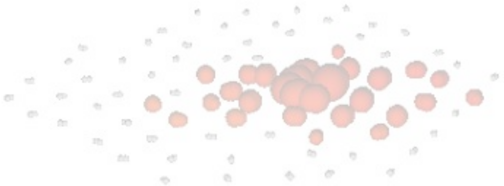


TeV muon bundles in air showers detected with IceTop & IceCube

Stef Verpoest for the IceCube Collaboration

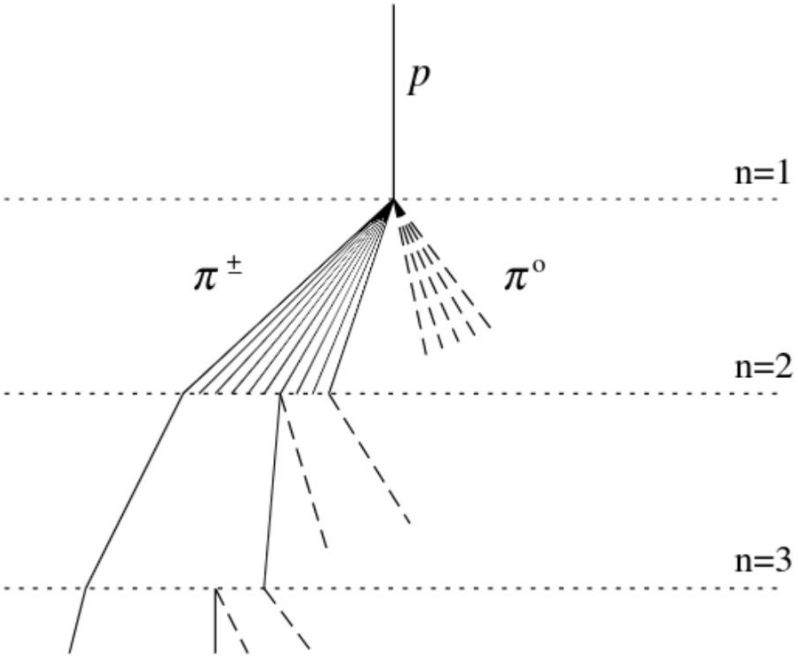
ISCRA Erice
01/08/2022

Introduction

- **Indirect CR measurements**
  - Primary nucleus: E_0, A, θ

    Air shower / Analysis
  - Observables: N_μ, N_e, X_{max}, …

- **Muons in air showers**
  - Mass sensitive
  - Tracers of the hadronic cascade
  - Heiter-Matthews model:
    - $$N_\mu = A\left(\frac{E_0}{AC}\right)^\beta$$
    - $$\ln N_\mu = (1-\beta)\ln A + \beta \ln\left(E_0/C\right) \qquad \beta \approx 0.9$$

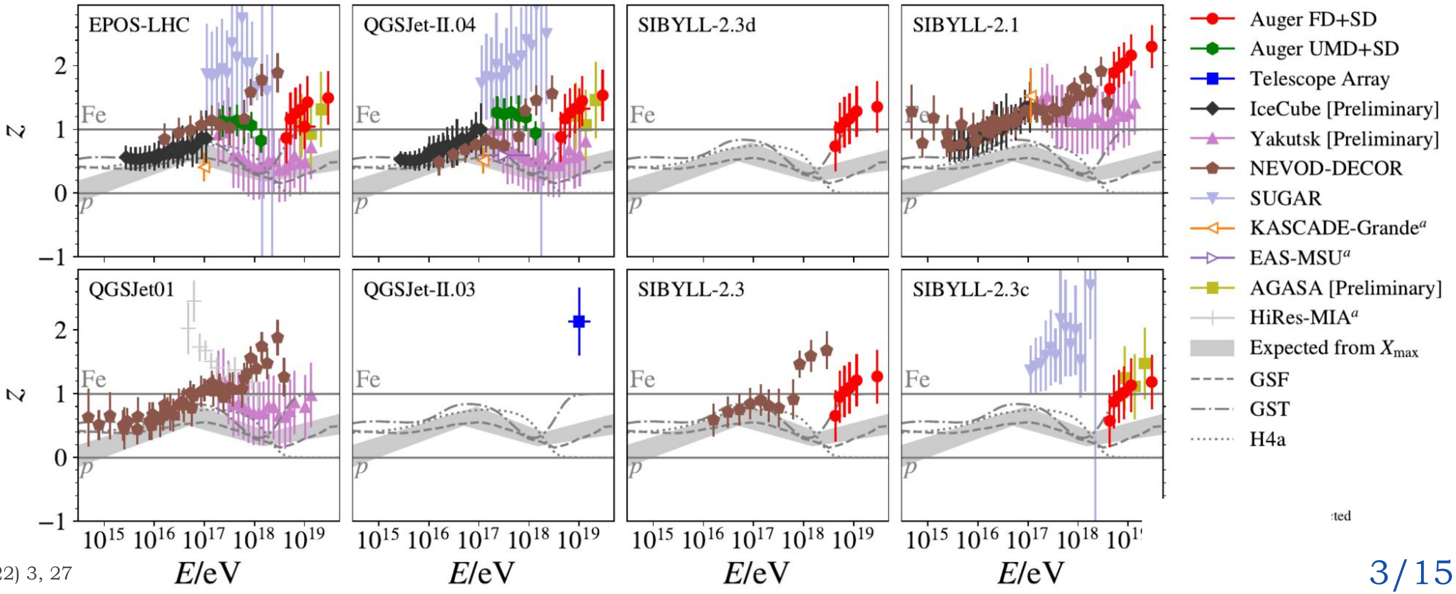


The Muon Puzzle

- ➢ Air shower simulations
  - ○ Necessary for interpretation of measurements
  - ○ Hadronic interaction models
  - ○ Uncertainties due to extrapolations outside of accelerator phase space

→ Discrepancies between data and MC established for state-of-the-art models

$$z = \frac{\overset{\text{data}}{\ln\langle N_\mu\rangle} - \overset{\text{MC}}{\ln\langle N_\mu\rangle_{\mathrm{p}}}}{\underset{\text{MC}}{\ln\langle N_\mu\rangle_{\mathrm{Fe}}} - \underset{\text{MC}}{\ln\langle N_\mu\rangle_{\mathrm{p}}}}$$



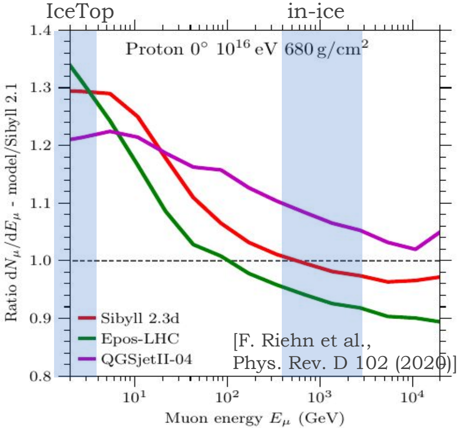
[J. Albrecht et al., Astrophys.Space Sci. 367 (2022) 3, 27

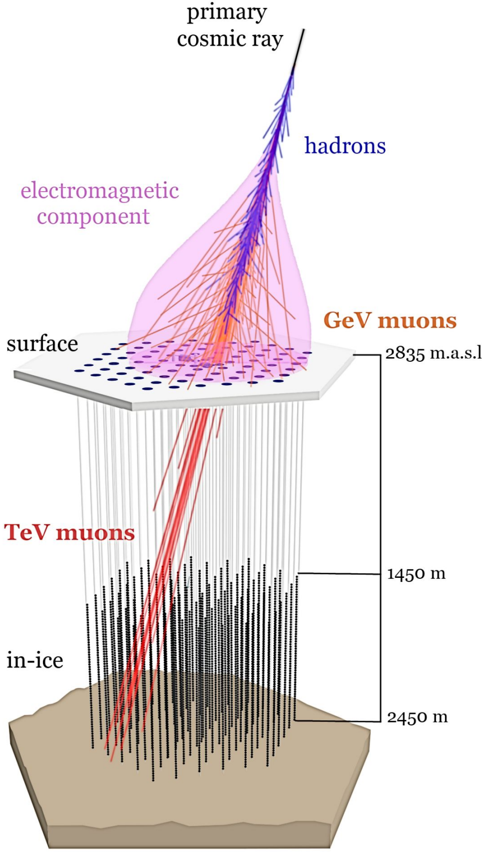
IceCube Neutrino Observatory

- 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

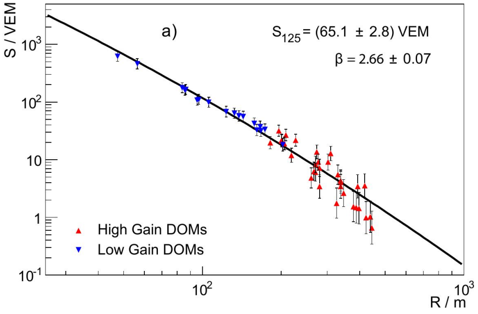
- Combined: Unique EAS Detector
  - Electromagnetic component
  - GeV muon content
  - **TeV muon content**

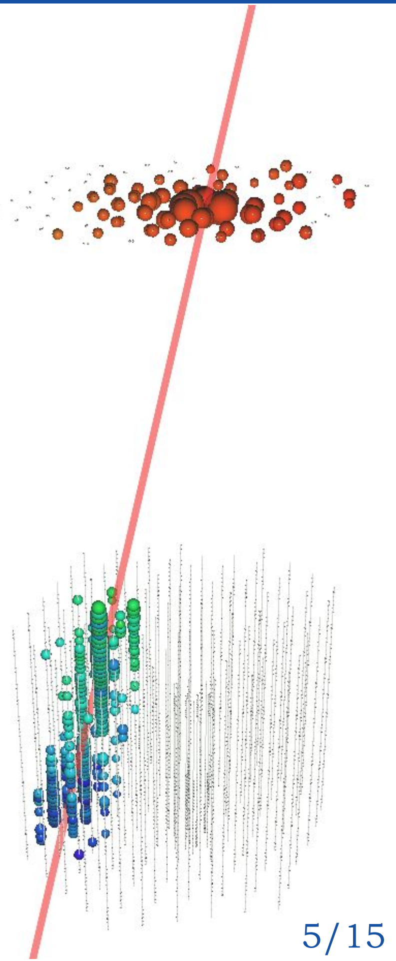




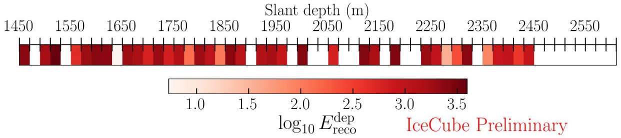
EAS Reconstruction

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



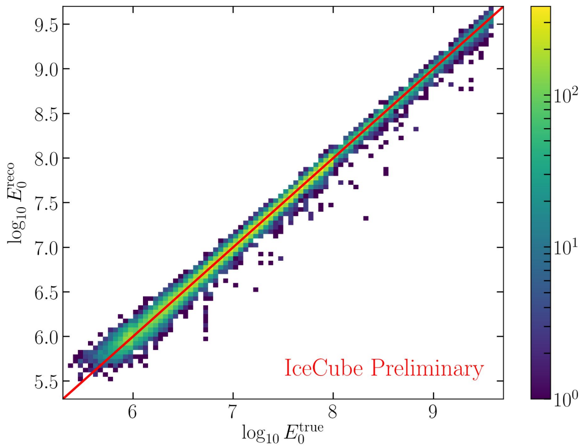


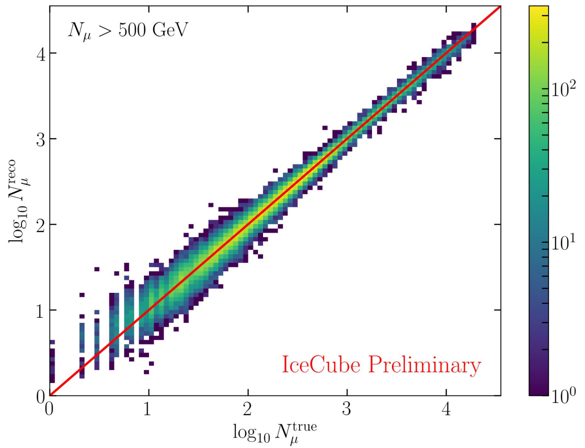
➢ In-Ice
- ○ Energy loss reconstruction
  - · Along reconstructed IceTop track
  - · In segments of 20 m
- → Vector of deposited energy along track



Neural Network

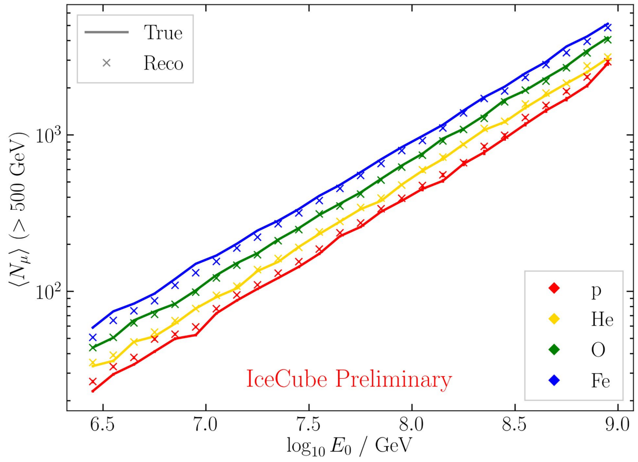
- Neural network reconstruction
  - Inputs
    - Shower size S_{125}
    - Zenith θ
    - Energy loss vector
  - Outputs
    - **Primary energy $\mathbf{E_0}$**
    - **Number of muons > 500 GeV** in shower at surface N_μ
  - RNN + Dense layers
- MC Dataset
  - Sibyll 2.1
  - p, He, O, Fe
  - Coincident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



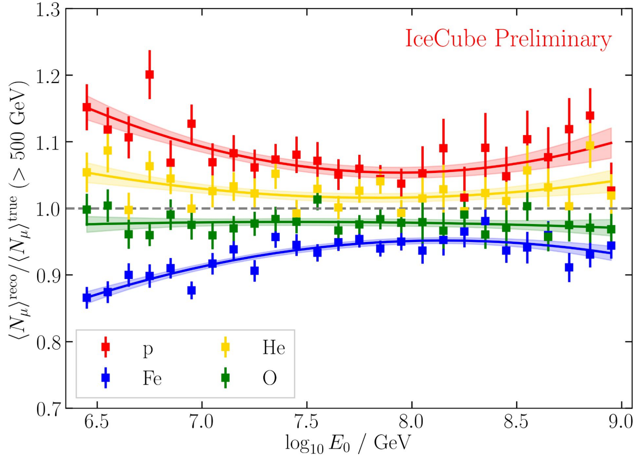


Correction factor

- Determination of $\langle N_\mu > 500\ \mathrm{GeV}\rangle$
  - 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
  - Linear combination of p & Fe corrections

$$\mathcal{C}_{\text{eff}} = f_{\text{p}} \mathcal{C}_{\text{p}} + f_{\text{Fe}} \mathcal{C}_{\text{Fe}}$$

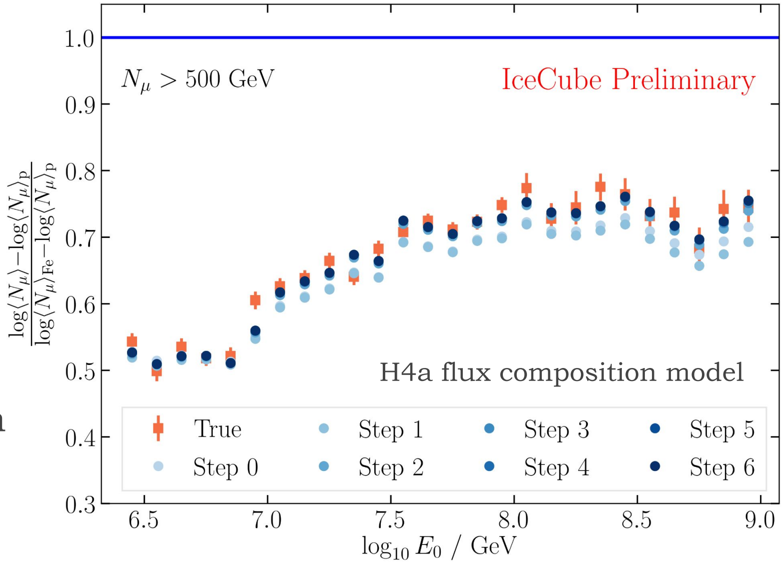
  - Fractions f_{p} and f_{Fe} describe average composition

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

  - Composition estimate:

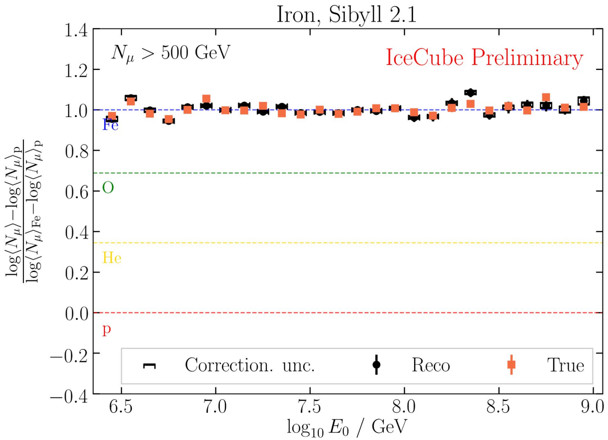
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_{\text{p}}}{\ln\langle N_\mu \rangle_{\text{Fe}} - \ln\langle N_\mu \rangle_{\text{p}}} \approx \frac{\langle \ln A \rangle}{\ln 56}$$

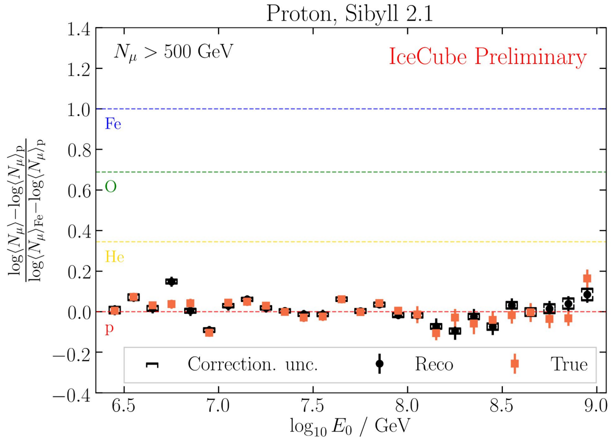
  - Update $\langle N_\mu \rangle$ → update C_{eff} → etc. until convergence

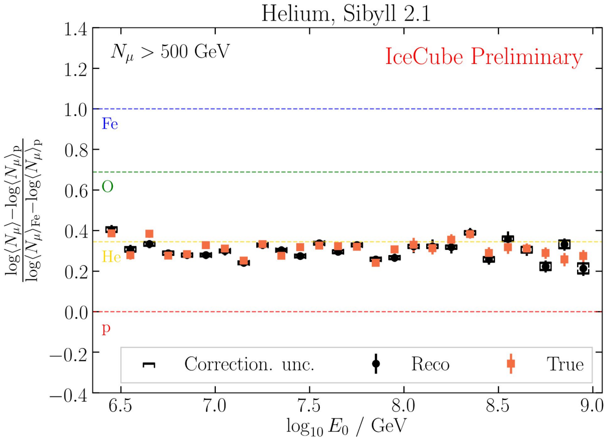


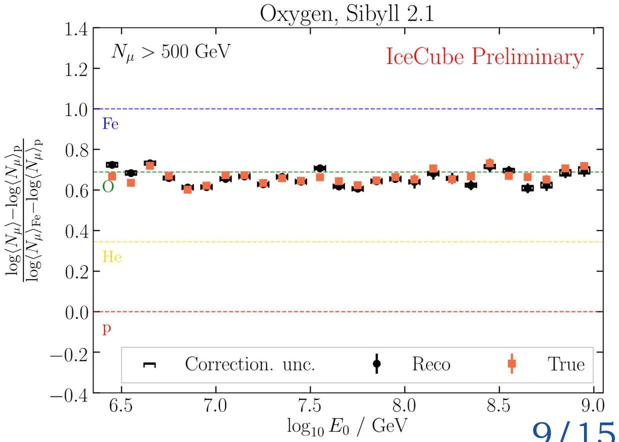
MC Tests

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





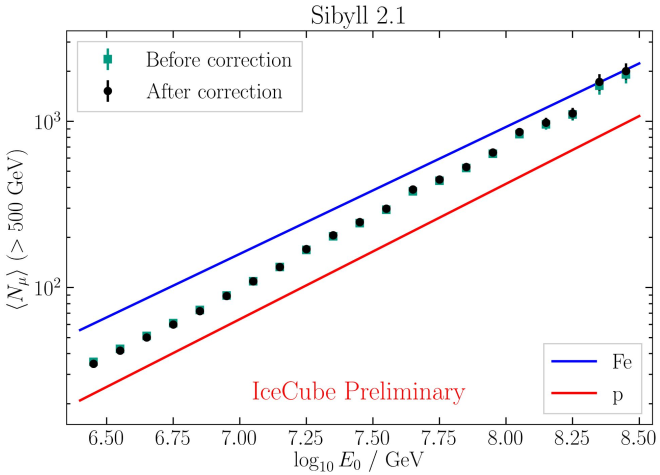


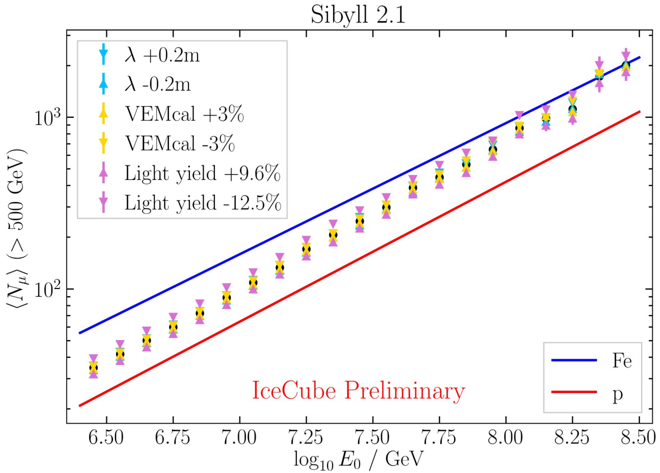


Results

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

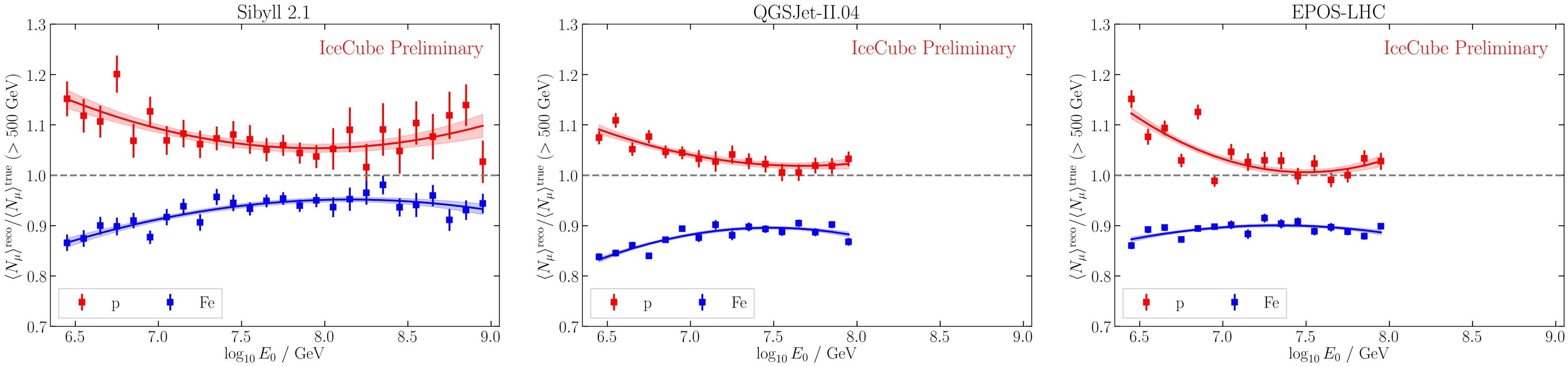
➢ Systematic uncertainties
- Correction uncertainty
- Detector uncertainties
  - Snow accumulation on IceTop
  - IceTop VEM definition / Energy scale
  - IceCube light yield (ice model, DOM eff.)





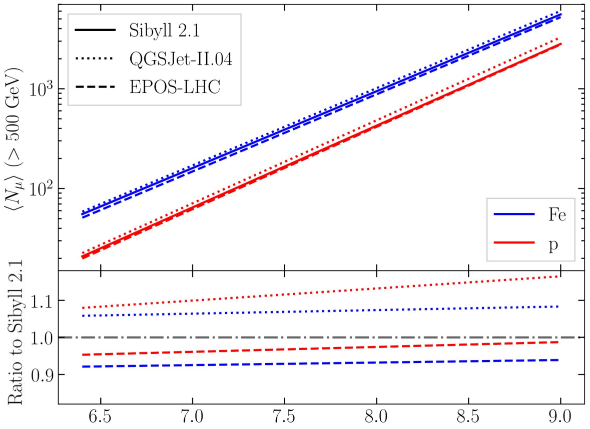
Other Hadronic Models

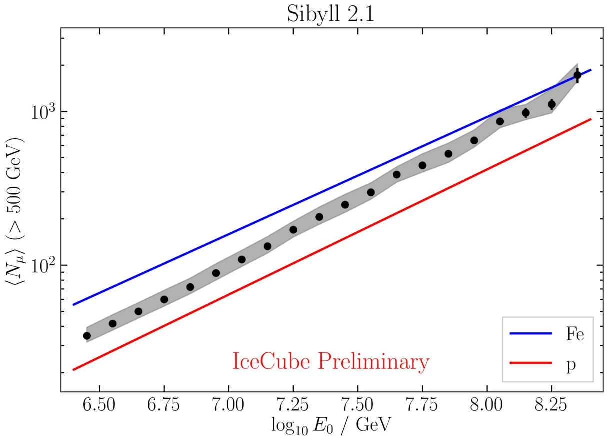
- Correction factors
  - From MC → model dependent results
  - Include other hadronic interaction models
    - QGSJet-II.04
    - EPOS-LHC
    - Limited to 100 PeV

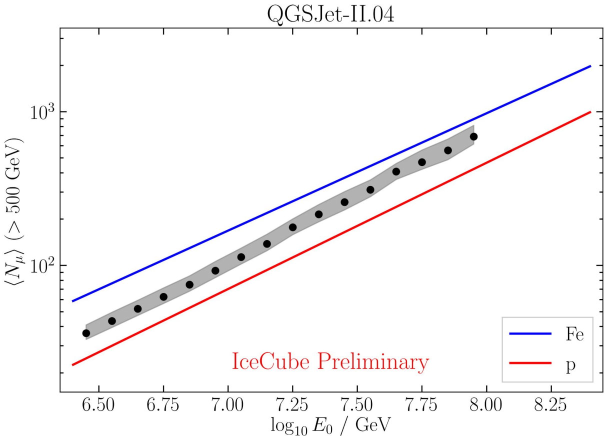


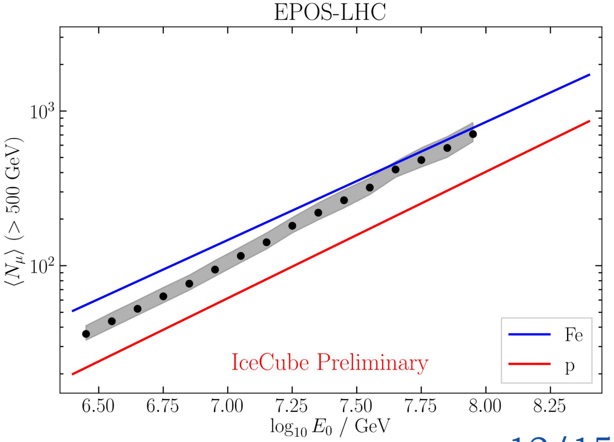
Results

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





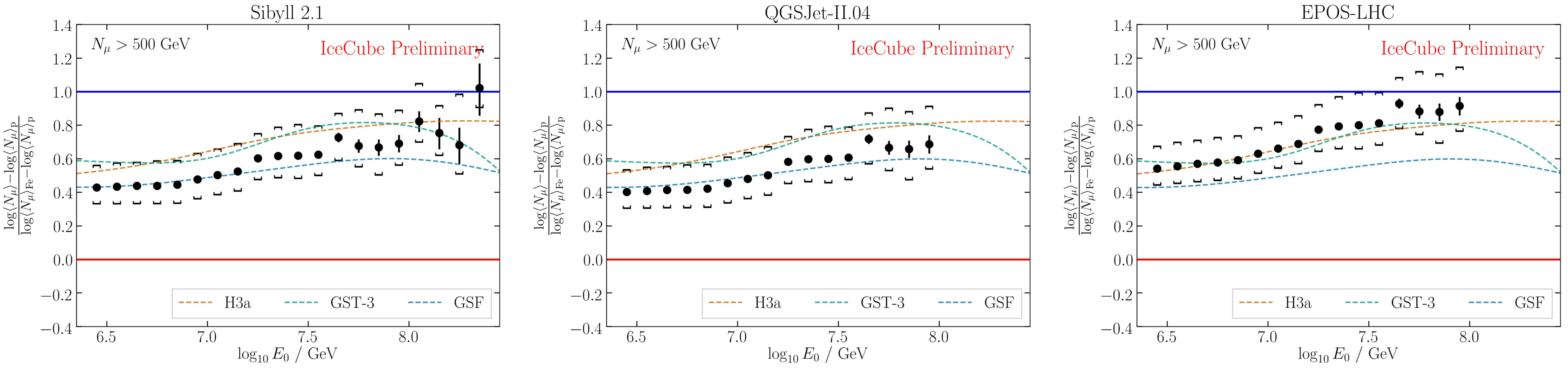




Results

➢ Results in "z-values"

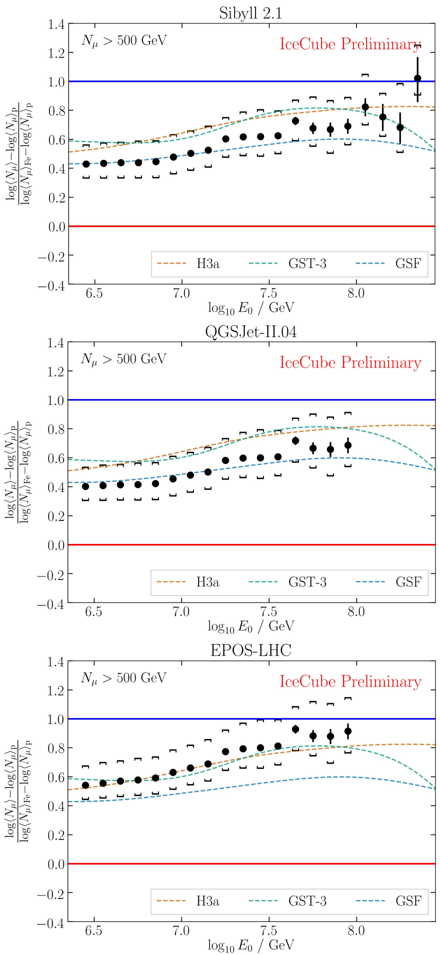
- $$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_\mathrm{p}}{\ln\langle N_\mu \rangle_\mathrm{Fe} - \ln\langle N_\mu \rangle_\mathrm{p}}$$
- Comparison to composition models H4a, GST-3, GSF
- Brackets: total systematic uncertainty



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**
  - No excess/deficit
  - Sibyll 2.1 and QGSJet-II.04: good agreement with composition models
  - EPOS-LHC yields slightly heavier mass composition



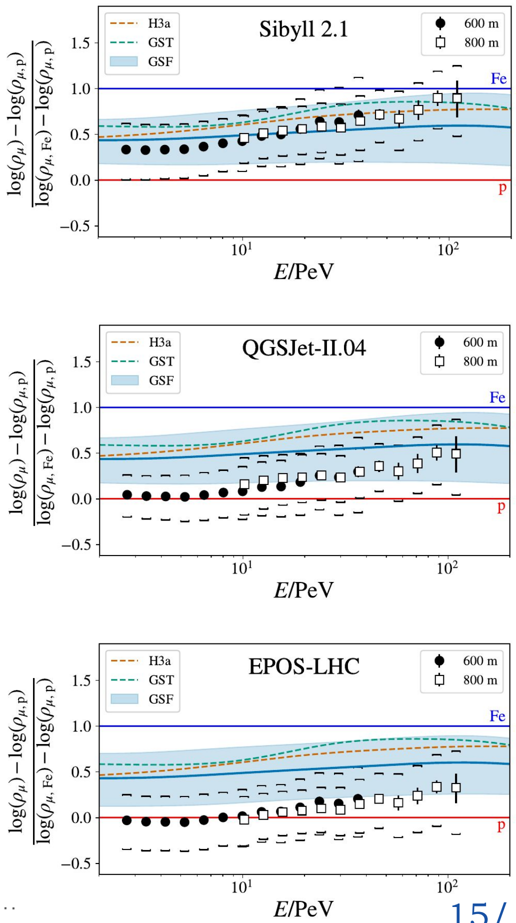
Outlook

- ➢ 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

→ Implies models do not correctly describe interactions

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



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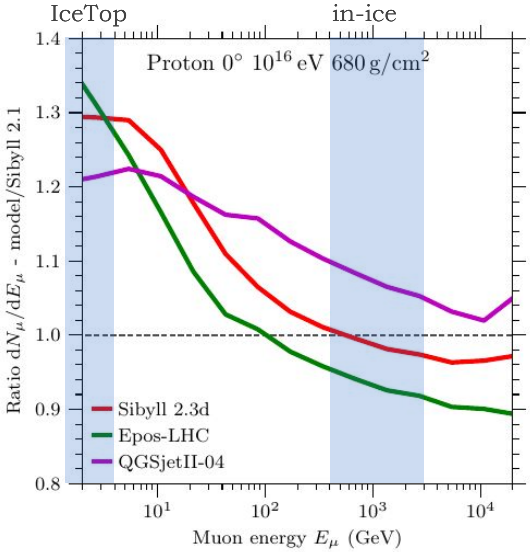
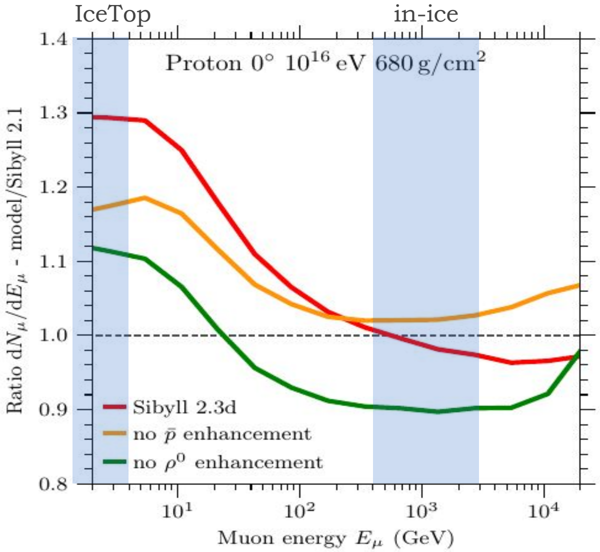
icecube.wisc.edu

Backup

Hadronic interaction models

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

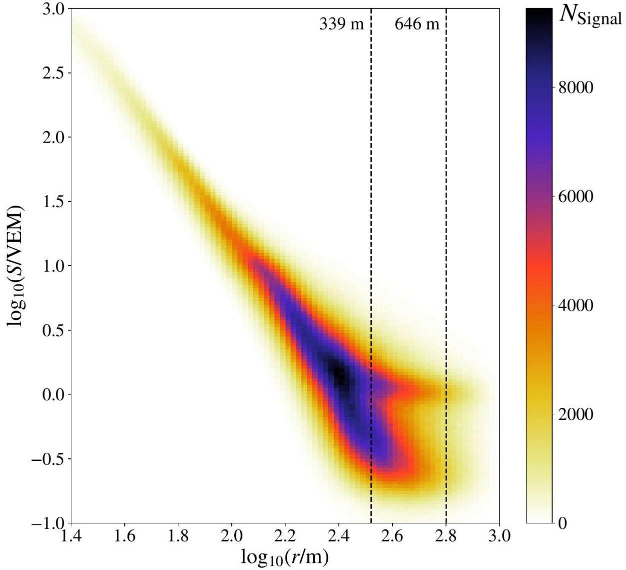


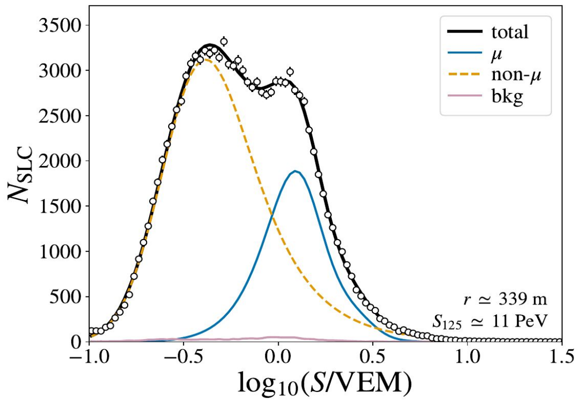


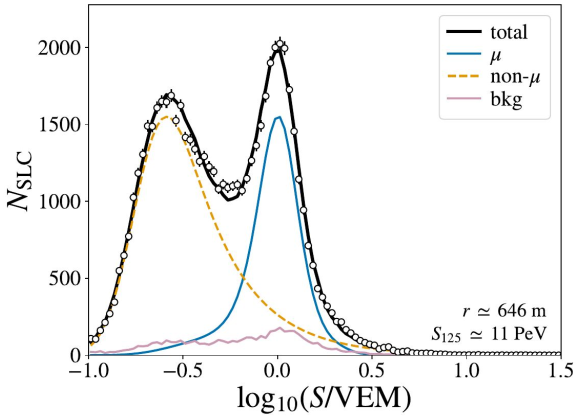
[F. Riehn et al., Phys. Rev. D 102 (2020)]

Density of GeV muons in IceTop

- ➢ Analysis method
  - At large lateral distance: typical 1 VEM muon signal > EM signal
  - Fit signals with different components
  - Fit muon LDF, obtain density @ 600 m, 800 m
  - Apply MC corrections



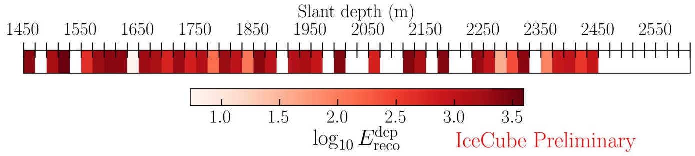


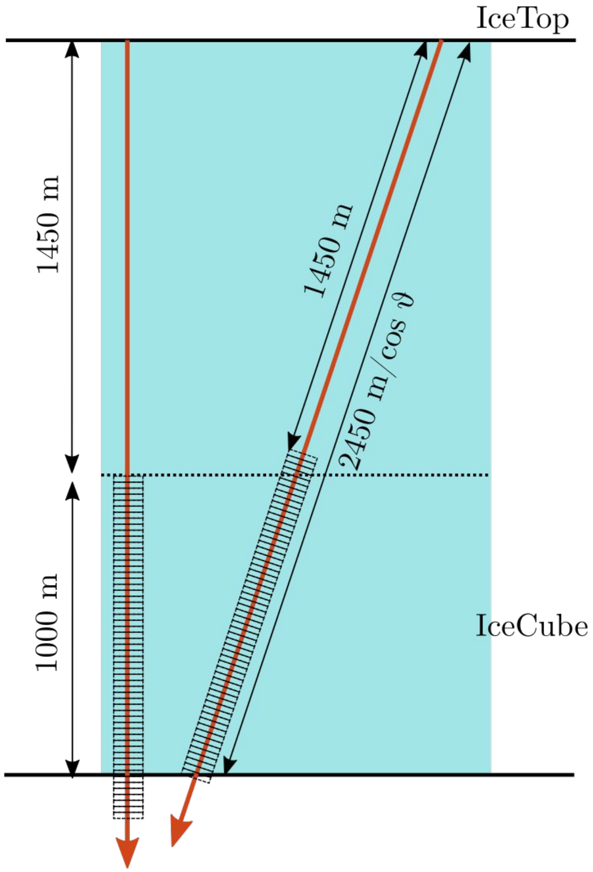


Energy loss input

- 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)

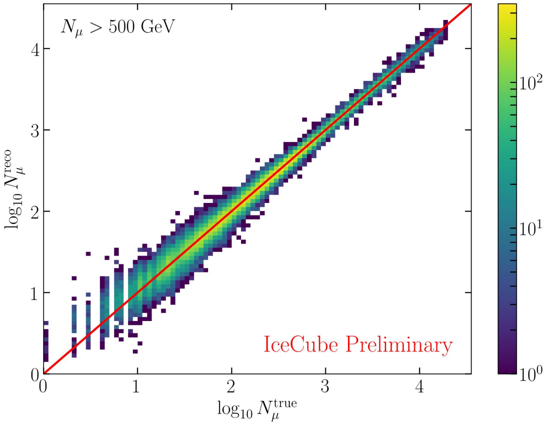
  - Vertical event example

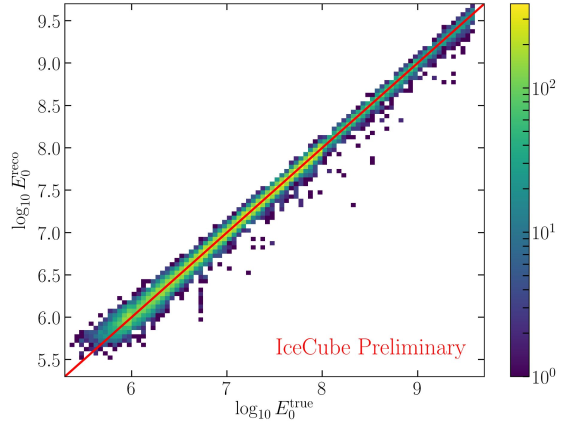


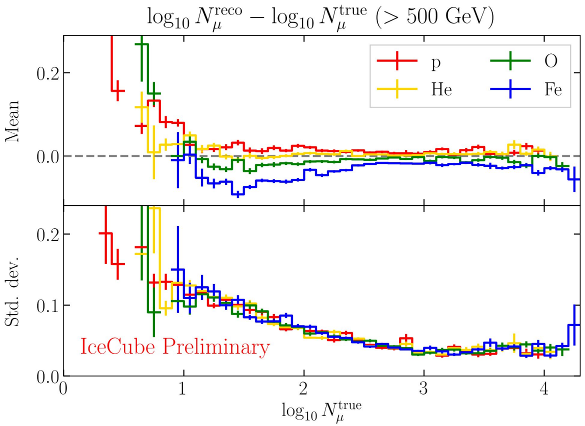


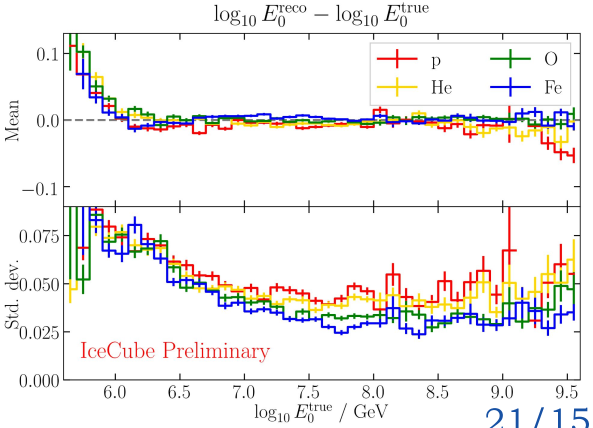
Neural Network Performance

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



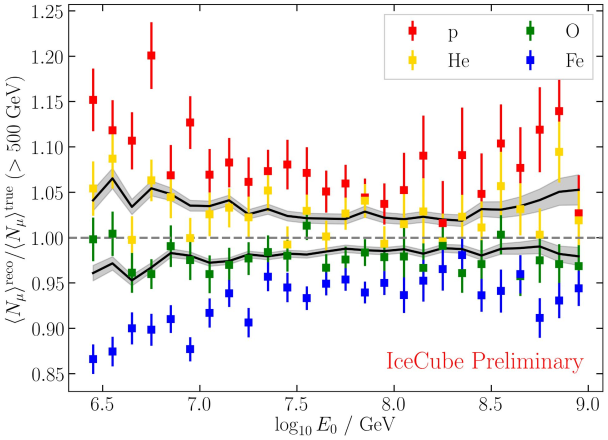


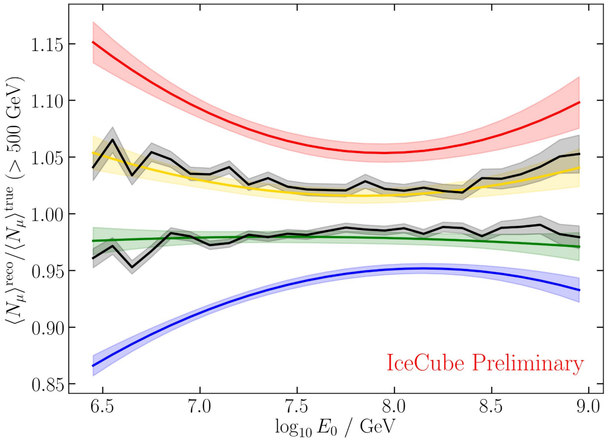




Iterative Correction

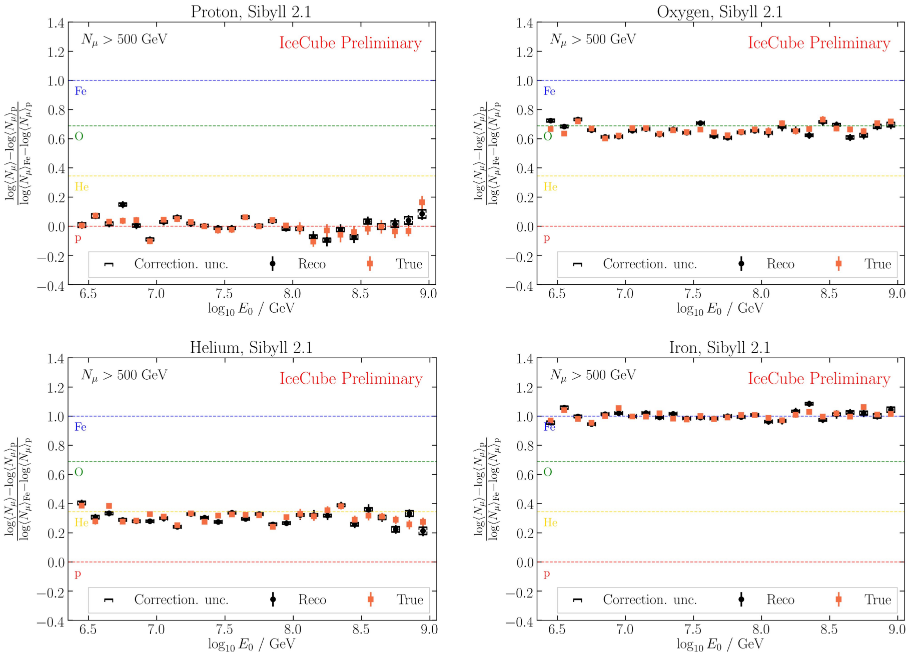
- Important check: can correction factor of intermediate elements be obtained by combining p & Fe correction factors?
  - Use pure He and O MC
  - Use true $\langle N_\mu \rangle$ in He and O
  - Based on this, calculate fractions f_p and f_{Fe}
  - Combine p & Fe correction factors with these fractions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

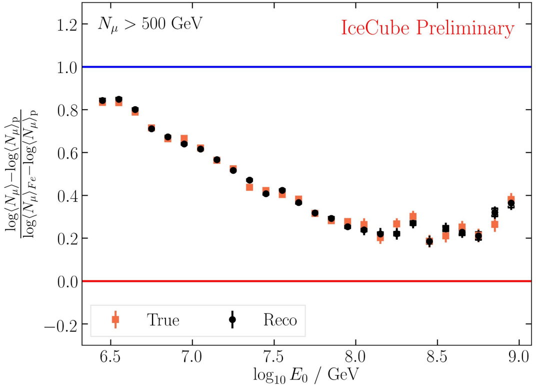


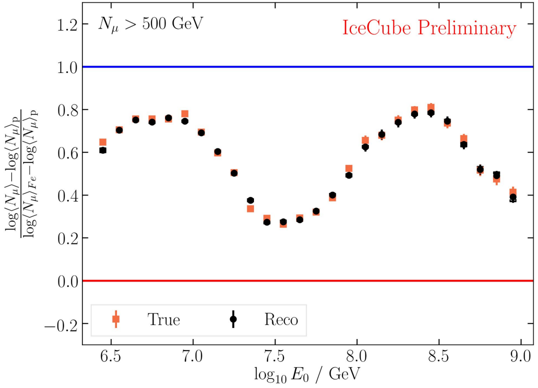


MC checks

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

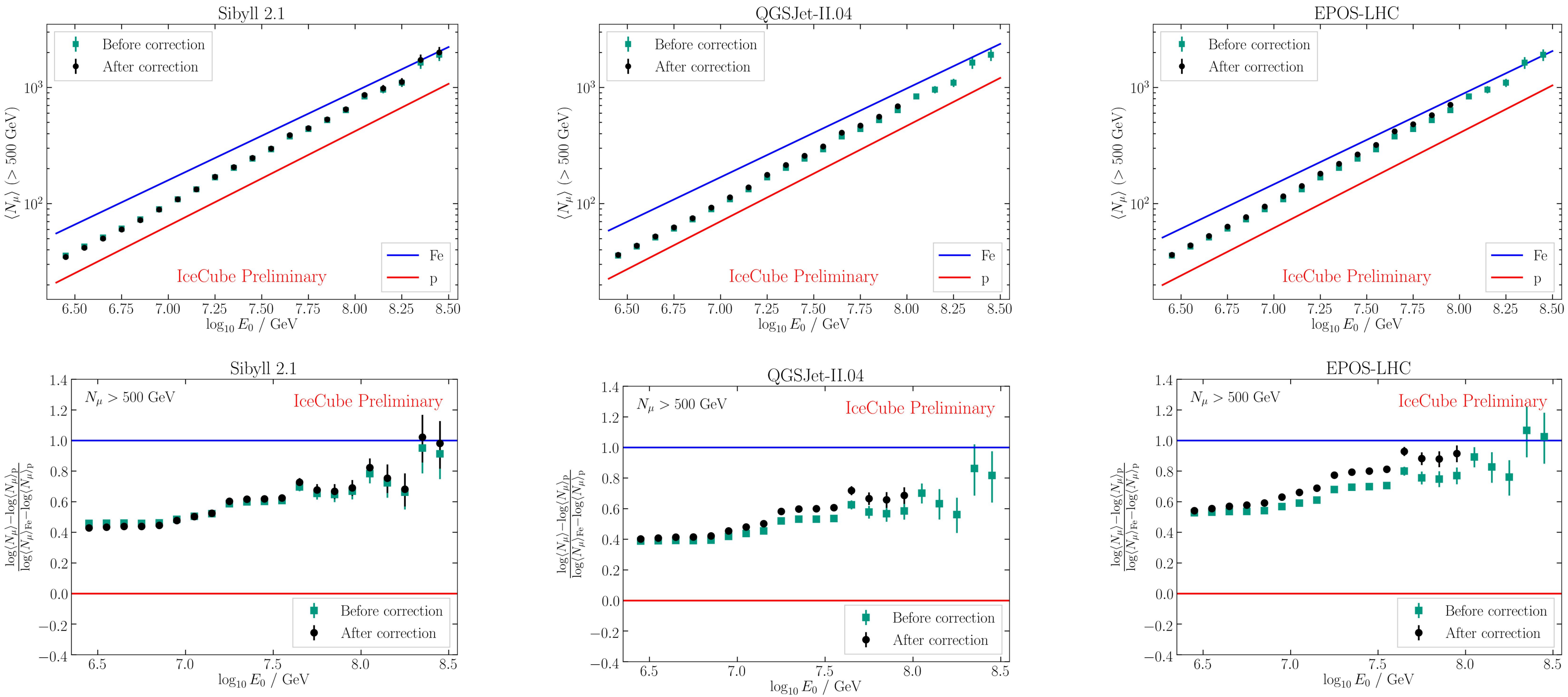






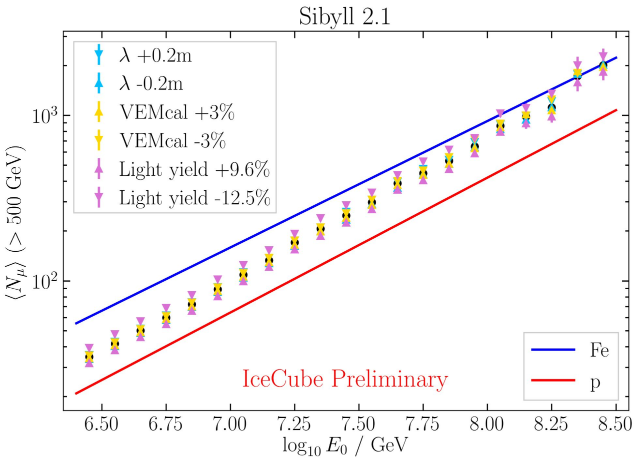
Application to data

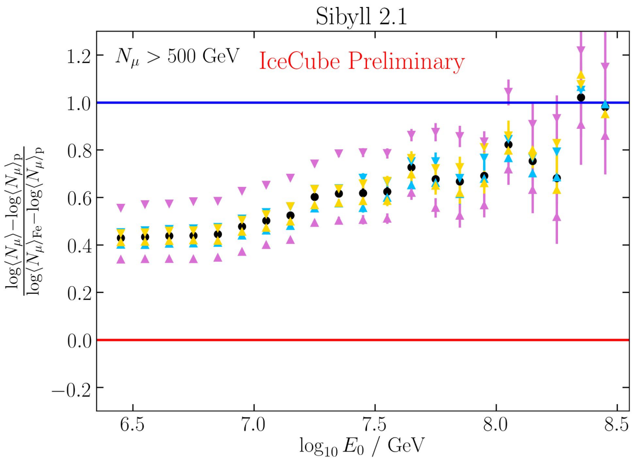
- ➢ Application of reconstructions and correction to experimental data
  - ○ 10% of IC86.2012
  - ○ Different model dependent results



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%





Results

- How do individual results compare?
  - Average given with envelope describing model differences
  - Less than ±5% variation around average