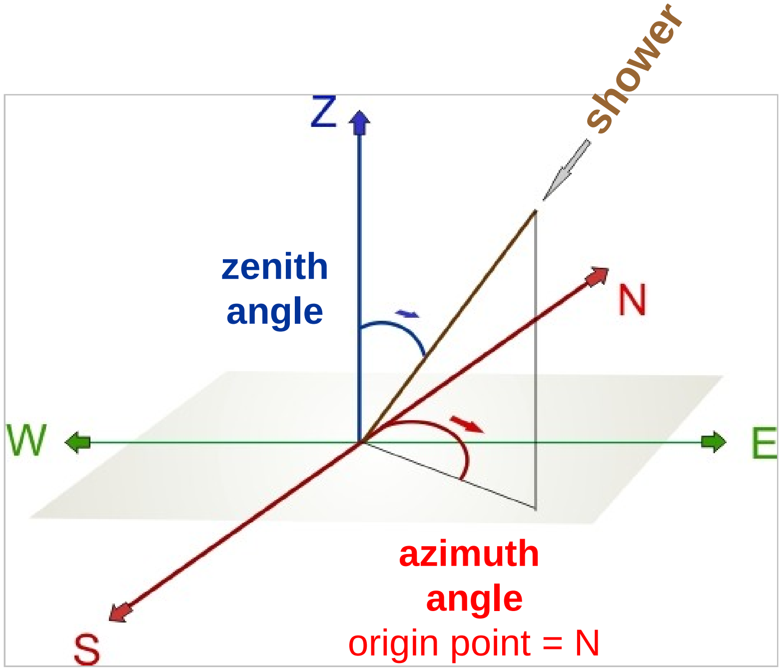
Analysis of the radio detection of inclined showers with LOPES

Alexandra Saftoiu
IFIN-HH, Romania
for the LOPES Collaboration

International Workshop on the Acoustic and Radio EeV Neutrino detection Activities, ARENA
Nantes, 29.06-02.07 2010

Inclined showers

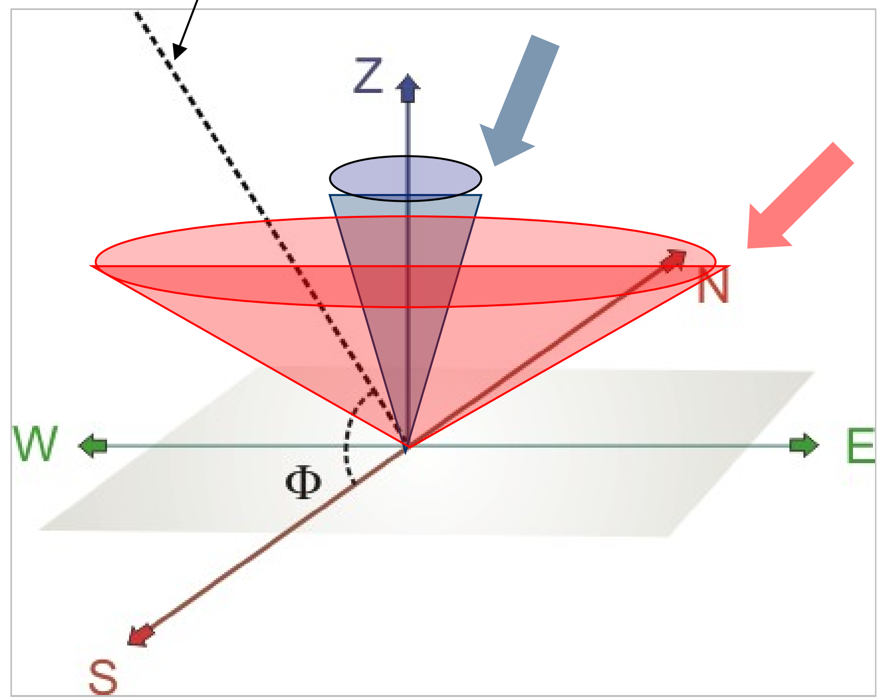


magnetic field line

Northern Europe

$\Phi = 70^0$

$\psi = 180^0\,50''$



Radio emission depends on shower geometry and geomagnetic angle

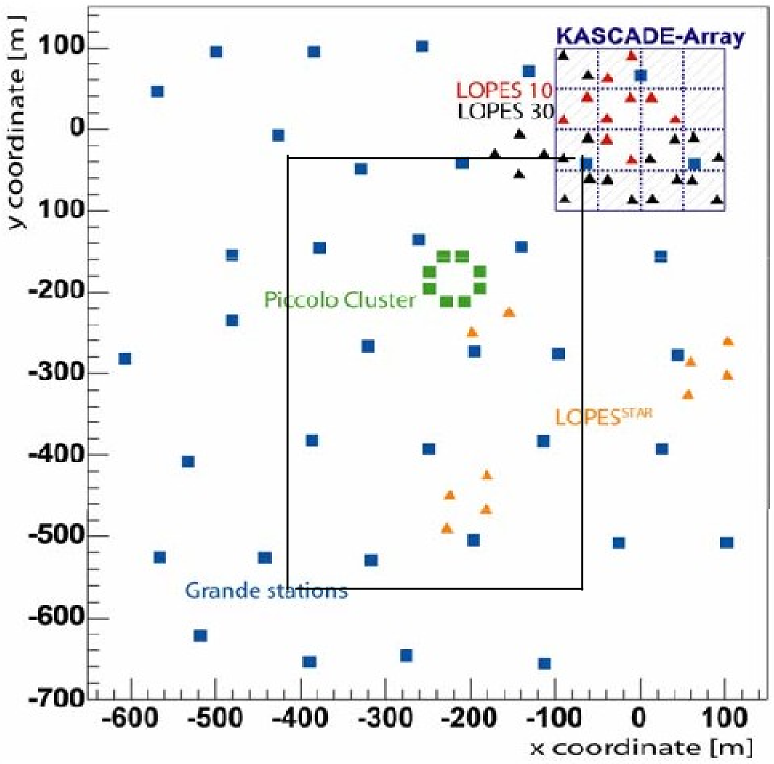
Geosynchrotron theory

Data selection

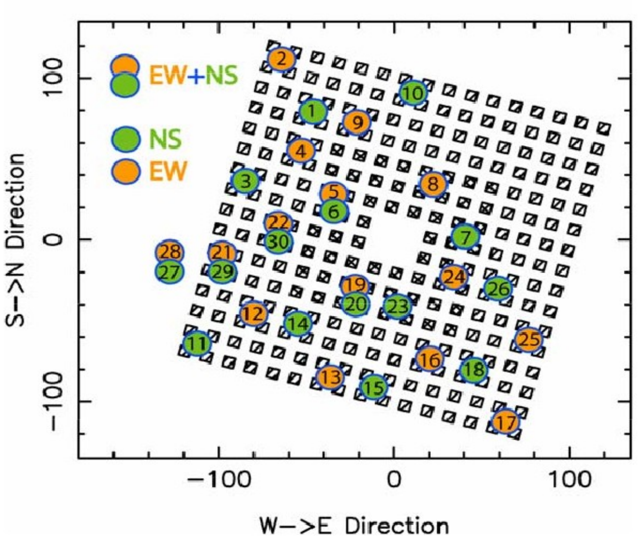
LOPES dual polarization data 2007-2008 in correlation with KASCADE-Grande events

1. KASCADE-Grande data selection:
Zenith angle > 40^0
Muon number > 10^6
Area cuts: $-420 < Xcore < 50$m,
$-550 < Ycore < -30$m
→ 8253 KASCADE- Grande events

2. Corresponding LOPES radio data
→ 5582 events



Antenna characteristics



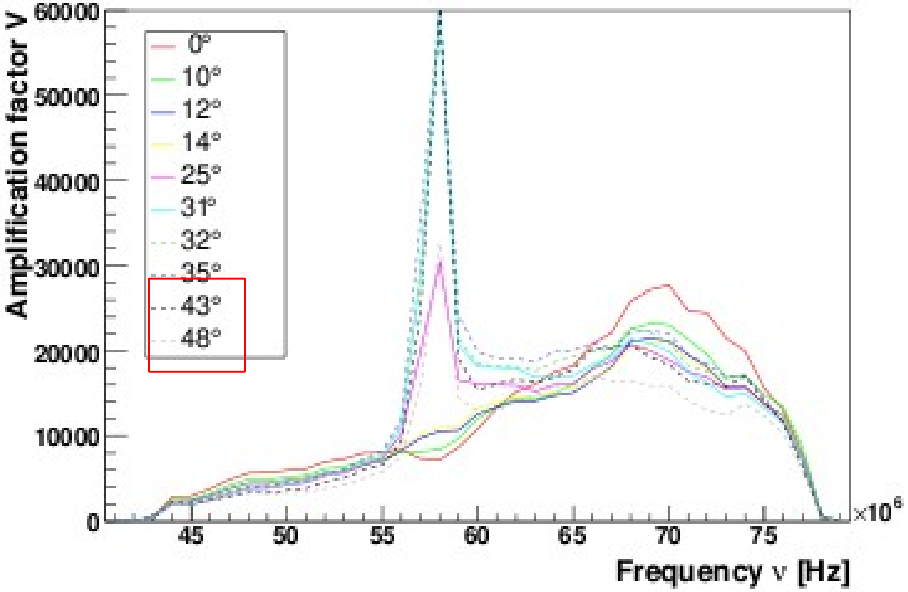
LOPES antennas:
V-shape rods + metal pedestal

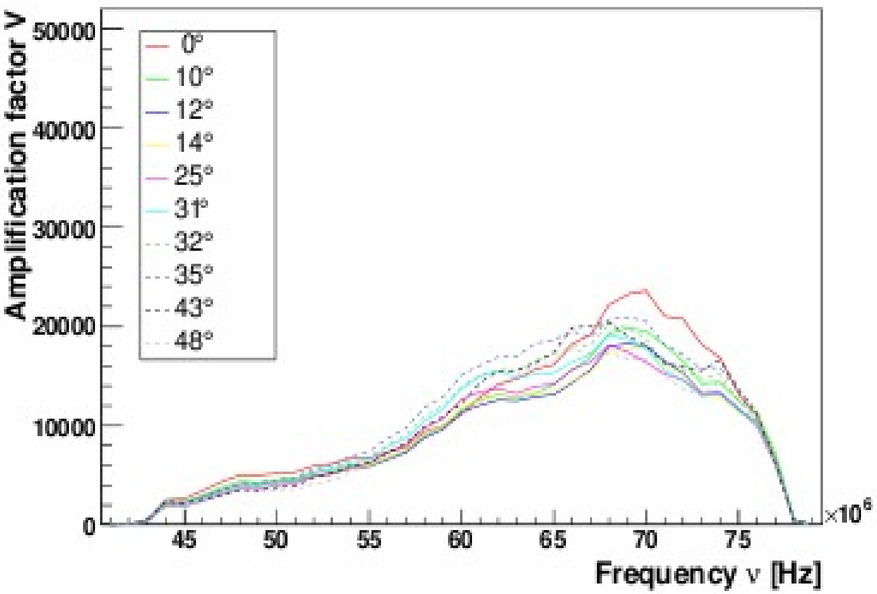
All included in the simulated model used in the processing

Antenna characteristics

Amplification factor:

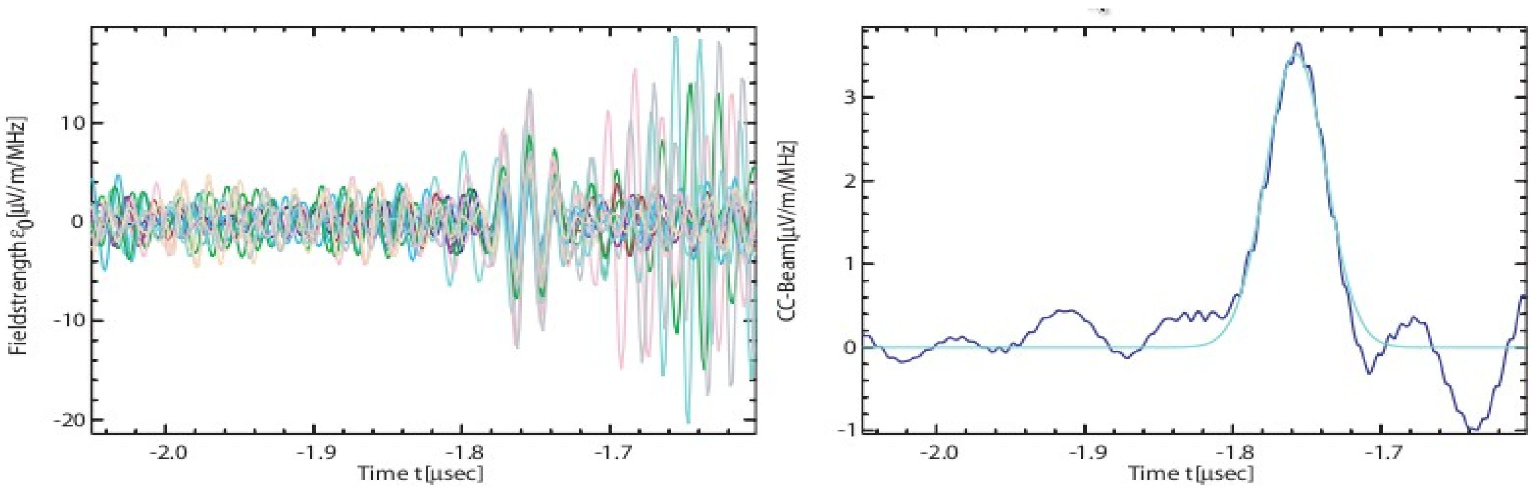
$$V(\nu)=\frac{P_M(\nu)}{P_R(\nu)}=\left(\frac{4\pi r\nu}{c}\right)^2\frac{P_M(\nu)}{G_r(\theta,\phi,\nu)G_t P_t(\nu)\cos^2(\beta)}$$





S. Nehls et al., NIM A, 589 (2008), 350-361

Data processing



- Cross-correlation:

$$cc(t) = \pm\sqrt{\left|\frac{1}{N_P}\sum_{i=1}^{N-1}\sum_{j>i}^{N} s_i(t)s_j(t)\right|}$$

$$x[t] = cc[t] \cdot \left|\frac{< cc[t] >}{< p[t] >}\right| ; \qquad p[t] = \sqrt{\frac{1}{N}\sum_{i=1}^{N} s_i^2[t]}$$

Data analysis

Quality selection:

- EW or NS: $CC_{height}/rmsCCbeam > 20$

$$CC_{height} = CC_{heightEW}$$

$$CC_{height} = CC_{heightNS}$$

- EW + NS: $\sqrt{((CC_{heightEW}/rmsCCbeam_{EW})^2 + (CC_{heightNS}/rmsCCbeam_{NS})^2)} > 20$

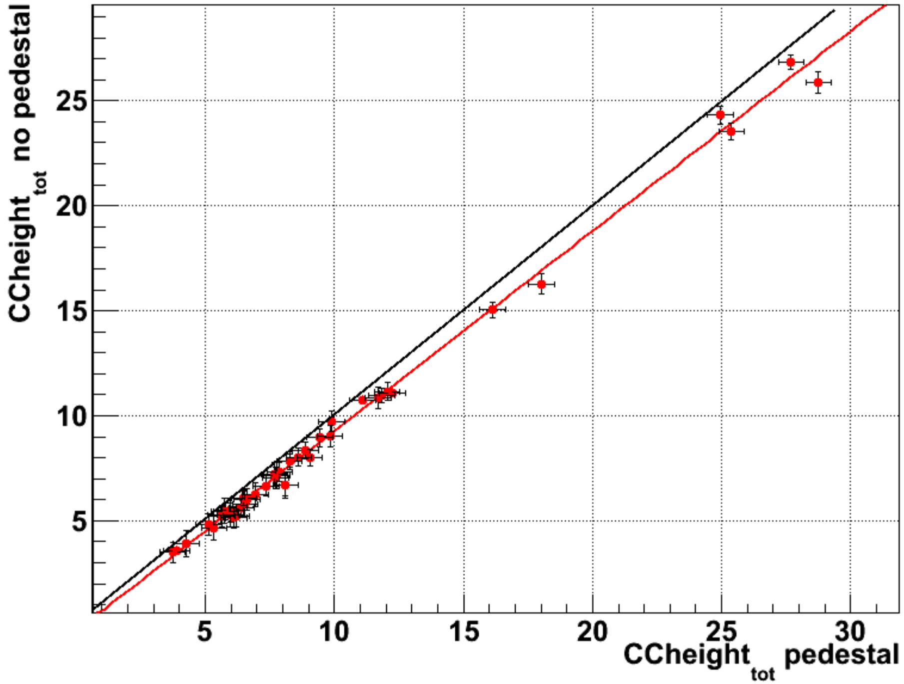
$$X_{height}/CC_{height} = 1 \pm 0.4$$

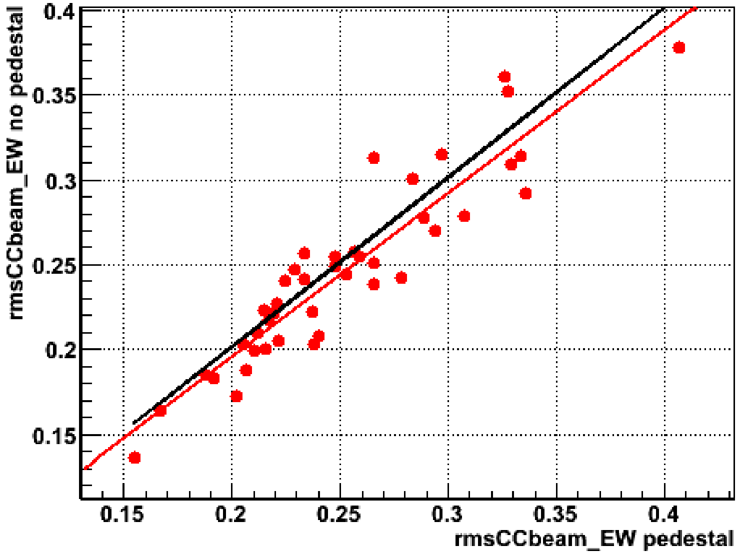
Errors:

- muon number: 50% error (inclined events!),
- geomagnetic angle: 0.6^{o} for direction,
- core: 20 m,
- radio error: 20% of pulse height as gain error + CC_{height} error and rmsCCbeam from pipeline.

Data analysis

With pedestal: 5176 events, processed with output.
No pedestal: 5266 events, processed with output.





Data analysis - correlations

$$\epsilon = \epsilon(|\vec{v} \times \vec{B}|, R, N_\mu)$$

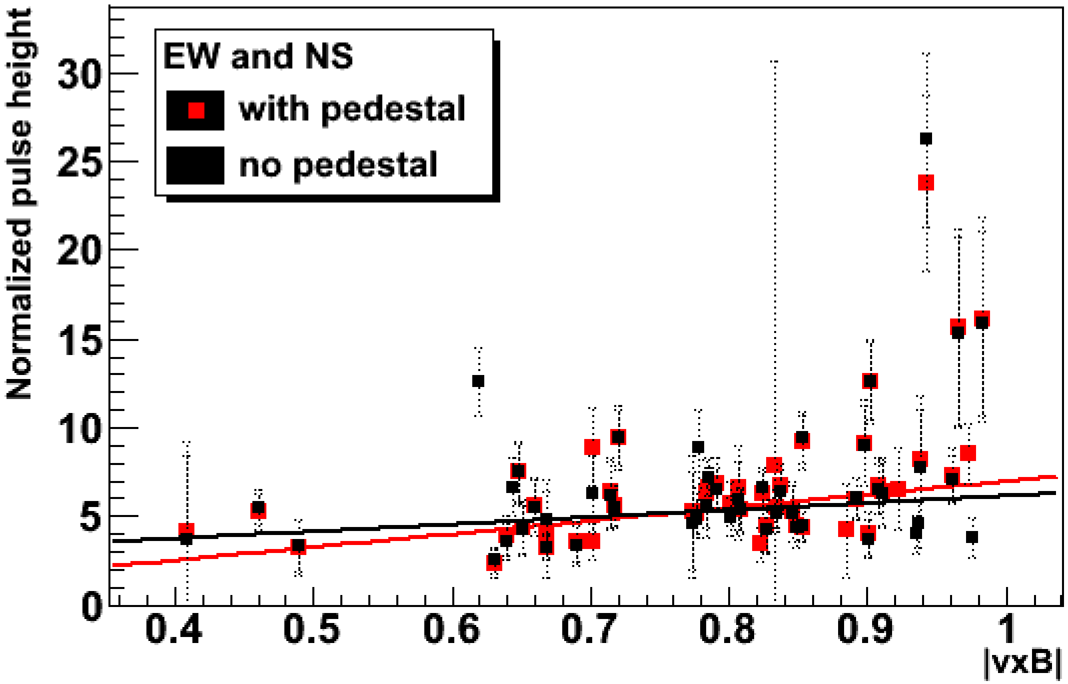
$$\epsilon = ct1 * (|\vec{v} \times \vec{B}| + ct2) \exp\left(\frac{-R_0}{R}\right)\left(\frac{N_\mu}{10^6}\right)^{ct3} \left[\frac{\mu V}{m\ MHz}\right]$$

$\vec{v}$ = direction of incoming shower
$\vec{B}$ = Earth's B-field at experiment location
R = distance from antennas to shower axis
N_μ = number of muons in shower, estimator for E_p

→ iterative separation of parameters

Data analysis – correlations, vxB

$$\epsilon = \epsilon(|\vec{v} \times \vec{B}|, R, N_{\mu}) \qquad P = |\vec{v} \times \vec{B}| = \sqrt{P_{EW}^2 + P_{NS}^2}$$



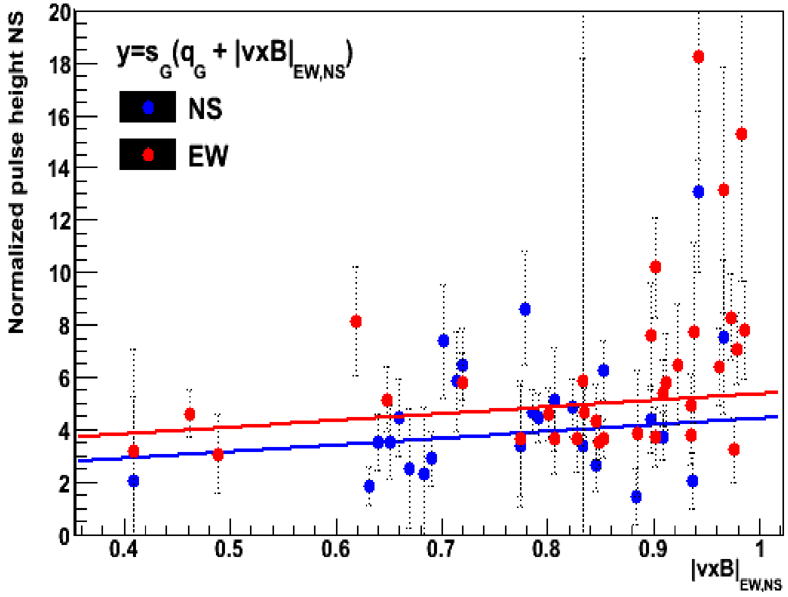
$$y = 6.94 \pm 1.6(0.03 \pm 0.18 + |\vec{v} \times \vec{B}|)$$

$$y = 4.02 \pm 1.50(0.53 \pm 0.50 + |\vec{v} \times \vec{B}|)$$

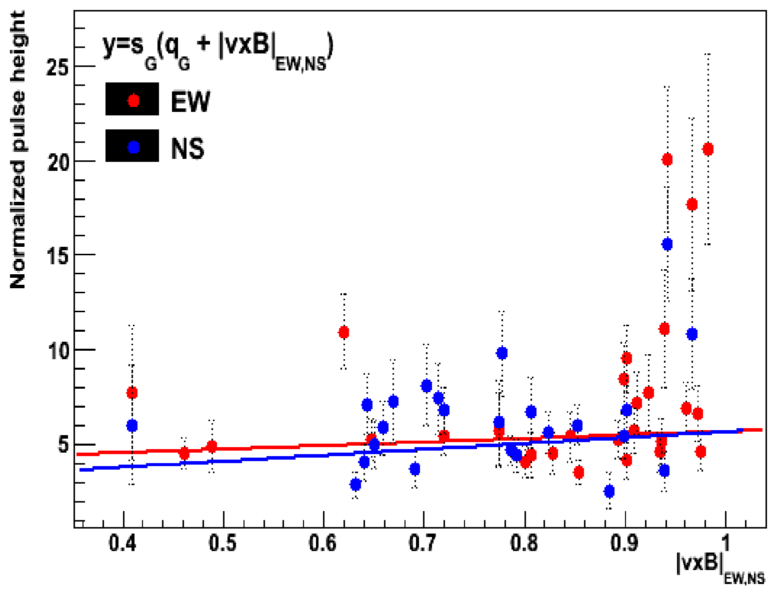
Data analysis – correlations, vxB

$$\epsilon = \epsilon(|\vec{v} \times \vec{B}|_{EW,NS}, R, N_\mu) \quad P_{EW,NS} = |\vec{v} \times \vec{B}|_{EW,NS}$$

With pedestal



No pedestal

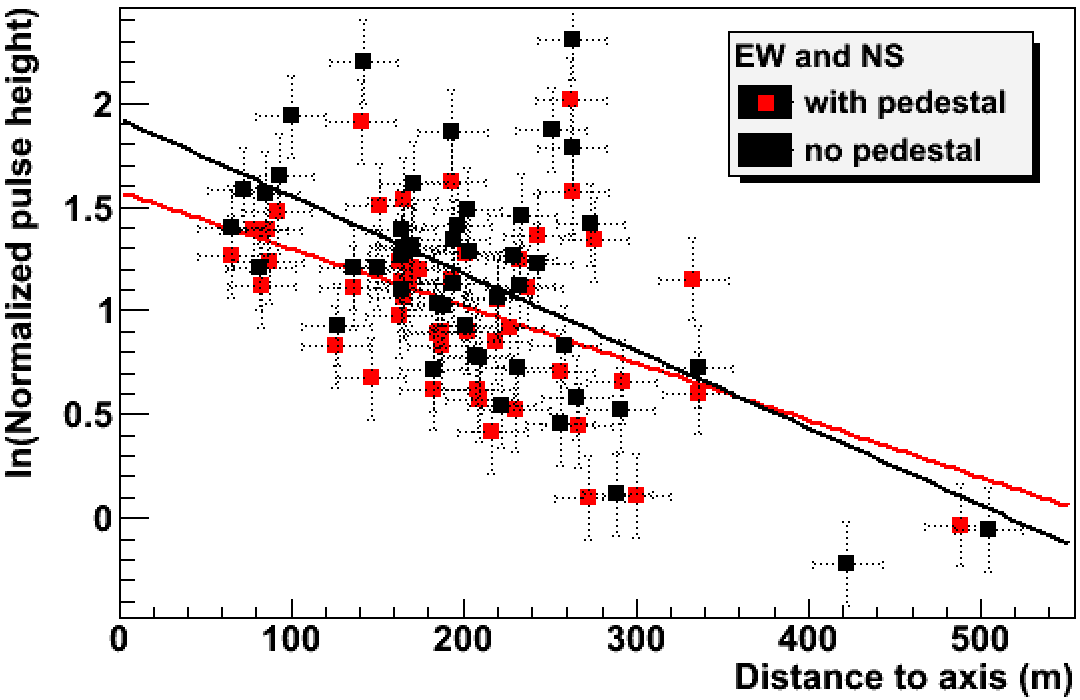


$$y = 2.58 \pm 1.80 (1.08 \pm 0.30 + |\vec{v} \times \vec{B}|_{EW}) \qquad y = 1.87 \pm 1.80 (2.04 \pm 2.80 + |\vec{v} \times \vec{B}|_{EW})$$

$$y = 2.53 \pm 2.3 (0.74 \pm 0.40 + |\vec{v} \times \vec{B}|_{NS}) \qquad y = 3.12 \pm 2.50 (1.00 \pm 2.30 + |\vec{v} \times \vec{B}|_{NS})$$

Data analysis – correlations, distance

$$\epsilon = \epsilon(|\vec{v} \times \vec{B}|, \boxed{R}, N_\mu) \qquad P = |\vec{v} \times \vec{B}| = \sqrt{P_{EW}^2 + P_{NS}^2}$$



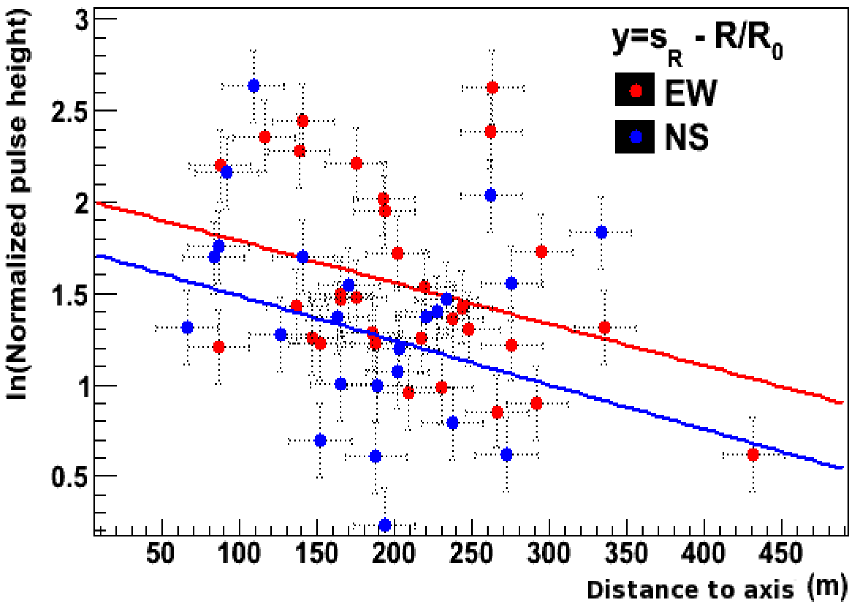
$$y = 1.75 \pm 0.07 - R/(281.77 \pm 26.00)$$

$$y = 1.93 \pm 0.08 - R/(268.18 \pm 25.00)$$

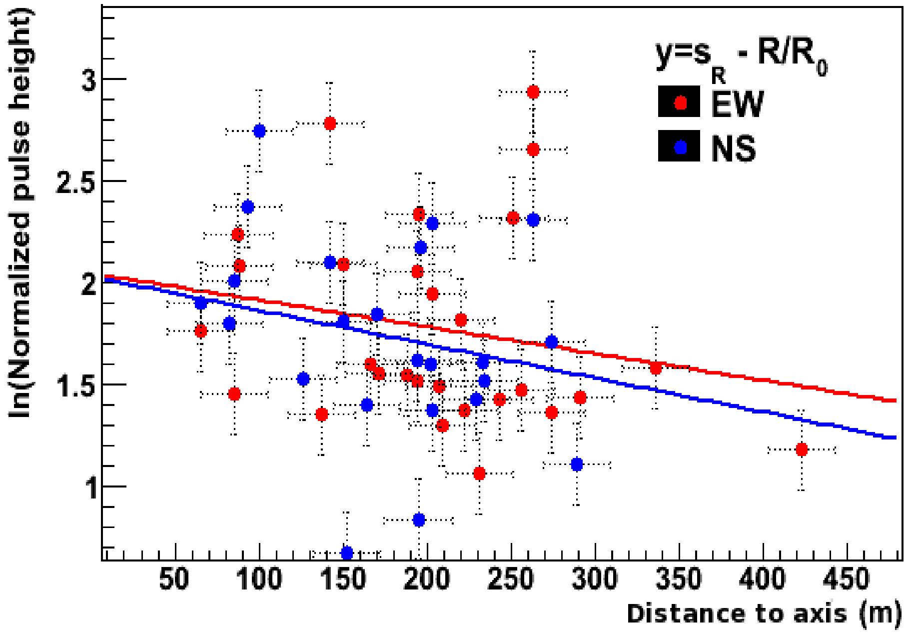
Data analysis – correlations, distance

$$\epsilon = \epsilon\left(|\vec{v}\times\vec{B}|_{EW,NS}, \boxed{R}, N_{\mu}\right) \qquad P_{EW,NS} = |\vec{v}\times\vec{B}|_{EW,NS}$$

With pedestal



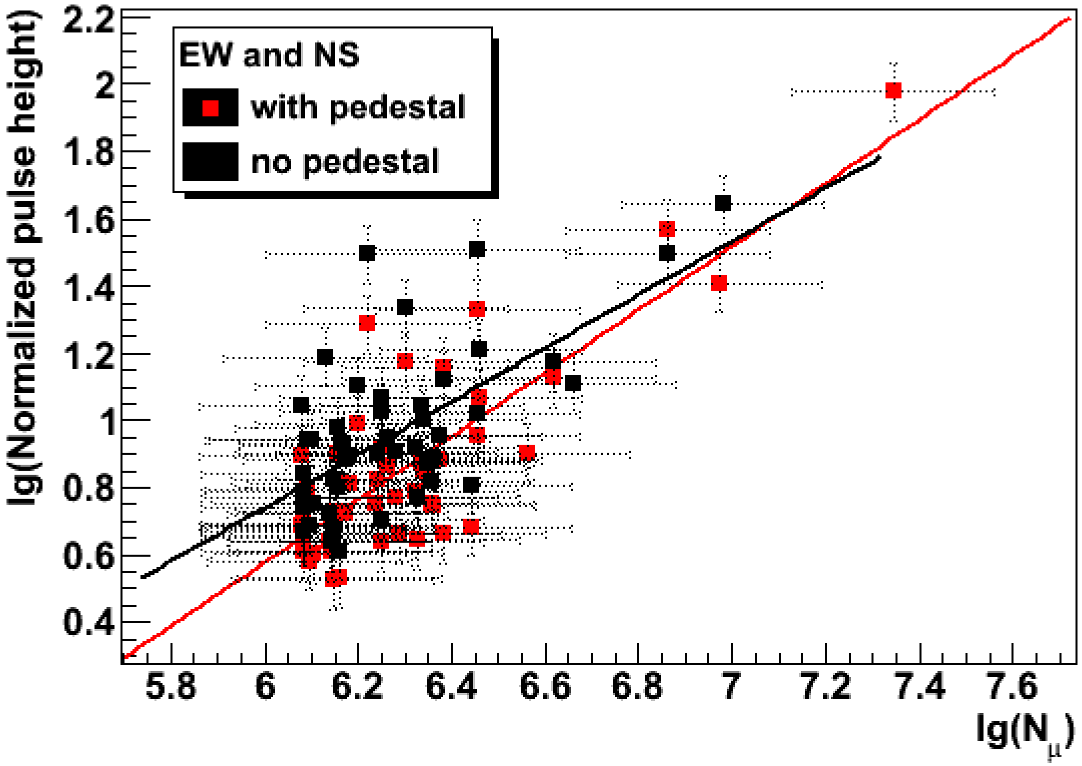
No pedestal



With pedestal	No pedestal
EW (red): $y = 2.01 \pm 0.1 - R/(434.99 \pm 86.00)$	$y = 2.05 \pm 0.01 - R/(760.82 \pm 270.00)$
NS (blue): $y = 1.73 \pm 0.09 - R/(411.33 \pm 70.00)$	$y = 2.03 \pm 0.09 - R/(600.76 \pm 160.00)$

Data analysis – correlations, muon number

$\epsilon = \epsilon(|\vec{v} \times \vec{B}|, R, \boxed{N_\mu})$ $\qquad P = |\vec{v} \times \vec{B}| = \sqrt{P_{EW}^2 + P_{NS}^2}$



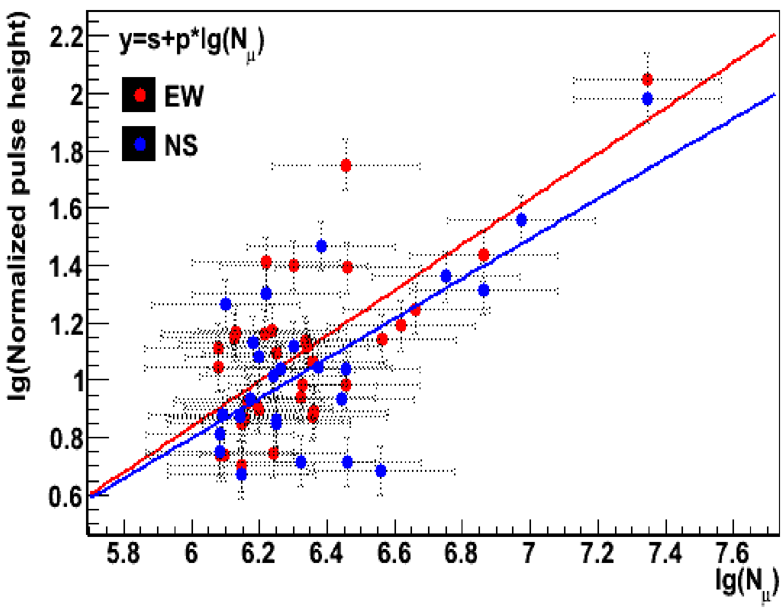
$y = -4.90 \pm 0.32 + (0.93 \pm 0.05)\, lg(N_\mu)$

$y = -4.00 \pm 0.41 + (0.79 \pm 0.06)\, lg(N_\mu)$

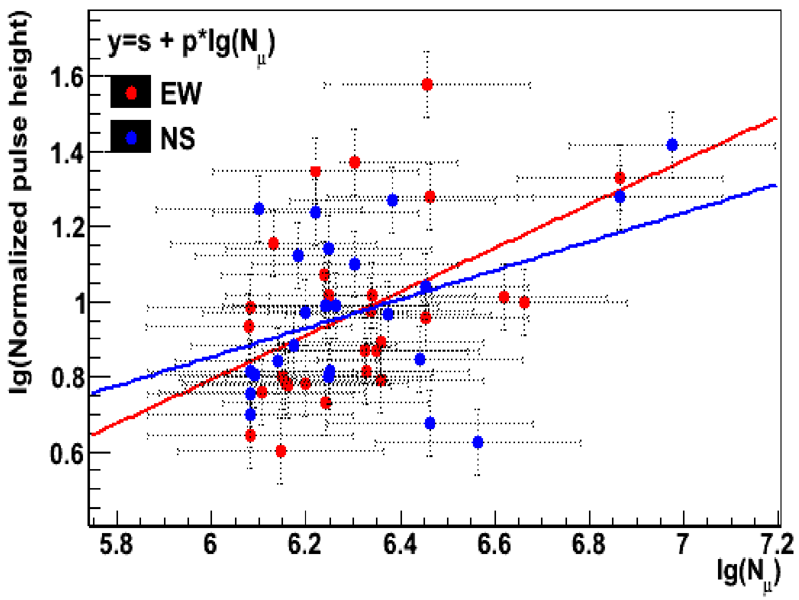
Data analysis – correlations, muon number

$$\epsilon = \epsilon(|\vec{v} \times \vec{B}|_{EW,NS}, R, \boxed{N_\mu}) \qquad P_{EW,NS} = |\vec{v} \times \vec{B}|_{EW,NS}$$

With pedestal



No pedestal



$$y = -3.90 \pm 0.38 + (0.79 \pm 0.06)\, lg(N_\mu)$$

$$y = -3.40 \pm 0.36 + (0.70 \pm 0.06)\, lg(N_\mu)$$

$$y = -2.70 \pm 0.56 + (0.58 \pm 0.09)\, lg(N_\mu)$$

$$y = -1.5 \pm 0.5 + (0.38 \pm 0.08)\, lg(N_\mu)$$

Pulse height parametrization

Pulse height estimation, EW+NS polarizations:

- with pedestal

$$\epsilon_{EW,NS} = 2.82 \pm 0.2 \left(1.03 \pm 0.18 + \sqrt{P_{EW}^2 + P_{NS}^2}\right) \exp\left(\frac{-R}{218.77 \pm 26.00}\right) \left(\frac{N_\mu}{10^6}\right)^{0.93 \pm 0.05} \quad \frac{\mu V}{m\,MHz}$$

- no pedestal

$$\epsilon_{EW,NS} = 3.21 \pm 0.40 \left(0.53 \pm 0.50 + \sqrt{P_{EW}^2 + P_{NS}^2}\right) \exp\left(\frac{-R}{268.18 \pm 25.00}\right) \left(\frac{N_\mu}{10^6}\right)^{0.79 \pm 0.06} \quad \frac{\mu V}{m\,MHz}$$

Pulse height parametrization

Pulse height estimation EW and NS polarizations:

- with pedestal

$$\epsilon_{EW} = 3.8 \pm 1.6\,(1.08 \pm 0.3 + |\vec{v} \times \vec{B}|)\exp\left(\frac{-R}{434 \pm 86}\right)\left(\frac{N_\mu}{10^6}\right)^{0.79 \pm 0.06} \frac{\mu V}{m\,MHz}$$

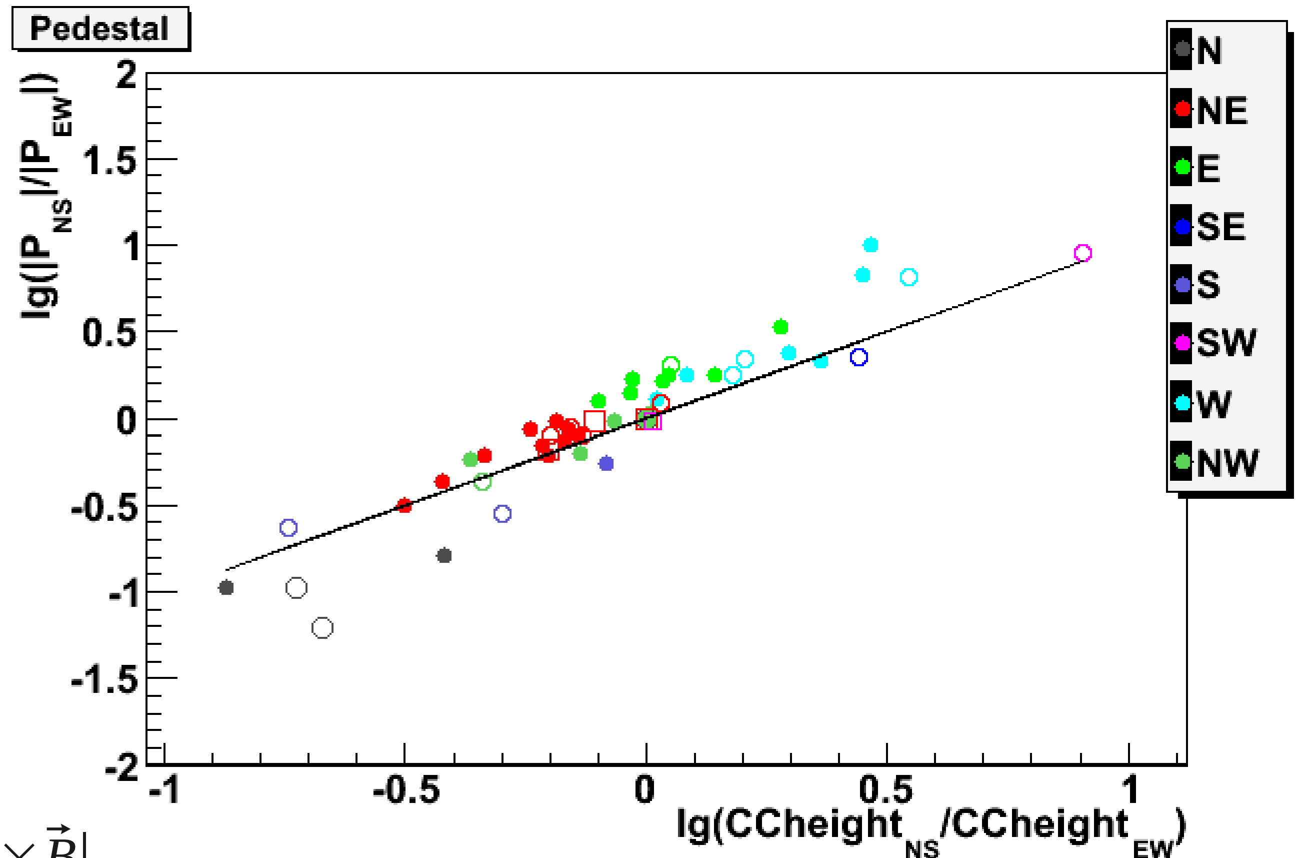
$$\epsilon_{NS} = 4.25 \pm 0.41\,(0.74 \pm 0.40 + |\vec{v} \times \vec{B}|)\exp\left(\frac{-R}{411 \pm 70}\right)\left(\frac{N_\mu}{10^6}\right)^{0.71 \pm 0.06} \frac{\mu V}{m\,MHz}$$

- no pedestal

$$\epsilon_{EW} = 2.97 \pm 1.90\,(2.04 \pm 2.80 + |\vec{v} \times \vec{B}|)\exp\left(\frac{-R}{760 \pm 270}\right)\left(\frac{N_\mu}{10^6}\right)^{0.58 \pm 0.09} \frac{\mu V}{m\,MHz}$$

$$\epsilon_{NS} = 1.37 \pm 1.02\,(1.00 \pm 2.3 + |\vec{v} \times \vec{B}|)\exp\left(\frac{-R}{600 \pm 160}\right)\left(\frac{N_\mu}{10^6}\right)^{0.38 \pm 0.08} \frac{\mu V}{m\,MHz}$$

Comparison with simplified geomagnetic model



$$P_{EW,NS} = |\vec{v} \times \vec{B}|_{EW,NS}$$

● data 40°-50°

○ data 50°-60°

□ data above 60°

Conclusions

- Antenna gain from simulation used in amplification factor
  - ➔ investigation of how changes in antenna model influence the results

- Investigation of the inclined shower

- Simplified geomagnetic model

Useful to look for inclined showers!

LOPES Collaboration

ASTRON, The Netherlands
H. Butcher, G.W. Kant
W. van Capellen, S. Wijnholds

Univ Wuppertal, Germany
D. Fuhrmann, R. Glasstetter
K.H. Kampert, J. Rautenberg

Max-Planck-Institut für Radio-astronomie, Bonn, Germany
P.L. Biermann, J.A. Zensus

Istituto di Fisica dello Spazio Interplanetario, Torino, Italy
E. Cantoni, P.L. Ghia
C. Morello, G.C. Trinchero

Soltan Institute for Nuclear Studies, Lodz, Poland
M. Franc, P. Łuczak
J. Zabierowski

Dipartimento di Fisica Generale dell'Universita, Torino, Italy
M. Bertaina, A. Chiavassa
F. Di Pierro, G. Navarra'

Dept of Astrophysics, Nijmegen, The Netherlands
L. Bähren, S. Buitink
H. Falcke, J.R. Hörandel
A. Horneffer, J. Kuijpers
S. Lafèbre, A. Nigl
K. Singh

LOPES
RADIO EMISSION FROM COSMIC RAY AIR SHOWERS

National Inst of Physics and Nuclear Engineering Bucharest, Romania
I.M. Brancus, B. Mitrica
M. Petcu, A. Saftoiu
O. Sima, G. Toma

IK, KIT, Germany
W.D. Apel, J.C. Arteaga
A.F. Badea, K. Bekk
J. Blümer, H. Bozdog
K. Daumiller, P. Doll
R. Engel, M. Finger
A. Haungs, D. Heck
T. Huege, P.G. Isar
H.J. Mathes, H.J. Mayer
S. Nehls, J. Oehlschläger
T. Pierog, H. Rebel
M. Roth, H. Schieler
F.G. Schröder, H. Ulrich
A. Weindl, J. Wochele
M. Wommer

IPE, KIT, Germany
T. Asch, H. Gemmeke
M. Helfrich, O. Krömer
L. Petzold, C. Rühle
M. Scherer, A. Schmidt

IEKP, KIT, Germany
F. Cossavella, V. De Souza
D. Huber, D. Kang
M. Konzack, K. Link
M. Ludwig, M. Melissas
N. Palmieri

Universität Siegen, Germany
P. Buchholz, C. Grupen
D. Kickelbick, S. Over

Thank you for your attention!

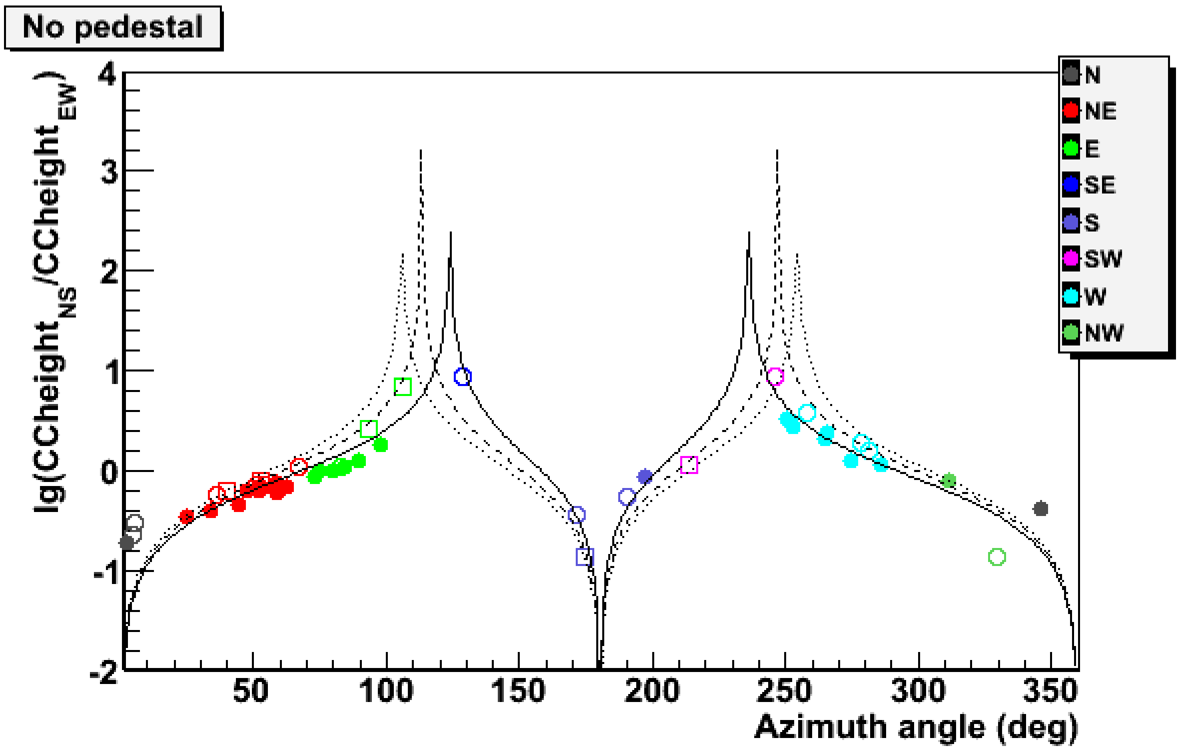
Back-up

$$p[t] = \sqrt{\frac{1}{N}\sum_{i=1}^{N} s_i^2[t]}$$

$$x[t] = cc[t] \cdot \left| \frac{< cc[t] >}{< p[t] >} \right| :$$

$$\epsilon_\nu = \frac{|\mathbf{E}|}{(\Delta\nu)} = \sqrt{\frac{4\pi\nu^2\mu_0}{cR_{\mathrm{ADC}}}} \cdot \sqrt{\frac{V(\nu)}{G_r(\nu,\theta,\phi)}} \cdot U_{\mathrm{ADC}}$$

Comparison with simplified geomagnetic model



P_{NS}/P_{EW} 40°

P_{NS}/P_{EW} 50°

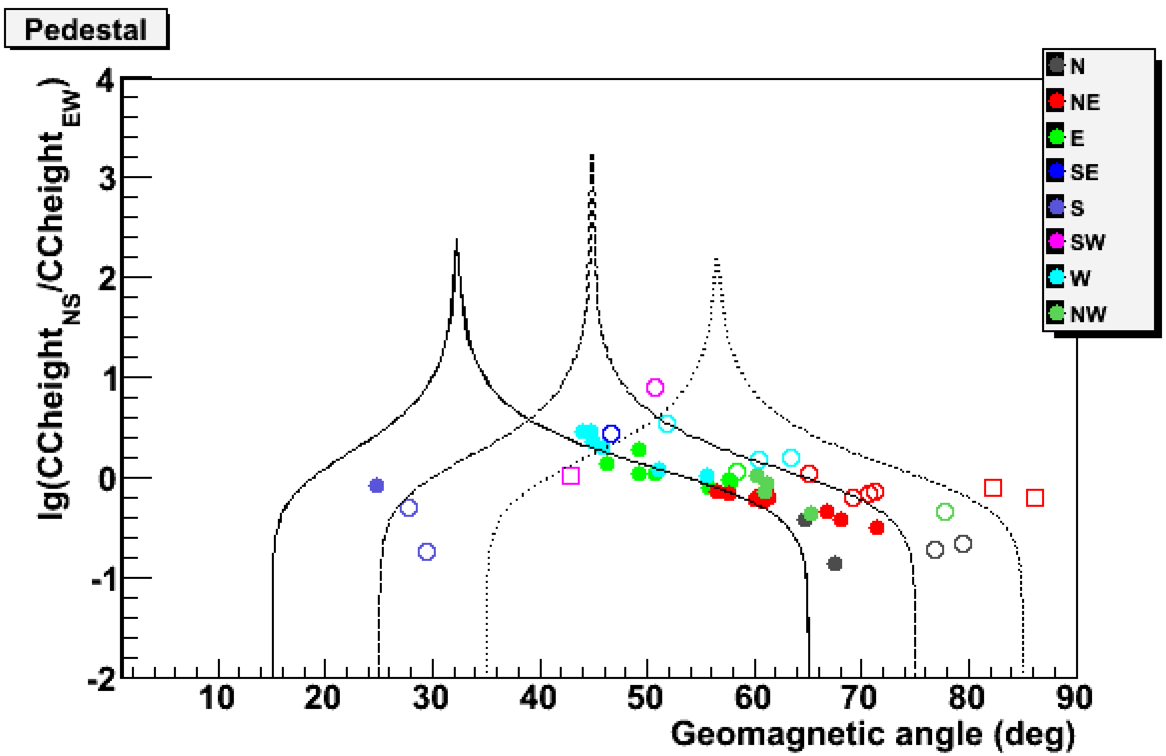
P_{NS}/P_{EW} 60°

● data 40°-50°

○ data 50°-60°

□ data above 60°

Comparison with simplified geomagnetic model



P_{NS}/P_{EW} 40°

P_{NS}/P_{EW} 50°

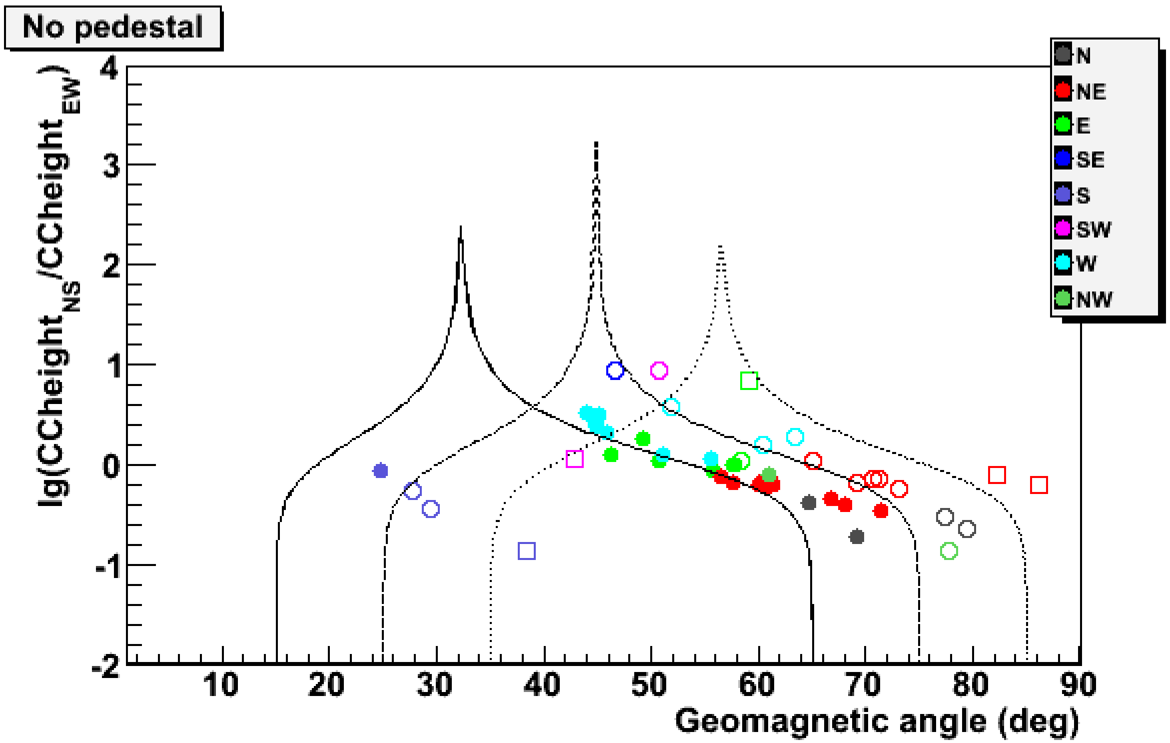
P_{NS}/P_{EW} 60°

● data 40°-50°

○ data 50°-60°

□ data above 60°

Comparison with simplified geomagnetic model



P_{NS}/P_{EW} 40°

P_{NS}/P_{EW} 50°

P_{NS}/P_{EW} 60°

data 40°-50°

data 50°-60°

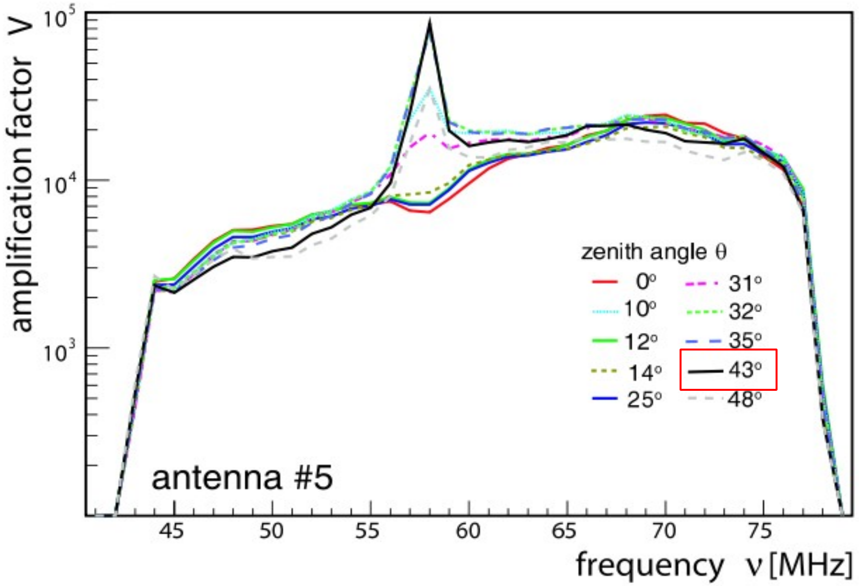
data above 60°

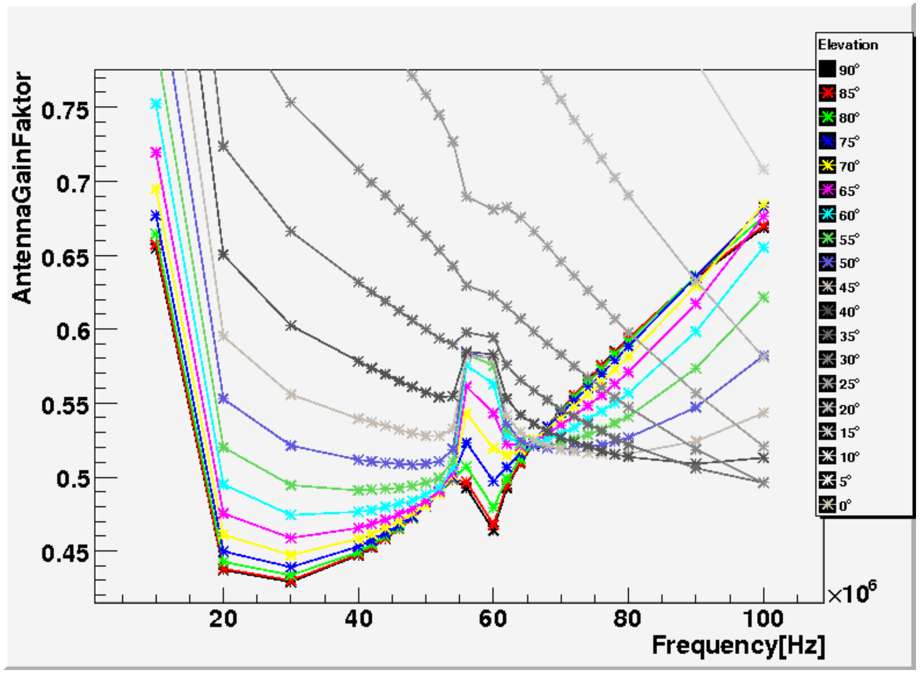
Antenna characteristics

Amplification factor:

$$V(\nu) = \frac{P_M(\nu)}{P_R(\nu)} = \left(\frac{4\pi r \nu}{c}\right)^2 \frac{P_M(\nu)}{G_r(\theta,\phi,\nu)\, G_t\, P_t(\nu) \cos^2(\beta)}$$

Gain of the LOPES antenna taken from simulation

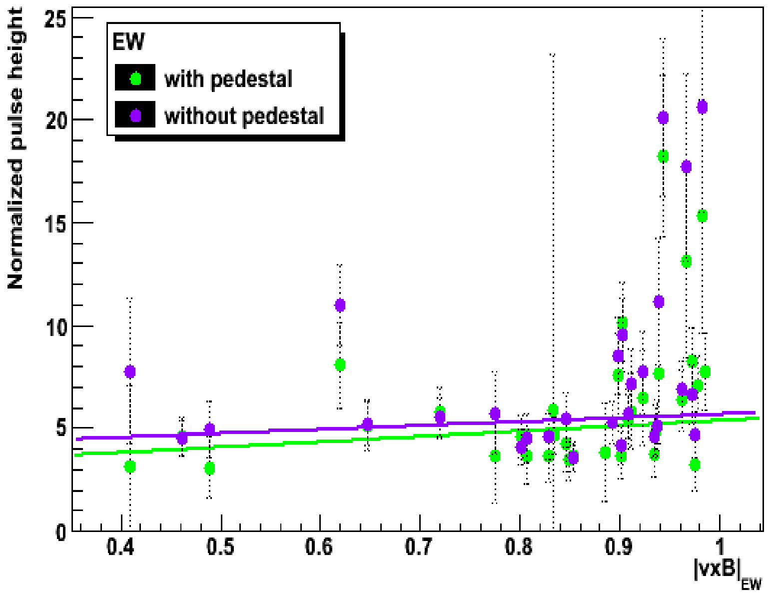




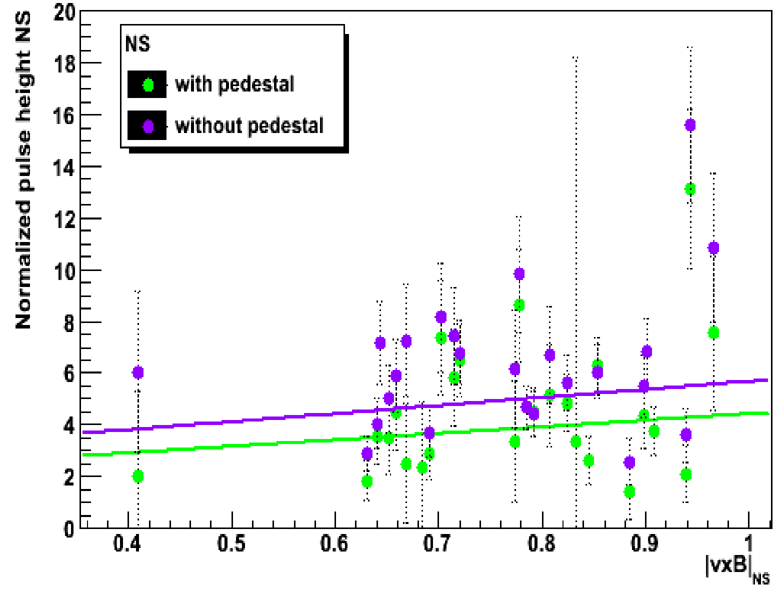
S. Nehls et al., NIM A, 589 (2008), 350-361

Data analysis – correlations, vxB

P_{EW}



P_{NS}



$y = 2.58 \pm 1.80 (1.08 \pm 0.30 + |\vec{v} \times \vec{B}|_{EW})$

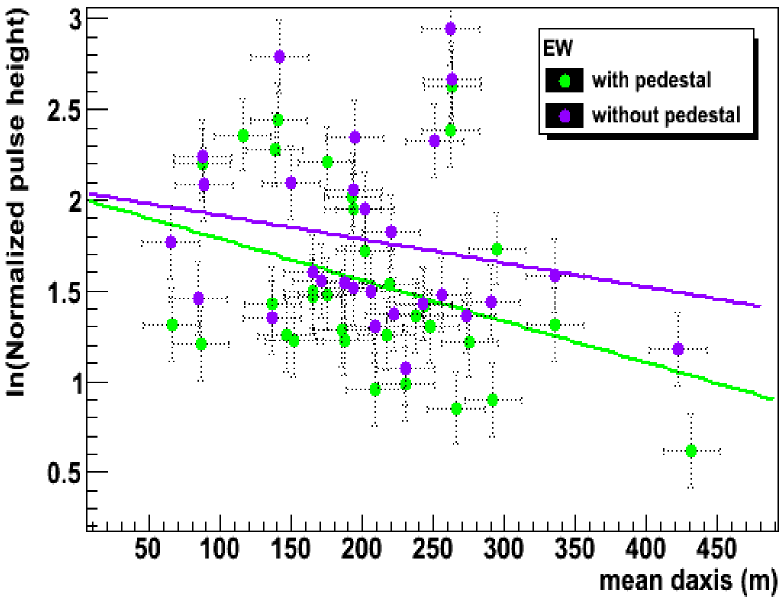
$y = 1.87 \pm 1.80 (2.04 \pm 2.80 + |\vec{v} \times \vec{B}|_{EW})$

$y = 2.58 \pm 1.80 (1.08 \pm 0.30 + |\vec{v} \times \vec{B}|_{NS})$

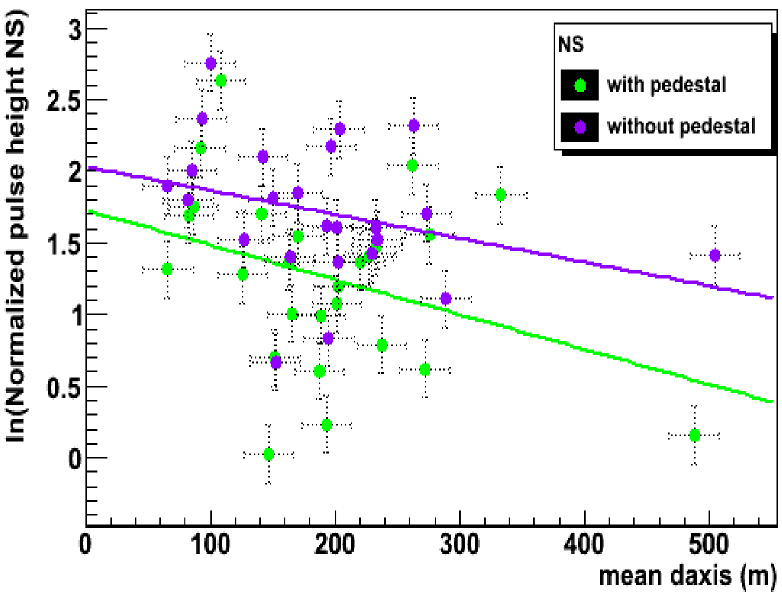
$y = 1.87 \pm 1.80 (2.04 \pm 2.80 + |\vec{v} \times \vec{B}|_{NS})$

Data analysis – correlations, distance

EW



NS



$y = 2.01 \pm 0.1 - R/(434.99 \pm 86.00)$

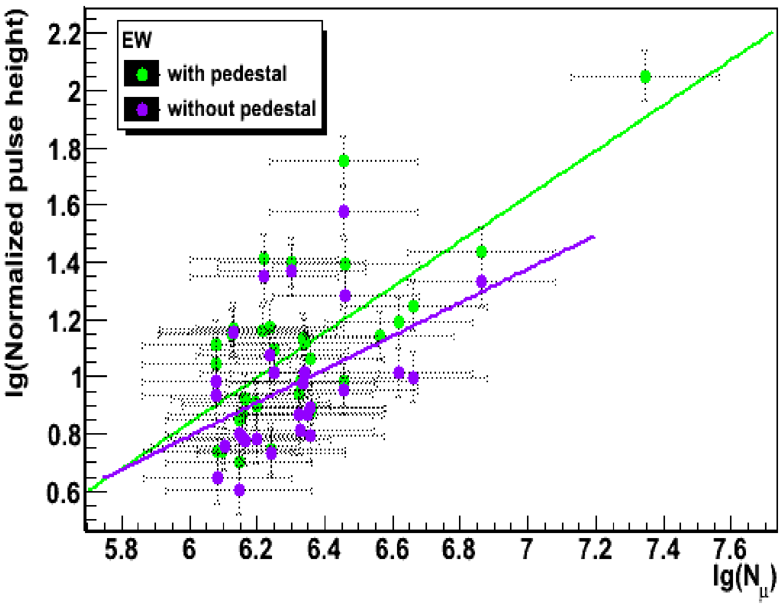
$y = 2.05 \pm 0.01 - R/(760.82 \pm 270.00)$

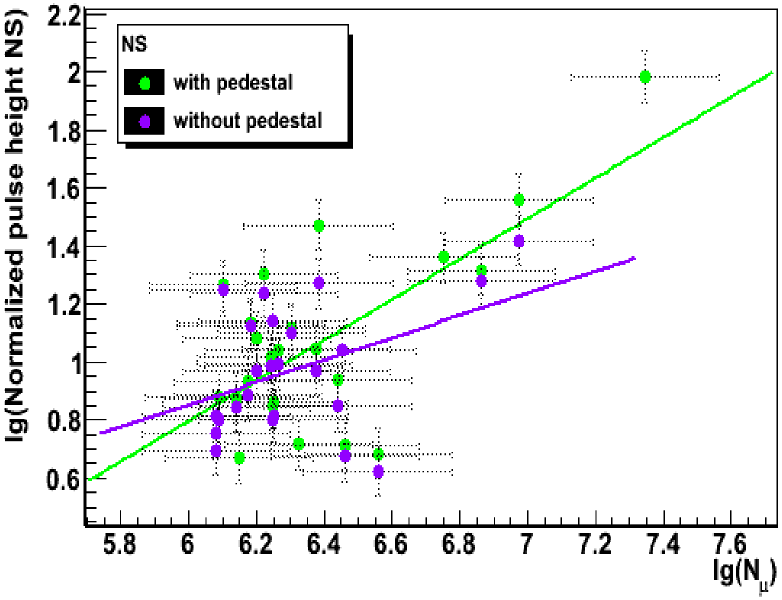
$y = 1.73 \pm 0.09 - R/(411.33 \pm 70.00)$

$y = 2.03 \pm 0.09 - R/(600.76 \pm 160.00)$

Data analysis – correlations, muon number

EW *NS*





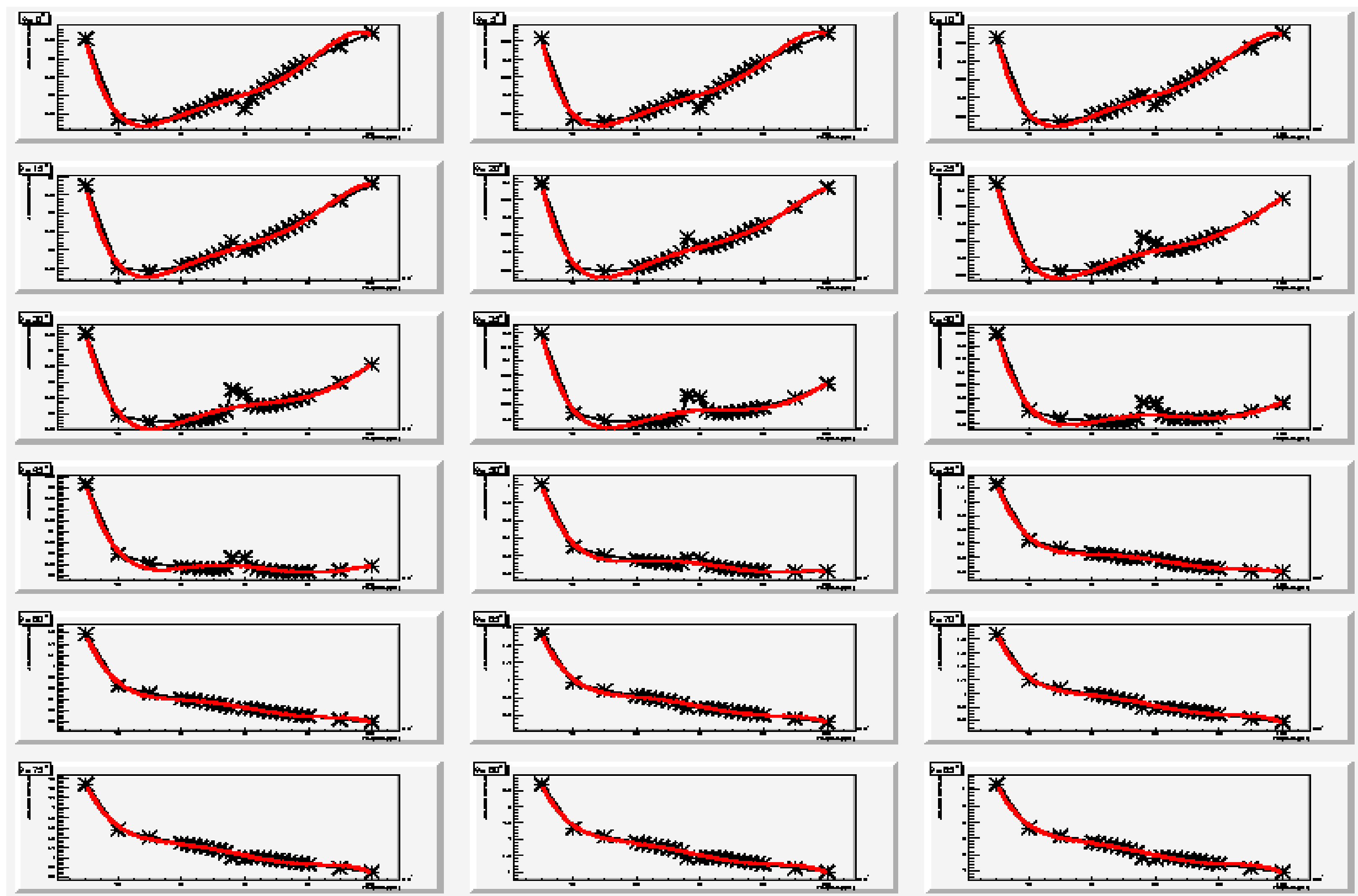
$y = -3.90 \pm 0.38 + (0.79 \pm 0.06)\, lg(N_\mu)$

$y = -2.70 \pm 0.56 + (0.58 \pm 0.09)\, lg(N_\mu)$

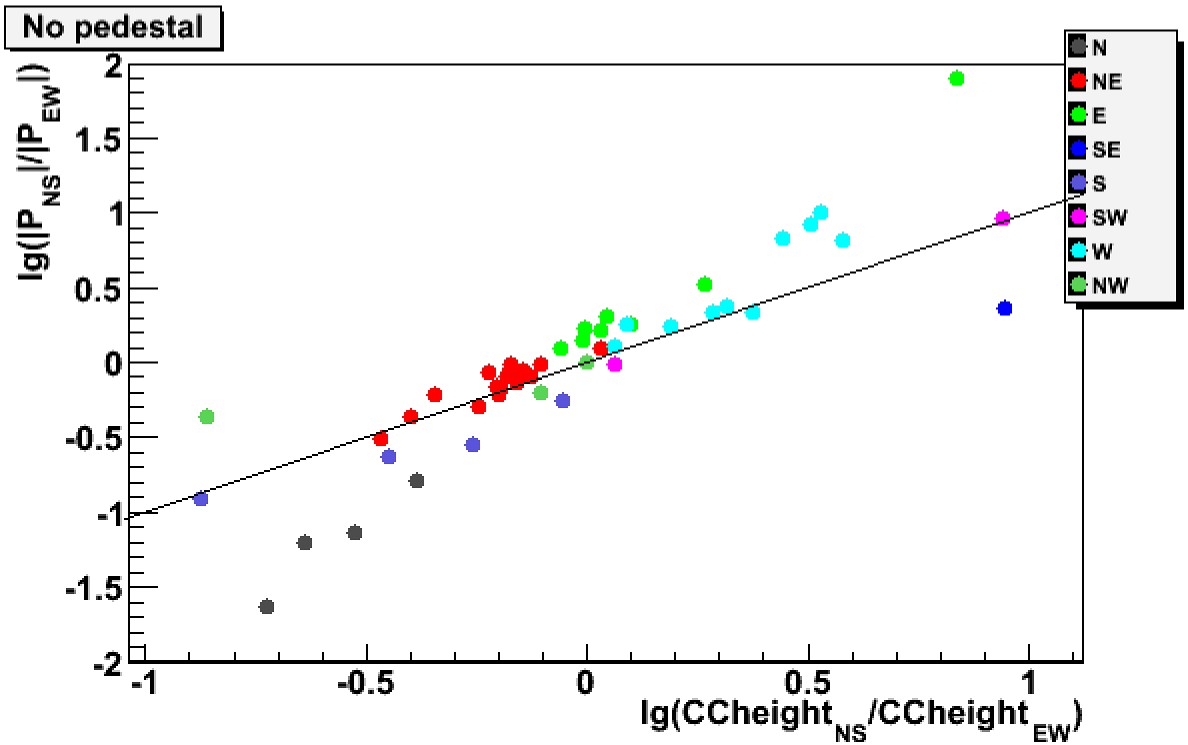
$y = -3.40 \pm 0.36 + (0.70 \pm 0.06)\, lg(N_\mu)$

$y = -1.5 \pm 0.5 + (0.38 \pm 0.08)\, lg(N_\mu)$

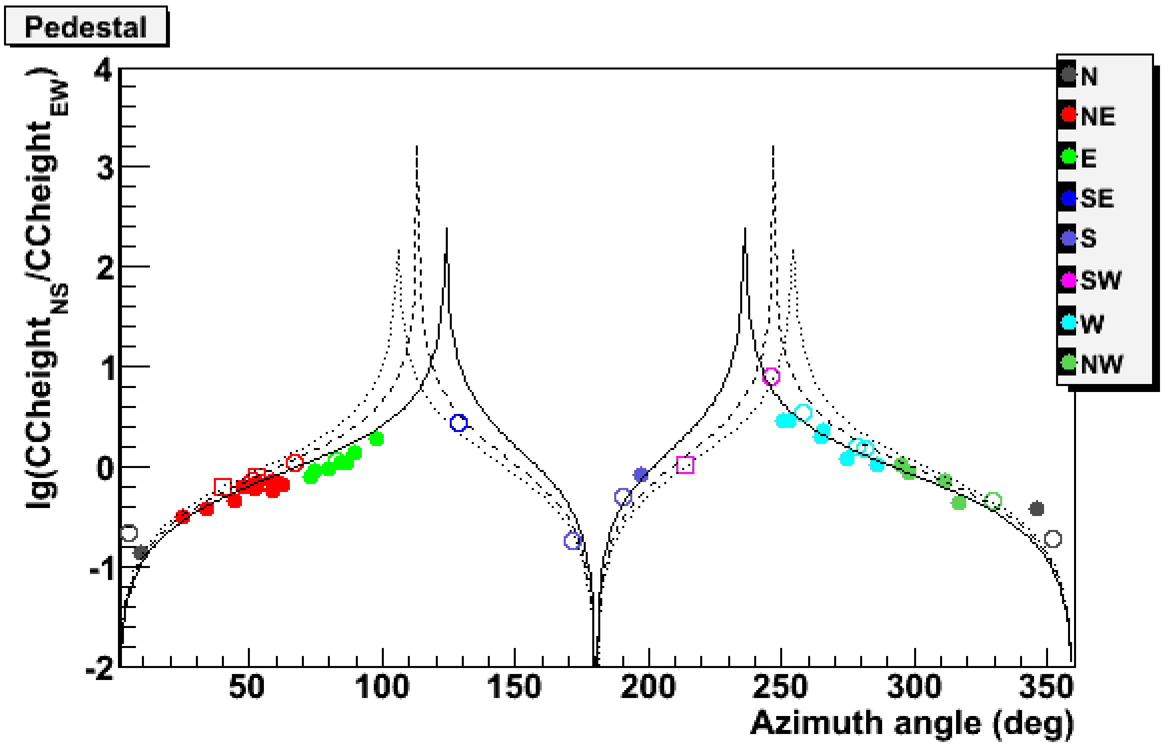
Antenna characteristics



Comparison with simplified geomagnetic model



Comparison with simplified geomagnetic model



● data 40°-50°

○ data 50°-60°

□ data above 50°