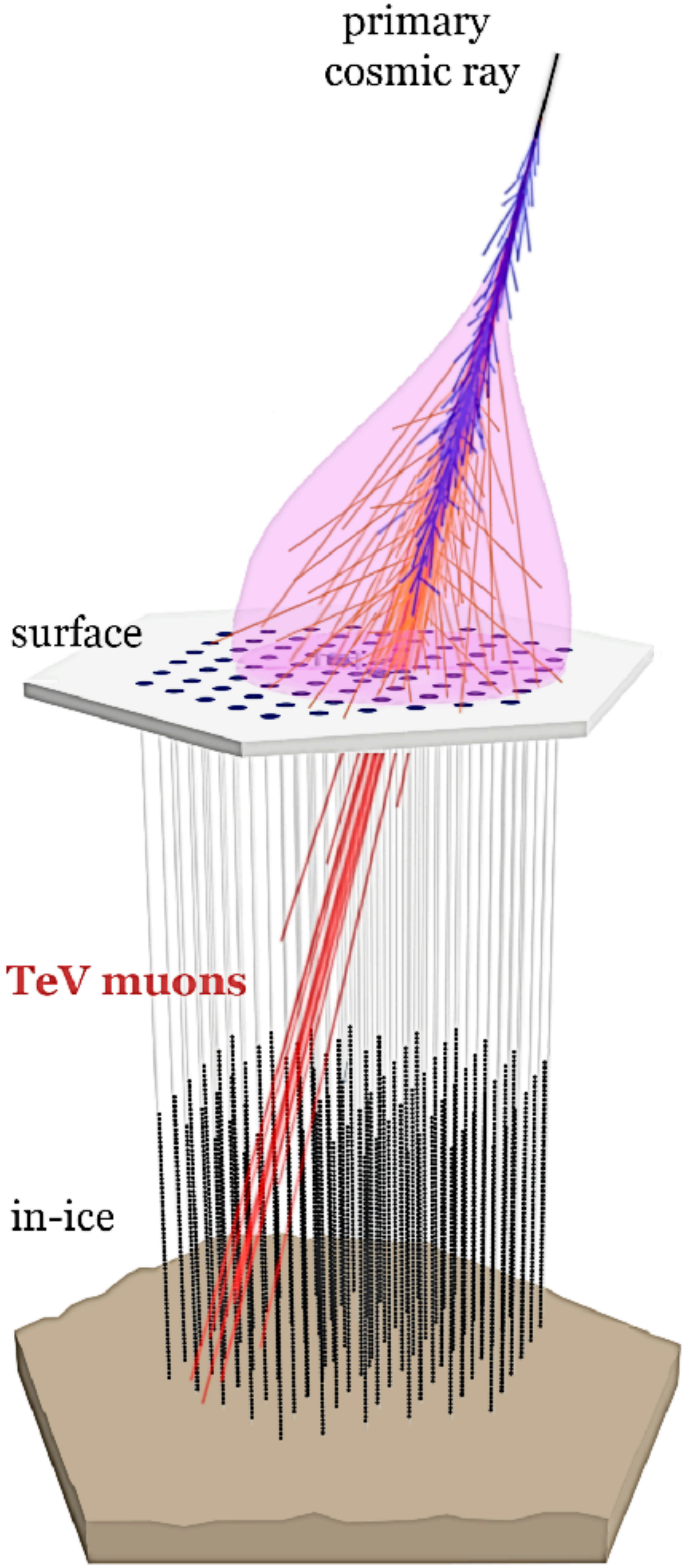
UNIVERSITY OF DELAWARE
BARTOL RESEARCH INSTITUTE

ICECUBE
NEUTRINO OBSERVATORY

Mean number of TeV muons in air showers measured with IceTop and IceCube

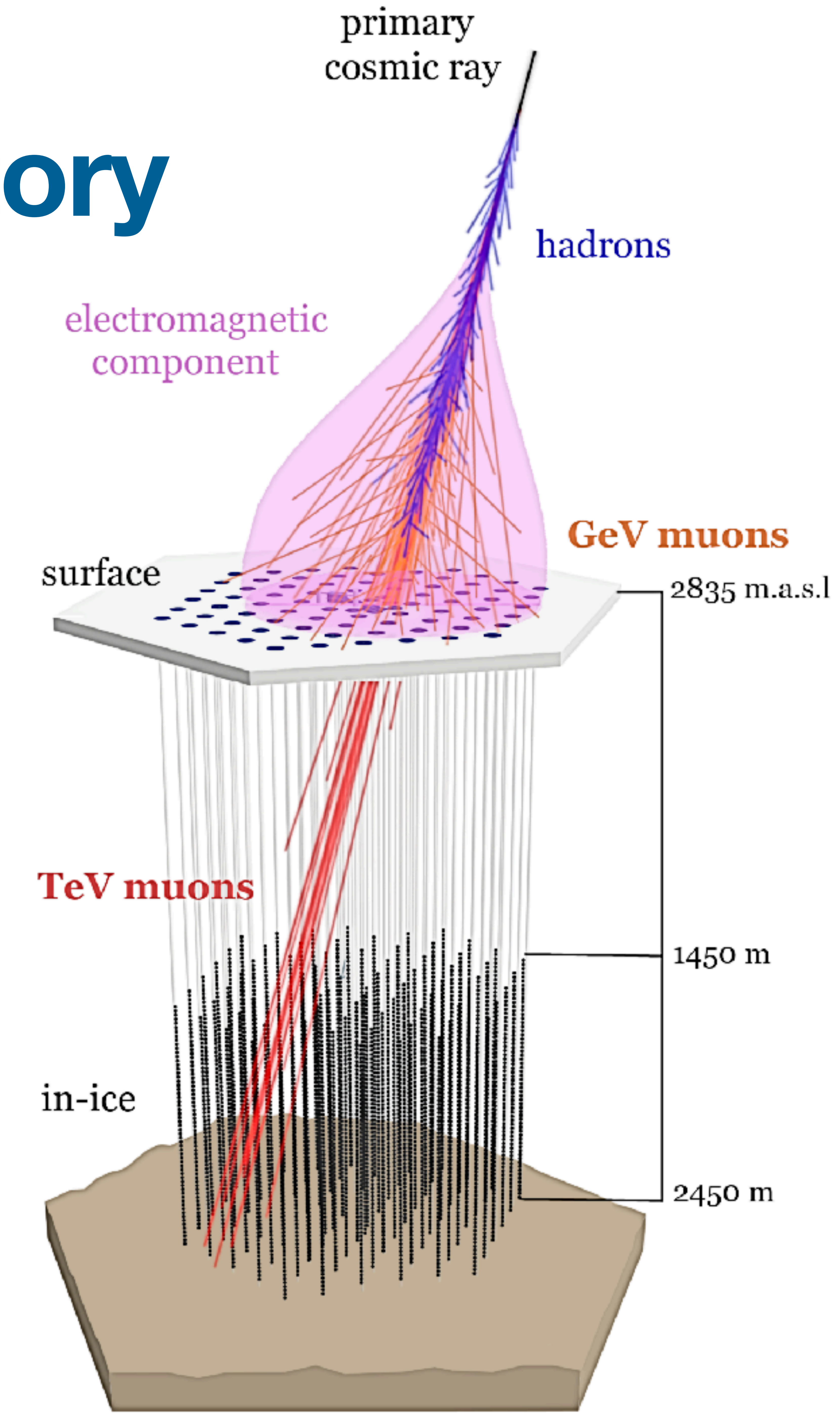


Stef Verpoest for the IceCube collaboration

ISVHECRI 2024, July 9, Puerto Vallarta, Mexico

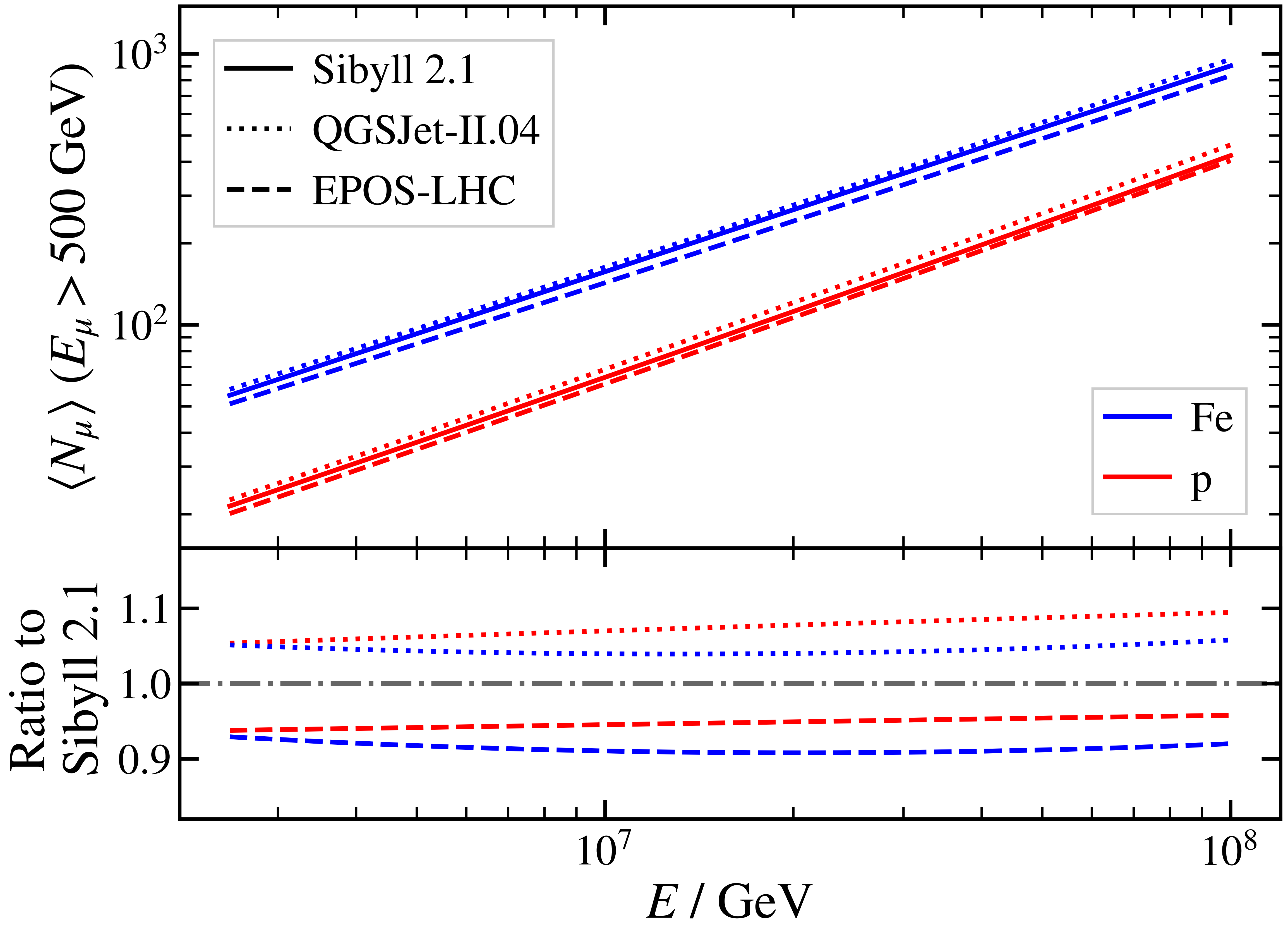
IceCube Neutrino Observatory

- IceTop
  - ~1 km² air-shower array
  - 162 ice-Cherenkov tanks
- IceCube
  - ~1 km³ Cherenkov detector
  - ~5000 Digital Optical Modules
- Combined: unique EAS detector!
  - Primary energy PeV - EeV
  - Electromagnetic component
  - ~GeV muons
  - **~TeV muons**

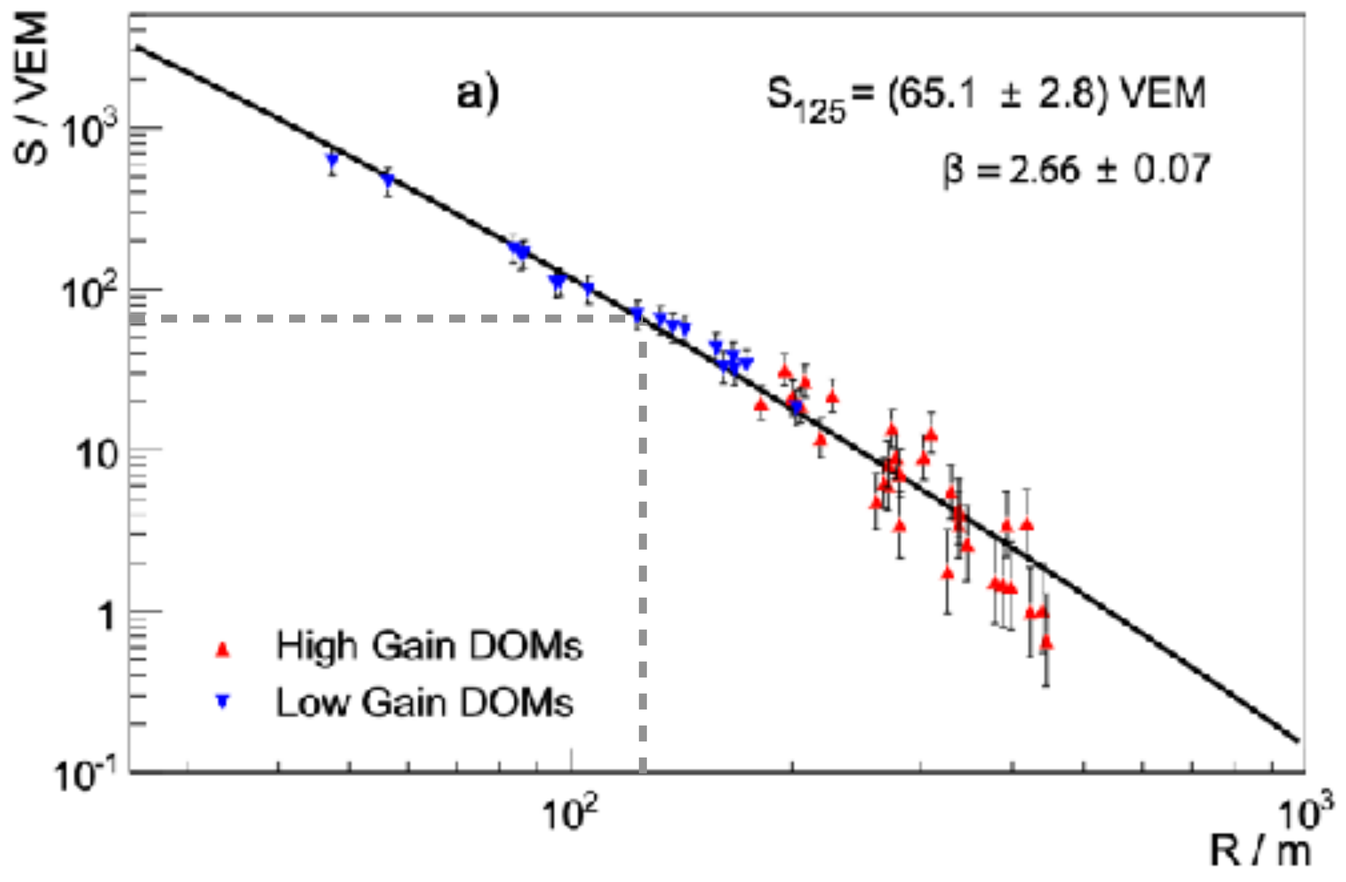


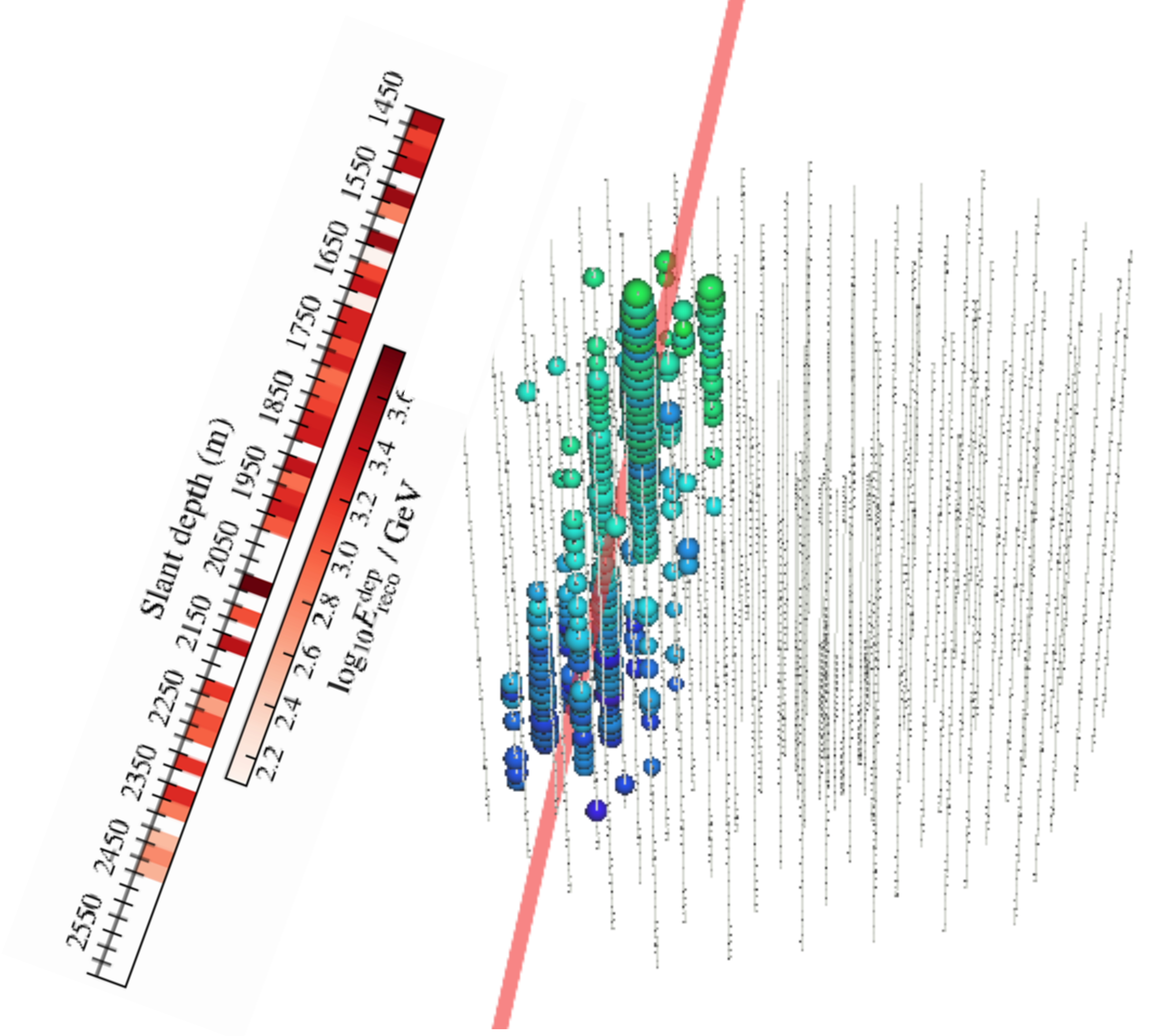
Analysis goal & motivation

- Muons in air showers
  - Mass composition
  - Tracers of hadronic cascade
- The Muon Puzzle
  - Disagreement in muon simulation/measurements
    - Muon deficit in MC at UHECR energies
  - Mainly ~GeV muon measurements
- Unique input from IceCube:
  - Observe muons in different kinematic regimes
  - This work: **average number of muons > 500 GeV in vertical showers**



Event selection & initial reconstruction





▸ Reconstruction

- IceTop air shower reconstruction
  - Core position
  - Direction (θ, ϕ)
  - Shower size S_{125}
- In-Ice energy-loss reconstruction
  - Muon bundle energy loss in 20 m segments

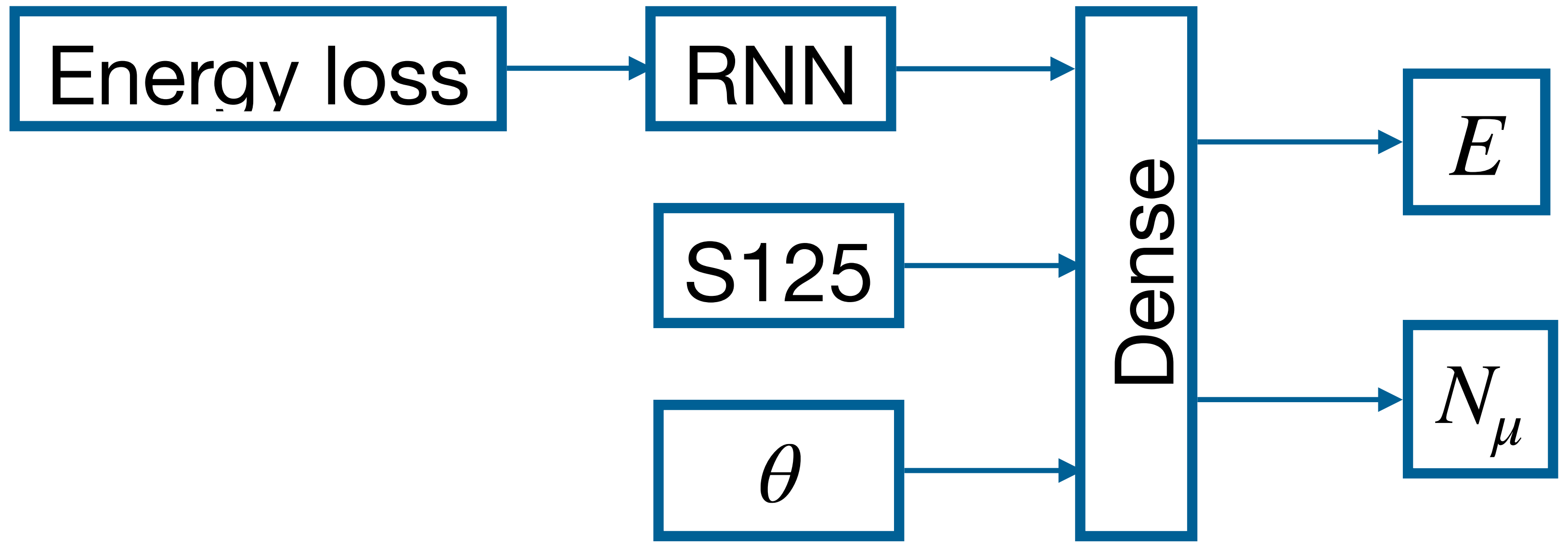
▸ Cuts

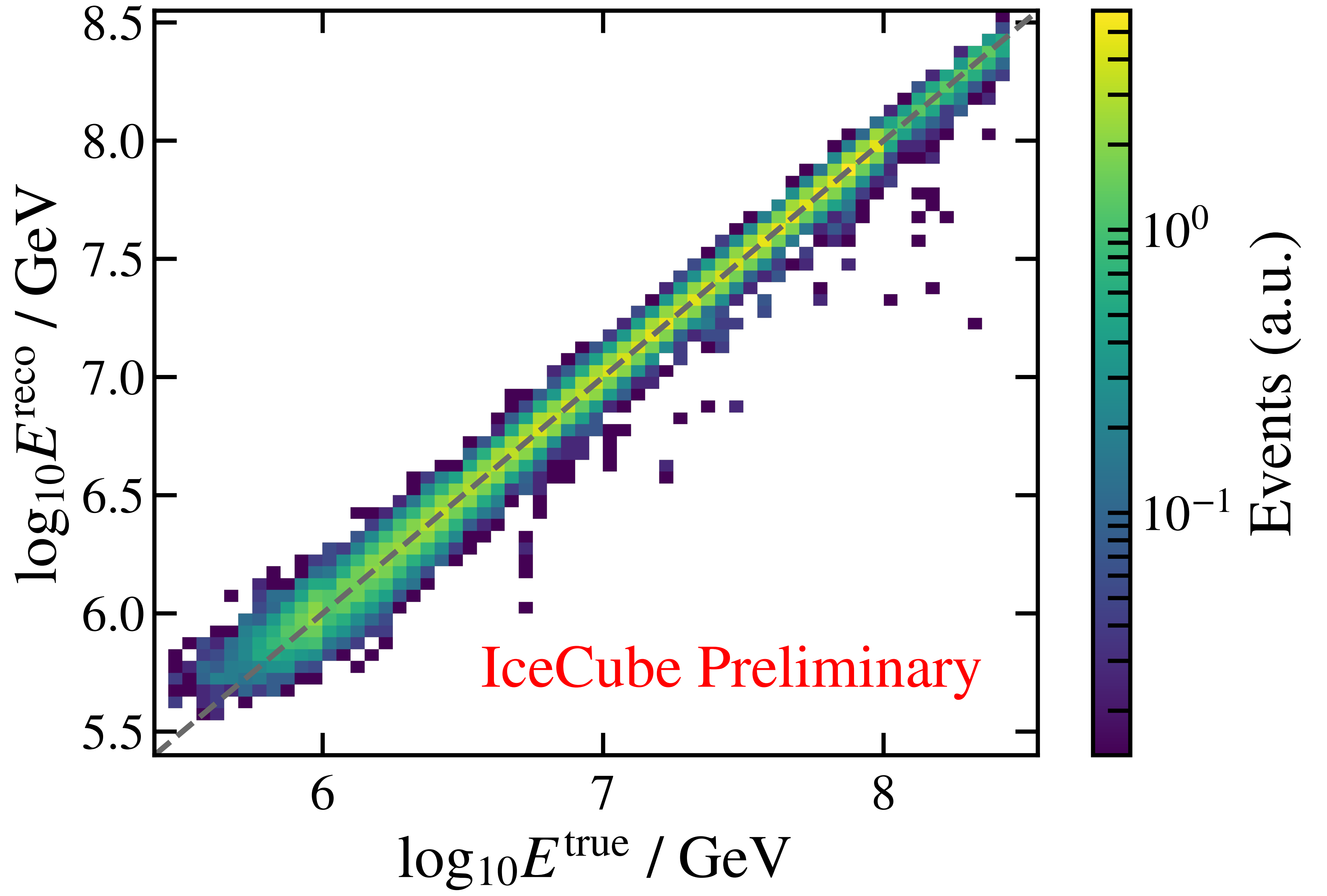
- Core contained in IceTop
- Coincident muon bundle
- Succesful reconstructions
- $\cos\theta > 0.95 \quad (\theta \lesssim 18^\circ)$

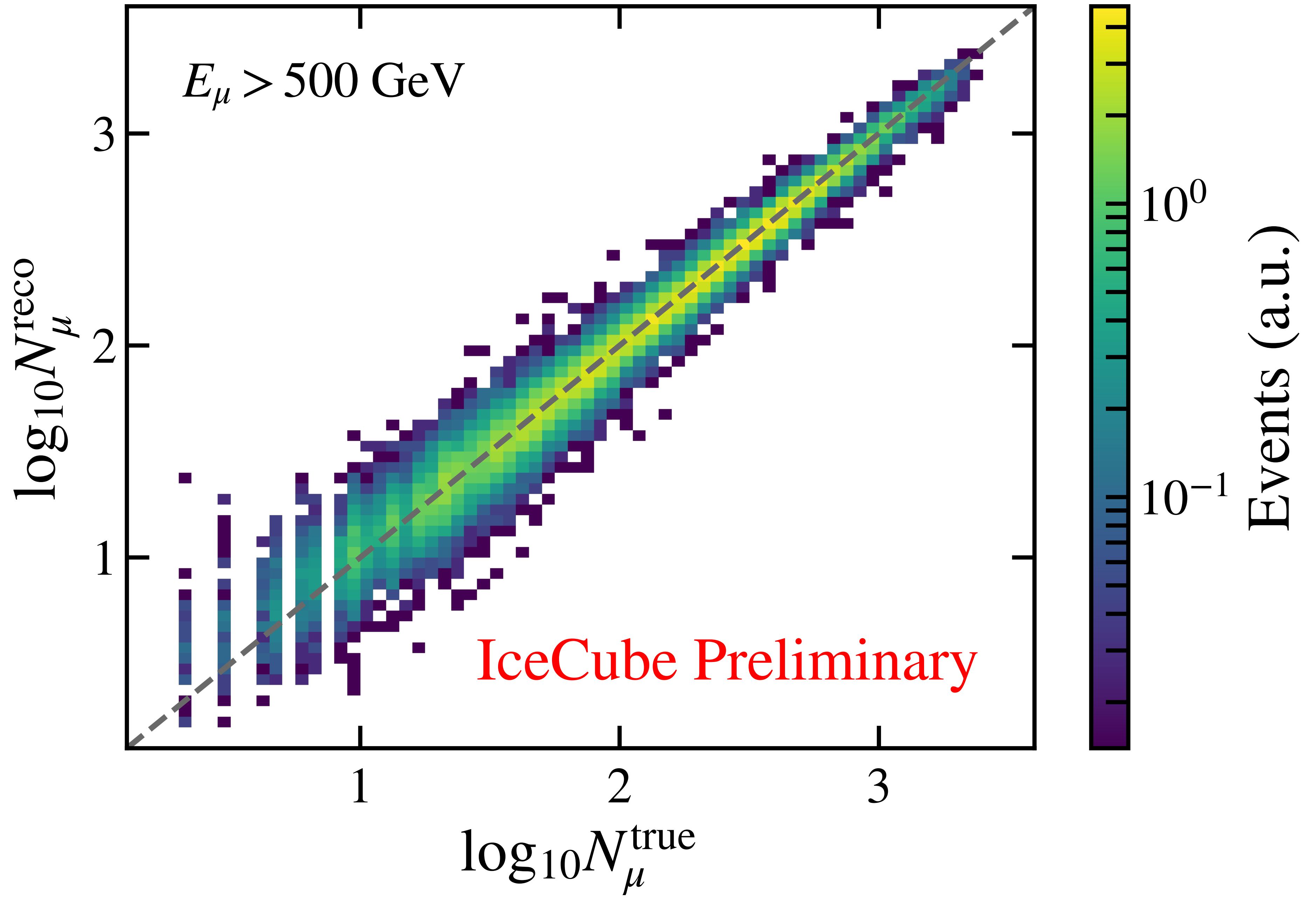
Neural network

- Neural network
  - Inputs:
    - IceTop: S_{125}, θ
    - In-Ice: energy loss vector
  - Output
    - **Primary energy** E
    - **# muons > 500 GeV in the shower** N_μ

- Training
  - Sibyll 2.1
  - p, He, O, Fe

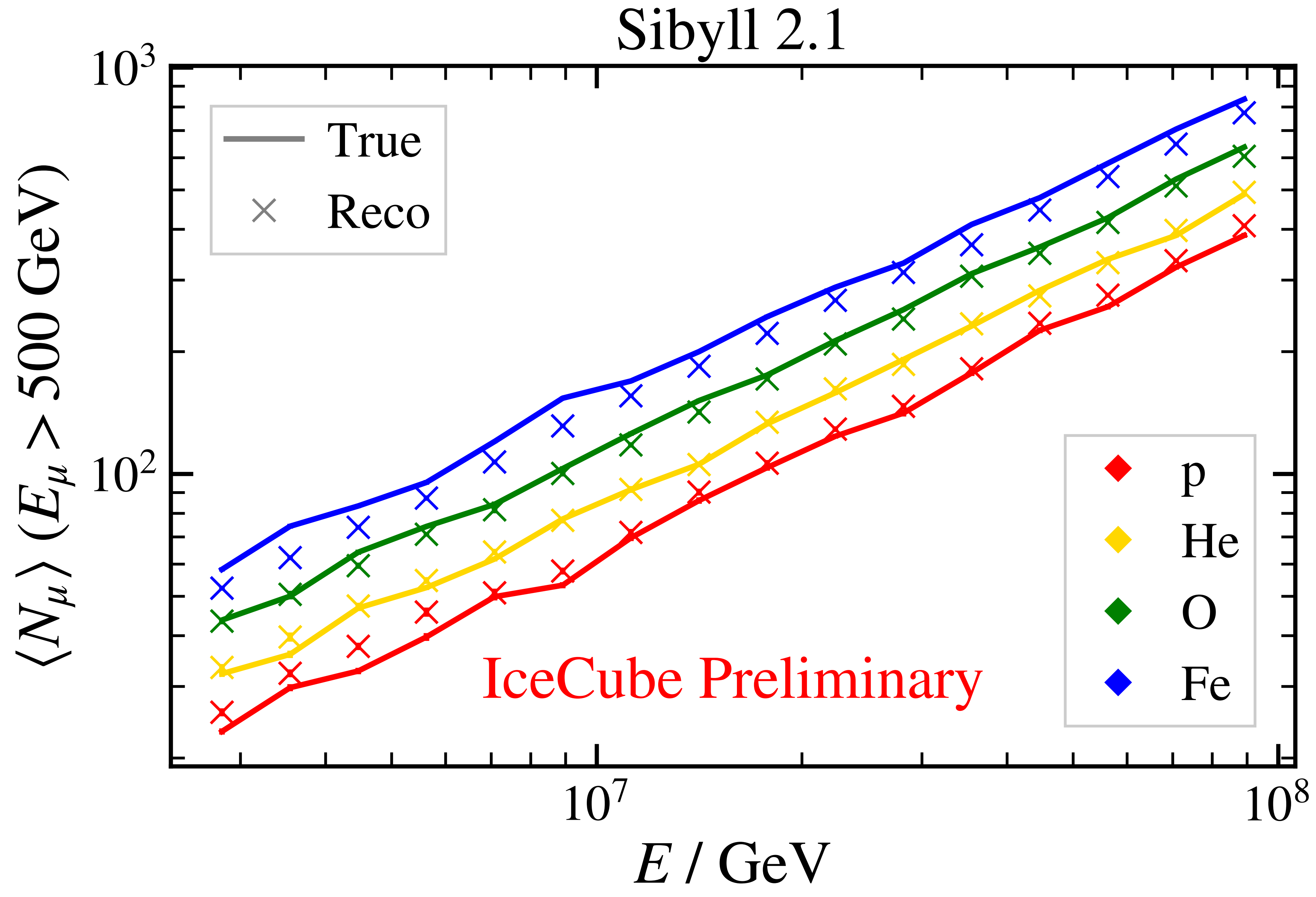


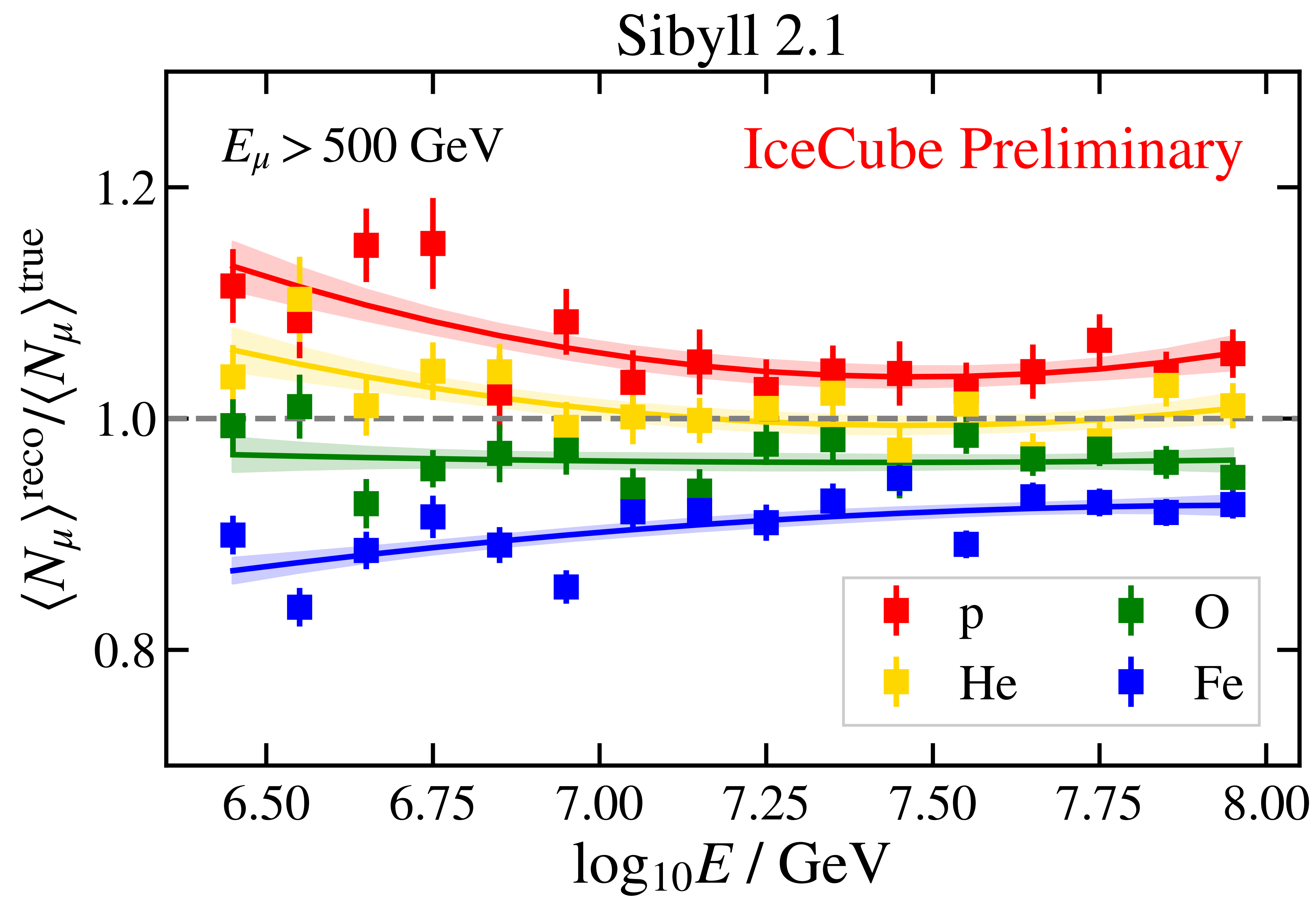




Correction factor

- Derive $\langle N_\mu \rangle$ in E_0 bins
- Resulting biases in MC
  - Reconstructed in bins of reconstructed
  - Ratio versus true values
- Correction factors
  - Fit with parabola
  - Depend on primary!





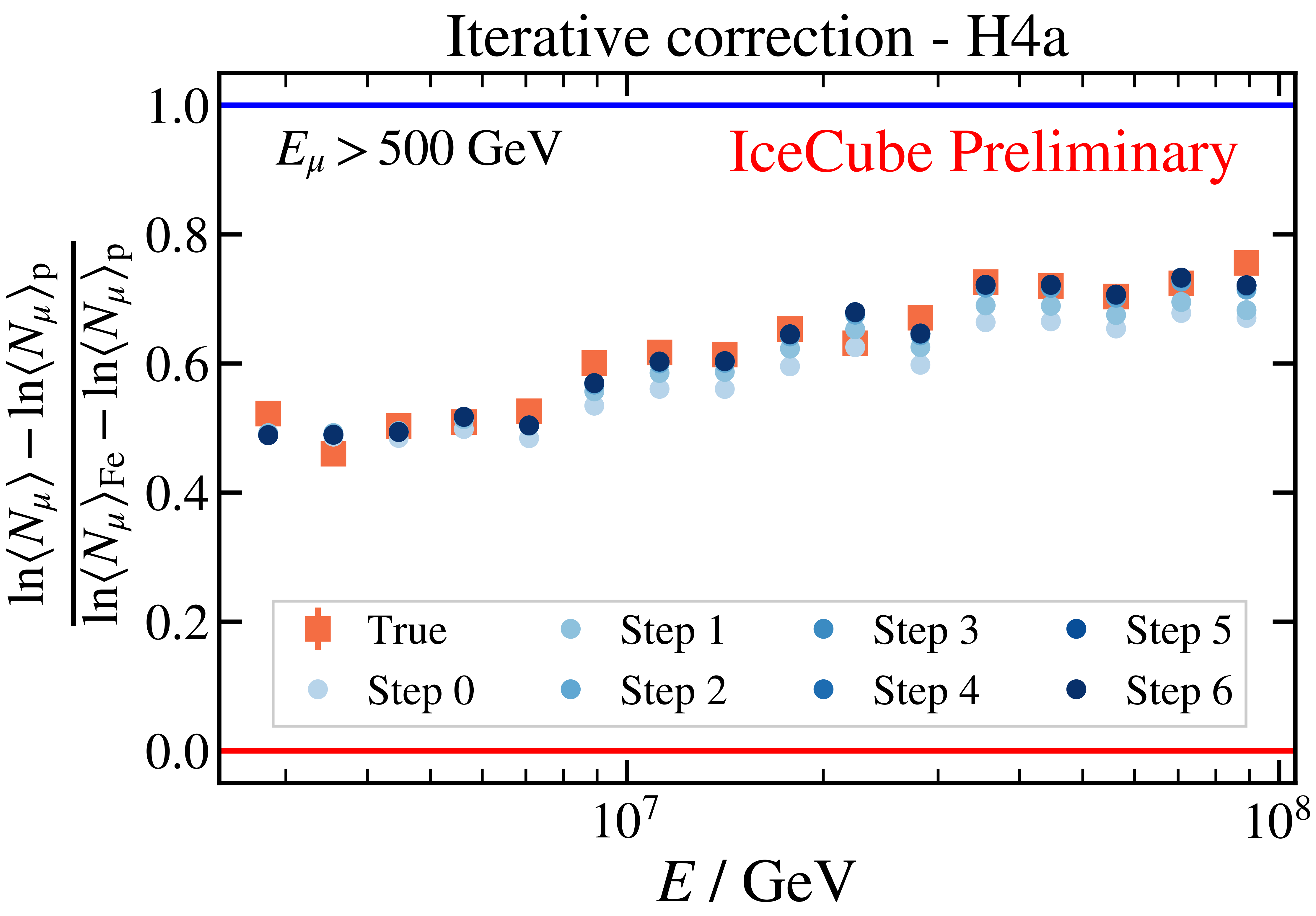
Iterative correction

- Correction factor is function of lnA
  - Interpolate correction factors for p & Fe

$$\mathscr{C}(\ln A) = \mathscr{C}_\mathrm{p} + \frac{\mathscr{C}_\mathrm{Fe} - \mathscr{C}_\mathrm{p}}{\ln 56} \ln A$$

  - Composition estimate from muon measurement

$$\frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_\mathrm{p}}{\ln\langle N_\mu \rangle_\mathrm{Fe} - \ln\langle N_\mu \rangle_\mathrm{p}} \approx \frac{\langle \ln A \rangle}{\ln A_\mathrm{Fe}}$$

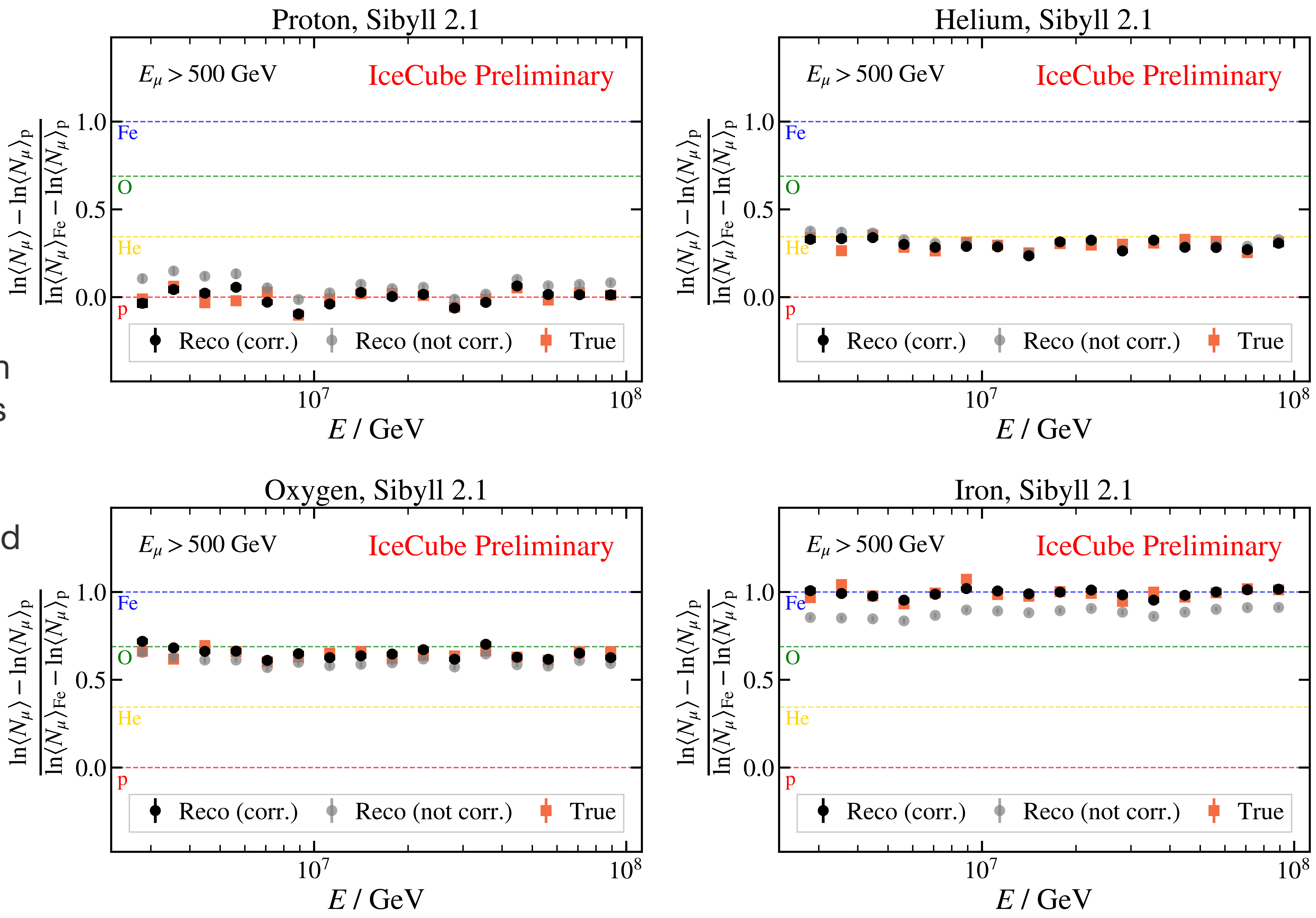


- Iterative procedure
  - $\langle N_\mu \rangle$ estimate → $\mathscr{C}$ → updated $\langle N_\mu \rangle$ → ... → convergence

MC tests

Method reproduces true muon multiplicity regardless of mass composition

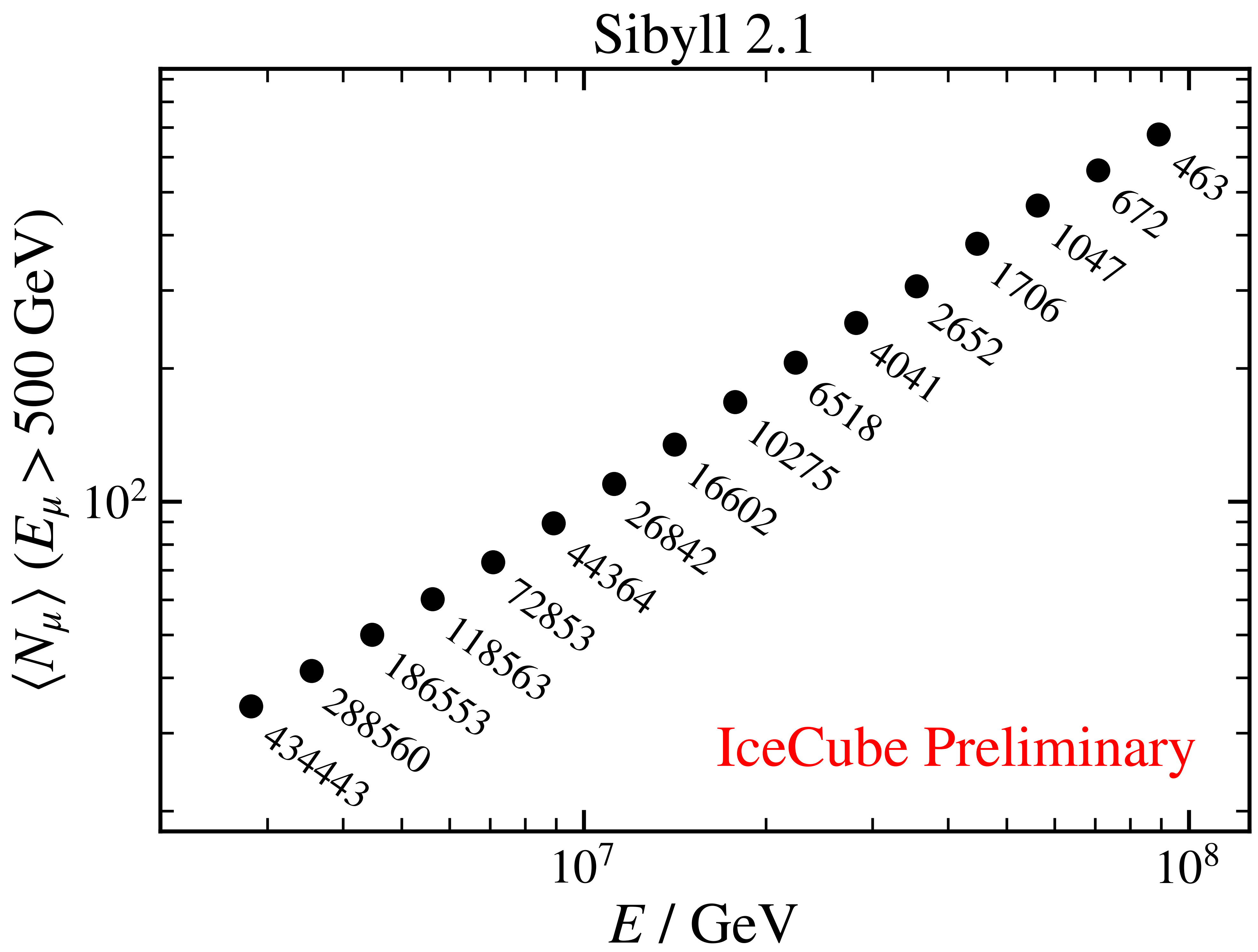
(remaining differences included as systematic uncertainty)

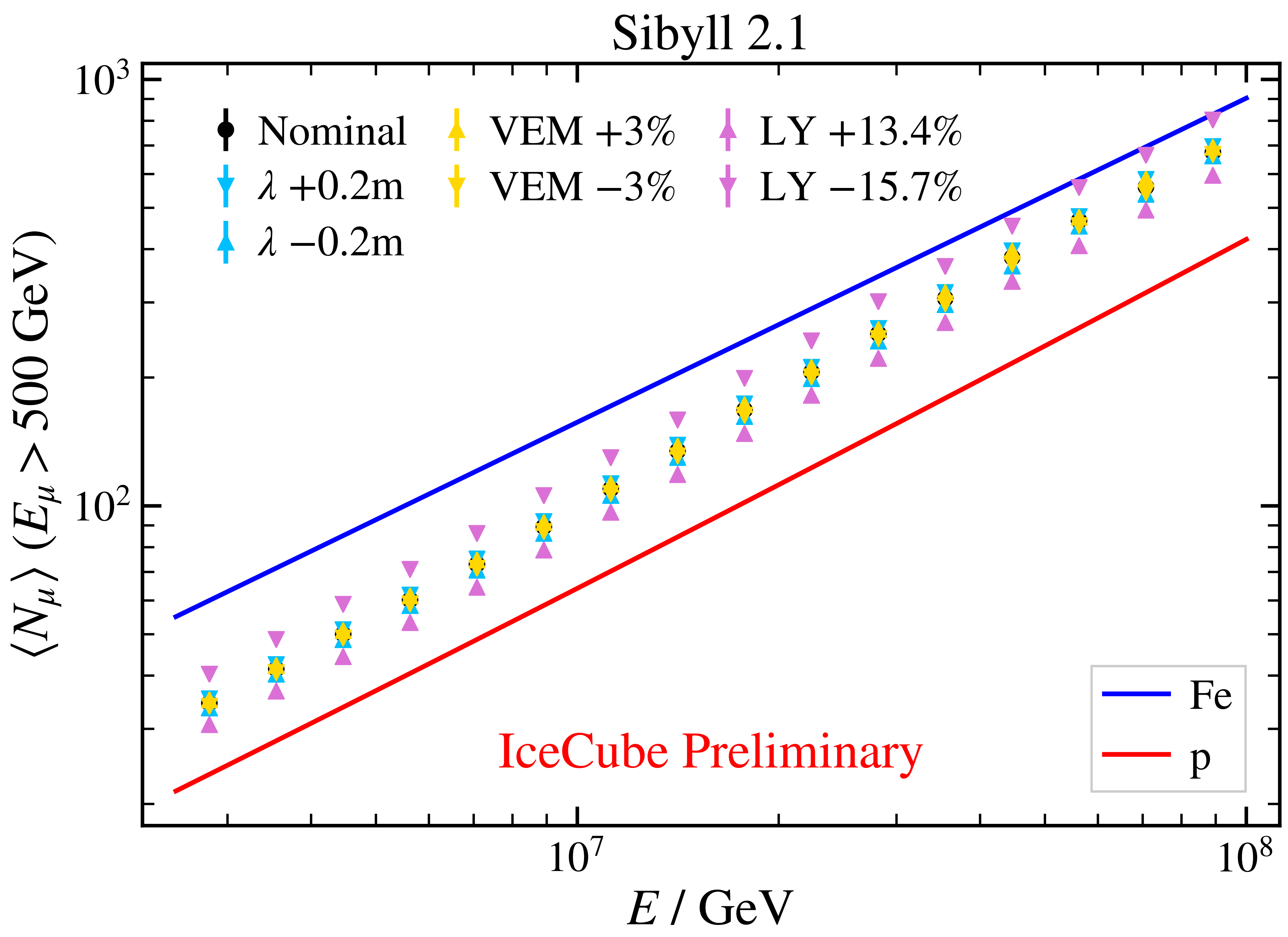


Application to data

- Results obtained using:
  - 1 year of data
    - May 2012 - May 2013
  - Sibyll 2.1 MC

- Systematic uncertainties
  - IceTop snow
  - IceTop VEM definition
  - In-ice light yield: ice model & DOM efficiency



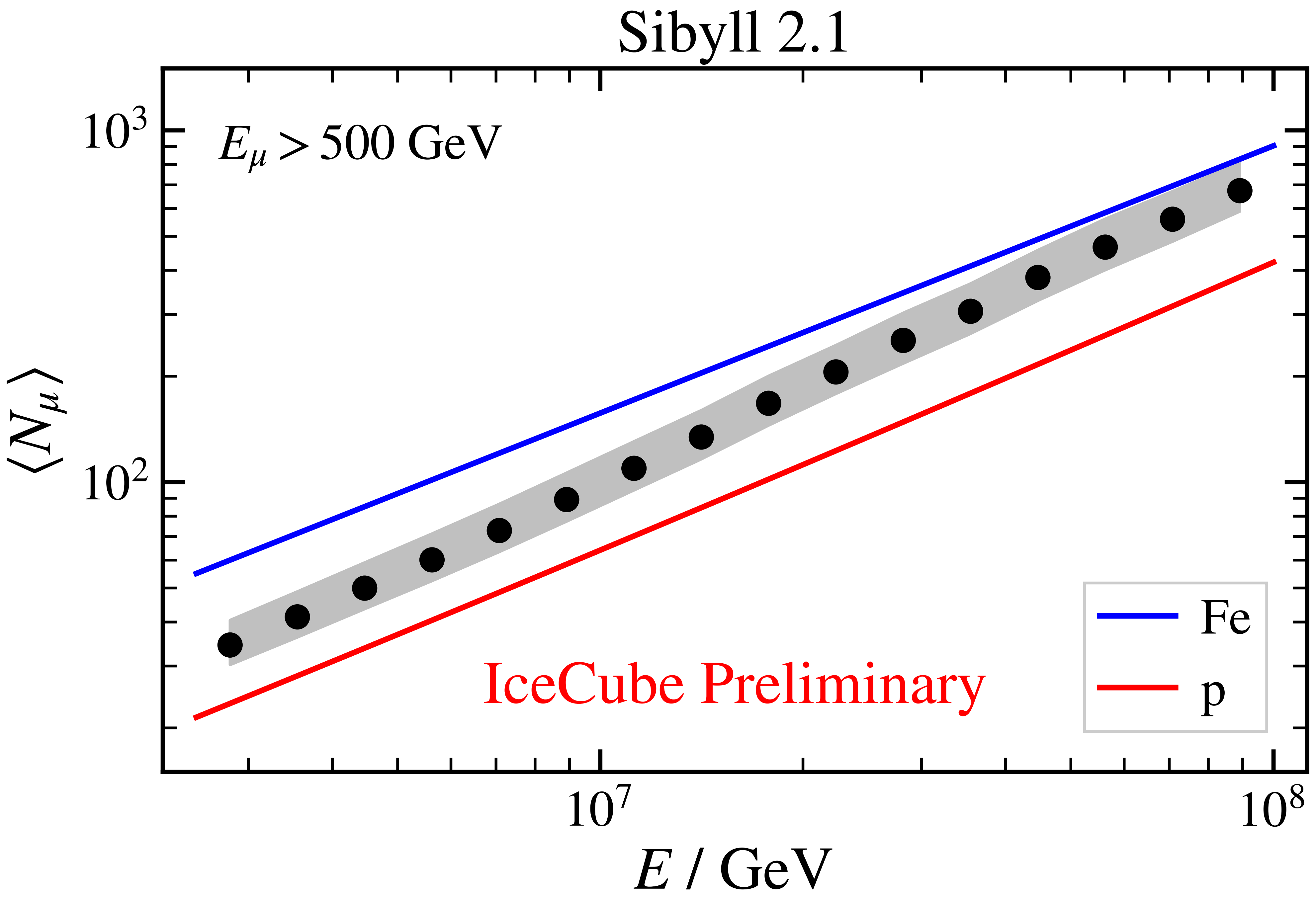


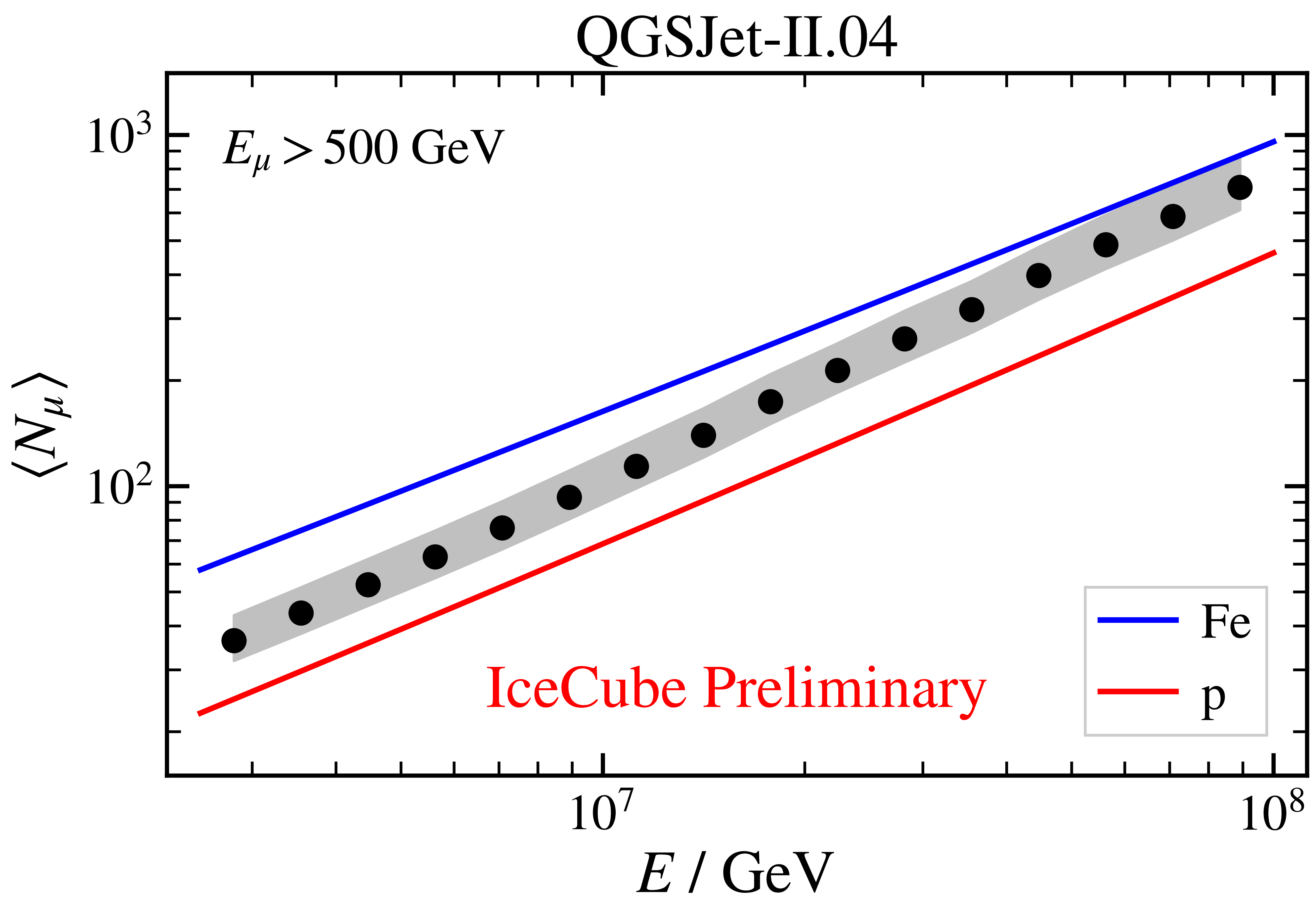
Correction factors: hadronic models

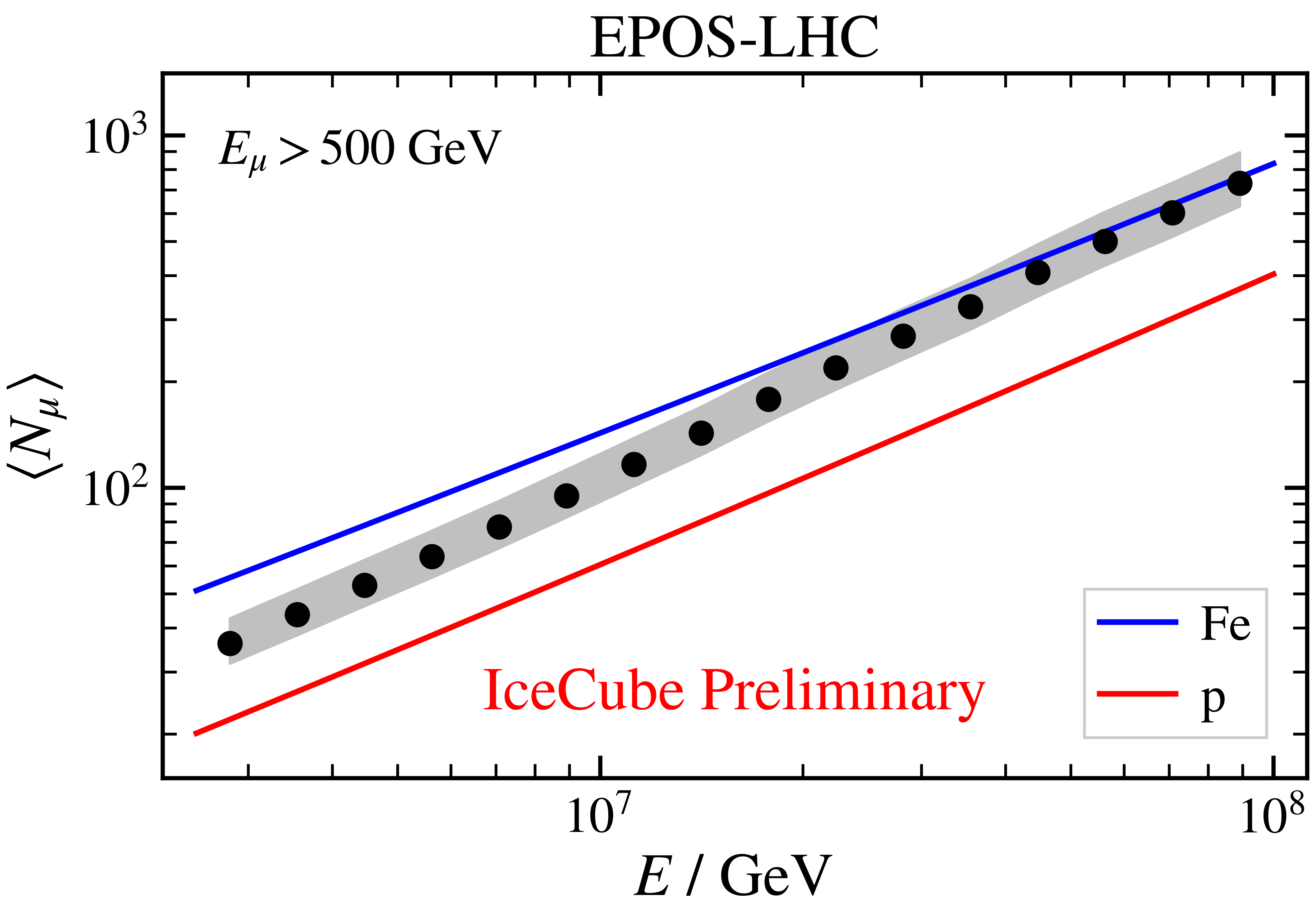
- Correction factors can be obtained from MC based on other hadronic models
  - QGSJet-II.04
  - EPOS-LHC

Results

- $\langle N_\mu \rangle$ (> 500 GeV) in near-vertical EAS
  - CR energy 2.5 PeV - 100 PeV
  - Depends on hadronic model
  - Shaded area: systematic uncertainty

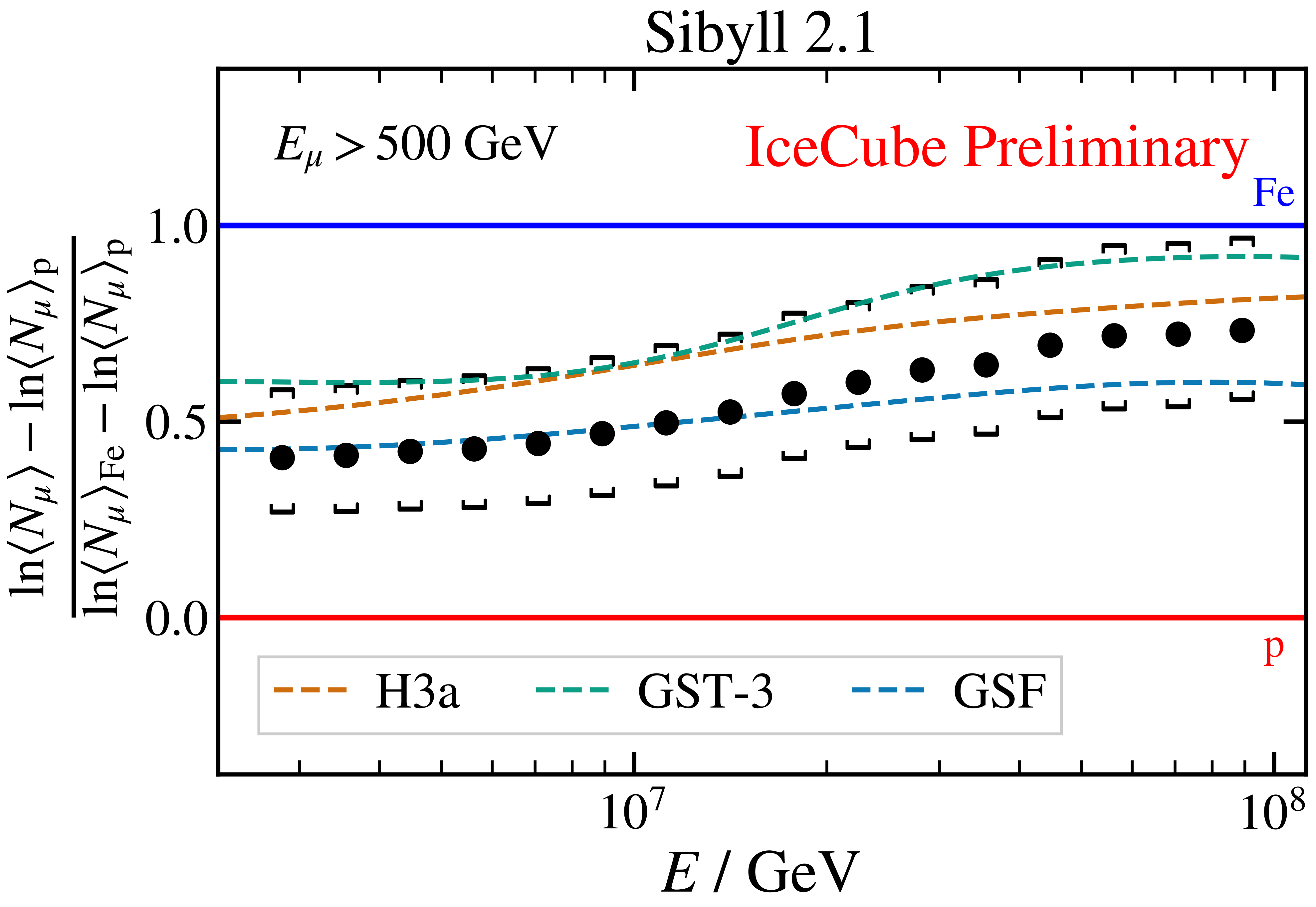


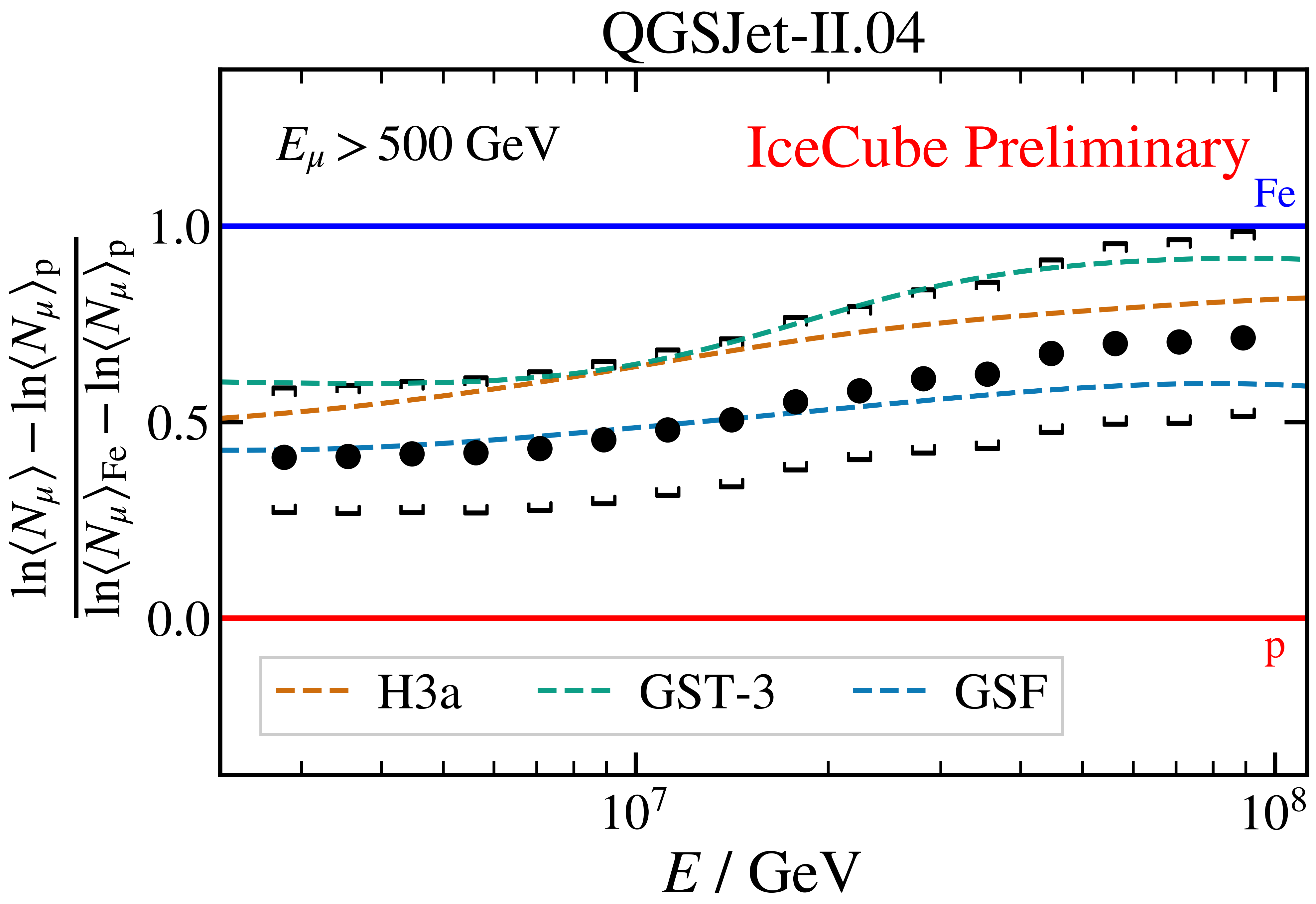


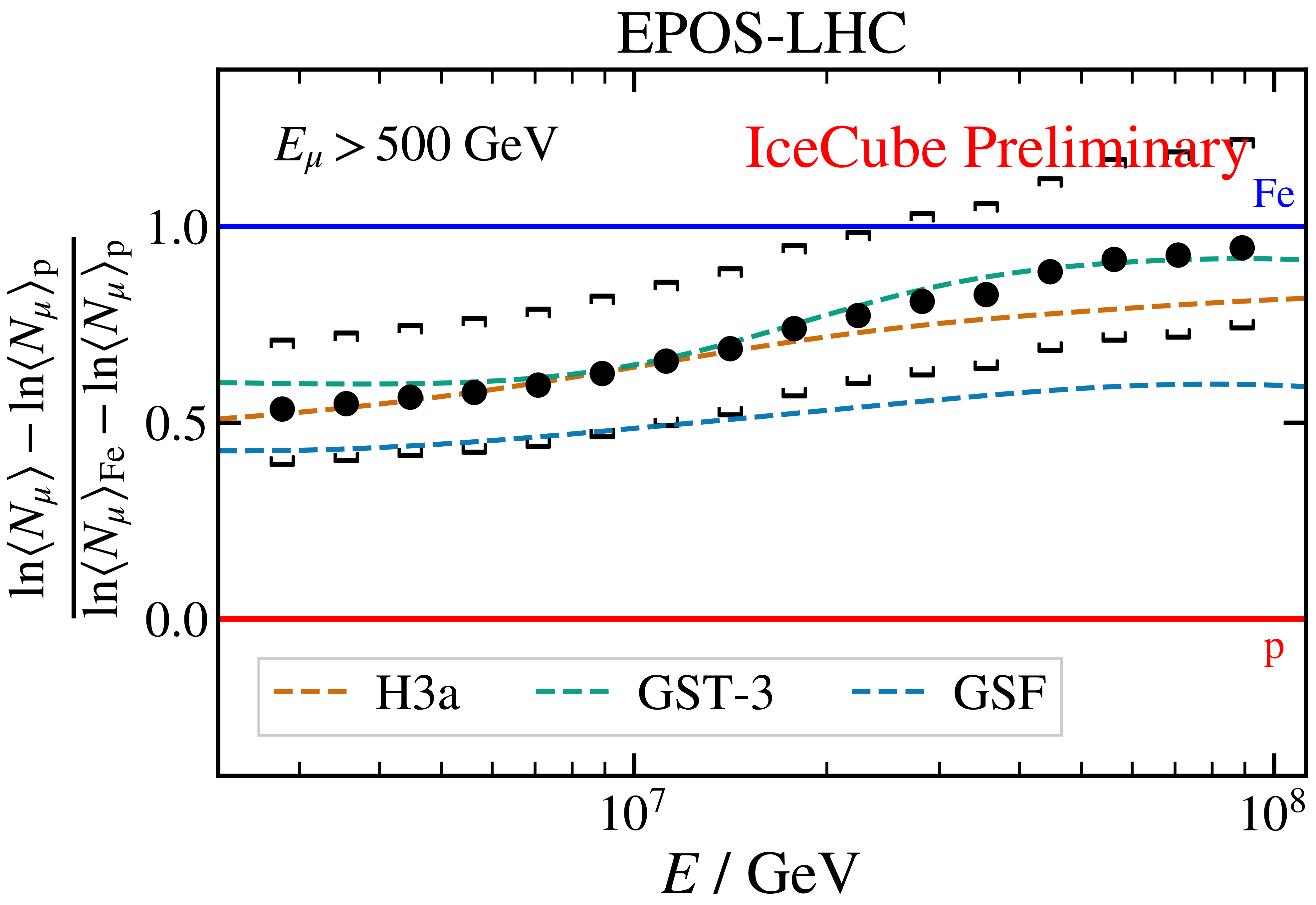


Results

- $\langle N_\mu \rangle$ (> 500 GeV) in near-vertical EAS
  - $$z = \frac{\ln\langle N_\mu \rangle^{\text{data}} - \ln\langle N_\mu \rangle_{\text{p}}^{\text{MC}}}{\ln\langle N_\mu \rangle_{\text{Fe}}^{\text{MC}} - \ln\langle N_\mu \rangle_{\text{p}}^{\text{MC}}}$$
  - Predictions from flux models: H3a, GST, GSF
  - Brackets: systematic uncertainty





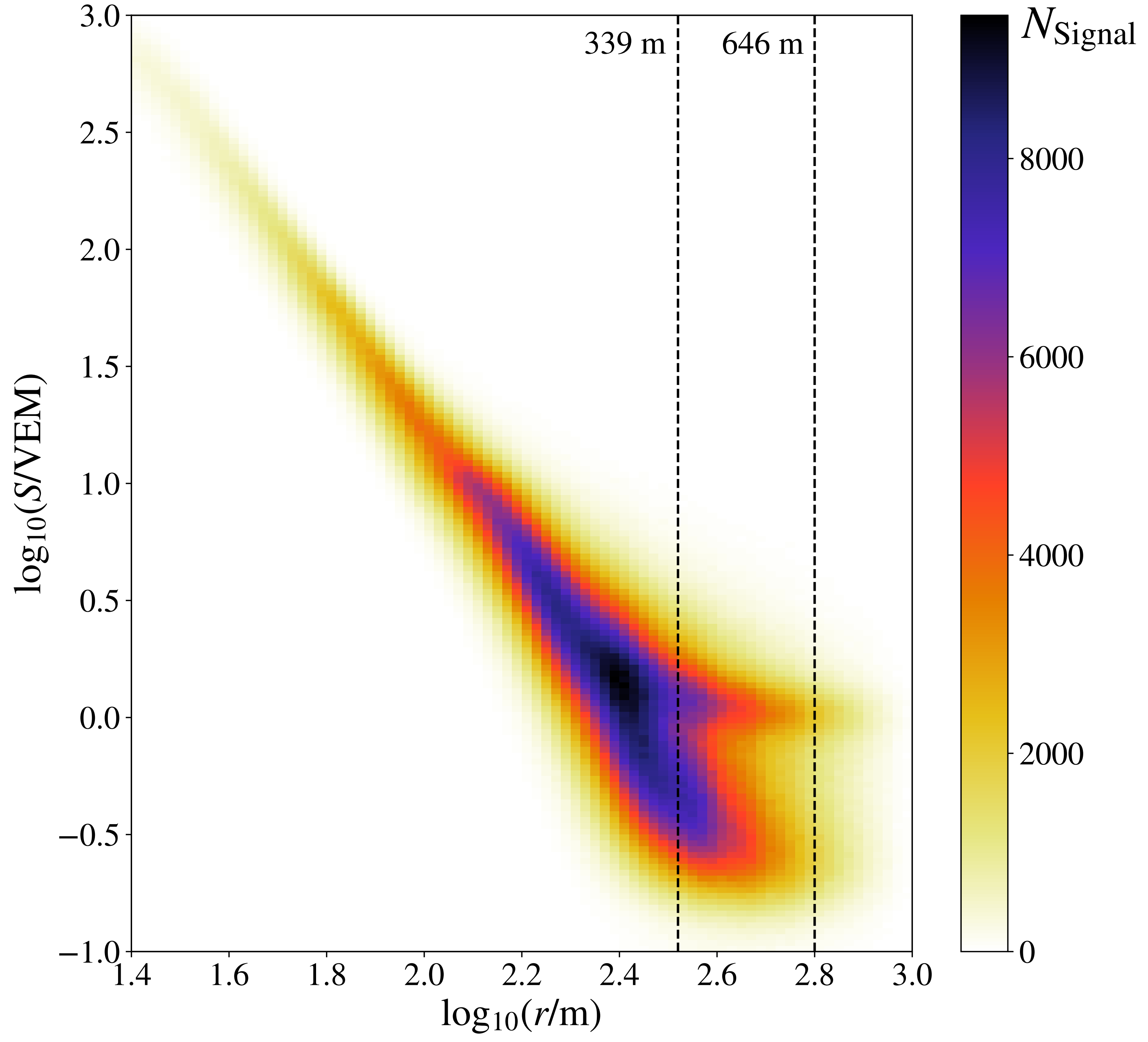


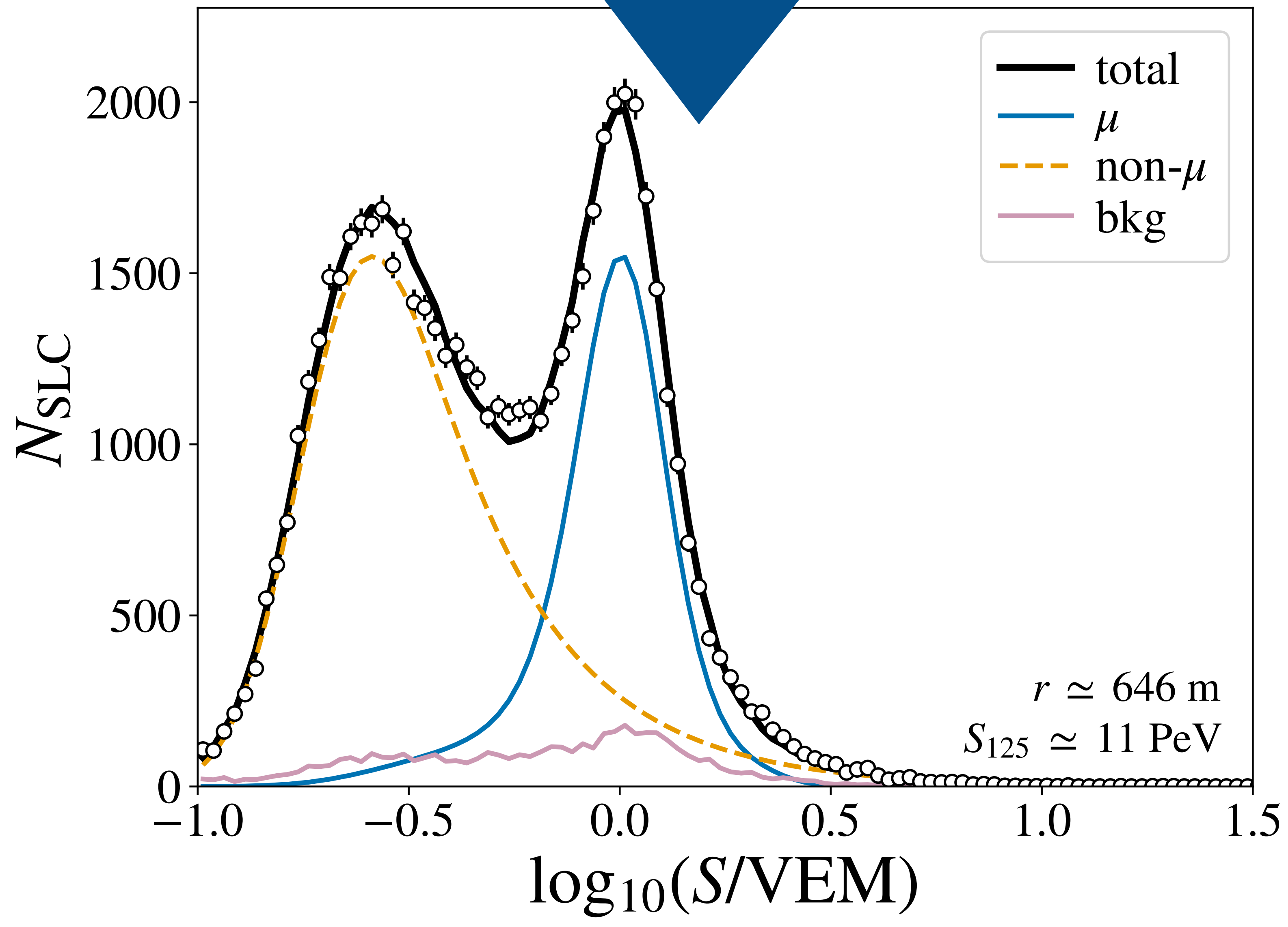
GeV vs TeV muons

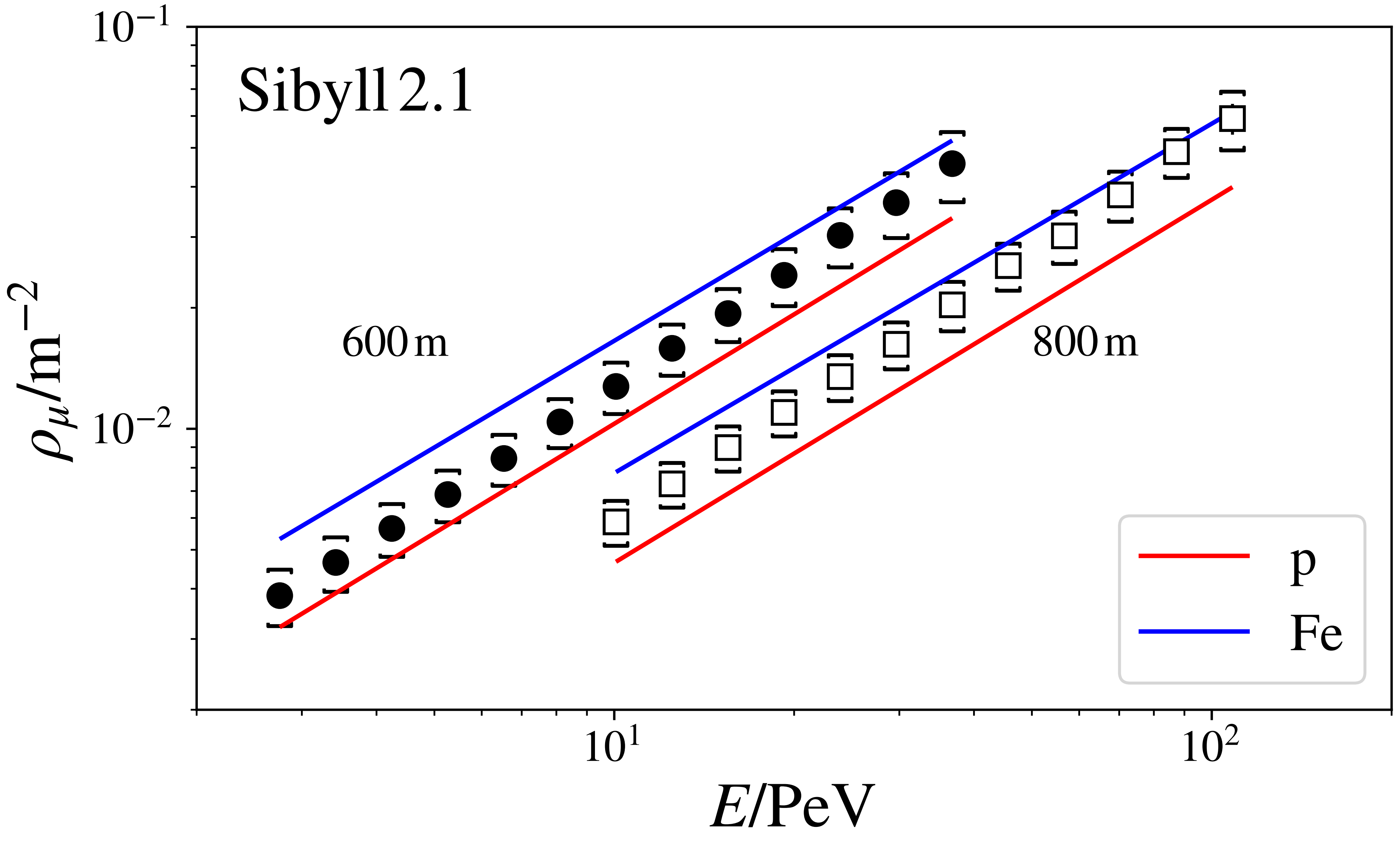
- IceTop muon density analysis

  [Phys. Rev. D 106 (2022)]

  - IceTop alone
  - Density of muons at 600 and 800 m from shower axis
  - Dominated by low-energy (~GeV) muons



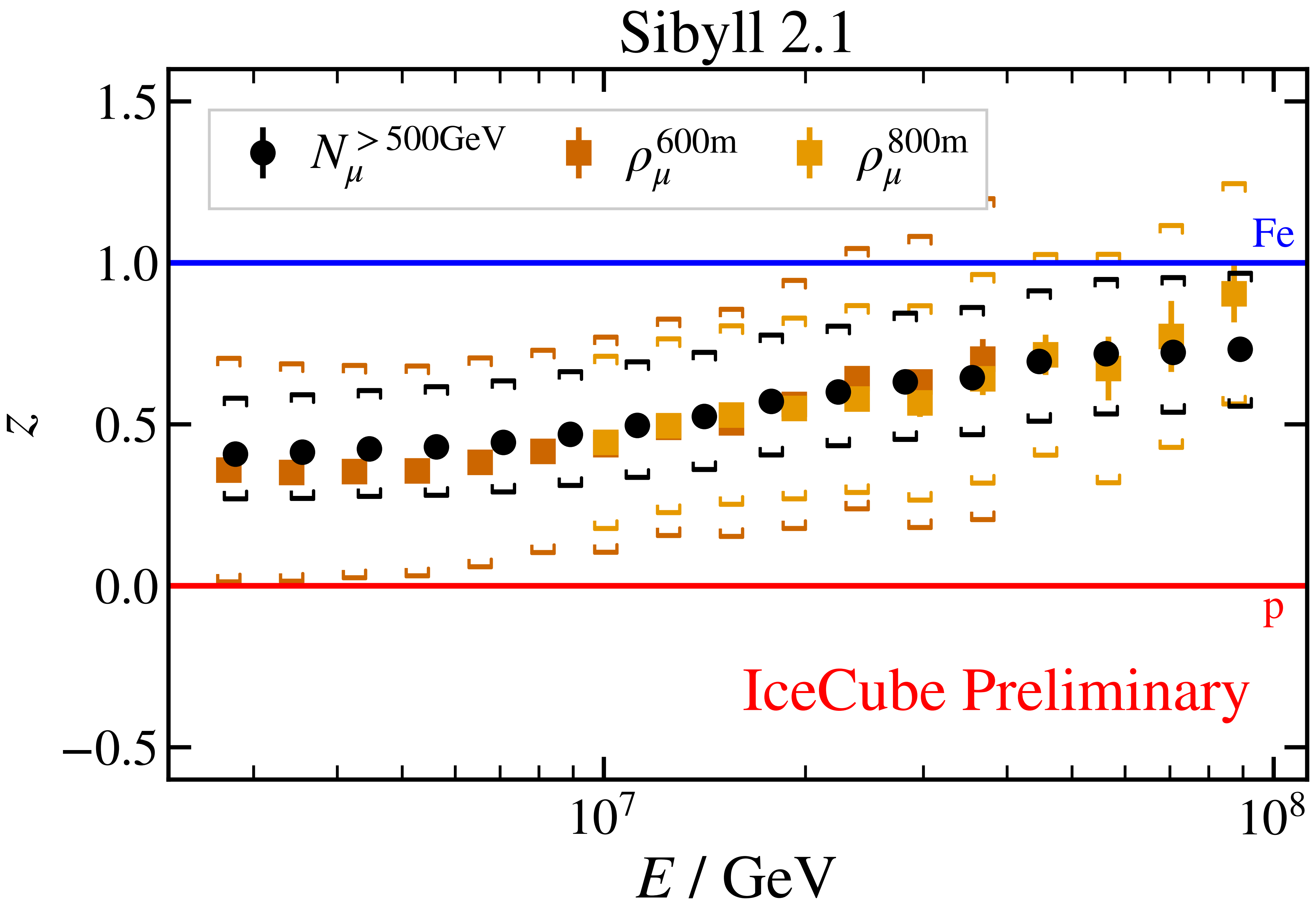




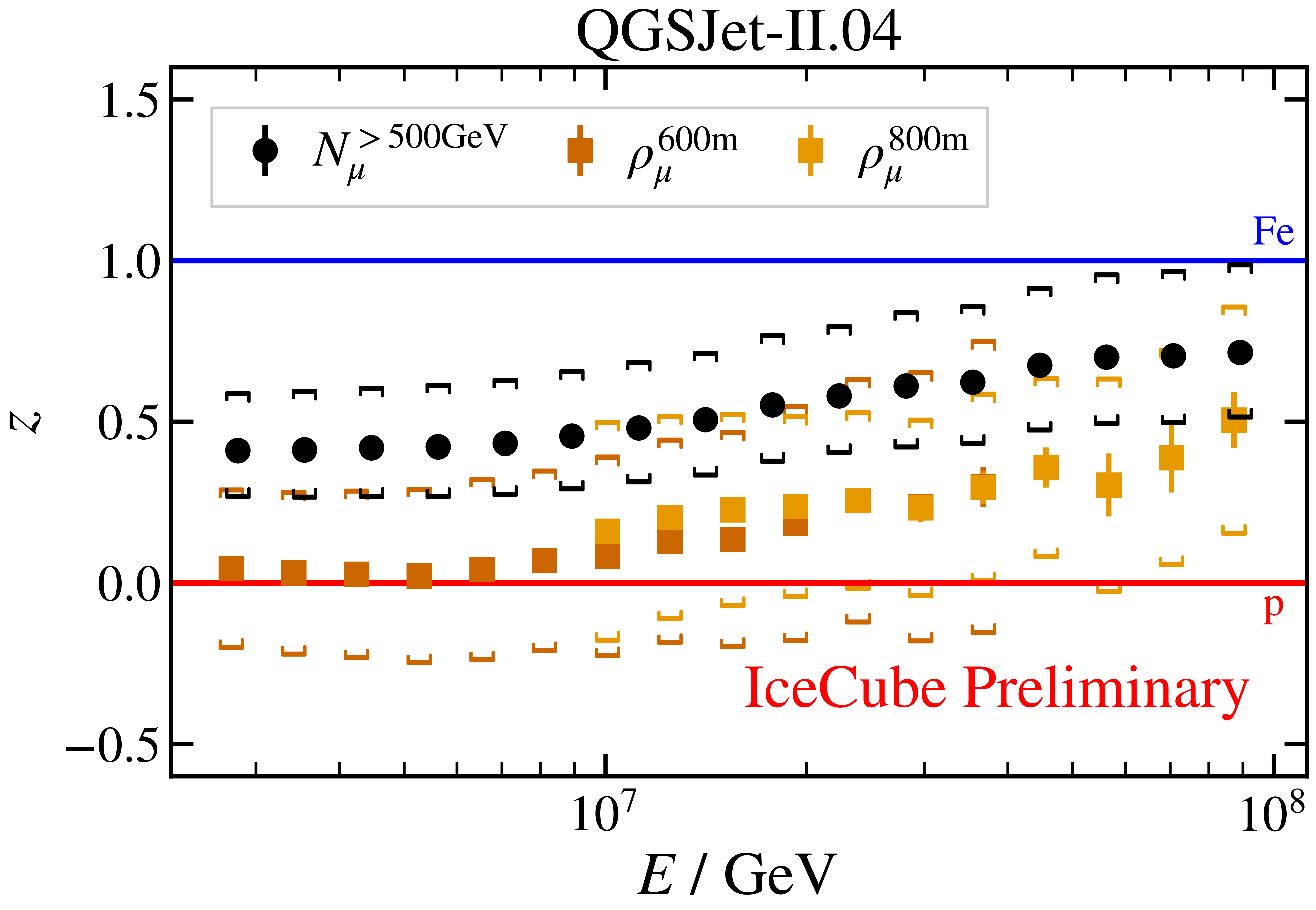
GeV vs TeV muons

- Comparison of two analyses
  - High-energy muons vs surface muons at large distance
  - Near-vertical air showers
  - GeV μ indicate lighter composition in post-LHC models

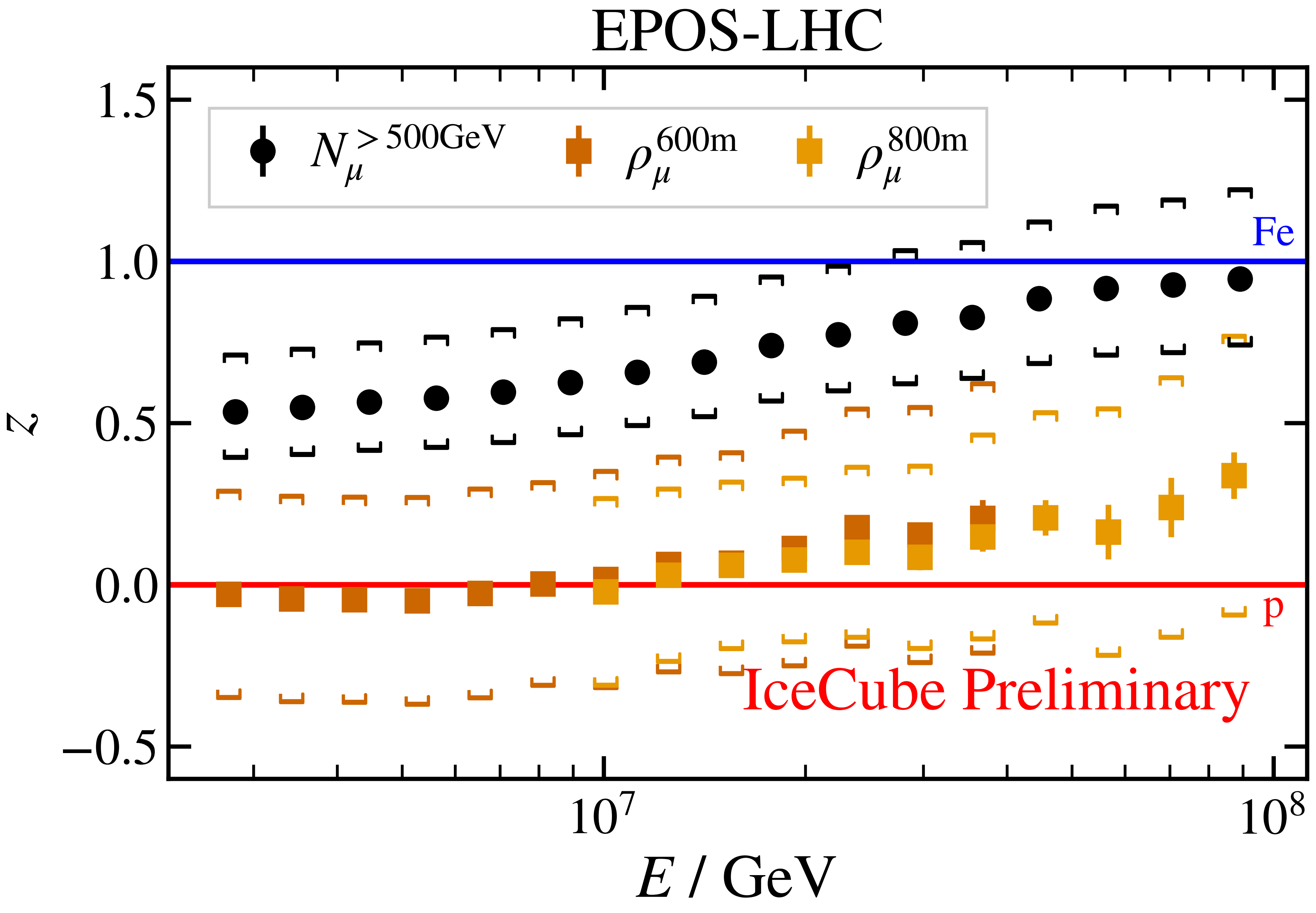
Sibyll 2.1



QGSJet-II.04



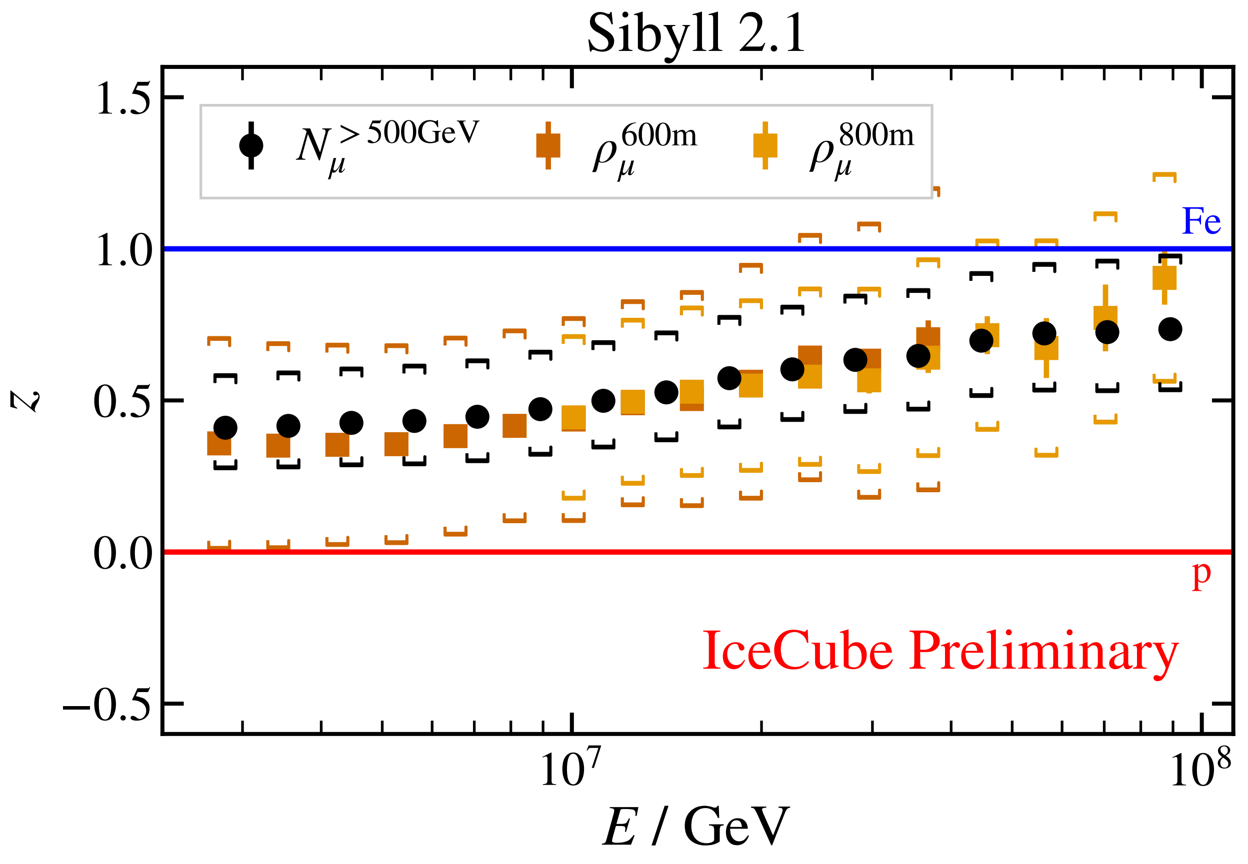
EPOS-LHC

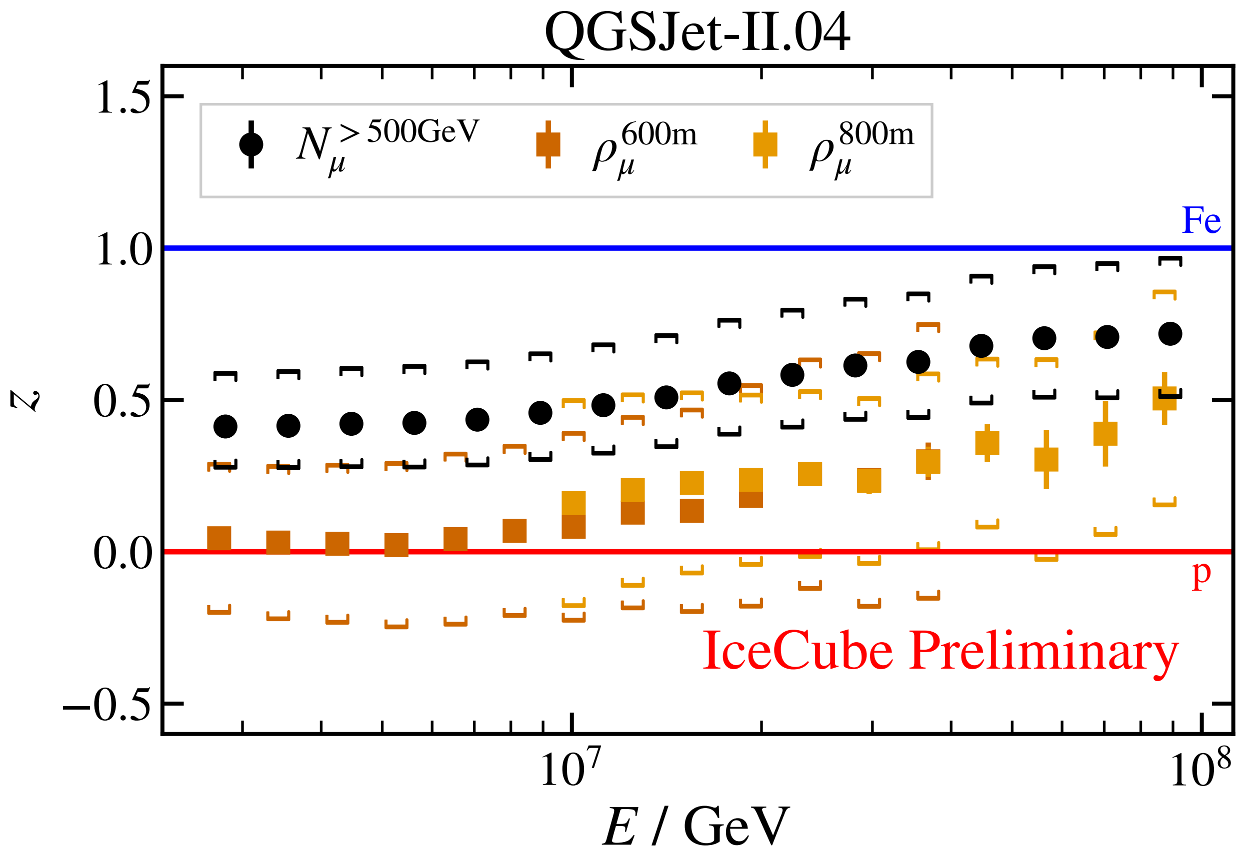


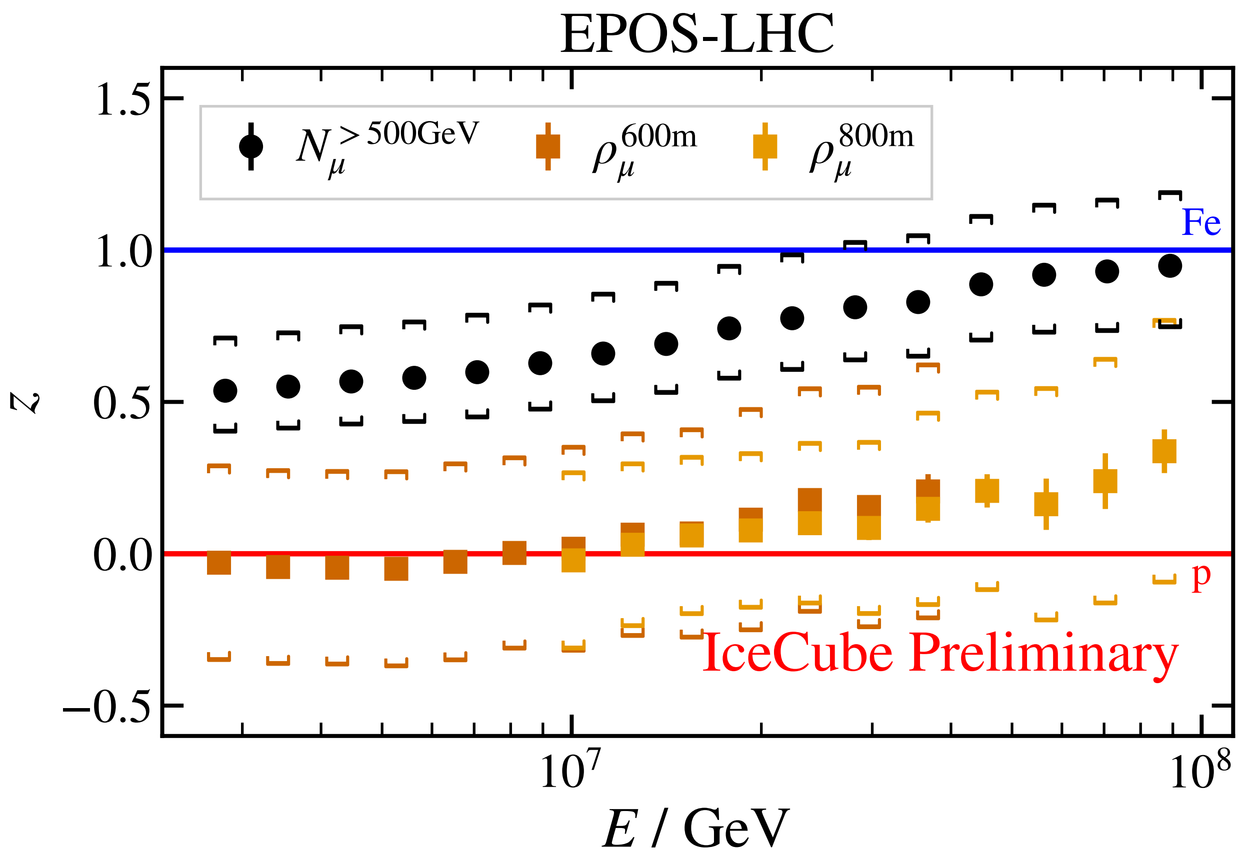
Summary & Outlook

- TeV muon multiplicity analysis
  - Mean number of muons > 500 GeV in near-vertical showers
  - **In line with expectations from simulations**
  - Comparison to GeV muon measurement from IceTop*
    - Best agreement with Sibyll 2.1
    - **Tension in QGSJet-II.04 and EPOS-LHC**
      - → too many low-energy muons in post-LHC models?

- Outlook
  - Paper in preparation
  - Efforts ongoing to improve IceCube constraints on hadronic models
    - Improved systematics & muon analyses; Surface Enhancement; ...





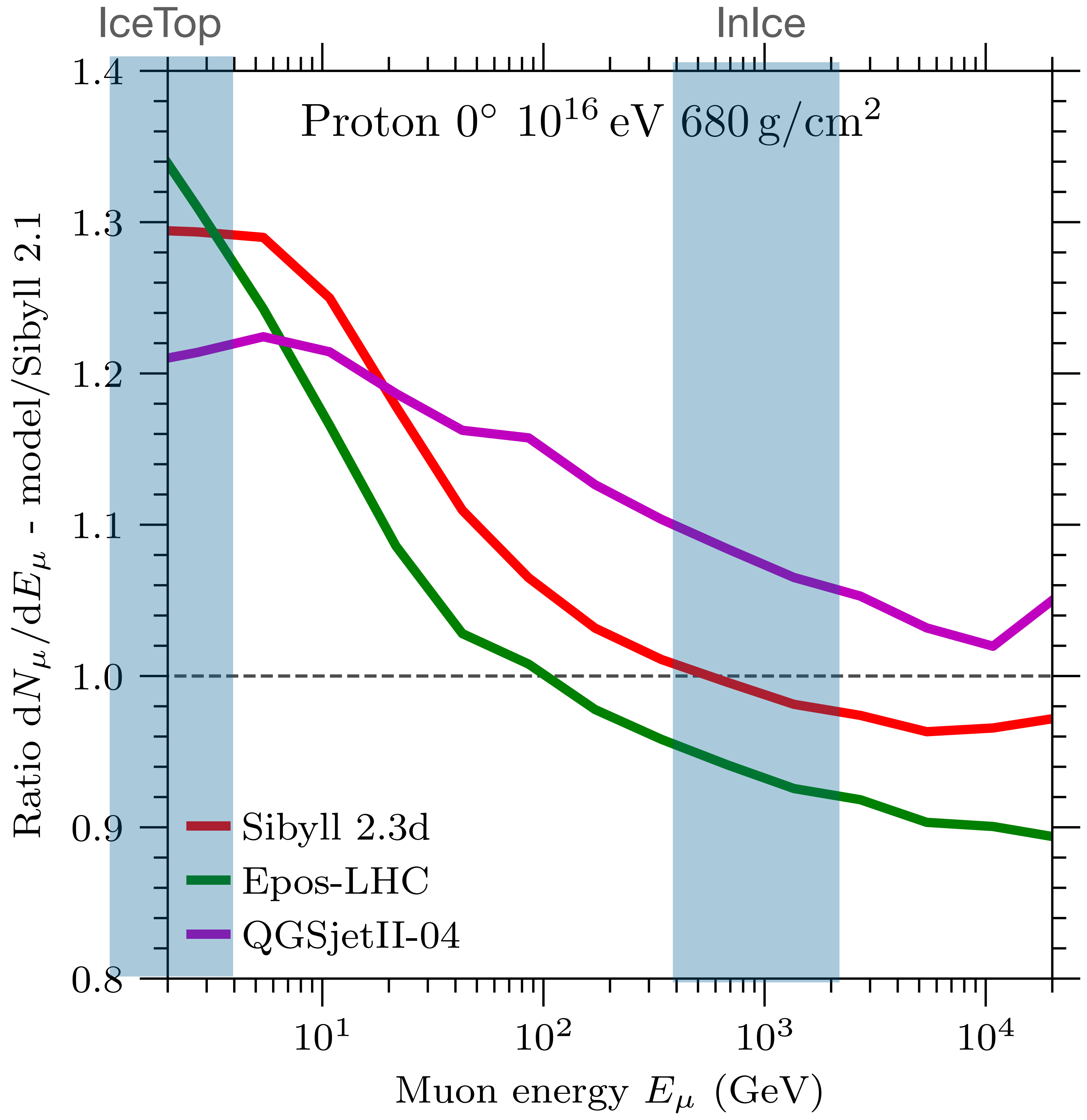


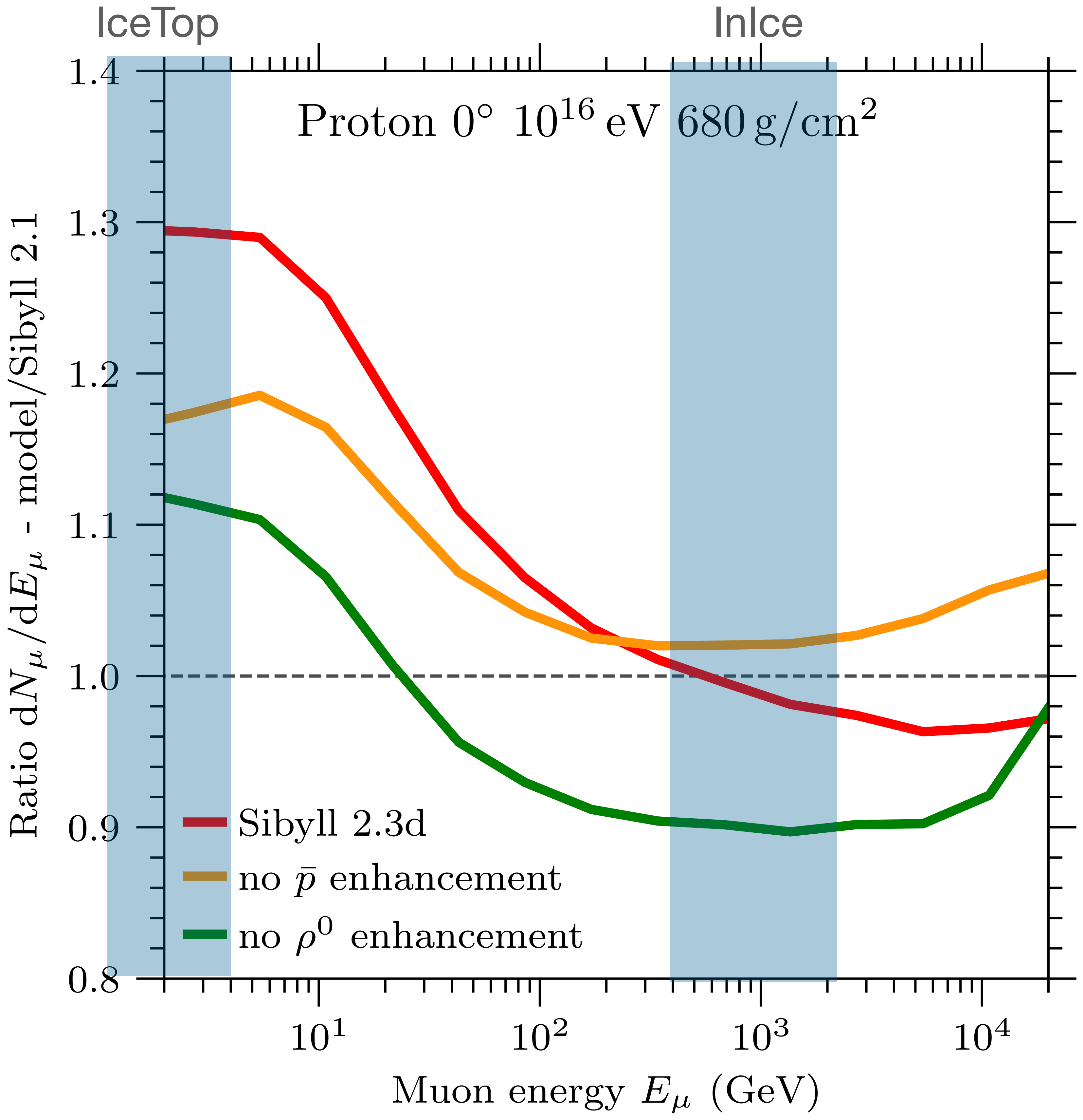
* there are indications for other inconsistencies in Sibyll 2.1, see backup

Backup

Muon measurements

- Differences in muon energy spectrum in EAS





[F. Riehn et al., Phys. Rev. D 102 (2020)]

Self-consistency of hadronic models

- Compare observables in data to p/Fe simulation
  - IceTop LDF slope
  - IceTop GeV muon density
  - High-energy muon bundle energy loss
- Inconsistencies in all models tested

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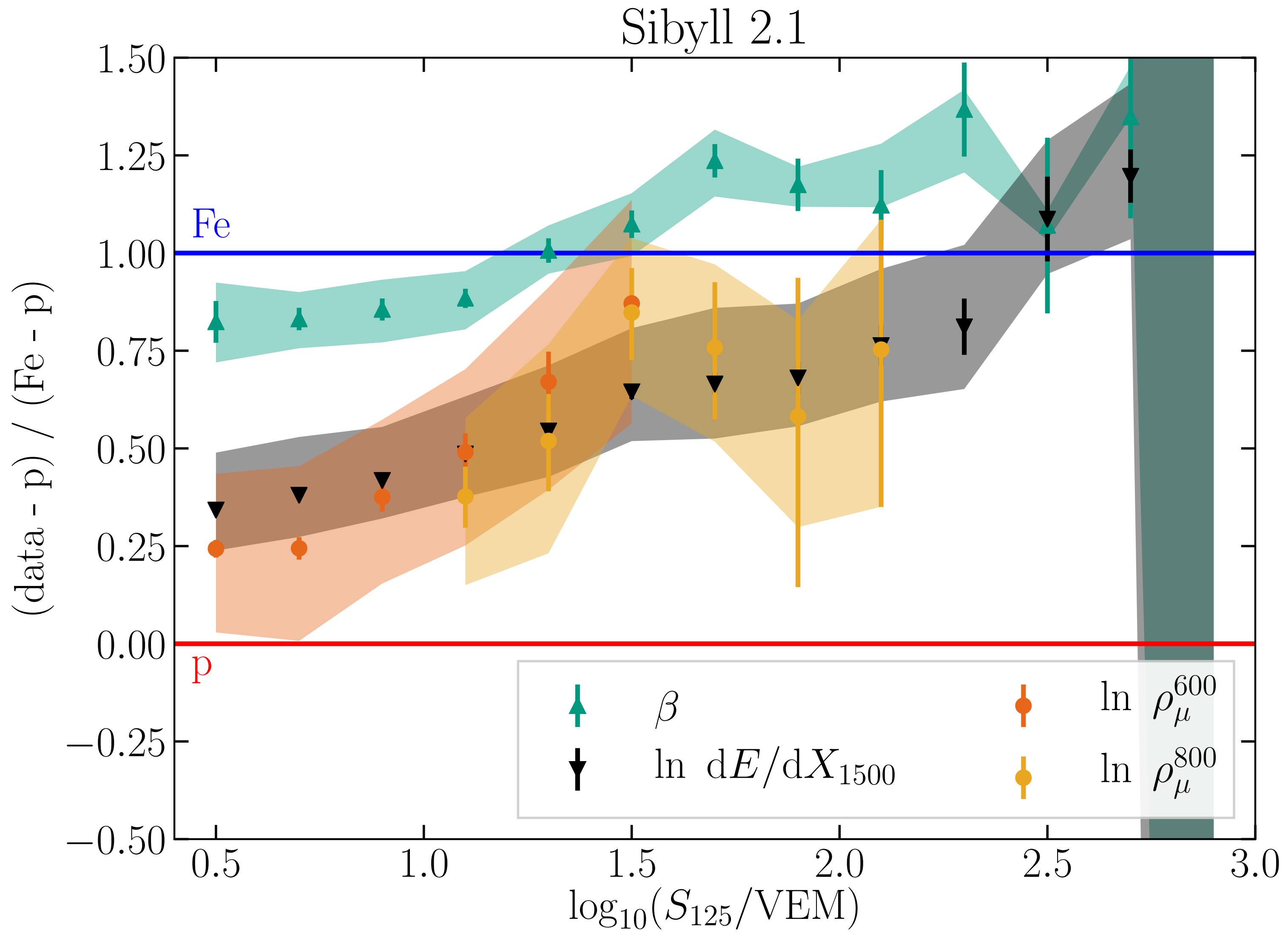
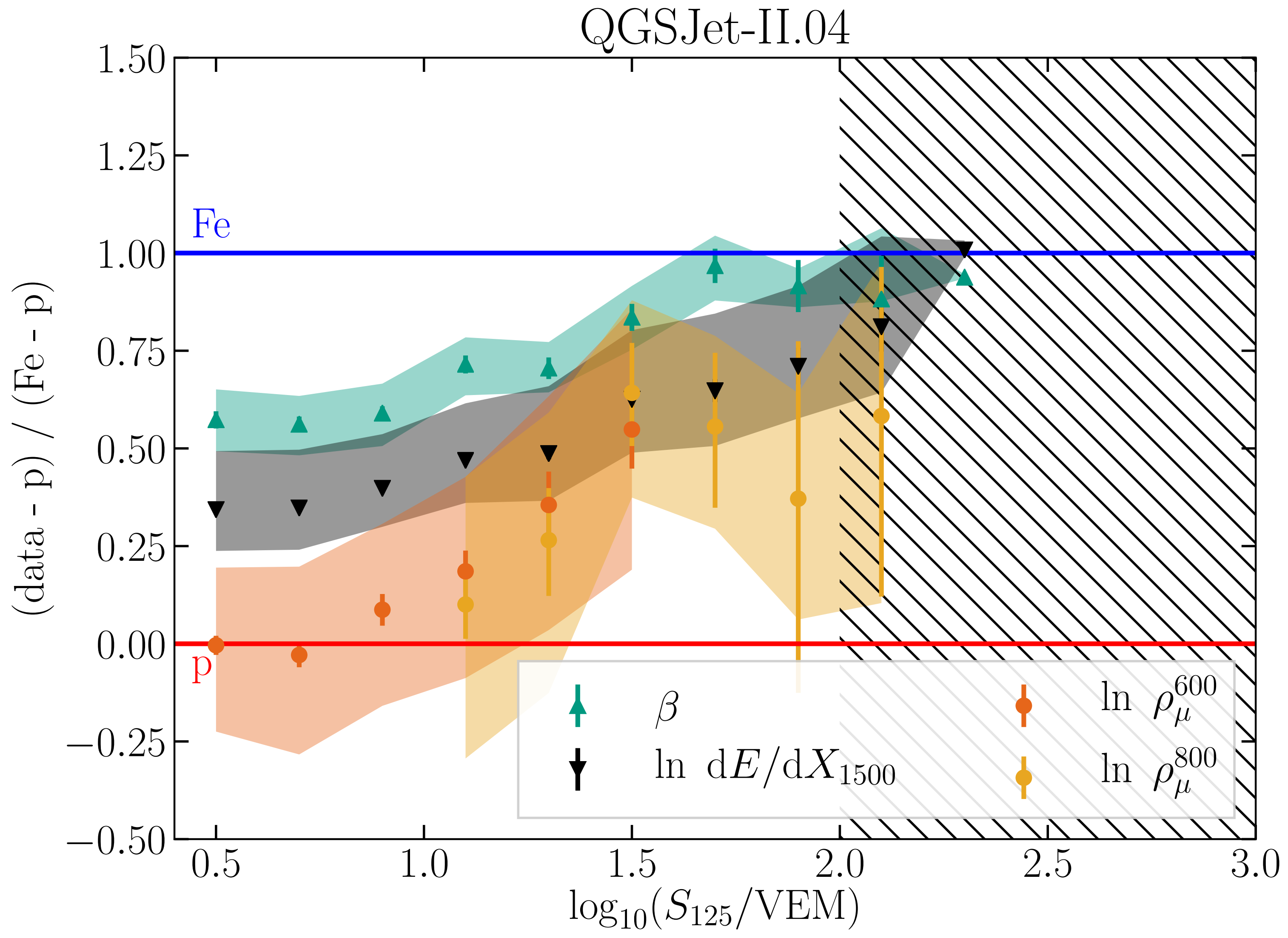
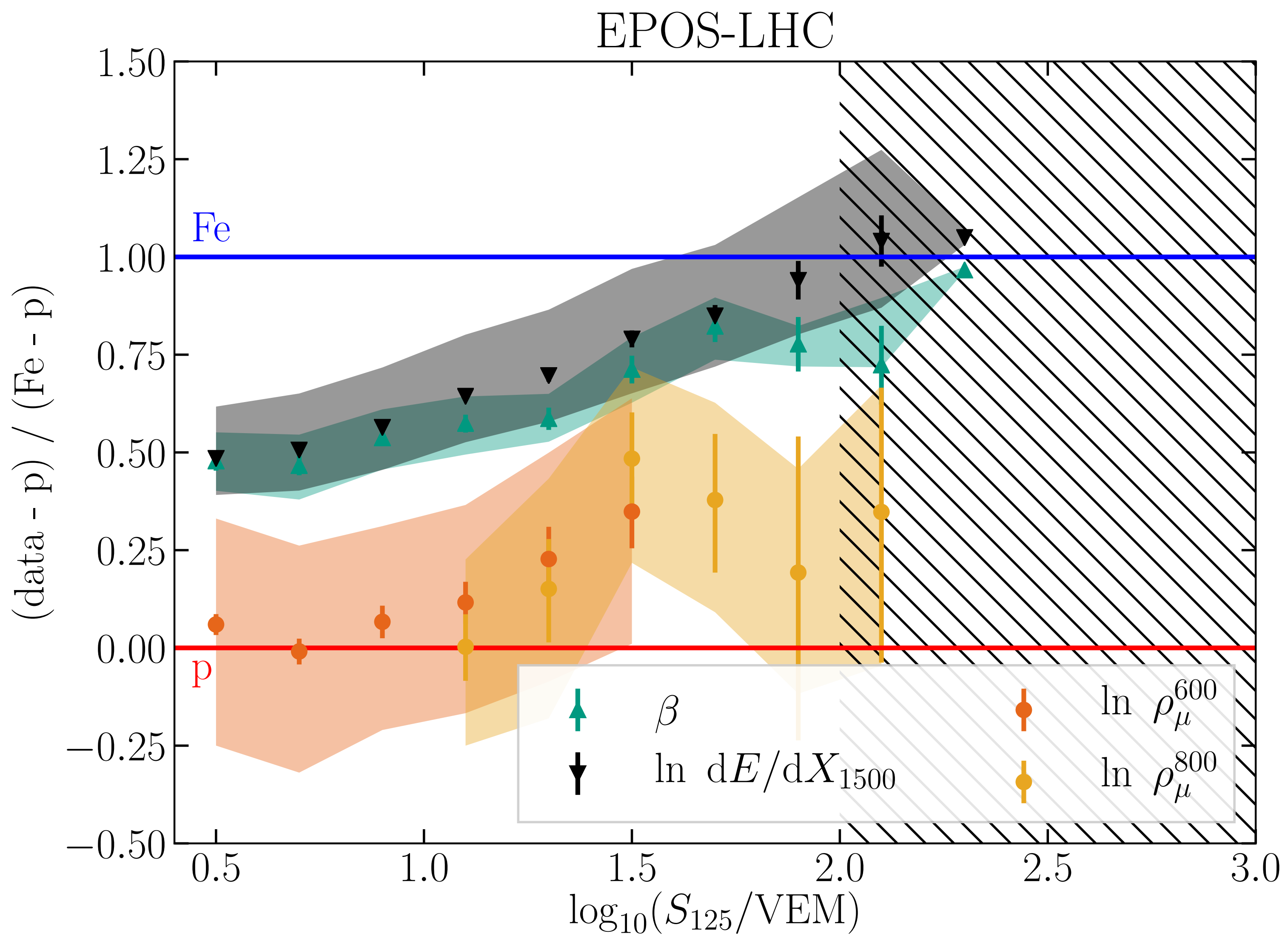


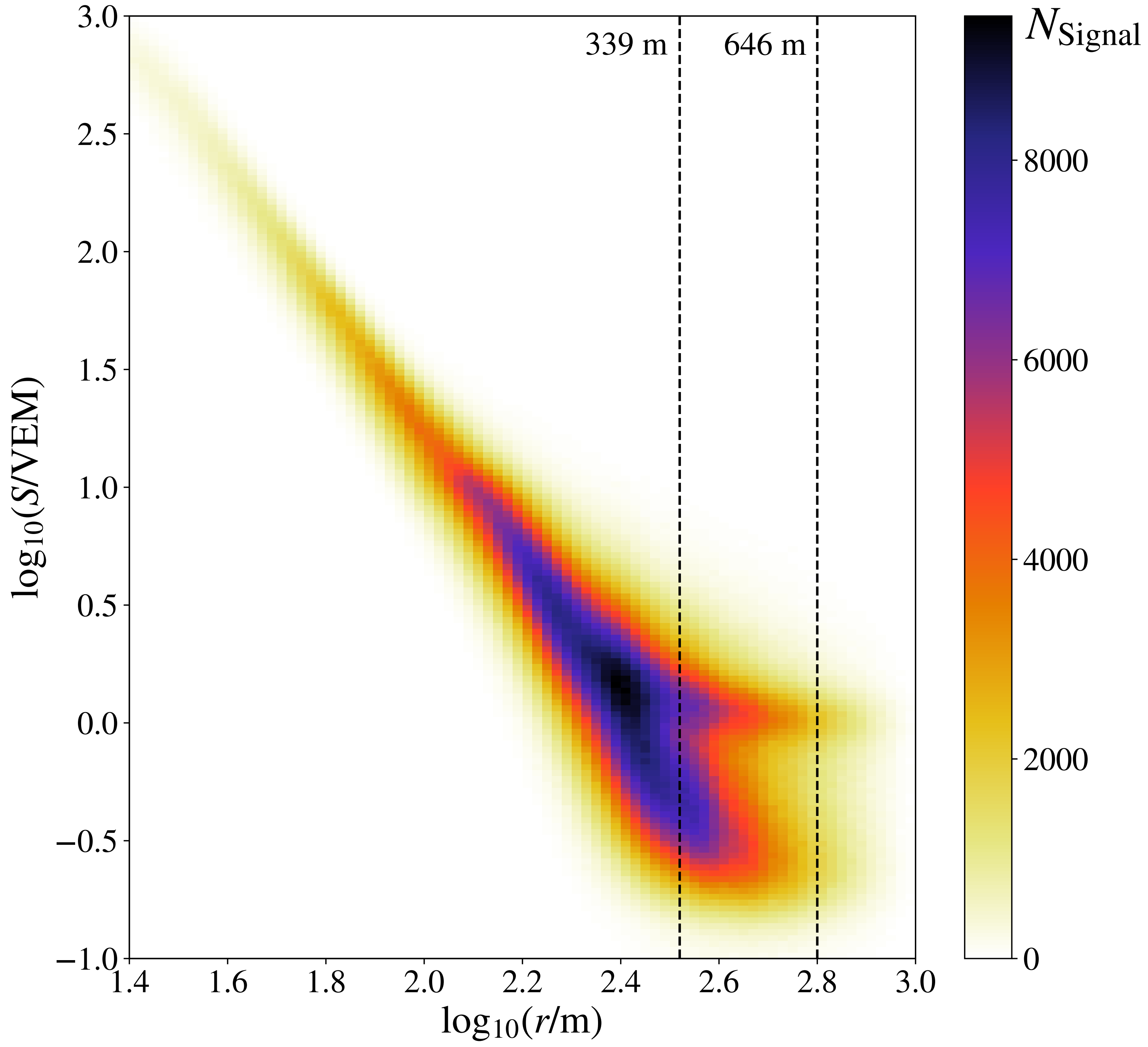


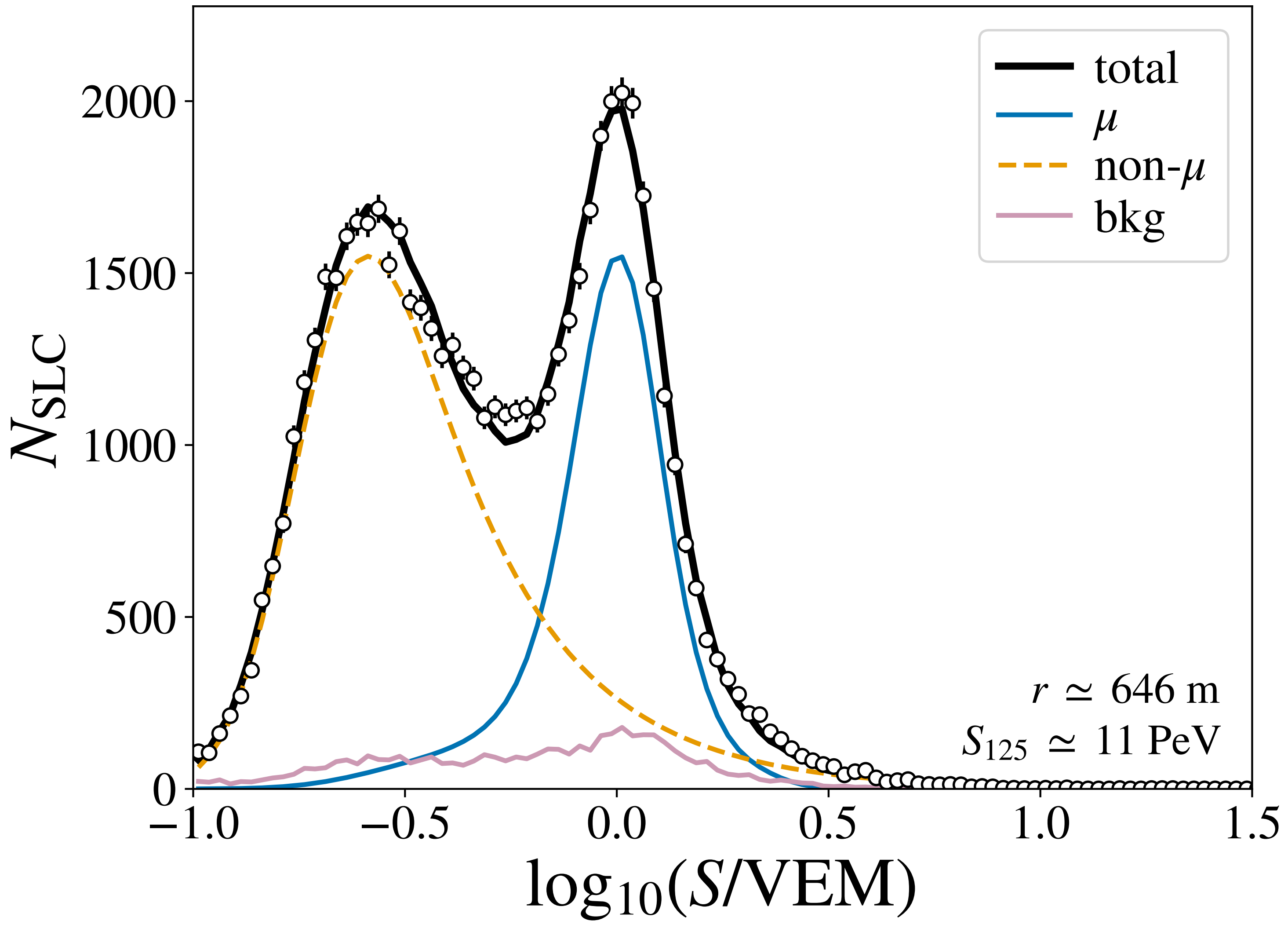


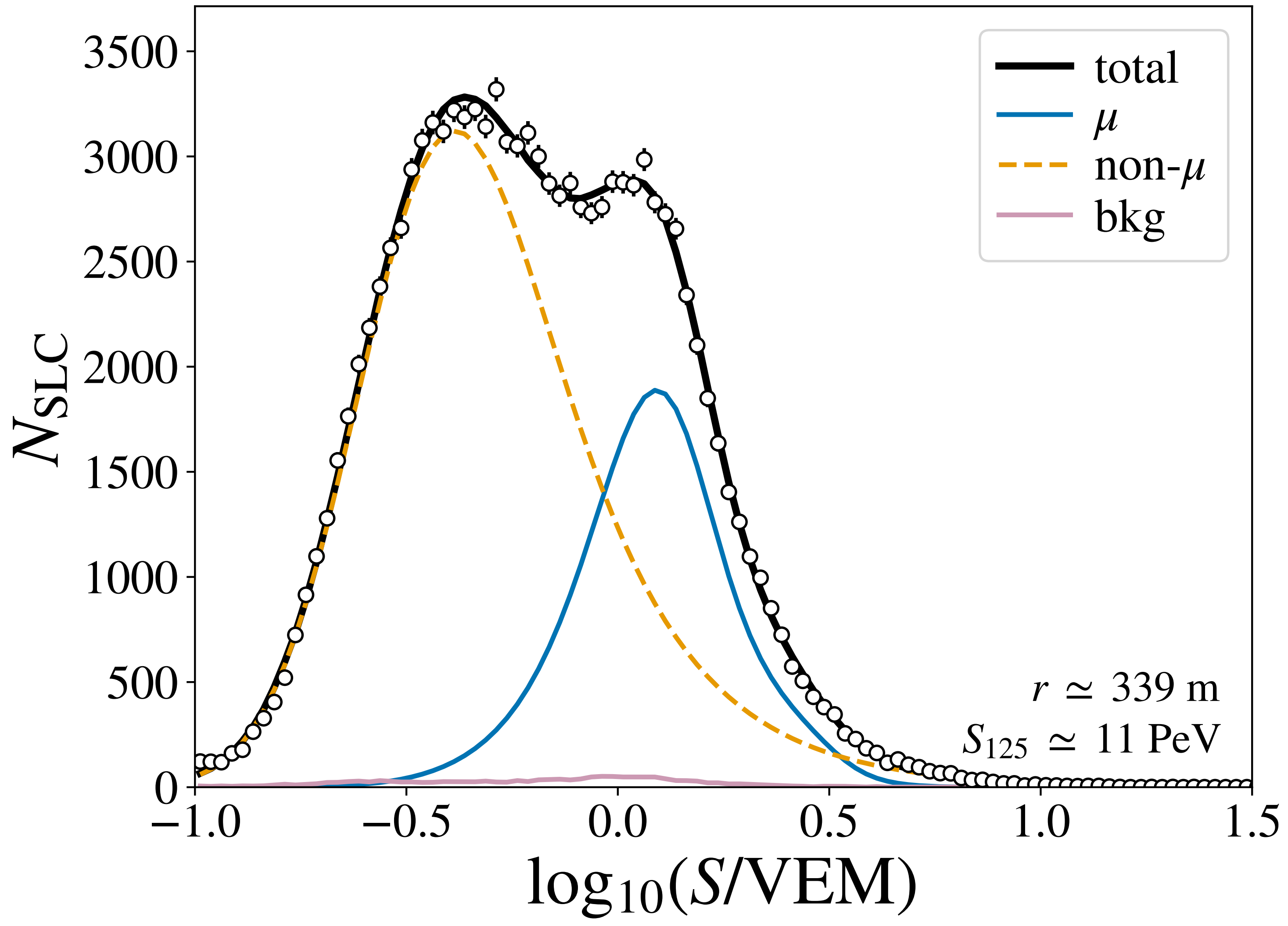
Density of GeV muons in IceTop (1)

[Phys. Rev. D 106 (2022)]

- Statistical analysis based on "muon thumb" in charge-distance histograms





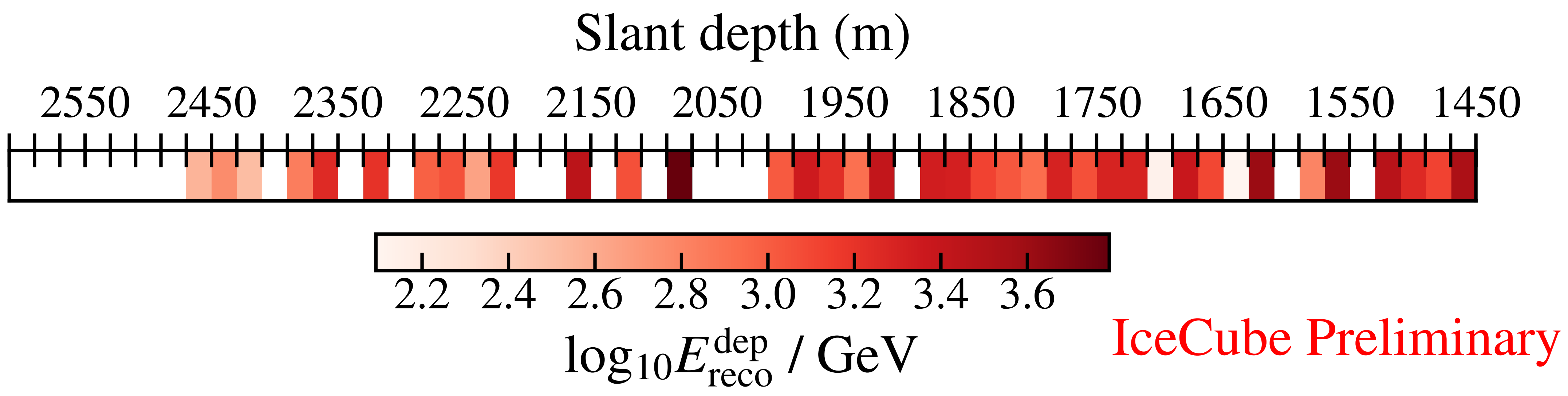


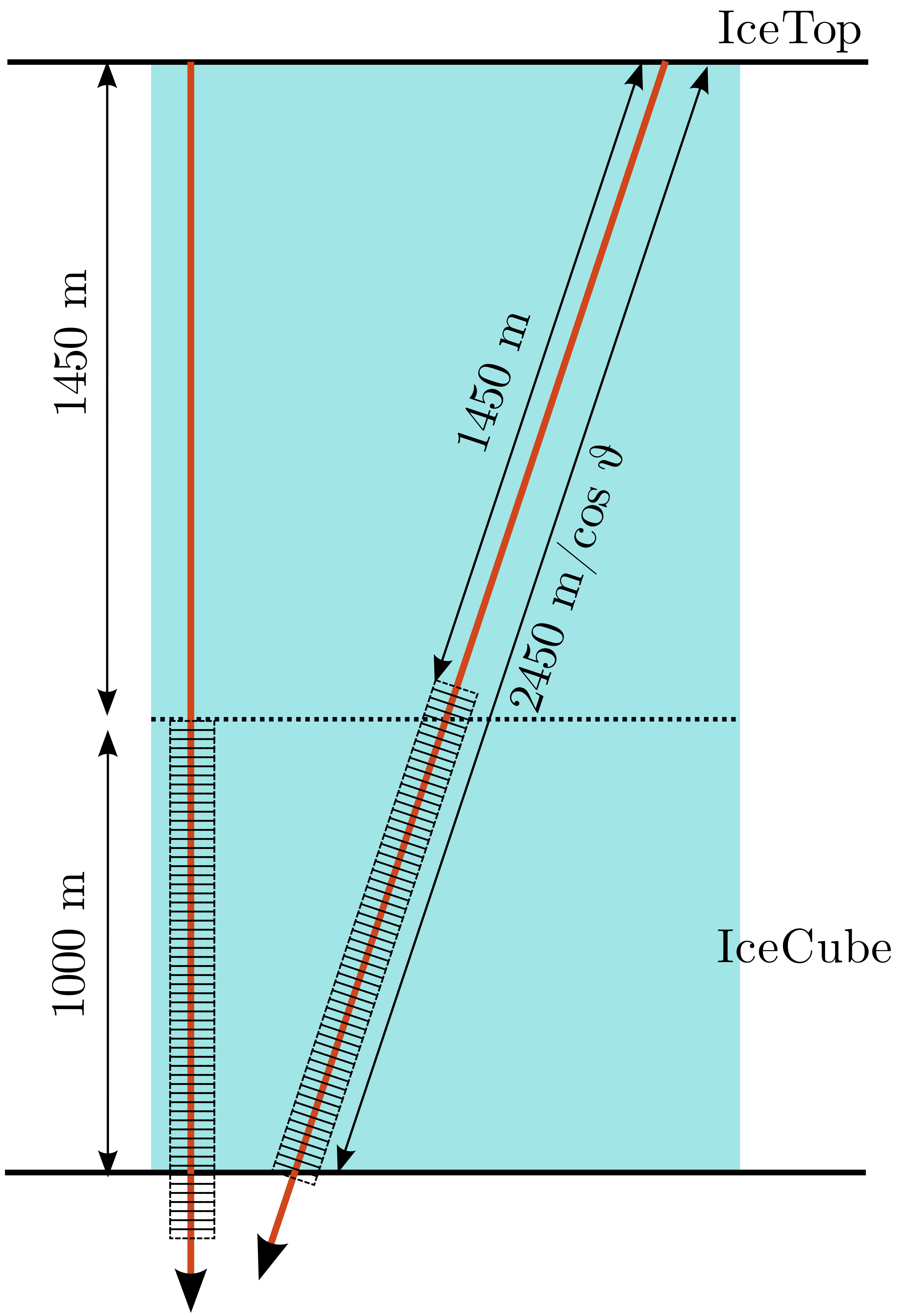
Density of GeV muons in IceTop (2)

[Phys. Rev. D 106 (2022)]

Energy loss vector

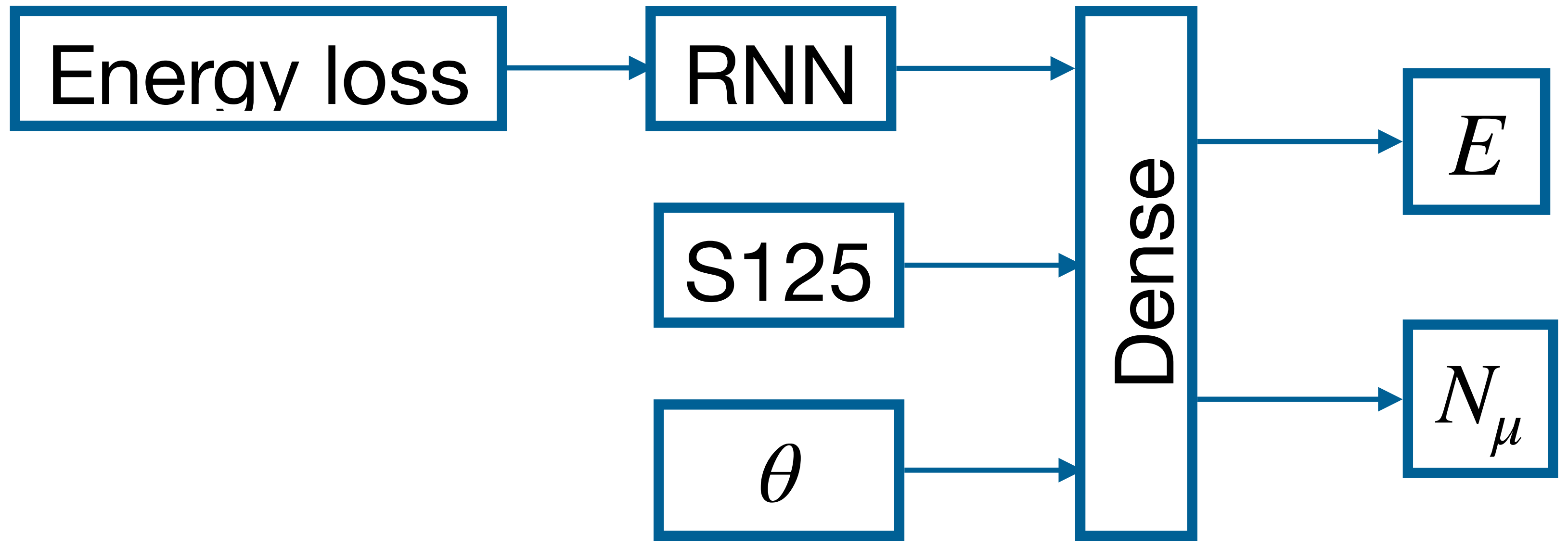
- InIce RNN input
  - Millipede output written as vector of length 57 (20 m segments)





Neural network reconstruction

- Neural network
  - Inputs:
    - IceTop: S_{125}, θ
    - In-Ice: energy loss vector
  - Output
    - Primary energy E
    - # muons > 500 GeV in the shower N_μ



Energy loss

RNN

S125

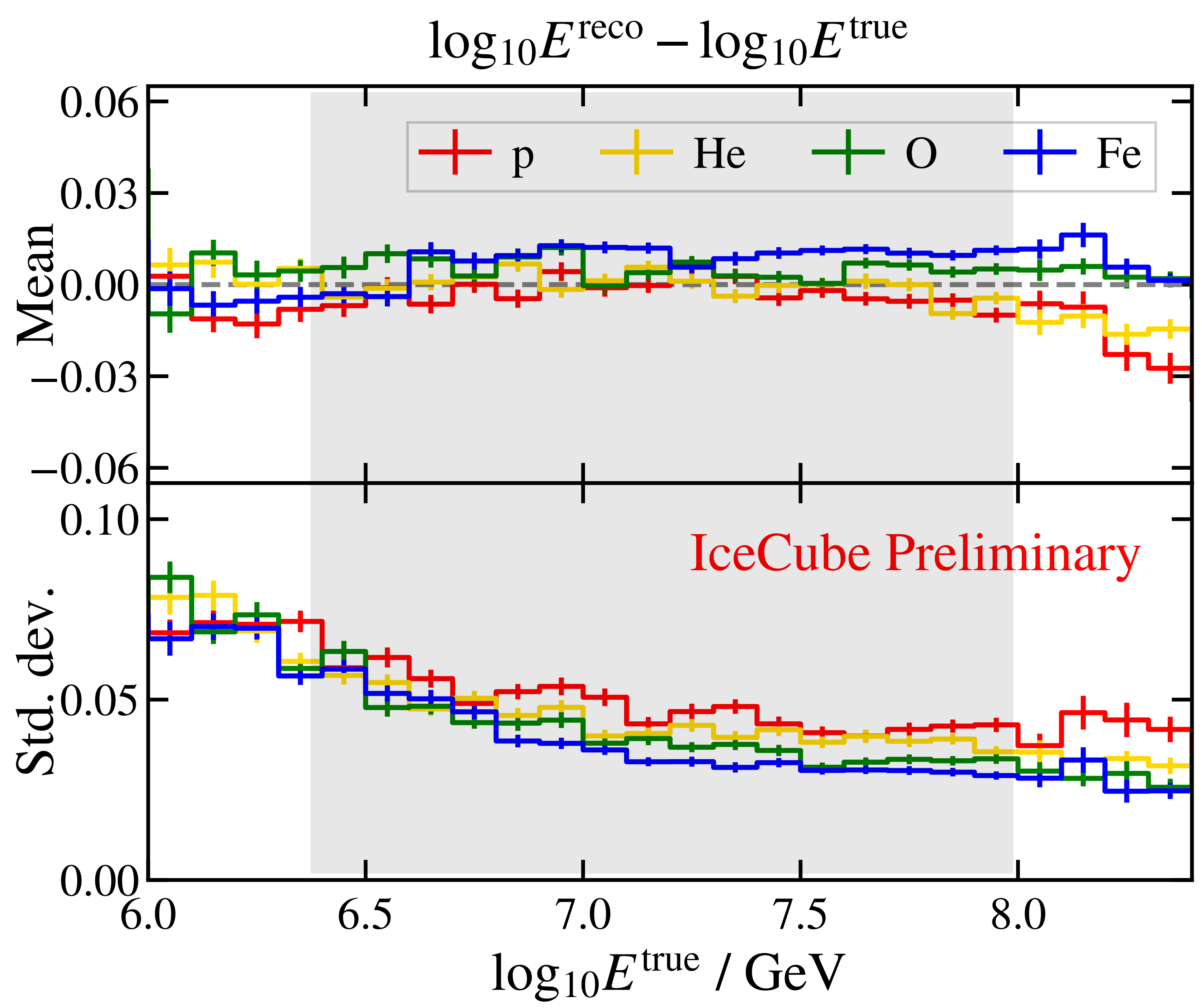
θ

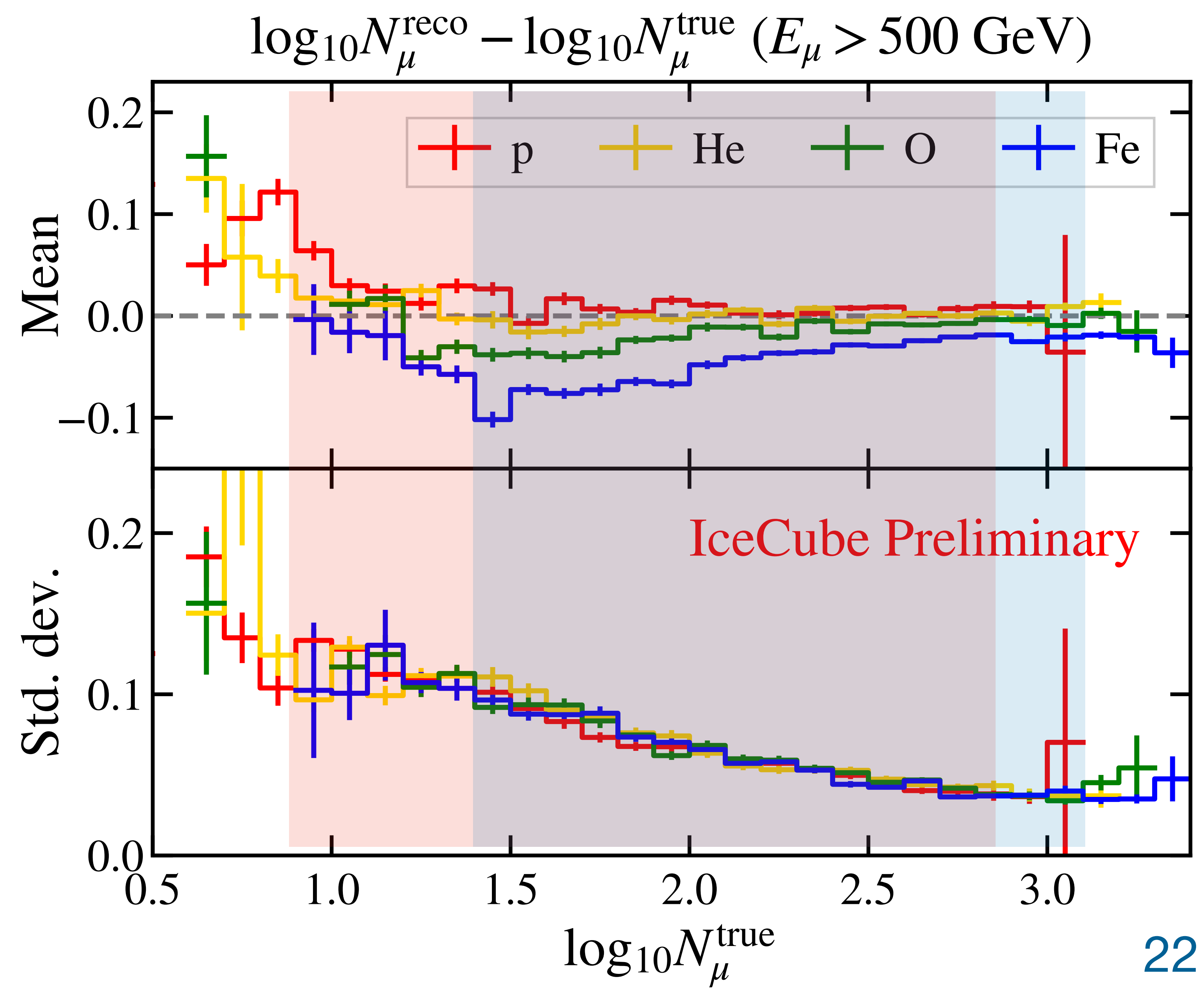
Dense

E

N_μ

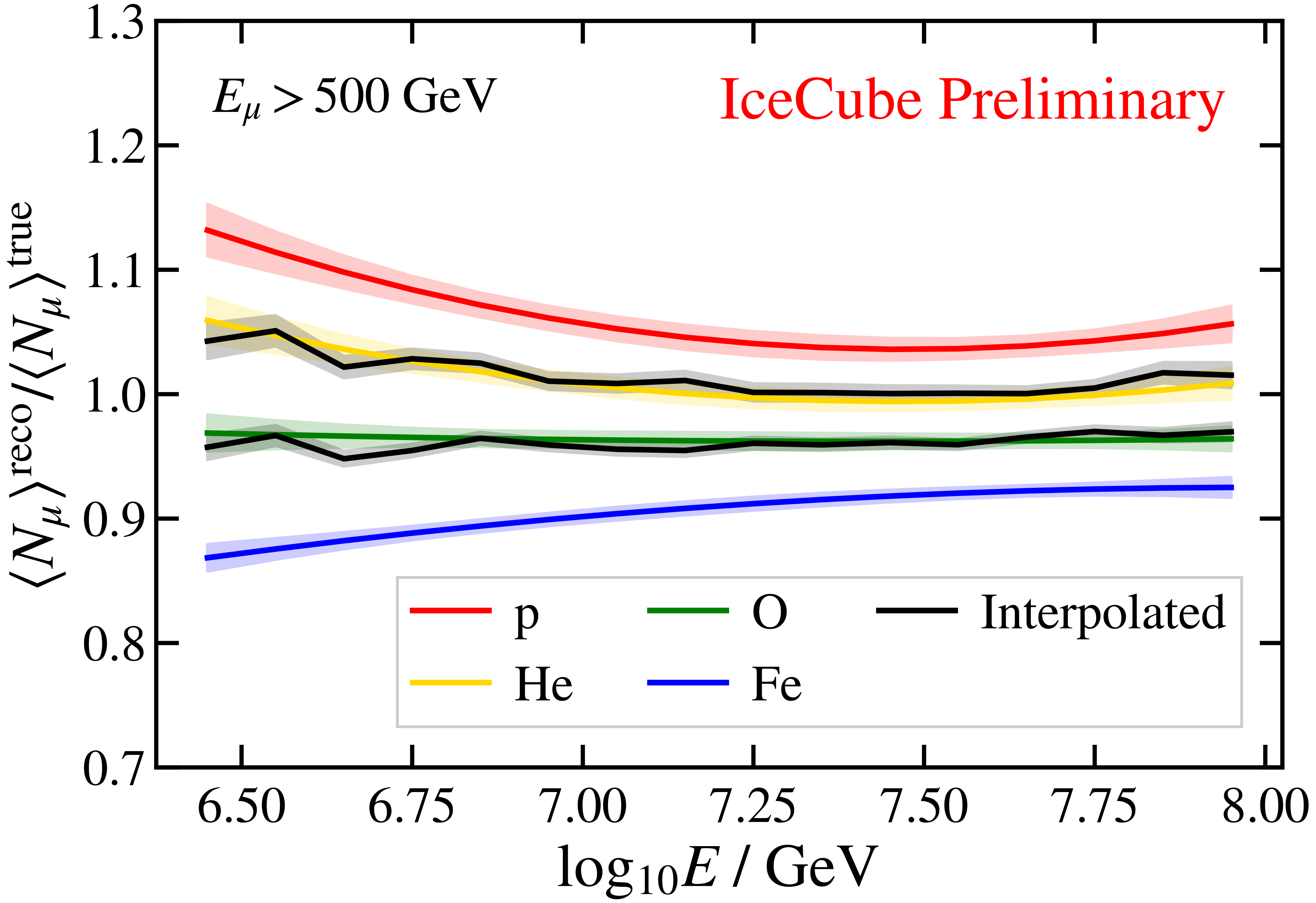
- Training
  - Sibyll 2.1
  - p, He, O, Fe



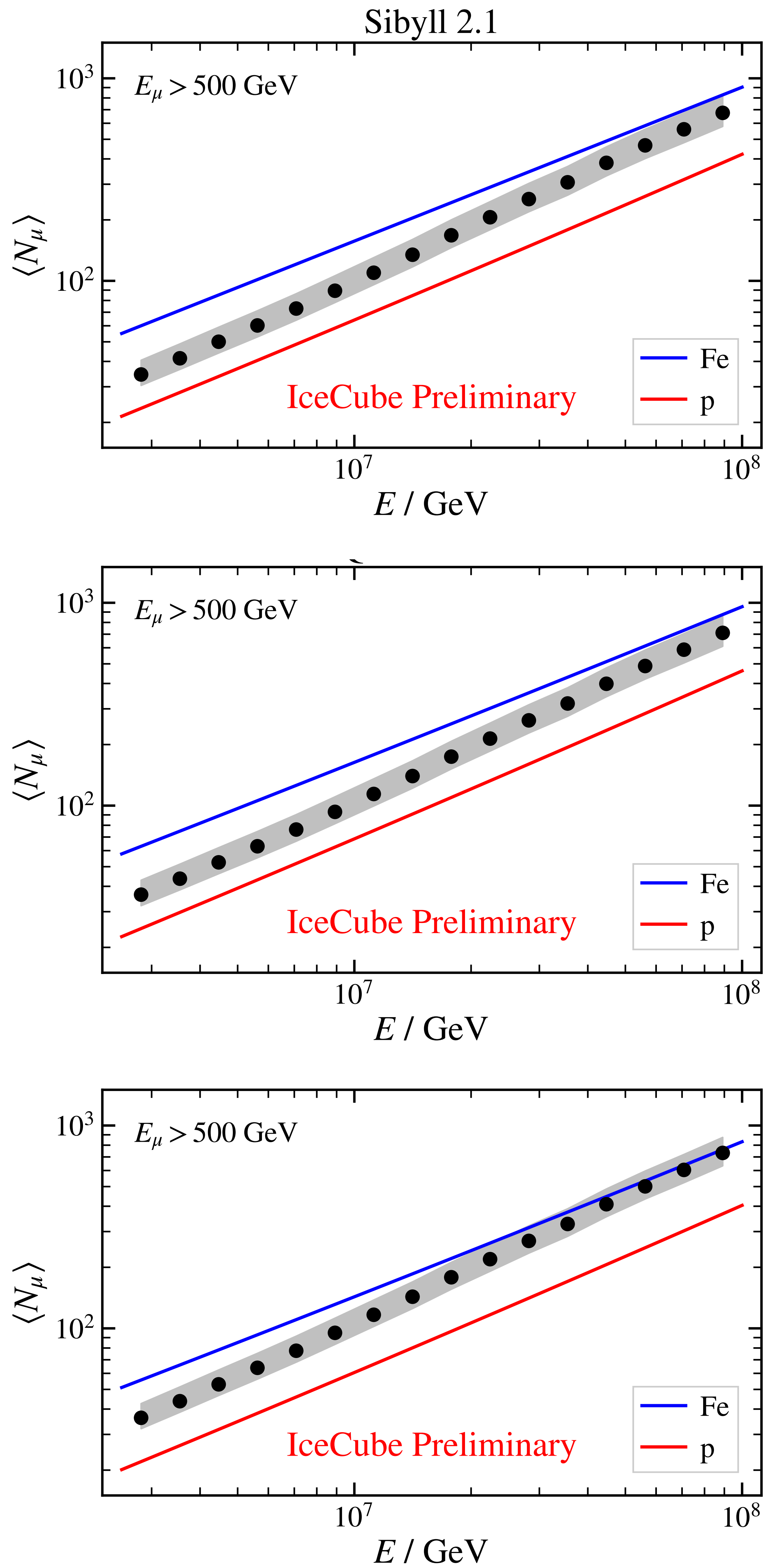


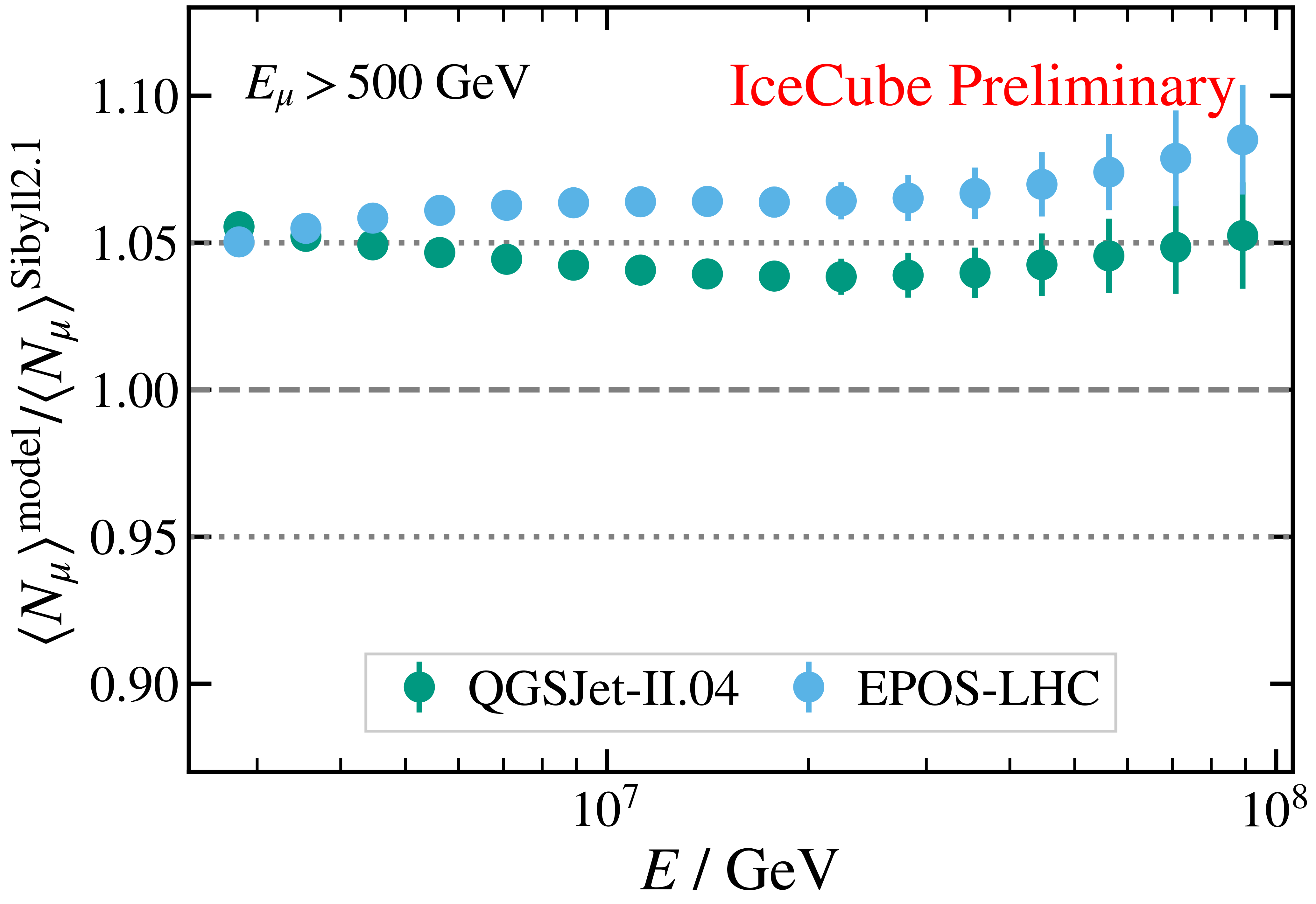
Correction factor mass dependence

- Constructing correction factor from p & Fe for $\langle N_\mu \rangle$ in He & O MC



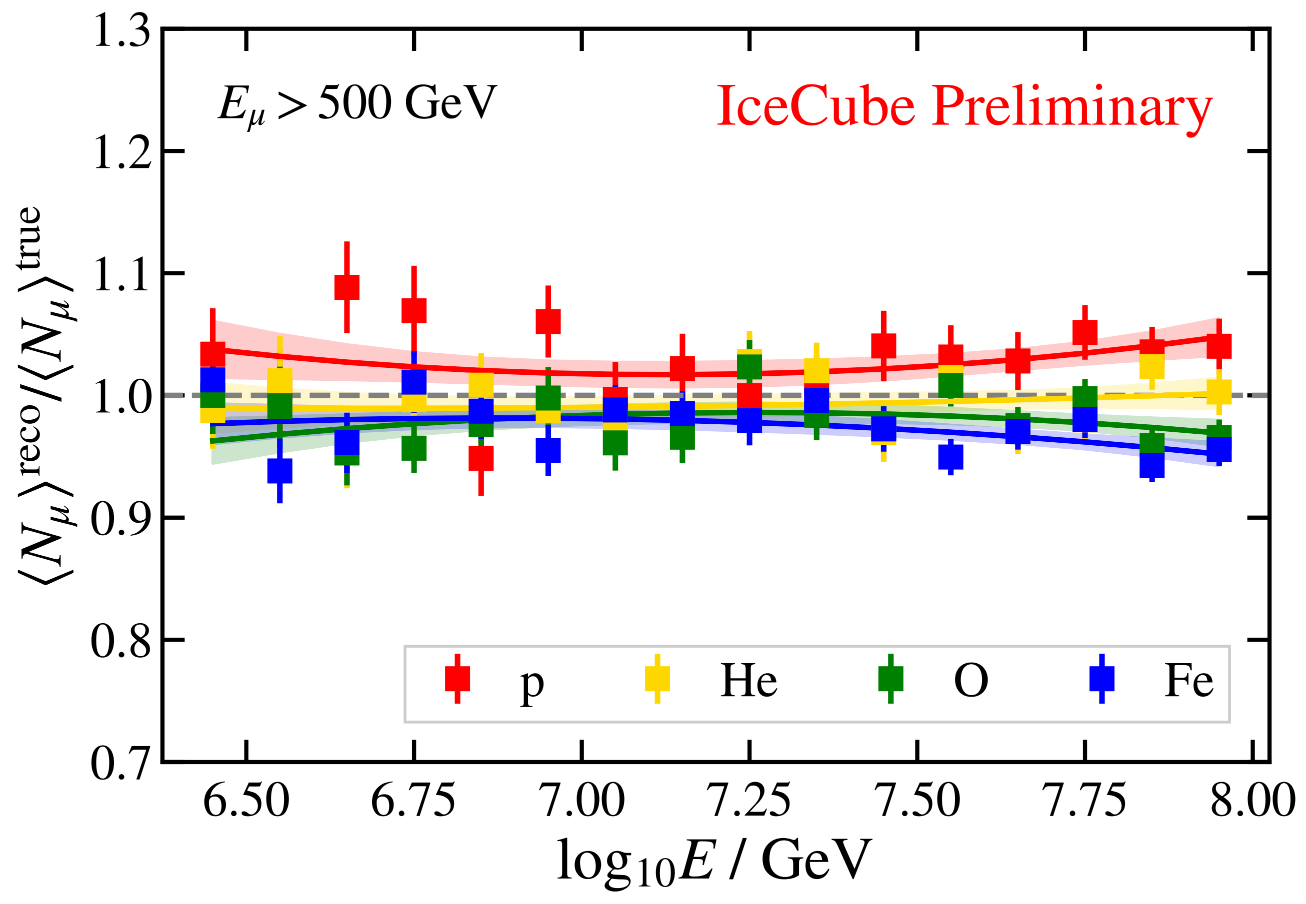
Comparison of individual results

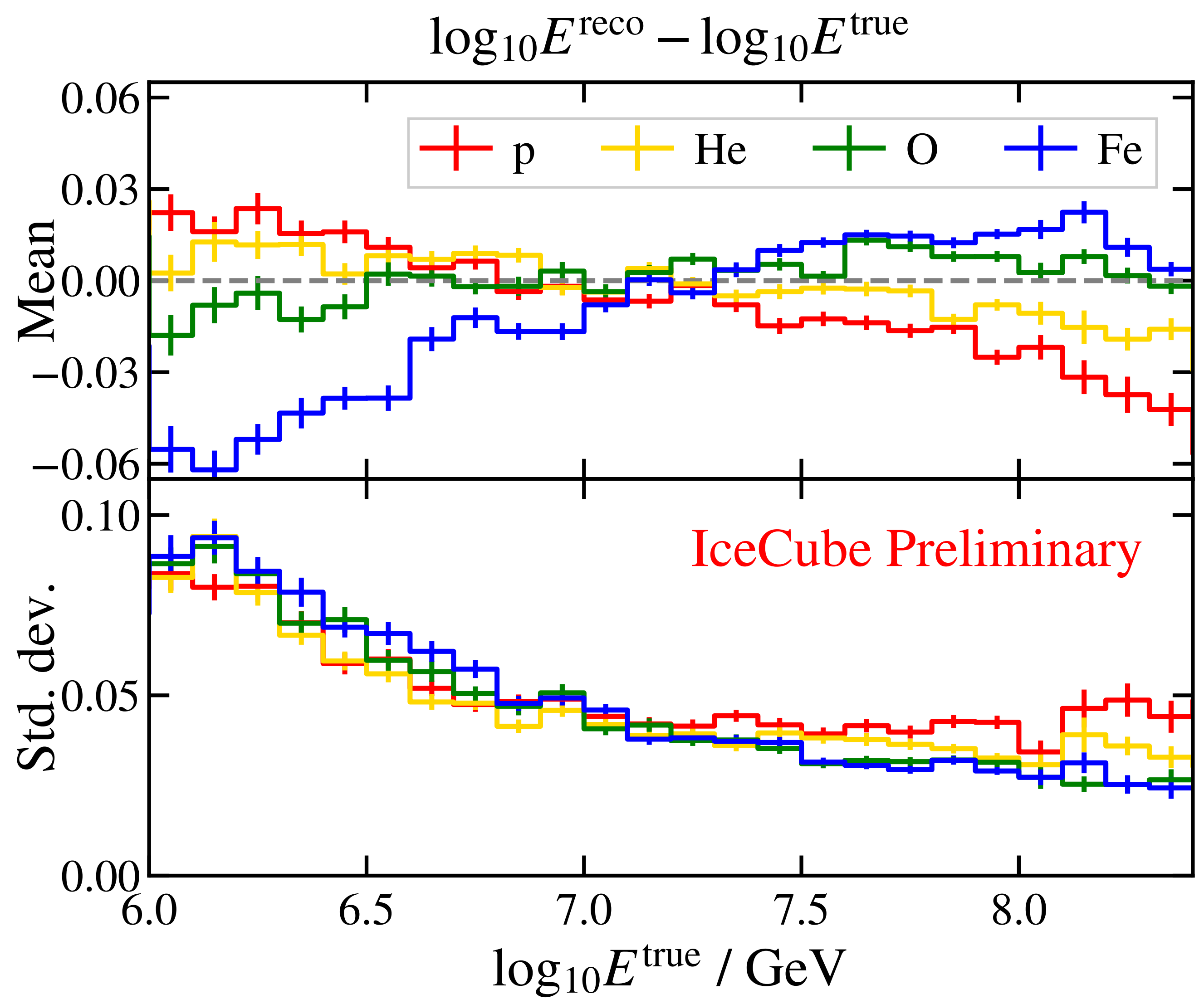


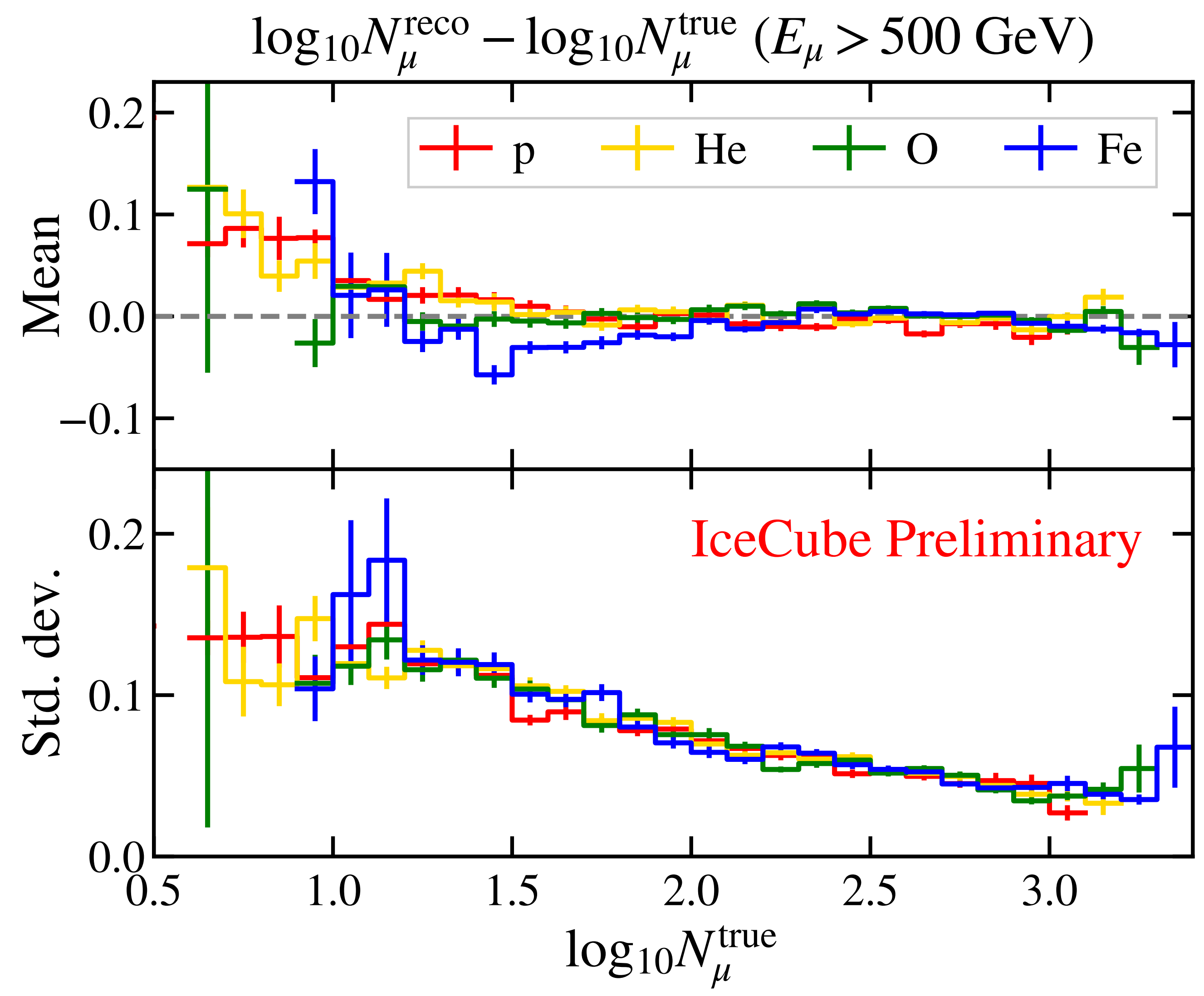


Check: separate neural networks (1)

- Nominal result:
  - IceTop input + IceCube input --> neural net --> E, N
- Separate NNs:
  - IceTop input --> neural net --> E
  - IceCube input --> neural net --> N

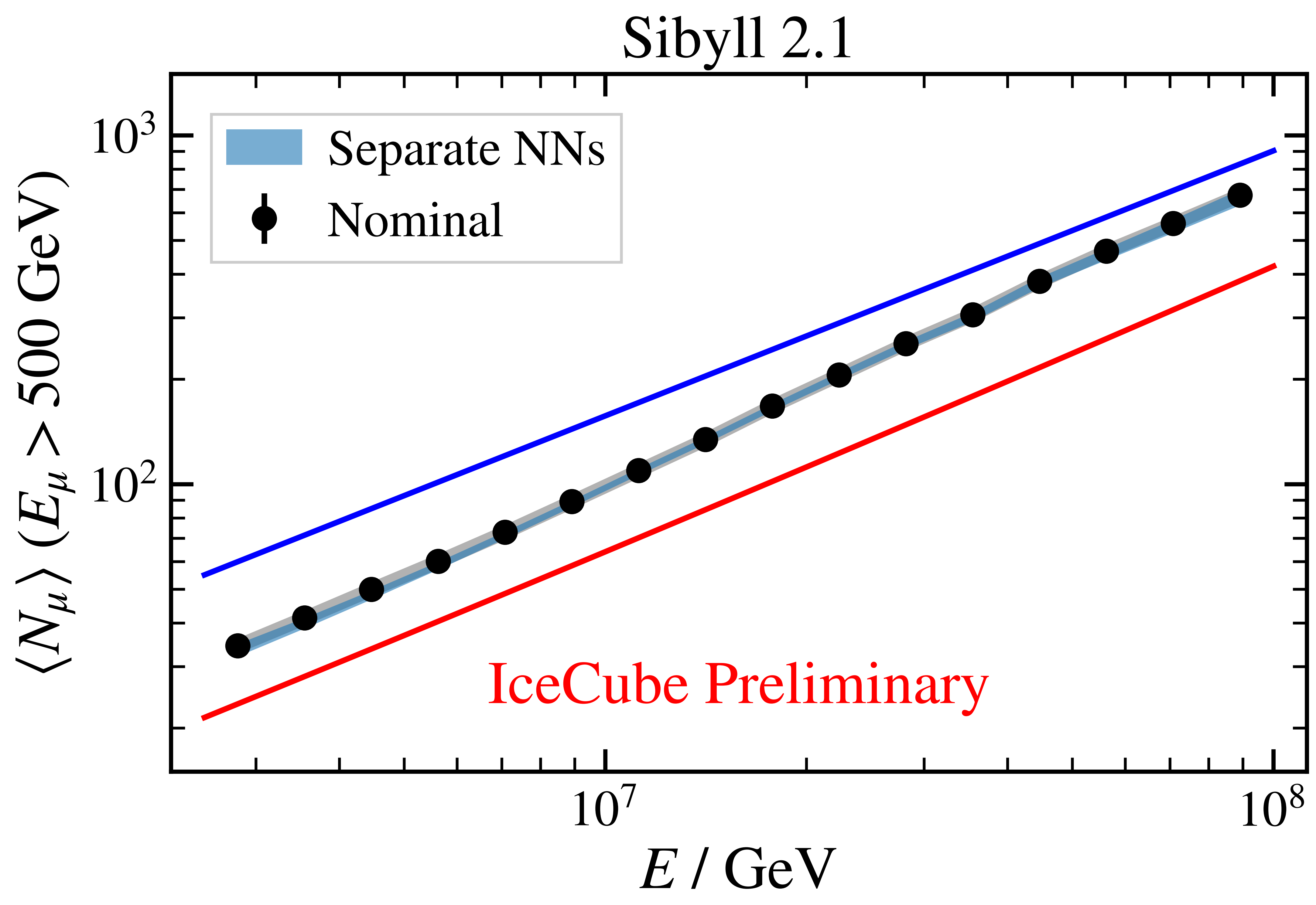






Check: separate neural networks (2)

- Nominal result:
  - IceTop input + IceCube input --> neural net --> E, N
- Separate NNs:
  - IceTop input --> neural net --> E
  - IceCube input --> neural net --> N
- Consistent results



Check: energy reconstruction

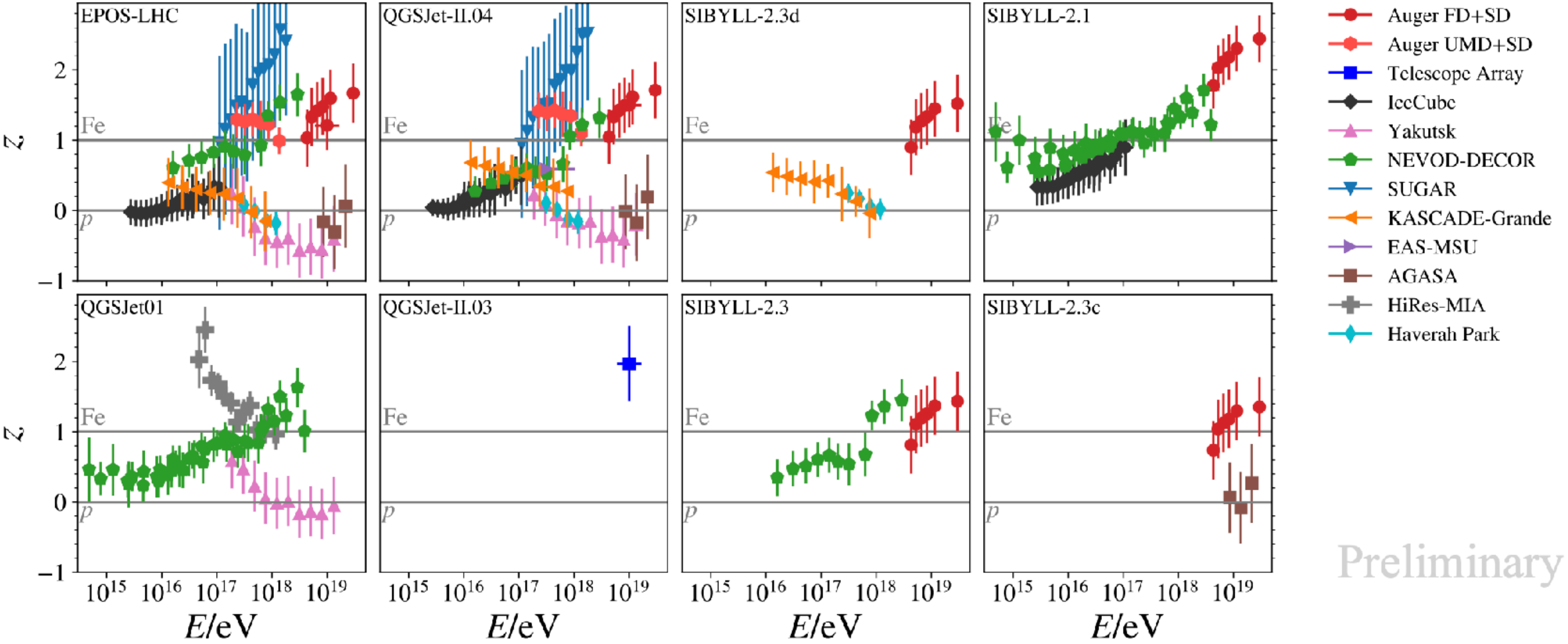
- Performed different checks related to energy reconstruction
  - Separate neural network from N_μ reconstruction
  - Energy reconstruction based on S125, as used in GeV muon density analysis
  - Neural network based on EPOS-LHC

→ **all agree with the nominal result!**

Plots will be included in paper.

Combined muon data analysis

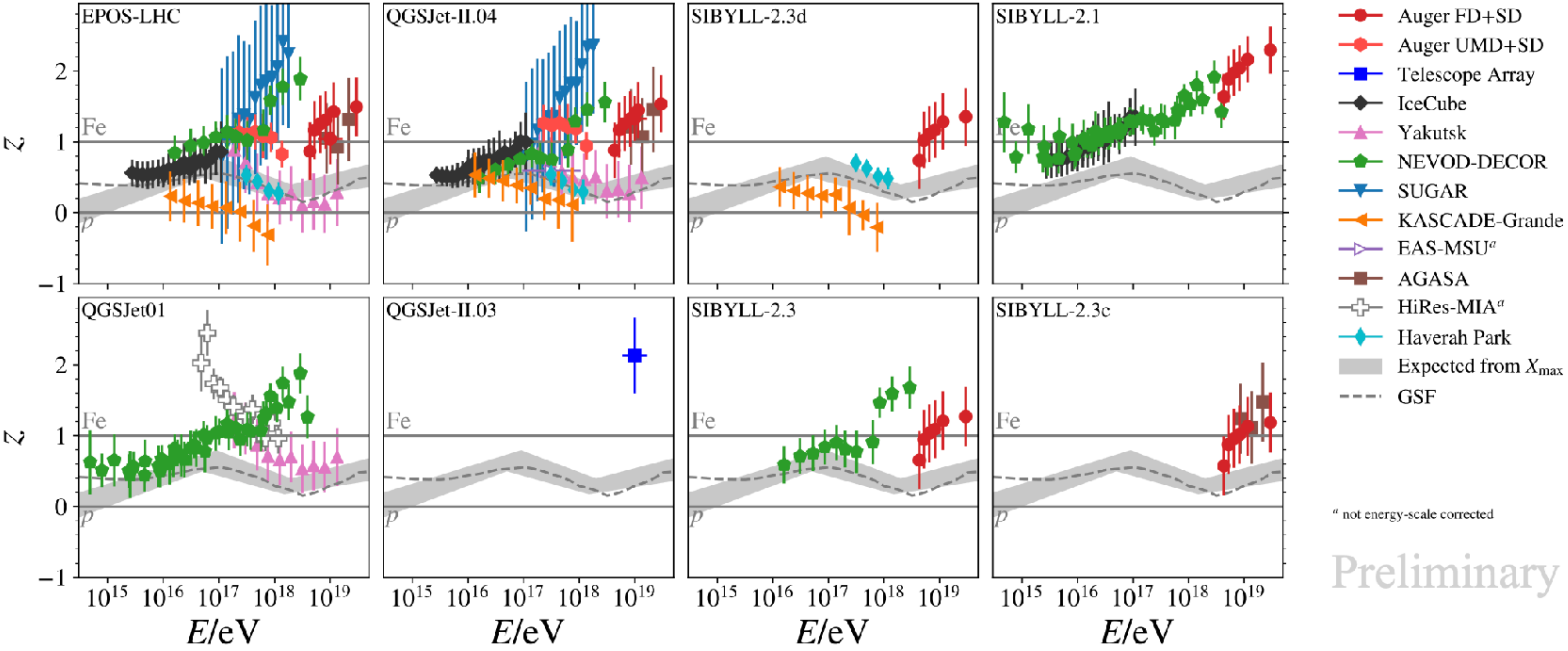
- by Working group on Hadronic Interacions and Shower Physics (WHISP)



Before energy cross calibration

Combined muon data analysis

- After cross-calibration of energy scales



After energy cross calibration