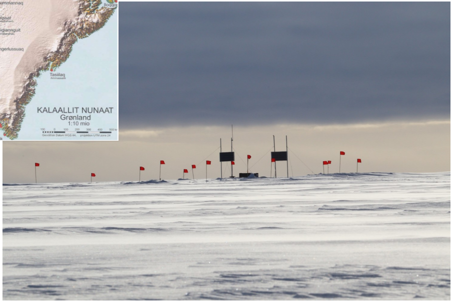
Friedrich-Alexander-Universität
Naturwissenschaftliche Fakultät

In-Ice Radio Detection of Neutrinos & Cosmic Rays

Sjoerd (👞rd) Bouma
April 9, 2024
ECAP

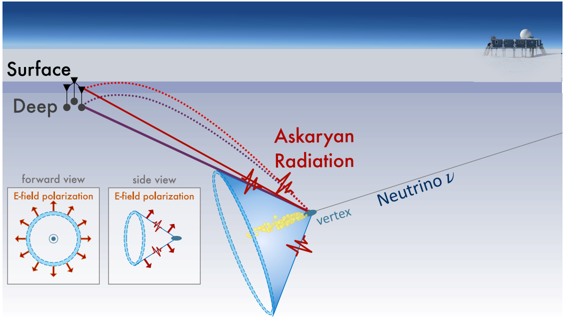
Who am I?

- Sjoerd ≈ 👞rd
- PhD student on the Radio Neutrino Observatory in Greenland (**RNO-G**)
- Mostly work on **reconstruction** and the open-source simulation/analysis framework NuRadioMC



Radio Neutrino Detection

- In-ice shower initiated by UHE neutrino develops a negative charge excess at the shower front, giving rise to **Askaryan radiation**.
- At radio wavelengths ($\mathcal{O}(100 - 1000)$ MHz), **coherent** emission close to **Cherenkov angle** ($\sim 56^\circ$)
- At energies > 10 PeV, strong enough to detect at $\mathcal{O}(1)$ km distances - in-ice radio detector for neutrinos!
- e.g. **RNO-G** in Greenland; ARIANNA, ARA, **IceCube-Gen2 (?)** in Antarctica



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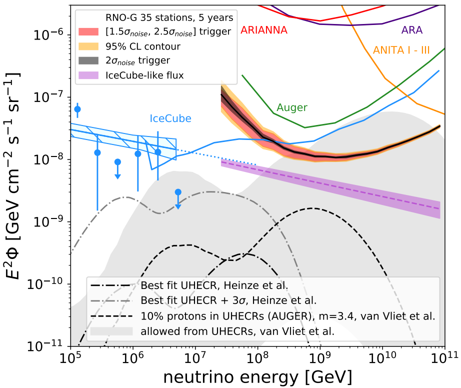

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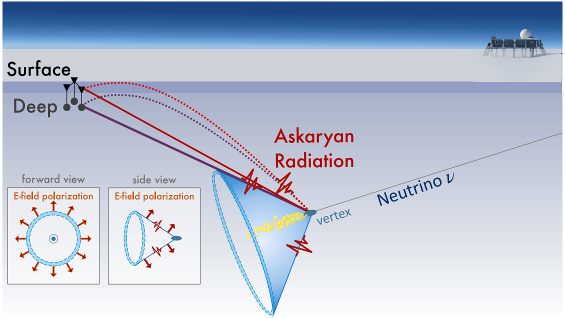
Neutrino reconstruction

Vertex reconstruction

- The **first** step in reconstructing the neutrino is finding the source of the emission: the **neutrino interaction vertex**
- Use template correlation
- Challenges:
  - **Ice** - refractive index changes ⇒ radio waves 'bend downwards'.



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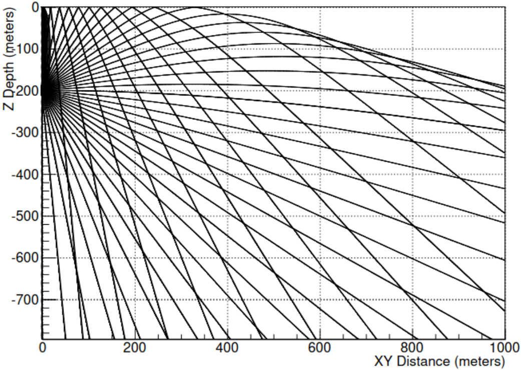
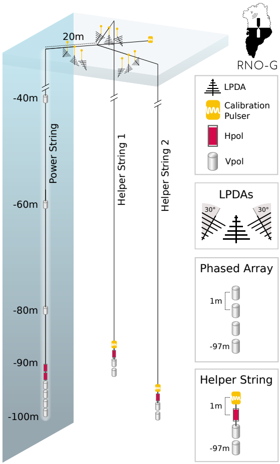


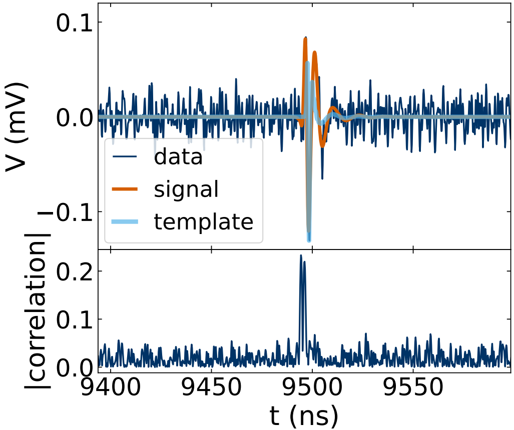
Vertex reconstruction

- The **first** step in reconstructing the neutrino is finding the source of the emission: the **neutrino interaction vertex**
- Currently one of the dominant limitations for neutrino reconstruction (2302.00054)
- Use template correlation
- Challenges:
  - **Ice** - refractive index changes ⇒ radio waves 'bend downwards'.
  - This leads to a 'shadow zone'.
  - Signal not visible in all antennas!



Vertex reconstruction

- Use a single template, compute correlation $\rho_i(t)$ for each channel i;
- Take absolute value (to account for polarity)



Vertex reconstruction

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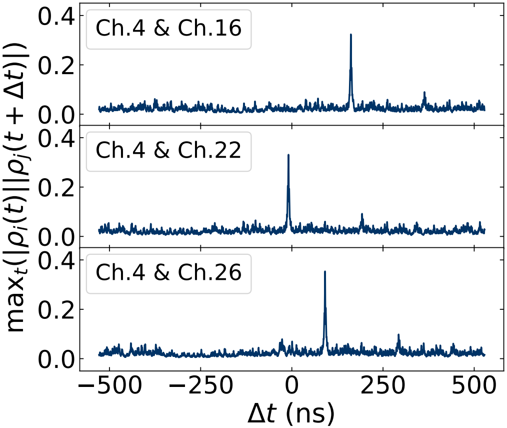
- To determine Δt, multiply them together:

$$\rho_{i,j}(\Delta t) = \max_t(|\rho_i(t)||\rho_j(t+\Delta t)|)$$



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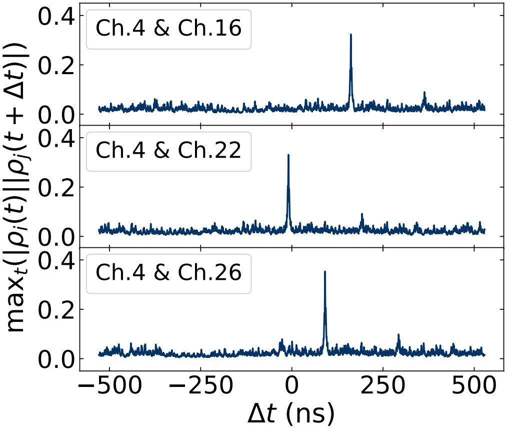
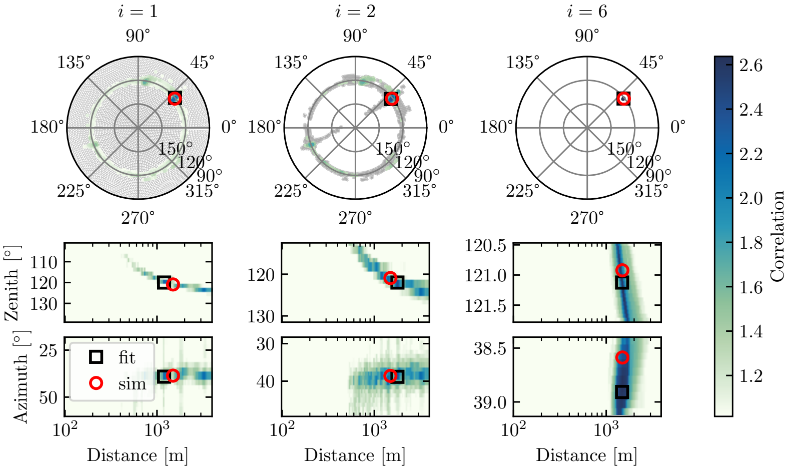
- Finally, use a lookup table to convert a vertex position $\vec{x}$ to expected time delays Δt



Vertex reconstruction

- Fit $\vec{x}$ by maximizing total correlation over all antenna pairs i, j
- To avoid local minima, use an iteratively refined brute force search.



Vertex reconstruction

- This works well at high enough SNR, and if the signal is visible in all antennas
- At low SNR, this algorithm will **bias** towards vertex position visible in all antennas (because *some* $|\rho|$ is more than *no* $|\rho|$)

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- Current strategy: median-subtraction:

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- Current strategy: median-subtraction:

$$\rho'_{i,j}(\Delta t) = \max\{0, \rho_{i,j}(\Delta t) - \tilde{\rho}_{i,j}\}$$

- **Question**: can we do something better?
- E.g. minimum correlation threshold for inclusion in fit, machine learning magic (see work with Luan)?

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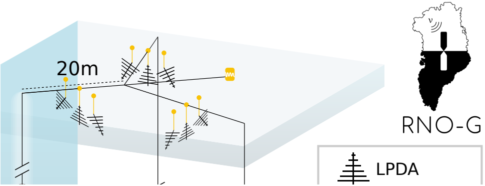
Cosmic Rays

Cosmic Rays

- RNO-G also detects cosmic rays.
- Mostly interesting for **veto** and **calibration**
- Previous reconstruction algorithm required stringent cuts on signal-to-noise ratio (SNR) → optimistic estimate of performance.



Shallow component of RNO-G detector

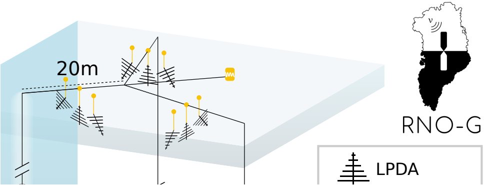
Cosmic Rays

– 'Standard' approach in radio: **unfolding** detected voltage V to estimate signal electric field E

$$V_r(f) = H_{rs}(f, \theta, \phi) E_s(f), \qquad (1)$$

– But 'actual' voltage is signal + noise: if H small, $N \gg HE$ and we end up overestimating the signal.

→ Use a forward-folding approach instead (1903.07023): fit V instead of E



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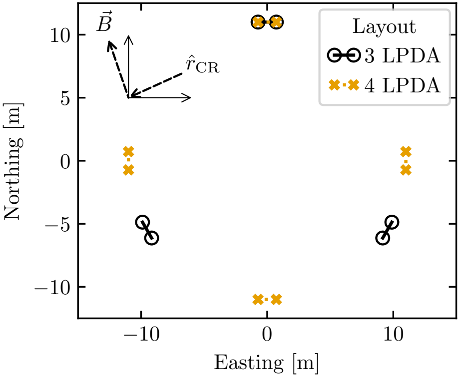
Cosmic Rays

- Previous algorithm (1903.07023) used two-step algorithm:
  1. Fit **direction** by correlation;
  2. Fit **emission** by forward-folding.
- But (1.) does not work (well) for RNO-G triangular layout - usually one of the three antennas does not see much signal

→ Combine both into single fit.



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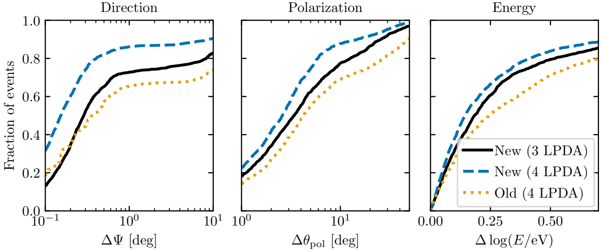
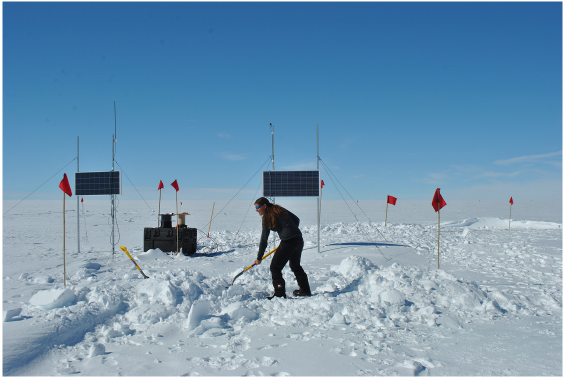
- Fraction of well-reconstructed events increases!



Conclusions

- **RNO-G** is an in-ice **radio** detector aimed at detecting **UHE neutrinos** (> 10 PeV)
- Already taking data!
- Reconstruction algorithms for both neutrinos and cosmic rays exist and are implemented in NuRadioMC
- ... but there is always room for improvement - clever suggestions welcome!



Deployment of first RNO-G station in 2021. Image credit C. Welling / Shovelling credit I. Plaisier

Backup

Recap: radio neutrinos

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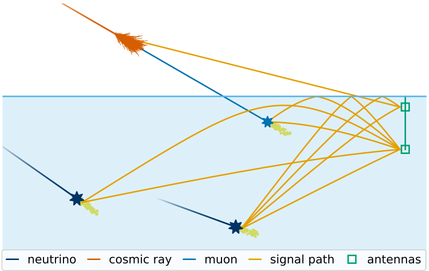

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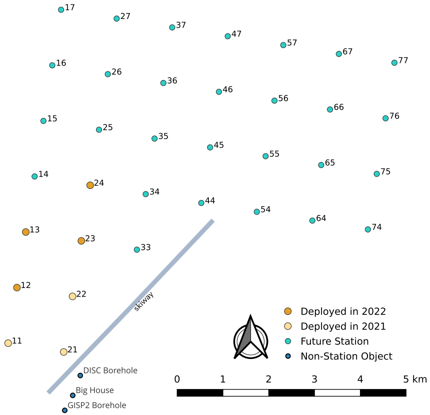
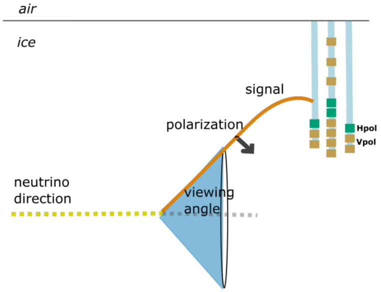


Direction reconstruction: the principle

– Three steps:
  1. **Signal direction** - direction of **emission** at the shower vertex
  2. **Viewing angle** - angle between the neutrino and the emitted signal
  3. **Polarization** - points **towards the shower axis**



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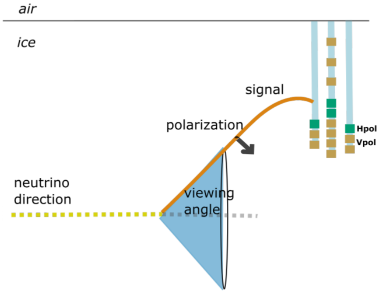

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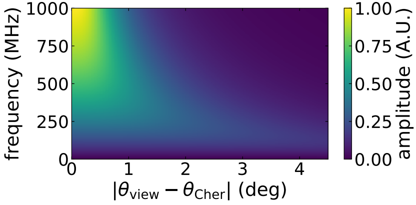

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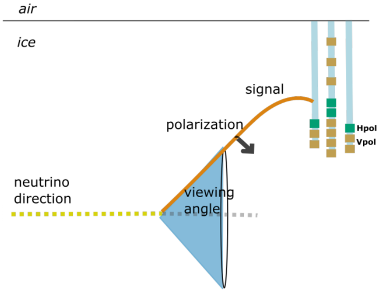
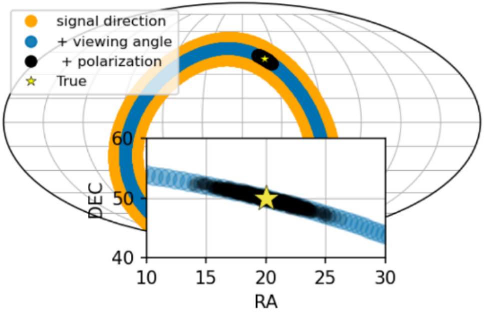
  3. **Polarization**: from different antennas ('Vpol' and 'Hpol')



Direction reconstruction: the principle

This is what it looks like...

– ...for a **single neutrino**: a small 'ellipse' on-sky.



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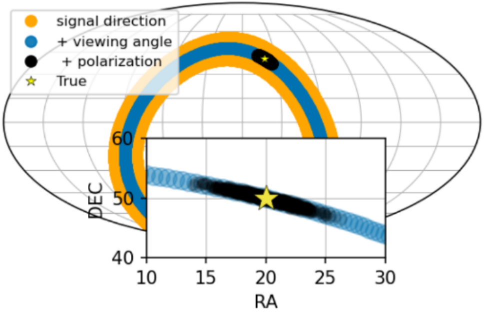
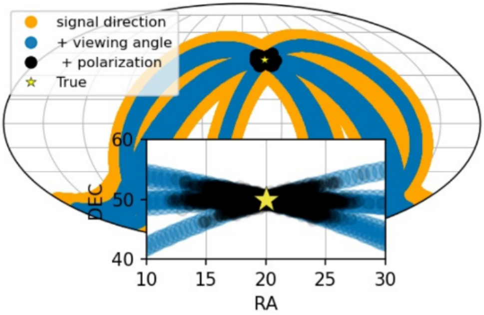


- ...for a **source** with multiple neutrinos detected ('point spread function').



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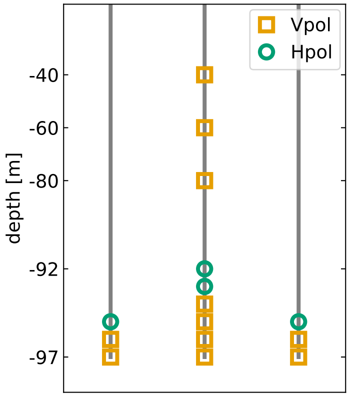
Performance

Simulation setup

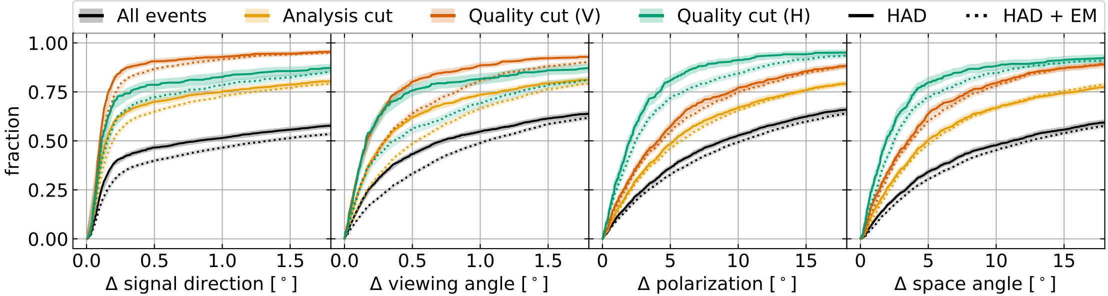
Test case:

- IceCube-like flux + GZK
- RNO-G-like detector:
  - Three strings on a triangular grid
  - Trigger (phased array of 4 Vpols) and Hpol antennas at ∼100 m to maximize sensitivity
  - 3 additional upper Vpols for increased baselines
- Include both hadronic and electromagnetic showers
  - Electromagnetic showers at ultra-high energies more irregular (LPM effect) - harder to fit, & algorithm designed for hadronic showers.



Results

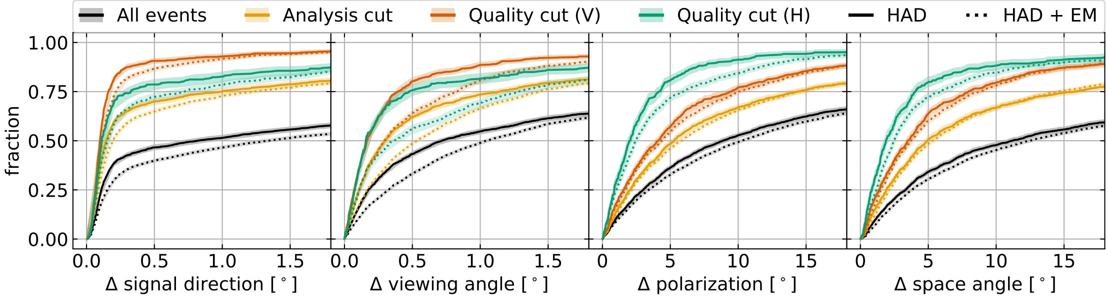
Analysis cut	SNR> 2.5 cut in lower Vpols
Quality cut (V)	SNR> 3.5 in upper Vpols
Quality cut (H)	SNR> 3 in any Hpol



Results

1. Signal direction (vertex reconstruction) limits successful reconstructions

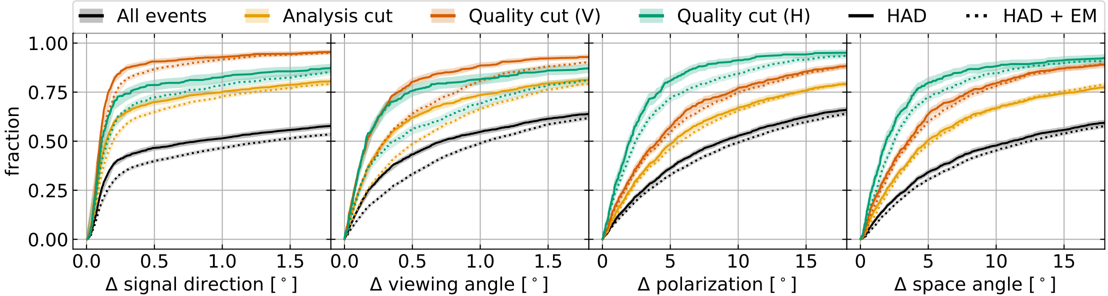
– Mostly (but not exclusively) at low SNR, failure to reconstruct the shower maximum results in 'bad' overall reconstruction.



Results

2. Polarization resolution is the dominant uncertainty

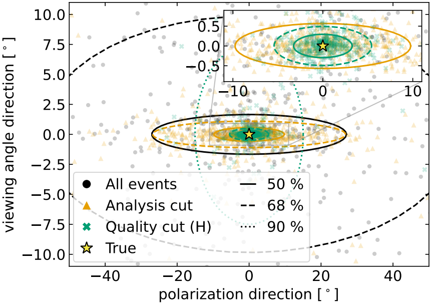
– Larger phase space & relatively less sensitive Hpol antennas lead polarization to dominate the angular uncertainty.



Results

3. Uncertainty contours are strongly asymmetric

- Dominant polarization uncertainty results in elongated ellipses.
- This means the 1D 'space angle' strongly overestimates the actual uncertainty!



Results

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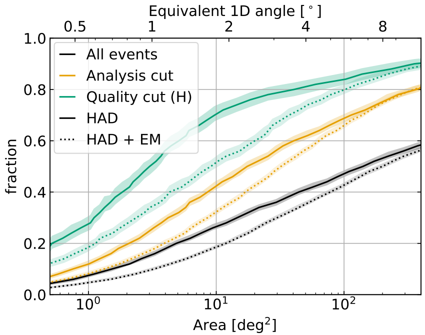
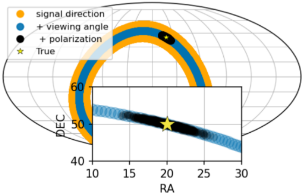
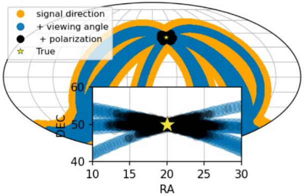
- This means the 1D 'space angle' strongly overestimates the actual uncertainty!
- E.g. median resolution for HAD, analysis cut: 4.9° (space angle) vs. 17 $\mathrm{deg}^2 \approx$ 2.4° 1D-equivalent.



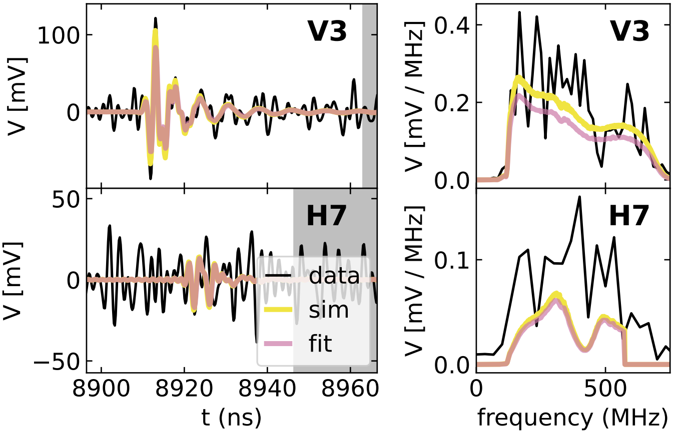
Conclusions

1. We **can reconstruct neutrinos** with a deep in-ice radio detector! (Now we just need to find some...)
2. Resolution limited by **vertex** and **polarization** reconstruction
3. Uncertainty contours are asymmetric - **can not just quote a space angle**!
   - Single event - **ellipse**
   - Point spread function - **bow tie**
4. Improvements expected!
   - Improve vertex reconstruction by better pulse finding at low SNR?
   - Dedicated algorithm for electromagnetic showers?
   - Machine learning?
   - ...

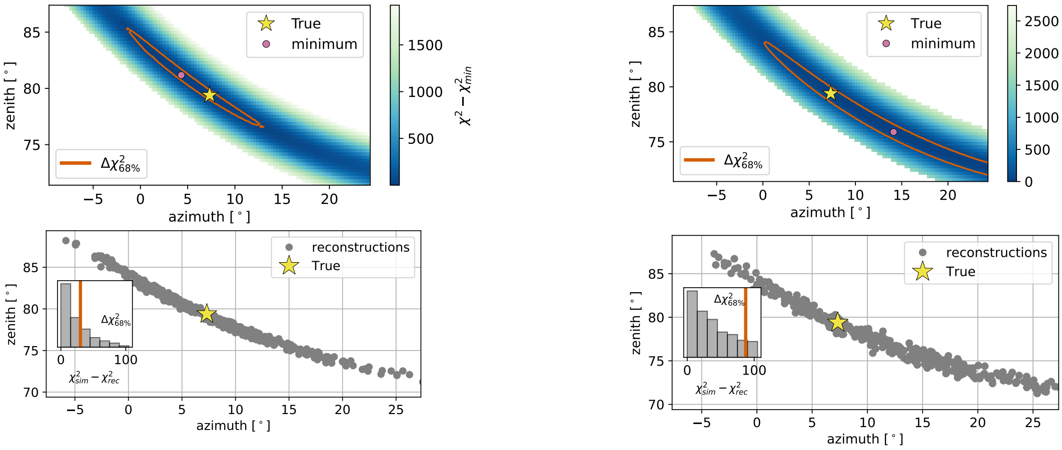




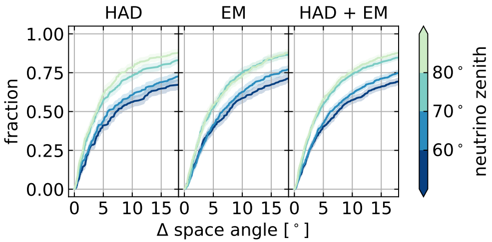
Example reconstruction

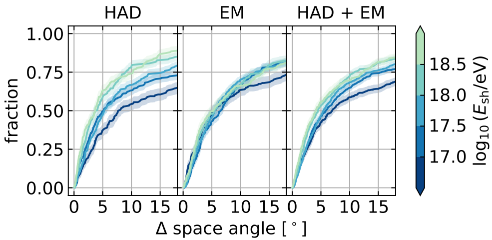


Systematic uncertainties



Zenith and energy dependence

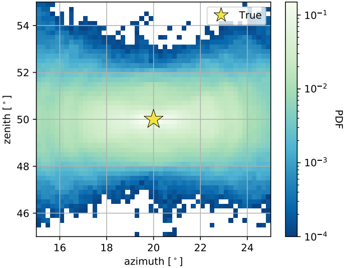




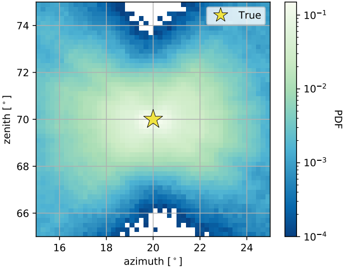
Point spread function

- Shape of the PSF depends on local zenith
- Orientation of the polarization direction geometrically constrained → **bow-tie** shape
- Area larger than single event contour, but smaller than for a symmetric PSF

$\theta = 50^\circ$

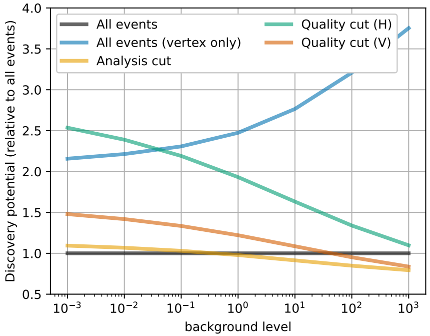


$\theta = 70^\circ$



Discovery potential

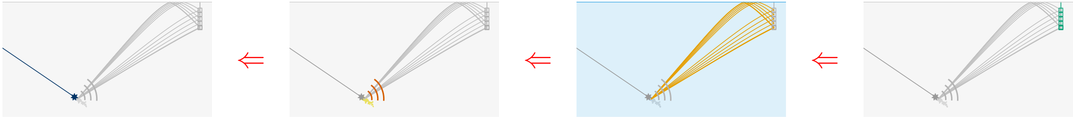
- Can study the source discovery potential for a source at a declination of 20°
- Shown normalized to 'all events' - **lower is better**
- At $\leq$ expected background flux, number of events detected is much more important than resolution.



The algorithm

The forward-folding approach

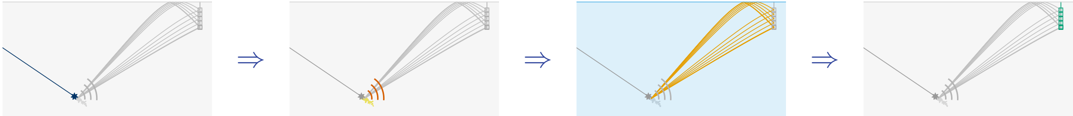
- **Unfolding**: invert the detector response & propagation effects, and fit the **electric field**
- Advantage: (Askaryan) model-independent
- But: inflates noise where detector response is weaker, hard to combine information from multiple antennas



neutrino properties ⇐ electric field ⇐ in-ice propagation ⇐ detector response

The forward-folding approach

- **Forward-folding**: for each direction hypothesis, take the electric field and **forward-fold** it with expected effects from propagation & detector response.
- Fit to measured **voltage traces**.
- Improved accuracy compared to standard unfolding, especially at low SNR [1]

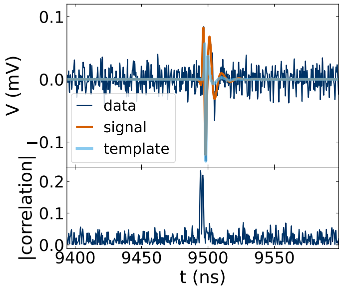


neutrino properties ⇒ electric field ⇒ in-ice propagation ⇒ detector response

[1] arXiv:1903.07023

Step 1: Signal direction

- 'Triangulation': use time differences at different antennas to obtain emission vertex (≈ shower maximum)
- Time differences obtained by template correlation



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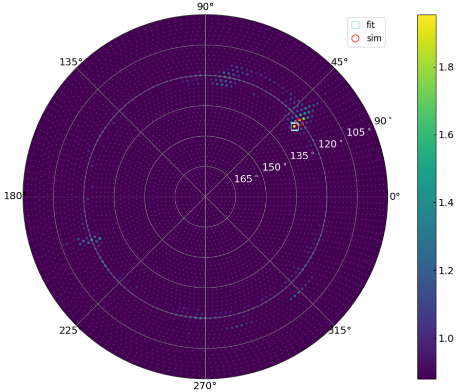

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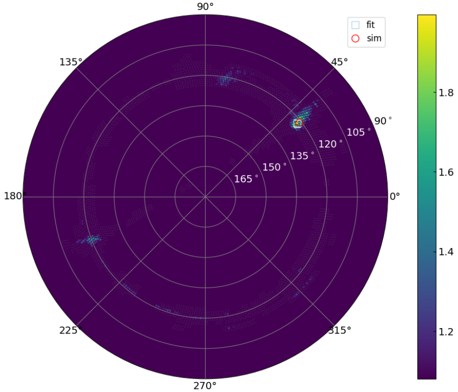
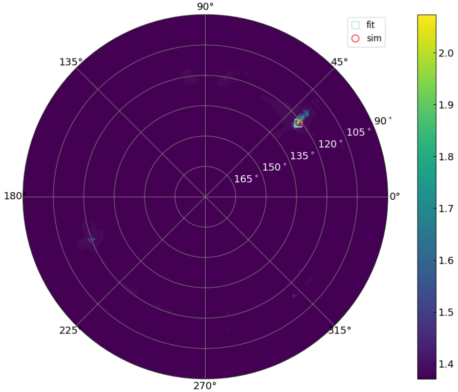


Step 1: Signal direction

- 'Triangulation': use time differences at different antennas to obtain emission vertex ($\approx$ shower maximum)
- Time differences obtained by template correlation
- Maximize total correlation over all channels in iterative grid search



Step 1: Signal direction

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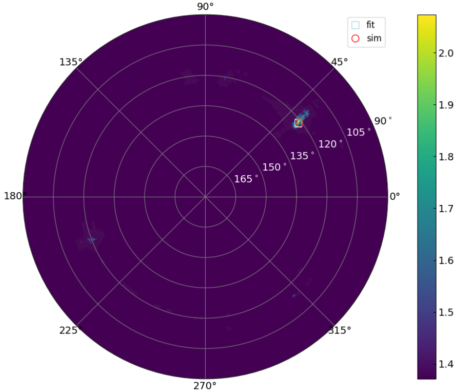
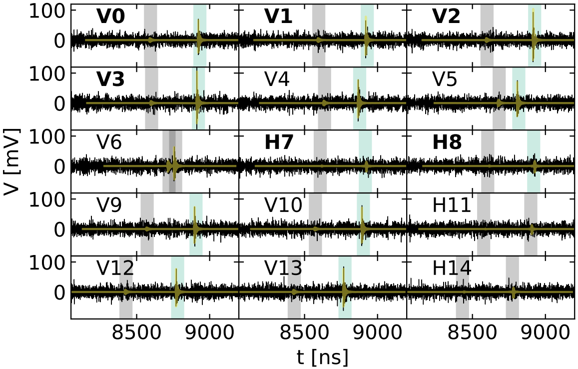
$\rightarrow$ Ice model + ray type + vertex position determine **signal direction**



Step 2: Find pulses

- Use emission vertex as input for the direction reconstruction.
- Exact pulse arrival times not known due to uncertainties in vertex, ice model, group delays...
- At low SNR, end up fitting random noise fluctuations.

→ identify approximate pulse windows, and include only those with amplitude $> 3.5\sigma_{\mathrm{noise}}$



Step 3: Fit neutrino properties

For each viewing angle, polarization and shower energy hypothesis:

- Forward-fold expected electric field with propagation & detector effects
- Determine exact pulse arrival time within each pulse window using correlation
- Compute
  $\chi^2 = \sum_{n=1}^{n_{\text{pulses}}} \sum_{i=1}^{n_{\text{samples}}} \frac{(x_i - f_i(\theta_{\text{view}}, \phi_{\text{pol}}, E_{\text{sh}}))^2}{\sigma^2_{\text{noise}}}$

→ Obtain neutrino properties that minimize χ^2