International Cosmic Ray Conference 2021

Density of GeV Muons measured with IceTop

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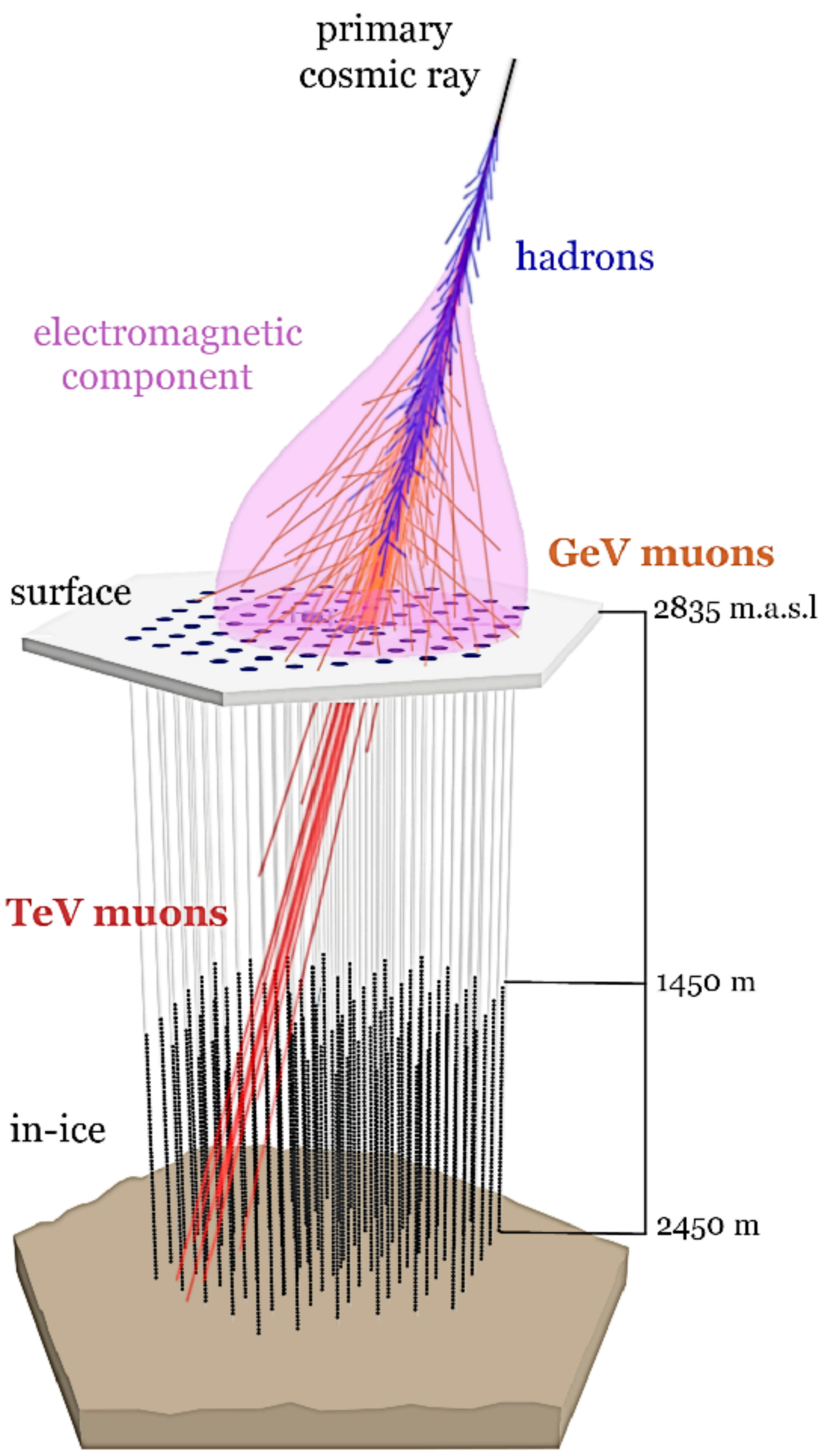
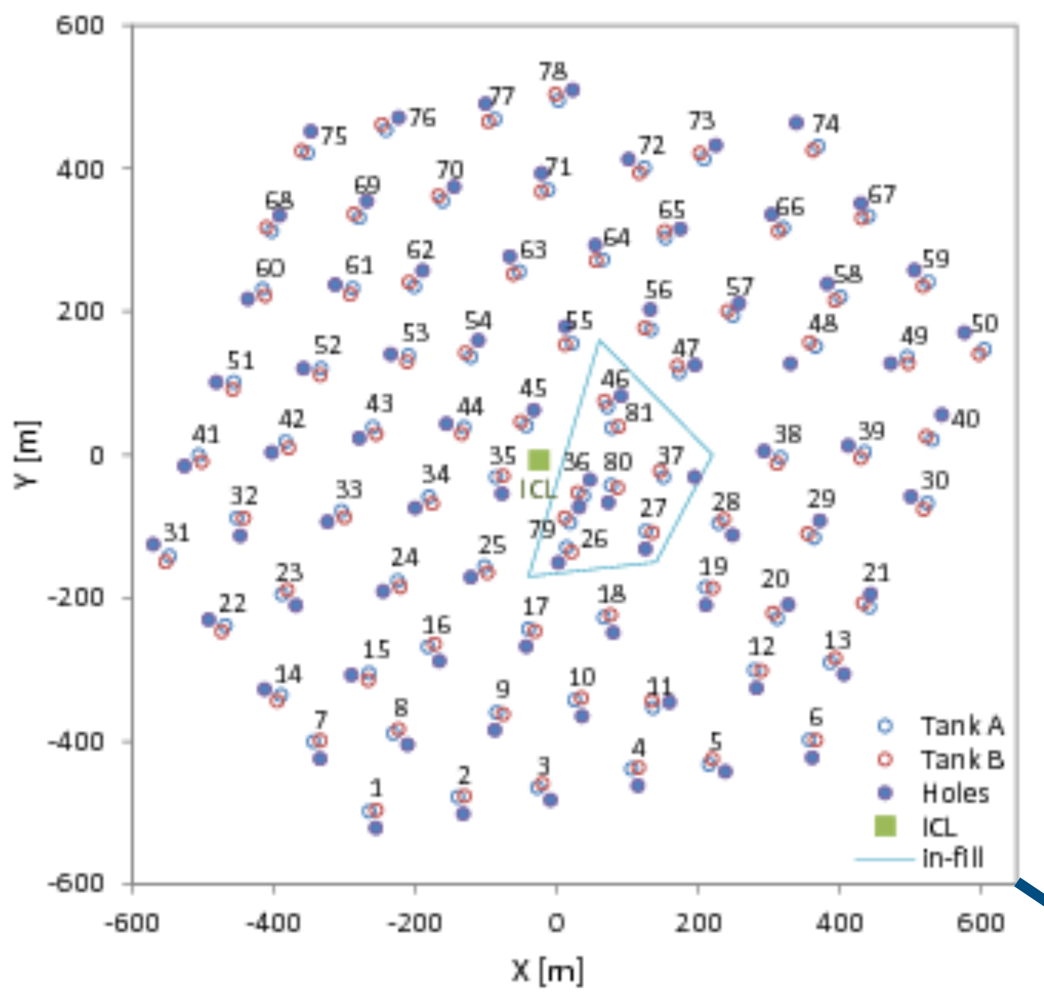
IceCube Neutrino Observatory

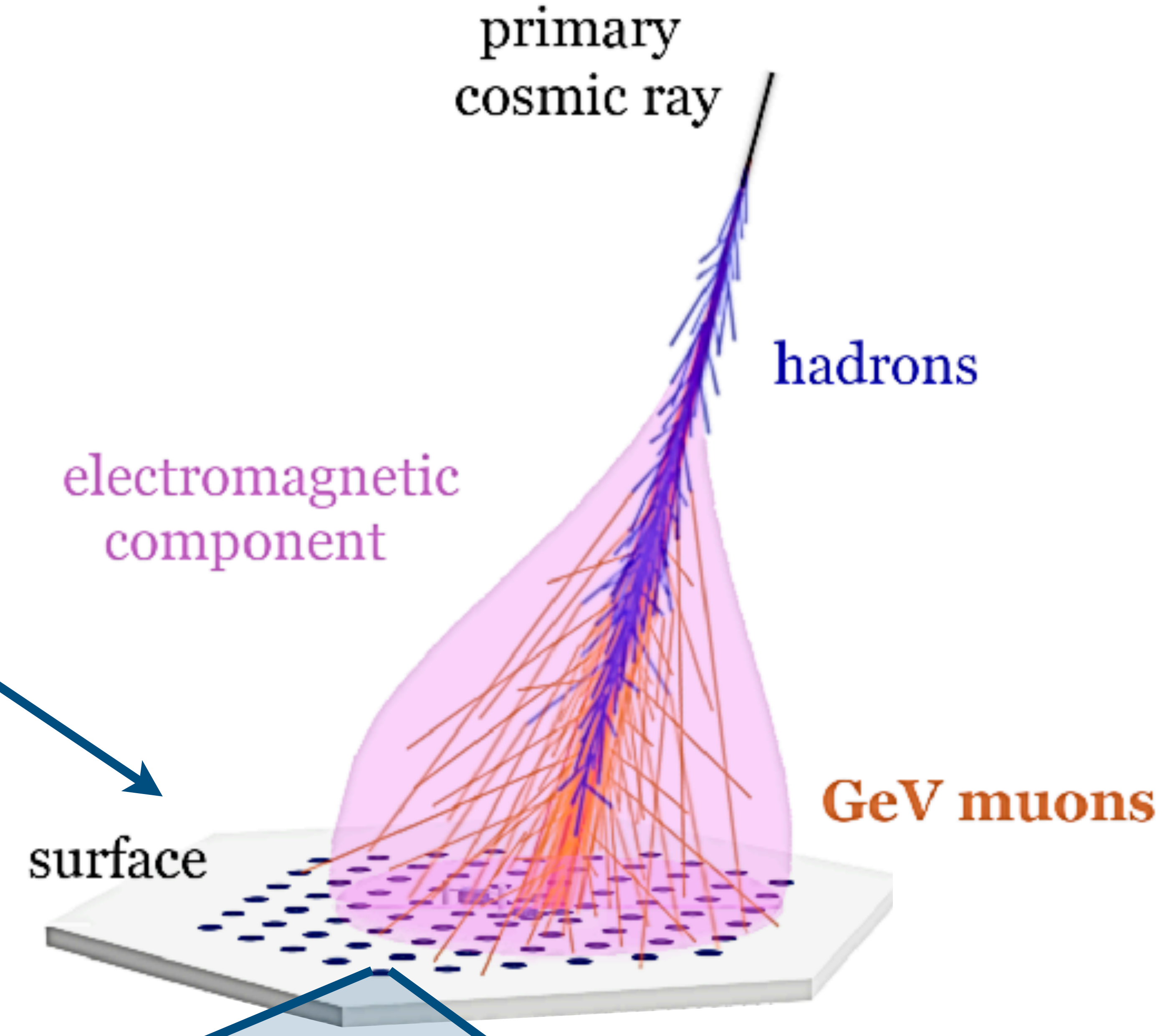
- Hybrid cubic-kilometer particle detector at the South Pole
- $\sim 1\,\mathrm{km}^3$ instrumented in-ice detector volume at depths between 1450 m and 2450 m
- 86 strings with 5160 digital optical modules (DOMs)
- In-ice measures mainly TeV (up to >PeV) muons from EAS
- Surface detector, IceTop:
  - Electromagnetic EAS component (EAS energy)
  - GeV muon content
- Ideal facility to study lepton production in EAS!
- This talk:
  - Measurement of GeV muons with IceTop (only)!

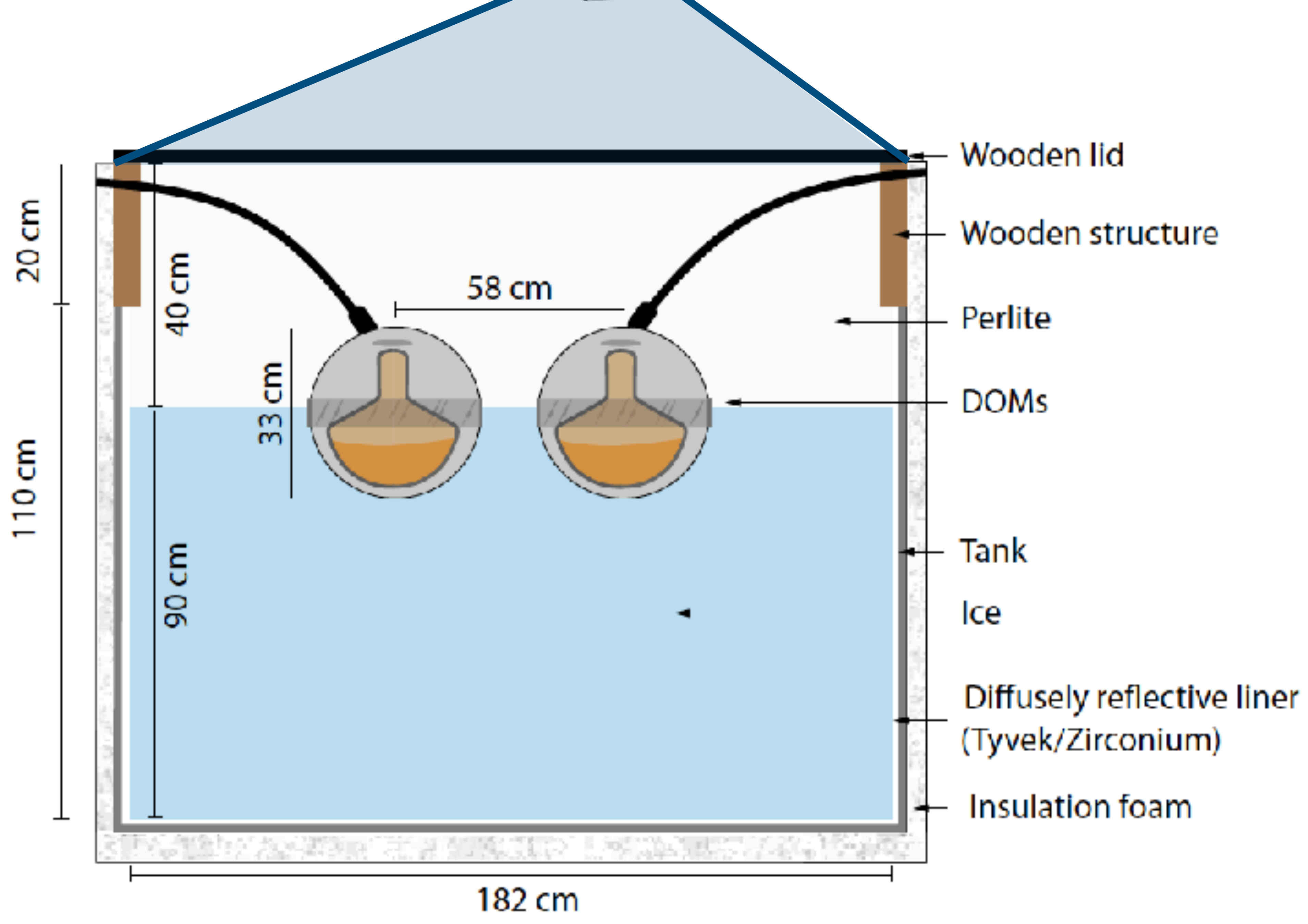


IceTop

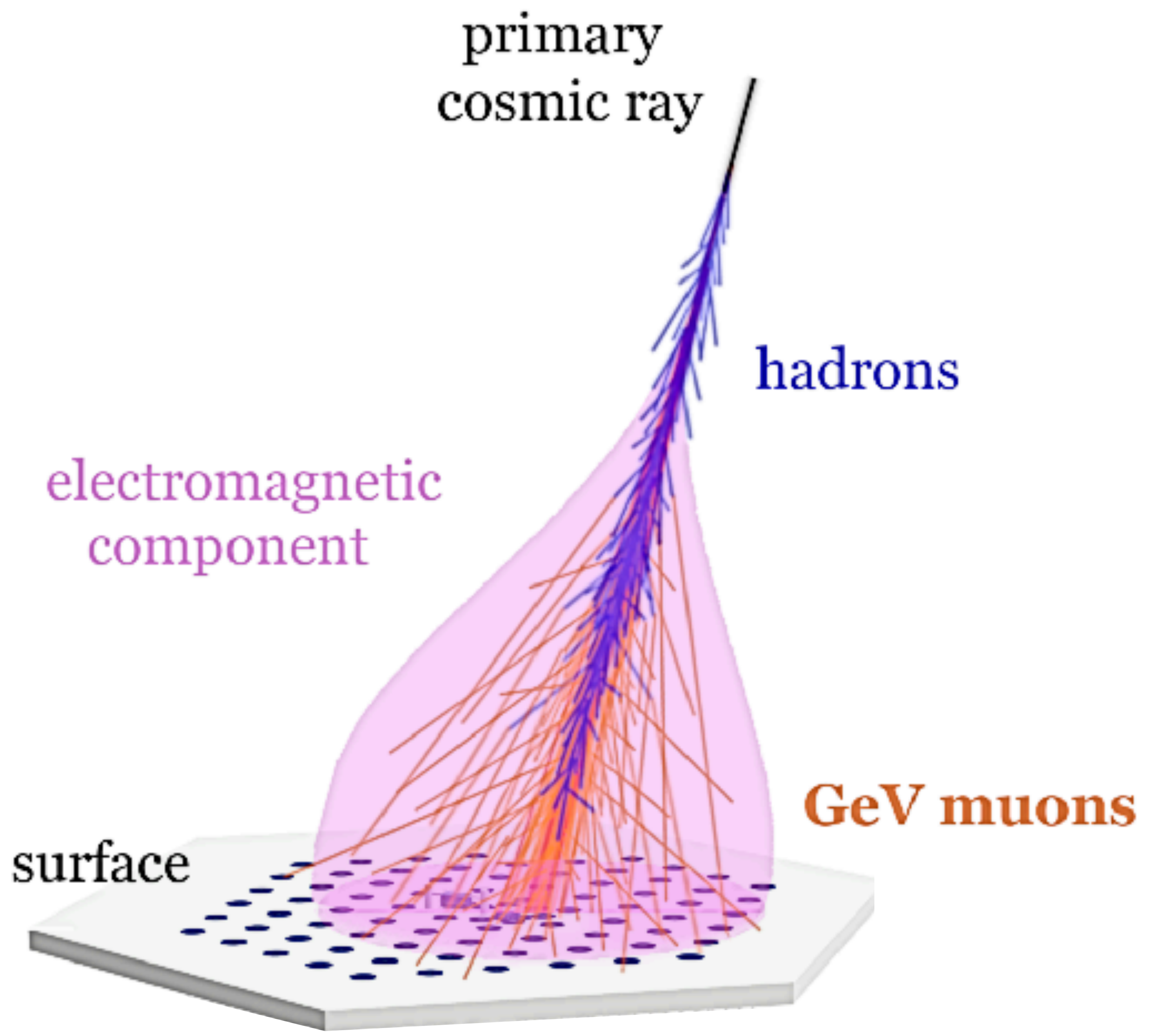
- IceCube's km^2 EAS detector array
- Atmospheric depth $\sim 690\,g/cm^2$
- 162 Cherenkov tanks in 81 stations
- 2 Digital Optical Modules (DOMs) per tank
- Measure Cherenkov light from EAS particles
  - Electromagnetic component
  - GeV muon content
- Snow accumulation over time
  - Accounted for during EAS reconstruction
- New surface enhancement under construction







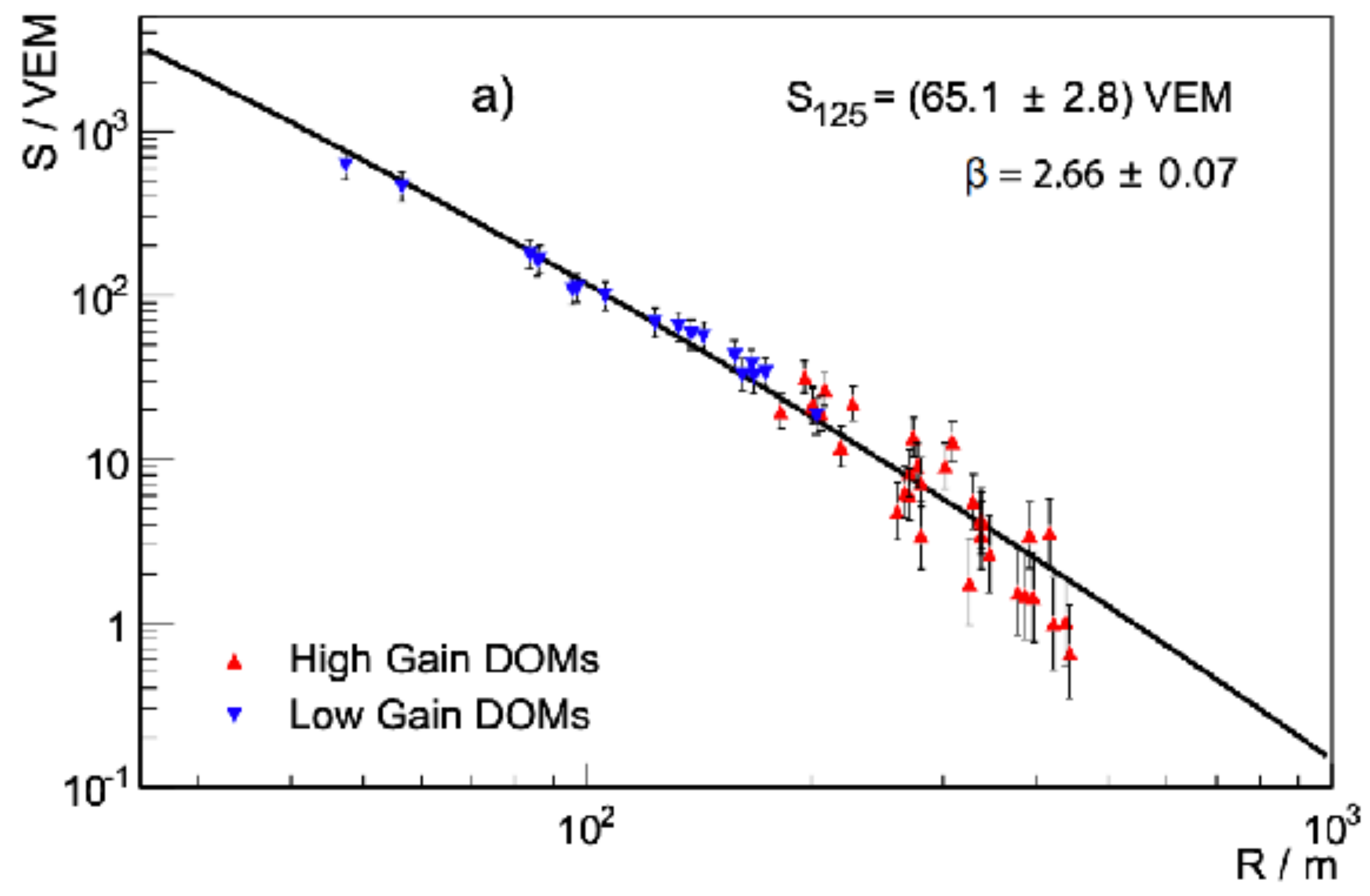
IceTop EAS Reconstruction

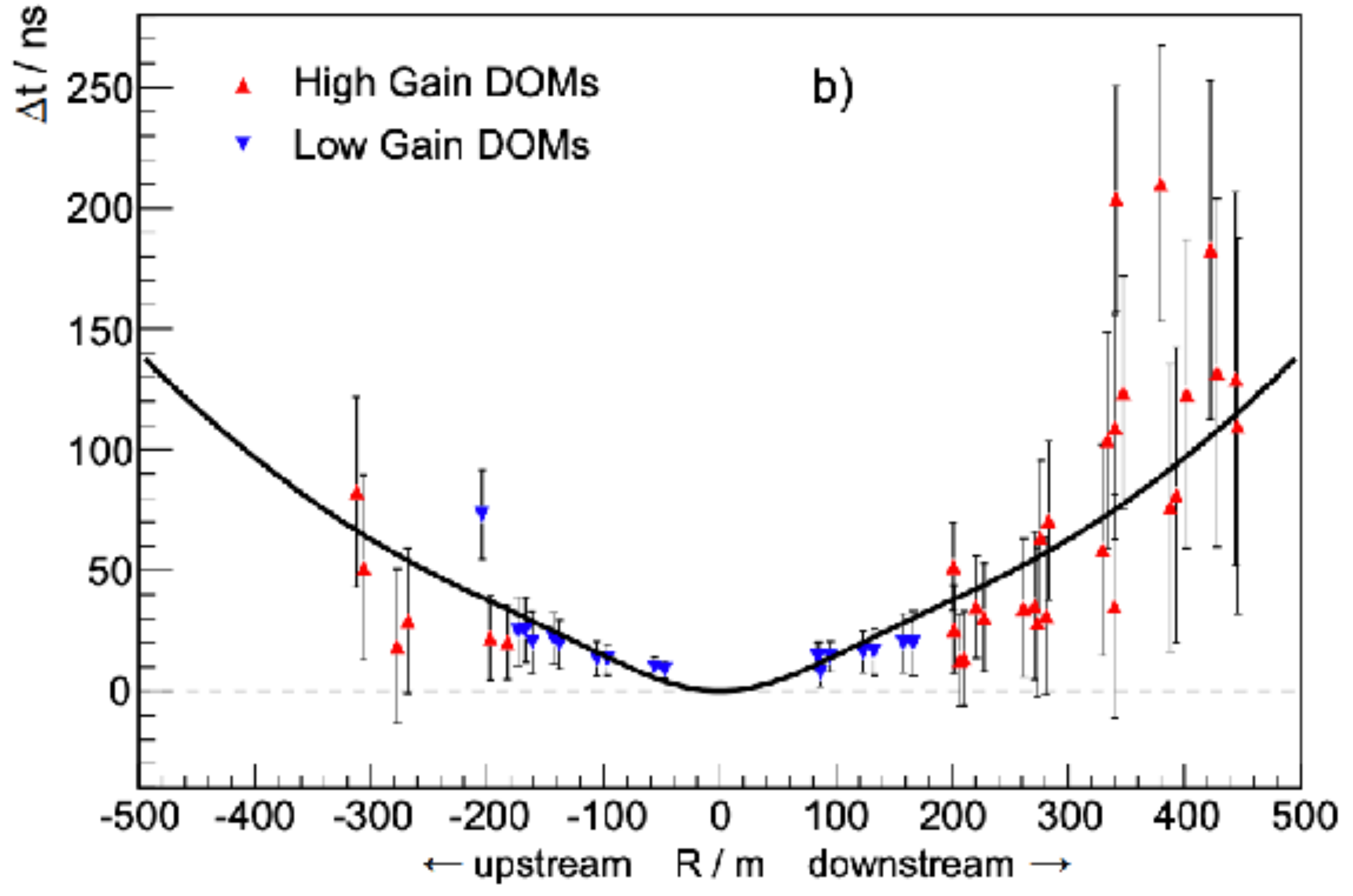


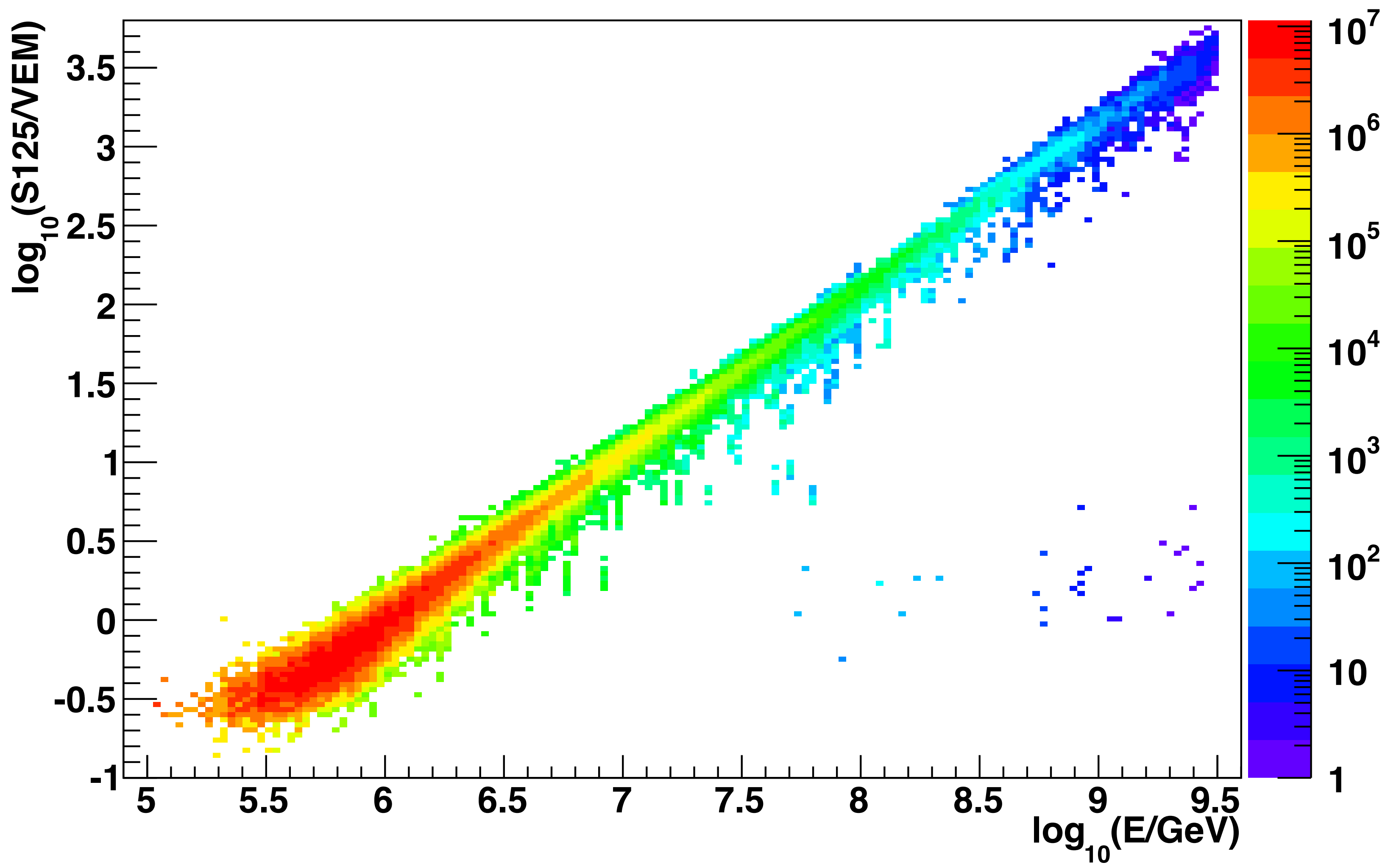
- Air shower reconstruction based on fit to IceTop signals, $S(r)$, using a Lateral Distribution Function (LDF)

$$S(r) = S_{125} \cdot \left(\frac{r}{125\,\mathrm{m}}\right)^{-\beta-\kappa\cdot\log_{10}(r/125\,\mathrm{m})}$$

- Simultaneous fit of the shower front curvature
- Signal at 125 m from the shower axis: S_{125} (in VEM)
- EAS energy from shower size $S_{125} \rightarrow E_0$ (resolution: < 0.1 in $\log_{10}(E_0)$)

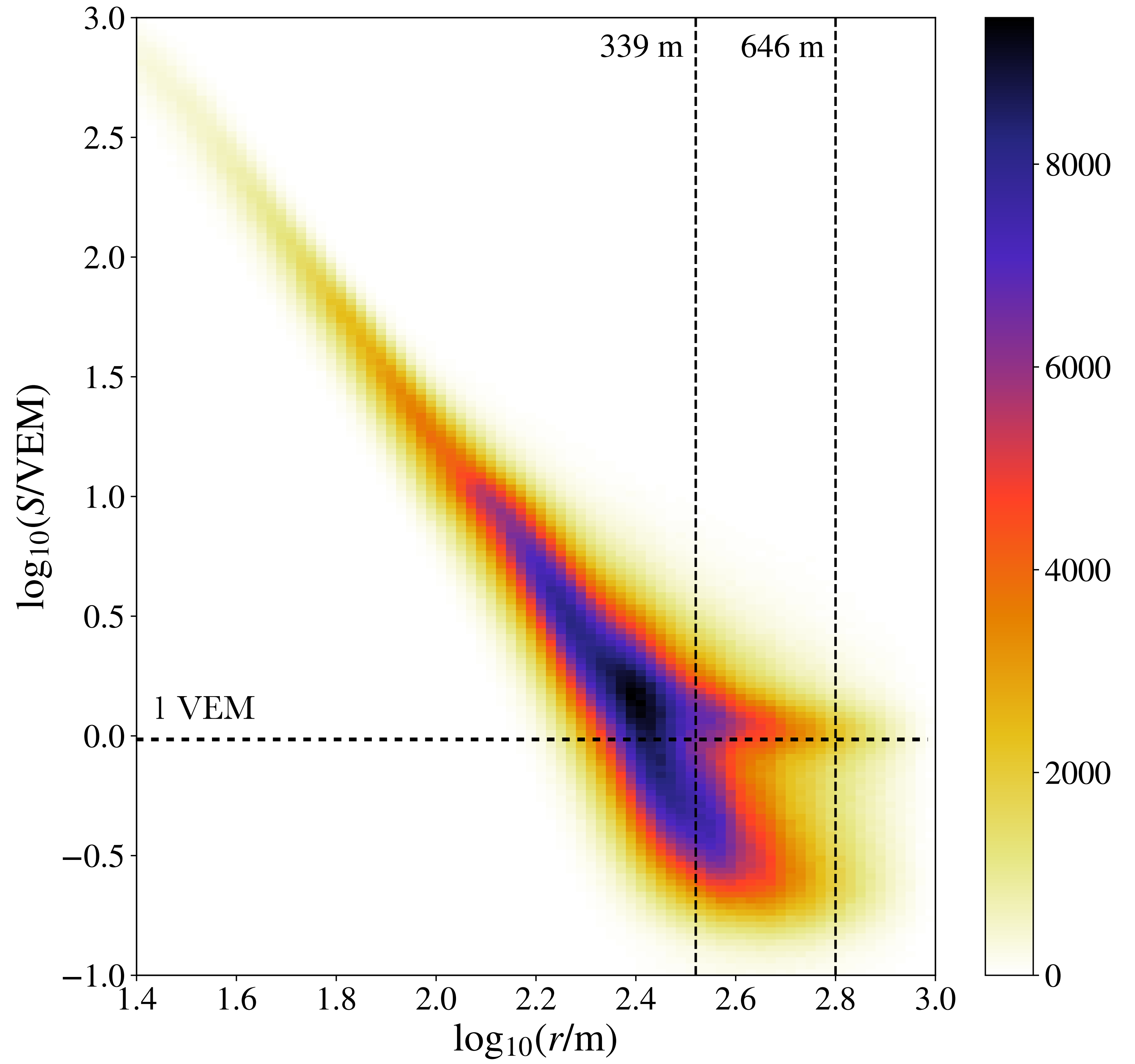


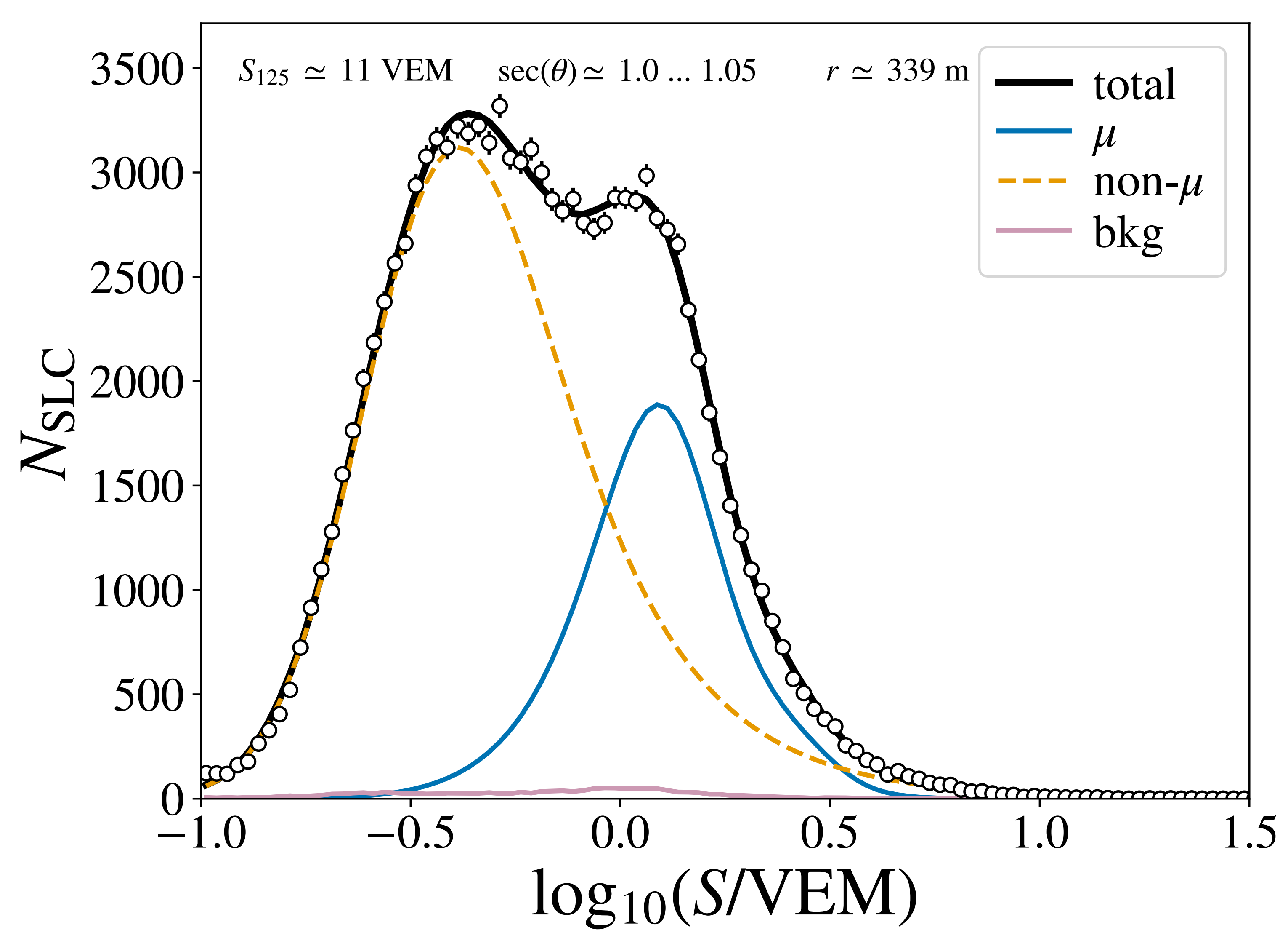


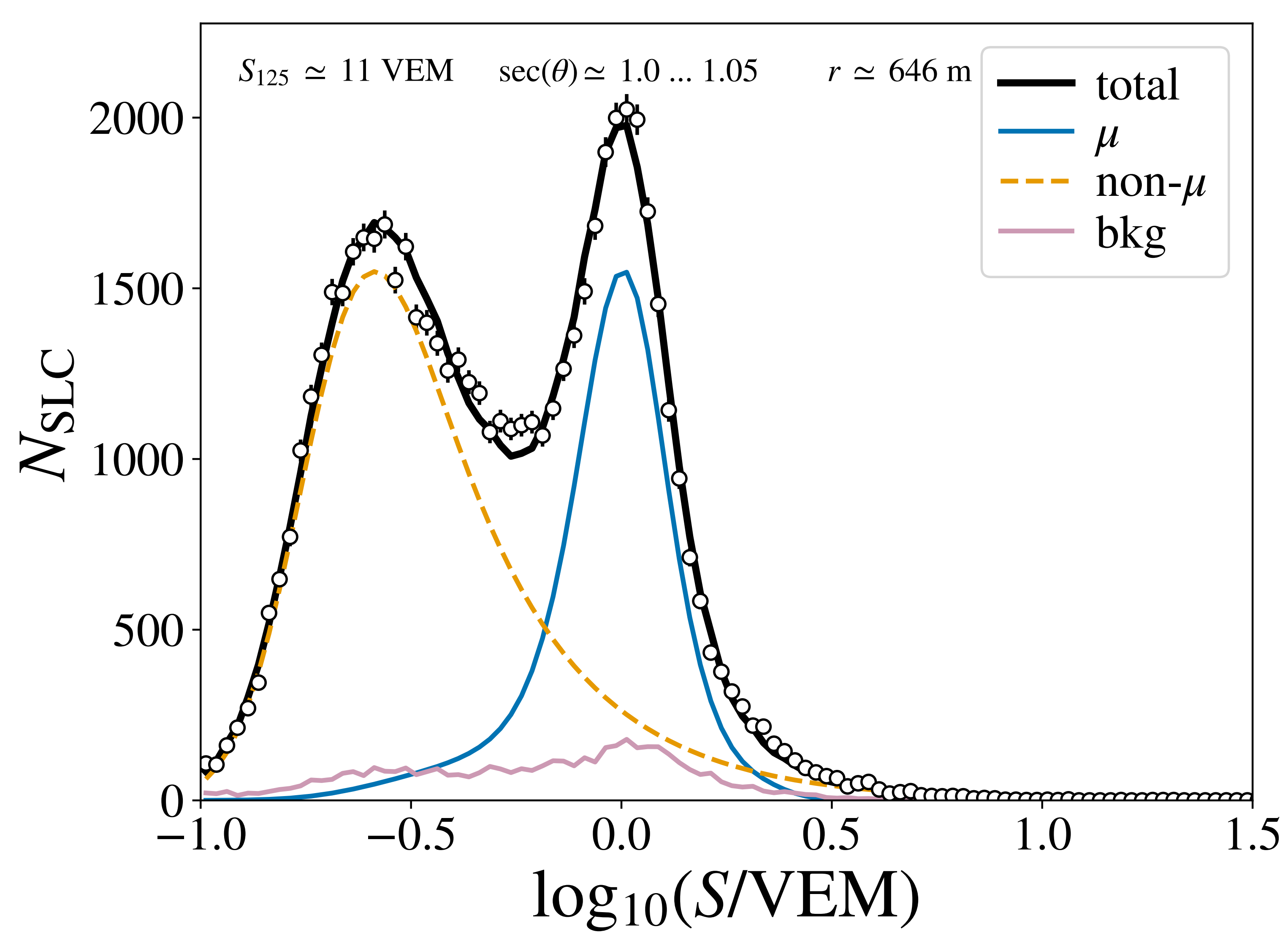


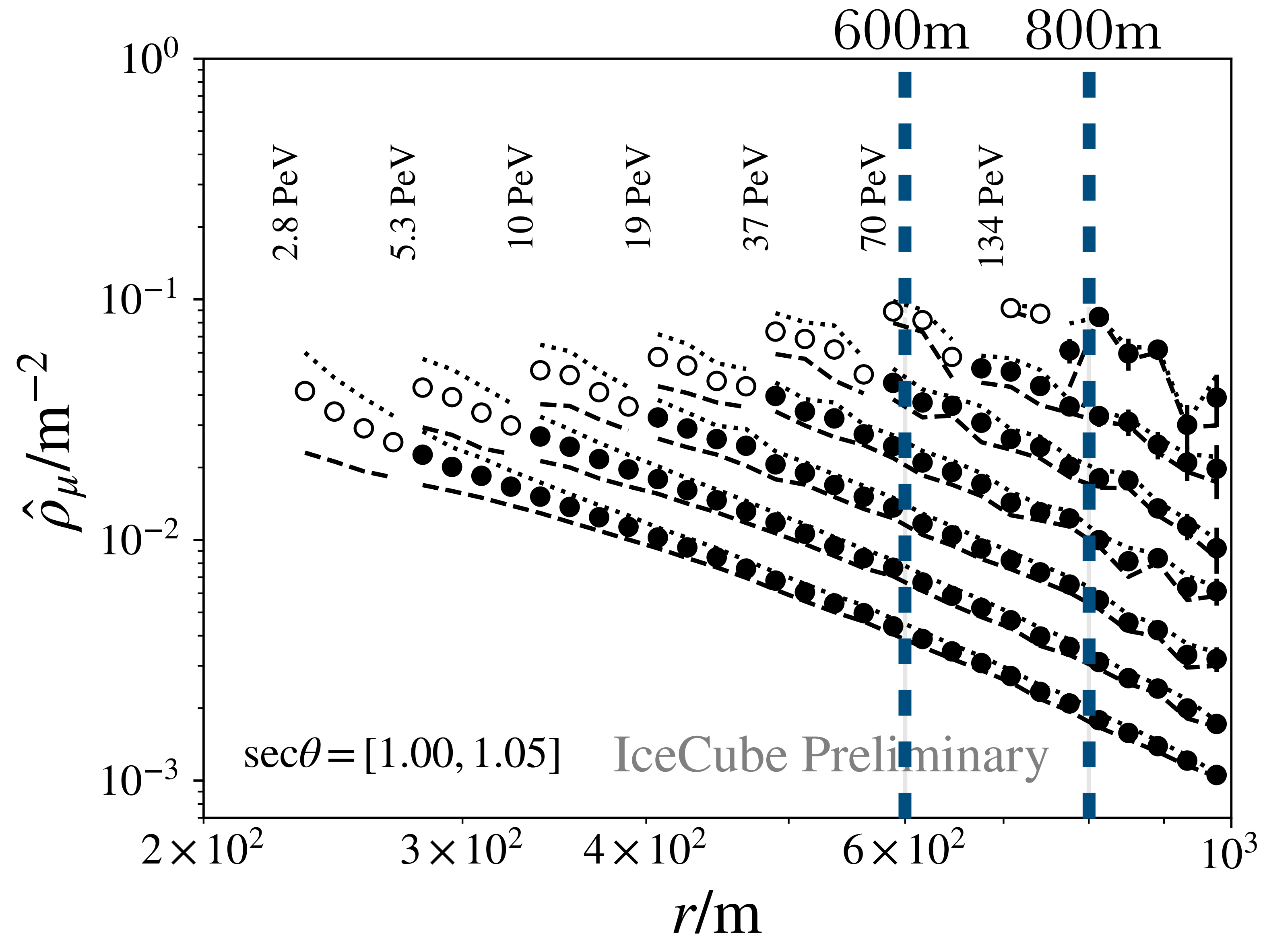
GeV Muons in IceTop

- Muon identification based on "muon thumb" at large distances in signal distribution
- Complex likelihood fit of charge distributions determines "raw" muon density $\hat{\rho}_\mu(r)$
- Measured at 600 m and 800 m for EAS energies between 2.5 – 40 PeV and 9 – 120 PeV, respectively
- Only near-vertical EAS ($\theta < 18°$)



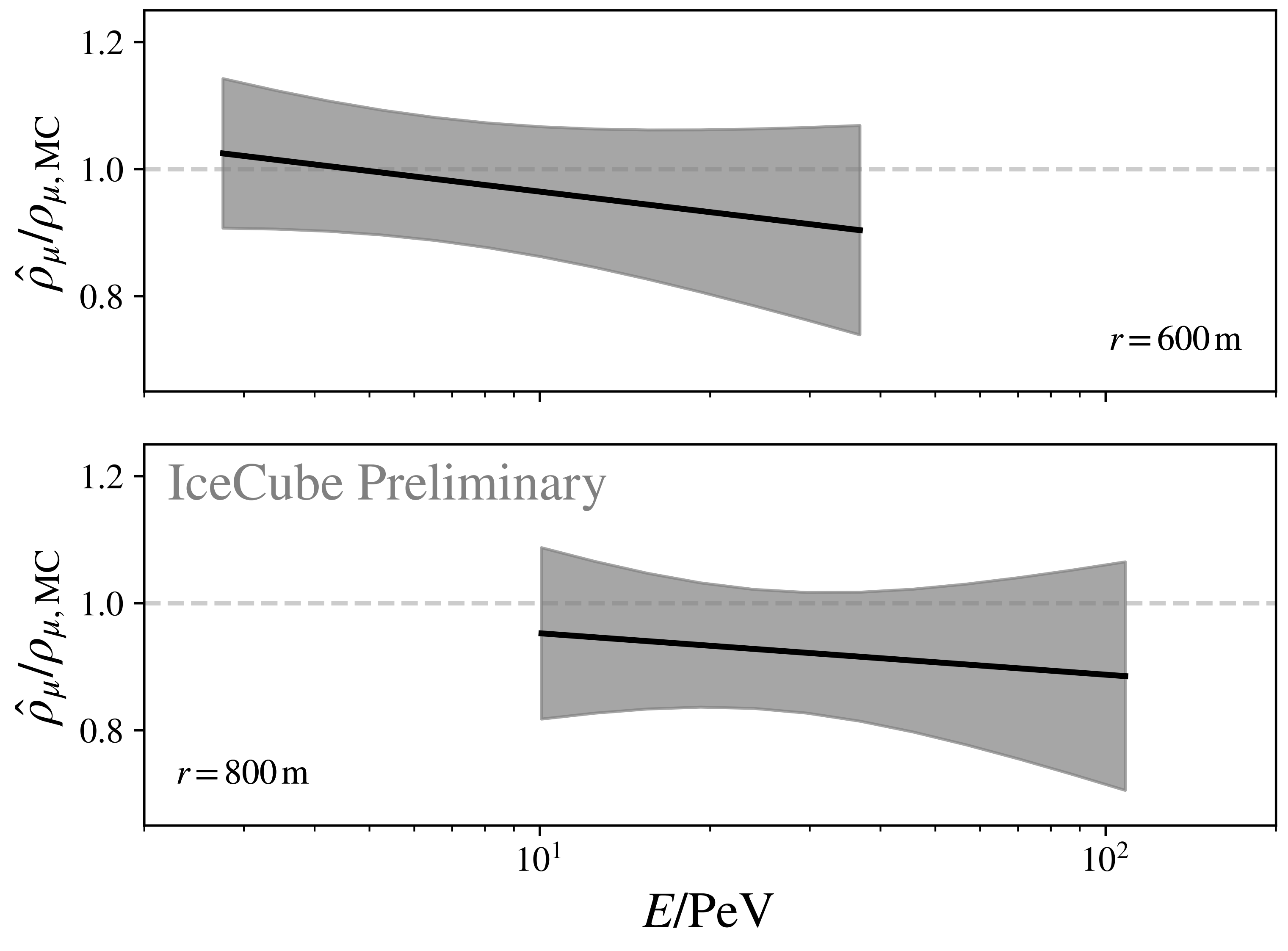


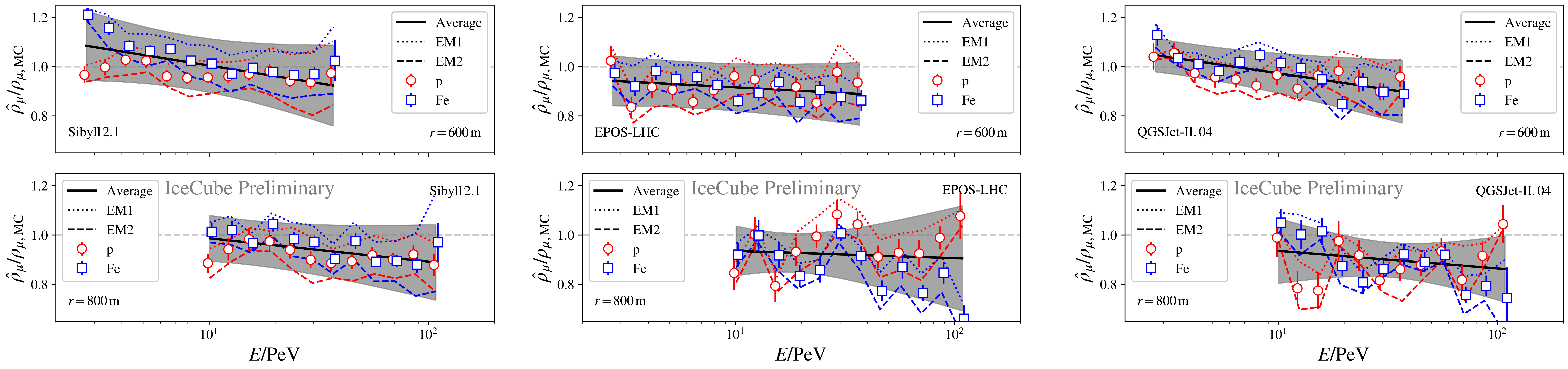




Monte-Carlo Correction

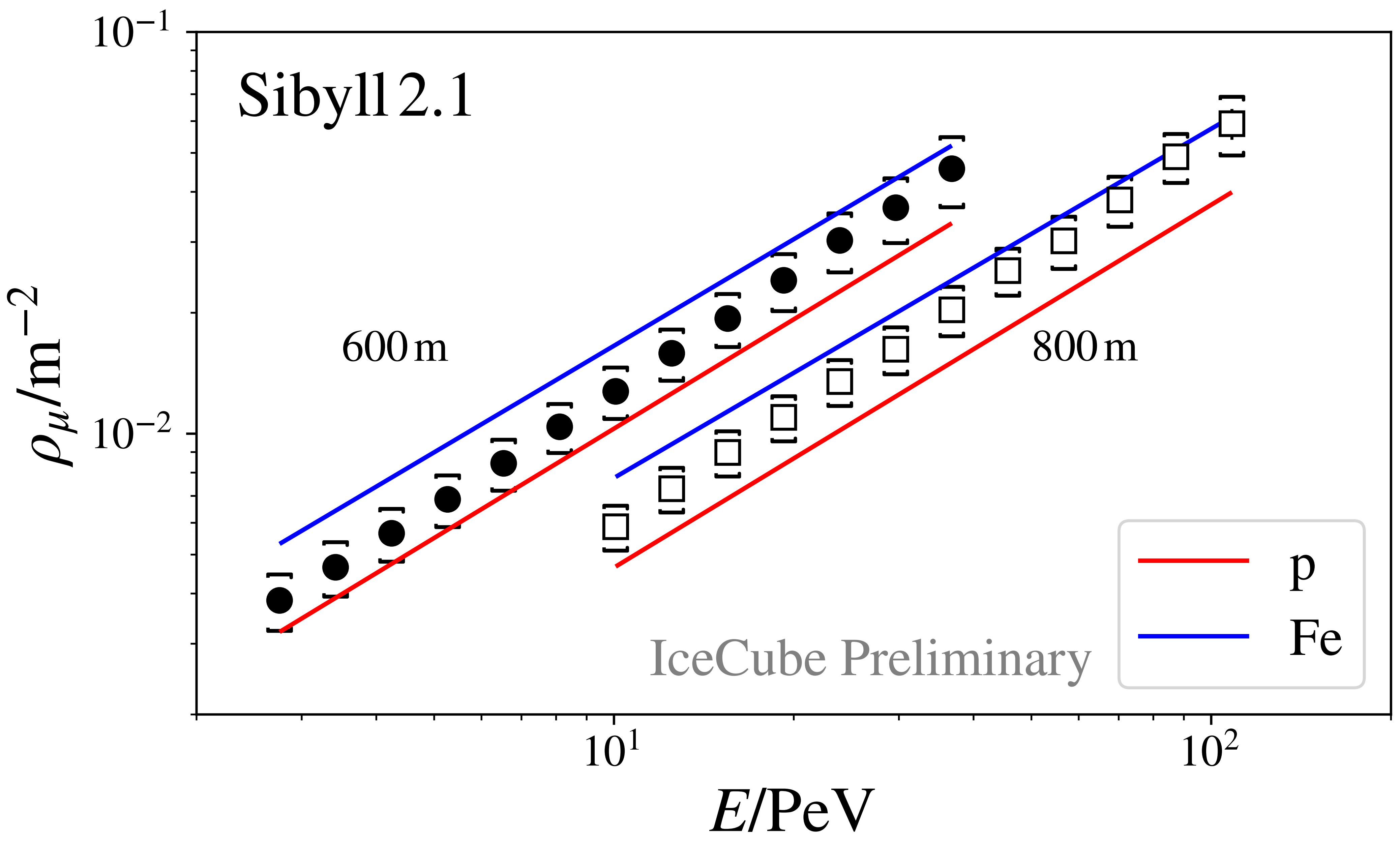
- Reconstructed raw muon densities in Monte-Carlo (MC) do not perfectly match truth
- MC correction applied
  - For Sibyll 2.1, EPOS-LHC, QGSJet-II.04
  - Average correction based on these models
- Systematic uncertainties (EM model, mass composition)

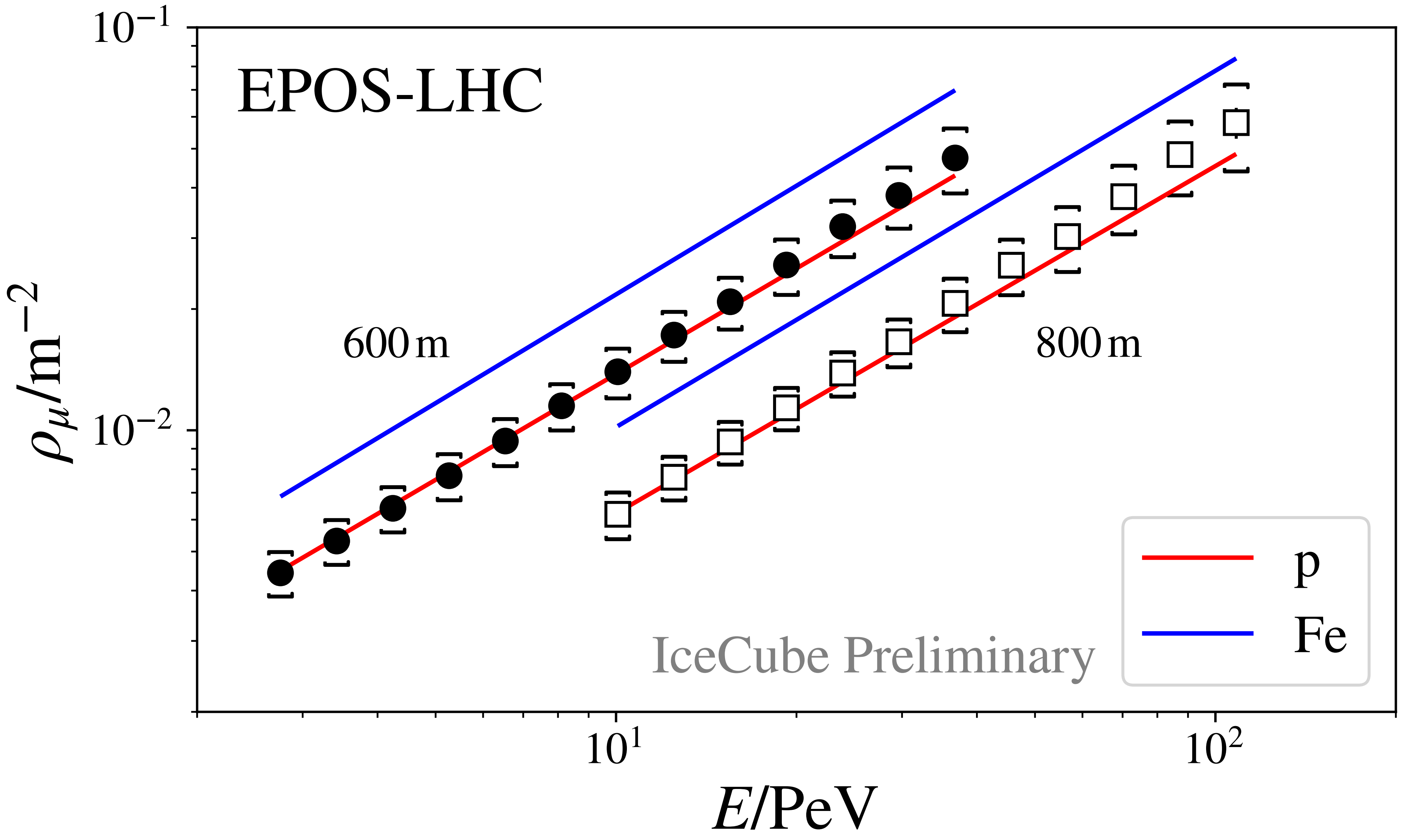


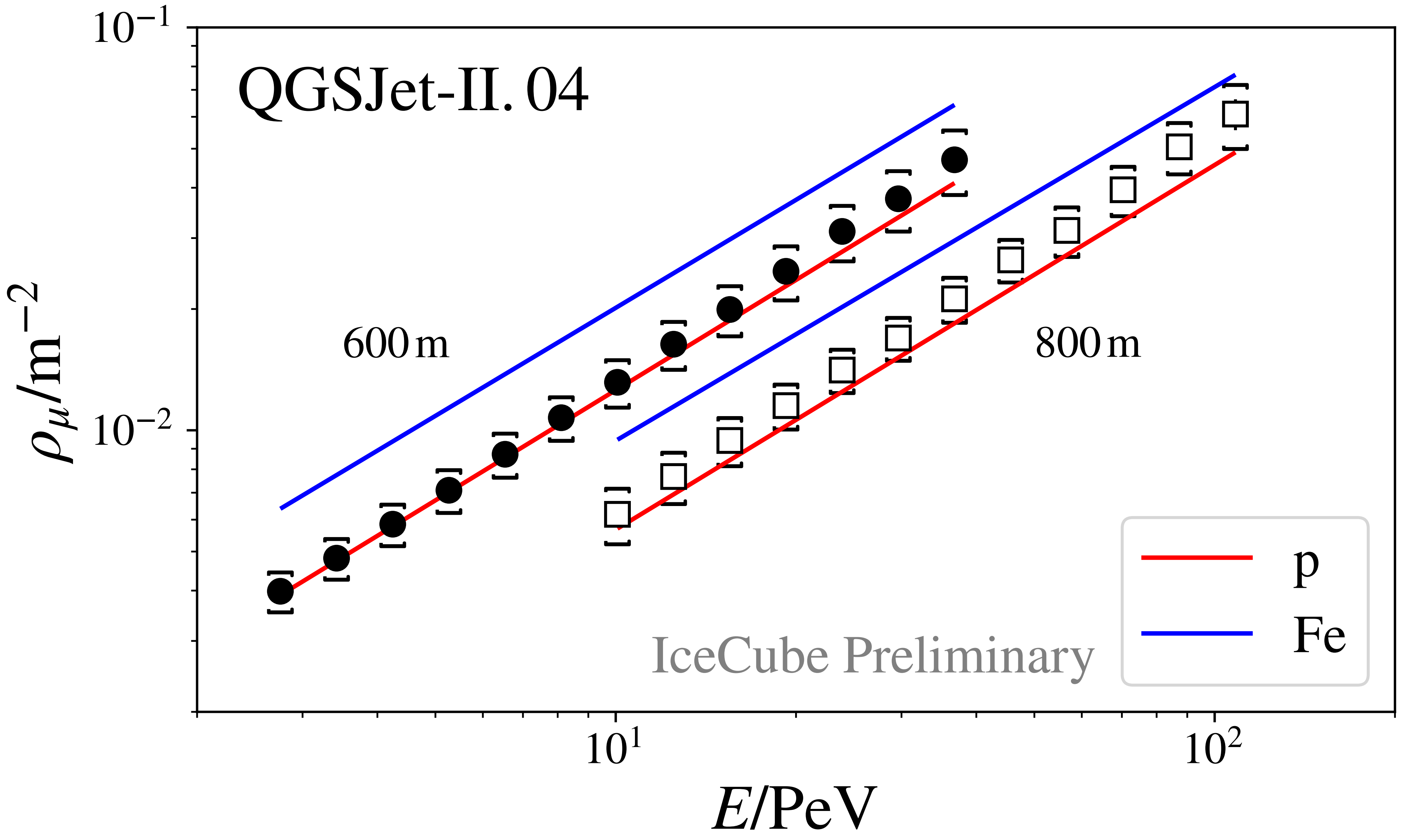


Results

- Muon densities, ρ_μ, at 600 m and 800 m in IceTop data taken May 2010 to May 2013
- EAS energies between 2.5 – 40 PeV and 9 – 120 PeV
- Data (roughly) bracketed by proton and iron for all models

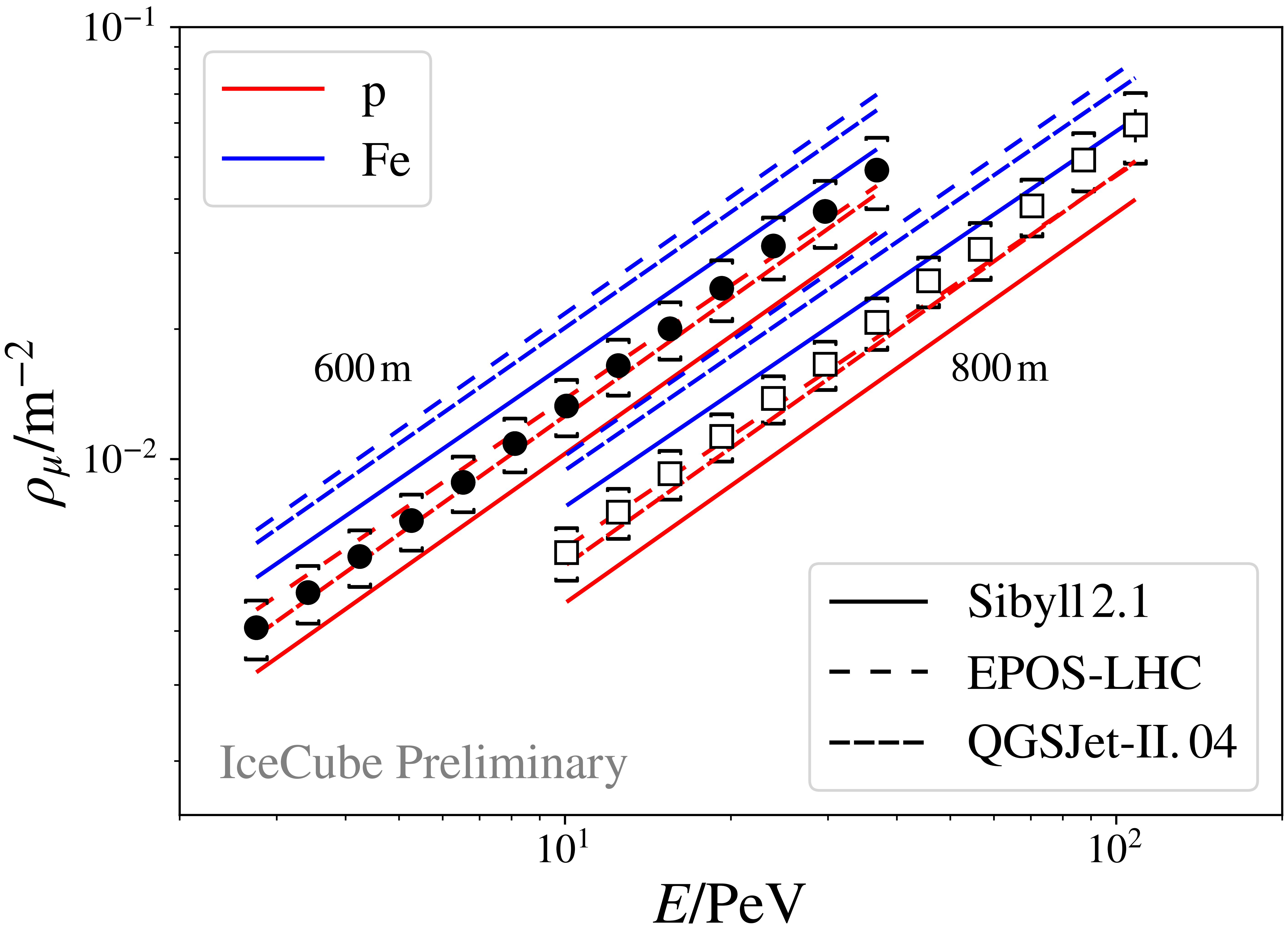






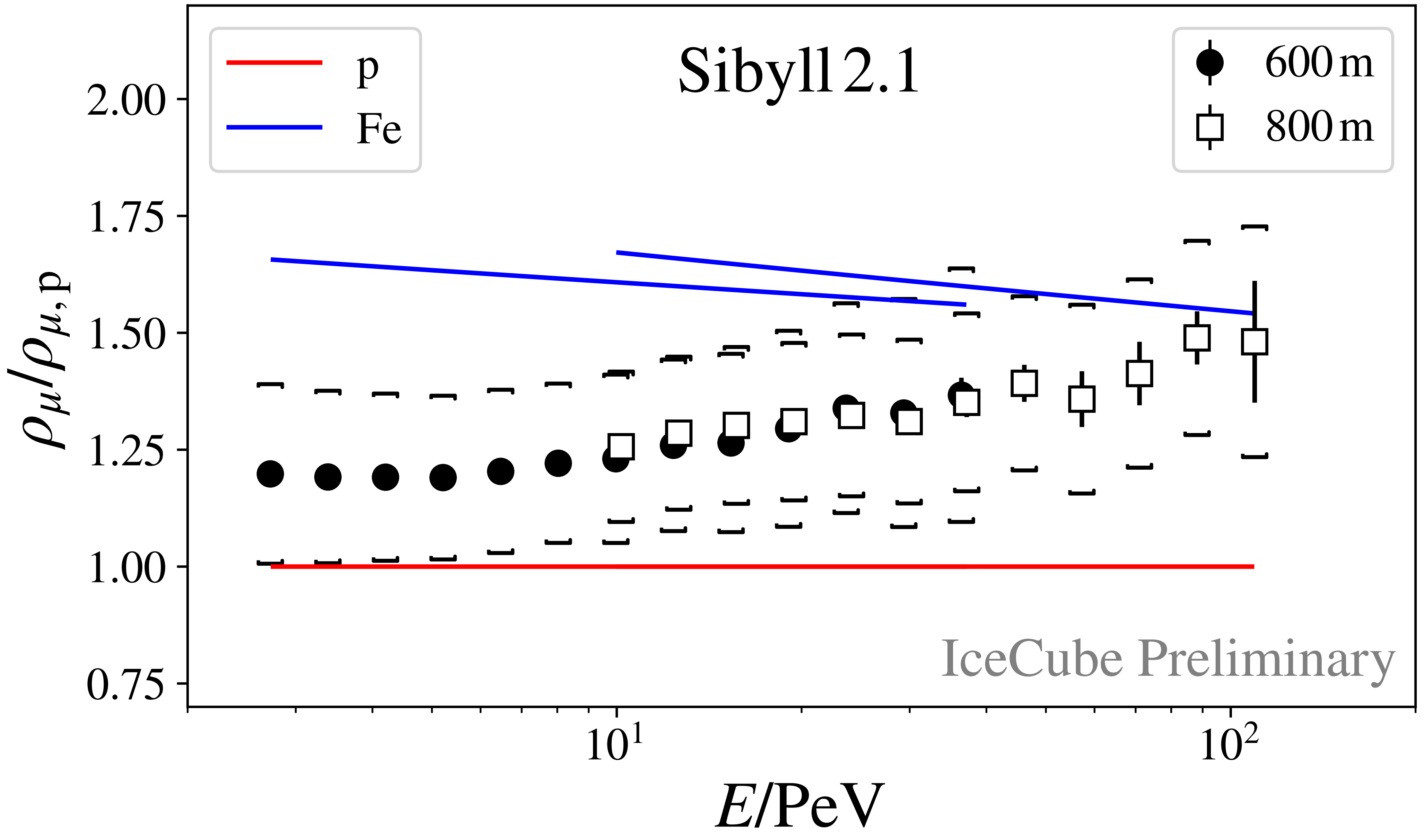
Results

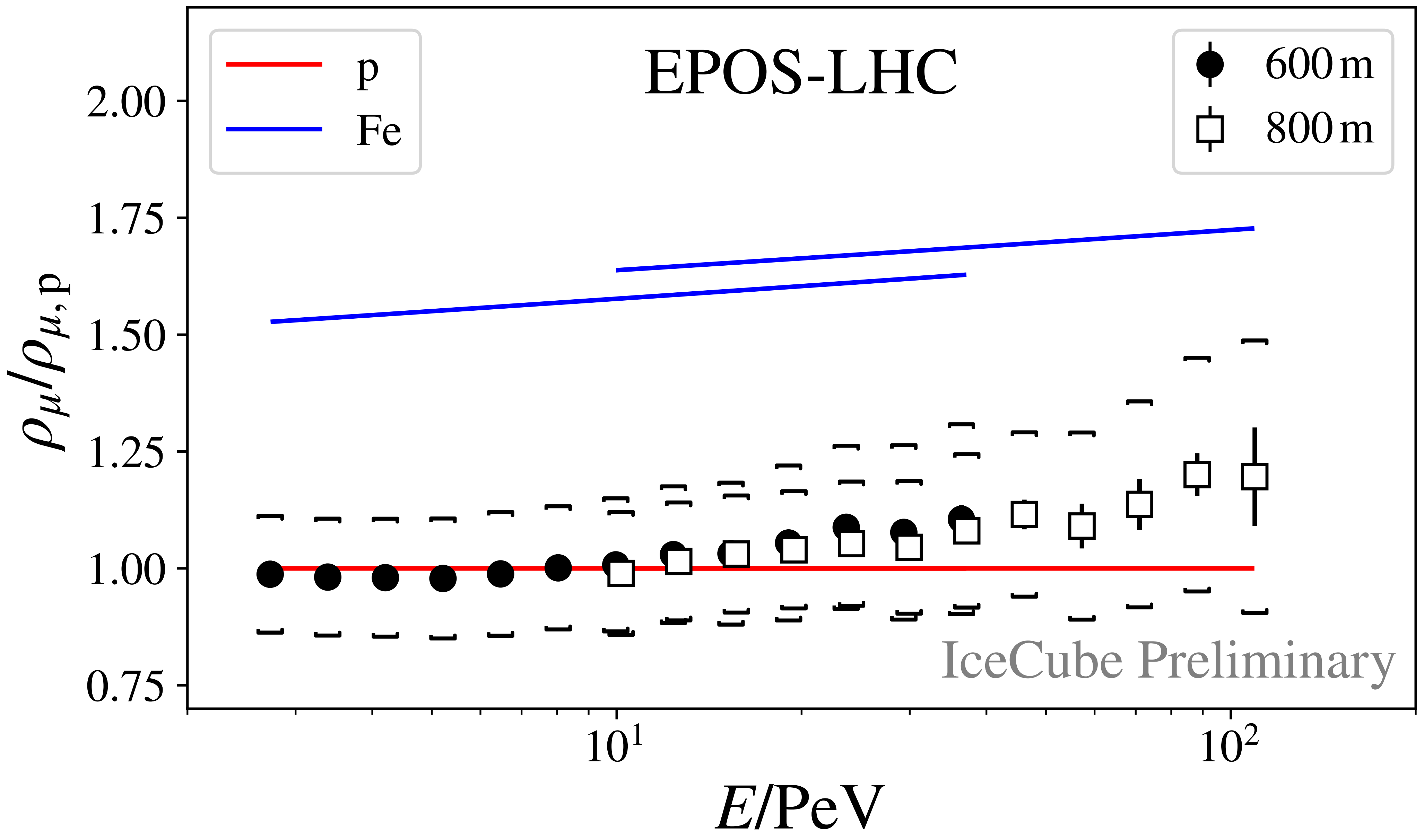
- Muon densities at 600 m and 800 m in IceTop using average MC correction

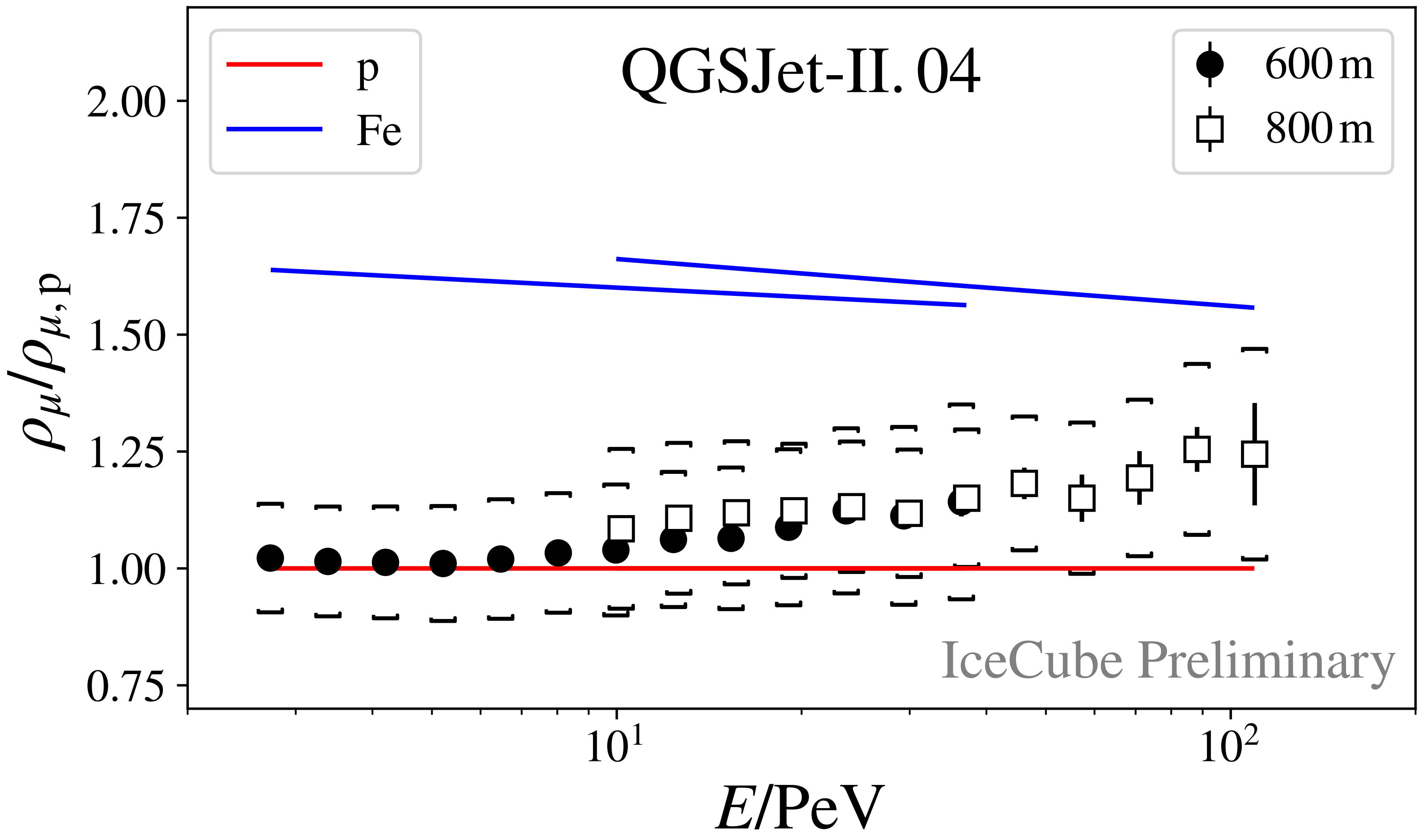


Results

- Muon densities scaled to the expectation for simulated proton air showers
- Obtained from simulations based on Sibyll 2.1, EPOS-LHC, QGSJet-II.04
- EPOS-LHC, QGSJet-II.04 yield very light mass composition





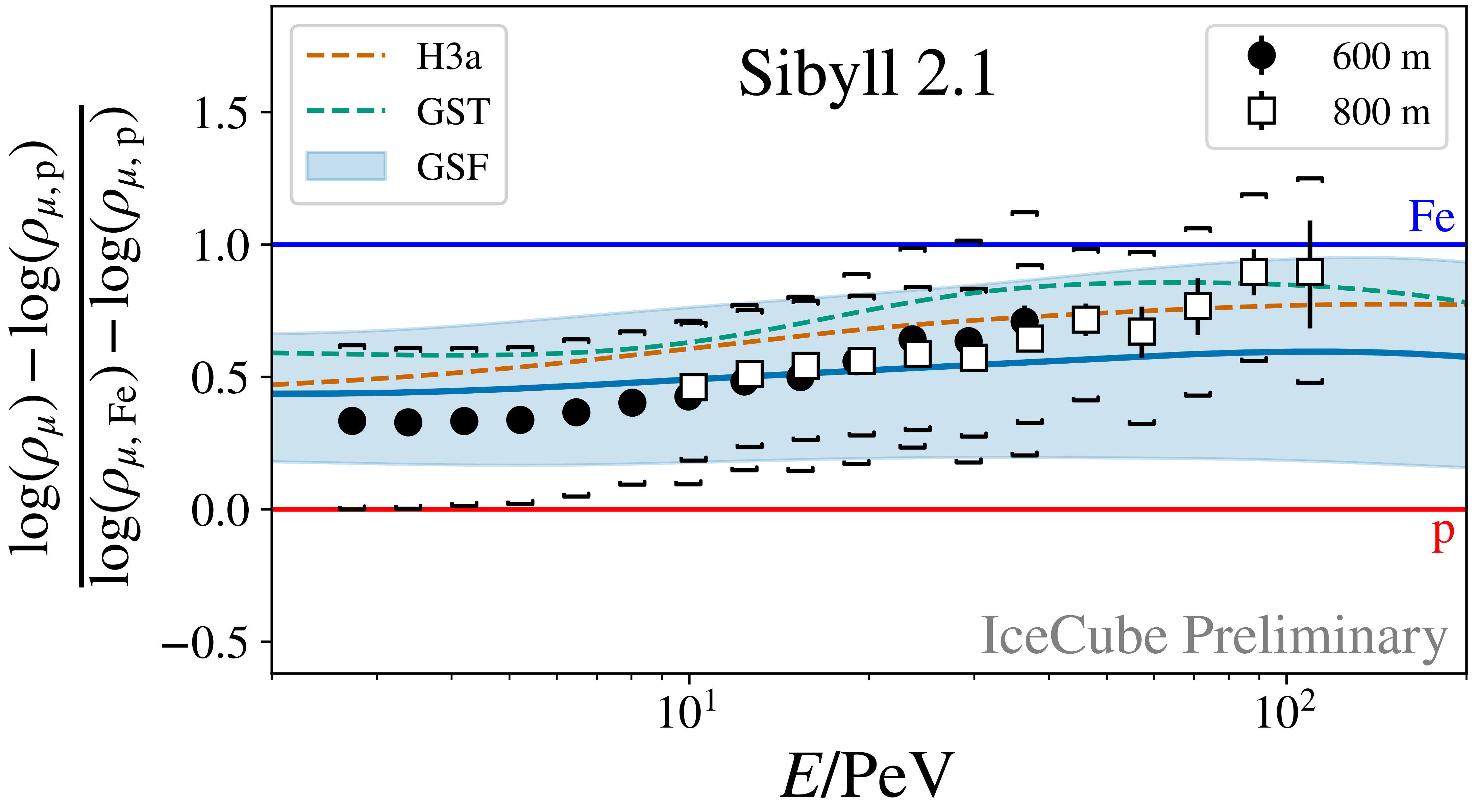


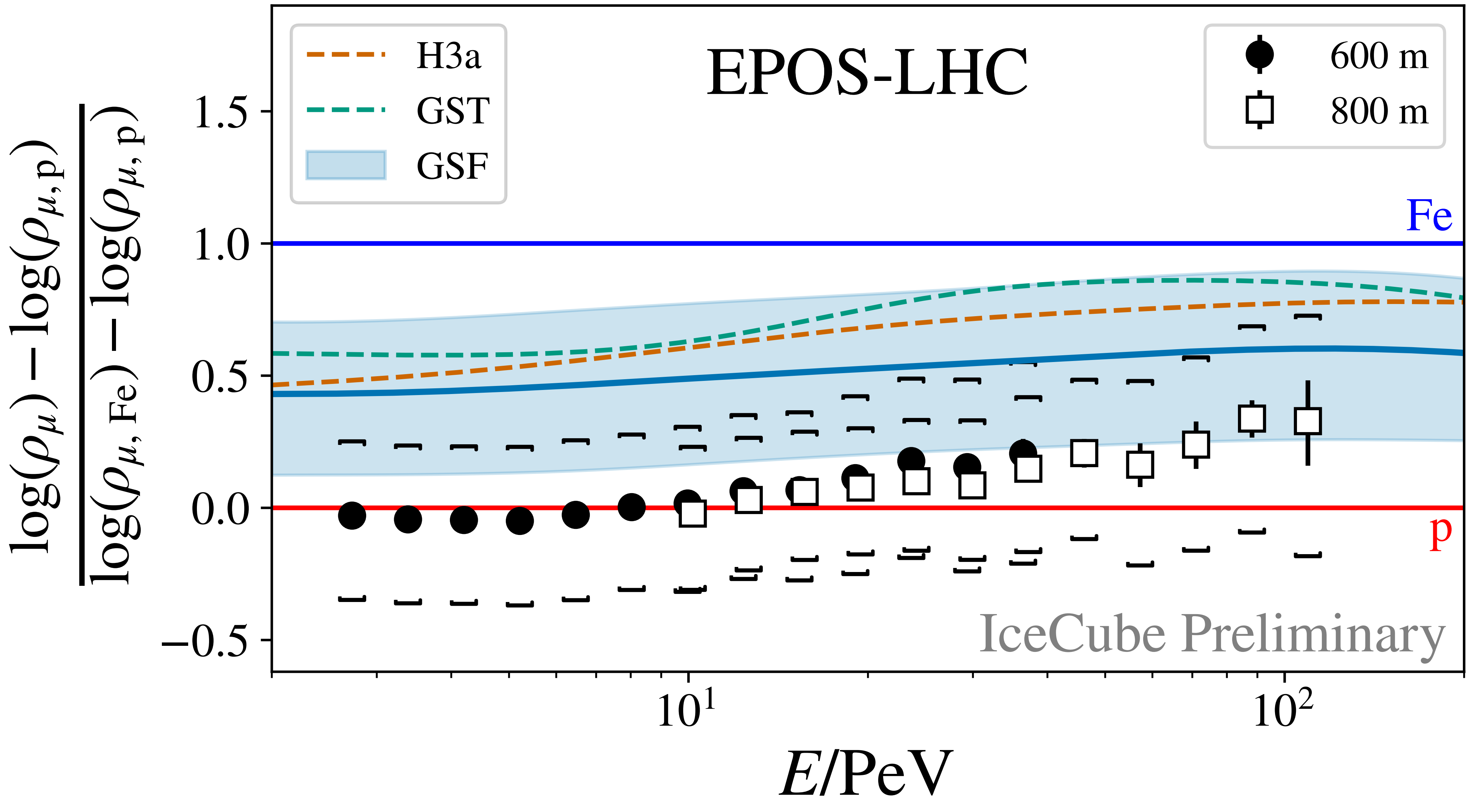
Results

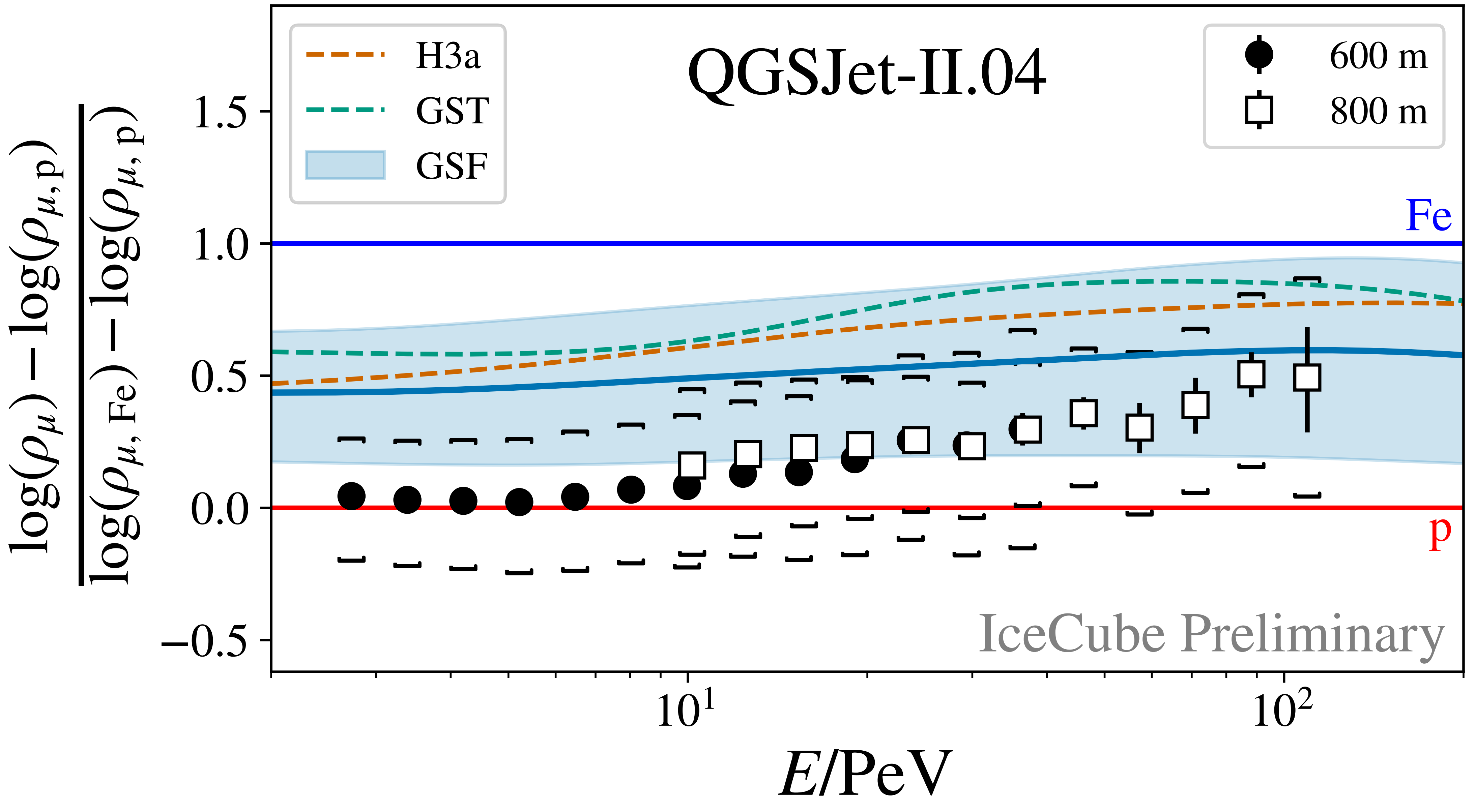
- Results in terms of "z-values":

$$z = \frac{\log(\rho_\mu) - \log(\rho_{\mu,\mathrm{p}})}{\log(\rho_{\mu,\mathrm{Fe}}) - \log(\rho_{\mu,\mathrm{p}})}$$

- Comparison to flux composition models H3a, GST, GSF

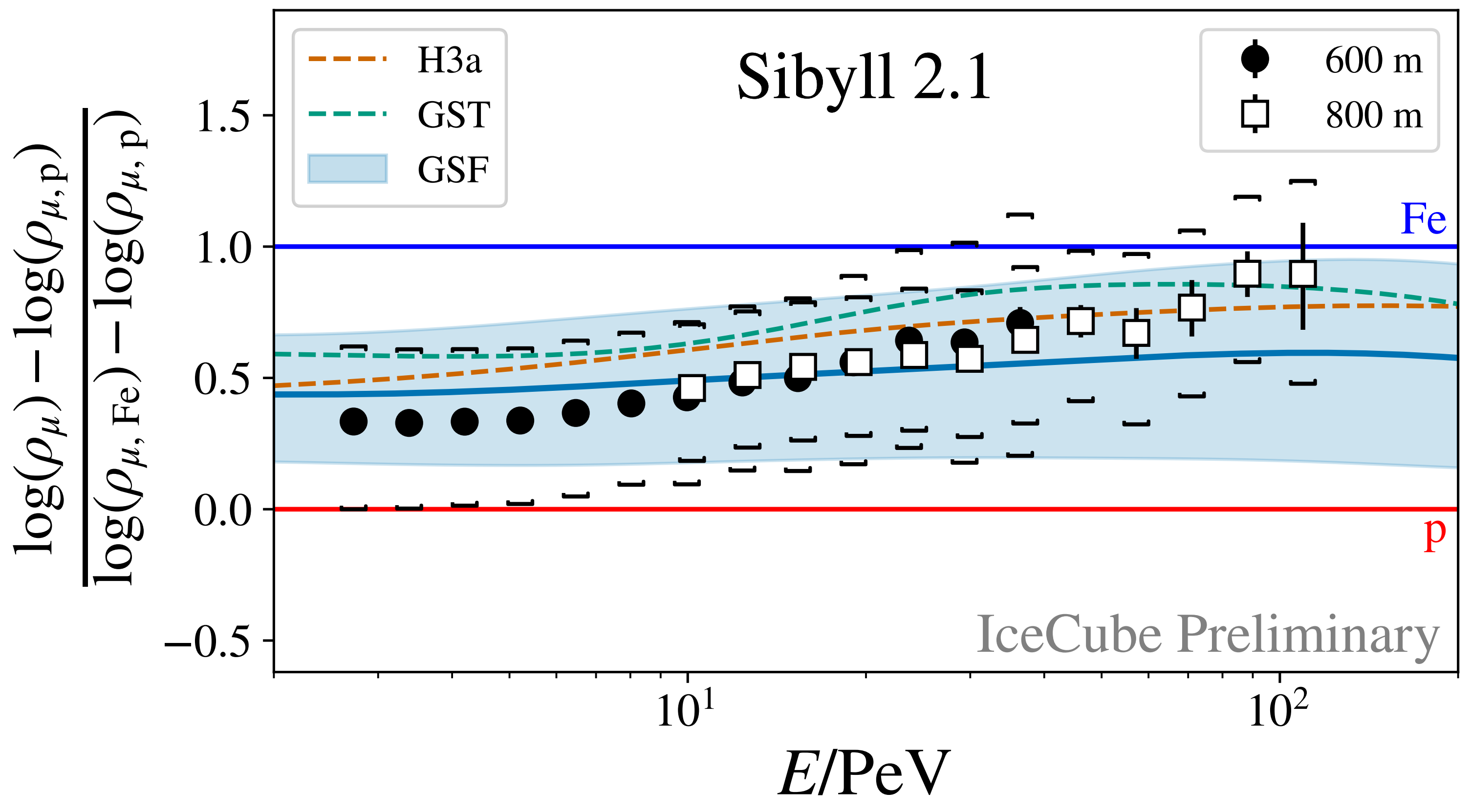


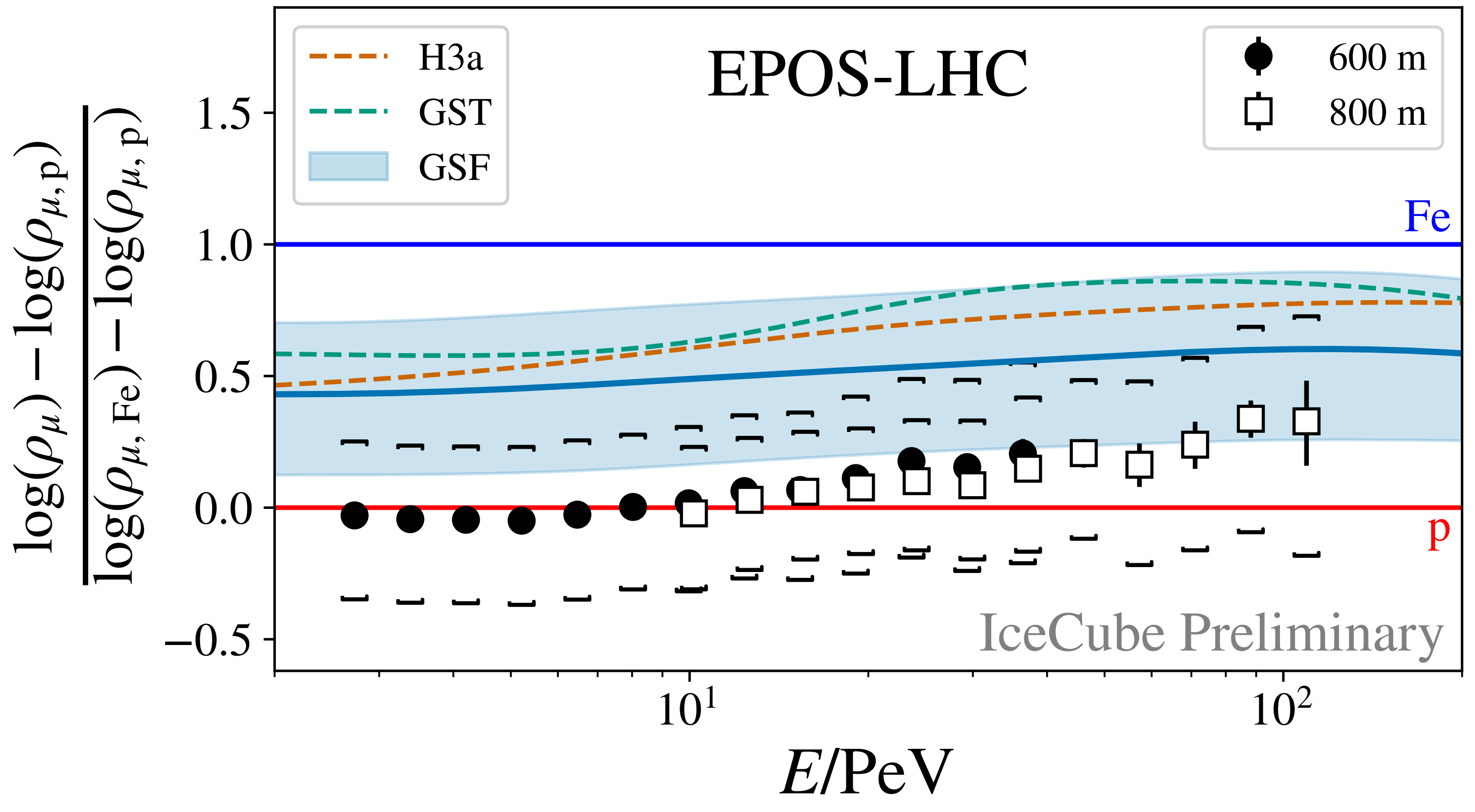


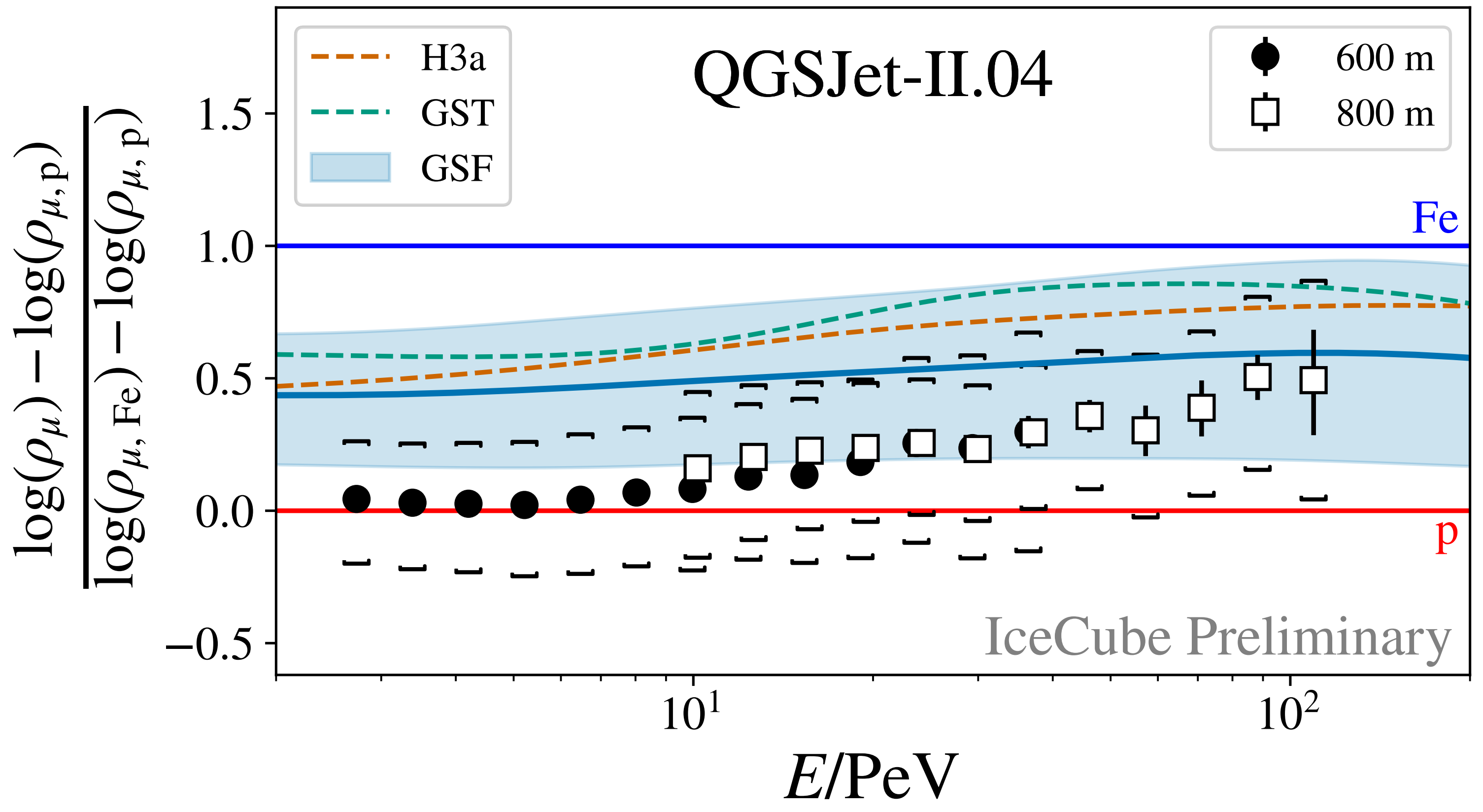


Summary & Conclusions

- Measurement of the GeV muon content in EAS using 3 years of IceTop data
- Muon densities at 600 m and 800 m for EAS energies between 2.5 – 40 PeV and 9 – 120 PeV, respectively
- Bases on multiple cosmic ray flux models best agreement with Sibyll 2.1 predictions
- EPOS-LHC and QGSJet-II.04 yield very light cosmic ray mass composition
    - Too many muons in post-LHC models?
    - Energy scale offset between data and MC?
    - Comparison to other experiments in [PoS(ICRC2021)349]
- IceCube's surface enhancement will reduce uncertainties!

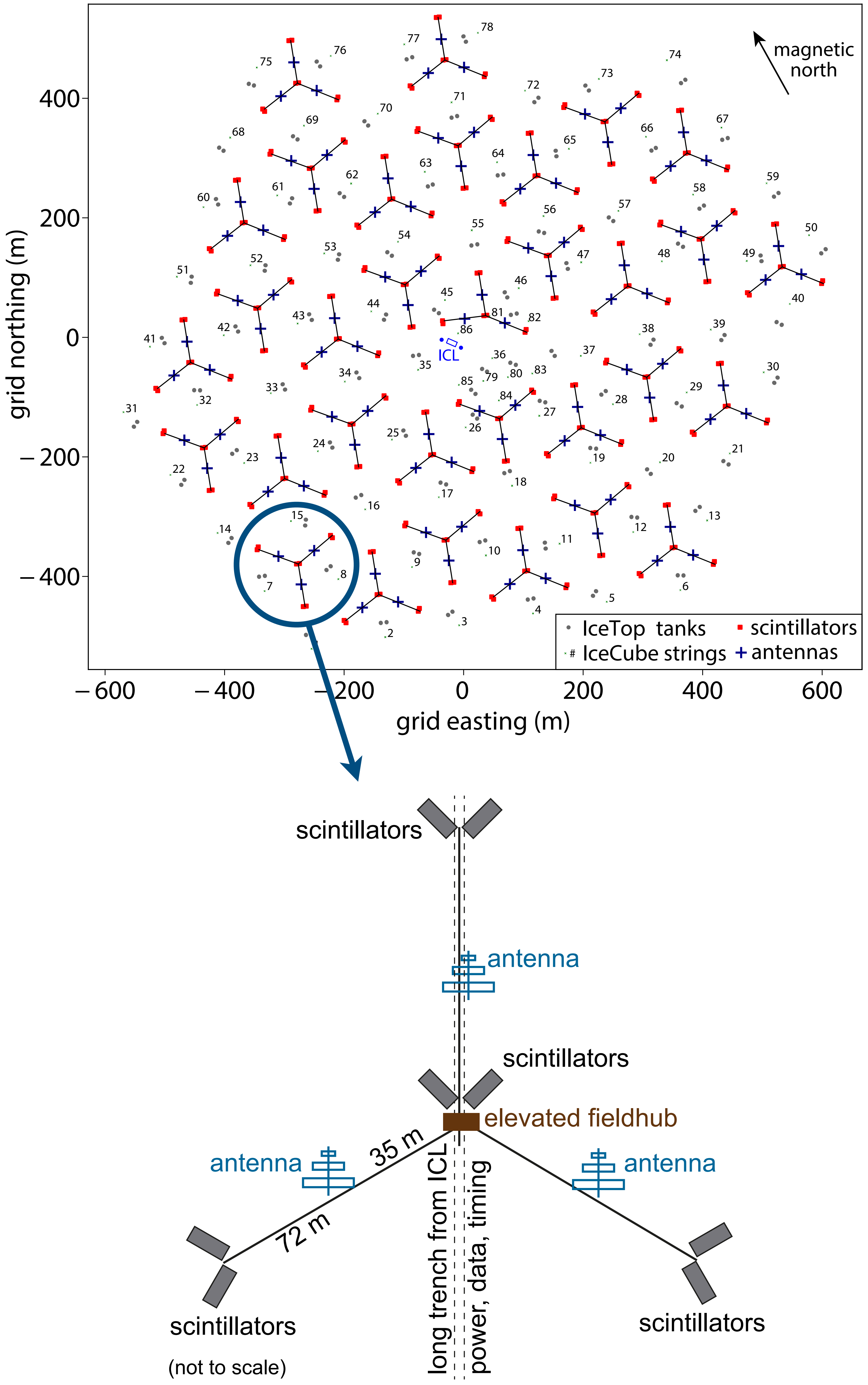






Outlook

- IceCube's surface enhancement will reduce uncertainties of EAS measurements in IceCube!
  - Scintillator detectors: [PoS(ICRC2021)317]
    - Reduced energy scale systematics
    - Improved muon separation
  - Radio antennas: [PoS(ICRC2021)314]
    - Reduced energy scale systematics
    - Primary composition..?
- Coincident measurements of GeV muons (IceTop) and TeV muons (in-ice) provide unique tests of hadronic interaction models! [PoS(ICRC2021)357]
- Multiple efforts ongoing… stay tuned!




IceCube
South Pole Neutrino Observatory
Thank you!
…I am looking forward to receiving
your comments and questions!