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Neural-Network-Based Estimation of Muon Content of Air Showers Using the SD-750 Array of the Pierre Auger Observatory

Alina Klingel | February 12, 2026

Outline

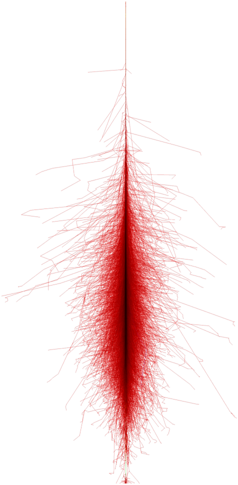
Motivation

- cosmic rays (CRs) around $10^{17.3} - 10^{19.0}$ eV: insight into physics (e.g. hadronic interactions) beyond human-made accelerators
- no direct detection, studied via air showers in Earth's atmosphere
- expectation:
  - hadronic multiparticle production increased with heavier primary nuclei (1 Fe $\approx$ 56 p)
  - hadronic showers with mesons ($\pi^{\pm}$) $\rightarrow$ muons
  - heavier primaries produces more muons

$\Rightarrow$ **number of muons produced in cascade**

η_{μ} = key mass proxy

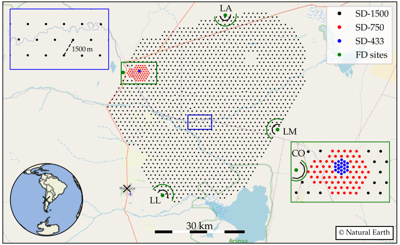
$\Rightarrow$ **clues to origin of CRs and muon puzzle**

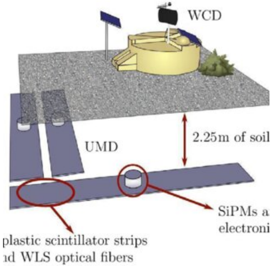


The Pierre Auger Observatory

$\sim$3000 km^2 ground based detector array

- **Surface Detector (SD)**:
  - $\sim$1600 water-Cherenkov detectors (WCDs) in triangular grids with 1500 / 750 m spacing
  - shower footprint = spatial distribution of particles, E-deposits, and time resolution of passing shower front
- **Underground Muon Detectors (UMD)**:
  - buried scintillator detectors next to SD 750
  - muon content
- Scintillator Surface Detector (SSD):
  - upgrade, mounted on top of the WCDs
  - shower footprint = more sensitive to EM component





Objectives

A) Develop a muon-based, mass-sensitive estimator

- Derived from Monte Carlo (MC) data
- Use neural networks for event-by-event prediction of muon estimators
- Input: air-shower footprints : Time-resolved signals of the SD-750

$\Rightarrow$ Proton or heavier primary?

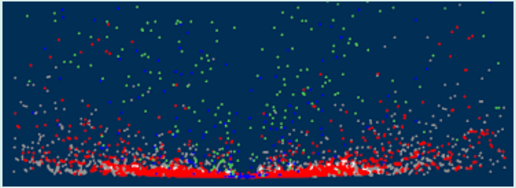
B) Cross-calibration with independent UMD measurements feasible?

- Validate the muon estimator against independent UMD measurements

Number of muons η_μ

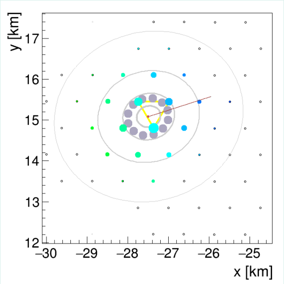
N_μ : Total number of muons

- Number of all muons at observation height
- Taken from `CORSIKA` shower simulations



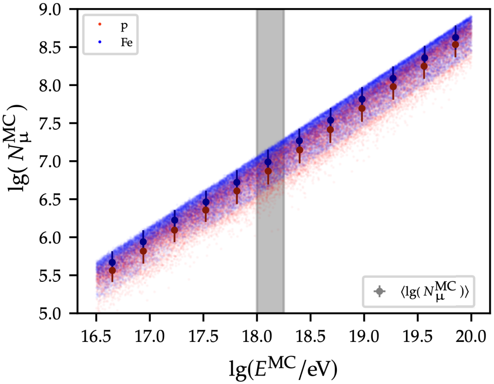
S_μ : Detector-level muon signal

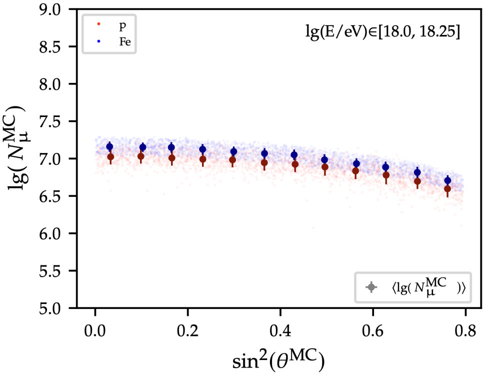
- Average muon signal recorded in virtual, off-grid stations
- Stations positioned on a ring with $r = 450\,\mathrm{m}$ in the shower plane



Assumption: N_μ and S_μ are proportional to the total muon content η_μ of the air shower

Number of muons η_μ : N_μ

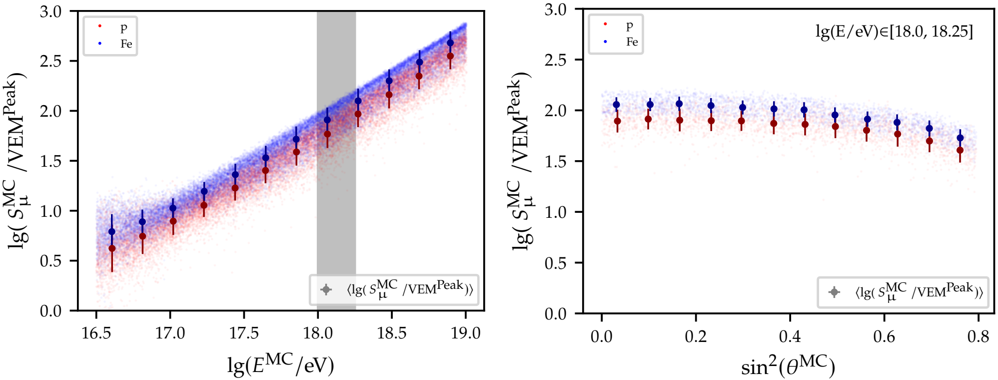




→ number of muons N_μ not a suitable target

→ use relative muon number $R_\mu = \frac{N_\mu(A)}{\langle N_\mu(A{=}1)\rangle}$

Number of muons η_μ: S_μ



→ number of muons S_μ not a suitable target

→ use relative muon number $R_\mu = \frac{S_\mu(A)}{\langle S_\mu(A{=}1)\rangle}$

Objective

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A) Develop a muon-based, mass-sensitive estimator

- Derived from Monte Carlo (MC) data
- Use neural networks for event-by-event prediction of η_μ
- Input: time-resolved SD-750 signals

$\rightarrow$ Proton or heavier primary?

B) Cross-calibration with independent UMD measurements feasible?

- Validate the muon estimator against UMD measurements

C) $R_\mu[N_\mu]$ vs $R_\mu[S_\mu]$

- S_μ standard approach (used e.g. in air-shower Universality), but requires additional simulations
- N_μ is available for "free" from CORSIKA shower simulations

$\rightarrow$ compare performance

Approach: $R_\mu[N_\mu]$ vs $R_\mu[S_\mu]$

$$R_\mu[\eta_\mu] = \frac{\eta_\mu(A)}{\langle \eta_\mu(A{=}1) \rangle}$$

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SD-750 Simulations

1. **Standardized construction of $\mathbf{R}_\mu^{\mathrm{MC}}$**
   - N_μ: all muons from CORSIKA shower simulation
   - S_μ: detector muon signal in simulated rings
   - ...
2. **NN prediction of $\mathbf{R}_\mu^{\mathrm{NN}}$**
   - training with R_μ^{MC} as labels
   - performance study: bias, precision, FOM

SD-750+UMD Simulations

4. **Comparison to UMD data**
   - R_μ^{MC} vs UMD
   - R_μ^{NN} vs UMD

SD-750 Measurements

5. **NN predictions of $R_\mu^{\mathrm{NN,Rec}}$**
6. **Corrections**
   - unphysical dependencies (detector aging, atmosphere)
   - NN bias using *SD-750 Simulations*

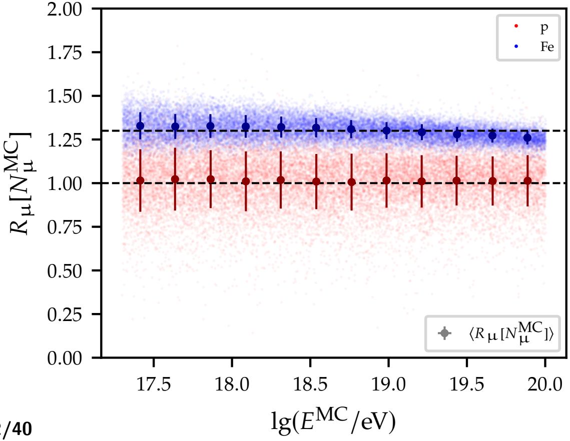
SD-750+UMD Measurements

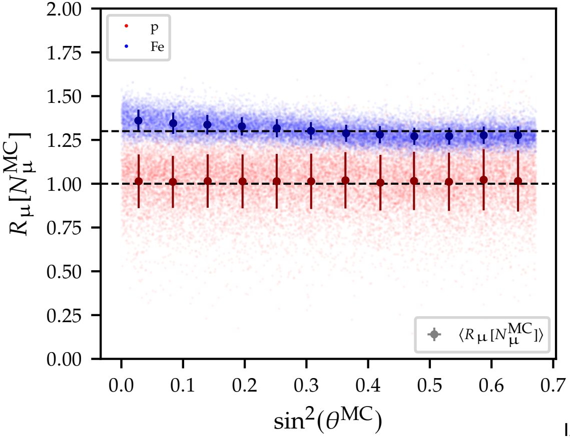
6. **NN predictions of $R_\mu^{\mathrm{NN,Rec}}$**
7. **Corrections**
   - *SD-750*: see above
   - *UMD*: E_{MC} vs E_{rec}
8. **⟨*SD-750–UMD*⟩ cross-calibration**
   - estimate using *SD-750+UMD Measurements*
   - apply to *SD-750 Measurements*

Outline

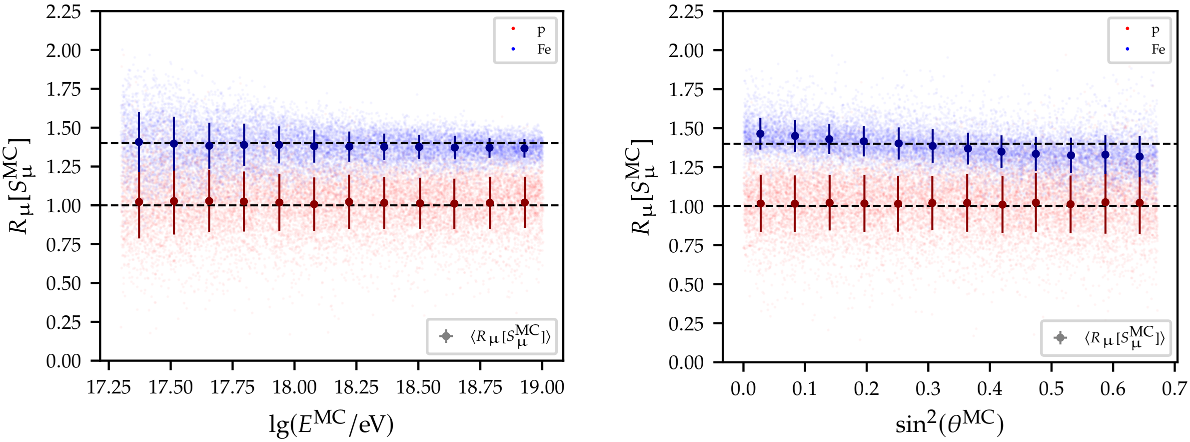
Relative muon number $R_\mu[N_\mu] = \frac{N_\mu(A)}{\langle N_\mu(A=1)\rangle}$

- $\langle N_\mu(A=1)\rangle$ = average behavior of N_μ for protons
- one-step fit to capture energy E and zenith angle θ dependency
- using energy region of interest: SD-750 + SD-1500

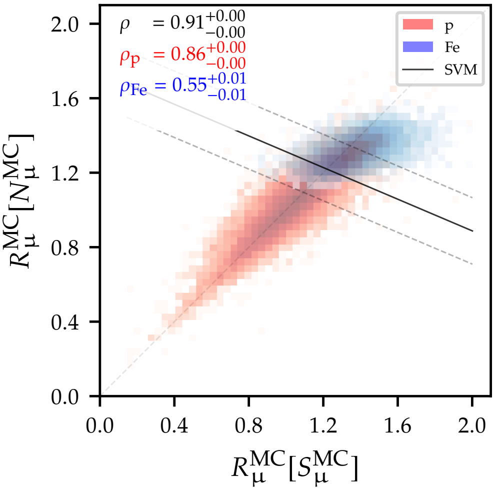




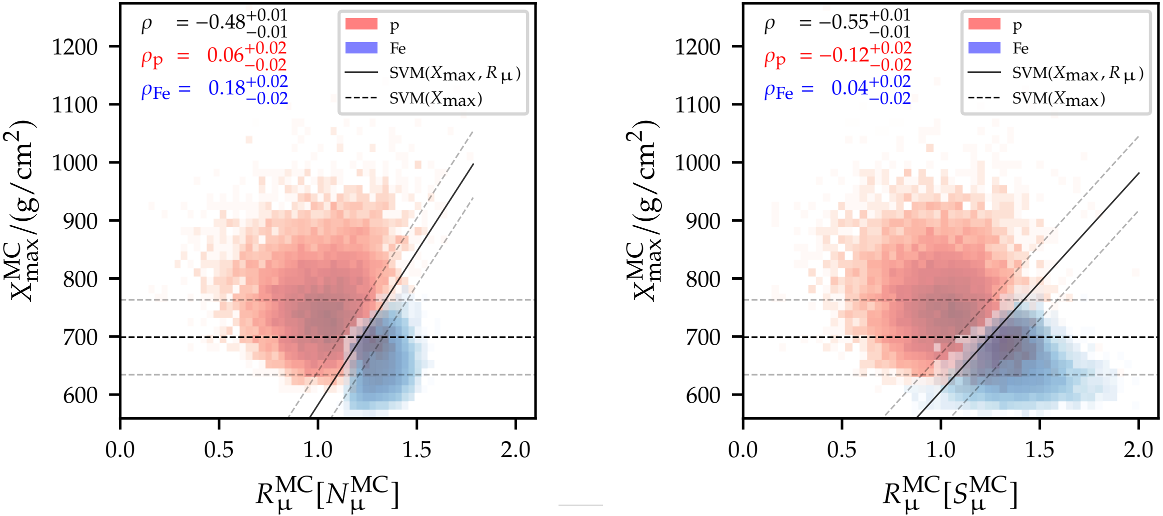
Relative muon number $R_\mu[S_\mu] = \frac{S_\mu(A)}{\langle S_\mu(A{=}1)\rangle}$



Correlation: $R_\mu[N_\mu]$ vs $R_\mu[S_\mu]$



Correlation: R_μ vs $X_{\max}$



Outline

Inputs

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Signal $\hat{S}(t)$

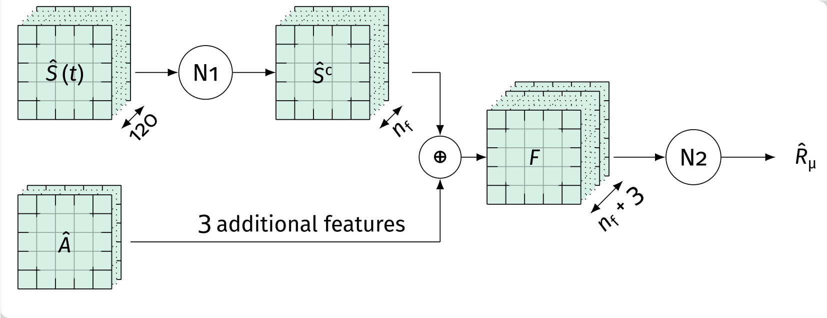
- Encoding: Triangular SD grid $\rightarrow$ rectangular 7x7 grid (hottest station $=$ center)
- For each triggered station: 3μs $=$ 120 bins of raw time traces/signals

Additional reconstructed features $\hat{A}$

- Encoding: just repeated 7x7
- 1. Total Signal S_{tot}: for potentially missing tails of long signals $>$ 120 bins
- 2. Relative trigger time $\hat{t}$: relative to the hottest station
- 3. No-Measurement Map (NoMeMa) i_{NoMeMa} : Stations outside of SD-750 or temporary non-functioning stations

Preprocessing / standardization: see Sec. 3.3.2

Architecture

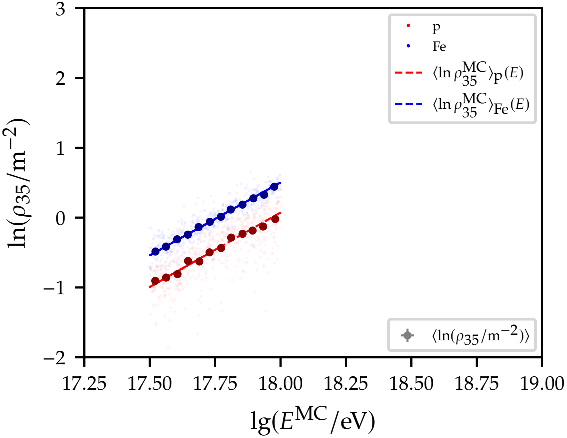


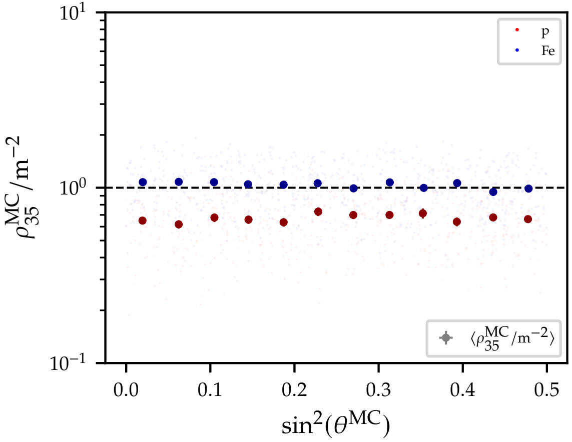
- **N1 - Trace analyzer:** CNN applied to raw time traces $\hat{S}(t)$, 1D compressing 120 time bins to $n_f = 10$ learned features per station
- **N2 - Spatial analyzer:** 2D CNN with skip connections to capture spatial correlations and stabilize training
- **Final predictor:** Flattened N2 output connected to a dense layer predicting standardized $\hat{R}_\mu$

Outline

UMD muon density ρ_{35}

- Zenith-angle (CIC, $\theta_{\mathrm{ref}} = 35^\circ$) corrected muon density at $r = 450\,\mathrm{m}$ from the shower core
- Measured with UMD

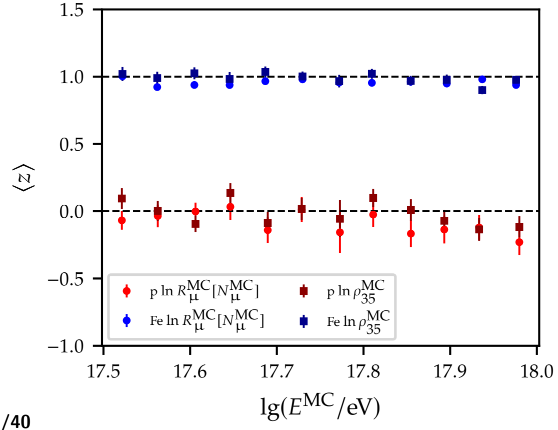


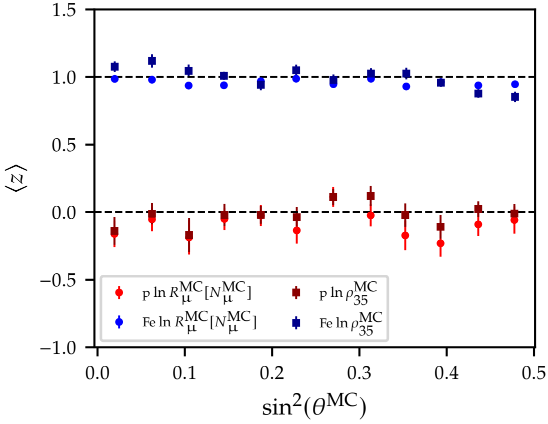


z-scale of R_μ^{NN} and UMD ρ_{35}

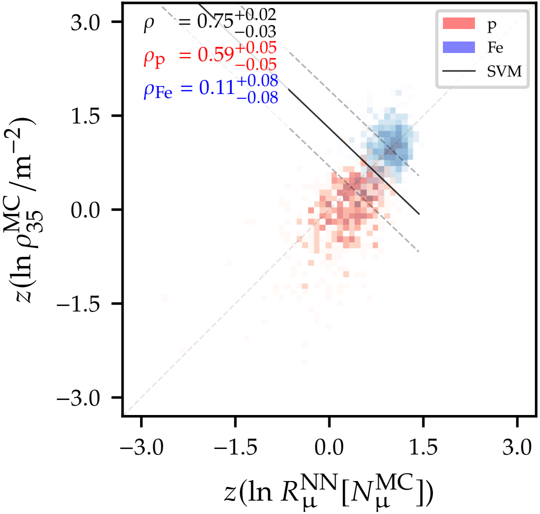
$$z(E,\theta) = \frac{x_A(E,\theta) - \langle x\rangle_p(E,\theta)}{\langle x\rangle_{Fe}(E,\theta) - \langle x\rangle_p(E,\theta)} = \begin{cases} 0 & \text{for proton} \\ 1 & \text{for iron} \end{cases} \quad (1)$$

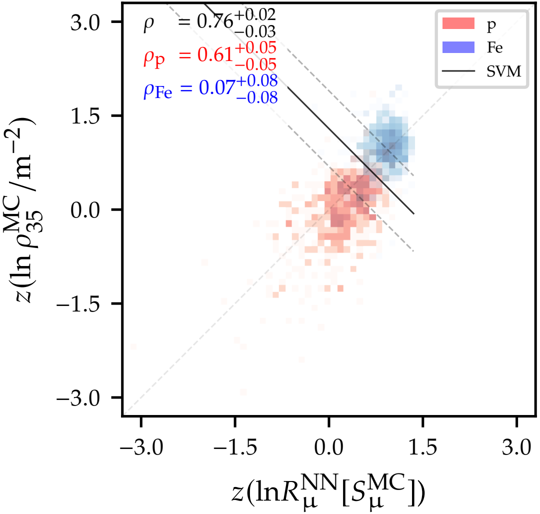
where $x \in \{\ln R_\mu[N_\mu], \ln \rho_{35}, \ldots\}$.





Correlation of R_μ^{NN} and UMD ρ_{35}





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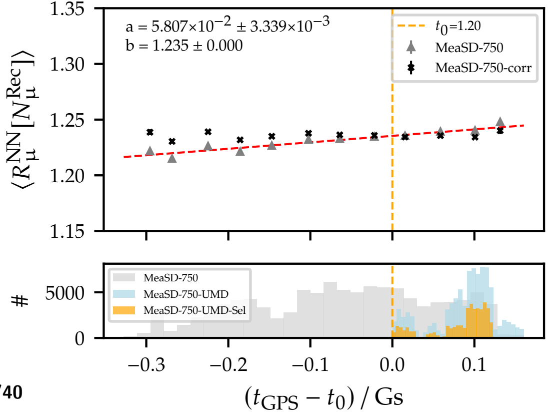
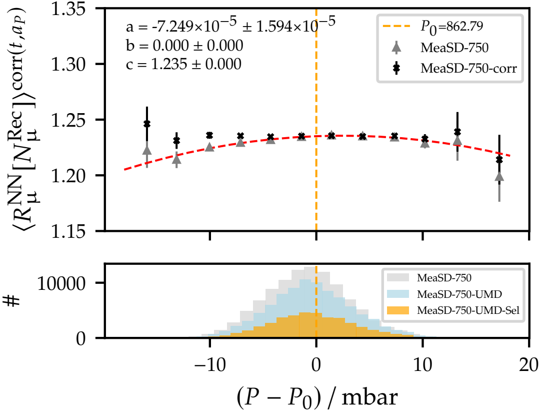
Correction for unphysical dependencies of R_μ^{NN}

$$R_\mu^{\mathrm{NN,\ corr}(x)} = R_\mu - f(x)\big|_{\mathrm{offset}=0} \quad (2)$$

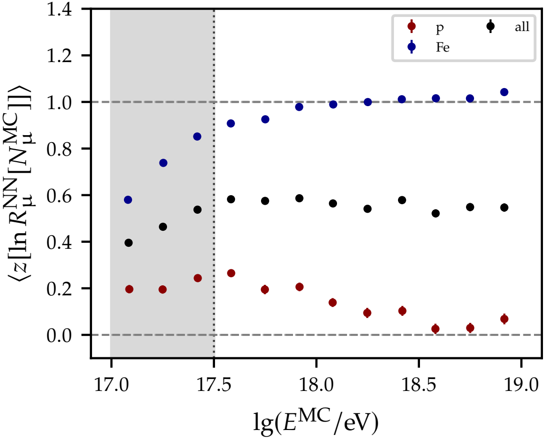
- **Detector aging:** runtime t and area-over-peak $\langle a_\mathrm{P} \rangle$
- **Geometry:** (zenith and azimuth angle)
- **Atmospheric conditions:** pressure p (and temperature T)

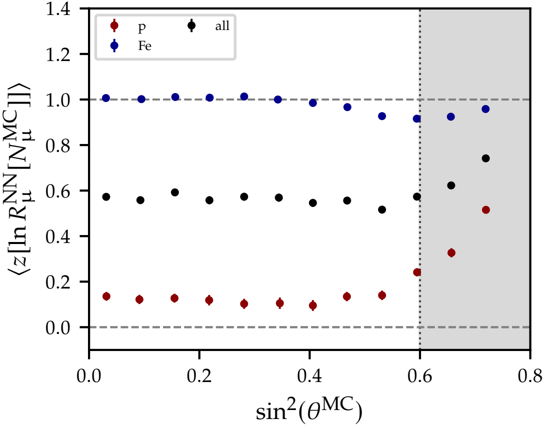
$\Rightarrow$ total correction < 1 %





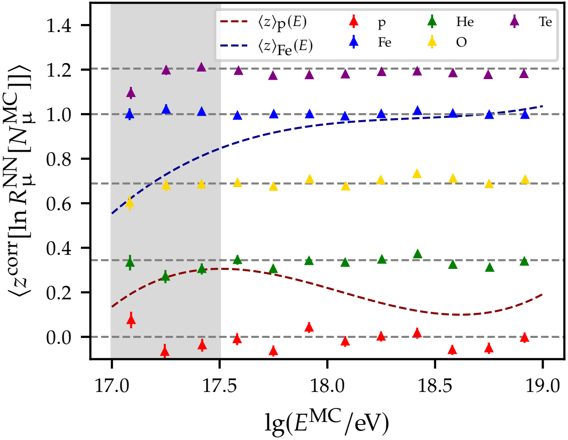
Correction for NN bias of $R_\mu^{NN}(E)$: SD-750 Sim

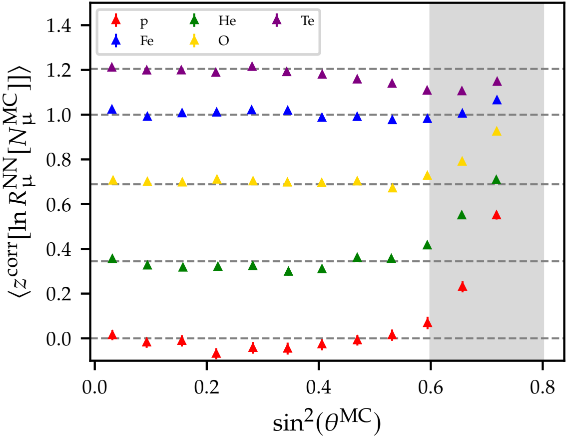




Correction for NN bias of $R_\mu^{\mathrm{NN}}(E)$: SD-750 Sim

- $\langle z[R_\mu^{\mathrm{NN}}[\eta^{\mathrm{MC}}]]\rangle_{\mathrm{p,Fe}}(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3$,
  $x = \lg(E/\mathrm{eV}) - 18, \quad \eta \in \{N_\mu, S_\mu\}$
- $$z^{\mathrm{corr(E)}} = \frac{z[R_\mu^{\mathrm{NN}}] - \langle z[R_\mu^{\mathrm{NN}}]\rangle_{\mathrm{p}}}{\langle z[R_\mu^{\mathrm{NN}}]\rangle_{\mathrm{Fe}} - \langle z[R_\mu^{\mathrm{NN}}]\rangle_{\mathrm{p}}}$$





Correction for NN bias of R_μ^{NN}: SD-750 Mea

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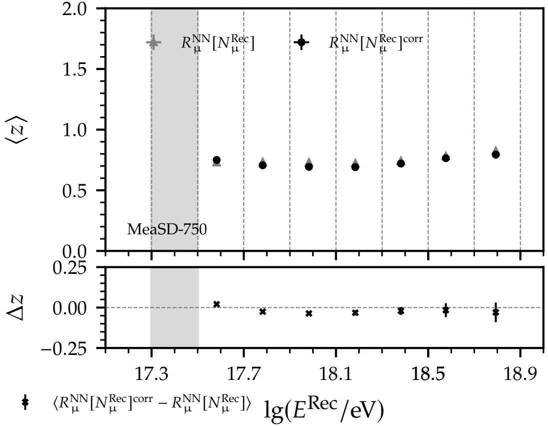
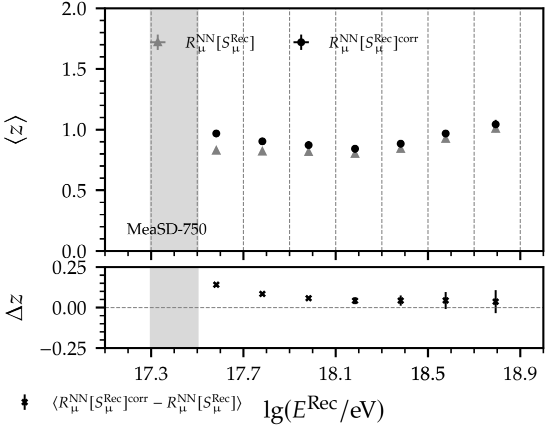
⇒ correction up to 10 %





Outline

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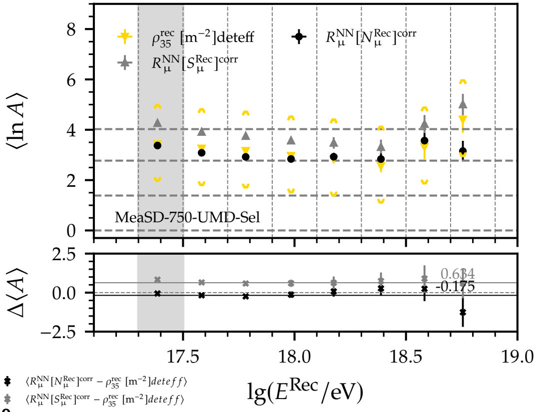
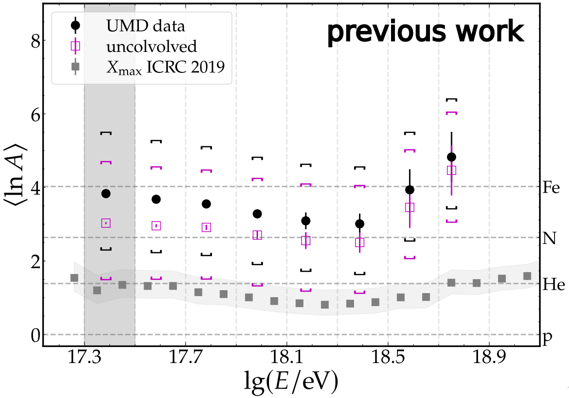
Reproduction of UMD Results

- Mass estimator:

$$\ln A = \ln(56)\, z$$

- Corrections:
  - R_μ: identical correction procedure
  - ρ_{35}: detector-efficiency correction for $E_{\mathrm{MC}} \rightarrow E_{\mathrm{rec}}$





Cross-Calibration:

Method

- Global mean difference:

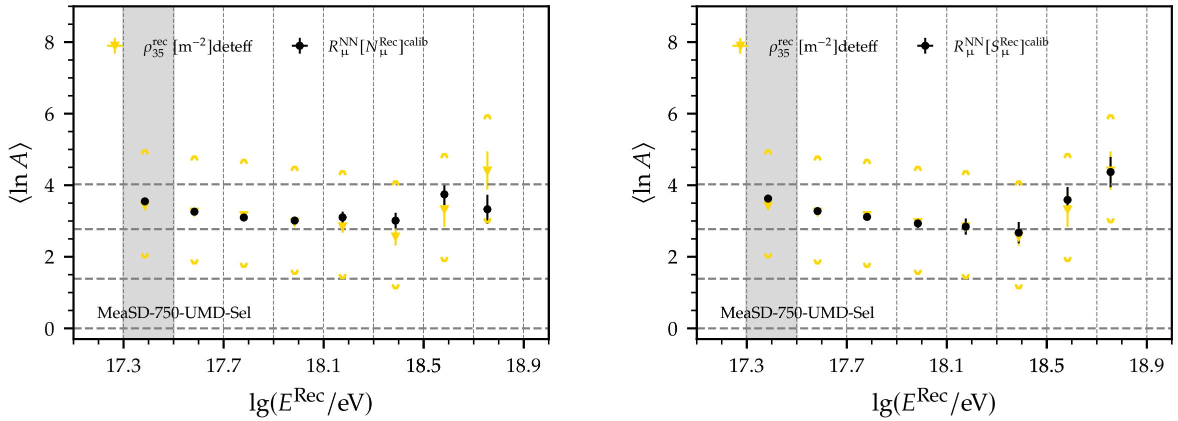
$$\Delta \ln A = \langle R_{\mu}^{\mathrm{NN}} \rangle - \langle \rho_{35} \rangle$$

- Results:
  - $\Delta \ln A_{N_{\mu}} = -0.175$
  - $\Delta \ln A_{S_{\mu}} = 0.634$
- Calibration:

$$\ln A(R_{\mu}^{\mathrm{calib}}) = \ln A(R_{\mu}^{\mathrm{NN}}) - \Delta \ln A$$

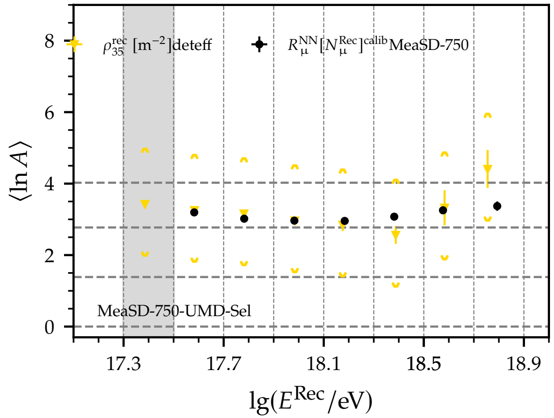
- Systematic uncertainties taken from ρ_{35} (lower boundary)

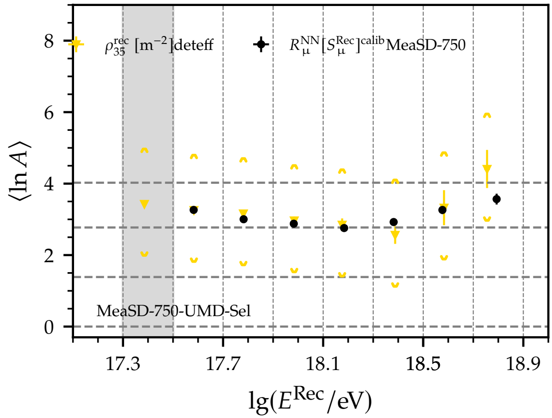
Cross-Calibration: *SD-750+UMD Mea*



Events: 8197 3125 1090 372 122 48 17 6

Cross-Calibration: full *SD-750 Mea*



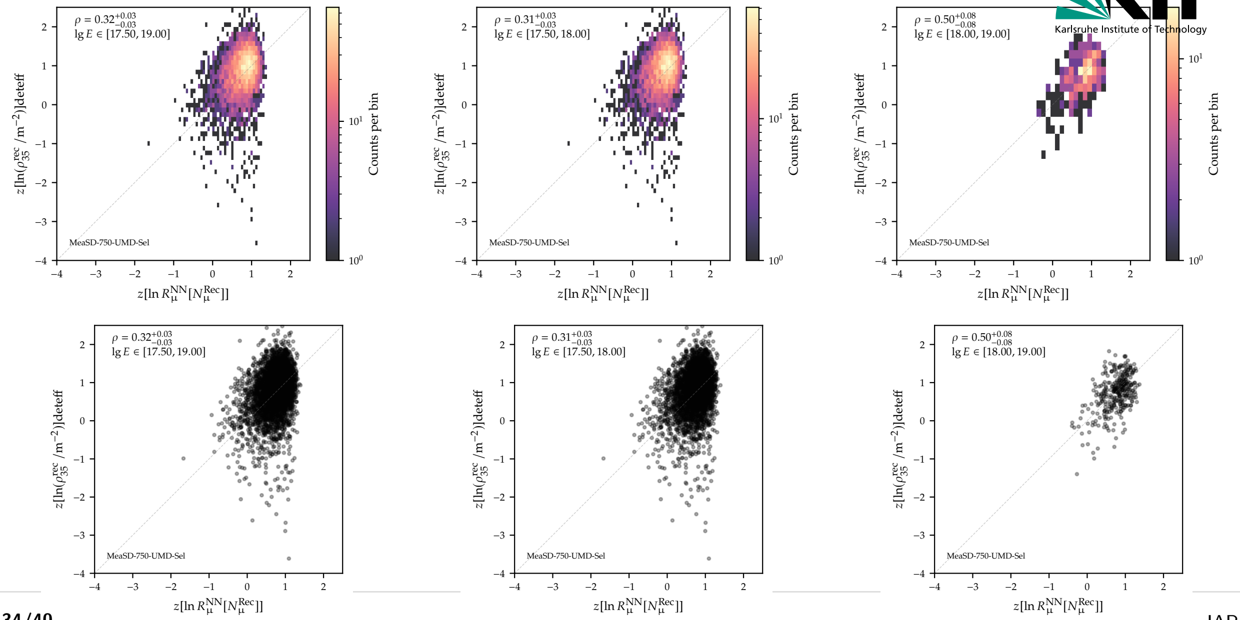


Events:	0	67843	22844	7784	2631	960	345	131

Outline

Correlation SD-750 vs UMD: BEFORE NN bias correction

full energy range | low energy range | high energy range



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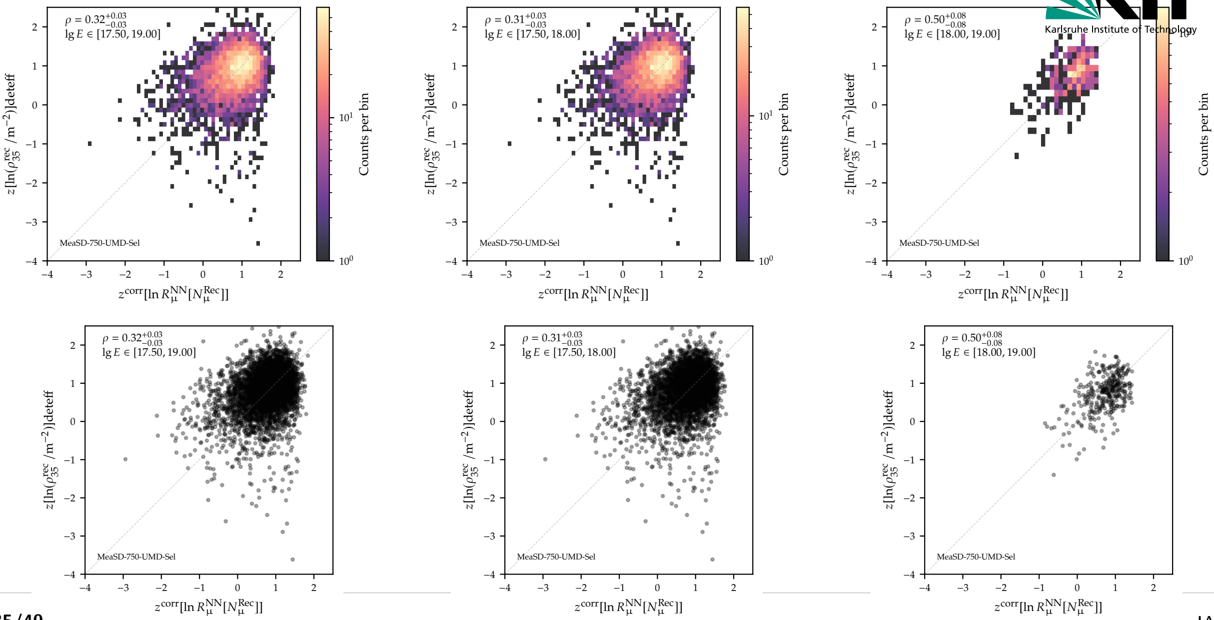
Correlation SD-750 vs UMD: AFTER NN bias correction

full energy range | low energy range | high energy range



⇒ no significant difference in correlation after NN bias removal

Correlation Coefficients (E): UMD vs UMD-Sel(Fig. 7.10)

(before NN bias correction)

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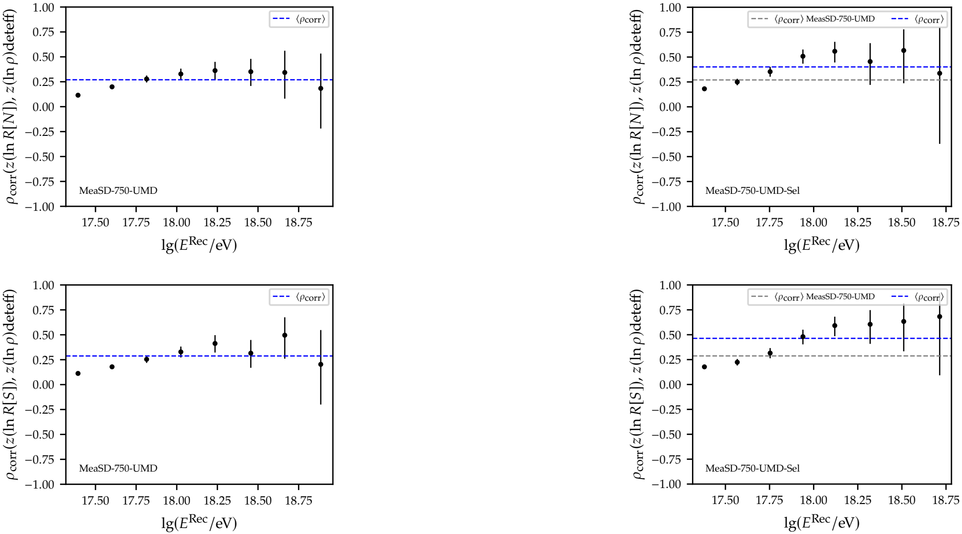
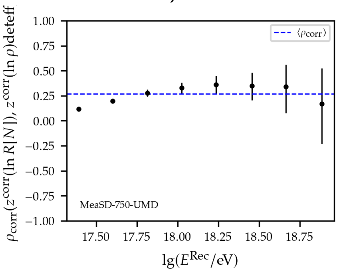
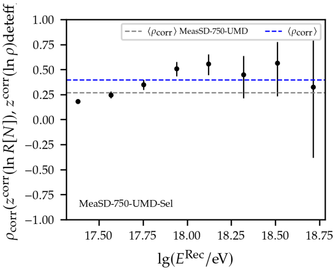


UMD counts:	16662	7041	2677	1024	350	161	53	26
UMDsel counts:	7867	3231	1192	421	172	57	27	10

Correlation Coefficients (E): UMD vs UMD sel(Fig. 7.10)

(after NN bias correction)





(no Smu, because looked very similar before and I need to go, sorry)

UMD counts:	16662	7041	2677	1024	350	161	53	26
UMDsel counts:	7867	3231	1192	421	172	57	27	10

⇒ do differences between Correlation coefficients over $\lg(E/\mathrm{eV})$ before and after NN bias correction
⇒ higher correlation for higher energies and quality UMD selection (UMD-Sel)

Outline

Conclusion

A) Develop a muon-based, mass-sensitive estimator

✓extra separation power to X_{max}

B) Cross-calibration with independent UMD measurements feasible?

✓works well (for one model)

C) $R_\mu[N_\mu]$ vs $R_\mu[S_\mu]$

- S_μ = standard, but requires additional simulations
- N_μ is available for "free"

→ Despite beeing very different quantities, performance is quite similar
→ N_μ is more economical and ecological option

Outlook

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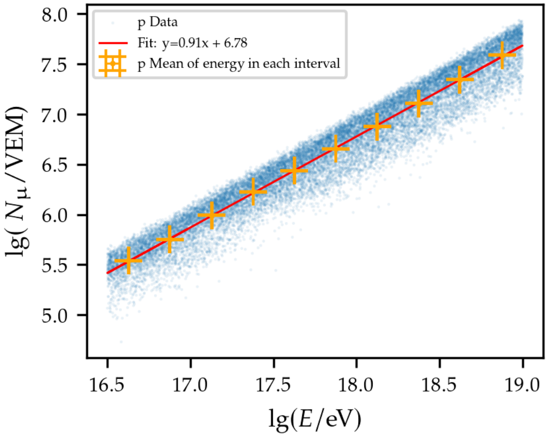
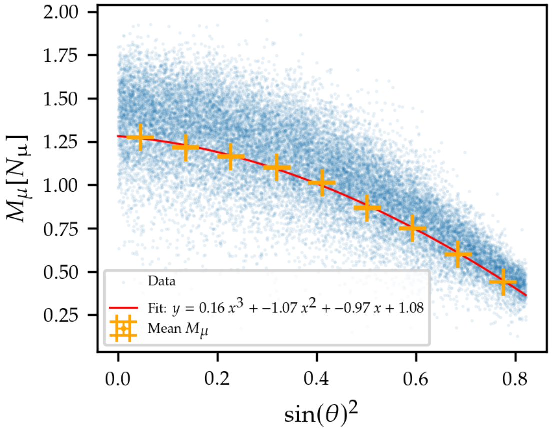
- **NN optimization**
  - Systematic exploration of NN architectures and hyperparameters
- **Systematic uncertainties**
  - Dependence on hadronic interaction models
  - Uncertainties of the UMD reference measurements
- **AugerPrime**
  - SSD signals as additional NN inputs
  - Cross-calibration of SD-750 NN predictions with SD-1500 coincidence events

Appendix: Target Calculation: Two-step Fit $R_\mu[N_\mu]$

1. Linear Fit to get $\log_{10}(\langle N_\mu \rangle) \rightarrow \langle N_\mu \rangle(E)$
2. $M_\mu(E) = \frac{N_\mu}{\langle N_\mu \rangle(E)}$
3. Cubic Fit to get $\langle M_\mu \rangle(\theta)$
4. Final Target: $R_\mu = \frac{M_\mu(E)}{\langle M_\mu \rangle(\theta)}$





Appendix: $R_\mu[N_\mu] = \frac{N_\mu(A)}{\langle N_\mu(A{=}1)\rangle}$ - one-step method

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One-step parameterization N_μ paramerization

$$\langle N_\mu \rangle_{\mathrm{p}}^{1\,\mathrm{step}}(E,\theta) = 10^{m'} \left(\frac{E/10^{18}\,\mathrm{eV}}{f'_{\mathrm{p}}(\theta)} \right)^{s'} . \quad (3)$$

$$\langle \lg N_\mu \rangle \approx \lg \langle N_\mu \rangle_{\mathrm{p}}^{1\,\mathrm{step}}(E,\theta) \quad (4)$$

$$= m' + s' \left[x - \lg \left(f'_{\mathrm{p}}(y) \right) \right] \quad (5)$$

$$= m' + (C + Dx)' \left[x - \lg \left(f'_{\mathrm{p}}(y) \right) \right] , \quad (6)$$

with

$$x = \lg E - \lg E_{\mathrm{ref}} , \qquad y = \sin^2\theta - \sin^2\theta_{\mathrm{ref}} .$$

and

$$f'_{\mathrm{p}}(y) = 1 + a'y + b'y^2 + c'y^3 + d'y^4$$

Final expression:

$$R_\mu[N_\mu] = 10^{\log_{10} N_\mu - \mathrm{corr}}$$

PhD Proposal

- **Service Job (early phase)**
  - Preparation of SD, SSD, and UMD data for physics analysis
  - Understanding detector effects, reconstruction biases, and data quality
- **Physics Analysis**
  - Event-by-event mass tagging using SD, SSD, and UMD information
  - Machine-learning–based reconstruction of muon-related observables
  - Cross-calibration of surface and underground muon measurements
  - Tests of hadronic-interaction models using the complementary detectors (on the muonic and electromagnetic components of air shower) like signal time distributions for reconstruction of muon production depth
  - Extension toward composition-enhanced anisotropy studies

$\rightarrow$ clear main goal to be developed

Correction for NN bias of $R_\mu^{\mathrm{NN}}(E)$: uncorrected