Recent Results of Cosmic Ray Measurements from IceCube and IceTop

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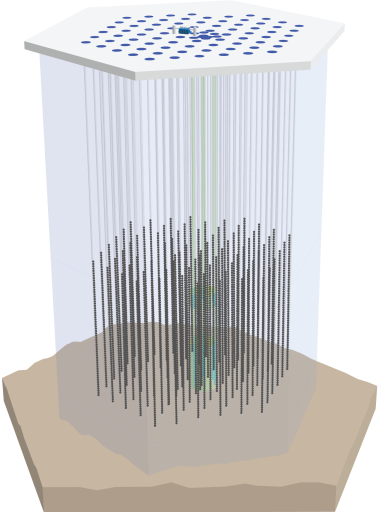
*University of Delaware

ICRC 2019
Madison, WI, USA

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

UNIVERSITY OF DELAWARE

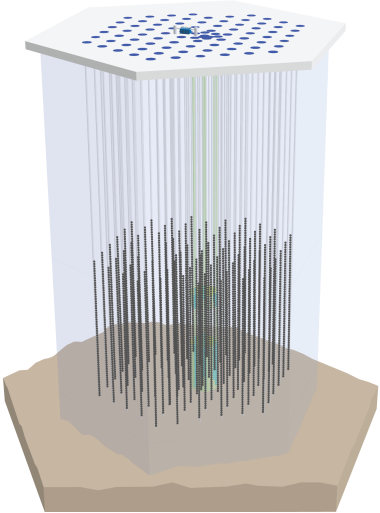
Outline



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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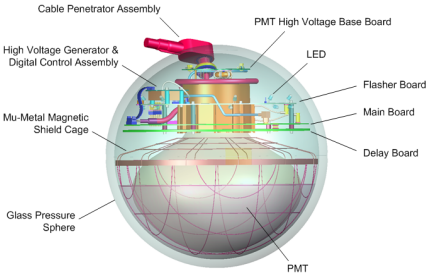
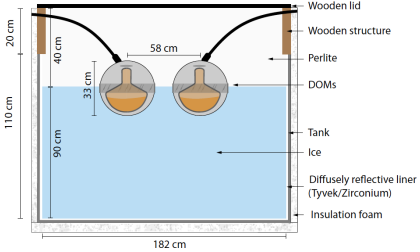


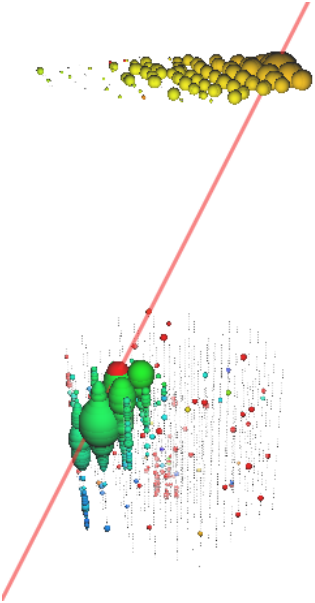


Cosmic Ray Physics with IceCube and IceTop

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

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

→ **3-dimensional cosmic ray detector!**

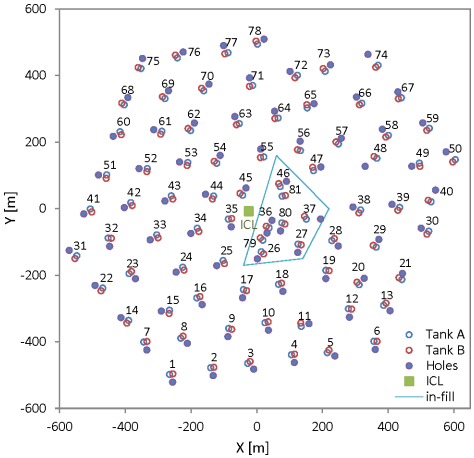


Cosmic Ray Spectrum

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

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

- 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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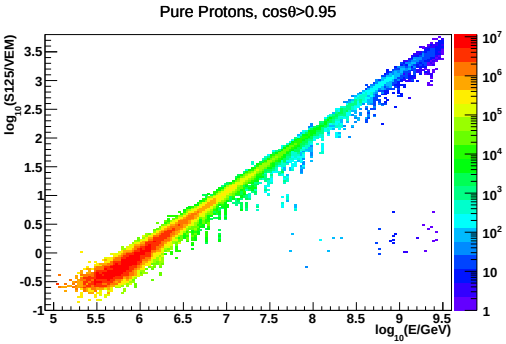
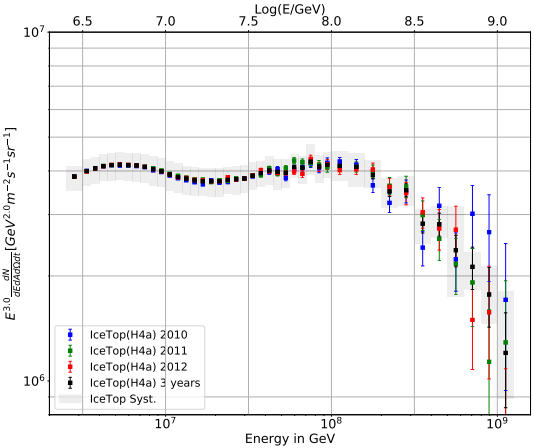


Cosmic Ray Spectrum

- 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))



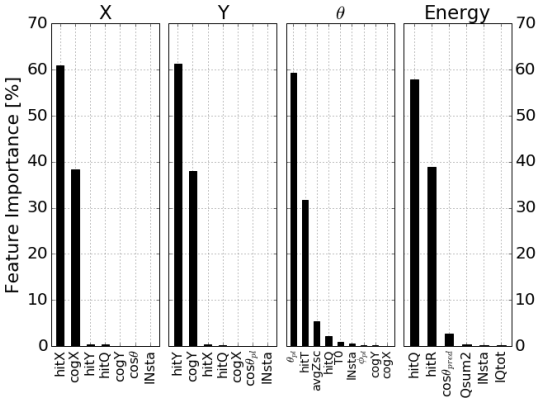
Submitted to PRD, see also CRI7b: K. Andeen, PoS(ICRC2019)172

Cosmic Ray Spectrum

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

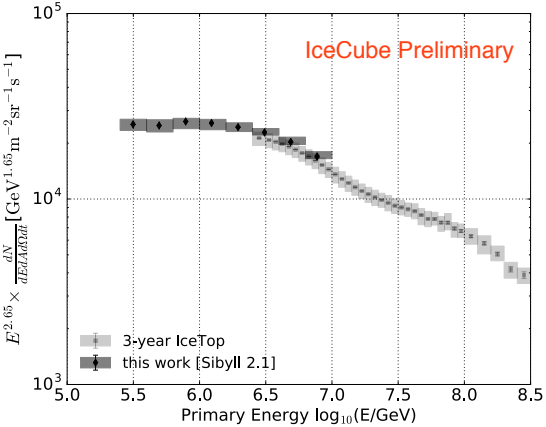
  $\rightarrow$ **Random Forest Regression**

- 3 steps
  - Core position
  - Direction
  - Energy
- Training/testing uses CORSIKA MC (Sibyll 2.1,H4a)
- Quality cuts & efficiency correction
- Iterative Bayesian unfolding



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



Paper in preparation, see also CRI4d: R. Koirala, PoS(ICRC2019)318

Cosmic Ray Mass Composition

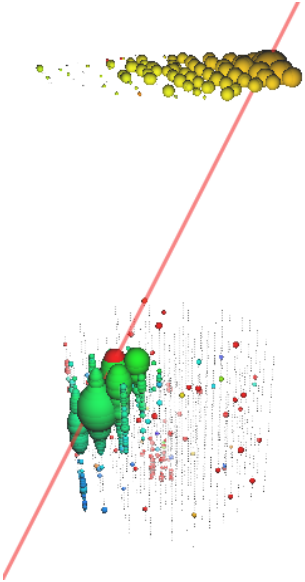
- IceTop & IceCube data
- Events with ≥ 5 hit stations, ≥ 8 in-ice hits
- Mean muon number

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

- Energy E from IceTop
- Muon number proxy from IceCube

$\rightarrow$ **Mass number A**

- Similar concepts apply for PeV gamma ray searches (Submitted to ApJ, see also Z. Griffith, H. Pandya, PoS(ICRC2017)715)



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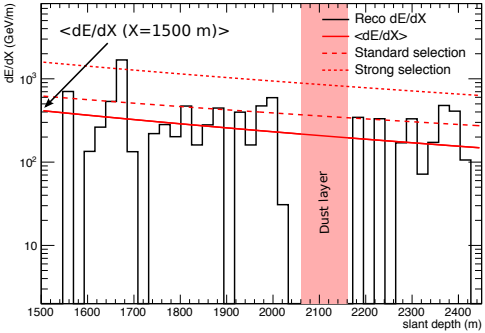
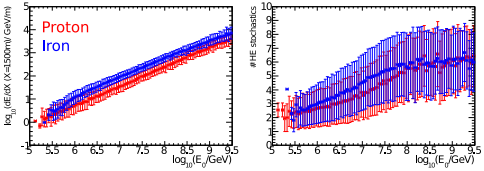
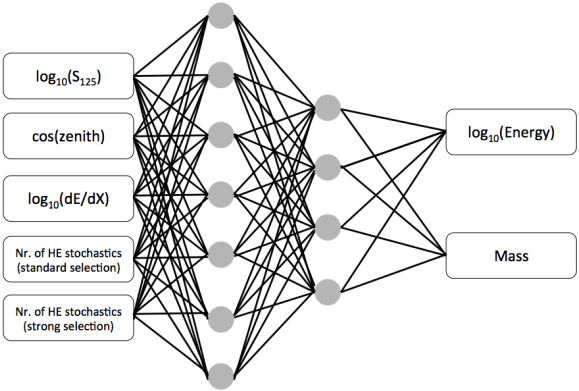
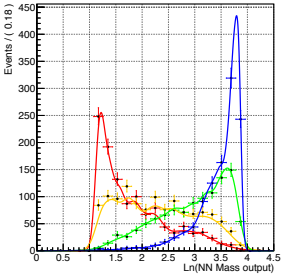


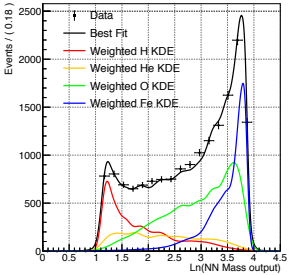


Cosmic Ray Mass Composition

- **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

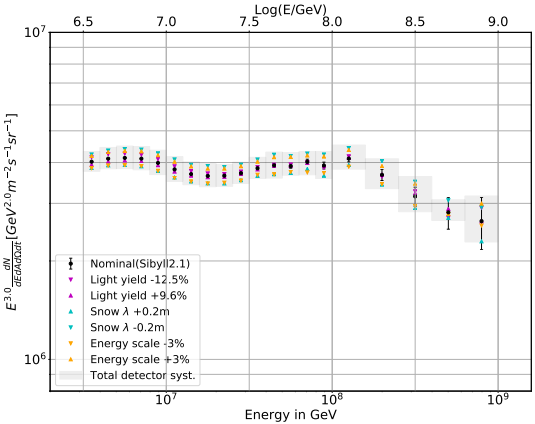






Cosmic Ray Mass Composition

- 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



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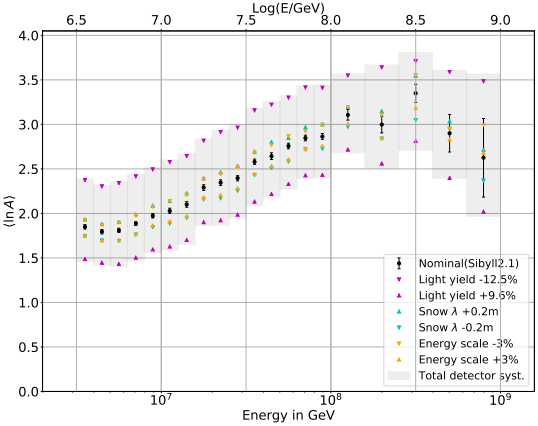

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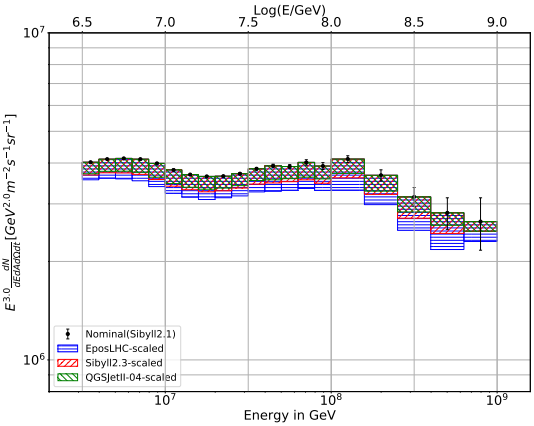
Cosmic Ray Mass Composition

- **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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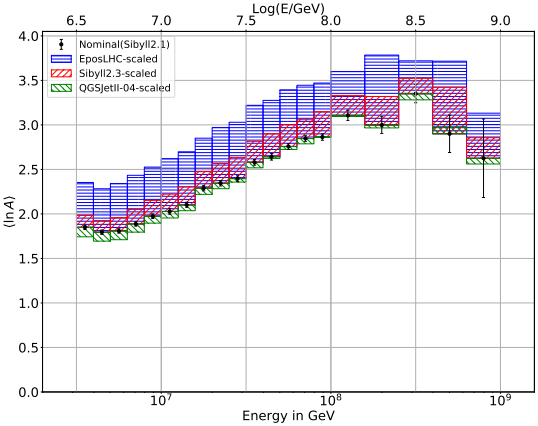

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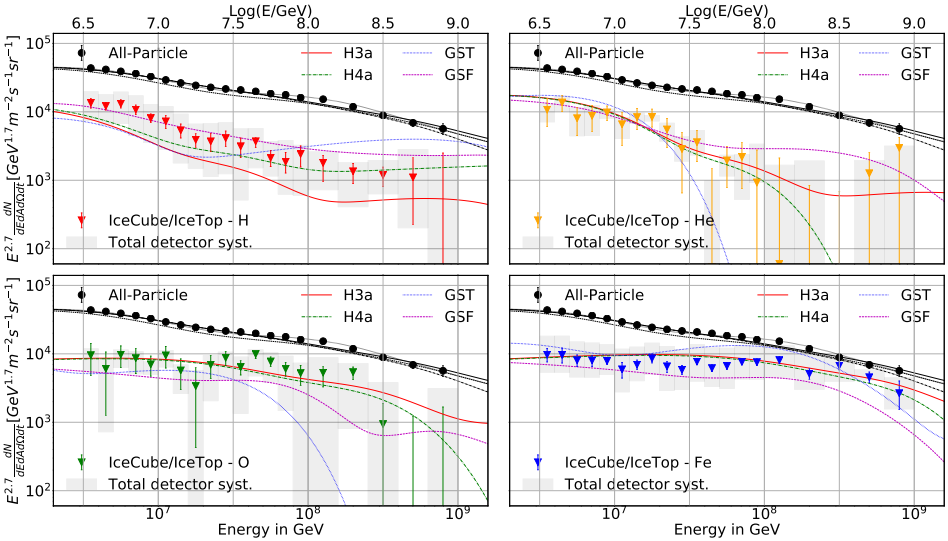

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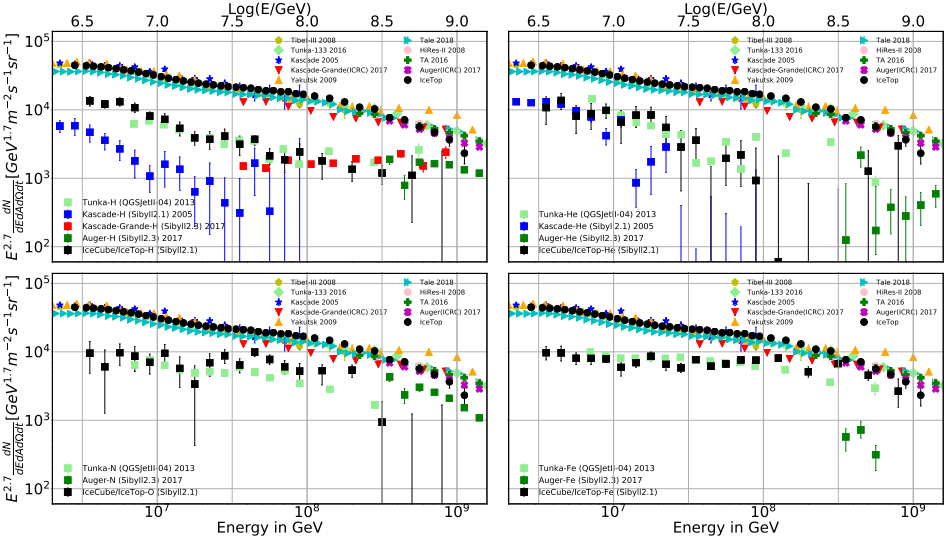
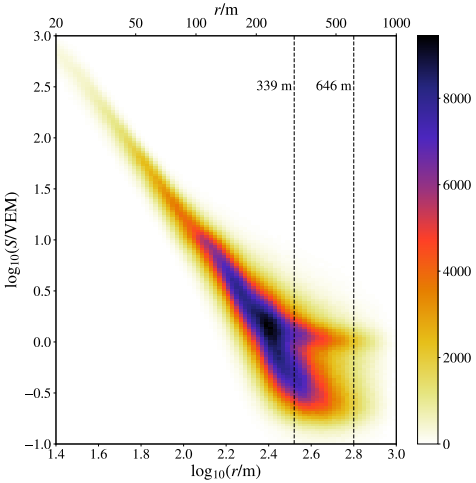


Density of GeV Muons in IceTop

- 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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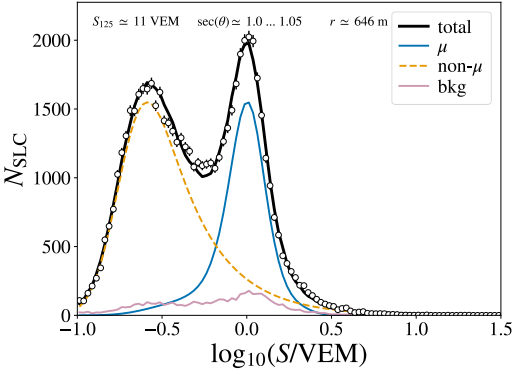
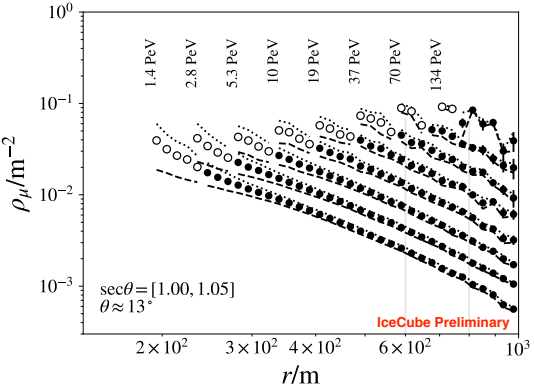


Density of GeV Muons in IceTop

- 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**

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

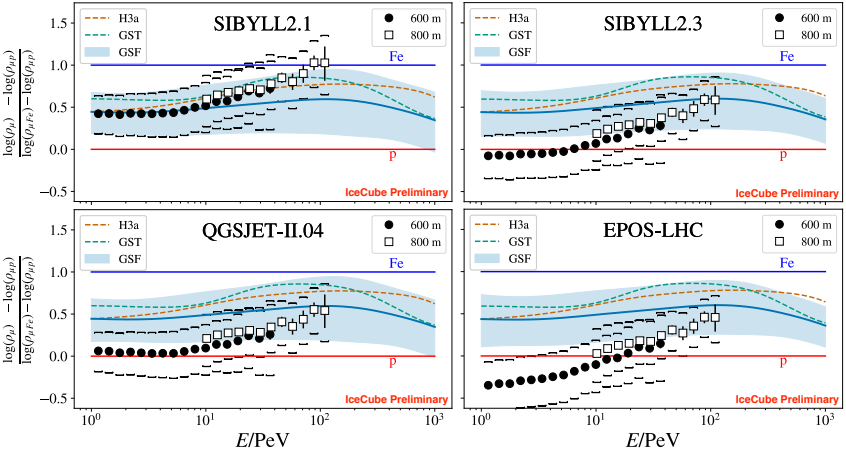
- Studies of hadronic interaction models



Paper in preparation

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

Density of GeV Muons in IceTop



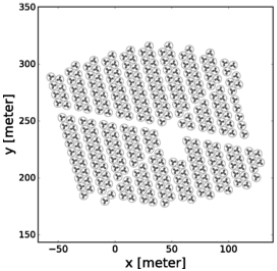
- Cross-calibration of experimental data can change the interpretation in the context of hadronic models (see also CRI15e: L. Cazon (WHISP), PoS(ICRC2019)214)

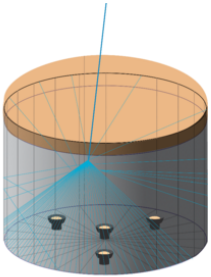
IceCube/HAWC All-Sky Anisotropy

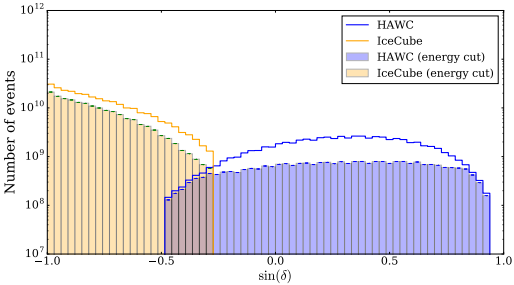
- **IceCube**
  - Dedicated cosmic ray event selection* of in-ice data
  - Angular resolution: $\sim 3°$
  - Median energy: $\sim 10\,\text{TeV}$

- **HAWC Observatory**
  - Located at Sierra Negra, Mexico
  - ~ 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)



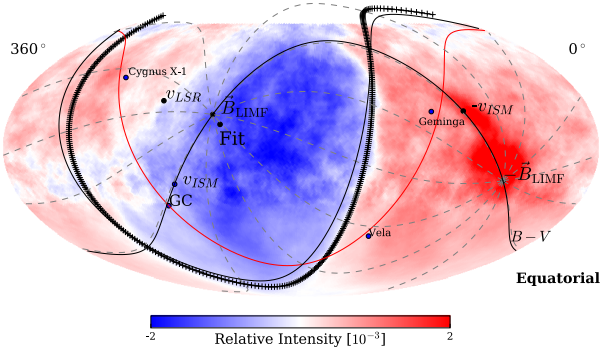




IceCube/HAWC All-Sky Anisotropy

- 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)

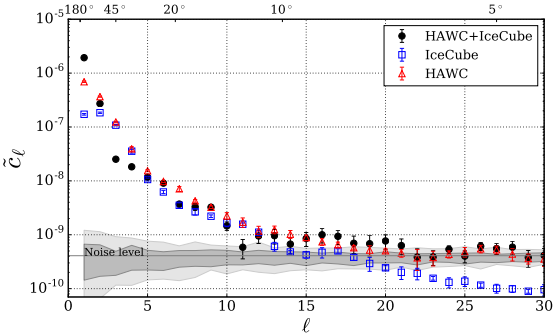


IceCube/HAWC All-Sky Anisotropy

- Decomposition in spherical harmonics ℓ

  $\rightarrow$ **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

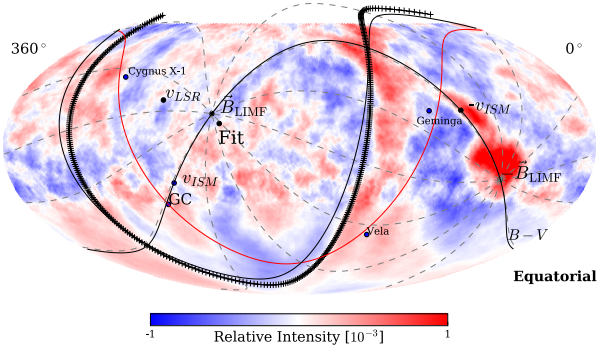


IceCube & HAWC, Astrophys. J. 871 (2019), 96.

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

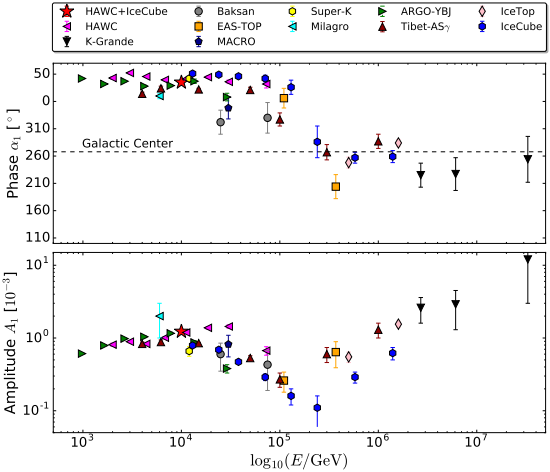
  $$\alpha = (38.4 \pm 0.3)^\circ$$

- Systematic uncertainties

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

- Also previous measurements from IceCube and IceTop

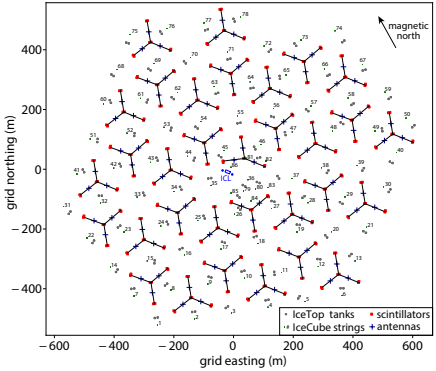
  Astrophys. J. 826 (2016)
  Astrophys. J. 765 (2013)

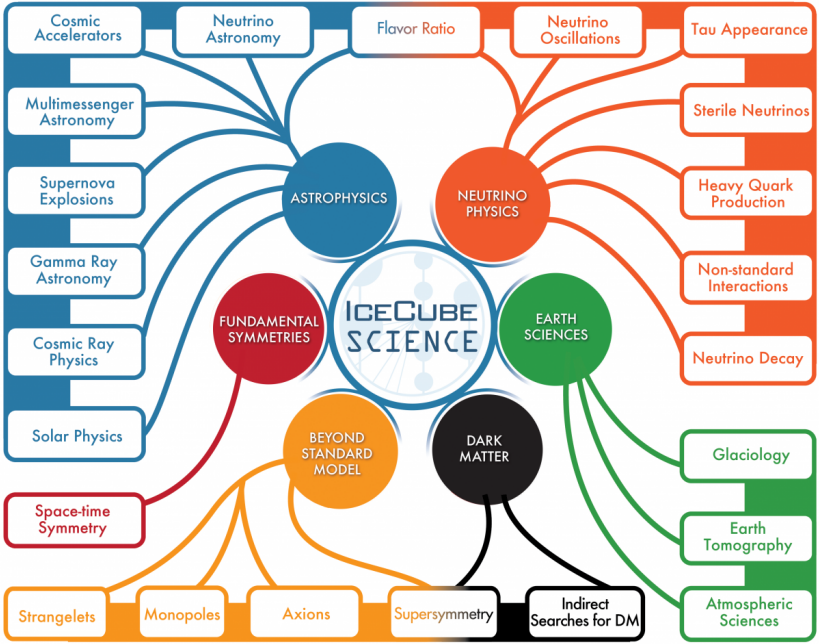


IceCube & HAWC, Astrophys. J. 871 (2019)

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 (H10,PS3-118)
- Scintillator array (CRI3b,PS1-210,PS1-190)
- Radio array (PS1-210,PS3-207)
- Cherenkov telescopes (PS1-140)
- Improved analysis methods (PS1-157,PS3-204)
- ...





- 82 contributions at ICRC 2019!
- See also H10: D. Williams, PoS(2019)016

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

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

JAPAN
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NEW ZEALAND
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Lawrence Berkeley National Lab
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Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
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
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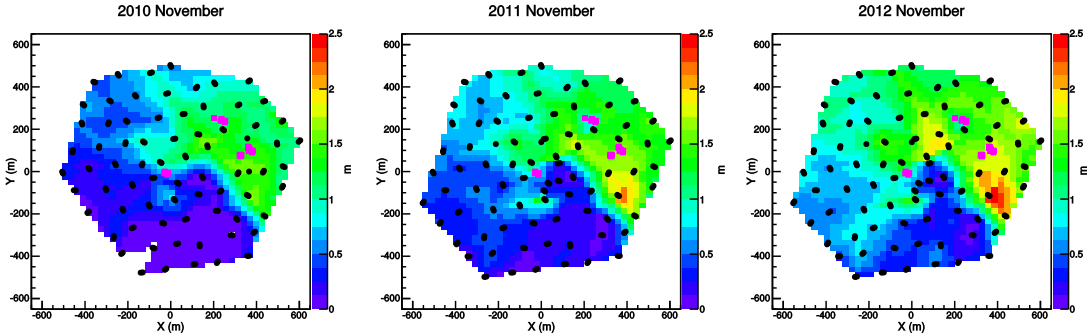
Thank you!

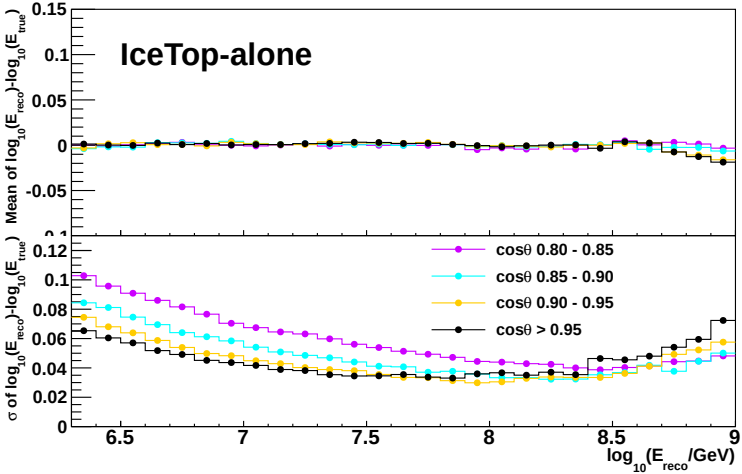
Backup

Cosmic Ray Spectrum

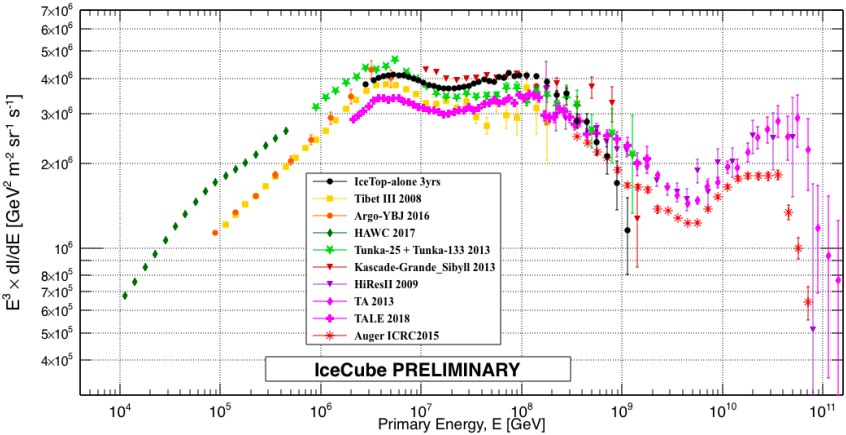
Snow depths



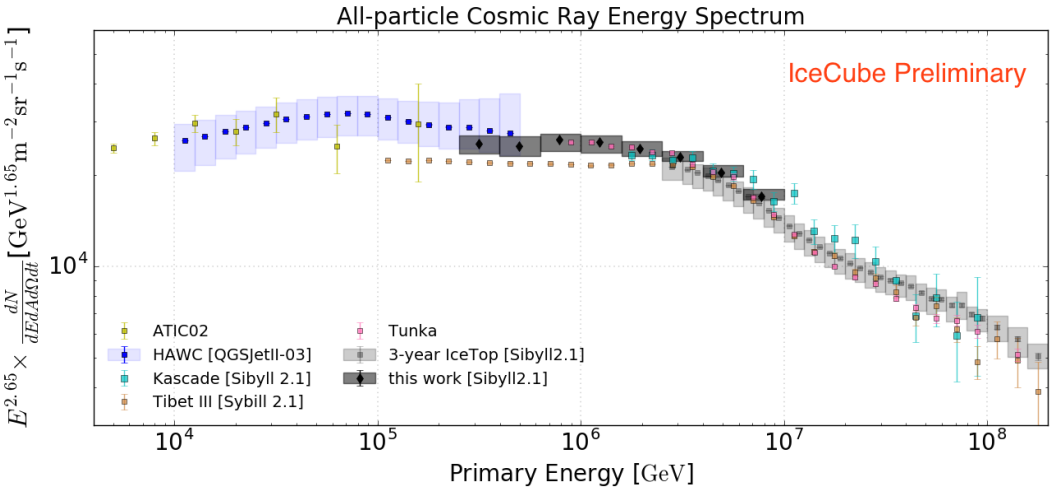
Cosmic Ray Spectrum



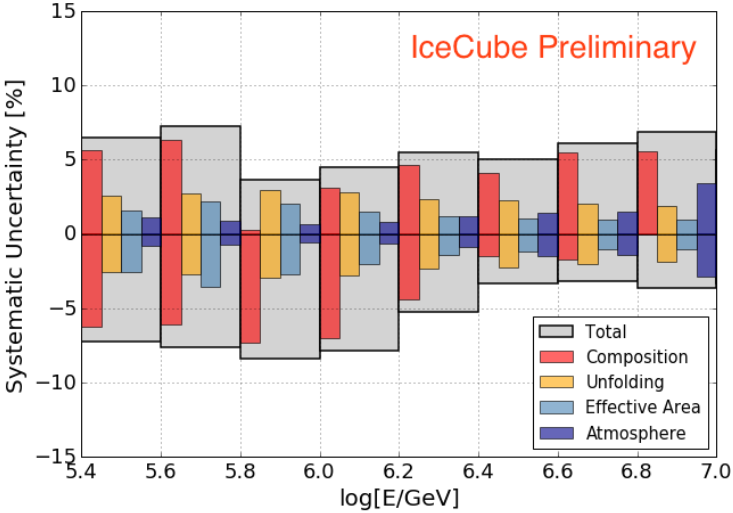
Cosmic Ray Spectrum



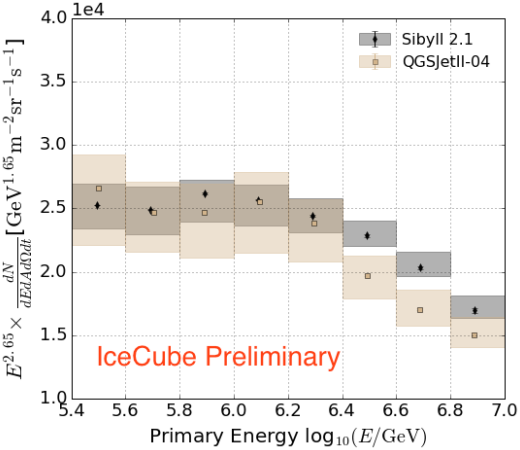
Cosmic Ray Spectrum

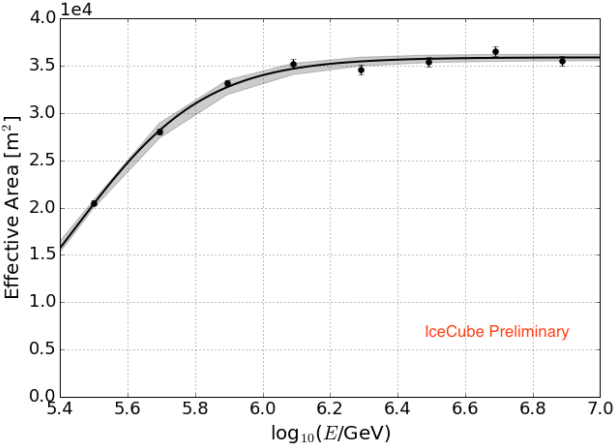


Cosmic Ray Spectrum

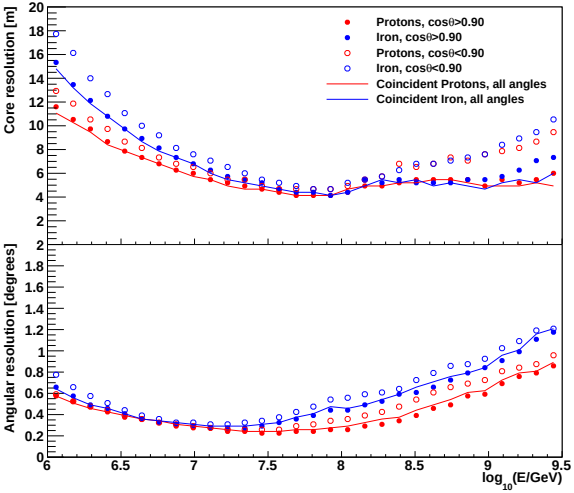


Cosmic Ray Spectrum

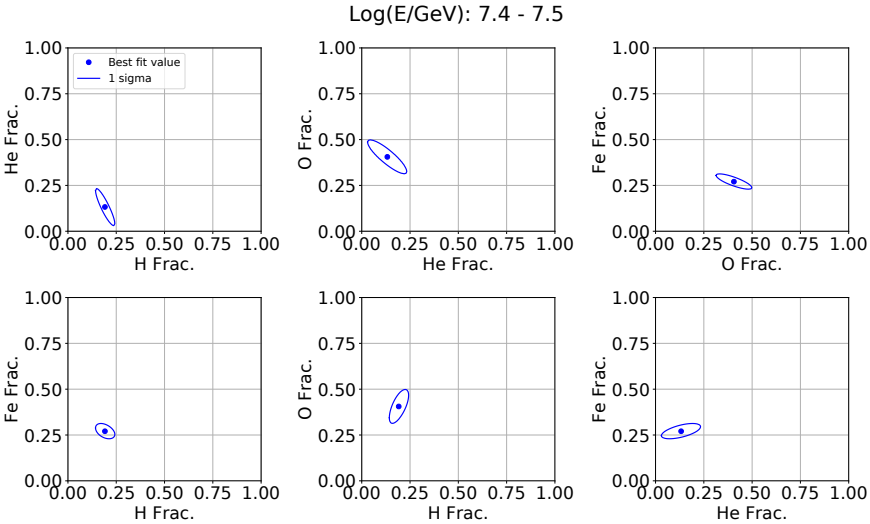




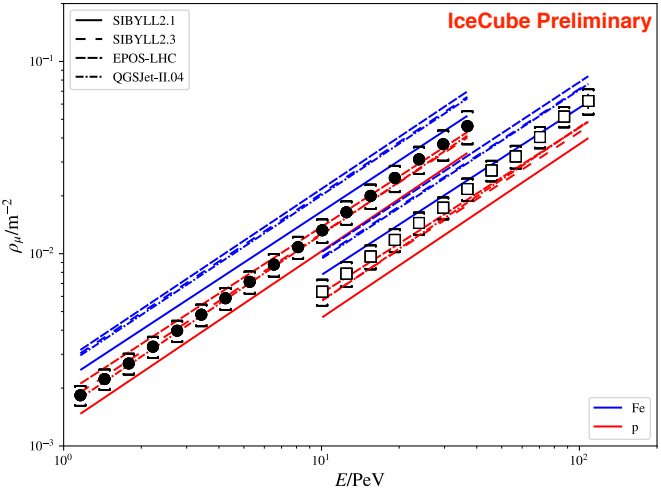
Cosmic Ray Mass Composition



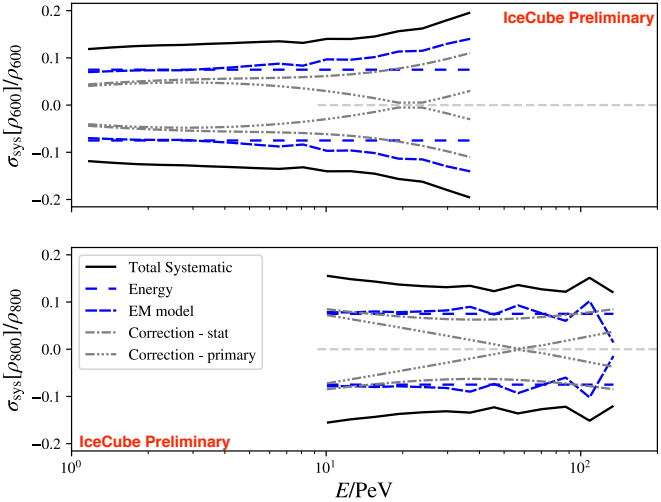
Cosmic Ray Mass Composition



Density of GeV Muons in IceTop

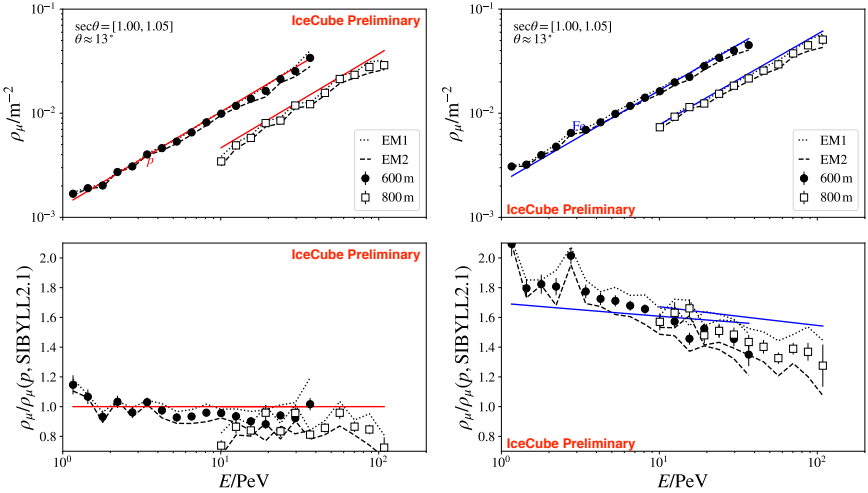


Density of GeV Muons in IceTop



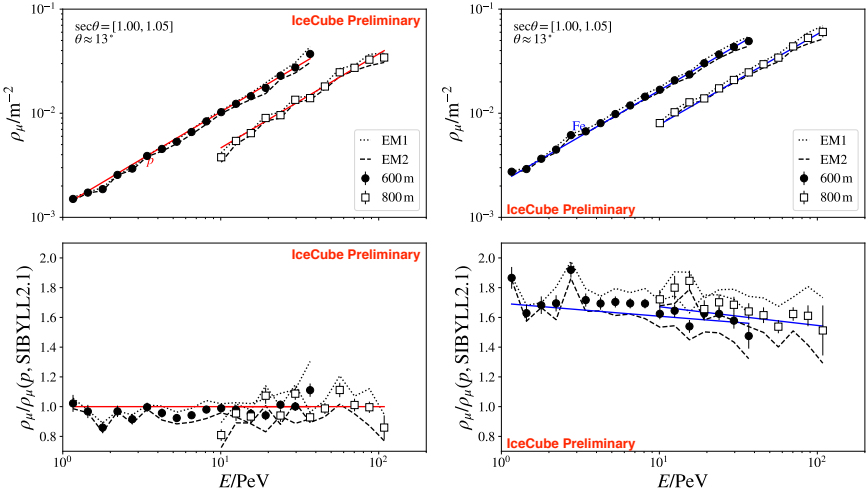
Density of GeV Muons in IceTop

MC self-consistency check (proton/iron)



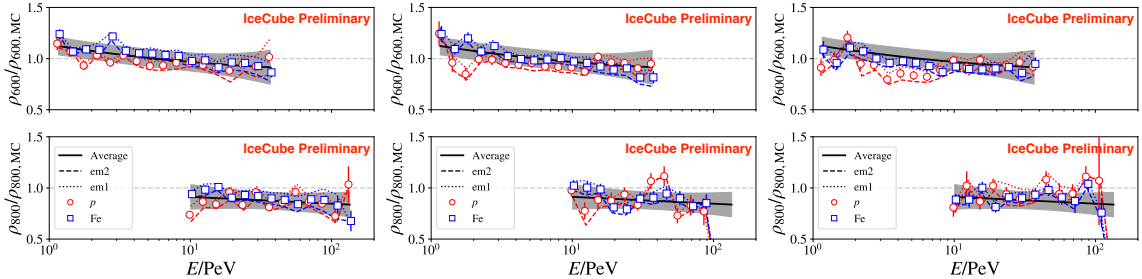
Density of GeV Muons in IceTop

Correction factor (proton/iron)

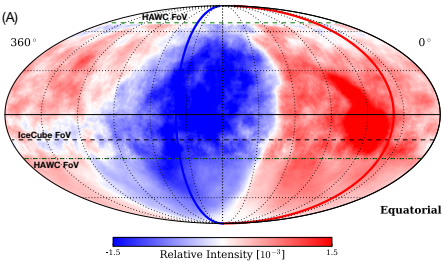


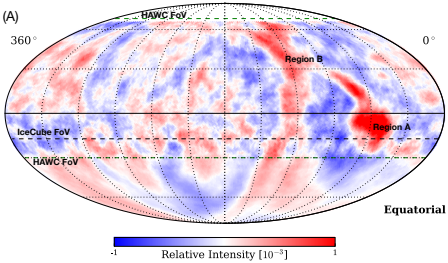
Density of GeV Muons in IceTop

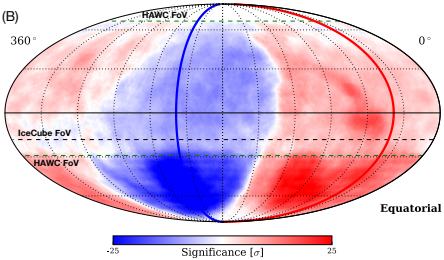
Correction factor (Sibyll 2.1/QGSJet-II-04/EPOS-LHC)

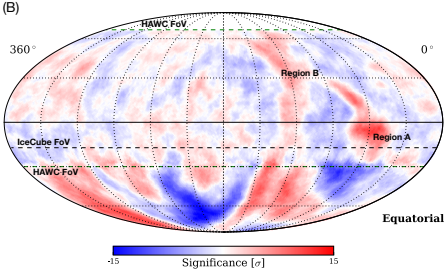


IceCube/HAWC All-Sky Anisotropy

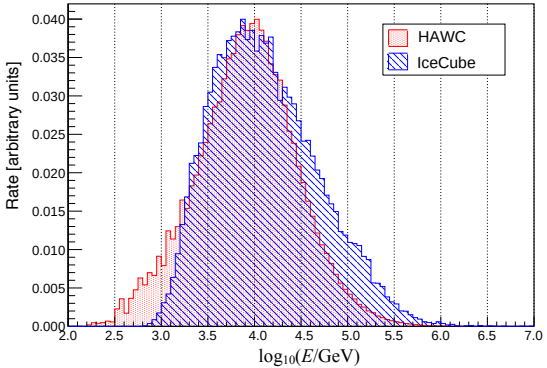


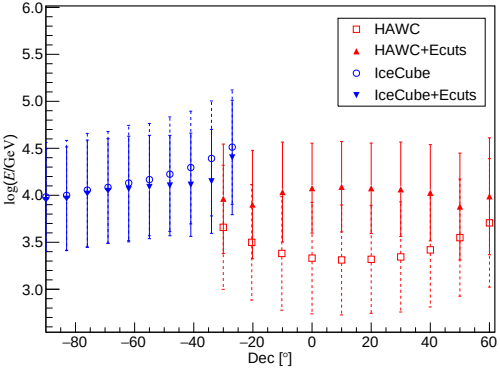






IceCube/HAWC All-Sky Anisotropy





IceCube/HAWC All-Sky Anisotropy