Spectral index analysis of the data from the Auger Engineering Radio Array

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on behalf of the Pierre Auger Collaboration

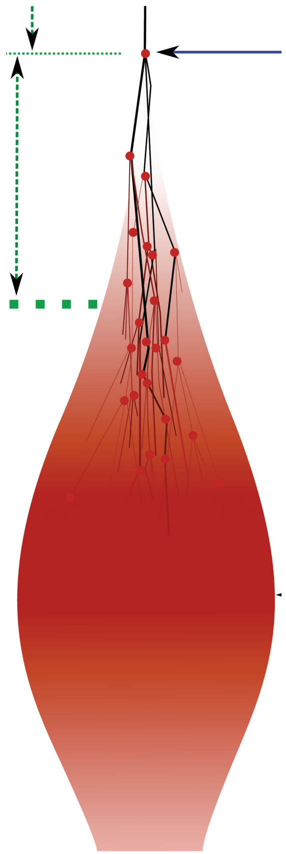
Outline

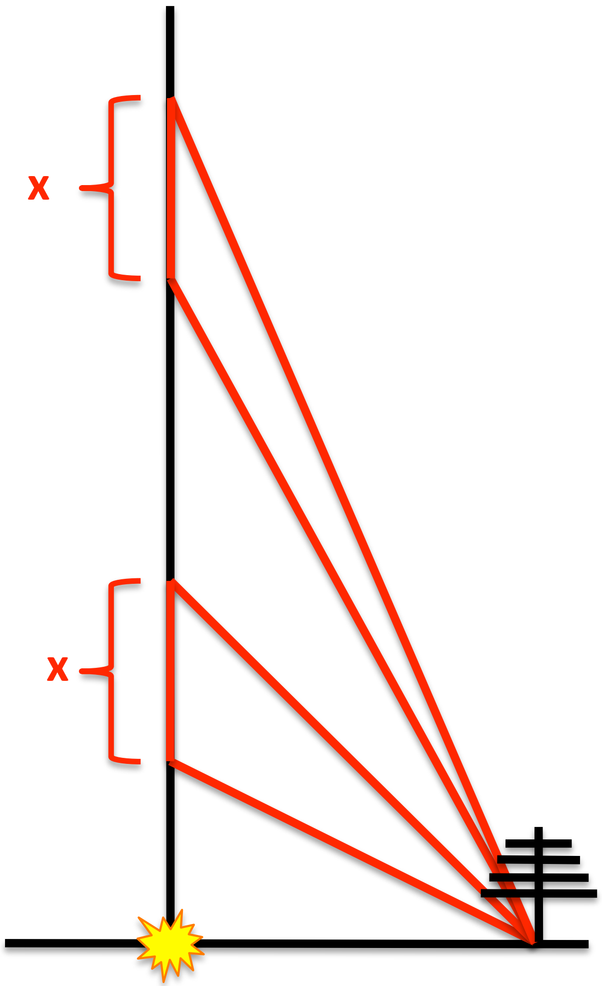
- Basic idea and introduction of spectral index
- Correction for noise
- Dependencies of spectral index on air shower geometry
- Outlook: sensitivity to composition
- Conclusions

AERA at the Pierre Auger Observatory

- Within dense part of the Auger surface detector array
- Overlooked by fluorescence telescopes (regular and high elevation)
- Energy threshold: ~10^{17} eV

Basic idea





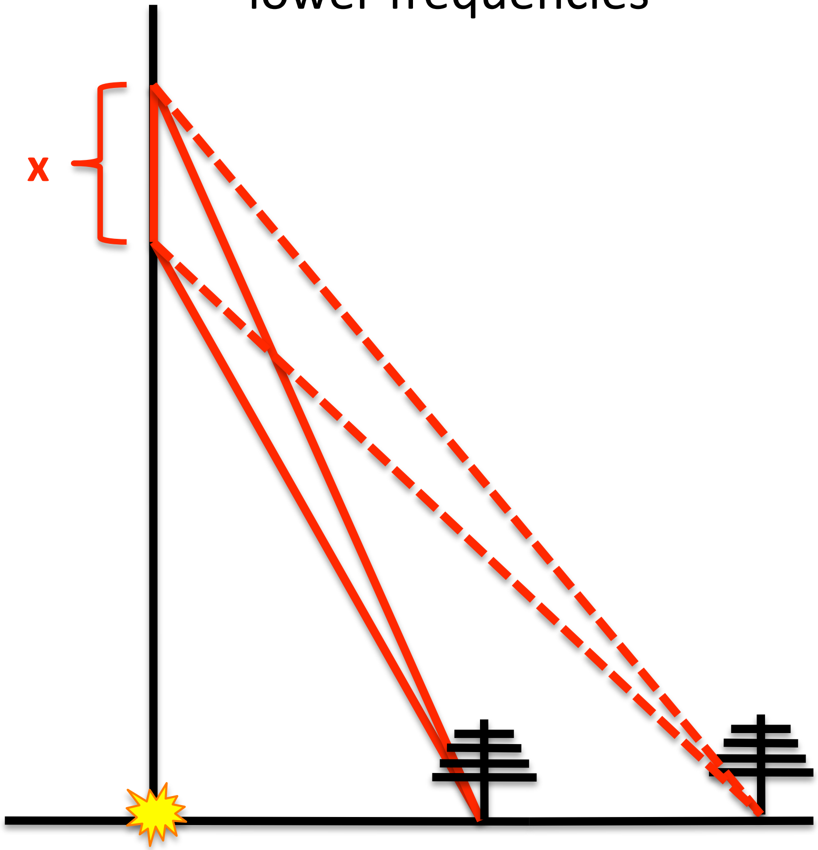
Geometric path difference

- smaller Δt
- shorter pulse
- higher frequencies

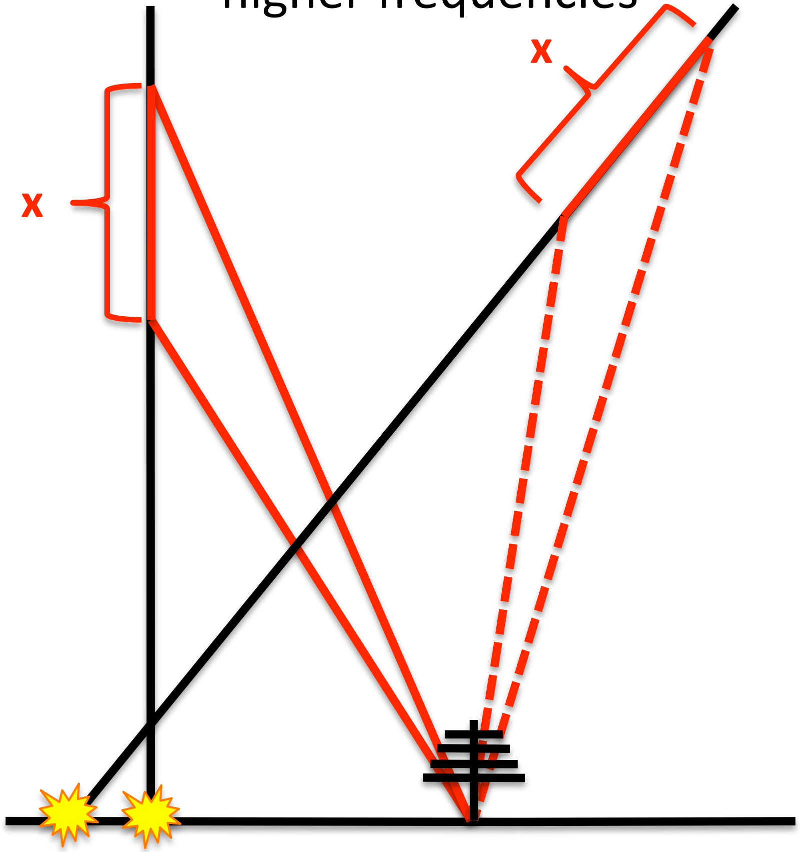
- larger Δt
- longer pulse
- lower frequencies

Distance and zenith dependence

Increasing distance
same zenith
- longer pulses
- lower frequencies

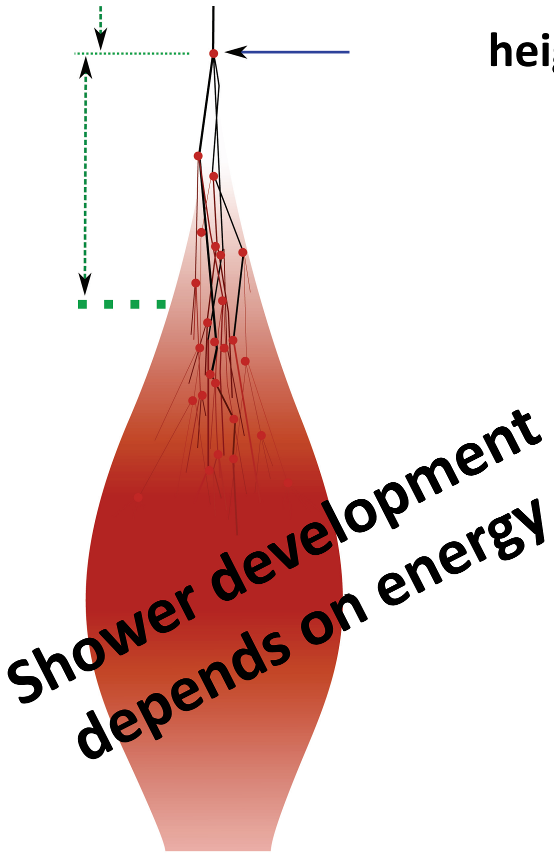


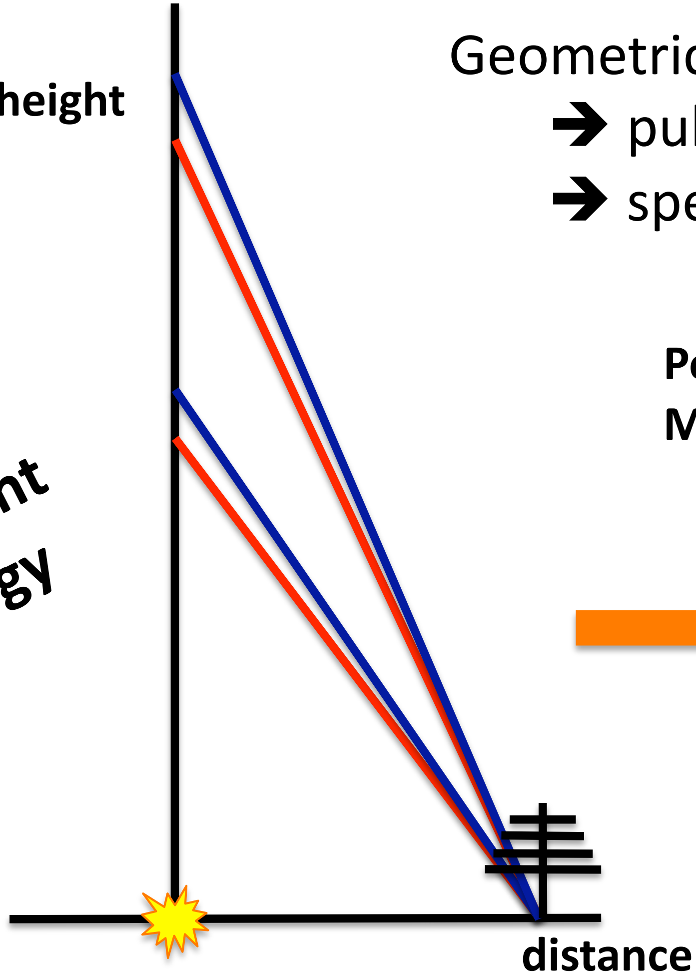
Increasing Zenith
same distance
- shorter pulses
- higher frequencies



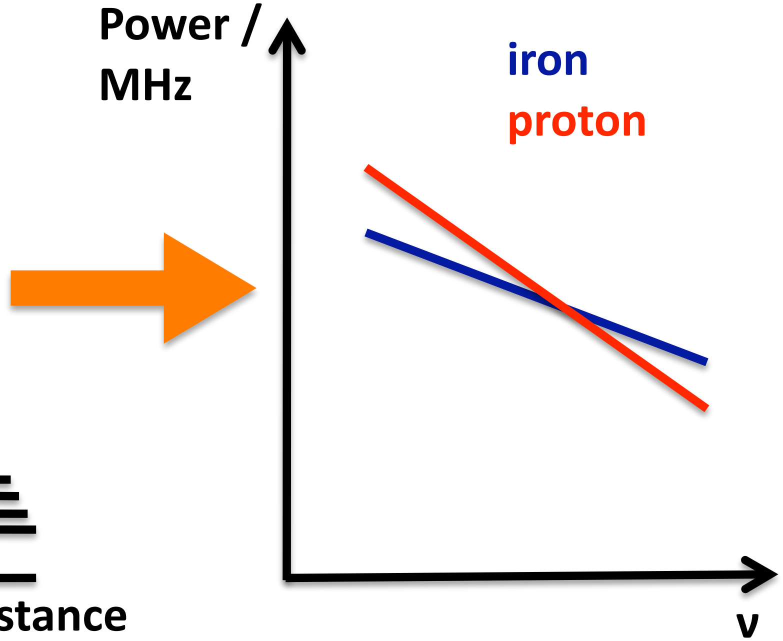
Basic idea

More complicated due to refractive index > 1



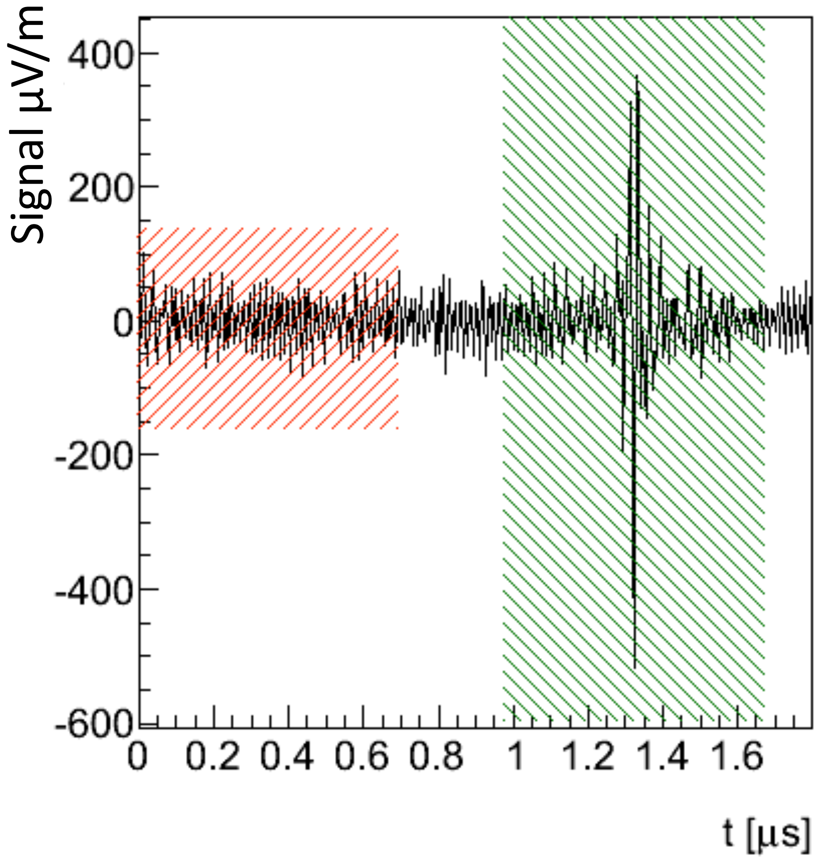


Geometric path difference
→ pulse length
→ spectral index

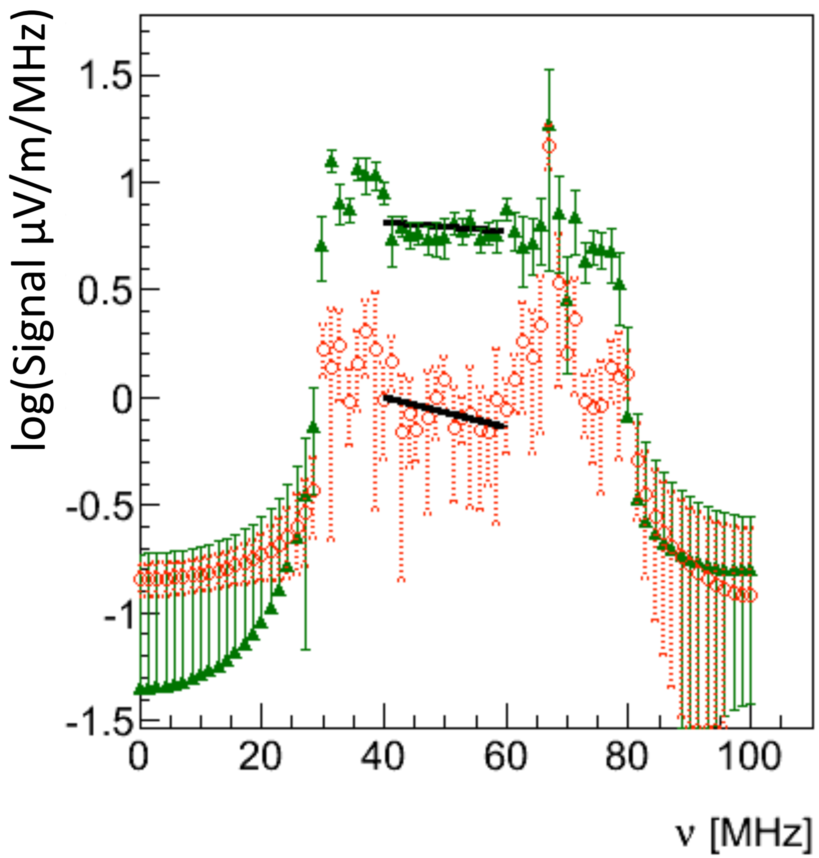


Example AERA signal

East-West polarization



Fitting range: 40 to 60 MHz



Data processing

Correct for detector response

Subtract noise

Determine spectral index in East-West polarization

Look for air shower dependencies

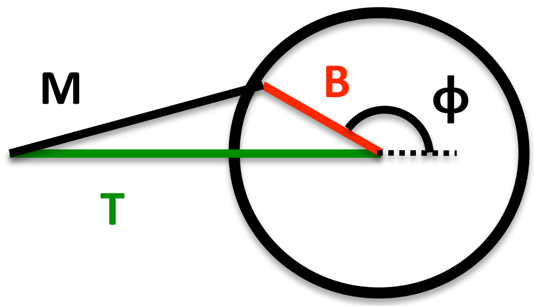
Offline

Definition:

$$\frac{S}{N} = \frac{\int_{\nu_{Min}}^{\nu_{Max}} S \, d\nu}{\int_{\nu_{Min}}^{\nu_{Max}} N \, d\nu}$$

Studying the effect of noise

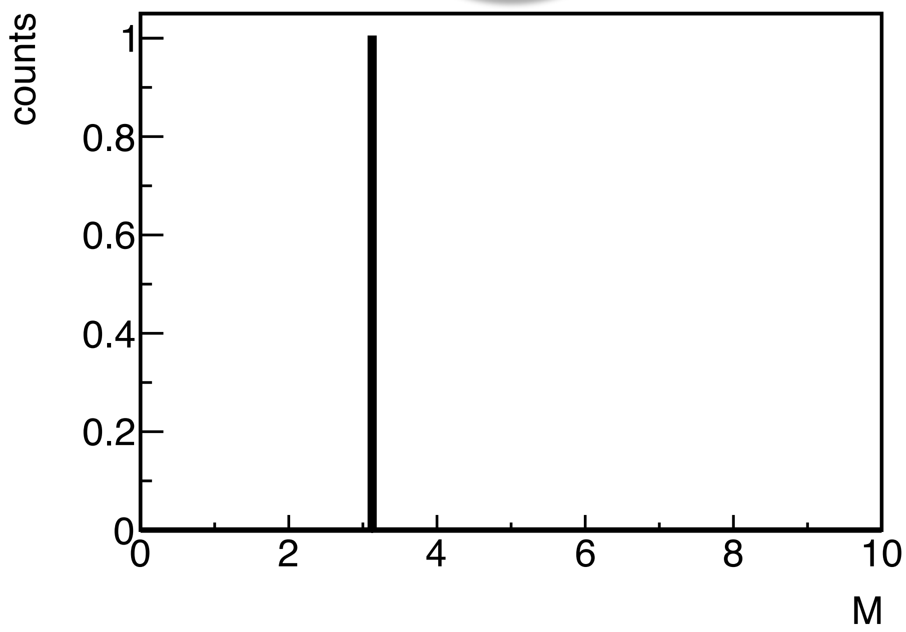
In each frequency bin: $M(\phi) = \sqrt{T^2 + B^2 + 2TB\cos\phi}$



T = 5, true signal

B = 2, background

M, measured signal



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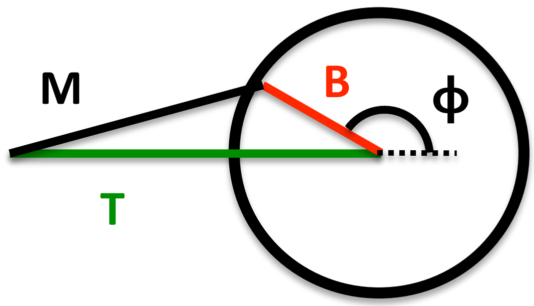

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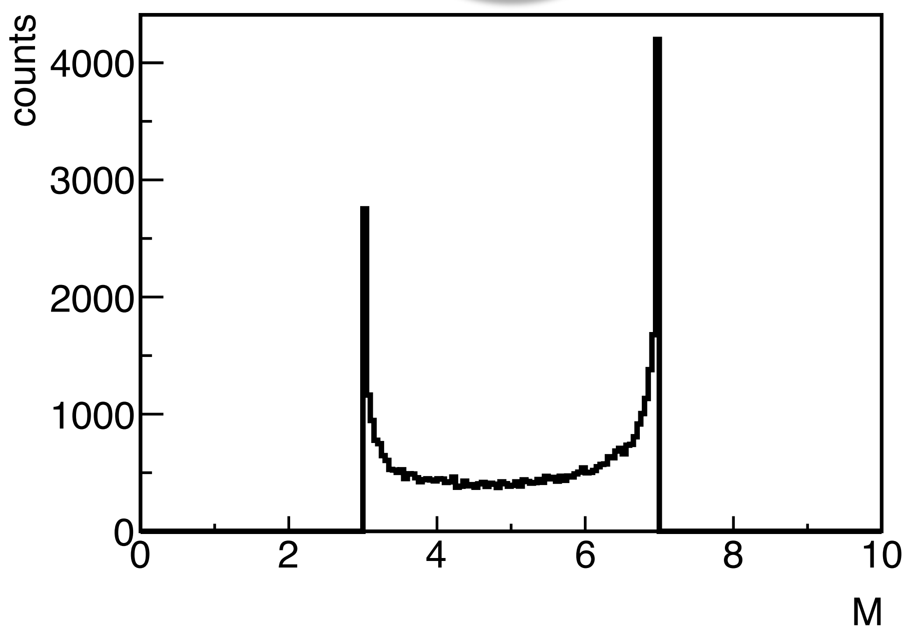


Uniform in ϕ

Noise correction for data

$$M\left(\phi\right) = \sqrt{T^2 + B^2 + 2TB\cos\phi}$$

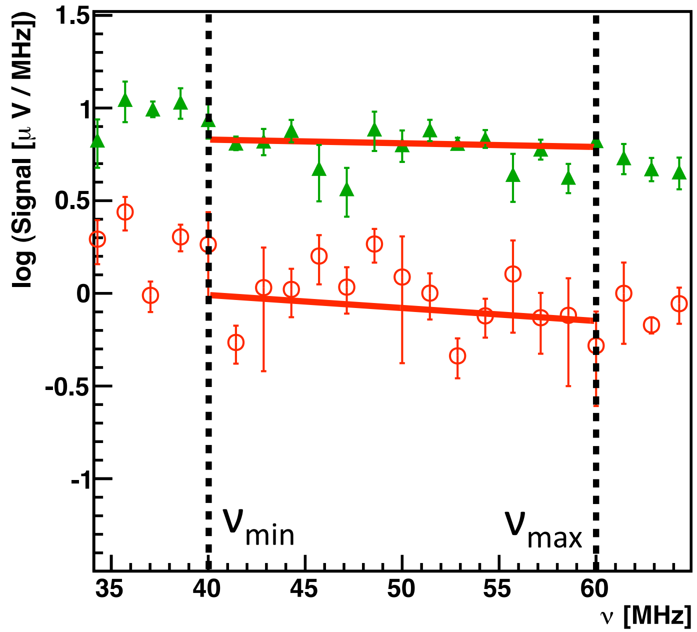
Phase between signal and background unknown

- Fit signal and background spectrum
- Determine amplitudes at ν_{min} and ν_{max} for M and B
- Calculate $M_{cor}(\nu_{min})$ and $M_{cor}(\nu_{max})$ with

$$M_{Cor} = \frac{1}{2\pi}\int_0^{2\pi}\sqrt{M^2 - \left(B\cdot\sin\phi\right)^2}\,d\phi$$

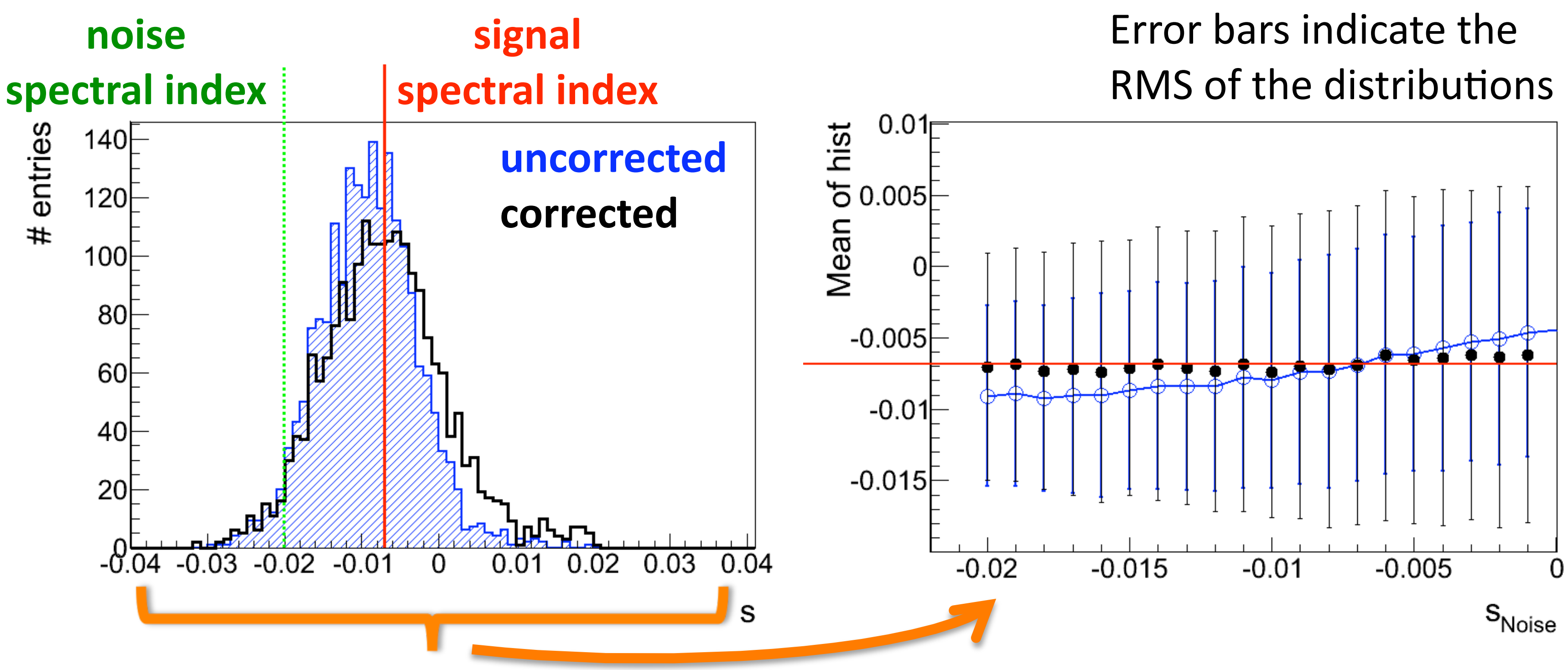
- Determine corrected spectral index s from $M_{cor}(\nu_{min})$ and $M_{cor}(\nu_{max})$

M: measured amplitude
B: background amplitude
T: true signal amplitude



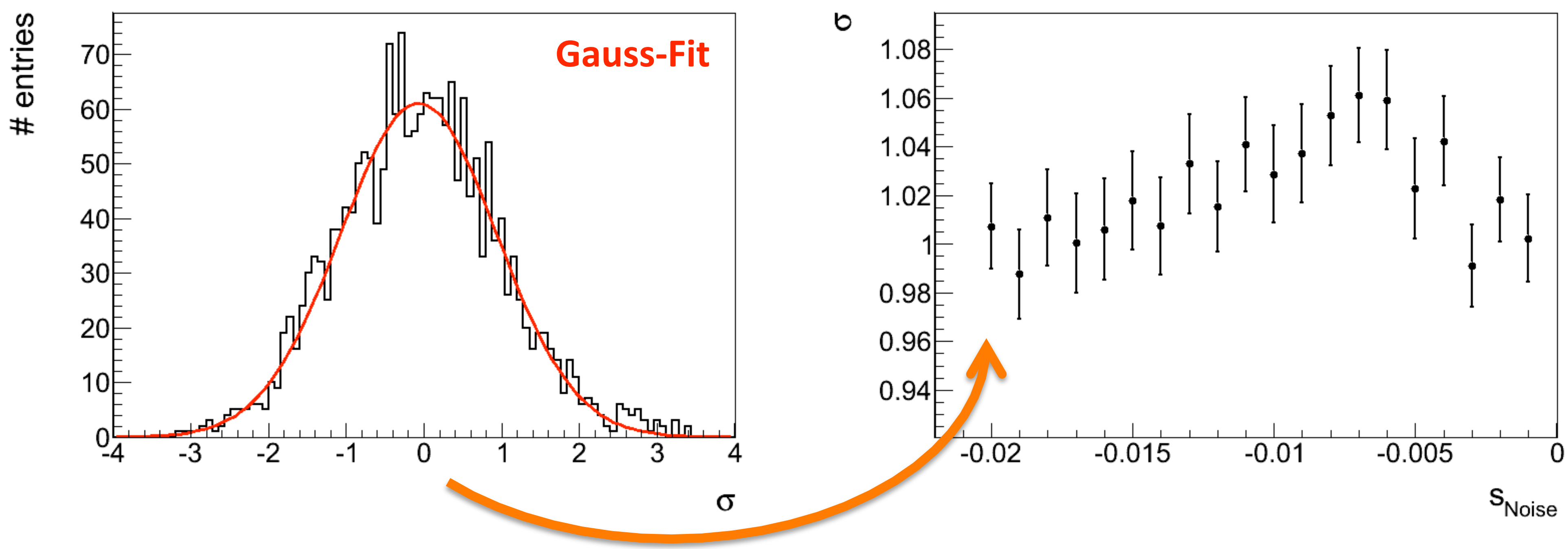
Validation of noise correction

- Use frequency spectra of MGMR simulations
- Add simulated noise spectra with different spectral indices and random phases (here: S/N = 2)
- Determine spectral index s



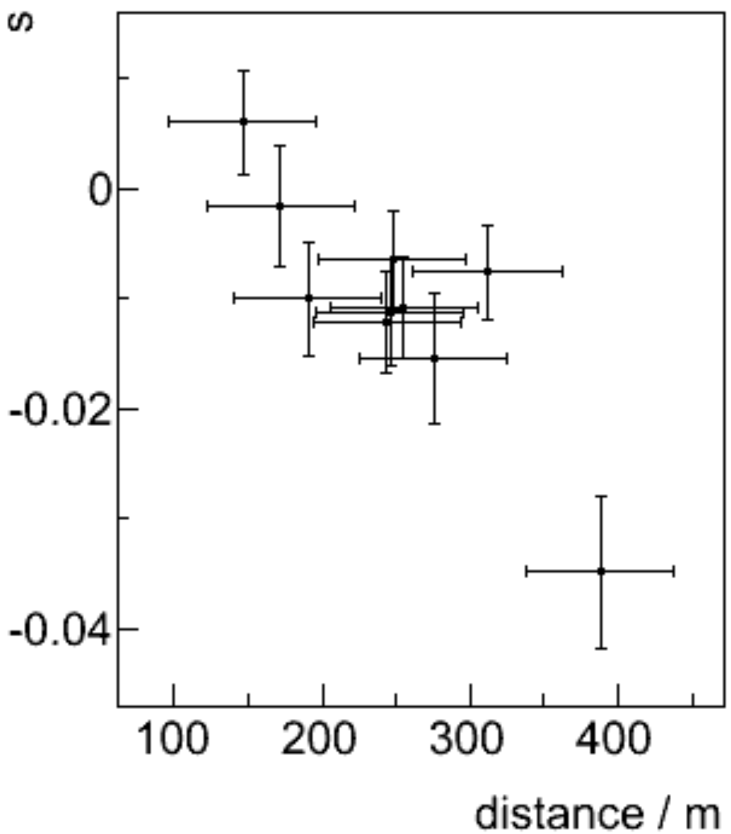
Validation of uncertainties

- Determine for each corrected spectral index how many σ it is away from the true slope
- Uncertainty correct on percent level

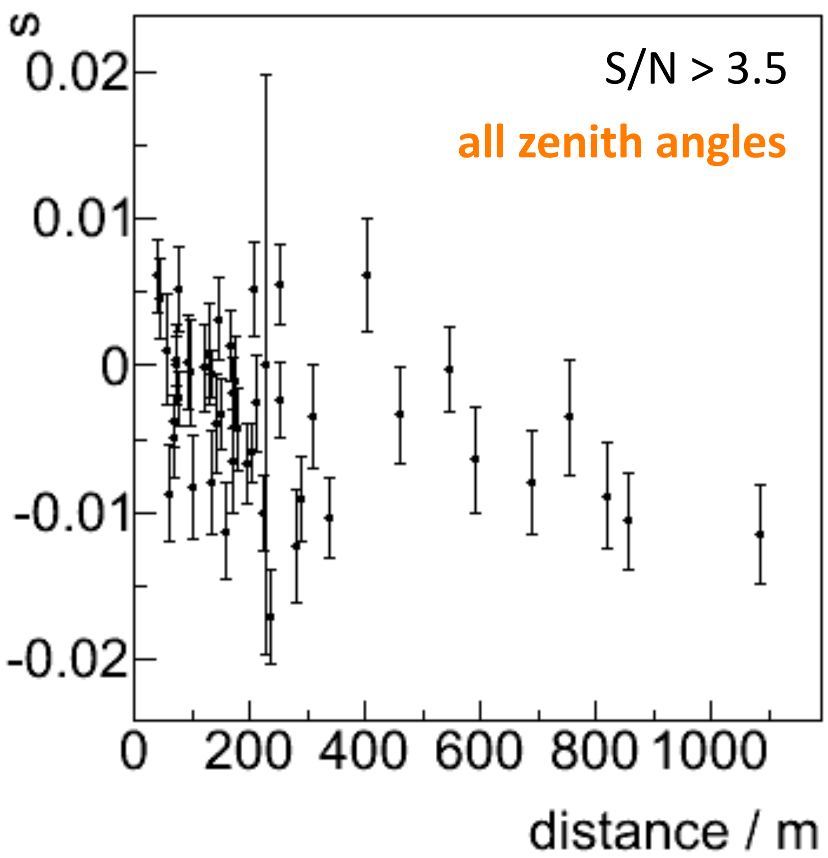


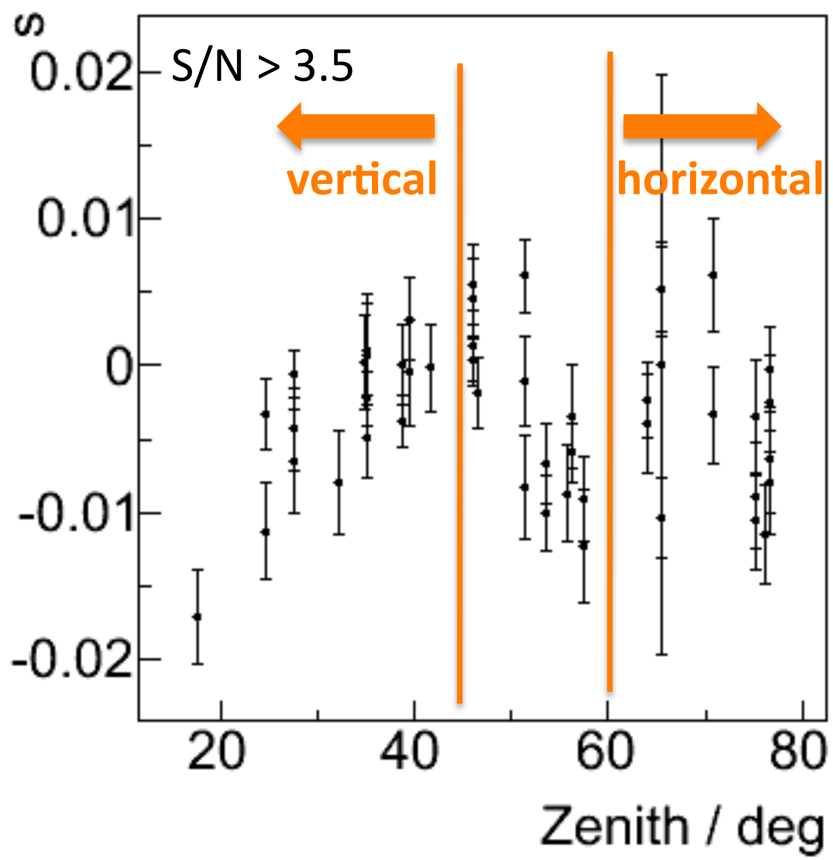
Single AERA event

10 AERA stations
Zenith = 61.7˚
Energy = 1.56 EeV

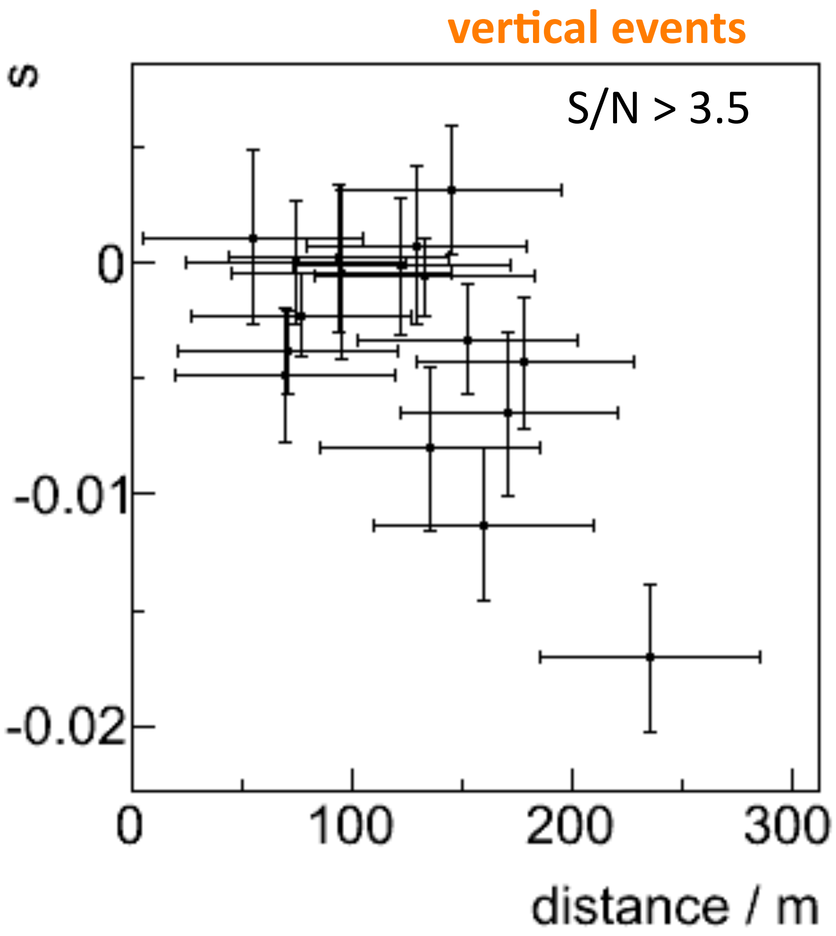


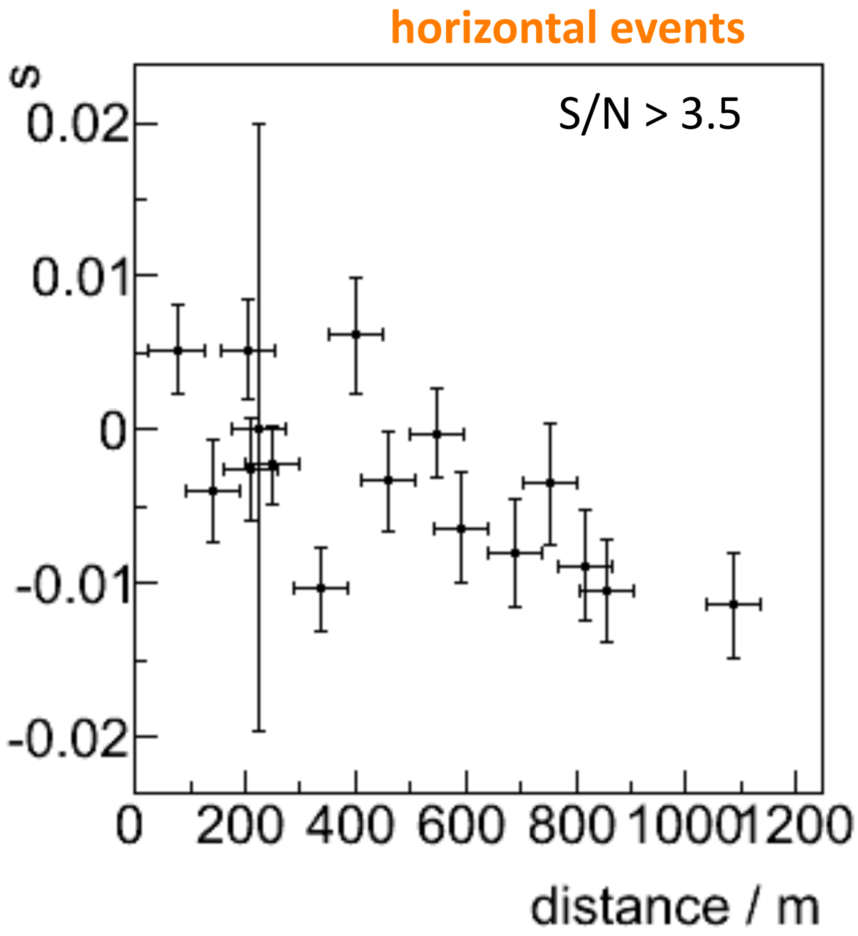
Distance and zenith dependence of measured spectral index





Distance dependence

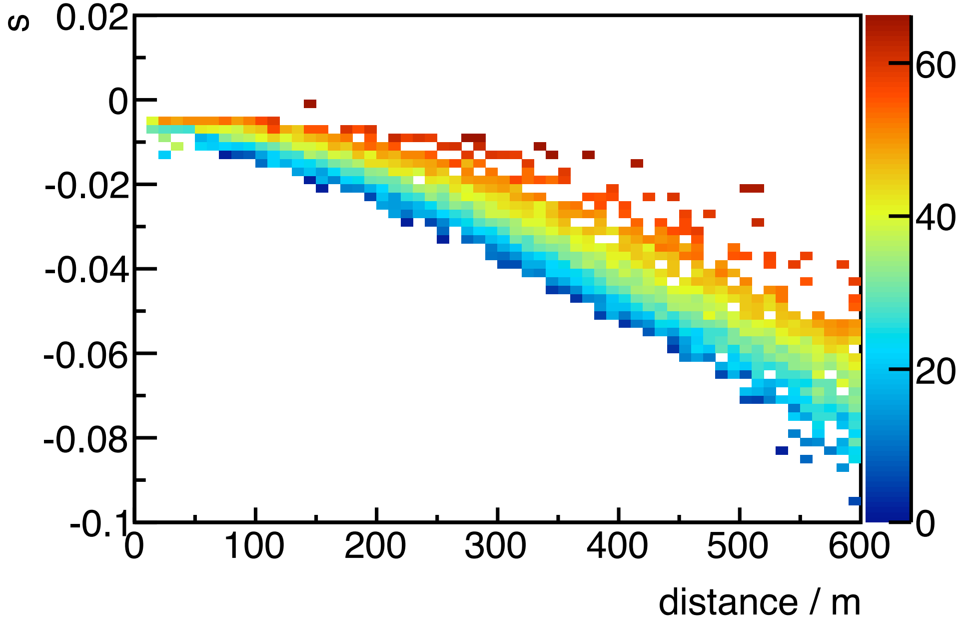




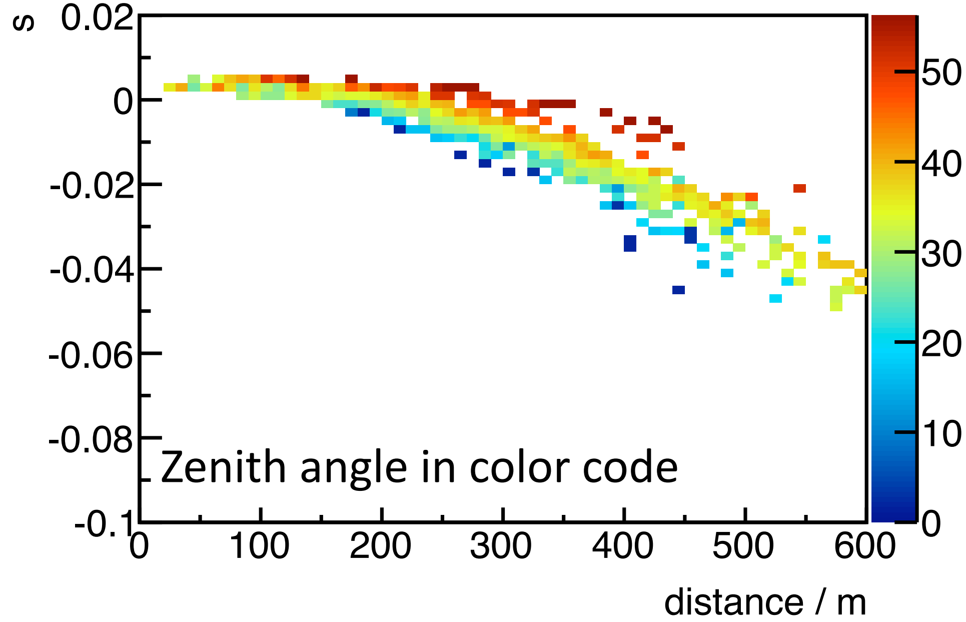
Fall-off at larger distances, at small distances not obvious

Comparison to MGMR simulations

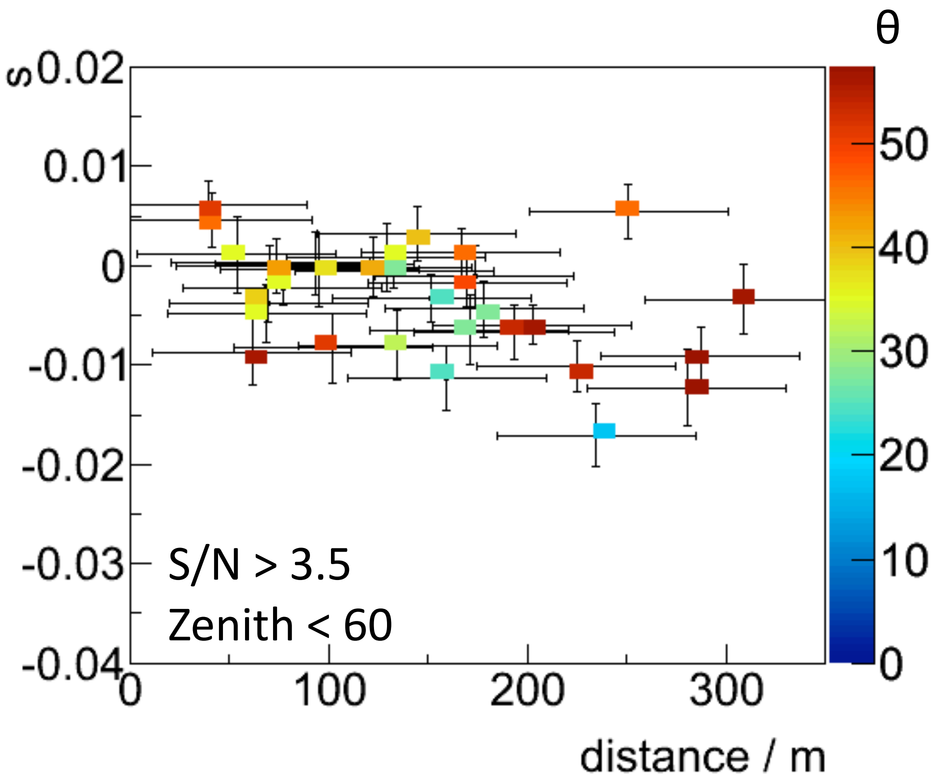
Refractive index n =1

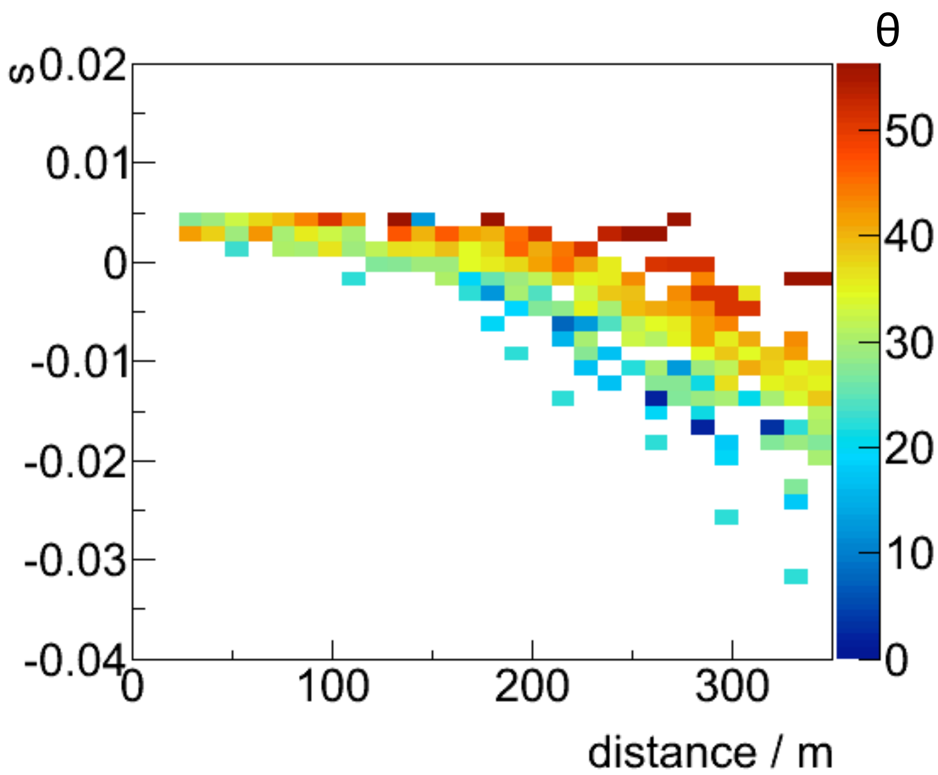


Realistic refractive index



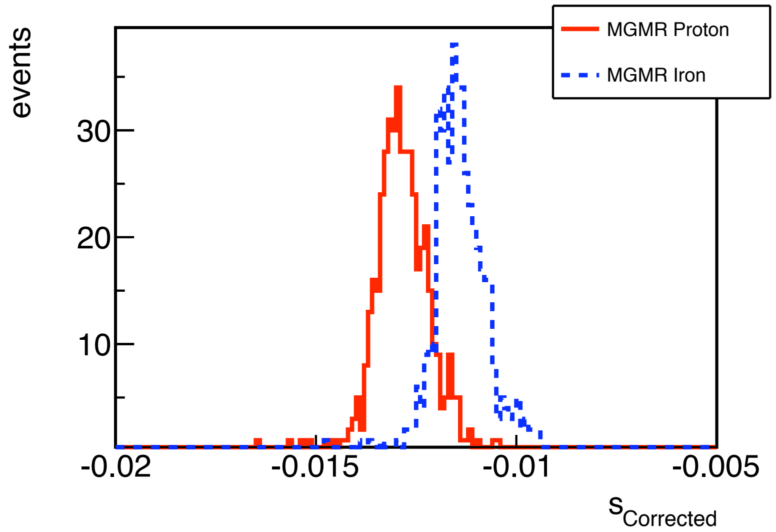
AERA data and MGMR

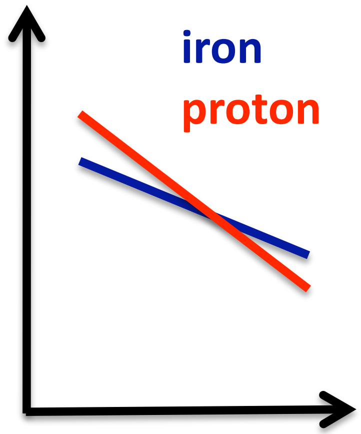




Outlook: Composition

- MGMR simulations (no shower-to-shower fluctuations)
- Correct spectral index for distance, zenith and energy dependence

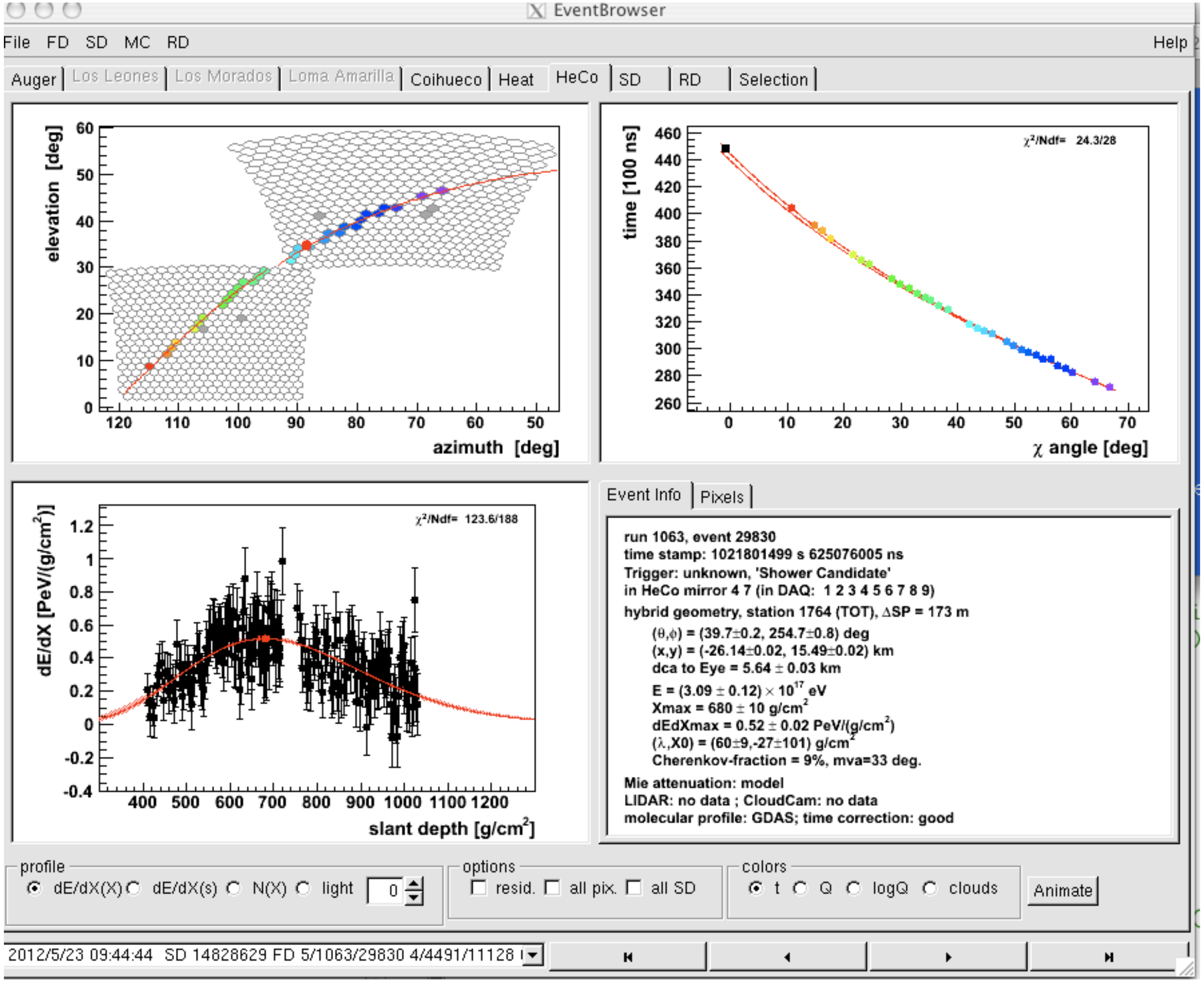




MGMR: Proton spectra are steeper than iron spectra

Need more statistics to study effect in data!

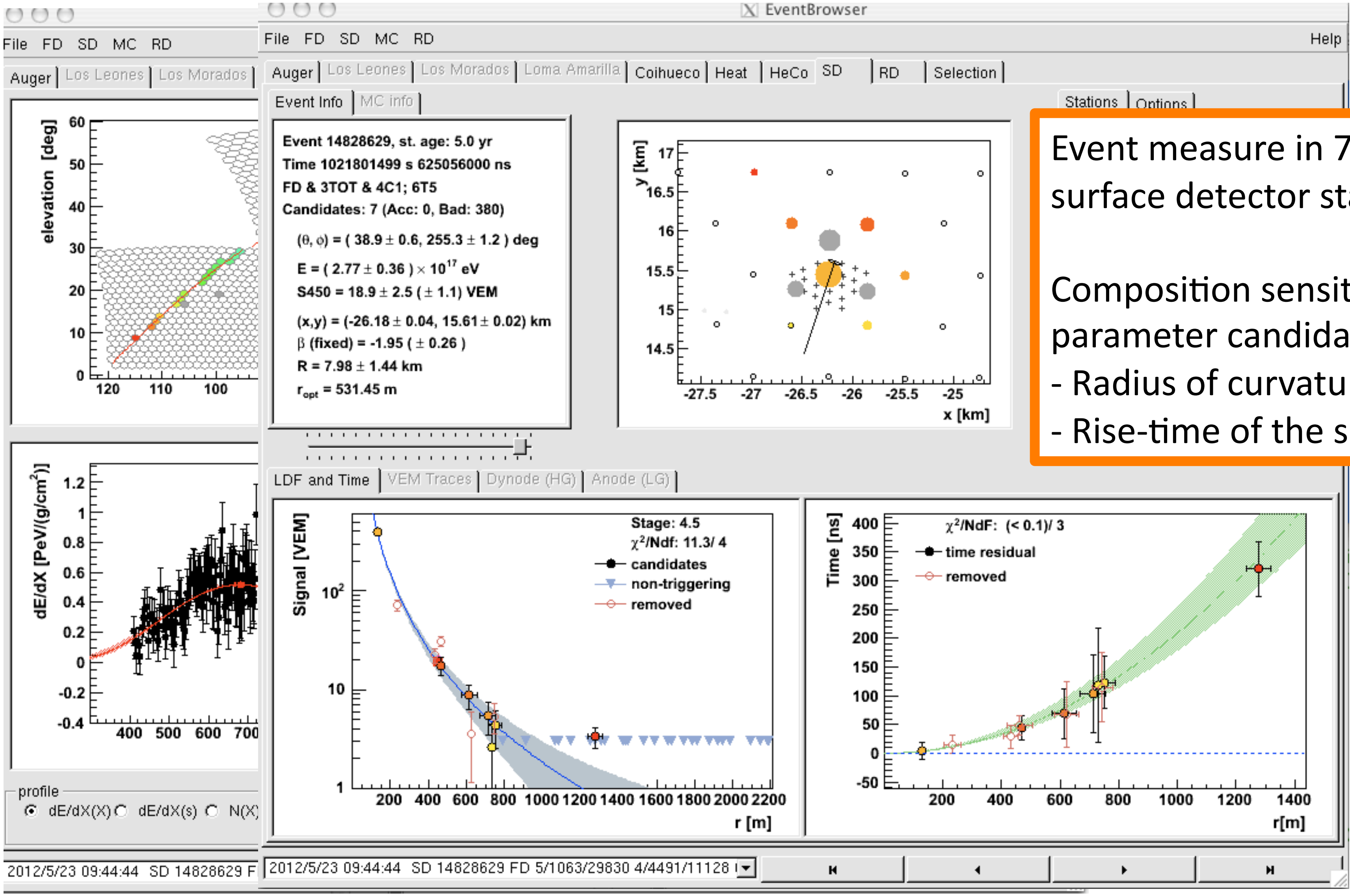
Example **FD**, SD, AERA coincidence



Event measured in two telescopes

Composition sensitive parameter: Xmax (shower maximum)

Example FD, **SD**, AERA coincidence



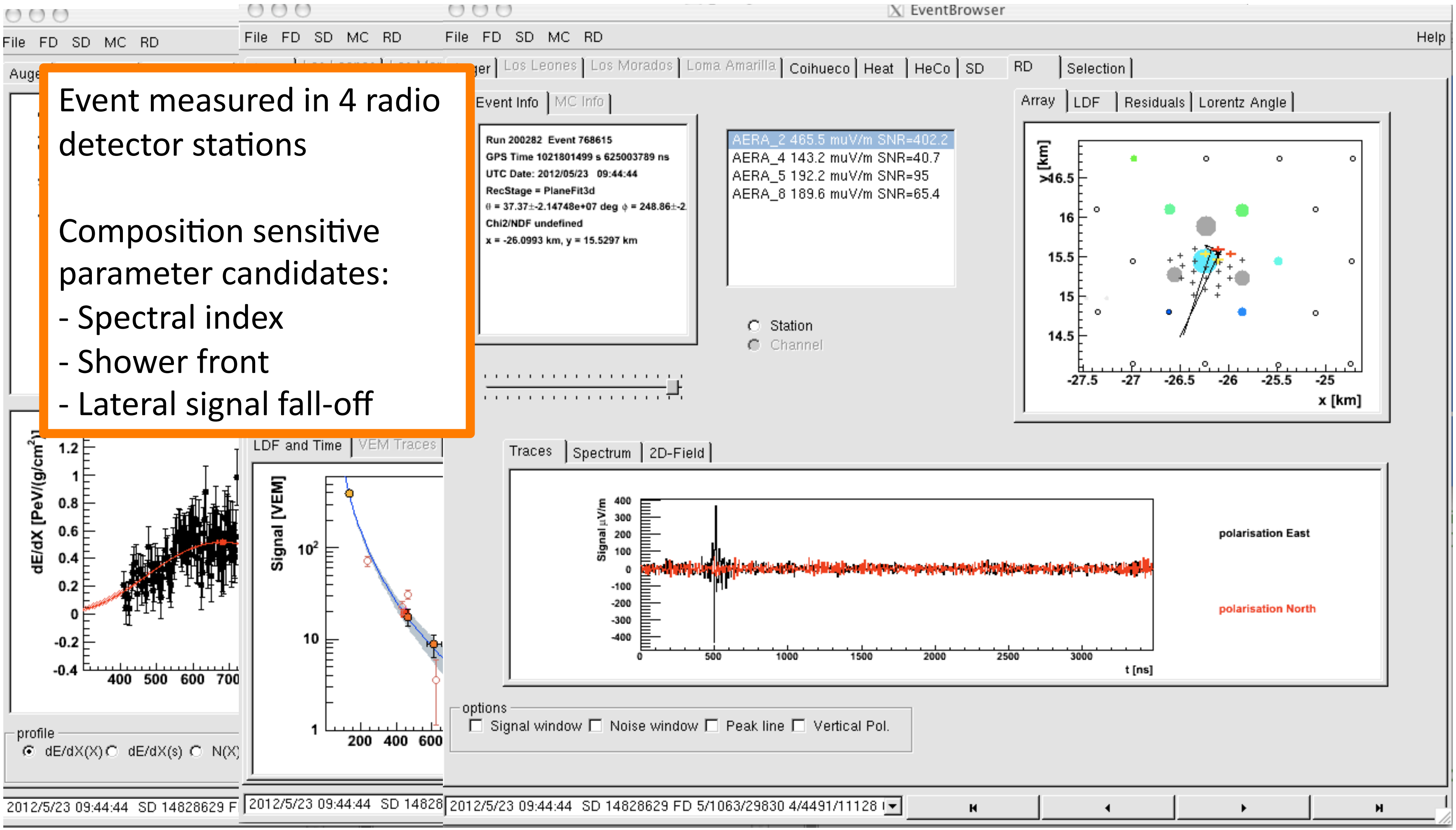
Event measure in 7 surface detector stations

Composition sensitive parameter candidates:
- Radius of curvature
- Rise-time of the signal

Example FD, SD, **AERA** coincidence

Event measured in 4 radio detector stations

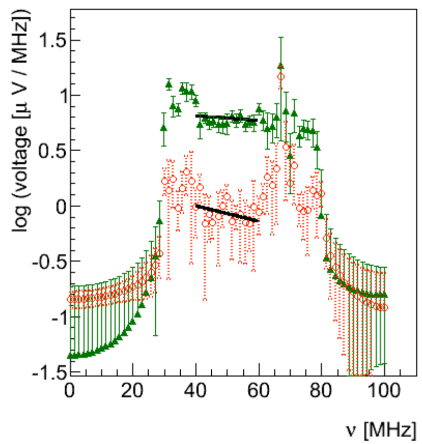
Composition sensitive parameter candidates:
- Spectral index
- Shower front
- Lateral signal fall-off

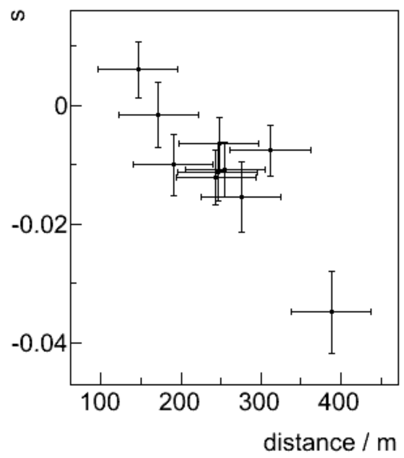


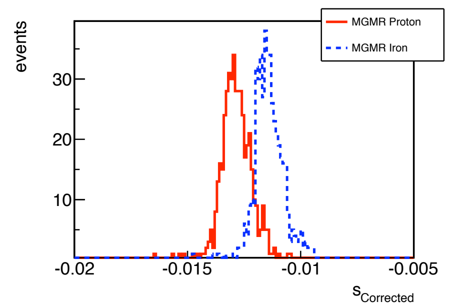
Conclusion

- Determine spectral index of cosmic ray induced signals between 40 and 60 MHz
- Spectral index shows geometrical dependencies

- Composition sensitivity obtained in simulations
- Comparison of AERA and other Auger data ongoing



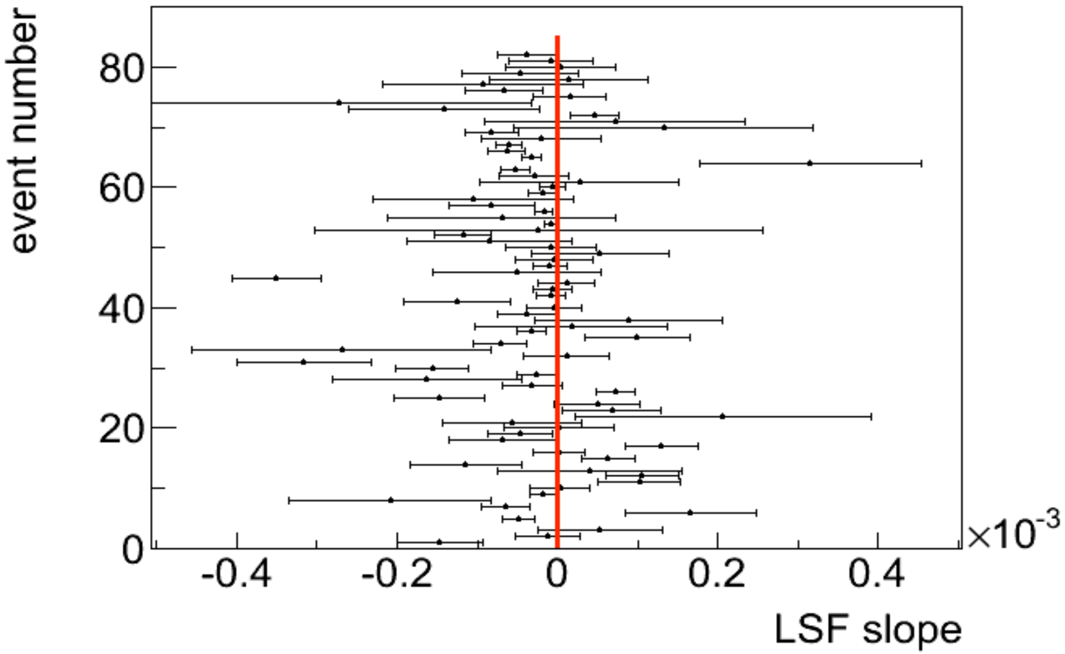




Backup slides

Slope of lateral spectral index distribution

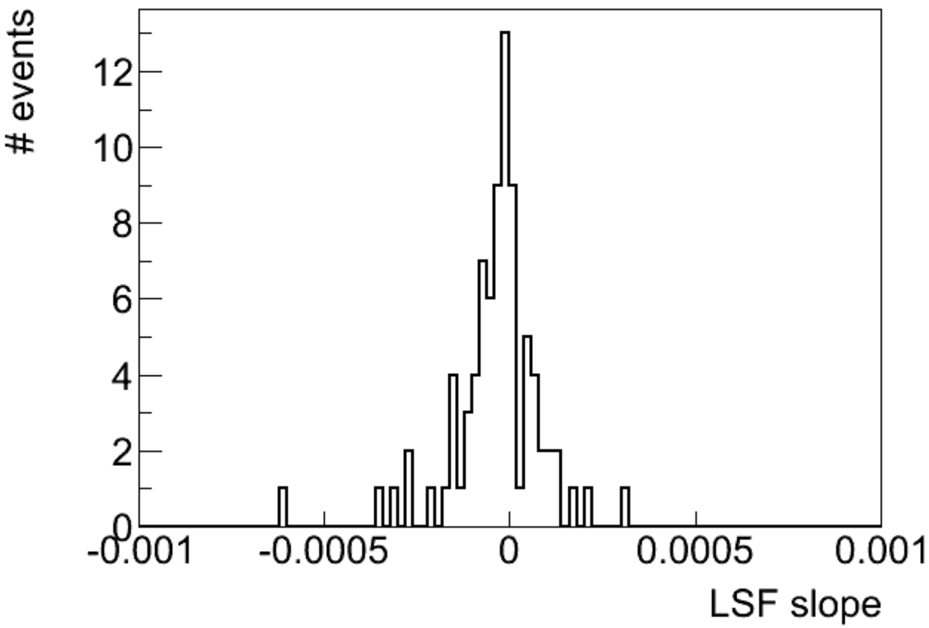
- All events with more than 3 stations
- No signal-to-noise cut
- Linear fit function
- Most events have a negative slope

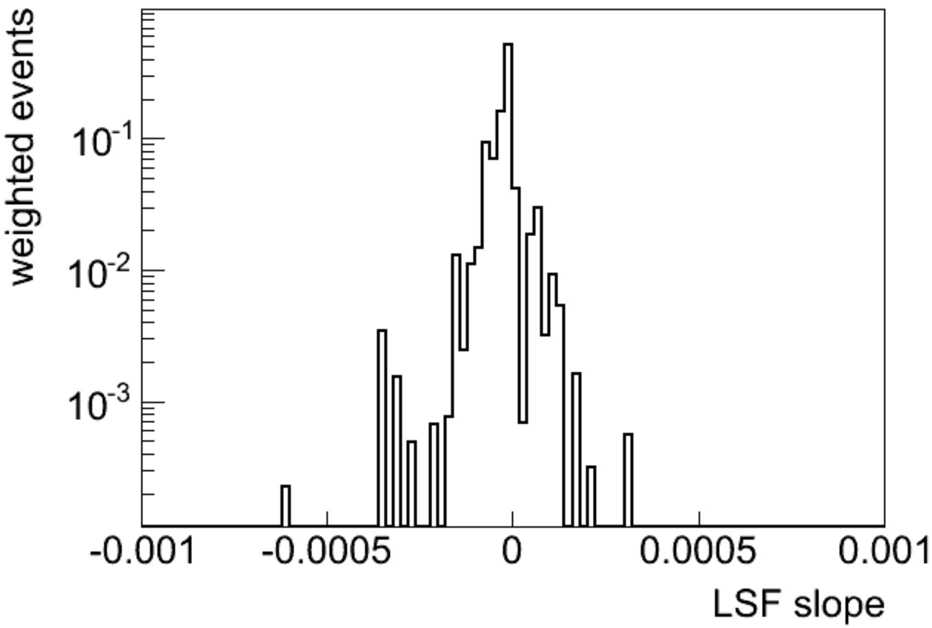


Average slope of LSF

Events weighted with uncertainty of spectral index

$$w_i = \frac{1}{\sigma_i^2}$$





Noise correction for different S/N