Studies for High Energy air shower identification using RF measurements with the ASTRONEU array

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On behalf of the ASTRONEU group
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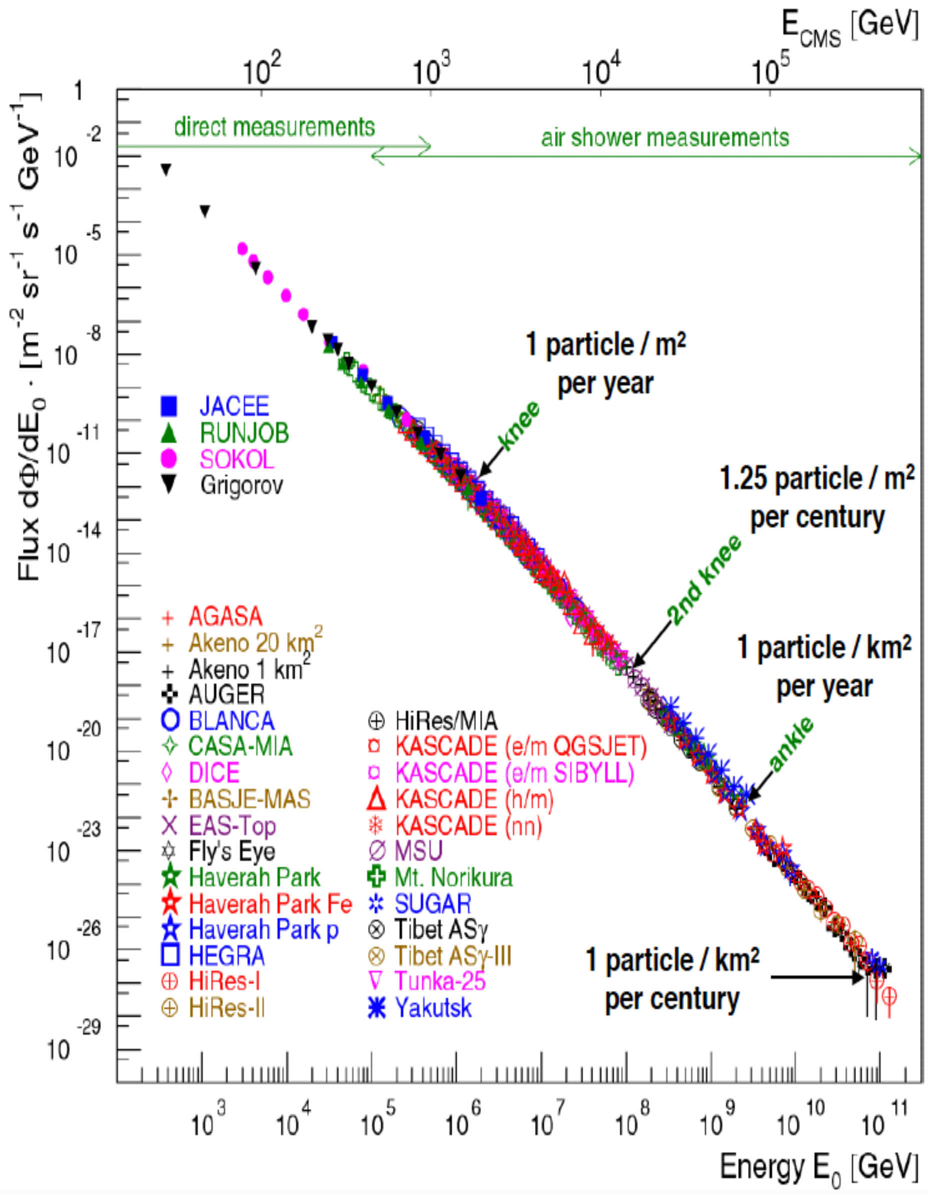
Outline

- Cosmic Rays-Extensive Air Showers (EAS)
- Radio signal (RF) production from the EAS
- The ASTRONEU array - Performance
- RF Analysis - Correlation Study and Combined Performance
- Reconstructing EAS direction using RF signal from single antenna
- Core-Energy-X_{max} reconstruction – Work in progress
- Conclusions - Future Plans

Cosmic Rays (CR) Physics

- CR spectrum described by a power law $dN/dE \sim E^{-3}$
- Beyond the ankle all CR from extra galactic sources
- Still some major open questions:
  - The nature of the Ultra High Energy Cosmic Rays (UHECR)?
  - What are the sources of UHECR
  - Production mechanism ?
  - Galactic vs extra-galactic origin?
  - Why the spectrum at ultra-high energy fall out? ($>6\times10^{19}$eV)
  - GZK cutoff or source limits ?
  - Why the flux goes down dramatically? (Flux/10^3 when energy x 10)



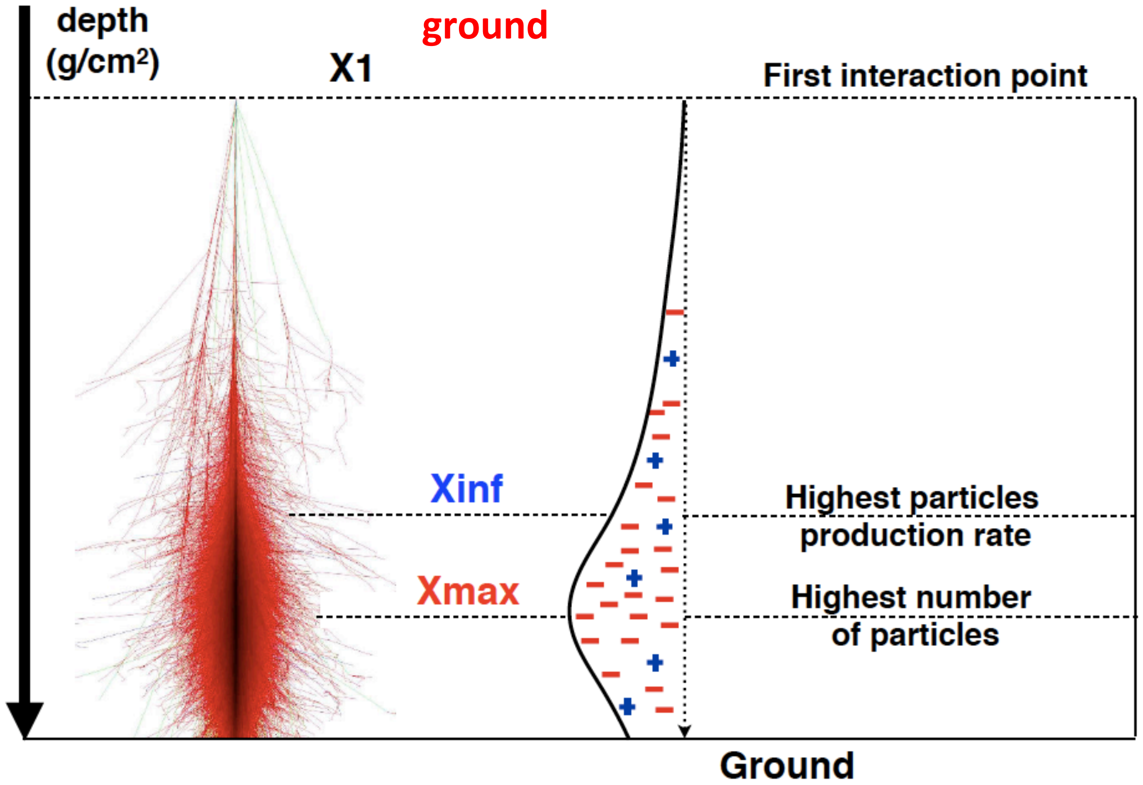
Extensive Air Shower (EAS)

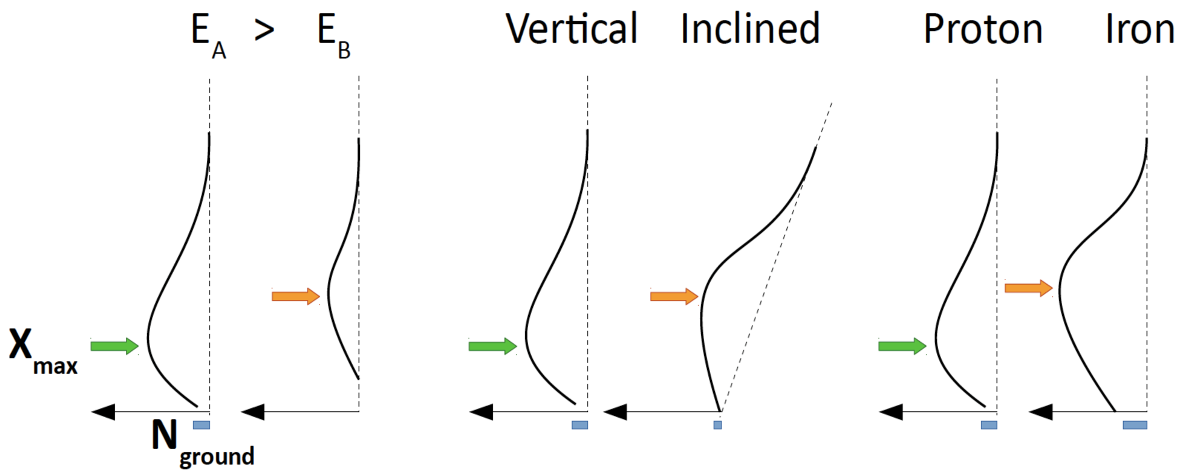
EAS: continuous cascade of particles (mostly e^-, p^+ and γ)

At 10^{19} eV (proton), the shower starts at about 12km high, contains 5×10^9 particles in Xmax and shines 10^2 Km^2 at ground

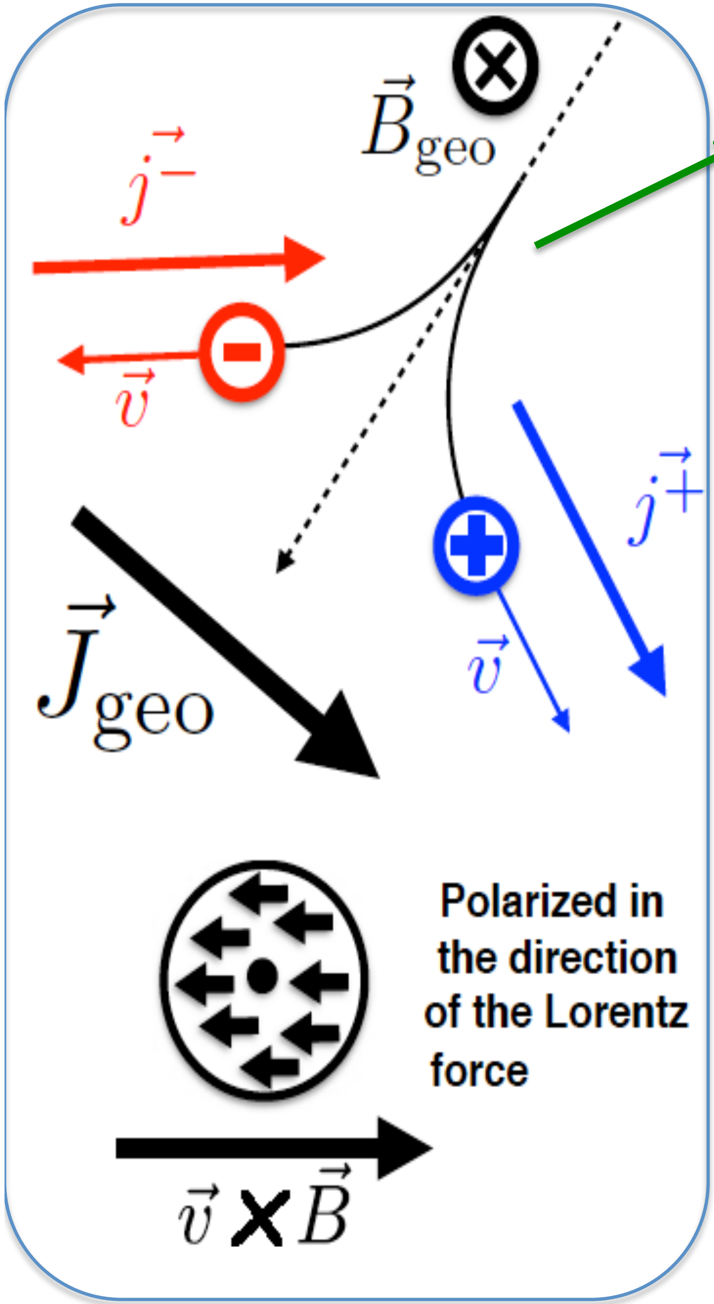
- X1: chain reaction of secondary particles creation is initiated.
- Longitudinal profile: The number of particles as a function of the atmospheric depth.
- Xinf: The inflection point of the profile.
- Xmax: The shower reaches its maximum number of particles.
- Lateral profile: the particle density as a function of the distance from the shower axis.

- The longitudinal and the lateral profile at ground are correlated to the cosmic ray properties : **direction, energy, mass**





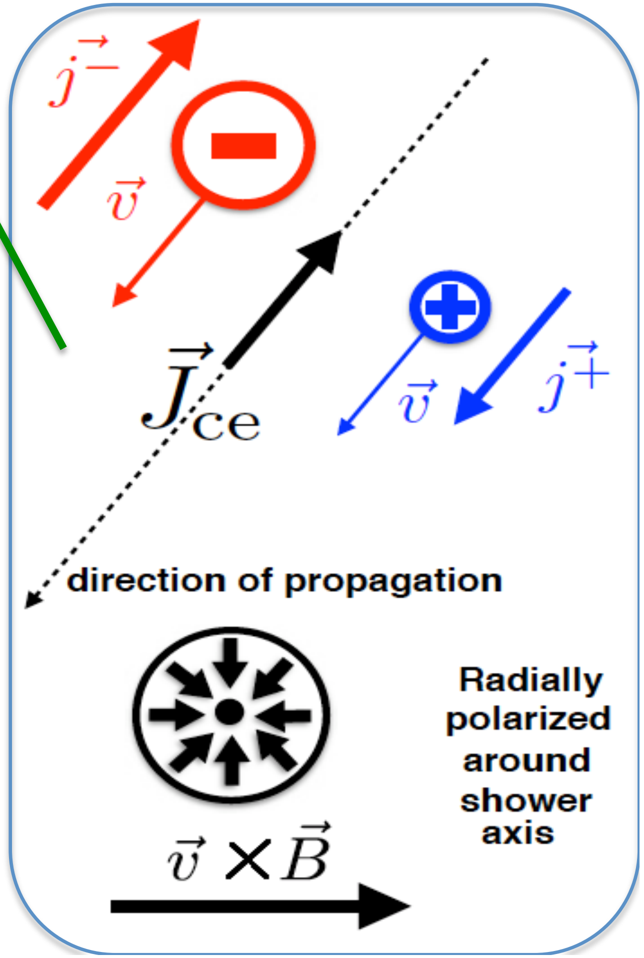
Radio signal (RF) production from the EAS



- **Two main mechanisms contribute to the RF signal**

1. Geomagnetic effect (Kahn and Lerche 1966)
 -Charges moving in the geomagnetic field : Lorenz force
 -Systematic and opposite deviation of the e^-, e^+
 -Transverse current (time variation)
 -polarized in the direction **vxB**

2. Charge excess effect
 (Askaryan 1962)
- e^+ annihilate with e^- of the medium.
- lead to a negative charge excess
- Radially polarized around the shower axis



- The amplitude and the polarization pattern of the 2 contributions depends on the shower properties (direction). The geomagnetic effect usually dominates.

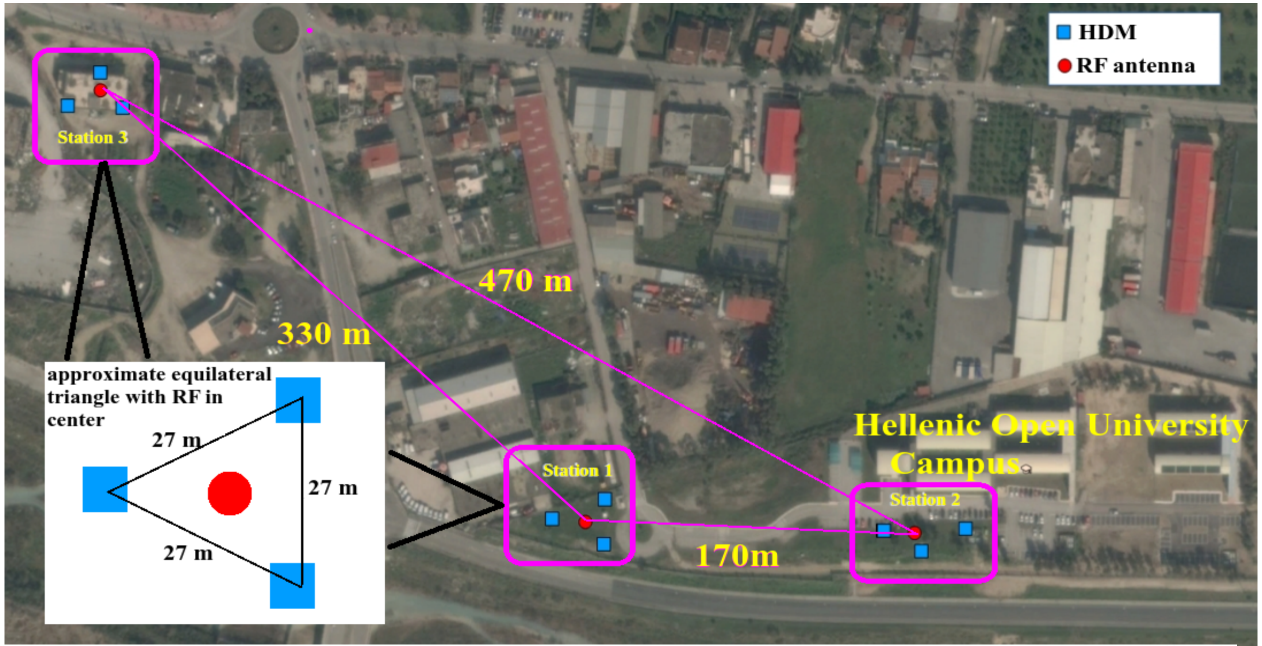
The ASTRONEU array

- ASTRONEU is a combined scintillator detector and RF antenna array (3 stations) which was developed in the campus of the HOU in the outskirts of the city of Patras

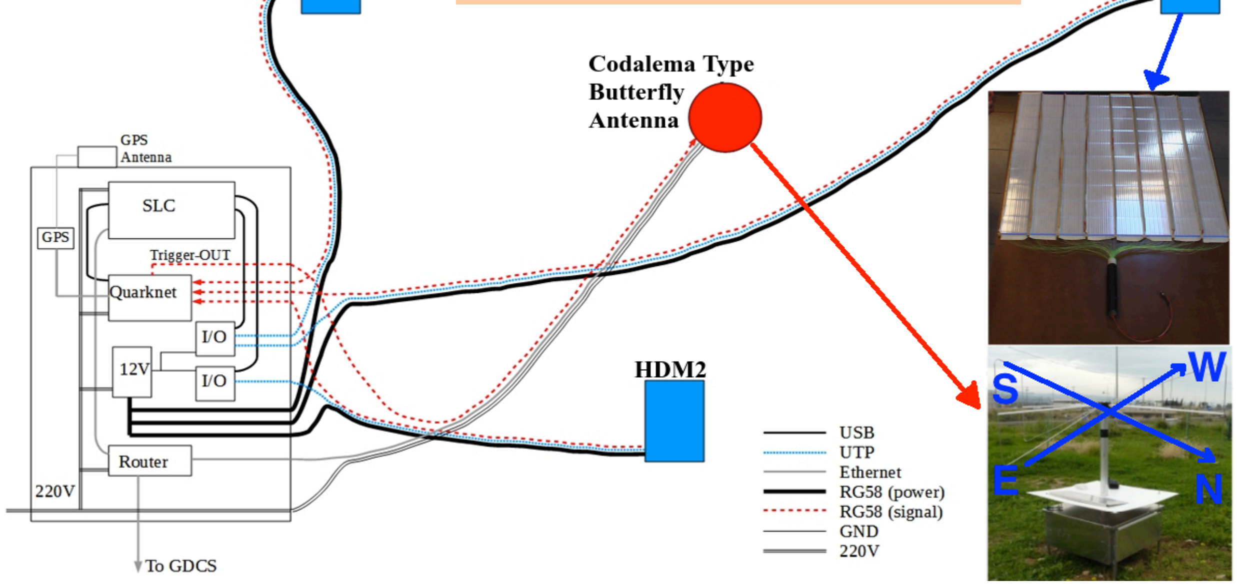
- Each station includes 3 HELYCON Detector Modules (HDM) scintillator counter + 1 Codalema type 2 dipole Butterfly antenna (BFA) connected to LNA.

- Station triggers when all HDM acquire a threshold signal and activates the BFA recording

- ASTRONEU cosmic ray telescope operates in an urban environment with a lot of man made RF signals.



arXiv:1702.04902 [physics.ins-det]

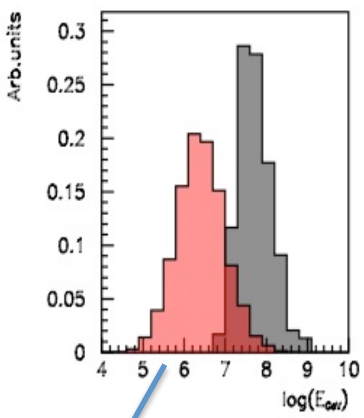


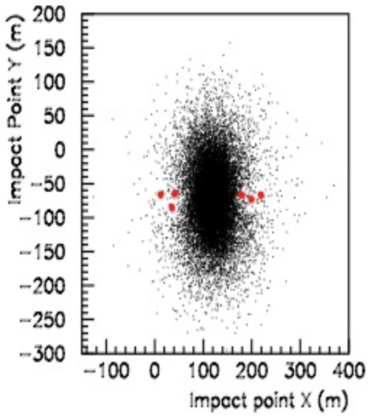
Performance of the Astroneu array

- Single station Performance

station	Event Rate (hr^{-1})	σ_θ (deg)	σ_ϕ (deg)	ω_{median} (deg)	E_{th} (TeV)
A	17.5	3.3	10.4	3.3	20
B	11.5	6.0	14.8	5.5	30
C	18.9	3.7	11.2	3.6	20

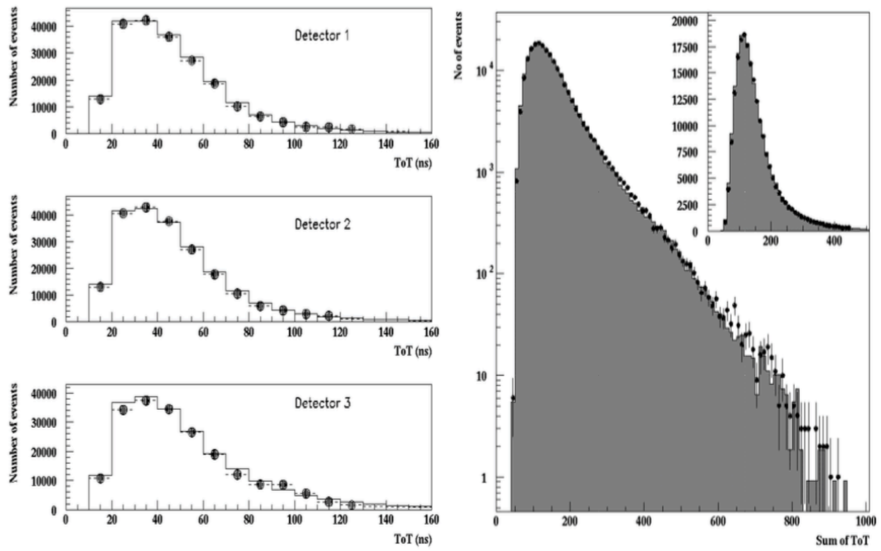
- Double station Performance

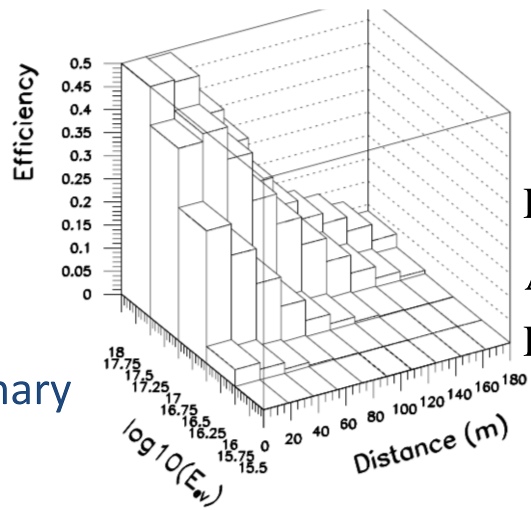




- The energy distribution of the EAS primary particle.
- Distribution of the shower core.

Distributions of the ToT





Energy Threshold: $5 \cdot 10^3$ TeV

Angular Resolution: 2.9°

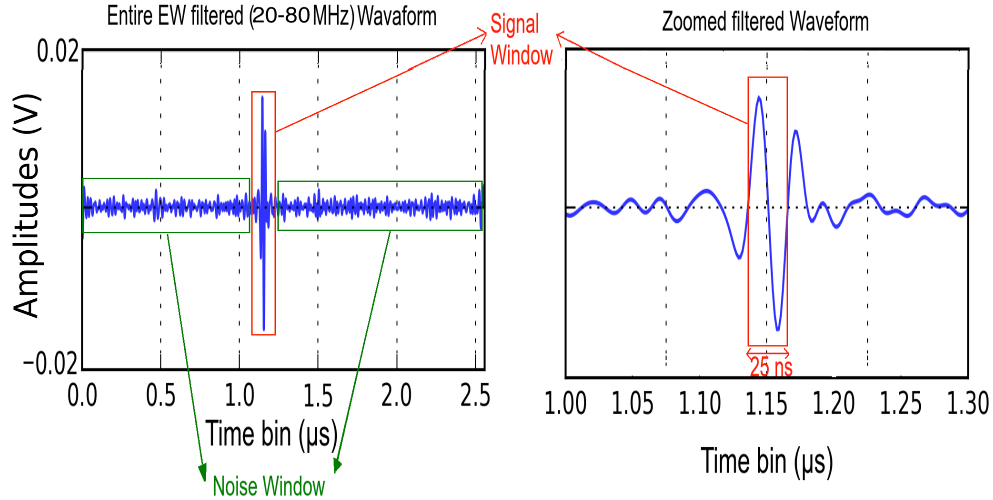
Rate : 0.15 events per hour

arXiv:1801.04768 [physics.ins-det]

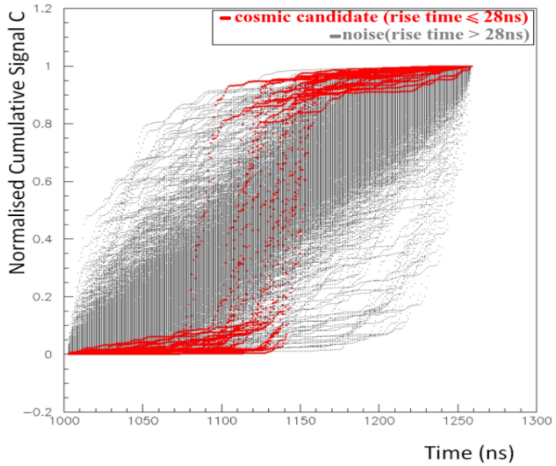
Event Selection-RF Analysis

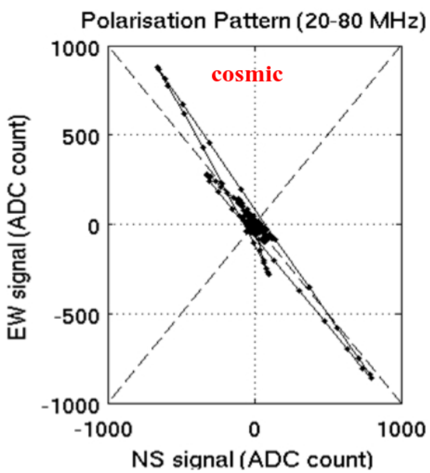
- **RF Signal criteria for characterizing an event as of cosmic origin**

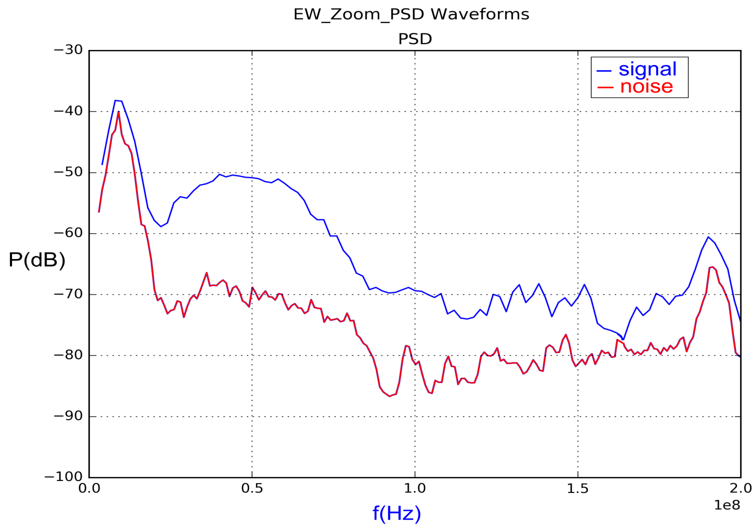
1. It presents an intense peak localized in a narrow time Interval (≈20-30ns)
2. Signal to Noise Ratio (SNR)>8.
3. Exhibits short signal rise time (≤28ns)
4. Its polarization is approximately linear



Transverse current and charge excess have different polarization patterns. Different ellipse's inclination correspond to different position of antennas with respect to the shower core.





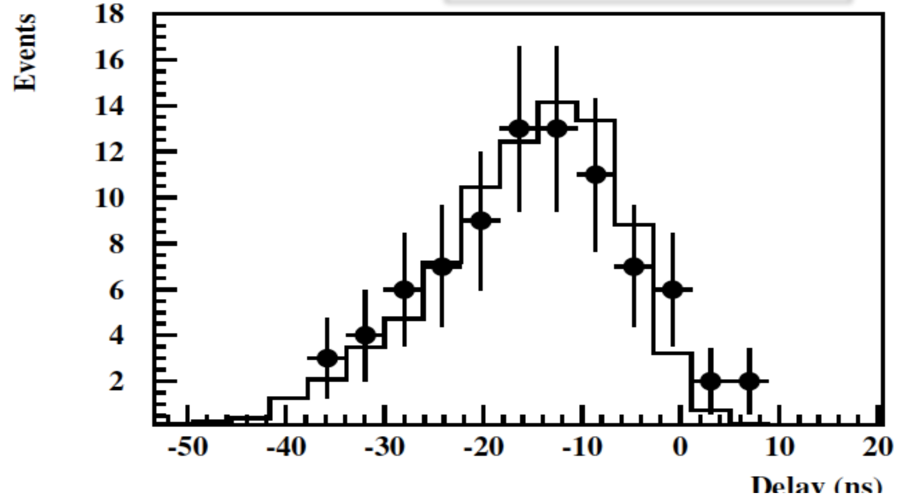


arXiv:1702.05794 [physics.ins-det]

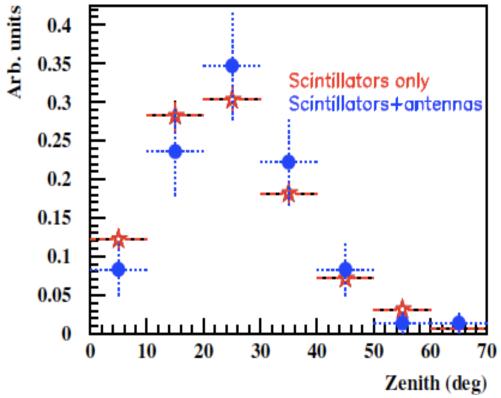
Correlation Study and Combined Performance

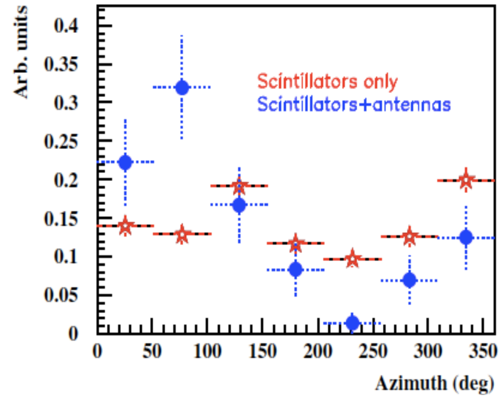
Sample 92 events

- Estimation of the RF signal timing using the reconstructed axis direction from the HDMs of a station + the position of the BFA.
- The evaluated RF timing using the peak of the EW RF pulse is in good agreement with the above estimation.

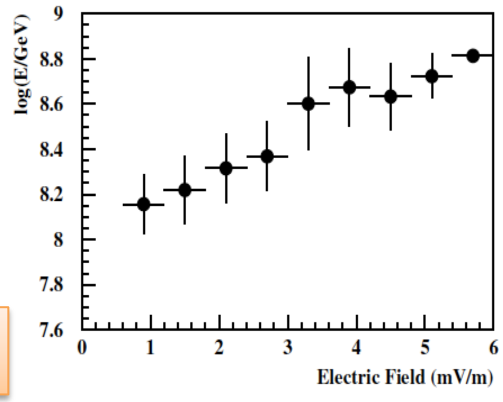


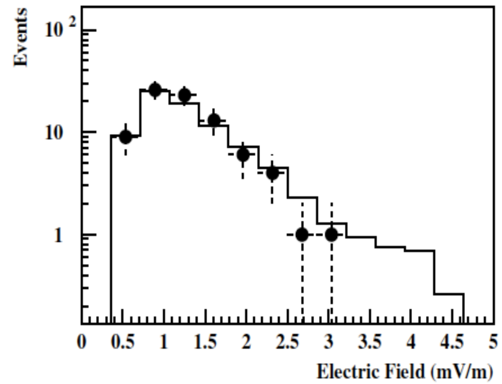
- Reconstructed showers axis direction using only HDM info and both HDM & BFA





- Using the SELFAS simulation package to predict the electric field at the RF positions for MC events we get the electric field as a function of the energy of the EAS primary particle.
- The RF data were used to calculate the electric field intensity and found in good agreement with the simulations.





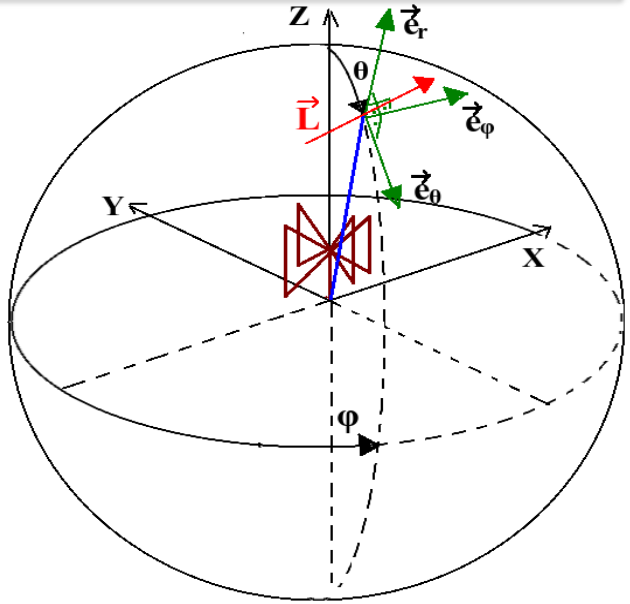
Leisos,A et al., Hybrid Detection of High Energy Showers in Urban Environments, Universe 2019 5(1) 3.

Reconstructing EAS direction using RF signal from one antenna

- Antenna+LNA Vector Effective Length (L)

$$L = \frac{V_{LNA}}{E_{Field}}$$

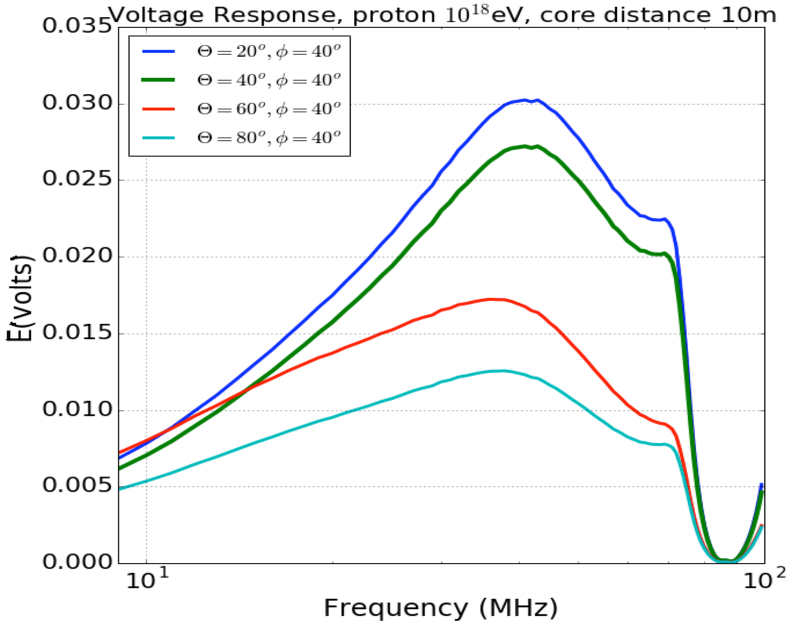
- VEL depends from the gain (θ,ϕ), structural features of the system and frequency.

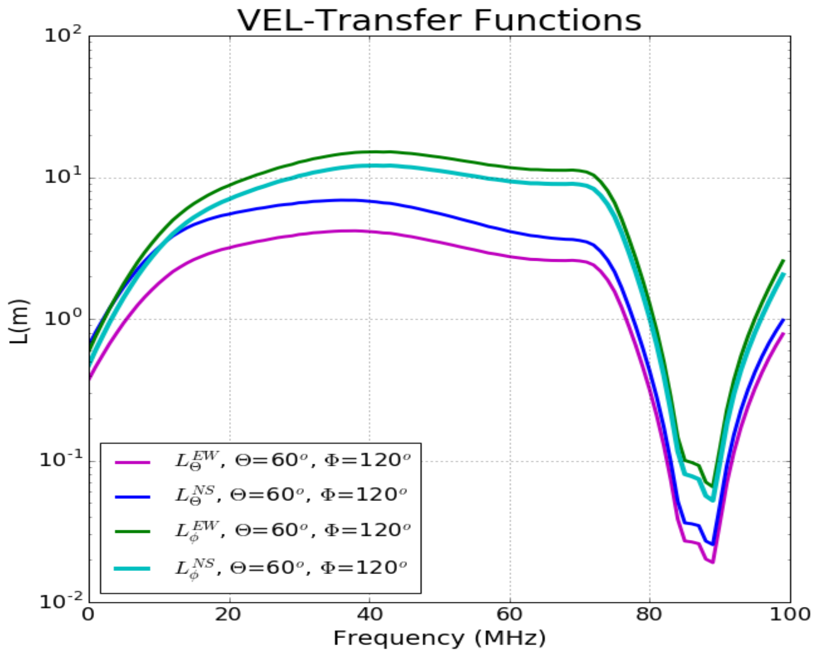


- Voltage Response Model (VRM) of the RF to an incident electric field from direction (θ,ϕ)

$V_{EW/NS}(\theta,\phi,\omega)=L_{EW/NS}(\theta,\phi,\omega)\bullet E_{EW/NS}(\theta,\phi,\omega)$

- Calculate VRM for the RF system combining NEC's + SELFAS simulations in frequency 30-80MHz.





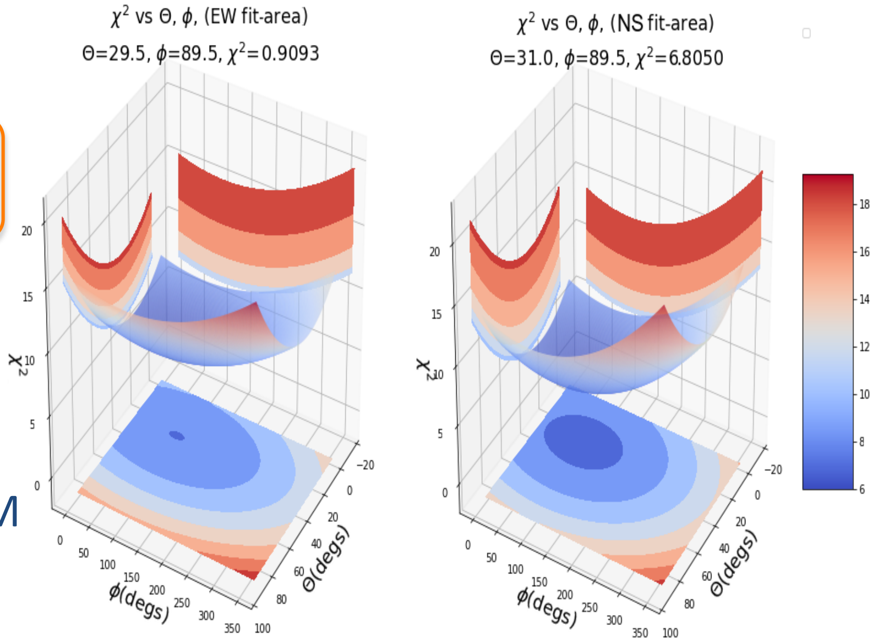
Reconstructing EAS direction using RF signal from one antenna

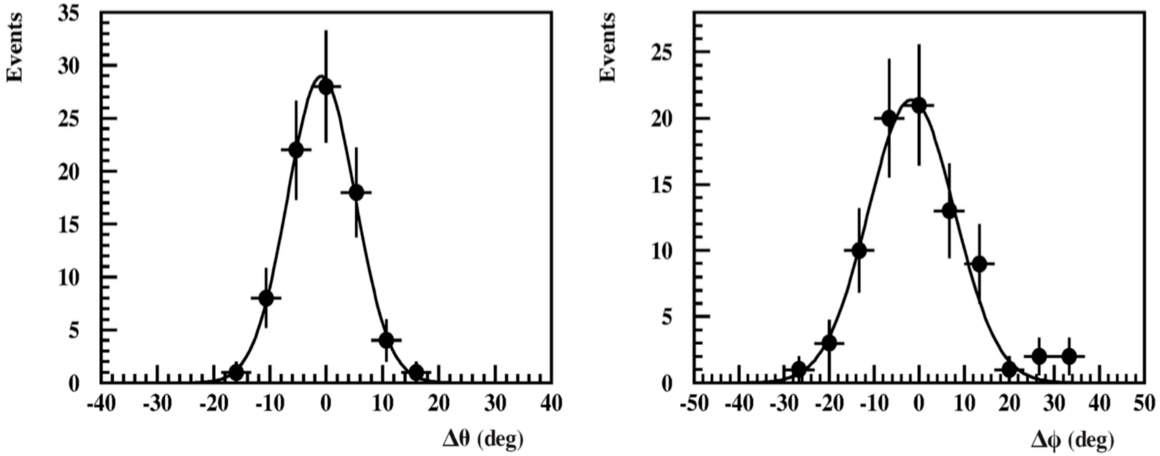
- Estimation of the CR arrival direction by fitting the spectrum of a real cosmic event and the response which is calculated for different (θ,ϕ), minimizing

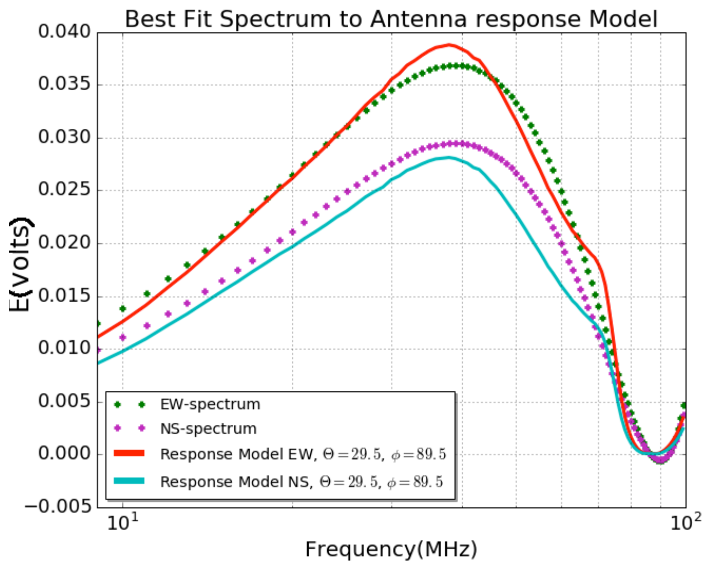
$$\chi^2 = \sum_{30-80\,MHz} (a \cdot V_{response}(\theta,\varphi,\omega) - V_{real}(\theta,\varphi,\omega))^2$$

- Plot χ^2 as a function of (θ,ϕ) and fit to these data points a surface. In the total minimum of this surface we have the event arrival direction.

- Analyzing 92 events and comparing with the HDM the distribution of the difference on θ,ϕ are well described by Gaussian functions centered near zero with $\sigma_{\Delta\theta}=6^o$, $\sigma_{\Delta\phi}=9.6^o$
- **This can be used also for event selection.**



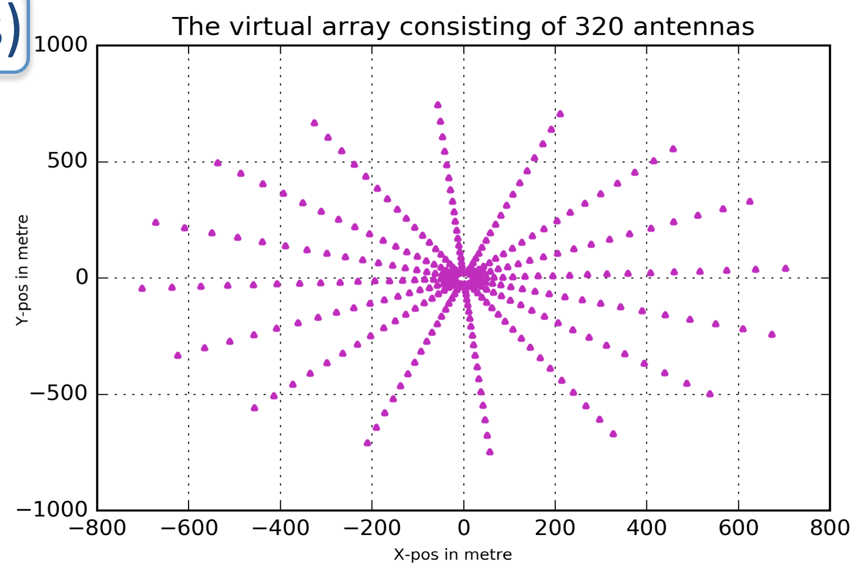




Nonis, S, et al, Proceedings of the UHECR 2018, Paris, France, 8–12 October 2018.

Core-Energy-X_{max} (Work in progress)

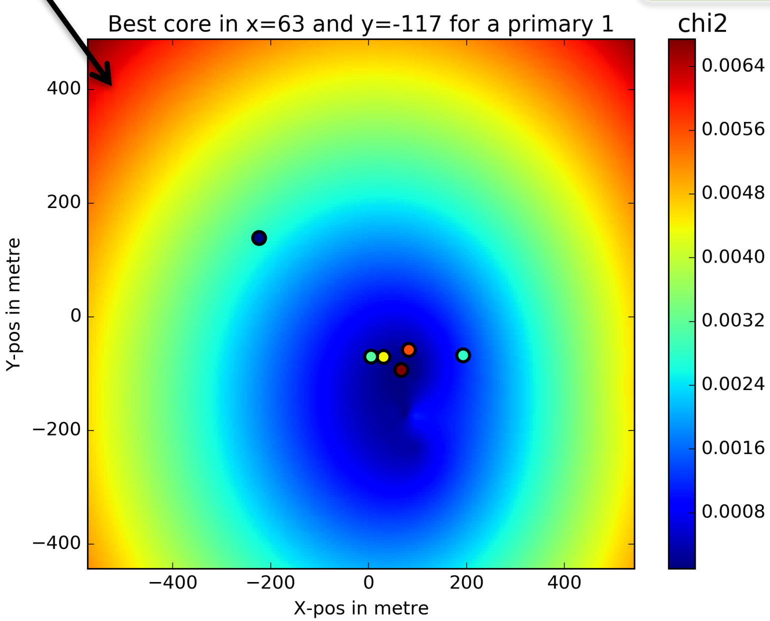
- Reconstruction of main shower parameters core, Energy, Xmax and mass from RF data and simulations.
- Simulation of 60 showers for the virtual array
  - > 40 protons + 20 iron nuclei
  - > experimental arrival direction
  - > primary energy: 1EeV
  - > realistic X1 & Xmax from simulations

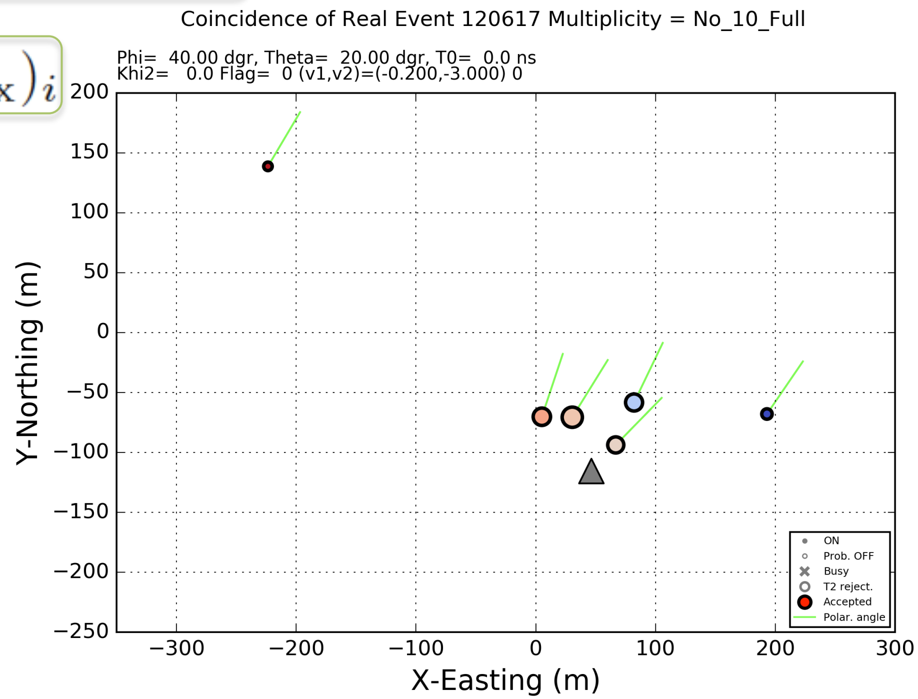


$$\chi^2(x_i, y_j) = \frac{1}{n}\sum_{k=1}^{n}\left(\frac{C_{ij}E_{ijk}^{\mathrm{sim}} - E_k^{\mathrm{det}}}{\sigma_k^{\mathrm{det}}}\right)^2$$

$$E_p^{\mathrm{exp}} = C \times E_p^{\mathrm{sim}}$$

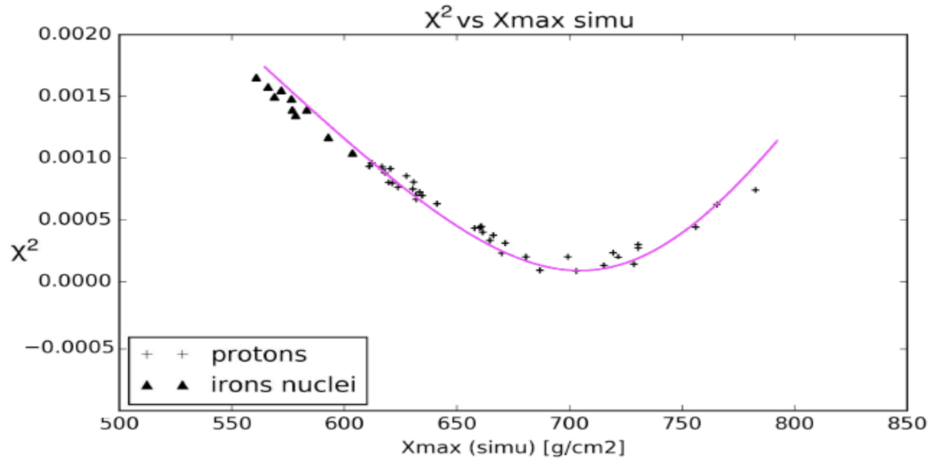
$$(\chi^2, X_{\mathrm{max}})_i$$

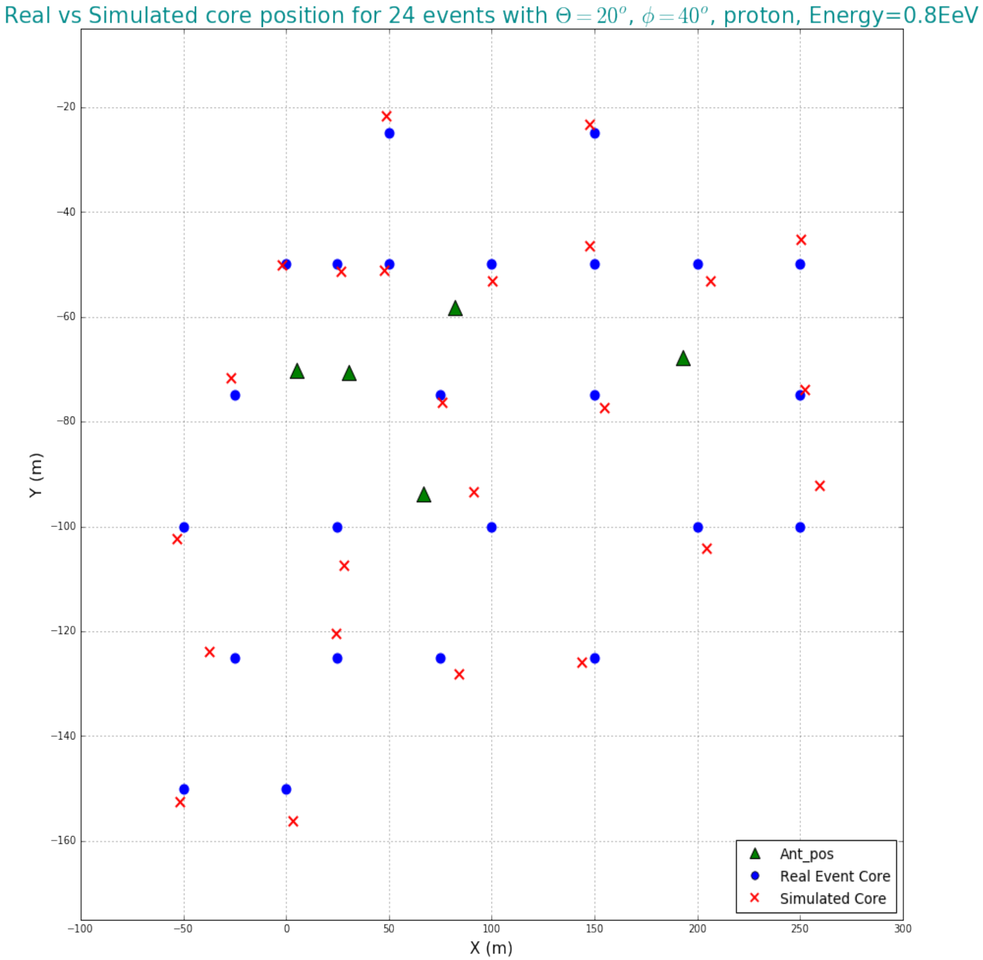




Core-Energy-X_{max}
(Work in progress)

- Since 2017 three more antennas were installed at station A
- First sample with 24 simulated events with energy 0.8EeV, θ=20°, ϕ=40°, primary=p
- The reconstructed core position in good agreement with the real.
- Need for more events statistics
- Shower core + energy -> search for sudden death pulses (electron deceleration in the ground).
- Showers with energy >5x10^{18}eV and core<100m create detectable amount of electrons in the ground.





Conclusions

- Confirm that the RF detection in environment with strong electromagnetic noise is possible even with small scale hybrid arrays.
- RF signal timing at the peak of the EW signal is compatible with the expectation using the HDM pulses timing. This confirm that the RF signal is of cosmic origin.
- The azimuth angle anisotropy agrees with the expectation due to the geomagnetic emission process .
- The VEL of the antennas which are strongly frequency and angular dependent show that the RF signal's spectrum are in agreement with the NEC simulations and MC expectations.
- The RF pulse from single antenna combined with MS simulations might give access to the cosmic ray arrival direction.
- Reconstructing core, energy, Xmax and primary mass is feasible with 5 RF antennas and simulations.

Future Plans

- Search for low frequency pulses (1-10MHz) from showers.
- Search for the sudden death pulse (so far no radio experiment detect it).
- Efforts from Hellenic Open University group to build a new low cost RF antenna.
- Expand the Astroneu array with more particle detectors and RF antennas. More accurate predictions and extended RF studies.

Thank you