The "muon puzzle" in air showers seen from the perspective of IceCube

MU Days 2022, GSI Darmstadt

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IceCube

South Pole Neutrino Observatory

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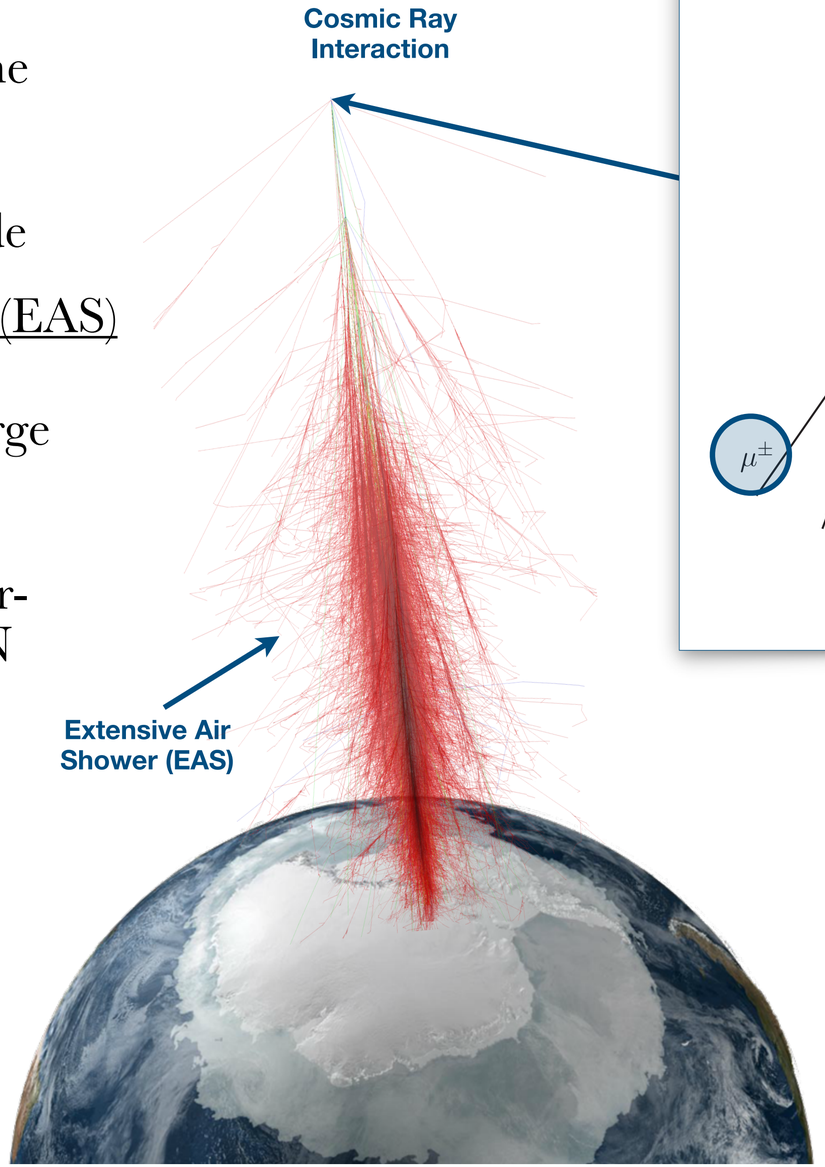
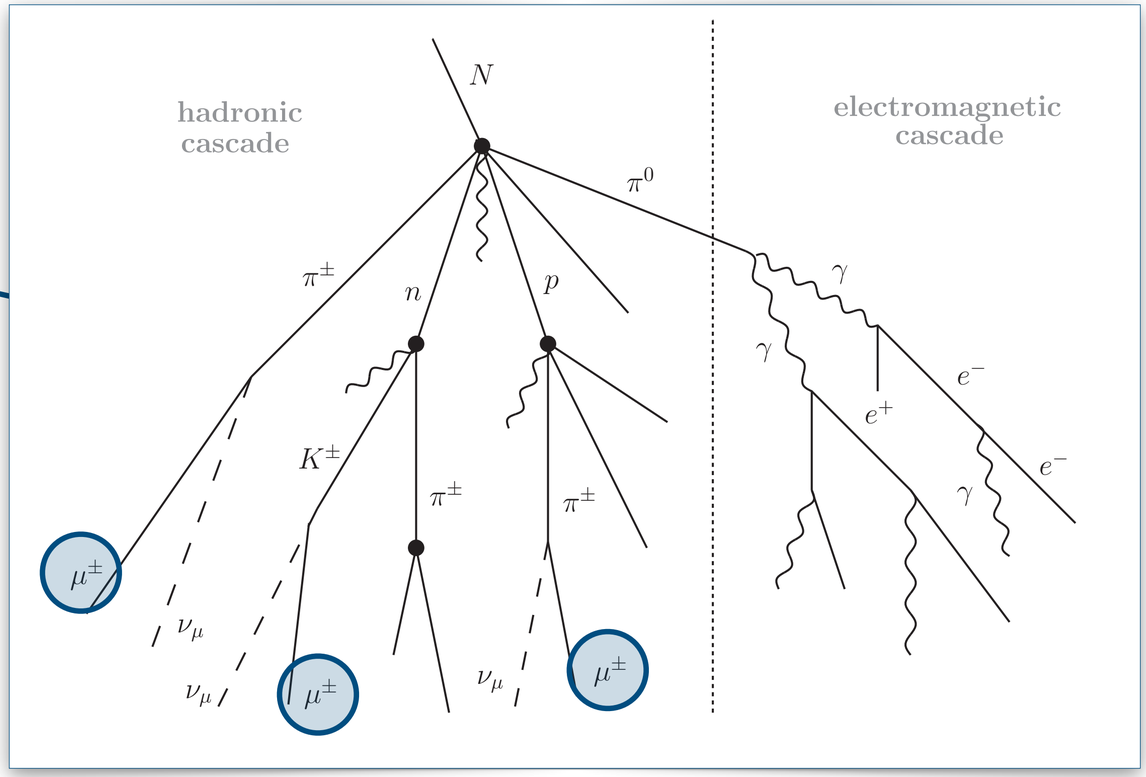
Extensive Air Showers

- Cosmic rays interact in the Earth's atmosphere
- Producing particle cascade
  - Extensive Air Shower (EAS)
- Particle detection with large ground-based detectors
- High-energy particle inter-actions at LHC @ CERN
  - Very well understood
  - Forward direction is not accessible!
- EAS: LHC energies but forward direction



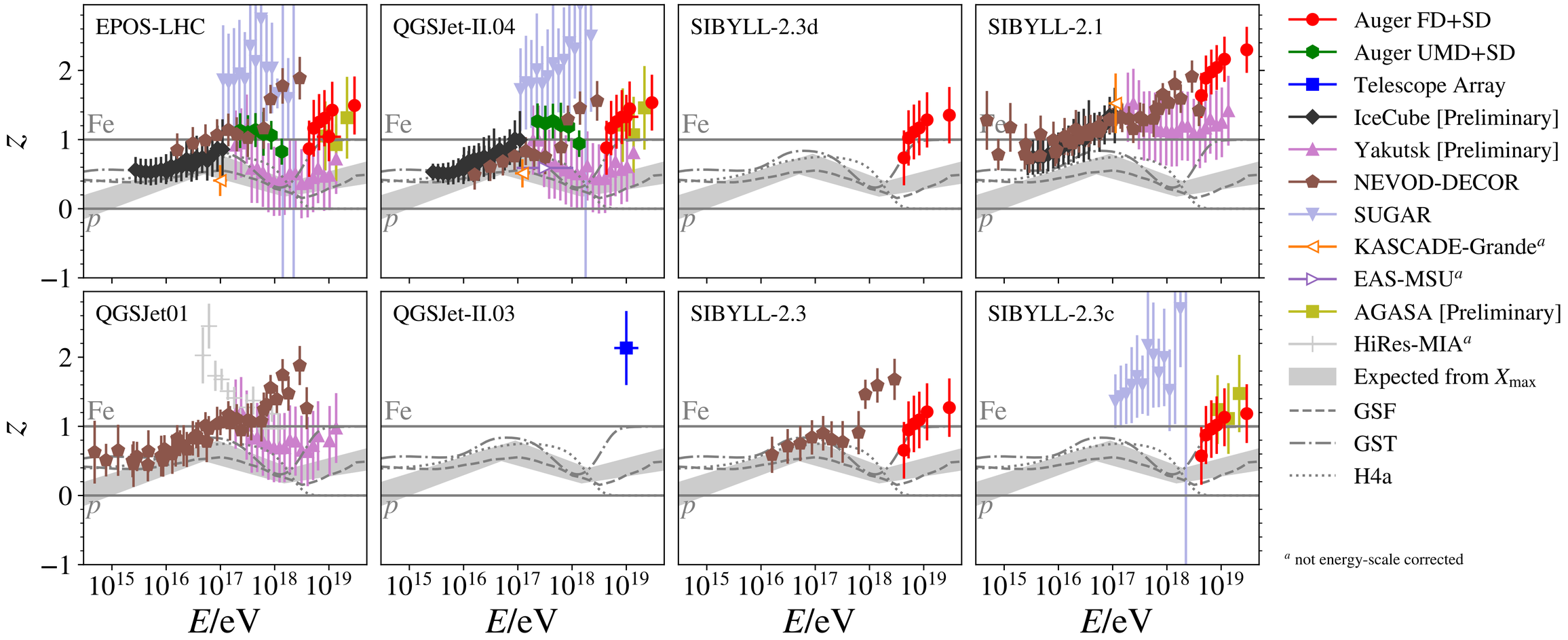


- EAS observations of particles at ground over the last 20 years
- ~ 30% more muons than expected!
  [Pierre Auger Collaboration, Phys. Rev. Lett. 117 (2016)]
  [D. Soldin et al., PoS(ICRC2021)349 (2021)]
  - Discrepancies not understood!

The Muon Puzzle in EAS

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

- Muon content in EAS: z-scale



- (Most) muon measurements indicate mass composition heavier than iron at high E_0!

[D. Soldin et al., PoS ICRC2021 (2021) 349]

The Muon Puzzle in EAS

observation

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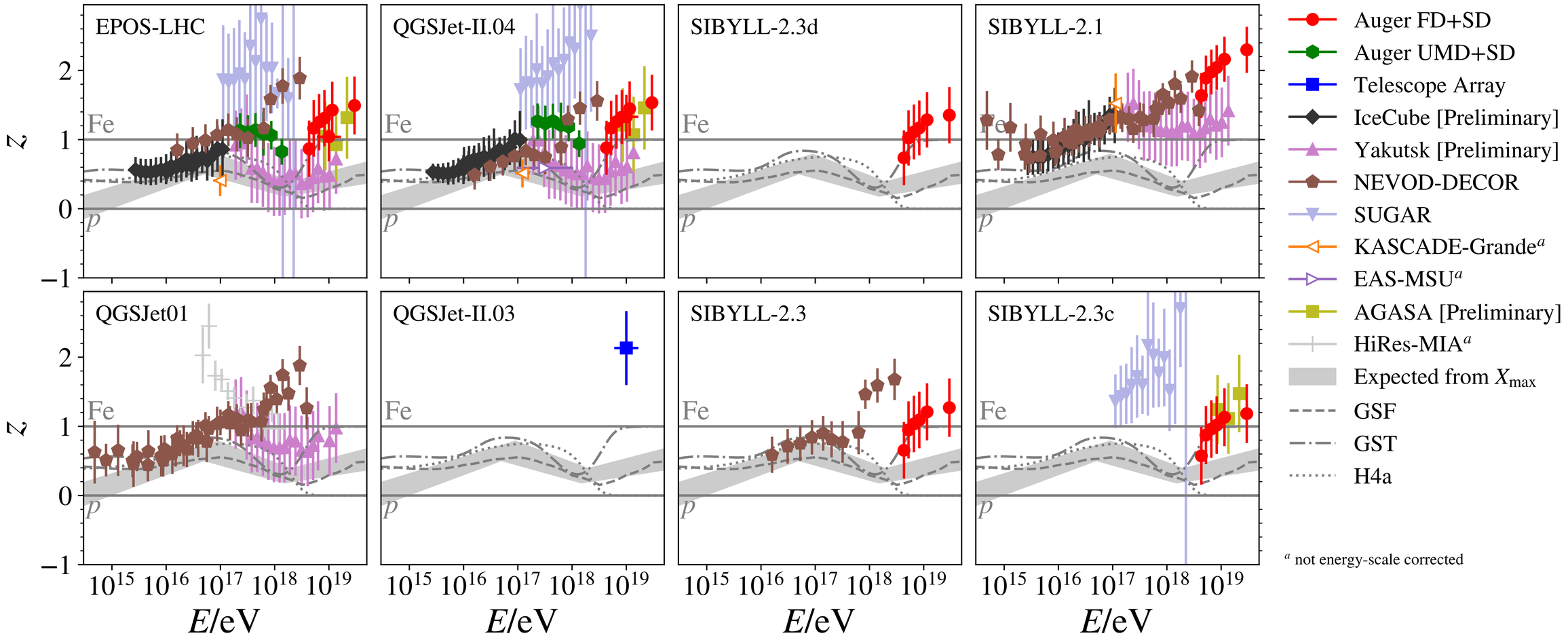

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[D. Soldin et al., PoS ICRC2021 (2021) 349]

The Muon Puzzle in EAS

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simulations

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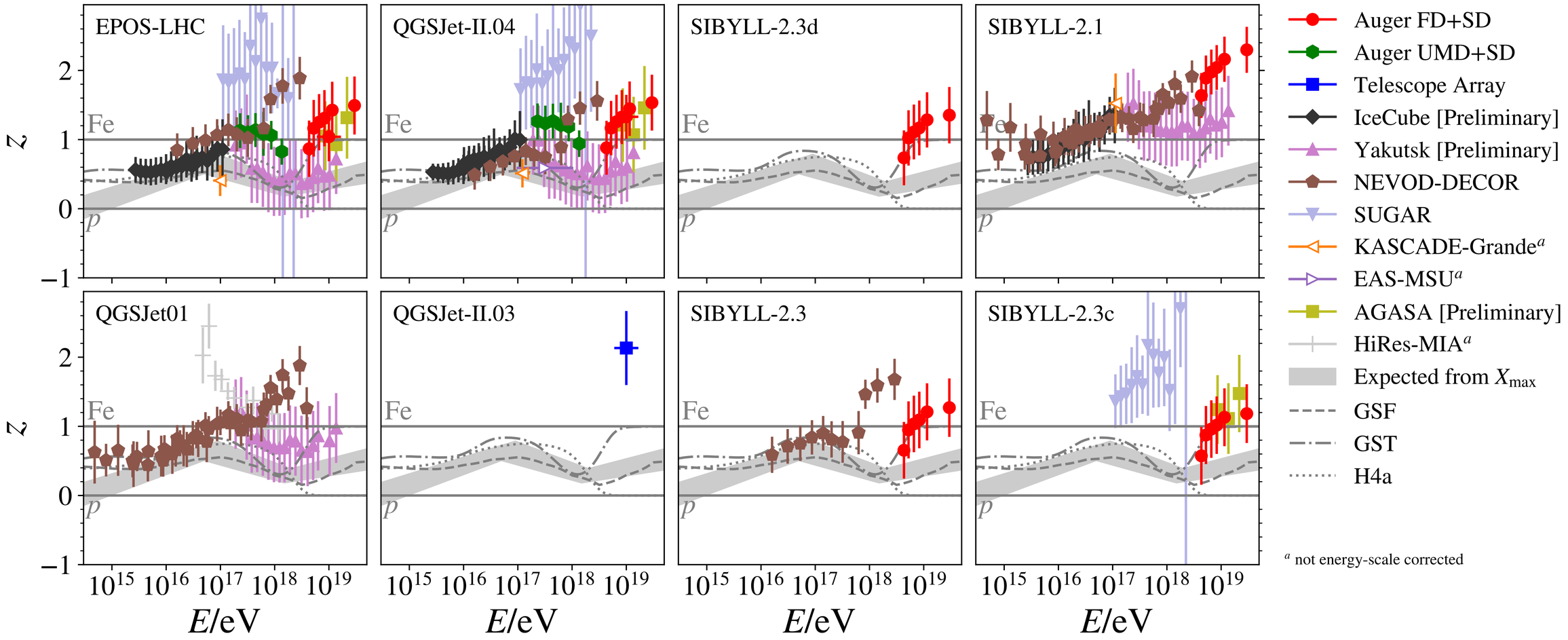

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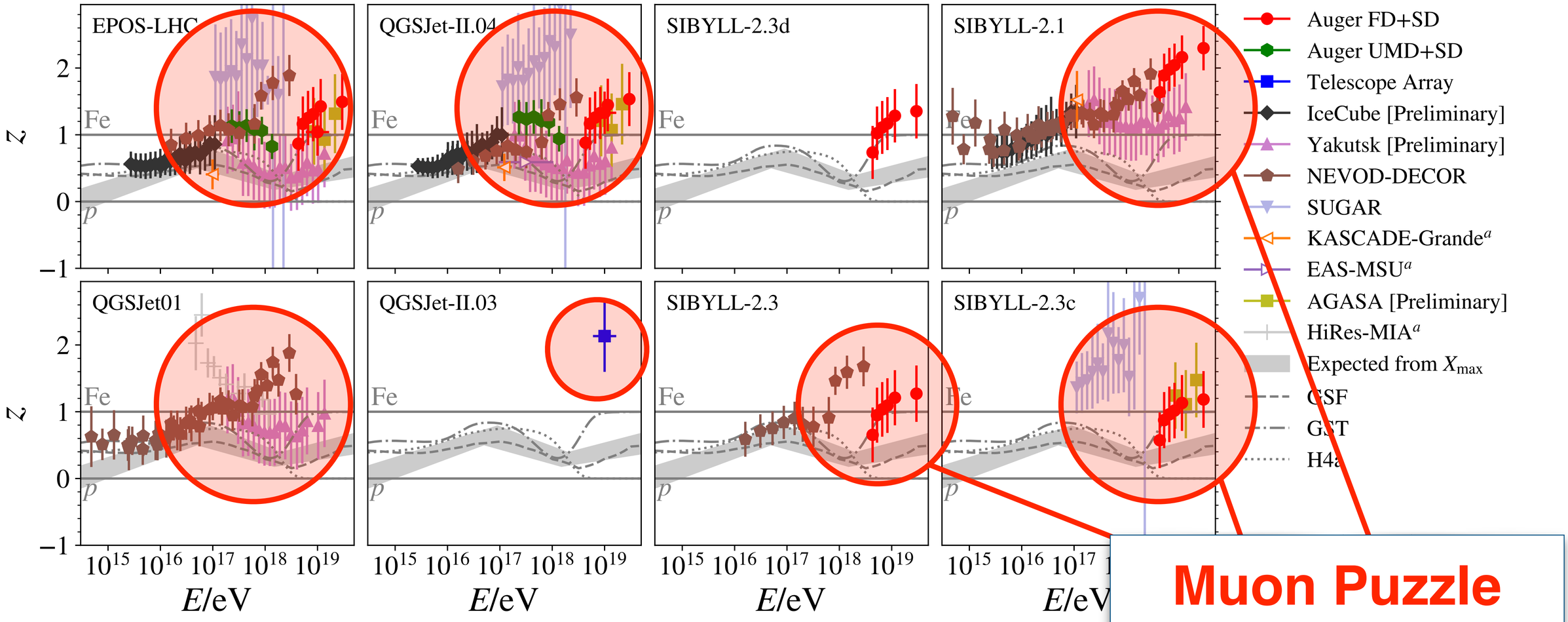


Muon Puzzle

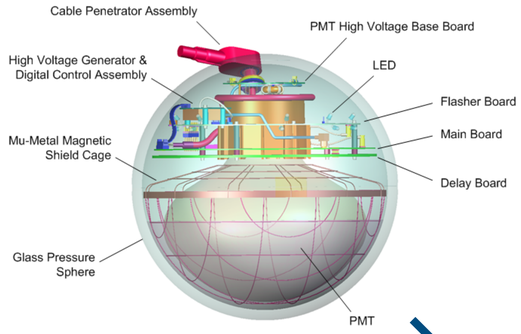
- (Most) muon measurements indicate mass composition heavier than iron at high E_0!

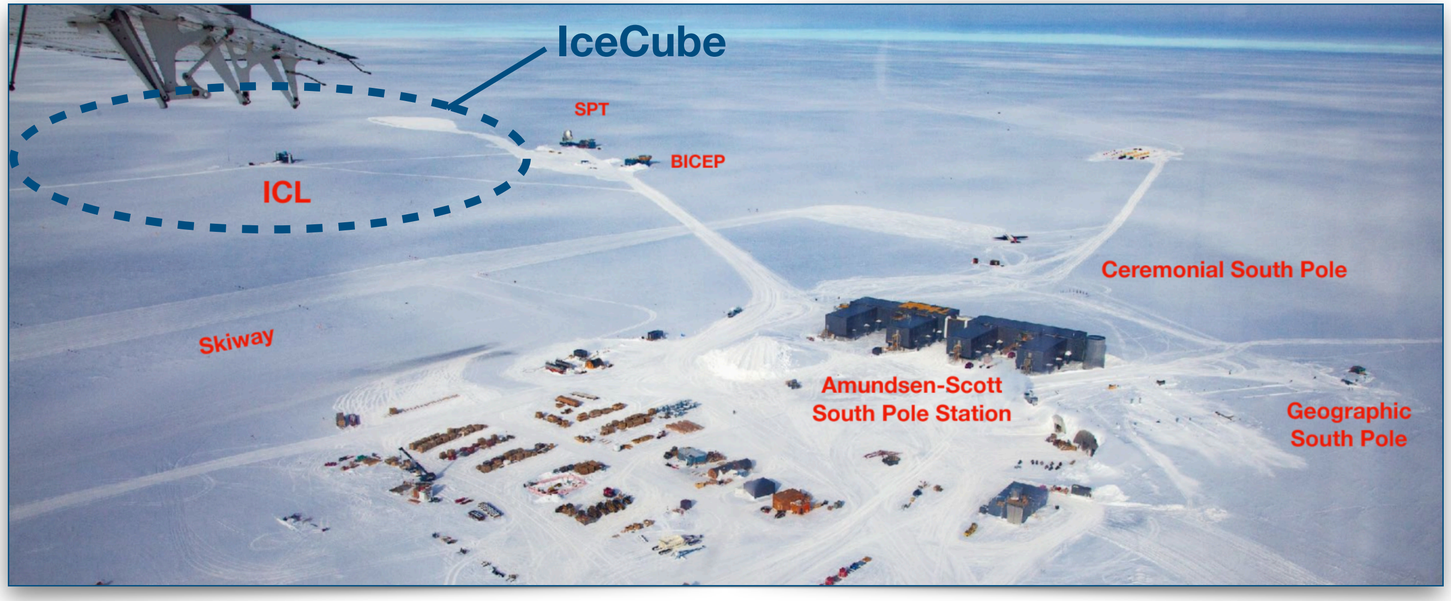
[D. Soldin et al., PoS ICRC2021 (2021) 349]

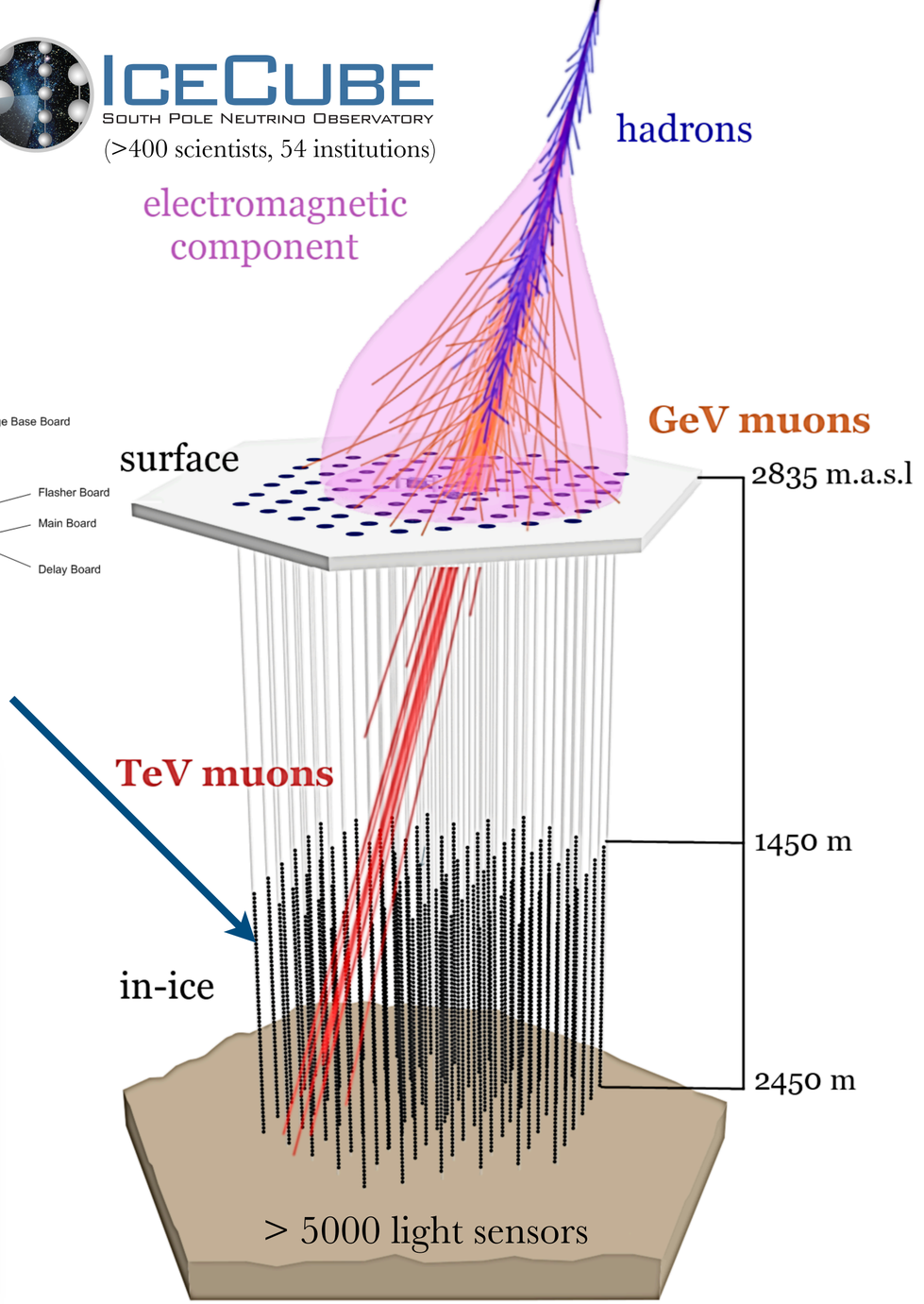
IceCube Observatory

- Cubic-kilometer particle detector at the South Pole
- Measures light produced by EAS particles in the ice
- Simultaneous measurement of low-energy and high-energy muons (surface/in-ice)
- Only IceCube can do this measurement!
- Unique probe of high-energy particle interactions

IceCube
South Pole Neutrino Observatory
(>400 scientists, 54 institutions)



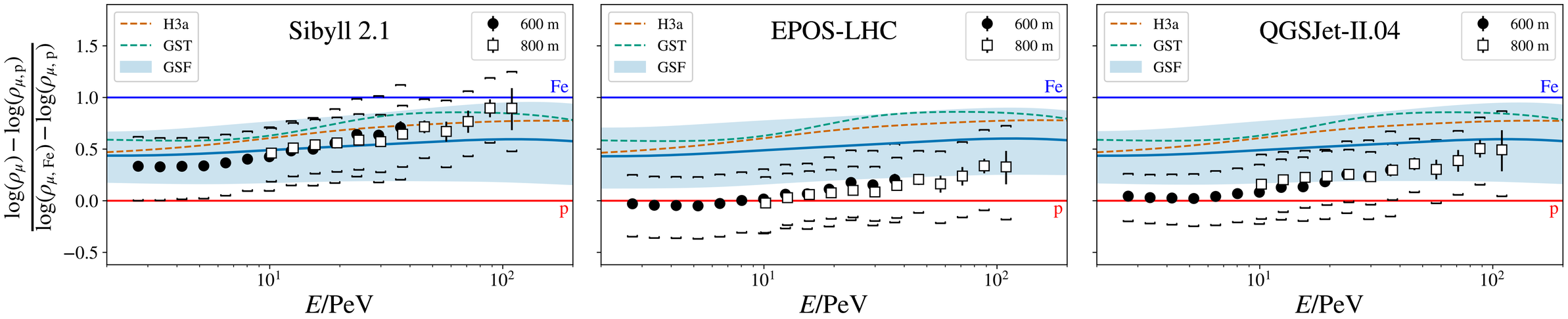




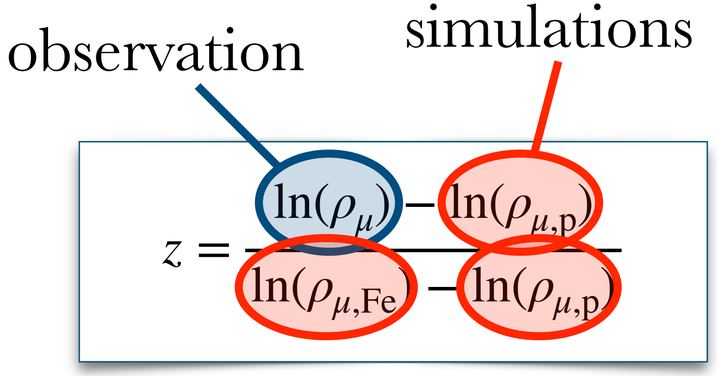
Low-Energy Muons in IceTop

- Low-energy (GeV) muons measured in IceTop

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



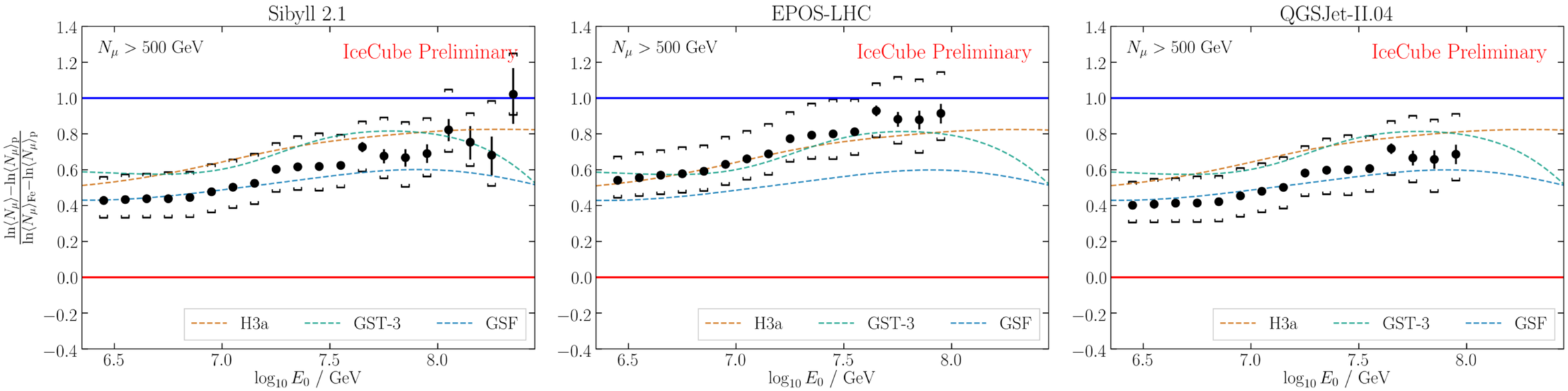
- "Old" (pre-LHC) Sibyll 2.1 model agrees with expectation (gray band)
- "New" (post-LHC) models show discrepancies with expectation
- Indicates too many muons in post-LHC models



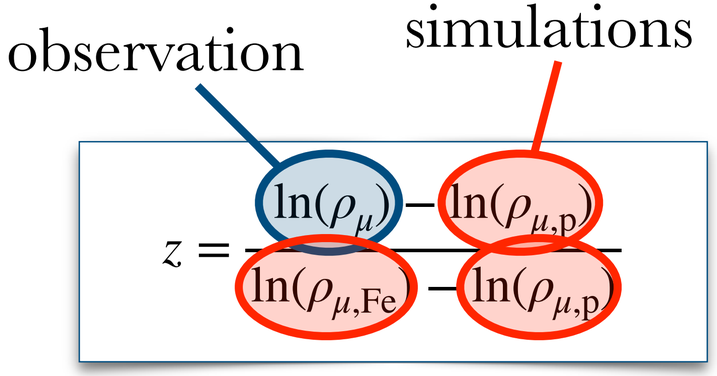
High-Energy Muons in IceCube

- High-energy (TeV) muons measured in the deep ice detector

[S. Verpoest (IceCube Collaboration), ECRS2022]

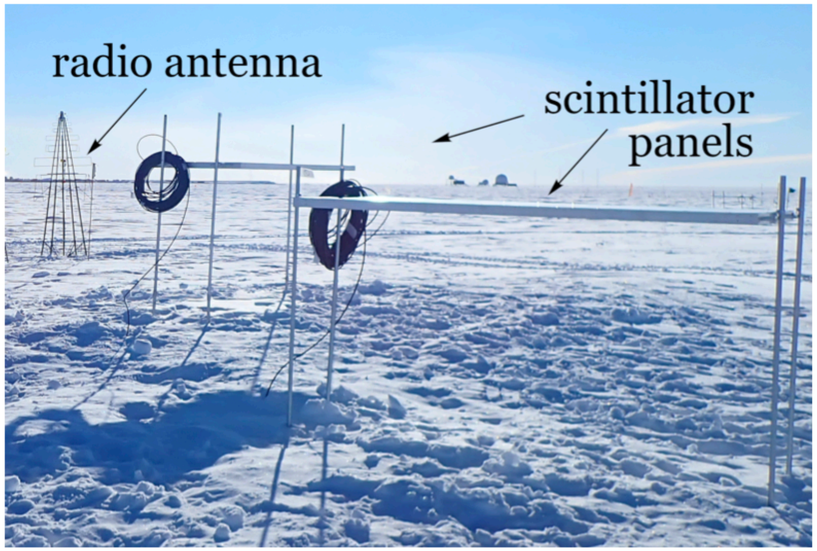


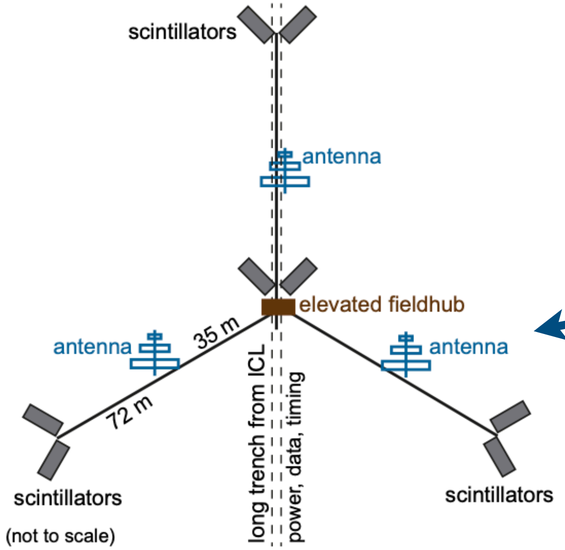
- All model agree with expectation within uncertainties
- Inconsistencies between low- and high-energy muon measurements!
- Detailed analysis of coincident events in progress…
- Will strongly constrain / exclude muon production models



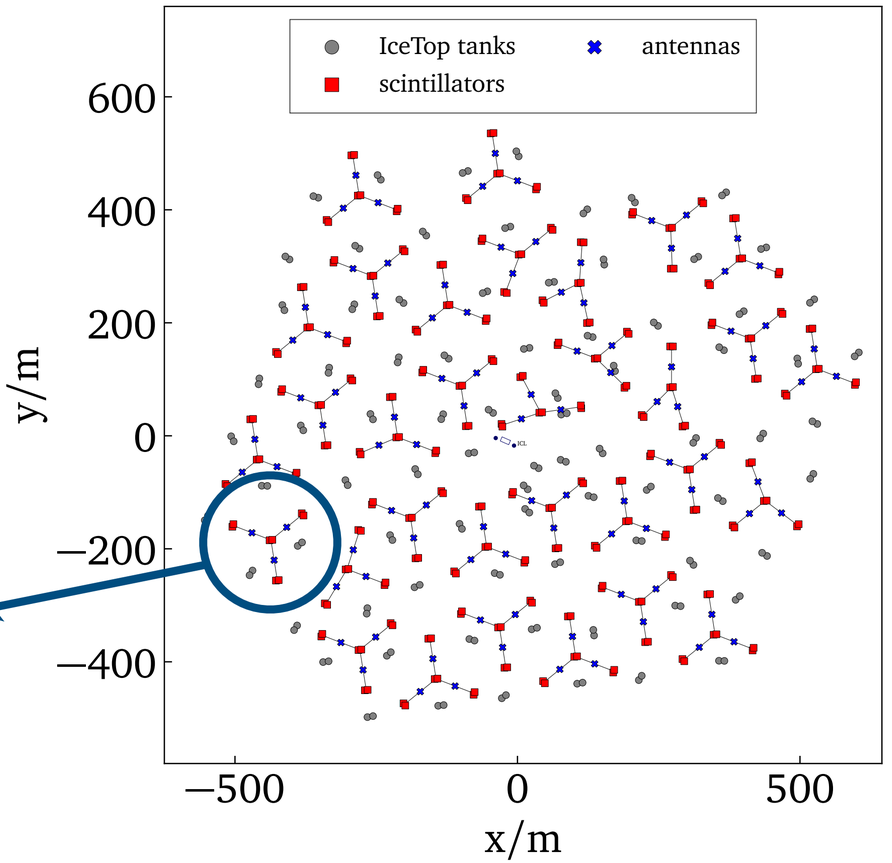
Ongoing Detector Improvements

- Surface enhancement in progress:
  - New scintillator array
    - Better GeV muon separation in EAS
  - New radio antenna array
    - Improved EAS energy reconstruction
    - Increased angular acceptance



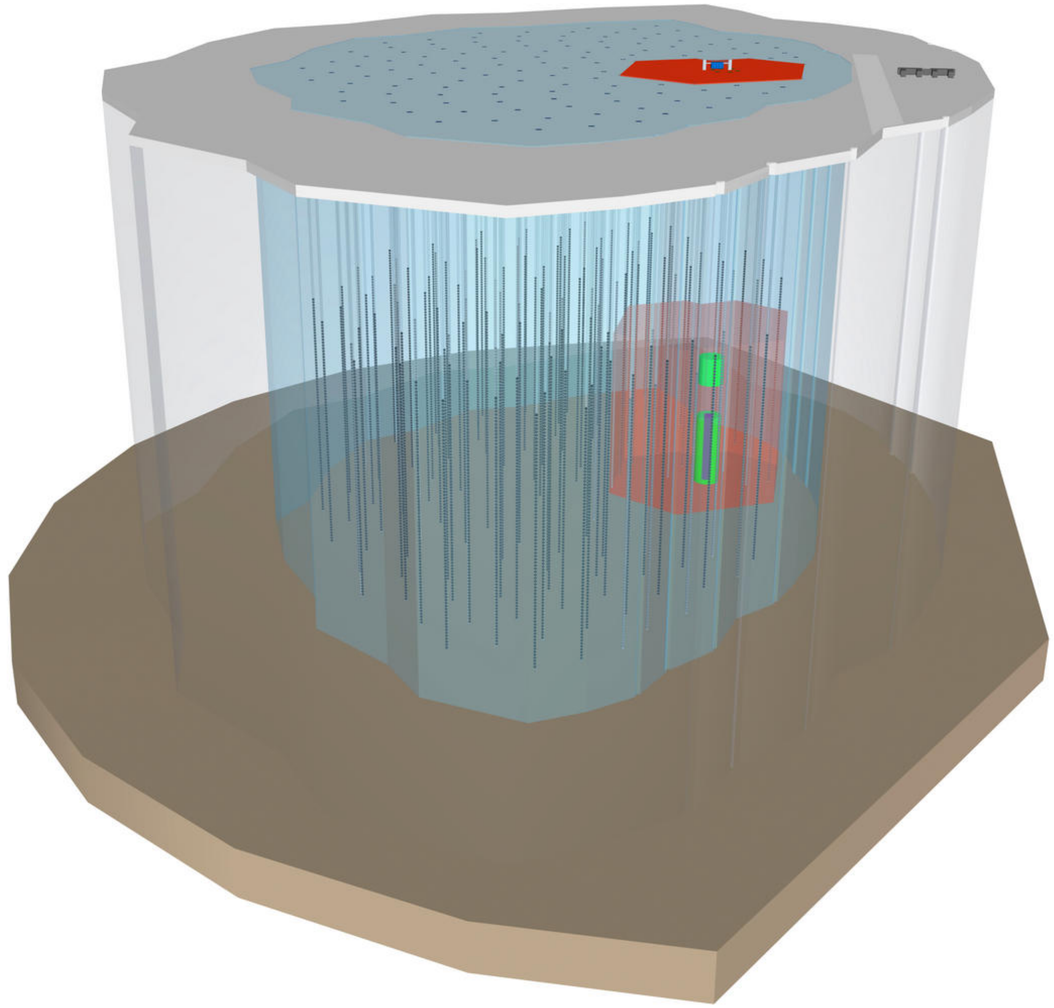


[A. Haungs et al., EPJ Web Conf. 210 (2019)]



Future: IceCube-Gen2

- IceCube-Gen2:
  - Significant larger in-ice and surface detectors
  - Increased solid angle, larger inclinations
  - Increased statistics at the highest energies
    - Close the gap to Pierre Auger Observatory in muon measurements!
  - Improved uncertainties:
    - Better muon separation
    - Better understanding of the absolute energy scale
    - Reduced in-ice systematics
  - Improved analysis methods under development



[IceCube-Gen2 Collaboration, J. Phys. G 48 (2021)]


IceCube
South Pole Neutrino Observatory
KIT
Karlsruhe Institute of Technology
Thank you!

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

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SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

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Chiba University

NEW ZEALAND
University of Canterbury

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University of California, Los Angeles
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

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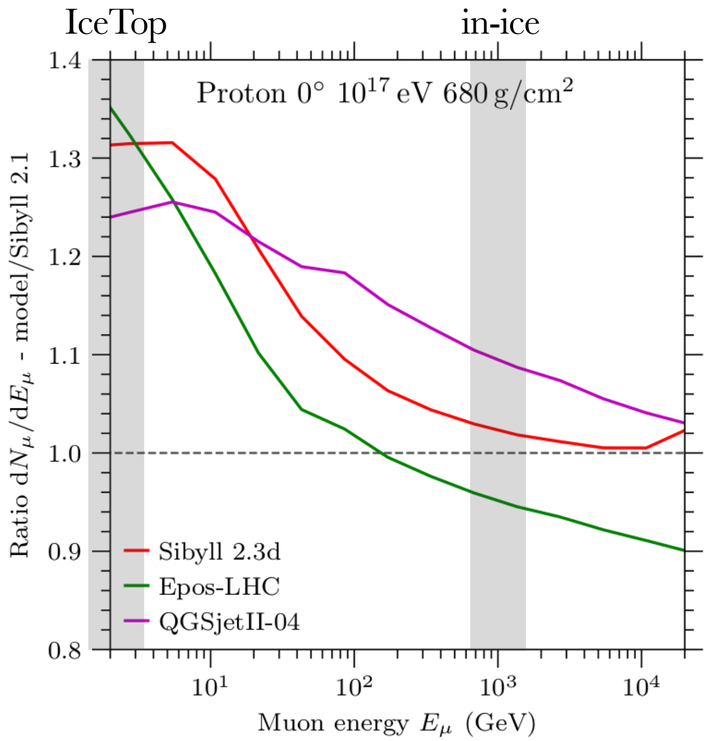
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

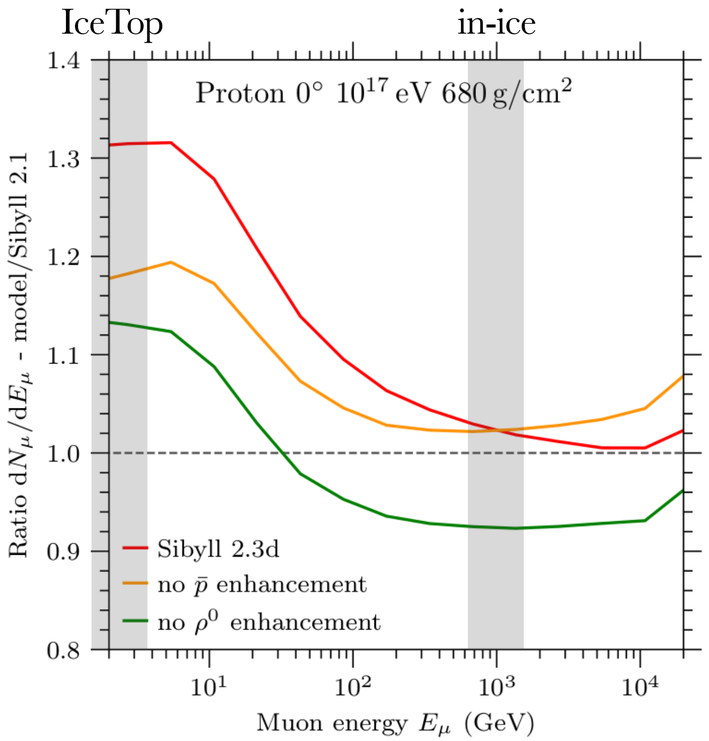
IceCube
South Pole Neutrino Observatory

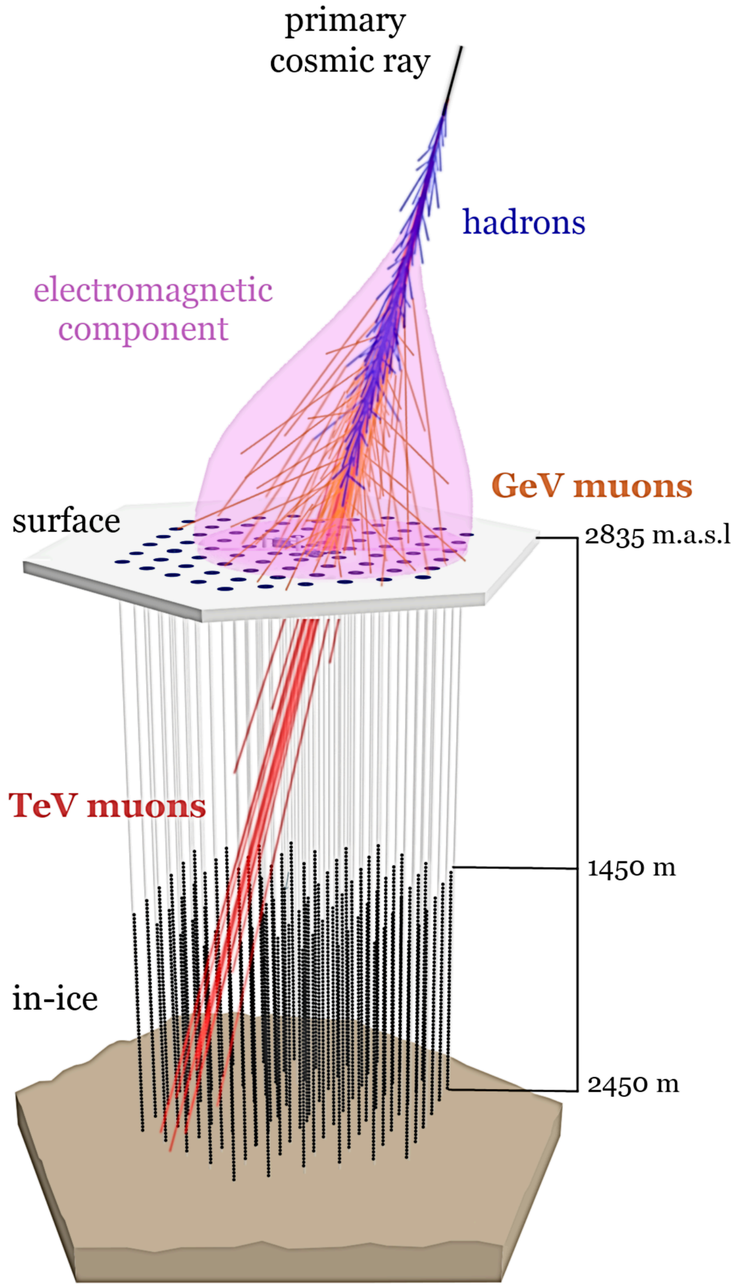
icecube.wisc.edu

The Muon Puzzle and IceCube

- Coincident measurements provide spectral muon information
- Unique tests of multi-particle production (forward region)!
- Will strongly constrain / exclude muon production models
- Crucial contribution to solve the Muon Puzzle



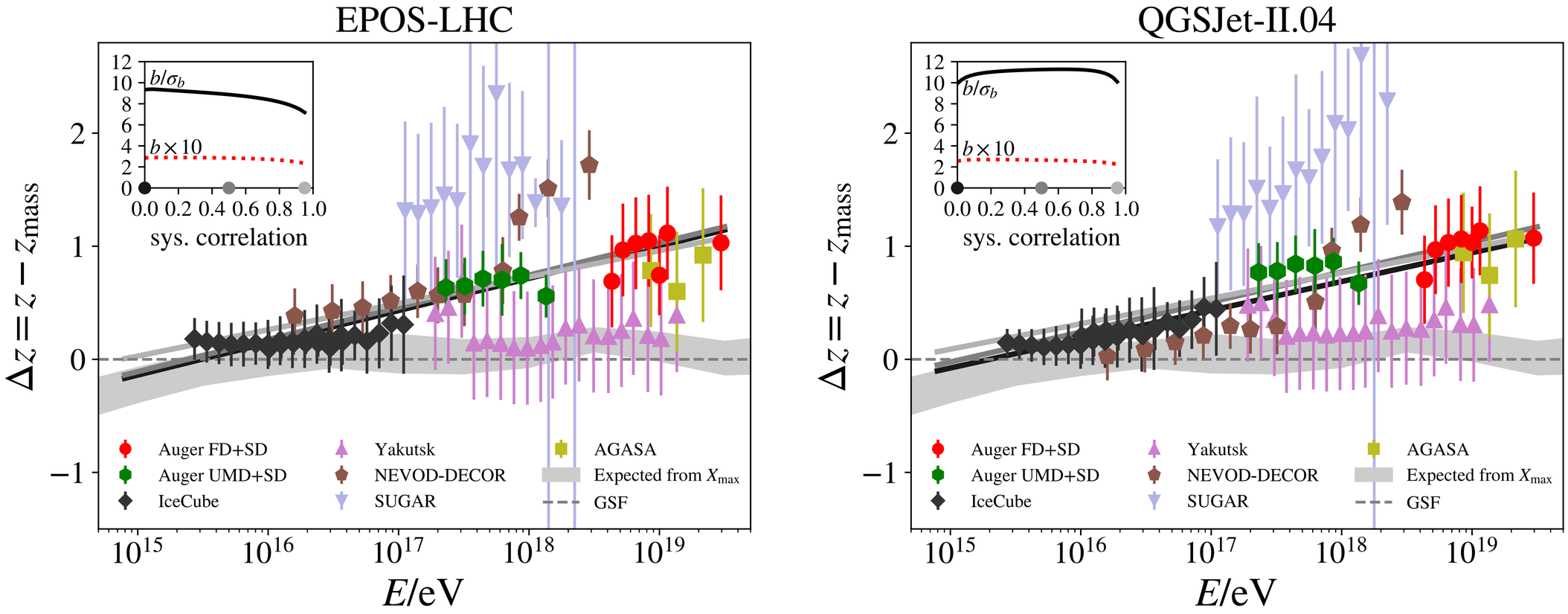




[F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser, T. Stanev, Phys. Rev. D 102 (2020)]

The Muon Puzzle in EAS

- Subtracting expected values z_{mass}, obtained from GSF flux model (consistent with X_{max} measurements)



- Slope of the excess is significant with more than 8σ!

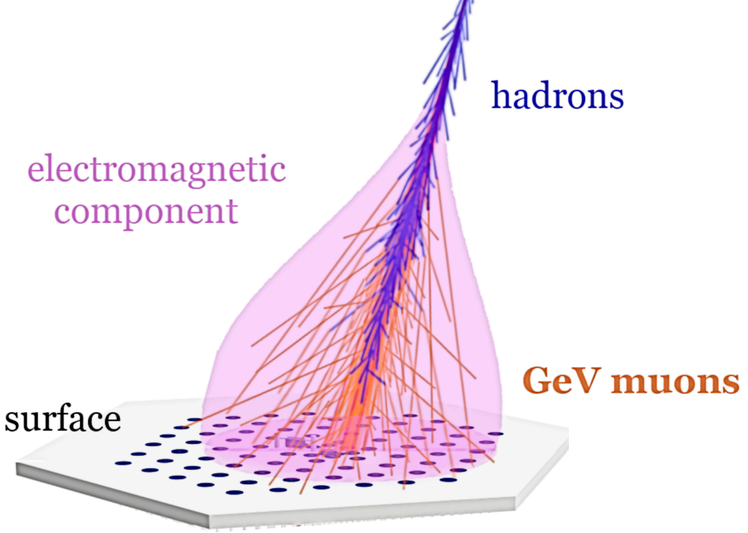
[D. Soldin et al., PoS ICRC2021 (2021) 349]

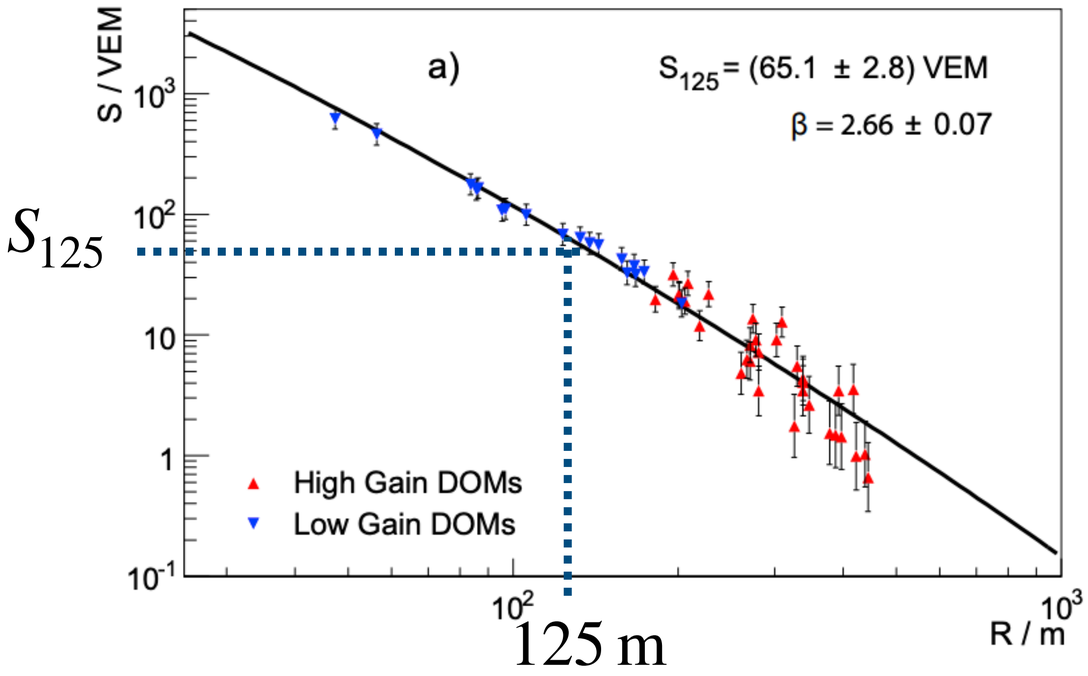
EAS Energy in IceTop

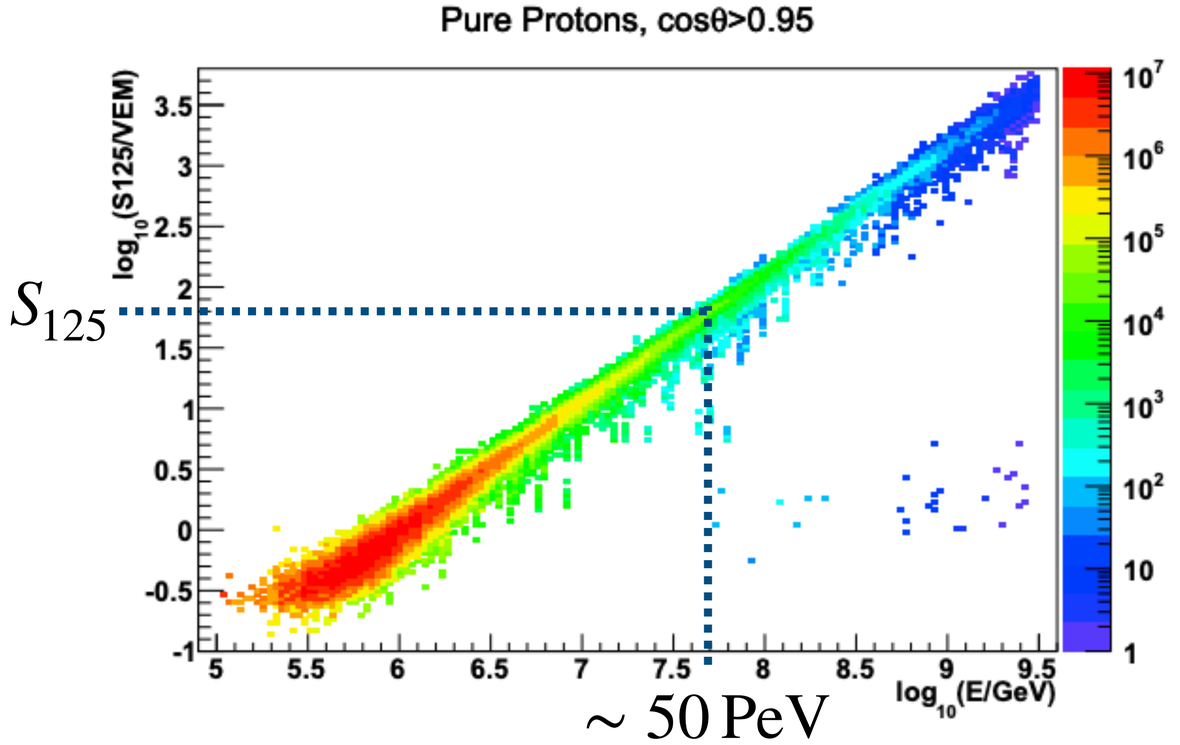
- EAS energy determined from surface signals
- Lateral Distribution Function (LDF)

$$S(r) = S_{125} \cdot \left(\frac{r}{125\,\mathrm{m}}\right)^{-\beta-\kappa\cdot\log_{10}(1/125\,\mathrm{m})}$$

- Shower size S_{125} (EAS energy), slope parameter β

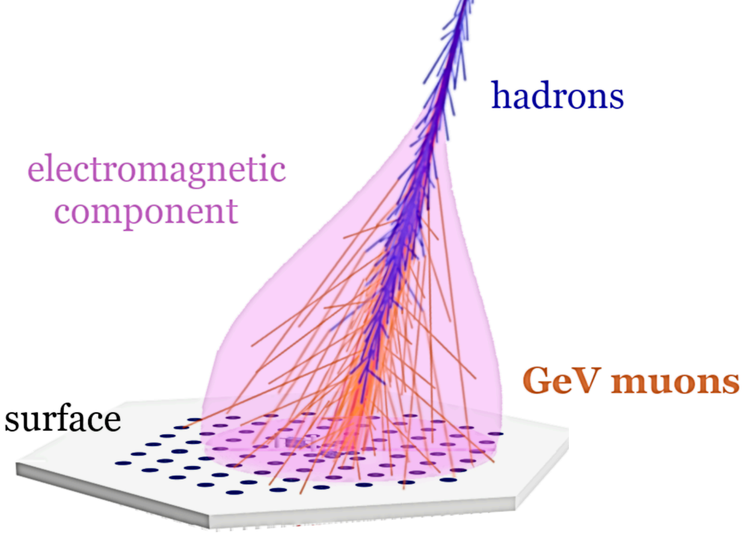


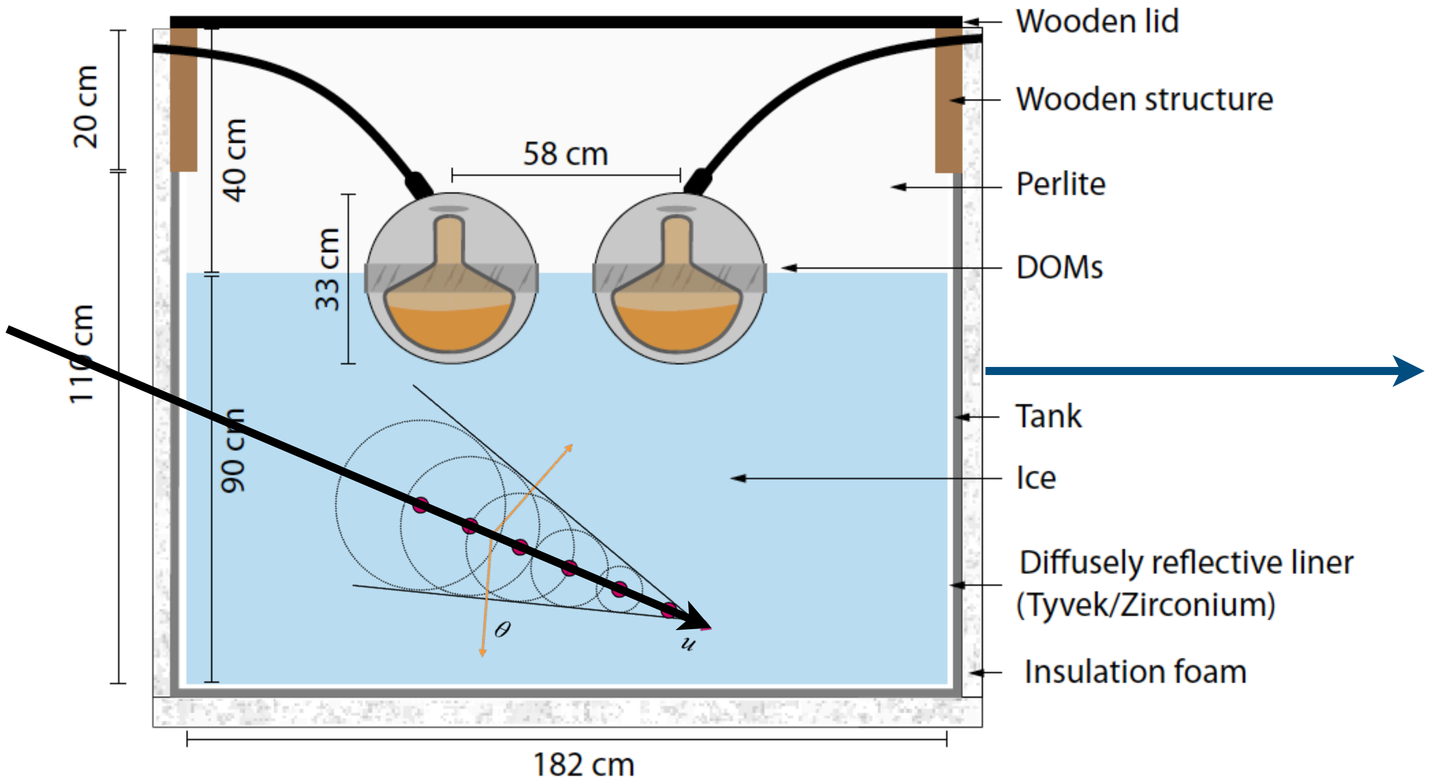


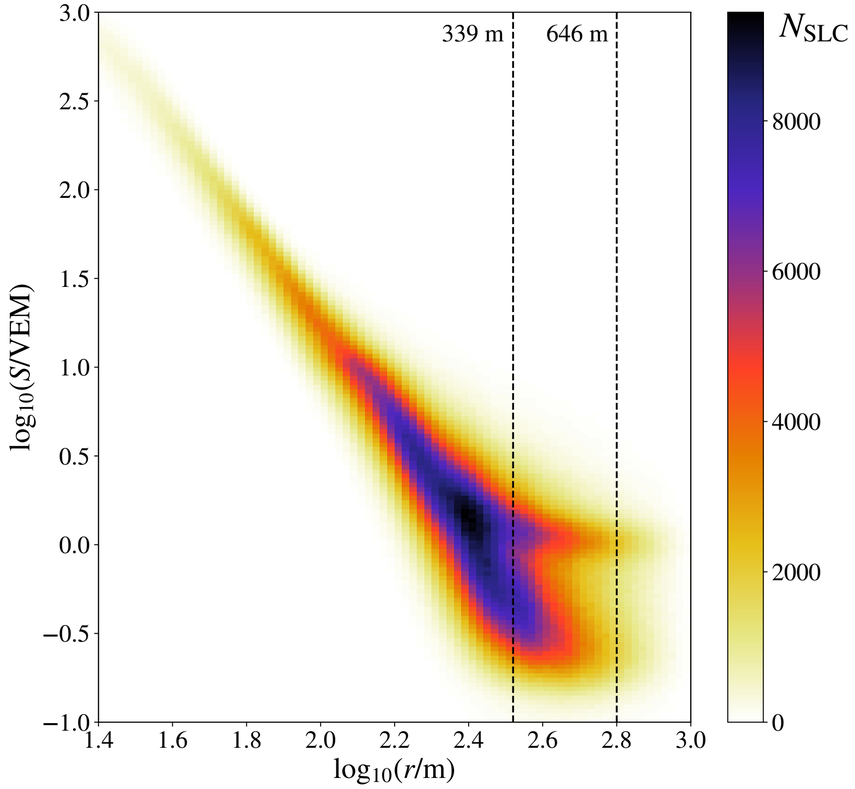


GeV Muons in IceTop

- Individual tank signals (vertical-equivalent-muon, VEM)
- Characteristic signal distributions for em part and muons
- Separation of GeV muons from other particles in EAS







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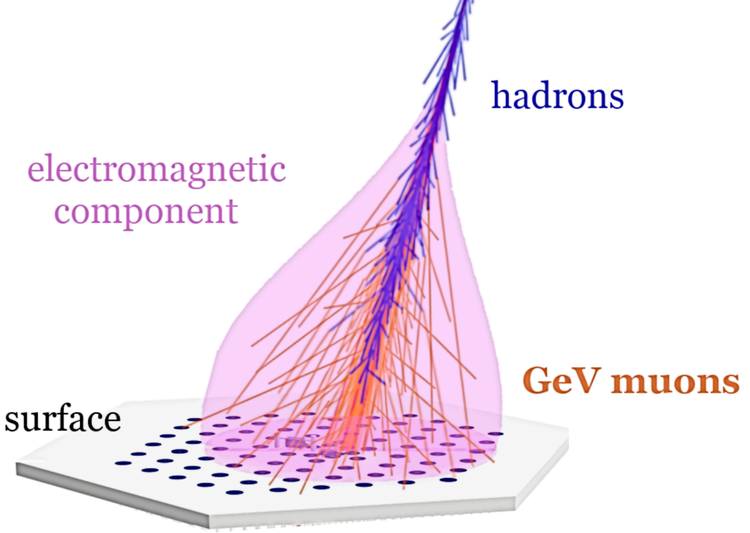

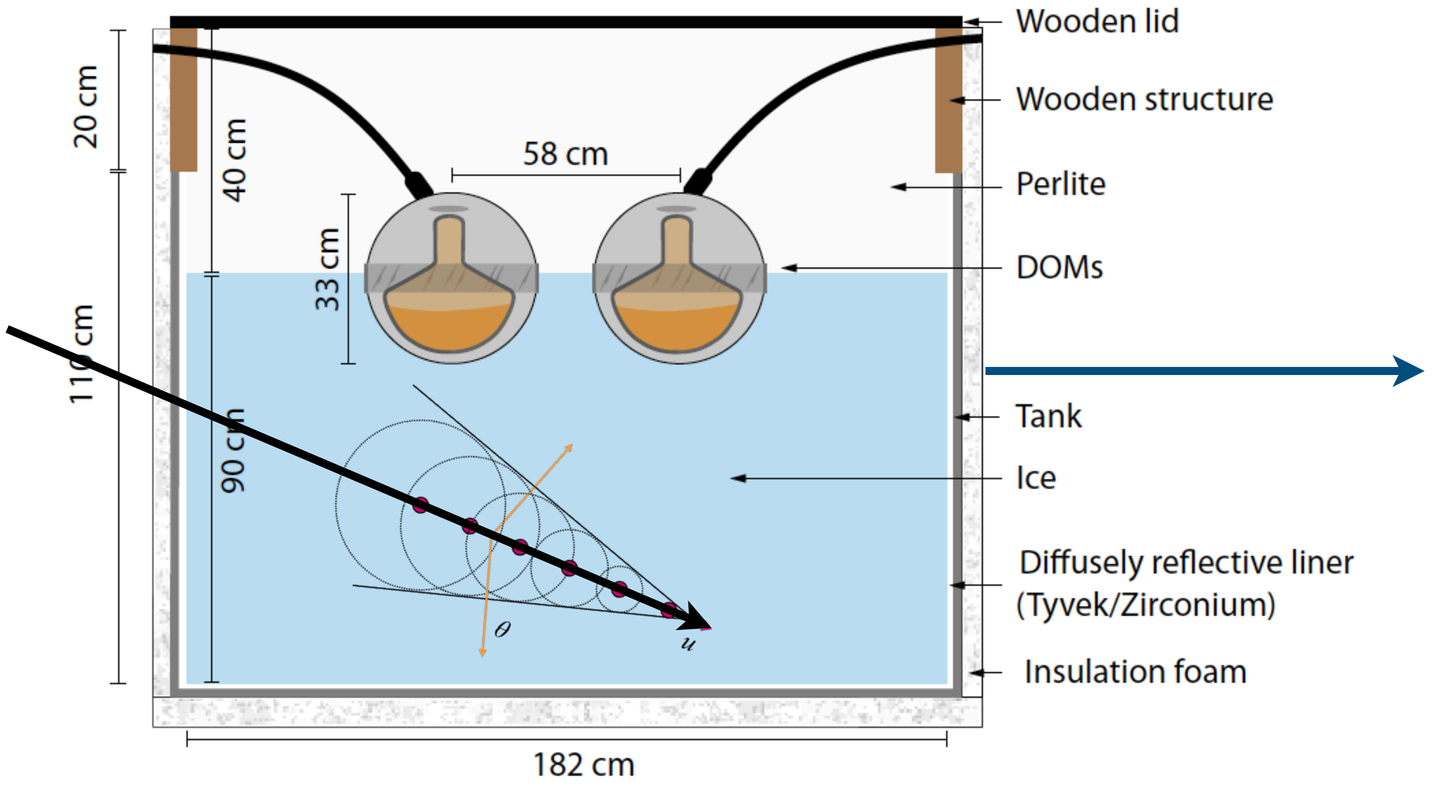

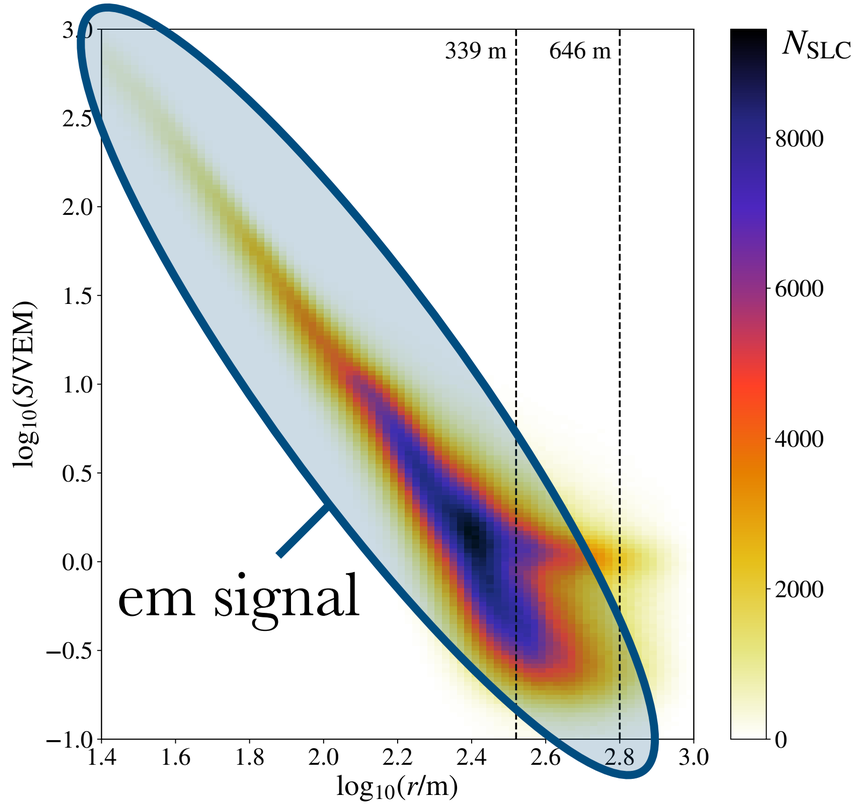

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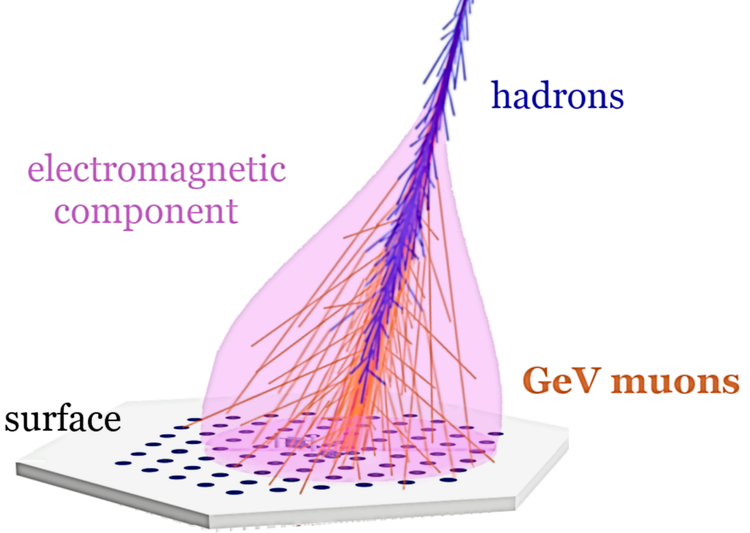
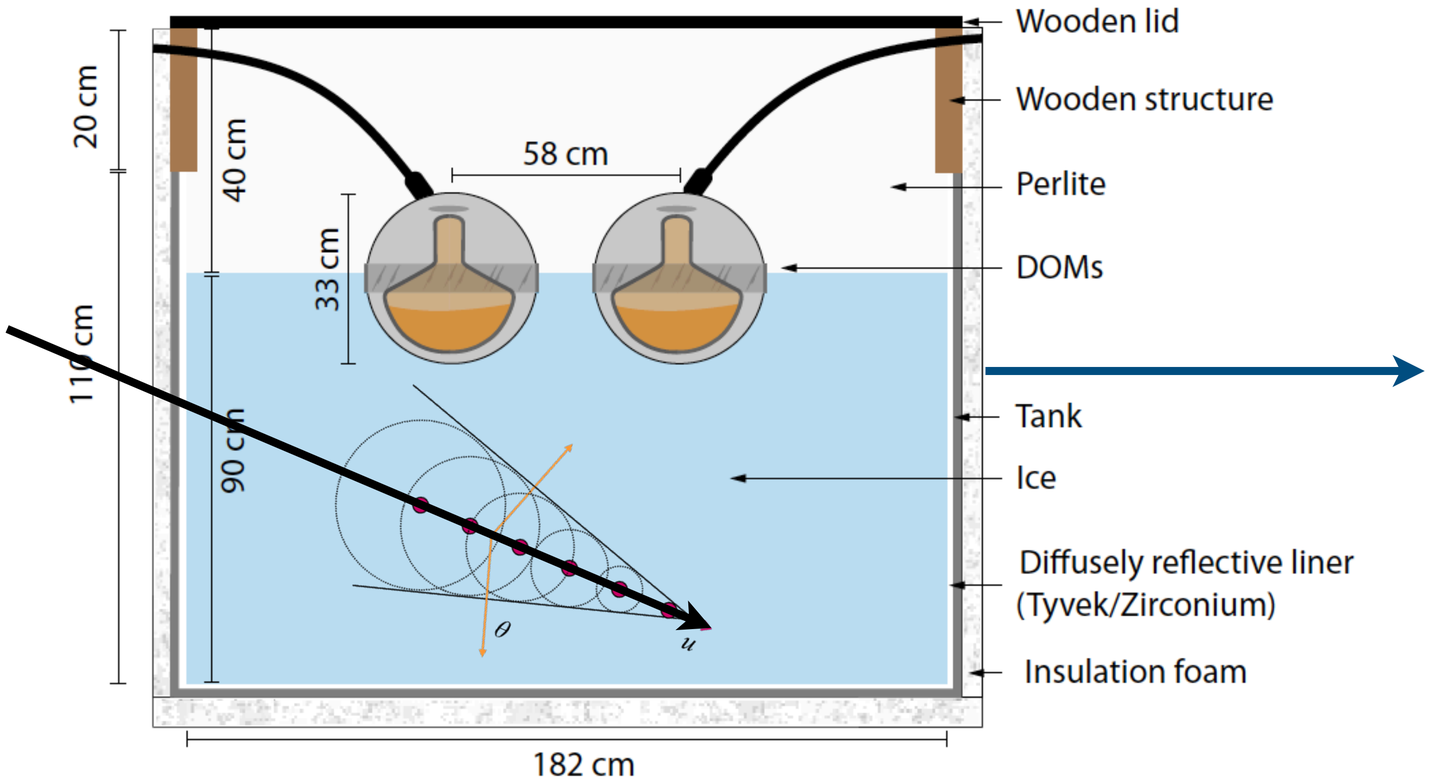
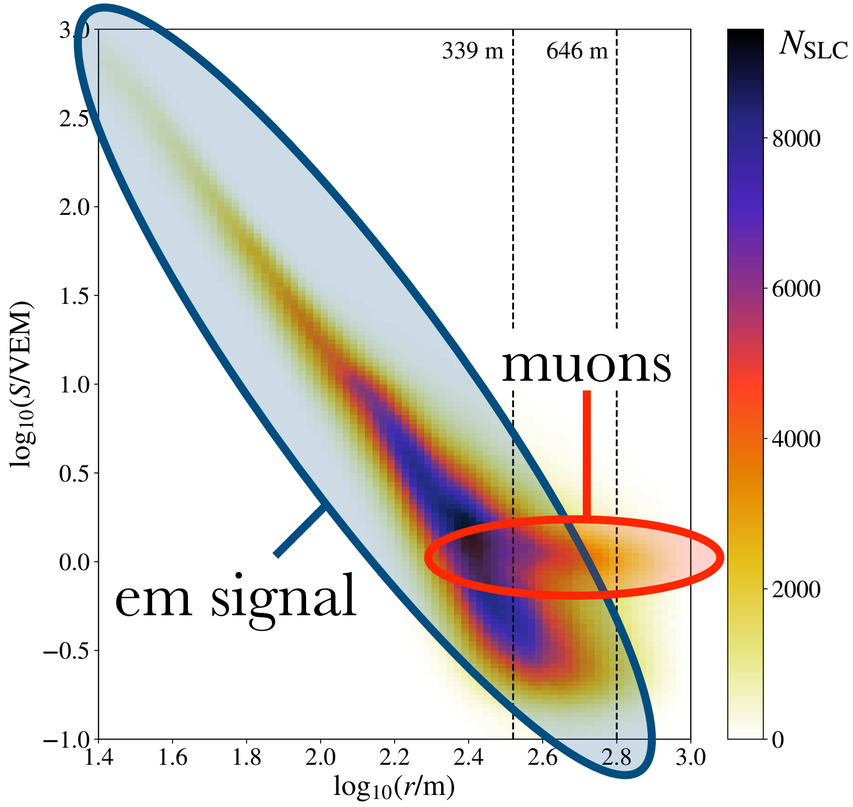


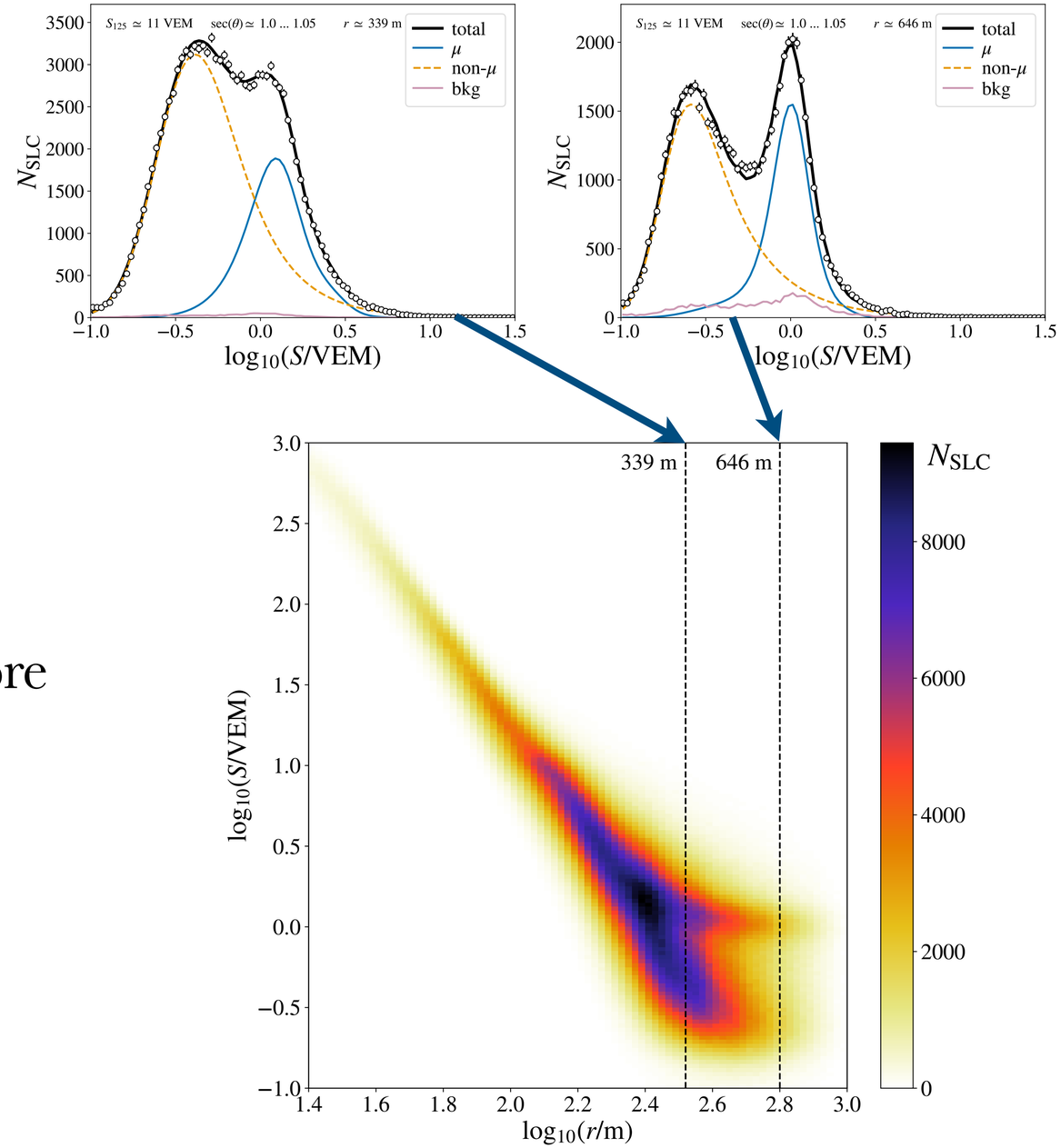




GeV Muons in IceTop

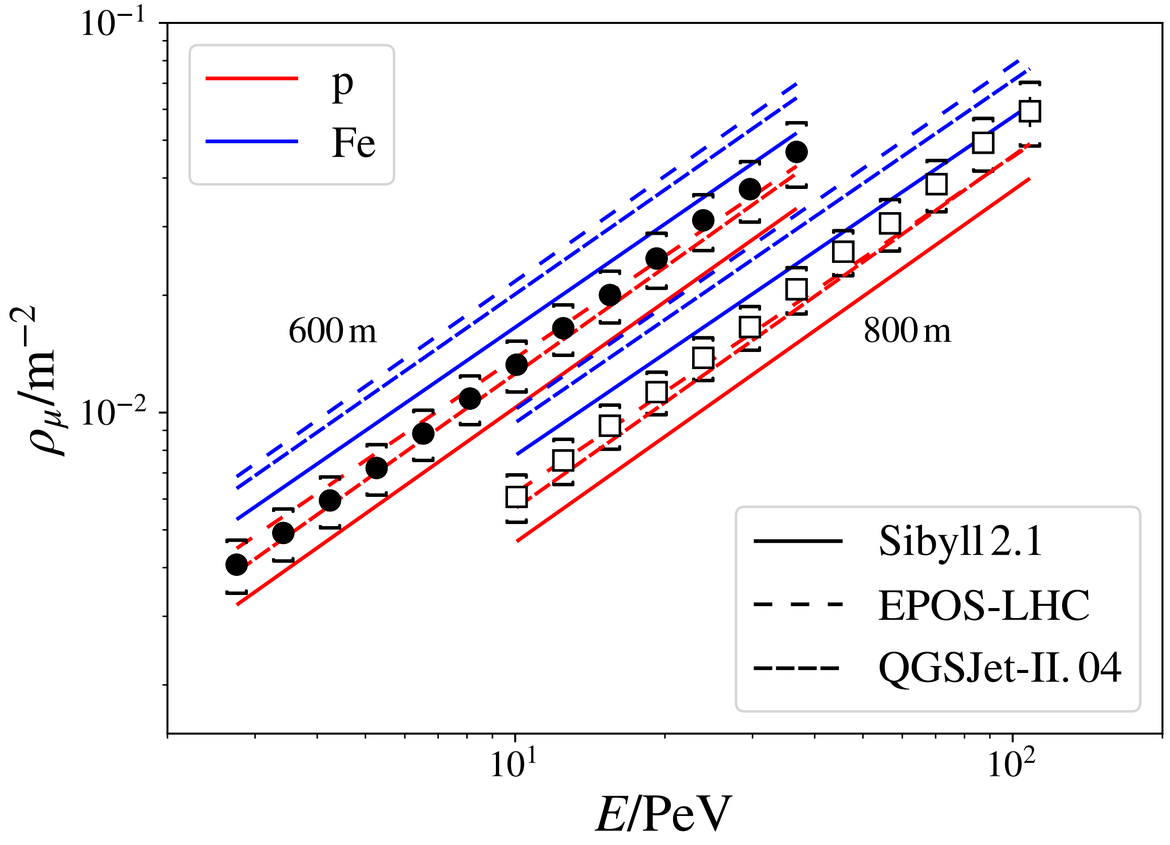
- Complex signal model, includes:
  - electromagnetic response model
  - muon response model
  - uncorrelated background
- Larger muon fraction at large distances from the shower central region
- Likelihood fits at 600 m and 800 m from the core in bins of the energy of inclined EAS ($\theta < 18°$)
- Muon density as a function of CR energy!
- Reminder: muons are messengers of the hadronic interactions in EAS!

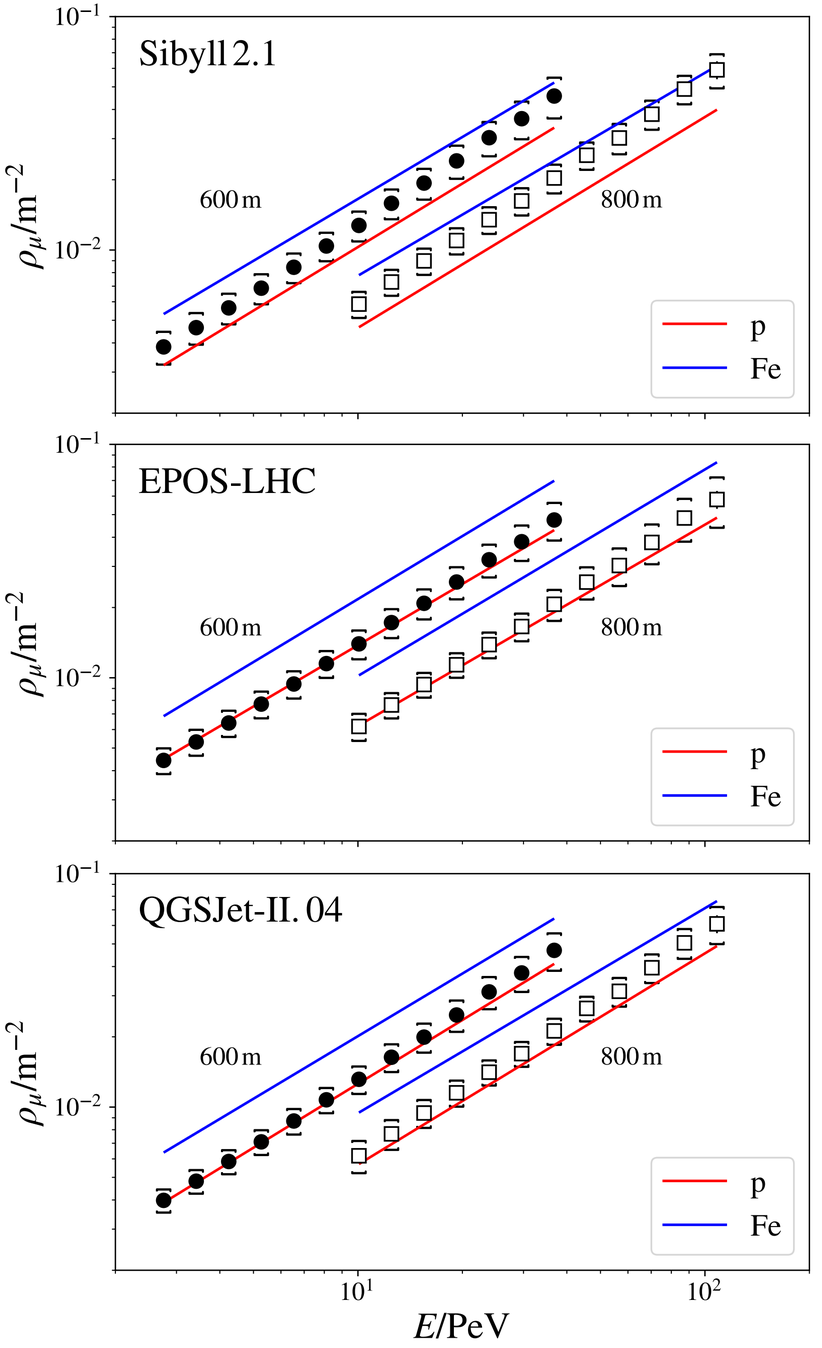
[IceCube Collaboration, Phys. Rev. D 106 (2022)]



GeV Muons in IceTop

- Muon densities compared to model predictions

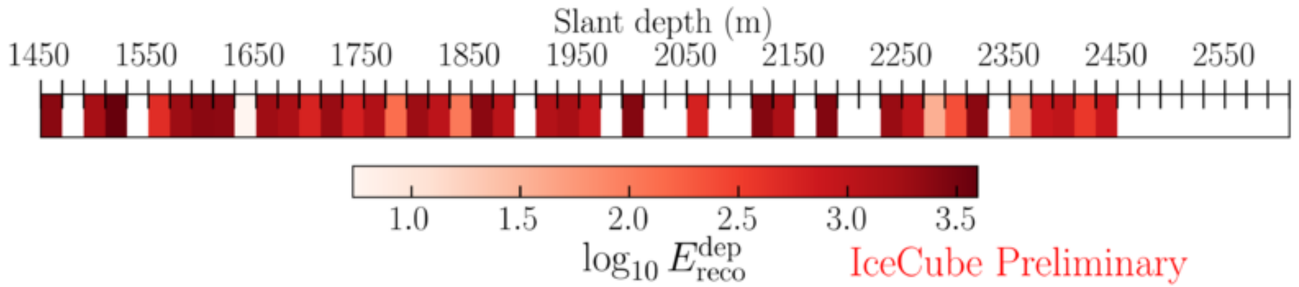


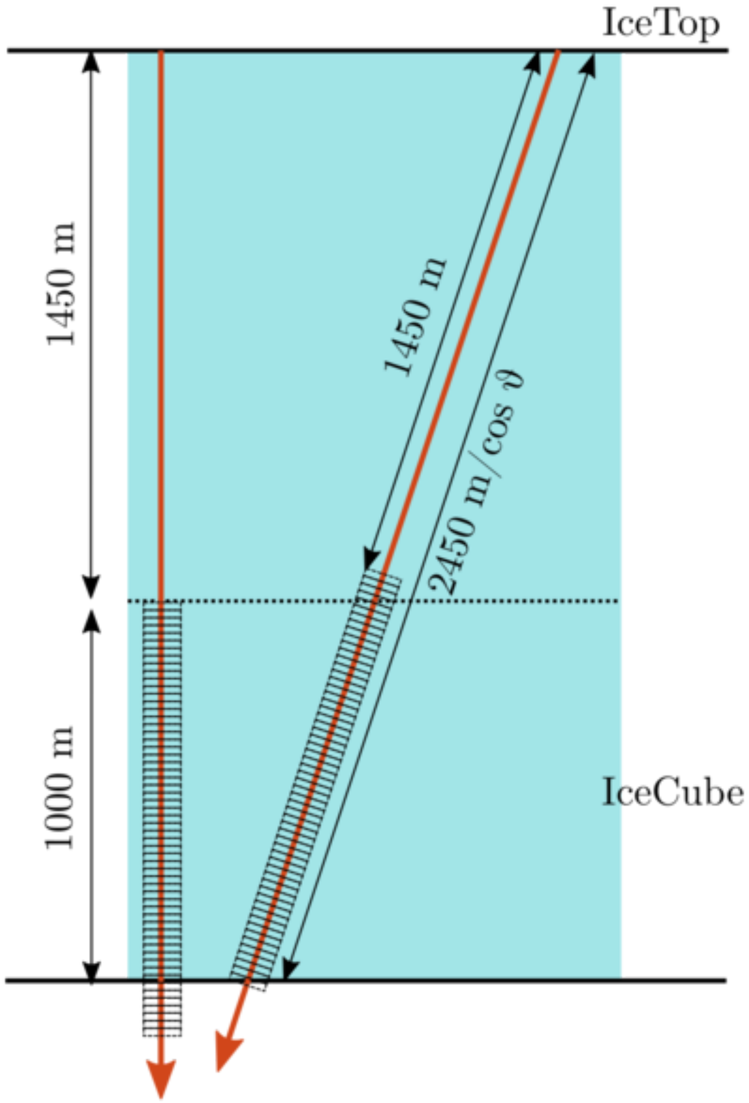


[IceCube Collaboration, Phys. Rev. D 106 (2022)]

TeV Muon Multiplicity

- Coincident machine learning analysis using IceTop and in-ice
- Neural network inputs:
  - IceTop: zenith angle, energy proxy S125 (laputop)
  - In-ice: energy loss profile vector (millipede)
- Neural network outputs:
  - Primary CR energy
  - Multiplicity of in-ice muons above 500 GeV

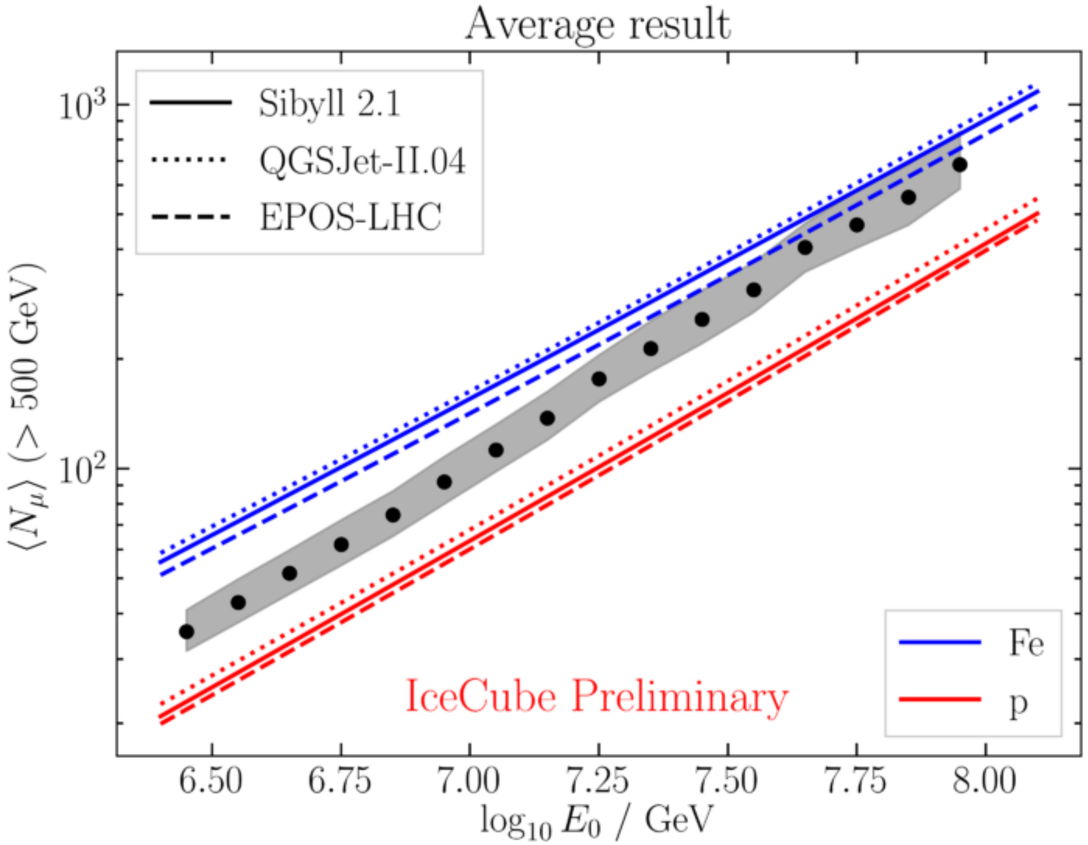


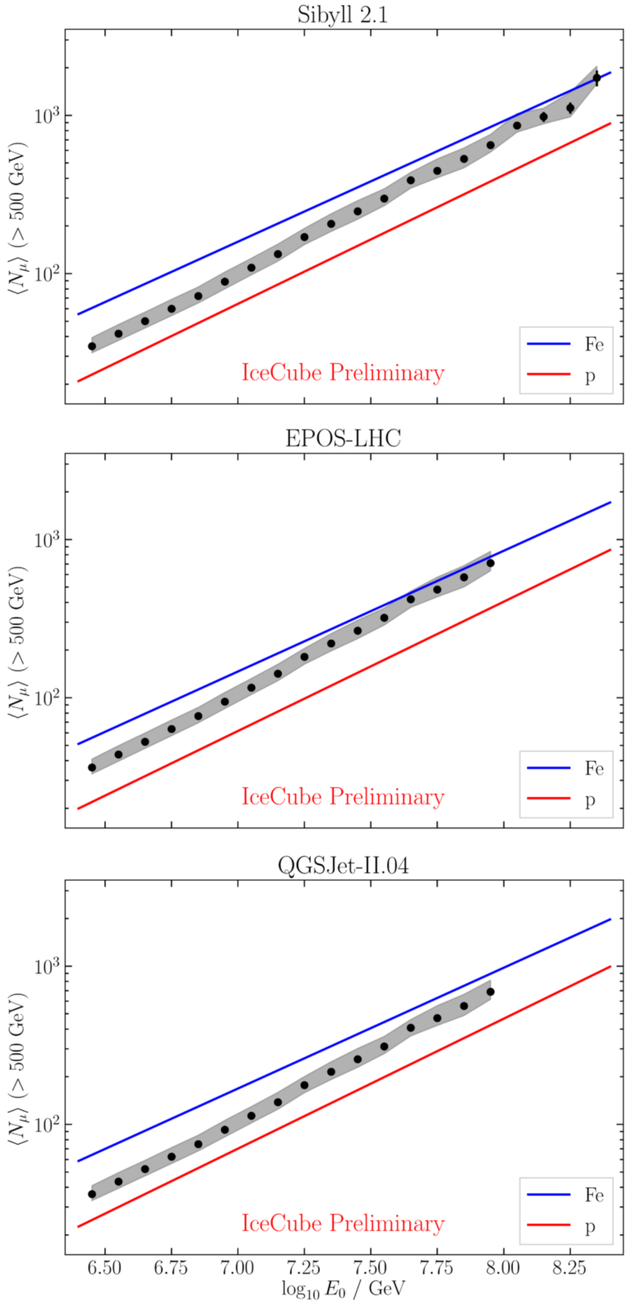


[S. Verpoest (IceCube Collaboration), ECRS2022 (proceedings in preparation)]

TeV Muons in IceCube

- Muon bundle multiplicity compared to model predictions





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