Direct Measurement of the Muon Density in Air Showers with the Pierre Auger Observatory

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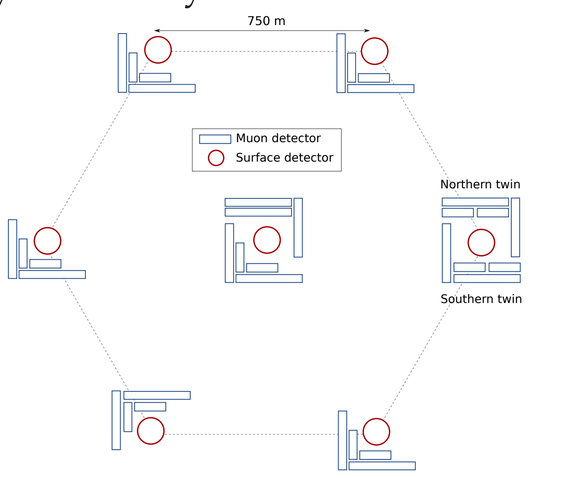
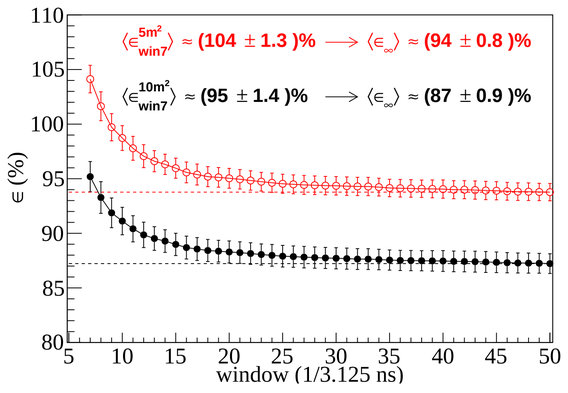
AMIGA Prototype Array

- Auger Muons and Infill for the Ground Array (AMIGA) prototype array 2014-2017
- Seven plastic-scintillation detectors buried at 2.3 m depth, $5 \times 30\,\mathrm{m}^2$ and $2 \times 60\,\mathrm{m}^2$
- Analysis of one year of calibrated data



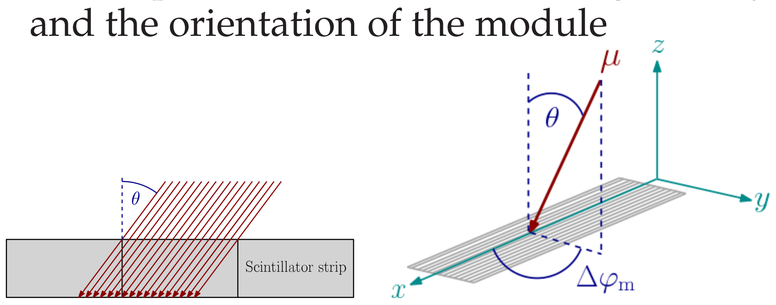
Efficiency Correction

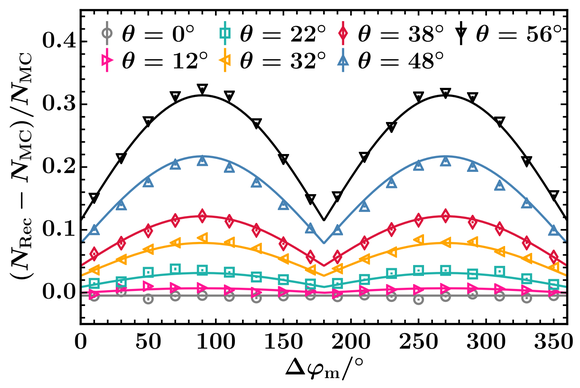
- Correction for different efficiencies of modules with 5 and 10 m^2 area due to light attenuation in WLS fibers and PMT after-pulsing



Corner Clip. Correction

- Geometrical correction for inclined muons leaving a signal in multiple detector strips
- Bias depends on both the shower geometry and the orientation of the module

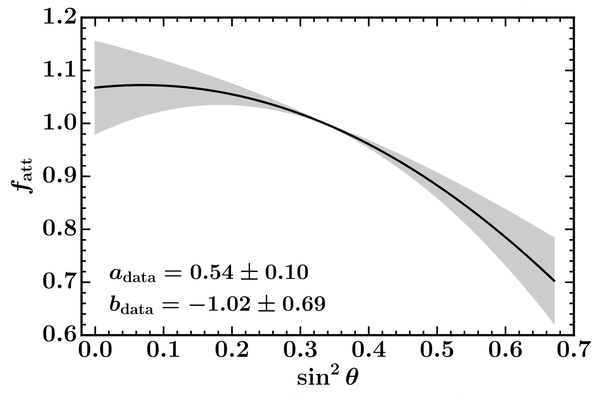




$$f_{\mathrm{clip}}\,(\theta, \Delta\varphi_{\mathrm{m}}) = a(\theta) + b(\theta) \cdot |\sin \Delta\varphi_{\mathrm{m}}|$$

Attenuation Correction

- Correction for the attenuation of the muon density due to the atmosphere and soil layer
- Zenith-independent muon density ρ_{35}



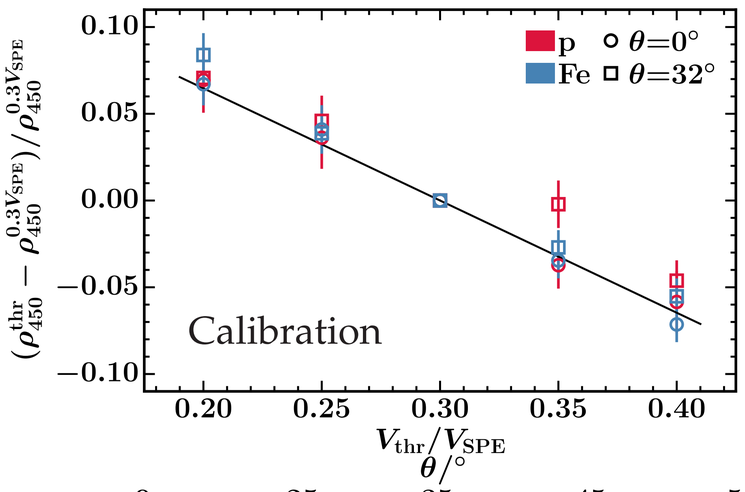
$$f_{\mathrm{att}}\,(\theta) = 1 + ax + bx^2,\; x = \cos^2\theta - \cos^2 35^\circ$$

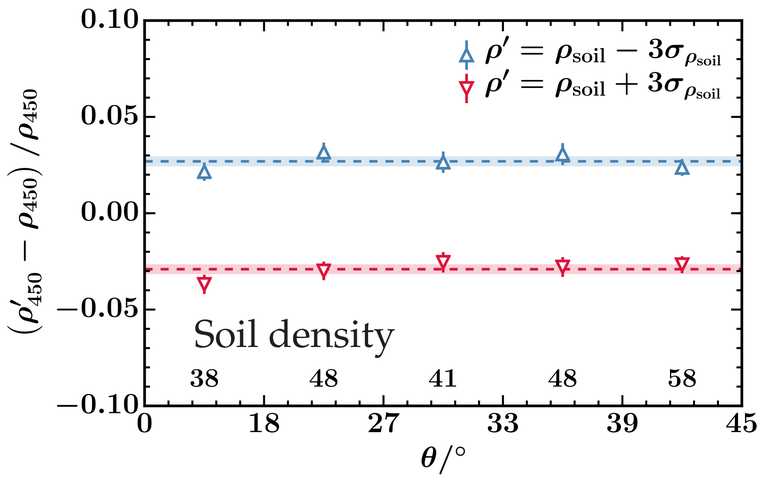
Systematic Uncertainties

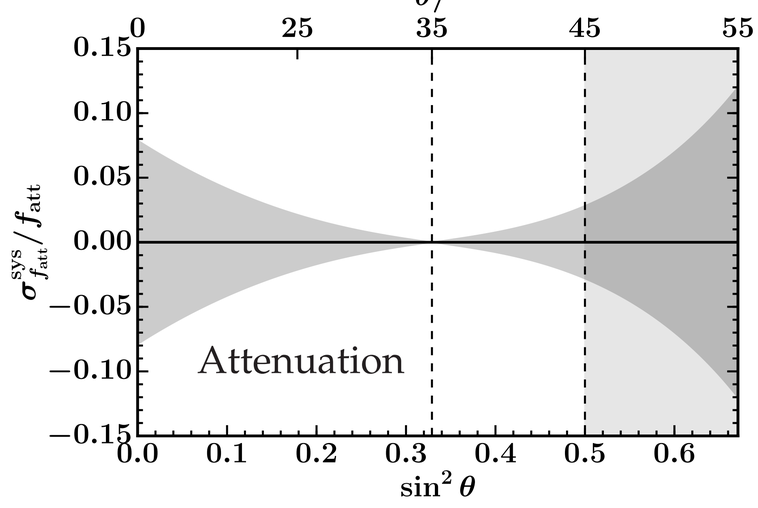
Systematic uncertainties arise from

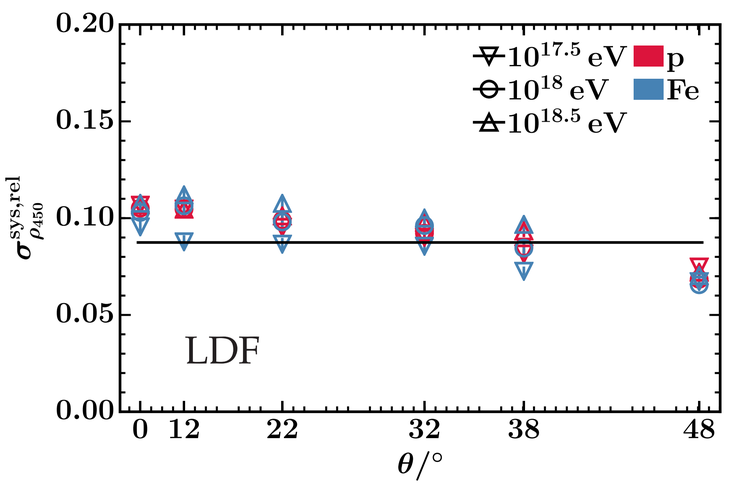
- Module efficiency correction
- Calibration of PMT channels
- Soil density variations in the field
- LDF shape for individual events
- Attenuation correction

Systematic Uncertainty		Percentage
Eff. corr.	$\sigma_{\mathrm{sys,eff}}/\rho_{450}$	9.9%
Calibration	$\sigma_{\mathrm{sys,thr}}/\rho_{450}$	3.9%
Soil density	$\sigma_{\mathrm{sys,soil}}/\rho_{450}$	2.8%
LDF	$\sigma_{\mathrm{sys,LDF}}/\rho_{450}$	8.8%
Atten. corr.	$\sigma_{\mathrm{sys},f_{\mathrm{att}}}/f_{\mathrm{att}}$	2.3%
Total	$\sigma_{\mathrm{sys},\rho_{35}}/\rho_{35}$	**14.3%**







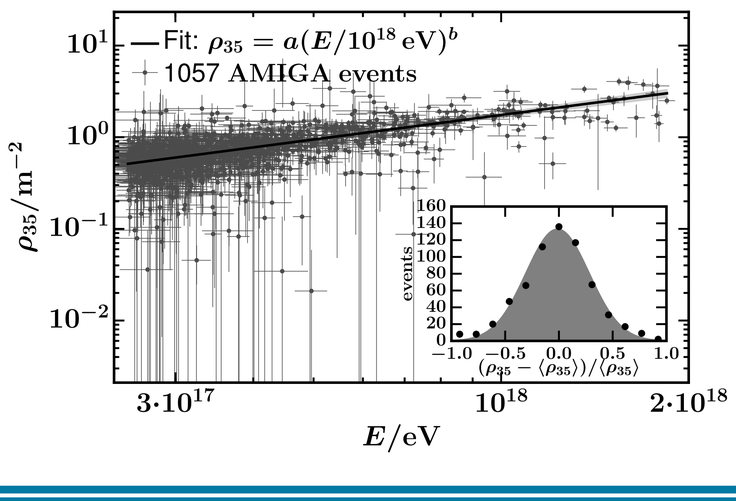


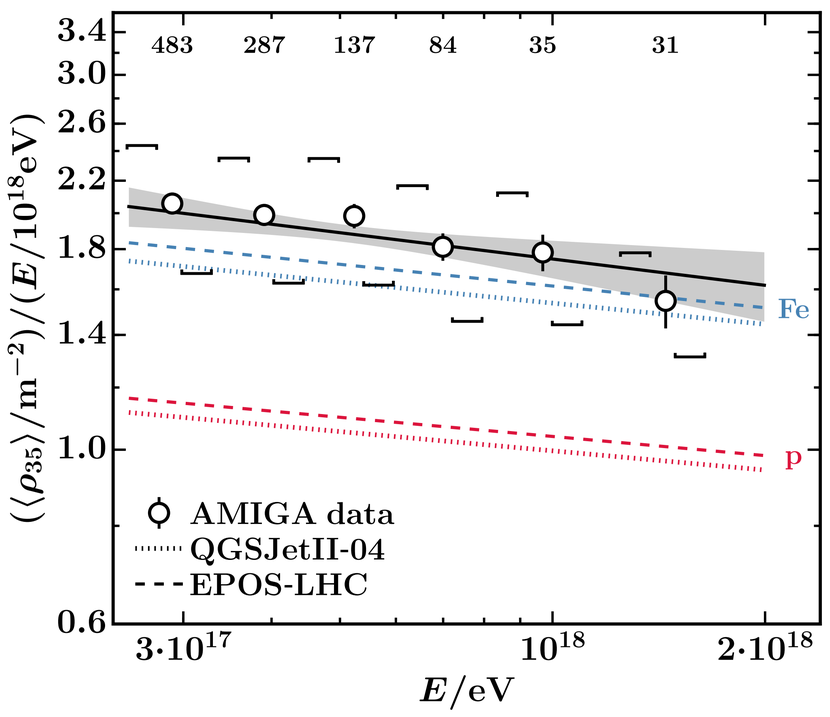
Energy Dependence of the Muon Density

- Power law fit of the energy dependence of the zenith-independent muon density

$$\rho_{35}\,(\mathrm{E}; \mathrm{a}, \mathrm{b}) = \mathrm{a}(E/10^{18}\,\mathrm{eV})^{\mathrm{b}}$$

$$a = 1.75 \pm 0.05 \pm 0.05(\mathrm{sys})$$
$$b = 0.89 \pm 0.04 \pm 0.04(\mathrm{sys})$$





Muon Density vs. Depth of Shower Maximum

- Average logarithmic muon density $\langle \ln \rho_{35} \rangle$ as a function of the average shower depth $\langle X_{\mathrm{max}} \rangle$ (statistical averages, no coincident measurements)
- 38% (EPOS-LHC) to 53% (QGSJetII-04) more muons in data than in simulations