Karlsruhe Institute of Technology

Institute for Space Sciences

Radio observations of cosmic ray air showers with LOPES

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Oct. 4th , 2010

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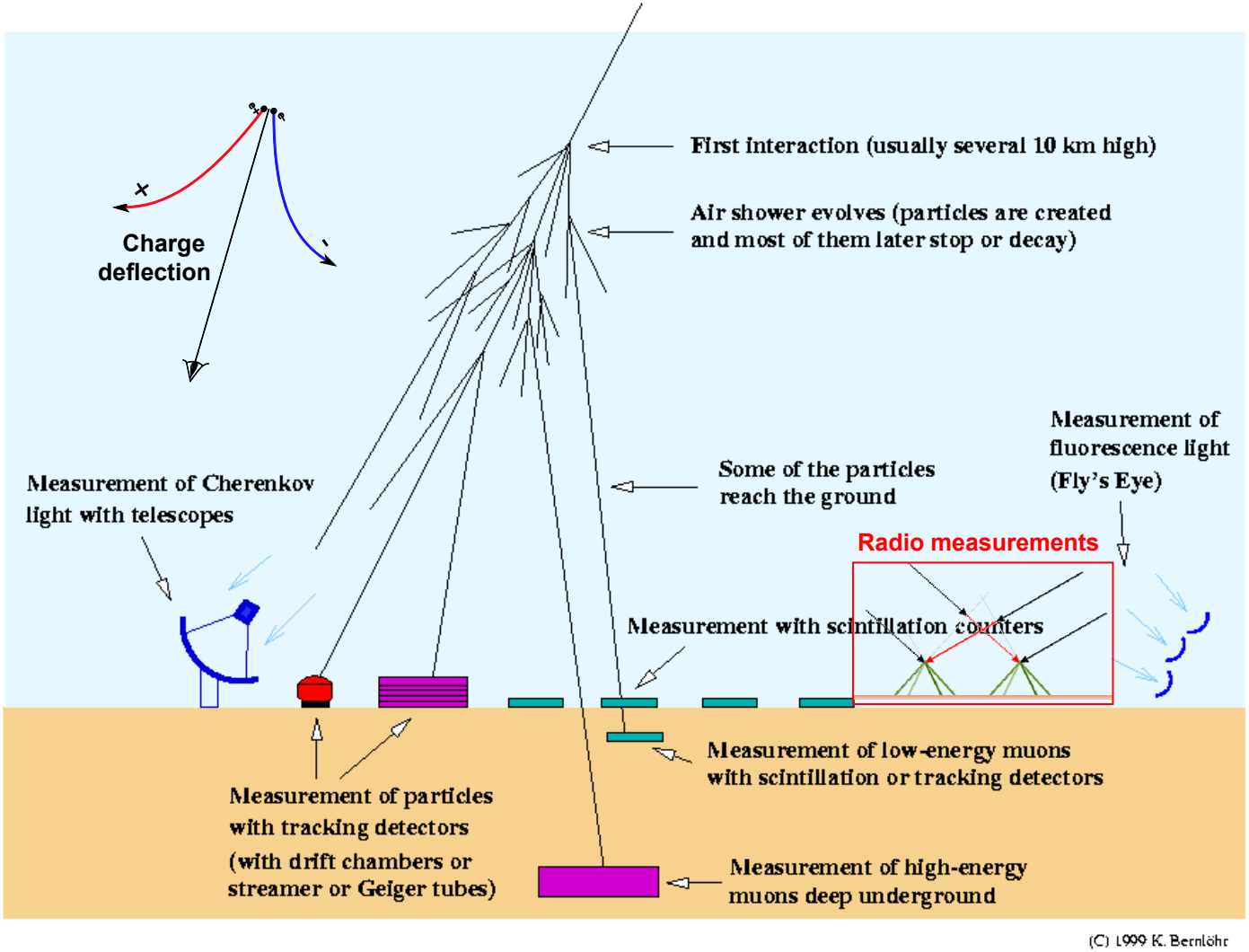




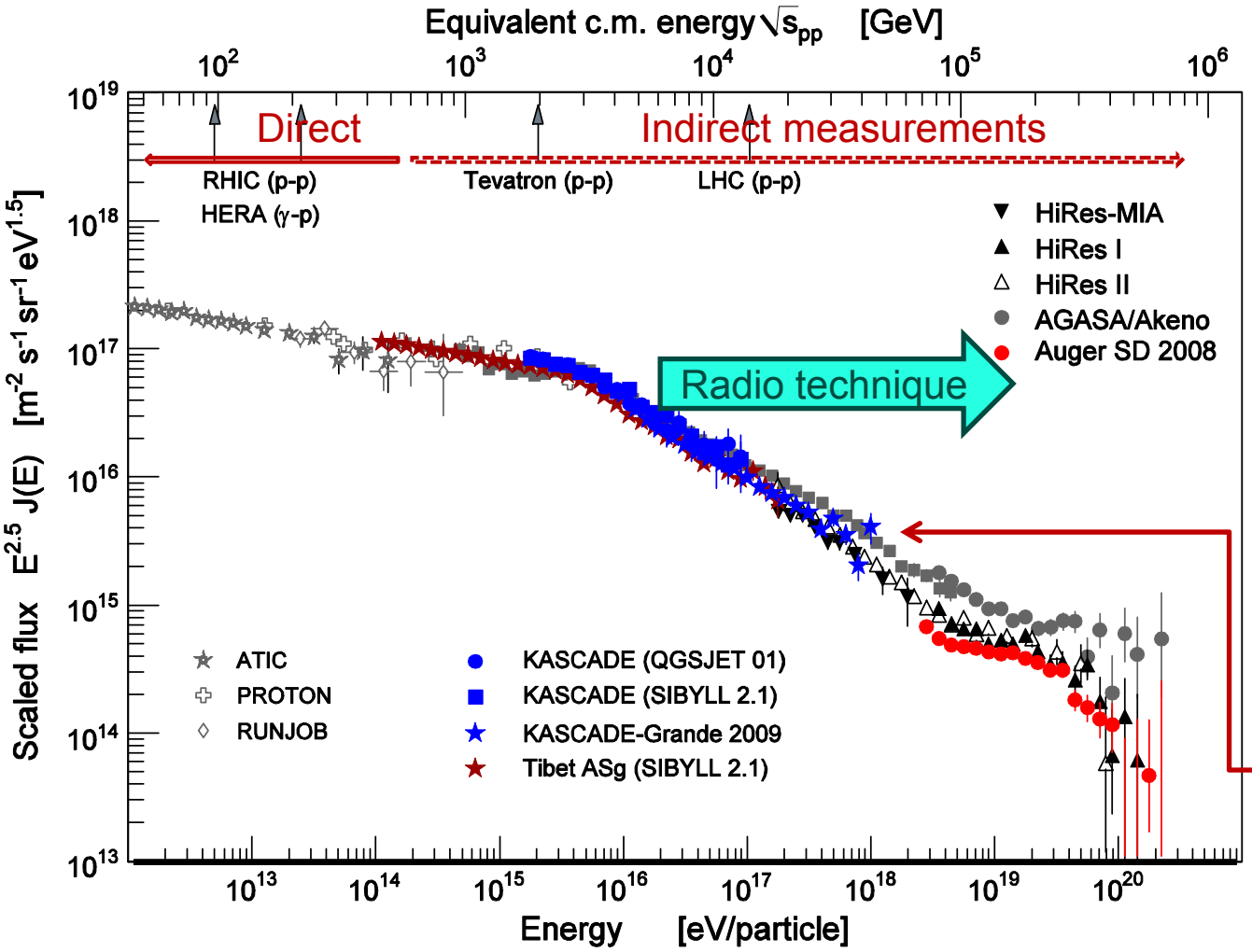
Outlook

- Introduction
  - Cosmic ray air showers
    - Radio emission
  - Detection techniques
    - LOPES experiment
      - Measurements & Simulations
- Summary

Cosmic ray air showers



Energy Spectrum

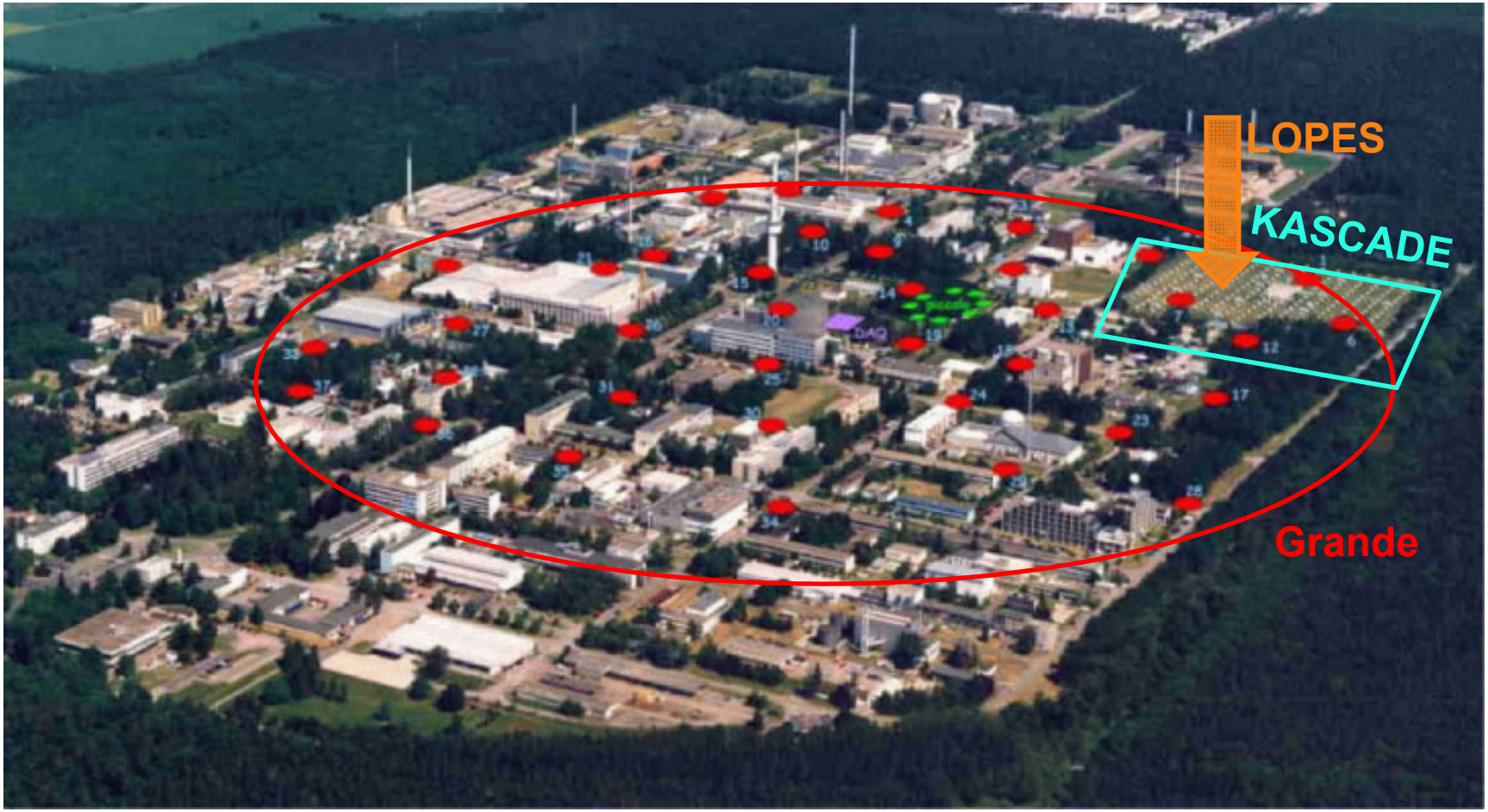


Transition from Galactic to Extragalactic origin of CRs?

Bertaina et al., ICRC'09, Lodz

LOPES @ KASCADE-Grande

*LO*FAR *P*rototyp*E* *S*tation



LOPES Collaboration

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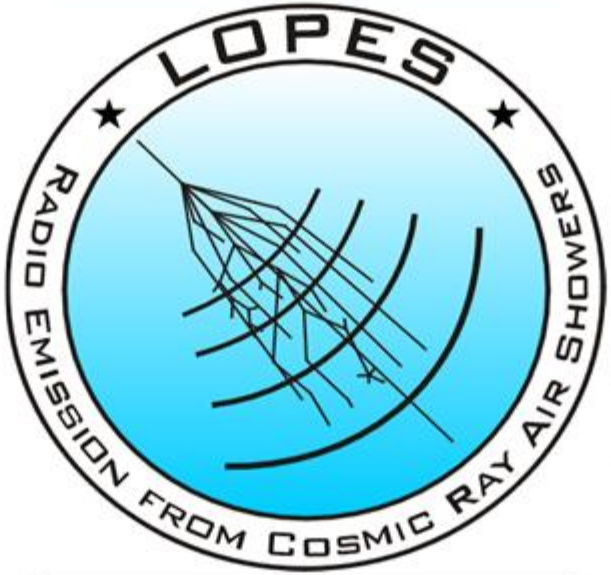
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Detection techniques



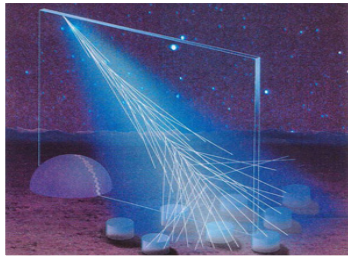
KASCADE - Grande

- Particle detector (scintillator + muon tracking detector)
- Measure the galactic CRs
- E_p:$10^{15 - 18}$ eV
- Grande - extended KASCADE
- Located At KIT



LOPES

- LOFAR Prototype Station
- Radio detector
- $E_p > 10^{16.5}$ eV
- 40 - 80 MHz
- Uses KASCADE & Grande trigger
- Self-trigger: LOPES^{STAR}

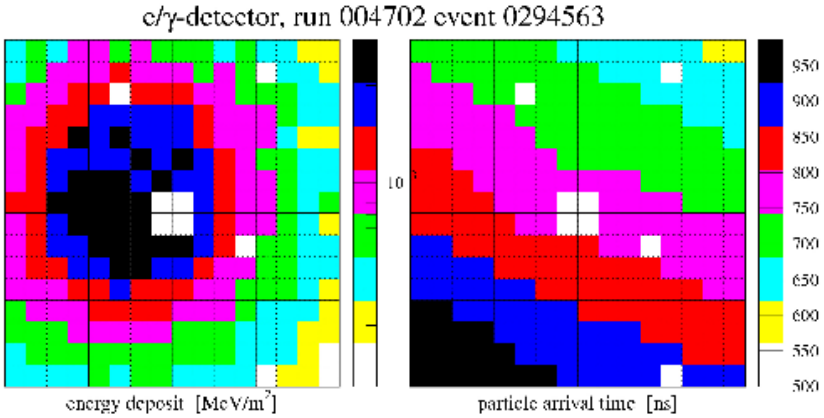


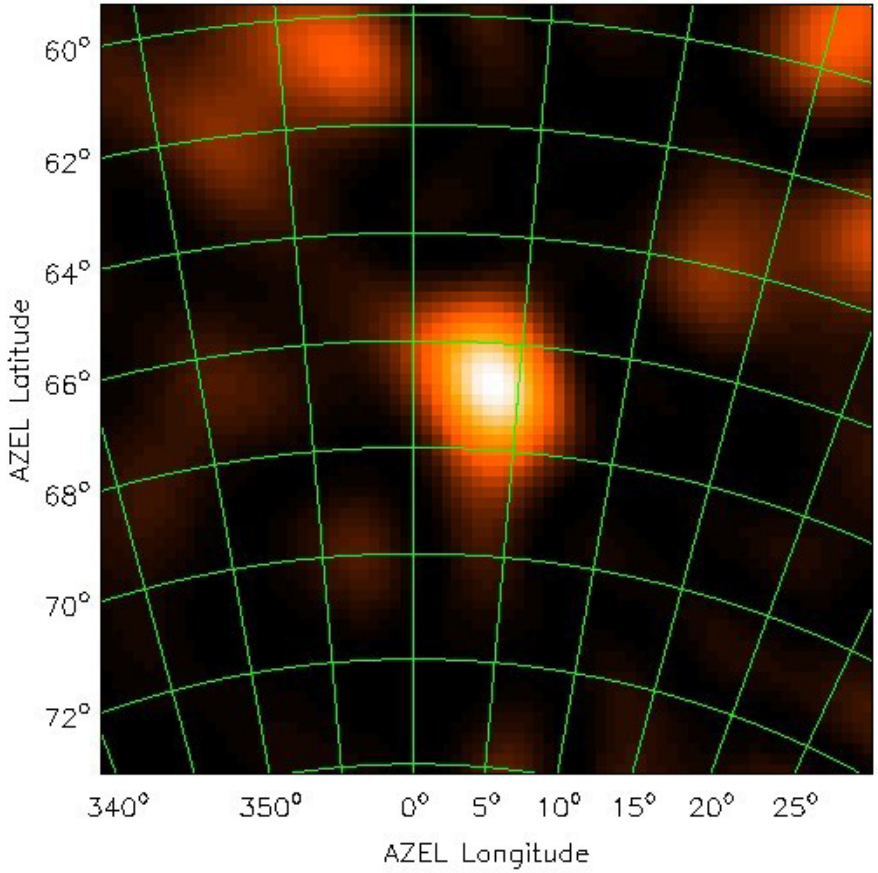
Pierre Auger Observatory

- Hybrid detector (fluorescence + water tank)
- Measure the extragalactic CRs
- $E_p > 10^{17.5}$ eV
- Located in Argentina
- Auger-radio: AERA

Proof-of-principle

- 1st unambiguously detected EAS generated radio flash!
- Dominant geomagnetic effect!





LOPES collaboration, Nature 435, 313 (2005)

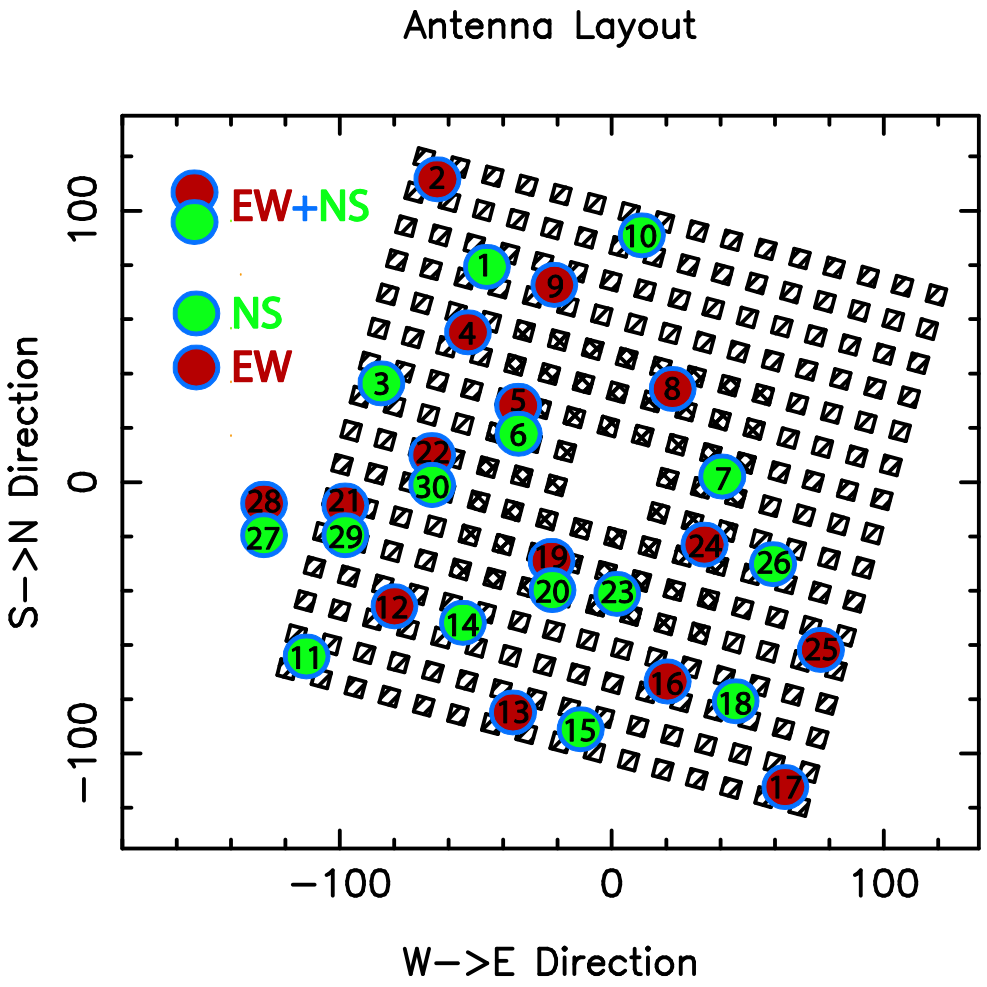
Polarization measurements

- Motivation:
  - Emission highly linearly polarized in the direction ⊥ to shower axis and B-field
- Antenna configuration:

  10 EW, 10 NS, 5 EW+NS

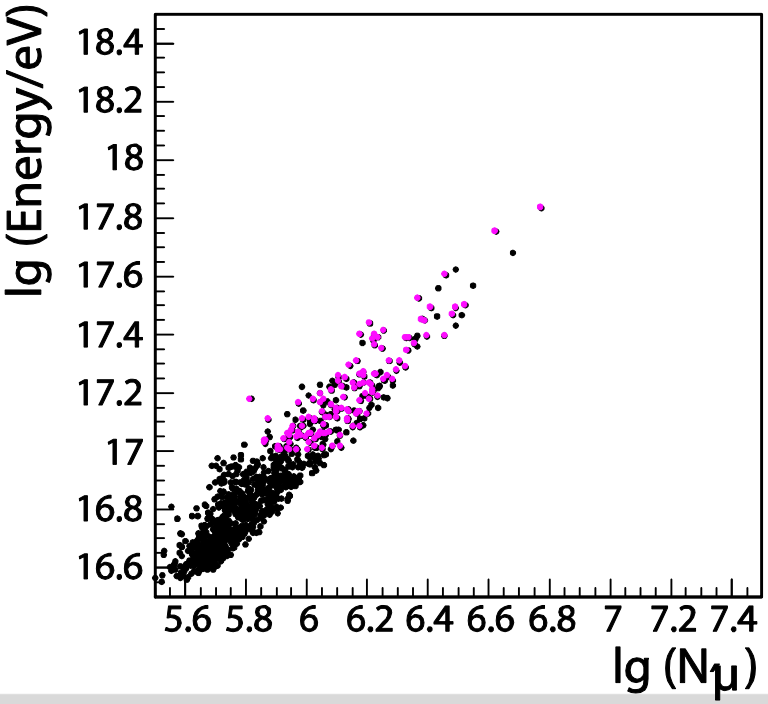
  (Dec'06 – Dec'09)
- Trigger source:

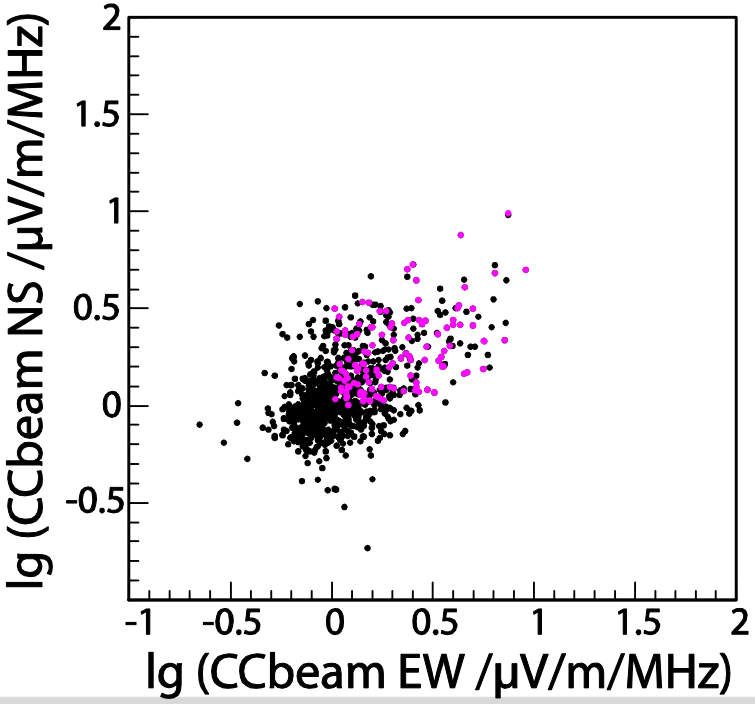
  KASCADE-Grande



Event selection: quality cuts

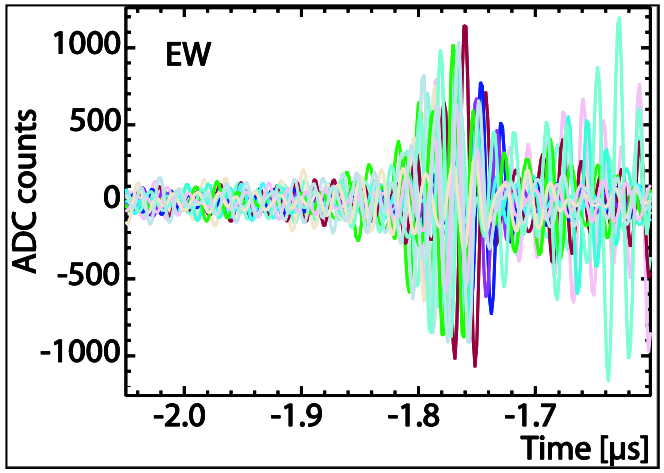
- EAS observables:
  - Core position (KASCADE or Grande)
  - Direction (φ ,$\theta < 40^{o}$)
  - Primary energy ($E_p > 10^{17}$ eV)
- Radio observables: SNR > 4, CCbeam > 1 μV/m/MHz



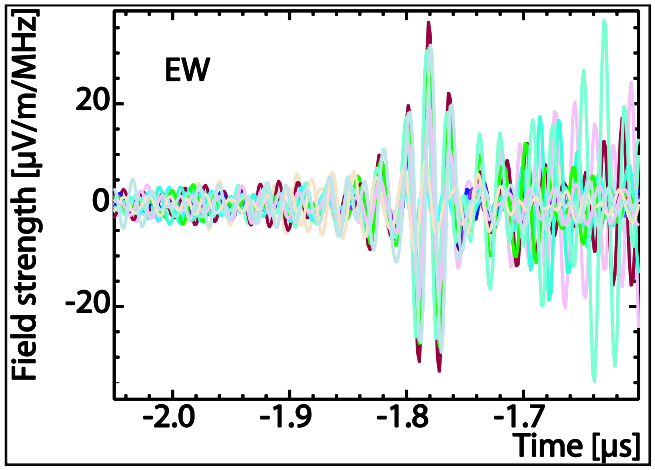


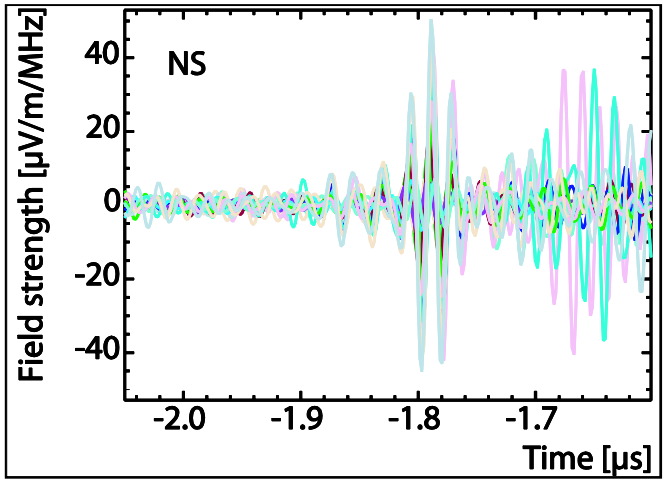
Event example

1. Raw data

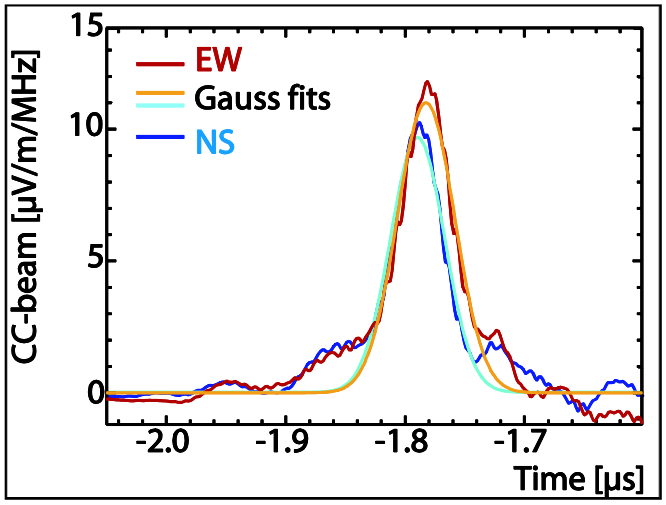


2. Radio signal reconstruction



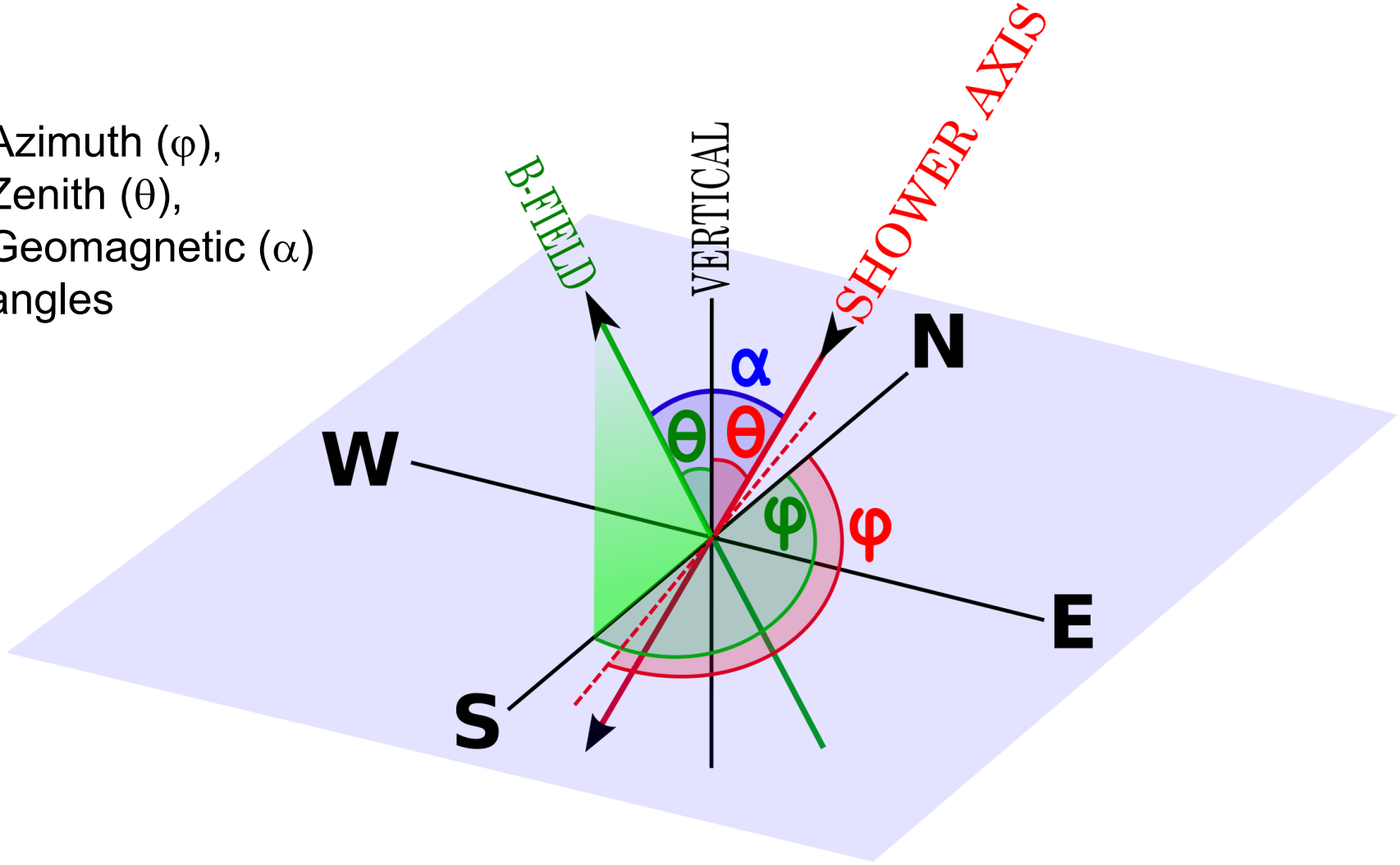


3. Pulse quantification



Sketch of an EAS and B-field

Azimuth (φ),
Zenith (θ),
Geomagnetic (α)
angles



Q: Is the geomagnetic effect the main radio emission mechanism?

Simplified geomagnetic model

- Geomag. dependence

$$\vec{P}_v = \vec{v} \times \vec{B} = f(\varphi, \theta, \alpha)$$

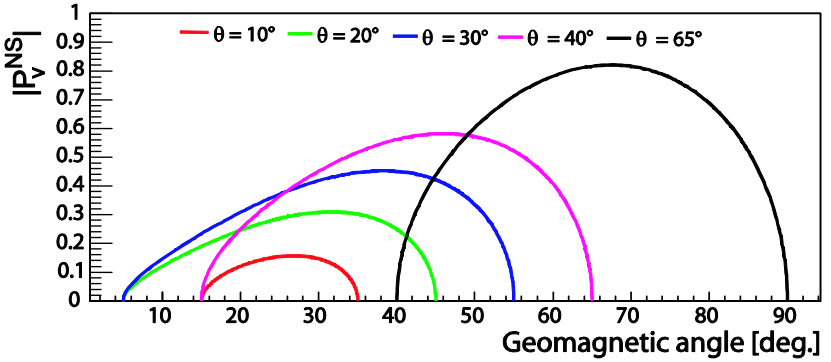
- Large α for θ=65°!

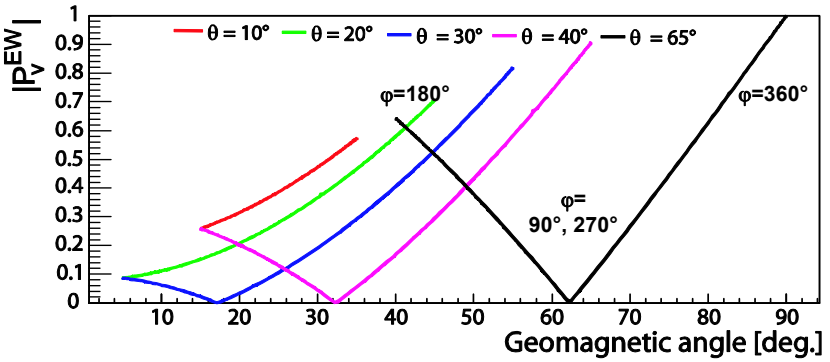
- Different dependences for:

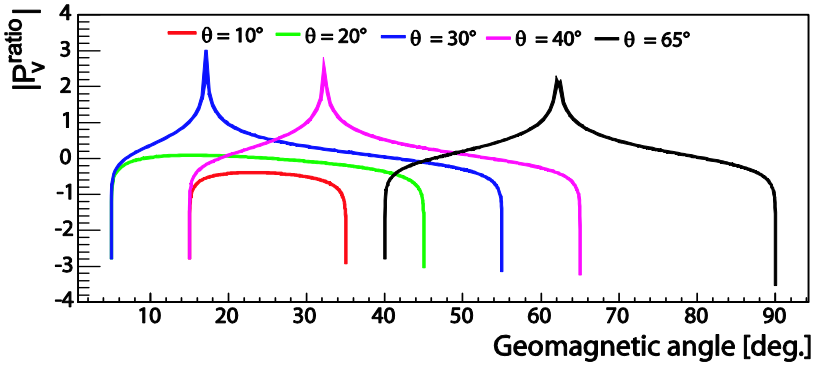
$$\vec{P}_{NS} \;\&\; \vec{P}_{EW}$$

- Characteristic dependences (on large θ) of:

$$\vec{P}_{ratio} = \vec{P}_{NS} \,/\, \vec{P}_{EW}$$





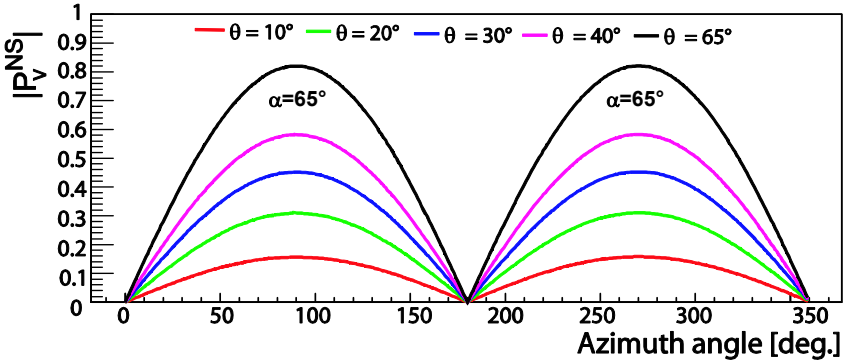


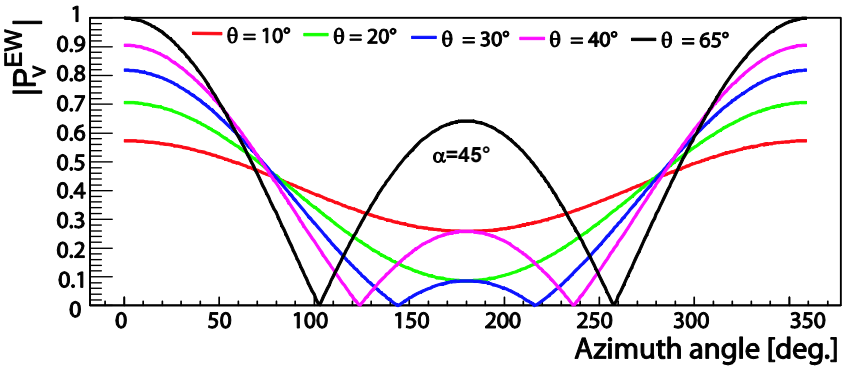
Simplified geomagnetic model

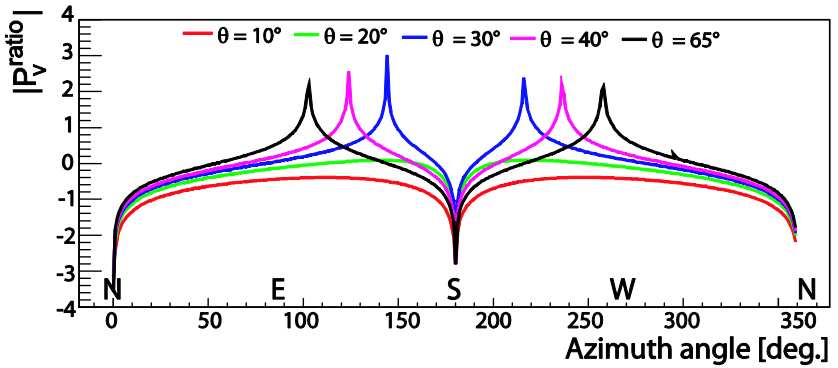
- Azimuth dependence

$$\vec{P}_v = \vec{v} \times \vec{B} = f(\varphi, \theta, \alpha)$$

- Large $\vec{P}_v$ for θ=65°!
- $\vec{P}_{NS}$:expect showers coming from E & W dir.
- $\vec{P}_{EW}$:expect showers coming from N & S dir.
- $\vec{P}_{ratio} = \vec{P}_{NS} / \vec{P}_{EW}$
  - > 0: NS dominat
  - < 0: EW dominat

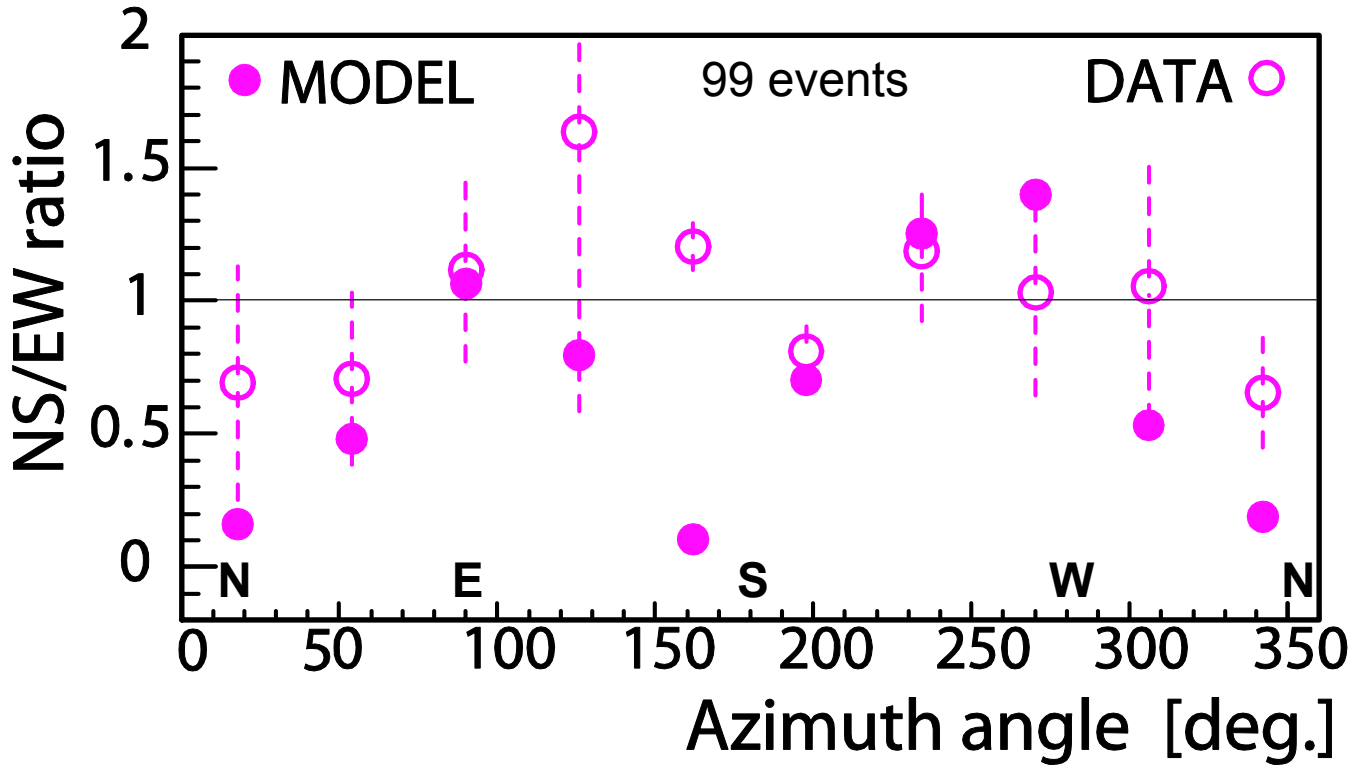






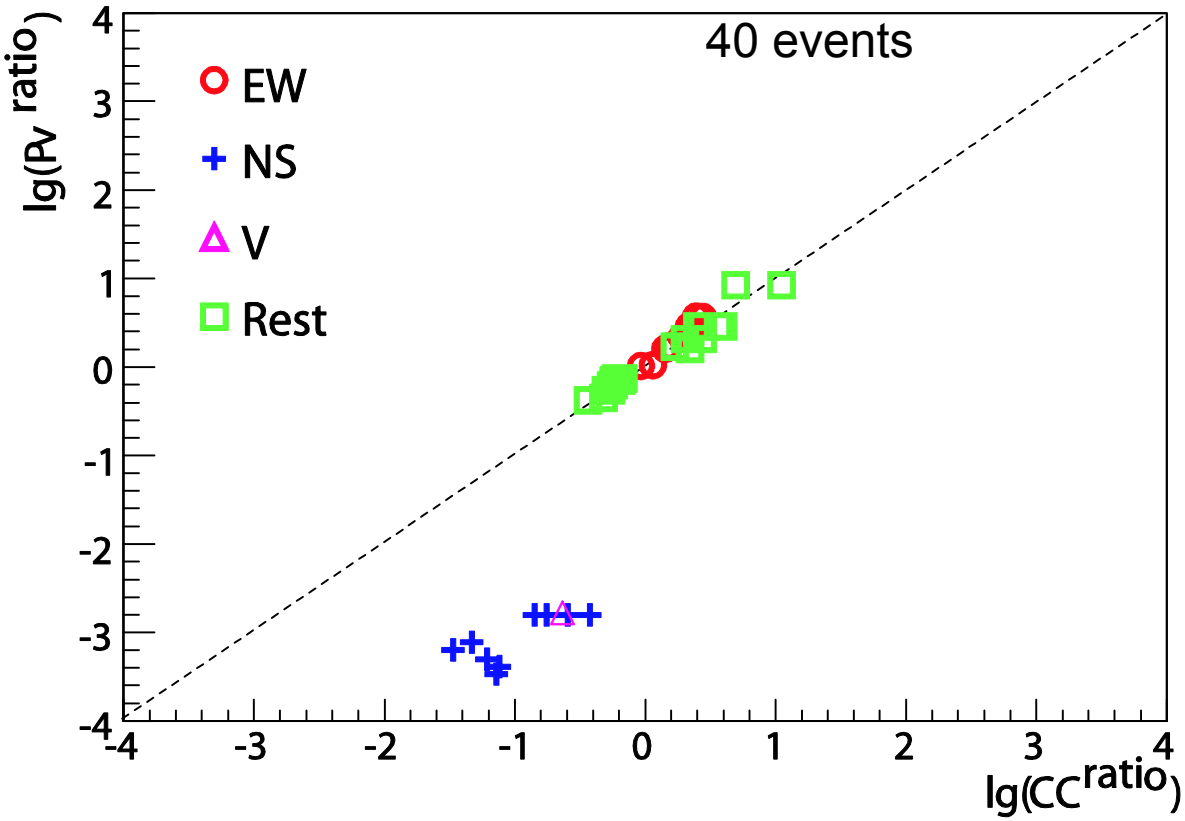
Comparison: Model & Data

Ratio >1 dominant NS detection, otherwise EW detection
Deviations obseved in the North and South directions:
Another emission mechanism?



Comparison: Model & Simulation

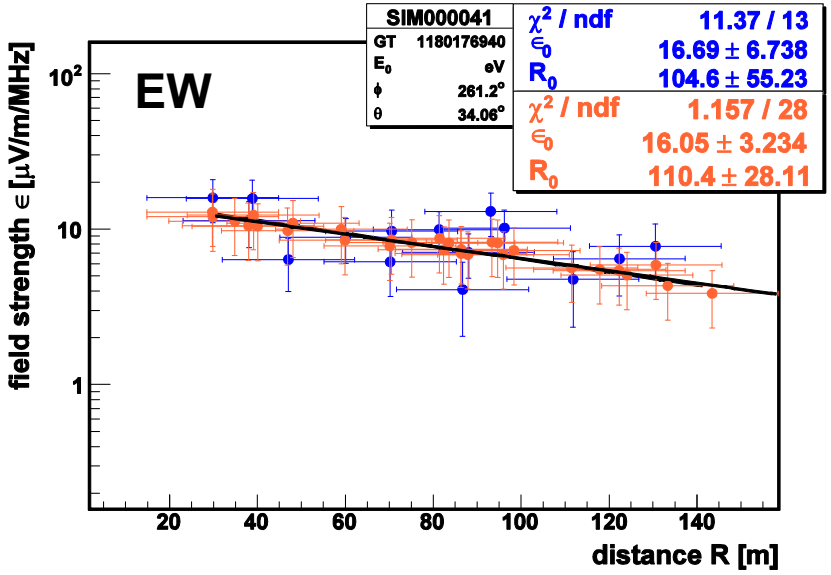
Good agreement observed, except incoming showers from North and South directions. Negative charge excess (~10%) joining the geomagnetic effect?

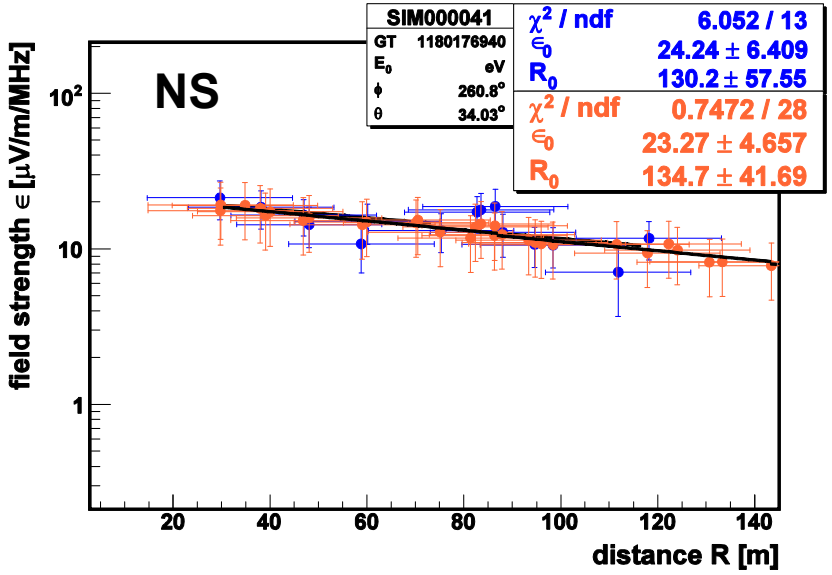


Lateral distribution

Event example: shower coming from West direction gives comparable results in both polarizations (for sim. and data)

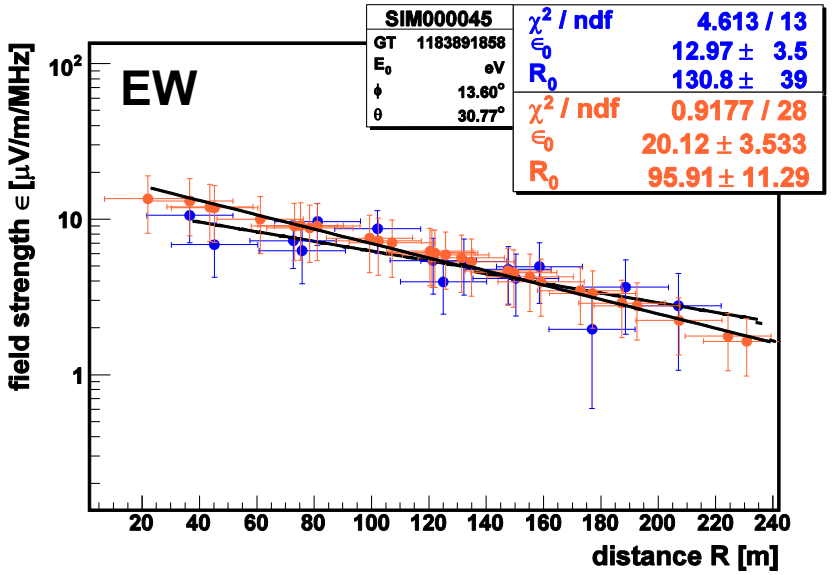
Fitting function: $\varepsilon \sim \varepsilon_0 \exp(-R/R_0)$

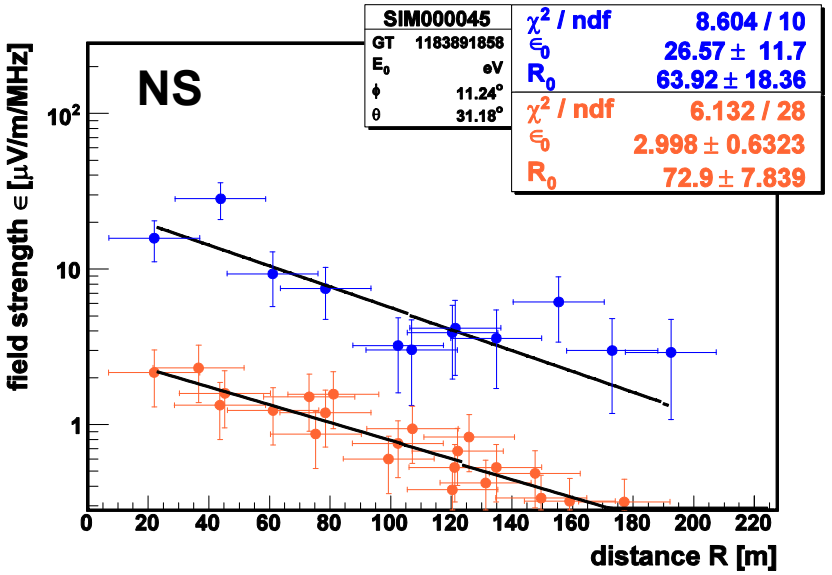




Lateral distribution

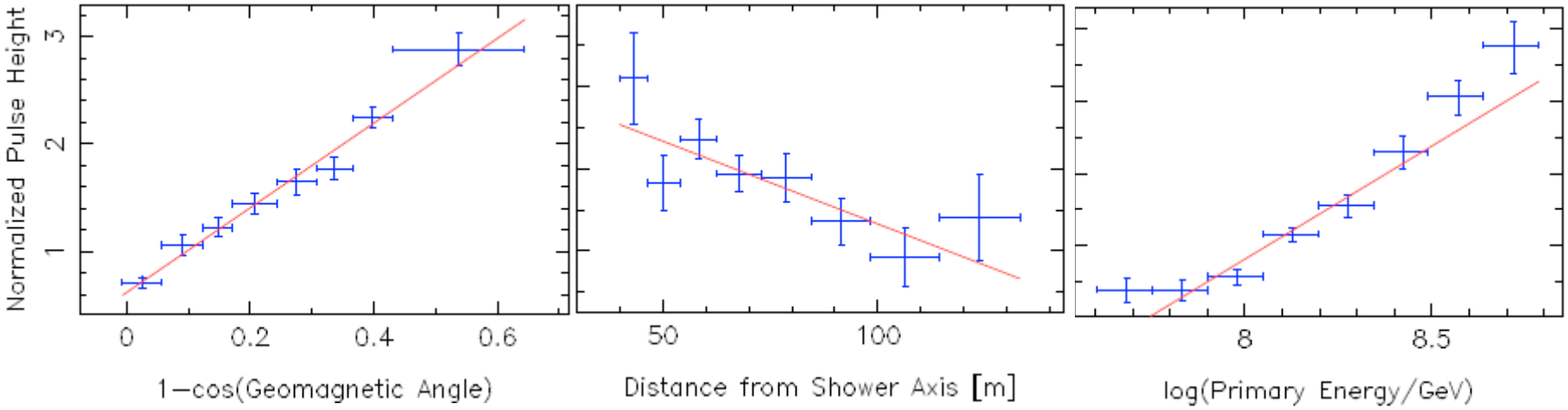
Event example: shower coming from North direction gives signal in both polarizations: another hint to an additional emission mechanism besides the geomagnetic effect.





Pulse height parametrization

- Function of: $f(1-\cos(\alpha), R, E)$, i.e. geomag. angle, direction, energy
- Single polarization (EW); abs. amplitude calibration, using KASCADE shower geometry



$$\varepsilon_{est}^{EW} = (11 \pm 1)[(1.16 \pm 0.025) - \cos(\alpha)]\cos(\theta)\exp\left(\frac{-R}{(236\pm81)m}\right)\left(\frac{E}{10^{17}\,eV}\right)^{0.95\pm0.04} \quad \mu V / m / MH$$

Horneffer et al., ICRC, Mexico 4 (2008) 83

Pulse height parametrization

- Function of: $f(|\vec{P}|_{EW,NS}, D, E_p)$, i.e. direction, distance, energy
- Dual polarization (EW, NS), abs. amplitude calibration, using KASCADE shower geometry

$$\varepsilon_{est}^{EW} = 1.68 \pm 0.11 \cdot (|\vec{P}|_{EW} + 0.69) \cdot e^{-\left(\frac{D}{(209.7\pm61.5)m}\right)} \cdot \left(\frac{E_p}{10^{17}\,eV}\right)^{0.90\pm0.1} \frac{\mu V}{m \cdot MHz}$$

$$\varepsilon_{est}^{NS} = 1.61 \pm 0.17 \cdot (|\vec{P}|_{NS} + 0.60) \cdot e^{-\left(\frac{D}{(156.4\pm30.5)m}\right)} \cdot \left(\frac{E_p}{10^{17}\,eV}\right)^{0.95\pm0.1} \frac{\mu V}{m \cdot MHz}$$

Summary

- LOPES: has opened a new window for observations of cosmic rays
- Radio: complementary technique to modern experiments
- Signal: linearly polarized, dependence on air shower direction, distance and energy
- Emission mechanism: geomagnetic effect dominant
- Simulations: general agreements with data
- R&D: large scale applications (Pierre Auger Observatory)
- Status: 3D polarization measurements currently