Improved Calibration and Reconstruction Methods of the Underground Muon Detector of the Pierre Auger Observatory

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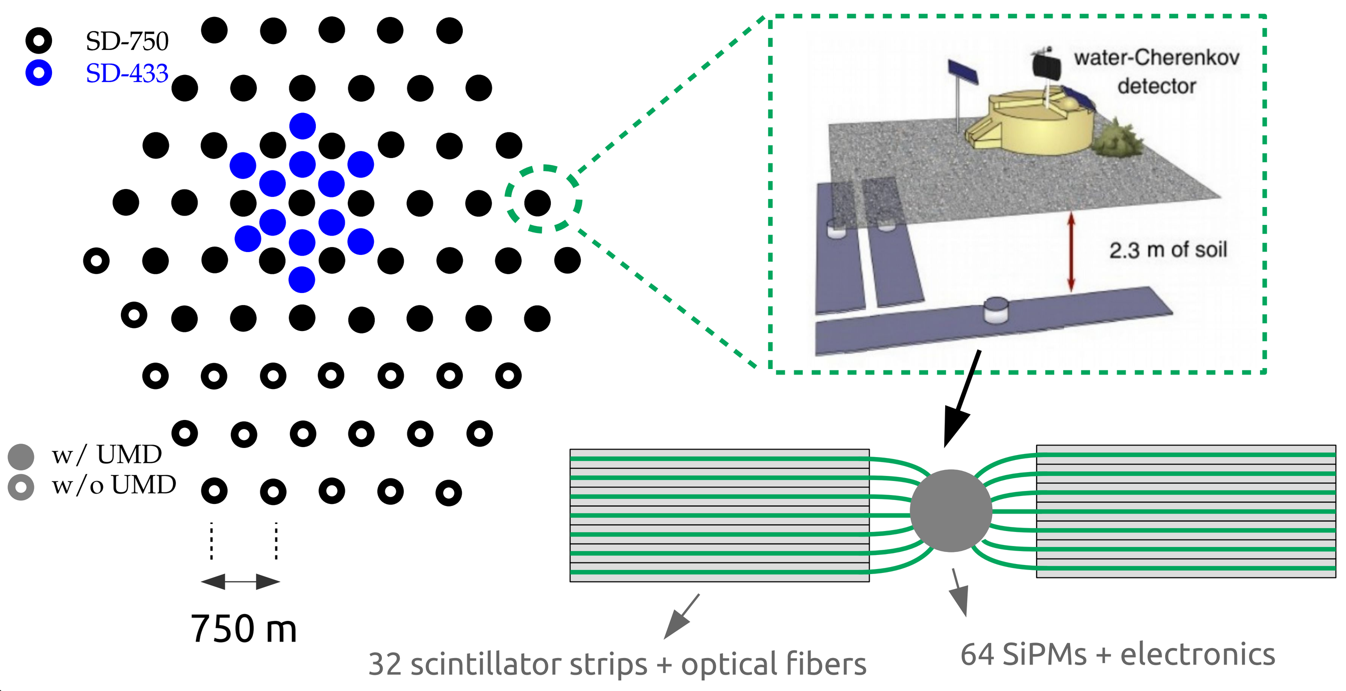
PIERRE AUGER OBSERVATORY

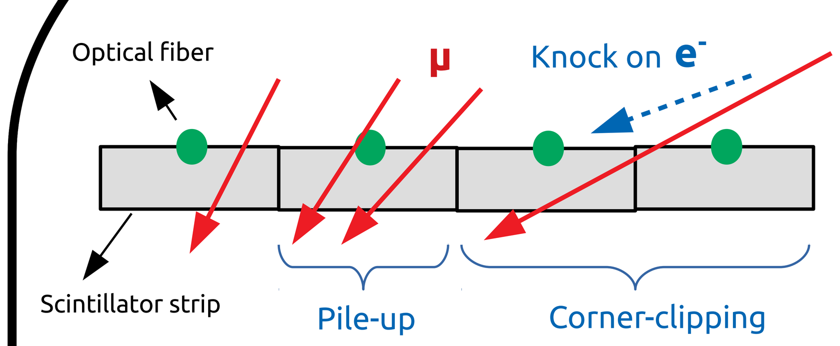
Underground Muon Detector (UMD)



- Array of muon detectors buried in the vicinity of water-Cherenkov detectors (WCD) in the low-energy extension of the Surface Detector (SD)
  - Muon content of air-showers with $10^{16.5}$ **eV < E < 10^{19} eV**
- Each detector comprises 3 modules of 10 m² of plastic scintillator
- Each module is segmented into **64 independent strips**

- Two complementary modes of acquisition:
  - Binary (low muon densities)
    - Relies on detector segmentation
    - Handles 64 signals independently
    - 64 **binary** traces of 2048 bits
    - Sensitive to signal amplitude
    - Muon signal → A bar is triggered if signal amplitude is above thresold (2.5 PEs) for ≥ 12.5 ns
  - ADC (high muon densities)
    - Treats the detector as a whole
    - Sums over 64 channels
    - Two ADC traces of 1024 samples
    - Sensitive to signal charge

Binary mode: LDF fit



Detector signal

- k = # of triggered bars
- ✔ Insensitive to knock-on e-
- ➔ It has to be corrected for
  - pile-up (2μ in the same bar)
  - corner-clipping (1μ in 2 bars)

Expected number of muons

$$\mu_j = \rho(r_j)\, A\, \cos\theta$$

LDF model

$$\rho(r) = \rho_{450}\left(\frac{r}{450\ \mathrm{m}}\right)^{-\alpha}\left(\frac{1+r/r_0}{1+450\ \mathrm{m}/r_0}\right)^{-\beta}\left(\frac{1+(r/10r_0)^2}{1+(450\ \mathrm{m}/10r_0)^2}\right)^{-\gamma}$$

- Optimal LDF parameters are obtained minimizing the event log-likelihood

$$\mathcal{L}(\rho_{450}) = -\sum_{i\in\mathrm{cand}} \ln L_{\mathrm{cand}} - \sum_{i\in\mathrm{sat}} \ln L_{\mathrm{sat}} - \sum_{i\in\mathrm{sil}} \ln L_{\mathrm{sil}}$$

candidates — saturated — silent

- Two likelihoods were tested to fit the LDF:
  - **Poisson [1]**
  - **Binomial [2]**

Poisson likelihood [1]

- Assumes N_μ estimator has Poisson fluctuations only
- So far used as the official reconstruction method

$$\hat{N}_\mu = \frac{1}{(1+p_{\mathrm{cc}})}\frac{\ln(1-k/64)}{\ln(1-1/64)}$$

Corner-clipping correction

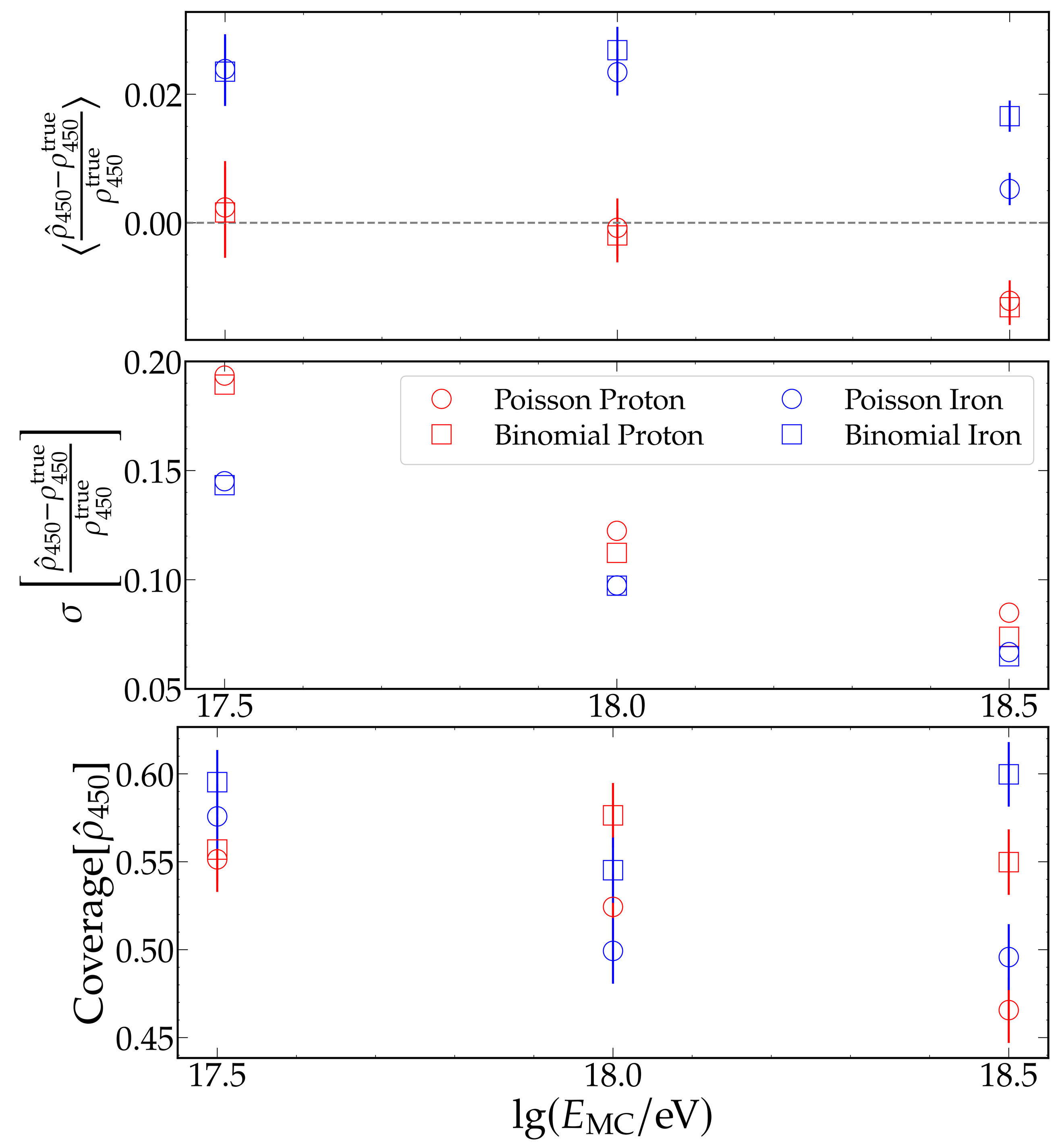
$$L(\mu) = \mathrm{Poisson}(\hat{N}_\mu|\mu)$$

Binomial likelihood [2]

- In addition to Poisson fluctuations, it accounts for detector segmentation
  - More realistic modeling of the signal fluctuations

$$L(\mu) = \binom{64}{k} e^{-\mu(1+p_{\mathrm{cc}})}\left(e^{\mu(1+p_{\mathrm{cc}})/64}-1\right)^k$$

- Library of CORSIKA showers of {p, Fe} + full detector simulations
- Set of 11 stations placed at 450 m from the core serve to obtain $\rho_{450}^{\mathrm{true}}$ and assess bias
- Each shower is reconstructed with Poisson and Binomial likelihoods



- ✔ Bias and resolution of both likelihoods are compatible
- Binomial likelihood yields larger error estimate due to better modeling of signal fluctuations
  - ✔ Improved coverage
- Binomial likelihood is prefered

ADC mode

Detector signal

- q = charge of ADC signal
- ✔ Insensitive to pile-up and corner-clipping
- ➔ It has to be corrected for knock-on e- depositing charge in the detector

$$\hat{N}_\mu = \frac{q\,\cos\theta}{q_{1\mu}}$$

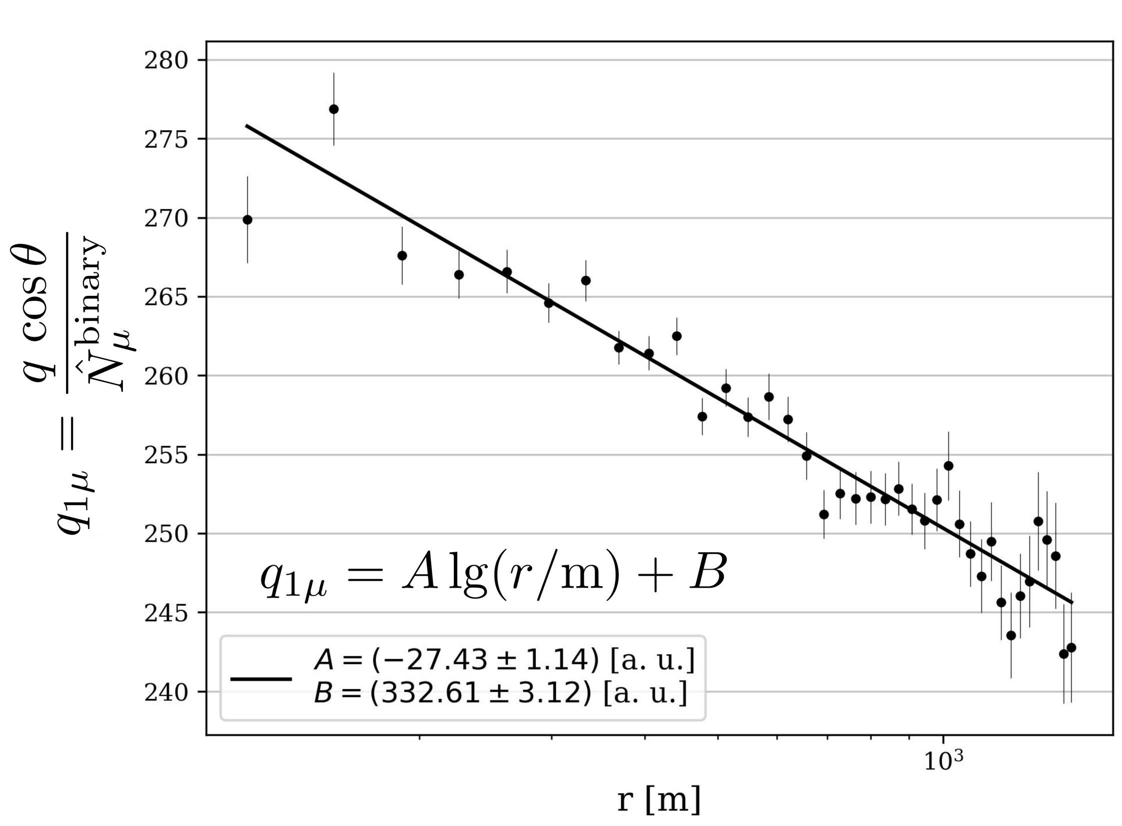
Charge of ADC signal (q); Mean charge produced by 1 vertical muon ($q_{1\mu}$)

- $q_{1\mu}$ is obtained for each module using events with $N_\mu^{\mathrm{binary}} < 70$

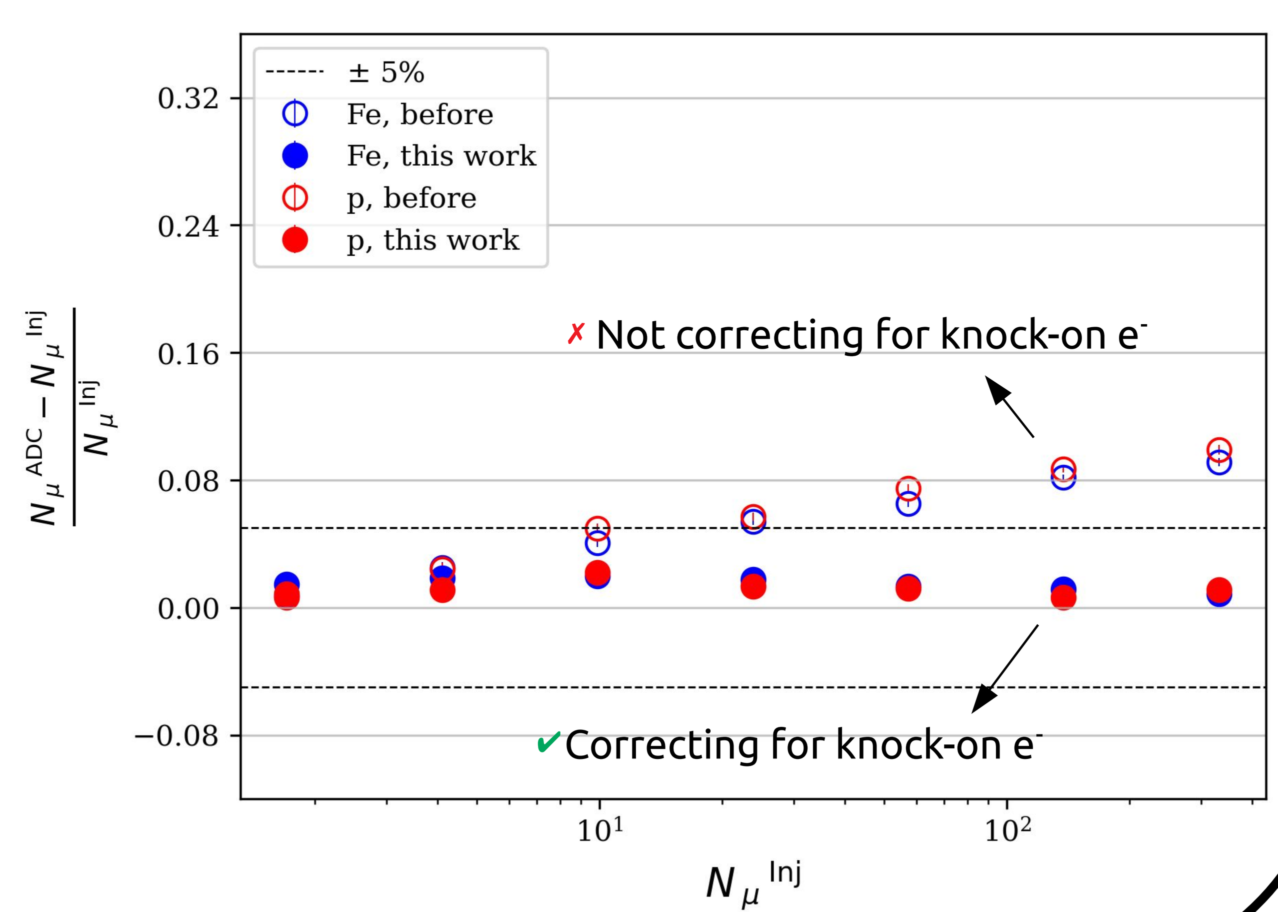
$$q_{1\mu} = \frac{q\,\cos\theta}{\hat{N}_\mu^{\mathrm{binary}}}$$

Zenith angle of the shower (θ)

- More energetic muons, produced closer to the core, generate **more knock-on e-** when transversing the soil
  - Introduces a dependence of $q_{1\mu}$ on r
  - It can **bias** the measurement up to ~10%



- $q_{1\mu}$ parameterized as a function of r
  - ✔ Bias reduced below 3%



Summary

- ✔ Likelihood model for the binary mode was switched from a Poisson to a binomial model, improving the modeling of signal fluctuations
- ✔ New method to calibrate the ADC mode to account for knock-on e-

Outlook

- Apply improved ADC calibration to data
- Combine ADC and binary information for the LDF fit

References

[1] Supanitsky, A. D., et al. *Astropart. Phys.*, 2008, vol. 29, no 6, p. 461-470.

[2] Ravignani, D.; Supanitsky, A.D, *Astropart. Phys.*, 2015, vol. 65, p. 1-10

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