Detection of Radio Emission from Air Showers in the MHz Range at the Pierre Auger Observatory

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for the Pierre Auger Collaboration

BERGISCHE UNIVERSITÄT WUPPERTAL

PIERRE AUGER OBSERVATORY

AERA
Auger Engineering Radio Array

ARENA 2014, Annapolis, 10.06.2014

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

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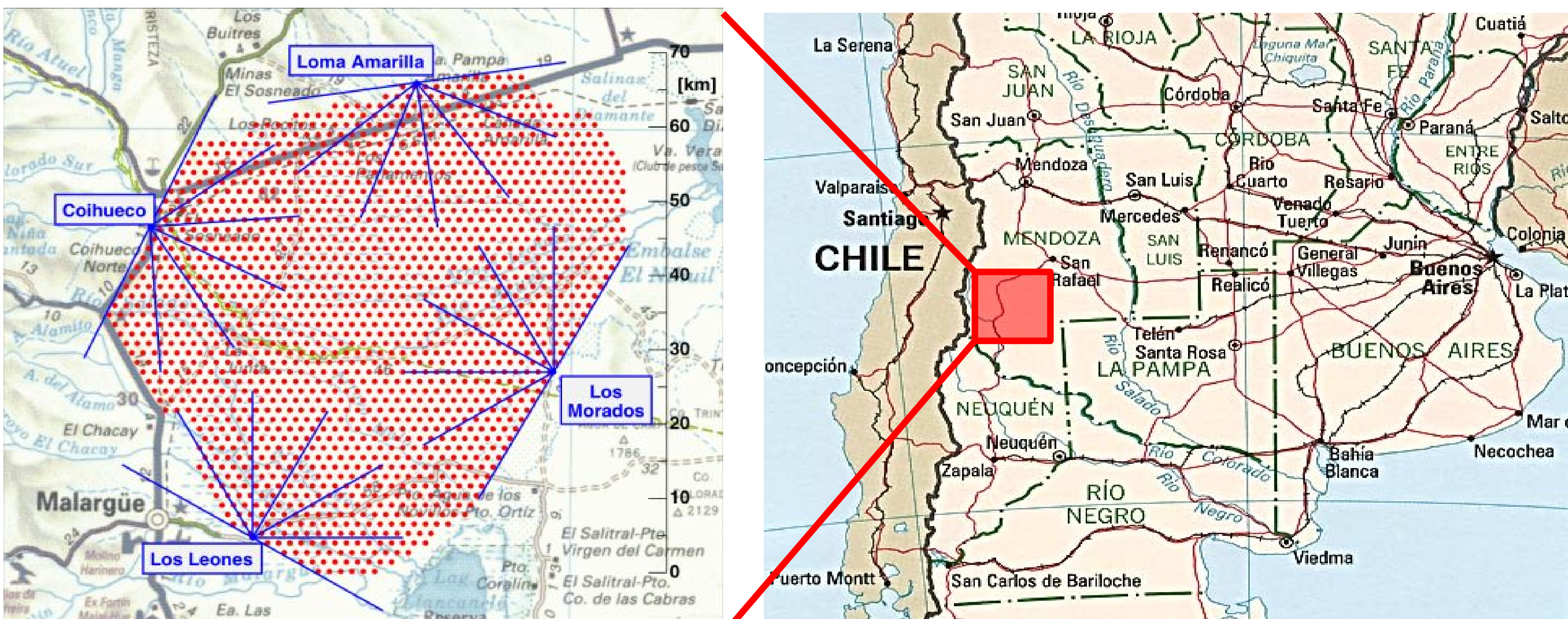
Pierre Auger Observatory

- Constructed in the rural environment of the Pampa Amarilla near Malargue, Mendoza in Argentina (~ 1.500 m a.s.l.)
- Hybrid detector spread over an area of ~ 3.000 km²
- 1660 autonomous water-cherenkov detectors (SD)
- 27 fluorescence telescopes with PMT-cameras (FD)
- Extensions: HEAT, AMIGA (Muon detector + Infill), AERA, ...



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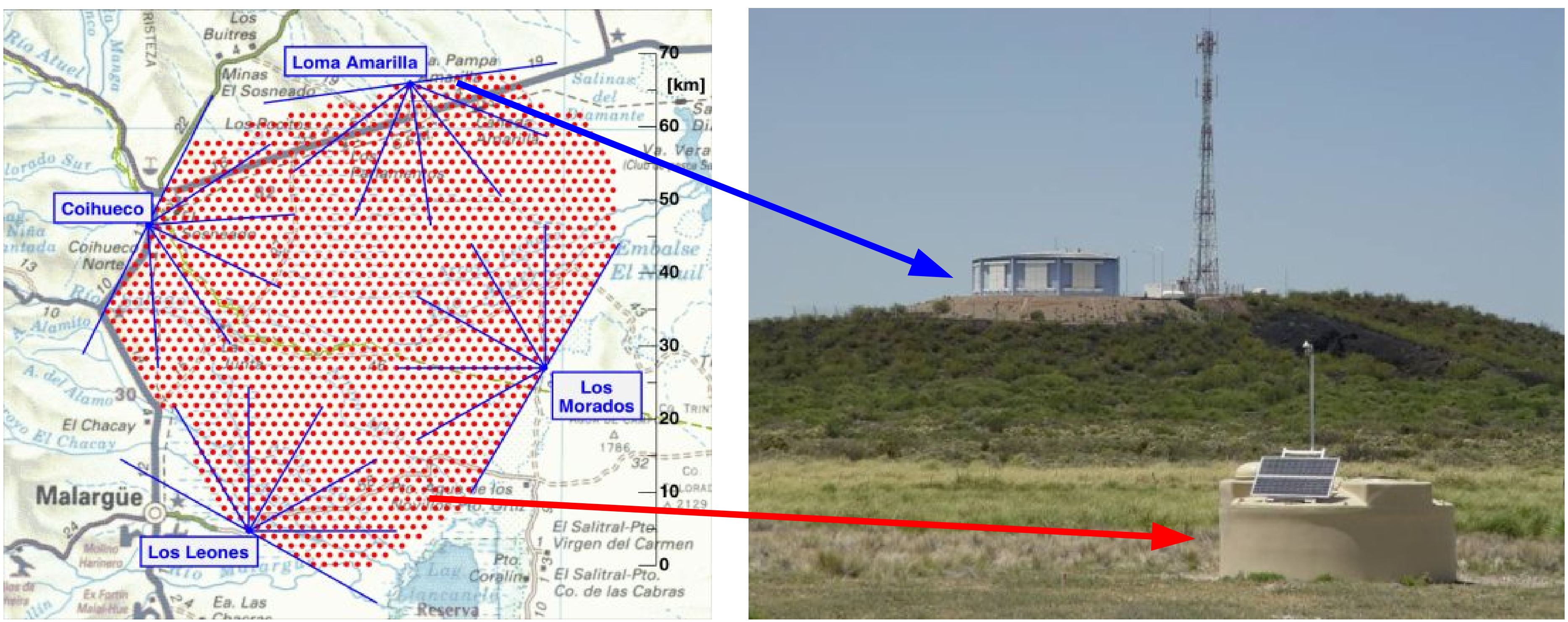
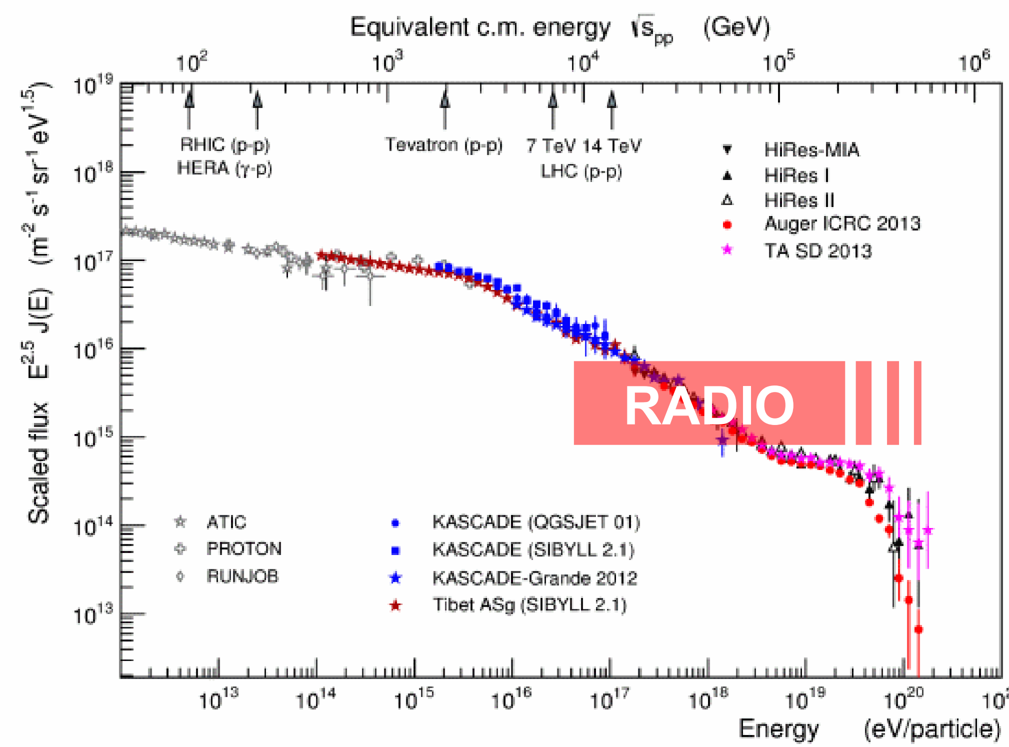


Auger Engineering Radio Array

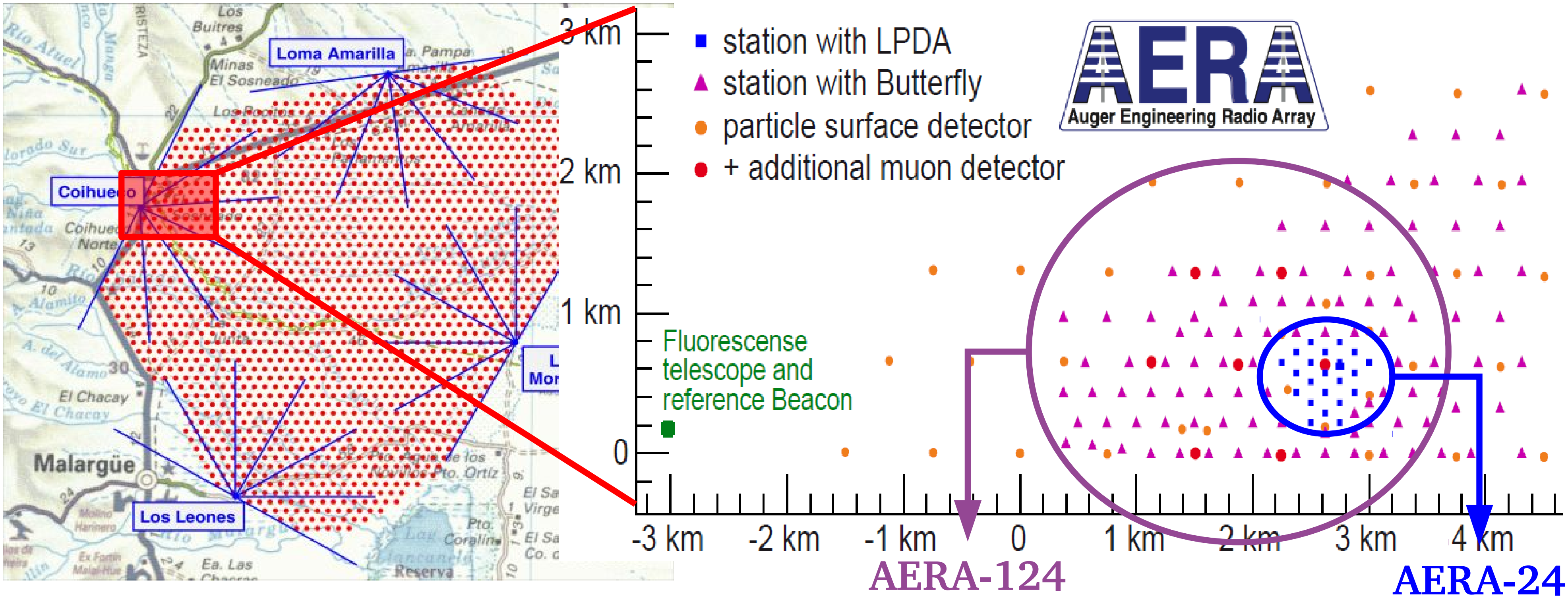
- Objectives:
  - Measure radio emission from air showers in frequency range 30 - 80 MHz
  - ~ 12 km^2 array with ~ 160 antennas
  - Operation together with HEAT/AMIGA
  - Three antenna spacings to cover efficiently 17.2 < lg E/eV < 19.0
  - Measure composition of cosmic rays in energy region of transition from galactic to extragalactic cosmic rays

- Advantages:
  - ~ 100% duty cycle (like SD)
    → large statistics
  - High angular resolution (like SD)
  - Measurement of shower development (like FD)
    → sensitive to composition
  - Low Costs per station

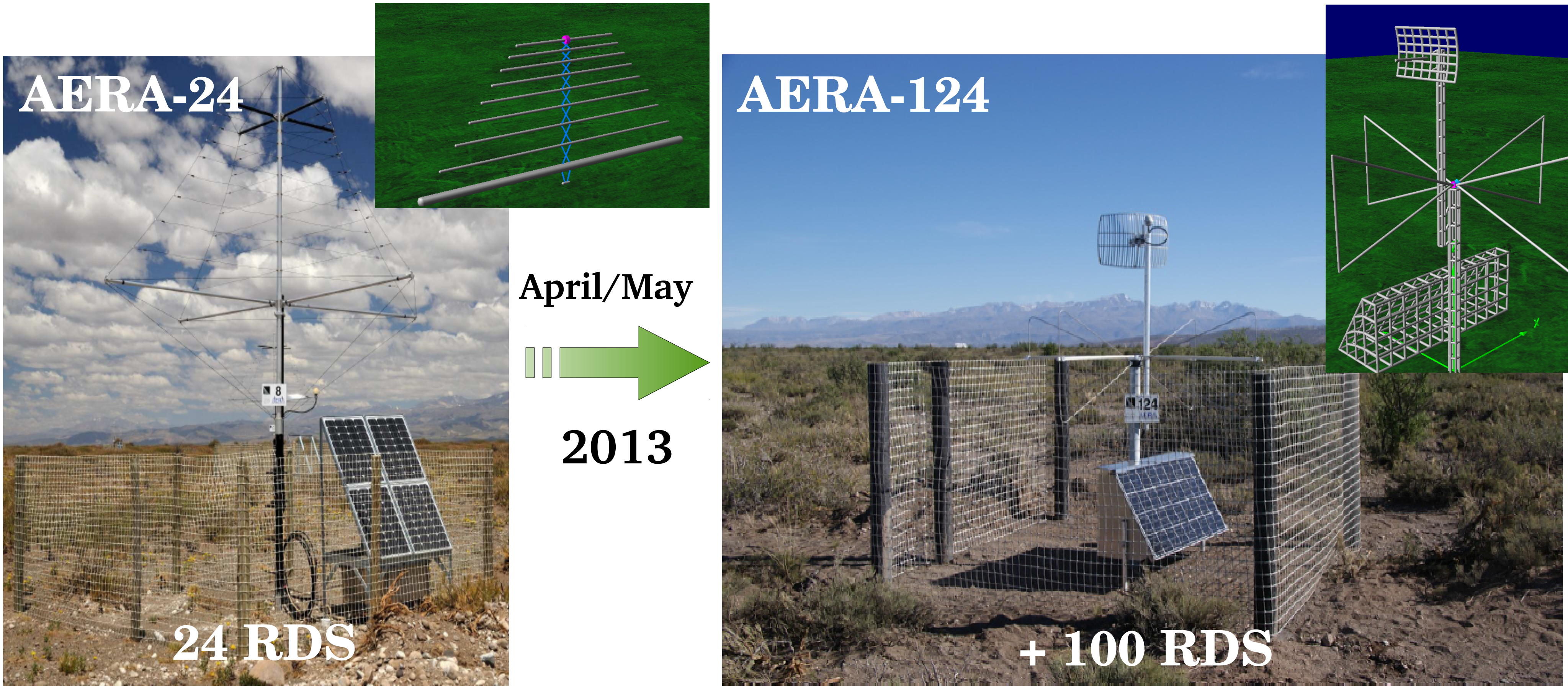


Auger Engineering Radio Array

- Radio extension of the Pierre Auger Observatory (PAO)
- Currently 124 antennas on ~ 6 km² to make PAO multi-hybrid
- Deployed inside the Infill: SD grid reduced from 1.500 m → 750 m
- Co-located with other Auger extensions
- AERA-24 data taking started in 10/2010, AERA-124 in 04/2013
- Coincidences with SD since 04/2011



Auger Engineering Radio Array



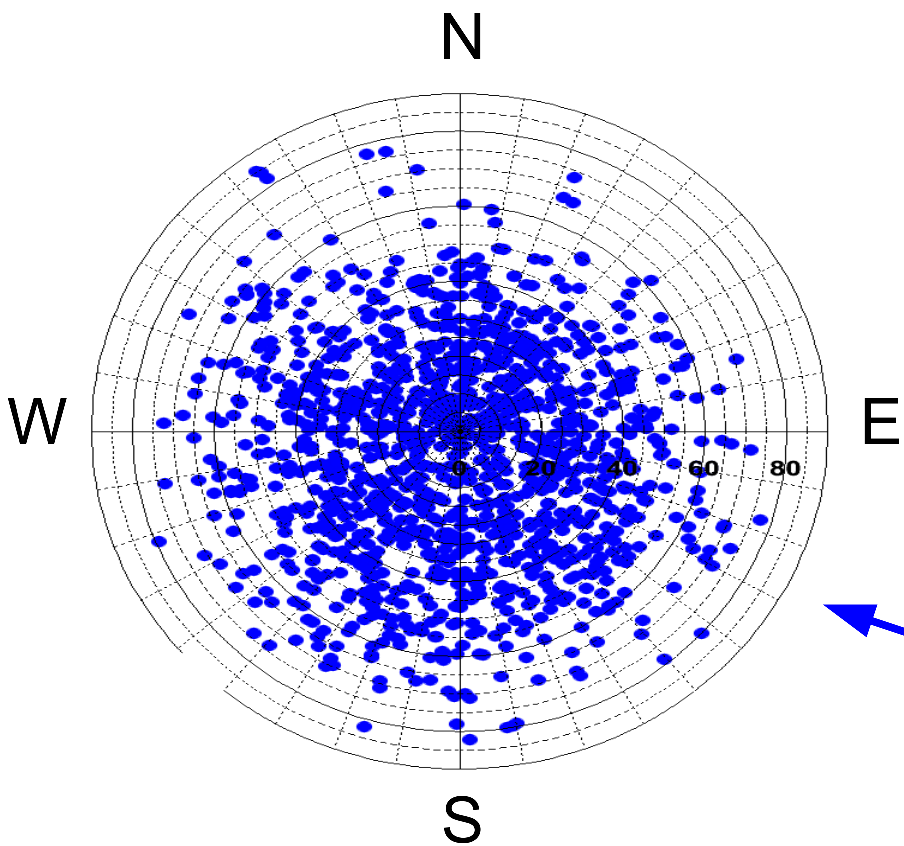
- AERA-24:
  - Log-Periodic Dipole Antenna + LNA + Digitizer
  - Fully automous operation with solar power, GPS
- AERA-124 (see talk by J. Maller):
  - Butterfly Antenna
  - New front-end electronics
  - Communication via WiFi
  - Partially equipped with scintillators

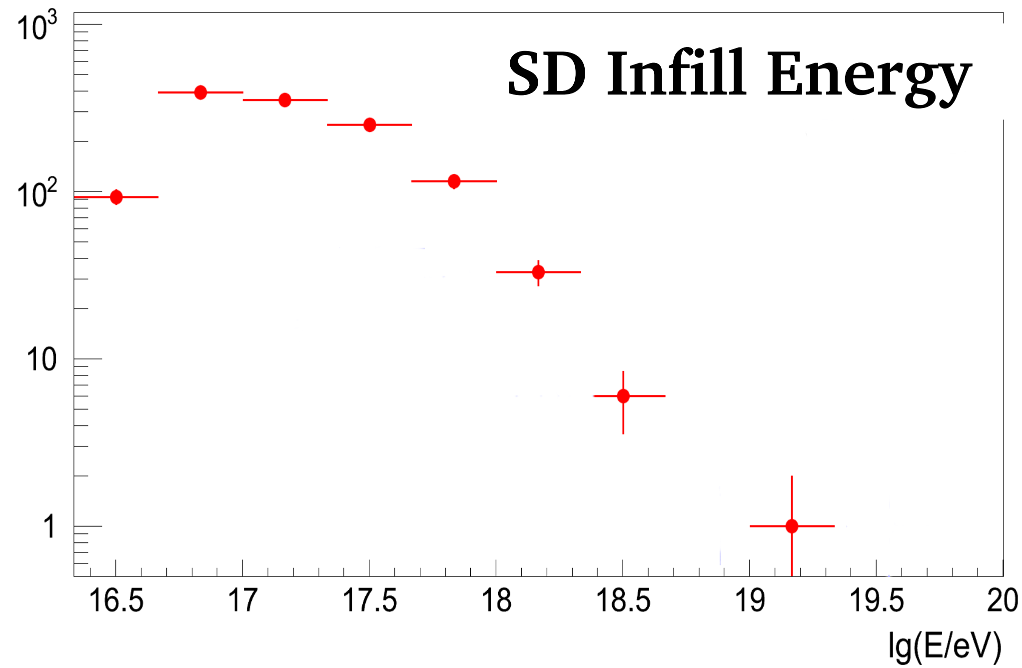
Auger Engineering Radio Array

Data

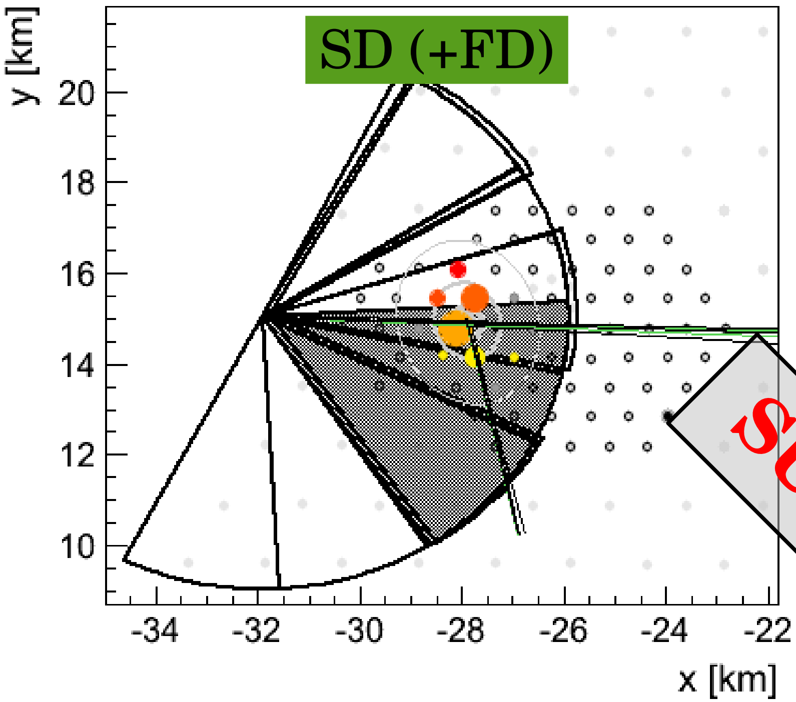
- Daily production of event files with standardized Offline-Hybrid-Reconstruction including SD Infill and FD in ARG
- Data transfered to central storage in Europe

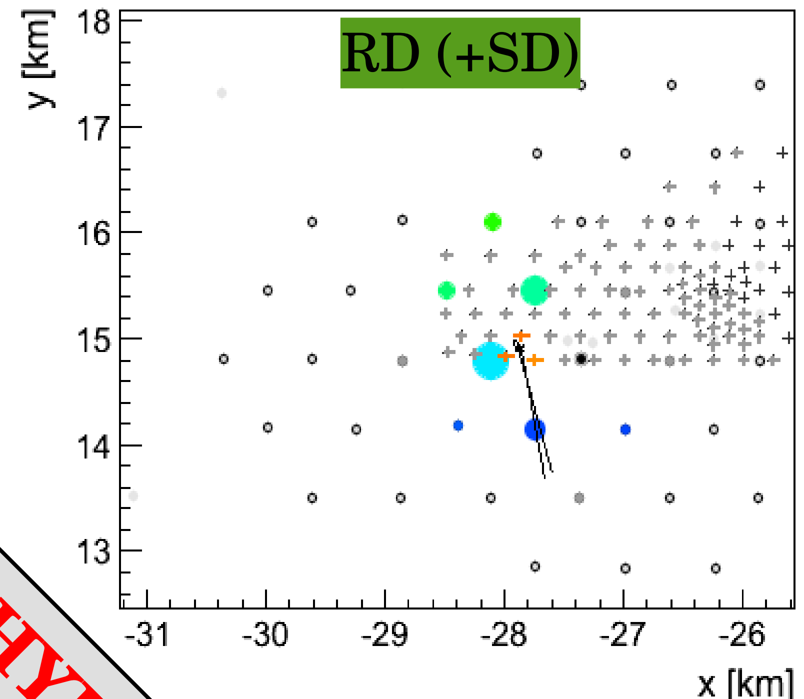
Dataset: Coincidences with SD from October '13 – March '14





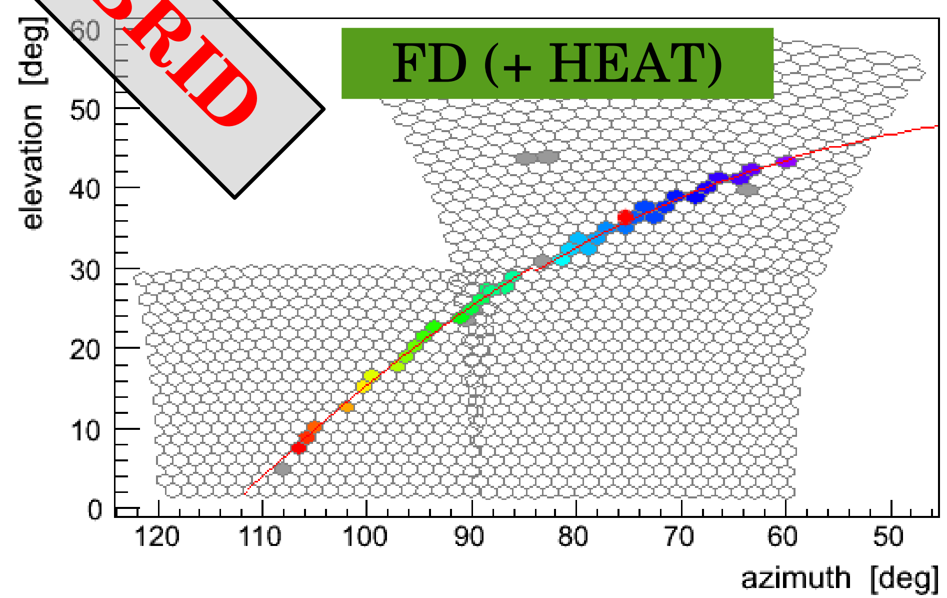
North-South asymmetry from **geomagnetic effect** folded with loss of sensitivity from **antenna pattern** towards horizon





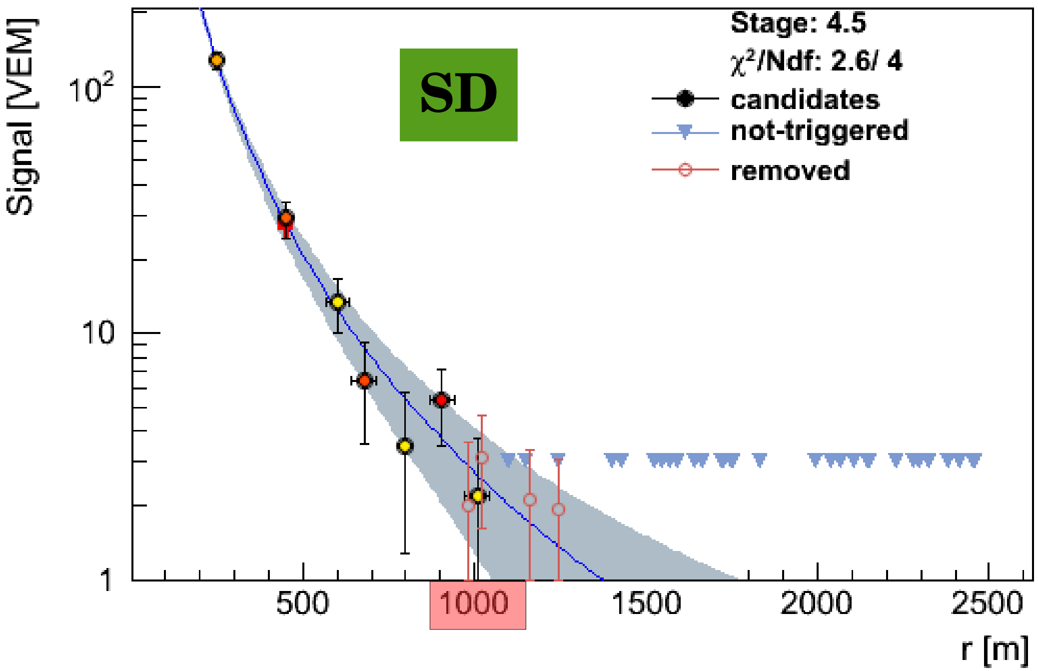
SUPERHYBRID

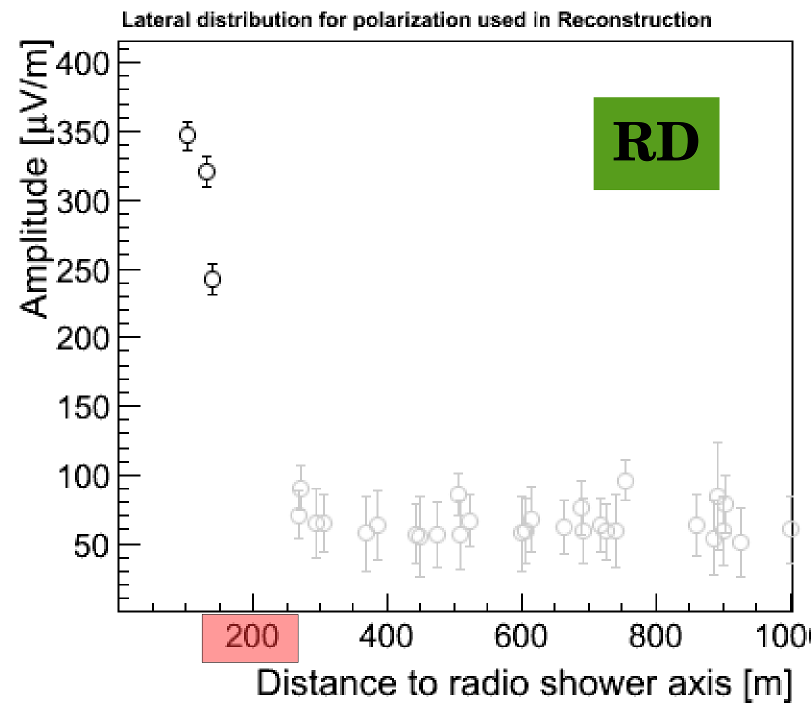
	Θ [deg]	Φ [deg]
SD	*41.1*	*283.4*
RD	*38.6*	*279.1*
FD	*41.1*	*282.3*

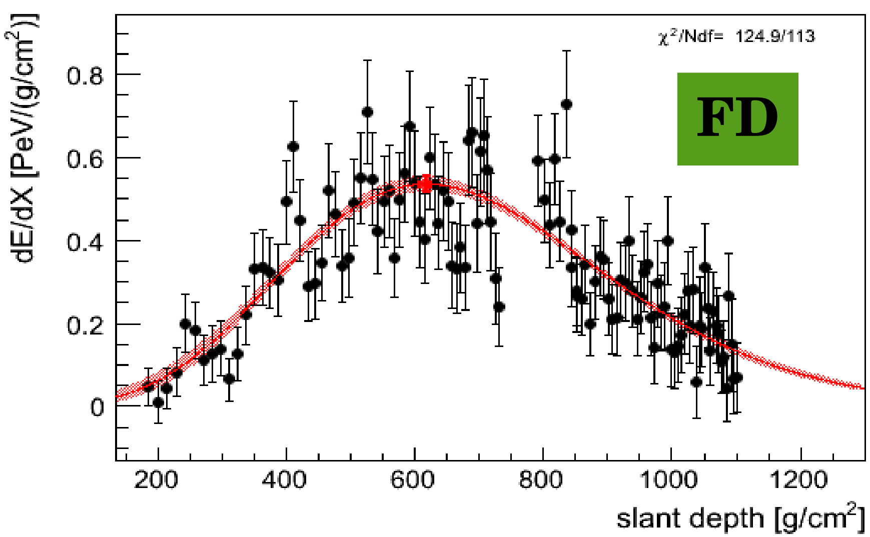


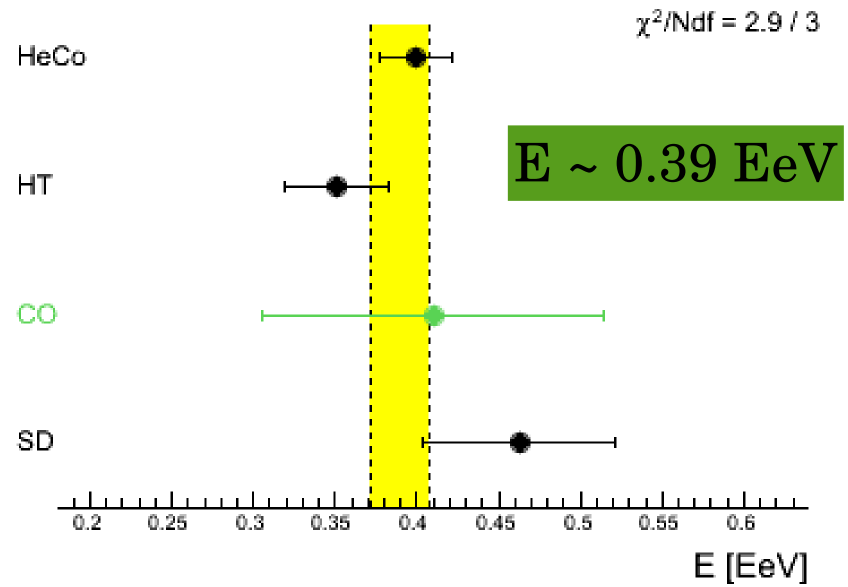
- ~ 4-5 (CR) coincidences / day
- Good RD reco with only 3 RDS

Example Event (SD Trigger)



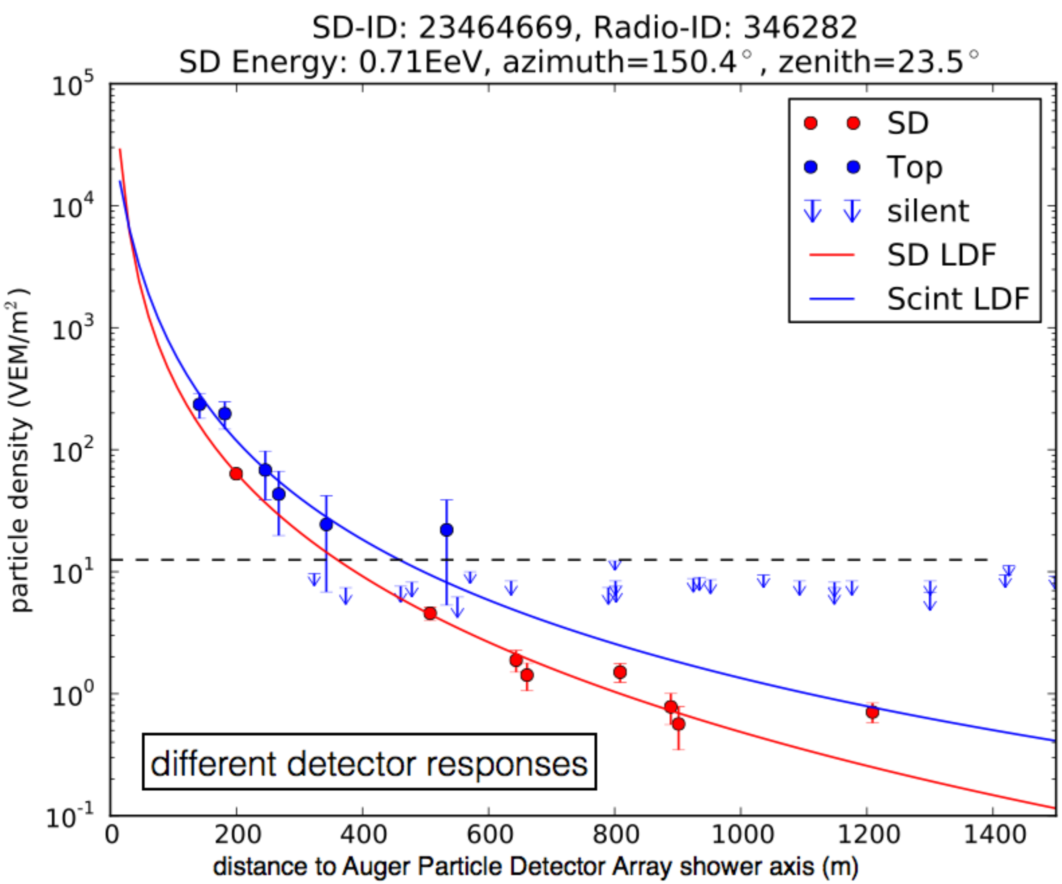


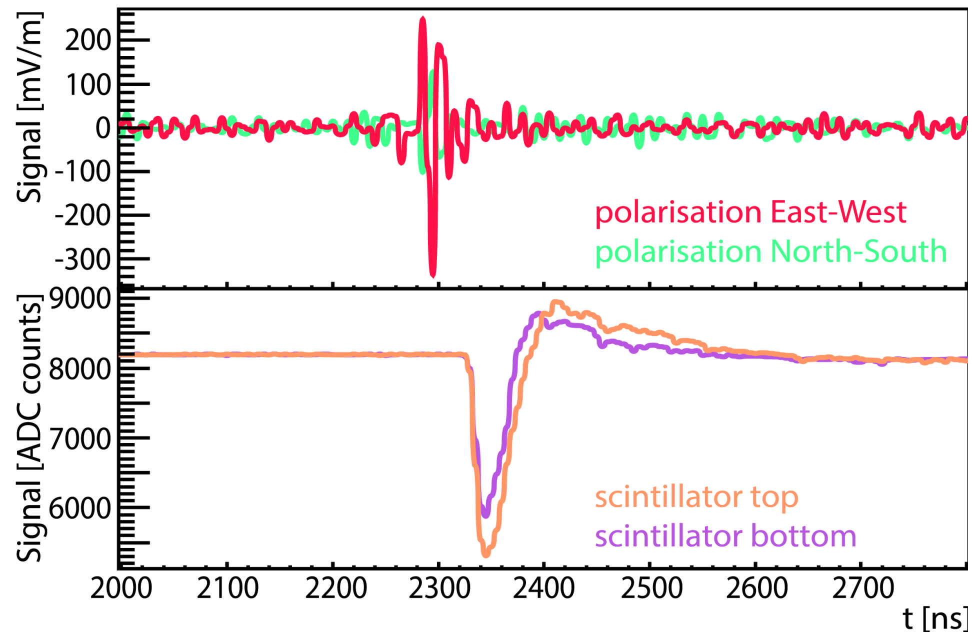


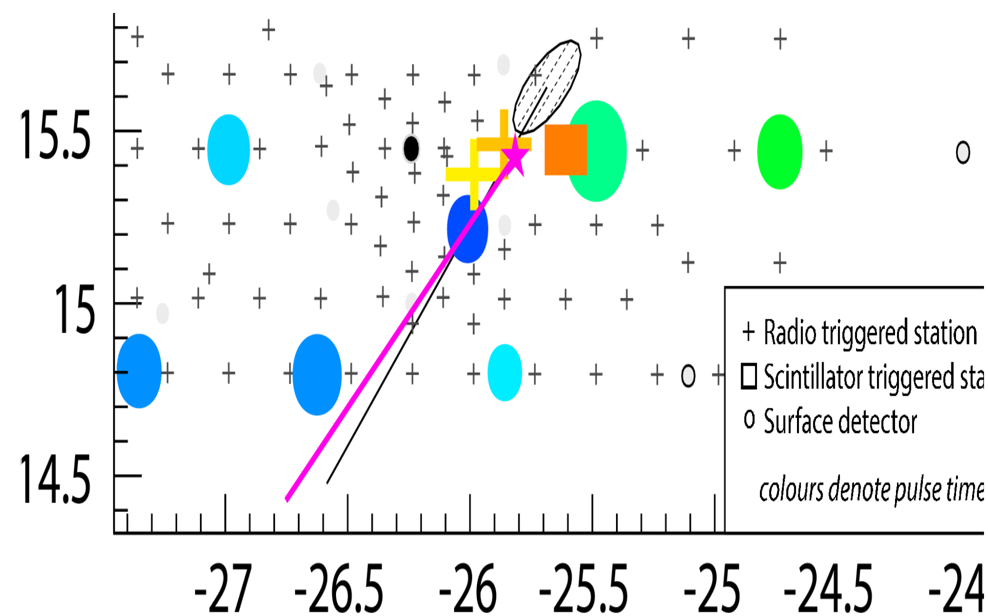


Example Event (SC Trigger)

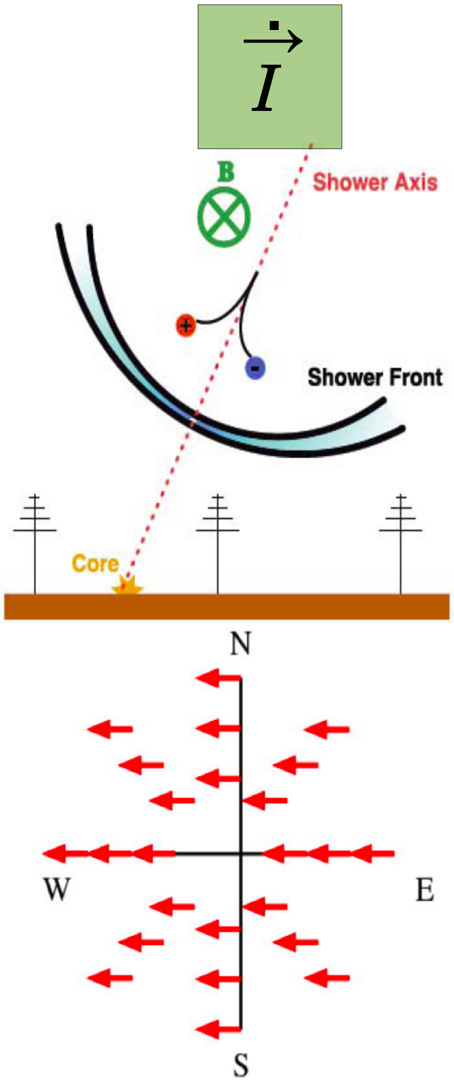
- SC core resolution limited
  → combination with RD and/or SD parameters planned to improve core position







Radio Emission



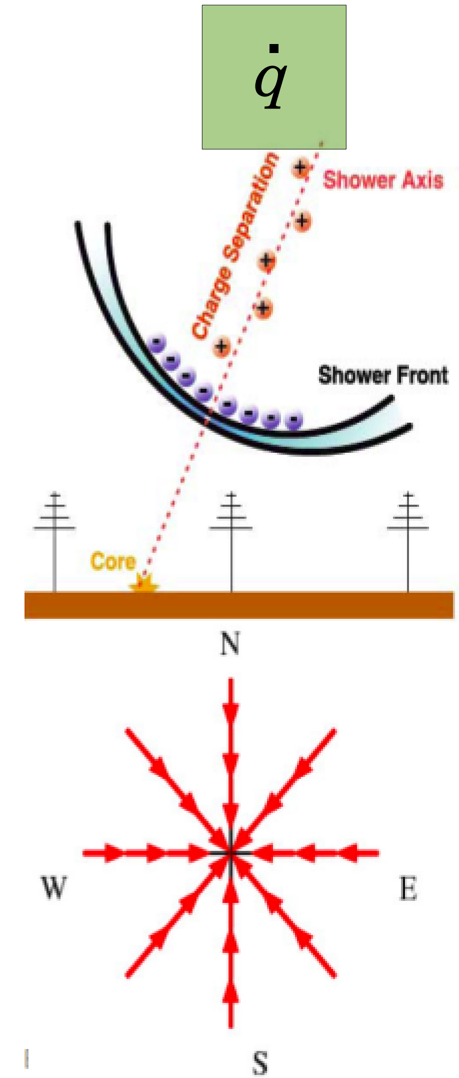
v x B

- *primary effect:* **Geomagnetic field** induces time-varying transverse currents

Kahn & Lerche (1967)

- *secondary effect:* time-varying net **charge excess**

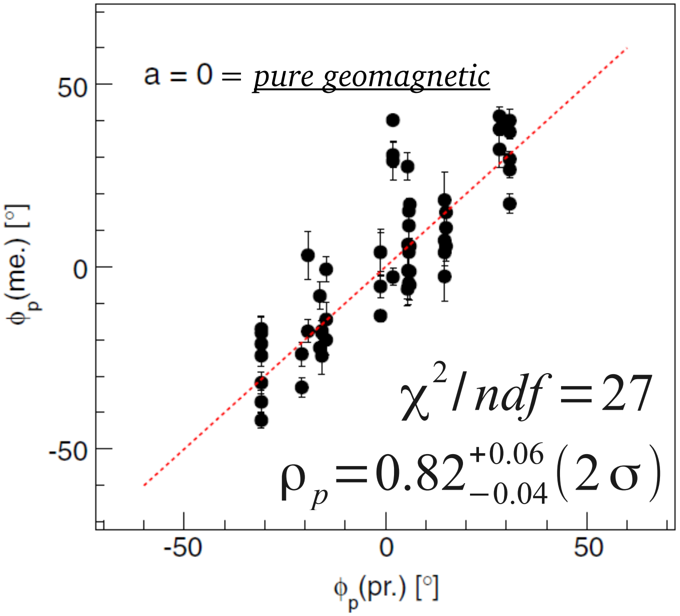
Askaryan (1962,1965)

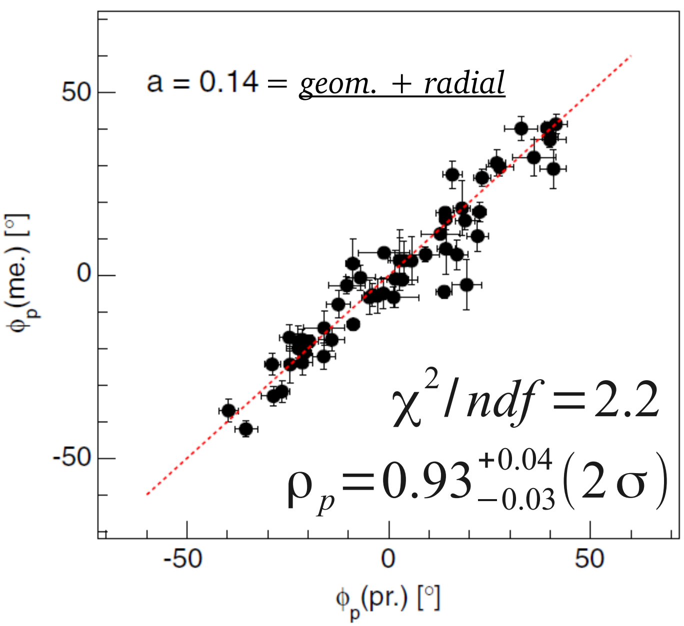


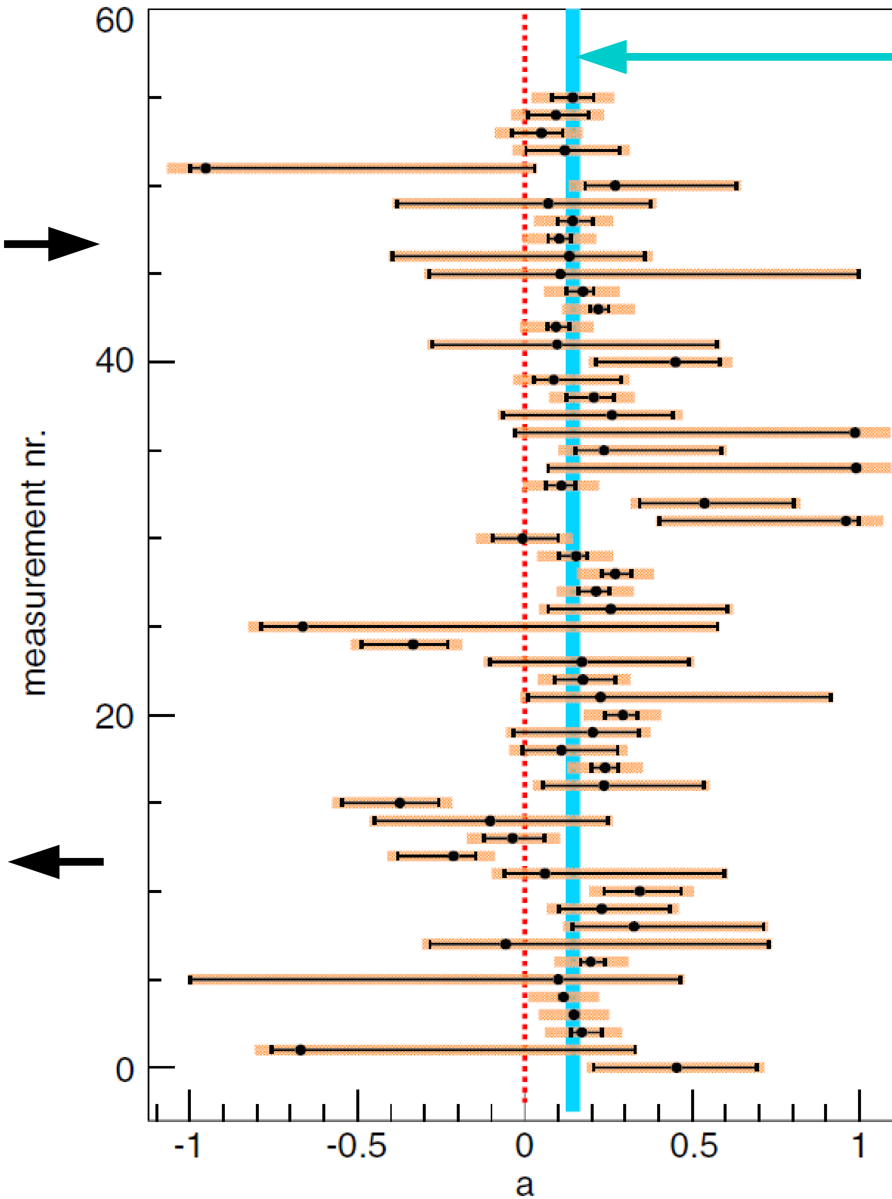
radial

Polarization Analysis

Evidence for an additional **radial polarized** electric field component





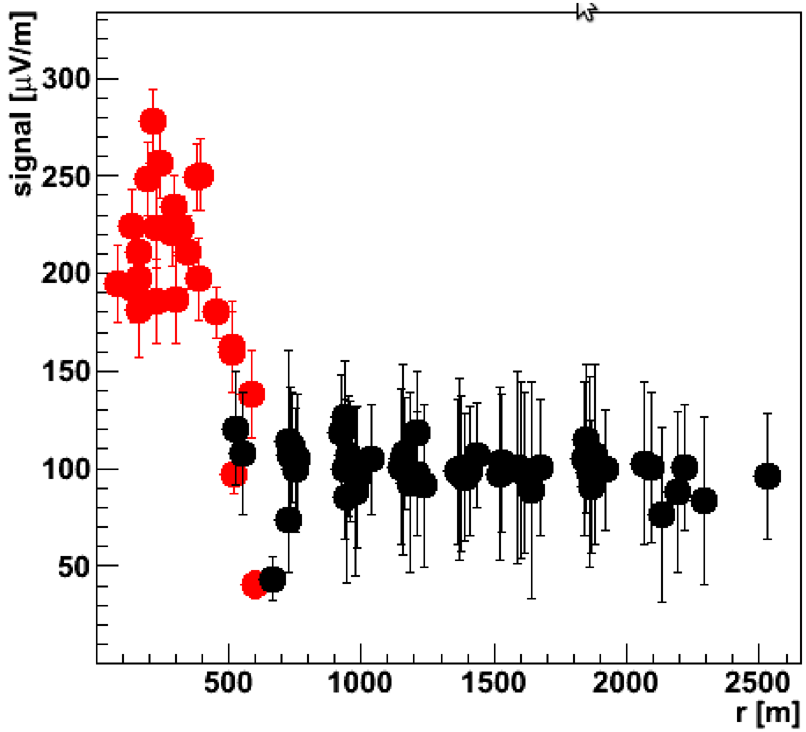


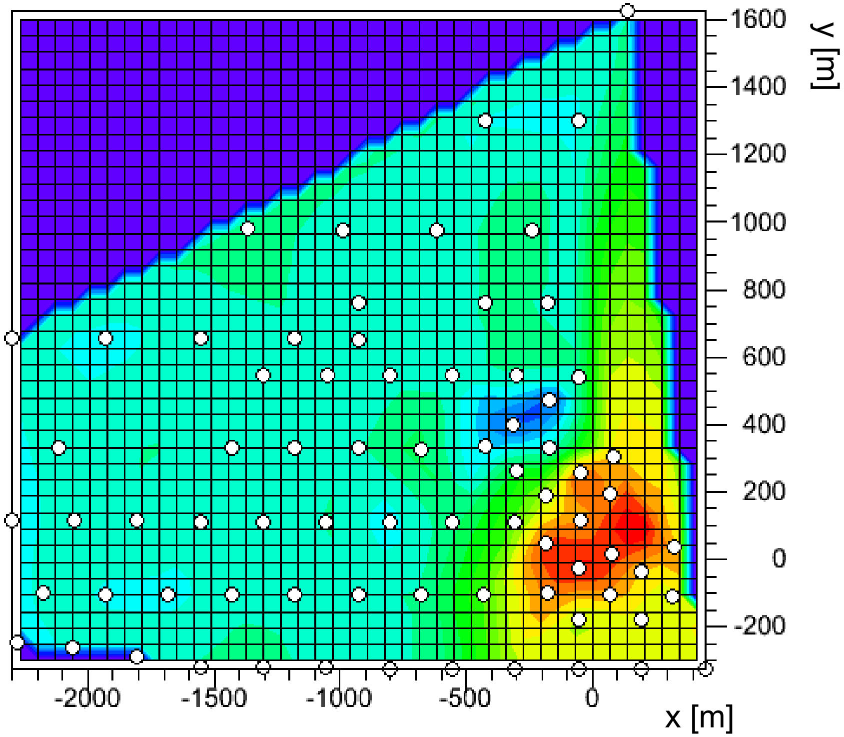
$$a \equiv \sin(\alpha)\frac{|E_A|}{|E_G|} = 0.14 \pm 0.02$$

Data from AERA-24

Phys. Rev. D 89, 052002 (2014)

Lateral Distribution Function (LDF)





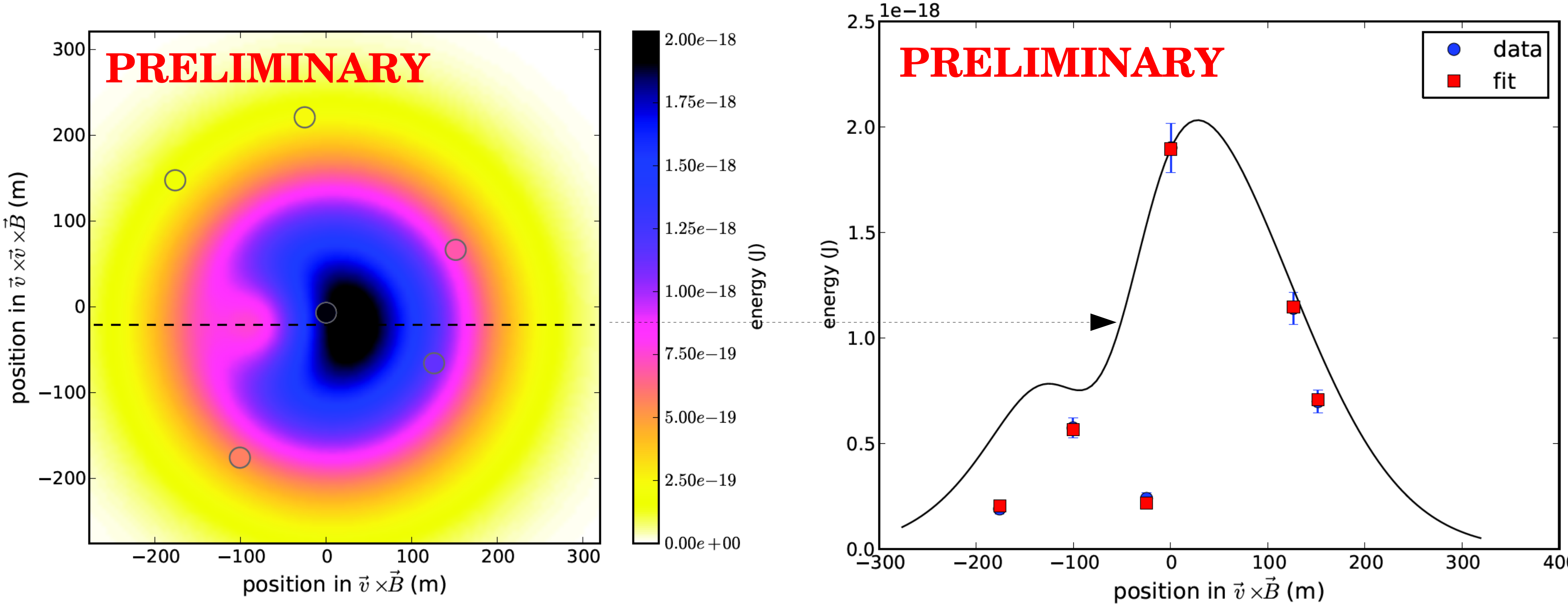
- Simple 1D or 2D approach probably not sufficient
- Double gaussian approach promising (see talk by A. Nelles)

$$P(x', y') \;=\; A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2 + (y'-Y_+)^2]}{\sigma_+^2}\right) \;-A_- \cdot \exp\left(\frac{-[(x'-X_-)^2 + (y')^2]}{\sigma_-^2}\right)$$

- Number of parameters can be reduced → still needs > 4 stations

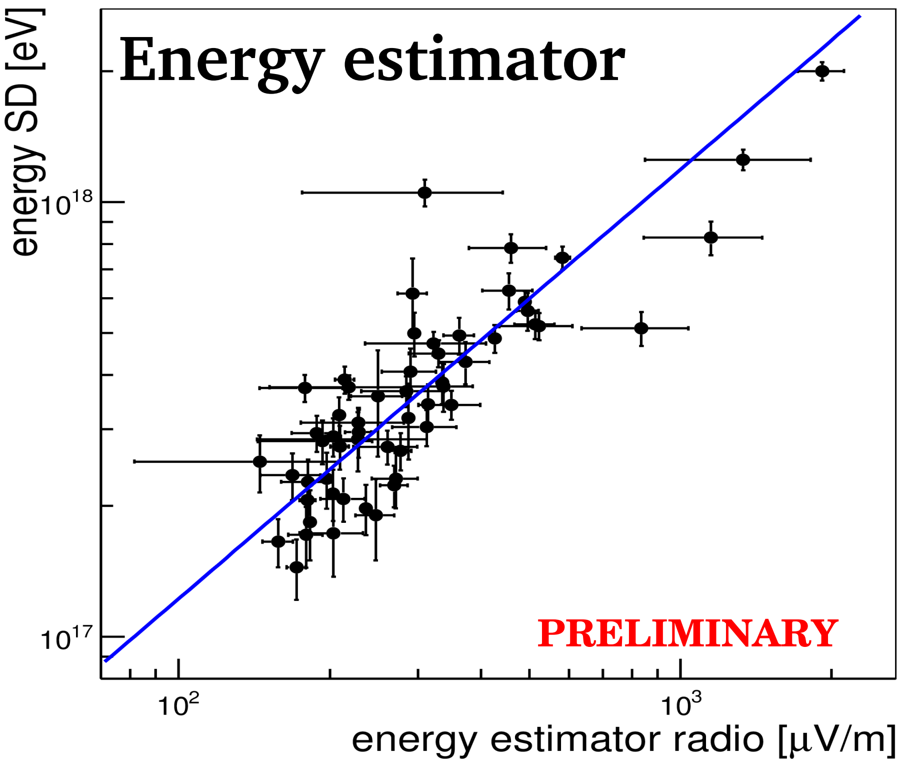
Lateral Distribution Function (LDF)

- Transformation into $v \times B$ and $v \times v \times B$ plane of shower
- Colored contour: Two-dimensional fit result
- Colored circles: Signal of individual stations

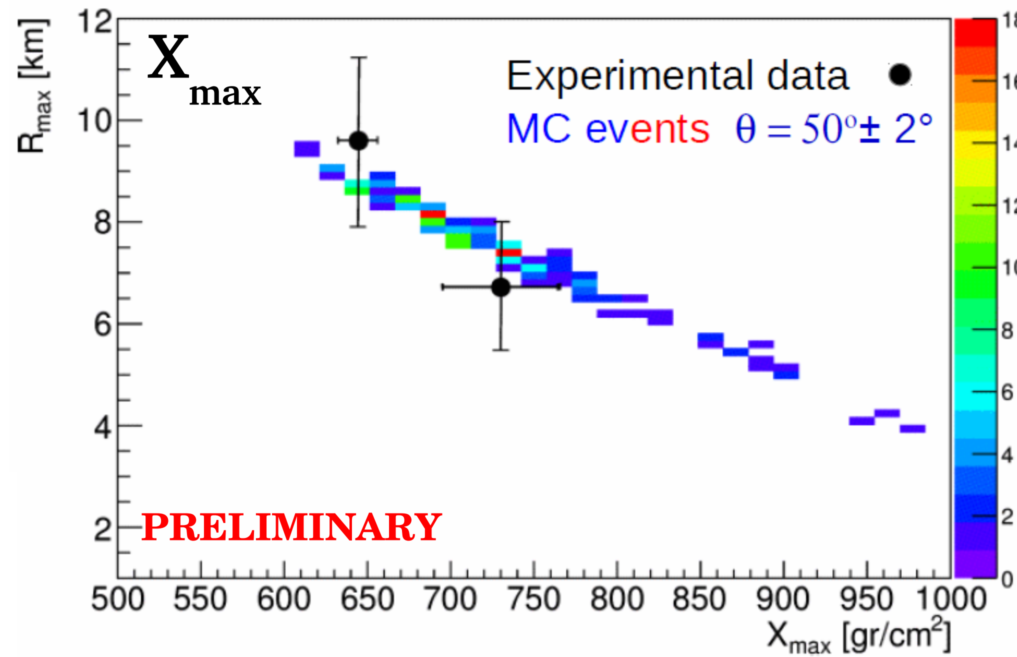


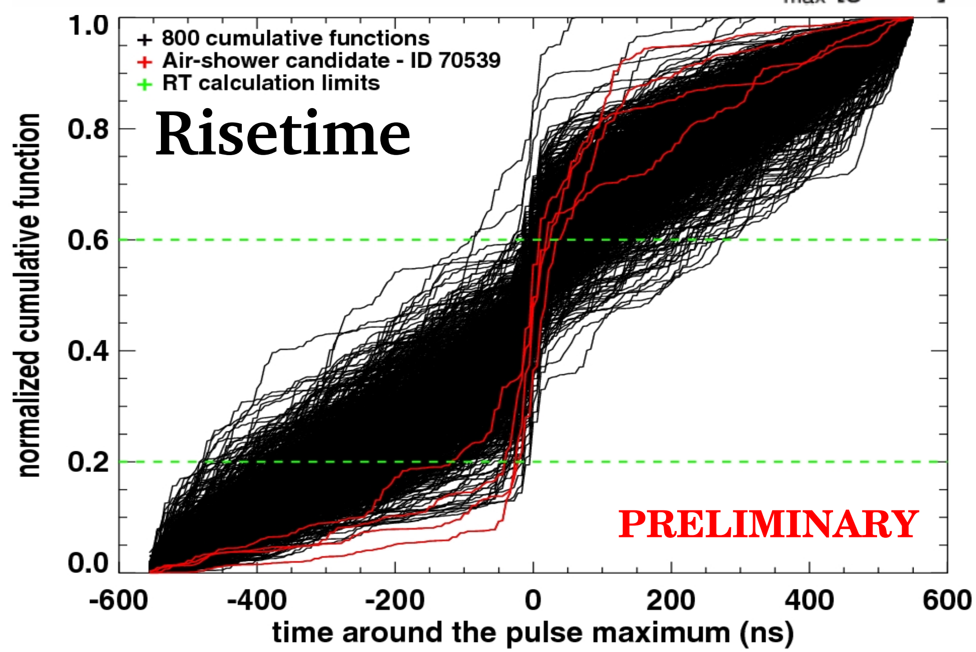
Successfully tested on first AERA events, but still under investigation

Further topics ...



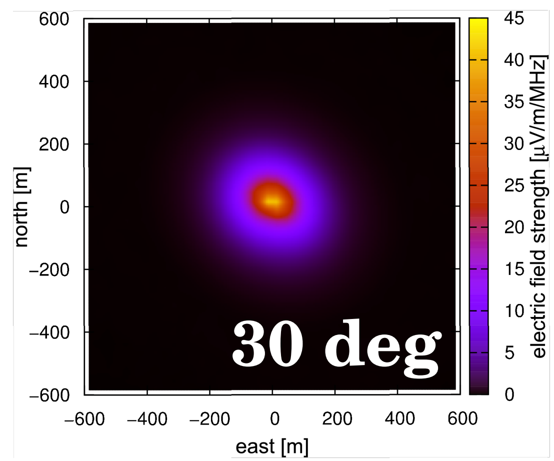
(see talk by Q. Dorosti)

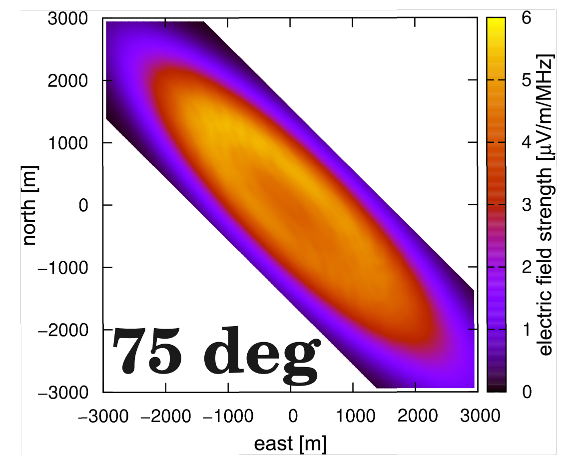


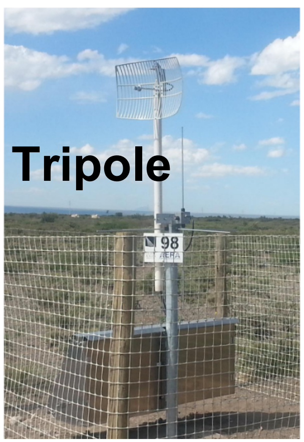


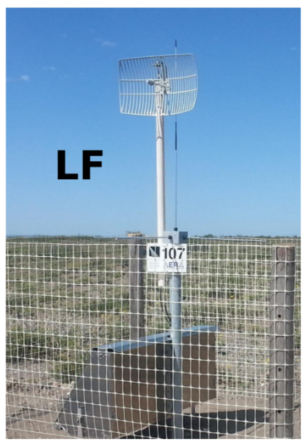
Outlook

Simulations suggest higher radio efficiency for inclined air showers
(see talk by O. Kambeitz)









Several 3D and low frequency prototypes have been deployed

- Deployment of 25 additional RDS planned
- SD and RD in the same location (order of ∼ m)
- Radio as detector for electro-magnetic shower component
- Combined analysis with muon detector

Conclusion

- Deployment of 2nd stage of AERA with 124 radio detection stations covering an area of about 6 km^2 completed in May 2013

- Automated data chain and hybrid-reconstruction pipeline in the $\overline{\text{Off}}\underline{\text{line}}$ analysis-framework available
- ~ 5 SD-RD coin's/day, ~0.3 FD-SD-RD coin's/day (when FD is operated)

- 14% contribution of an Askaryan-like radial polarization found
- Analysis on energy estimator, X_{max}, LDF, risetime and HAS on-going

- Deployment of additional RDS (incl. 3D and low frequency) planned
- Possibilites for large scale extensions under investigations

- Unique opportunity for super-hybrid shower-detection
- Measurement of different shower components at the same location


THANKS !!!
AERA
Auger Engineering Radio Array

Backup

AERA – Auger full author list papers:

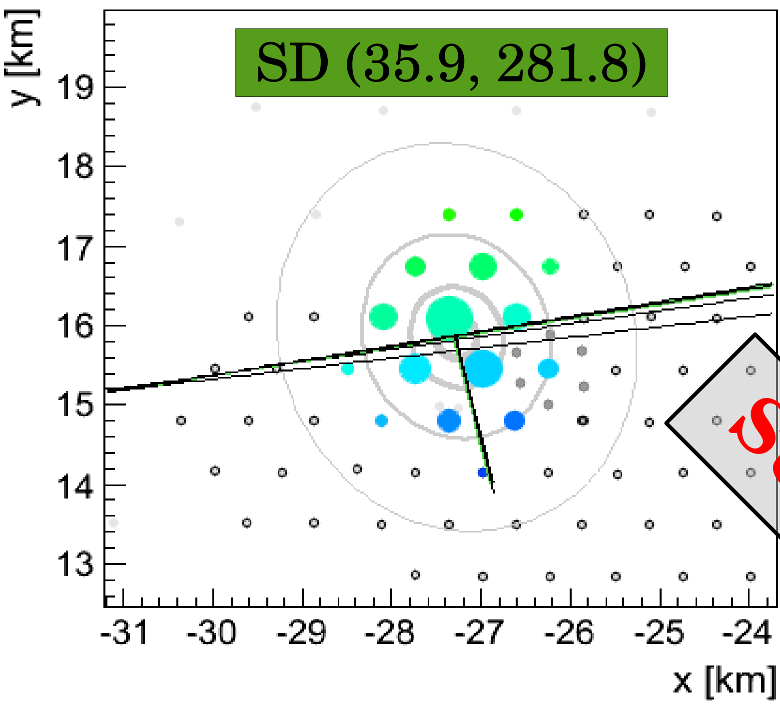
Advanced functionality for radio analysis in the Offline software framework of the Pierre Auger Observatory *The Pierre Auger Collaboration 2011,* NIM A 635, 92-102

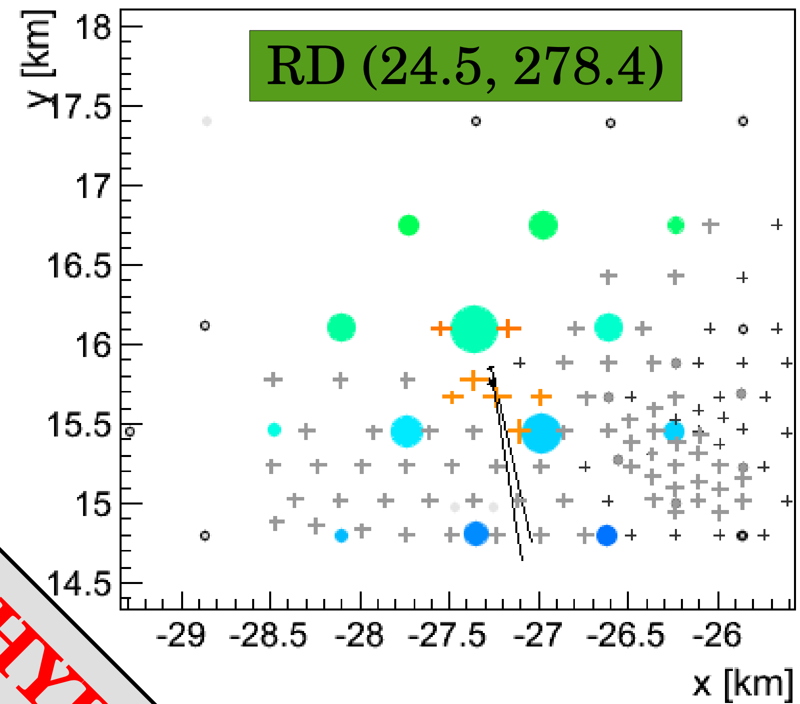
Antennas for the Detection of Radio Emission Pulses from Cosmic-Ray induced Air Showers at the Pierre Auger Observatory *The Pierre Auger Collaboration 2012,* JINST 7, P10011

Results of a self-triggered prototype system at the Pierre Auger Observatory for radio-detection of air showers induced by cosmic rays *The Pierre Auger Collaboration 2012*, JINST 7, P11023

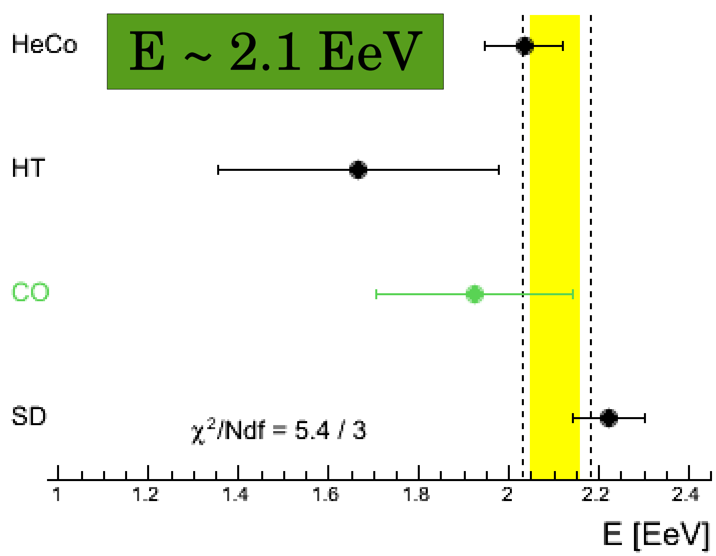
Probing the radio emission from cosmic-ray-induced air showers by polarization measurements *The Pierre Auger Collaboration 2014*, Phys. Rev. D *89, 052002 (2014)*

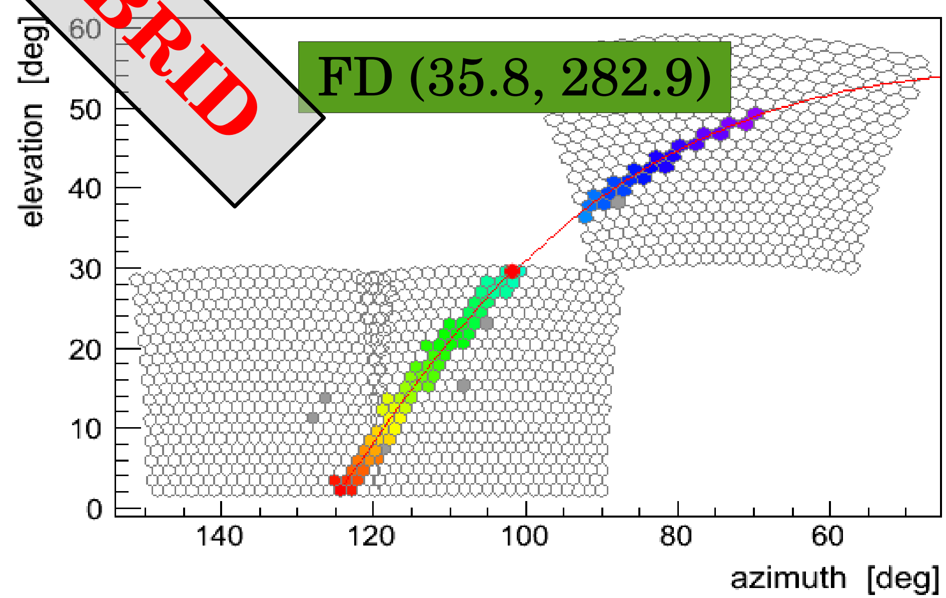
Example Event (SD Trigger)





SUPERHYBRID





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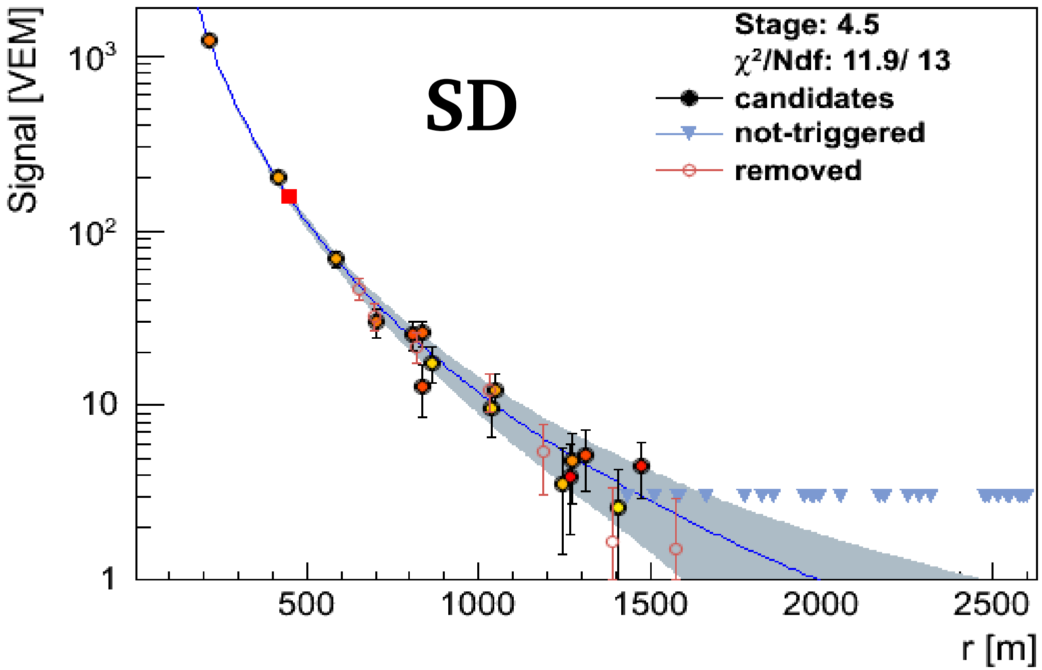
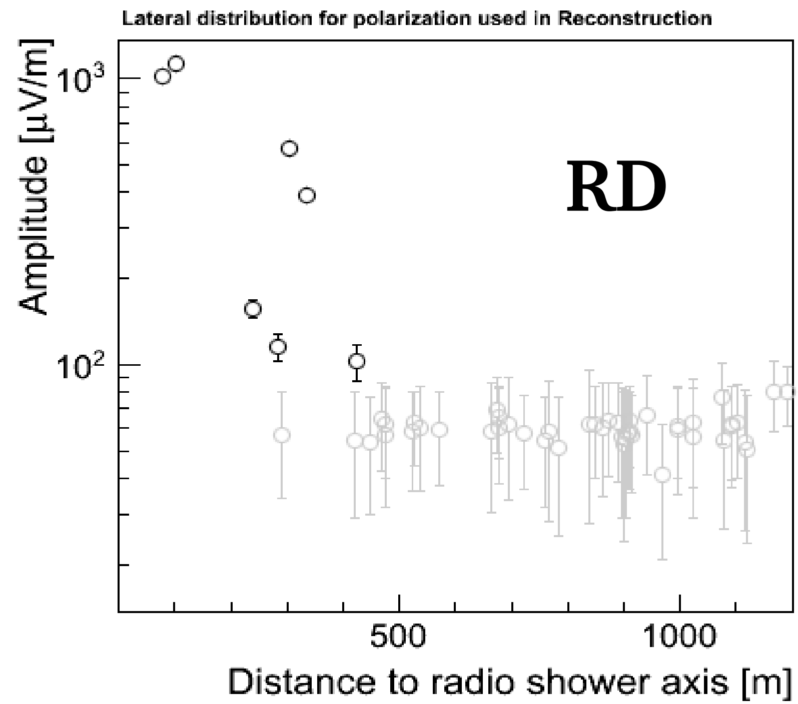
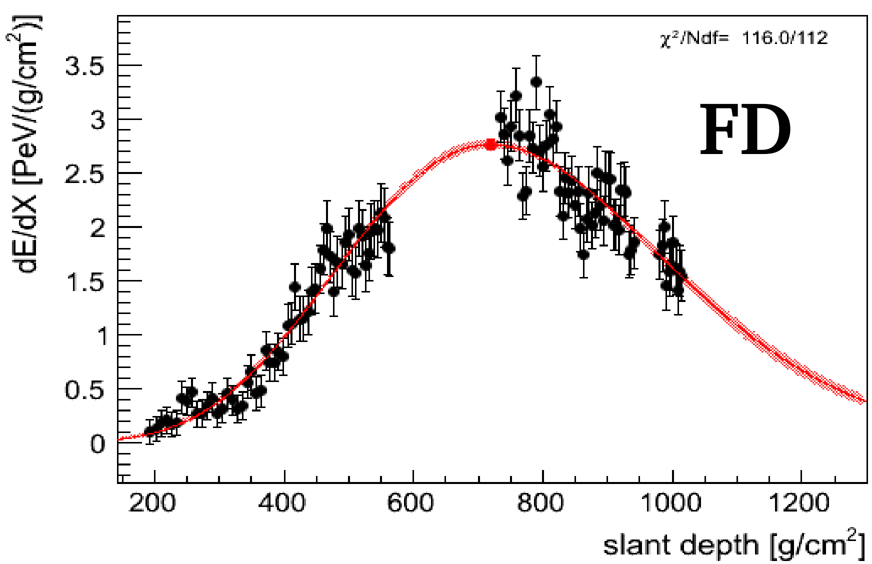






- ~ 4-5 (CR) coincidences / day
- Nice agreement among detectors in direction, core & energy
- Good RD reco with only 3 RDS

Data Handling / Reconstruction

- Huge data volume (~ 40 GB/day)
- Low bandwidth for transfer
- Merging to combined data-set with other Auger data (SD/FD/MD)
- Dedicated 16-core server in ARG

Offline

OBSERVER

- Daily production of event files
- Standardized Offline-Reconstruction including SD and FD
- Treatment of different detector components via mysql-based time-dependent detector description
- Data transfered to central storage in Europe

Time-Dependent Detector Description (TD³)

Highly flexible treatment of detector components in reconstruction required

HardwareAssociation

Commission/Decommission, Station, Channel, ADC, ResponseMapList

managed and updated by 'AERA-Experts'

description of LNA, filters, digitizers

Station

Position, Name

Channel

Type, Antenna, Orientation

ADC

Min/MaxVoltage, Sampling, Bits

ResponseMapList

Response, Weight

Response

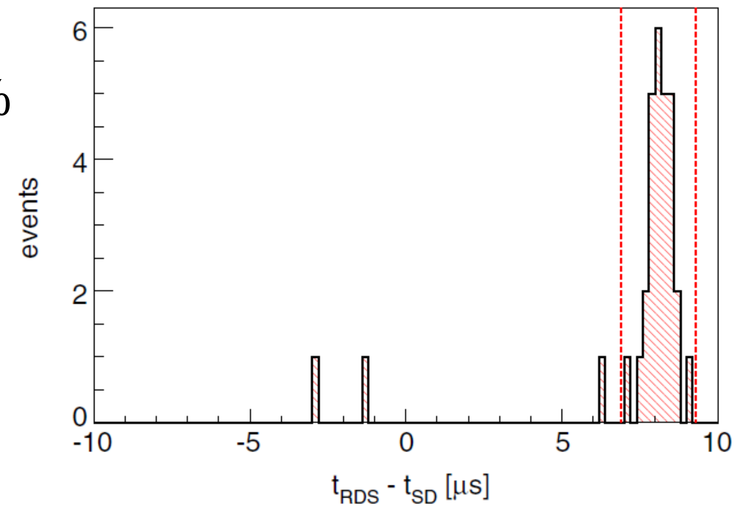
Frequency, Phase, Amplitude

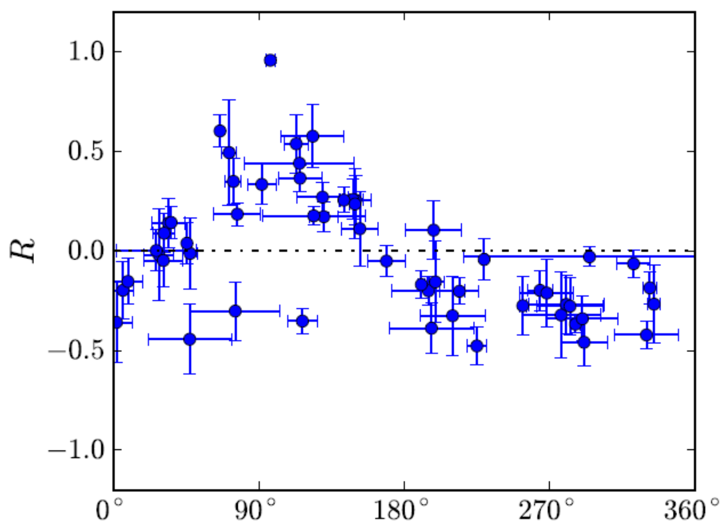
Polarization

- SD EventSelection:
  - Prototype: Theta < 40 deg; AERA-24: Theta < 40 deg
  - Prototype: Nearest Infill Station with highest signal, E > 0.2 EeV
  - AERA-24: Distance Shower Axis to Infill Station < 2.5 km

- SD Uncertainties:
  - Directional: 1 deg at 0.1 EeV, 0.5 deg at 1 EeV
  - Core: 60 m at 0.1 EeV, 20 m at 1 EeV

- RD EventSelection:
  - Difference of rel. Gain for two polarizations < 5%
  - Coincident with SD in between 10 us





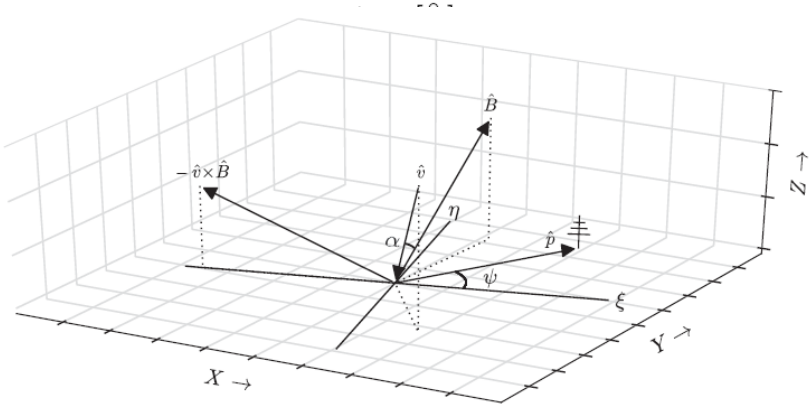


FIG. 3. Direction of the incoming shower, denoted as $\hat{v}$, with respect to the position of RDS which is symbolically indicated by an antenna. The direction of the magnetic field vector is denoted by $\hat{B}$ and the direction ξ is defined by the projection of the vector $\hat{v} \times \hat{B}$ onto the ground plane. The direction η is perpendicular to ξ and is also in the ground plane. The angle between the shower axis and the geomagnetic field direction is denoted as α, while ψ is the azimuthal angle between the ξ axis and the direction of the RDS measured at the core position.

$$R(\psi) \equiv \frac{2\sum_{j=1}^{25} \mathrm{Re}(\mathcal{E}_{j+k,\xi}\mathcal{E}^*_{j+k,\eta})}{\sum_{j=1}^{25}(|\mathcal{E}_{j+k,\xi}|^2 + |\mathcal{E}_{j+k,\eta}|^2)},$$

Predicted:

$$\phi_p = \tan^{-1}\left(\frac{E_y^{\mathrm{G}} + E_y^{\mathrm{A}}}{E_x^{\mathrm{G}} + E_x^{\mathrm{A}}}\right)$$

$$= \tan^{-1}\left(\frac{\sin(\phi^{\mathrm{G}})\sin(\phi) + a\,\sin(\phi^{\mathrm{A}})}{\cos(\phi^{\mathrm{G}})\sin(\alpha) + a\,\cos(\phi^{\mathrm{A}})}\right)$$

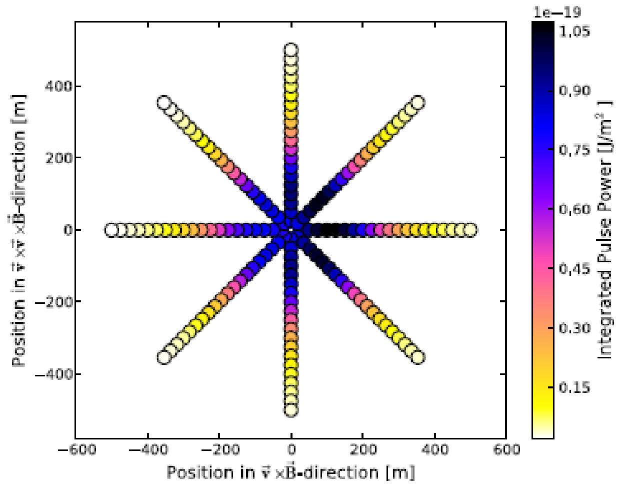
Measured:

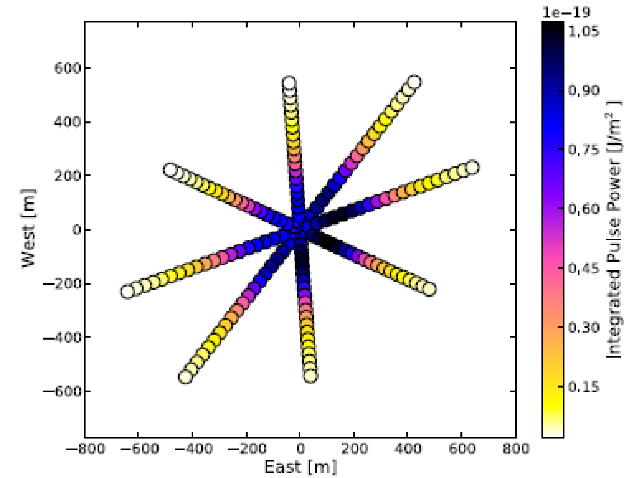
$$Q = \frac{1}{n}\sum_{j=1}^{n}(E_{j,x}^2 + \tilde{E}_{j,x}^2 - E_{j,y}^2 - \tilde{E}_{j,y}^2)$$

$$U = \frac{2}{n}\sum_{j=1}^{n}(E_{j,x}\,E_{j,y} + \tilde{E}_{j,x}\,\tilde{E}_{j,y}),$$

$$\phi_p = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right),$$

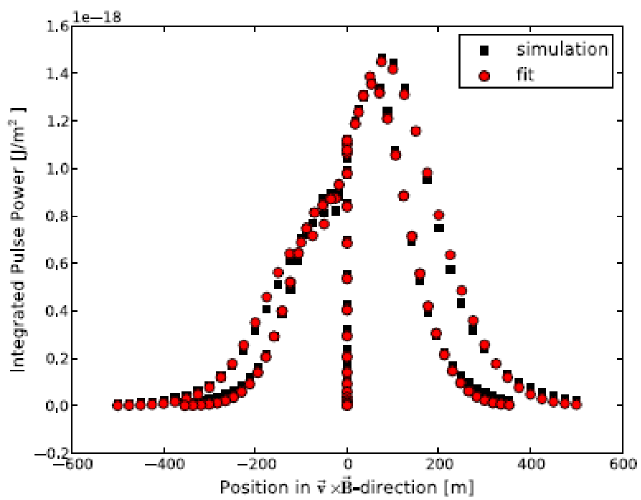
Antenna Positions:

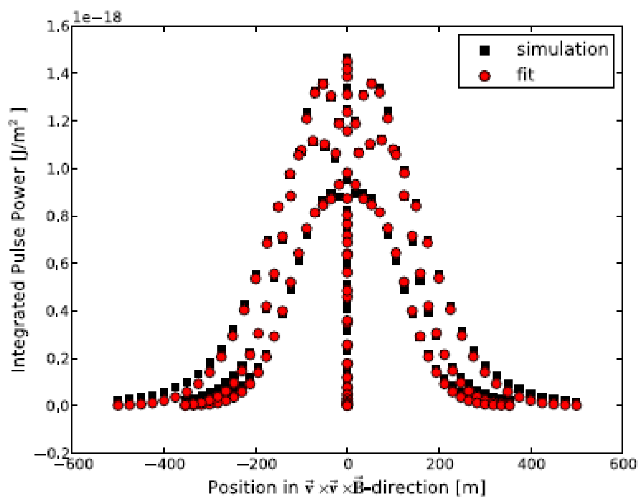




PRELIMINARY

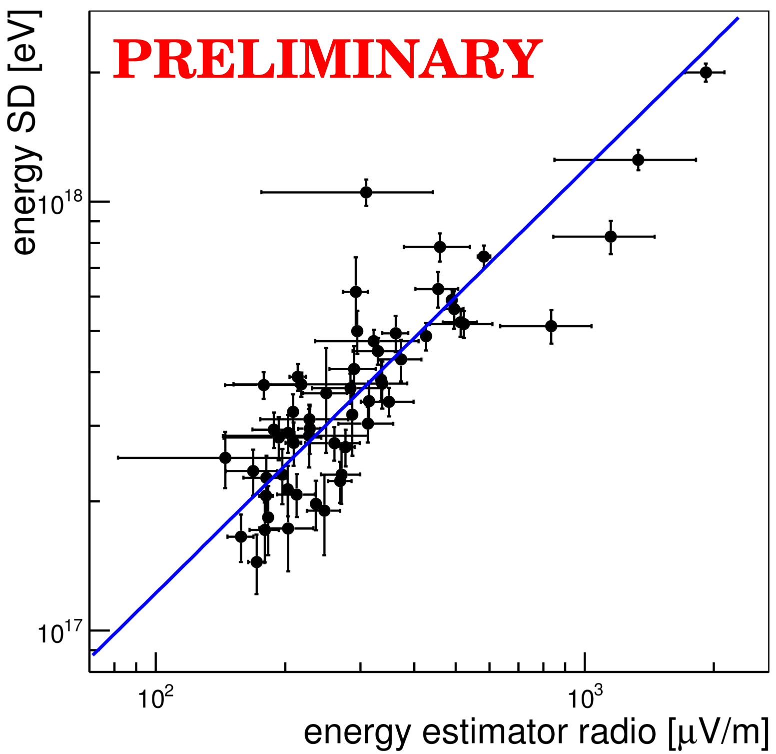
Fitted simulations:

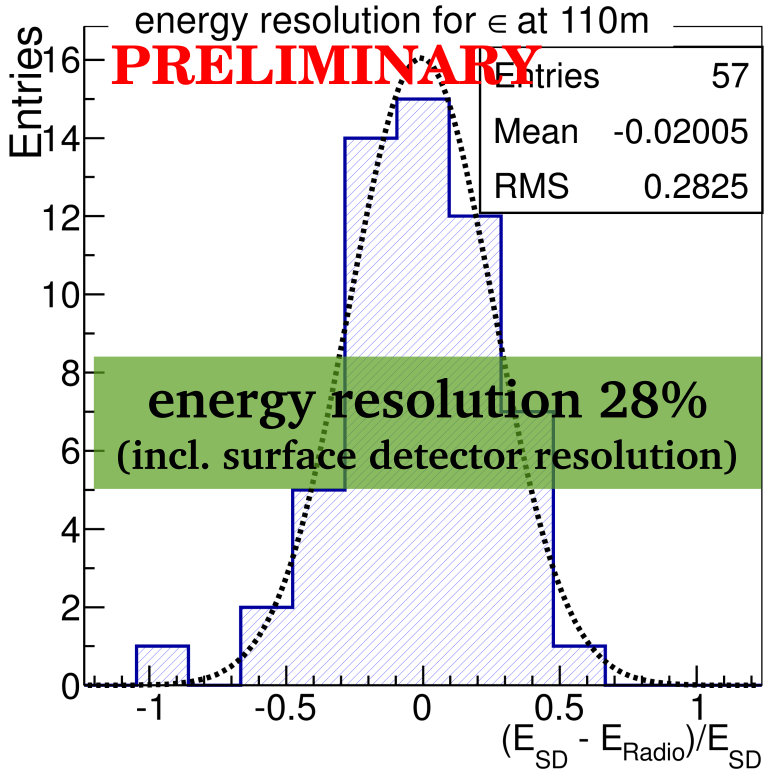




Energy Estimator

- Correct signal amplitude for incoming direction: $c = \left| \sin\alpha \cdot \vec{e}_L + a \cdot \vec{e}_{CE} \right|$
- Radio signal measured at discrete positions
- Use exponential to interpolate between data points $E_{scaled} = A \cdot exp(D/R_0)$
- Energy estimator taken at d = 110 m from shower axis

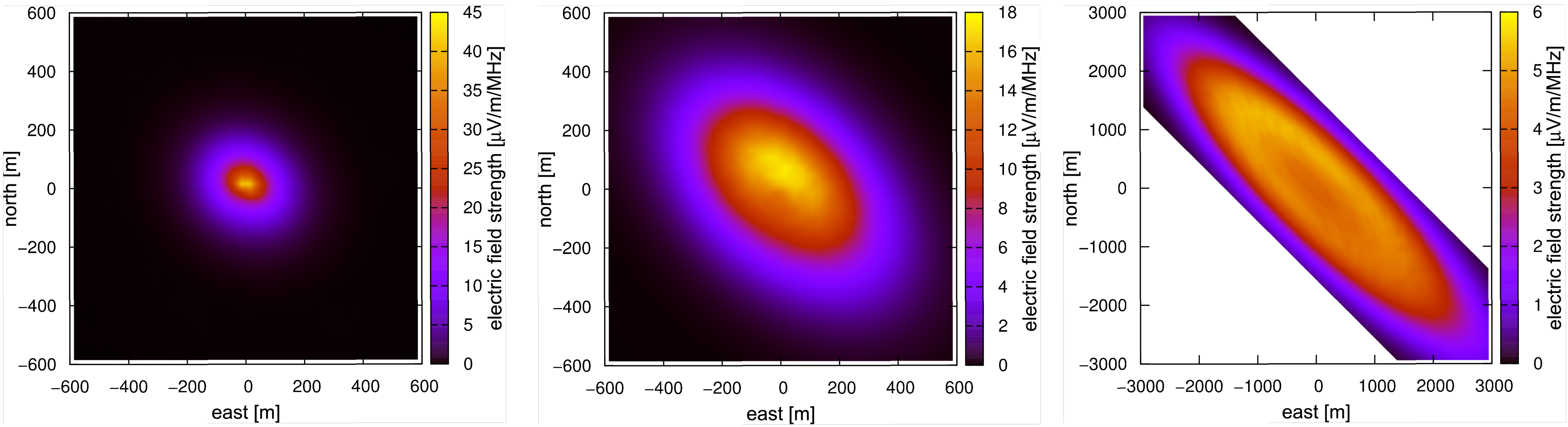




Horizontal Air Showers (HAS)

- Simulations suggest higher radio efficiency for inclined air showers
- Significant vertical component

$E = 10^{18}$ eV

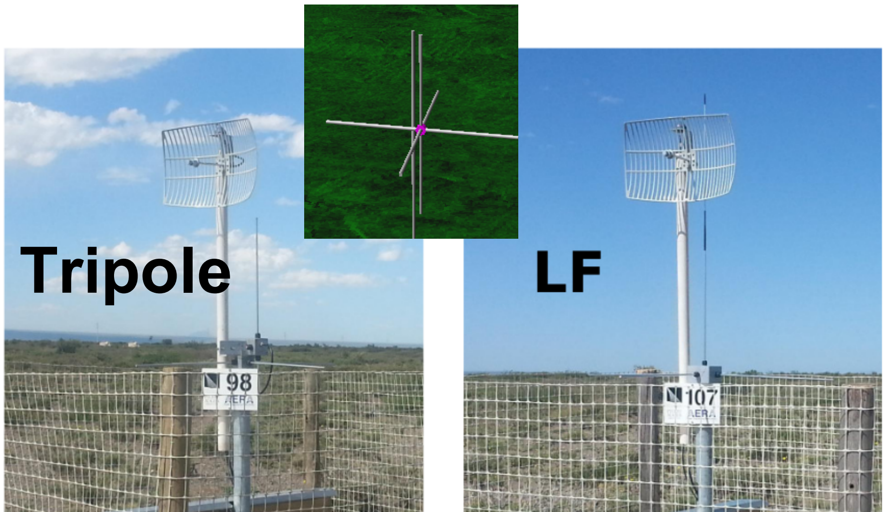


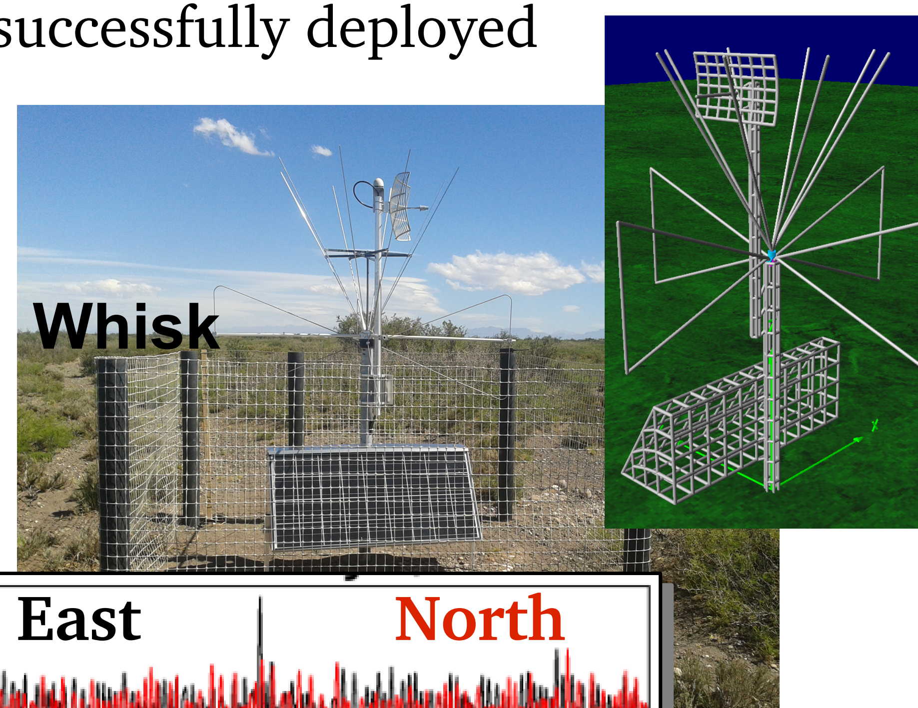
30 deg **50 deg** **75 deg**

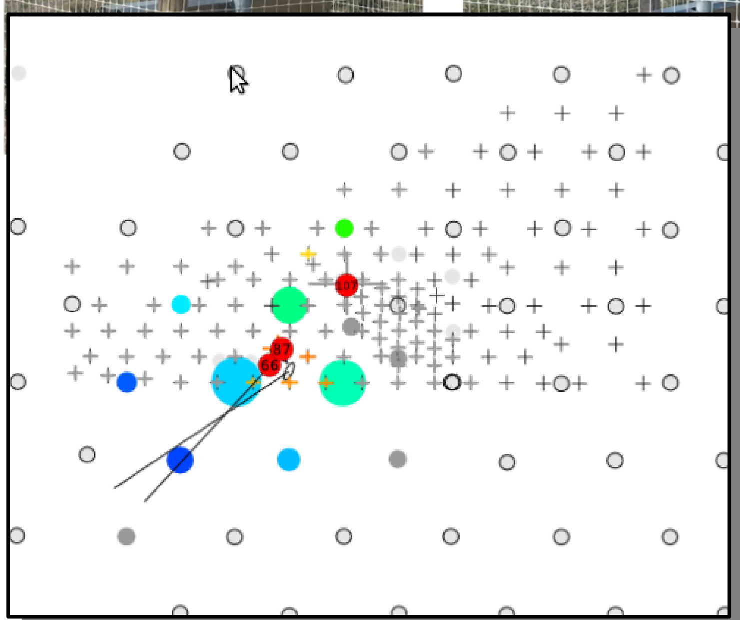
- Simulations predict strong radio signal at low (< 10 MHz) frequencies

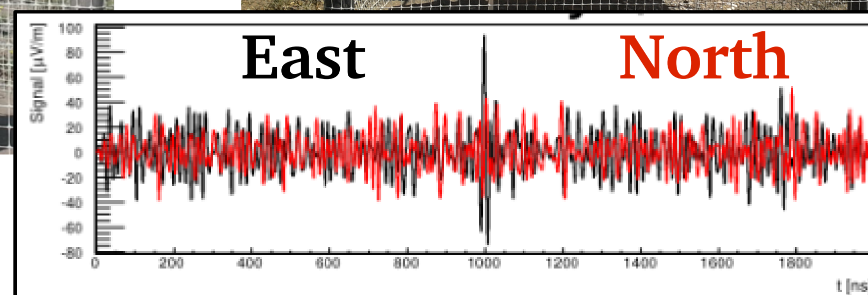
3D & Low Frequency

- Three tripole stations (40 – 80 MHz), one low frequency station (1.5 – 6 MHz) and five Whisk antennas successfully deployed

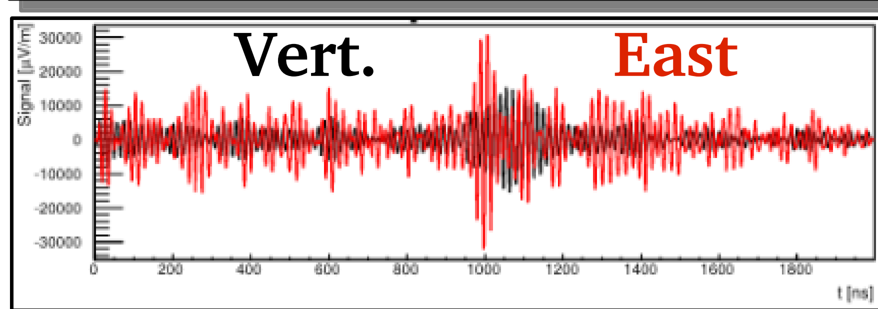








Station 66
Butterfly



Station 87
Tripole