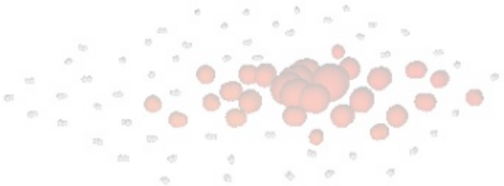


Multiplicity of TeV muons in air showers detected with IceTop and IceCube

Stef Verpoest for the IceCube Collaboration

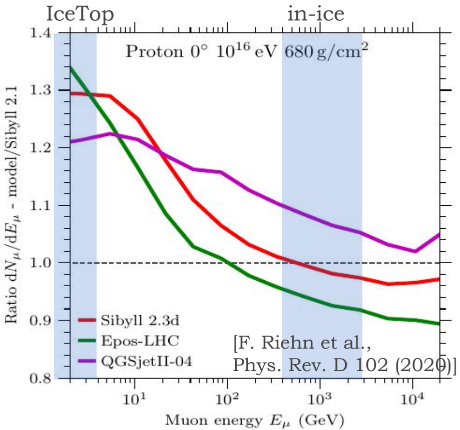
27th European Cosmic Ray Symposium
28/07/2022

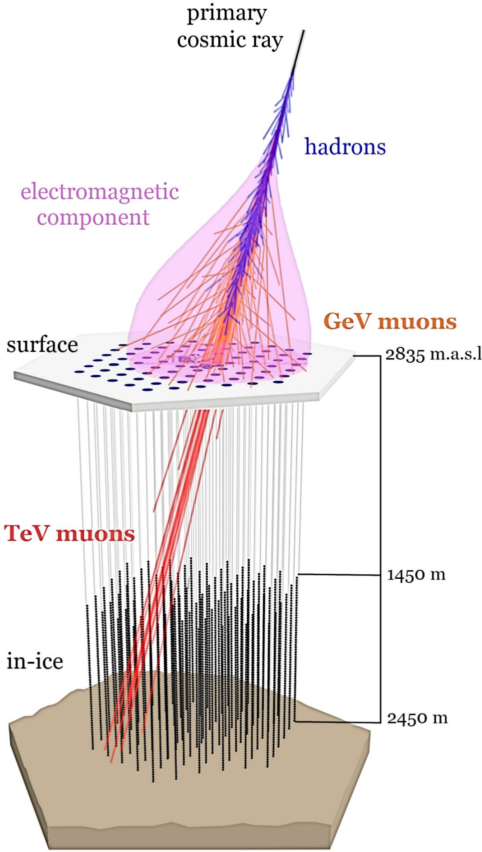
IceCube Neutrino Observatory

- IceCube
  - ~ 1 km^3 instrumented volume
  - 86 strings with ~5000 Digital Optical Modules (DOMs)

- IceTop
  - ~ 1 km^2 air shower array
  - Atmospheric depth ~ 690 g/cm^2
  - 81×2 Ice Cherenkov Tanks with 2 DOMs
  - Primary energies ~ PeV - EeV

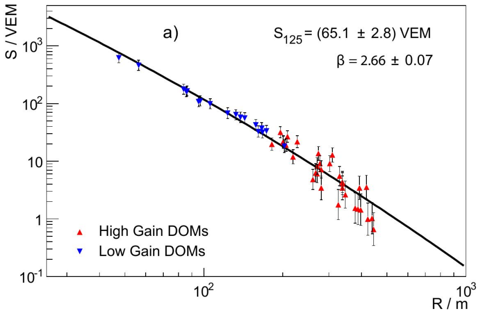
- Combined: Unique EAS Detector
  - Electromagnetic component
  - GeV muon content
  - <u>TeV muon content</u>



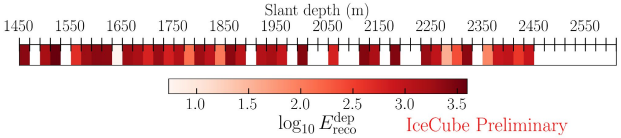


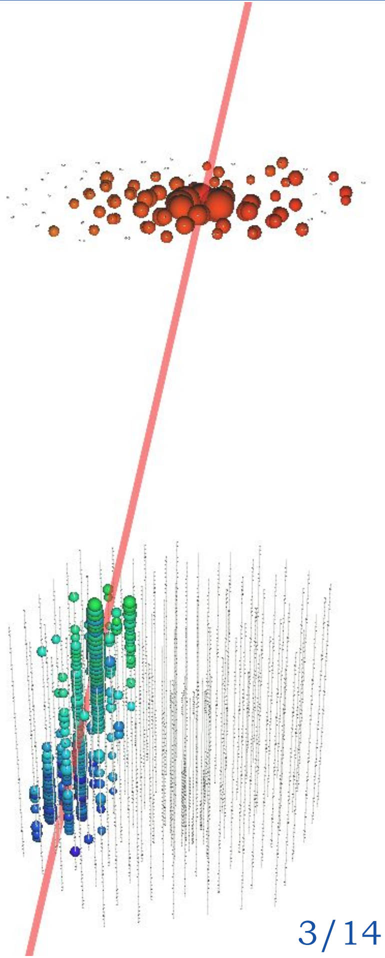
EAS Reconstruction

- ➢ IceTop
  - ○ Fit to IceTop signals
    - · Lateral distribution function (charge)
    - · Shower front (time)
  - → Direction & core position
  - → Shower size S_{125}: proxy for primary energy



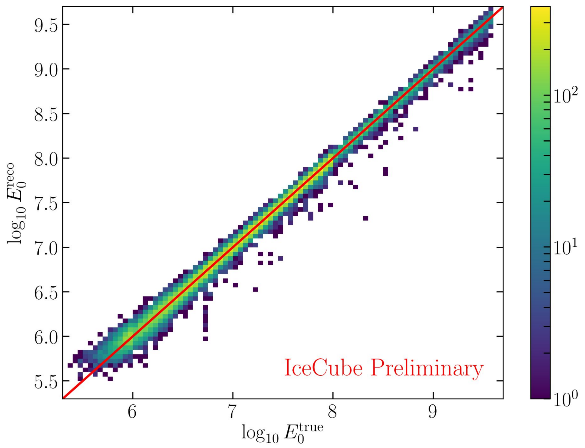
- ➢ In-Ice
  - ○ Energy loss reconstruction
    - · Along reconstructed IceTop track
    - · In segments of 20 m
  - → Vector of deposited energy along track

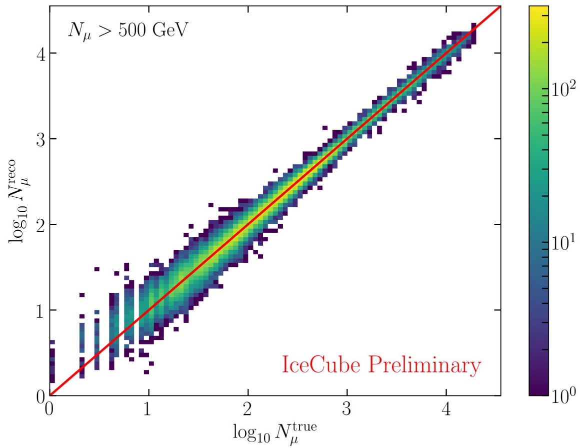




Neural Network

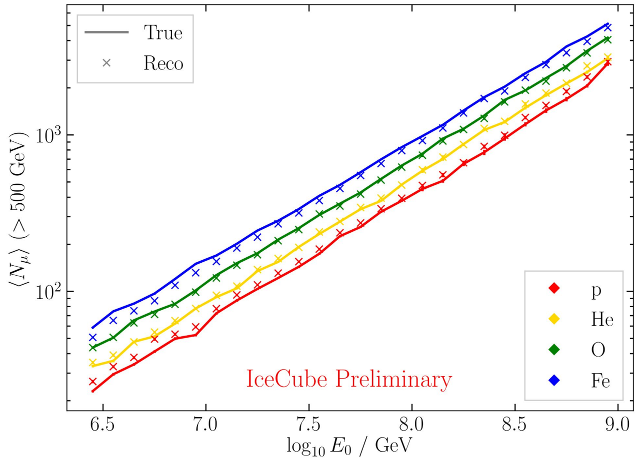
- ➢ Neural network reconstruction
  - ○ Inputs
    - · Shower size S_{125}
    - · Zenith θ
    - · Energy loss vector
  - ○ Outputs
    - · **Primary energy $\mathbf{E_0}$**
    - · **Number of muons > 500 GeV** in shower at surface N_μ
  - ○ RNN + Dense layers
- ➢ MC Dataset
  - ○ Sibyll 2.1
  - ○ p, He, O, Fe
  - ○ Coincident events, contained in IceTop
  - ○ $\cos\theta > 0.95$ ($\theta \lesssim 18°$)



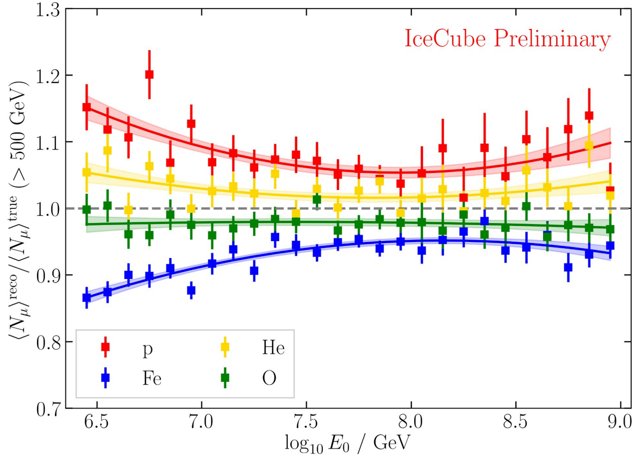


Correction factor

- Determination of $\langle N_\mu > 500\ \text{GeV} \rangle$
  - Bins of $\log_{10}E_0$
  - Low-energy limit: IceTop threshold
  - Comparison between
    - MC true values
    - neural-network reconstructions



- Correction factor
  - Composition dependent over/underestimation
  - Ratios fitted with quadratic function
  - Used to correct bias



Iterative Correction

- ➢ Reconstruction bias
  - Bias / correction composition dependent
  - $\langle N_\mu \rangle$ has composition information

  → Iterative procedure

- ➢ Iterative correction procedure
  - Describe average composition with p & Fe

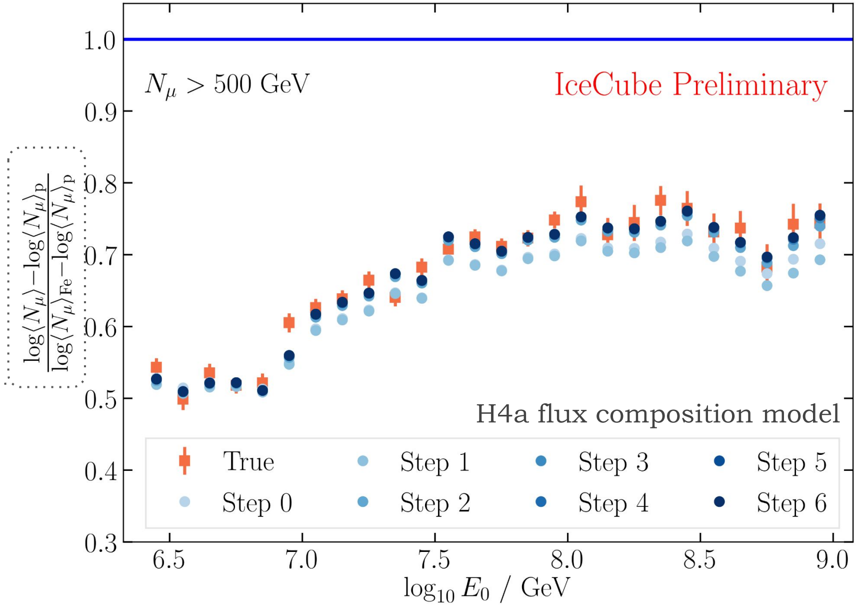
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_\mathrm{p}}{\ln\langle N_\mu \rangle_\mathrm{Fe} - \ln\langle N_\mu \rangle_\mathrm{p}} \approx \frac{\langle \ln A \rangle}{\ln 56}$$

$$f_\mathrm{p} \ln A_\mathrm{p} + f_\mathrm{Fe} \ln A_\mathrm{Fe} = \langle \ln A \rangle$$

  - Effective correction factor combining p & Fe correction factors

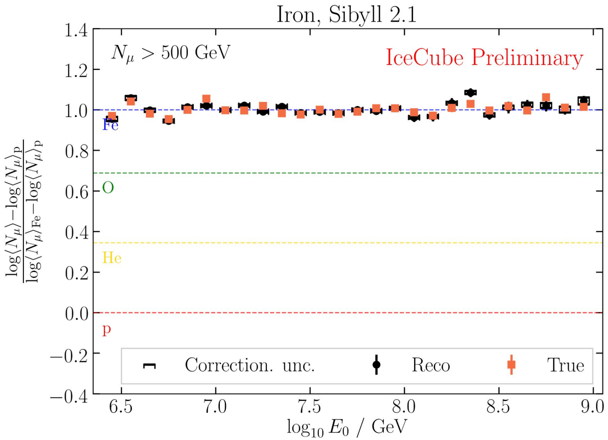
$$C_\mathrm{eff} = f_\mathrm{p} C_\mathrm{p} + f_\mathrm{Fe} C_\mathrm{Fe}$$

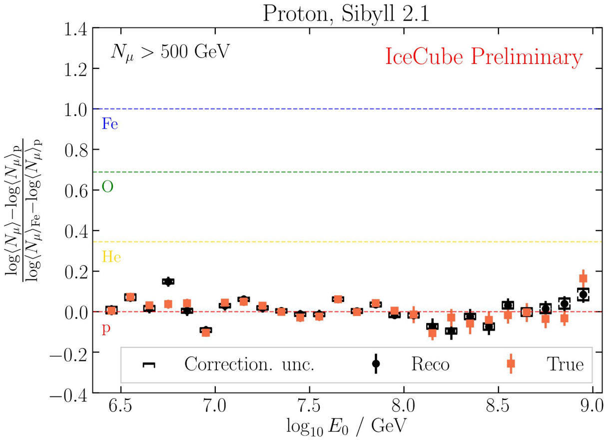
  - Update $\langle N_\mu \rangle$ → update C_{eff} → etc. until convergence

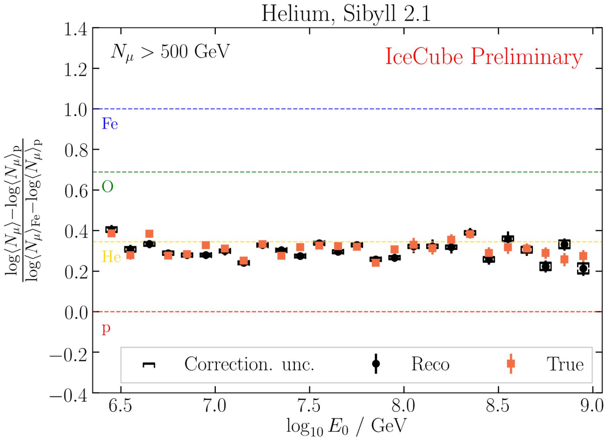


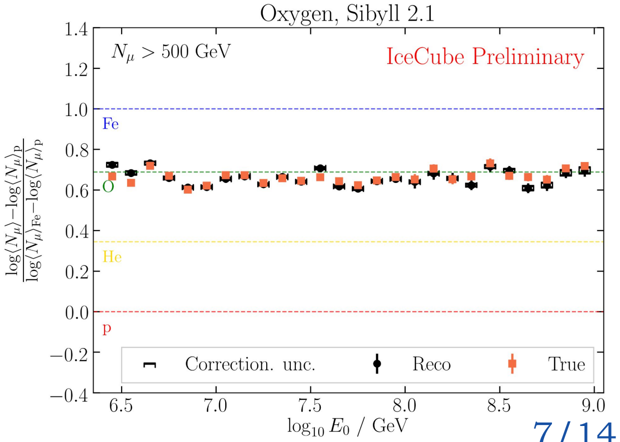
MC Tests

- ➢ Application of Neural Network & Correction to MC
  - ○ Pure p, He, O, Fe
  - ○ Random combinations (see backup)
  - → Good agreement between true and reconstructed!



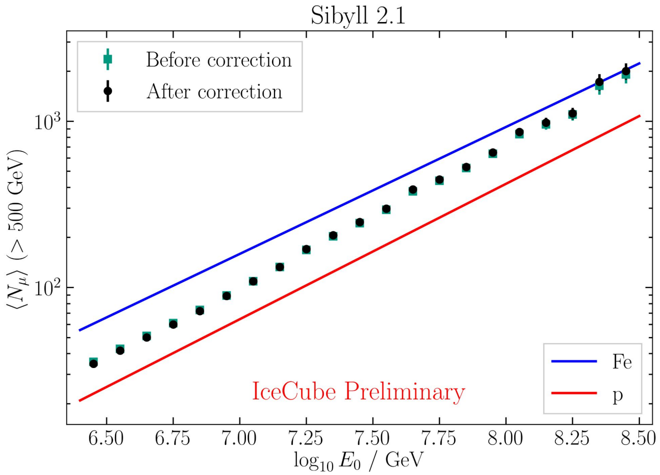




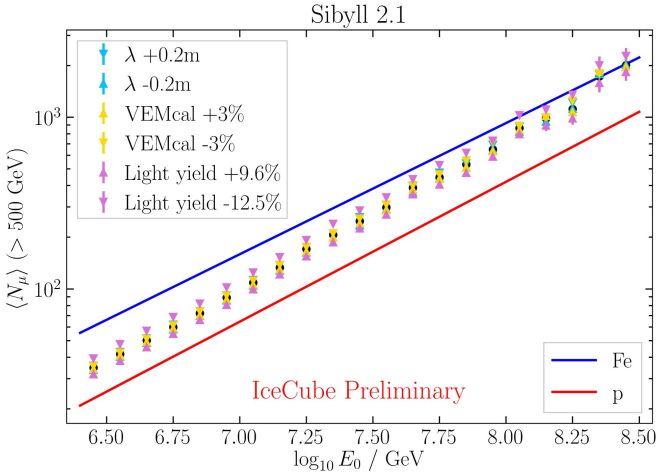


Results

- ➢ Application to experimental data
  - 10% of 1 year (05/2012 - 05/2013)
  - Compared to expectations from Sibyll 2.1

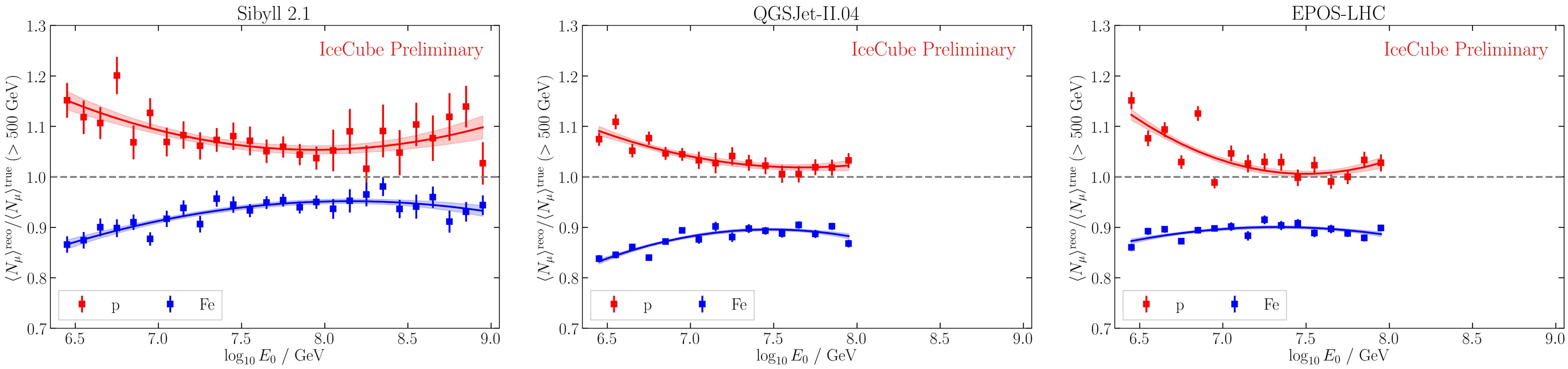


- ➢ Systematic uncertainties
  - Correction uncertainty
  - Detector uncertainties
    - Snow accumulation on IceTop
    - IceTop VEM definition / Energy scale
    - IceCube light yield (ice model, DOM eff.)



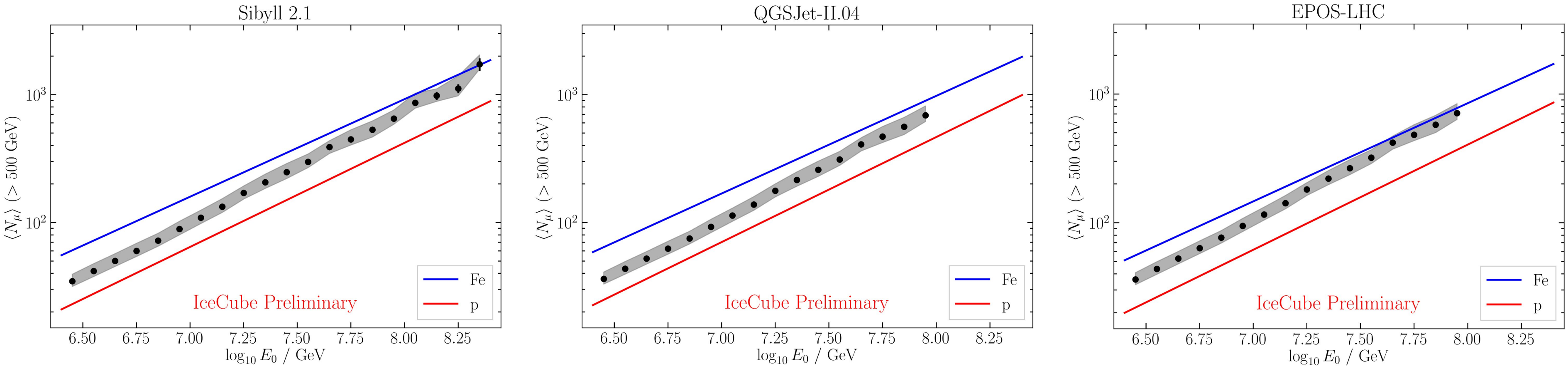
Other Hadronic Models

- Correction factors
  - From MC → model dependent results
  - Include other hadronic interaction models
    - QGSJet-II.04
    - EPOS-LHC
    - Limited to 100 PeV



Results

- Average muon multiplicity > 500 GeV
  - Hadronic model dependent
  - Compared to corresponding MC predictions
  - Shaded area: total systematic uncertainty



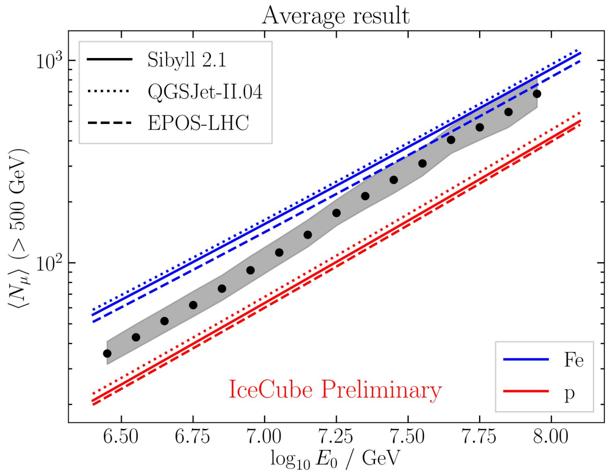
Results

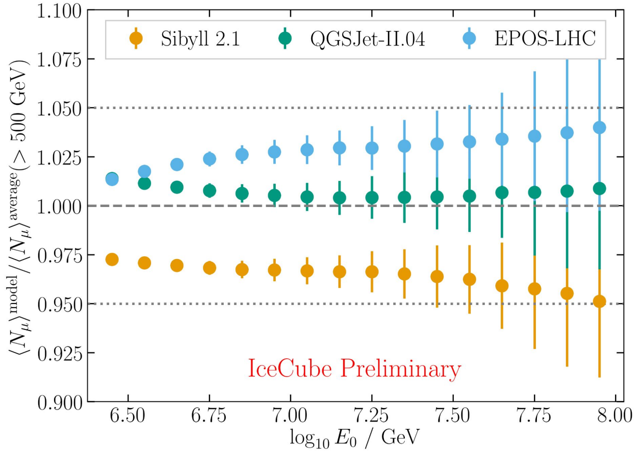
➢ How do model predictions compare?

- ~7% more muons in QGSJet-II.04 than Sibyll 2.1
- ~6% less muons in EPOS-LHC than Sibyll 2.1

➢ How do individual results compare?

- Average given with envelope describing model differences
- Less than ±5% variation around average

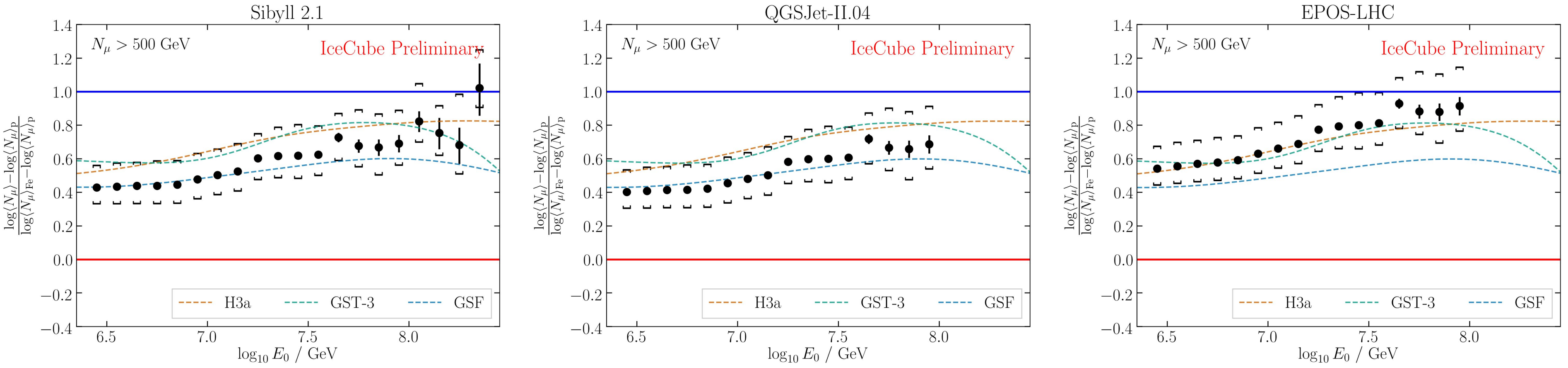




Results

➢ Results in "z-values"

- $$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_\mu\rangle_\mathrm{p}}{\ln\langle N_\mu\rangle_\mathrm{Fe} - \ln\langle N_\mu\rangle_\mathrm{p}}$$
- Comparison to composition models H4a, GST-3, GSF
- Brackets: total systematic uncertainty



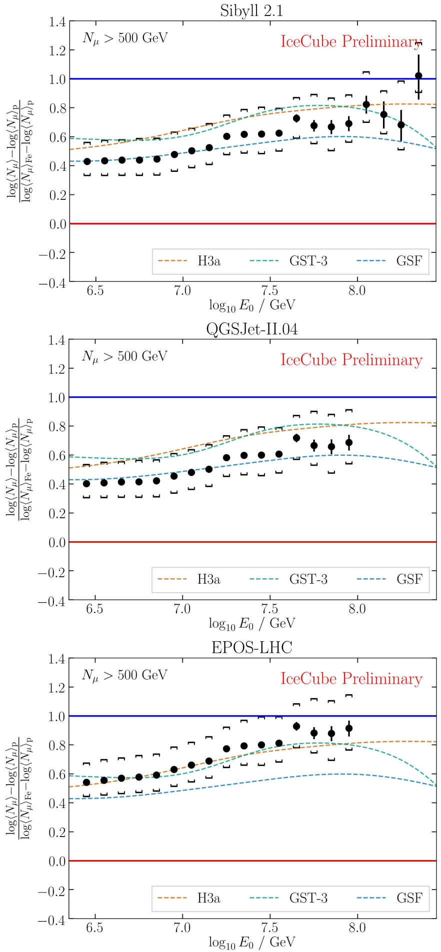
Summary & Conclusions

➢ Measurement of TeV muon content in EAS

- IceTop-IceCube coincident events
- # muons > 500 GeV in showers at surface
- Energies between 2.5 PeV –
  - 250 PeV (Sibyll 2.1)
  - 100 PeV (QGSJet-II.04, EPOS-LHC)

➢ Conclusions

- Bracketed by p & Fe
- Sibyll 2.1 and QGSJet-II.04: good agreement with composition models
- EPOS-LHC yields slightly heavier mass composition

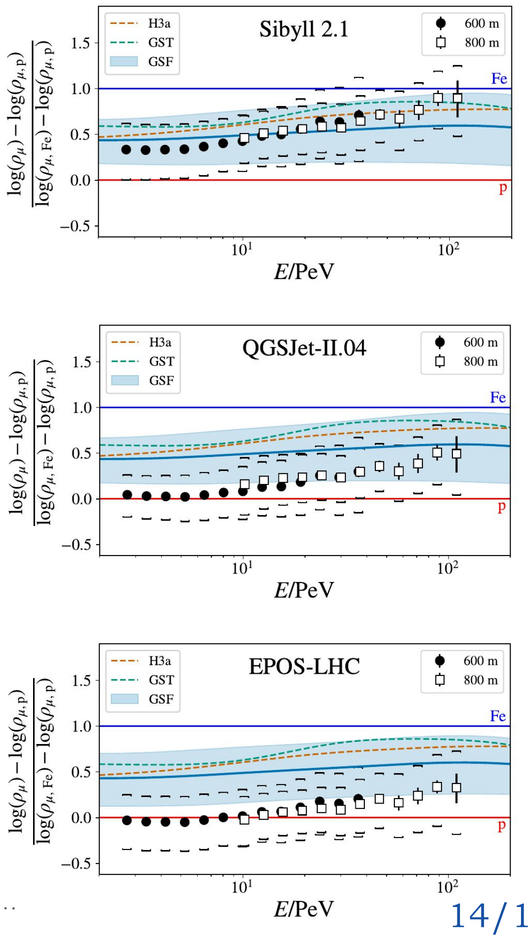


Outlook

- TeV muon analysis
  - Update with more data coming soon
  - Several possible improvements (zenith range, in-ice systematics, seasonal variations...)

- Coincident measurements of GeV and TeV muons
  - Unique tests of hadronic interaction models
  - Density of GeV muons in IceTop [arXiv:2201.12635]
    - Agreement with TeV muons for Sibyll 2.1
    - Tension for QGSJet-II.04 and EPOS-LHC
  - GeV-TeV muon correlations?

- IceCube Gen2 & Surface Enhancement
  - Solid angle, EM/muon separation, energy scale, $X_{\max}$... [PoS(ICRC2021)407]



THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

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University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
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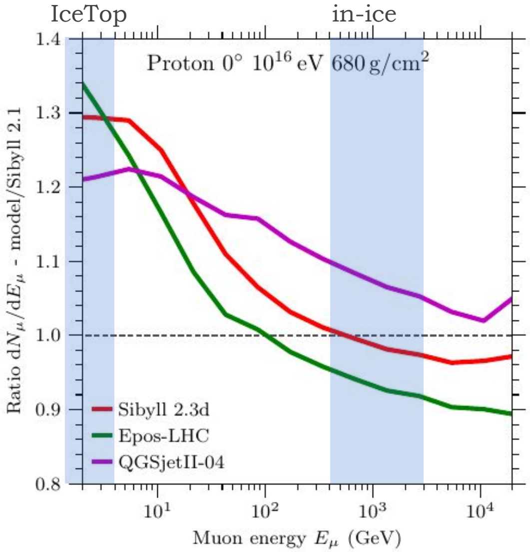
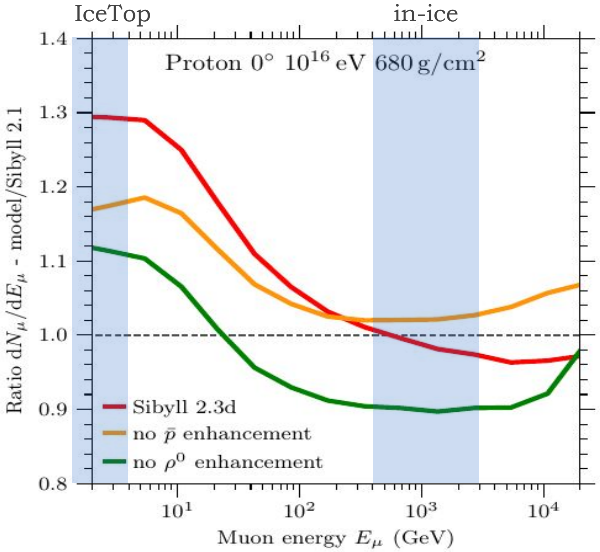
Backup

Hadronic interaction models

➢ Measurements of GeV and TeV muons can uniquely constrain hadronic interaction models

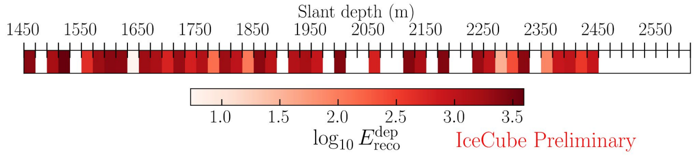


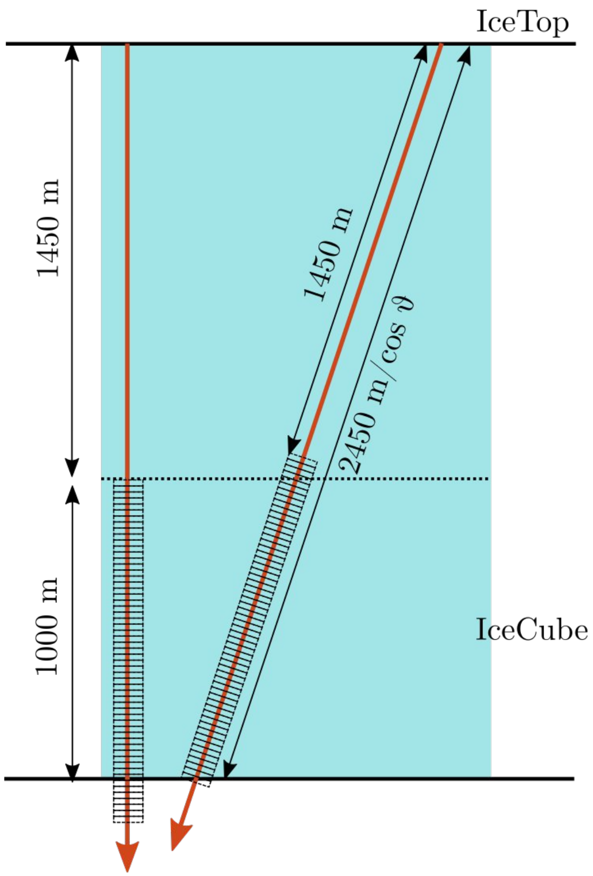


[F. Riehn et al., Phys. Rev. D 102 (2020)]

Energy loss input

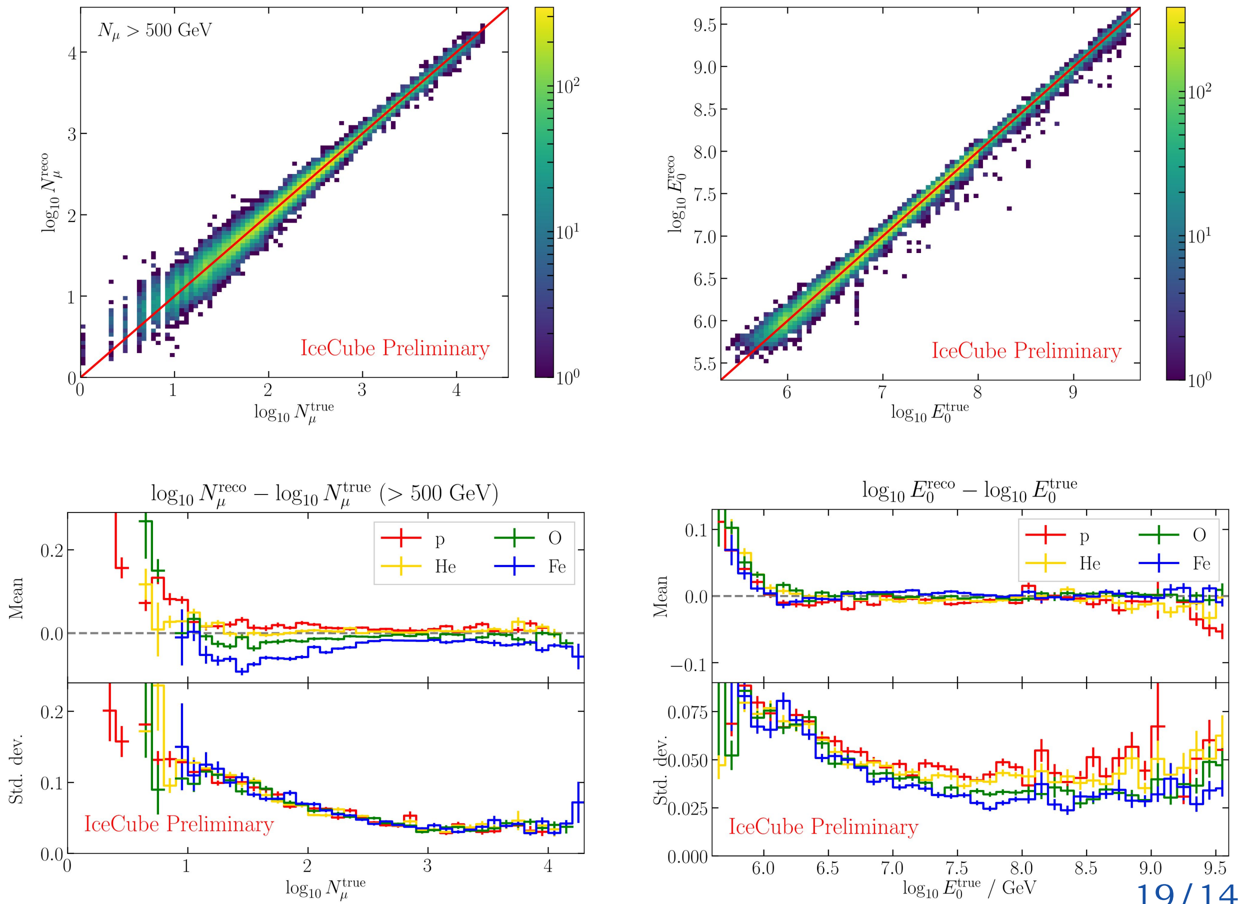
- Energy loss input
  - Deposited energy reconstruction in segments along shower axis track
  - Remove segments outside detector
  - Pad to vector of fixed length 57 (based on zenith angle, limited to cos θ > 0.95)
  - Vertical event example





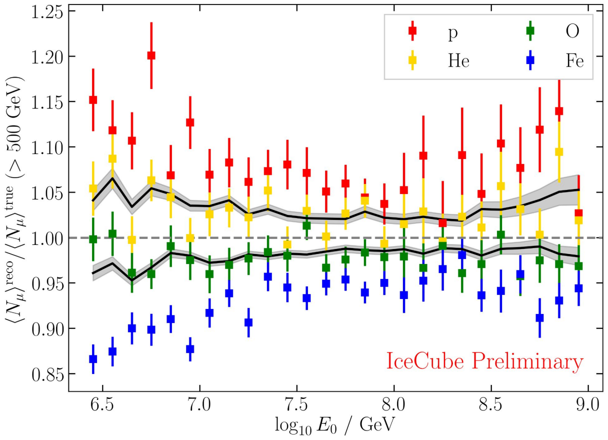
Neural Network Performance

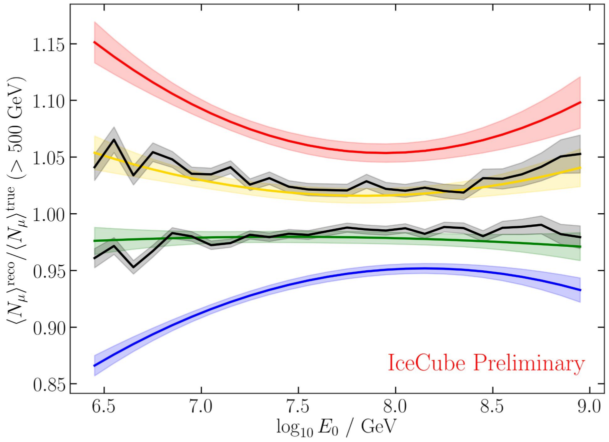
- ➢ Performance on test set
  - ○ Correlation plots (p, He, O, Fe combined)
  - ○ Bias & resolution plots (by primary type)



Iterative Correction

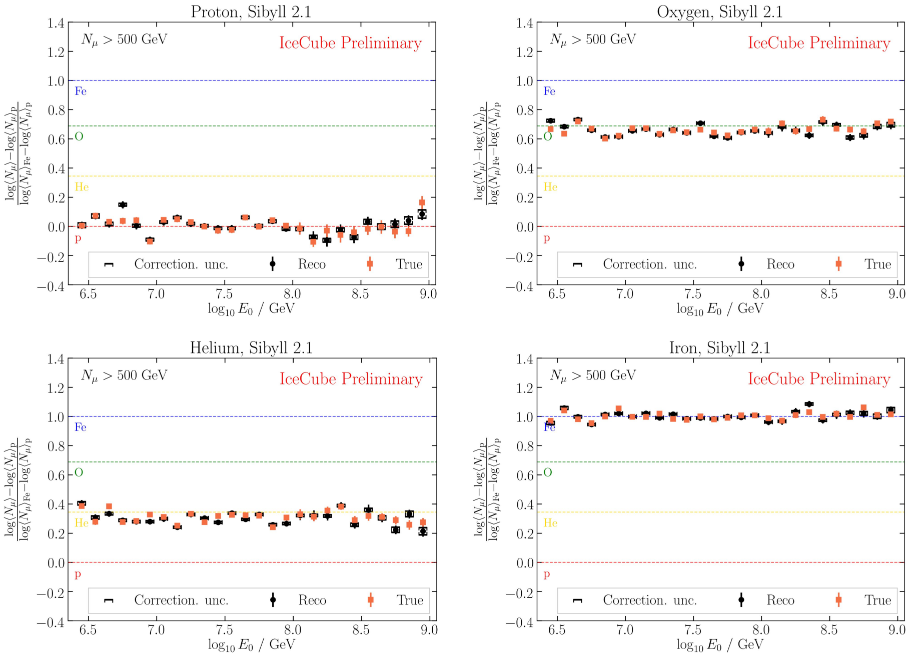
- Important check: can correction factor of intermediate elements be obtained by combining p & Fe correction factors?
  - Use pure He and O MC
  - Use true $\langle N_\mu \rangle$ in He and O
  - Based on this, calculate fractions f_p and f_{Fe}
  - Combine p & Fe correction factors with these fractions → Grey lines in plots
  - Agrees with true He and O correction factors!

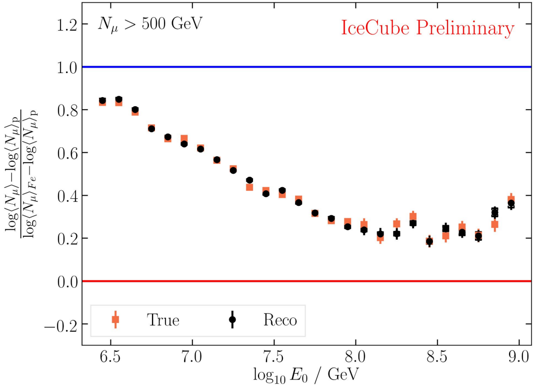


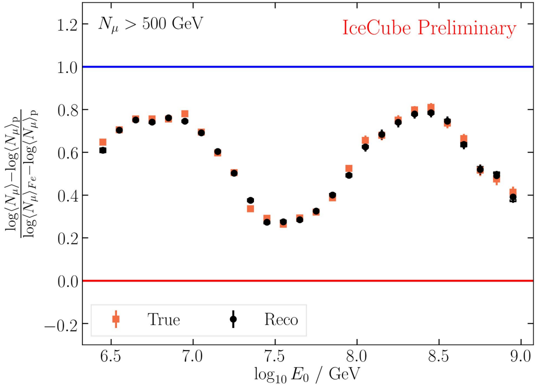


MC checks

- Application of reconstructions and correction to different composition cases
  - 1 component MC (left)
  - 4 component weighted to artificial composition (right)

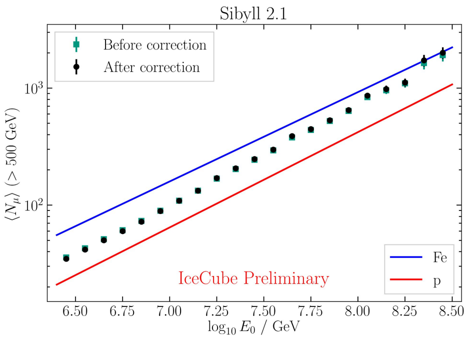


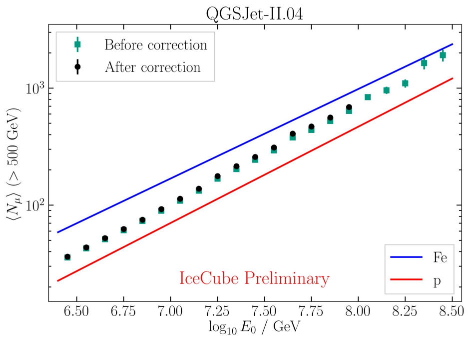


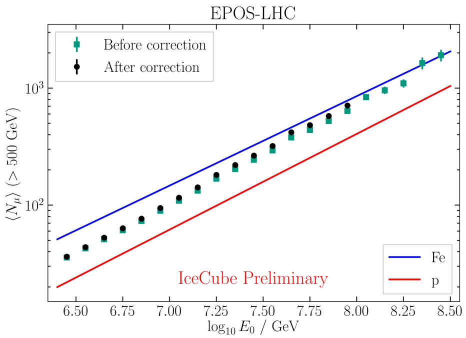


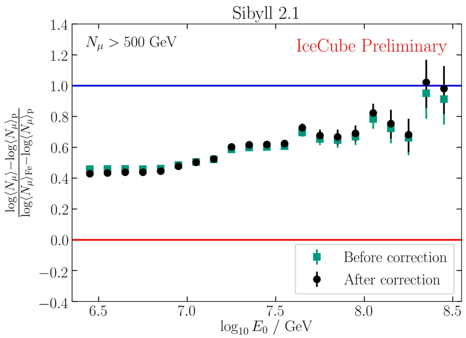
Application to data

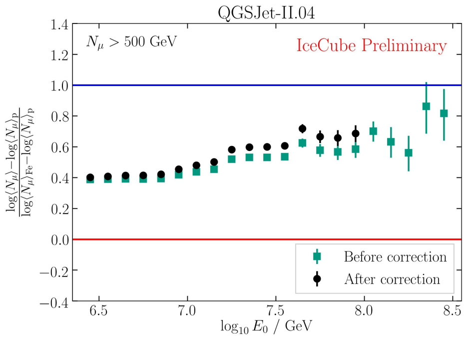
- Application of reconstructions and correction to experimental data
  - 10% of IC86.2012
  - Different model dependent results

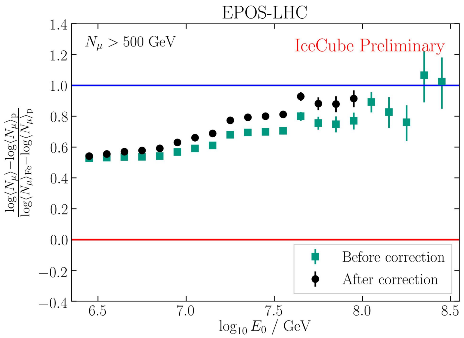












Systematic Uncertainties

- ➢ Correction uncertainty
  - ○ Propagated from p & Fe correction factor uncertainty
- ➢ Detector uncertainties
  - ○ Following 3-year composition & spectrum paper [M. G. Aartsen et al., Phys. Rev. D 100 (2019)]
    - · Snow correction λ ±0.2m
    - · VEMCal ±3%
    - · InIce combined light yield uncertainty +9.6%, -12.5%