Comparison of the shape of the MLDF obtained from simulations and data

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Recap

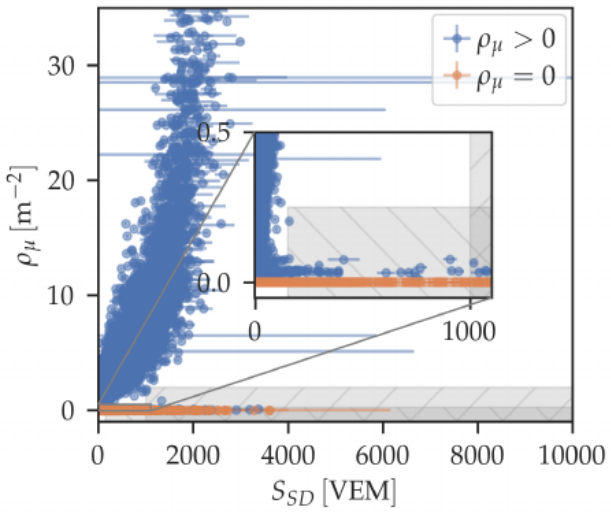
- Developed a method to reconstructed the mldf based on the ADC mode
- Developed a mass sensitive observable that depends on the muon density
- Reproduced the X_{max} using Delta method for the SD 750 array
- Developed a method to distinguish between pure and mixed compositions using correlation coefficients

Goal

- Study the compatibility between data and simulations using the average muon ldf
- Study the evolution of the average muon density as a function of core distance at different regions of the distances.

Simulations and Data

- Phase 1 data 2018 Jan 1 to 2021 Dec 31
- Phase 2 data 2023 Jan 1 to 2025 Jan 31
- Simulations: Corsika v7.7402 with EPOS-LHC and UrQMD
- Primaries – Iron, proton, Helium, Nitrogen
- Uniform distribution ∈ $16.8 \leq \log(E/eV) \leq 18.7$
- Isotropic distribution of zenith angles $0° \leq \theta \leq 48°$
- Cuts:
  - Candidate counters with null or small muon densities that have a paired SD counter with large signal[1].



[1]GAP2023_004

Spectrum

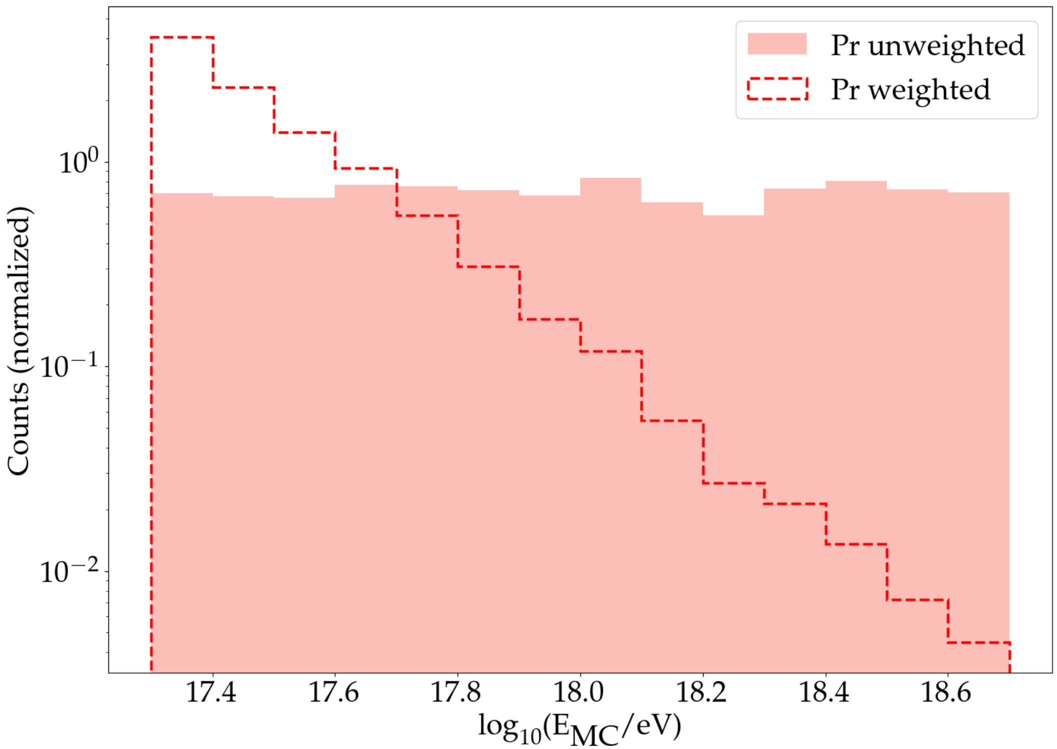


Table 6 Best-fit values of the spectral parameters (Eq. (11)). The parameter ω_{12} is fixed to the value constrained in [21]. Note that the parameters γ_0 and E_{01} correspond to features below the measured energy region and are treated only as aspects of the unfolding fixed to their best-fit values to infer the uncertainties of the measured spectral parameters

Parameter	Value $\pm\sigma_{stat} \pm \sigma_{syst}$
$J_0/(\mathrm{km}^2\ \mathrm{yr\ sr\ eV})$	$(1.09 \pm 0.04 \pm 0.28) \times 10^{-13}$
ω_{01}	$0.49 \pm 0.07 \pm 0.34$
γ_1	$3.34 \pm 0.02 \pm 0.09$
E_{12}/eV	$(3.9 \pm 0.8 \pm 1.1) \times 10^{18}$
γ_2	$2.6 \pm 0.2 \pm 0.1$
γ_0	2.64 – fixed
E_{01}/eV	1.24×10^{17} – fixed
ω_{12}	0.05 – fixed

$$w(E_i) = E_i\, J_{\mathrm{Auger}}(E_i)$$

$$J(E,k) = J_0 \left(\frac{E}{10^{17} eV}\right)^{-\gamma_0} \prod_{i=0}^{1} \left[1 + \left(\frac{E}{E_{ij}}\right)^{1/\omega_{ij}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}$$

$$w_i^{(\mathrm{norm})} = \frac{w(E_i)}{\sum_j w(E_j)} N$$

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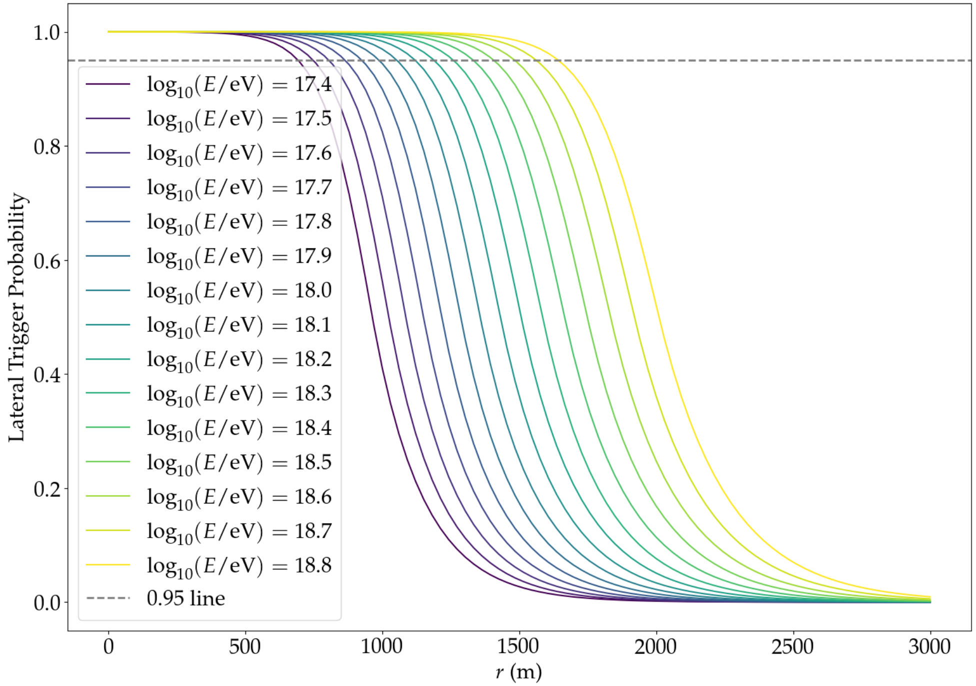
Maximum distance cut: Lateral trigger probability of the surface detector

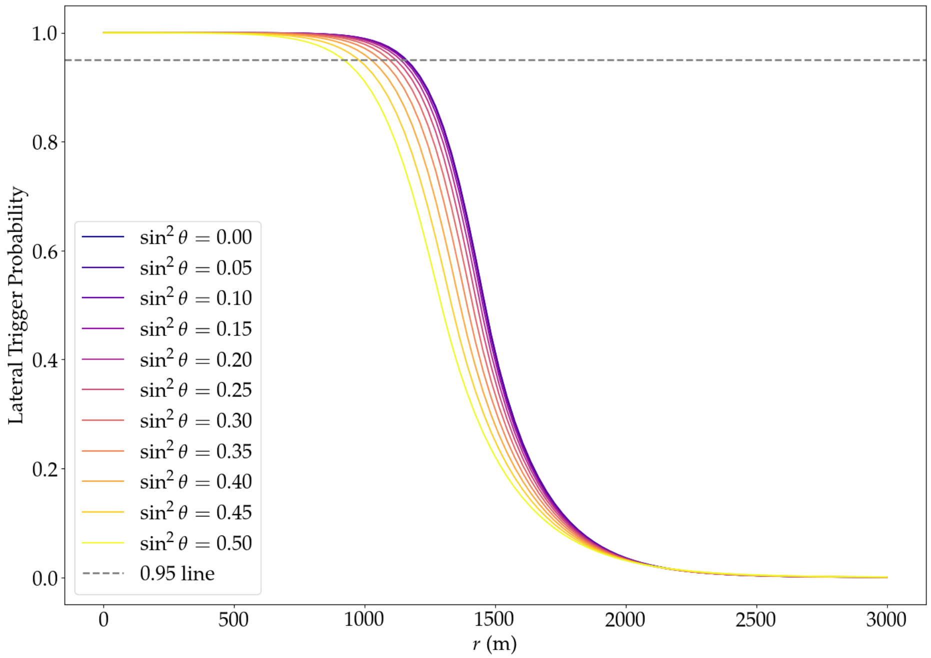
Removes upward fluctuations due to decreased trigger efficiency.

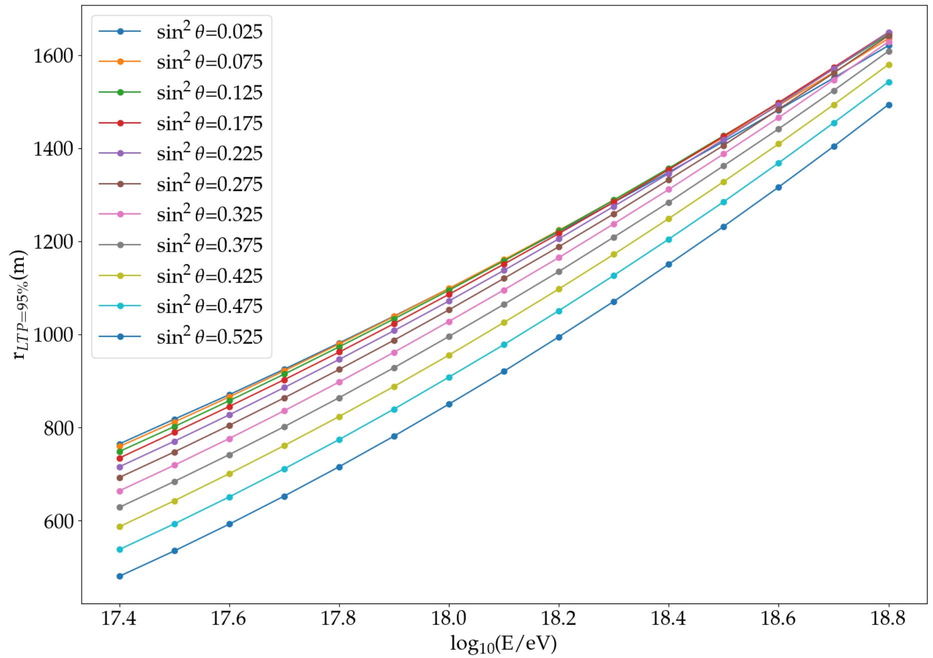


$$LTP(r) = \begin{cases} \dfrac{1}{1 + \exp\left(\dfrac{r - R_0}{\Delta R}\right)} & \text{for} \quad r < R_0 \\ \dfrac{1}{2\exp\left(\dfrac{r - R_0}{2\Delta R}\right)} & \text{for} \quad r > R_0 \end{cases}$$

R_0 and ΔR free fit parameters parameterized as a function of the energy and zenith angle[2]

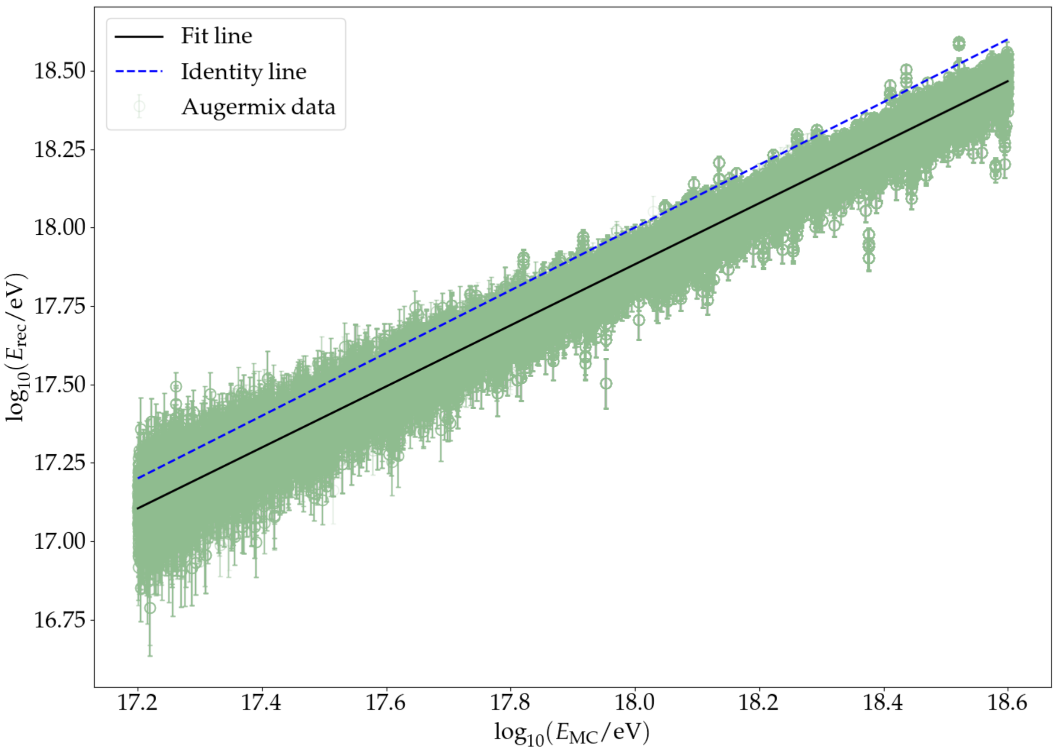
[2] LTP dervied from Hybrid Data GAP2018_038





distance in which the trigger probability of the tank reaches 95%

Energy correction for simulations

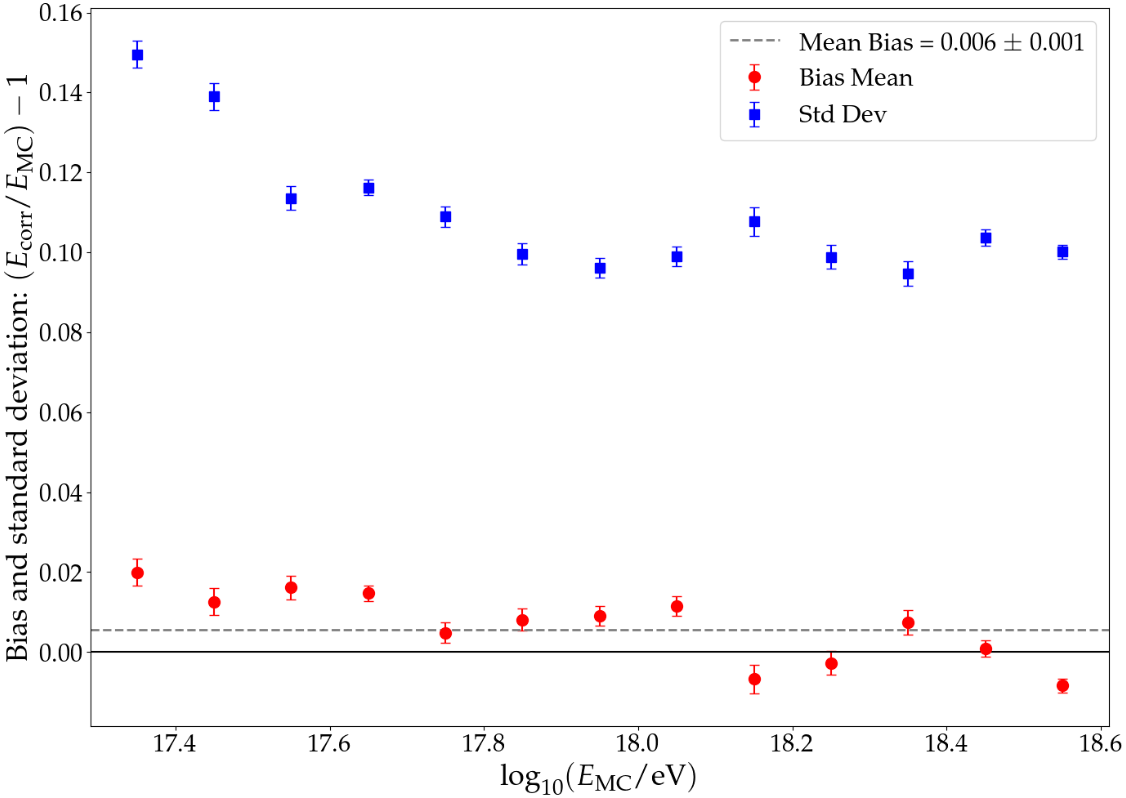


Auger mass fractions from ICRC 2017

$$E = A \left(\frac{E_{\mathrm{rec}}}{E_{\mathrm{ref}}} \right)^{B}$$

where $E_{\mathrm{ref}} = 10^{18}$ eV

A = $(1.309 \pm 0.01) \times 10^{-36}$
B = 0.9731 ± 0.0001



$$\mathrm{E}_{\mathrm{ratio}} = \frac{E_{\mathrm{corr}}}{E_{\mathrm{MC}}} - 1$$

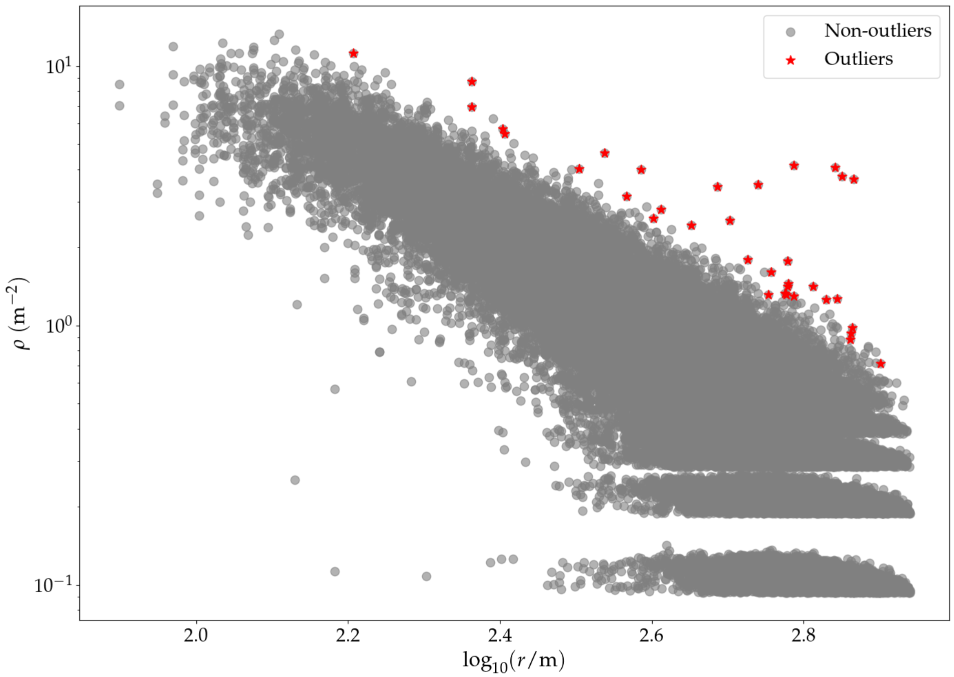
The distribution of $\mathrm{E}_{\mathrm{ratio}}$ is fitted with a Gaussian

$$f(x) = A\ \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]$$

μ ➡ mean bias $(E_{\mathrm{corr}}/E_{\mathrm{MC}} - 1)$

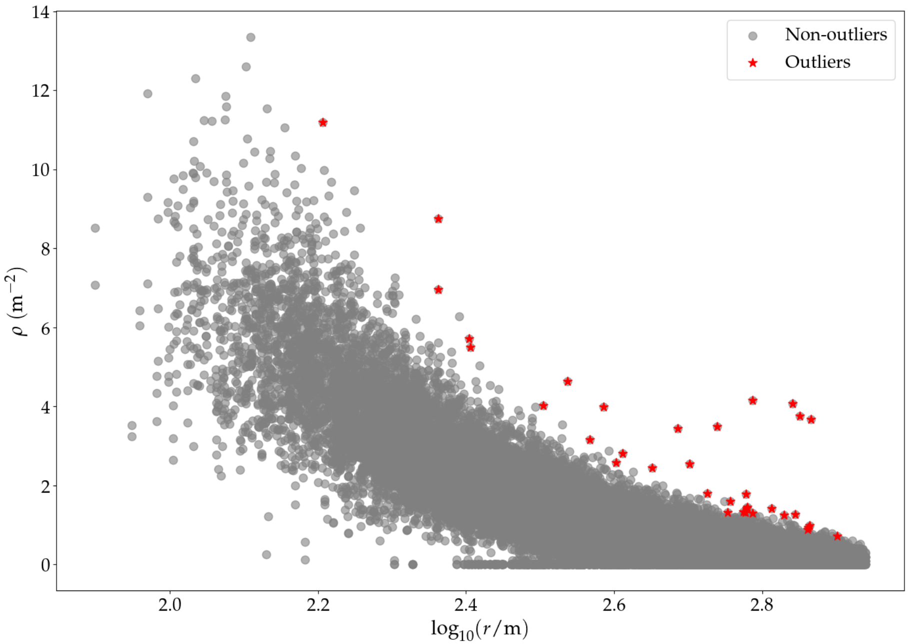
σ ➡ standard deviation $\sigma \approx \dfrac{\Delta E}{E}$

Outlier detection



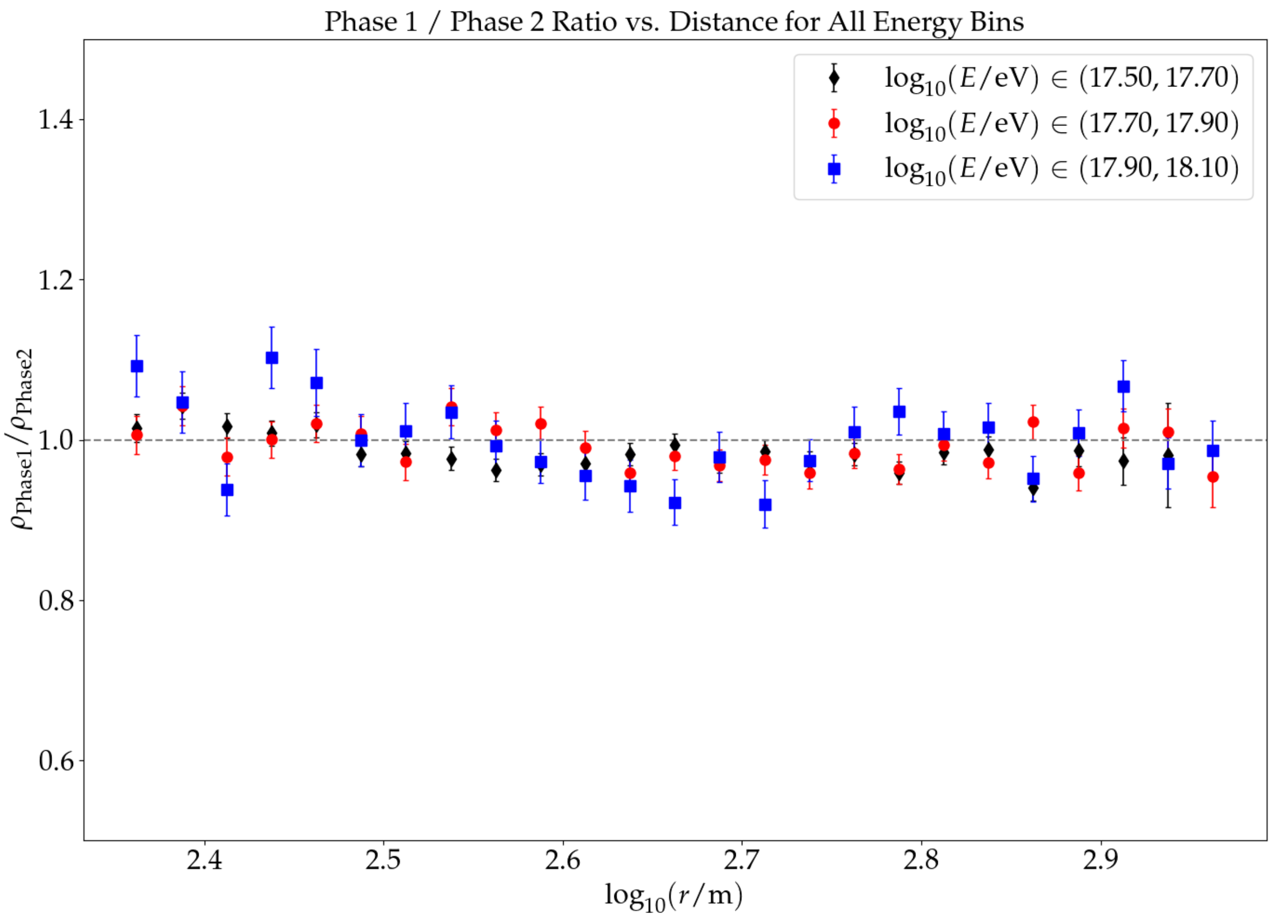
$\log_{10}(E_{rec}/eV) \in [17.5, 17.7)$ Phase 1 data

Outliers defined as >5σ from median
(σ = 68% central spread)
Method repeated for all the energy bins

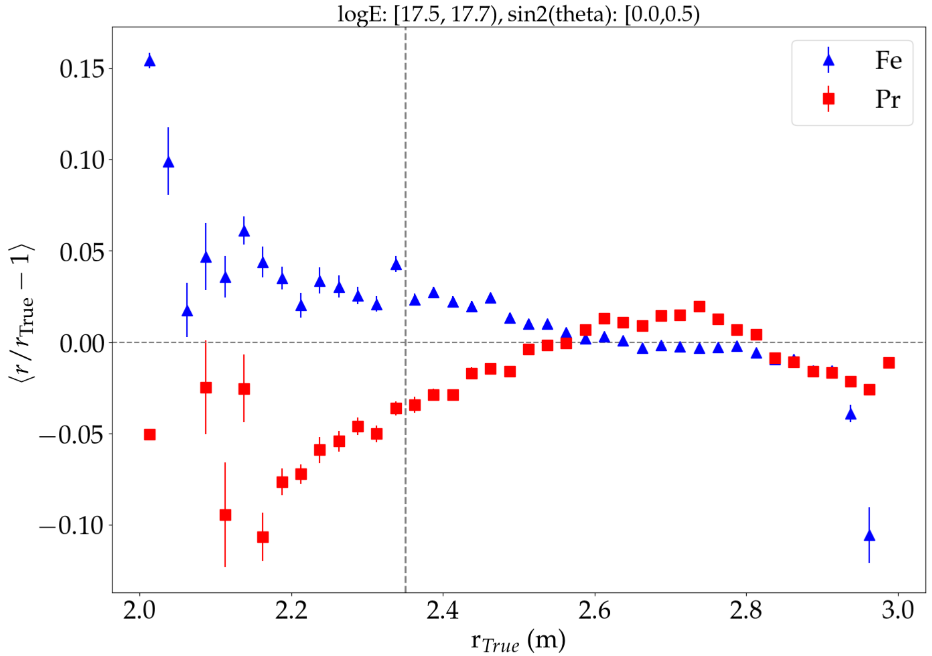


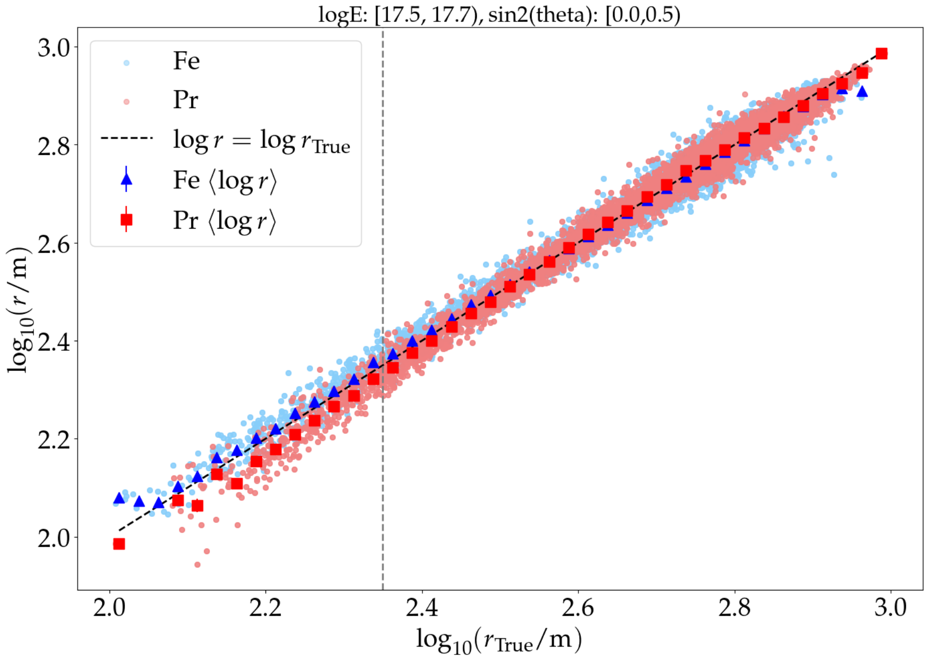
Total original data points: 1492331
Total number of outliers removed: 126
Percentage of data removed as outliers: 0.0084%

Phase 1-Phase 2 data comparison



Distance cut : fixed core





Distance cut at 2.35

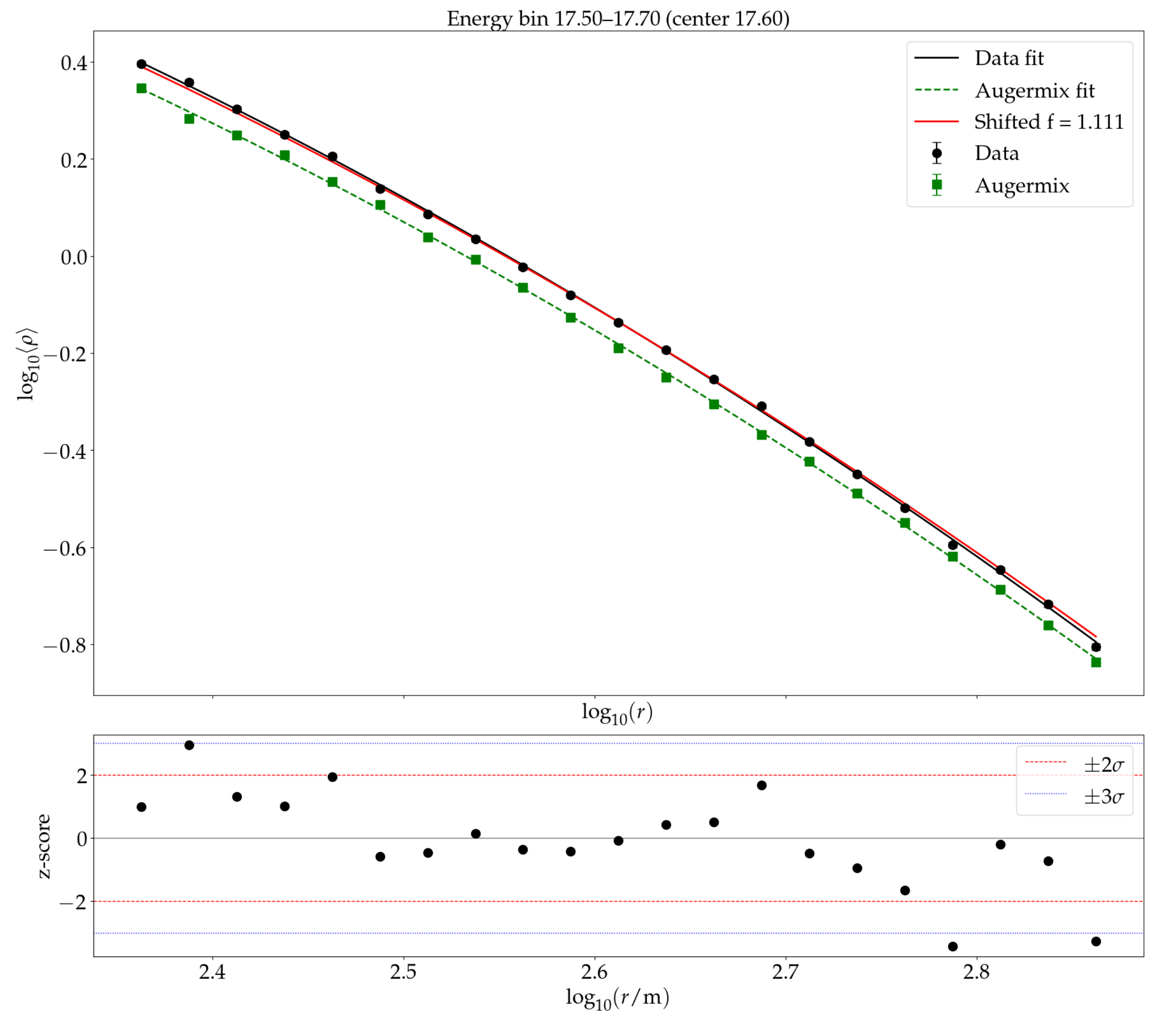
Weighted mean $\langle \rho_i \rangle = \dfrac{\sum_k w_k \, \rho_k}{\sum_k w_k}$

$$\langle \rho_{\text{mix}} \rangle_j = \sum_i f_i \, \langle \rho_i \rangle_j$$

$$\sigma_{\text{j}}^2 = \sum_i f_{0,i}^2 \, \sigma^2_{\langle \rho_i \rangle, j}$$

f0 Auger mass fractions from ICRC 2017

$$\log_{10}(y_{\text{model}}) = a_0 + a_1 x + a_2 x^2$$



Fit performed in $\log_{10}$ space using weighted least squares

$$\rho(r) \approx f \cdot \rho_{\mathrm{Mix}}(r)$$

f → multiplicative correction applied to the simulated muon densities to best match the data.

$$\log_{10} \rho(r) \approx \log_{10} \rho_{\mathrm{Mix}}(r) + \log_{10}(f)$$

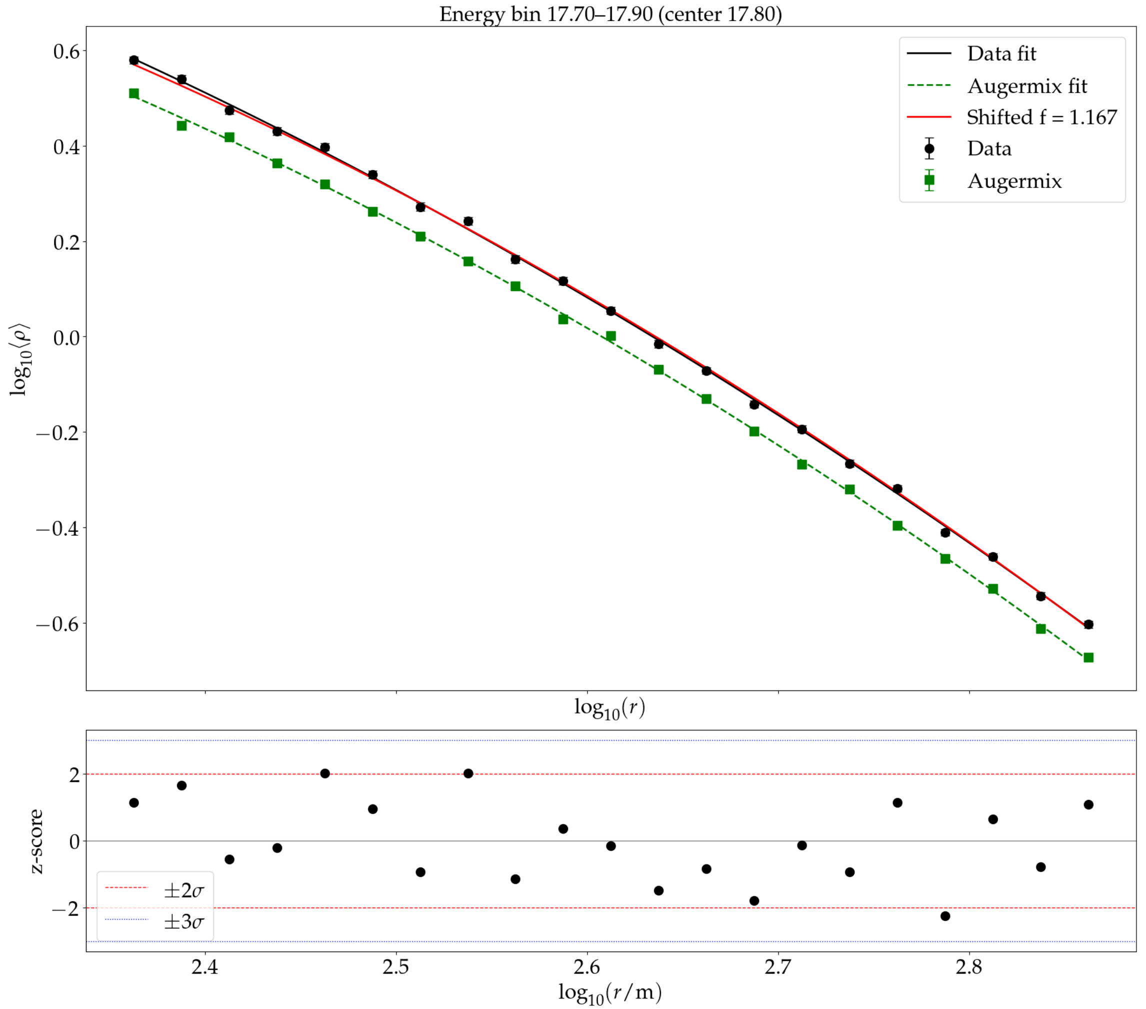
$$a = \log_{10}(f)$$

$$\chi^2(a) = \sum_{i=1}^{N} \left(\frac{y_i - (m_i + a)}{\sigma_i} \right)^2$$

$$y_i = \log_{10} \rho_{\mathrm{data},i}$$

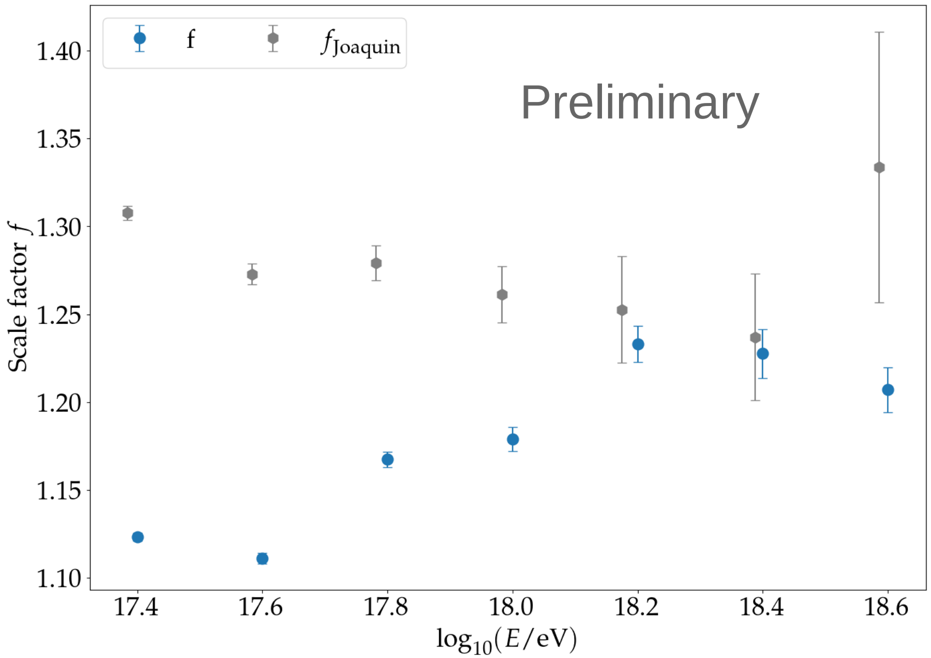
$$m_i = \log_{10} \rho_{\mathrm{Mix},i}$$

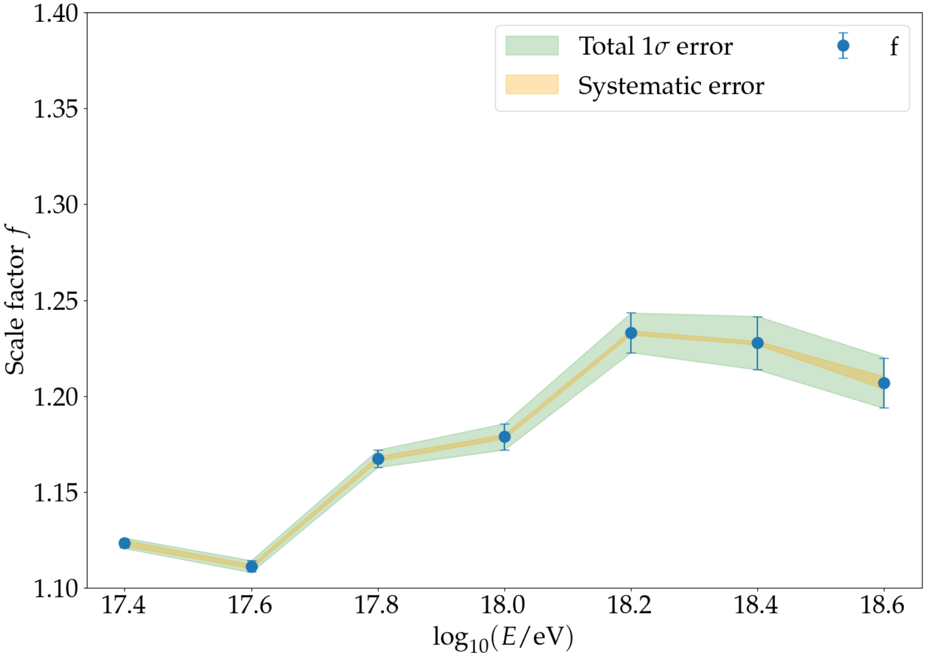
$$\sigma_i \to \text{uncertainty of } y_i$$



systematics due to MLDF shape (parameter covariance)

Scale factor as a function of energy



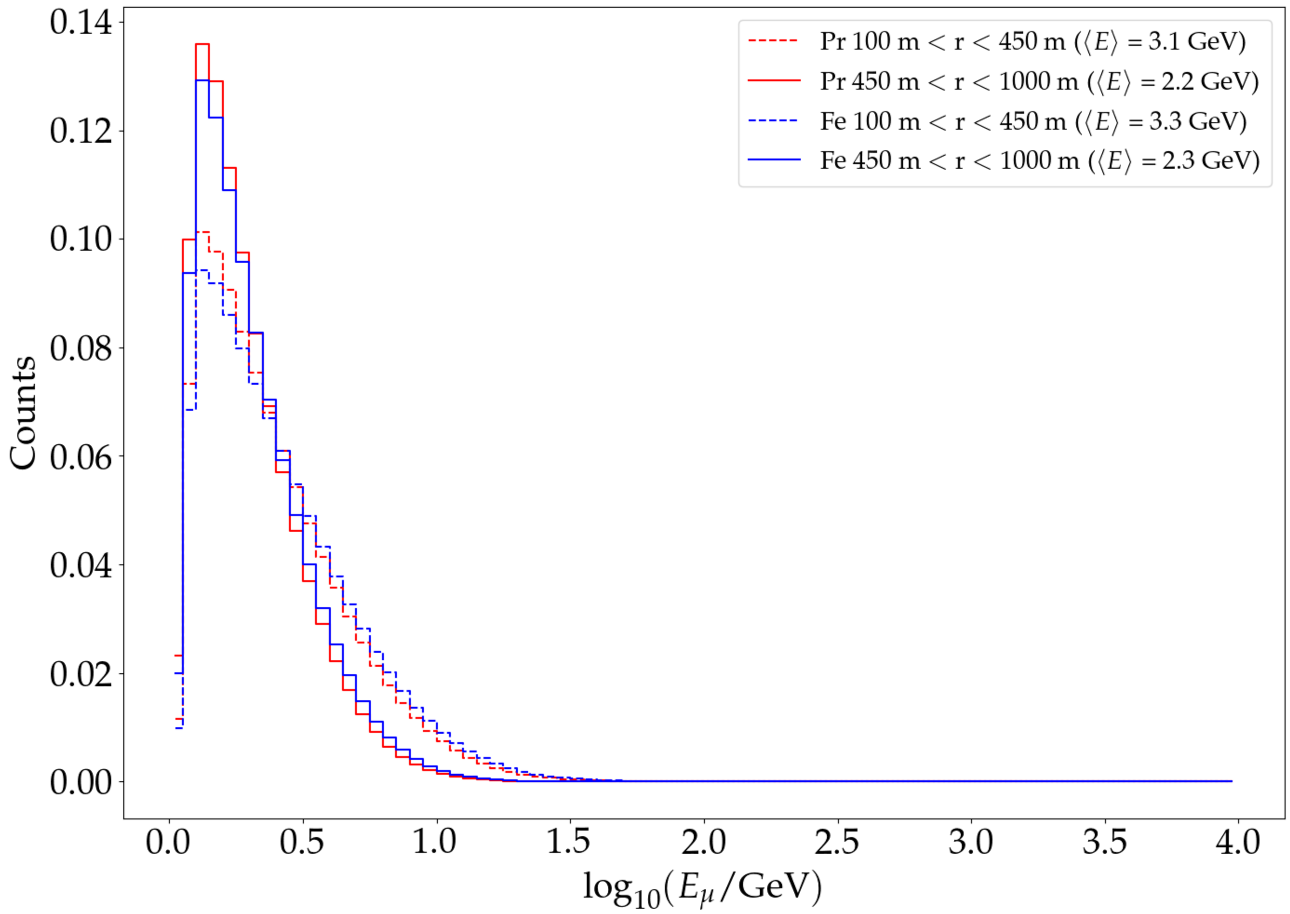


Outlook

- Phase 1 and phase 2 data are compatible for the mldf analysis
- The data needs to be further analyzed to obtain a robust measurement of f
- Future work :
  - Include systematic errors (detector, model, energy scale, composition)

Backup

Muon energy distribution



$\log_{10}(E_{rec}/\mathrm{eV}) \in [17.4, 17.6)$