Muon counting with the Underground Muon Detector of The Pierre Auger Observatory

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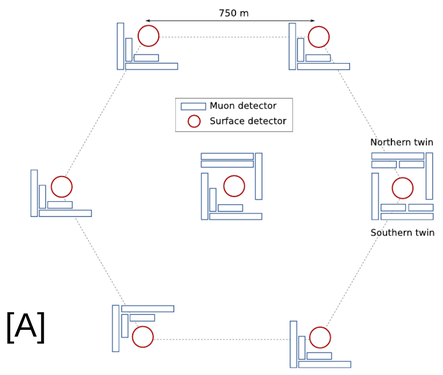
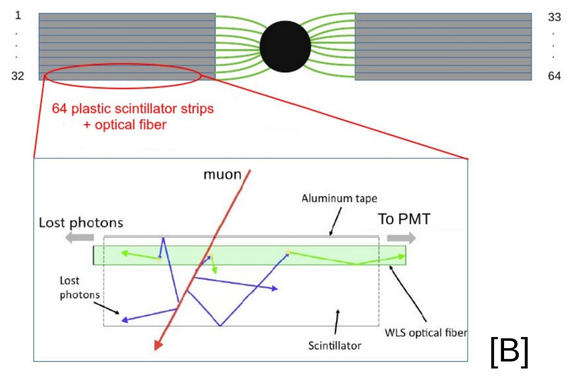
Abstract: The Underground Muon Detector (UMD) aims to extend the detection range of the Pierre Auger Observatory to observe cosmic rays of energies greater than $10^{16.6}$ eV and performs a direct measurement of the muon component (sensitive observable to the mass composition) of the air showers. In this work, we will present an overview of the final design of the UMD and its reconstruction techniques alongside the observations obtained during the engineering array phase. First results suggest that the current hadronic interaction models have a muon deficit at energies between 2 x 10^{17} eV and 2 x 10^{18} eV.

1. UMD prototype array



[A]



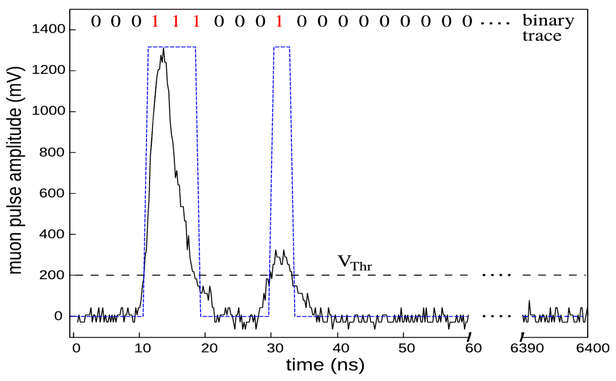
[B]

Engineering array:
7 sets of 2 **modules** of 5 m² and 2 **modules** of 10 m² **buried** [A]

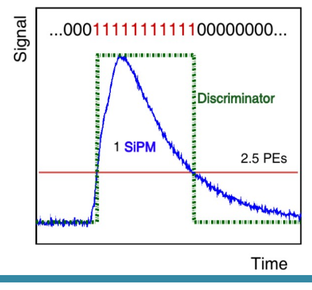
Soil shielding → only **muon** detection
64 **scintillator** strips, 64 **PMTs** [B]

2. Muon counting

[C]



- **64 PMTs independently** through discriminator threshold [C]
- **Direct counting of muons** (low densities)
- Threshold calibration measuring background rate for each channel

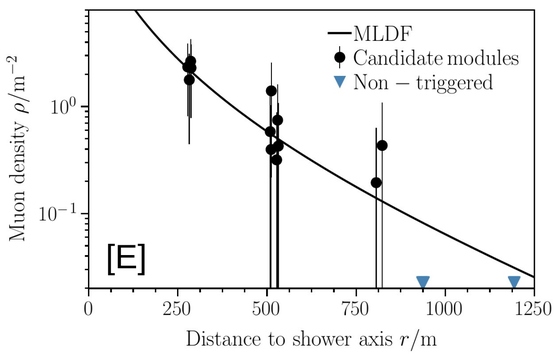


[D]

3. Results from engineering array

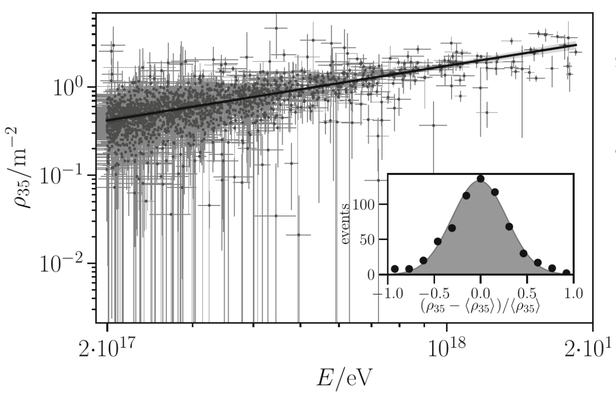
Data set: 1742 events (energies [2 x 10^{17}, 2 x 10^{18}] eV and θ ≤ 45°)

- Average **muon lateral distribution function** (MLDF) *ρ(r)* from Monte-Carlo simulations
- *ρ(450)* estimated with maximum likelihood [E] and corrected for attenuation $\rho_{35} = \rho(450)/f_{att}(\theta)$

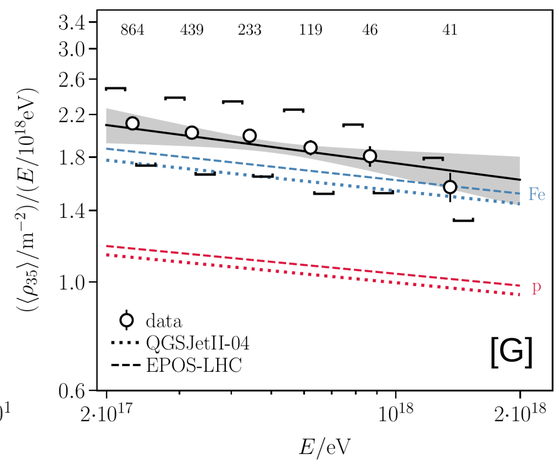


[E]

- ρ_{35} power-law dependence with energy (from Monte-Carlo simulations)
- Fit ρ_{35} with **maximum likelihood,** energy from Surface Detector [F]
- **Muon densities are larger in data** than in models [G]



[F]

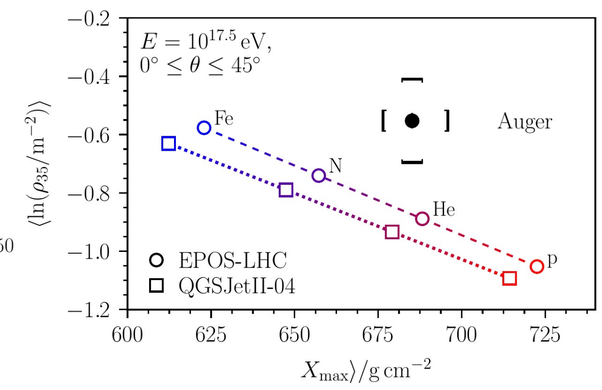


[G]

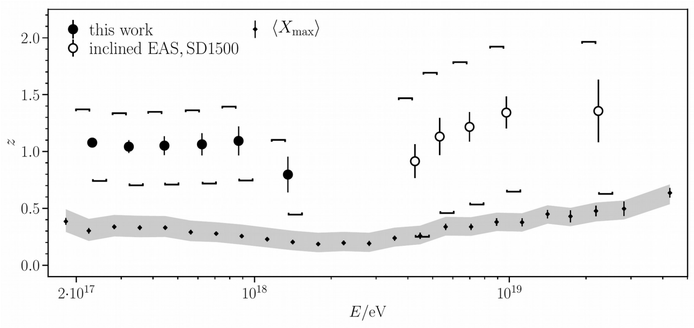
- *ln* ρ_{35} and X_{max} (directly observed with fluorescence detectors) linear with mean logarithmic mass <*ln A*> (Heitler model)

- For **EPOS- LHC increase of 38%**, for **QGSJetII- 04 of 50%** required to explain data [H]
- z-scale factor [I] where *x* is ρ_{35} and R_μ (previous results in inclined air showers)

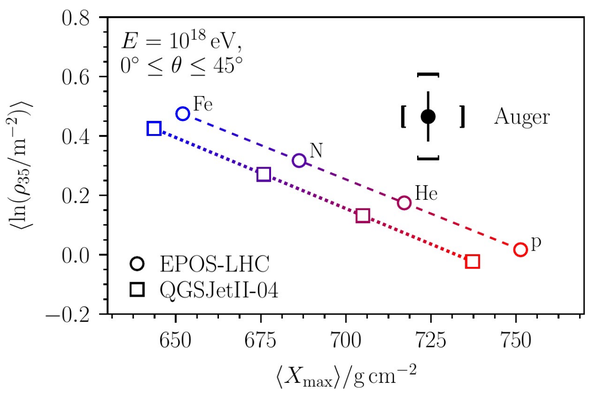
$$z = \frac{\langle \ln x \rangle - \langle \ln x \rangle_p}{\langle \ln x \rangle_{Fe} - \langle \ln x \rangle_p} \quad [I]$$



(a) $E = 10^{17.5}$ eV

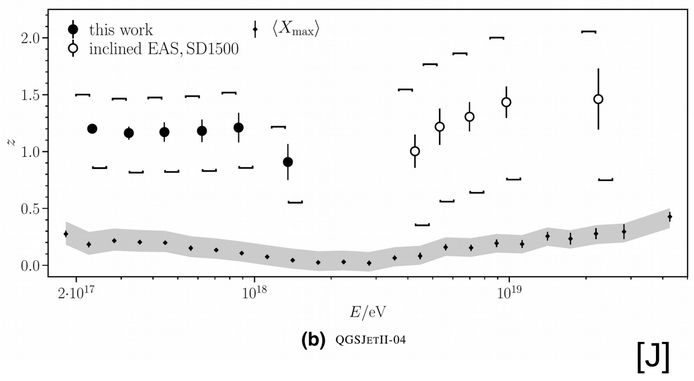


(a) EPOS-LHC



(b) $E = 10^{18}$ eV

[H]



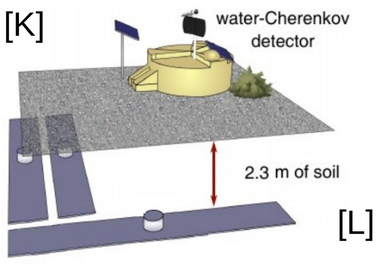
(b) QGSJetII-04

[J]

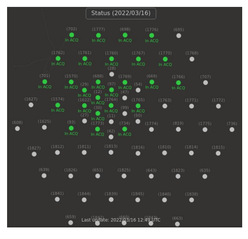
- **Hadronic interaction models fail to reproduce the z-scale factor** [J]
- Positive shift of energy scale would reduce the tensions

4. Final design: production status & performance

[K]



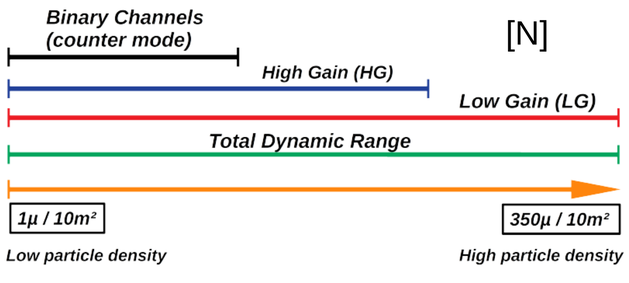
[L]



- 3 **modules** of 10 m² **buried** [K]
- **SiPM** as photodetectors [D][M]
- **number of muons** in 2 complementary ways: **counting** and **integrated signal** [N]

Positions in Acquisition [L]

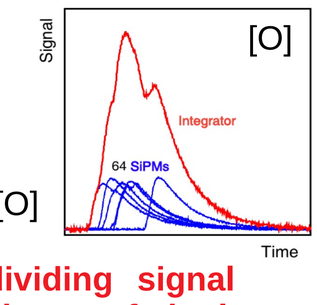
[M]



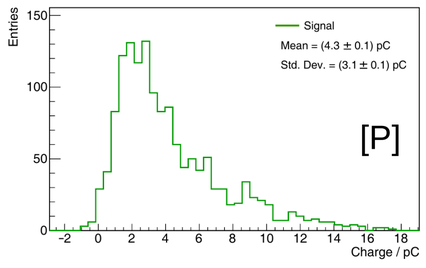
[N]

Integrated signal:

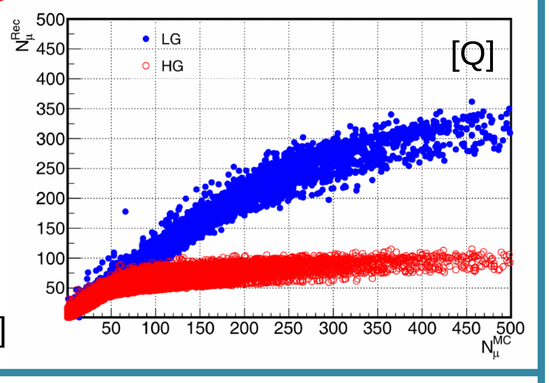
- **64 SiPMs summed** [O]
- Muons estimated **dividing signal charge by mean charge of single muon** (high densities)
- Two independent channels: **high gain (HG)** and **low gain** (LG)
- **Calibration histogram** [P] (selecting muon with binary)
- **LG/HG saturation 60/250** muons [Q]



[O]



[P]



[Q]

5. Conclusions

✗ **Hadronic interaction models produce fewer muons than those observed in EAS**
✔ Full UMD array will be completed by mid 2023

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