Effect of the knock-on electrons in the calorimetric mode of an underground muon detector

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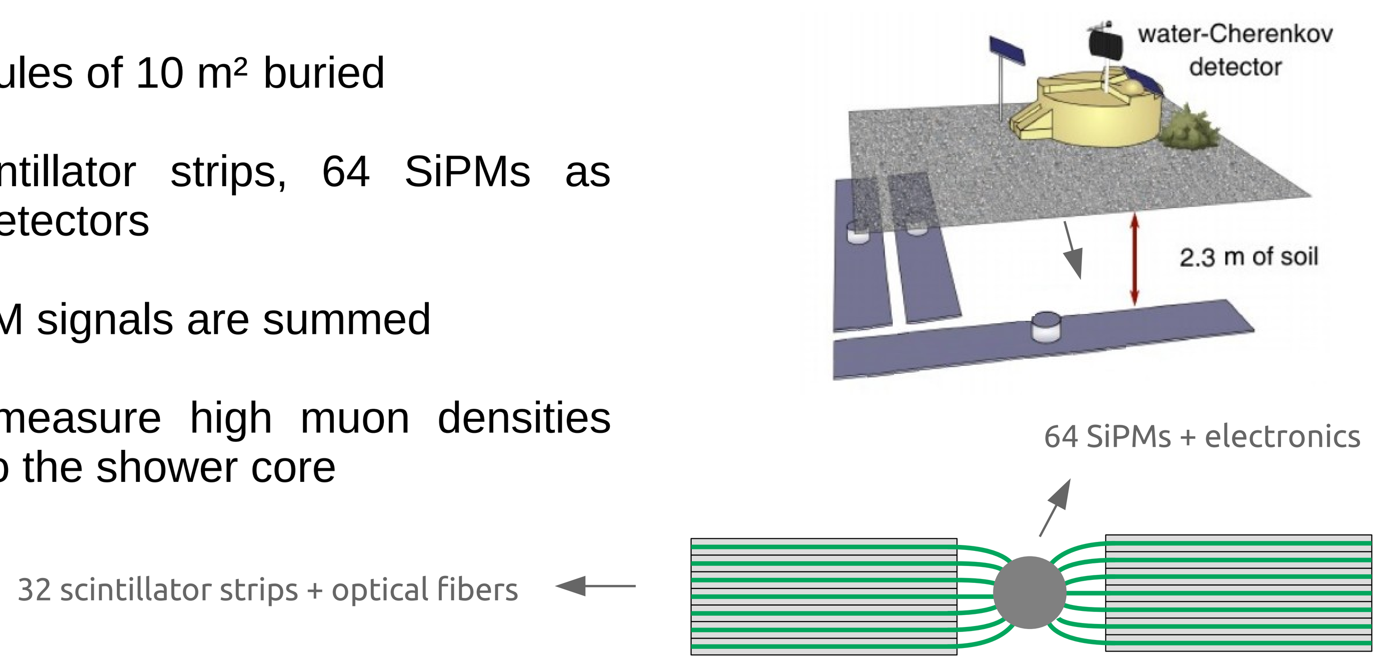
Abstract: Calibrating underground detectors necessitates careful consideration of the passage of penetrating particles through matter. In muon detectors based on plastic scintillators, like the Underground Muon Detector (UMD) at the Pierre Auger Observatory, the energy deposition within the plastic is significantly influenced by the generation of delta (knock-on) electrons in the surrounding ground as muons pass through. In this study, we analyzed the energy deposition by various particles impacting a 2.3 m deep underground detector and assessed its effect on the reconstruction of muon density in extensive air showers induced by energetic nuclei.

1 Calorimetric mode of muon detector

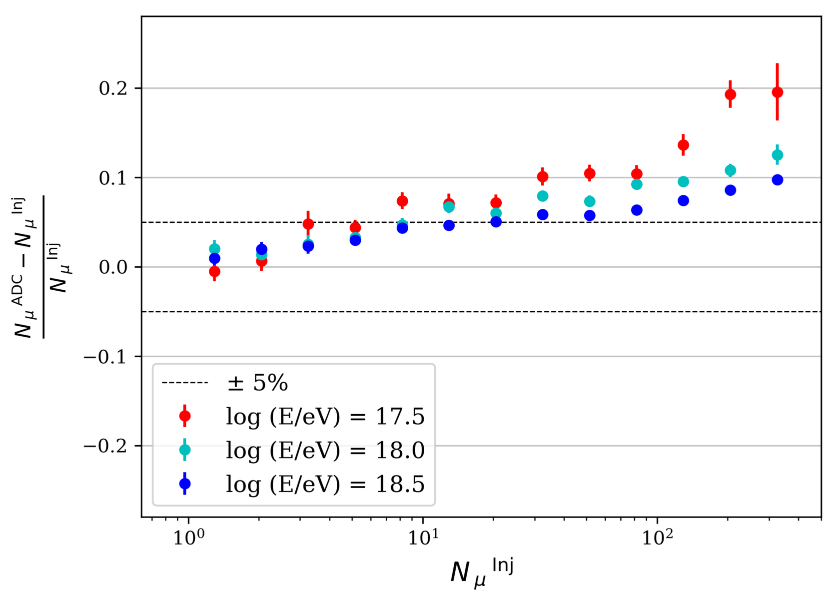
- 3 modules of 10 m² buried
- 64 scintillator strips, 64 SiPMs as photodetectors
- 64 SiPM signals are summed
- Goal: measure high muon densities close to the shower core



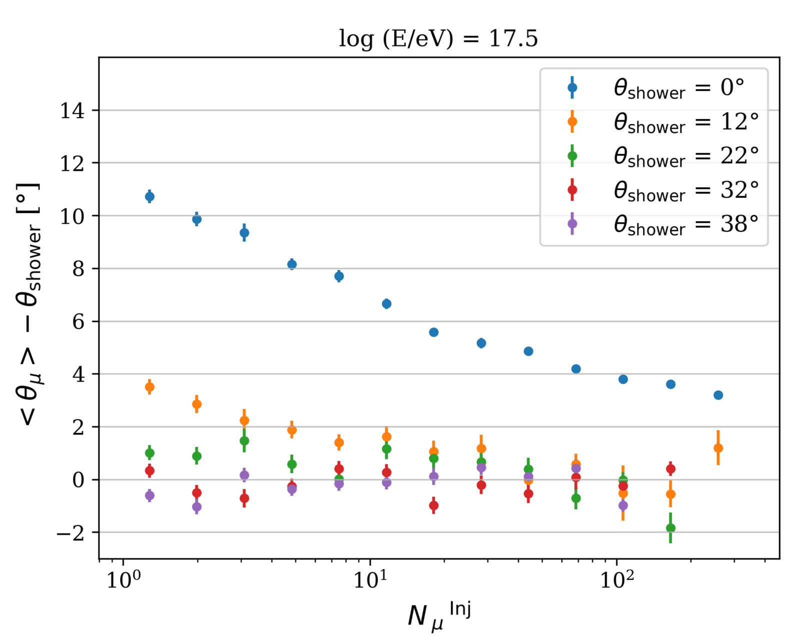
2 Bias in muon reconstruction

- Data set: proton showers (simulated with the hadronic interaction model EPOS-LHC) of energies E = [1 x $10^{17.5}$, 1 x 10^{18}, 1 x $10^{18.5}$] eV and zenith angles θ = [0, 12, 22, 32, 38]°
- Muons estimated dividing the measured charge by the mean charge deposited by a vertical muon:

$$N_\mu^{\mathrm{ADC}} = \frac{q_{\mathrm{meas}} \cos\theta}{\langle q_{1\mu}(\theta{=}0)\rangle}$$



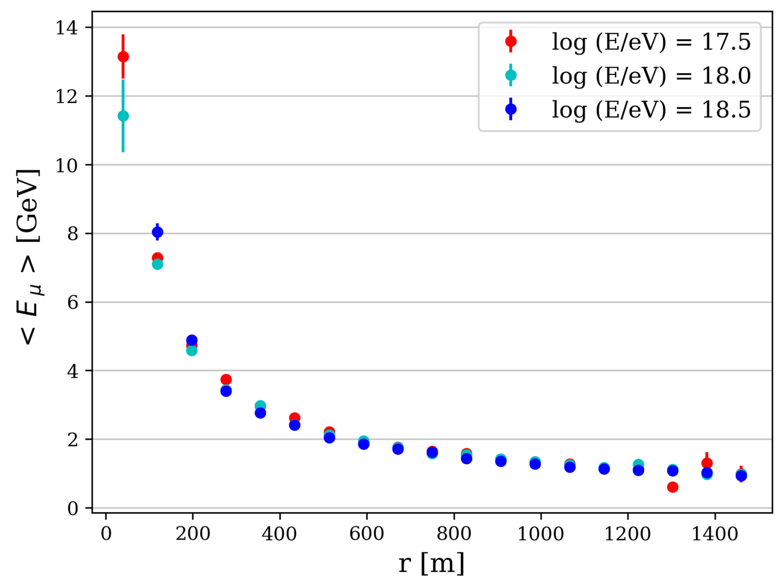
- Bias obtained in the muon reconstruction increases with muon density
- Bias cannot be attributed to the approximation $\cos\langle\theta_\mu\rangle \approx \cos\theta_{\mathrm{shower}}$



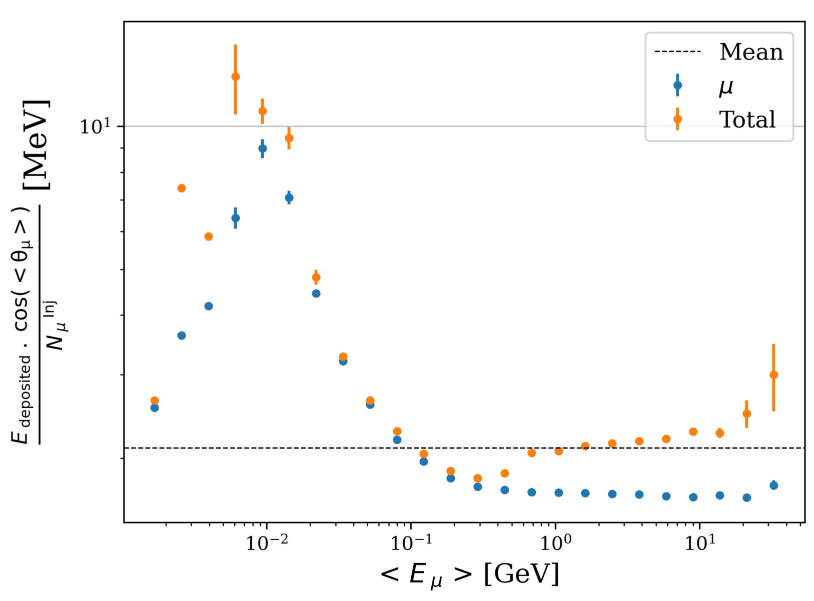
3 Energy deposited on scintillators

- Average energy of muons arriving to the detector increases closer to the shower axis
- Total energy deposited on the scintillators per injected muon per vertical-path length:

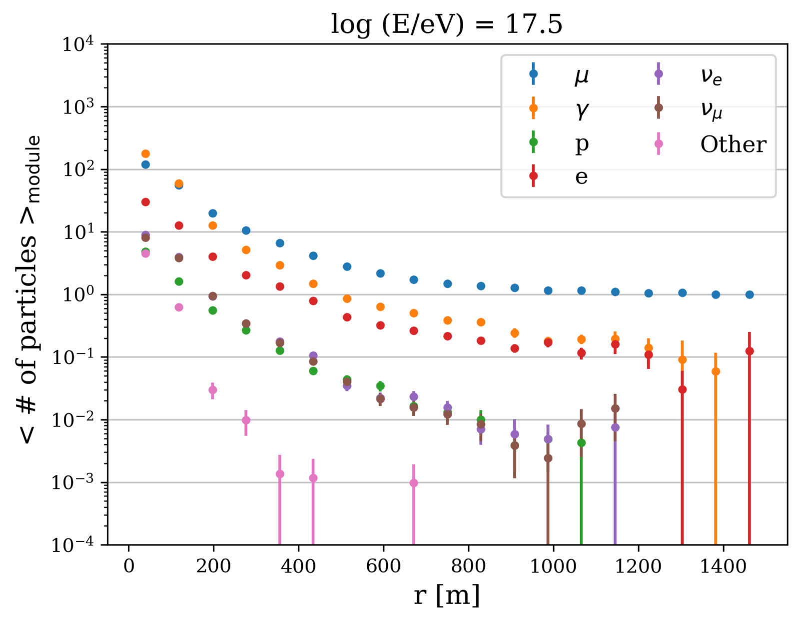
$$\frac{E^{\mathrm{total}}_{\mathrm{deposited}} \cos\langle\theta_\mu\rangle}{N_\mu^{\mathrm{Inj}}}$$



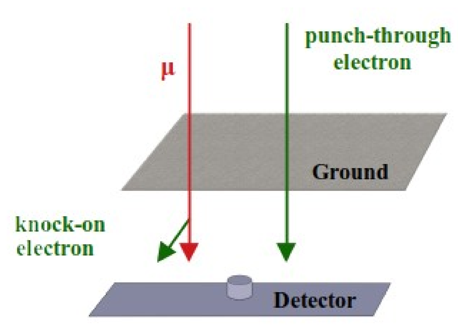
- Muon energy loss rate exhibits rapid rise for muons of E_μ < 0.3 GeV (expected from Bethe regime). Beyond this point, the total energy deposited per muon per vertical-path length increases with muon energy due to additional particles (mainly knock-on electrons)



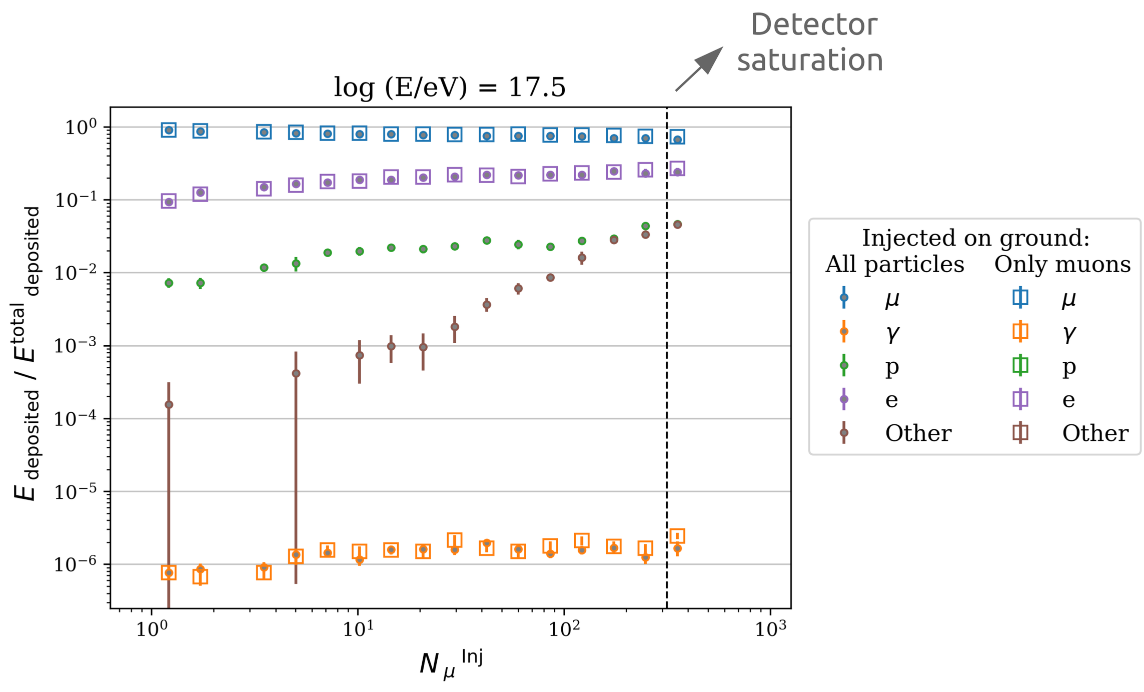
- Particles most likely to arrive: μ±, γ, e±, p±, $\nu_\mu^{\pm}$ and $\nu_e^{\pm}$. Any other particle (π⁺, K⁺, etc.) categorized as "Other"

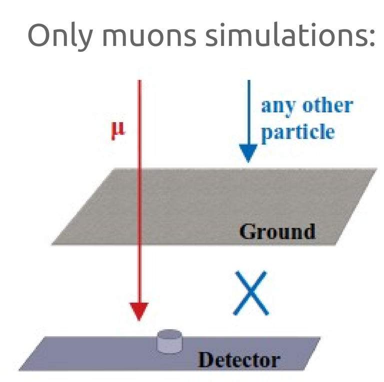


- Electrons at the detector: knock-on electrons produced in the soil or punch-through electrons from electromagnetic component of the shower?

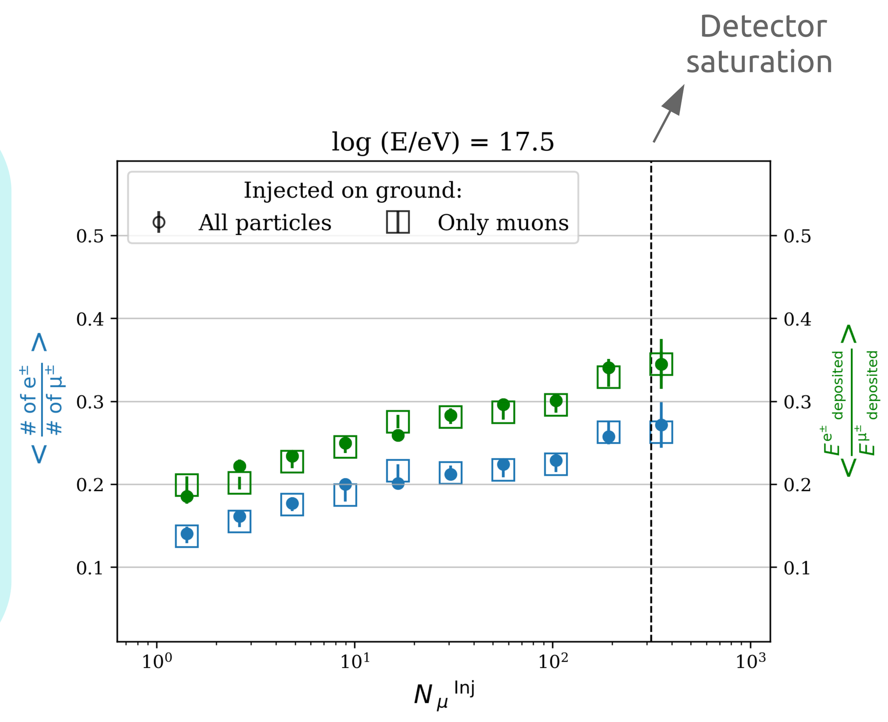


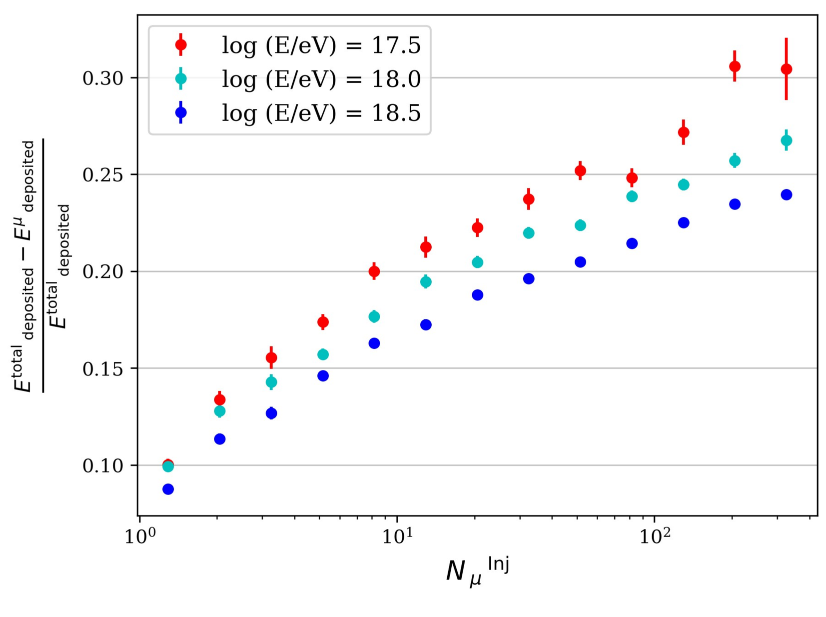
- Events were simulated where only muons were allowed to be injected on the ground
- No relative contamination from punch-through electrons and photons. Relative contamination by knock-on electrons increases near the shower core. Excluding muons, knock-on electrons are the primary contribution to energy deposited

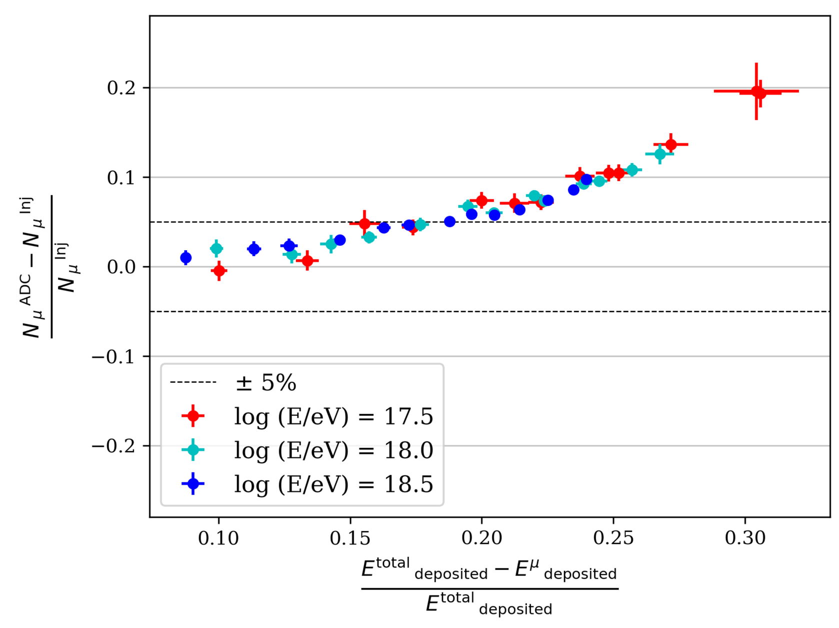




- Fraction of energy deposited by other particles rises with muon densities. The effect is more pronounced for less energetic showers, since at the same muon density they tend to have more energetic muons
- Bias in muon reconstruction increases in accordance with the increase in energy deposited by other particles







4 Conclusion

- Calibrating the calorimetric mode of underground muon detectors based on plastic scintillators using the average charge from atmospheric background muons can introduce a bias in the reconstructed muon density. For a detector like the UMD, this reconstruction bias can reach up to 20% for proton showers with energies of $10^{17.5}$ eV near the shower axis
- Bias due to increased energy deposition per muon, especially near shower axis, where higher-energy muons produce more knock-on electrons
- Calibration methods should account for variations in the charge with the energy of the incoming muons, or any other related observable

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