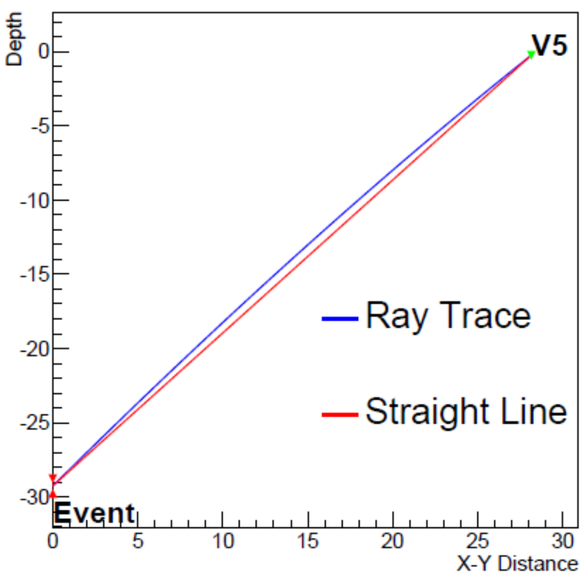




Event Reconstruction

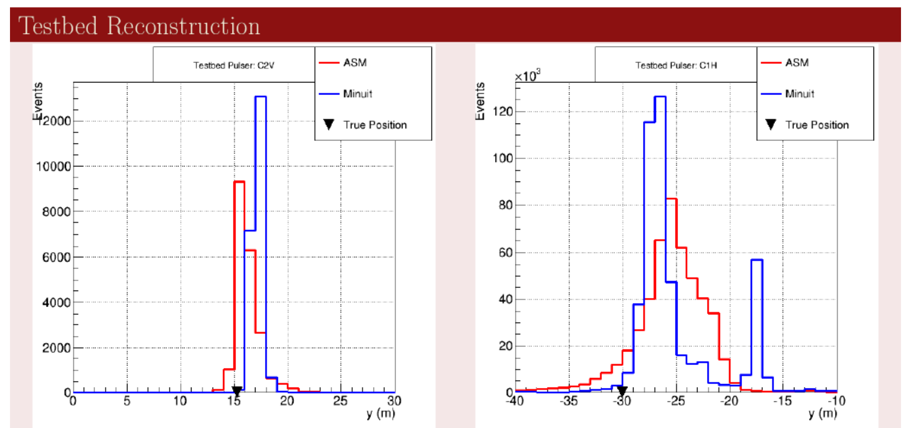
TMinuit reconstruction (Dave Besson, KU):

- Set of time differences through maximum correlation
- Compares expected time for a vertex to measured times
- Uses Tminuit to find minimal Chi2
- Accounts for changing index of refraction



Analytic Sphere Method:
(A. Schultz, I. Kravchenko, C. Bora, S. Avdeev, Univ. Nebraska)

- Determines timing through hit-finder in time domain
- Calculate analytic vertex position with all combinations of four antennas
- Remove outliers and calculate the average result
- Uses straight line approximation to account for changing index of refraction



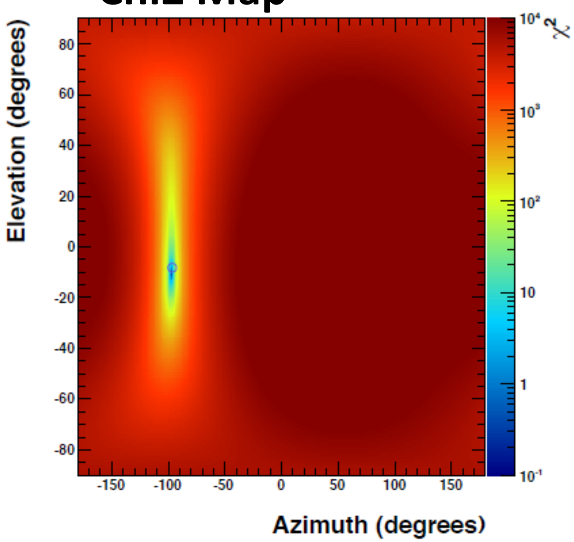
Precision to be determined

Event reconstruction

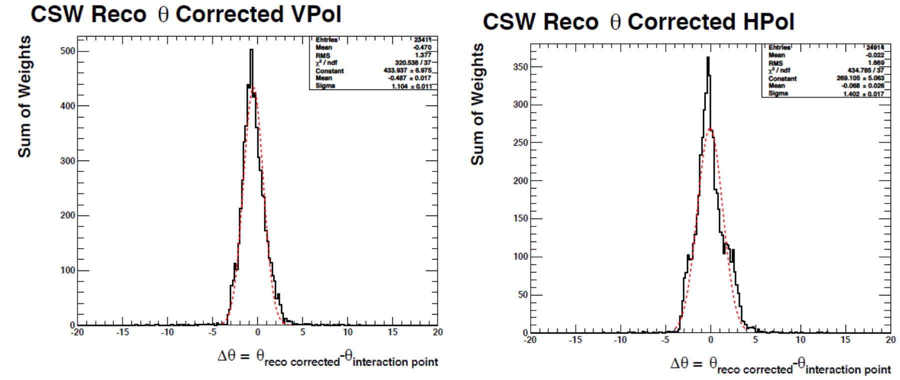
Coherently summed wave method (by Jonathan Davies, UCL, GB):

- Find timing set with best correlation
- Search the sky for a vertex position that gives a minimal chi2, when comparing measured timing to estimated timing

Chi2 Map

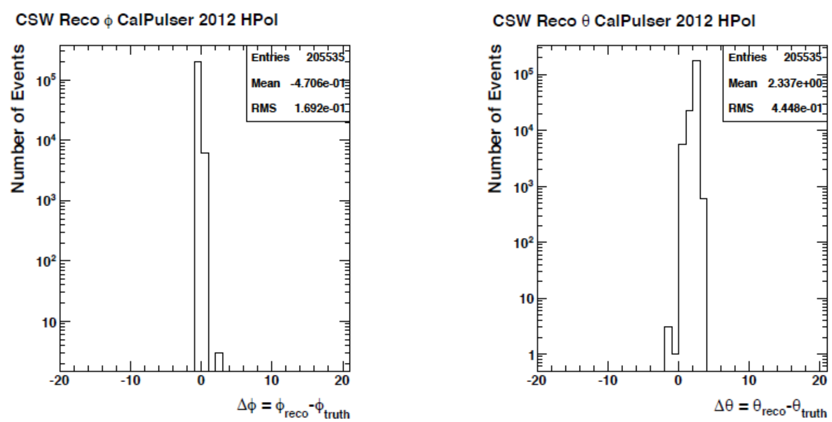


Test this on simulated events for the ARA-TestBed



Angular precision of about 1 degree

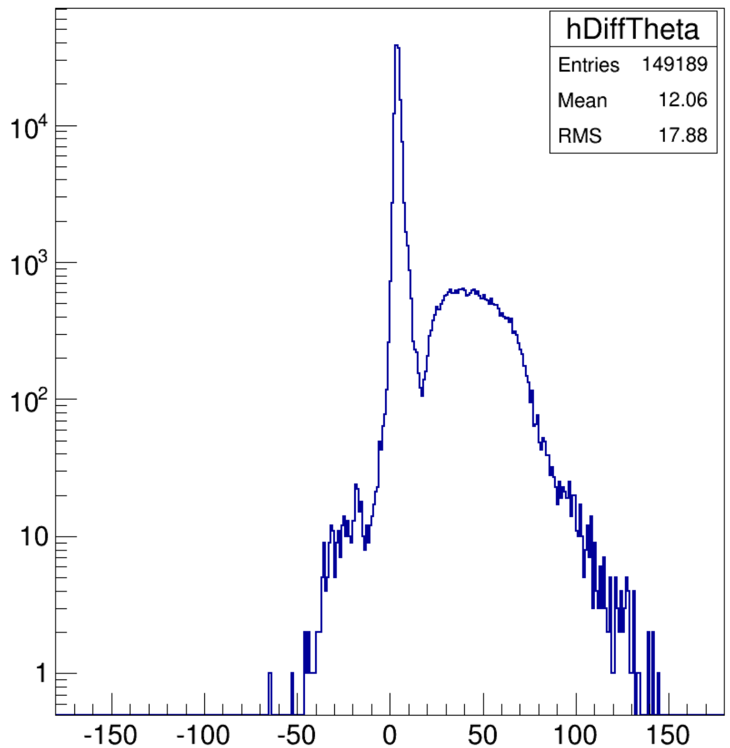
TestBed calibration pulser:

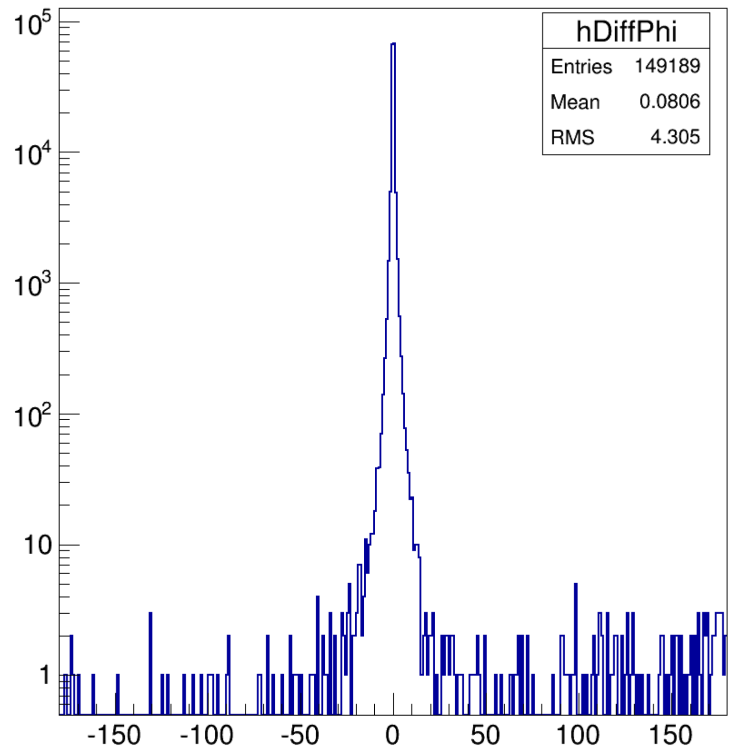


Angular precision of <0.5 degree

Event reconstruction

Matrix based reconstruction:
Precision:





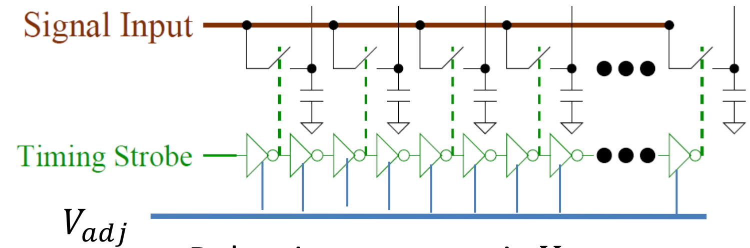
Digitizer calibration

ARA uses the IRS2 ASIC, designed in Hawaii for DAQ

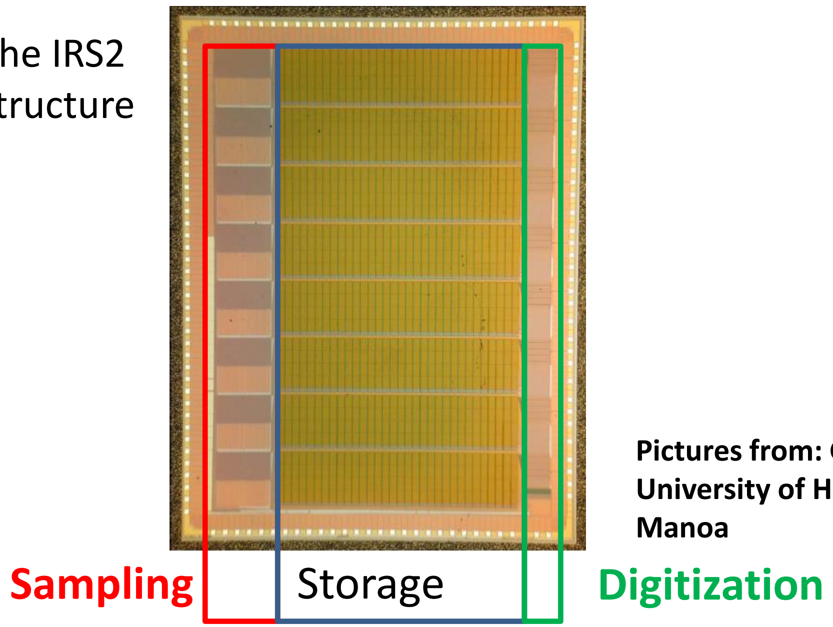
Special features of this digitizer:

- High sampling speed up to 4 GHz
- Extra deep storage: 32k samples/channel = 10µs
- Designed for low power consumption (using CMOS technology, low speed elements)

Sampling through 2 **S**witched **C**apacitor **A**rrays:

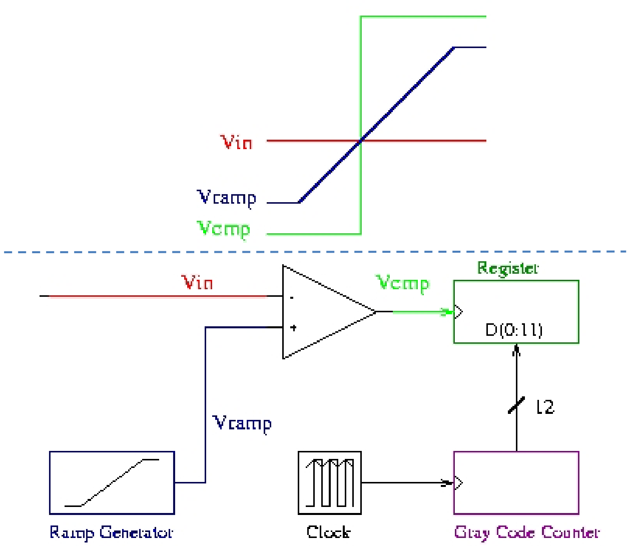


The IRS2 structure



Pictures from: Gary Varner, University of Hawaii, Manoa

Digitization using Wilkinson method



Digitizer calibration

Timing calibration:

Calibration of SCA:

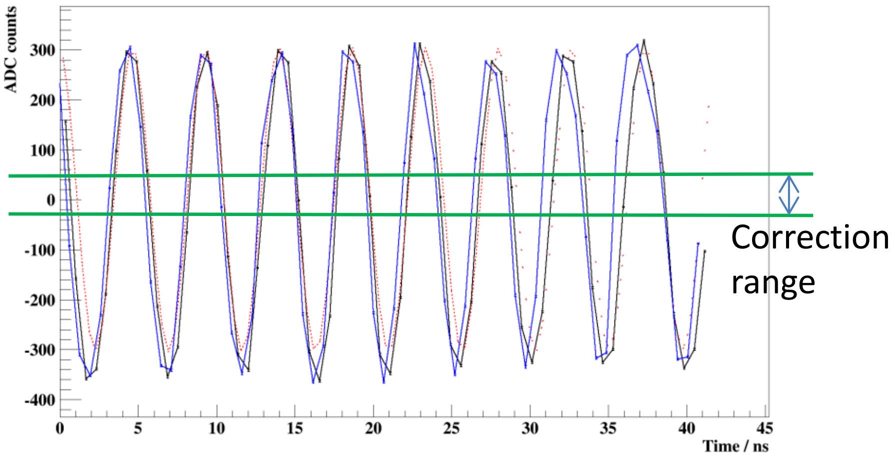
Sampling speed $V_{sB} = \frac{\#\, samples}{second}$,

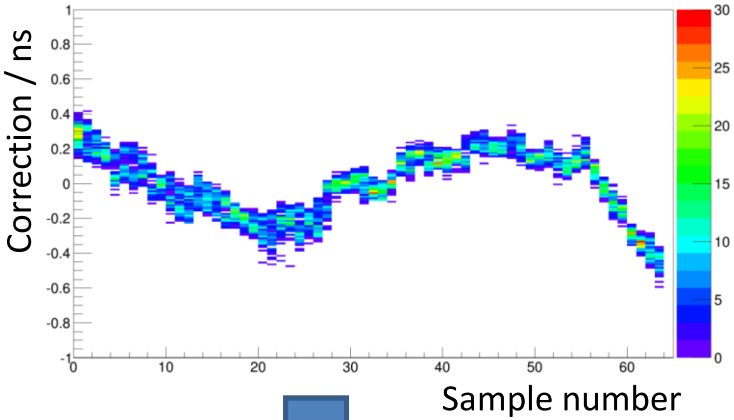
set via Vadj, **for even/odd samples**

→ 2 parameters

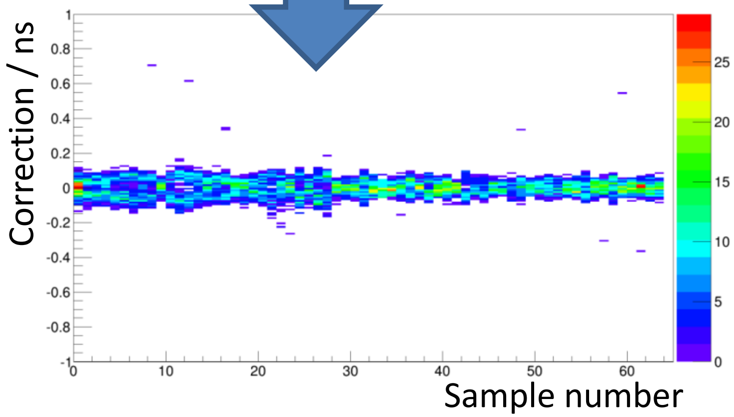
+ individual jitter from delay elements

Use zero crossing method to calibrate delay elements:





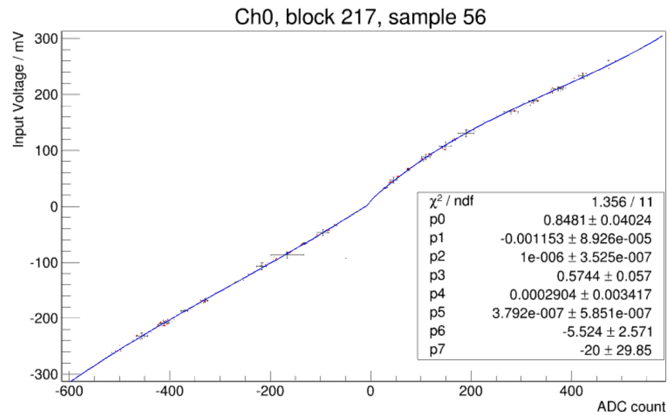
After some iterations



Digitizer calibration

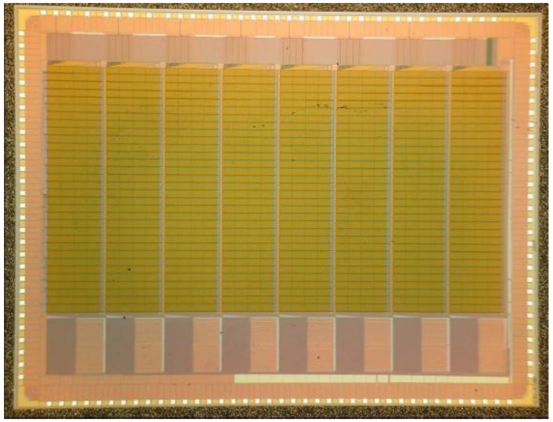
Voltage calibration:

Need to calibrate:
32 768 storage elements
64 sampling capacitors
64 Wilkinson channels
Voltage transfer processes

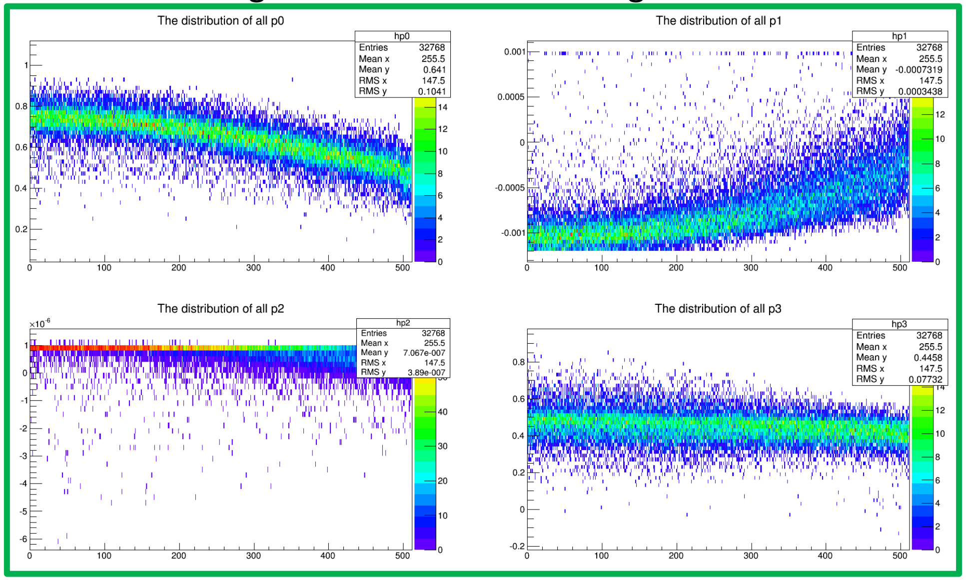


Non-linearities found in the ADC to voltage conversion

As opposed to timing calibration:
Use high amplitude samples from input waveforms and compare to fit for voltage calibration



Fit ADC to voltage relation for each storage element:

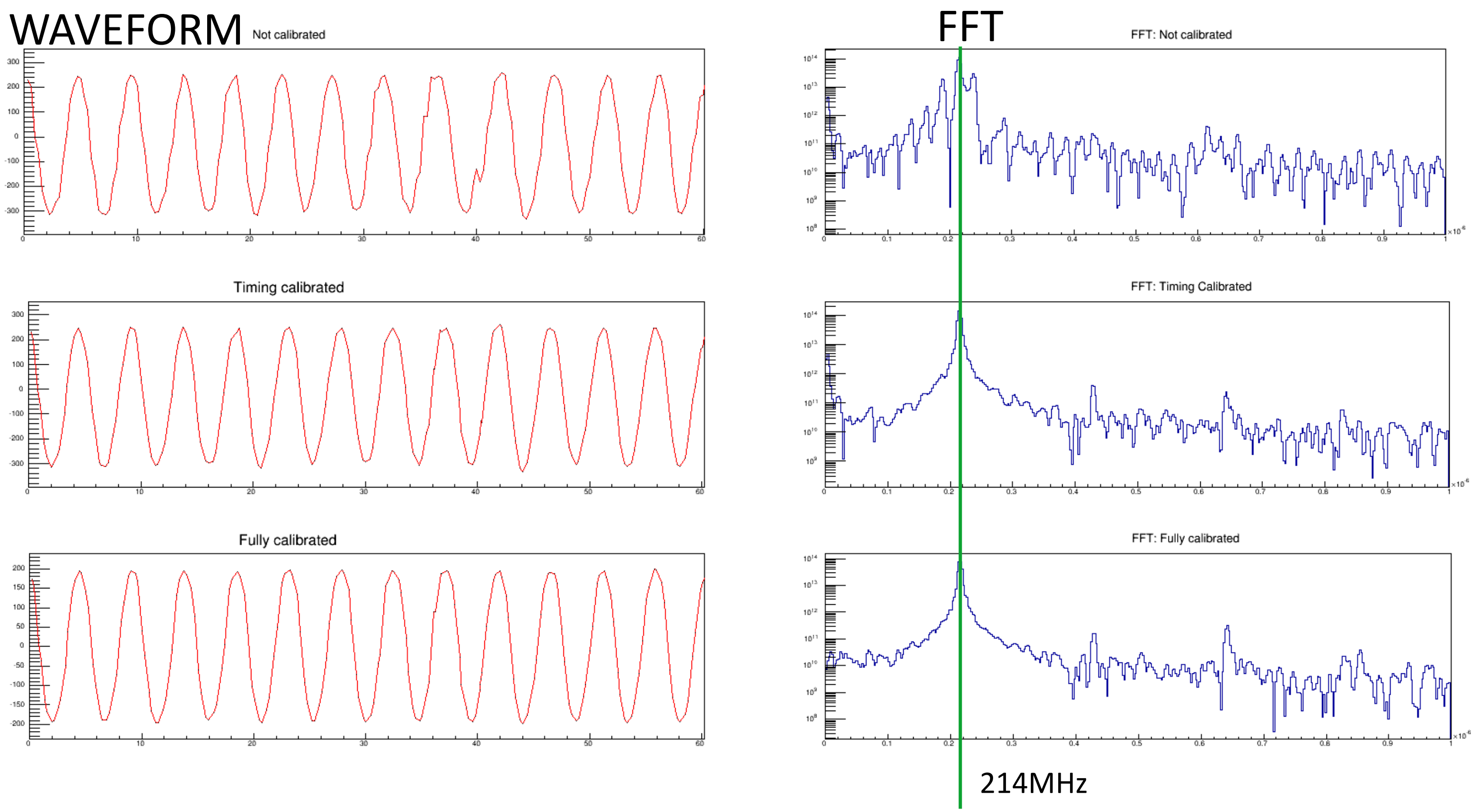


ARA calibration

No calibration

After timing calibration

Fully calibrated



Also investigated:

Inter channel crosstalk, sample memory effects, temperature dependence

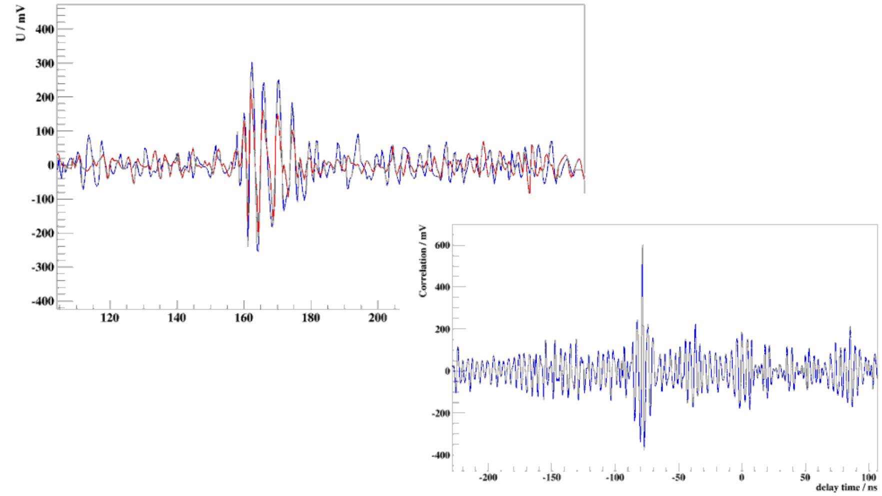
→ can be excluded as significant effects

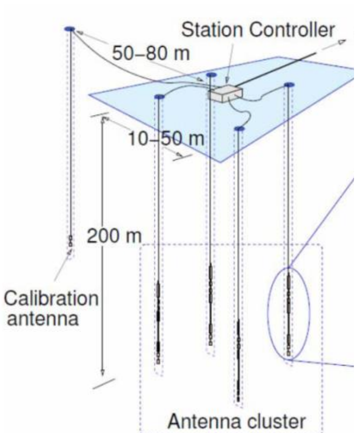
ARA calibration

We need calibration for neutrino reconstruction:

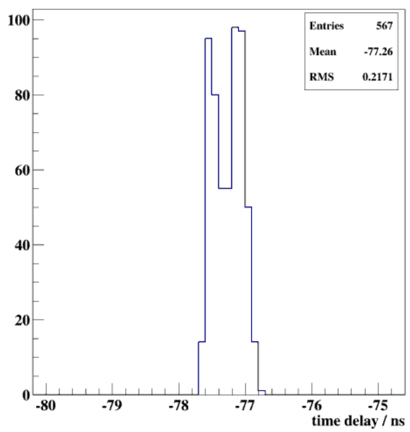
- Calibrated 128 timing elements per chip
- 32 678 storage cells per chip

→ Test stability of timing between calibration signals through cross-correlation

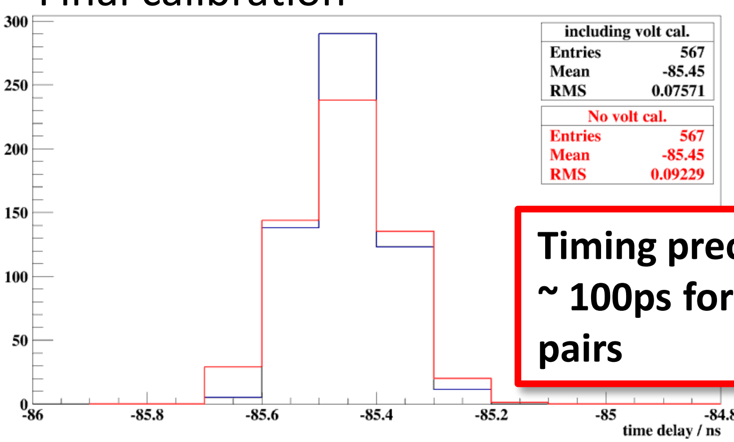




Basic calibration



Final calibration



Timing precision of ~ 100ps for antenna pairs