Cross-Validation of Muon Content in Extensive Air Showers with Surface and Underground Detectors of AugerPrime

Carmina Pérez Bertolli

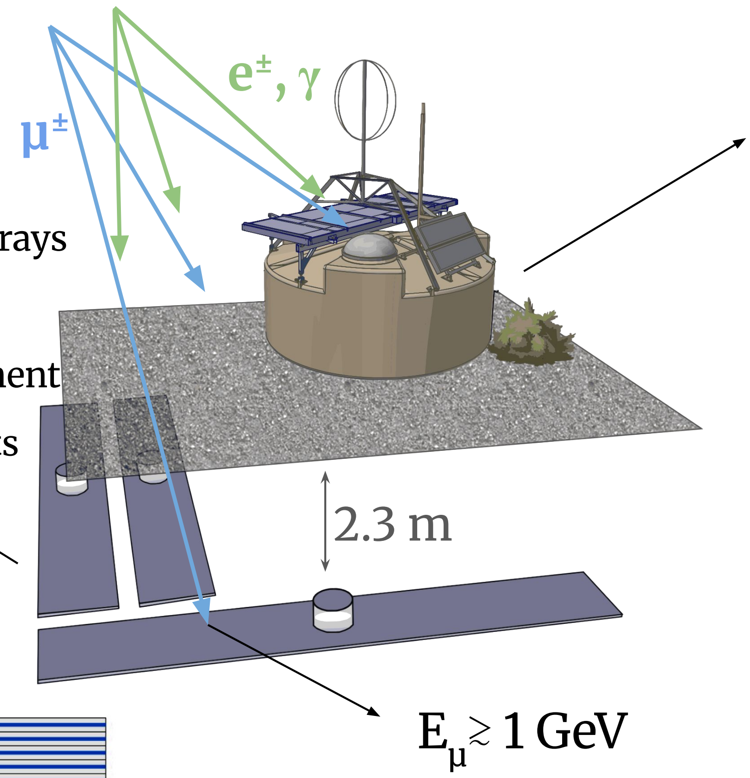
ITeDA
Instituto de Tecnologías en Detección y Astropartículas

KIT
Karlsruher Institut für Technologie

Referee: Prof. Dr. Brian Wundheiler
Co-referee: Prof. Dr. Ralph Engel
Supervisors: Dr. Nicolás González, Dr. Markus Roth

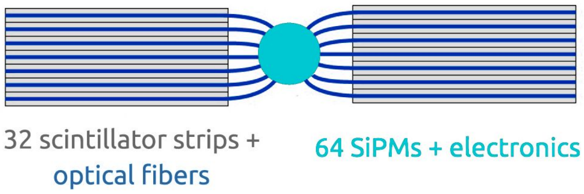
The Underground Muon Detector

- 750 m and 433 m nested arrays
- Paired to an SD station
- Buried to filter EM component
- Direct muon measurements



- Signal from muonic and electromagnetic component
- Constant efforts from the PAC to estimate the *pure* muonic signal

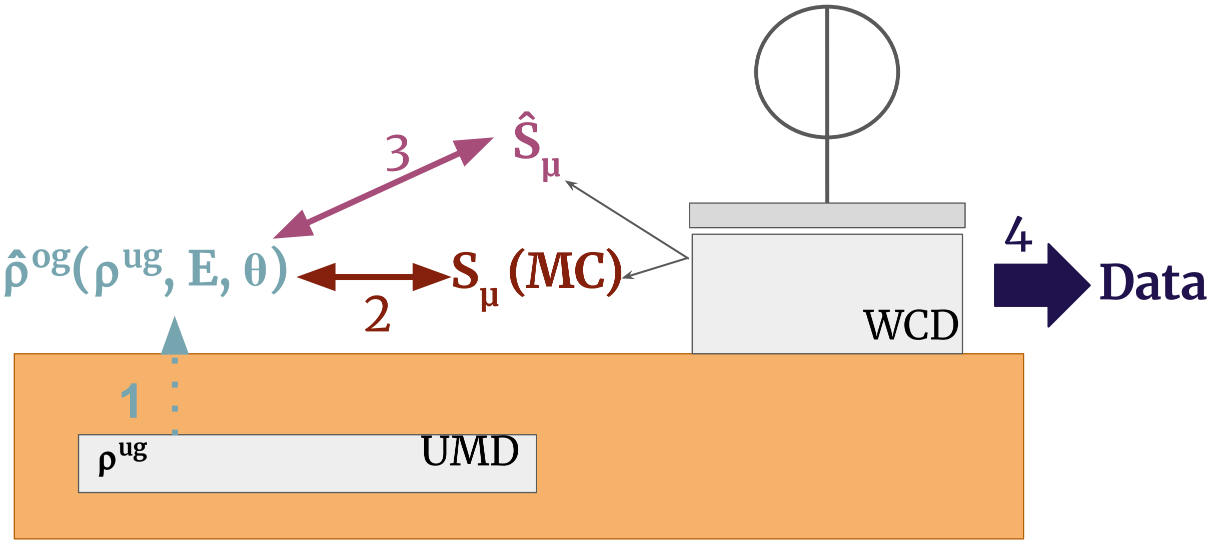
<u>Goal:</u> Calibrate the estimated muonic signal in the surface using the UMD to estimate muon density on ground



The UMD will provide important direct measurements of the shower muon content and its time structure, while serving as verification and fine-tuning of the methods used to extract muon information with the SSD and WCD measurements. (AugerPrime Design Report)

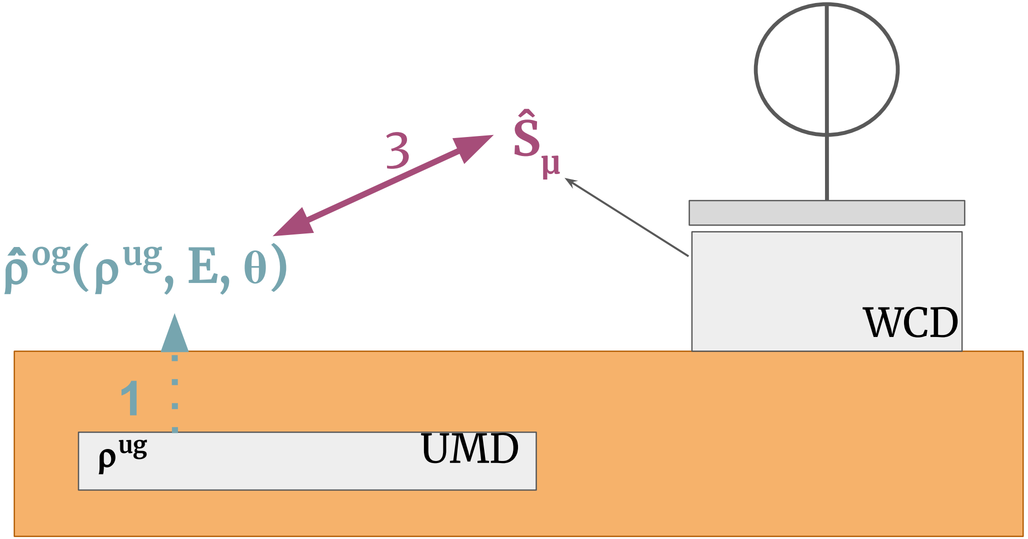
Outline

1. Estimation of muons density on ground using the UMD
2. Validation and proof of concept in the 750 m Infill of the calibration procedure
3. Calibration using Neural Network outputs from WCD
4. Estimation of muon content on ground with Data

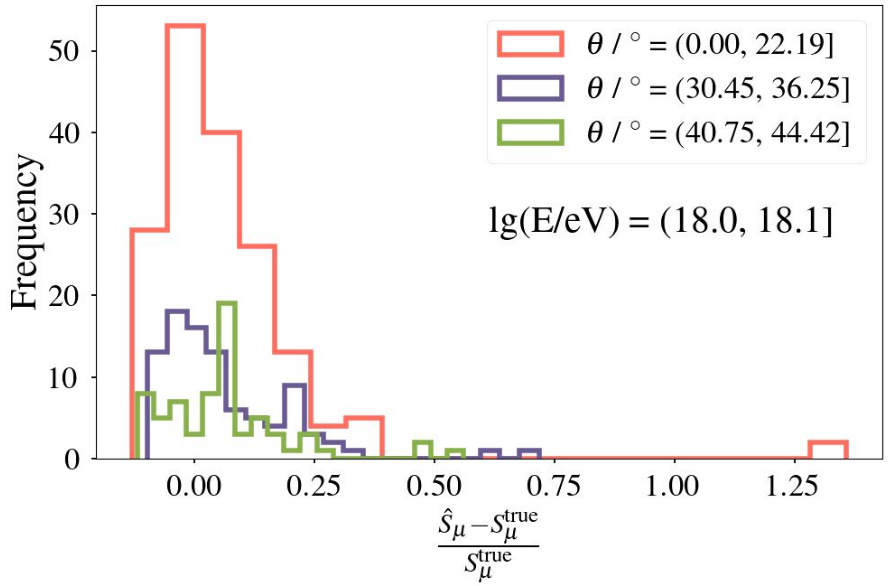


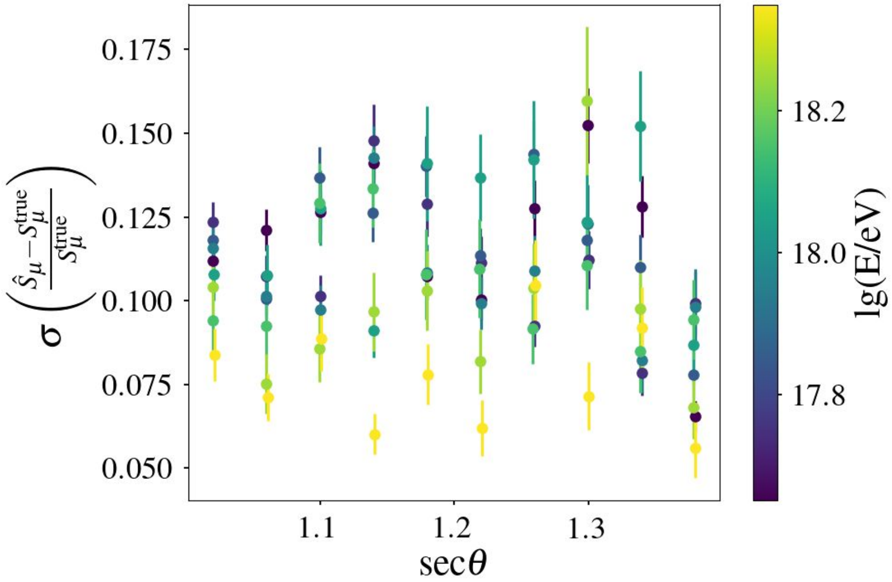
Outline

1. Estimation of muons density on ground using the UMD
2. Validation and proof of concept in the 750 m Infill of the calibration procedure
3. Calibration using Neural Network outputs from WCD
4. Estimation of muon content on ground with Data



NN-based $\hat{S}_\mu$ from WCD

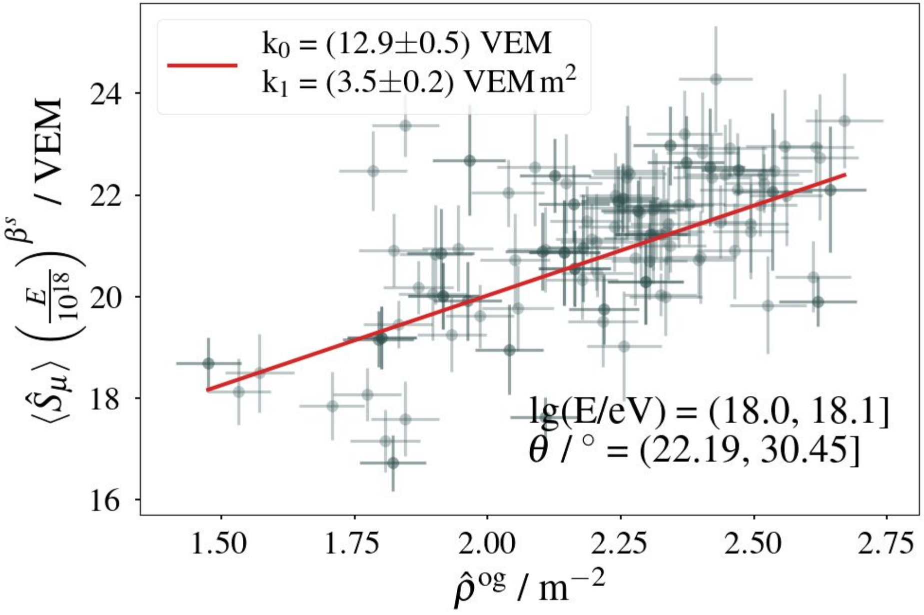


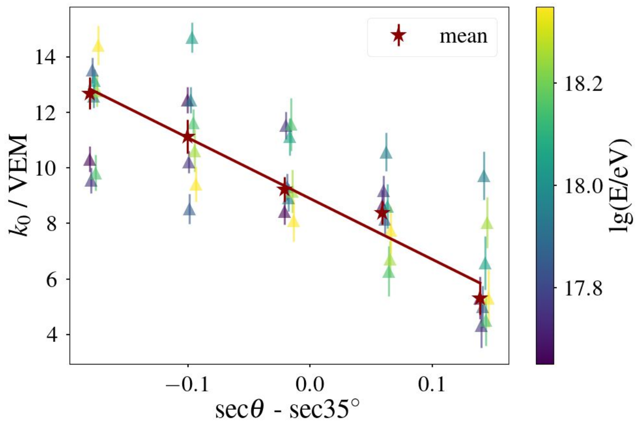


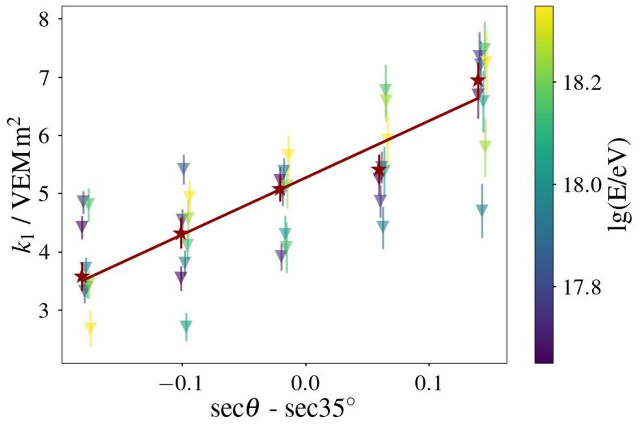
- Use NN-based $\hat{S}_\mu$ as a proxy for the true muon signal.
- Enables data-driven calibration using real data observables.

★ Data provided by the FZU group from the PAC

Calibration using $\hat{S}_\mu$ from NNs (WCD)

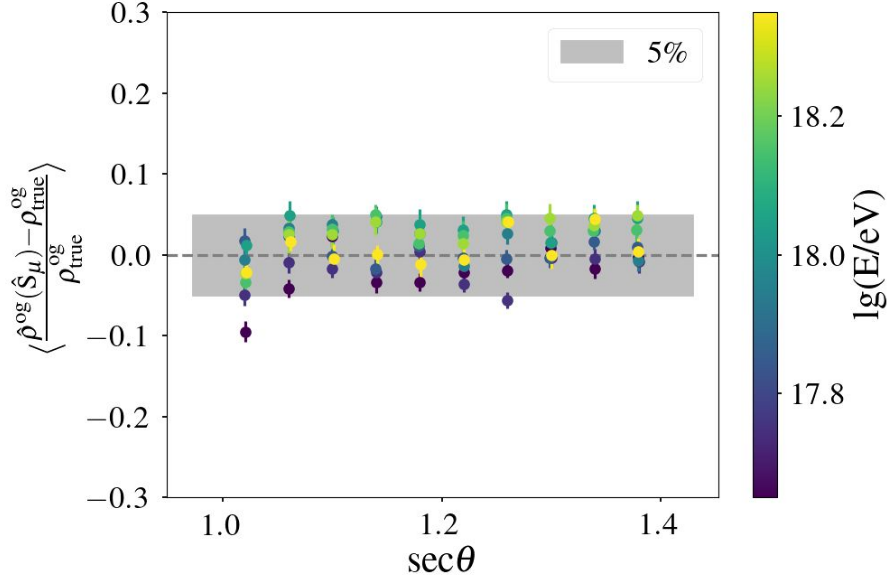


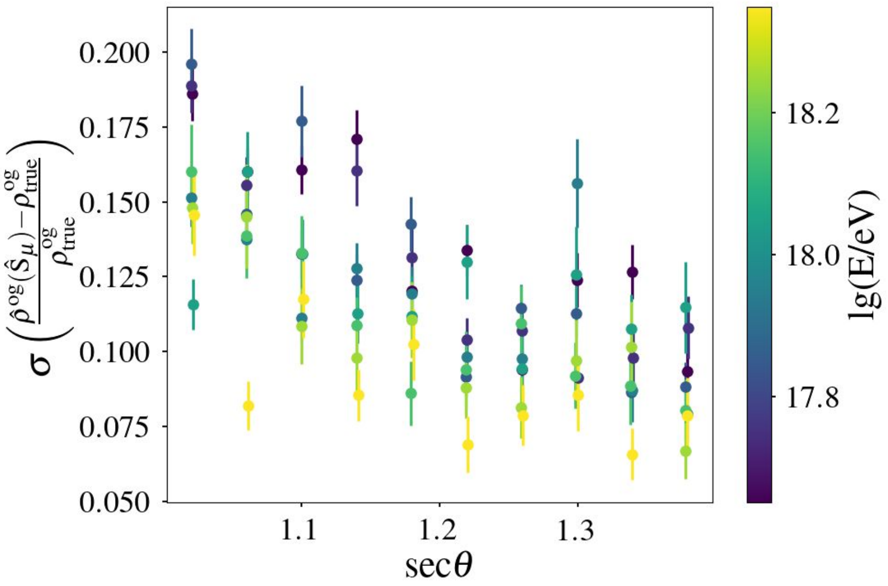




- Extract linear parameters k_0 and k_1 vs. energy and zenith.
- Both k_0 and k_1 well-described as linear functions of $s = \sec\theta - \sec 35^\circ$

Bias and resolution of $\hat{\rho}^{og}$ as a function of $\hat{S}_{\mu}$

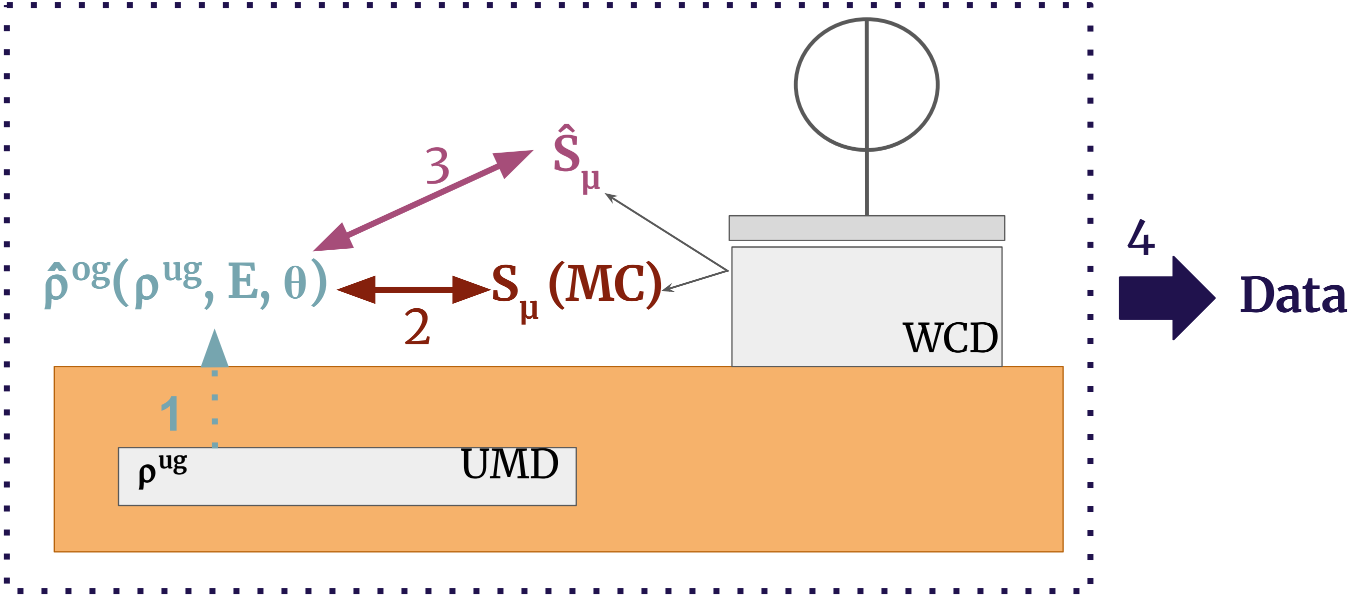




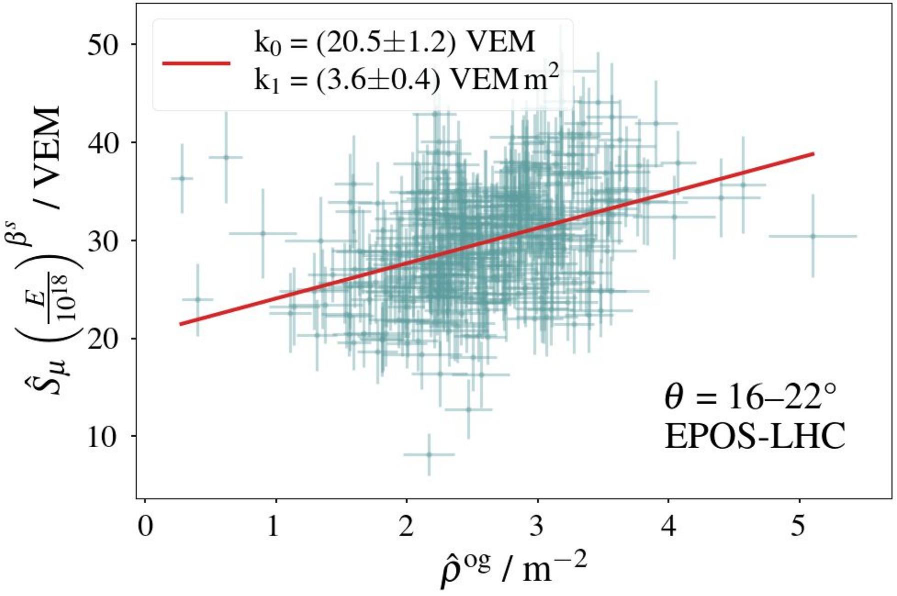
- Bias zenith-independent; mild energy trend, mostly within ±5%
- Resolution < 20%, improving to ~6% at highest energies
- **The NN muon-signal estimator can be validated and calibrated using the UMD-based reference**

Outline

1. Estimation of muons density on ground using the UMD
2. Validation and proof of concept in the 750 m Infill of the calibration procedure
3. Calibration using Neural Network outputs from WCD
4. Estimation of muon content on ground with Data

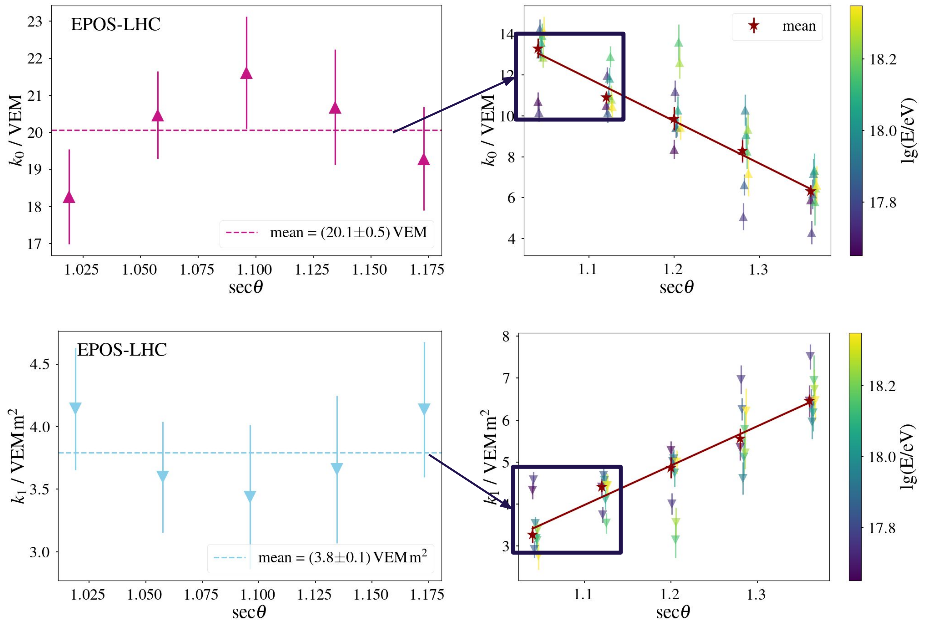


Binned calibration in data



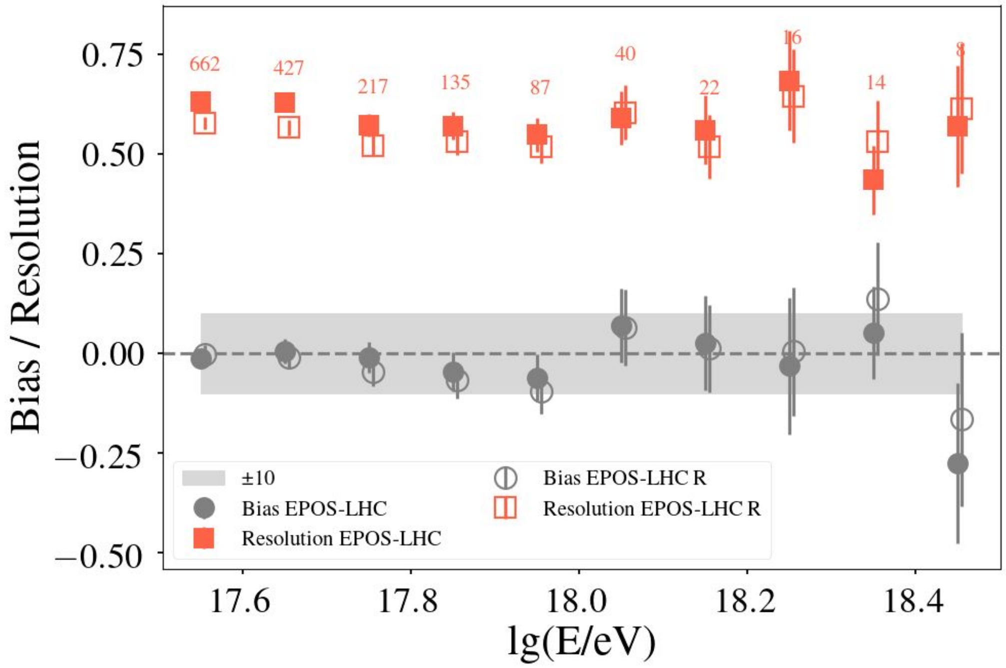
Data

Simulations



- Quality cut: 33°
- Zenith binned calibration
- k_1 in agreement with simulations
- k_0 ~40% higher

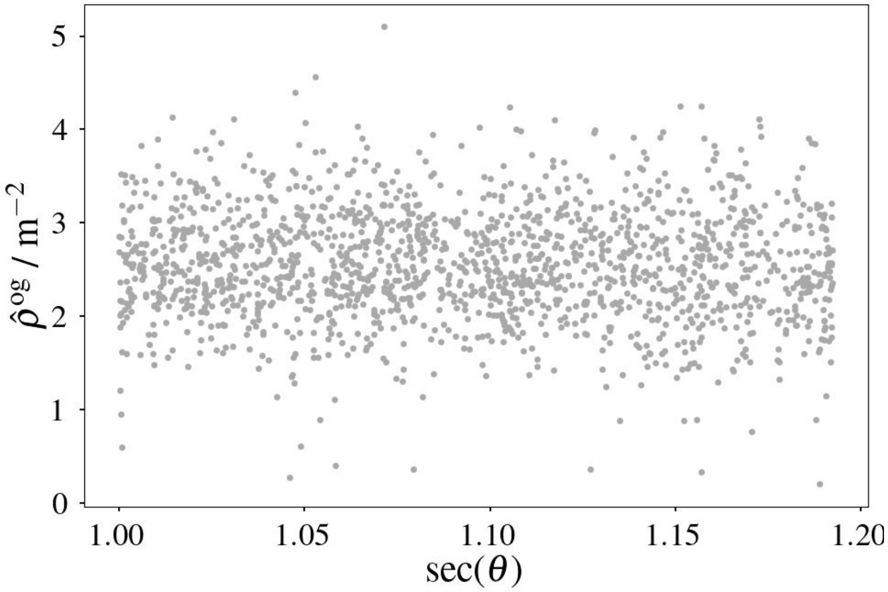
Bias and resolution of calibration in data

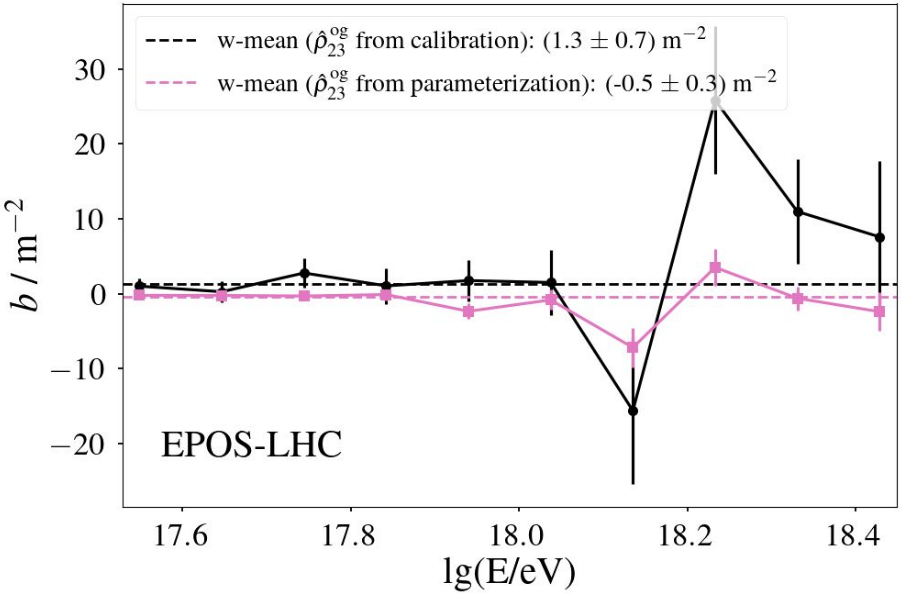


- Bias <10%, though resolution remains limited (>50%).

Zenith correction

- Parametrization: ρ^{ug} (UMD) to $\hat{\rho}^{og}$
- Calibration: $\hat{\rho}^{og}(\hat{S}_{\mu})$



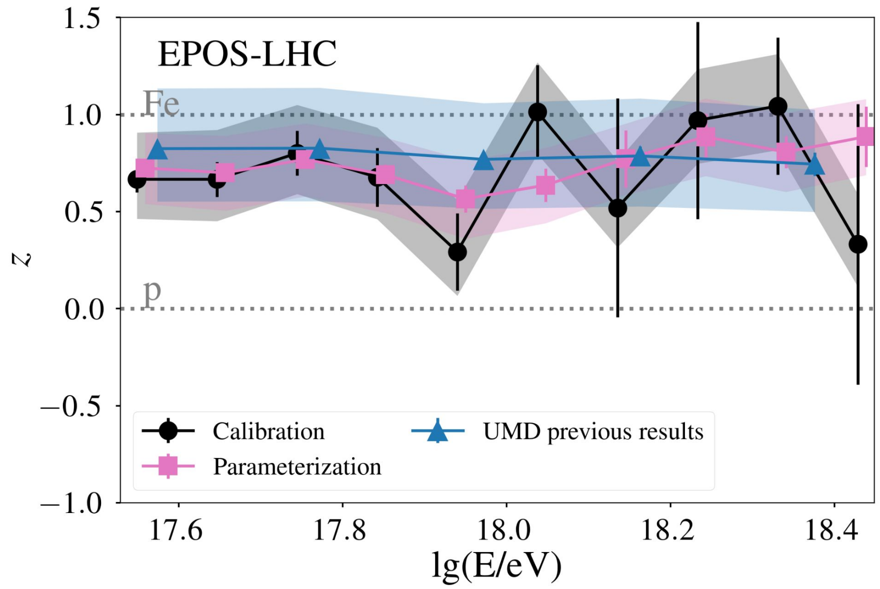


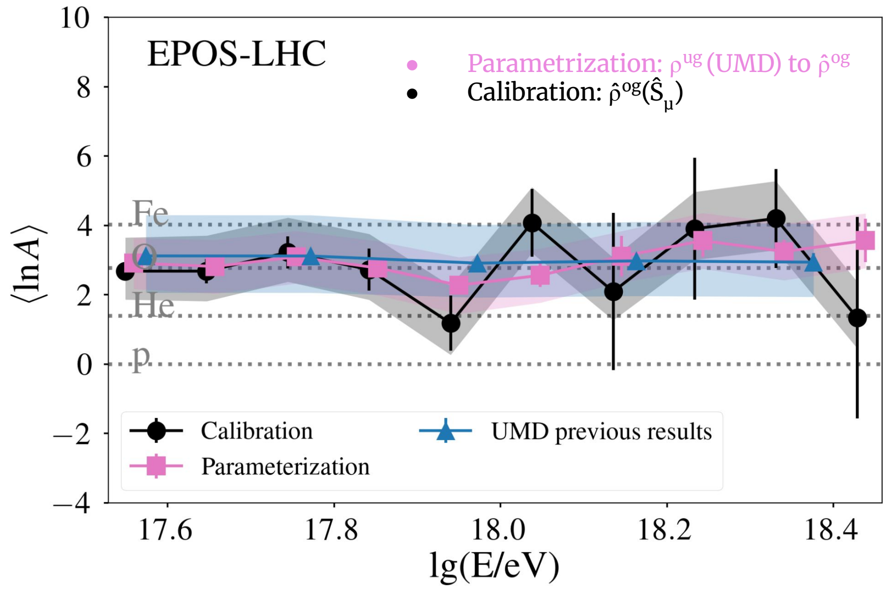
$$\hat{\rho}^{og}_{23}\, f_{att}(\theta) = \hat{\rho}^{og}(\theta)$$

$$f_{att}(\theta) = \hat{\rho}^{og}_{23} + b\ (\sec\theta - \sec\theta_{ref})$$

- Remove linear zenith dependence
- Reference zenith θ_{ref} = 23°

z-scale and mass composition



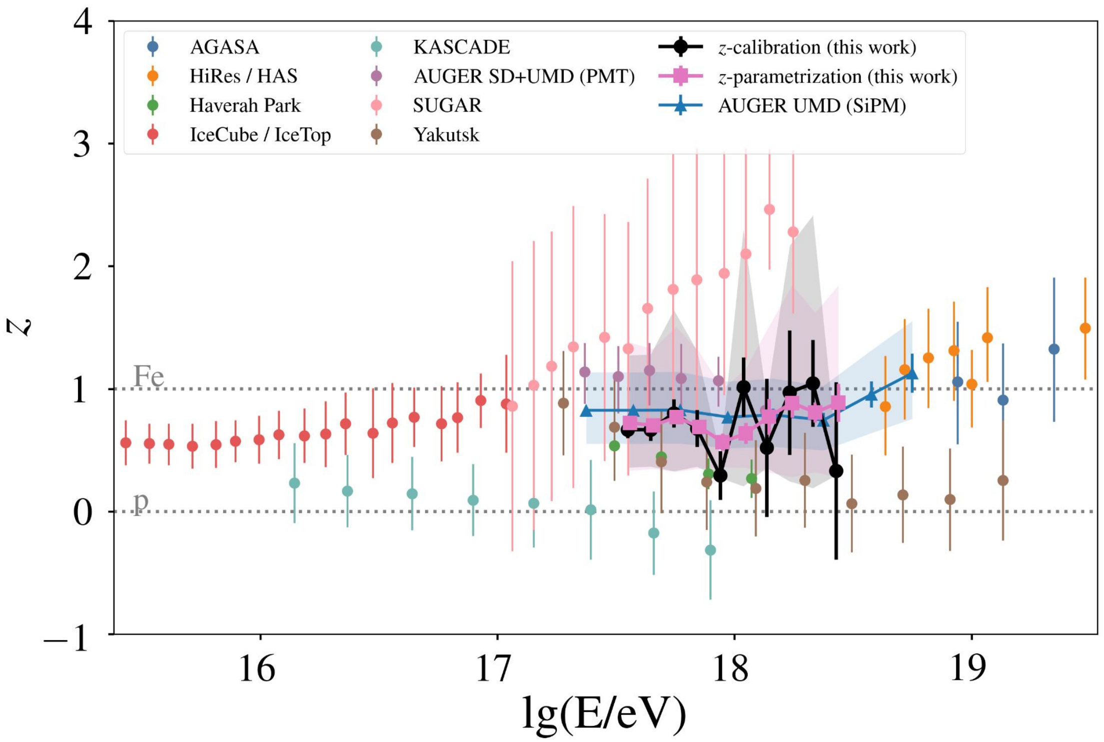


$$z = \frac{\ln(\langle \hat{\rho}_{23}^{\text{og, data}} \rangle) - \ln(\langle \rho_{23}^{\text{og, p}} \rangle)}{\ln(\langle \rho_{23}^{\text{og, Fe}} \rangle) - \ln(\langle \rho_{23}^{\text{og, p}} \rangle)}$$

$$\langle \ln A \rangle = \ln(56) \frac{\langle \ln(\hat{\rho}_{23}^{\text{og, data}}) \rangle - \langle \ln(\rho_{23}^{\text{og, p}}) \rangle}{\langle \ln(\rho_{23}^{\text{og, Fe}}) \rangle - \langle \ln(\rho_{23}^{\text{og, p}}) \rangle}$$

- Parameterized and calibrated $\hat{\rho}^{og}$ give consistent z and ⟨lnA⟩ at low energies; calibrated values fluctuates at high energies due to limited stats
- **Agreement with previous UMD results**

Comparison with other experiments

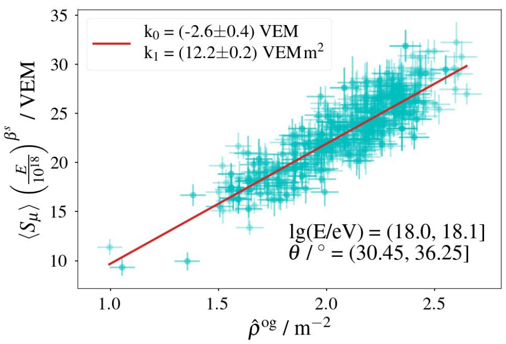


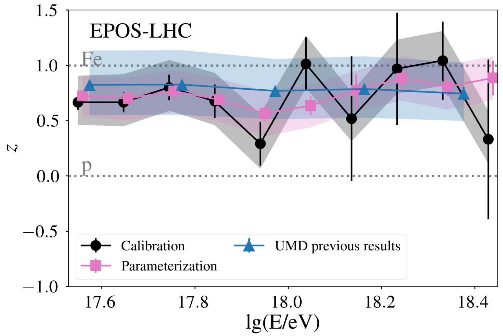
- Parametrization: ρ^{ug} (UMD) to $\hat{\rho}^{og}$
- Calibration: $\hat{\rho}^{og}(\hat{S}_{\mu})$

- *z*-scale allows direct comparison of muon content across different detector setups.
- Parametrized results follow the same energy trend as previous Auger UMD analyses.
- Calibrated estimator shows strong fluctuations at high energy → limited interpretability.
- Some tension persists with early UMD-PMT and Yakutsk measurements, as seen in previous studies.

Summary and conclusions

- Developed and validated a framework to estimate on-ground muon density using UMD measurements
- Built a global parameterization of $\hat{\rho}^{og}(\rho^{ug}$, energy, zenith); bias <5% and resolution <15%
- Established calibration between underground and surface observables, including a NN-based S_μ estimator
- Application to real data: cross-calibration between SD and UMD demonstrated
- Results compatible with previous mass-composition studies





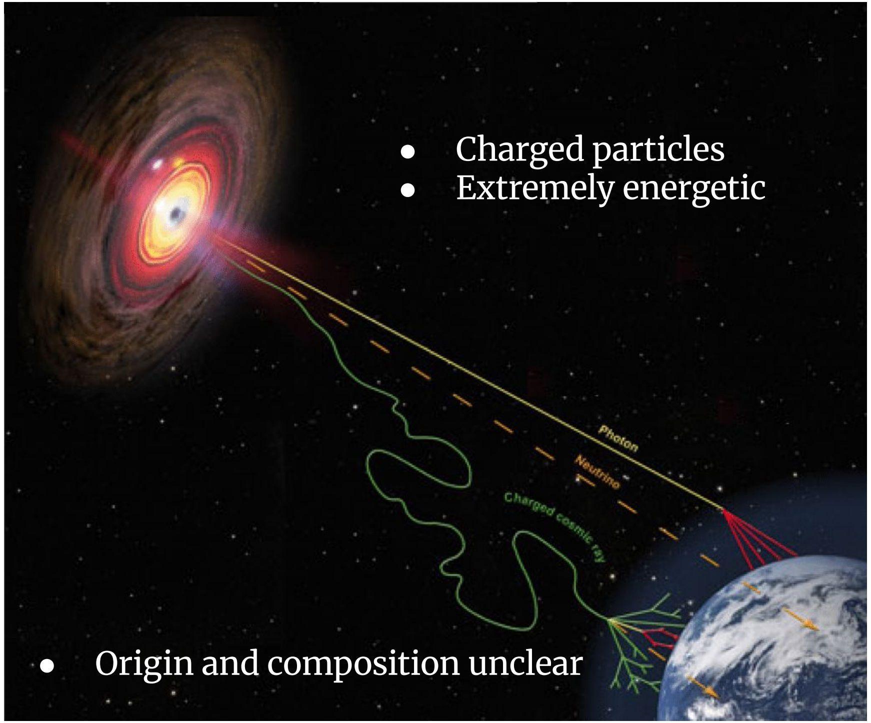
Outlook:

- Wider muon energy spectrum
- Extrapolation to 1500 m array -> Highest energies
- Calibrate new surface estimators

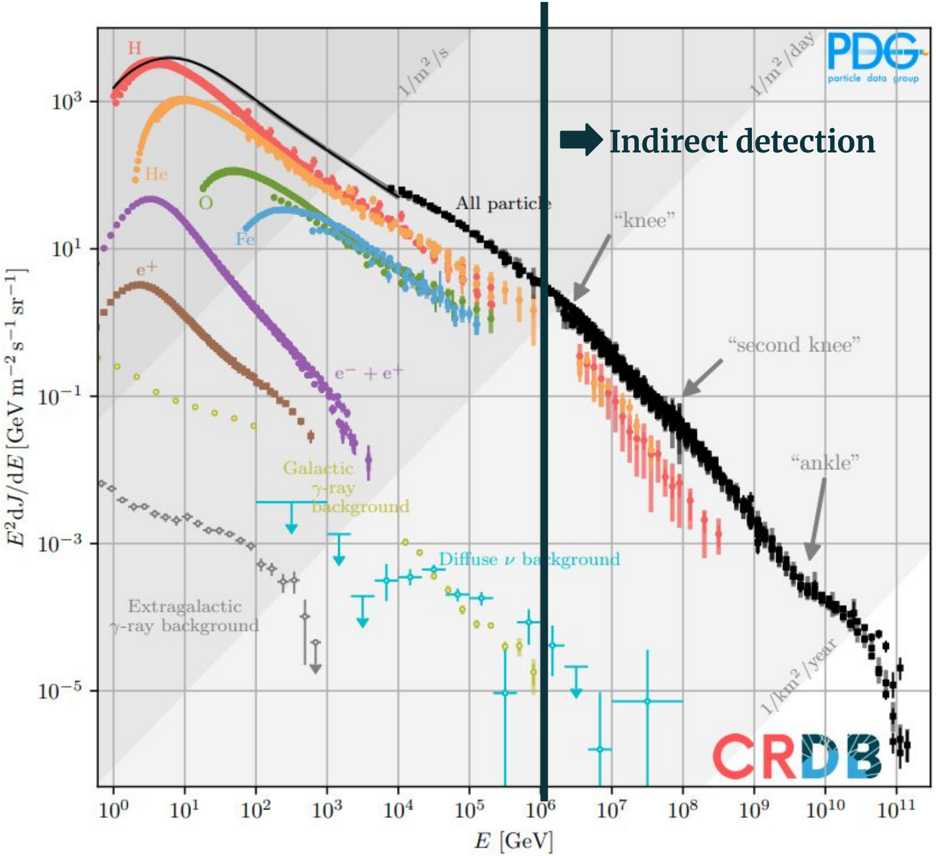
Backup

Cosmic Rays

- Charged particles
- Extremely energetic



- Origin and composition unclear



PDG, "Cosmic Rays," Rev. Part. Phys. 110 (2024).

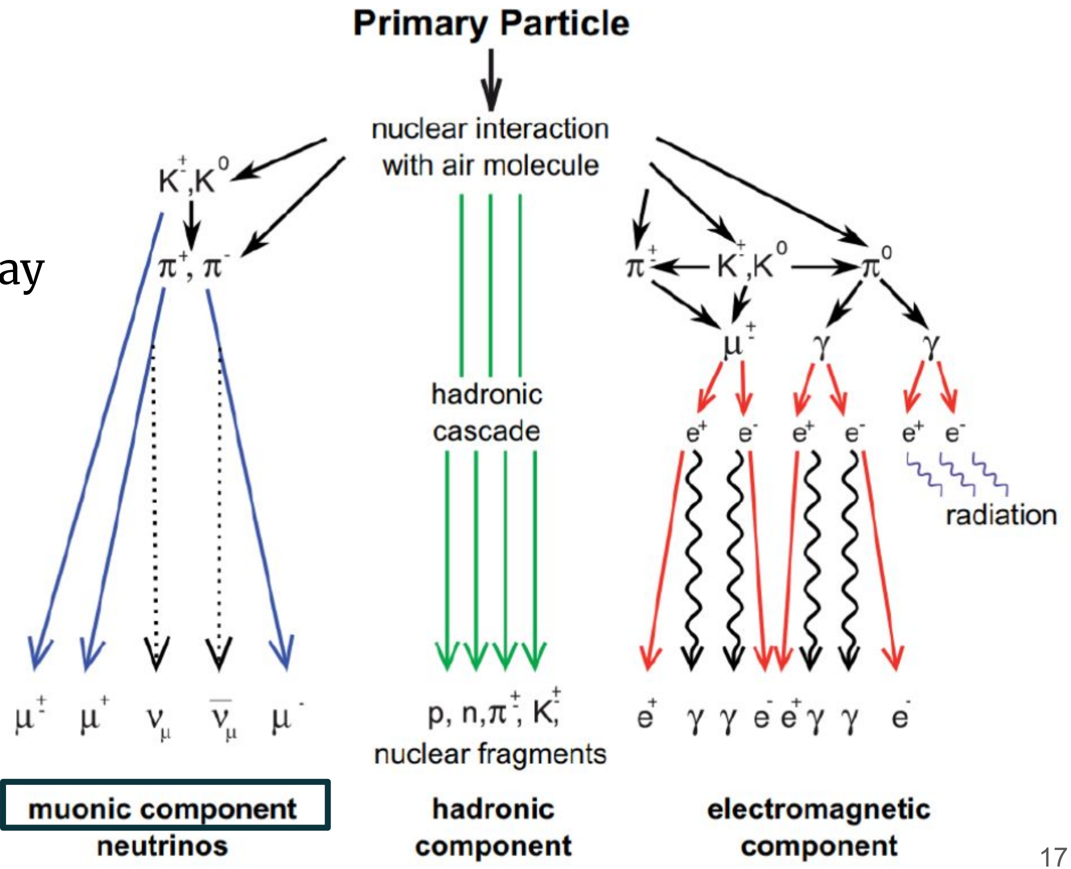
Extensive air showers

Number of muons N_μ in an air shower

Atomic mass number A of the cosmic ray

$$N_\mu^A = A^{1-\beta} N_\mu^p$$

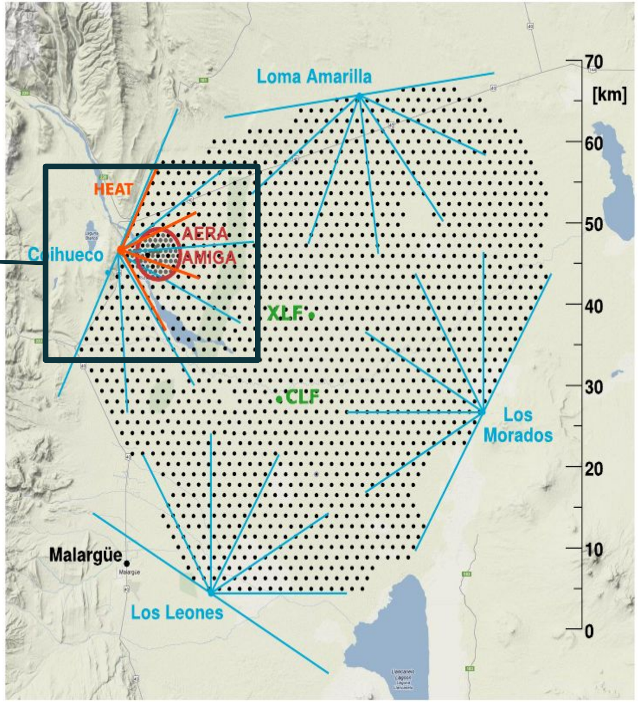
Composition-sensitive observable

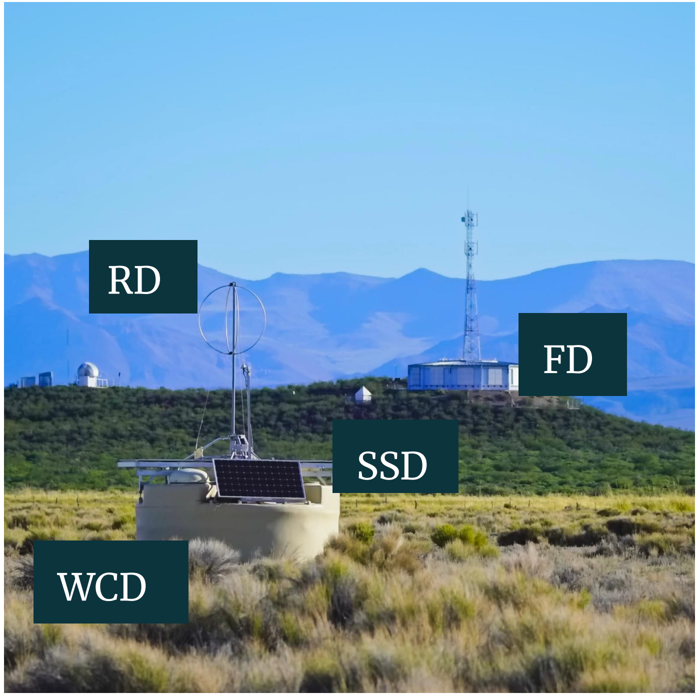


The Pierre Auger Observatory

- Largest UHECR observatory: **3,000 km^2 array in Argentina**
- **Hybrid detection (SD + FD)** enables accurate shower reconstruction and calibration

nested arrays
“infills”

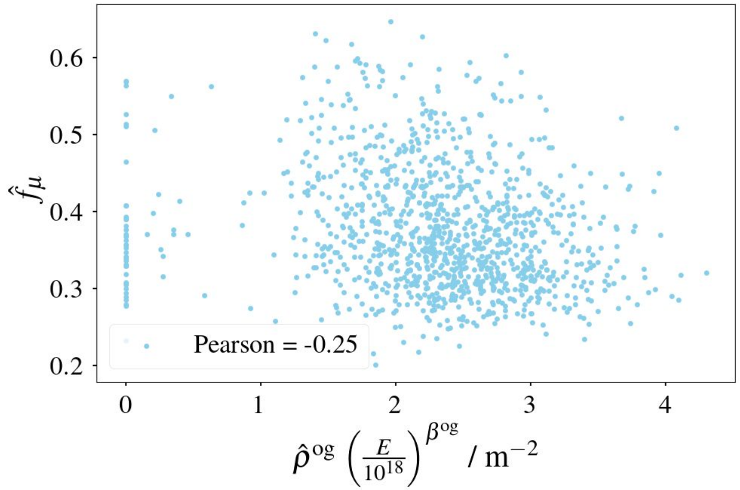




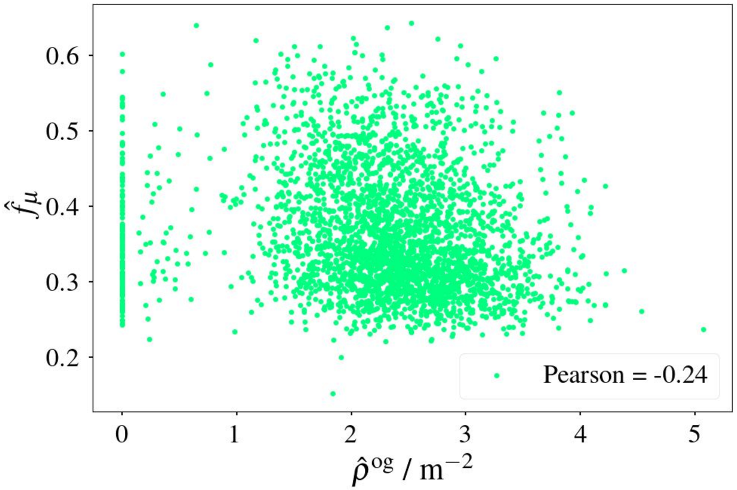
- **AugerPrime upgrade** to improve **mass-composition sensitivity:**

  SSD, RD, sPMT, FD increased duty cycle, UUB electronics, **UMD**

Muon Fraction



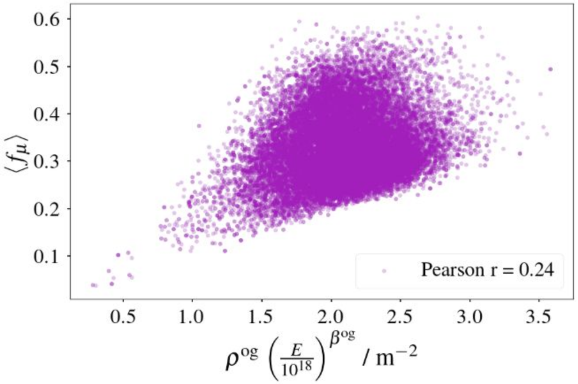
from Margita

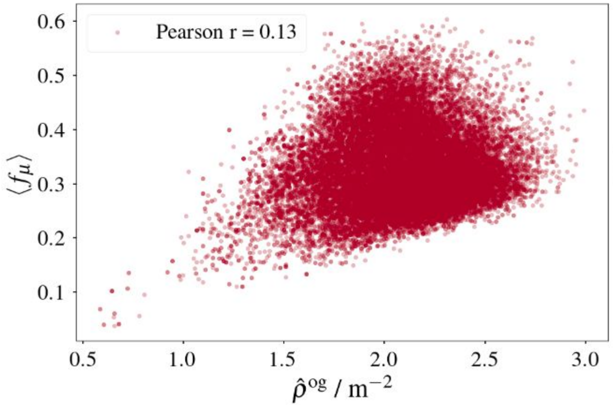


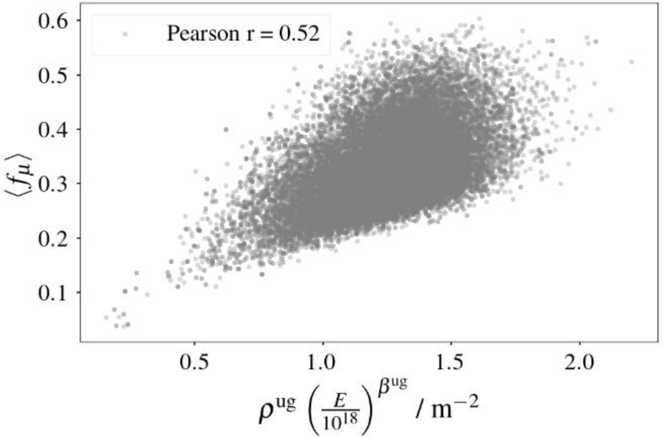
from Steffen

- check E and theta dependence
- check binned pearson

fμ in simulations

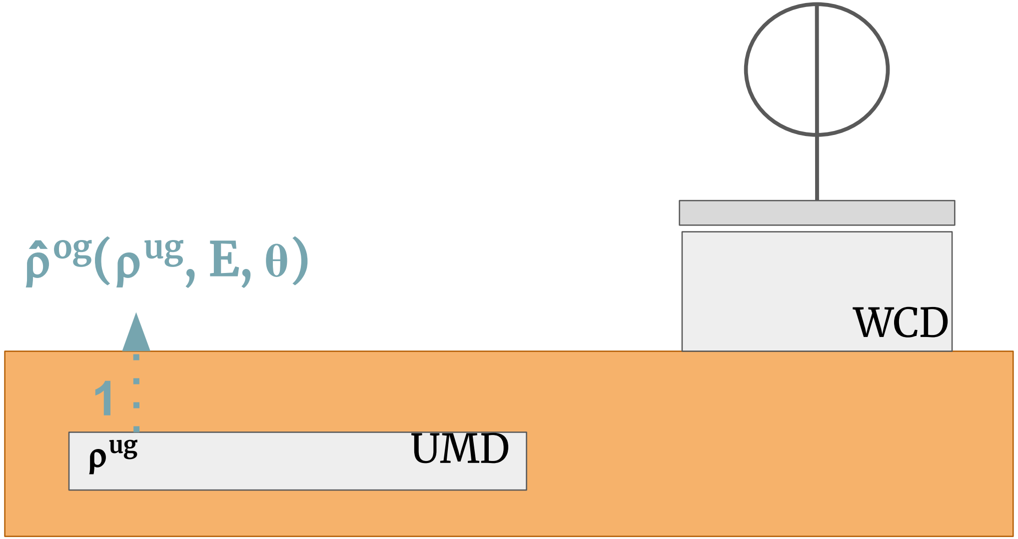




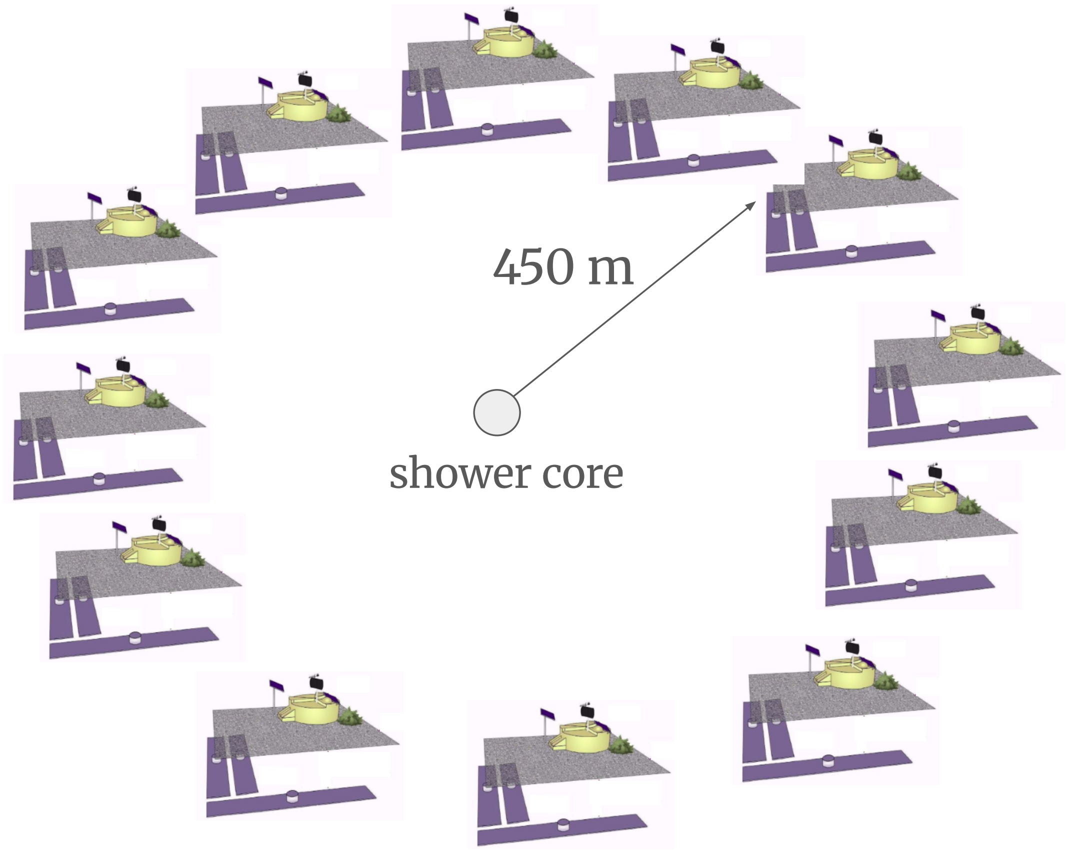


Outline

1. Estimation of muons density on ground using the UMD
2. Validation and proof of concept in the 750 m Infill of the calibration procedure
3. Calibration using Neural Network outputs from WCD
4. Estimation of muon content on ground with Data



Dense ring in simulations

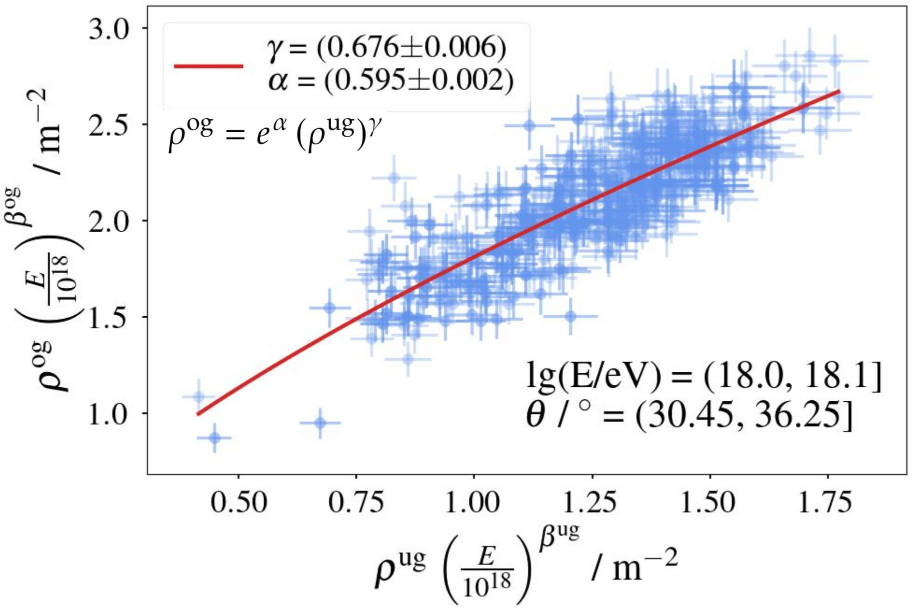


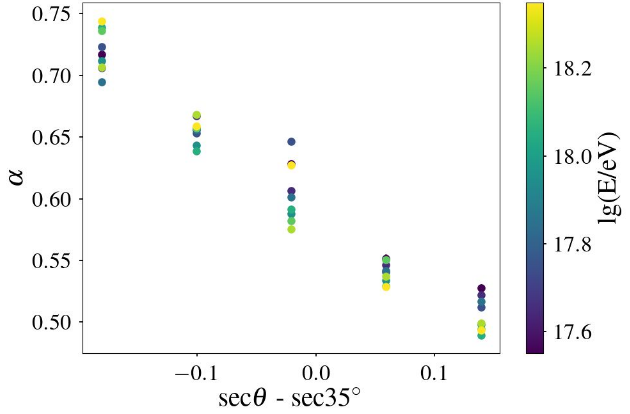
- 12 stations at 450 m from the shower core
- 450 m: optimal distance of the 750 m array

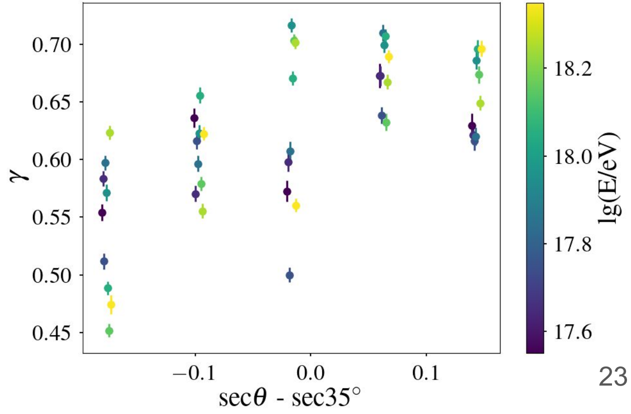
$$\rho^{\mathrm{og},\ \mathrm{ug}} = \frac{\sum_i^{12} N_\mu^{i,\mathrm{MC}}}{\sum_i^{12} A_{\mathrm{eff}}^{\mathrm{WCD},\mathrm{UMD}}}$$

Event-level quantities

Parametrization of muon density on ground



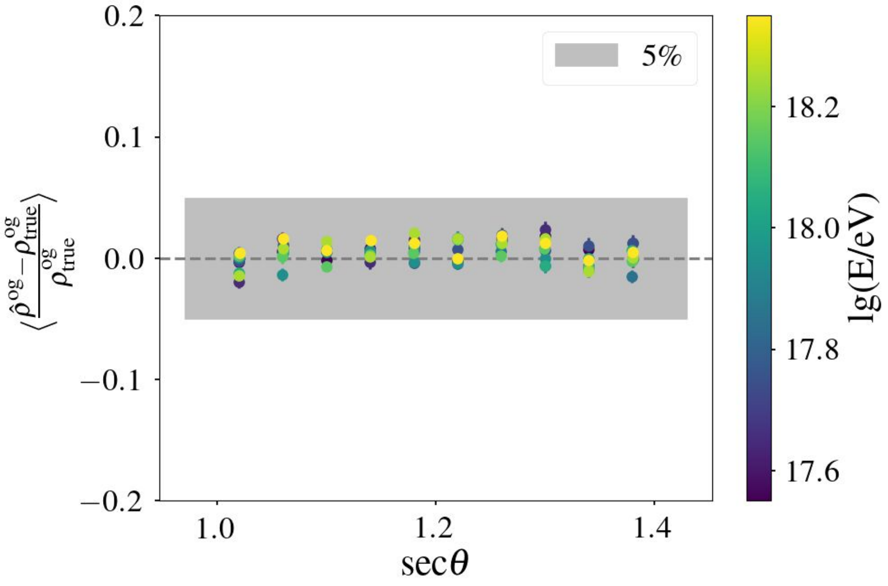


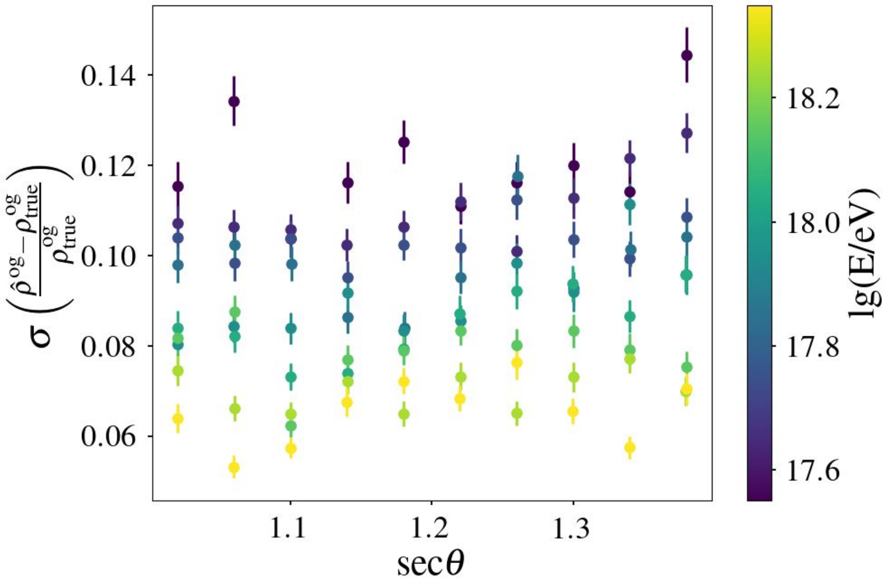


- The relationship is fitted independently in energy–zenith bins
- α encodes the average survival of muons
- $\gamma < 1$ captures the nonlinear attenuation

C. Pérez Bertolli et al. GAP Note (2025)002

Bias and resolution of the estimated muon density

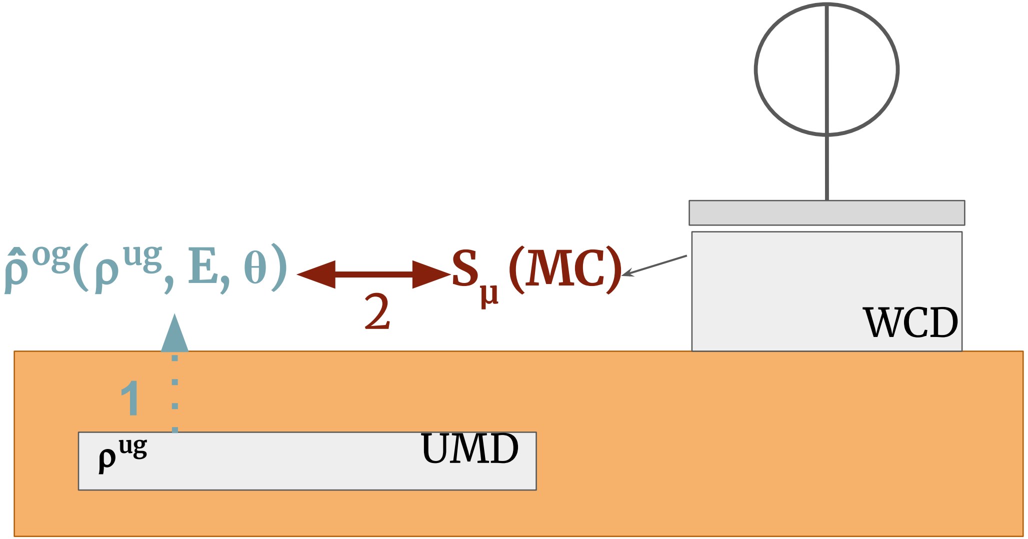




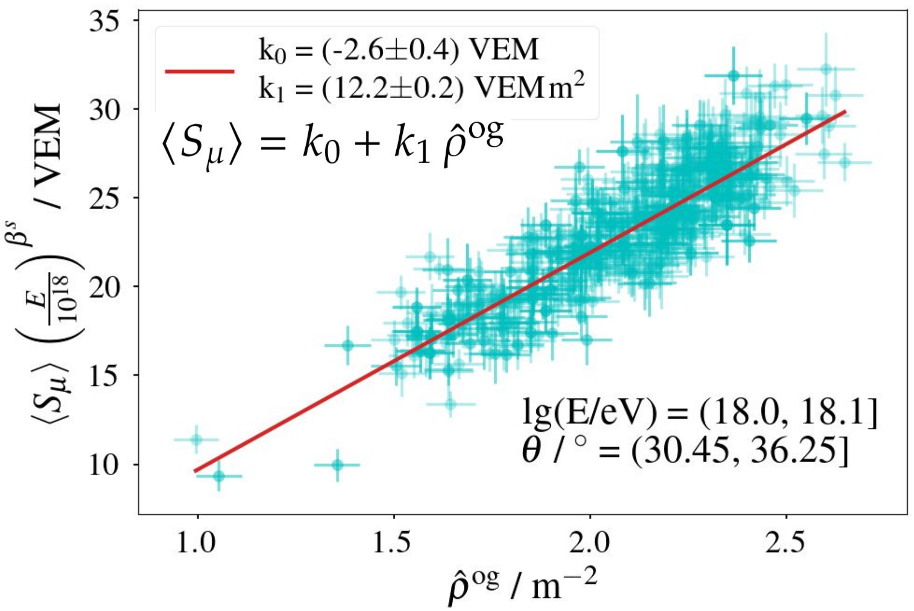
- The estimator shows a stable bias below 5% over all energy and zenith bins
- The resolution stays better than 15% across the phase space, reaching ≈ 6% at the highest energies
- **UMD enables a reliable estimation of the muon density on ground**

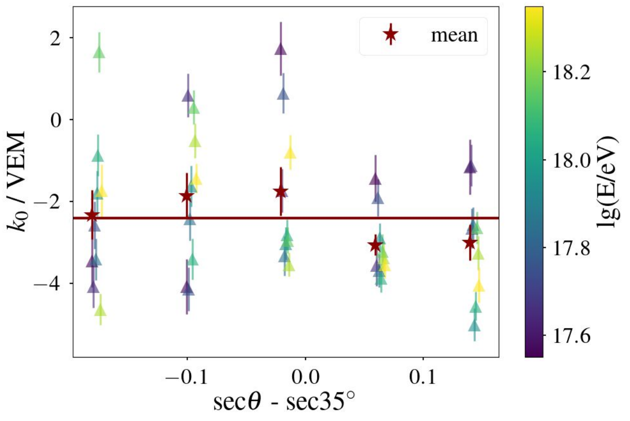
Outline

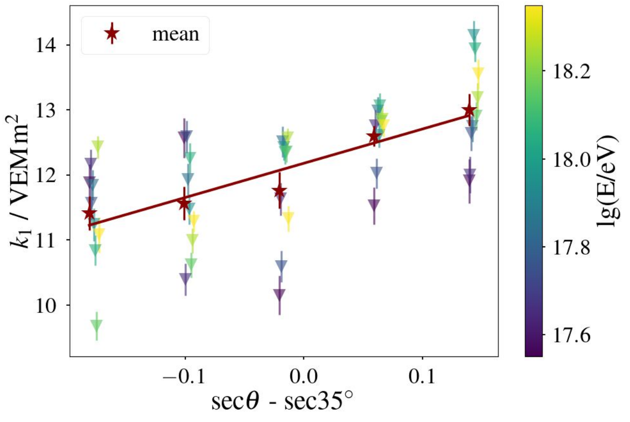
1. Estimation of muons density on ground using the UMD
2. Validation and proof of concept in the 750 m Infill of the calibration procedure
3. Calibration using Neural Network outputs from WCD
4. Estimation of muon content on ground with Data



Calibration of simulated S_μ from SD using $\hat{\rho}^{og}$

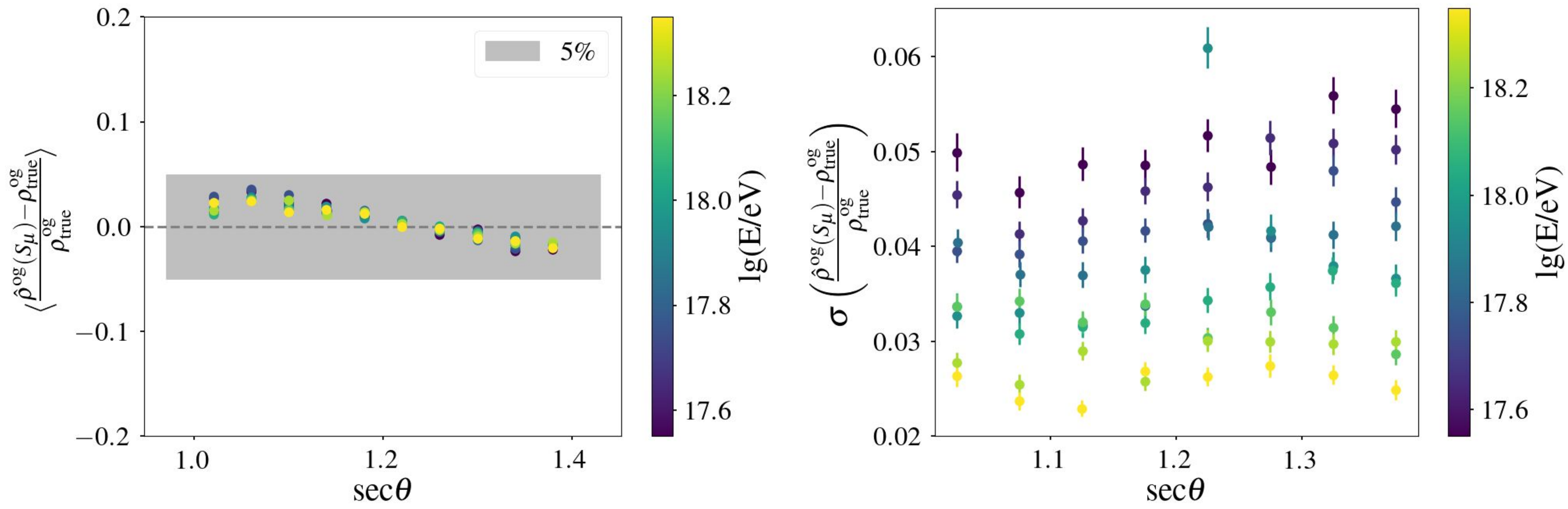






- Linear fits between $\langle S_\mu \rangle$ and $\hat{\rho}^{og}$ in energy–zenith bins, yielding calibration parameters k_0 and k_1
- The parameters show energy-independence, k_1 increases with zenith angle, indicating a stronger muon contribution in inclined showers

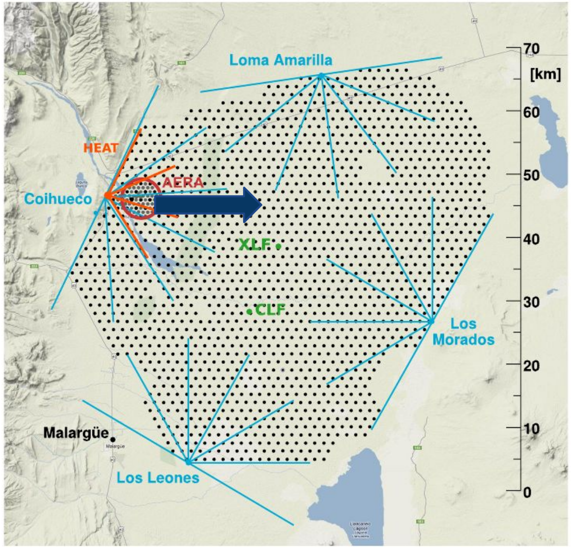
$\hat{\rho}^{og}$ as a function of S_μ



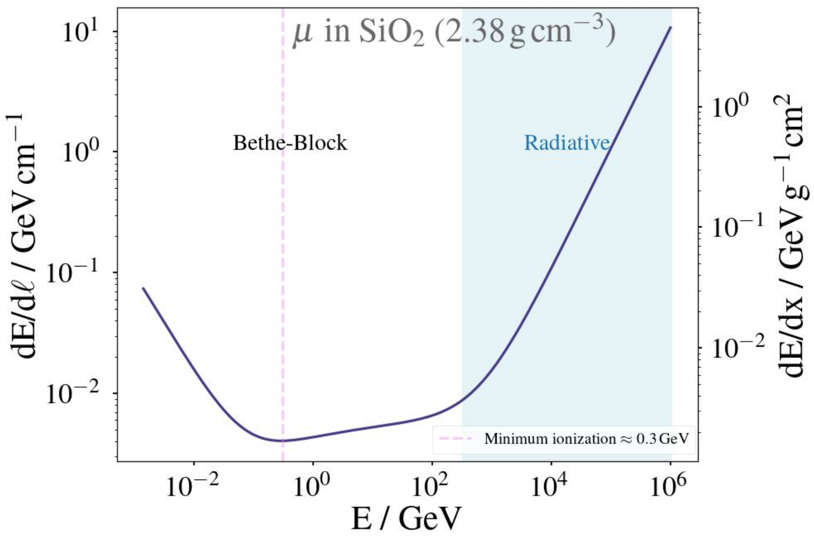
- Bias is energy-independent; mild zenith trend within ±5%
- Resolution better than 6%, reaching ~2.5% at highest energies
- **Reconstructed ground-level muon density can reliably calibrate the WCD muonic signal**

Future prospects

- Apply the method to the latest Auger **Phase II** data set.
- Extrapolate calibration to higher energies → extend to the full SD array where UMD is not deployed.
- Incorporate other detectors (e. g SSD) information to enhance muon-signal separation.
- Use framework to refine constraints on hadronic models and quantify systematic deviations in muon production.



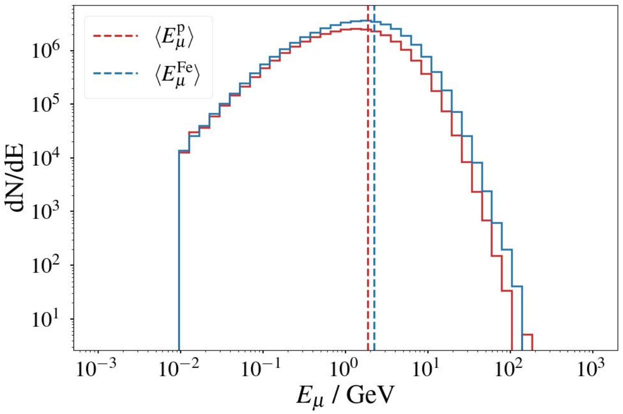
Muons through soil

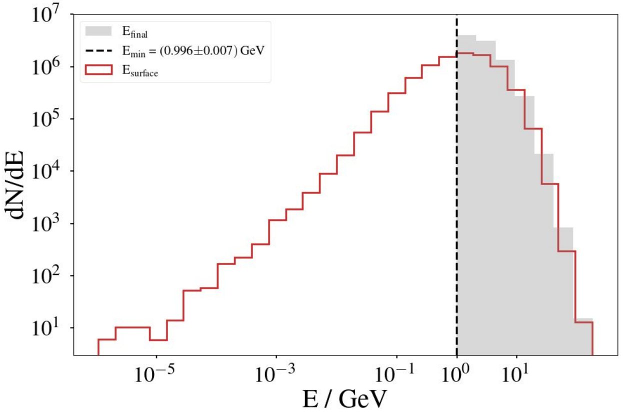


$$\left\langle \frac{dE}{dX} \right\rangle = a(E) + b(E)\,E$$

electronic → $a(E)$

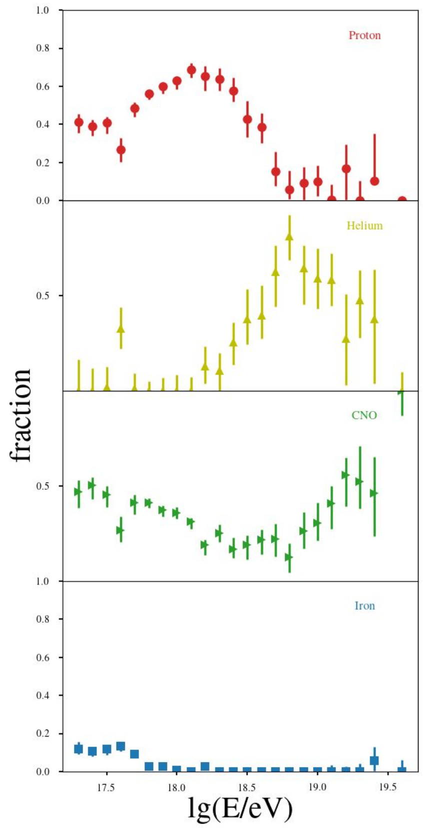
radiative → $b(E)$



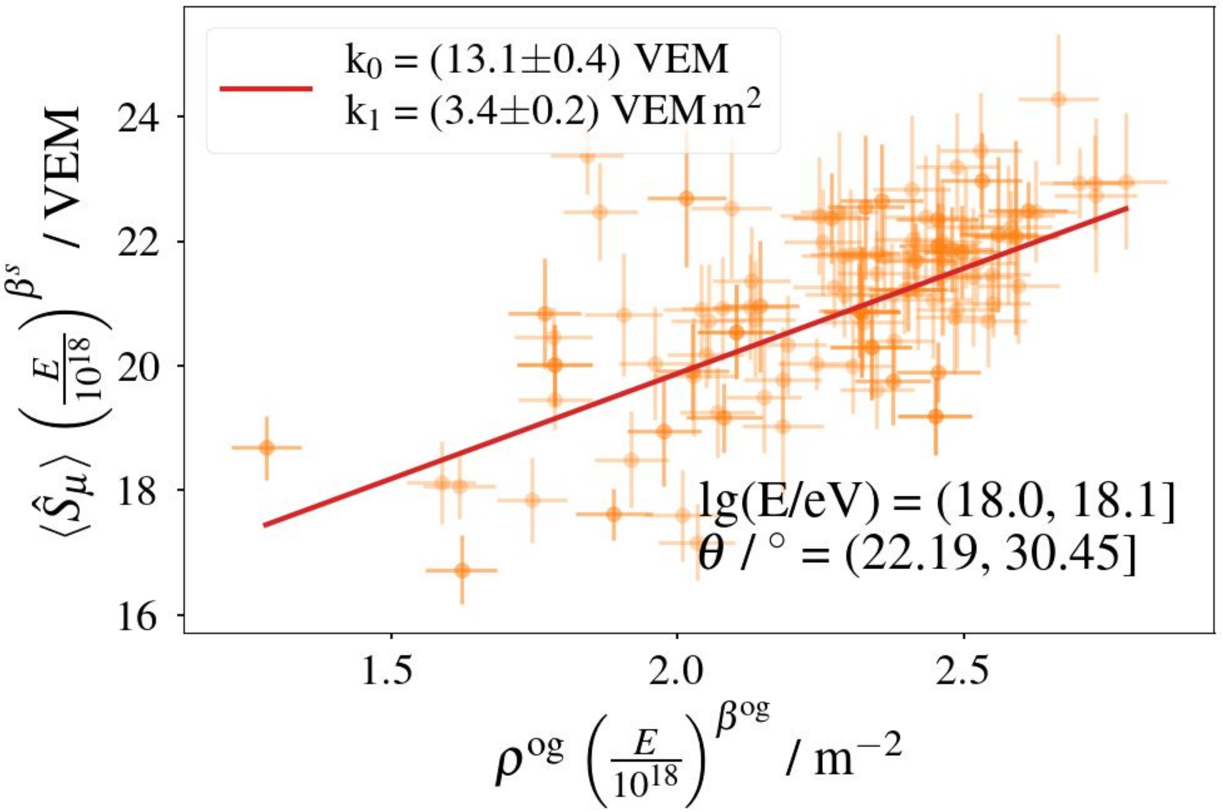


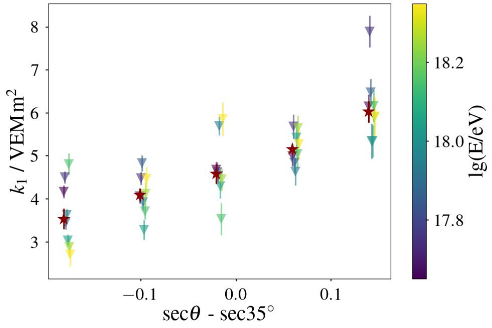
Simulation library and selection

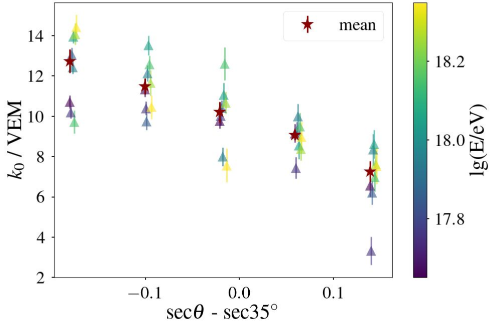
- EPOS-LHC
- p, He, N, Fe and Auger Mix from ICRC2017
- lg(E/eV) bins: [17.5, 18.0], [18.0, 18.5]
- ϴ from 0° to 45°
- 750 m infill
- 450 m dense ring
- 6T5 events
- 10 times resampled



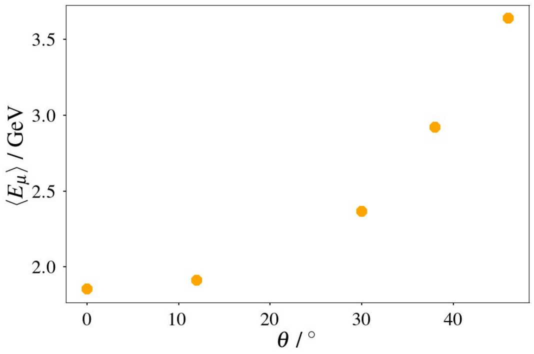
$\hat{S}_\mu$ and its relation to muons on ground

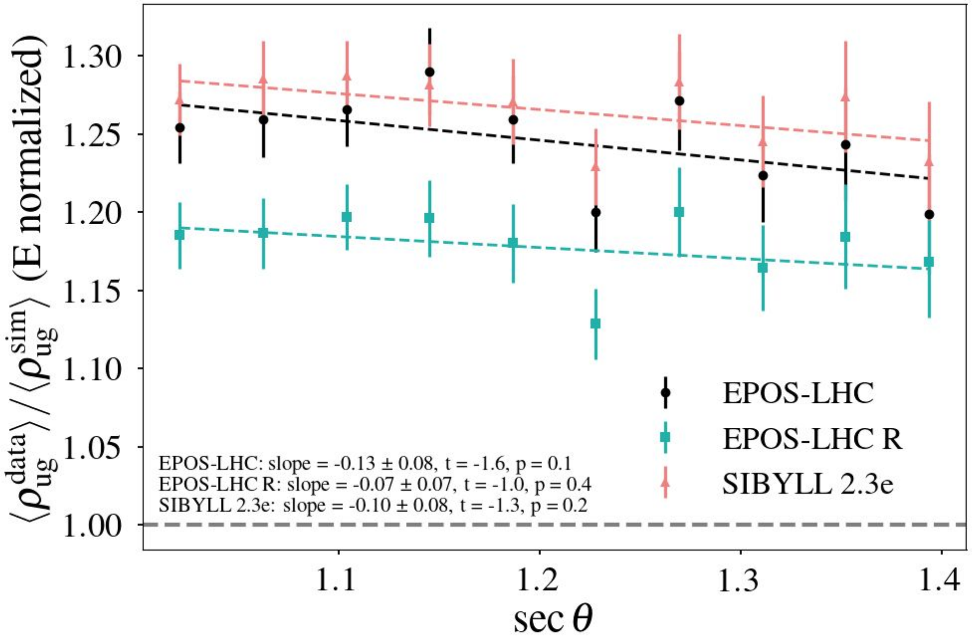






Angular dependence of the muon discrepancy





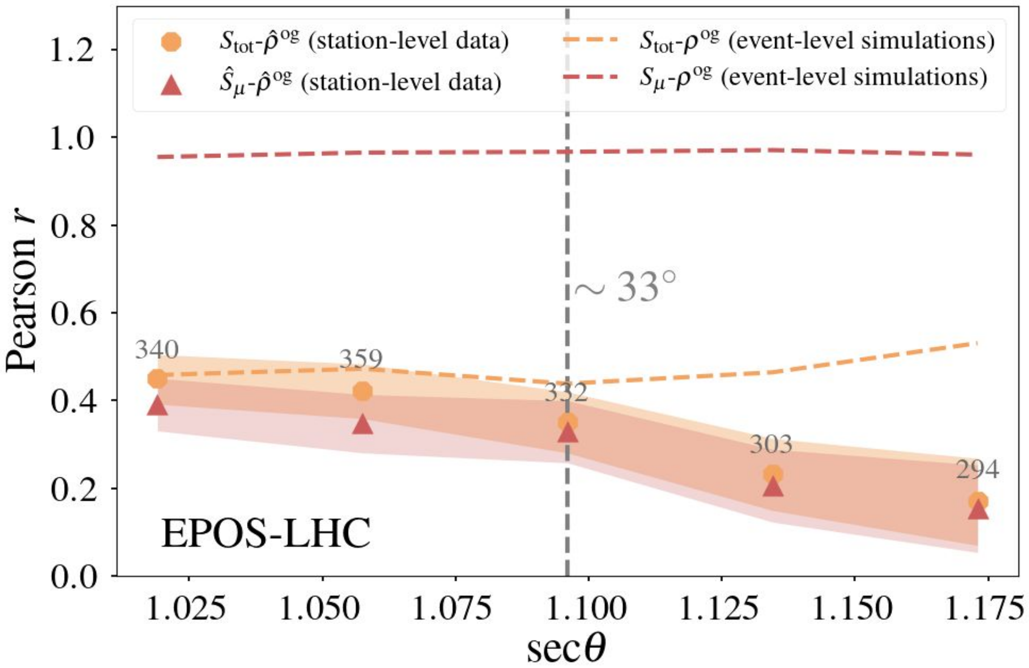
- Mean muon energy increase with zenith.
- Data/simulation ratio of underground muons is **flat vs. sec θ** for all models.
- Muon deficit is **energy-independent above ≈1 GeV**

Zenith-binned data correlation

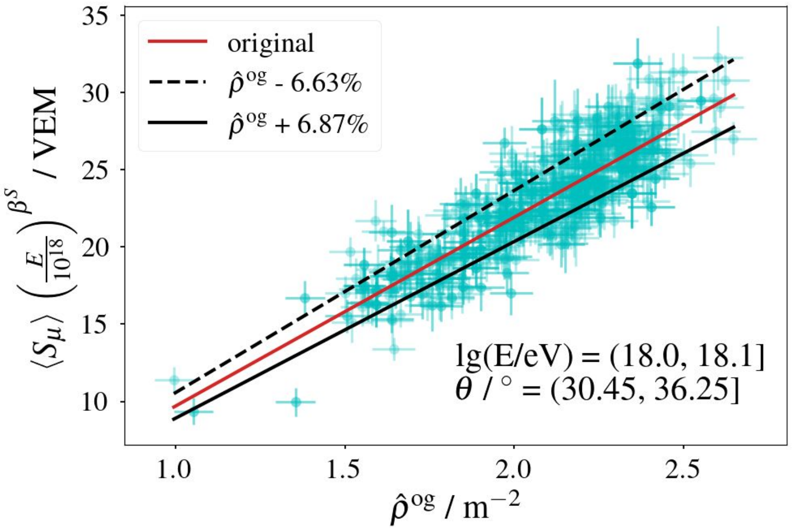
- No event level reconstruction of $\hat{S}_\mu$ yet
- Stations selected between 400 and 500 m

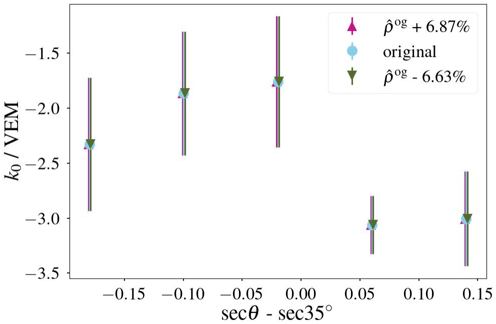
Event level ➡ **Station level**

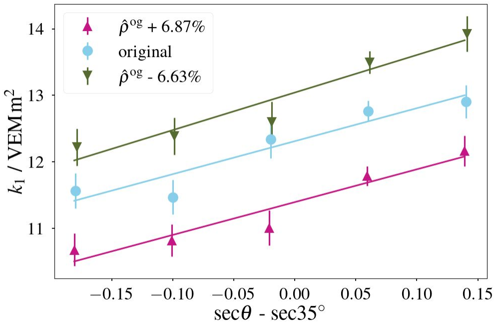
- Consistency between data and simulations is recovered up to $\theta \approx 33^\circ$, beyond which station-level effects dominate
- This motivates restricting the application of the calibration to $\theta \lesssim 33^\circ$

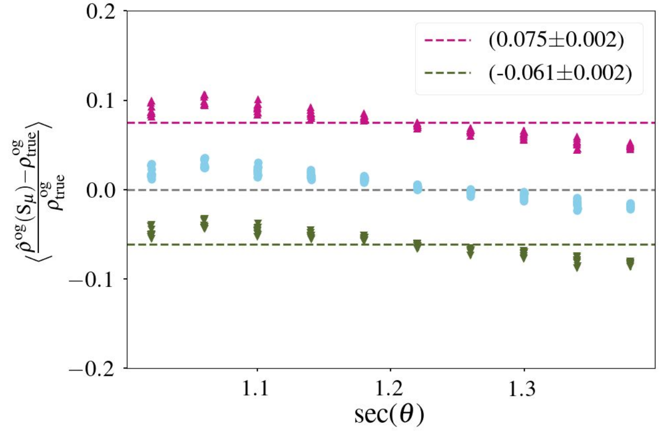


Systematic Uncertainties of calibration



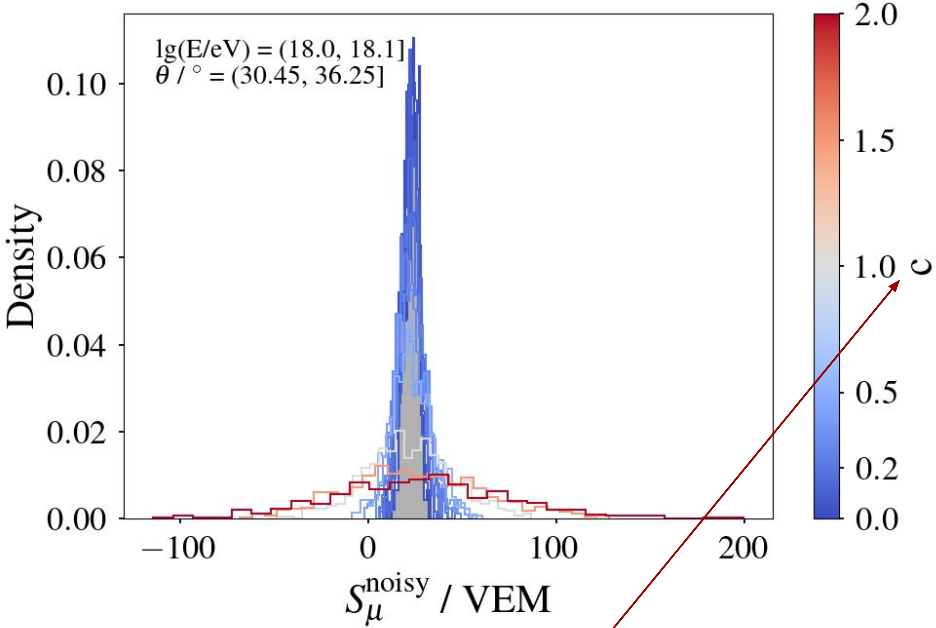




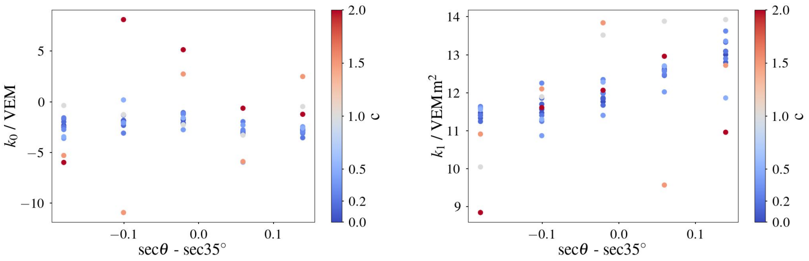


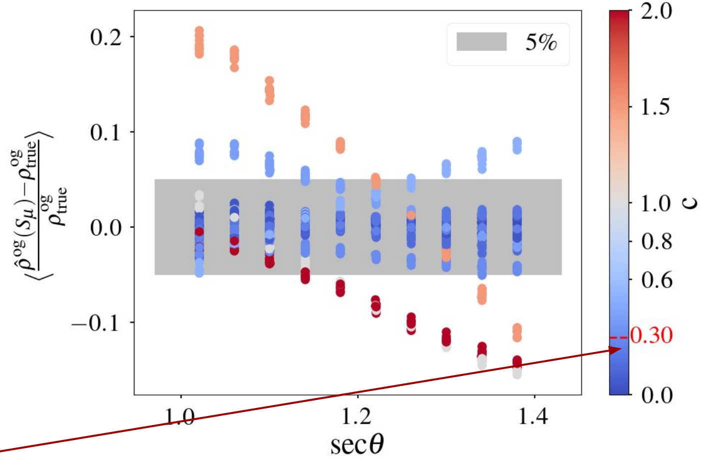
Source	Upper Bound	Lower Bound
$\hat{\rho}^{og}$ uncertainty	+8%	-6%
Mass composition	+1%	0%
Energy Resolution	+7%	-3%
Total	**+10.67%**	**-6.71%**

S_μ artificial fluctuations



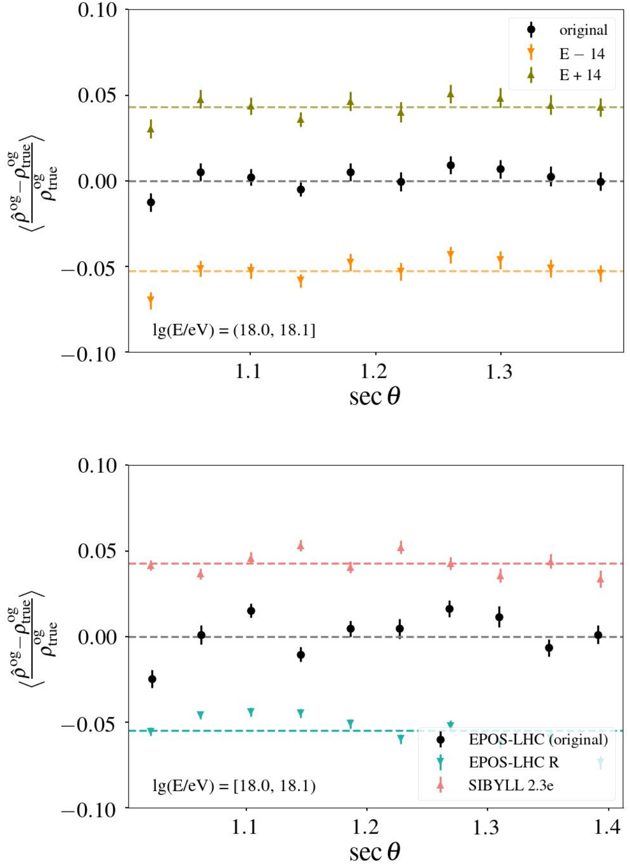
$$S_\mu^{noisy} = S_\mu + \mathcal{N}(0, (c\, S_\mu)^2)$$





- Relative resolution better than 30% needed for calibration

Systematic uncertainties



Source	Upper Bound	Lower Bound
Mass Composition	+1%	-1%
Hadronic Model	+4%	-4%
Energy Resolution	+5%	-5%
Soil Density Fluctuations	+2%	-1%
Detector Reconstruction	+1%	0%
MLDF fit	0%	-1%
Total	**+6.87%**	**-6.63%**

Global optimization of parameters

$$\ln(\rho^{og}) = \alpha(e,s) + \gamma(e,s)\ \ln(\rho^{ug})$$

$$\gamma(e,s) = \gamma_0 + \gamma_1\, e\, s + \gamma_2\, s^2$$
$$\alpha(e,s) = \alpha_0 + \alpha_1\, s + \alpha_2\, e^2$$

where $e = \lg(E/\mathrm{eV}) - 18.0$ and $s = \sec\theta - \sec 35°$

- A global model was fitted, with energy and zenith encoded through simple second-order polynomials.
- Statistically insignificant terms were removed, yielding compact forms for α(e,s) and γ(e,s) with good performance ($R^2 \simeq 0.70$).
- The final fit shows unbiased residuals (σ~0.10) and strong correlation with true values (r≃0.84).