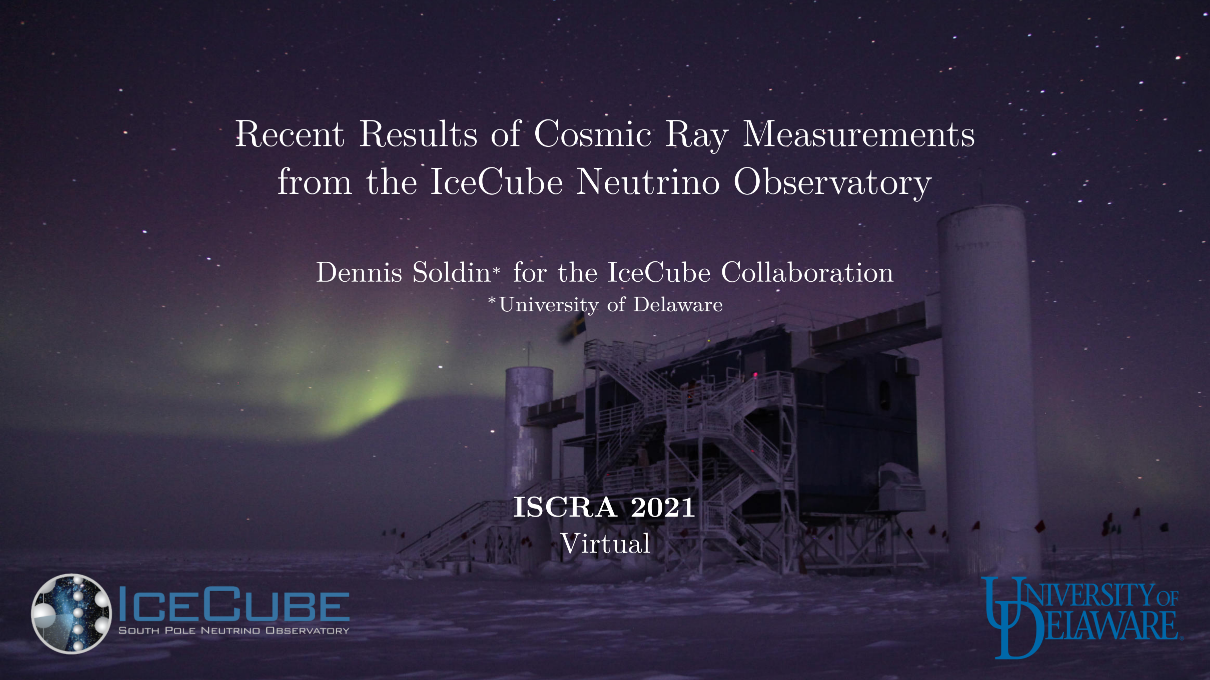
Recent Results of Cosmic Ray Measurements from the IceCube Neutrino Observatory

Dennis Soldin* for the IceCube Collaboration
*University of Delaware

ISCRA 2021
Virtual



IceCube
South Pole Neutrino Observatory

University of Delaware

Outline

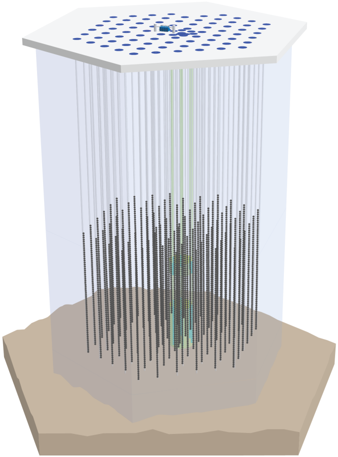
Introduction

Spectrum & Composition

Density of GeV Muons

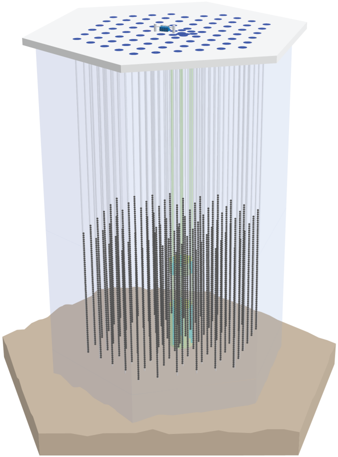
All-Sky Anisotropy

Summary & Outlook



The IceCube Neutrino Observatory

- **IceCube**
  - Located at geographic South Pole
  - $\sim 1\,\mathrm{km}^3$ instrumented volume
  - 86 strings with 5160 digital optical modules (DOMs)
  - Depths between 1450 m and 2450 m
  - Trigger rate of $\sim 2.15\,\mathrm{kHz}$, mainly atmospheric muons ($E_\mu \gtrsim 400\mathrm{GeV}$)
- **IceTop**
  - $\sim 1\,\mathrm{km}^2$ surface array
  - Atmospheric depth $\sim 690\,\mathrm{g/cm}^2$
  - 162 ice Cherenkov tanks in 81 stations
  - 2 DOMs per tank



$\rightarrow$ **CR air shower measurements!**

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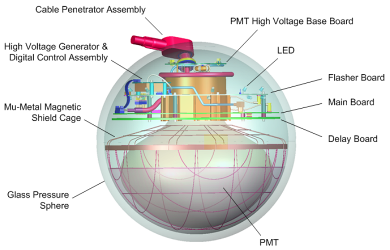

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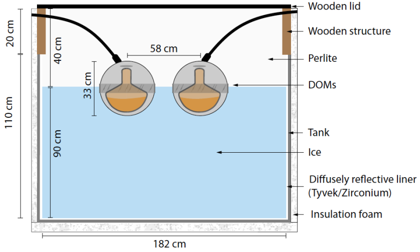


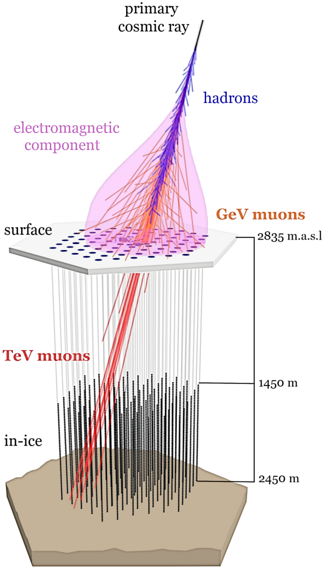
$\rightarrow$ **CR air shower measurements!**

Cosmic Ray Physics with IceCube and IceTop

- **IceTop**
  - Electromagnetic and muonic signal ($E_\mu \simeq 1\,\mathrm{GeV}$, "GeV muons")
  - Shower axis reconstruction
  - Cosmic ray energy estimator

- **IceCube**
  - Muon tracks/bundles in the ice ($E_\mu \gtrsim 400\,\mathrm{GeV}$, "TeV muons")
  - Track reconstruction
  - Deposited energy along the track dE/dX

$\rightarrow$ **3-dimensional cosmic ray detector!**

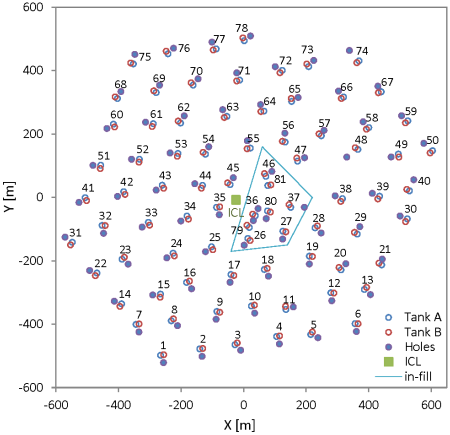


Cosmic Ray Spectrum

- IceTop data with ≥ 5 stations hit
- Lateral Distribution Function (LDF)

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

- Simultaneous fit of shower front curvature
- Energy proxy S_{125}: signal at $r = 125\,\mathrm{m}$ in Vertical Equivalent Muons (VEM)
- Snow depth taken into account
- Conversion function $S_{125} \rightarrow E(S_{125})$ based on CORSIKA MC (Sibyll 2.1,H4a)
- Quality cuts & efficiency correction



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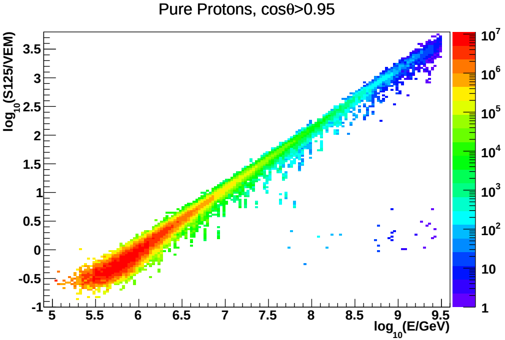
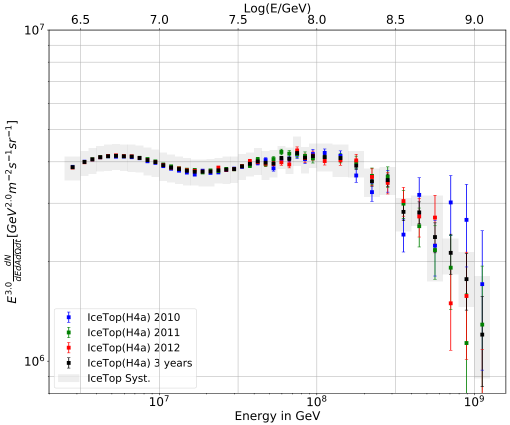


Cosmic Ray Spectrum

- Data from June 2010 to May 2013
- $\sim 5.1 \cdot 10^7$ selected events
- Detector systematics
  - Snow accumulation
  - Energy scale
- Agreement between years
- Agreement with previous results
  (e.g. IceCube, Phys. Rev. D 88 (2013))

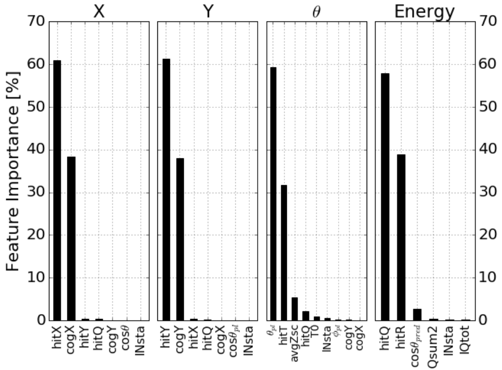


IceCube, Phys. Rev. D 100 (2019)

Cosmic Ray Spectrum

- Low energy extension
- Dedicated infill trigger: ≥ 2 stations hit
- LDF fit not feasible

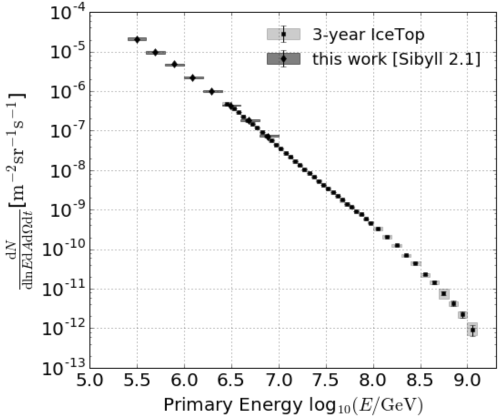
  $\rightarrow$ **Random Forest Regression**
- 3 steps
  - Core position
  - Direction
  - Energy
- Training/testing uses CORSIKA MC (Sibyll 2.1,H4a)
- Quality cuts & efficiency correction
- Iterative Bayesian unfolding



IceCube, Phys. Rev. D 102 (2020)

Cosmic Ray Spectrum

- Data from May 2016 to May 2017
- $\sim 7.4 \cdot 10^6$ selected events
- Detector systematics
  - Mass composition
  - Unfolding
  - Efficiency correction
  - Pressure correction
- Agreement in overlap region



IceCube, Phys. Rev. D 102 (2020)

Cosmic Ray Mass Composition

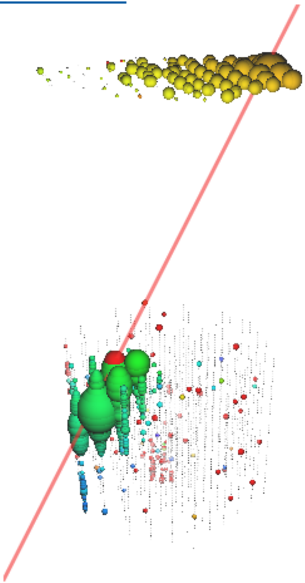
- IceTop & IceCube data
- Events with ≥ 5 hit stations, ≥ 8 in-ice hits
- Mean muon number

$$\mathrm{N}_{\mu}(E, A) \propto A \cdot (E/A)^{\beta} \quad , \; \beta \simeq 0.9$$

- Energy E from IceTop
- Muon number proxy from IceCube

  $\rightarrow$ **Mass number A**

- Similar concepts apply for PeV gamma ray searches (IceCube, Astrophys. J. 891 (2020))



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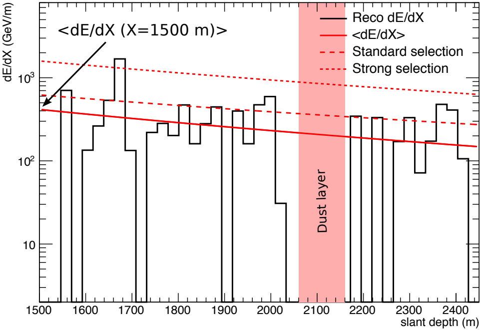
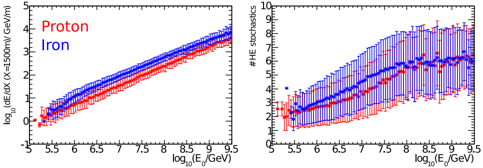
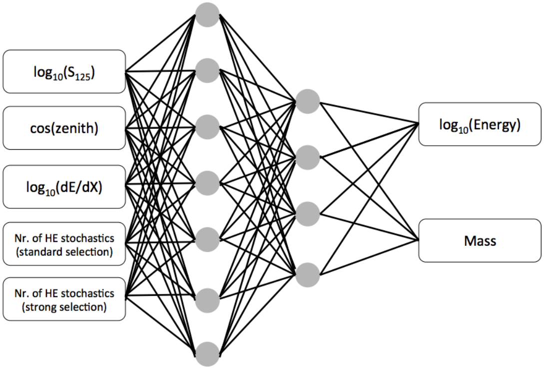
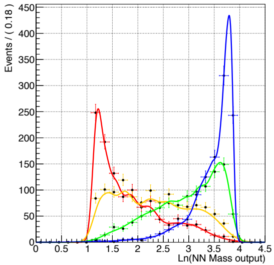


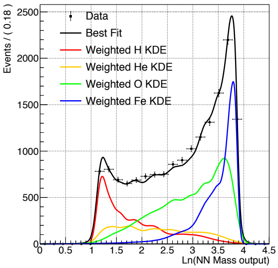


Cosmic Ray Mass Composition

- **Artificial Neural Network**
- Template PDFs are obtained from CORSIKA MC for 4 mass groups (H, He, O, Fe)
- Template fits to data distributions for each energy bin

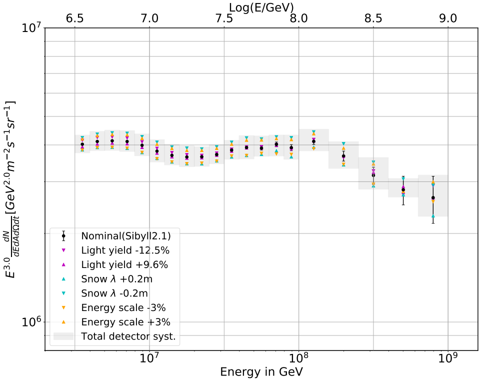






Cosmic Ray Mass Composition

- Data from June 2010 to May 2013
- $\sim 7.3 \cdot 10^6$ selected events
- Detector systematics
  - Snow accumulation
  - Energy scale
  - In-ice light yield
- Agreement with IceTop-alone spectrum and with previous results
- Mass spectrum highly dominated by in-ice light yield uncertainties



IceCube, Phys. Rev. D 100 (2019)

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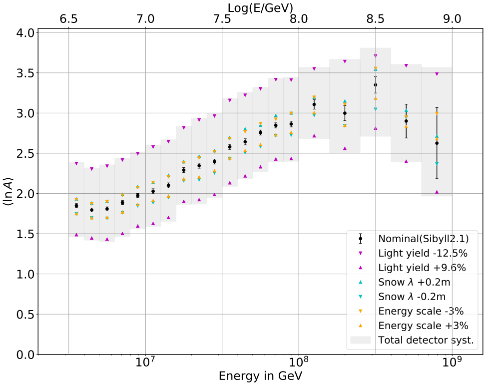
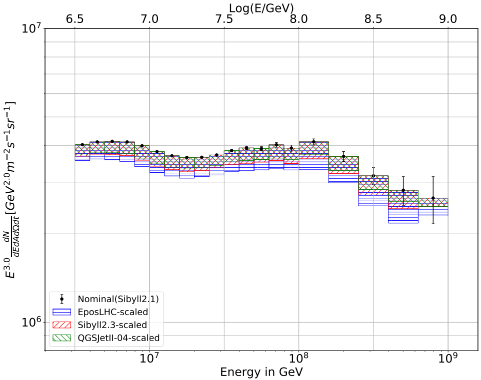


IceCube, Phys. Rev. D 100 (2019)

Cosmic Ray Mass Composition

- **Hadronic interaction models**
  - Sibyll 2.3
  - QGSJet-II-04
  - EPOS-LHC
- Limited statistics (10%) and H/Fe only
- Repetition of full analysis with these MC simulations not possible
- Instead, uncertainty estimates are derived based on the differences observed in S_{125} and dE/dX



→ Interpretation of results in the context of hadronic models not possible

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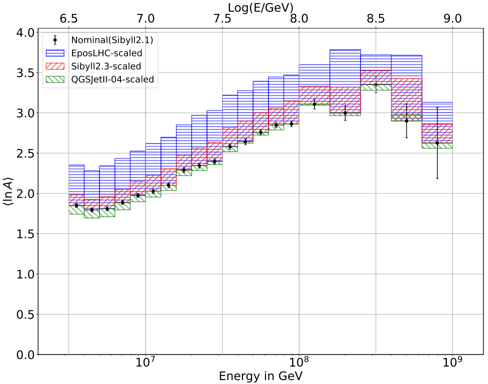

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IceCube, Phys. Rev. D 100 (2019)

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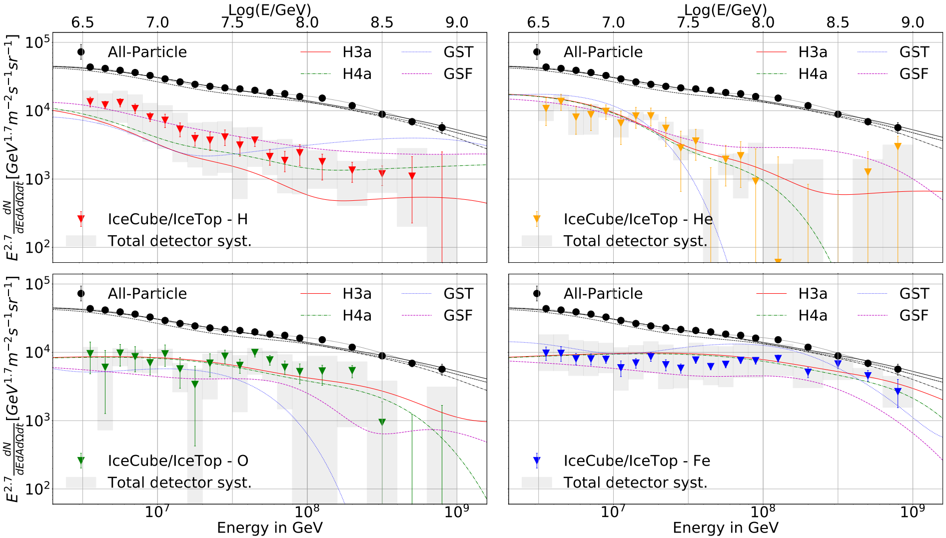

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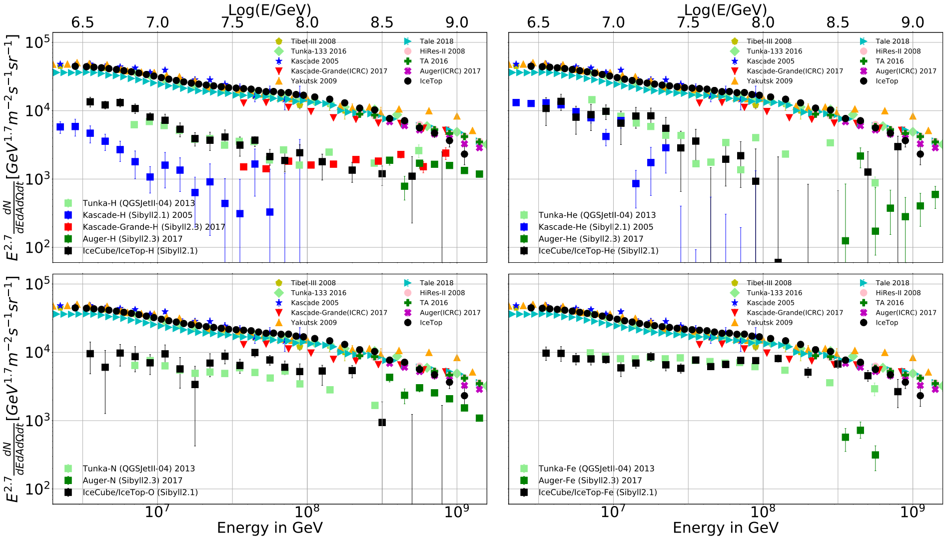
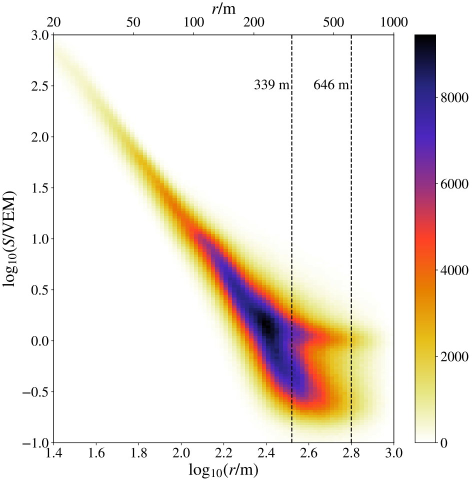


Density of GeV Muons in IceTop

- IceTop data only, including single hit tanks
- At large distances structure around 1 VEM
- Caused by single muons (*"muon thumb"*)
- Signal model
  - Electromagnetic component
  - Muon component
  - Uncorrelated background noise
- Fits for several energy bins and radial distances



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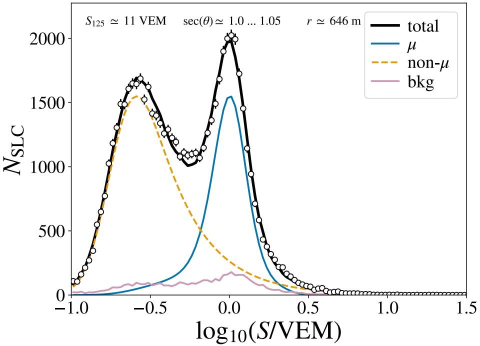
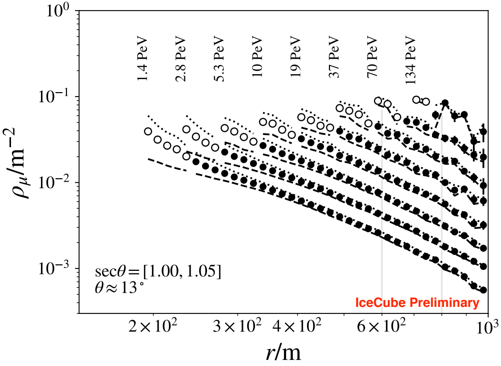


Density of GeV Muons in IceTop

- Data from May 2010 to May 2013
- $\sim 1.8 \cdot 10^7$ selected events
- Muon density ρ_μ is given by the muon number per tank area
- Systematic uncertainties
  - Snow accumulation
  - Energy scale
  - Electromagnetic model
  - Correction factor
- **z-parameter**

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

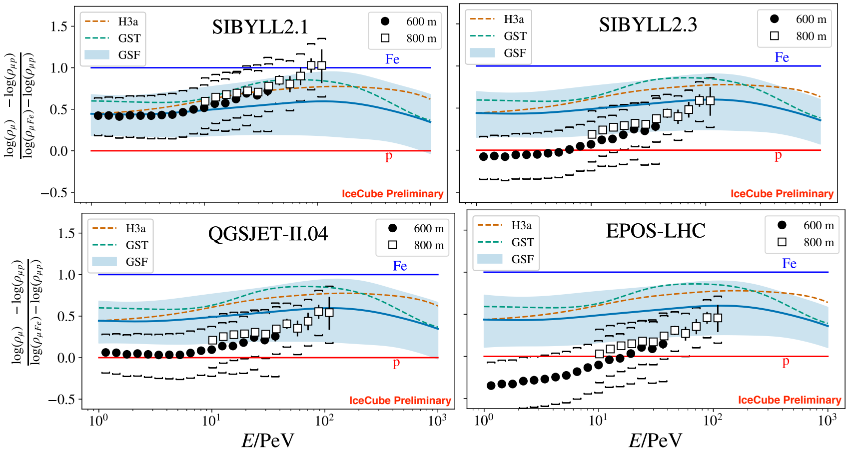
- Studies of hadronic interaction models



Paper in preparation

See also J. Gonzalez, EPJ Web Conf. 208 (2019)

Density of GeV Muons in IceTop

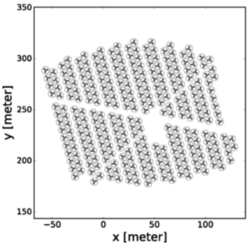


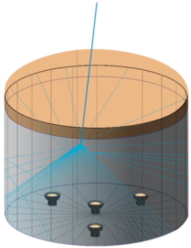
- Cross-calibration of experimental data can change the interpretation in the context of hadronic models

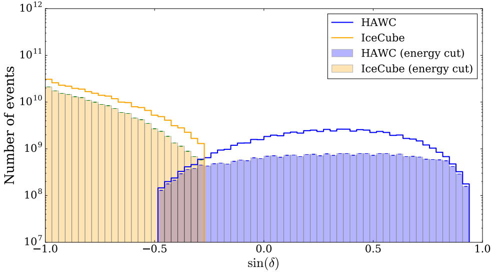
IceCube/HAWC All-Sky Anisotropy

- **IceCube**
  - Dedicated cosmic ray event selection* of in-ice data
  - Angular resolution: $\sim 3°$
  - Median energy: $\sim 10\,\text{TeV}$
- **HAWC Observatory**
  - Located at Sierra Negra, Mexico
  - $\sim$ 4100m a.s.l.
  - 300 water Cherenkov tanks
  - 4 PMTs per tank
  - Dedicated cosmic ray event selection*
  - Angular resolution: $\sim 0.4°$
  - Median energy: $\sim 10\,\text{TeV}$

*For details see
IceCube & HAWC, Astrophys. J. 871 (2019)



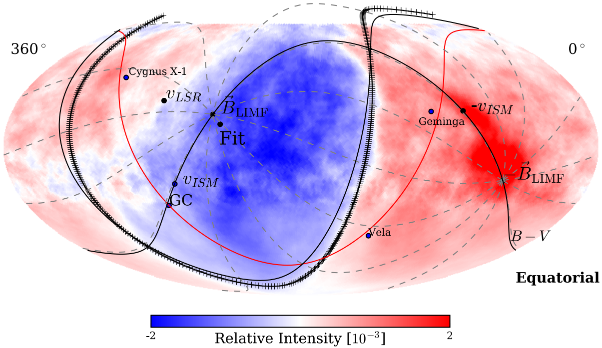




IceCube/HAWC All-Sky Anisotropy

- IceCube data from May 2011 to May 2016 ($\sim 2.8 \cdot 10^{11}$ events)
- HAWC data from May 2015 to May 2017 ($\sim 2.8 \cdot 10^{10}$ events)
- **Relative intensity map at 10 TeV**

IceCube & HAWC, Astrophys. J. 871 (2019)

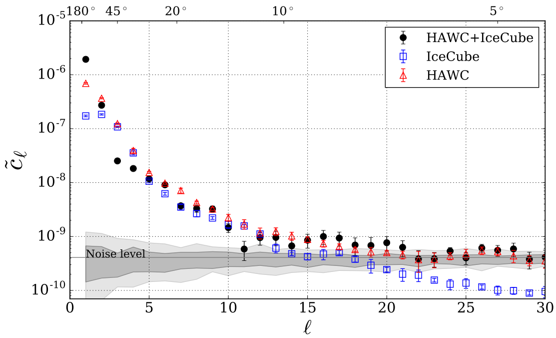


IceCube/HAWC All-Sky Anisotropy

- Decomposition in spherical harmonics ℓ

  → **Angular power spectrum**

- Individual measurements show differences due to partial sky coverage
- All-sky measurement removes these biases of the power spectrum
- Noise level dominated by limited statistics for HAWC

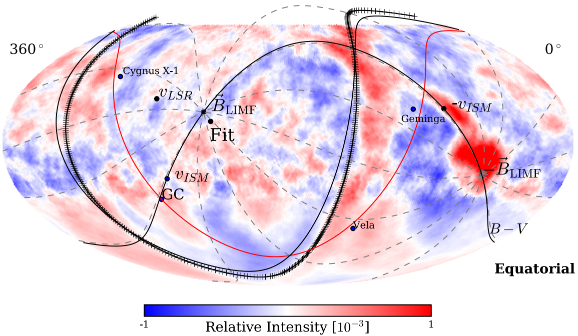


IceCube & HAWC, Astrophys. J. 871 (2019), 96.

IceCube/HAWC All-Sky Anisotropy

- Subtraction of the fitted multipole components with $\ell \leq 3$
- Small-scale structures correspond to large gradients, aligned with features in the local interstellar magnetic field (LIMF) and heliosphere
- Inferred direction of LIMF (compatible with independent observations)
- Estimate of North-South dipole component

IceCube & HAWC, Astrophys. J. 871 (2019)



IceCube/HAWC All-Sky Anisotropy

- Dipole amplitude

  $$A = (1.17 \pm 0.01) \cdot 10^{-3}$$

- Dipole phase

  $$\alpha = (38.4 \pm 0.3)^\circ$$

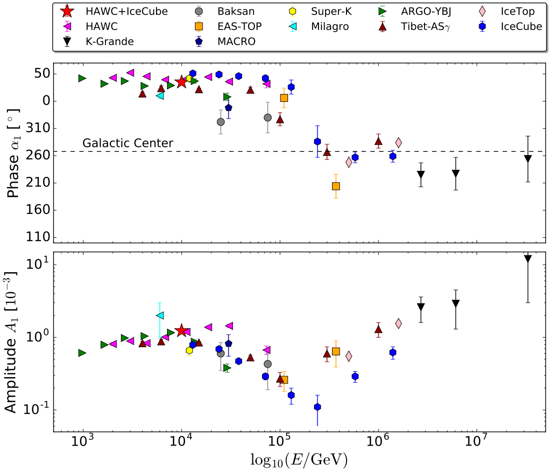
- Systematic uncertainties

  $$\Delta A \simeq 0.006 \cdot 10^{-3}$$
  $$\Delta\alpha \simeq 2.6^\circ$$

- Also previous measurements from IceCube and IceTop

  IceCube, Astrophys. J. 826 (2016)

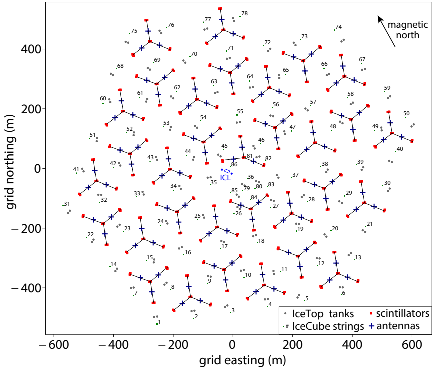
  IceCube, Astrophys. J. 765 (2013)



IceCube & HAWC, Astrophys. J. 871 (2019)

Summary & Outlook

- **IceCube and IceTop are perfect facilities for cosmic ray measurements**
  - Energy spectrum and mass composition
  - Anisotropy studies
  - Muons and air shower physics
  - ...
- Dedicated calibration devices will reduce in-ice uncertainties
- Scintillator array
- Radio array
- Cherenkov telescopes
- Improved analysis methods
- ...



see also F. Schröder, PoS(ICRC2019)418 (2020)

THE ICECUBE COLLABORATION

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University of Copenhagen

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Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
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The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

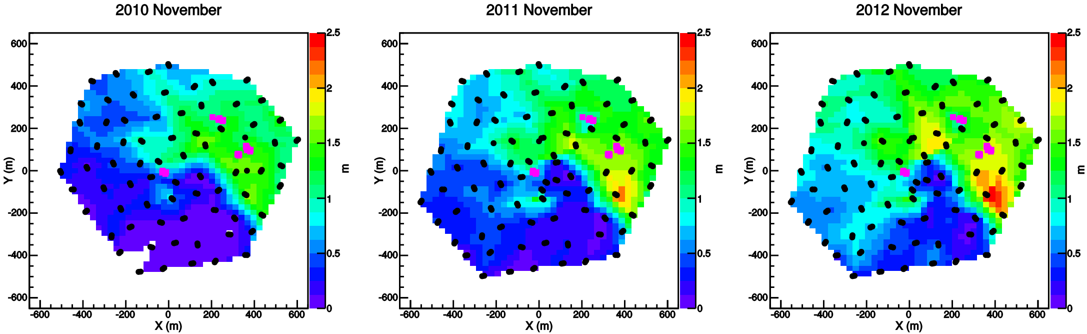
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu


Thank you!

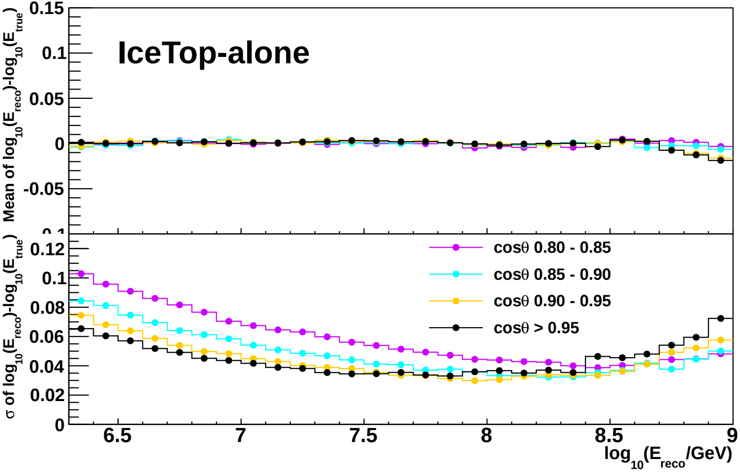
Backup

Cosmic Ray Spectrum

Snow depths



Cosmic Ray Spectrum



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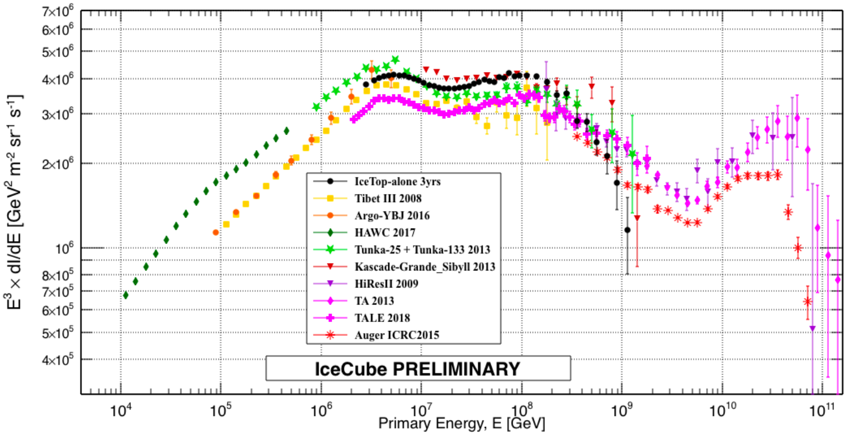

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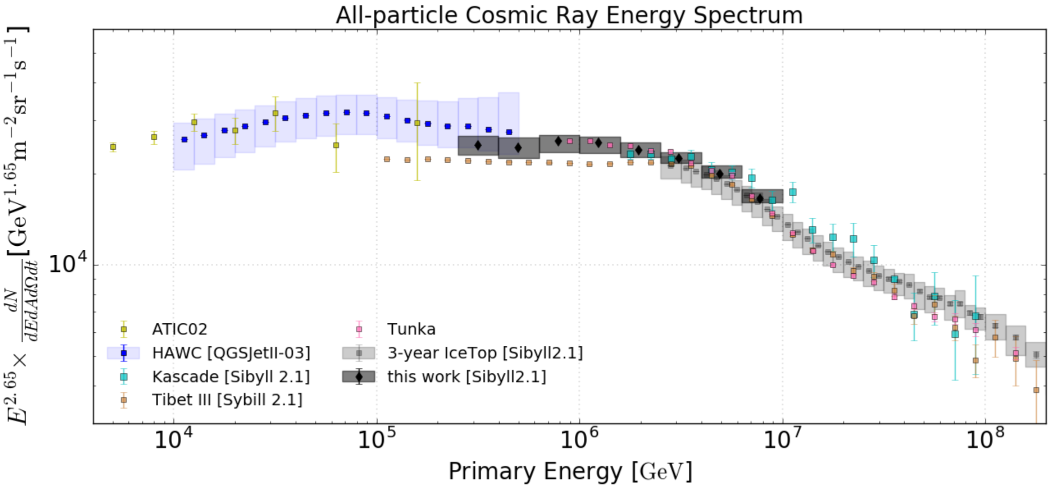

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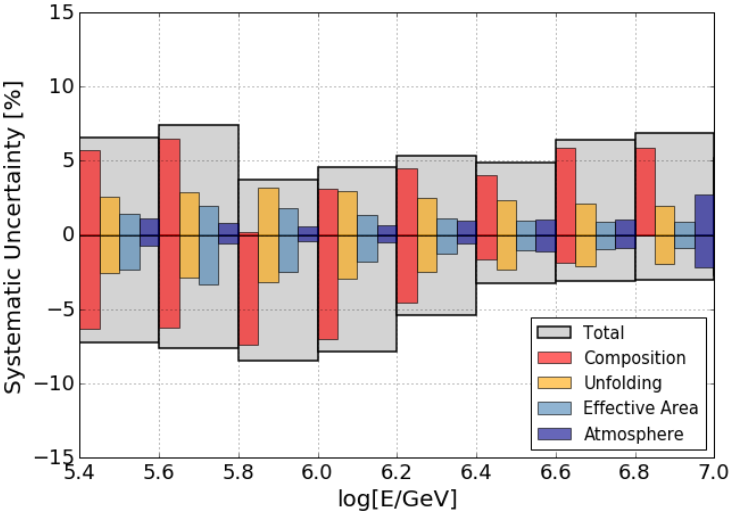
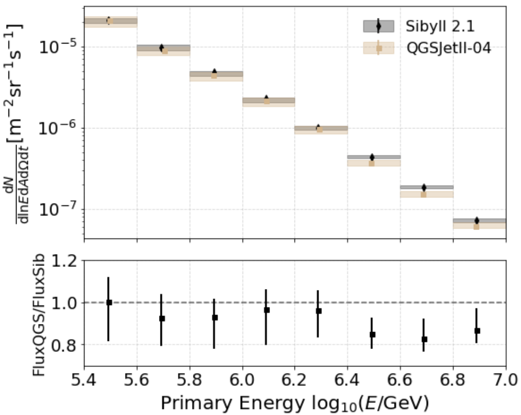
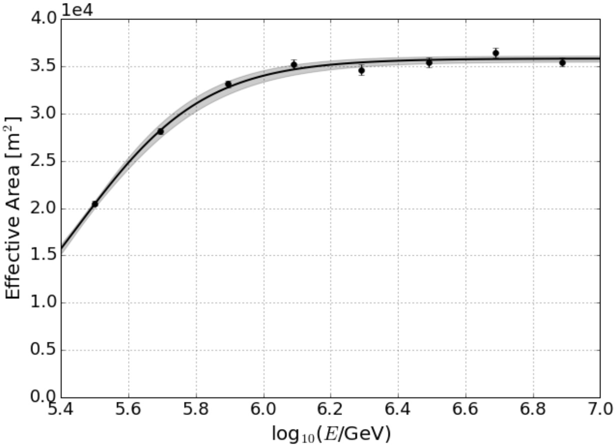
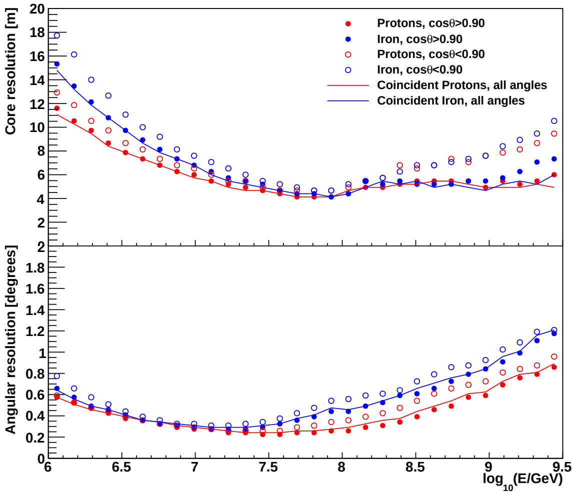


Cosmic Ray Spectrum

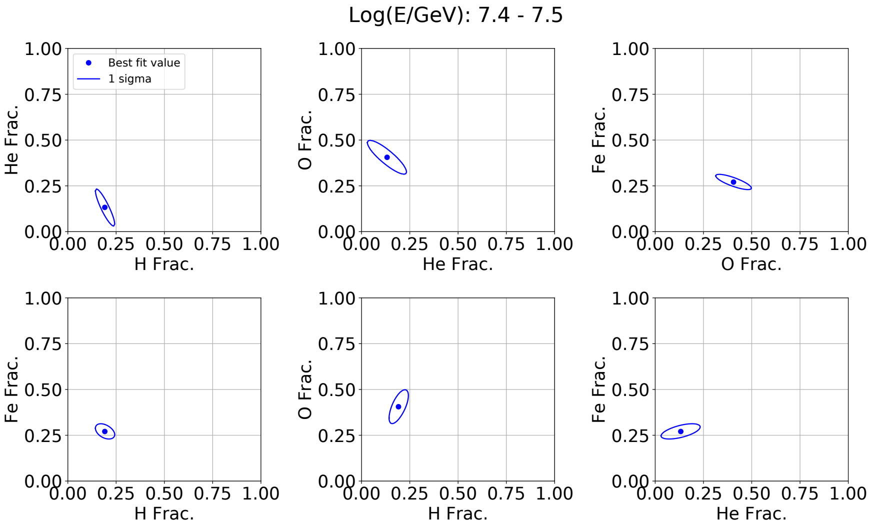




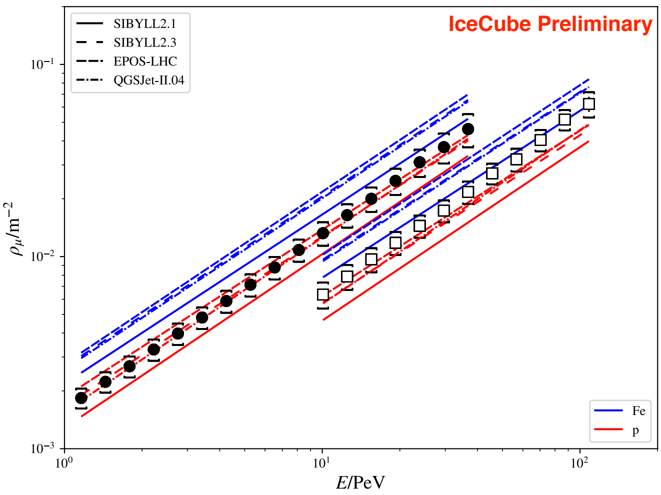
Cosmic Ray Mass Composition



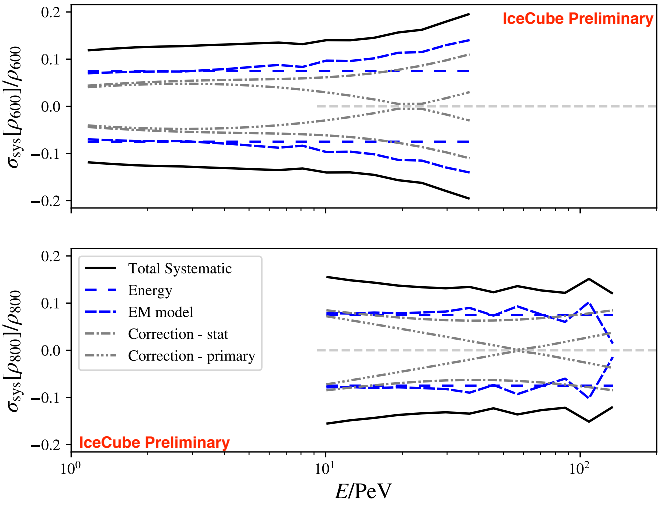
Cosmic Ray Mass Composition



Density of GeV Muons in IceTop

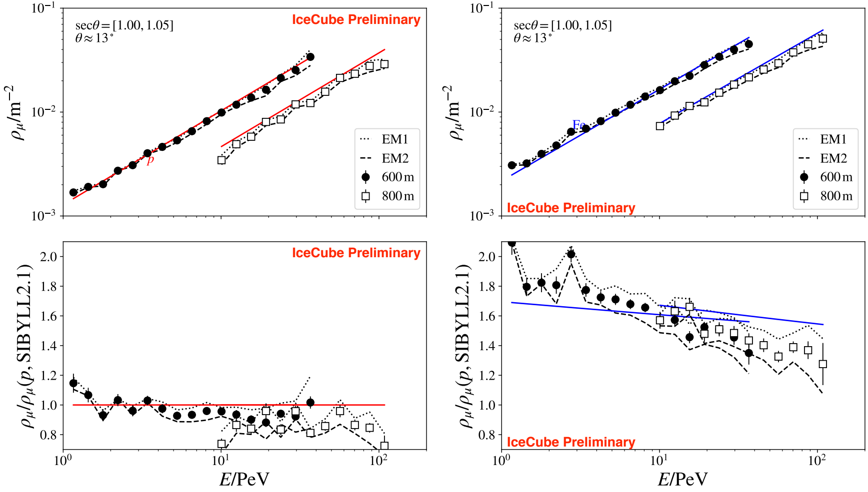


Density of GeV Muons in IceTop



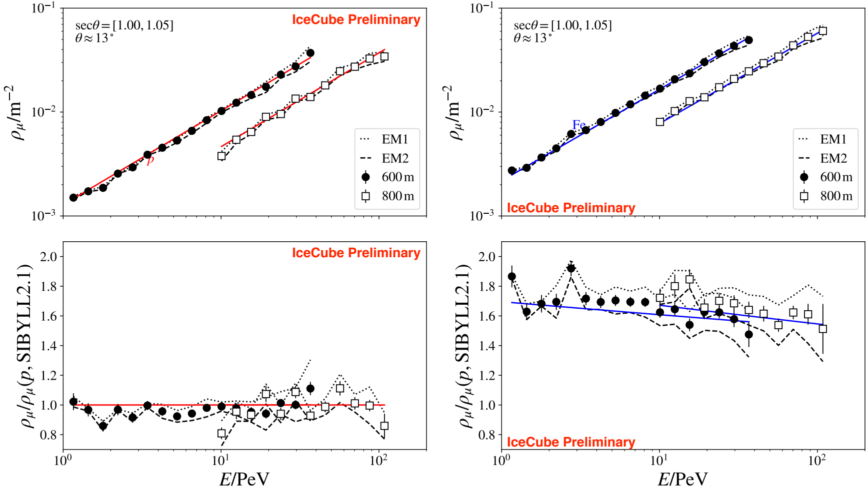
Density of GeV Muons in IceTop

MC self-consistency check (proton/iron)



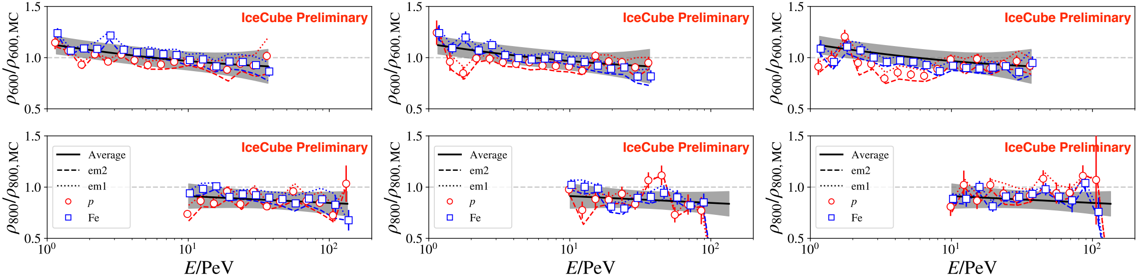
Density of GeV Muons in IceTop

Correction factor (proton/iron)

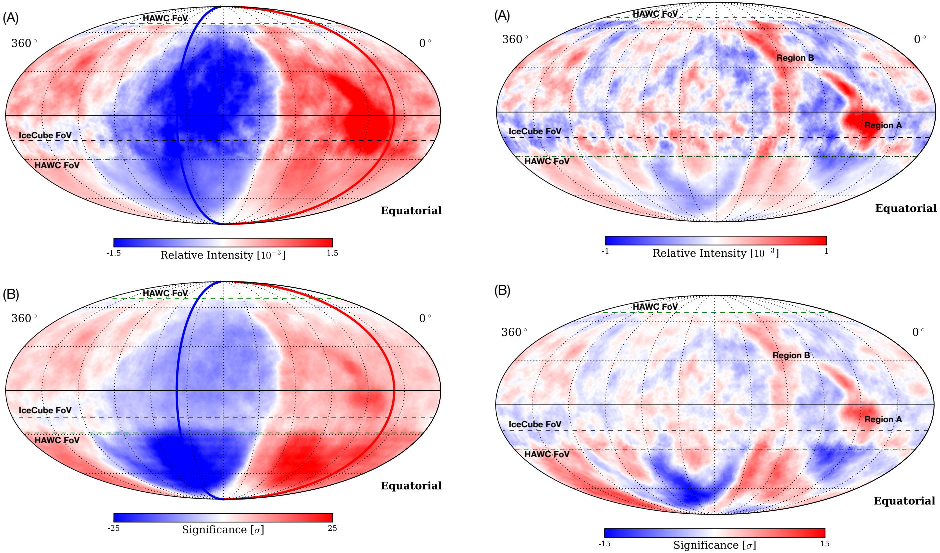


Density of GeV Muons in IceTop

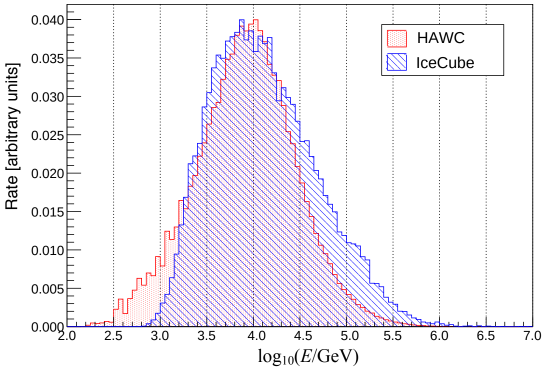
Correction factor (Sibyll 2.1/QGSJet-II-04/EPOS-LHC)

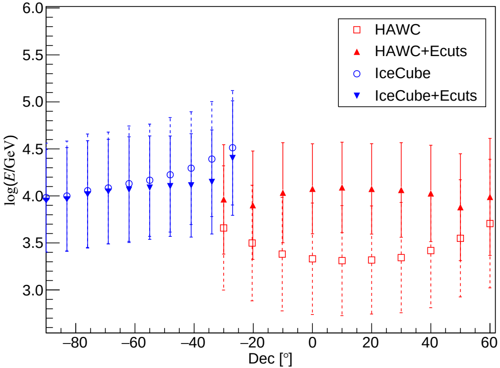


IceCube/HAWC All-Sky Anisotropy



IceCube/HAWC All-Sky Anisotropy





IceCube/HAWC All-Sky Anisotropy