UNIVERSITY OF DELAWARE
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Muons in air showers with IceCube

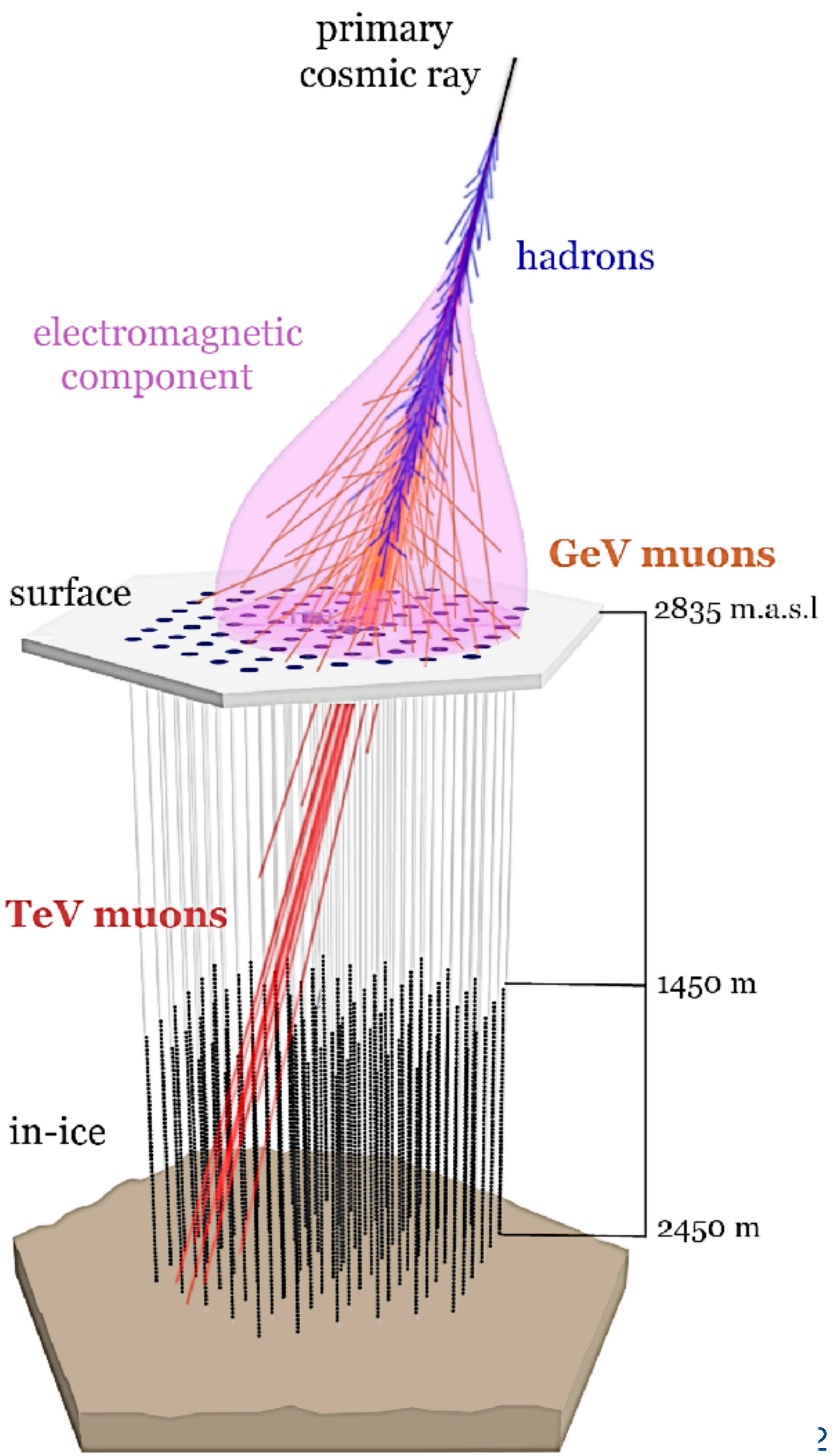
Muon density at ground and high-energy muon multiplicity

Stef Verpoest for the IceCube collaboration

UHECR 2024, November 20, Malargüe, Argentina

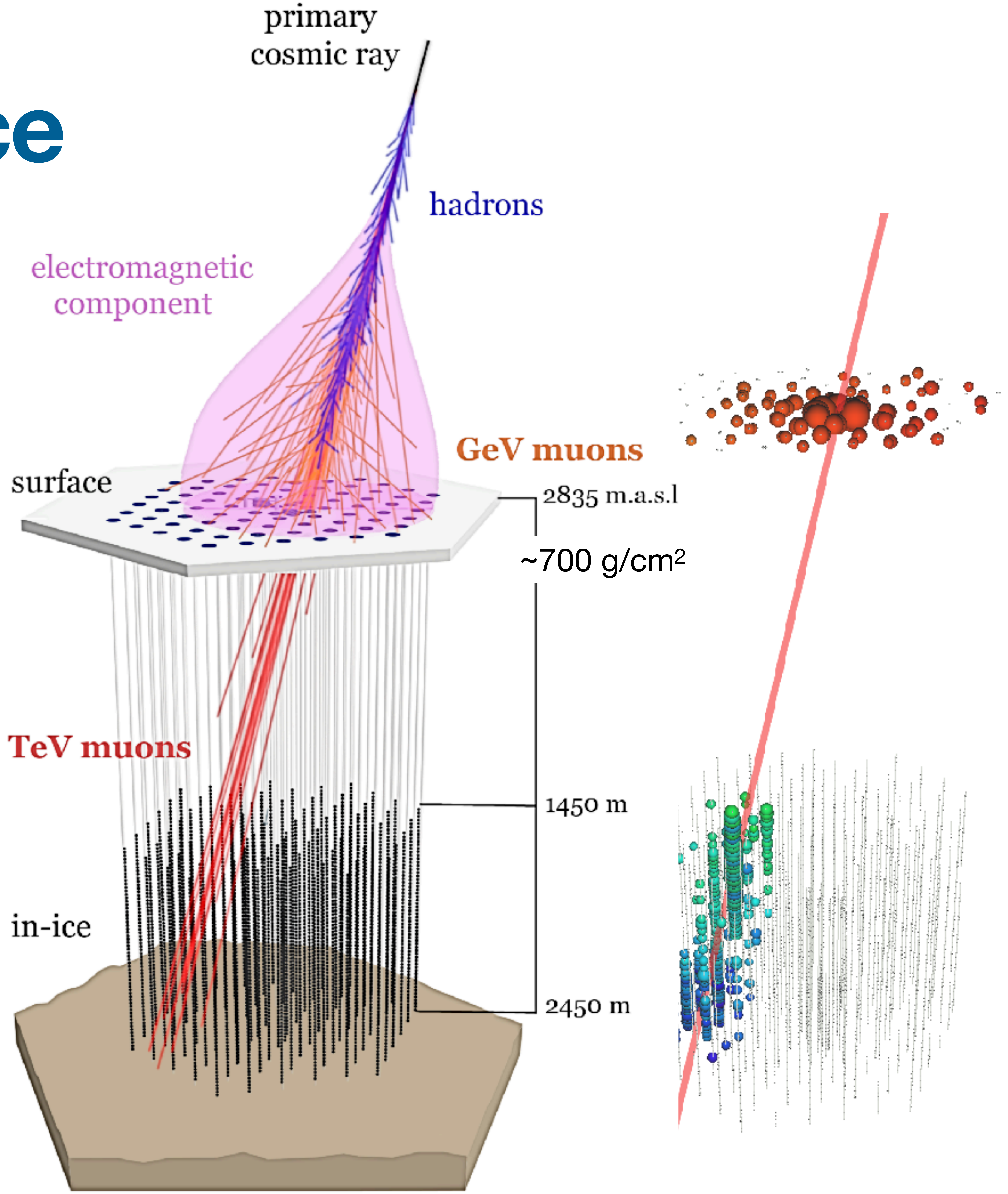
Outline

- Cosmic rays with IceCube
- Low-energy muons with IceTop
- High-energy muons in IceTop-InIce coincidences
- Consistency of observations
- Future instrumentation
- Summary



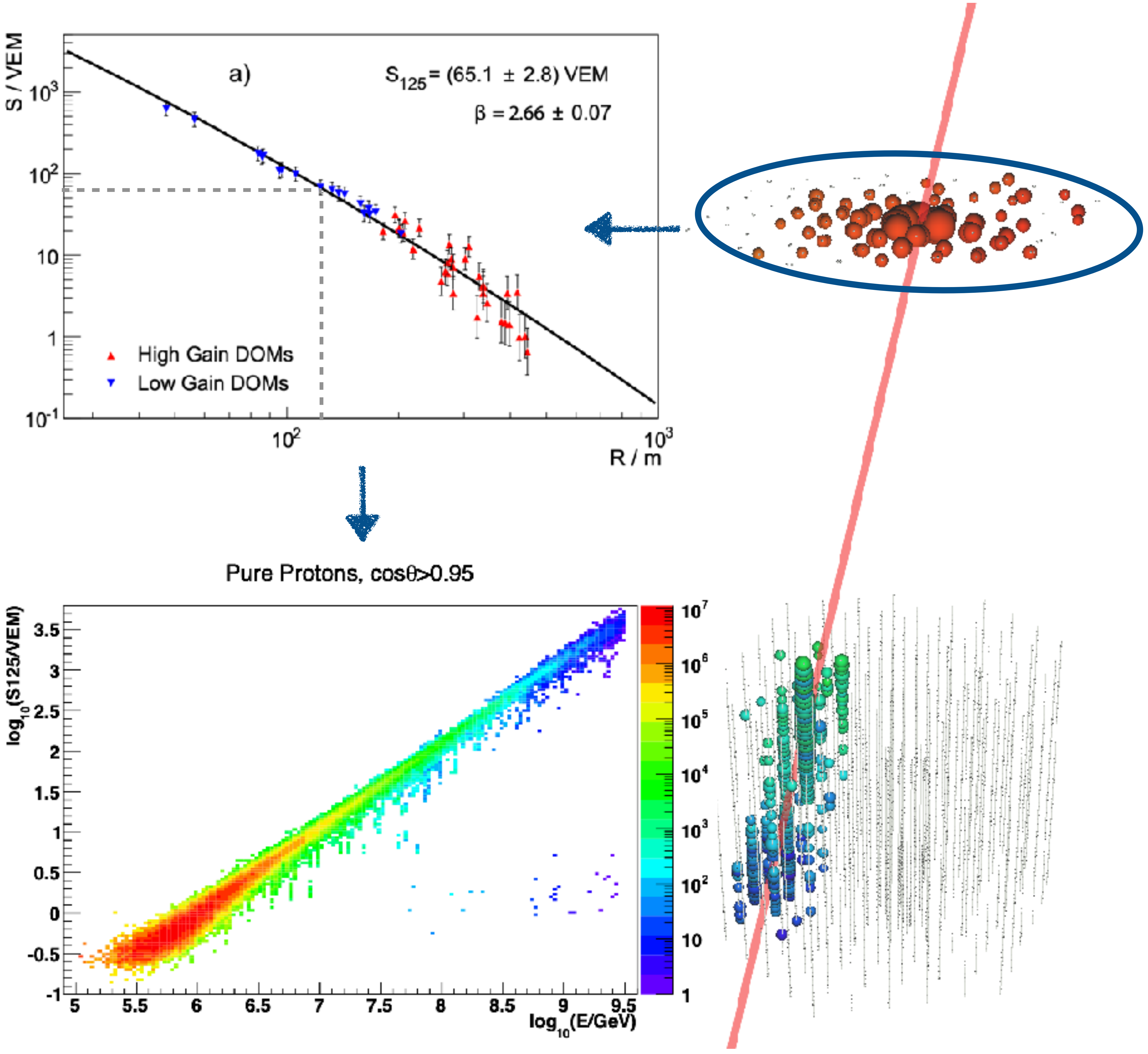
IceTop & IceCube in-ice

- IceTop
  - ~1 km² air-shower array
  - 162 ice-Cherenkov tanks
- IceCube in-ice array
  - ~1 km³ Cherenkov detector
  - ~5000 Digital Optical Modules
- Combined: unique EAS detector
  - **PeV - EeV primary energy**
  - Electromagnetic component
  - **Surface muons & high-energy muons**



Shower reconstruction with IceTop

- Reconstruction using surface signals
  - Core position
  - Direction (θ, ϕ)
  - **Shower size** S_{125}
  - LDF slope β
- Shower size - energy relation
  - Dominated by EM component
  - S_{125} **proxy for shower energy**
- Analyses in this presentation
  - **Core contained** in IceTop
  - **Near-vertical**: $\cos\theta > 0.95$ $(\theta \lesssim 18°)$

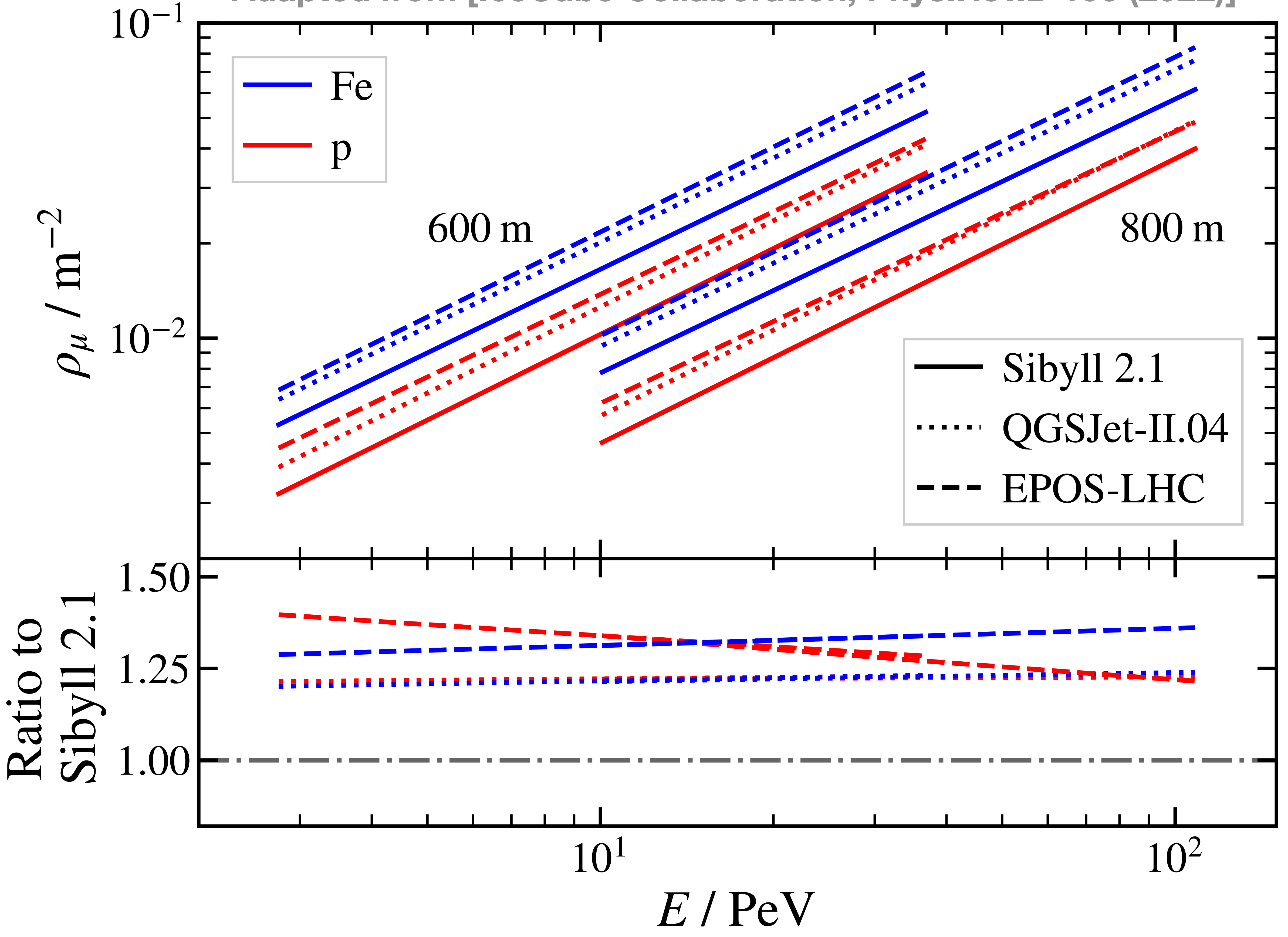


GeV muons in IceTop

Goal & simulation predictions

- Surface muon density
  - **IceTop-only** analysis
  - Near-vertical $\cos\theta > 0.95$ ($\theta \lesssim 18°$)
  - **Lateral distance of 600 m and 800 m**
  - Model dependence
    - QGSJet-II.04 / Sibyll 2.1 ≈ 1.2
    - EPOS-LHC / Sibyll 2.1 ≈ 1.3

Adapted from [IceCube Collaboration, Phys.Rev.D 106 (2022)]

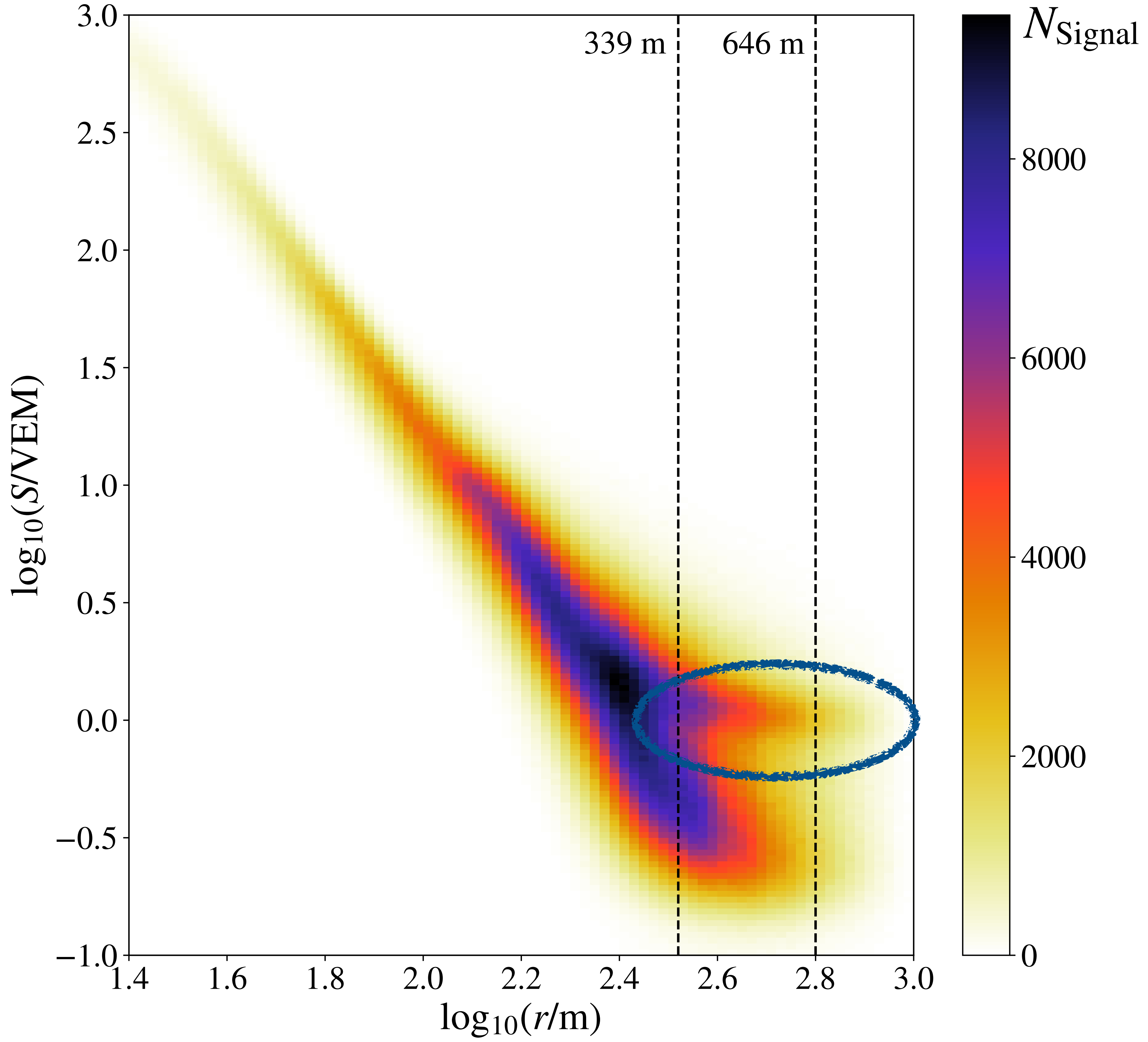


*Sibyll 2.3d not included in this work

GeV muons in IceTop

Muon signature

- Muon signals
  - Single muons produce typical signal in tanks
  - ~1 Vertical Equivalent Muon or VEM
- Muon thumb signature
  - Charge-distance histogram of many events
  - **Muon signal visible at large lateral distance**

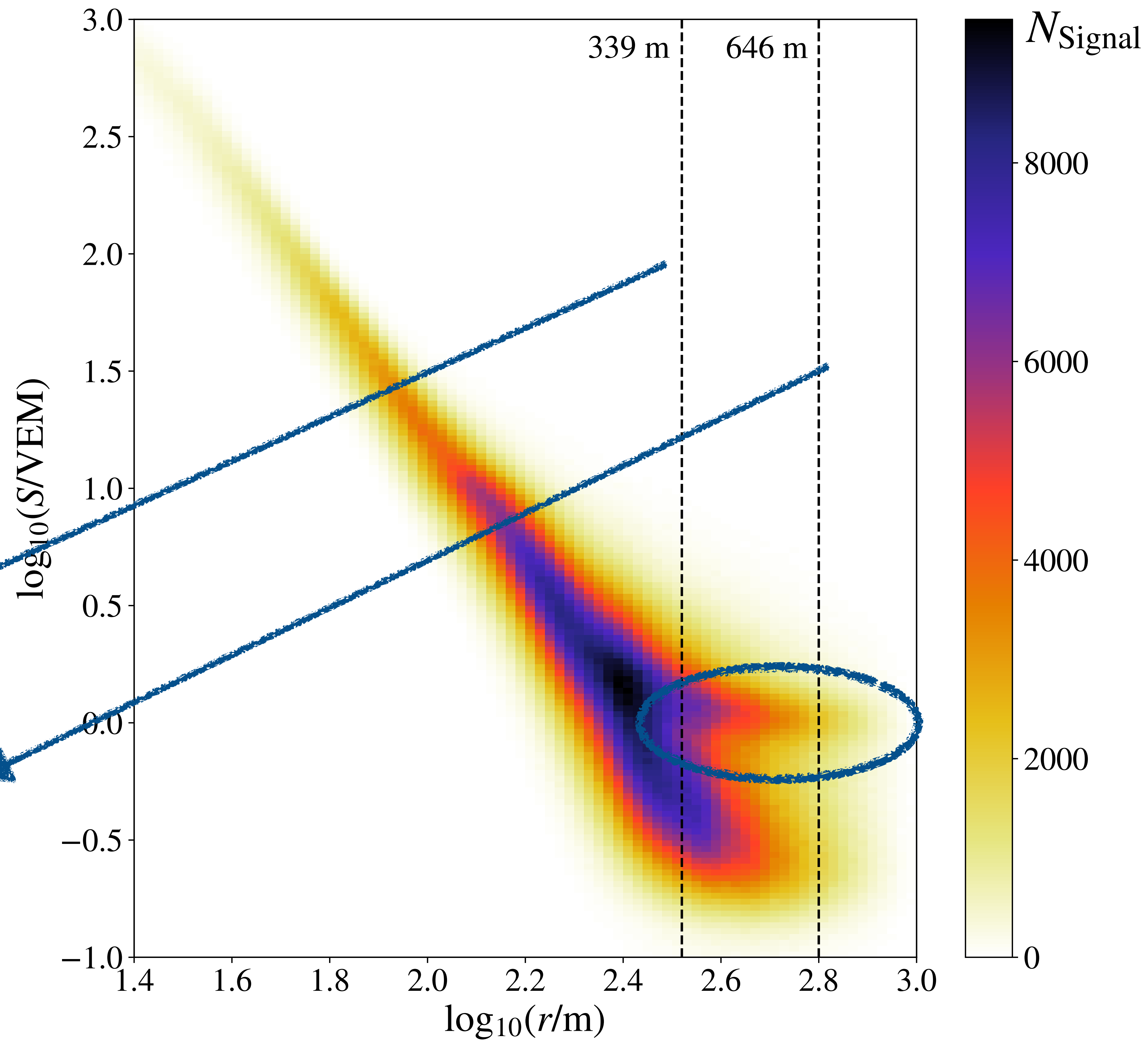


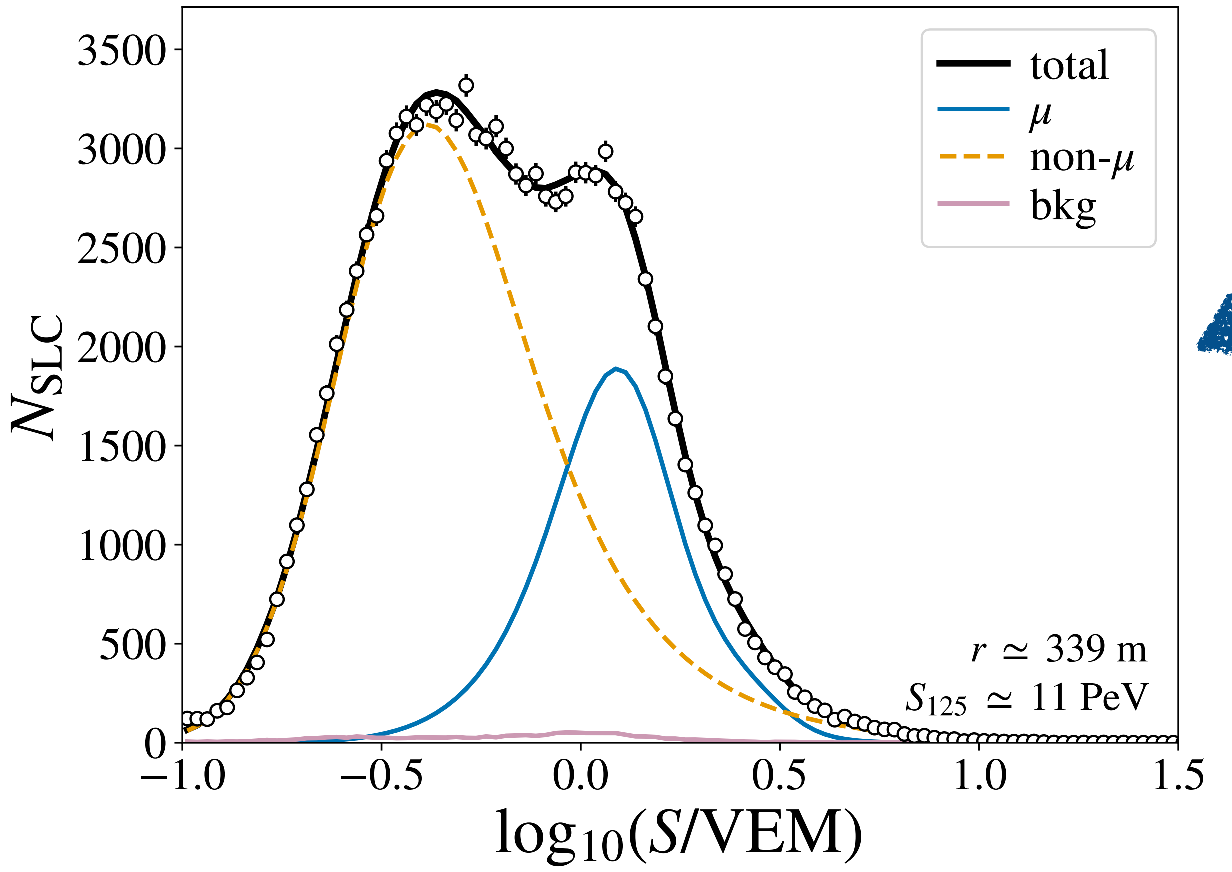
[IceCube Collaboration, Phys.Rev.D 106 (2022)]

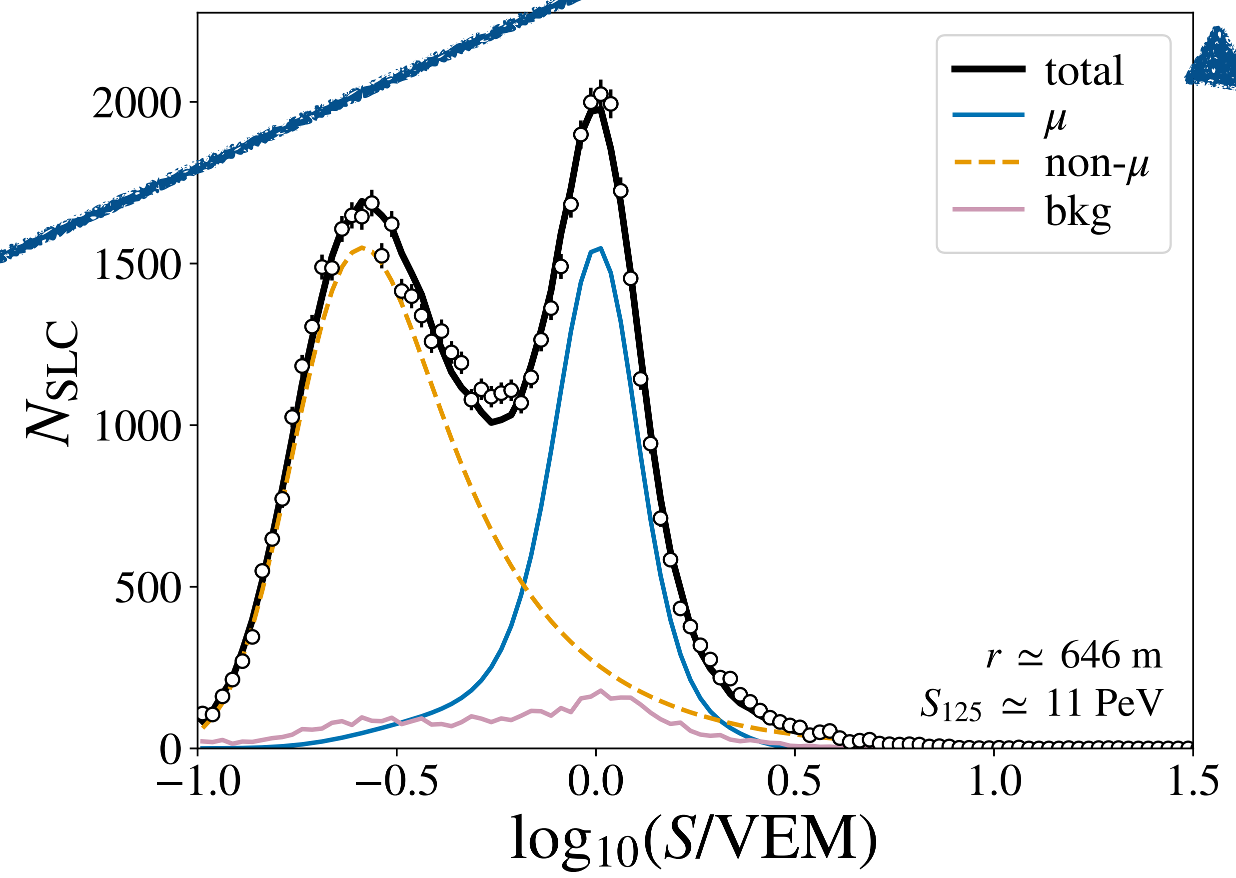
GeV muons in IceTop

Signal distribution fits

- Distribution at various distances fit with
  - EM response model
  - Muon response model
  - Uncorrelated background
- $\langle \rho_\mu \rangle$ as function of energy and distance
  - Final results derived for 600 m and 800 m

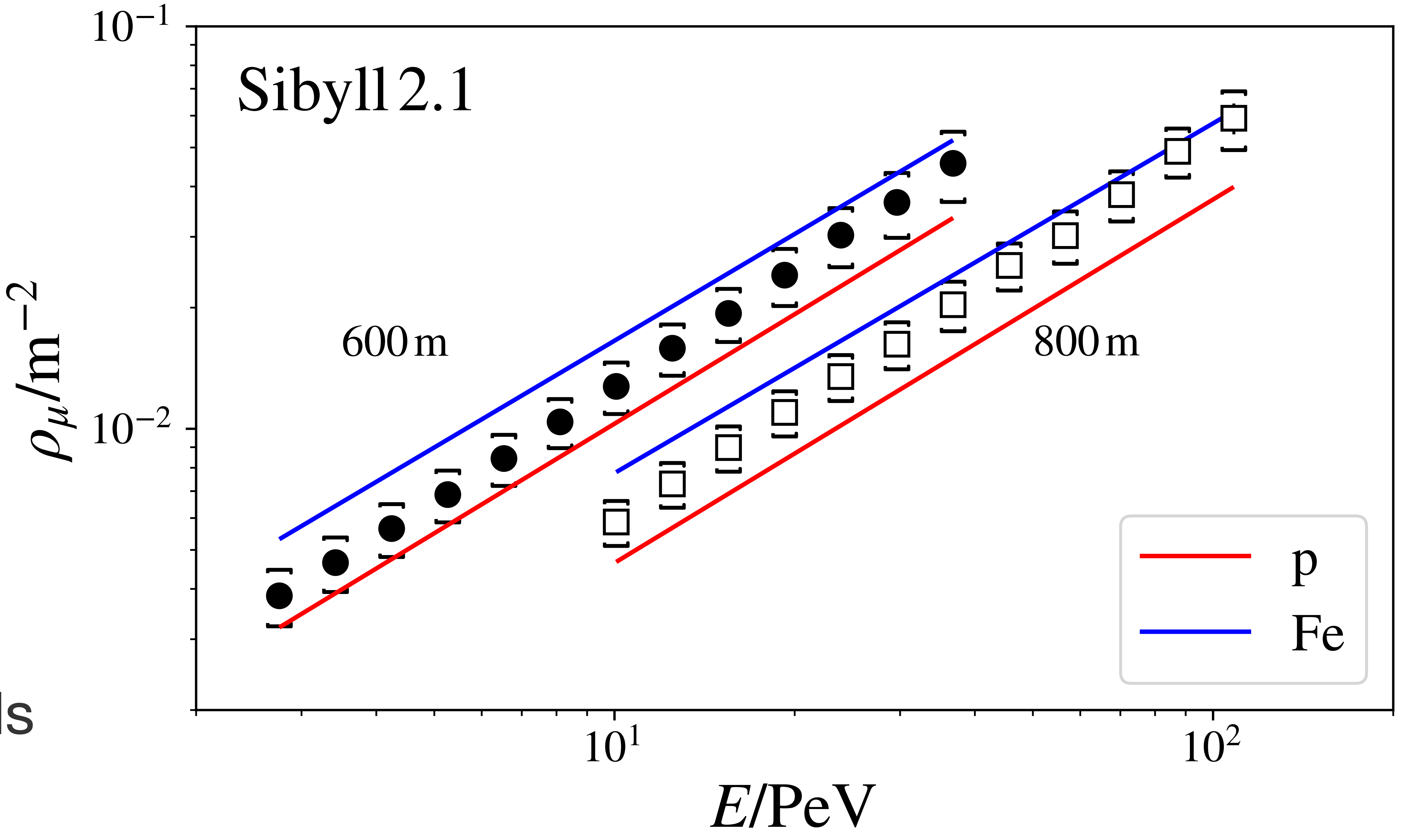


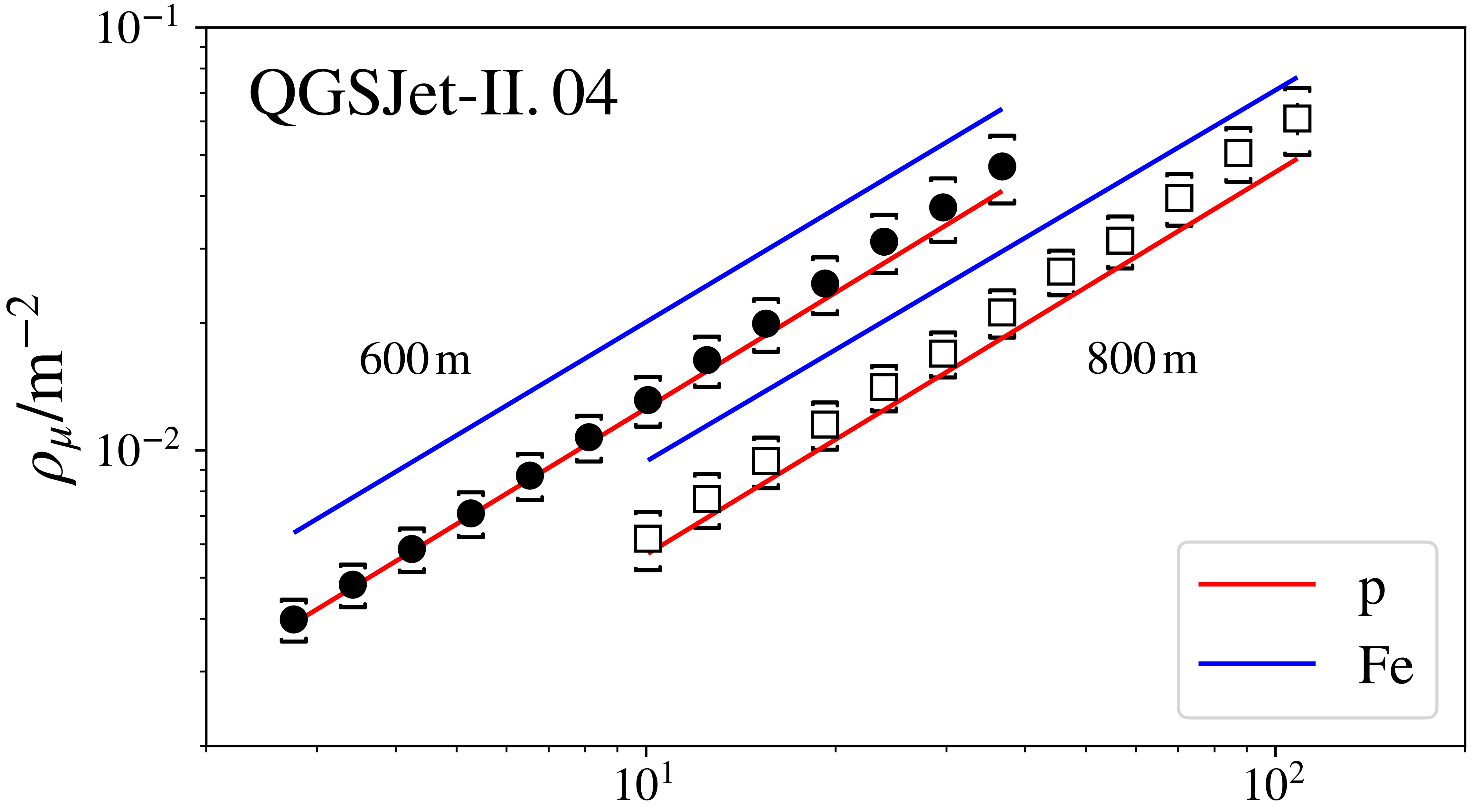


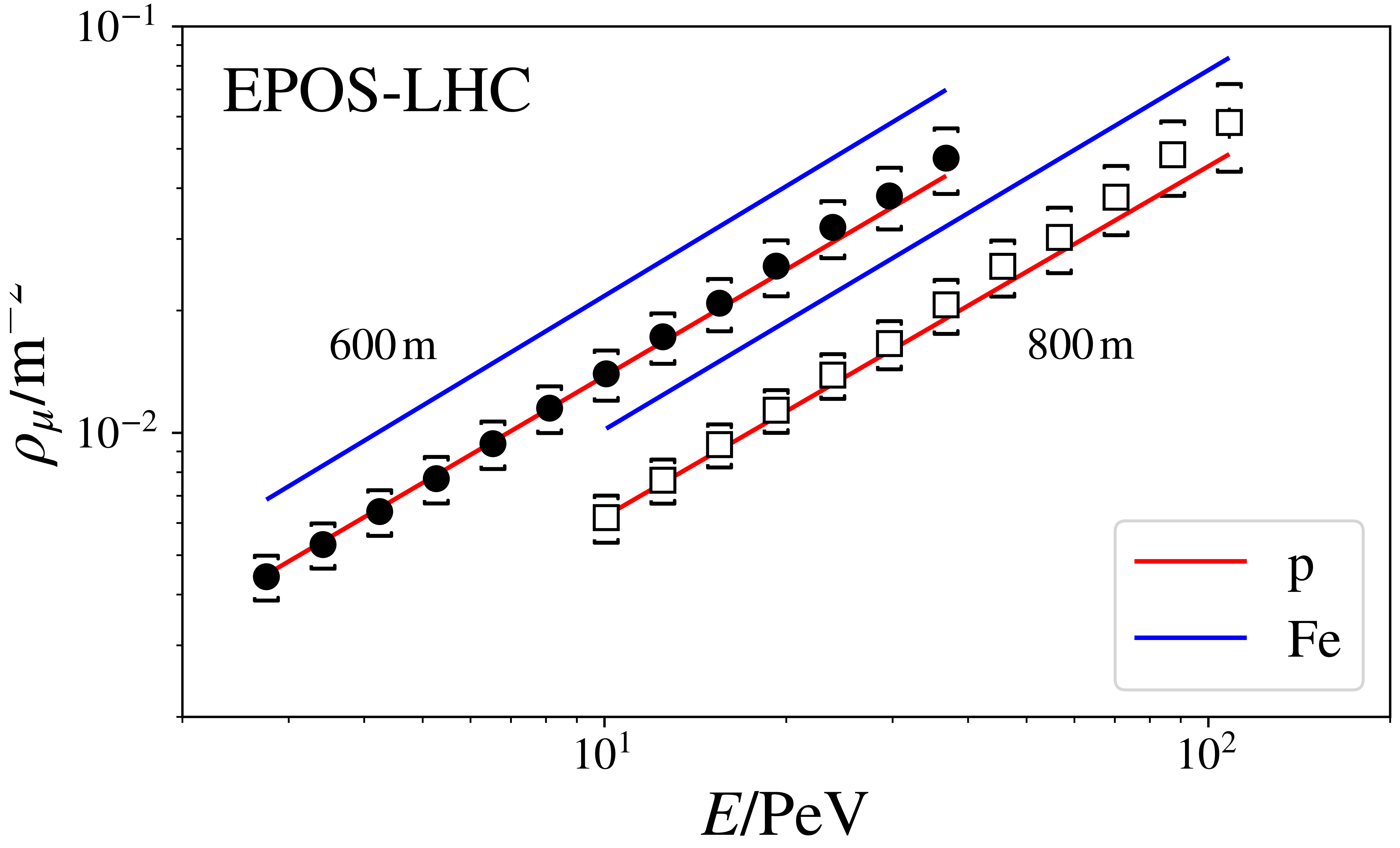


GeV muons in IceTop

- ρ_μ in near-vertical EAS (600m & 800m)
  - **MC correction factors** applied based on different hadronic interaction models
  - 5%-15% difference in ρ_μ derived with different models



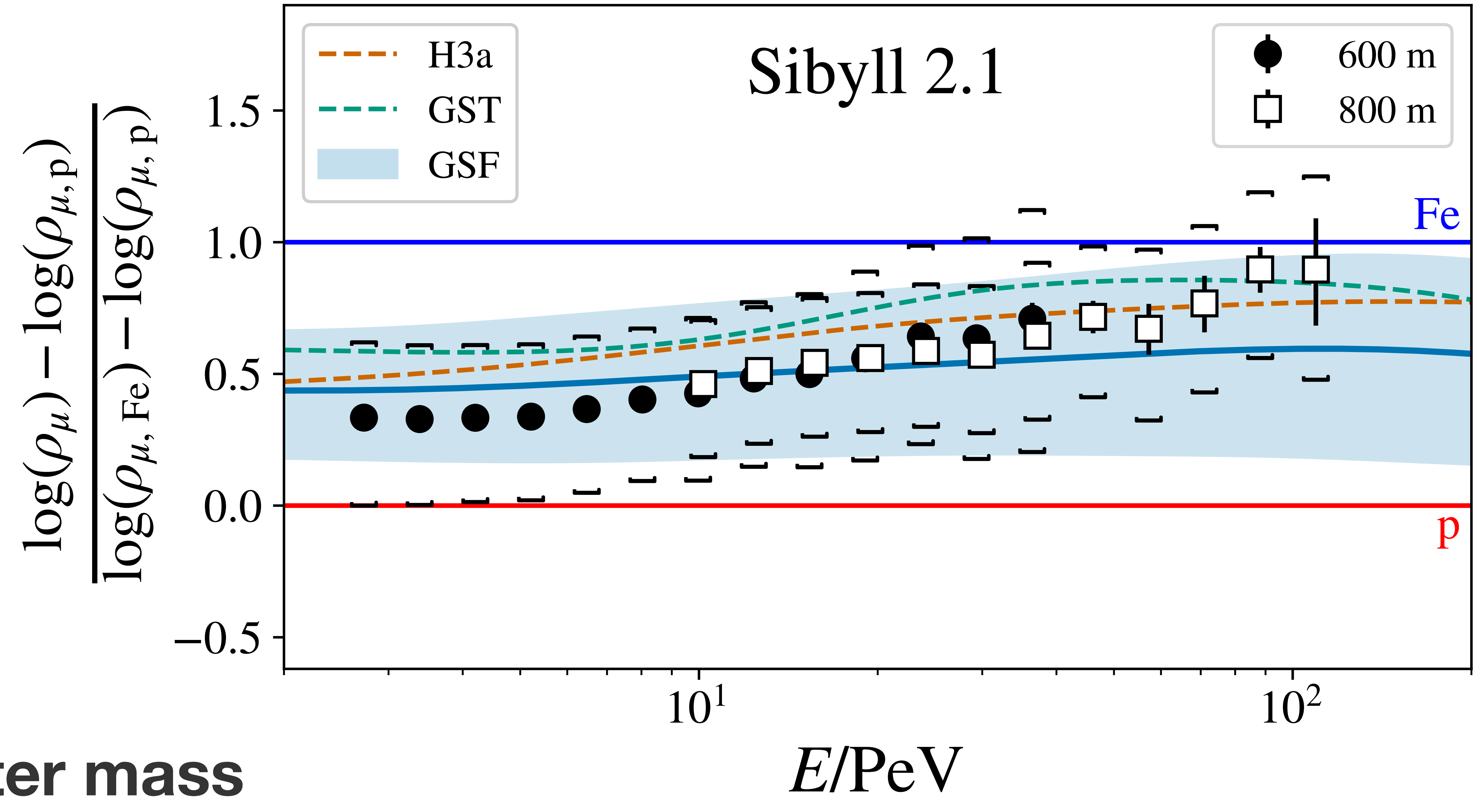


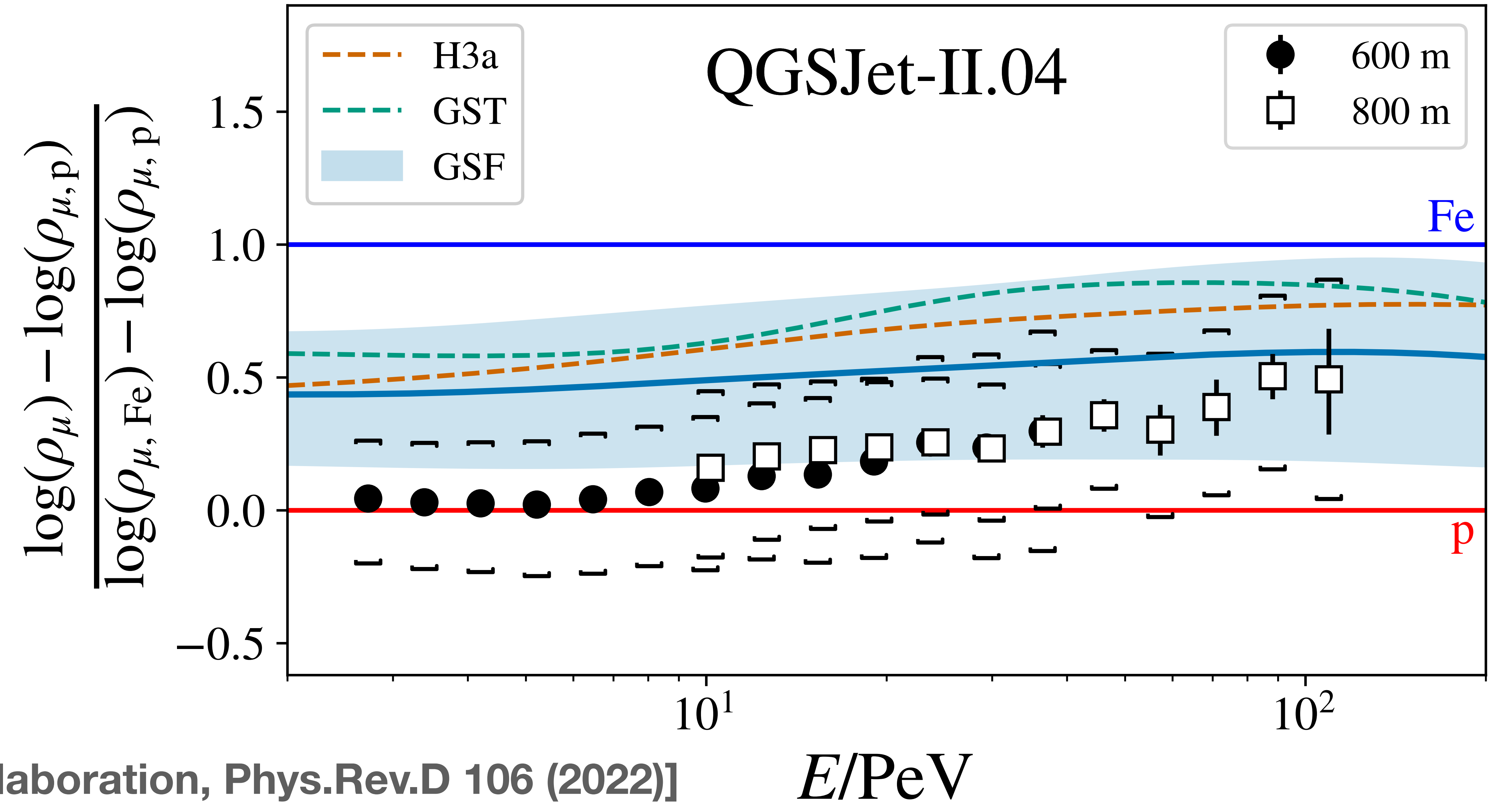


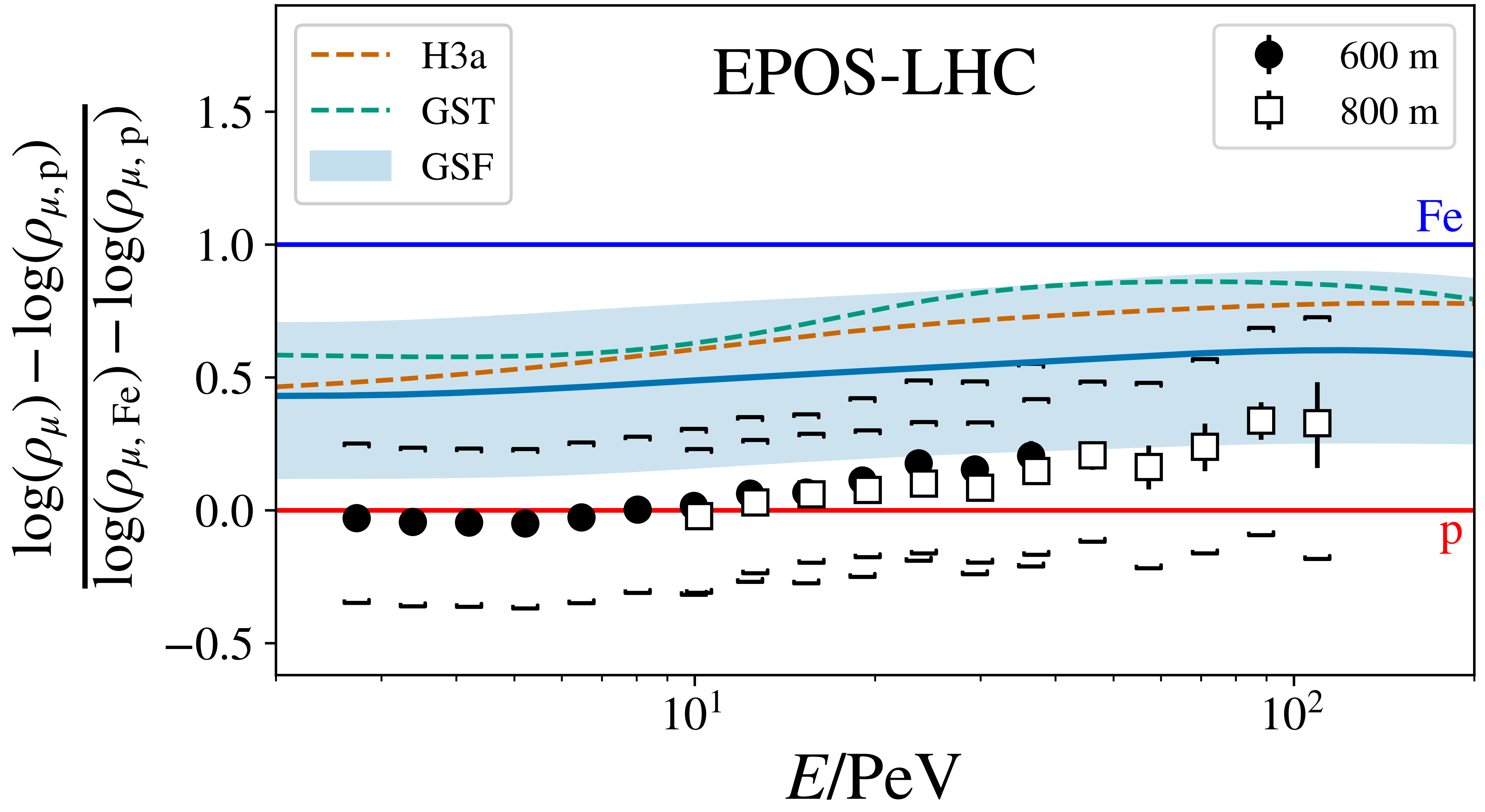
[IceCube Collaboration, Phys.Rev.D 106 (2022)]

GeV muons in IceTop

- ρ_μ in near-vertical EAS (600m & 800m)
  - $z = \dfrac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_{\mathrm{p}}}{\ln\langle N_\mu \rangle_{\mathrm{Fe}} - \ln\langle N_\mu \rangle_{\mathrm{p}}}$
  - Predictions from flux models: H3a, GST, GSF
  - **Sibyll 2.1 agrees best, post-LHC models show lighter mass**





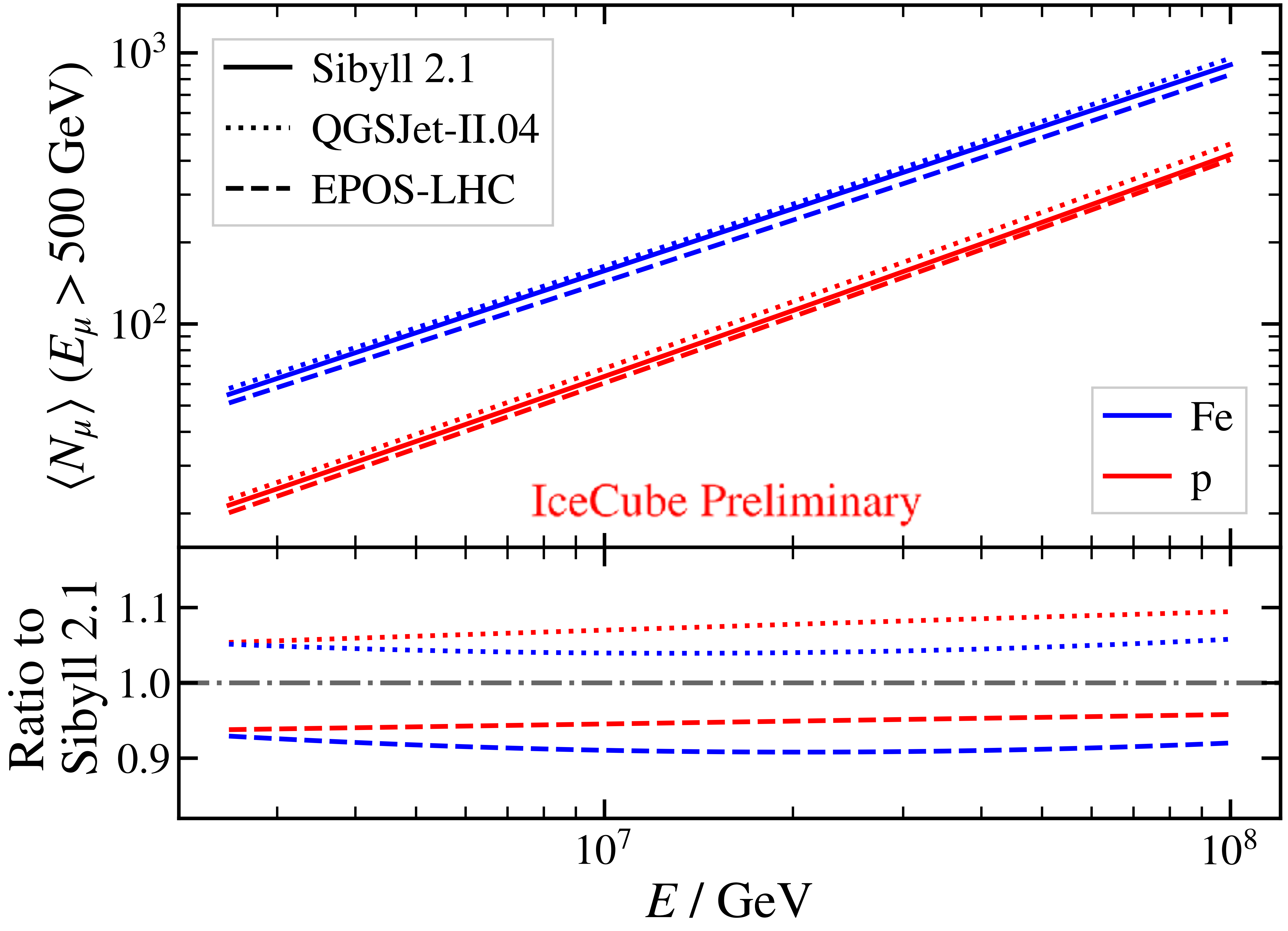


[IceCube Collaboration, Phys.Rev.D 106 (2022)]

TeV muons in coincident events

Goal & simulation predictions

- High-energy muon multiplicity
  - **IceTop-InIce coincident** events
  - Near-vertical $\cos\theta > 0.95$ ($\theta \lesssim 18°$)
  - **Muons with** $E_\mu > 500$ GeV **at surface**
  - Model dependence
    - QGSJet-II.04 / Sibyll 2.1 ≈ 1.05
    - EPOS-LHC / Sibyll 2.1 ≈ 0.95

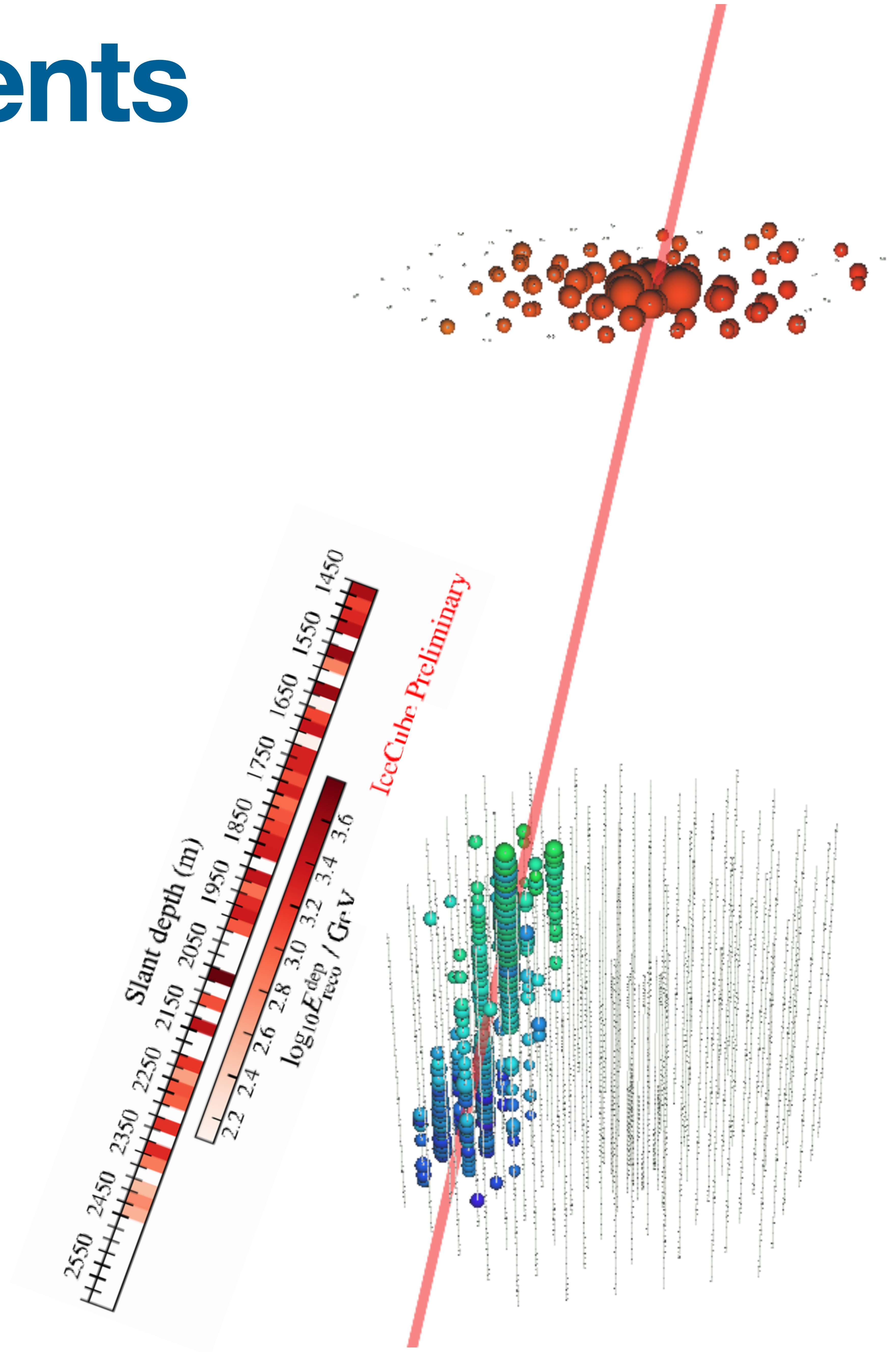


[S. Verpoest, PoS ICRC2023 (2023) 207]

TeV muons in coincident events

Bundle energy loss

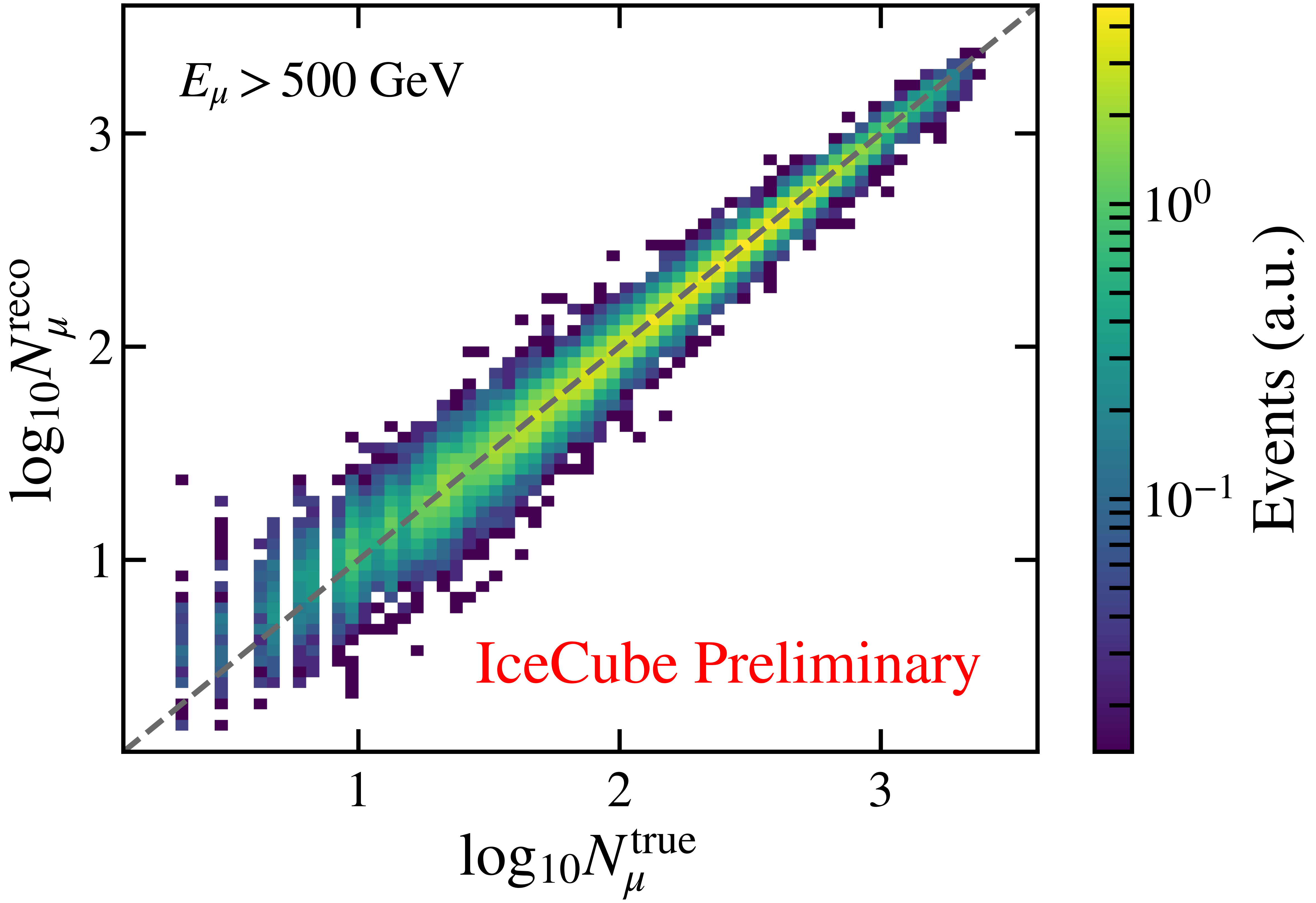
- Energy loss reconstruction
  - Signal is combination of energy loss of many muons
  - Algorithm reconstructs **energy deposited in 20 m segments** along shower axis
  - Energy loss profile becomes input to neural network



TeV muons in coincident events

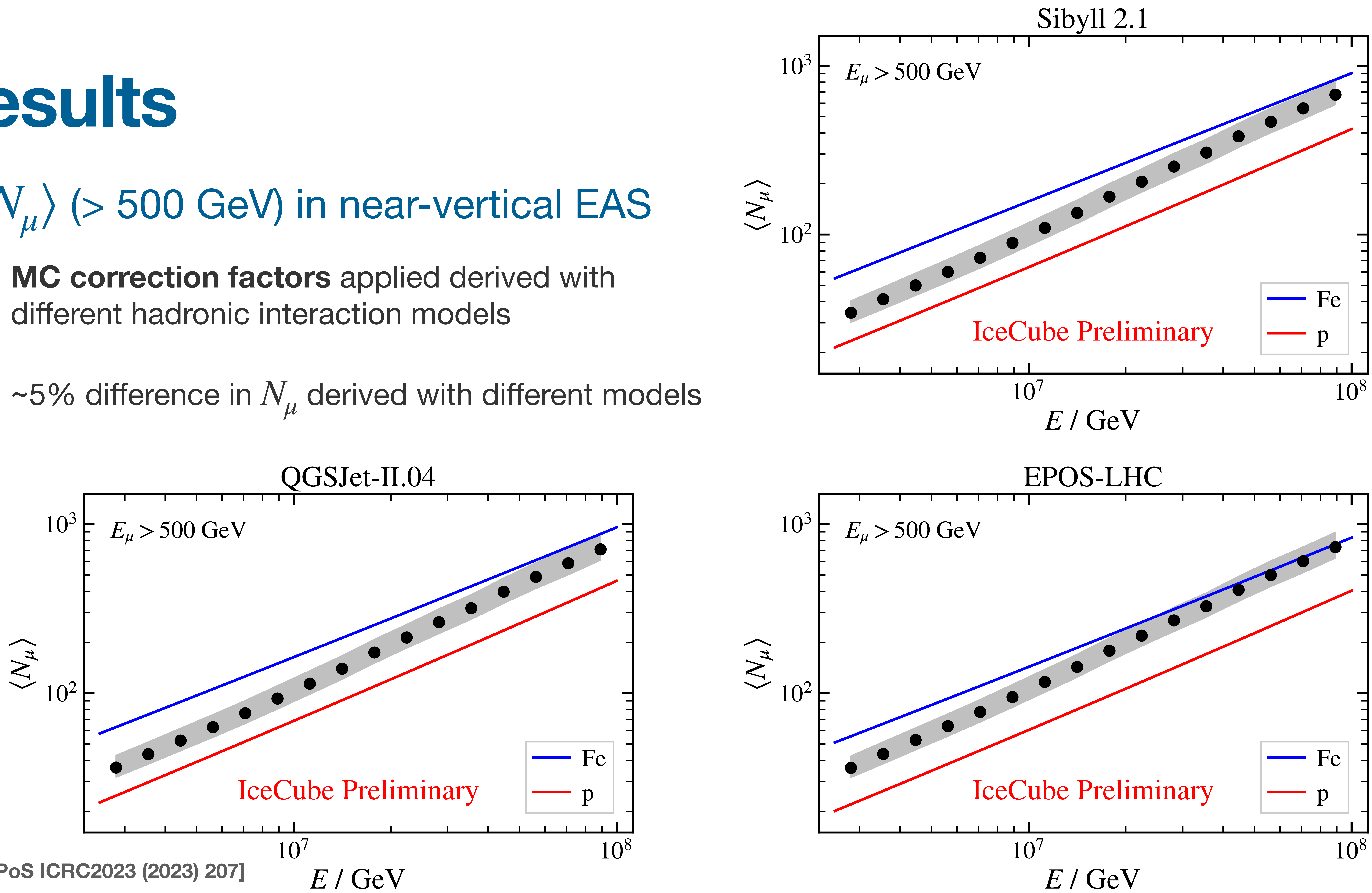
Neural network

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



Results

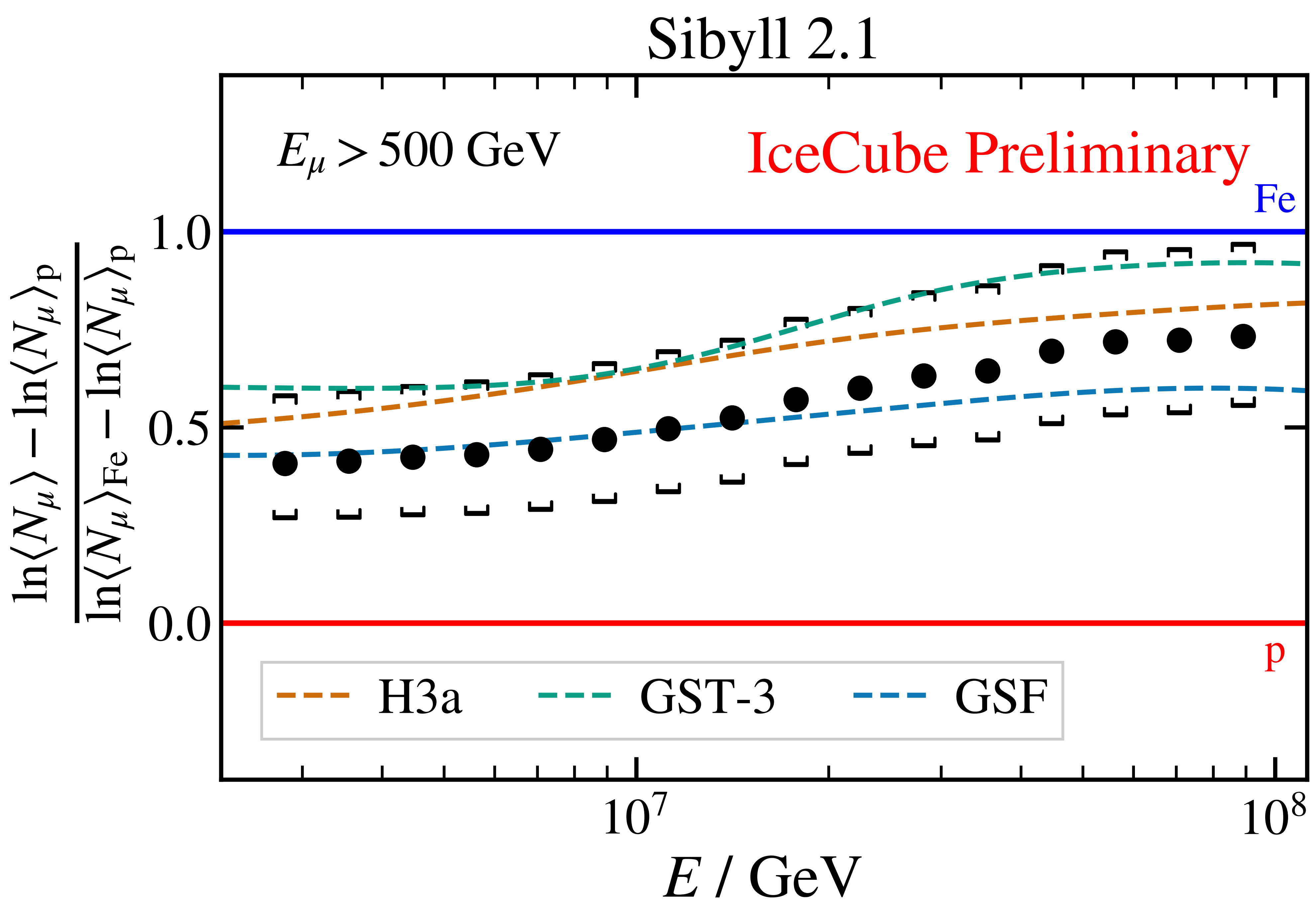
- $\langle N_\mu \rangle$ (> 500 GeV) in near-vertical EAS
  - **MC correction factors** applied derived with different hadronic interaction models
  - ~5% difference in N_μ derived with different models

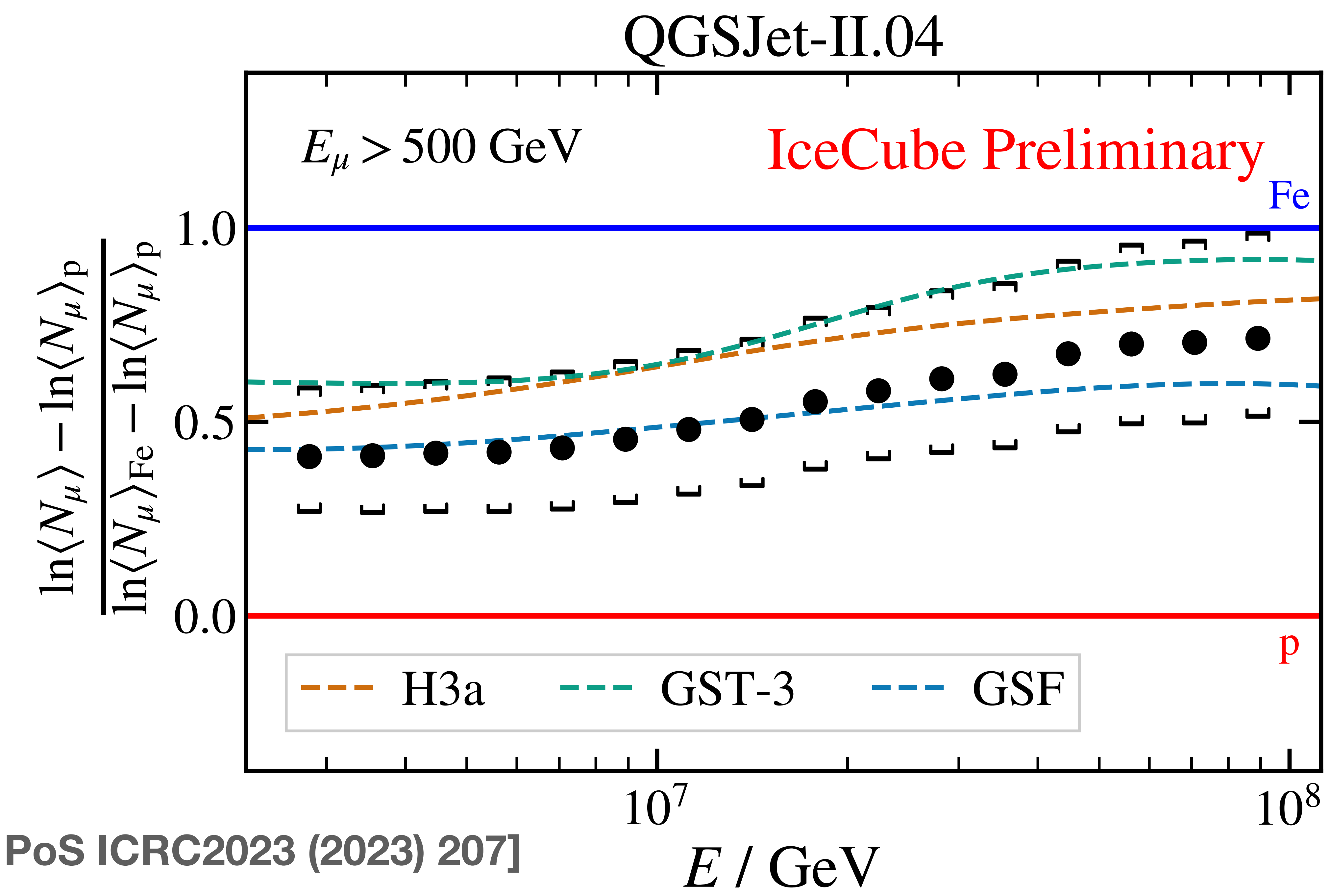


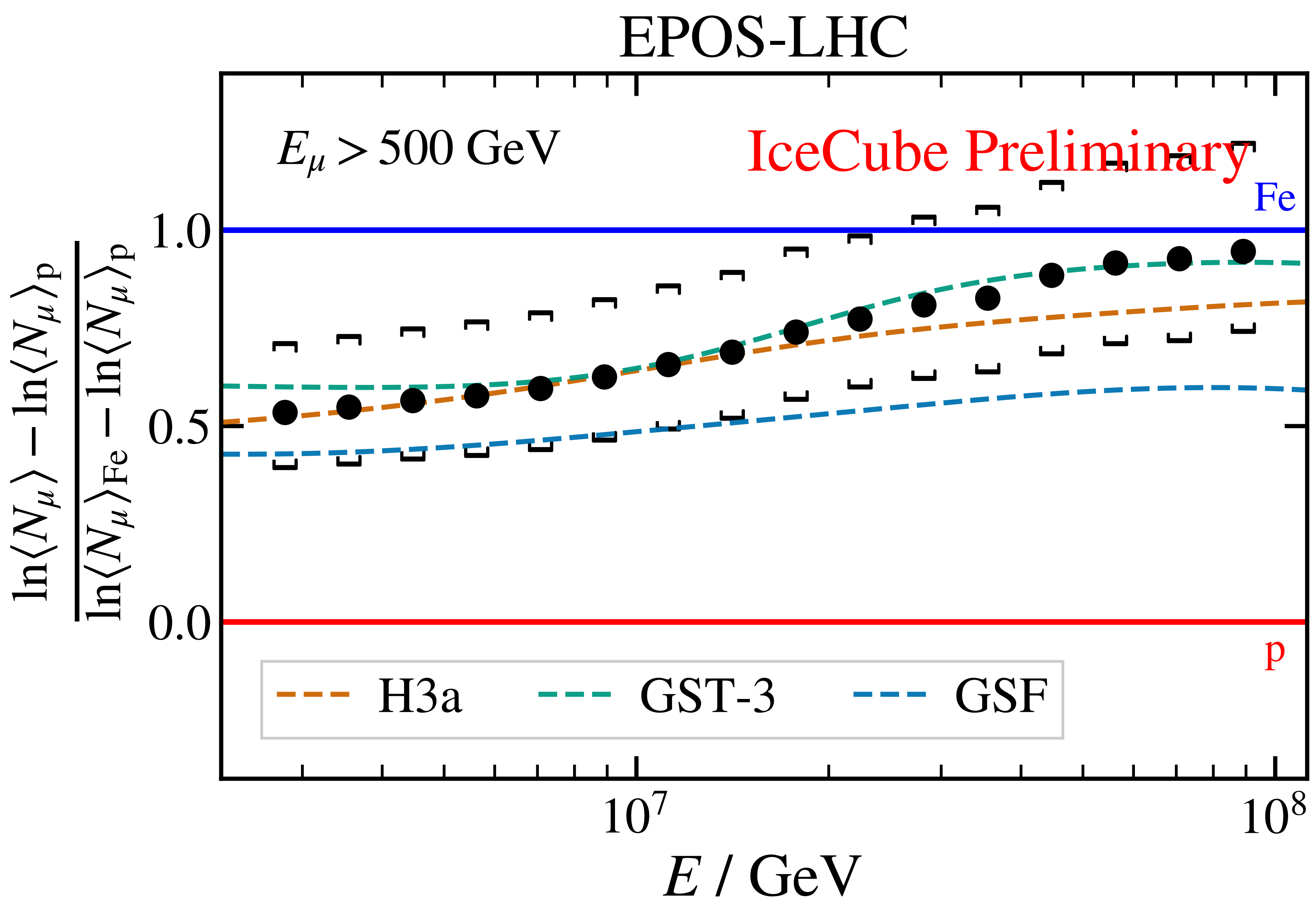
[S. Verpoest, PoS ICRC2023 (2023) 207]

Results

- $\langle N_\mu \rangle$ (> 500 GeV) in near-vertical EAS
  - $z = \dfrac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_\mathrm{p}}{\ln\langle N_\mu \rangle_\mathrm{Fe} - \ln\langle N_\mu \rangle_\mathrm{p}}$
  - Predictions from flux models: H3a, GST, GSF
  - **All models agree well**



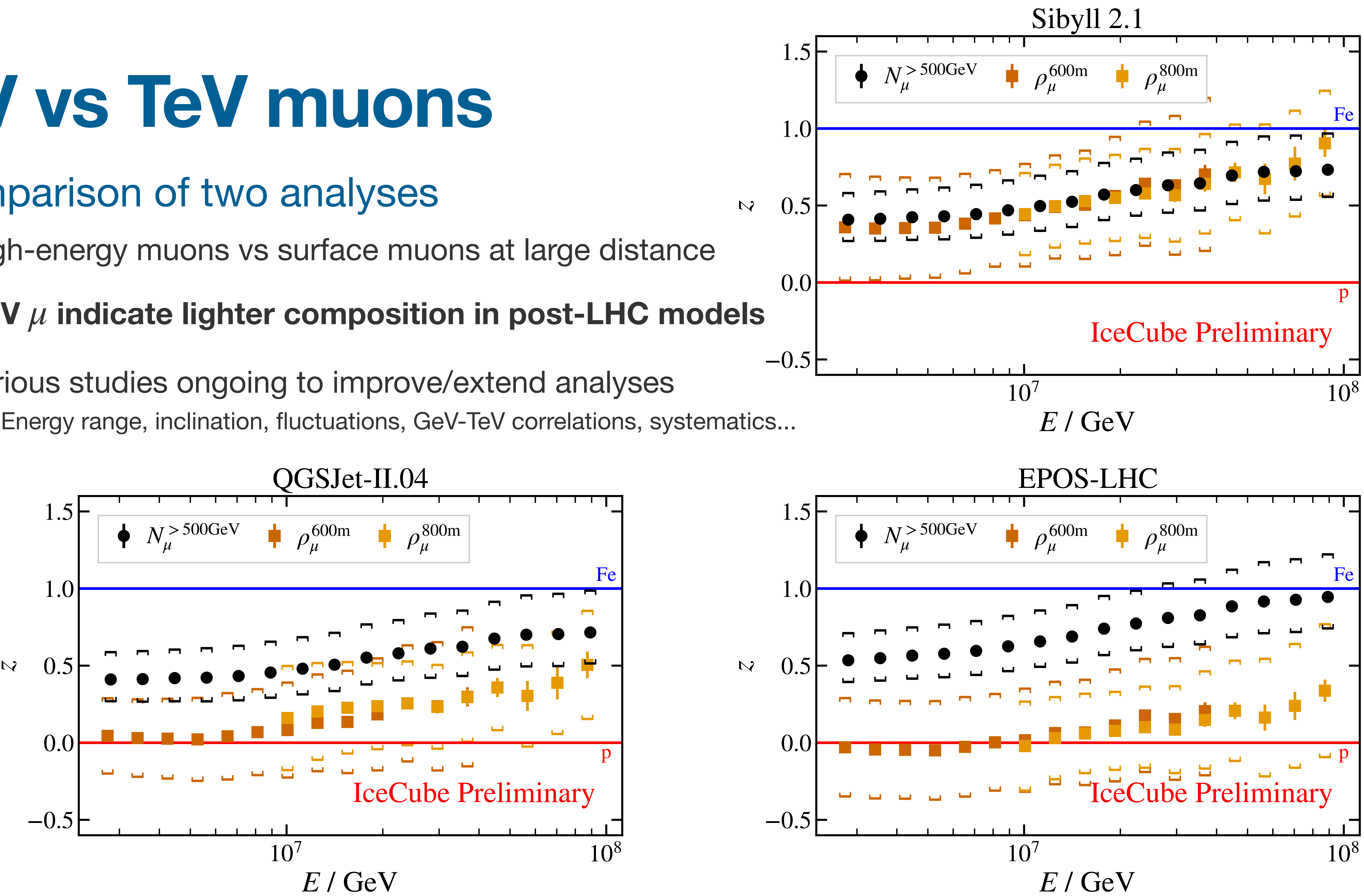




[S. Verpoest, PoS ICRC2023 (2023) 207]

GeV vs TeV muons

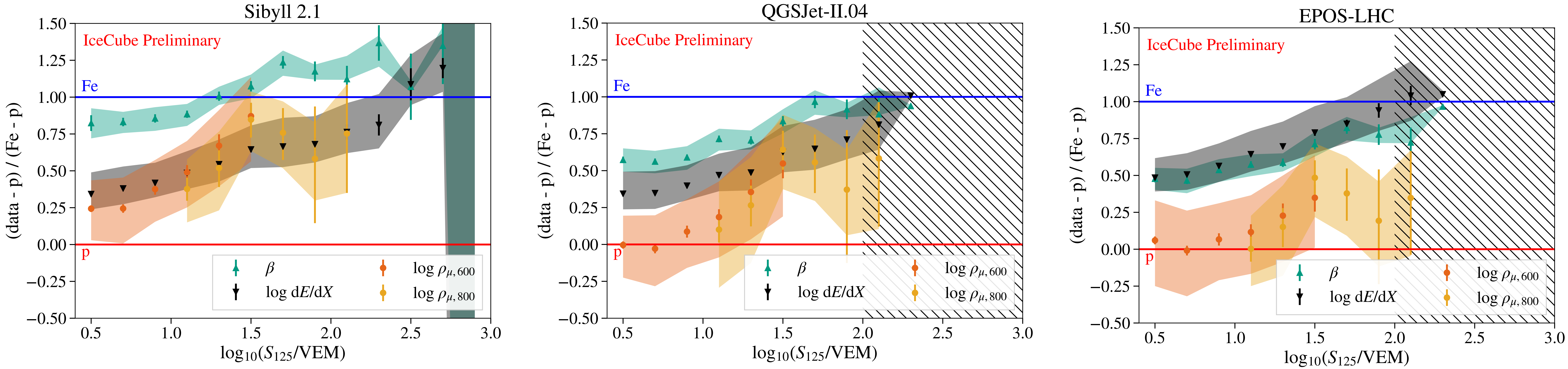
- Comparison of two analyses
  - High-energy muons vs surface muons at large distance
  - **GeV μ indicate lighter composition in post-LHC models**
  - Various studies ongoing to improve/extend analyses
    - Energy range, inclination, fluctuations, GeV-TeV correlations, systematics...



Other observables

- Preliminary work compares
  - IceTop GeV muon density ρ_μ
  - High-energy muon bundle energy loss $\mathrm{d}E/\mathrm{d}X$ (~ N_μ)
  - IceTop LDF slope β

→ Inconsistencies in all models tested!



[S. Verpoest, PoS ICRC2021 (2021) 357]

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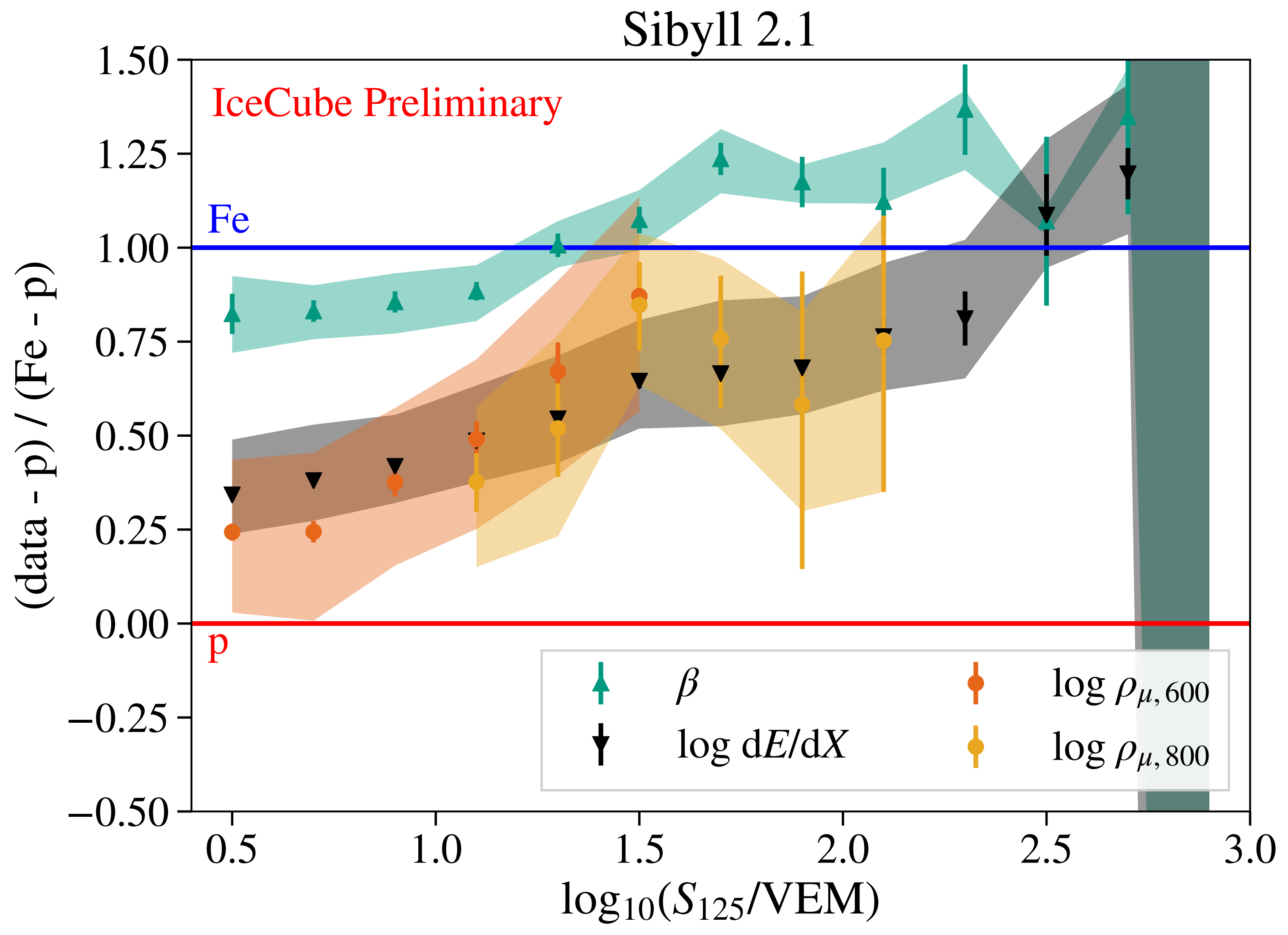
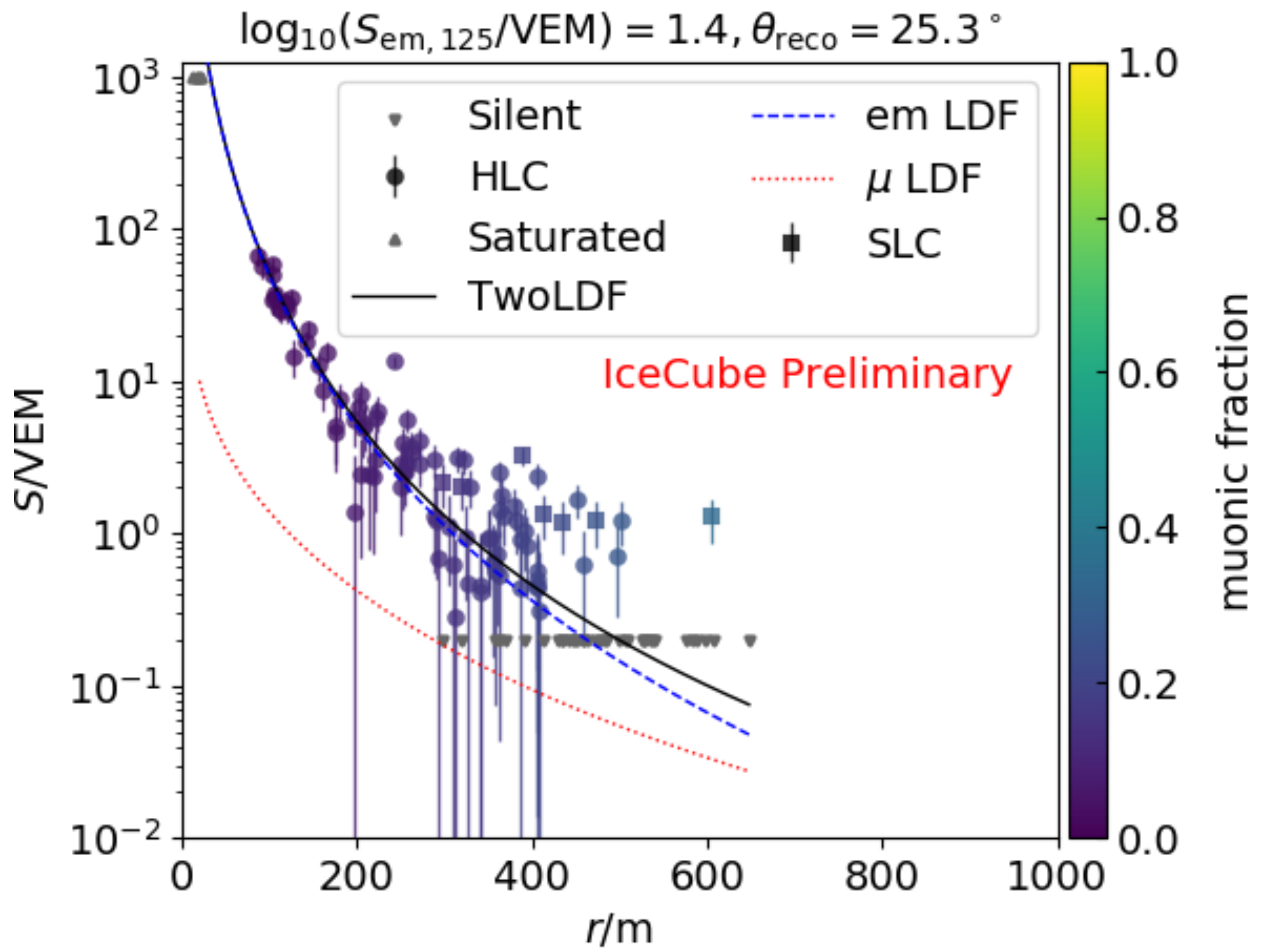


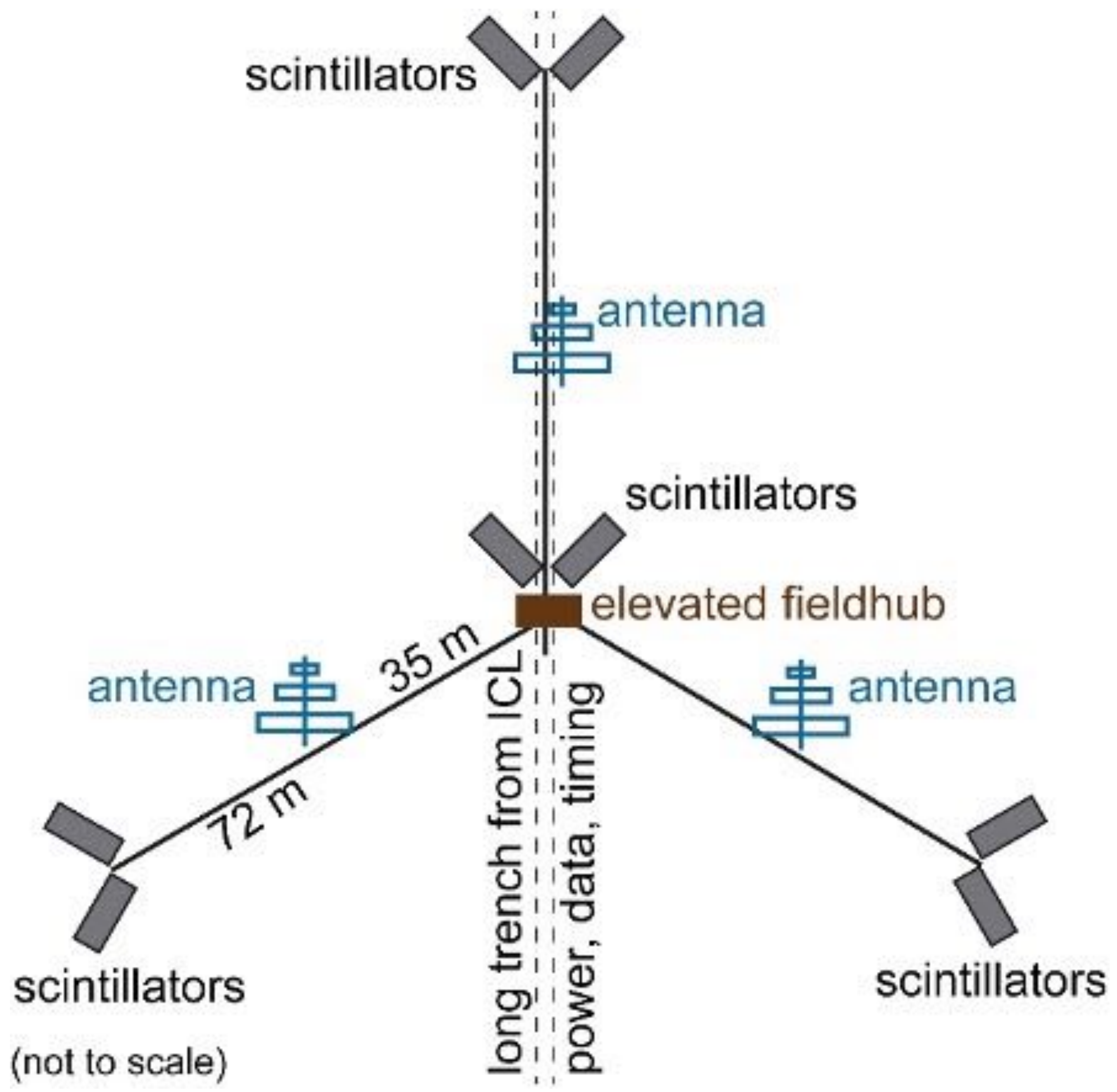


[M. Weyrauch & D. Soldin, PoS ICRC2023 (2023) 357]

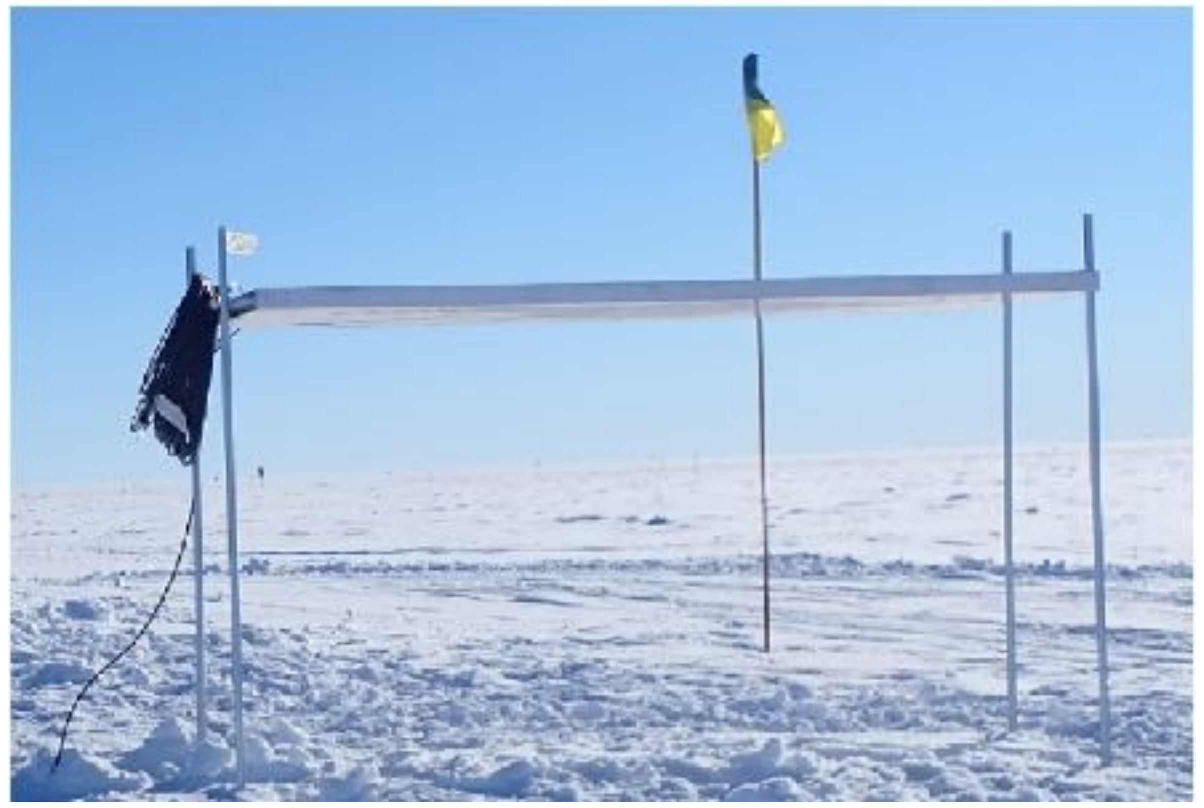
- LDF slope β
  - Combination of EM and muons
  - New reconstruction attempts to disentangle, fitting signal models for both → will give more clarity on origin of issue

Future instrumentation

- Surface Enhancement
  - Scintillators → Improved EM/μ separation
  - Radio antennas → Shower maximum & energy

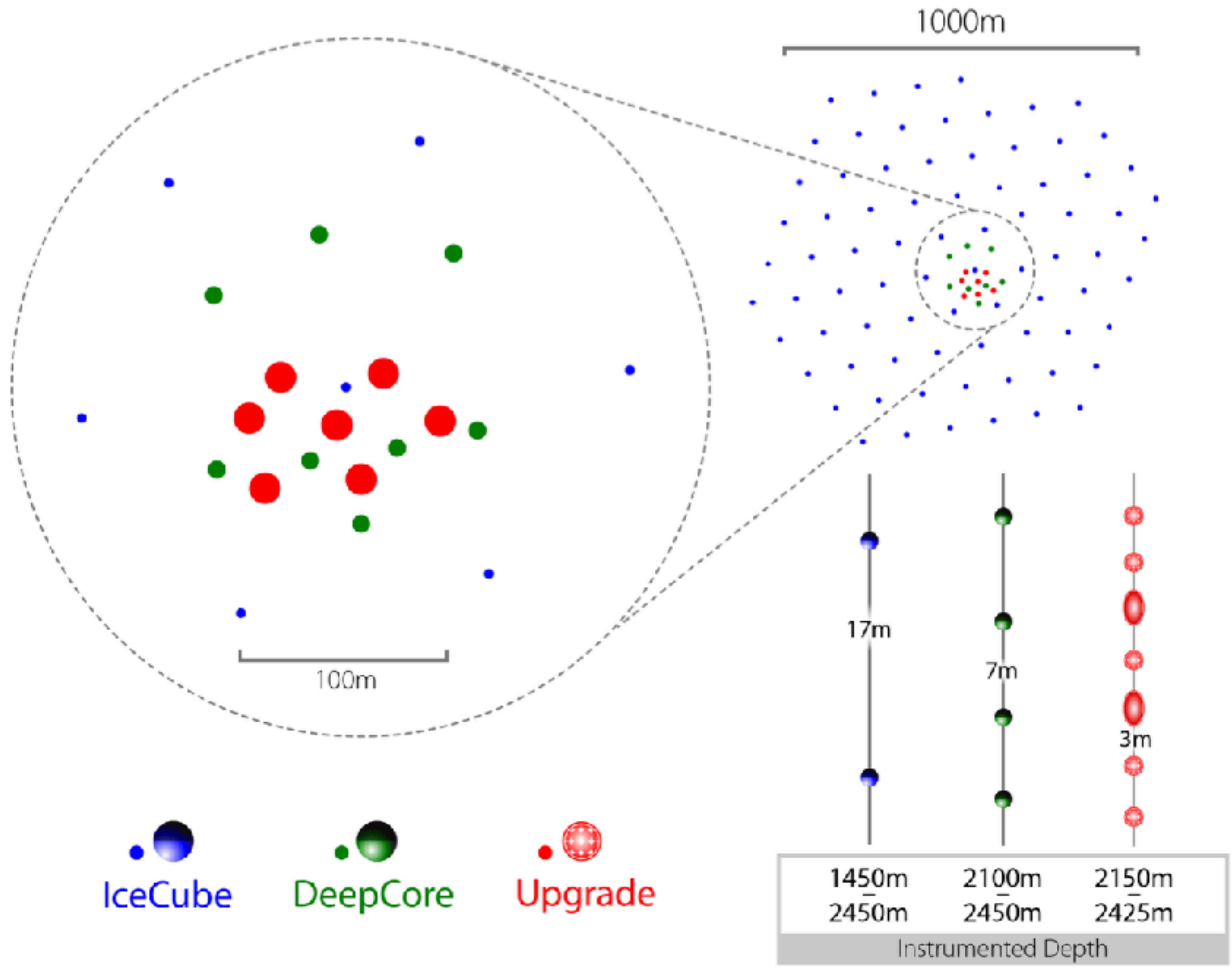


Prototype station @ IceTop



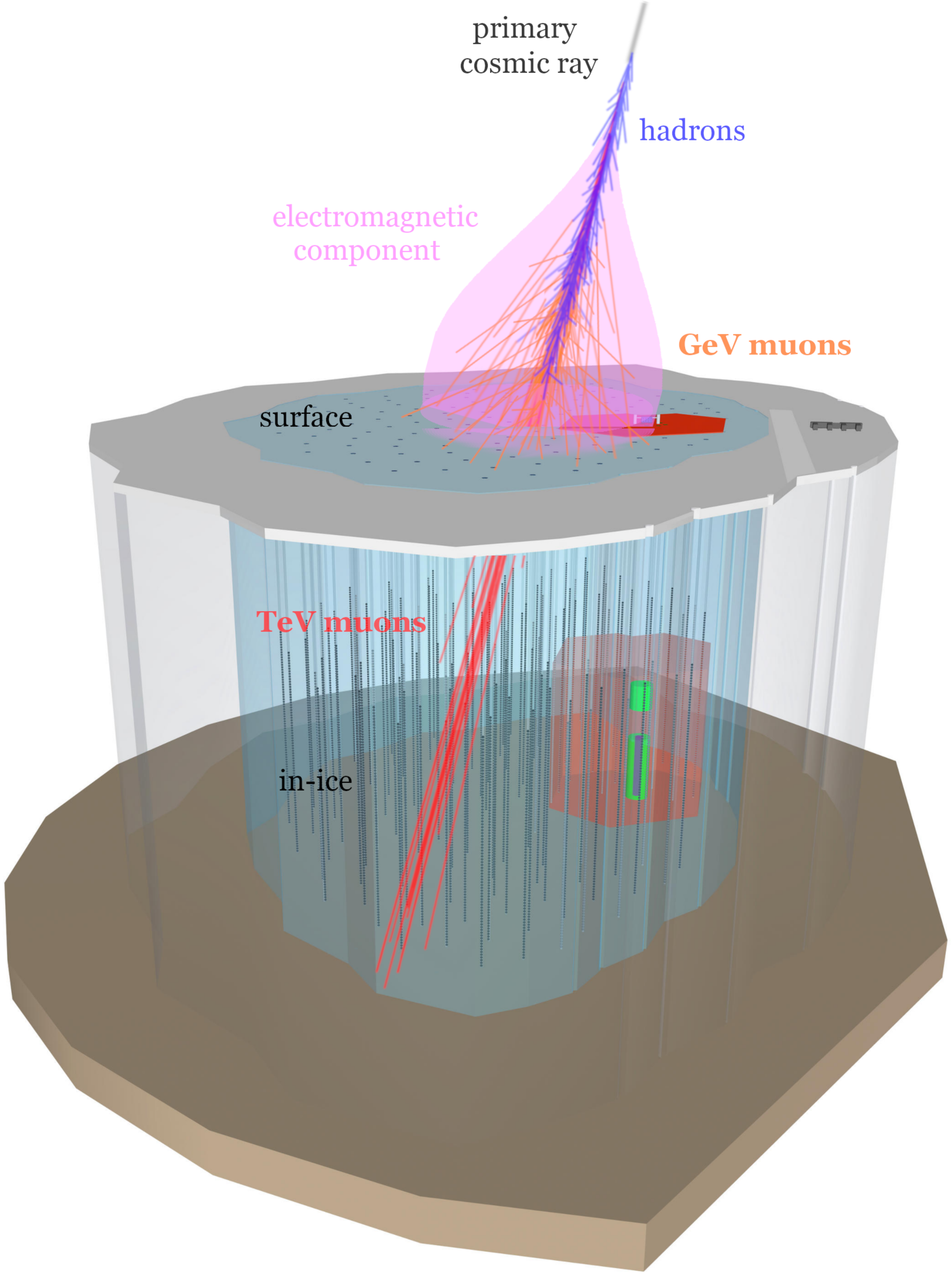
Future instrumentation

- Surface Enhancement
  - Scintillators → Improved EM/μ separation
  - Radio antennas → Shower maximum & energy
- IceCube Upgrade
  - Denser instrumentation may benefit bundle studies
  - Calibration devices → improved ice models



Future instrumentation

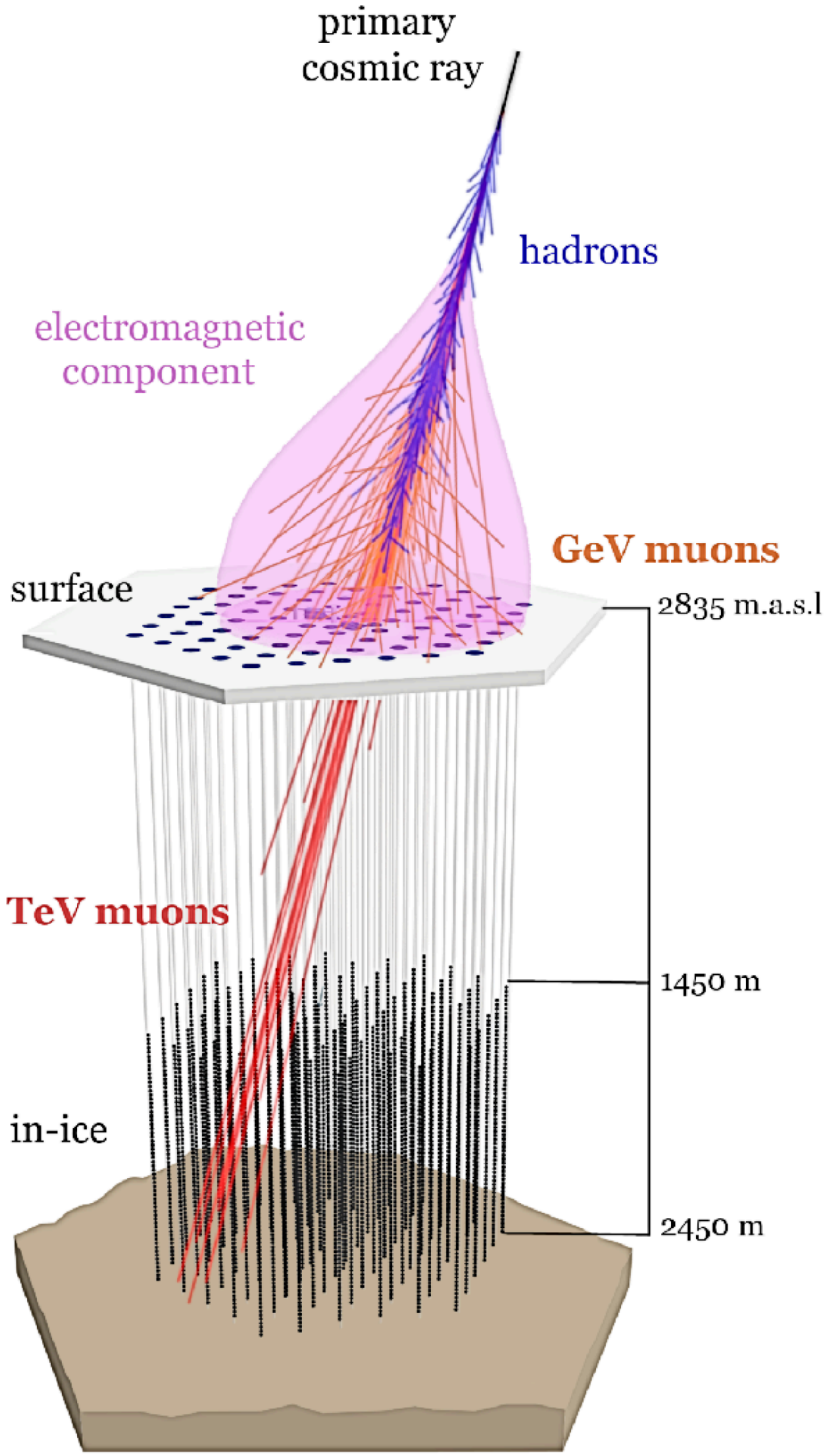
- ▸ Surface Enhancement
  - Scintillators → Improved EM/μ separation
  - Radio antennas → Shower maximum & energy
- ▸ IceCube Upgrade
  - Denser instrumentation may benefit bundle studies
  - Calibration devices → improved ice models
- ▸ IceCube-Gen2
  - Increased statistics
  - Larger opening angle for coincidences



Summary

- ▸ Muon analyses in IceCube
  - GeV muon density & TeV muon multiplicity in near-vertical showers
  - 2.5 PeV - 100 PeV primary energy
    - TeV muons
      - Agree with expectations from flux models
    - GeV muons at large distance
      - Post-LHC models yield lighter mass than expected

→ **tension between GeV & TeV muons in QGSJet-II.04 and EPOS-LHC!**



- Outlook
  - Extension of existing analyses & new analyses
  - Additional instrumentation

→ **IceCube will continue to provide tests and constraints for hadronic interactions in EAS!**

THE ICECUBE COLLABORATION

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Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

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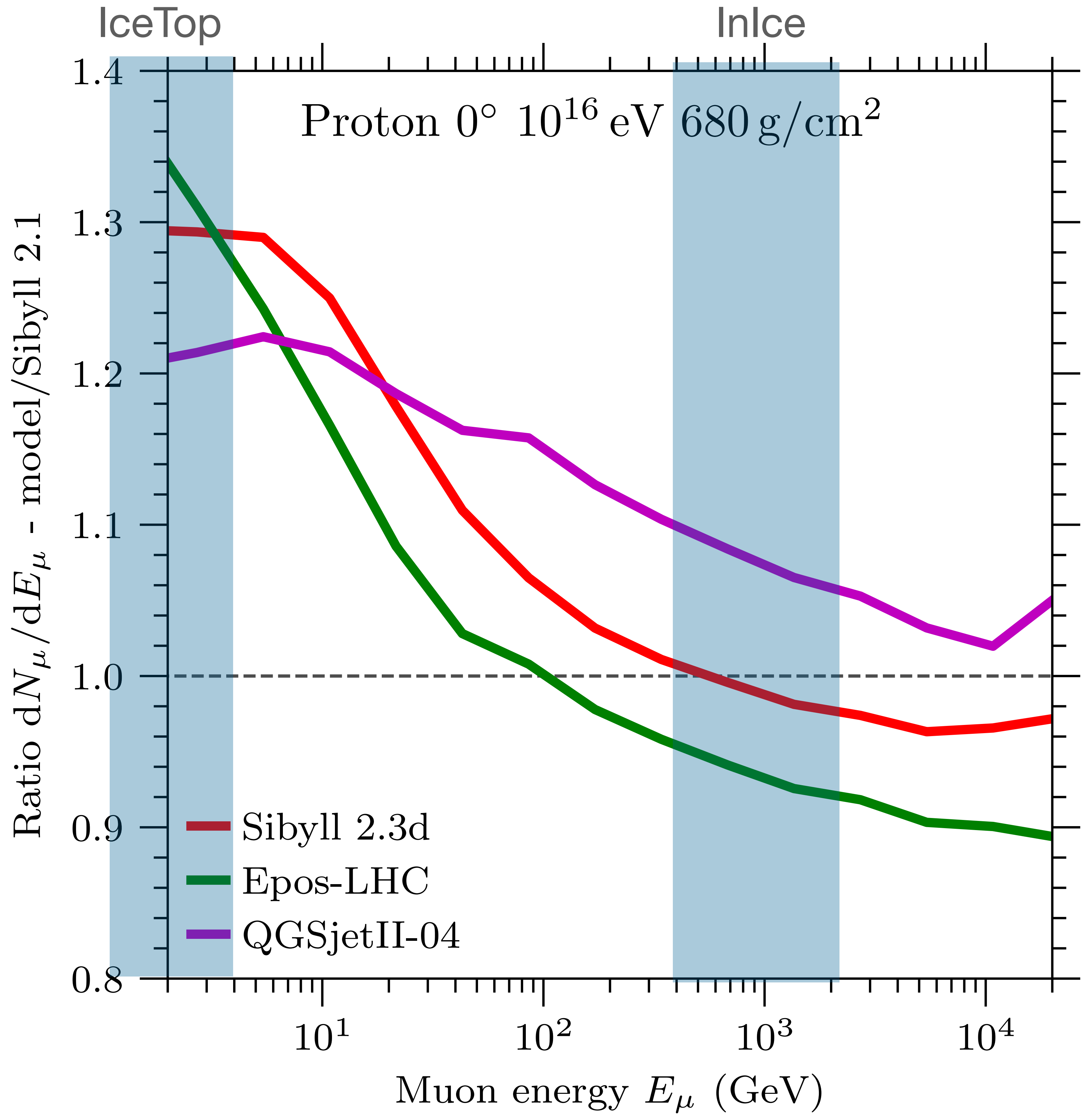
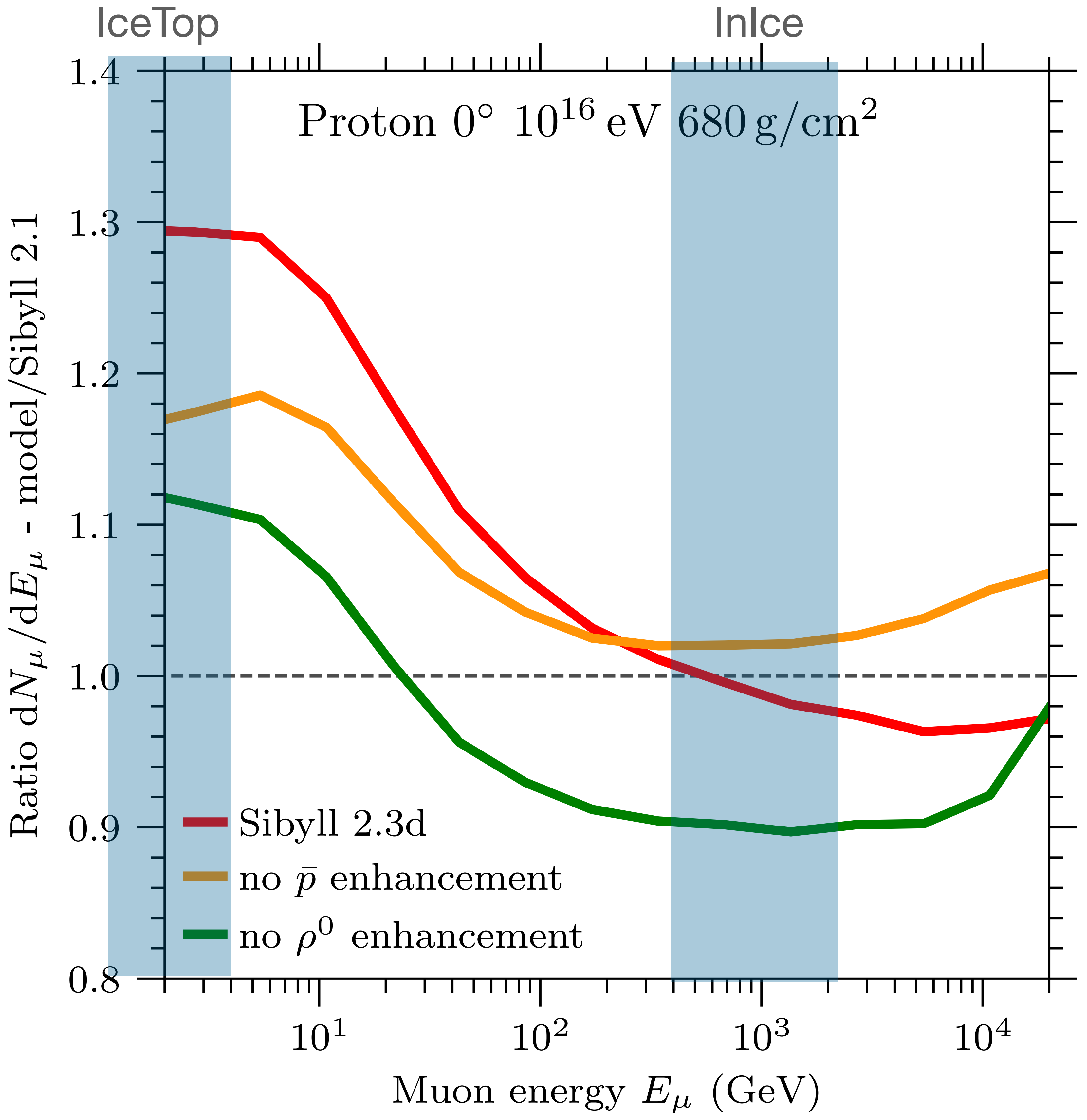
Backup

Muon measurements

- Differences in muon energy spectrum in EAS

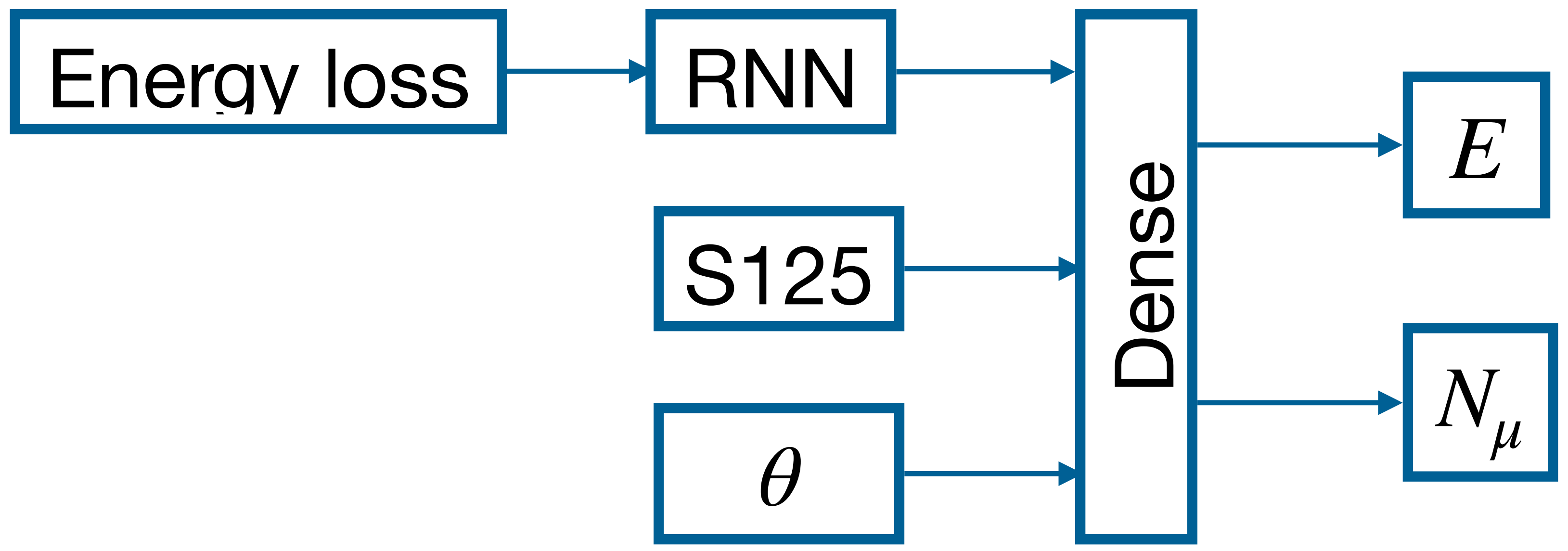


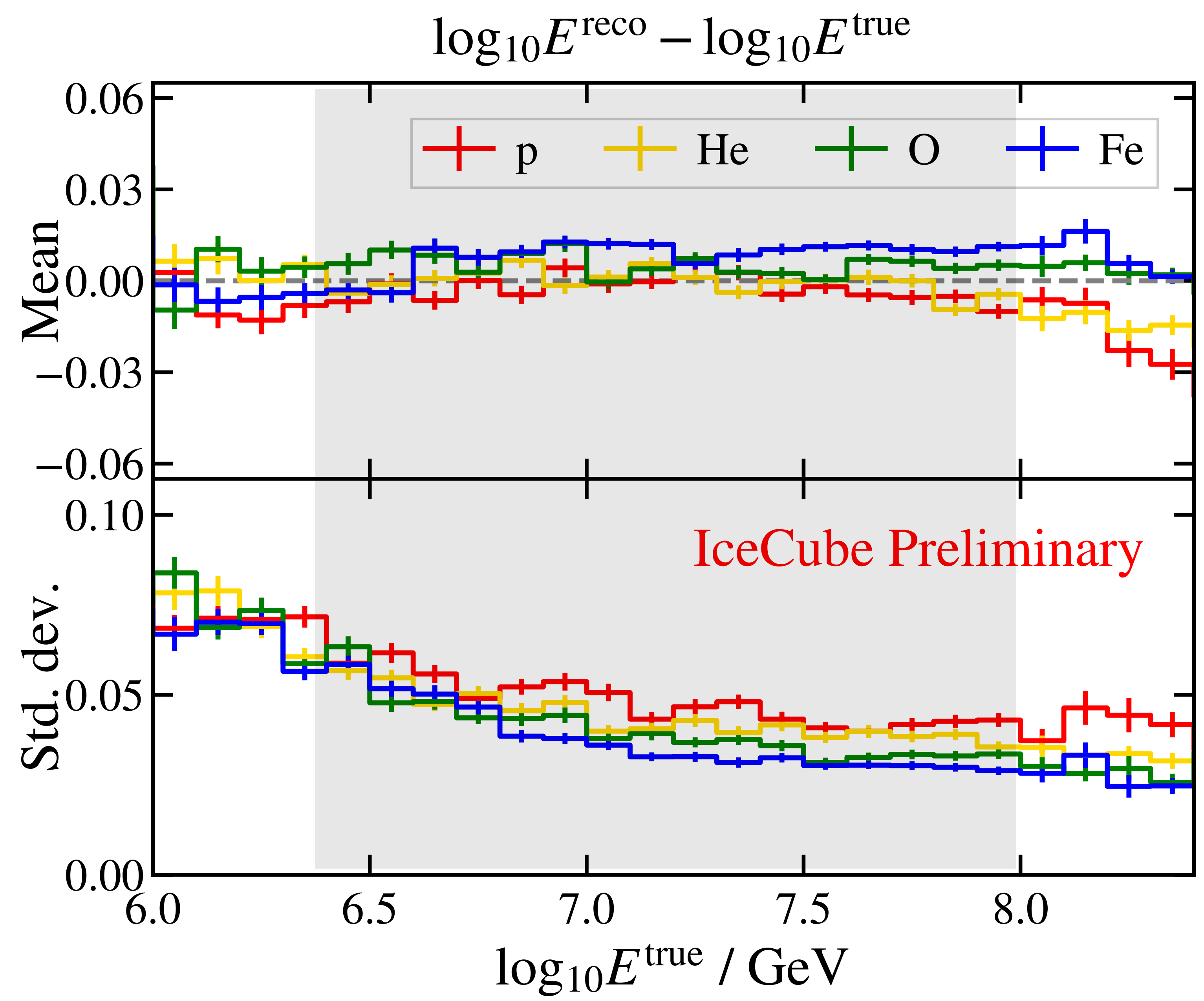


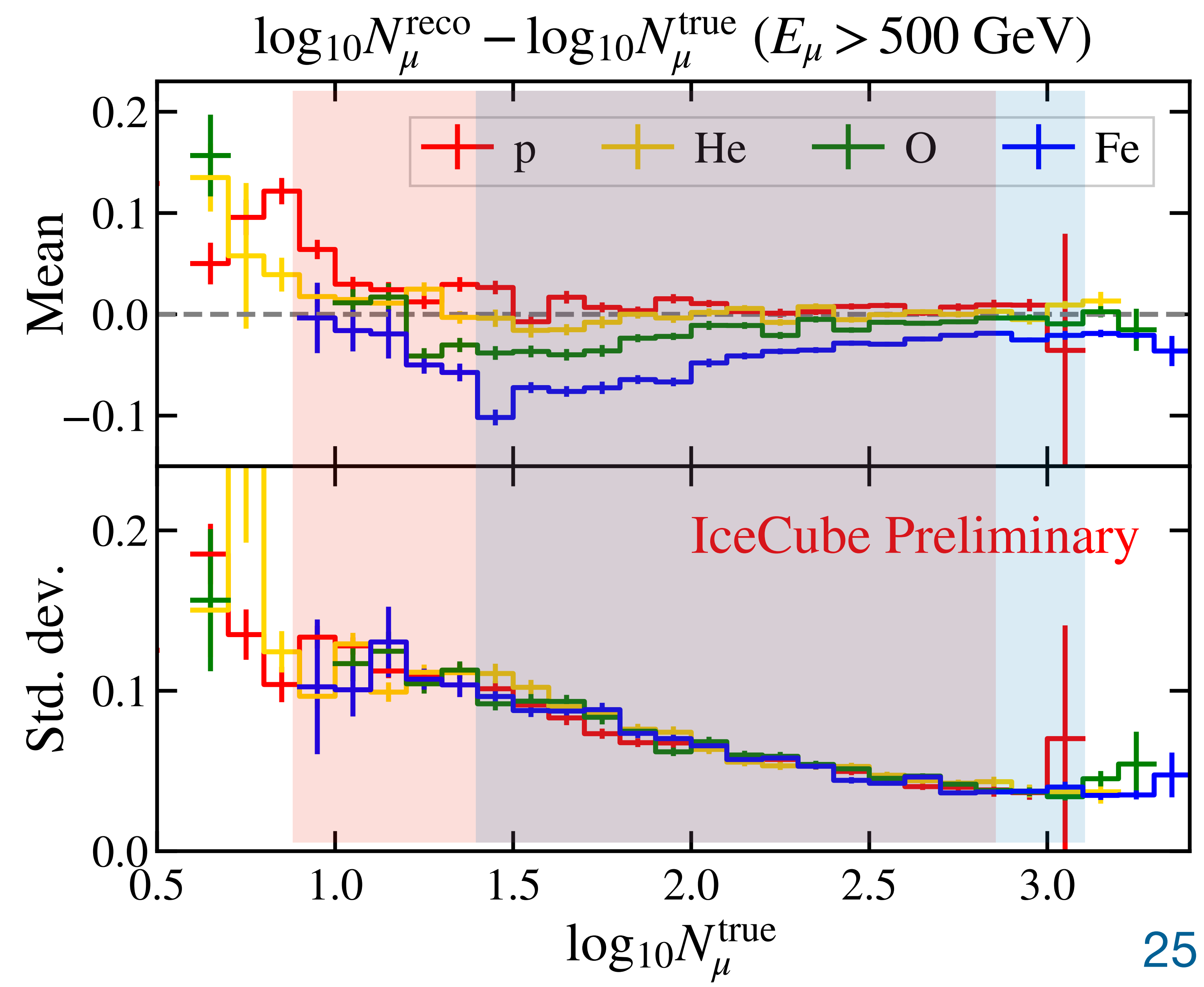
[F. Riehn et al., Phys. Rev. D 102 (2020)]

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



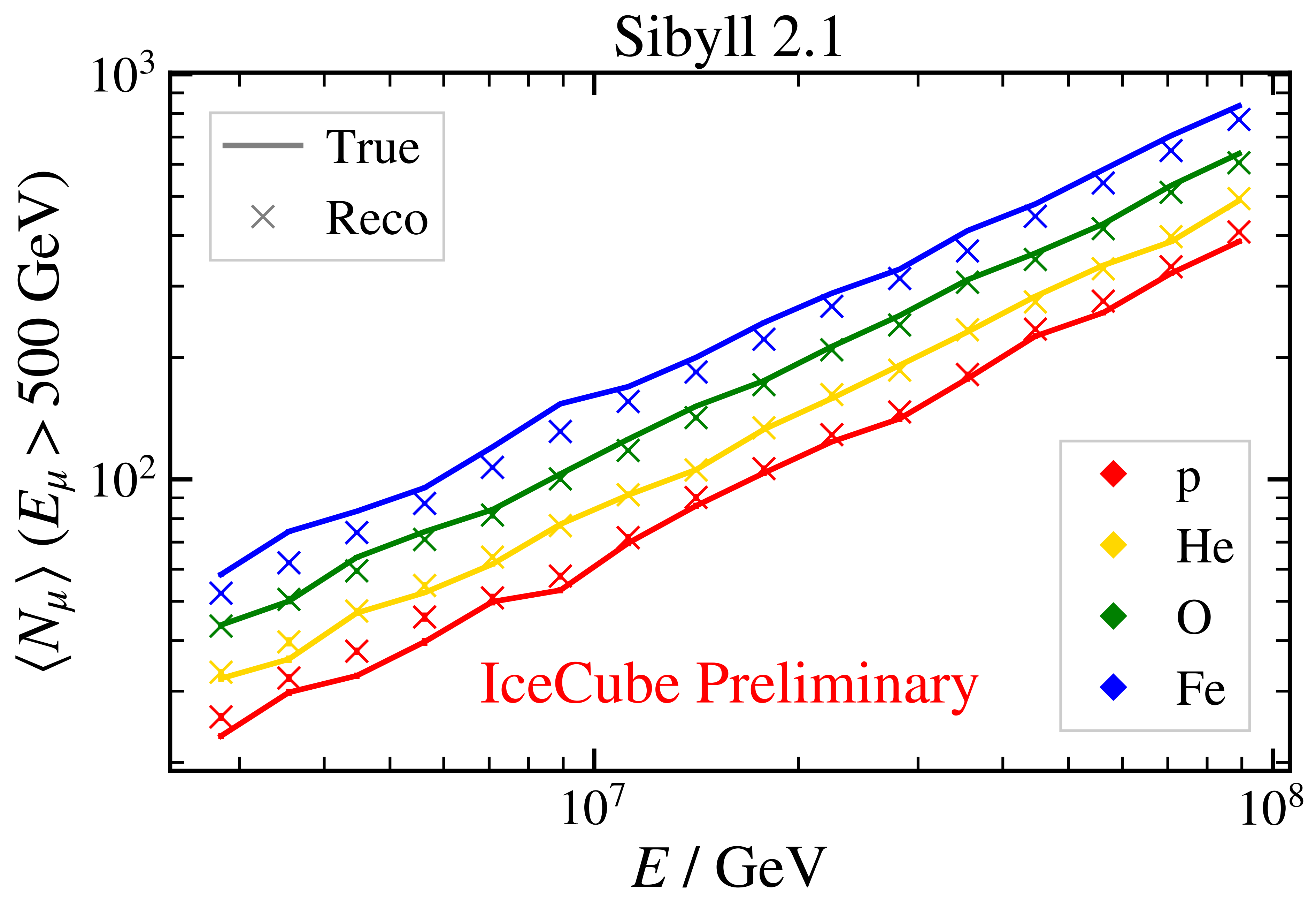


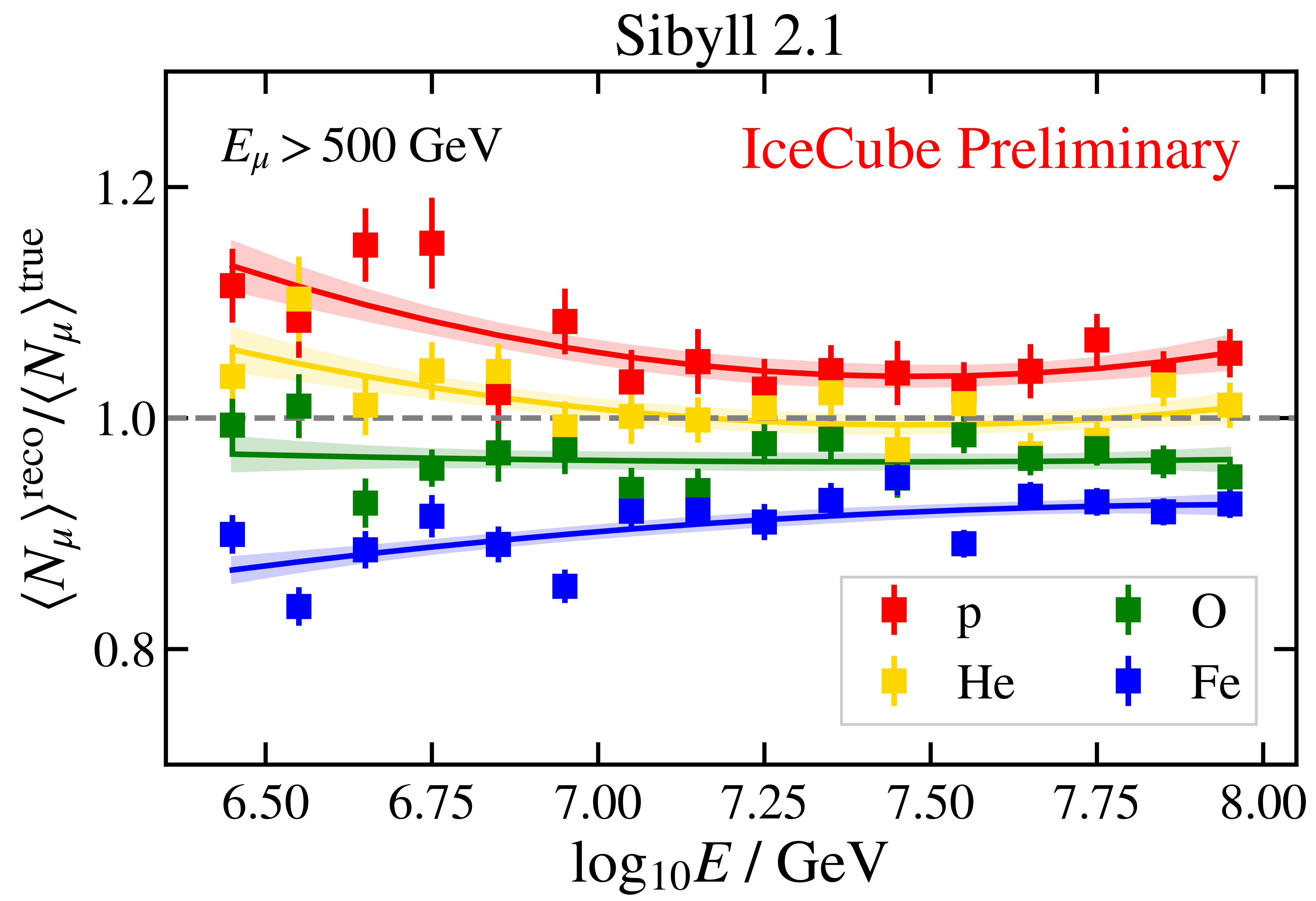


- Training
  - Sibyll 2.1
  - p, He, O, Fe

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!





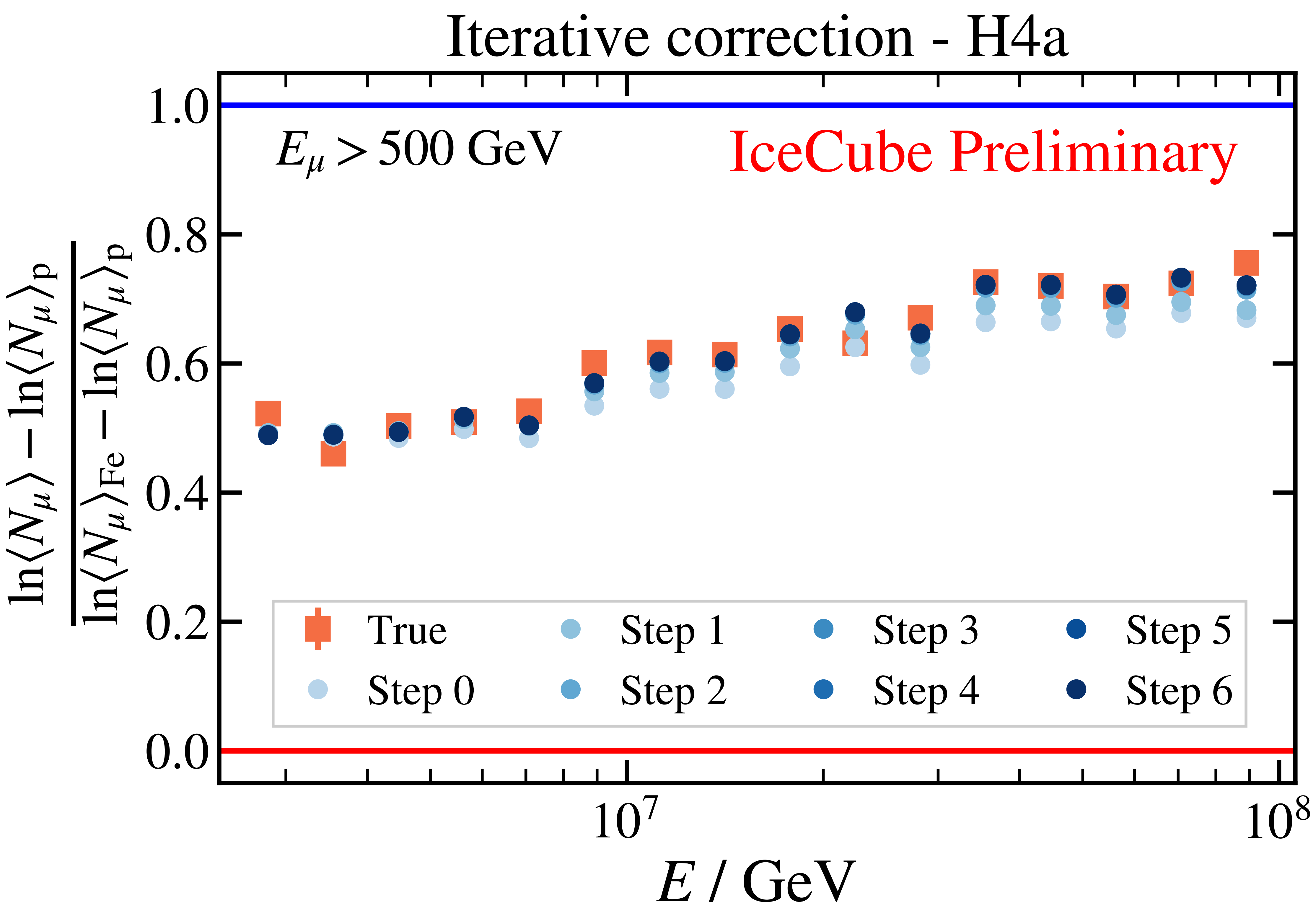
Iterative correction

- 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

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

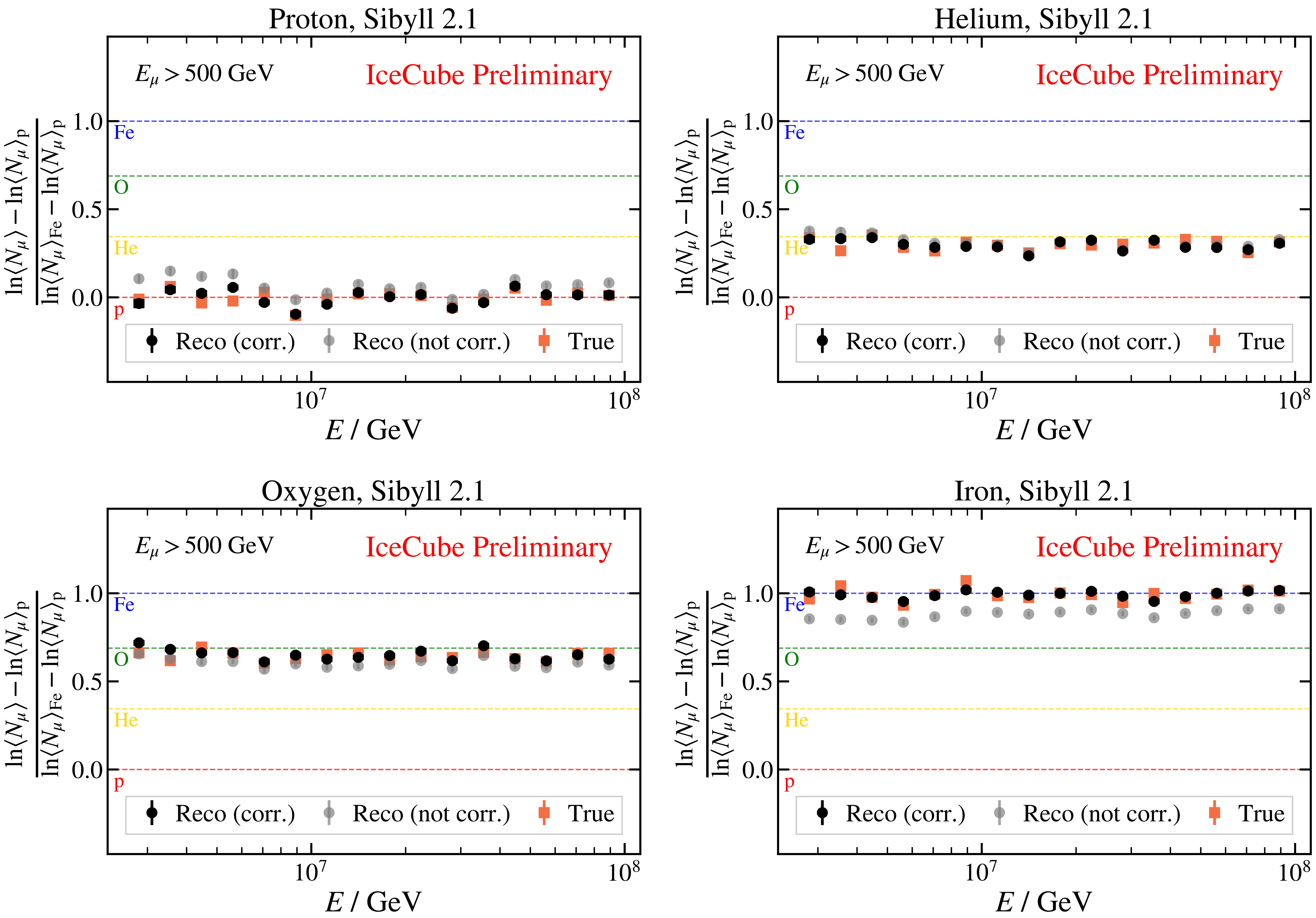


- Iterative procedure
  - $\langle N_\mu\rangle$ estimate → $\mathscr{C}$ → updated $\langle N_\mu\rangle$ → ... → convergence

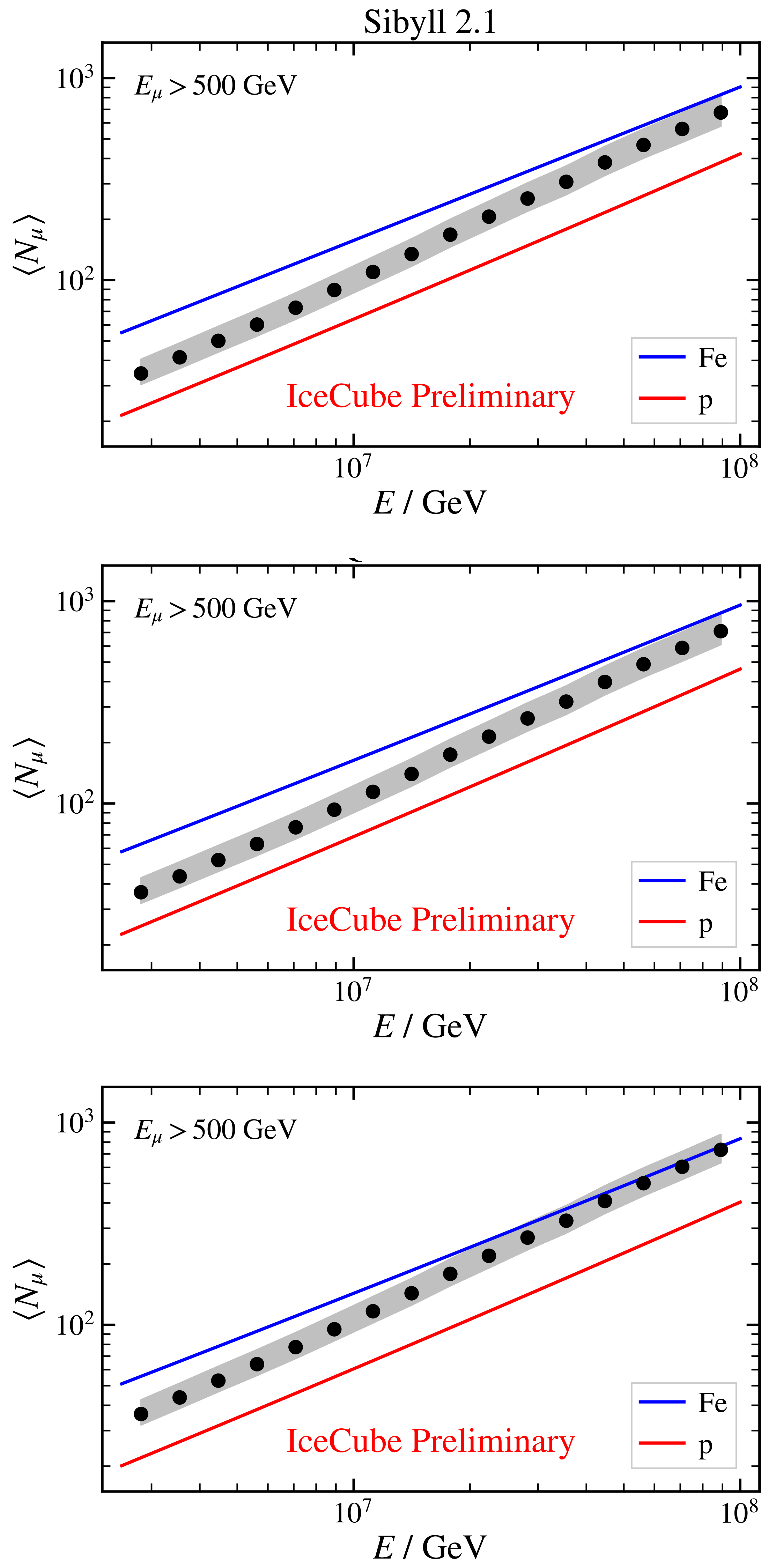
MC tests (TeV mu)

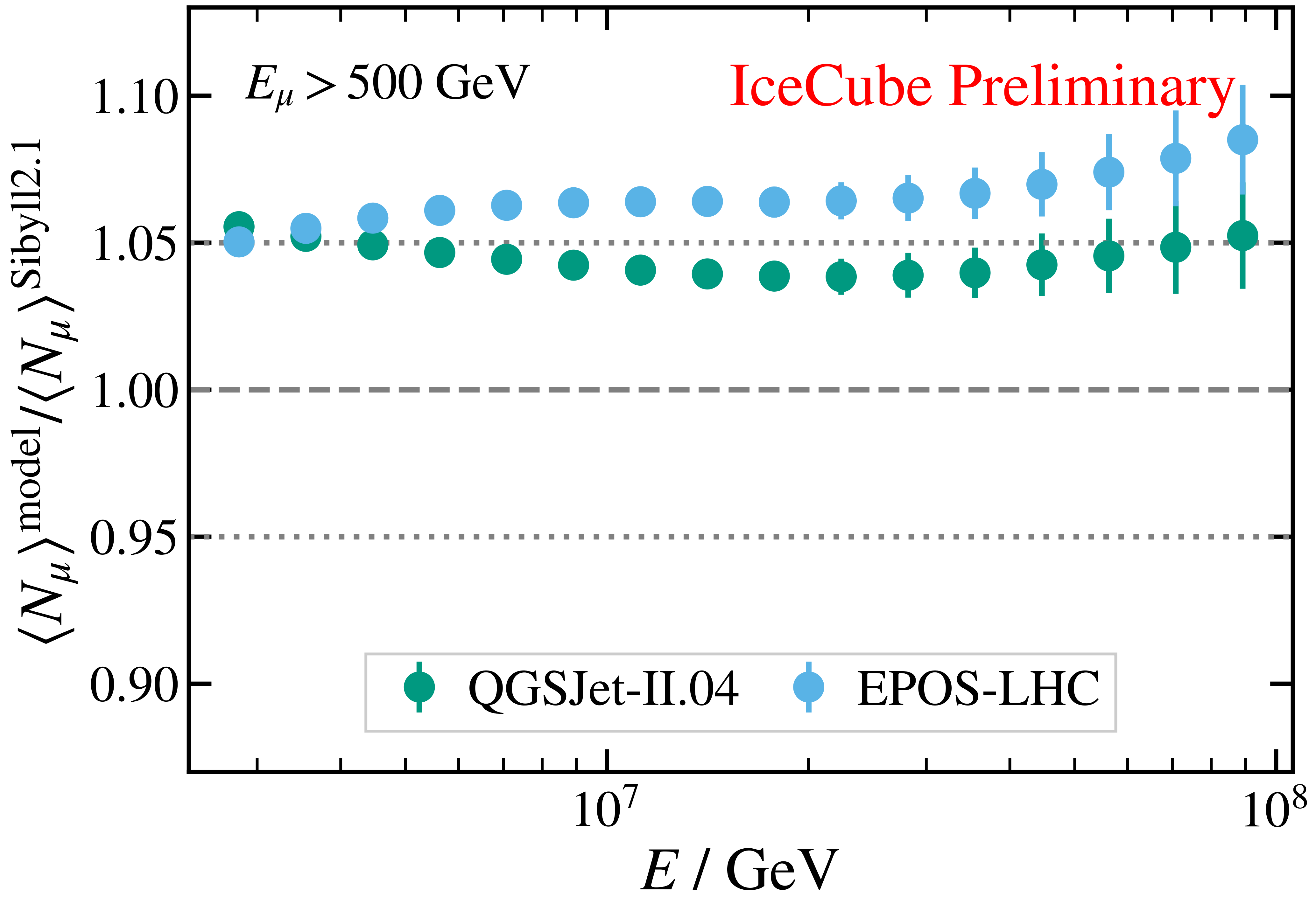
Method reproduces true muon multiplicity regardless of mass composition

(remaining differences included as systematic uncertainty)



Comparison of individual results



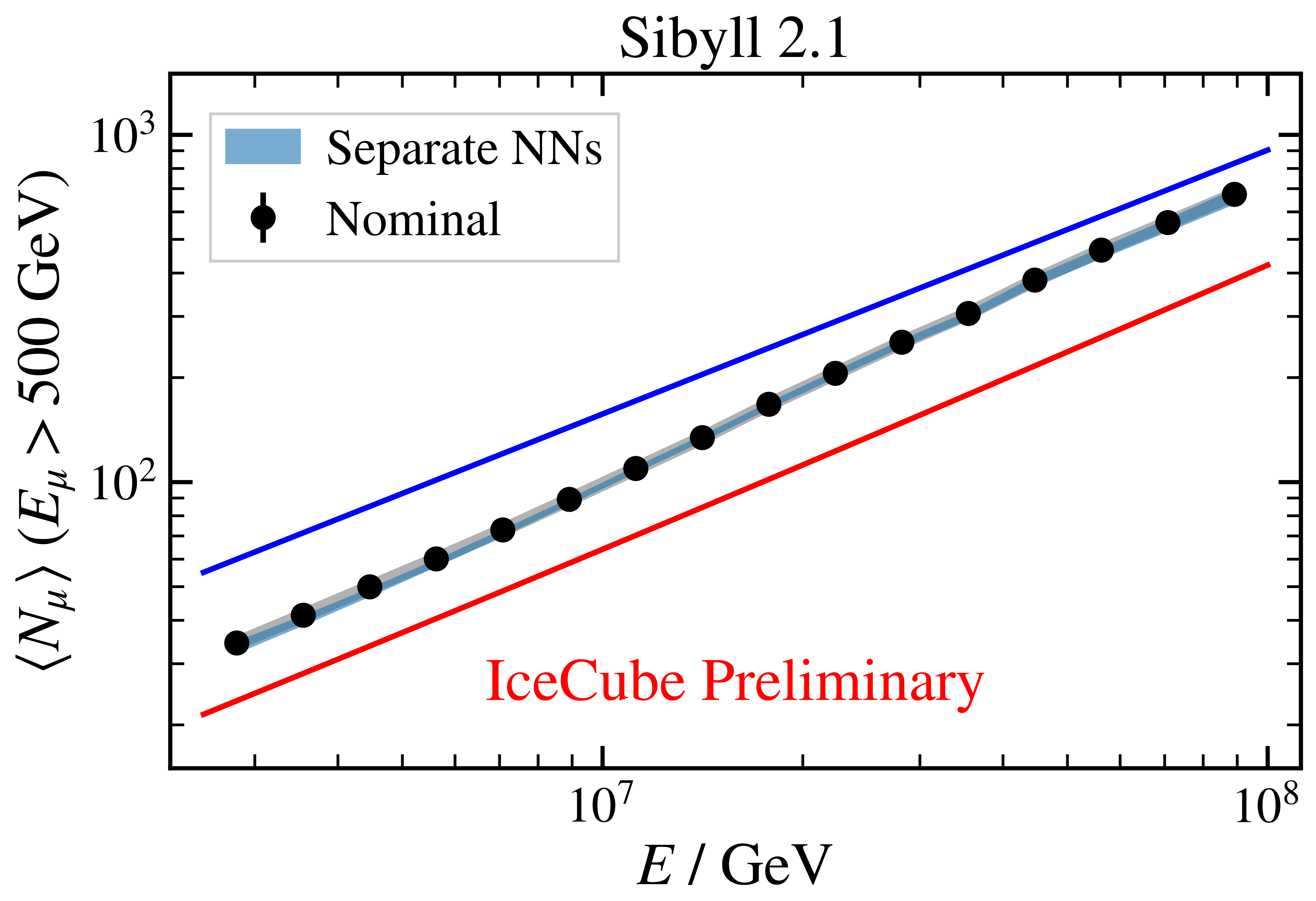


Checks of neural network analysis

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

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

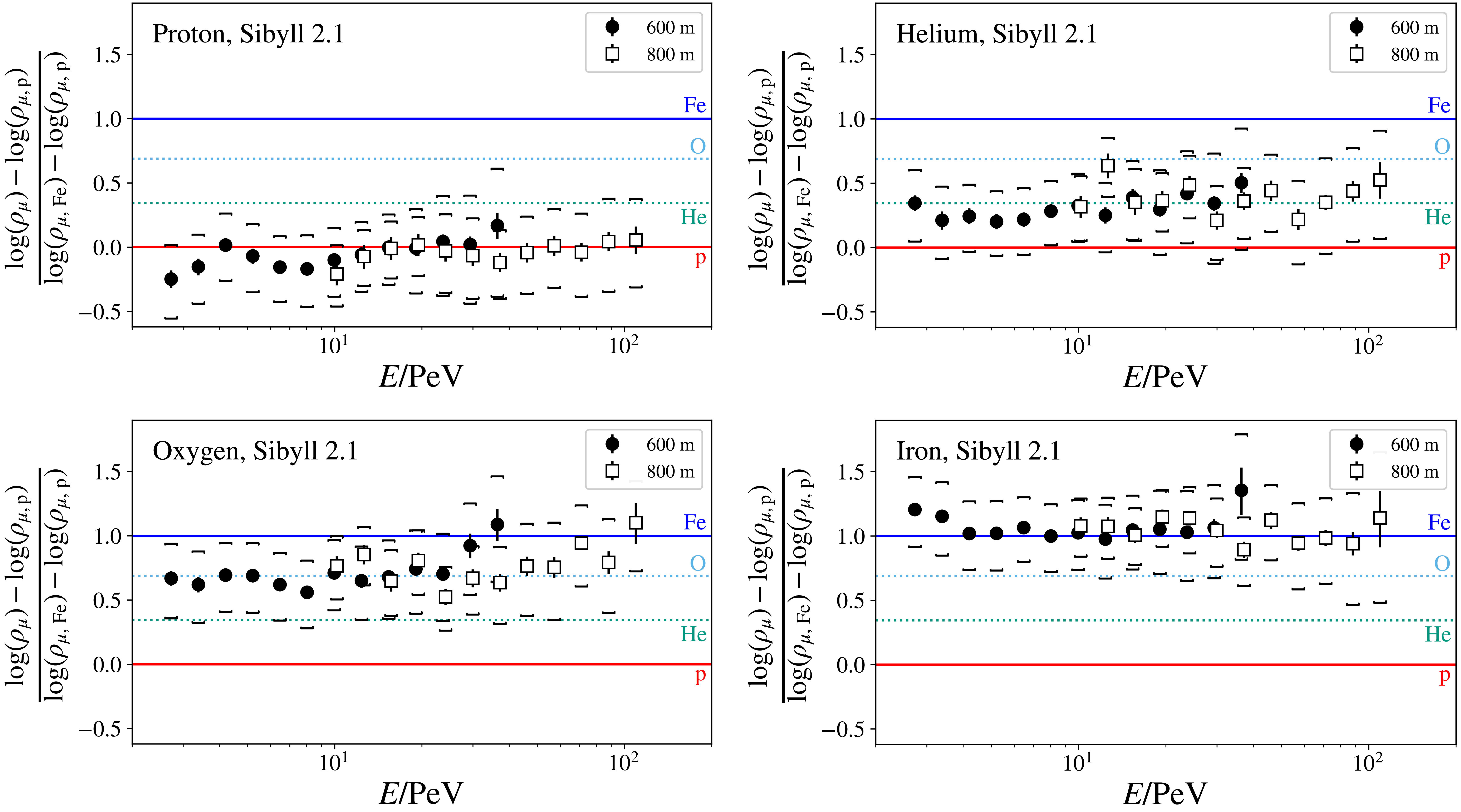
Plots will be included in paper (in progress).



MC tests (GeV mu)

Muon density reproduced well for different primaries

Large uncertainty from mass uncertainty in corrction factor



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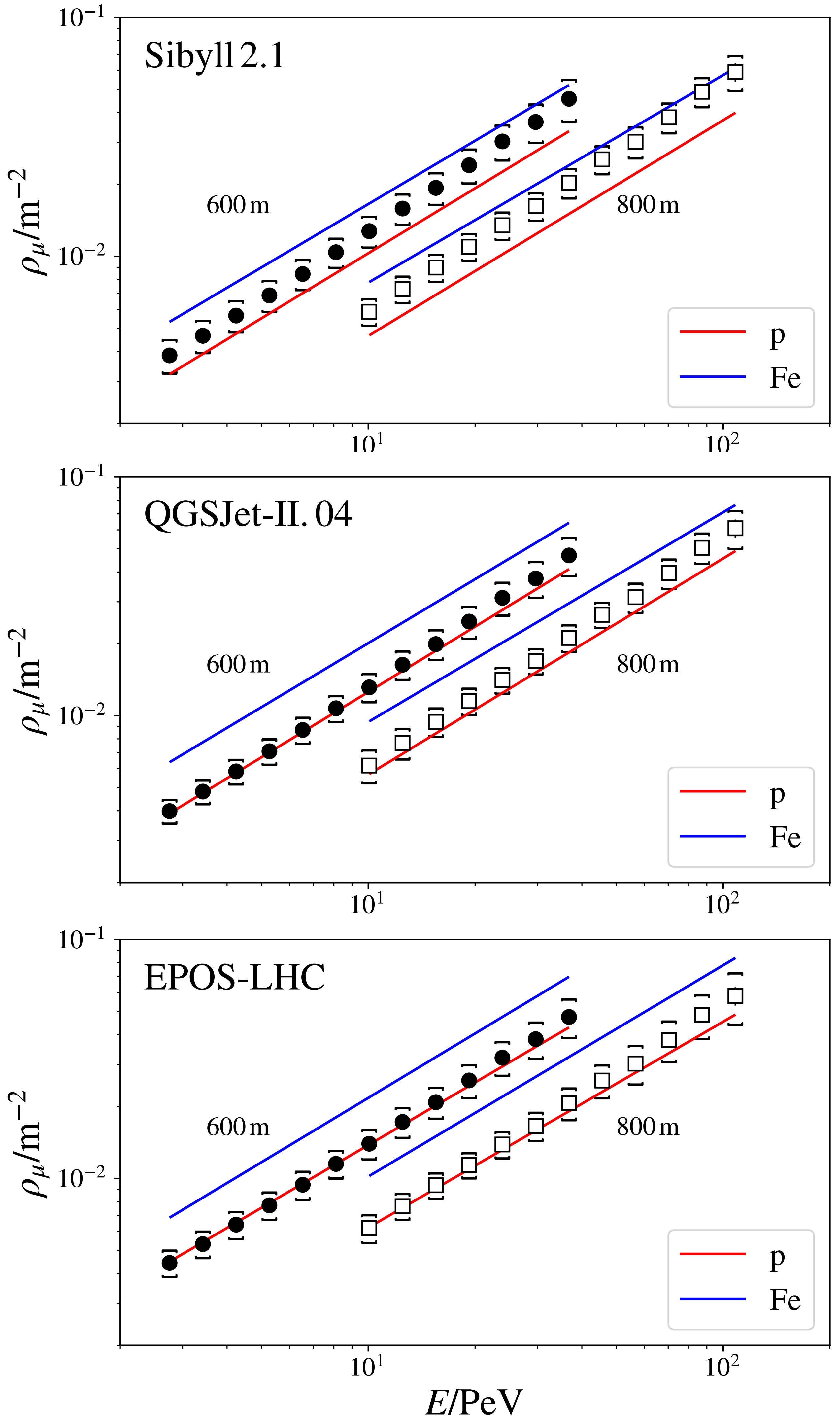
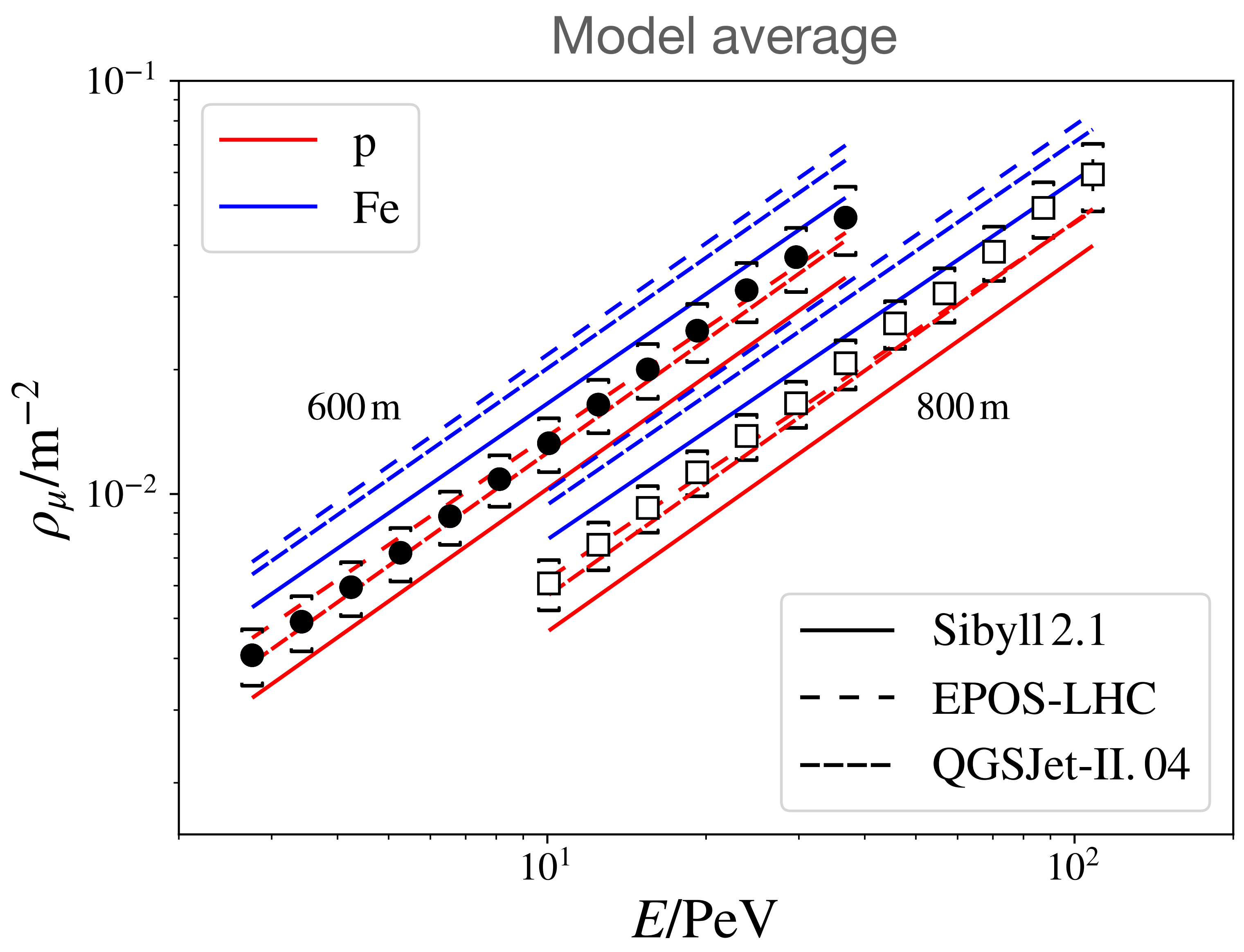
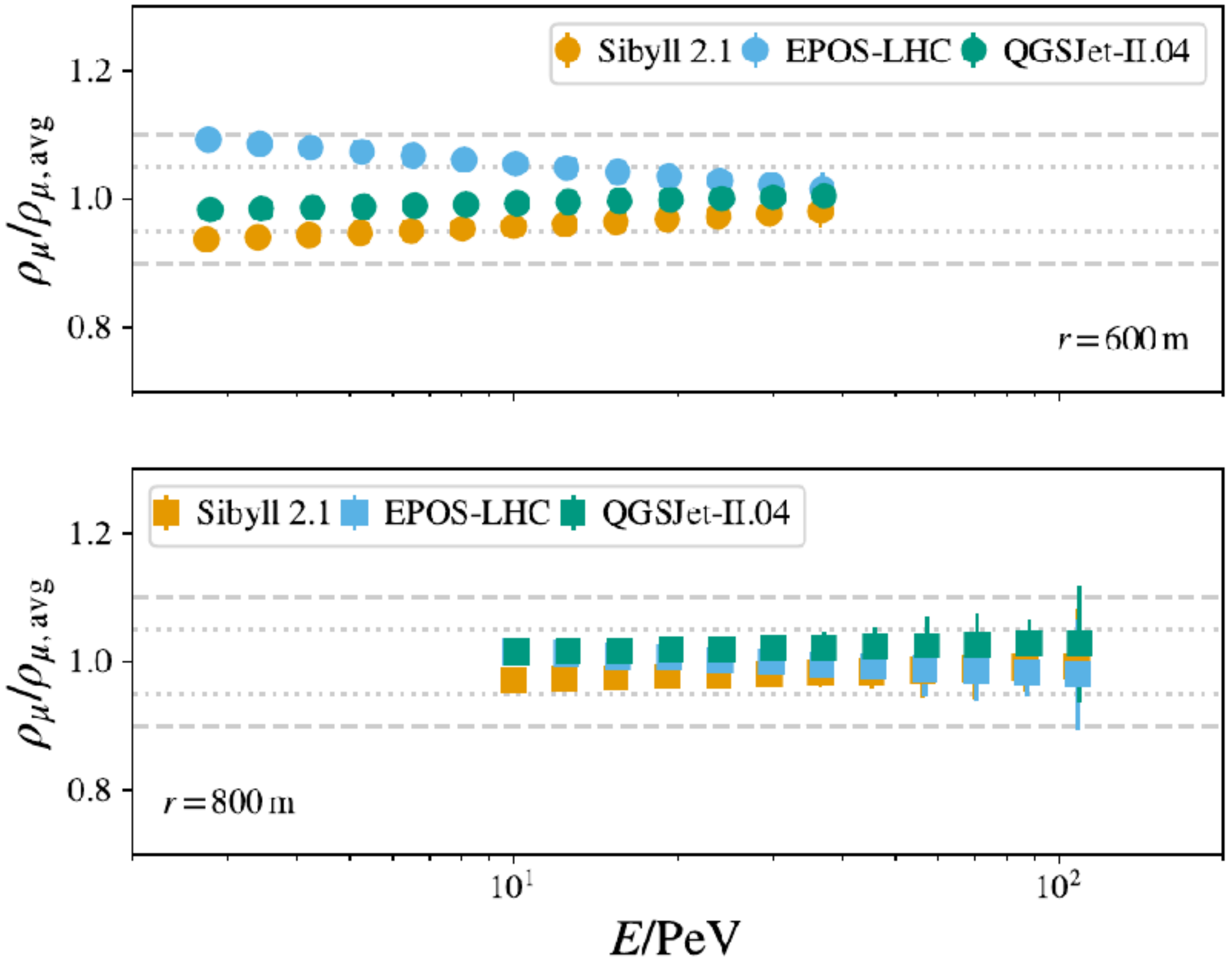
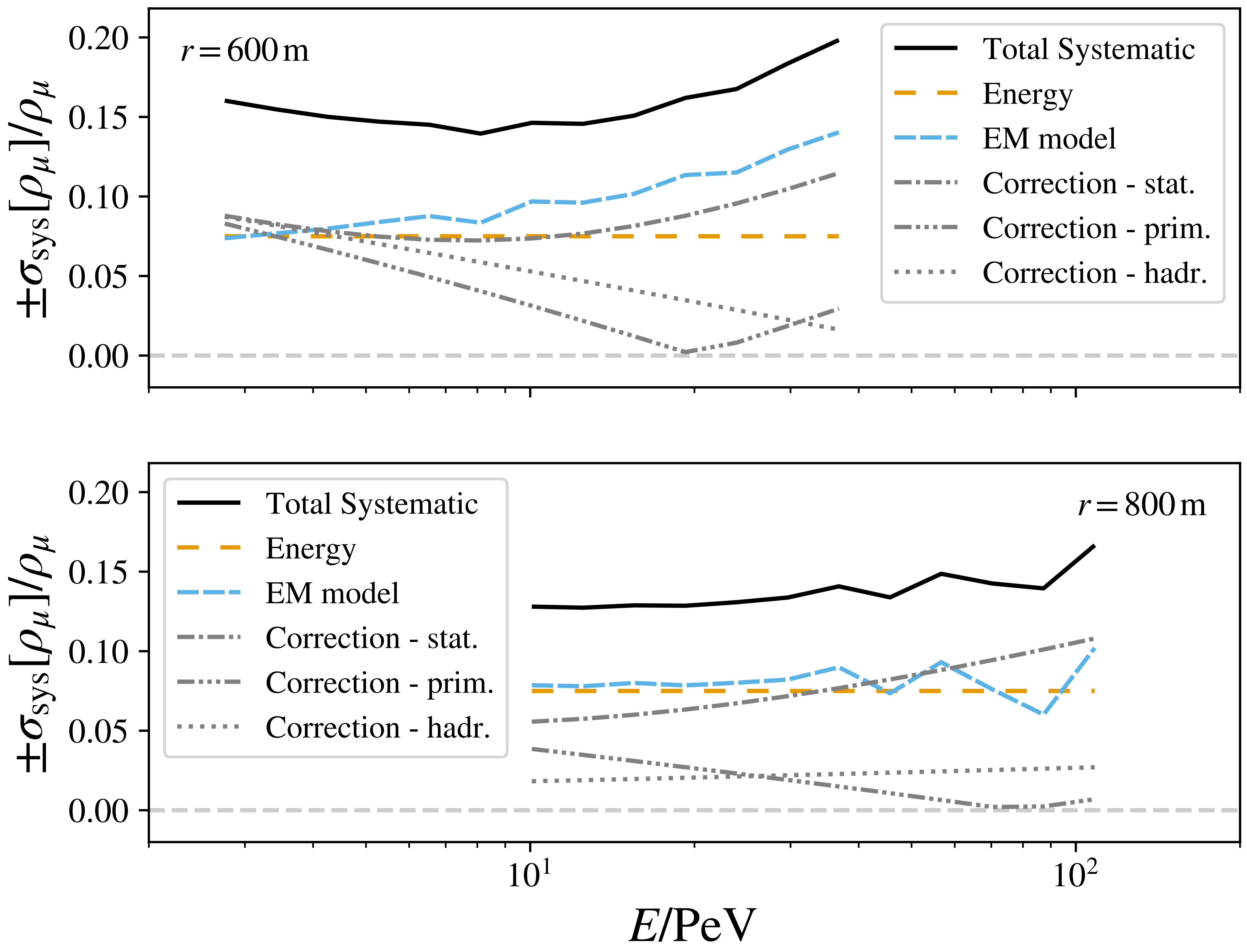






Systematics

GeV muon density



TeV muon multiplicity

Snow correction: ~3%

VEM calibration: ~3%

Ice model & DOM efficiency: ~ +14%, -9%

Correction method: ~4%

Atmosphere: ~2.5%