Measurements of Inclined Air Showers with the Auger Engineering Radio Array at the Pierre Auger Observatory

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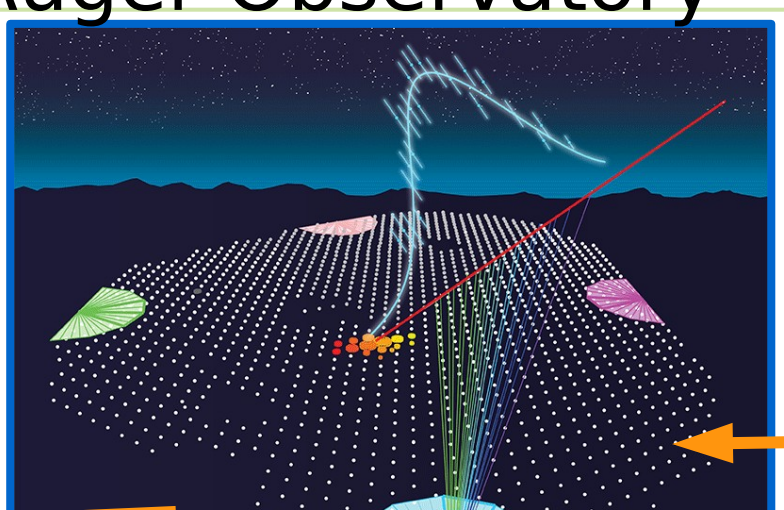
und Forschung

PIERRE AUGER OBSERVATORY

AERA
Auger Engineering Radio Array

The Pierre Auger Observatory

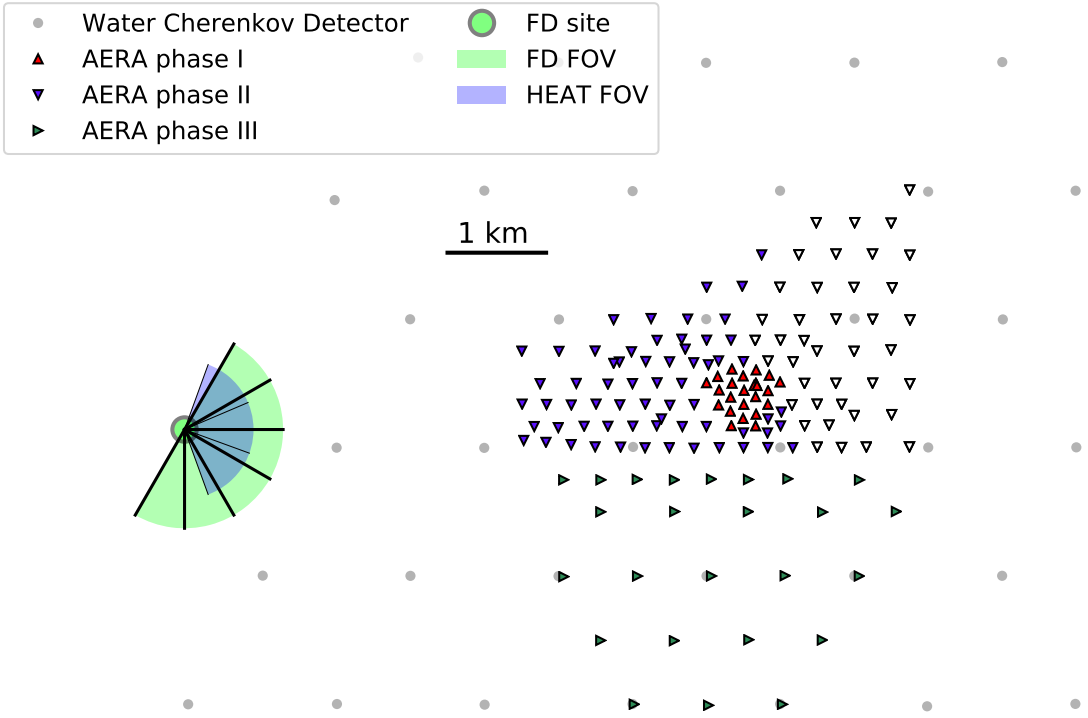


Fluorescence Detector (FD)
27 telescopes at
4 sites with 180° view

Surface Detector (SD)
1660 water-Cherenkov stations
1.5 km spacing
3000 km^2 covered area

Radio Detector (RD)
153 antennas
17 km^2 covered area
→ **AERA**

Auger Engineering Radio Array (AERA)

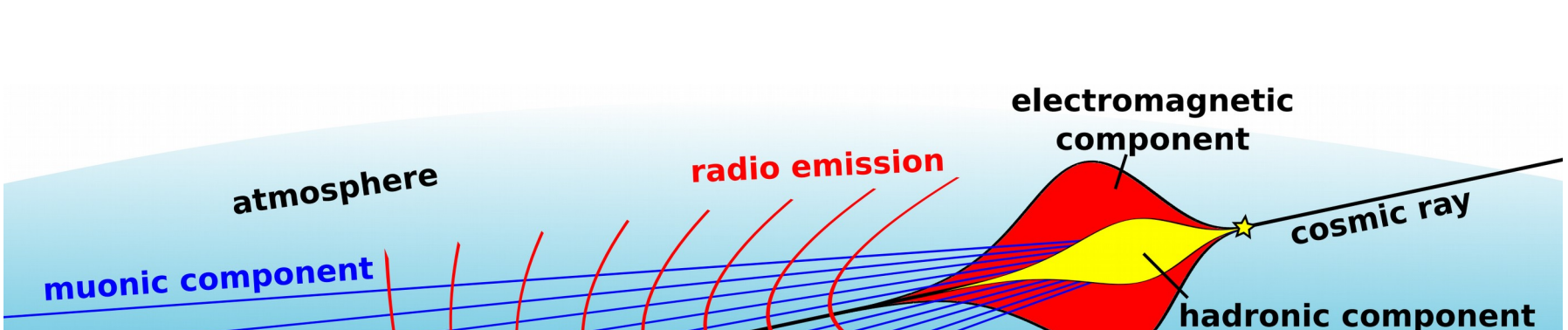


- Largest radio detector for cosmic rays
- Energy range: 10^{17} – 10^{19} eV
- Different antenna types, electronics and spacings (144 m to 750 m)

- 2 polarizations (NS, EW)
- Bandwidth 30 – 80 MHz

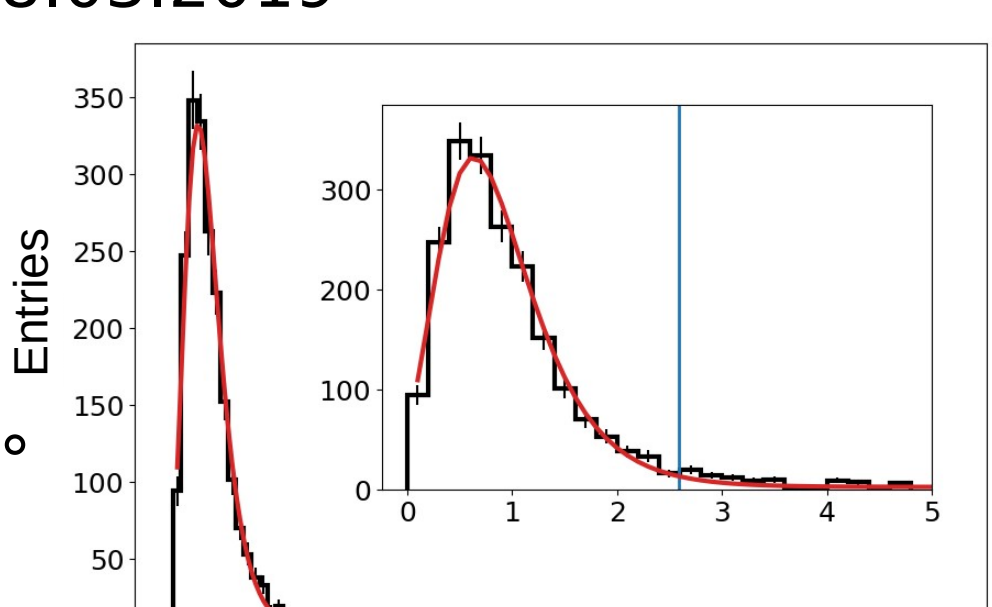
Horizontal Air Showers (HAS)

- Increase available phase space for detection of EAS
- Direct access to EM energy with radio
- Physics potential: Muon content, independent energy scale, SD-RD mass composition



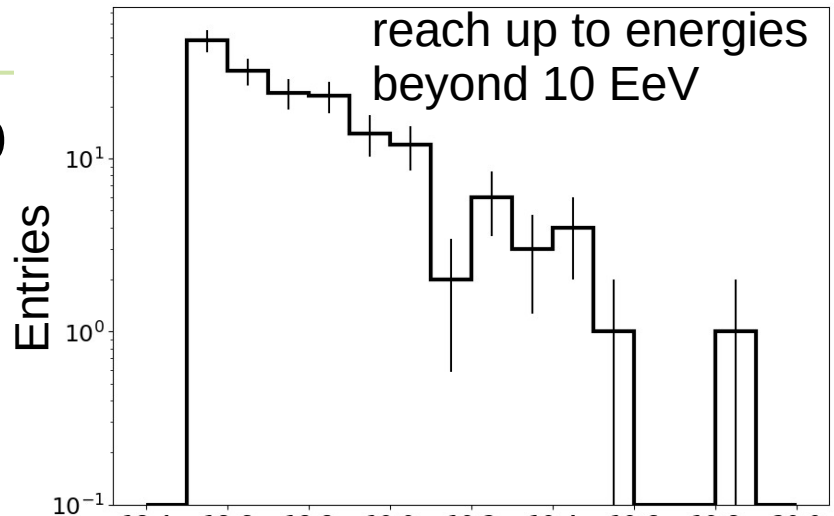
Data selection

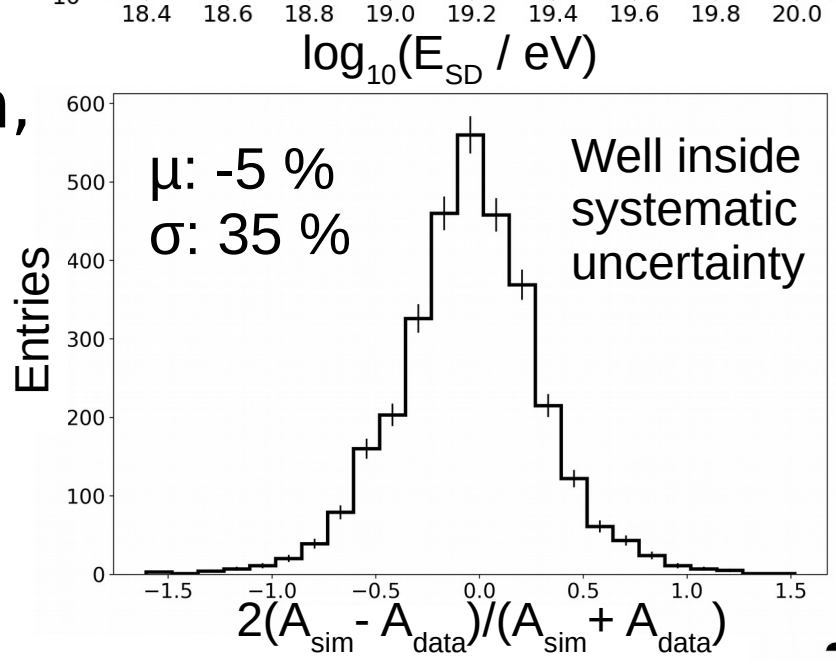
- Data period 26.06.2013 – 08.03.2019
  - 26.06.2013 start of AERA II
  - 08.03.2019 most recent data
- Zenith angles in (60 – 84)°
  - 84° motivated by SD
- SD RD opening angle < 2.6°
  - 3σ of Gumbel fit
- 1972 events in total
  - ~ 1 event / day



MC comparison

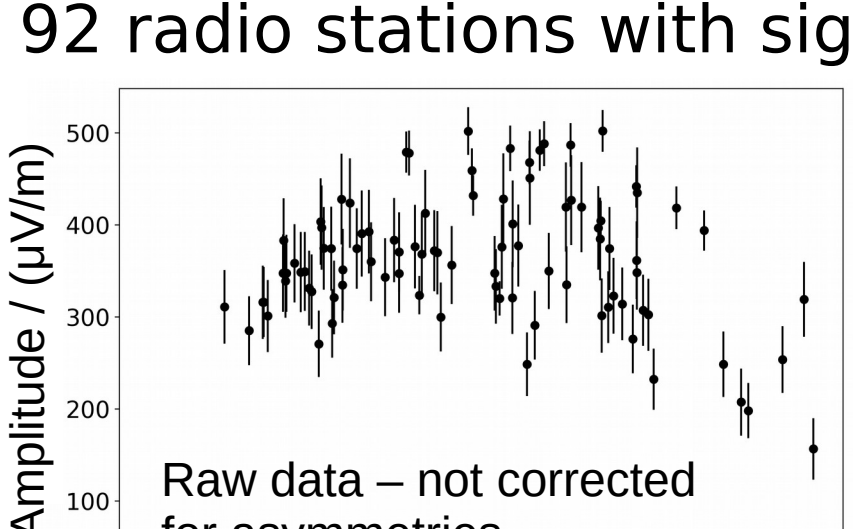
- 170 events with reconstructed SD energy
  - Adapt standard selection, esp. $60° < \theta < 84°$ and $E > 10^{18.5}$ eV: bias-free, resolution better than 25%
- CoREAS proton simulation, detailed radio-detector simulation, adding measured noise
- Clear correlation for measured and simulated amplitudes
  - Amplitudes underpredicted, spread related to energy and core uncertainty

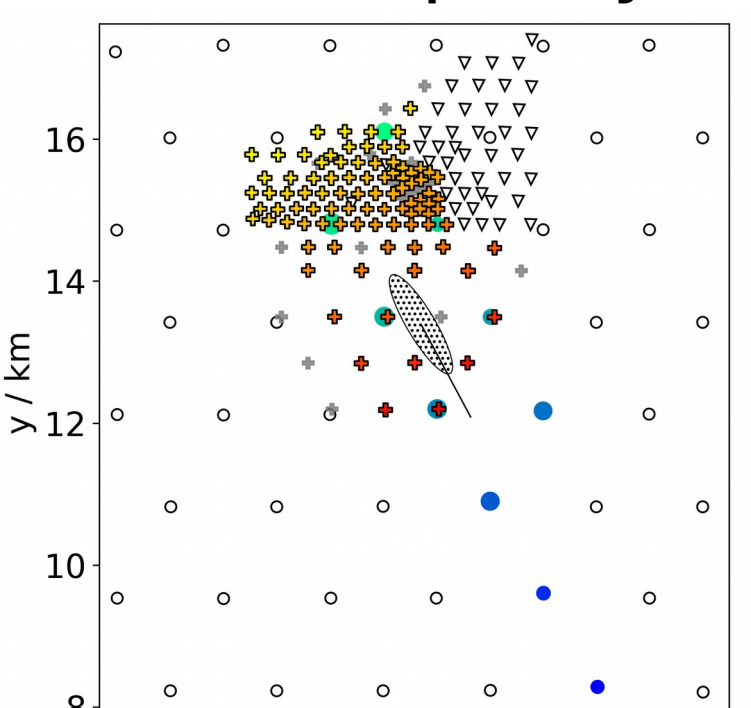




Example event – highest station multiplicity

- SD reconstruction
  - Energy ~2 EeV
  - Zenith 81°, Azimuth 298°
- 92 radio stations with signal





- AERA too small to measure full footprint

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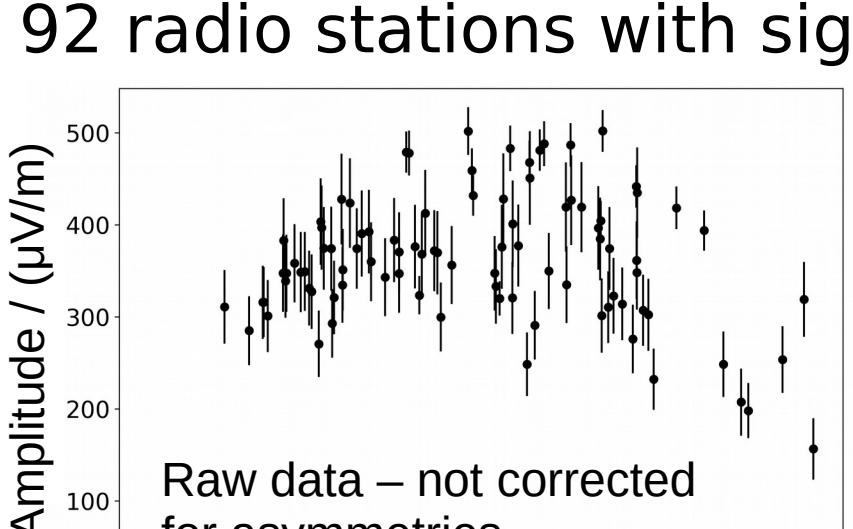
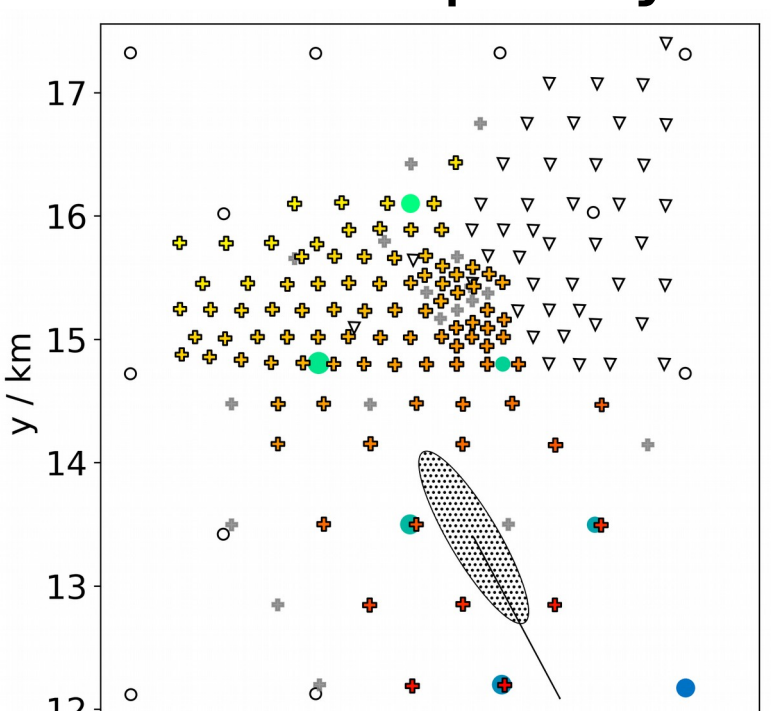
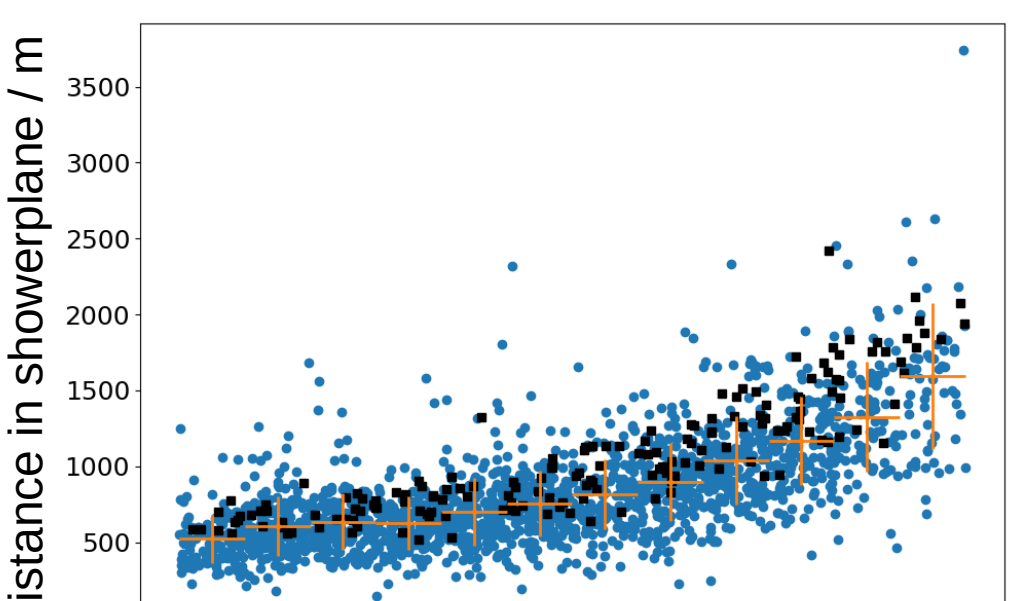
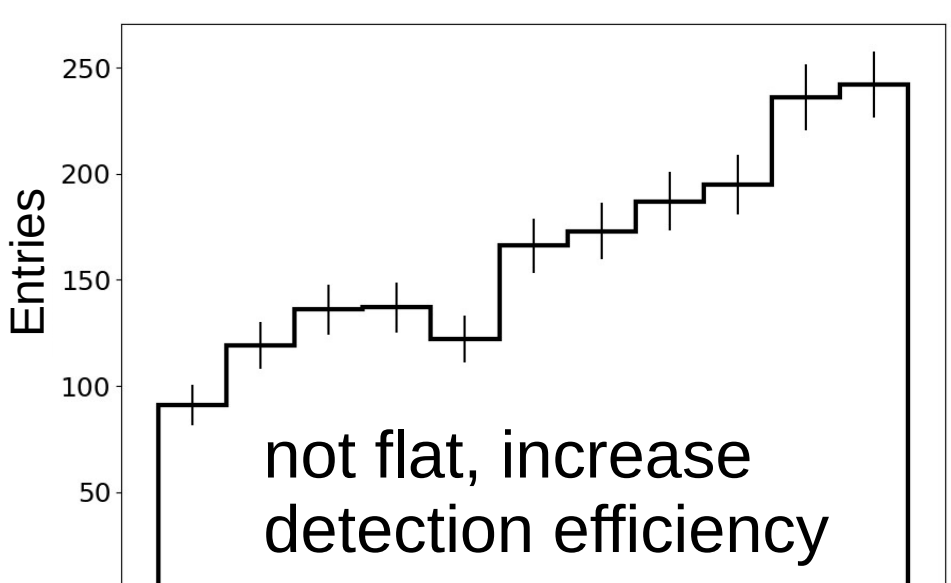




- AERA too small to measure full footprint

Increasing footprint size



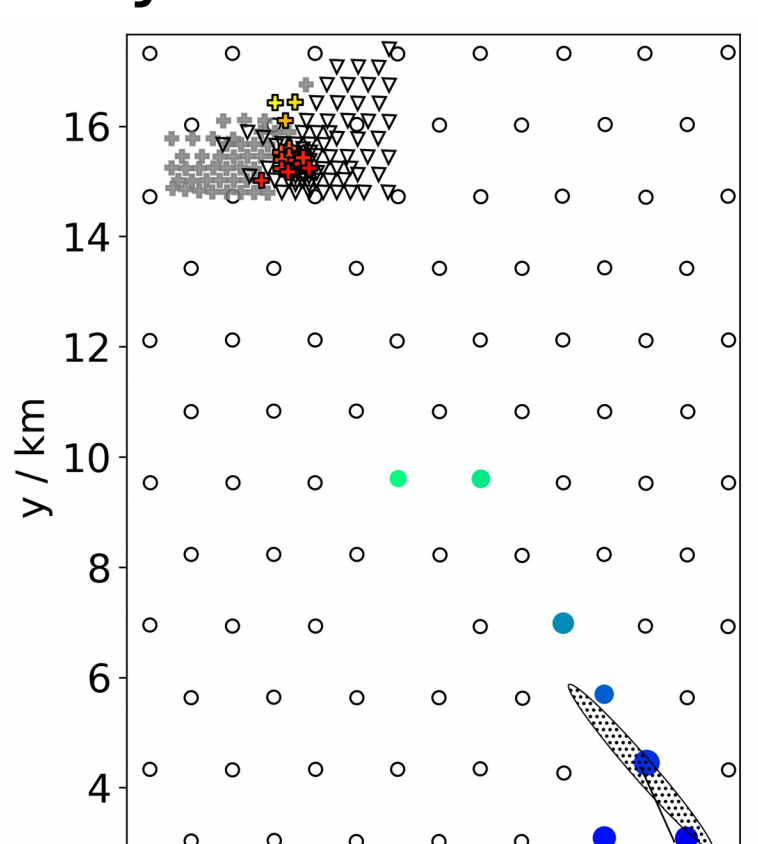


- Footprint size **in shower plane** increases with θ, longer distance to source (X_{max})

Blue dots: events not passing SD selection

Black squares: events passing SD selection

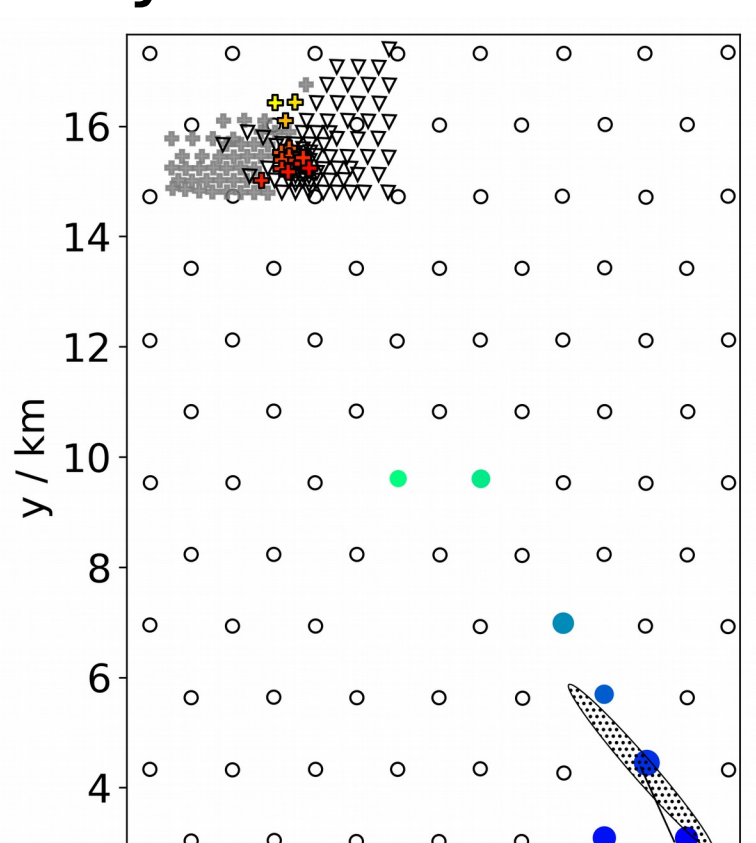
Very inclined event

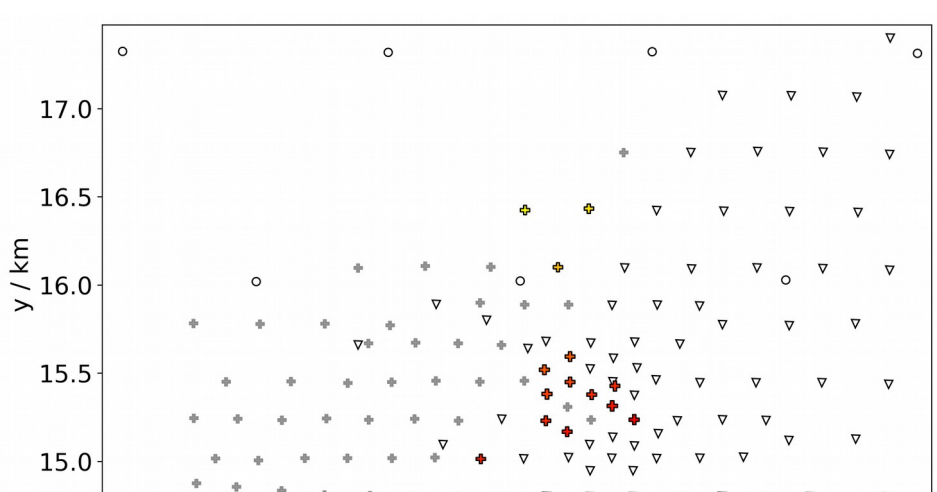


- **Example event for:**

  “radio footprint > particle footprint”
- SD core ~12 km from AERA
- 14 RD stations with signal
- Opening angle 1.2°
- E_{SD} : 1.2 EeV
- $(\theta,\phi)_{SD}$:(82.2±0.3, 294.2±0.3)°
- $(\theta,\phi)_{RD}$:(83.2, 294.6)°

Very inclined event

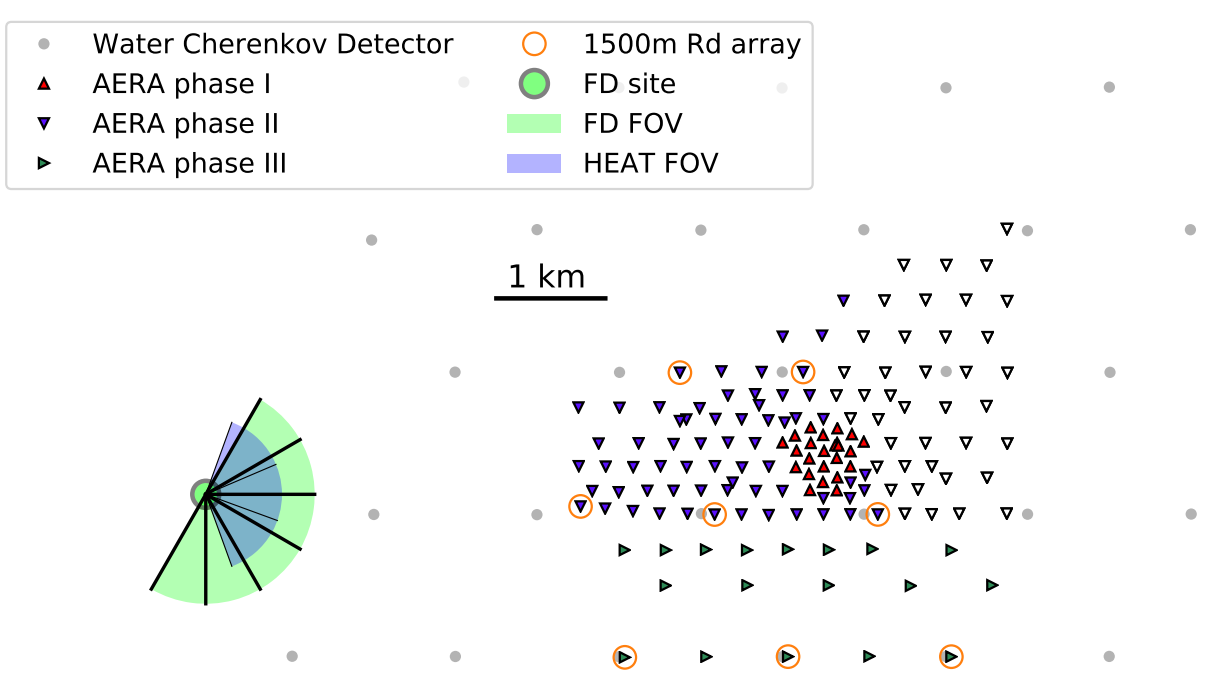




- Several stations offline
- Average $X_{max}(E)$ (730 g/cm²) off-axis angle: 1.1° – 1.4° plausible

1500 m radio array

- Thin out AERA to a 1500 m grid
- 189 events found with similar setup as before
- Minor loss in direction accuracy for same events:
  ∠(SD, RD):
  0.6° → 0.7°



Radio upgrade @ Auger
Poster: PoS(ICRC2019)395

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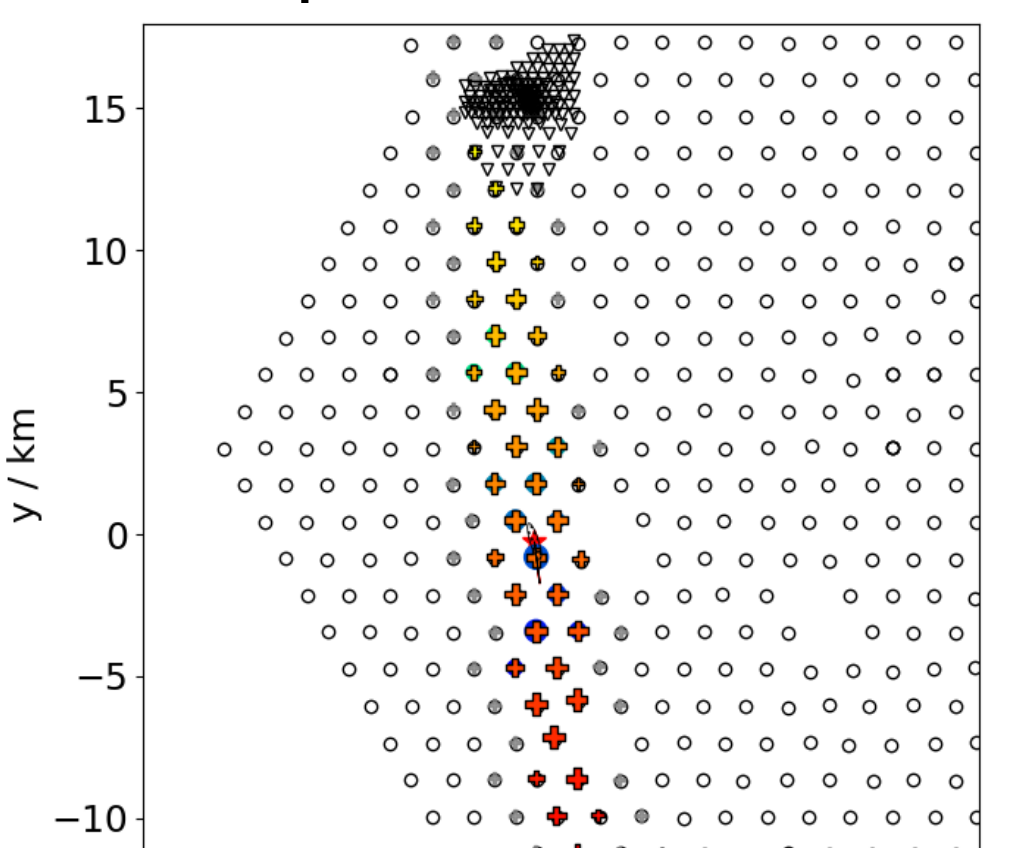
Prototype station in the field
Poster: PoS(ICRC2019)395

Example event with radio upgrade

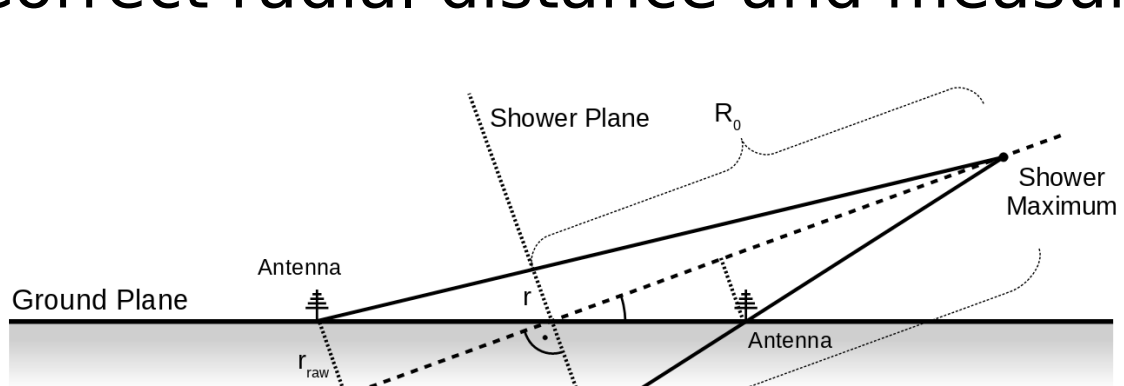


- Based on measured event as MC input
  - E_{SD} : 2.9 EeV
  - $(\theta,\phi)_{SD}$: (82.6°, 277.4°)
- 40 radio stations with signal
- CoREAS simulation, reconstructed without noise

Inclined radio reconstruction: new asymmetries

1. Early-Late effect (geometry) [arXiv:1808.00729, ARENA18]

- Project radio antenna into shower plane along line of sight of antenna and shower maximum
- Correct radial distance and measured fluence



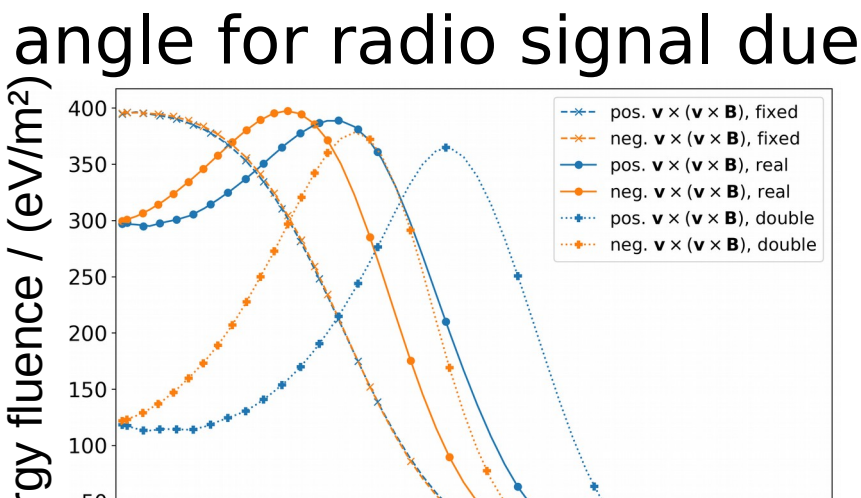
$$f = f_{\mathrm{raw}} \cdot \left(\frac{R}{R_0}\right)^2$$

$$r = r_{\mathrm{raw}} \cdot \frac{R_0}{R}$$

Inclined radio reconstruction: new asymmetries

1. Early-Late effect (geometry) [arXiv:1808.00729, ARENA18]
2. Refractive index

- Different effective refractive index → different off-axis angle for radio signal due to Cherenkov compression



- Disturbs radial symmetry for LDF fit
- Vanishes for constant refractive index (fixed) and increases for higher indexes

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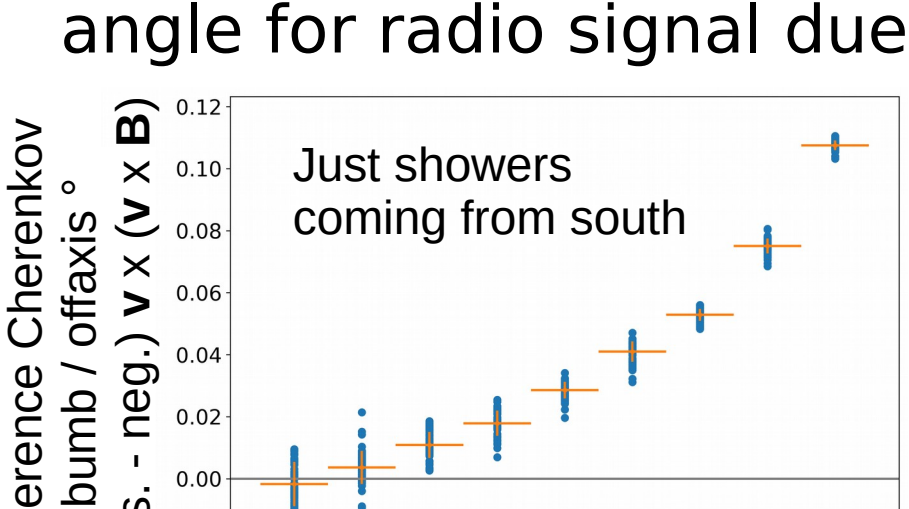


- Estimate peak position from interpolated fluence
- Difference increases with zenith angle
- Correction under investigation

Summary

- 1972 HAS observed in total
- Simulated amplitudes agree well with data
- Large radio footprints for HAS measured
  - Signal up to 2 km from shower axis
  - Even „radio footprint > particle footprint“
- 189 events observed with 1500 m grid

  → Radio Upgrade @ Auger
- Inclined radio reconstruction under investigation
  - New asymmetries in radio footprint
  - See PoS(ICRC2019)294 (T. Huege et al., CRI8d)

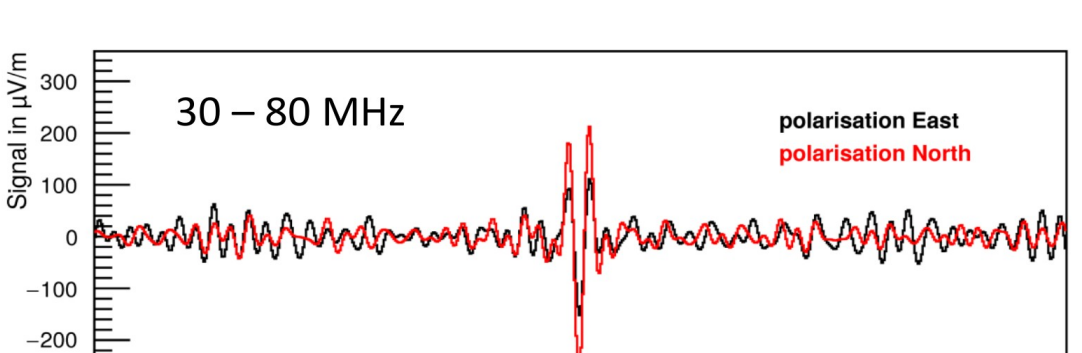
Auger Publication JCAP 1810 (2018) 026

Outlook: radio upgrade

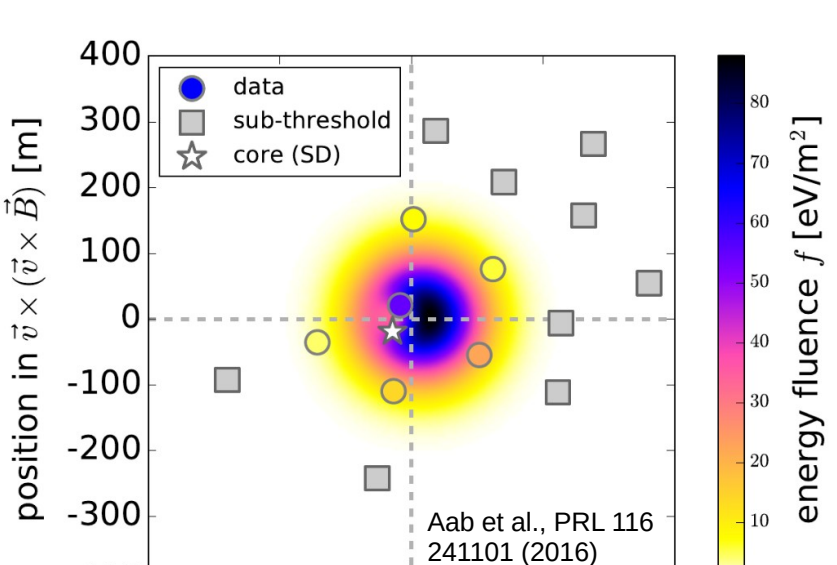
- Radio antenna for each SD station
- 3000 km² area with 1.5 km spacing
- Prototype station with scintillator and radio antenna installed in the field
- Taking promissing data
- Poster for further Details: PoS(ICRC2019)395

RD energy estimator

Measure time trace in each antenna
➔ energy fluence

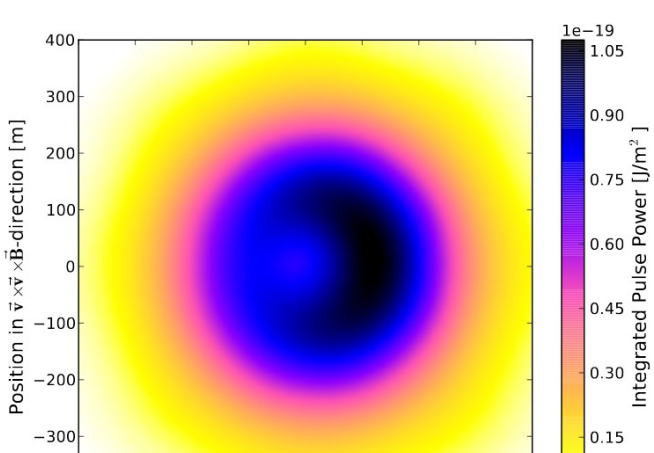


Fit 2-dimensional lateral distribution

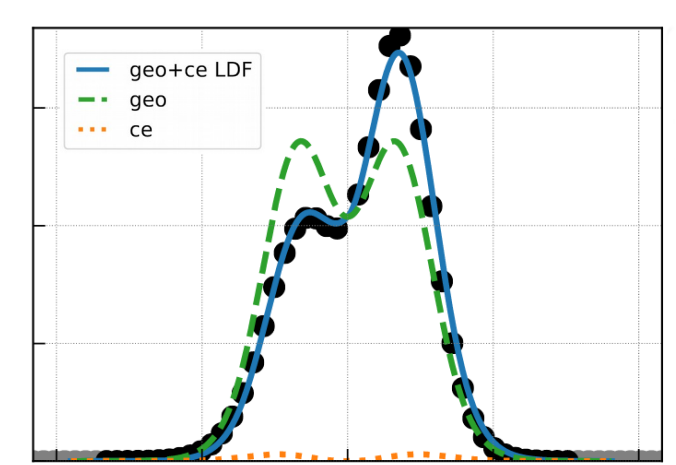


- Energy estimator
  - Integral over lateral distribution
    → energy contained in radio emission: E_{rad}
  - Apply geometry corrections of E_{rad} ➔ S_{rad}

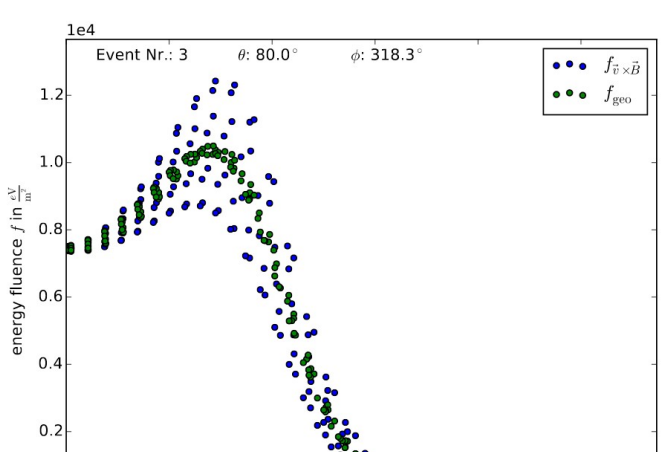
Radio LDFs



- „Double Gaussian“ (arXiv:1402.2872)
- Up to 60° zenith angle so far
- Excluded for HAS



- „GeoCE LDF“ (arXiv:1806.03620)
- Up to 60° zenith angle so far
- Under investigation for HAS



- „Symmetrized LDF“ (arXiv:1806.00729)
- Specifically developed for HAS, performce under investigation