Friedrich-Alexander-Universität
Naturwissenschaftliche Fakultät

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Radio detection & reconstruction of neutrinos

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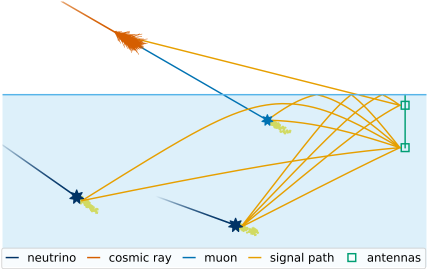
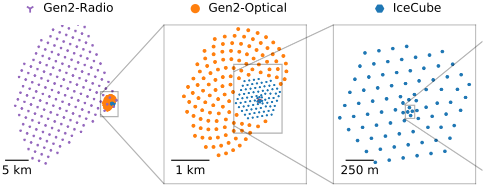
ECAP

Recap: radio neutrinos

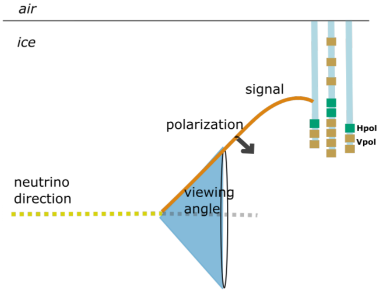
- In-ice shower initiated by UHE neutrino develops a negative charge excess at the shower front, giving rise to **Askaryan radiation**.
- At radio wavelengths ($\mathcal{O}(100-1000)$ MHz), **coherent** emission close to **Cherenkov angle** ($\sim 56^\circ$)
- At energies > 10 PeV, strong enough to detect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





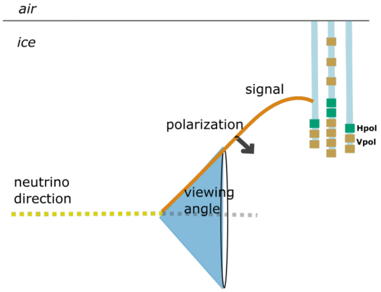
Direction reconstruction: the principle

- 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**



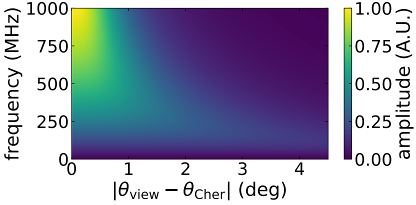
Direction reconstruction: the principle

- Three steps:
  1. **Signal direction**: from 'triangulation'



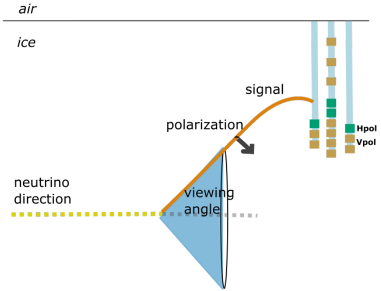
Direction reconstruction: the principle

- Three steps:
  1. **Signal direction**: from 'triangulation'
  2. **Viewing angle**: from shape of spectrum - the emission **loses coherence** further from the Cherenkov angle, with the higher frequencies losing coherence first.



Direction reconstruction: the principle

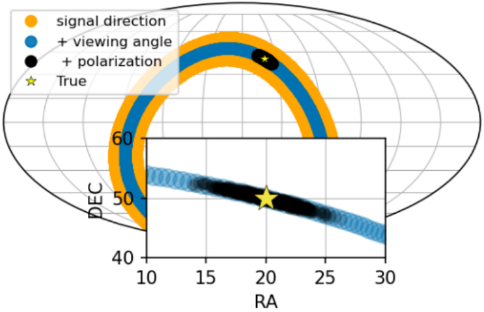
- Three steps:
  1. **Signal direction**: from 'triangulation'
  2. **Viewing angle**: from shape of spectrum - the emission **loses coherence** further from the Cherenkov angle, with the higher frequencies losing coherence first.
  3. **Polarization**: from different antennas ('Vpol' and 'Hpol')



Direction reconstruction: the principle

This is what it looks like...

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



Direction reconstruction: the principle

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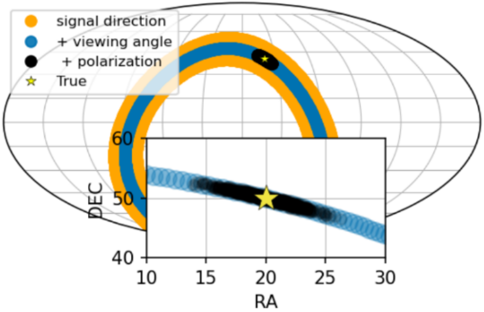
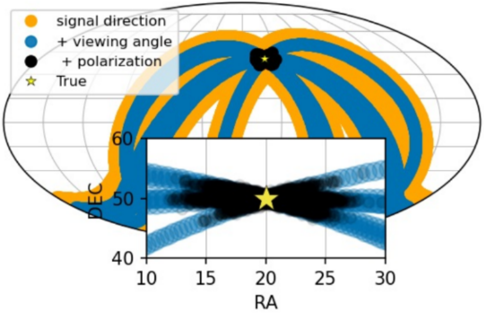


- ...for a **source** with multiple neutrinos detected ('point spread function').

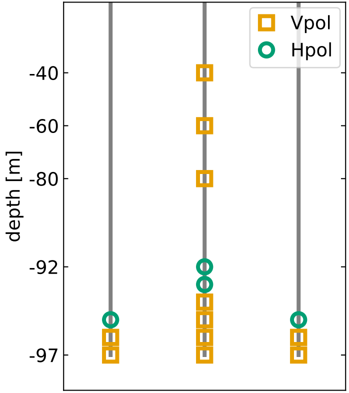


Performance

Simulation setup

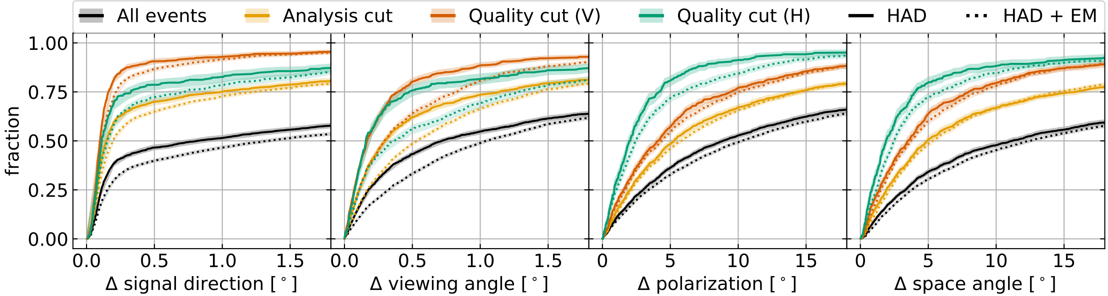
Test case:

- 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

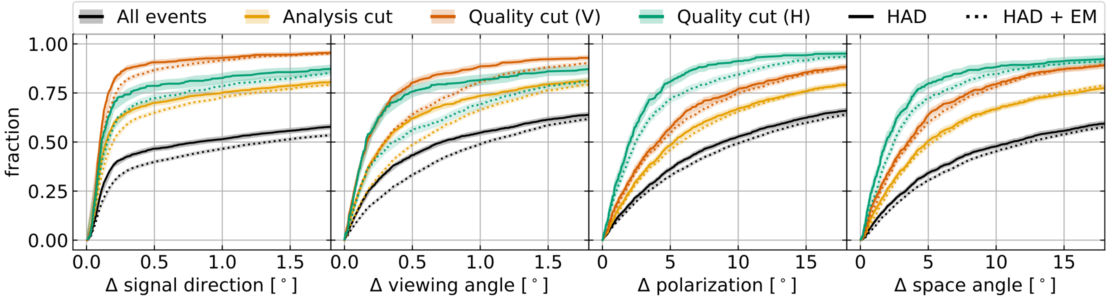
Analysis cut	SNR> 2.5 cut in lower Vpols
Quality cut (V)	SNR> 3.5 in upper Vpols
Quality cut (H)	SNR> 3 in any Hpol



Results

1. Signal direction (vertex reconstruction) limits successful reconstructions

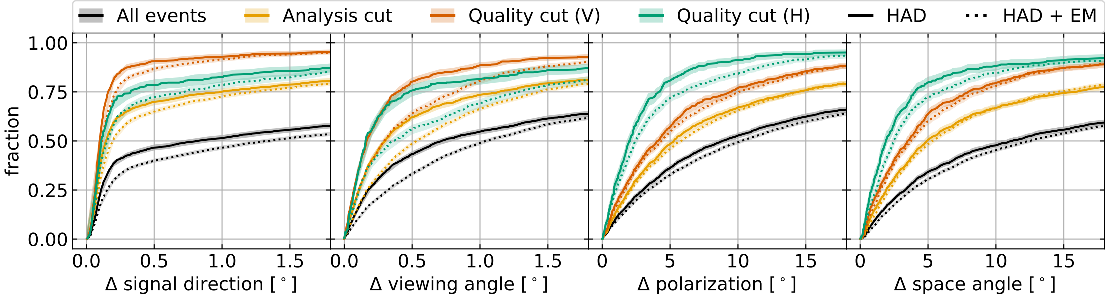
– Mostly (but not exclusively) at low SNR, failure to reconstruct the shower maximum results in 'bad' overall reconstruction.



Results

2. Polarization resolution is the dominant uncertainty

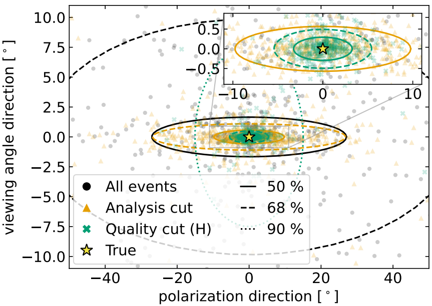
- Larger phase space & relatively less sensitive Hpol antennas lead polarization to dominate the angular uncertainty.



Results

3. Uncertainty contours are strongly asymmetric

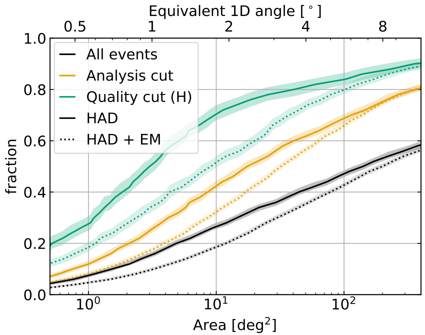
- Dominant polarization uncertainty results in elongated ellipses.
- This means the 1D 'space angle' strongly overestimates the actual uncertainty!



Results

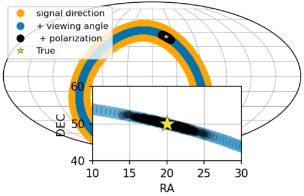
3. Uncertainty contours are strongly asymmetric

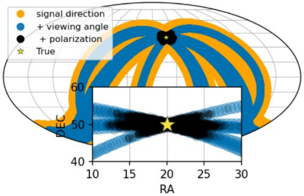
- Dominant polarization uncertainty results in elongated ellipses.
- This means the 1D 'space angle' strongly overestimates the actual uncertainty!
- E.g. median resolution for HAD, analysis cut: 4.9° (space angle) vs. $17\ \mathrm{deg}^2 \approx 2.4^\circ$ 1D-equivalent.



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?
   - ...





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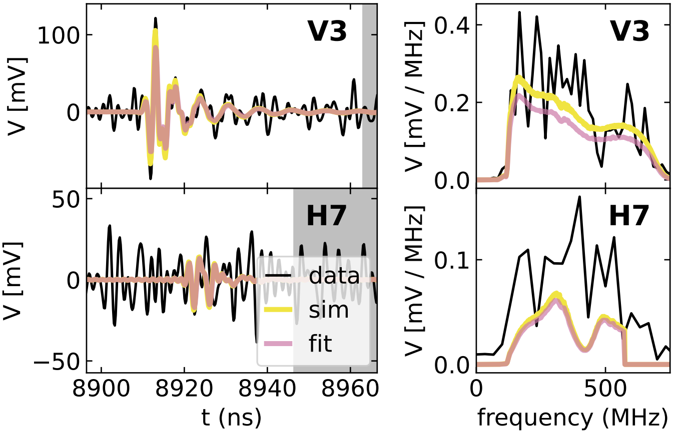
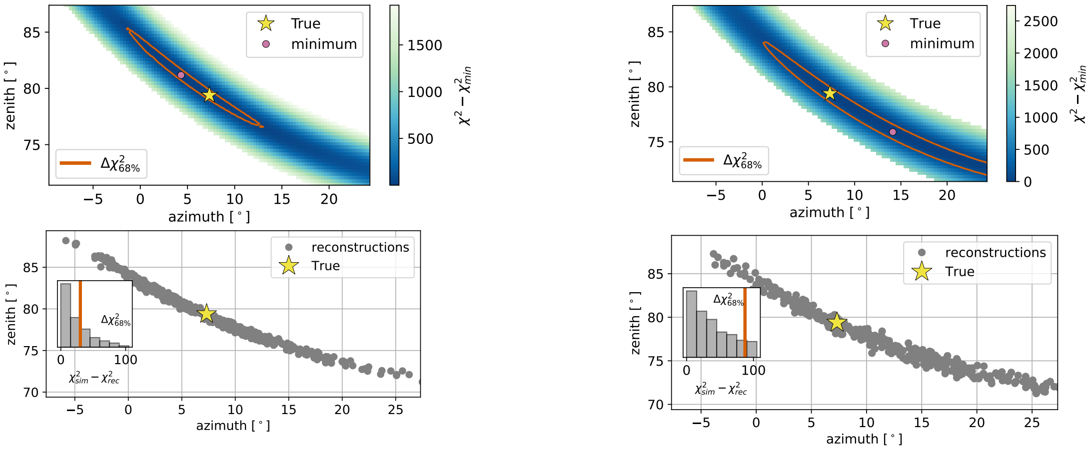
Backup

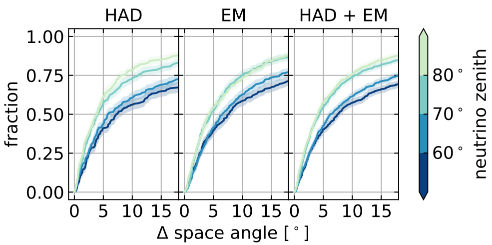
Example reconstruction

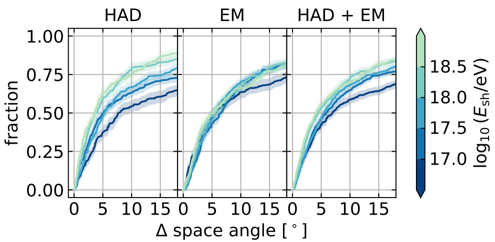


Systematic uncertainties



Zenith and energy dependence

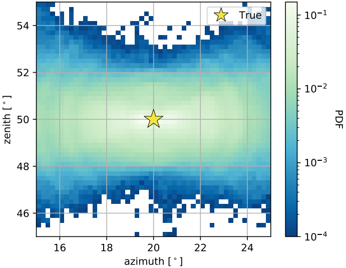




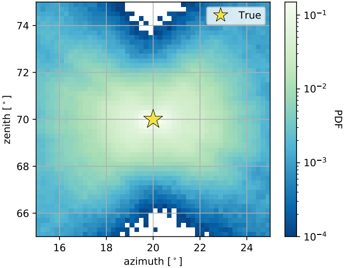
Point spread function

- 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

$\theta = 50^\circ$

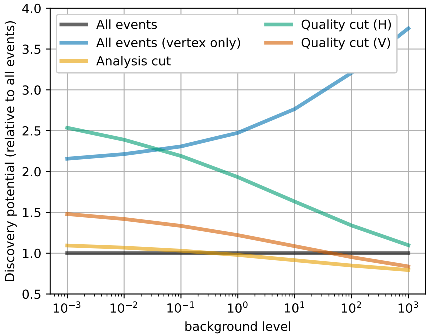


$\theta = 70^\circ$



Discovery potential

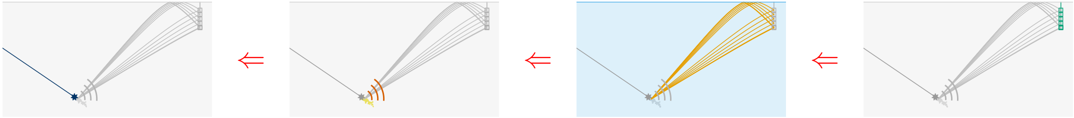
- Can study the source discovery potential for a source at a declination of 20°
- Shown normalized to 'all events' - **lower is better**
- At $\leq$ expected background flux, number of events detected is much more important than resolution.



The algorithm

The forward-folding approach

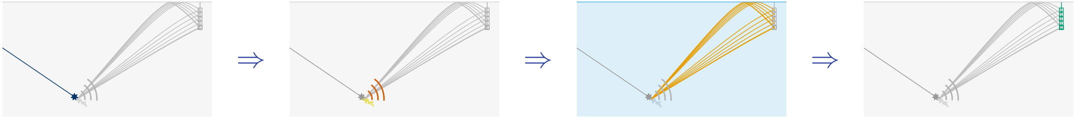
- **Unfolding**: invert the detector response & propagation effects, and fit the **electric field**
- Advantage: (Askaryan) model-independent
- But: inflates noise where detector response is weaker, hard to combine information from multiple antennas



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]

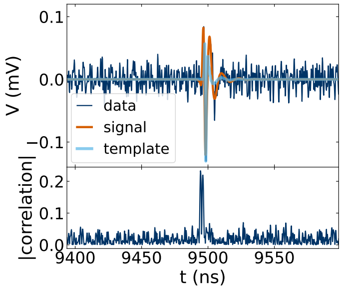


neutrino properties ⇒ electric field ⇒ in-ice propagation ⇒ detector response

[1] arXiv:1903.07023

Step 1: Signal direction

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



Step 1: Signal direction

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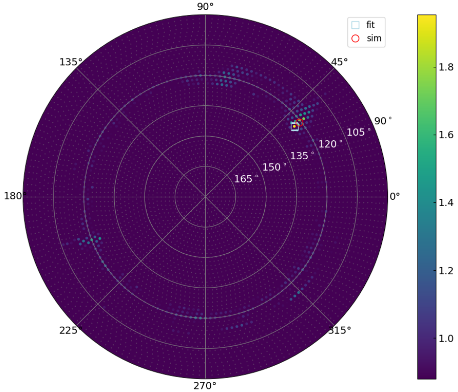
- Maximize total correlation over all channels in iterative grid search



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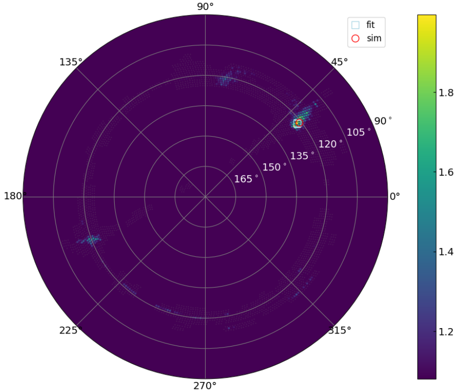

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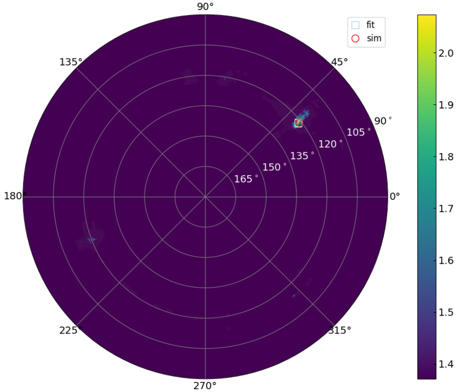

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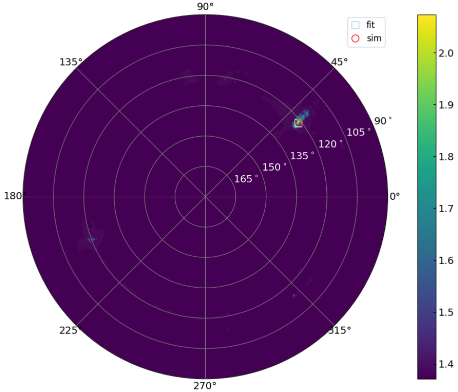
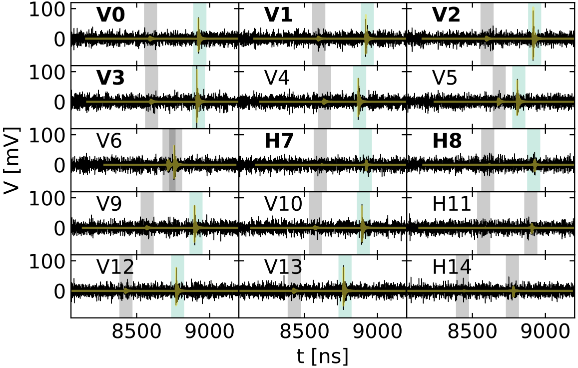
$\rightarrow$ Ice model + ray type + vertex position determine **signal direction**



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

$$\chi^2 = \sum_{n=1}^{n_{\mathrm{pulses}}} \sum_{i=1}^{n_{\mathrm{samples}}} \frac{(x_i - f_i(\theta_{\mathrm{view}}, \phi_{\mathrm{pol}}, E_{\mathrm{sh}}))^2}{\sigma^2_{\mathrm{noise}}}$$

→ Obtain neutrino properties that minimize χ^2