Auger SD Energy calibration with MC

using Telescope Array lookup table approach

Francesco Salamida, Valerio Verzi

Outline

- Goal: Estimate the primary cosmic ray energy using the surface detector (SD) form parameter S_{1000} and zenith angle θ through MC instead that using CIC (lookup table TA approach)

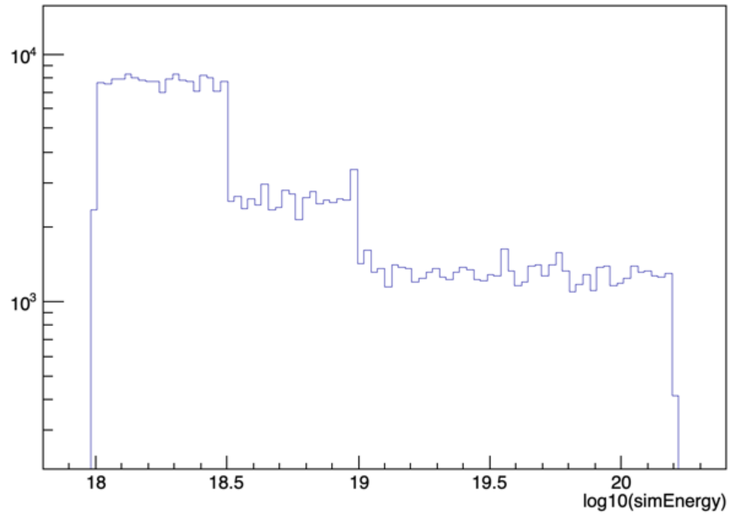
- Motivation: exploit the possible distortion of the spectrum shape at the highest energies coming from the mass unknown (TA is using just proton simulations for the energy conversion)

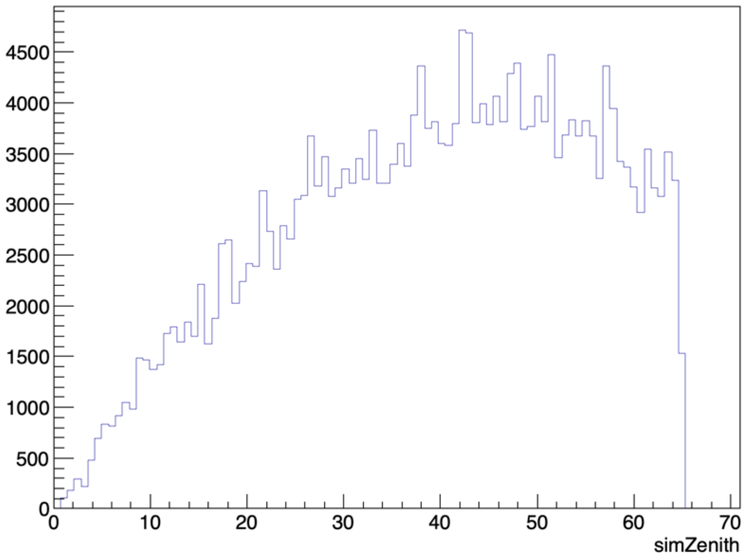
- Method: Build a 3D table S1000:theta:energy and parametrize through a fit a functional form to simulated data and store parameters for later use.

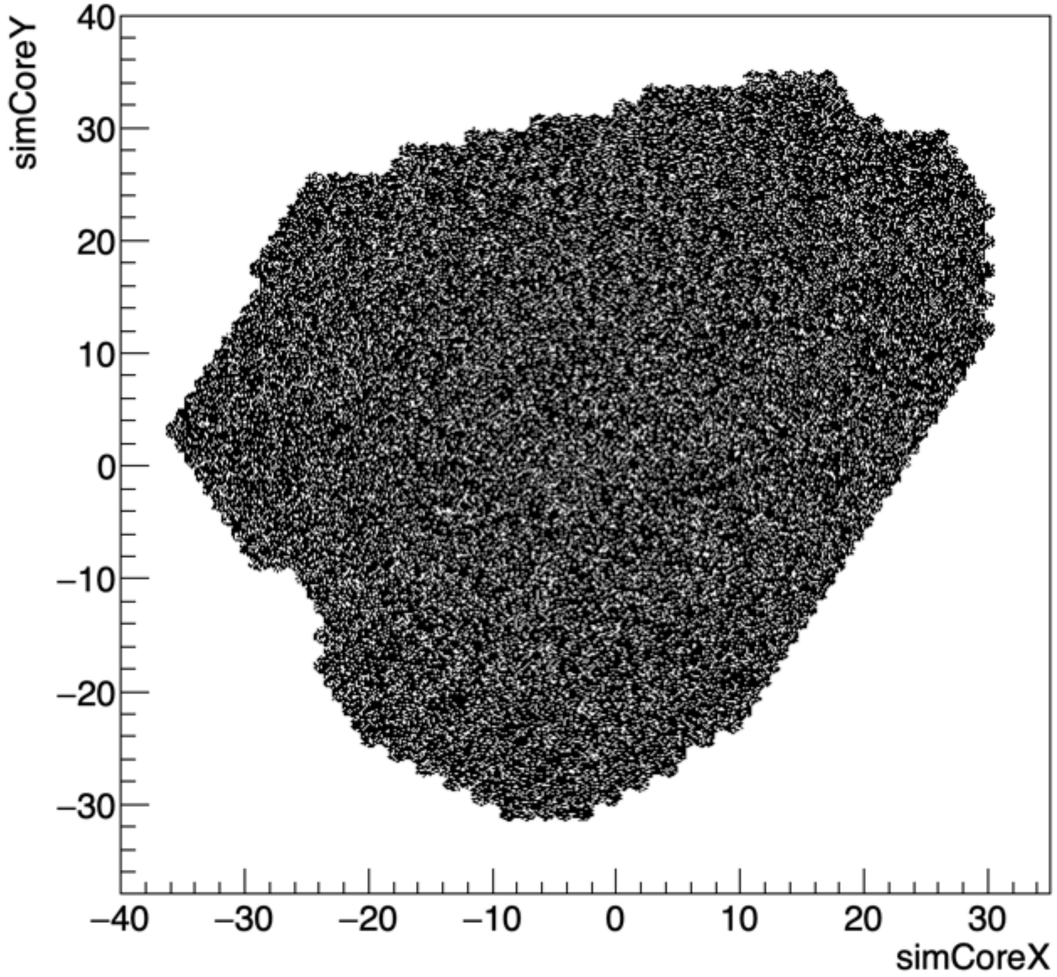
MC Data for Lookup Table Generation

- CORSIKA Monte Carlo simulations with different hadronic interaction models (thanks to Roberta for help with iRods):
  - EPOS-LHC
  - SIB23d
- Primary masses: 100 (proton), 400 (helium), 1600 (oxygen), 5600 (iron).
- Energy, flat in log10(E) in 18-20.5
- ~200000 events per mass per model
- Full working SD array configuration (fixed GPStime)
- Variables:
  - S_{1000}: signal at 1000 m form LDF fit
  - θ: zenith angle
  - E_{MC}: simulated primary energy

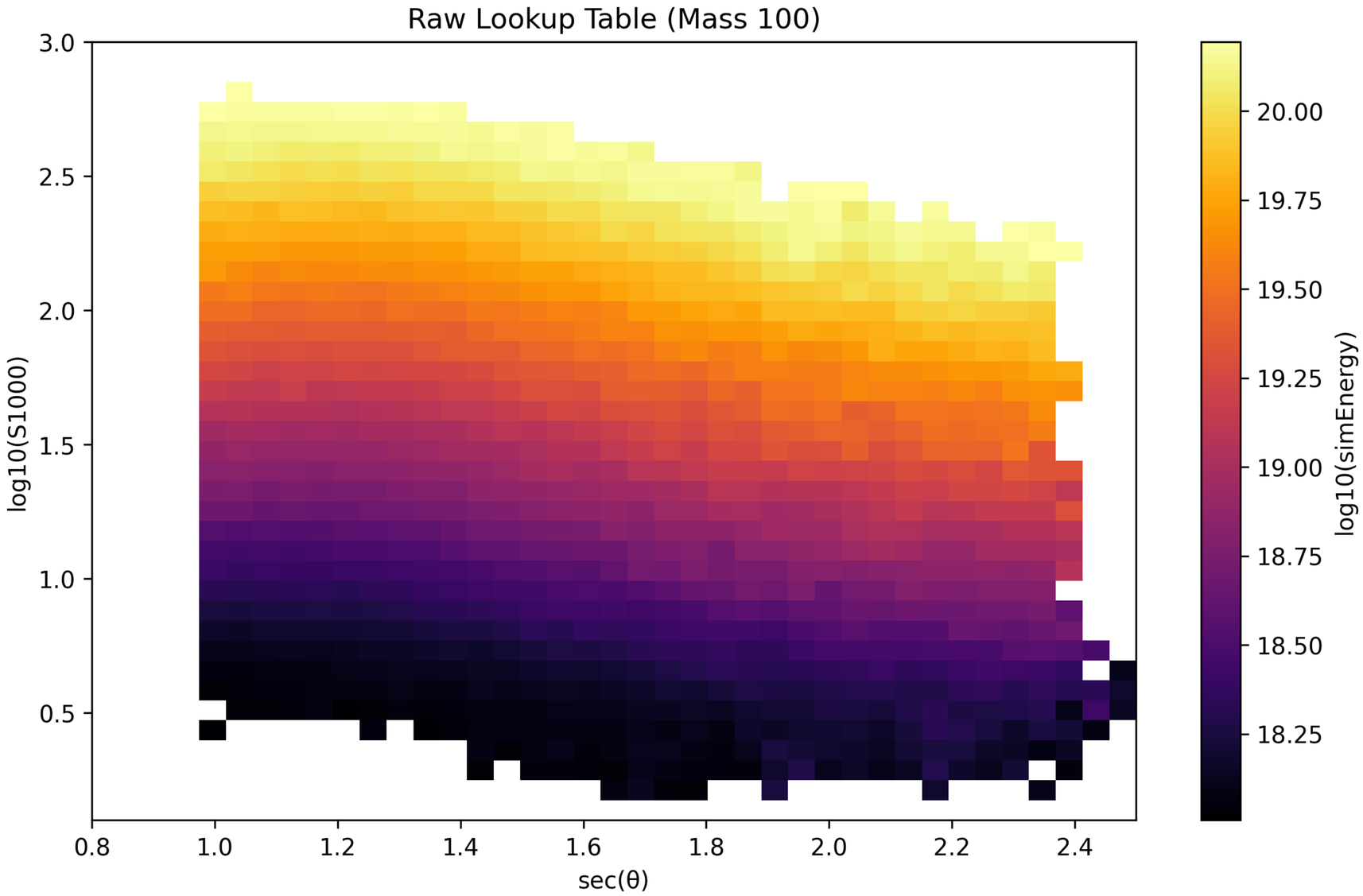
MC Data for Lookup Table Generation



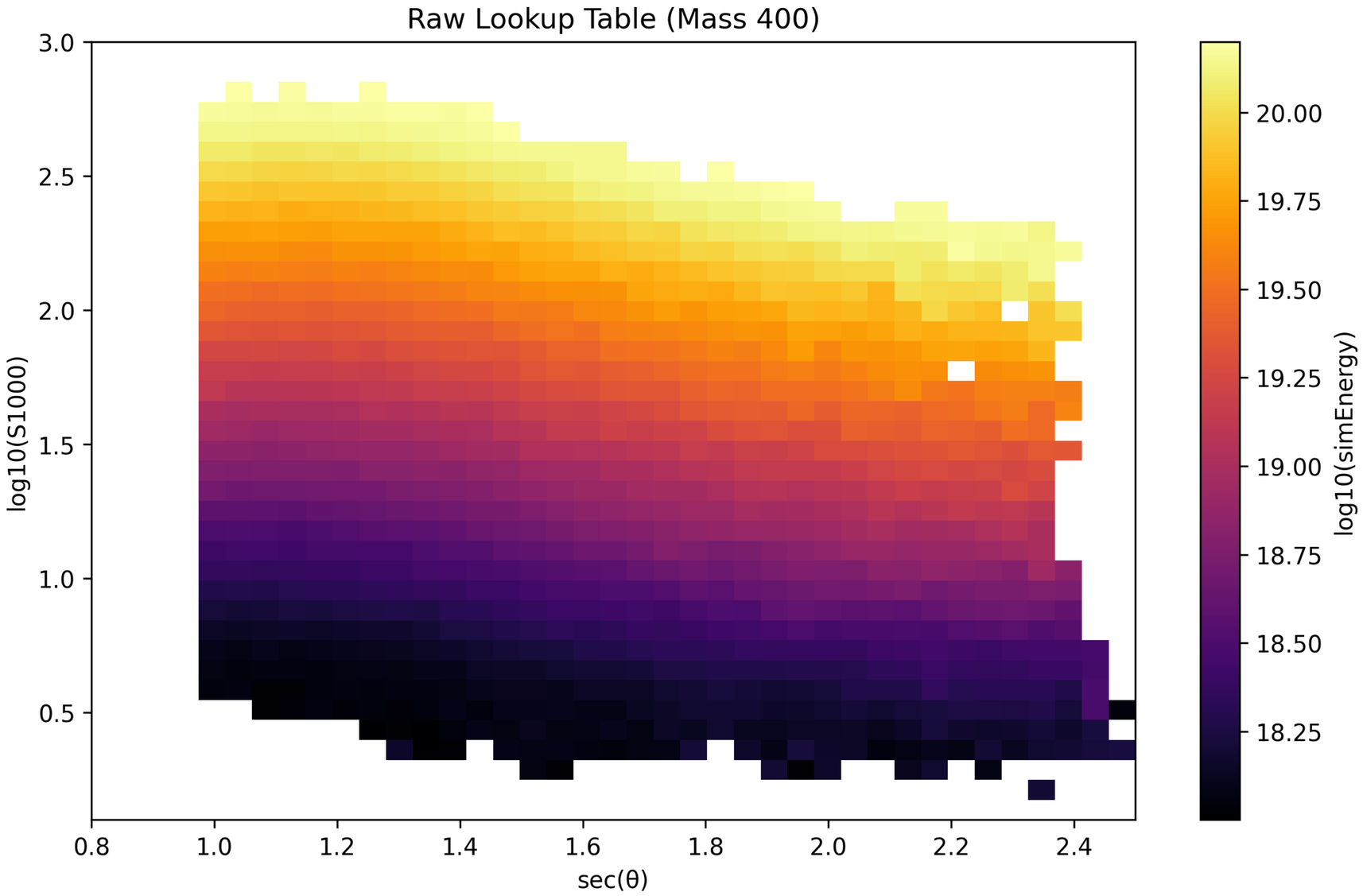




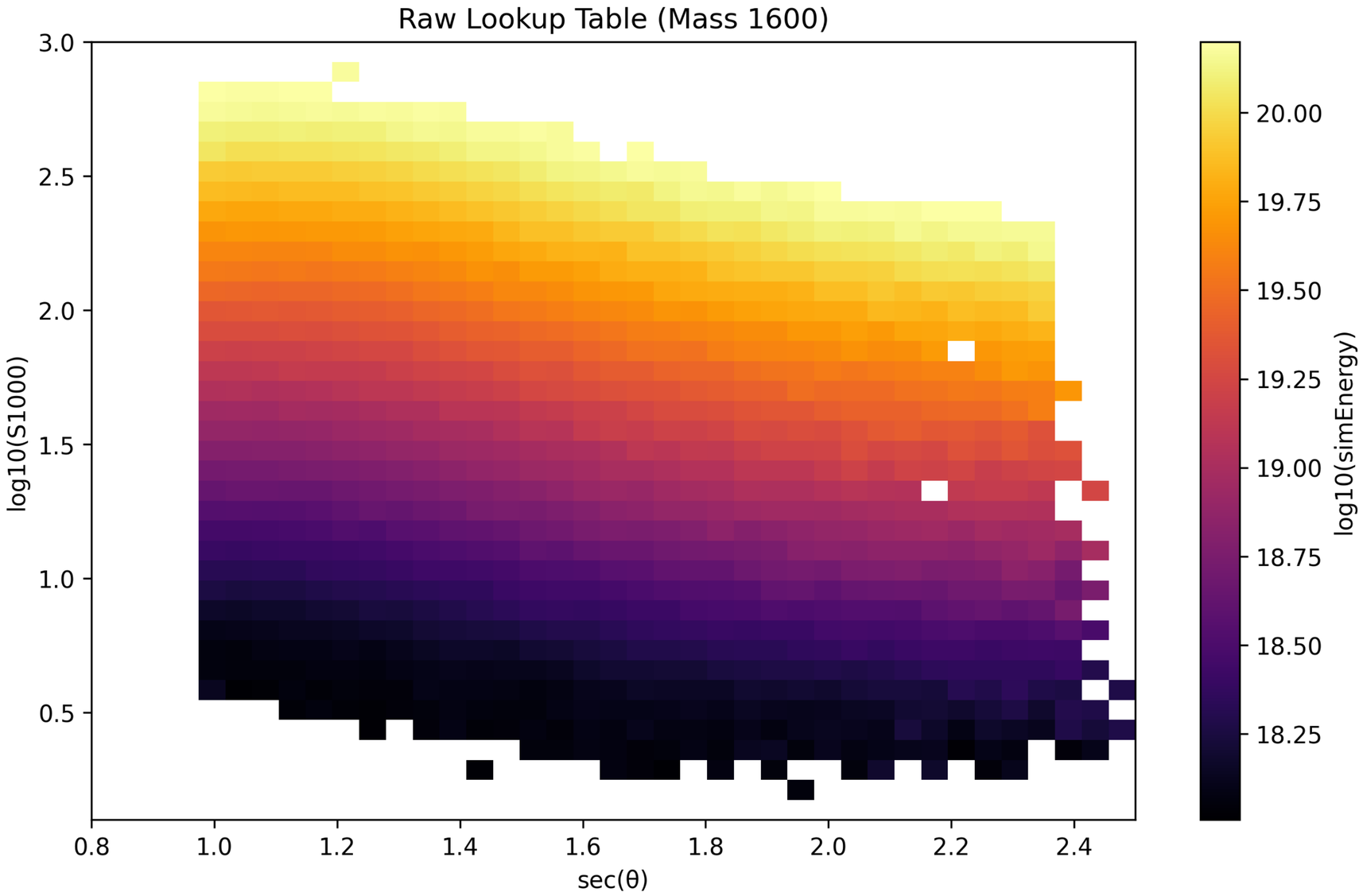
Raw Lookup table - Proton



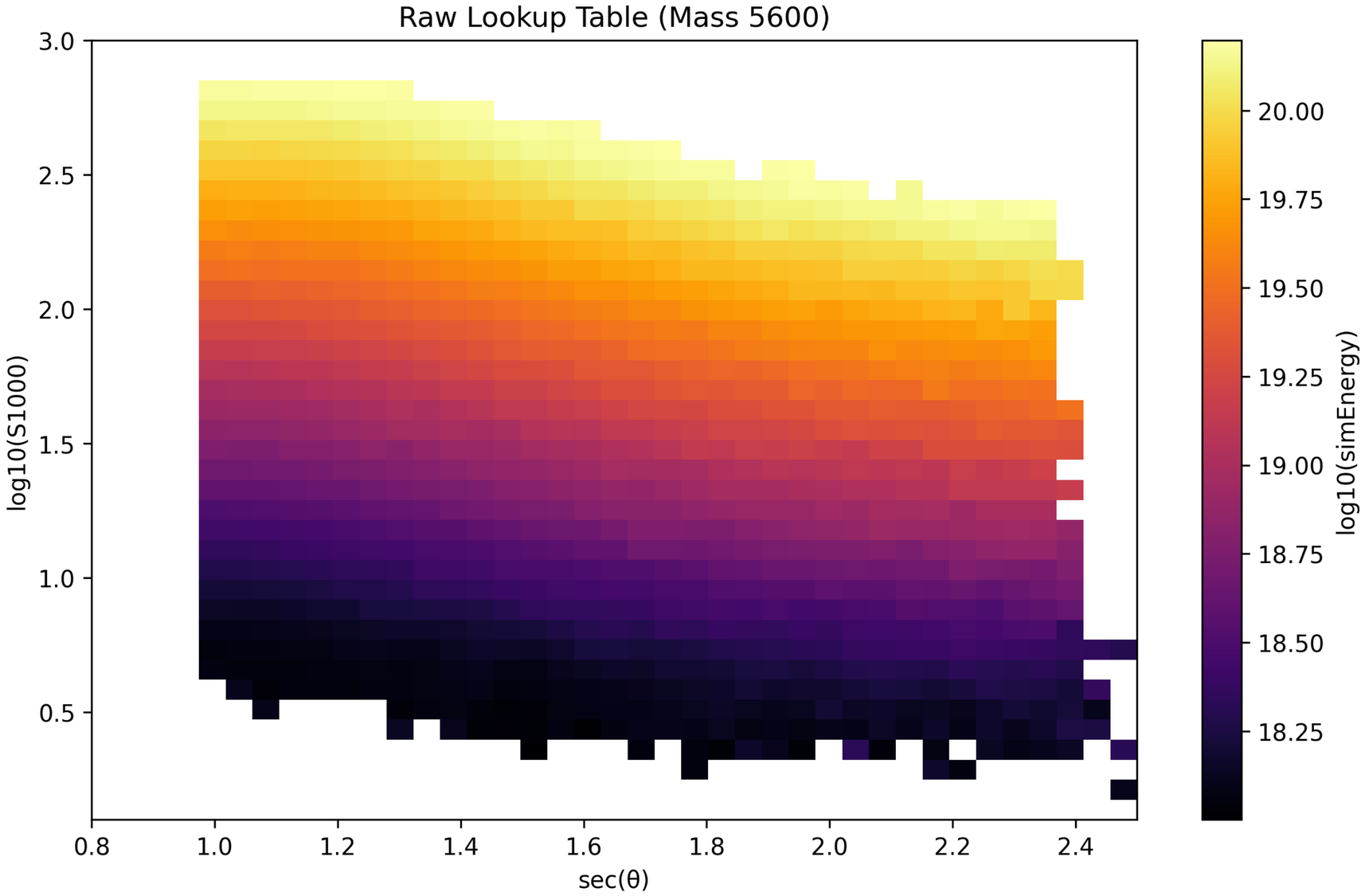
Raw Lookup table - Helium



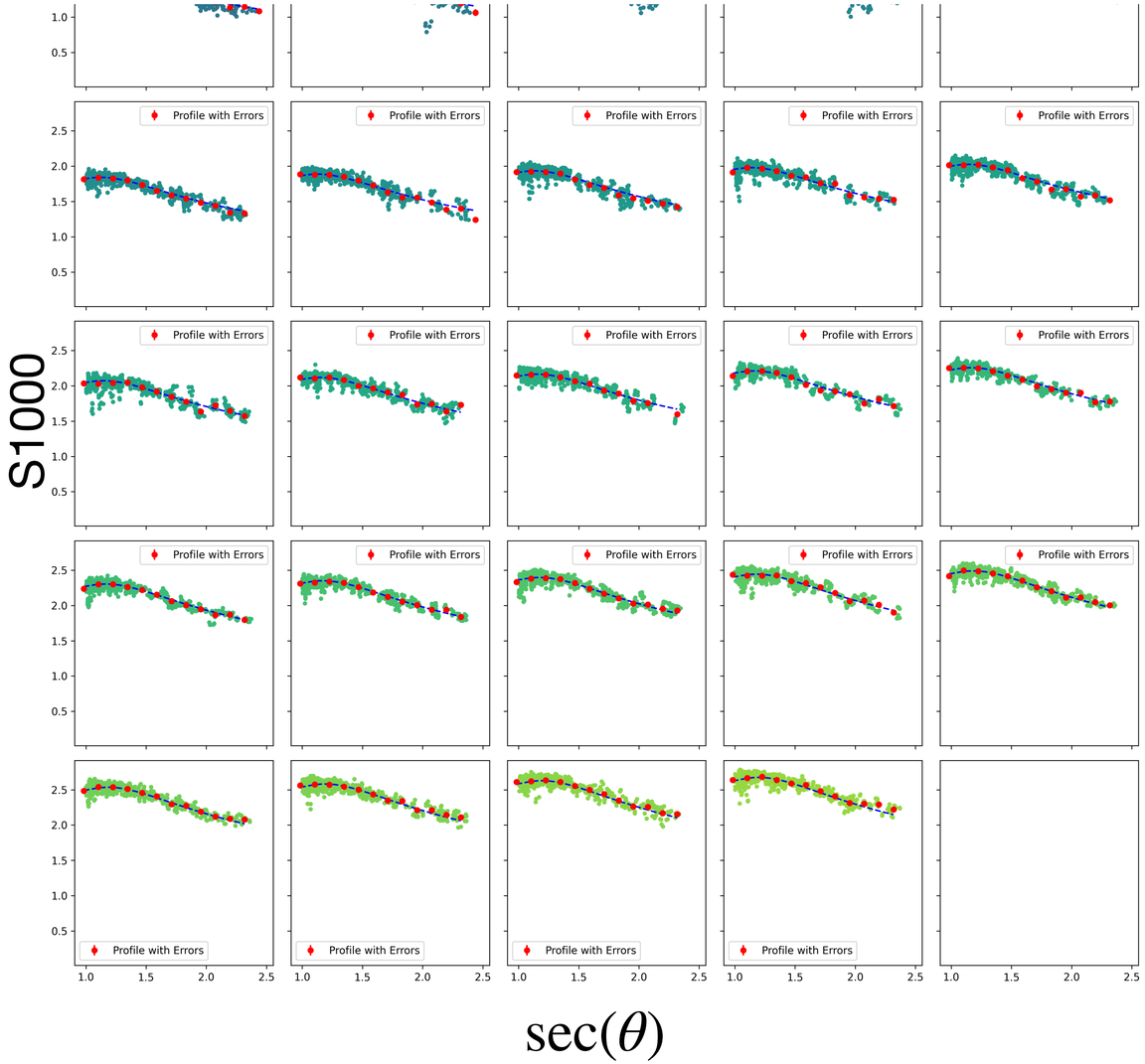
Raw Lookup table - Oxygen



Raw Lookup table - Iron



Fitting energy bins



We **parameterize relationship** between the shower size S1000 and the estimated primary energy E(SD) as a function of the zenith angle.

This is done via a **bin-by-bin fitting** over discrete energy intervals

Energy Binning and Fitting Approach

The dataset is divided into bins of width **0.1 in** log10(E).

Within each energy bin, we fit the variation of S1000 with the secant of the zenith angle

Functional Form

For each energy bin, the dependence on the zenith angle is modeled as:

$$S_{1000}(\theta, E) = a(E) + b(E) \cdot x + c(E) \cdot x^2 + d(E) \cdot x^3$$

with: $x = 1/\sec^2(\theta)$

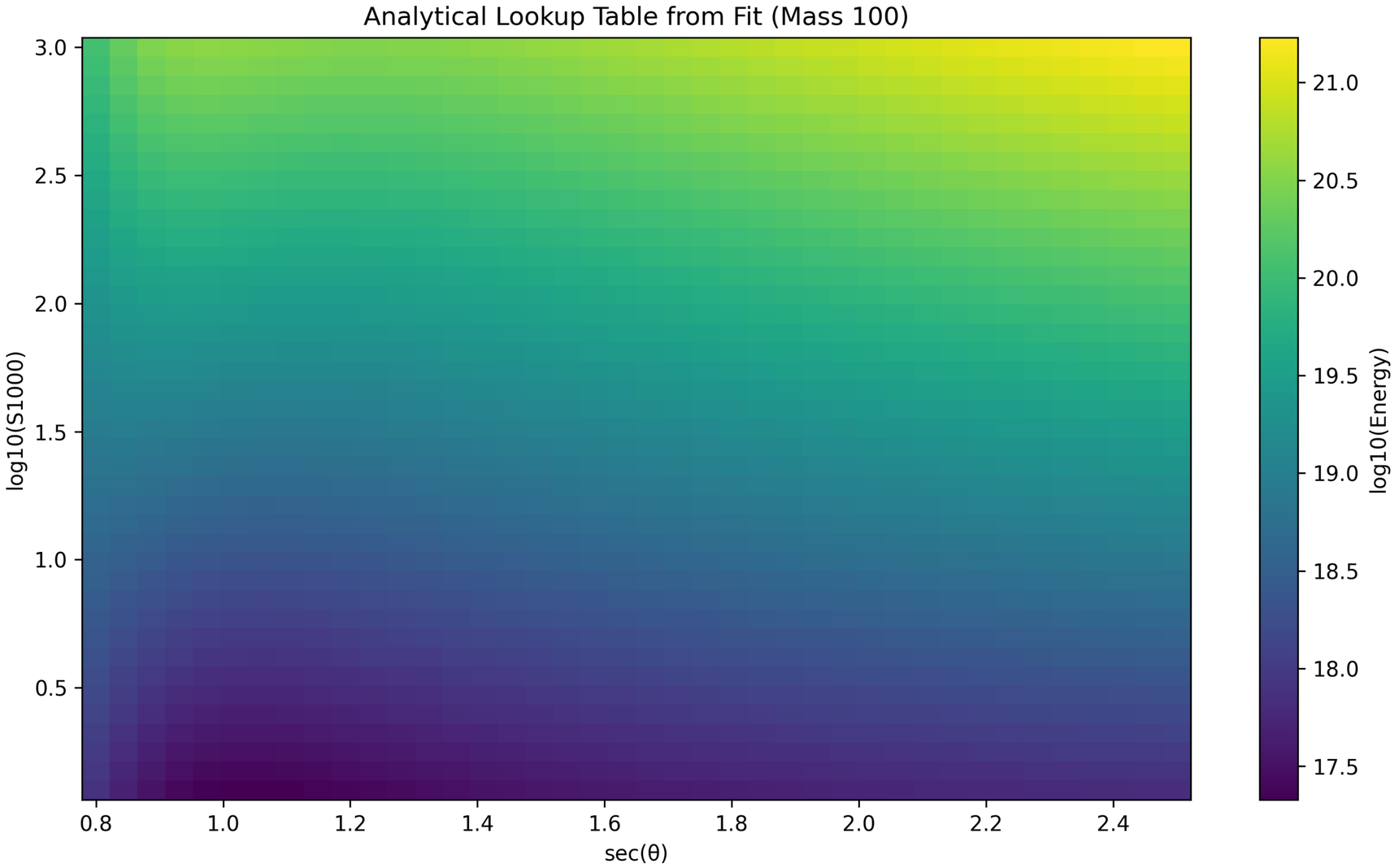
This function ensures smooth corrections based on the shower angle

Parameterization of Energy Dependence

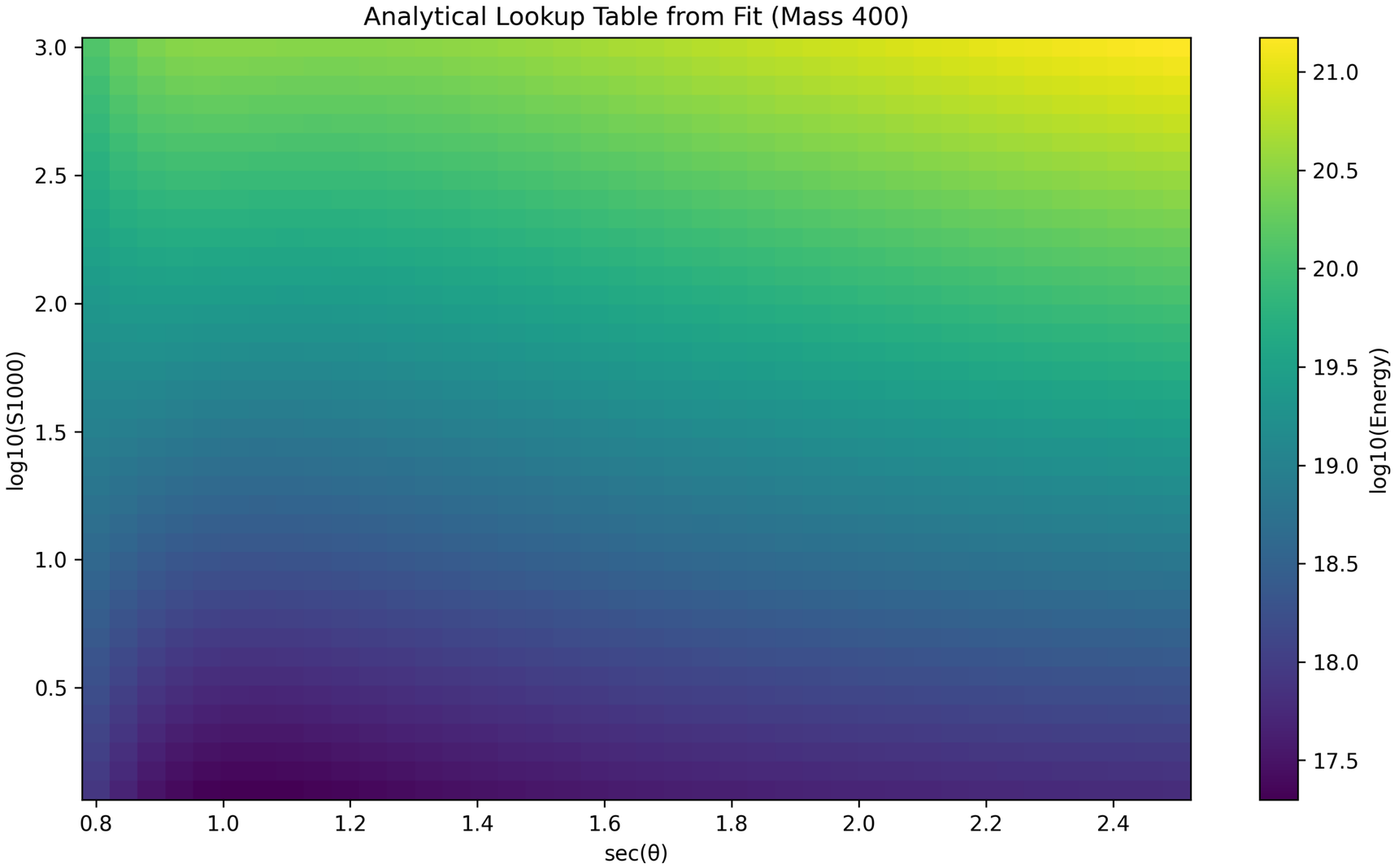
The parameters a, b, c, d are fitted in each $\log_{10}(E)$ bin assuming a linear **dependence**

$$\text{par(E)} = \text{par}_0 + \text{par}_1 \log_{10}(E)$$

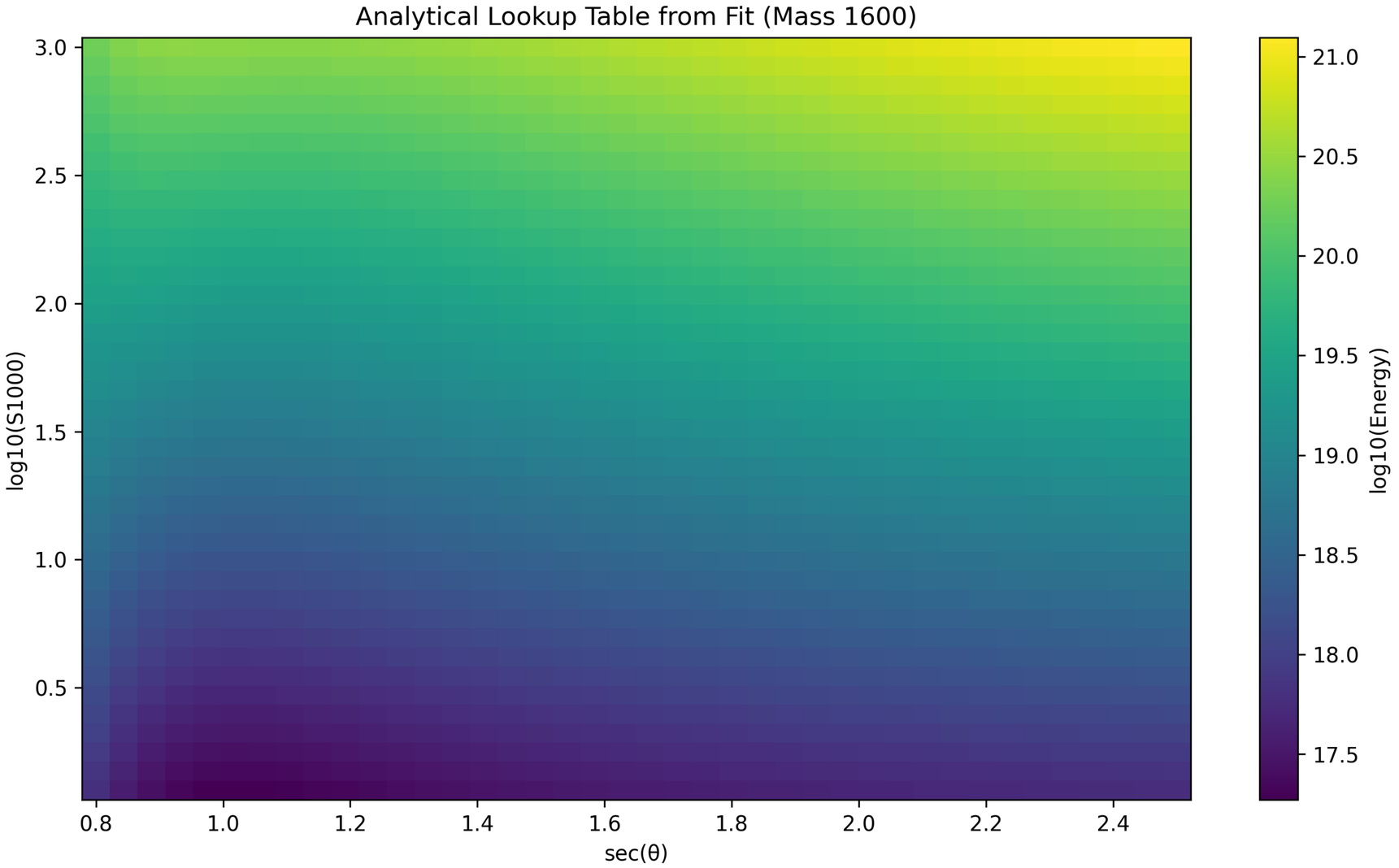
Analytical Lookup table - Proton



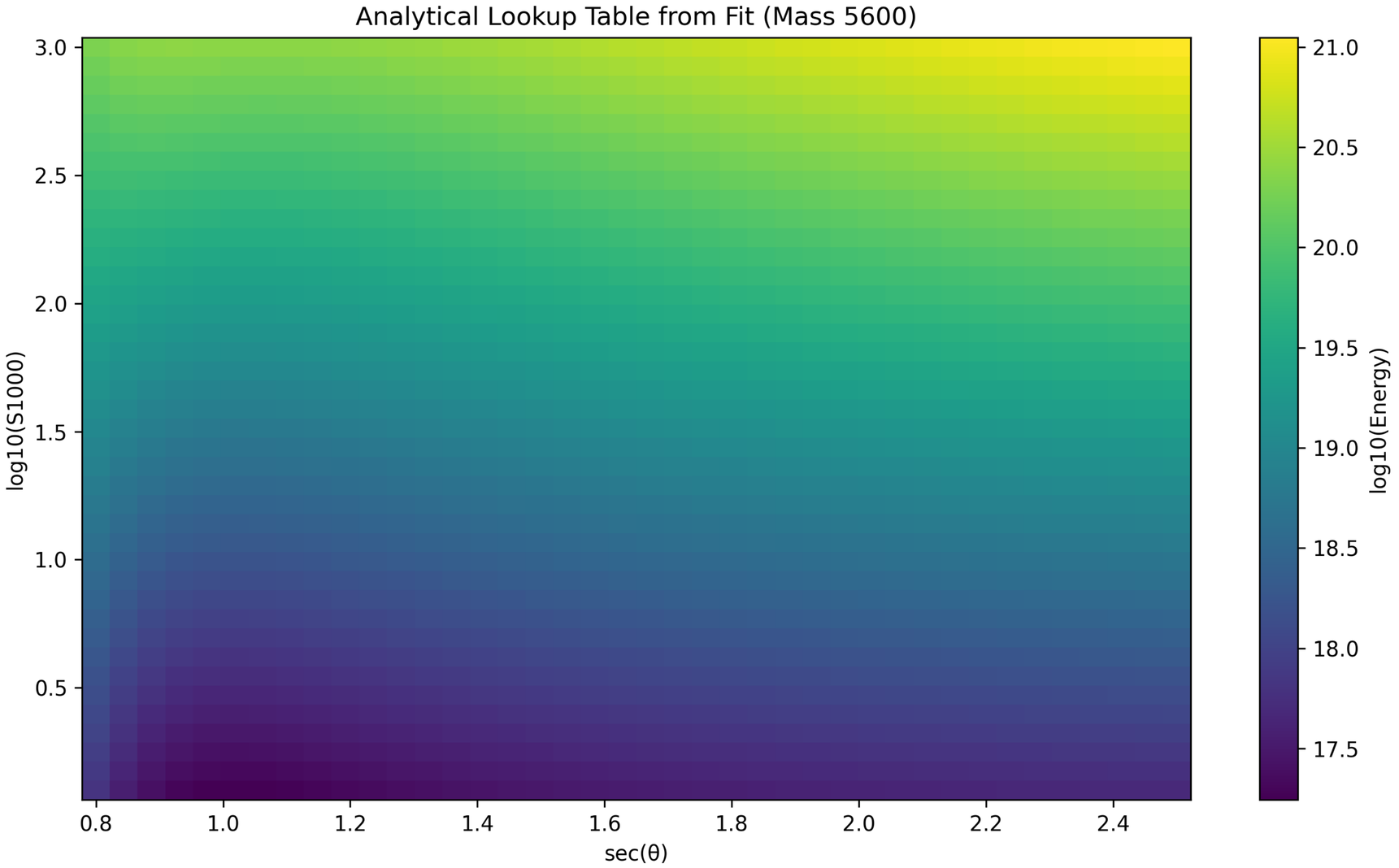
Analytical Lookup table - Helium



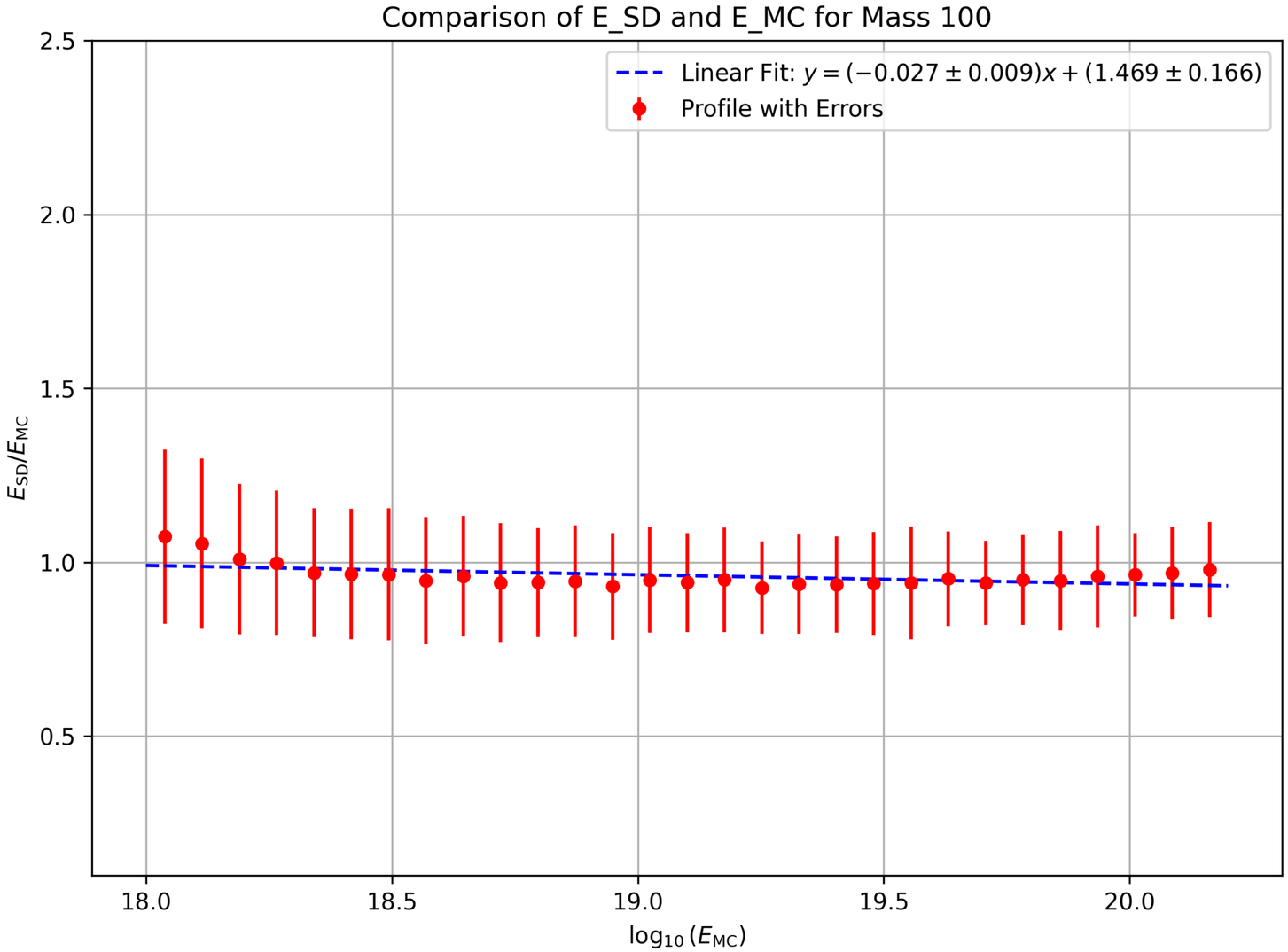
Analytical Lookup table - Oxygen



Analytical Lookup table - Iron



Comparison with MC energy



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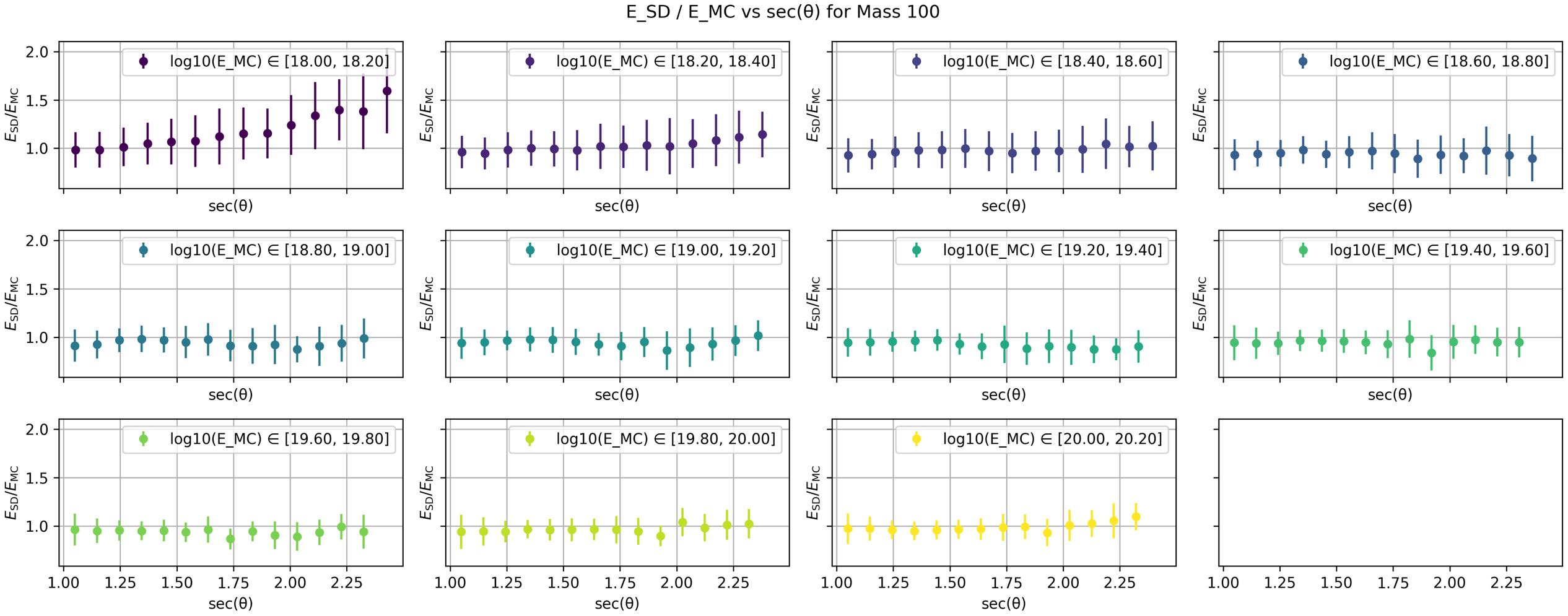

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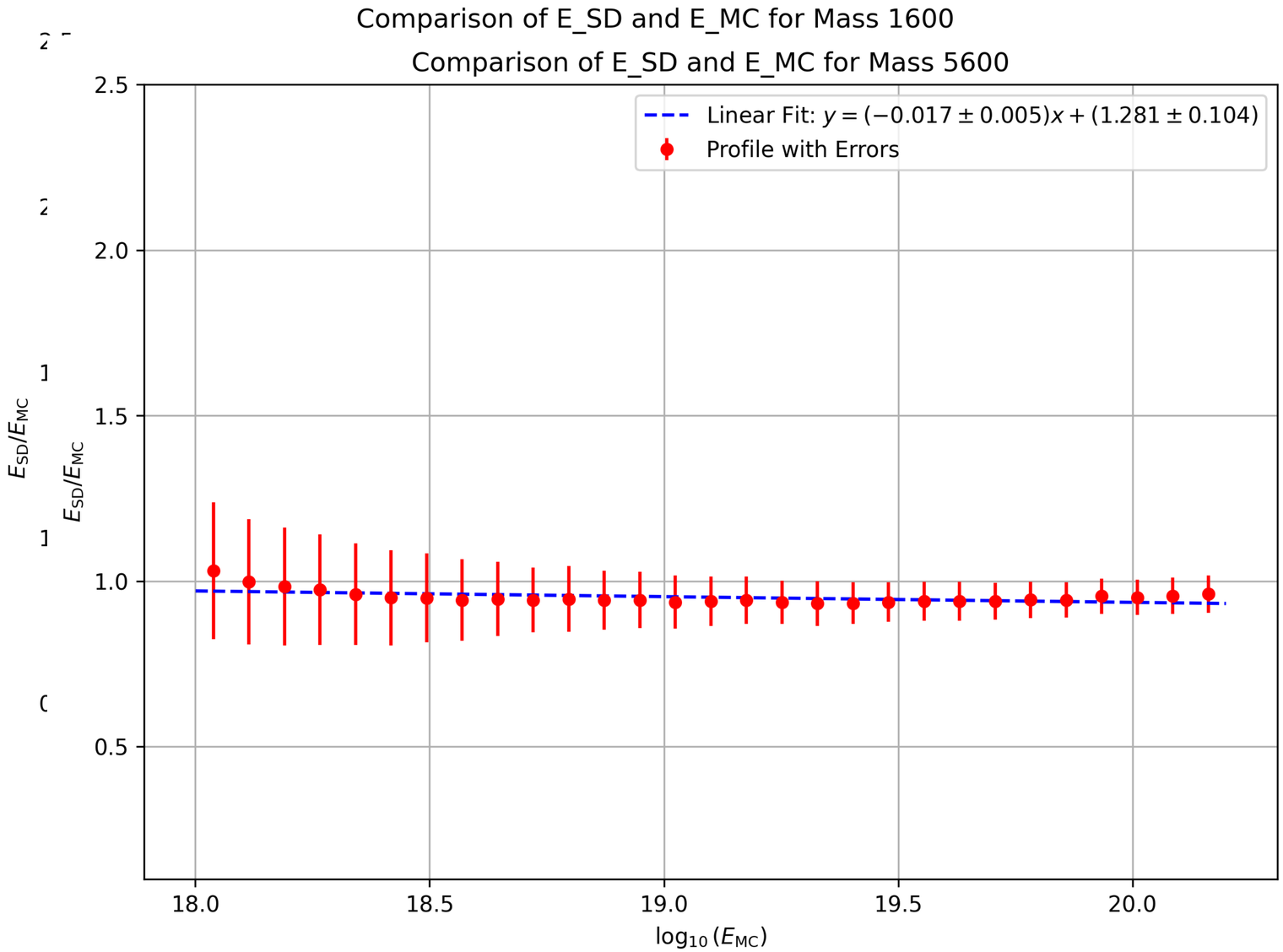

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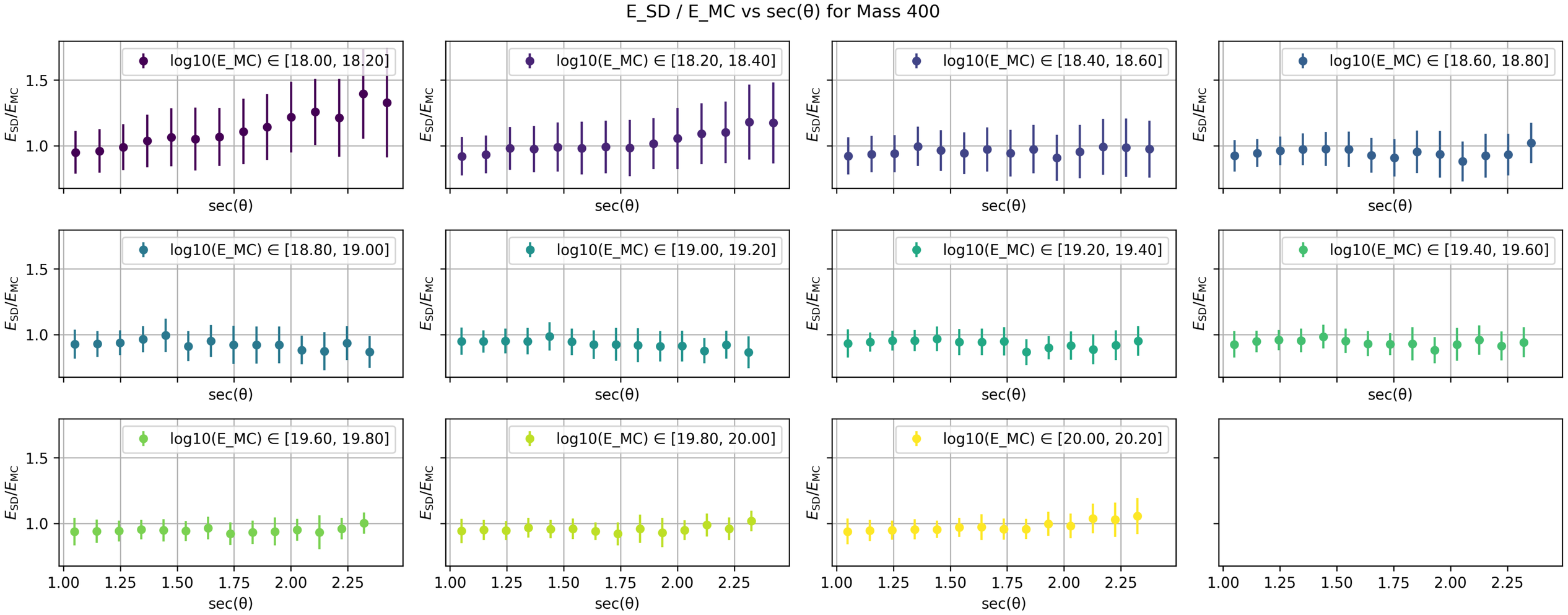

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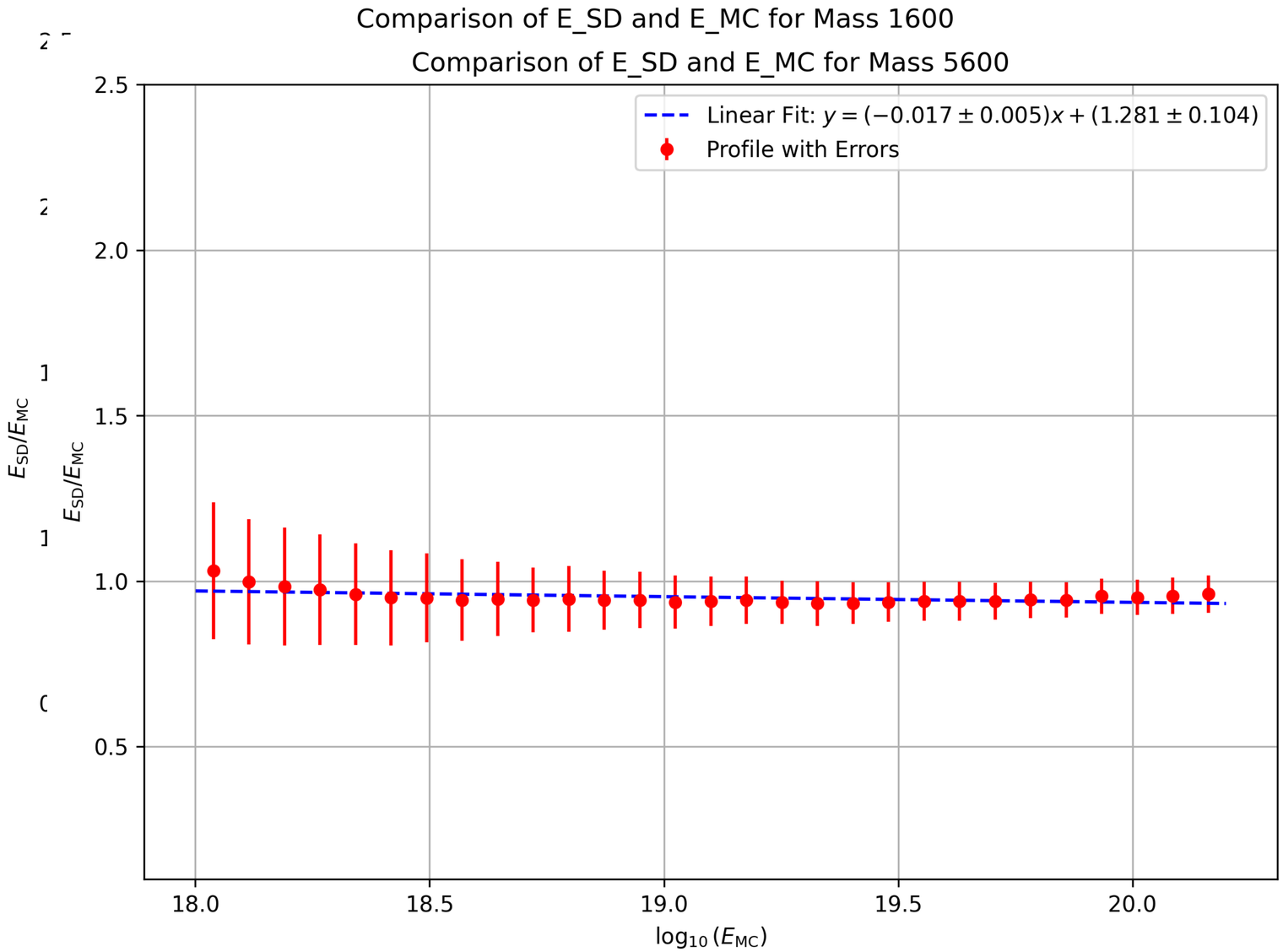

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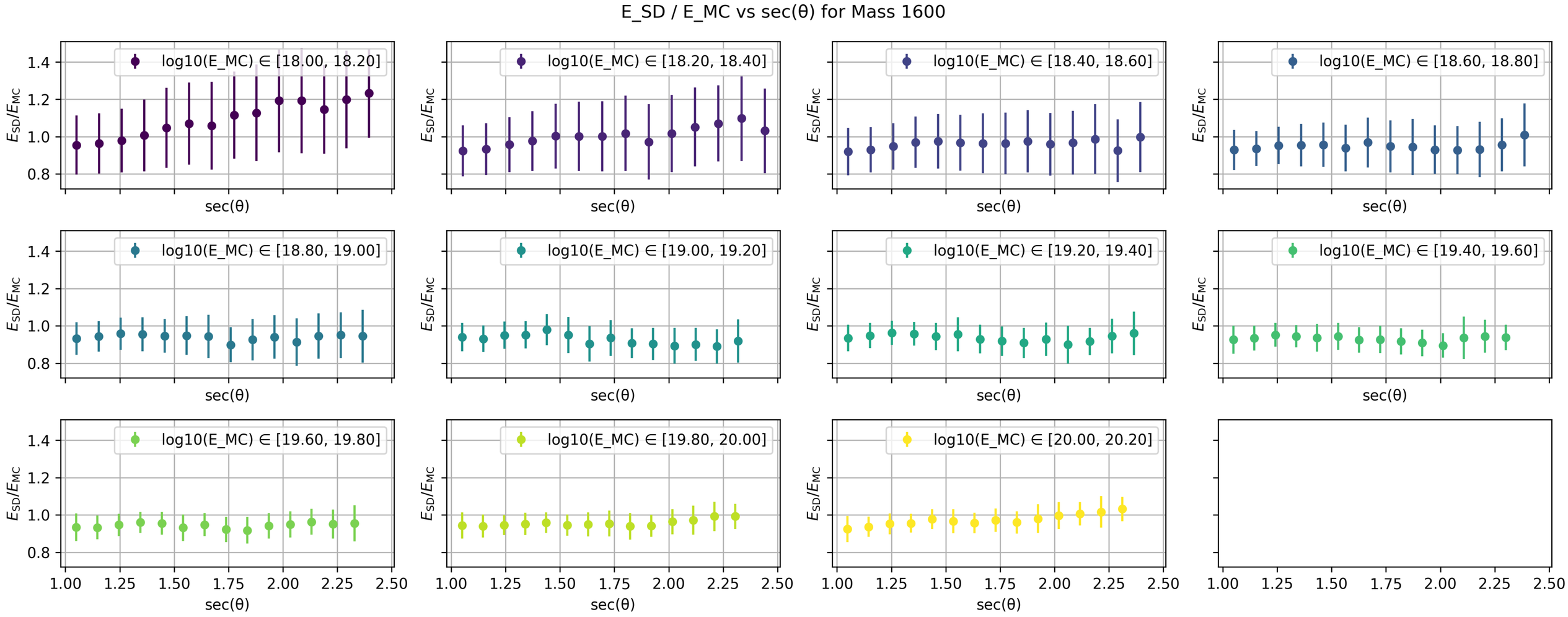

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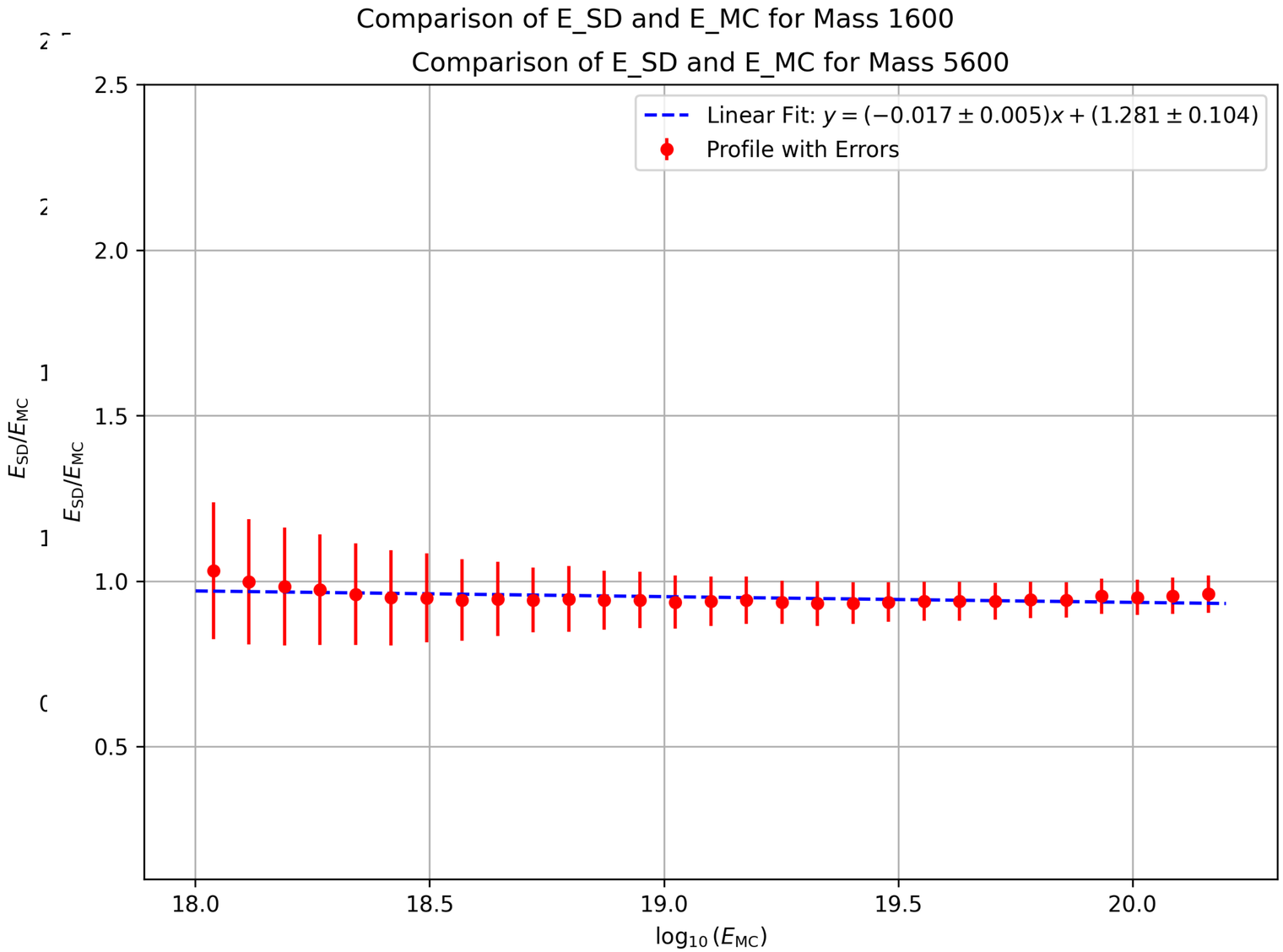

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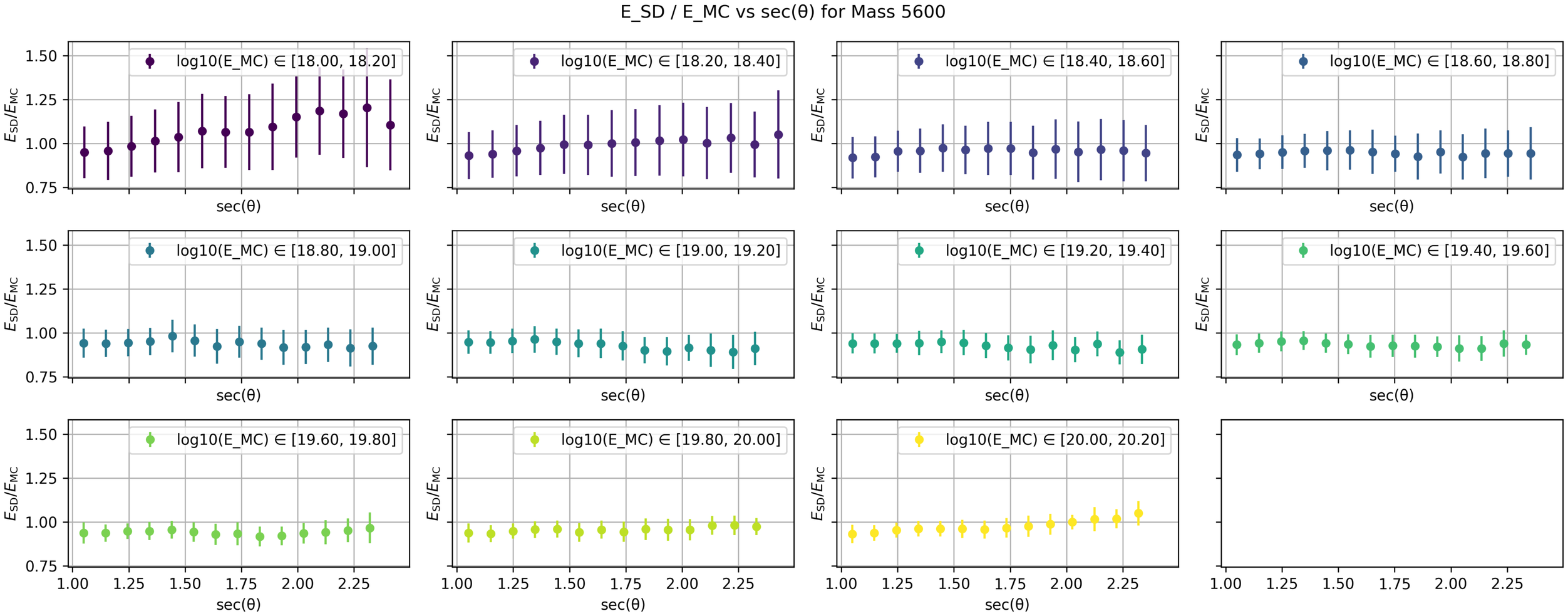
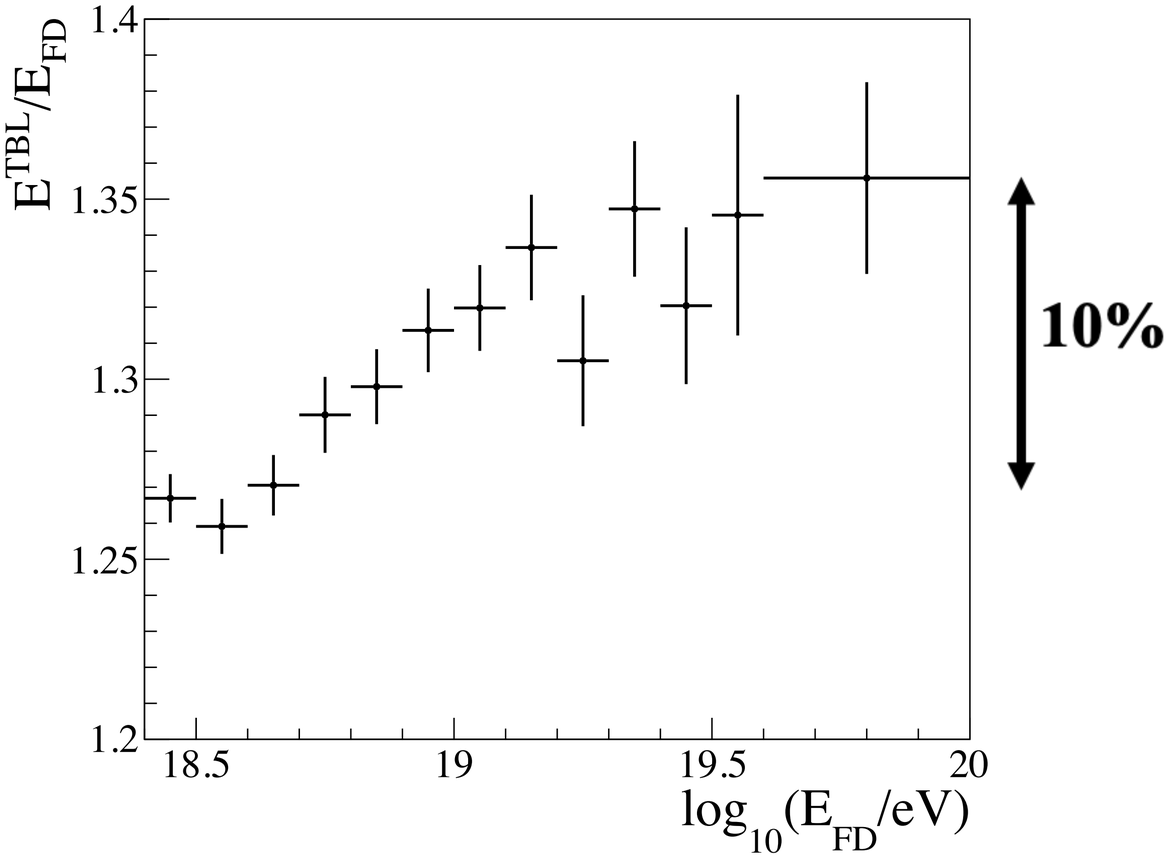
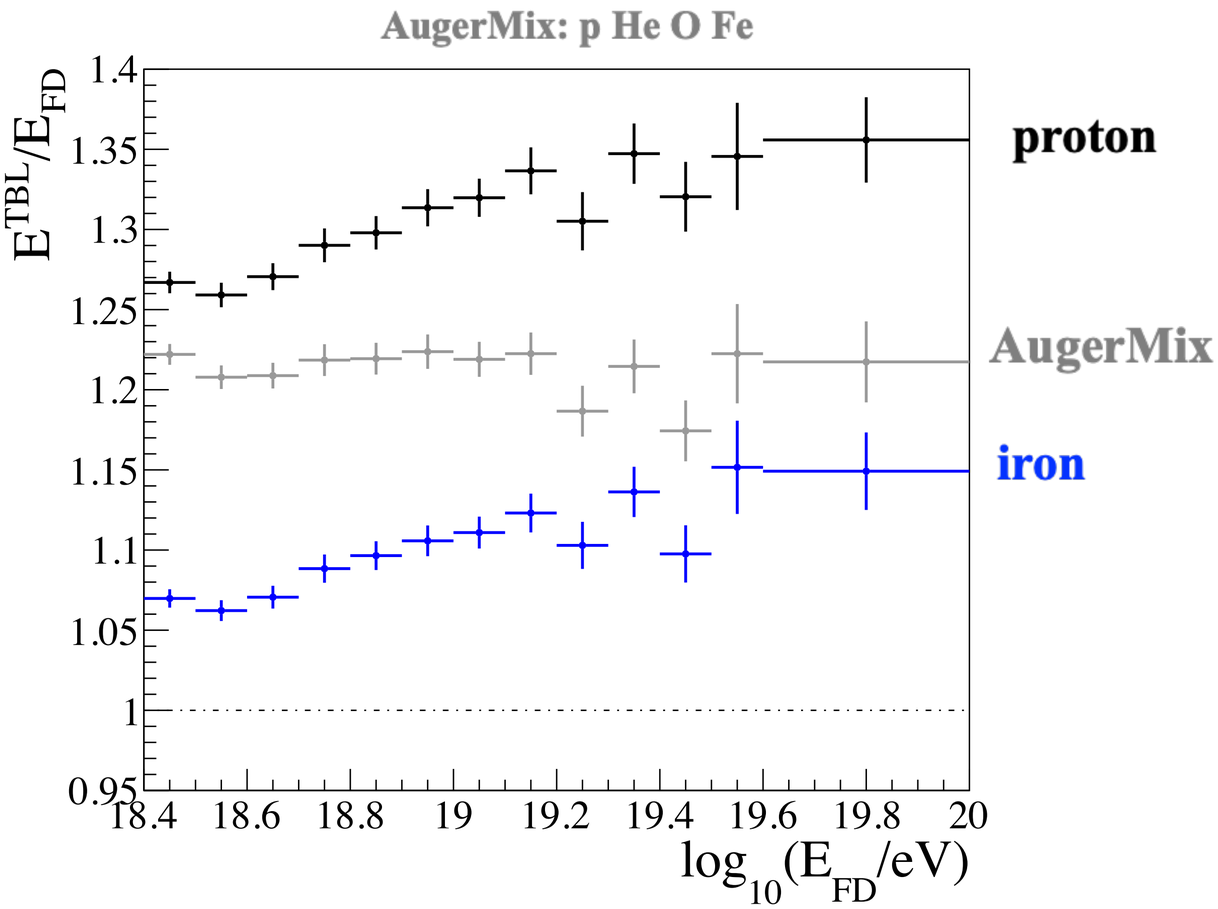


E_{TBL} vs E_{FD} – data

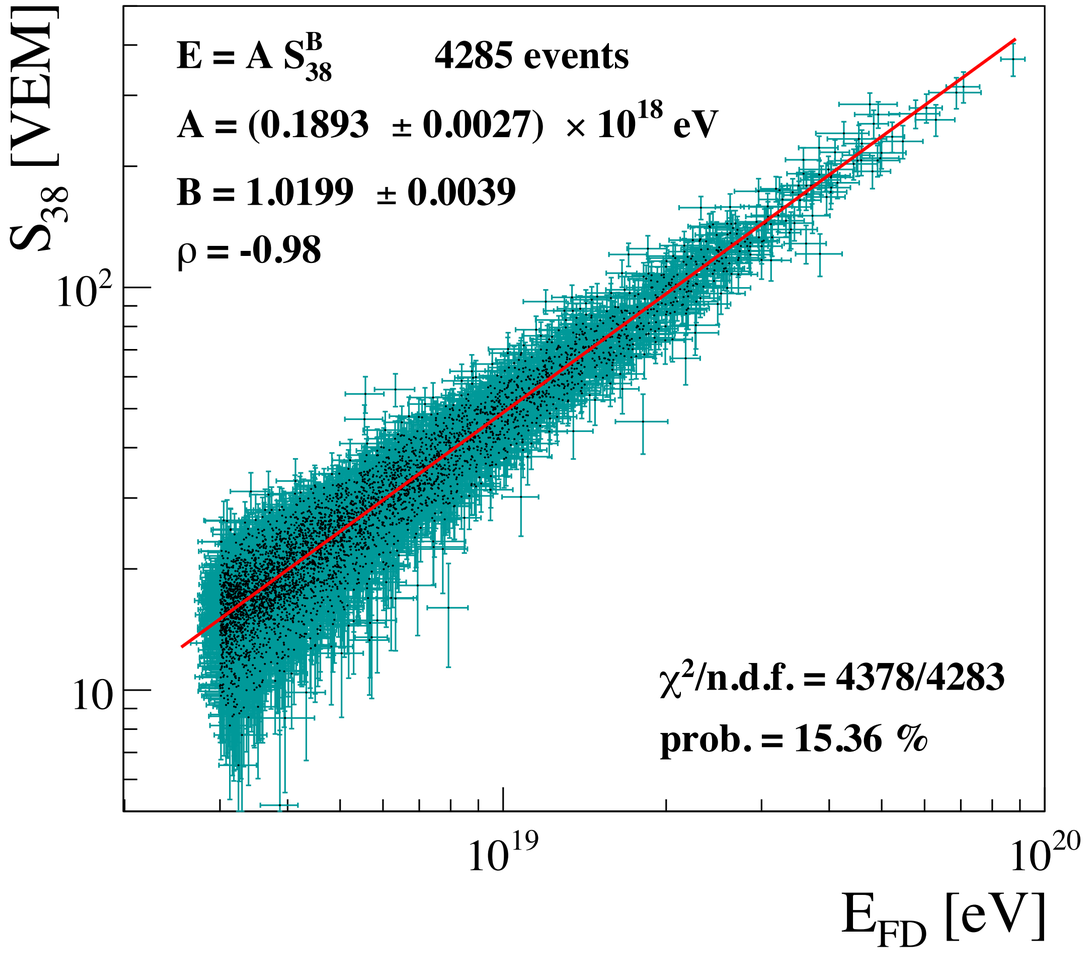




- offset from 10% (Fe) to 30% (p)
- 10% energy dependent shift with a single primary
- constant energy shift with AugerMix !

Energy calibration

reference data production: ICRC 2023



Calibration of E^{TBL}

$$E = A\left(\frac{E^{TBL}}{f}\right)^{B}$$

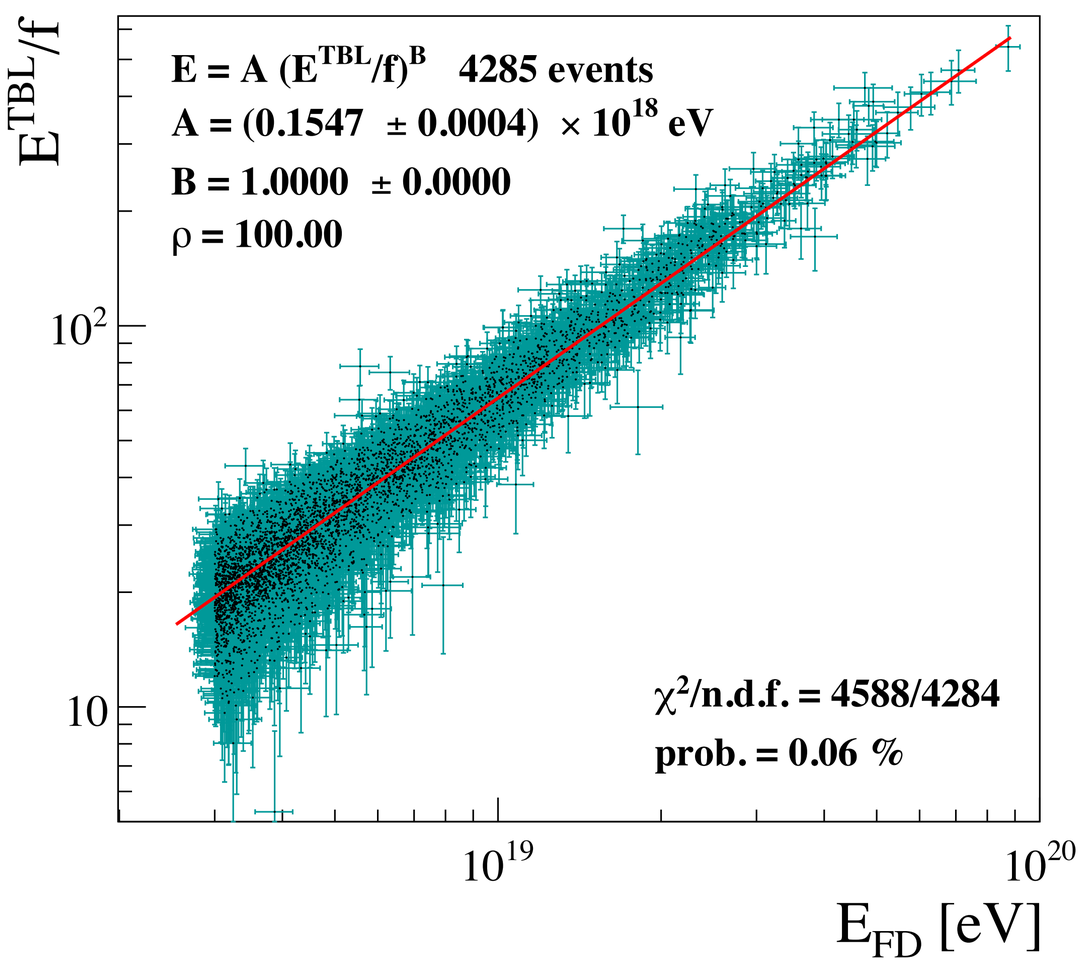
$$f = 0{,}2 \times 10^{18}\ eV$$

A and B: fit parameters

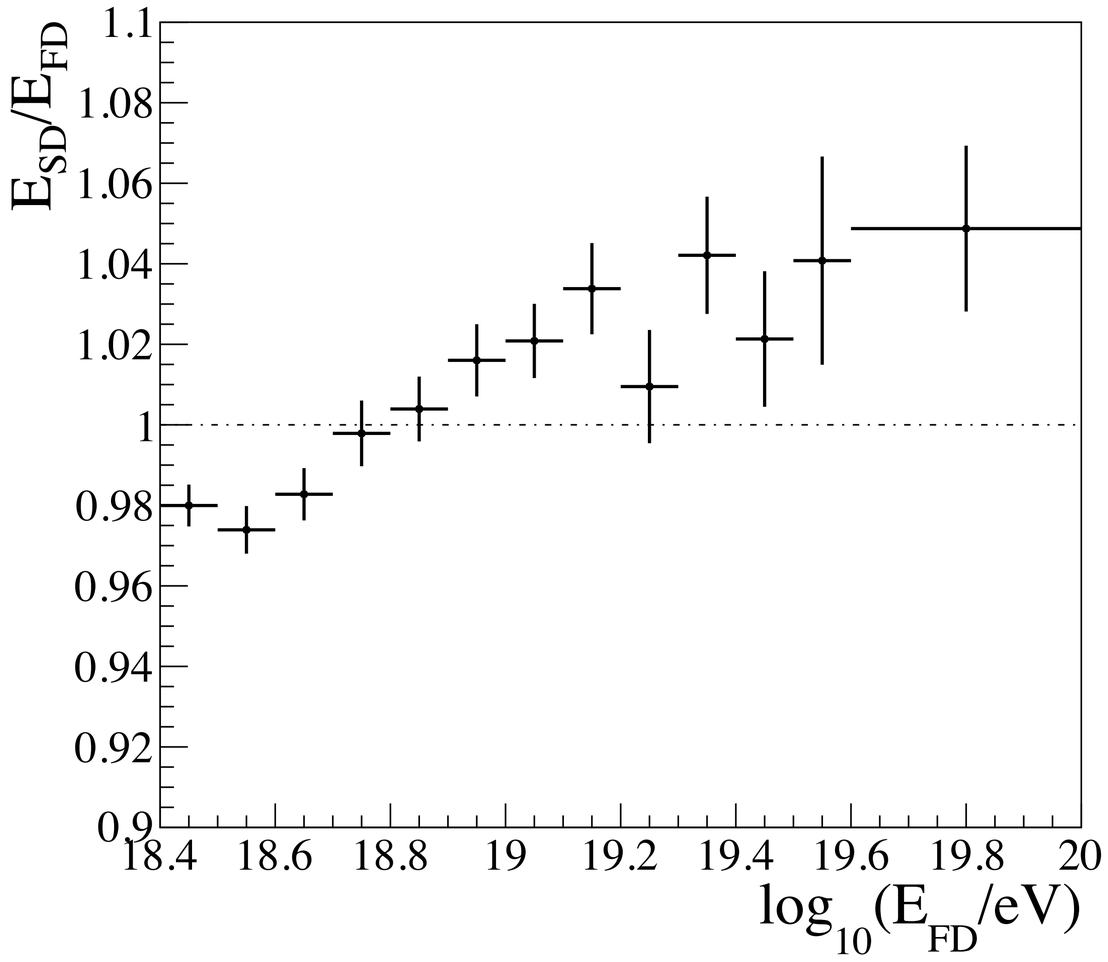
sh-to-sh fixed to 12.6%

Energy calibration

lookup table: proton

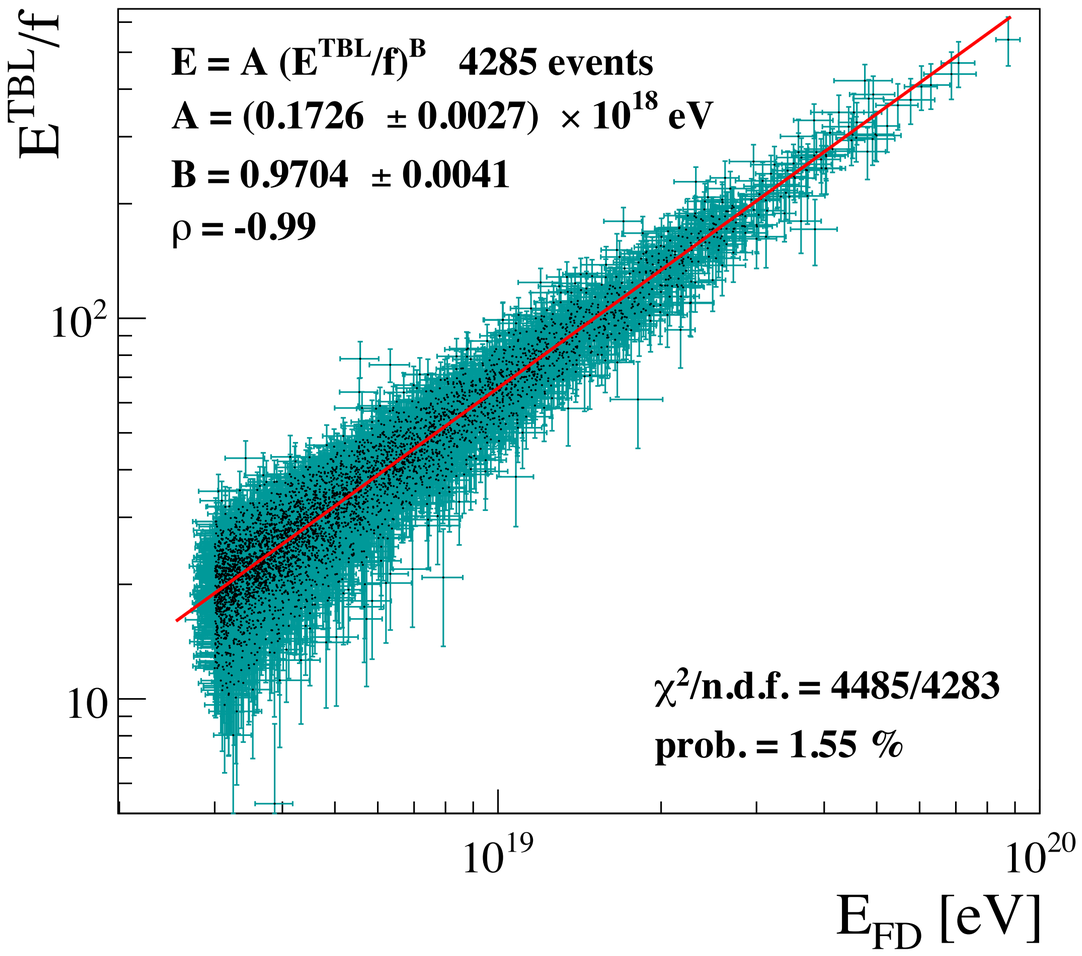


B fixed to 1 (like TA)

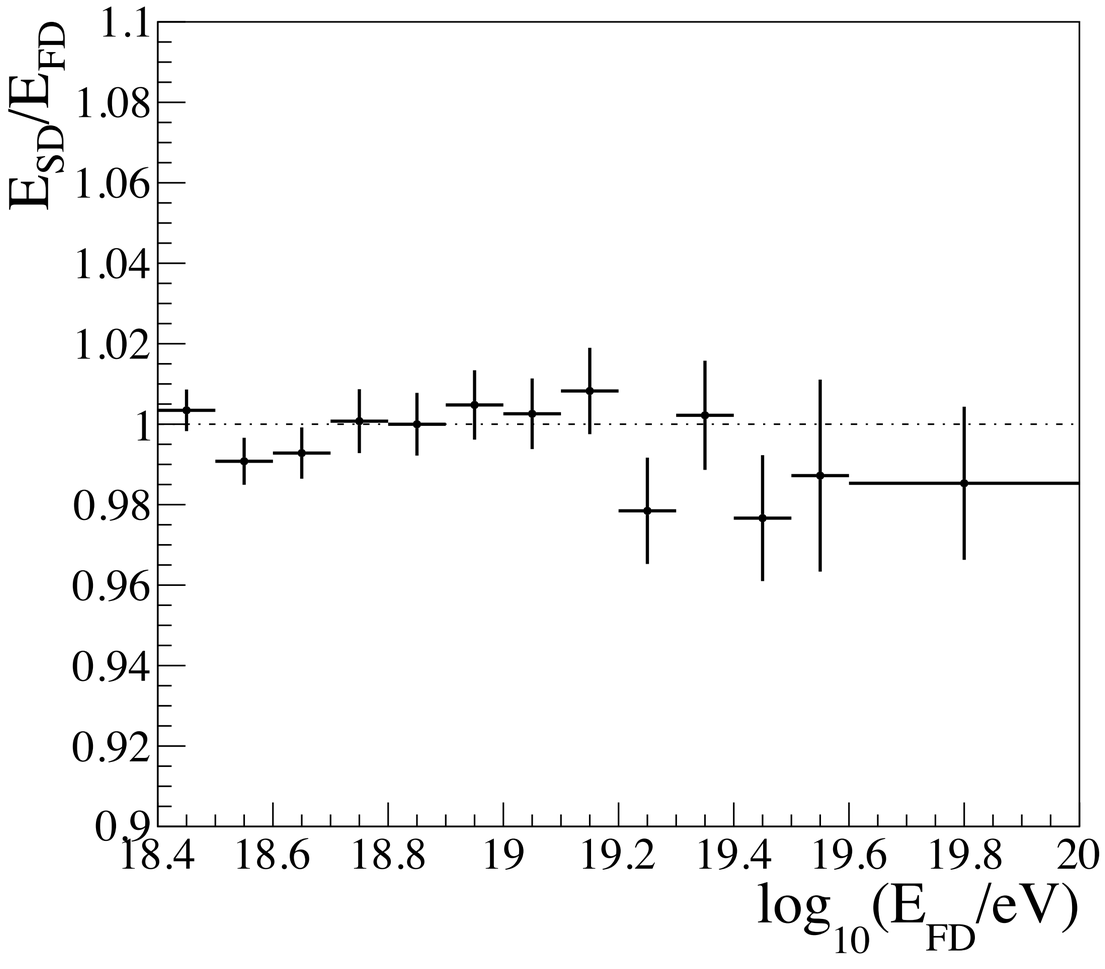


Energy calibration

lookup table: proton

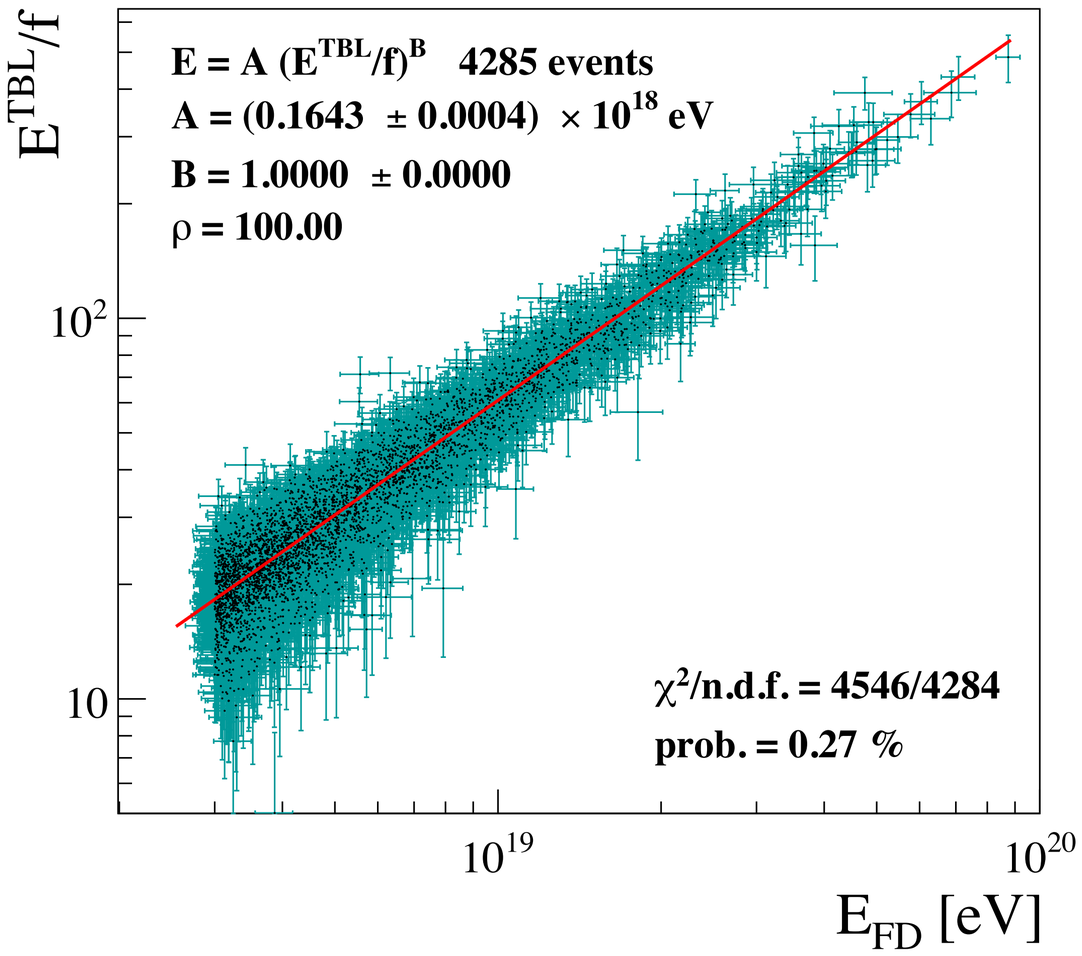


B fitted



Energy calibration

lookup table: Auger Mix



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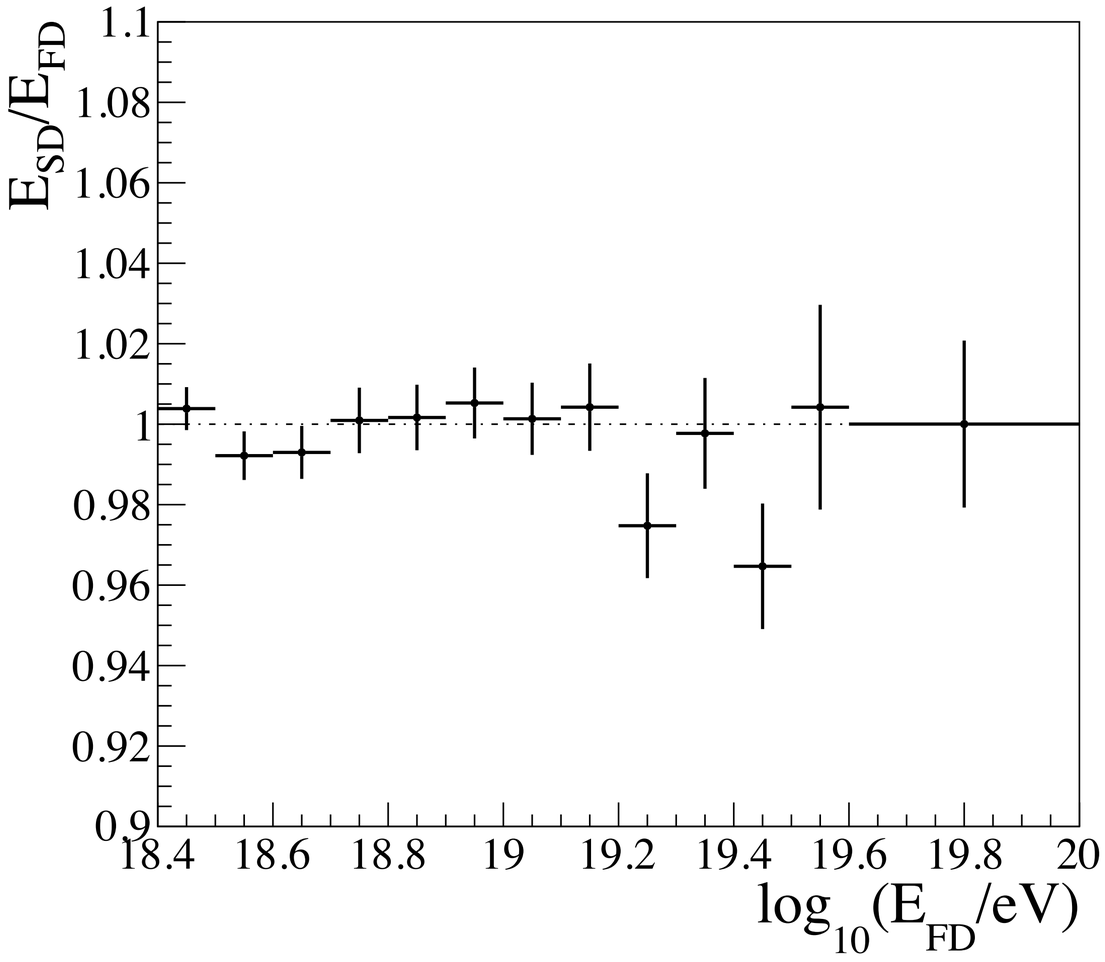


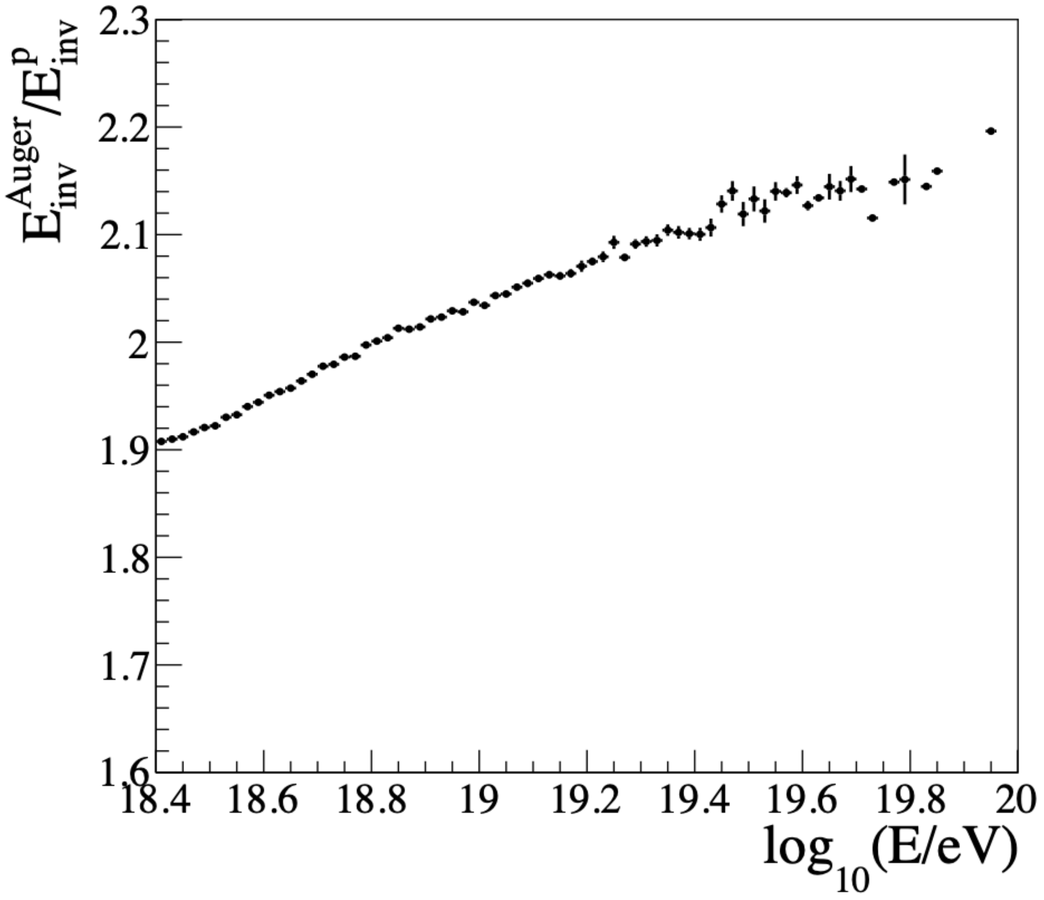
Conclusions

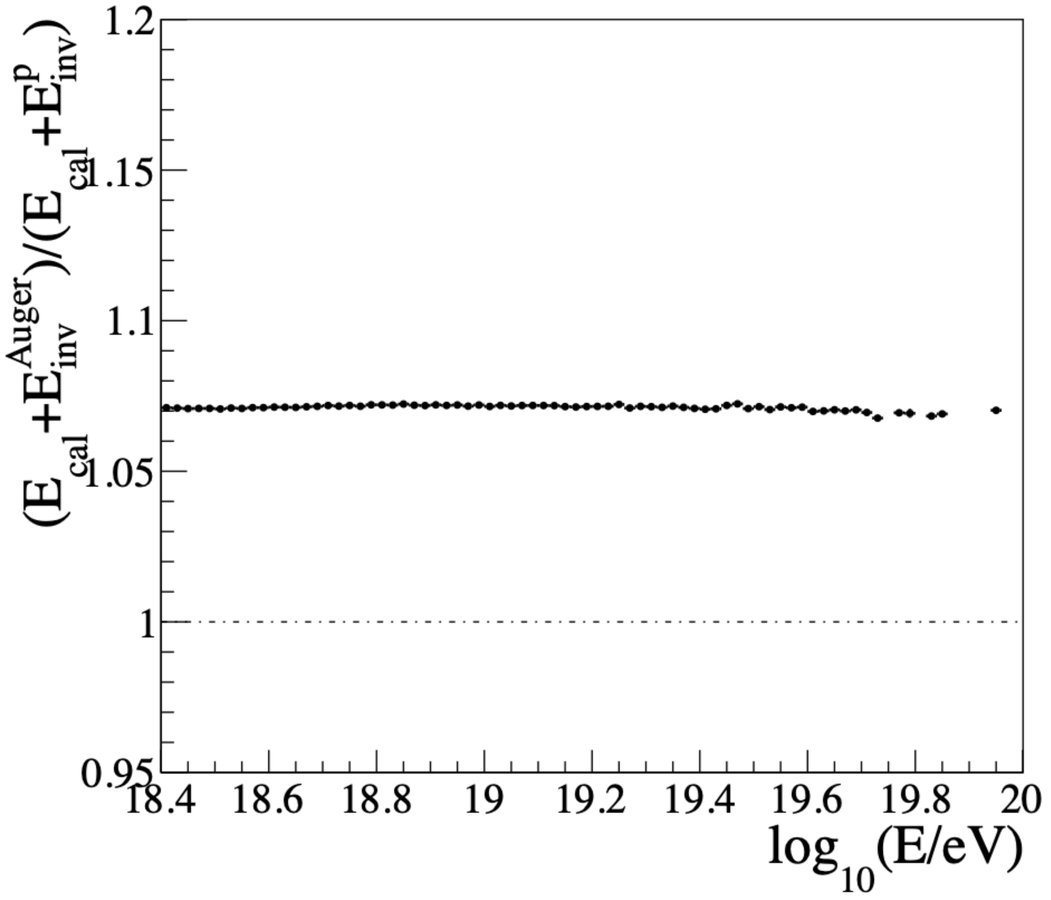
- The Lookup Table method introduces an energy-dependent drift when assuming a pure composition of protons or iron
- the drift aligns with the observed energy-dependent discrepancy between Auger and Telescope Array (TA) energy scales
- the E_{SD}/E_{FD} ratio remains flat when a mass composition trend is introduced with energy (AugerMix scenario)
- while the current dataset does not provide enough sensitivity to distinguish composition, it provides a strong indication that mass evolution plays a role in energy reconstruction and cannot be neglected
- this work will be presented at the Auger-TA Spectrum WG

Backup slides

backup slide

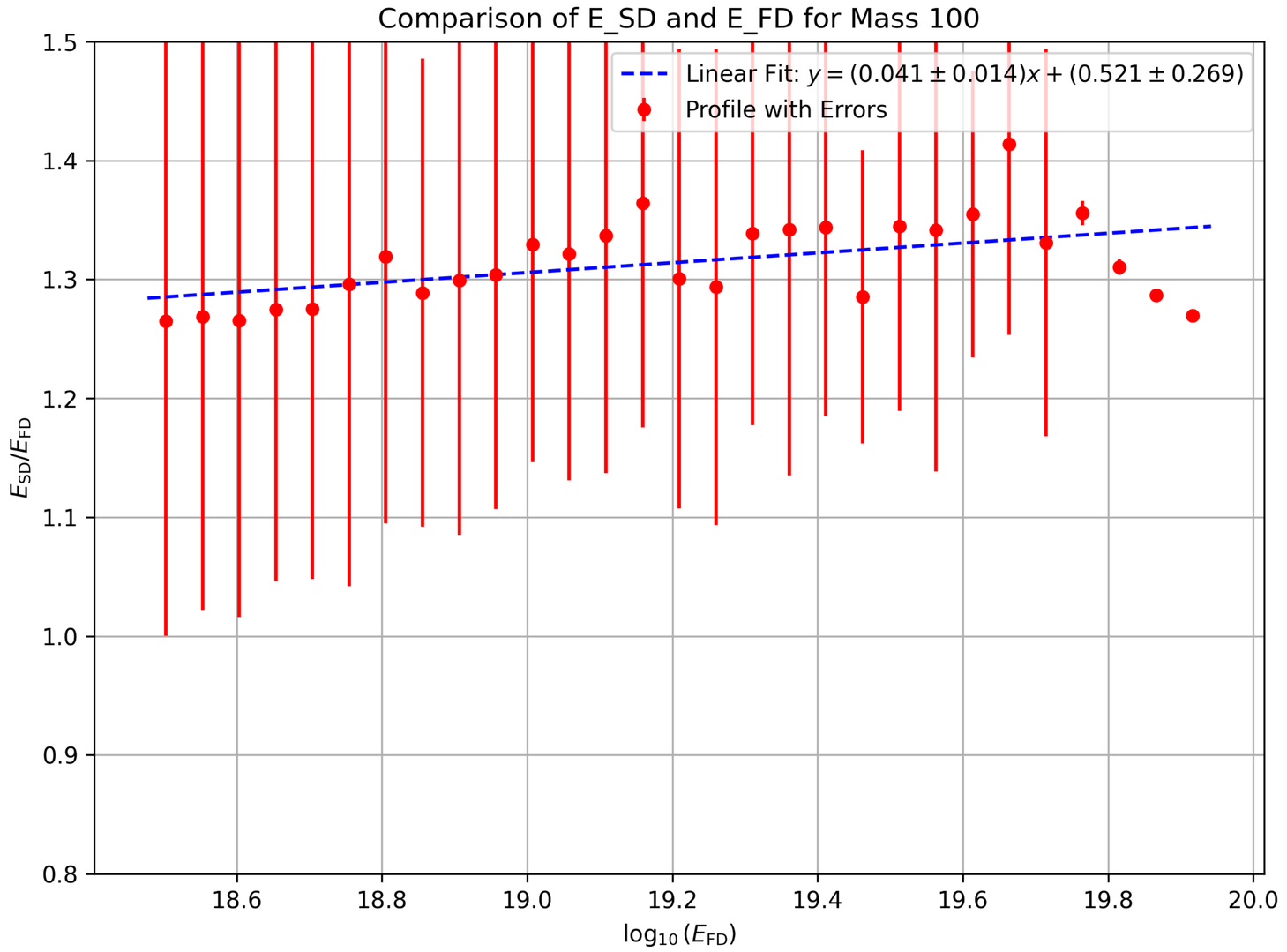
Invisible energy





- **E_{inv} from data (Auger) incorporates the energy dependence of the mass composition**
- **not significant effect at the level of total shower energy ($E_{inv}/E \sim 15\%$)**

Comparison with FD energy



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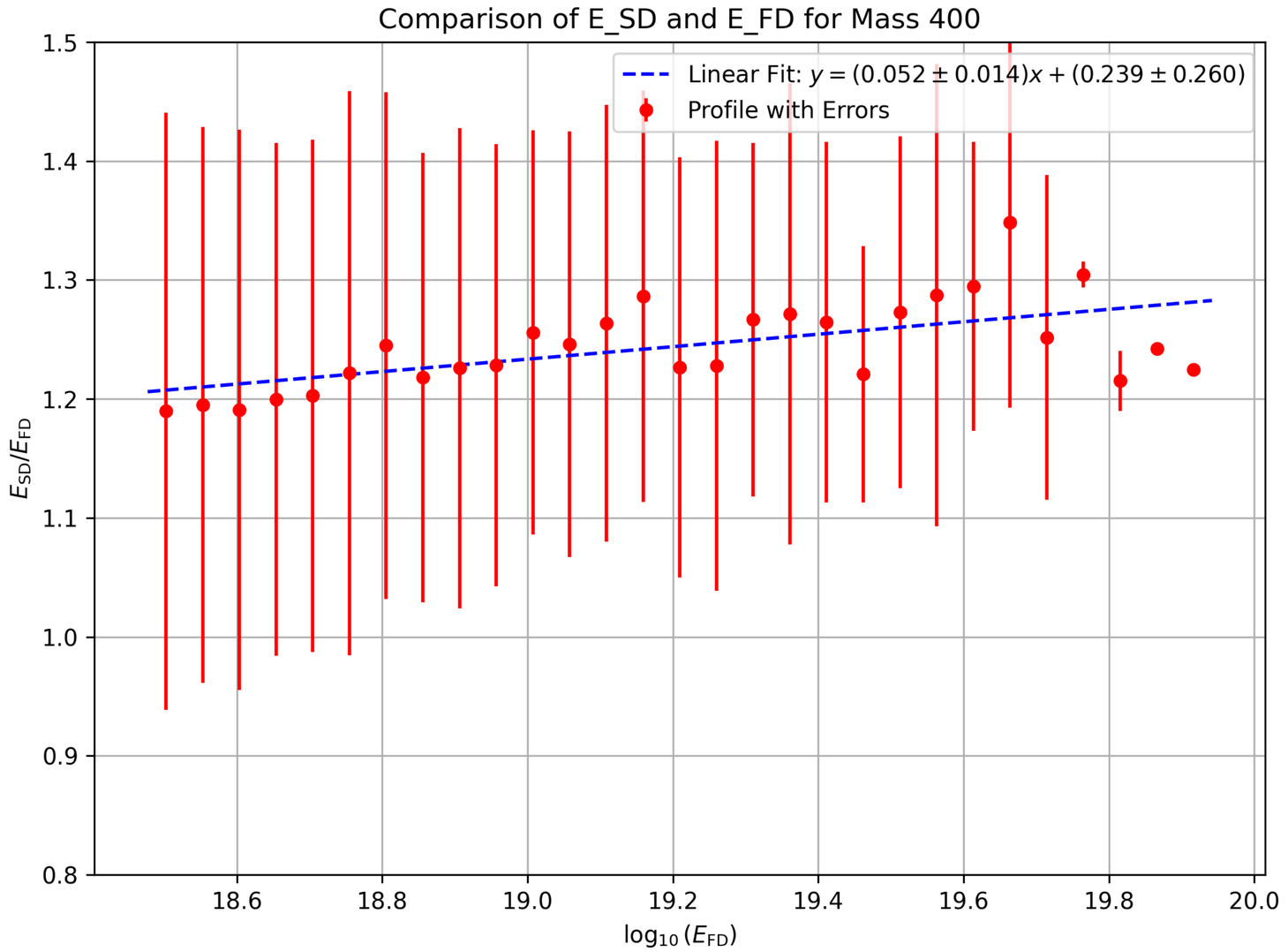
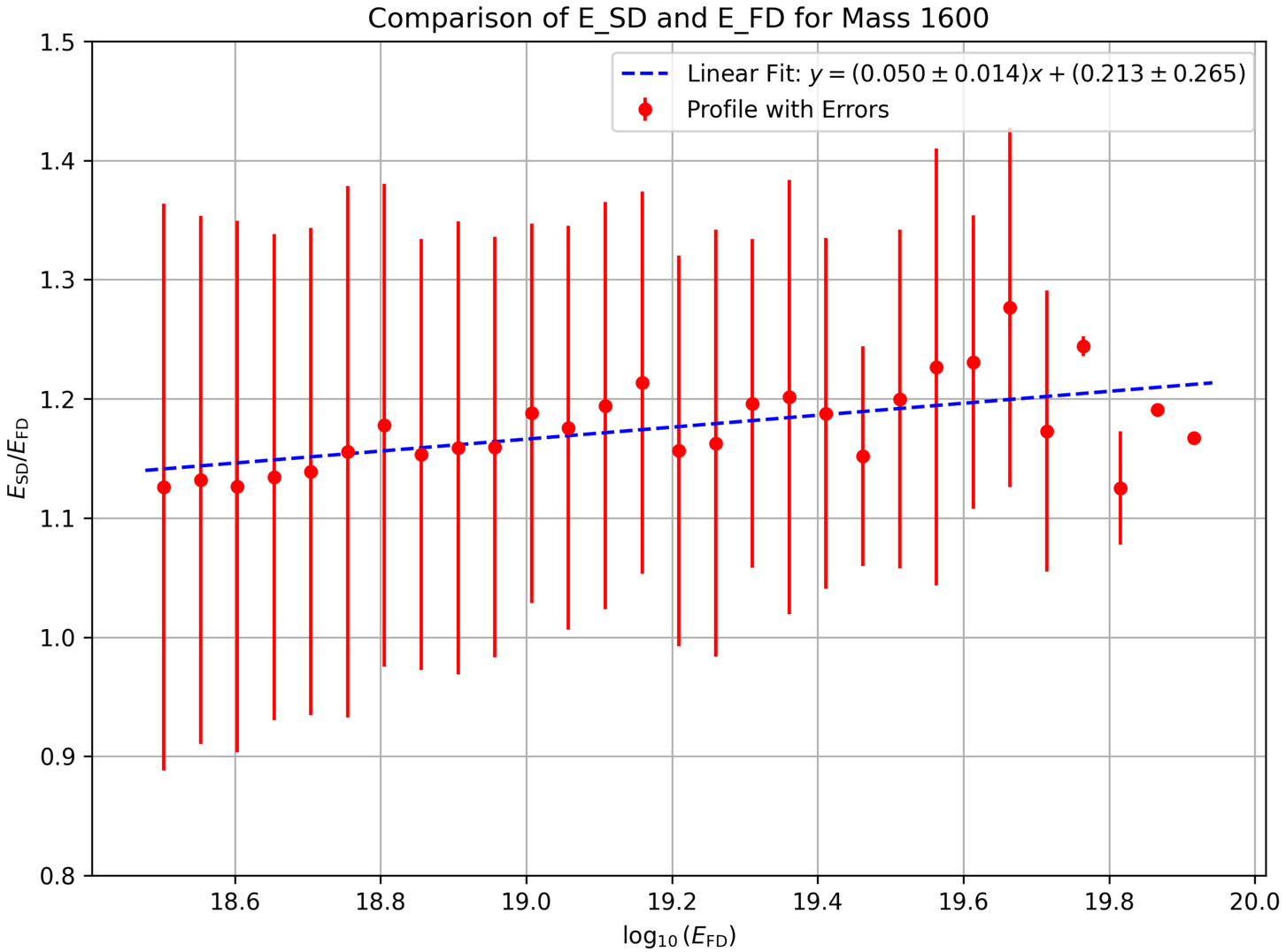


Comparison with FD energy



Comparison with FD energy