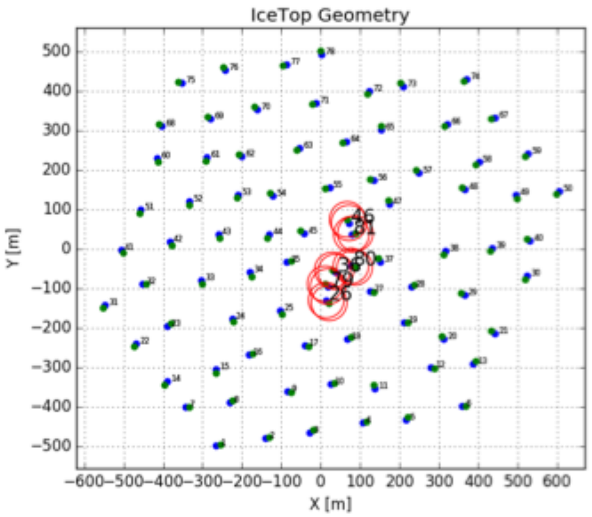
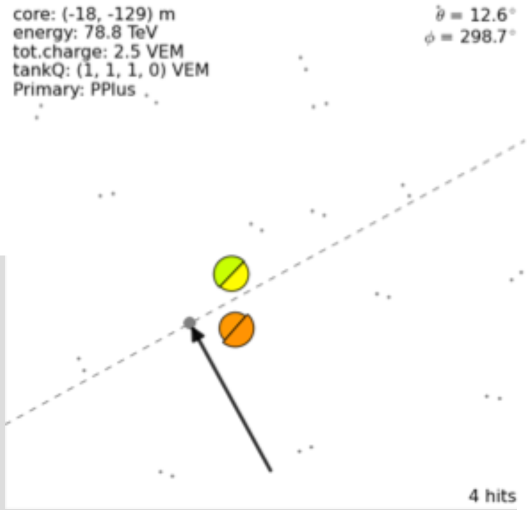
LOW ENERGY COSMIC RAY SPECTRUM FROM 250 TEV TO 10 PEV USING ICETOP



RAMESH KOIRALA & THOMAS K. GAISSER

(FOR ICECUBE COLLABORATION)



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Motivation

- This work:

  Lower the energy threshold for the cosmic ray spectrum of IceTop

  (~2 PeV ⟶ 250 TeV).

- How?
  - Use dense array of the IceTop detector.
  - Use air showers that hit a smaller number of tanks.

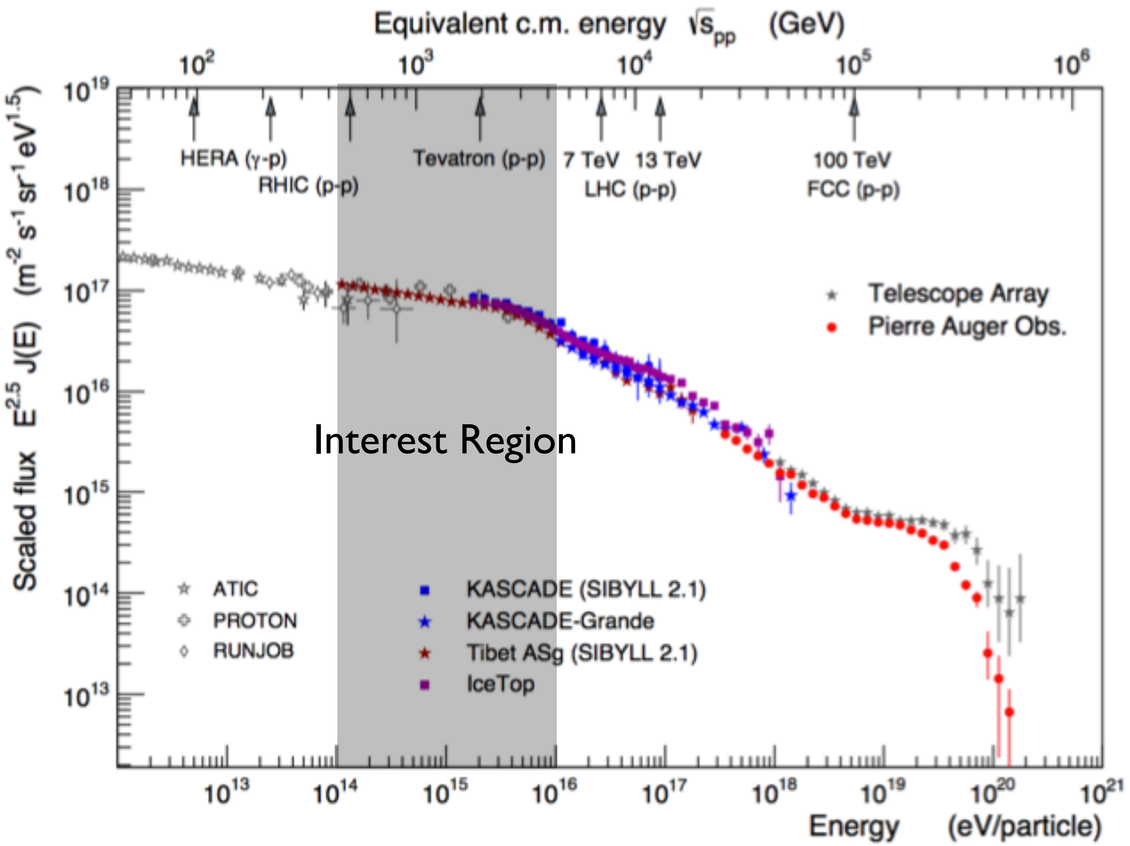

Fig: Auger Collaboration. Updated version of DOI: 10.1088/1367-2630/12/7/075009

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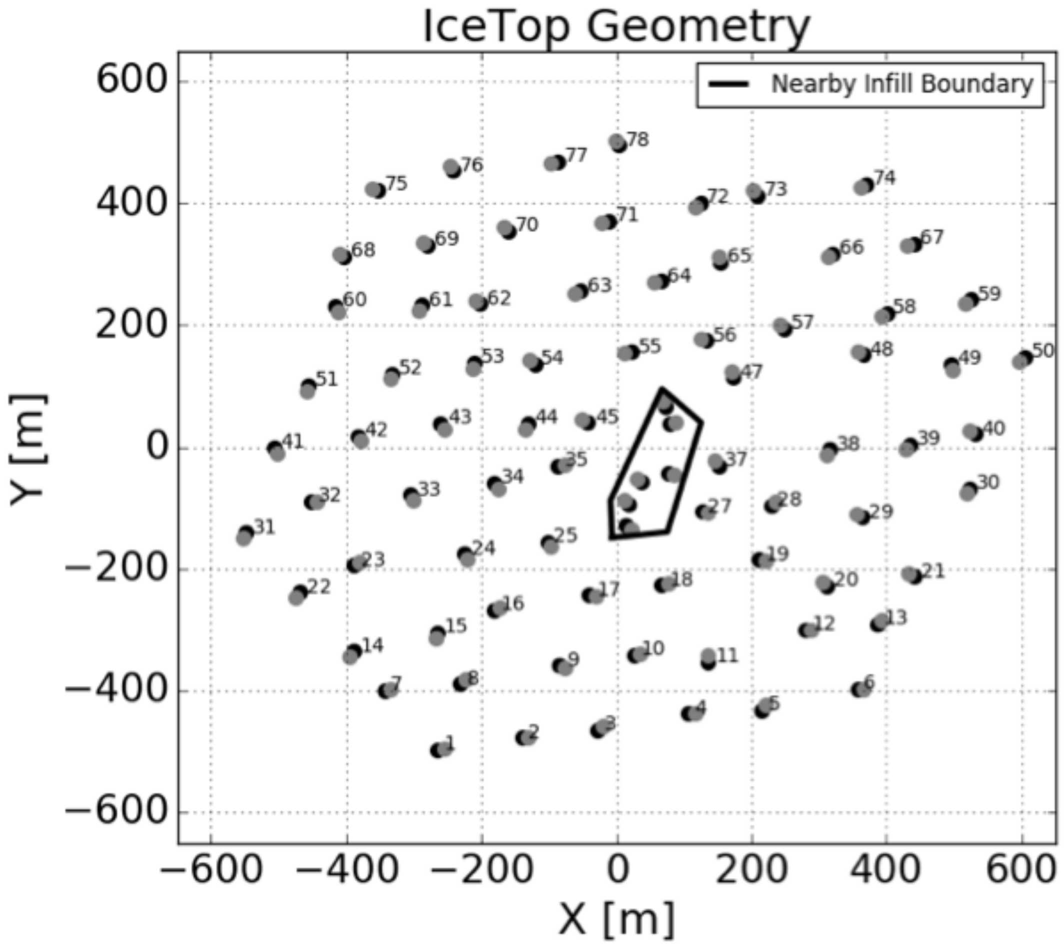
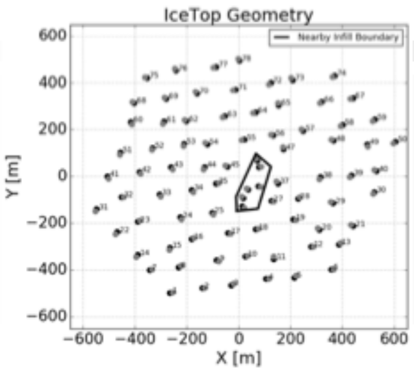
Detector: IceTop

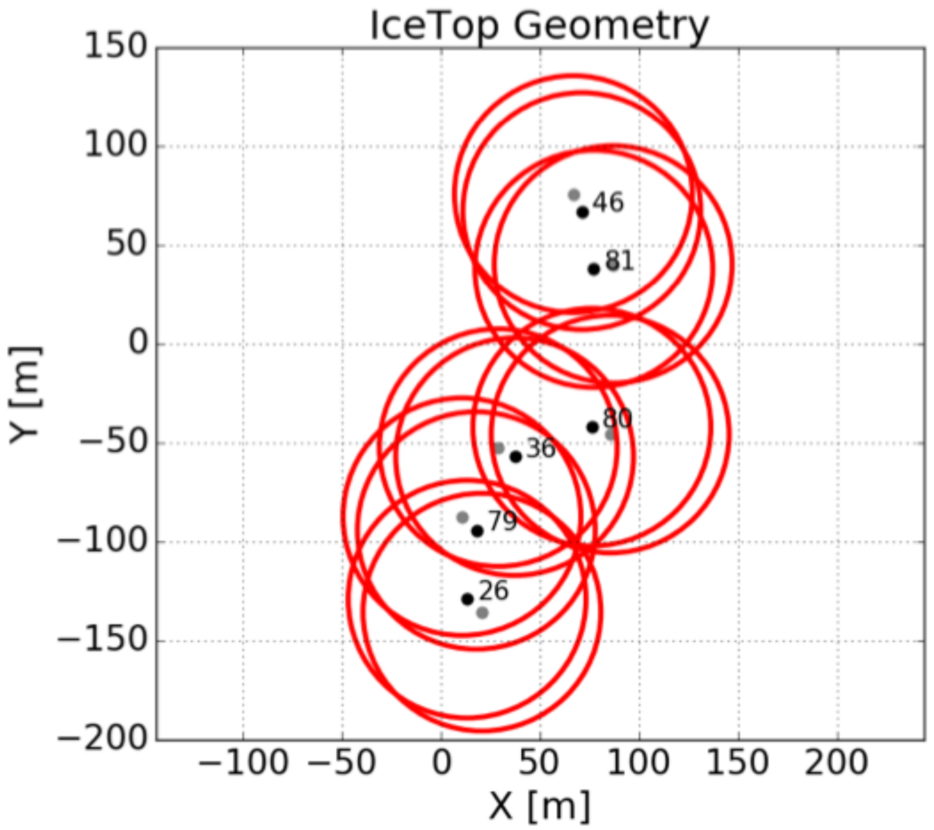
- 81 stations
- 2 tanks/station, 2 DOMs/tank
- Distance between stations: 125 m
- Denser infill arrays for lower energy



New Trigger



- Trigger Condition:
  - 4 tanks within 60 m radius are hit in 200 ns time window.
- Data collection started on May 20, 2016.
- Total duration: ~330.43 days.



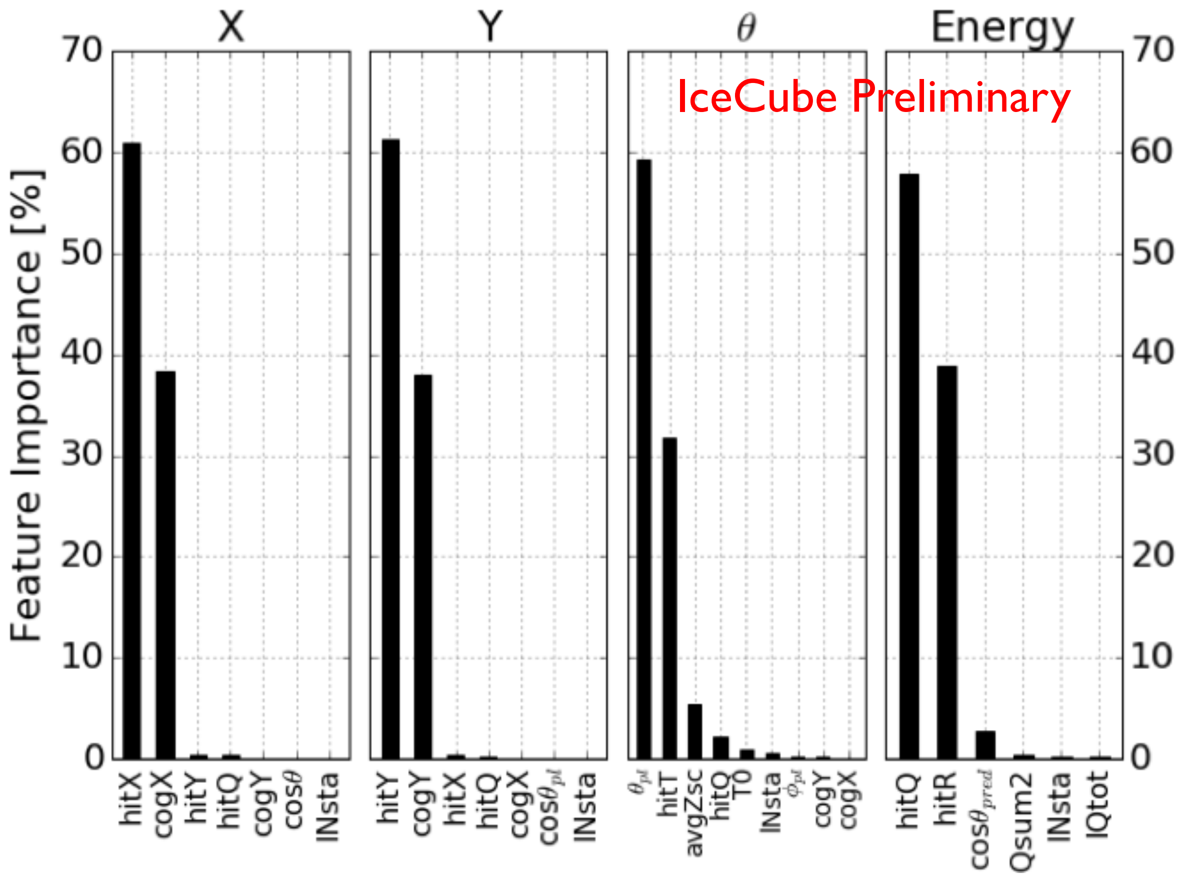
Reconstruction

- Random Forest Regression (RFR) is used for reconstruction of core position (X, Y), zenith angle, and energy.
- CORSIKA simulations are used to train the RFR.
- Energy prediction uses reconstructed X, Y, and zenith angle.
- Major features for energy prediction are charge on hit tanks and their distance from the core.

Reconstruction: Feature Importance

- hitX/Y= x/y-coordinate of hit tanks
- hitT = time at which tanks are hit
- hitQ = charge on hit tanks
- hitR = hit tank distance from core
- Θ_{pl} = plane shower front zenith
- Θ_{pred} = predicted zenith angle
- avgZsc = average tank distance from shower plane.

$$X_{COG} = \frac{\sum_i \sqrt{Q_i} x_i}{\sum_i \sqrt{Q_i}}$$



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Resolution

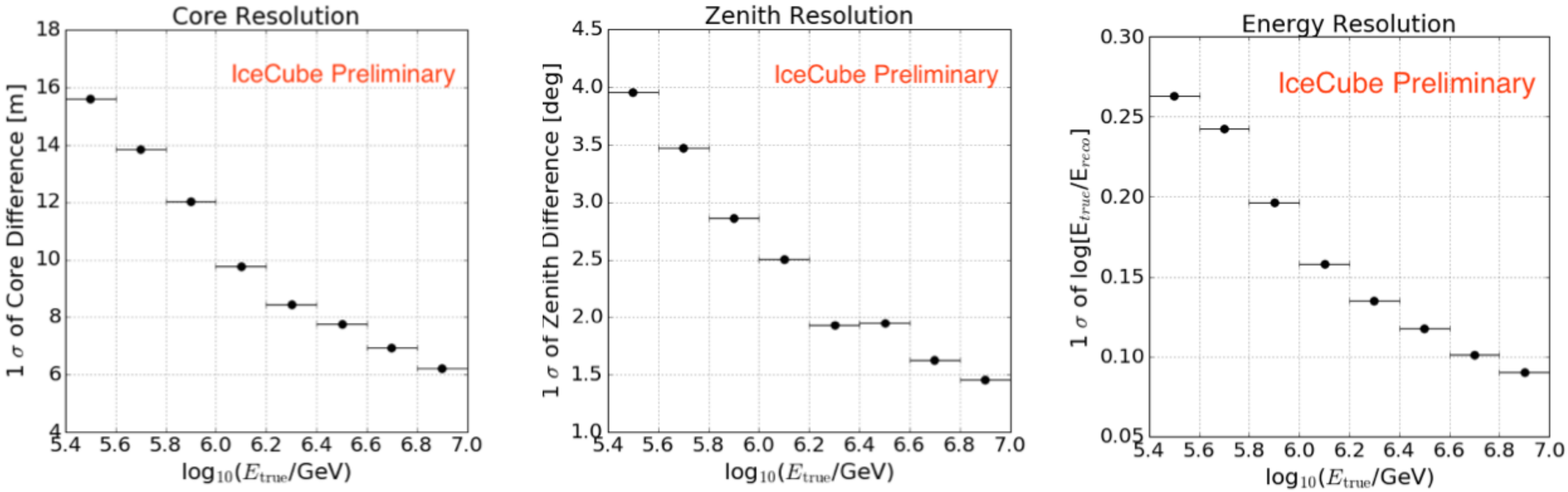


Figure 2: Left: Core resolution in meter; Middle: zenith resolution in degree; Right: energy resolution in unit-less quantity.

Systematic Uncertainty

- Composition model assumption (+6.3 , -7.4%)*
- Unfolding method (+/- 3.24%)*
- Effective area (+2.2%, -3.6%) *
- Atmosphere (+3.5%, -2.9%) *
- Total (+7.4%, -8.6%) *

* Upper and lower bound.

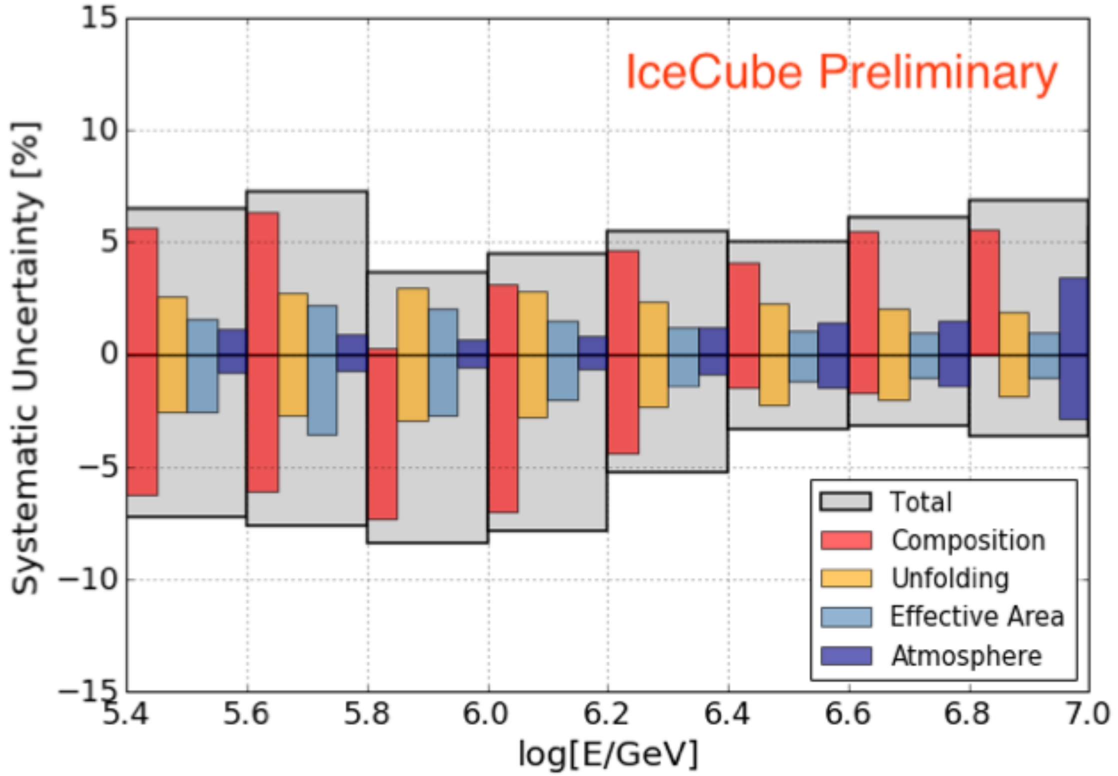


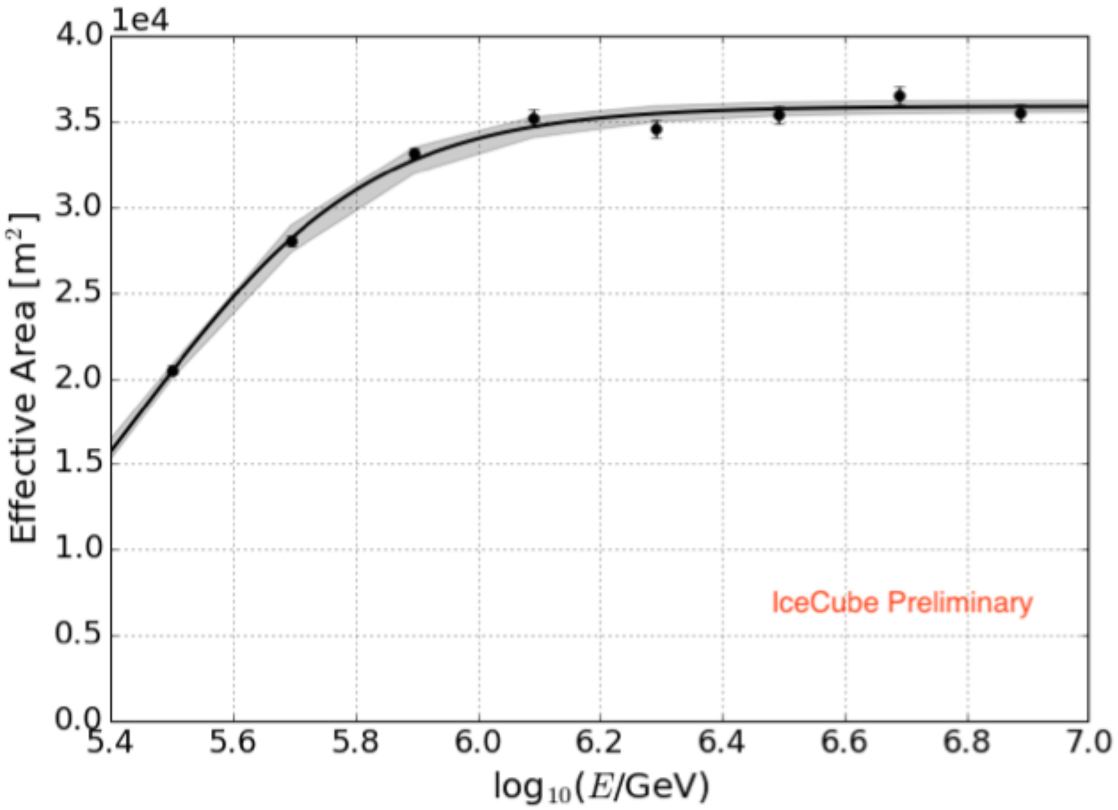
Figure 3: The individual systematic uncertainties for each energy bins. Total systematic uncertainty is the sum of individual uncertainties added in quadrature.

Energy Spectrum

Cosmic Ray energy spectrum (Flux) is given by

$$J(E) = \frac{\Delta N(E)}{\Delta lnE\pi(cos^2\theta_1 - cos^2\theta_2)A_{eff}T}$$

$\Delta N(E)$ = energy histogram after unfolding
ΔlnE = energy bin width in natural log
$cos\theta_1$ = 1.0
$cos\theta_2$ = 0.9
A_{eff} = Effective area
T = 28548810 s (~330.42 days)



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Result

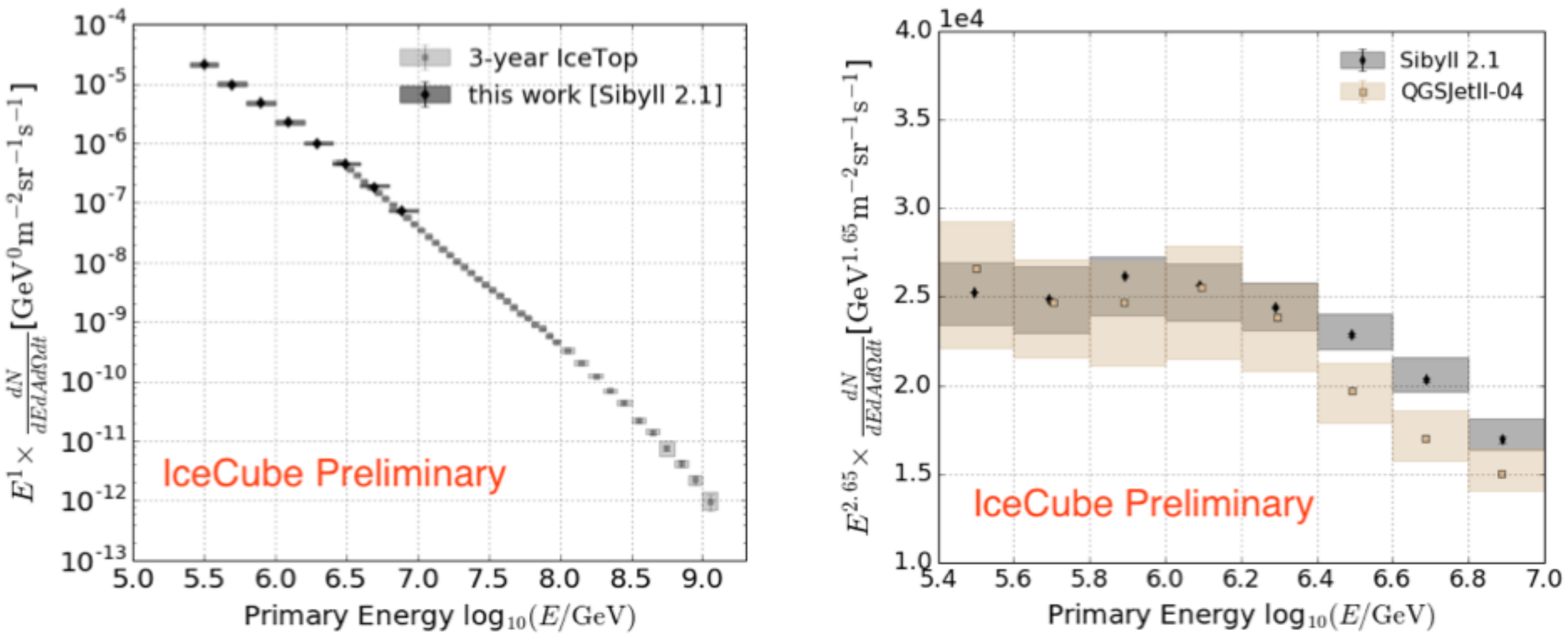

Figure 4: Left: The all-particle cosmic ray energy spectrum using IceTop 2016 data. The analysis is done using simulations with Sibyll 2.1 as the hadronic interaction model. Right: The all-particle cosmic ray energy spectra using simulations with Sibyll2.1 and QGSJetII-04 as hadronic interaction models. The same analysis as with Sibyll 2.1 was repeated with QGSJetII-04. The right plot is scaled by $E^{1.65}$. The shaded region in both plots indicates the systematic uncertainties.

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Result

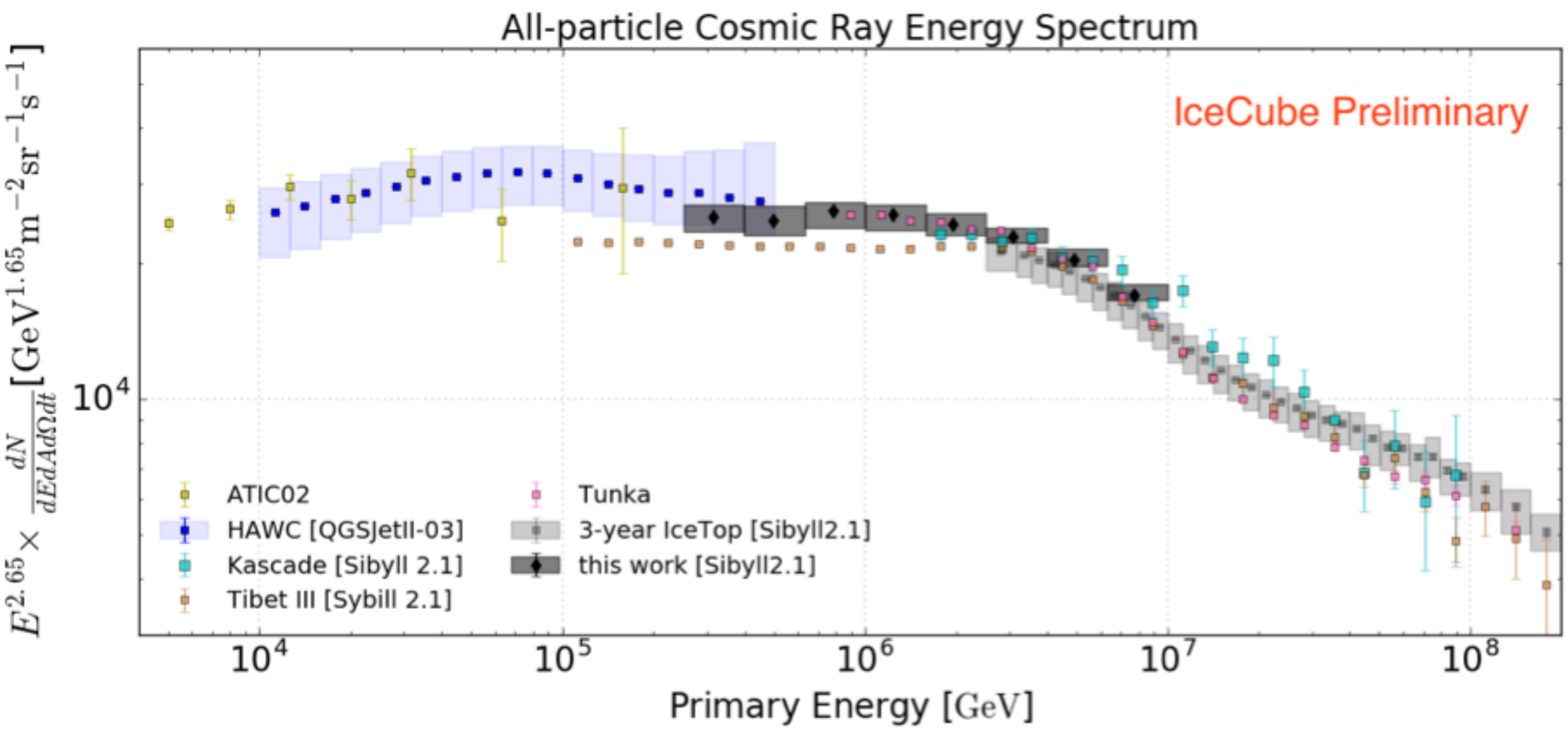

Figure 5: Cosmic ray flux using IceTop 2016 data scaled by $E^{1.65}$ and compared with flux from other experiments. This analysis and HAWC's energy spectrum analysis use different hadronic interaction models. The shaded region indicates the systematic uncertainties.

Summary

- Developed and implemented a new IceTop trigger to collect lower energy air shower events.
- Implemented a machine learning technique to do air shower reconstruction.
- Successfully lowered the energy threshold of IceTop to 250 TeV.
- Result is comparable to energy spectrum from other experiments.

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Backup

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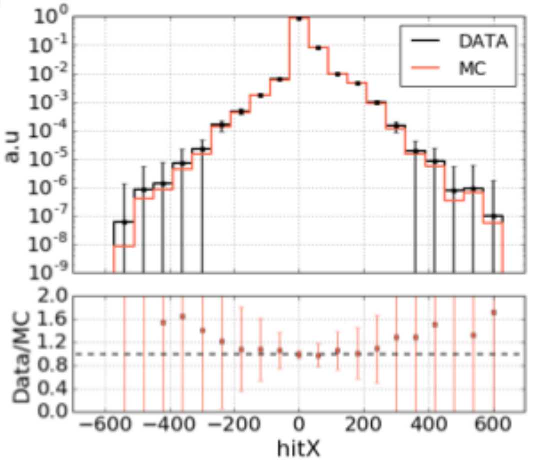
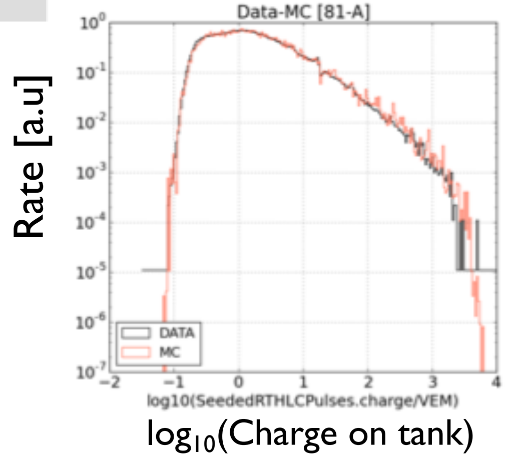
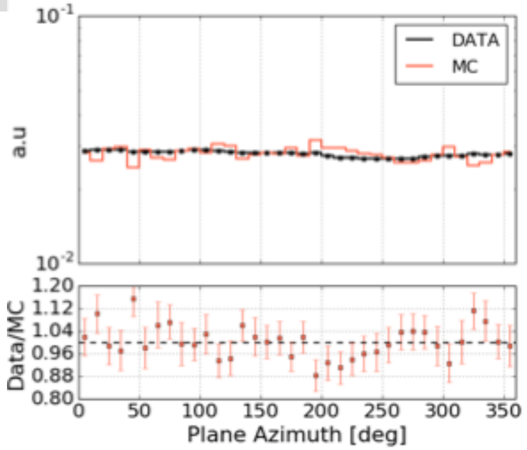
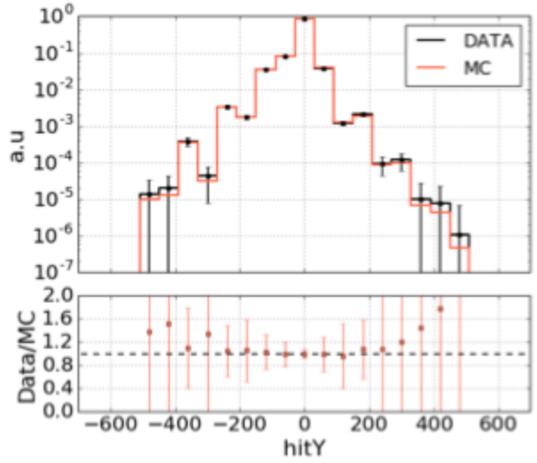
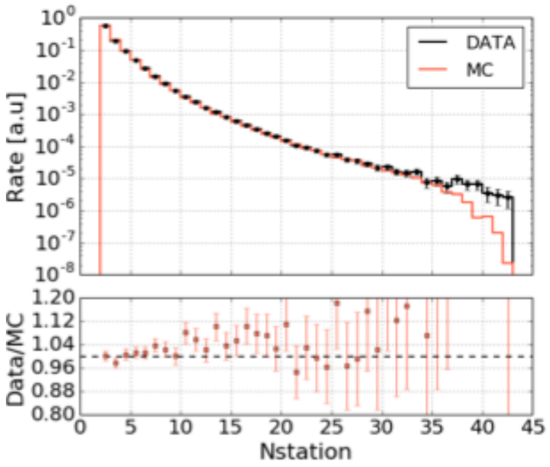
Data-MC Comparison

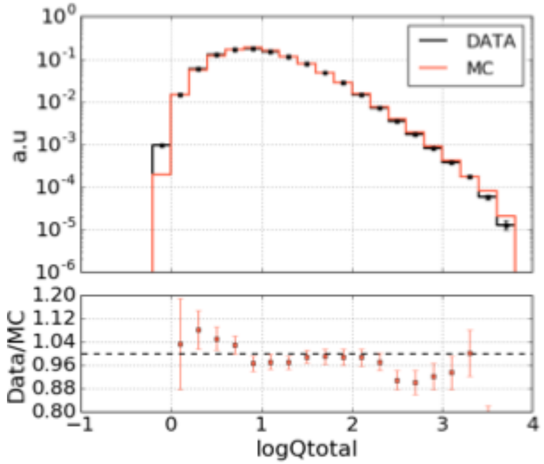












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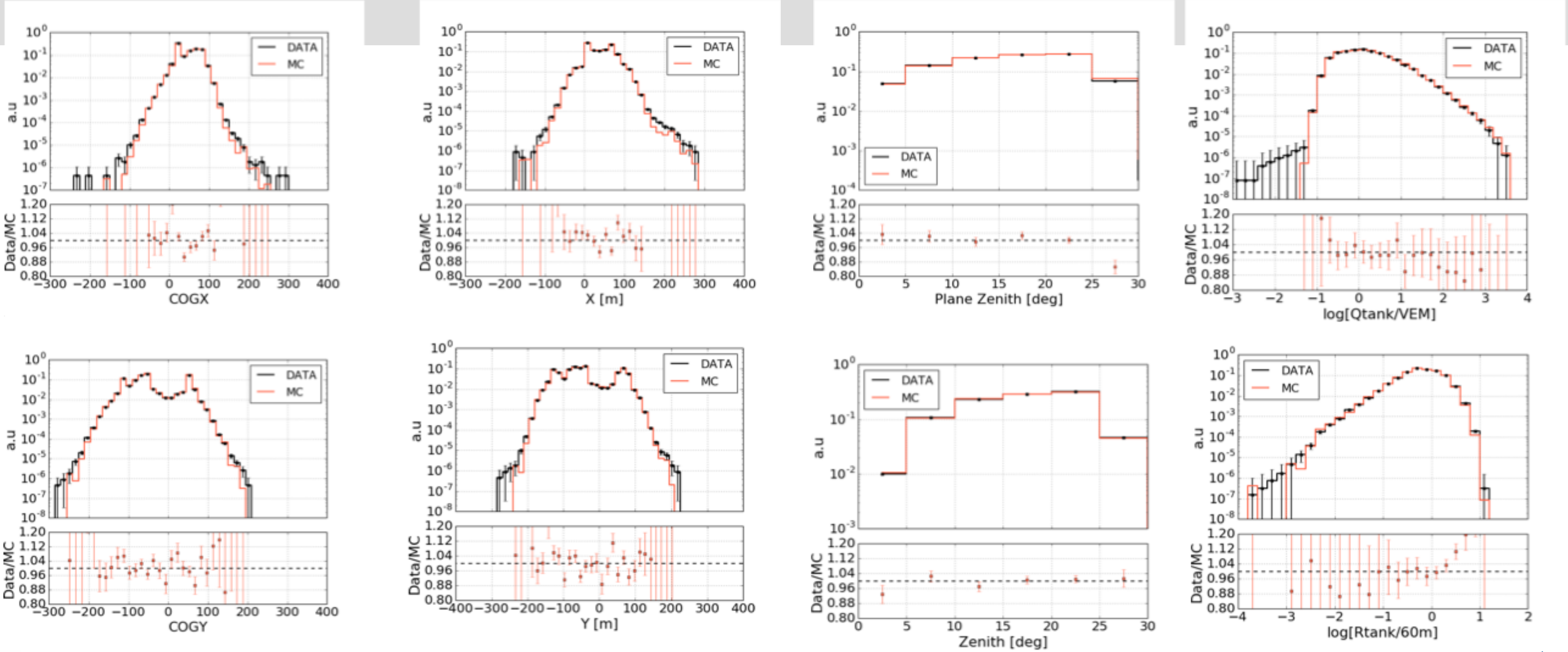
Data-MC Comparison



Iterative Bayesian Unfolding

- Implemented in pyUnfolding package [J. Bourbeau and Z. Hampel-Arias, arXiv:1806.03350]

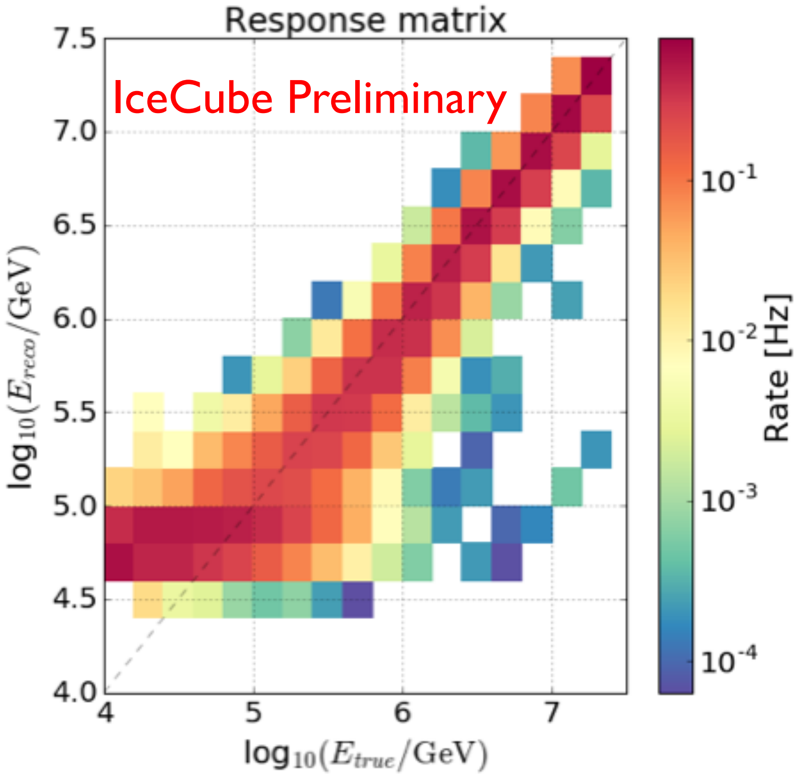
$$P(C_\mu) = Prior$$

$$P(C_\mu|E_j) = \frac{P(E_j|C_\mu)P(C_\mu)}{\sum_\nu^{n_c} P(E_j|C_\nu)P(C_\nu)}$$

$$\phi(C_\mu) = \frac{1}{\epsilon_\mu}\sum_i^{n_E} P(C_\mu|E_i)n(E_i)$$

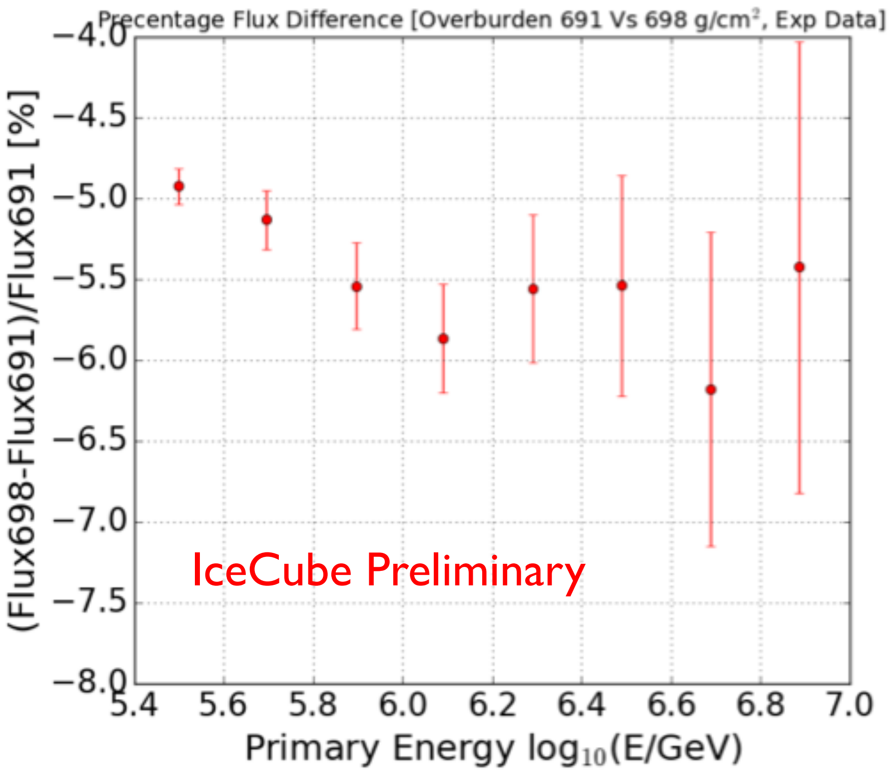
$$P(C_\mu) = \frac{\phi(C_\mu)}{\sum_\mu \phi(C_\mu)}$$

- n(E_i) is the histogram of reconstructed energy.
- Iterate until consecutive output energy spectrum does not change.



Pressure Correction

Percentage deviation of cosmic rays flux when atmospheric pressure is $\sim 698\,\mathrm{g/cm^2}$ from the flux when pressure is $\sim 691\,\mathrm{g/cm^2}$. This deviation is used as the correction factor to correct the final flu. Error on the correction factor is used as the systematic uncertainty due to Pressure difference between average pressure of 2016 South Pole atmosphere and pressure due to atmosphere profile used in simulation.



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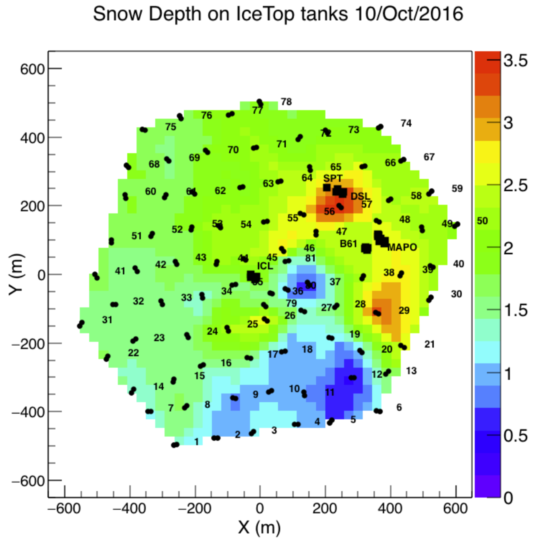
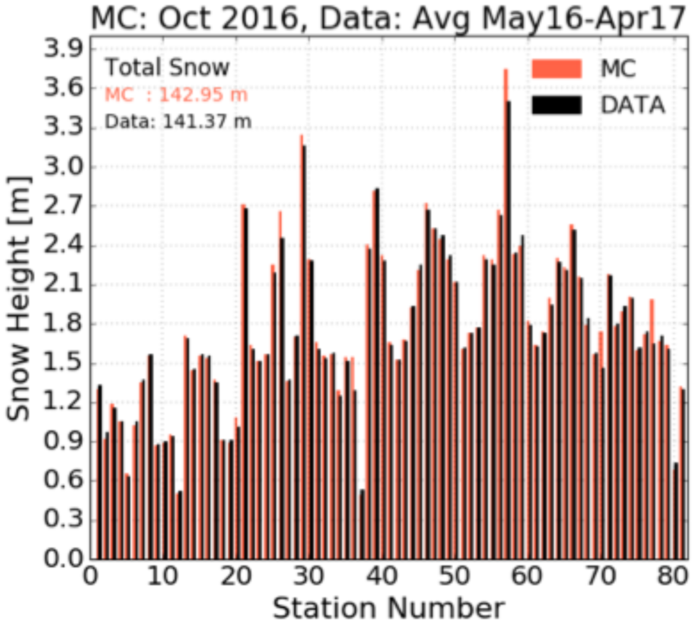
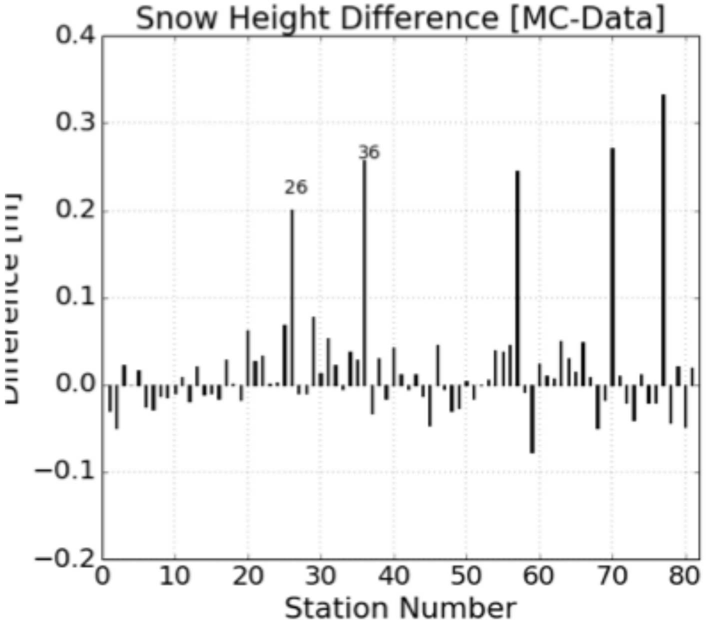
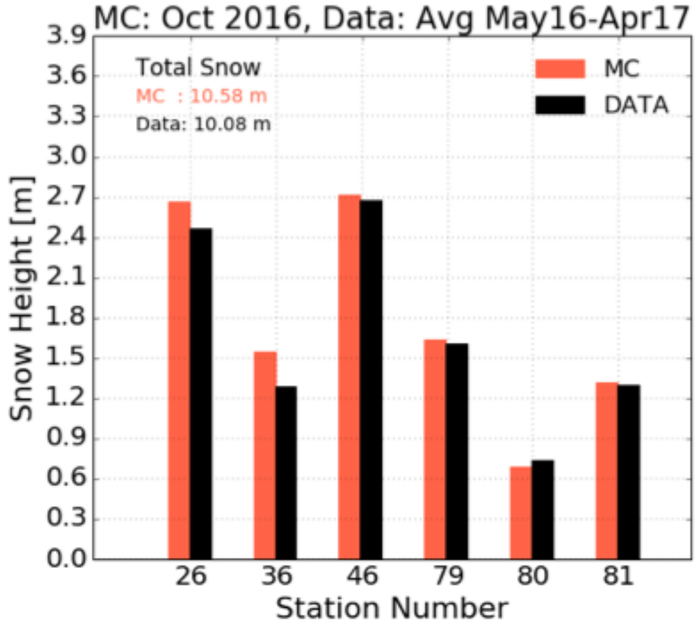
Snow Height









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