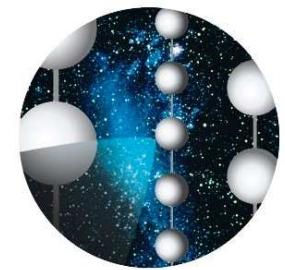




# IceTop Results on Cosmic Rays

Javier G. Gonzalez  
for the IceCube Collaboration

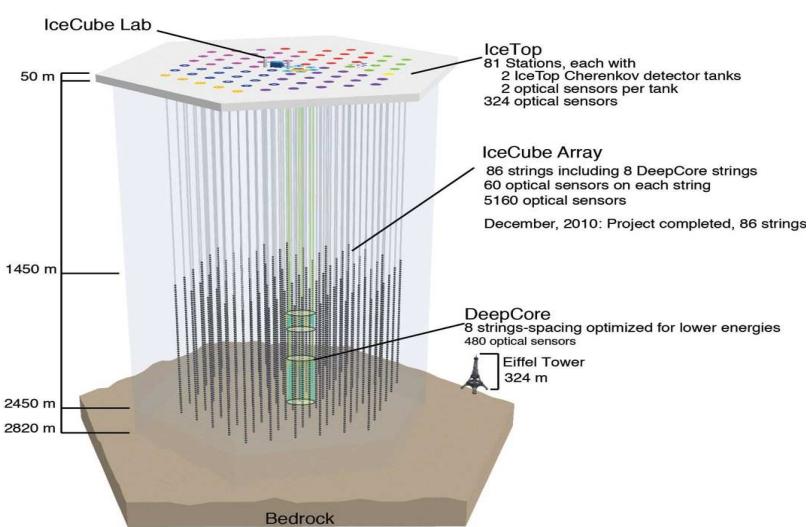
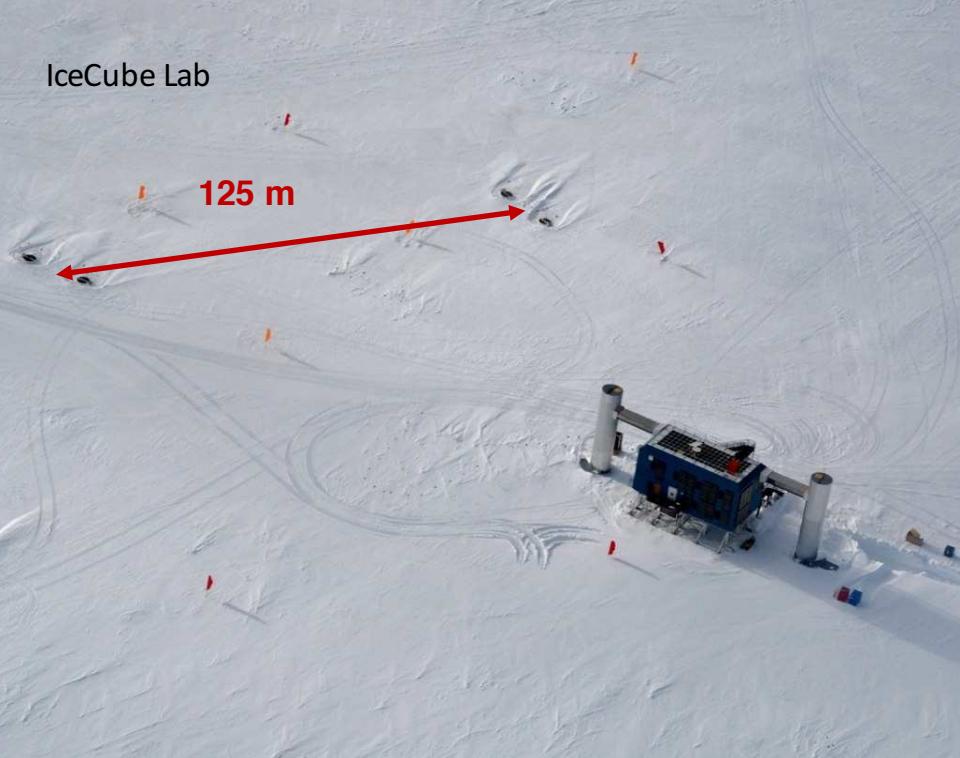


IceCube

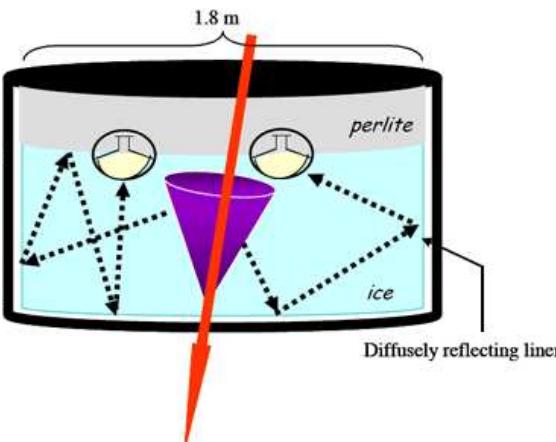
# The IceCube Detector

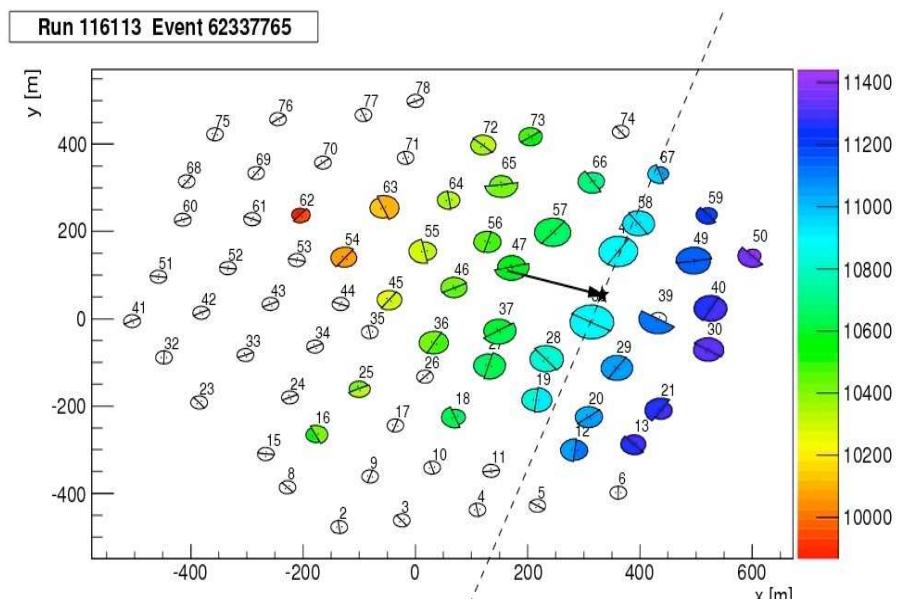
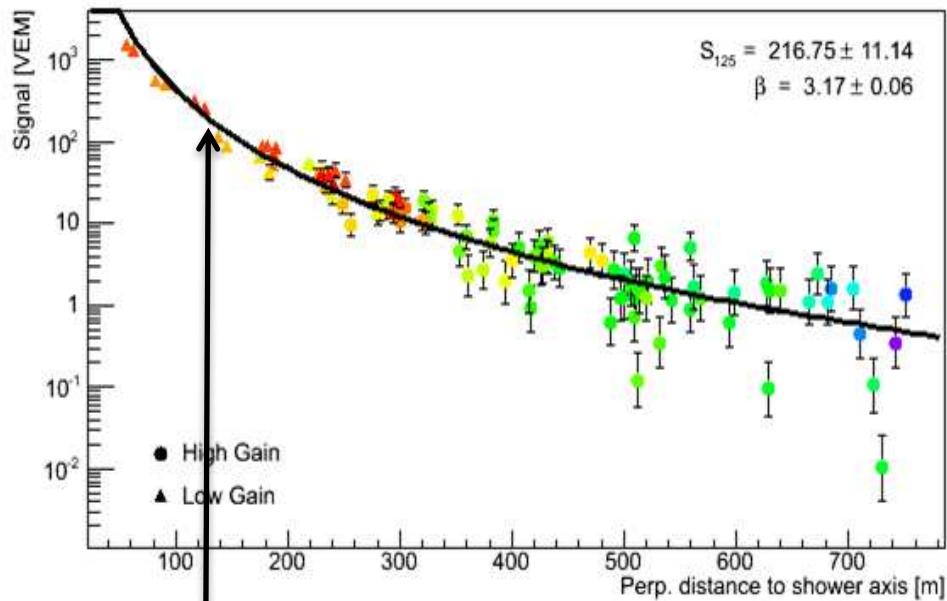


# IceCube Lab



2835 m above sea level  
( $692 \text{ g/cm}^2$ )



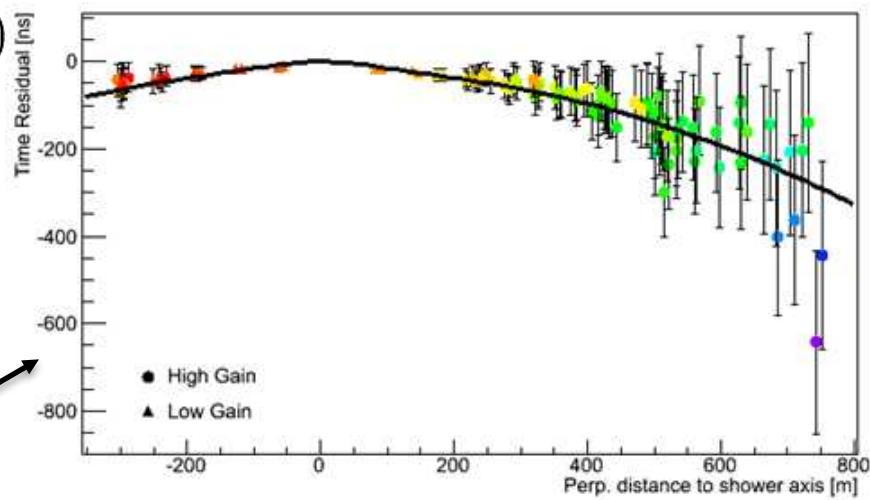


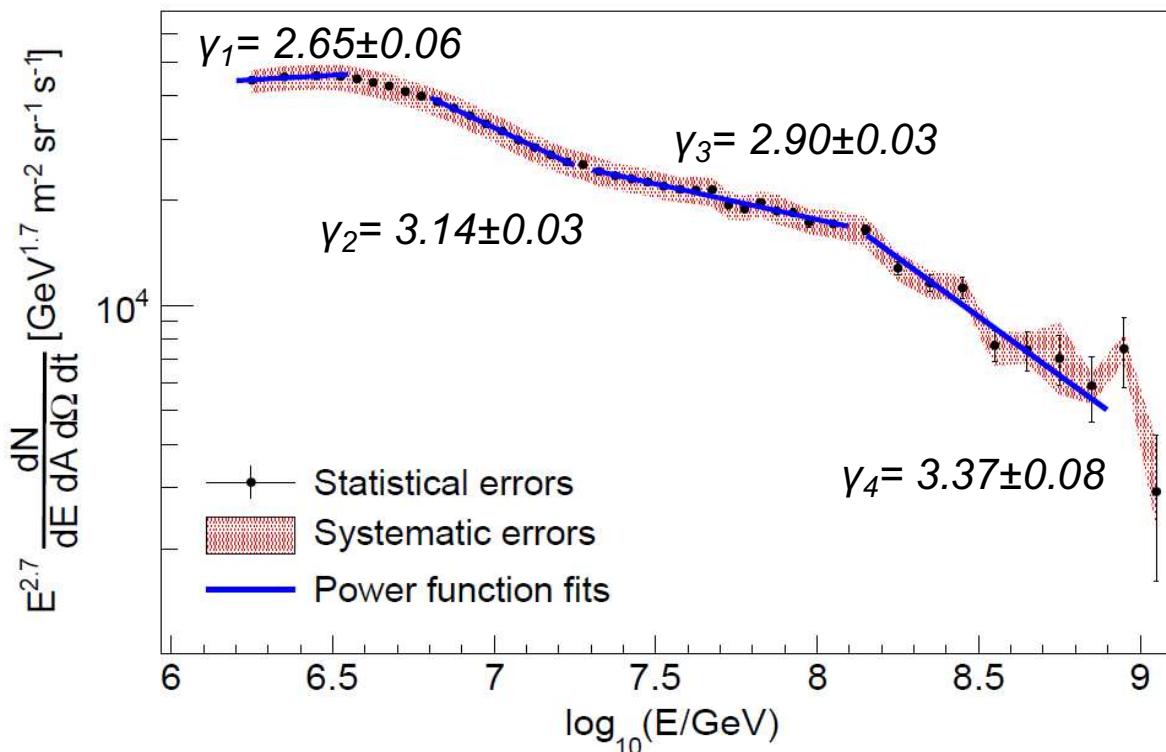
$$S(r) = S_{125} e^{-\frac{d \sec \theta}{\lambda}} \left( \frac{r}{125 \text{ m}} \right)^{-\beta - k \log \left( \frac{r}{125 \text{ m}} \right)}$$

Attenuation due to snow

$$t(x) = t_0 + \left( \frac{x_c - x}{c} \right) \cdot \mathbf{n} + \Delta t(R)$$

$$\Delta t(R) = aR^2 + b \left( \exp \left( -\frac{R^2}{2\sigma^2} \right) - 1 \right)$$





- We measured the energy spectrum in 1.58 PeV to 1.26 EeV energy range.
- The spectrum does not follow a simple power law above the knee up to 1 EeV.
- We observe a spectral hardening at  $18 \pm 2$  PeV.  
(124800 events expected, 139880 observed)
- The spectrum steepens at  $130 \pm 30$  PeV.  
(4213 events expected, 3673 observed)

Phys. Rev. D 88, 042004 (2013),  
URL: <http://link.aps.org/doi/10.1103/PhysRevD.88.042004>  
DOI: 10.1103/PhysRevD.88.042004

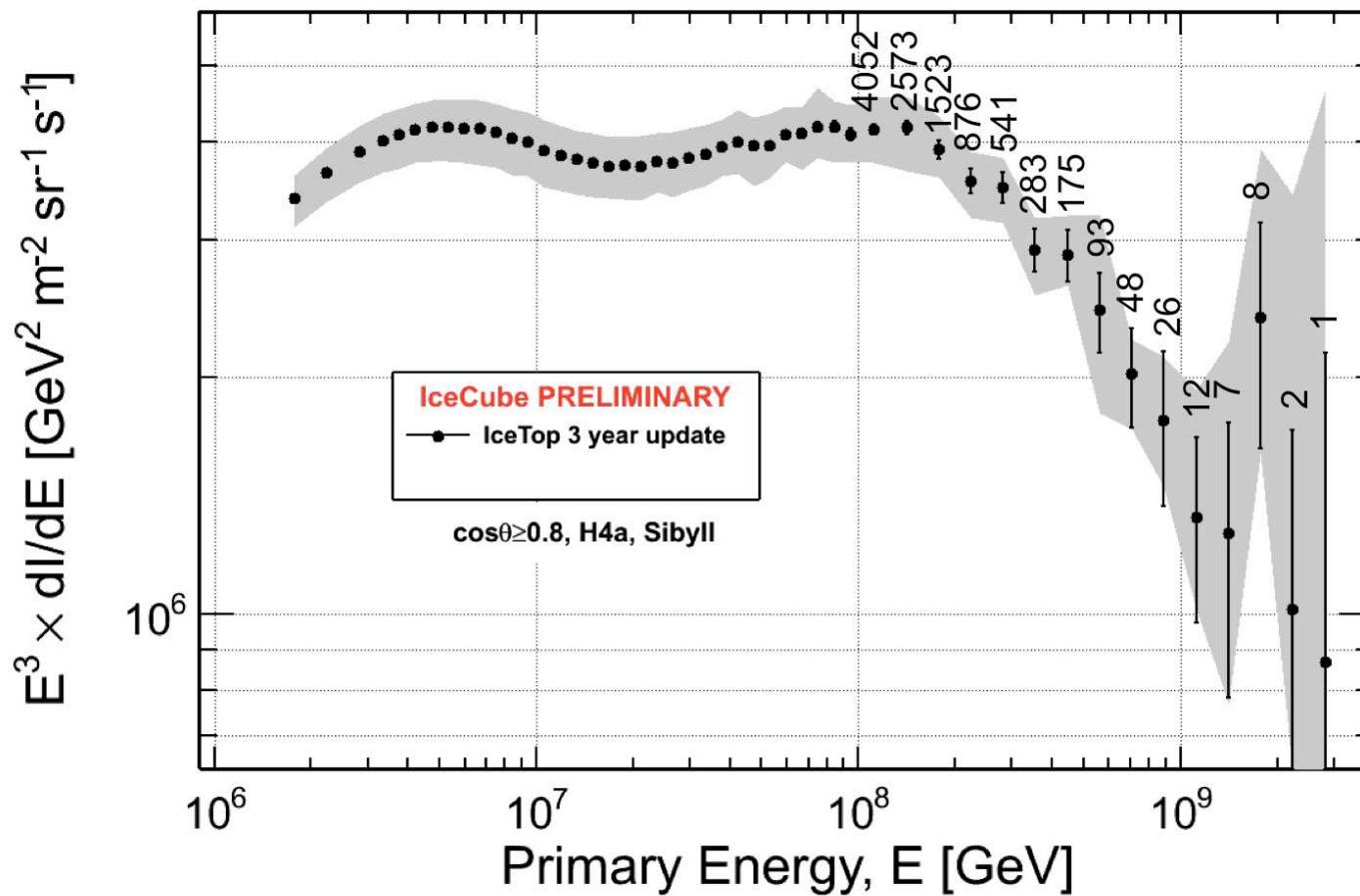


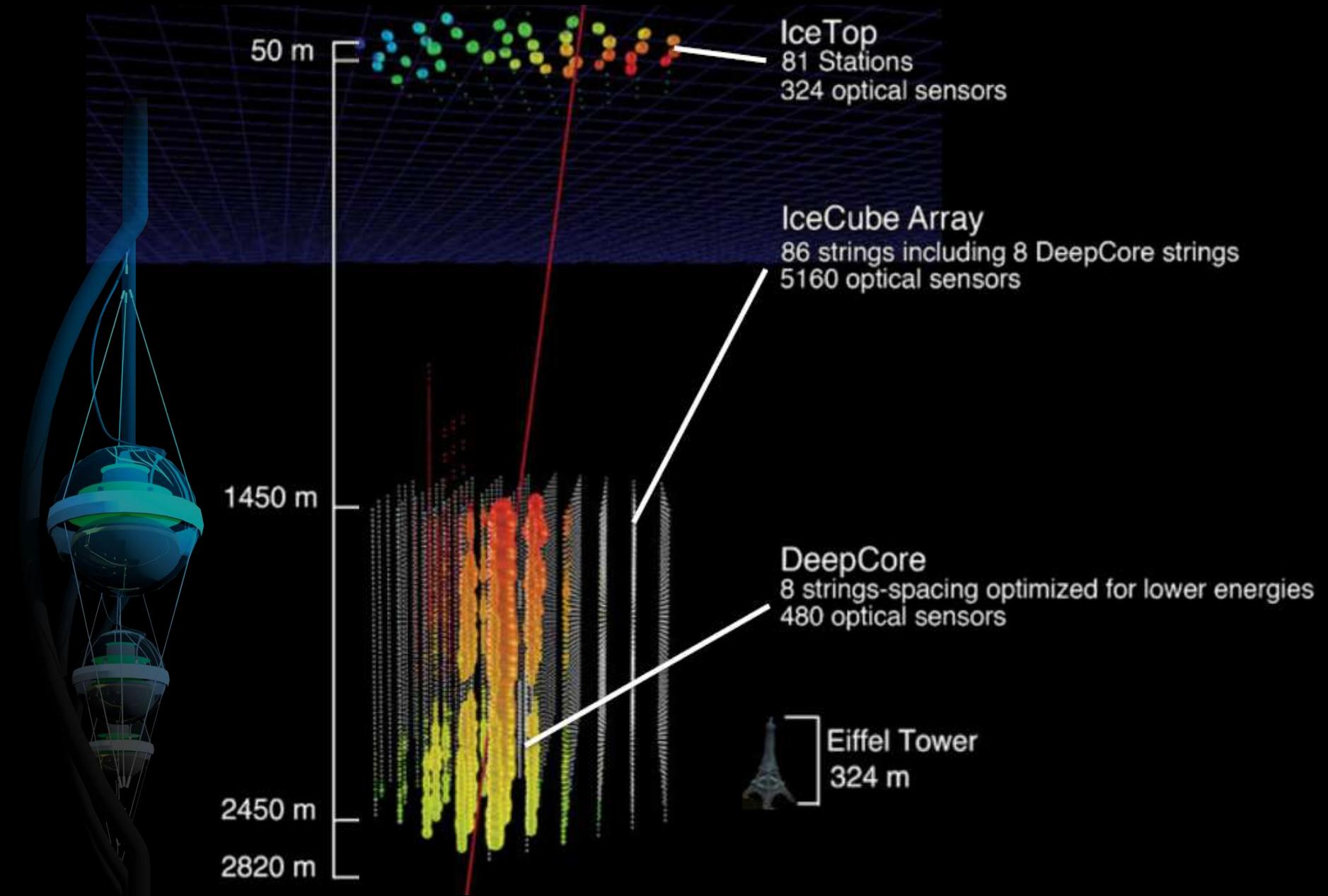
	3 PeV	30 PeV
Energy scale (VEM calibration)	±4%	±5%
Snow Correction $\lambda = 2.1 \pm 0.2m$	±5%	±6%
Interaction models (a)	-2%	-4%
Composition (b)	±7%	±7%
Ground pressure (c)	±2%	±0.5%

<sup>a</sup> From the difference between QGSJet-II-03 and SYBILL 2.1.

<sup>b</sup> Fixed for all energies. Given by the differences between spectra at different zenith angles.

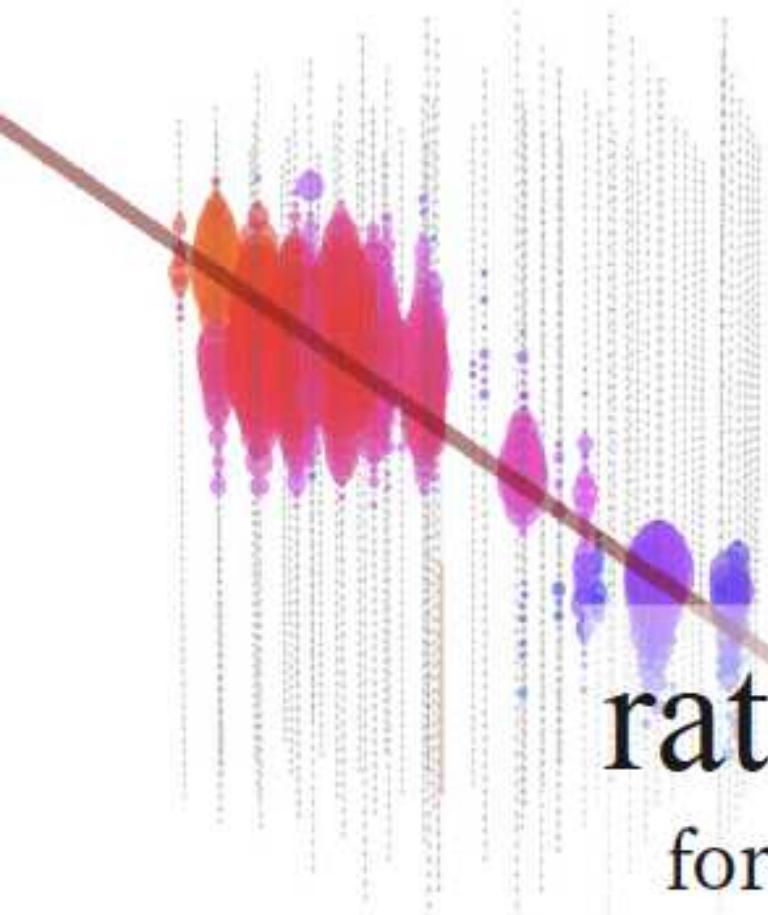
<sup>c</sup> From difference between high/low pressure sub-samples (690 hPa/670 hPa).







High Energy Muon



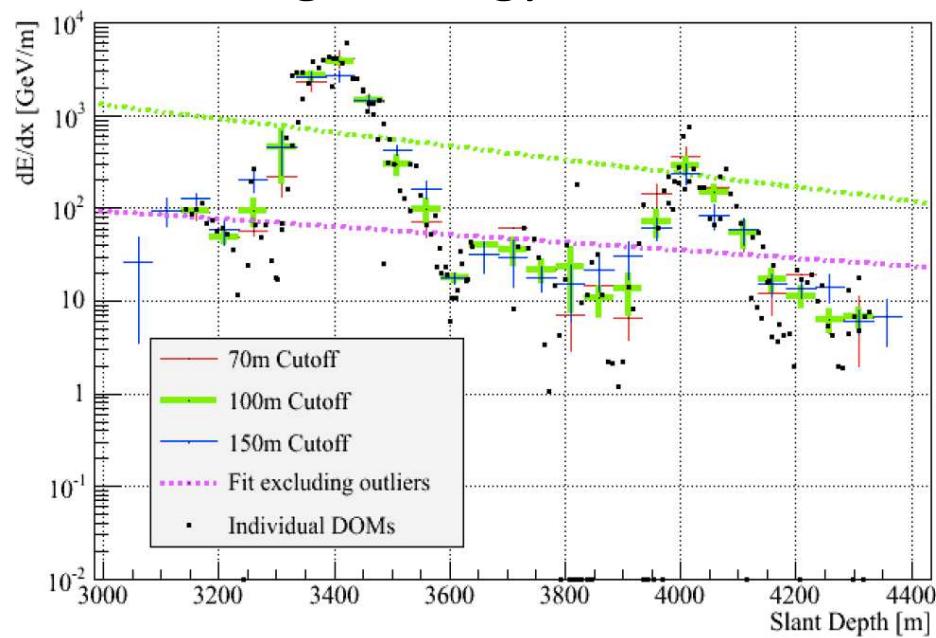
High Multiplicity Muon Bundle



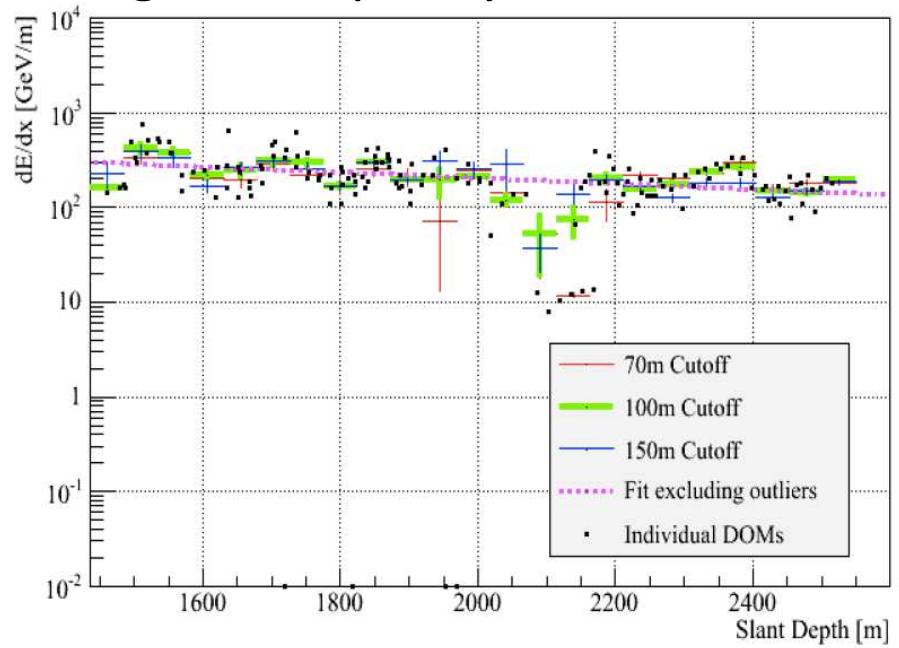
$\text{ratio} \approx 1:10$   
for bright events

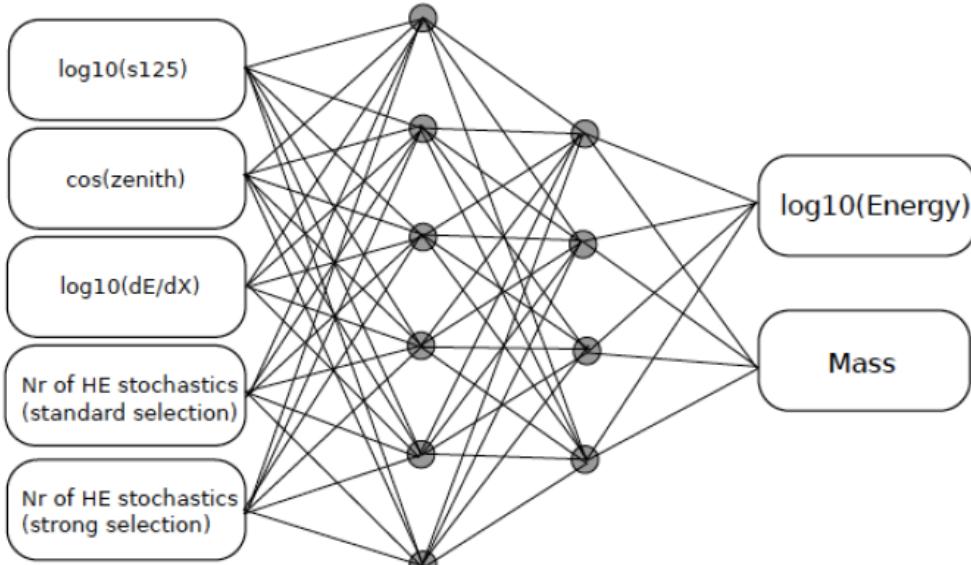
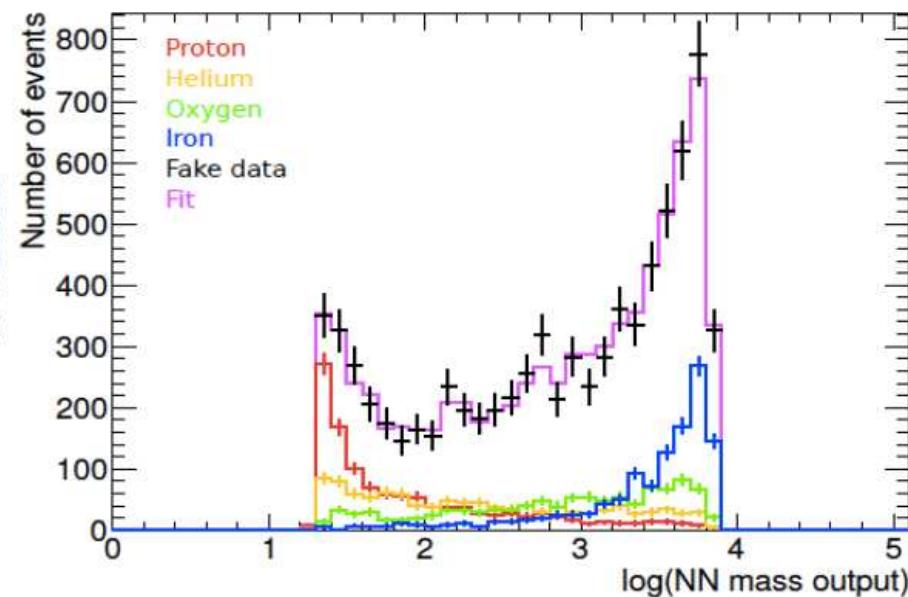
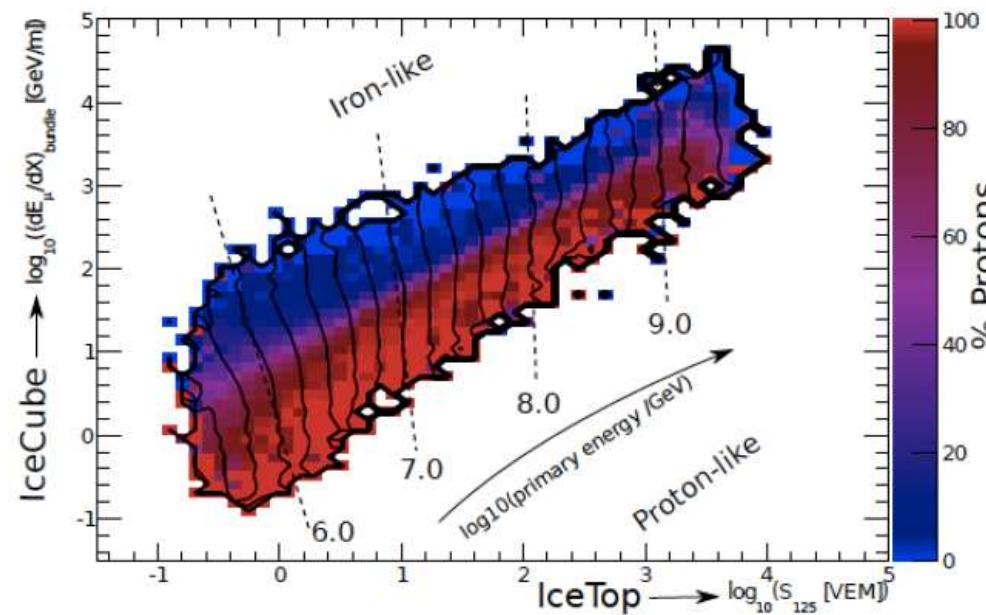


## High Energy Muon



## High Multiplicity Muon Bundle

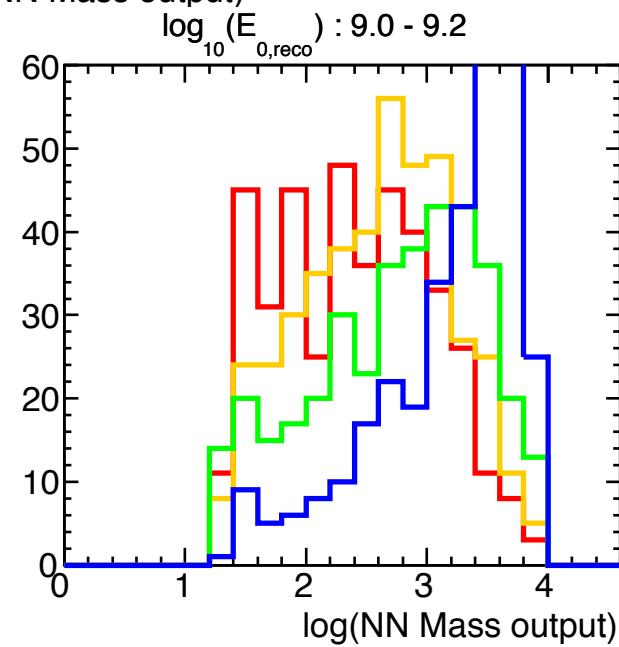
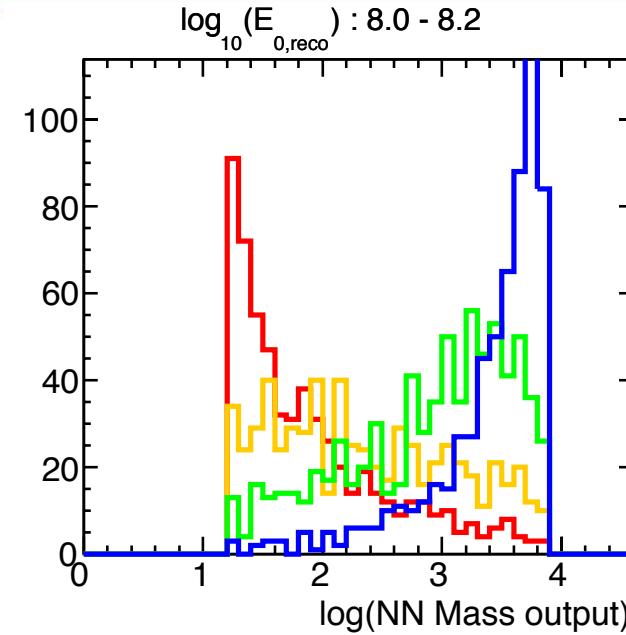
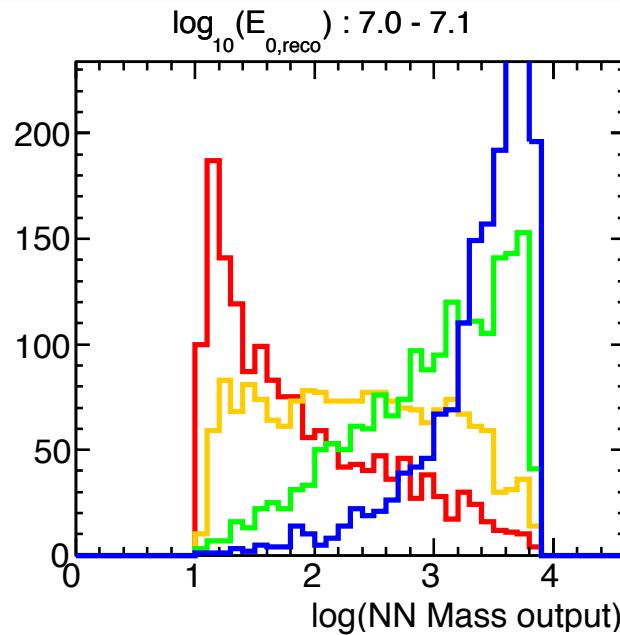


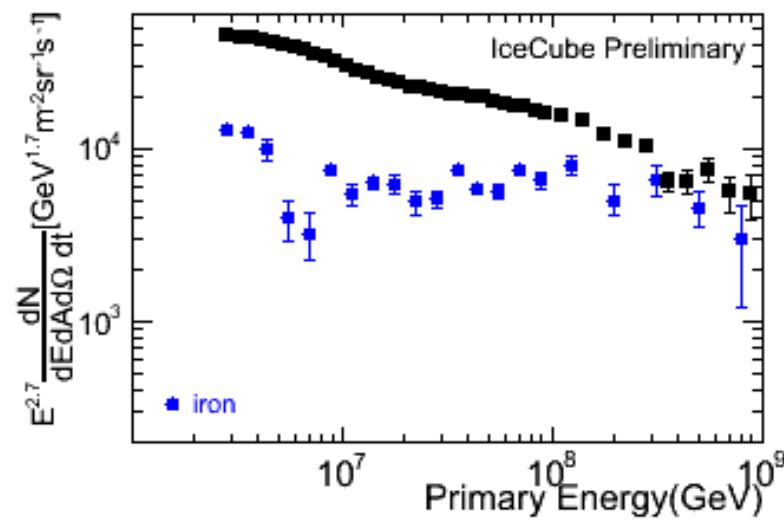
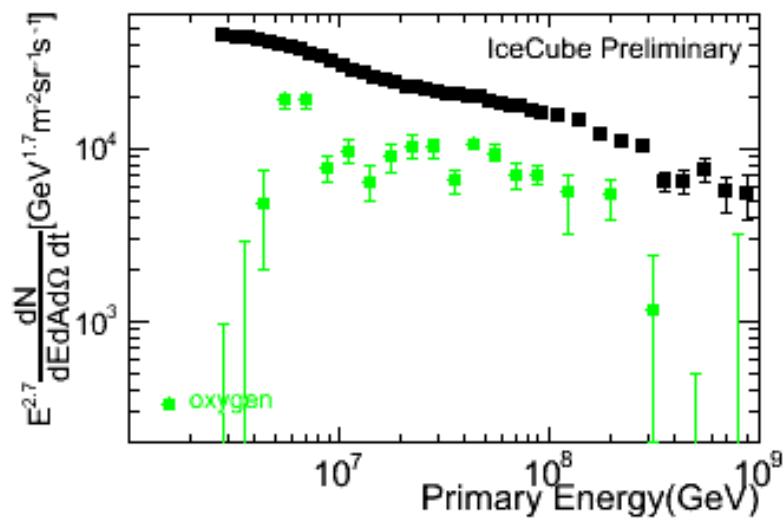
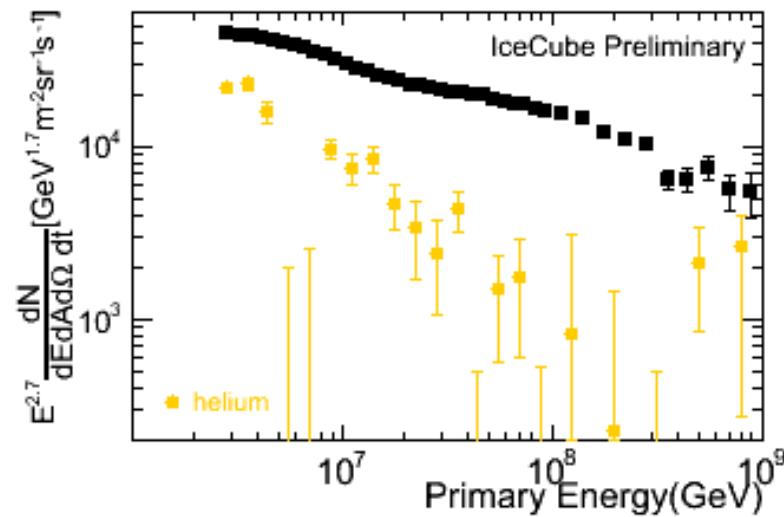
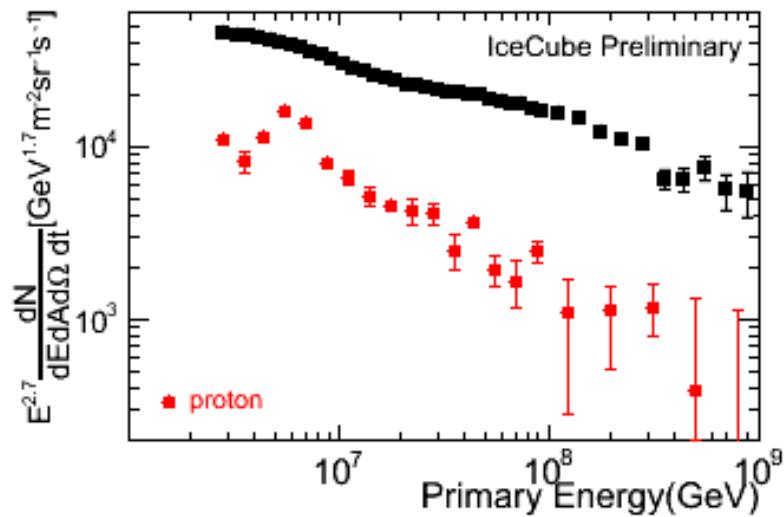


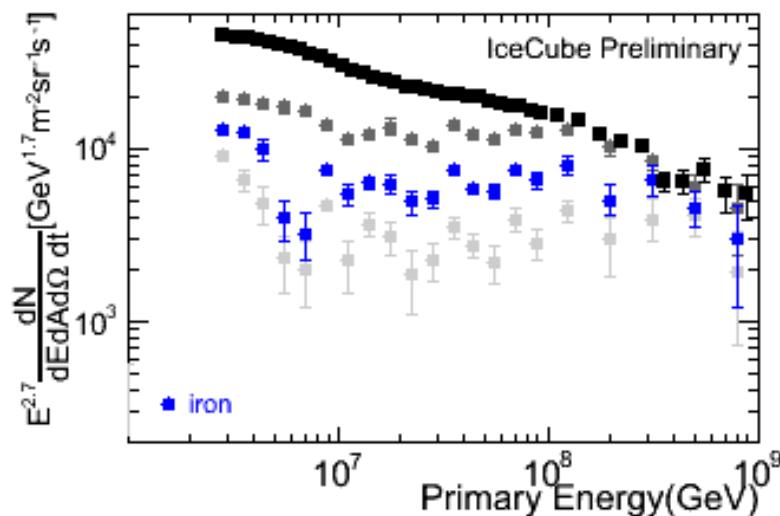
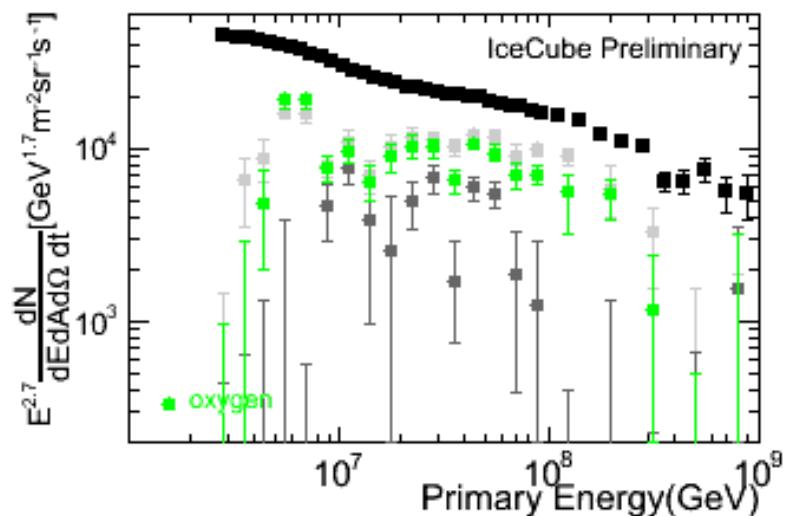
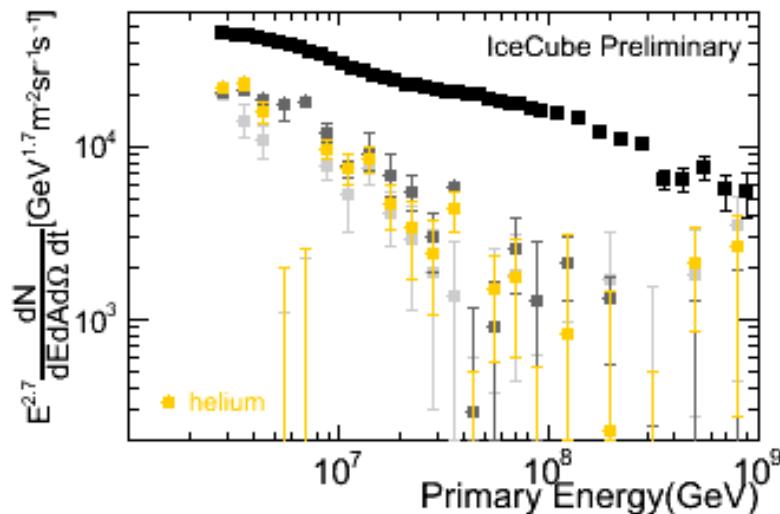
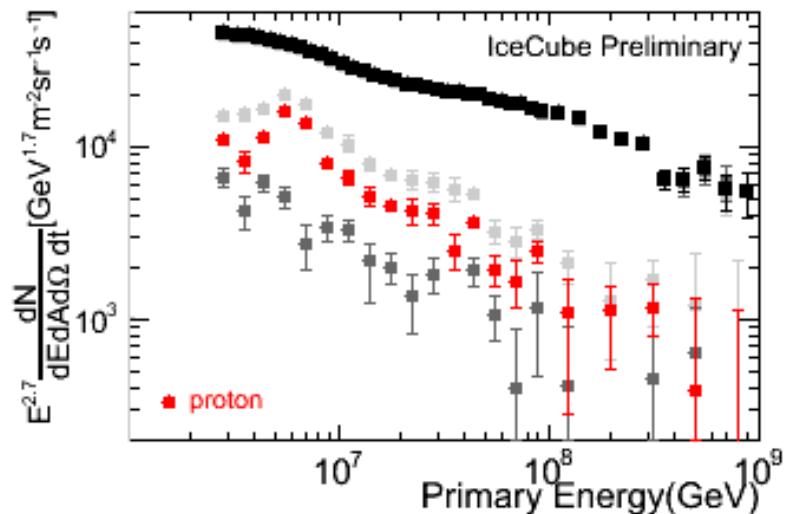
Template histograms for 4 mass groups in one energy bin for a fake dataset scrambled from MC.

5-6-4-2 Neural Network to map 5 observables to Primary Energy and Mass

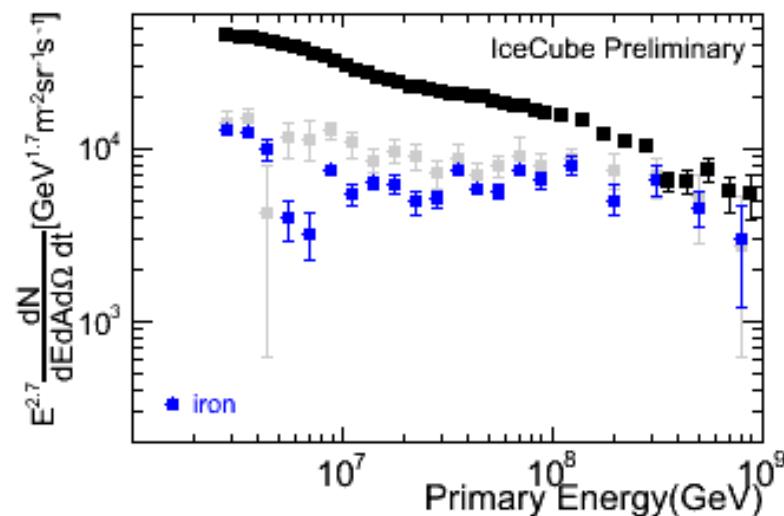
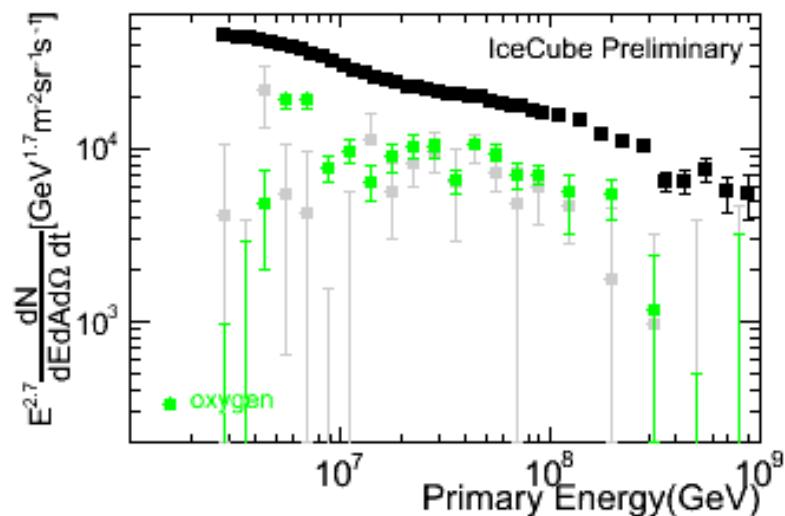
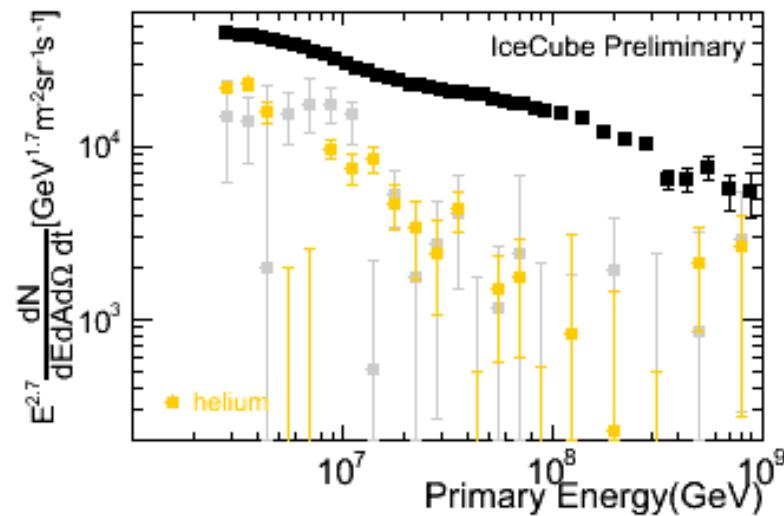
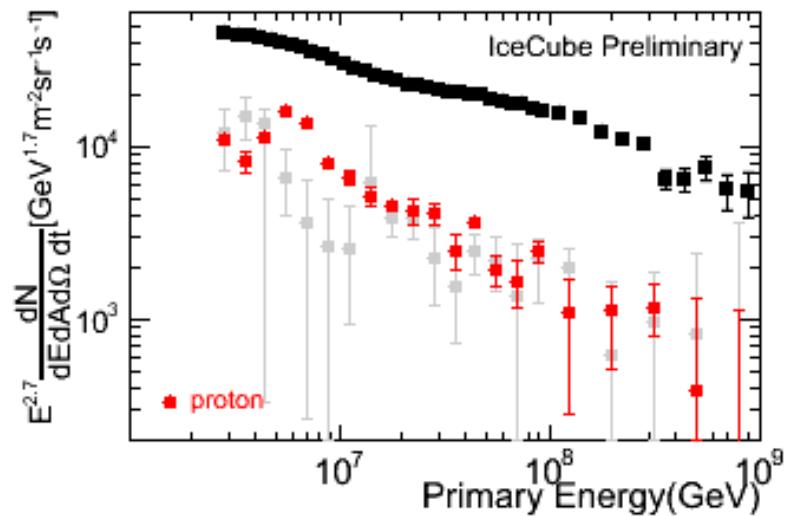
Energy spectrum directly from NN output  
Composition from fitting data in  $E_{\text{reco}}$  bins to template histograms (H,He,O,Fe) from NN mass output



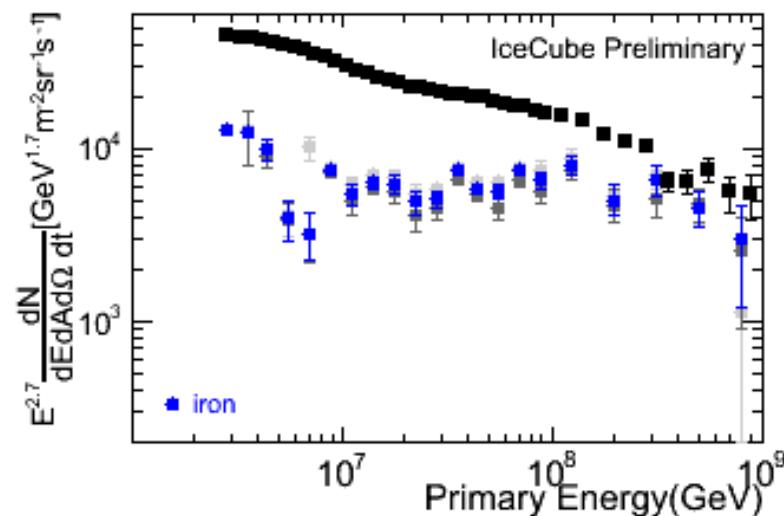
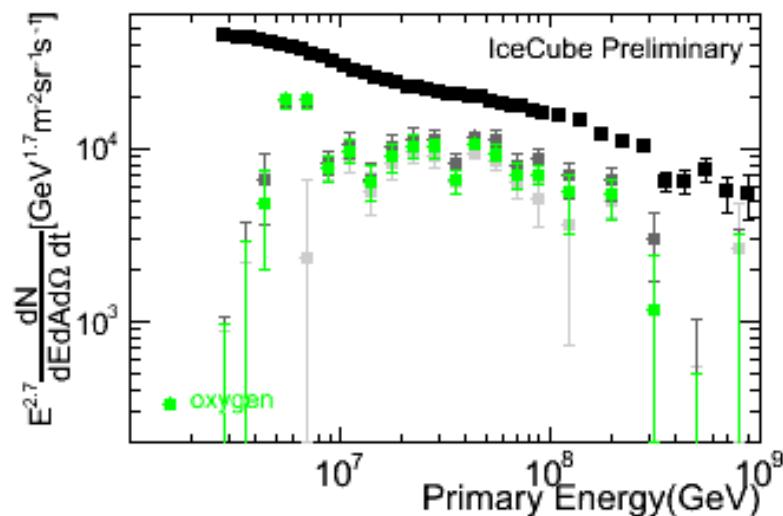
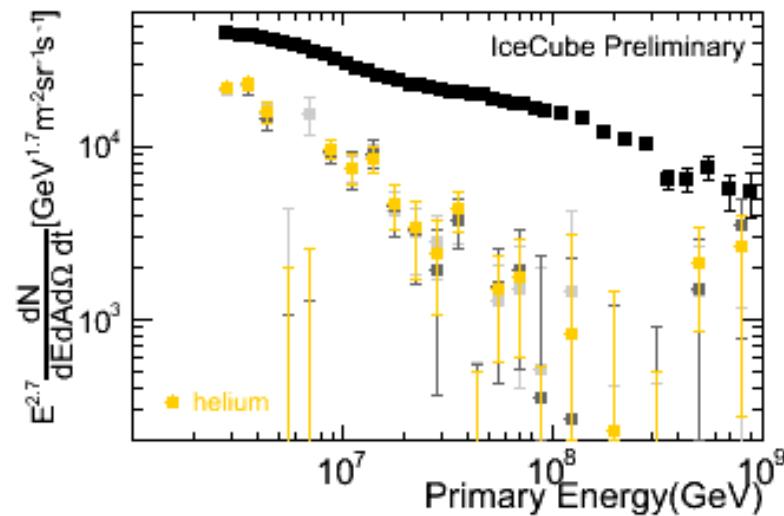
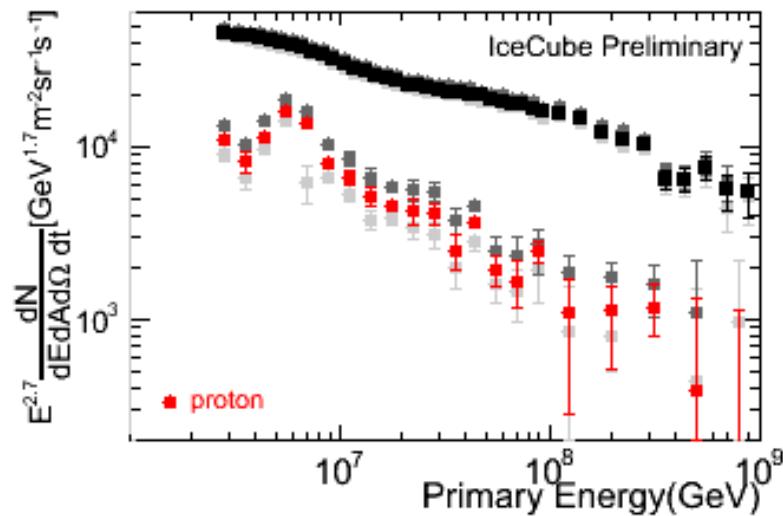




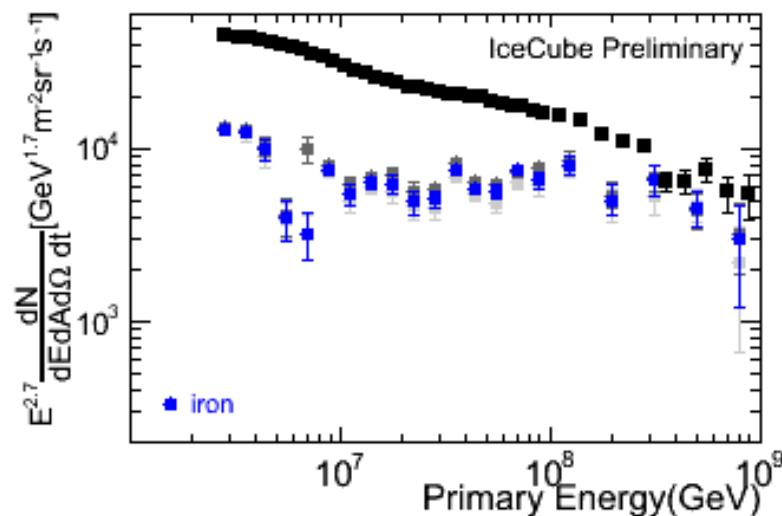
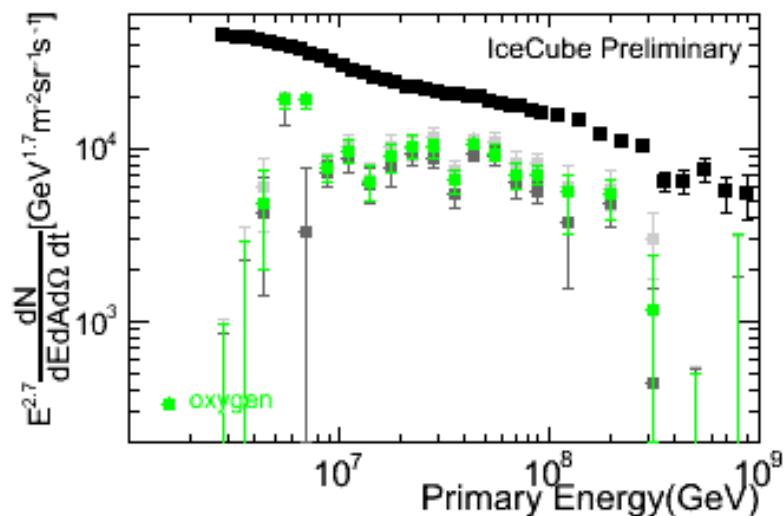
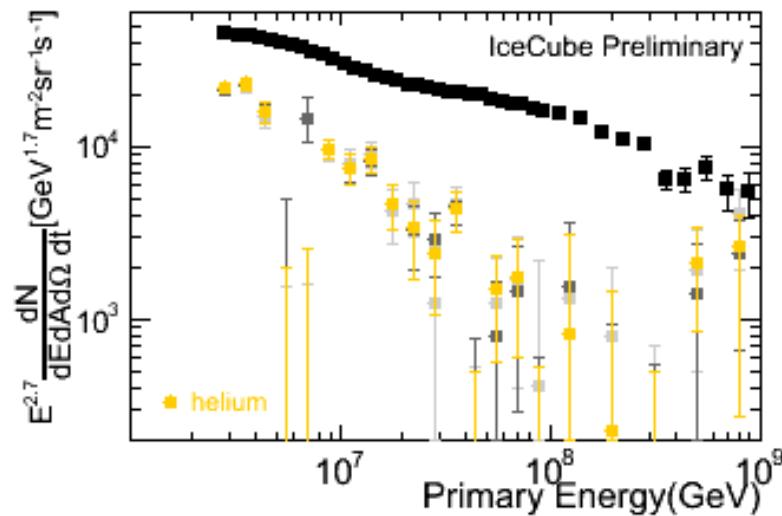
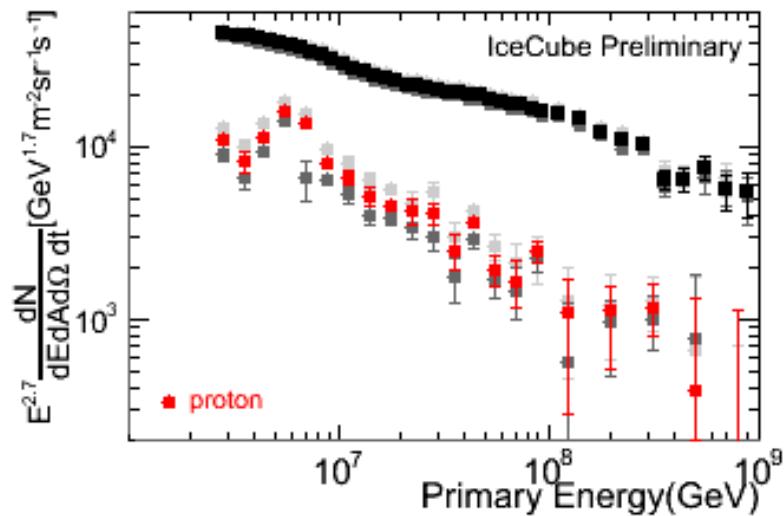
light yield uncertainty (dark gray: -12.5%, light gray: +9.6%).



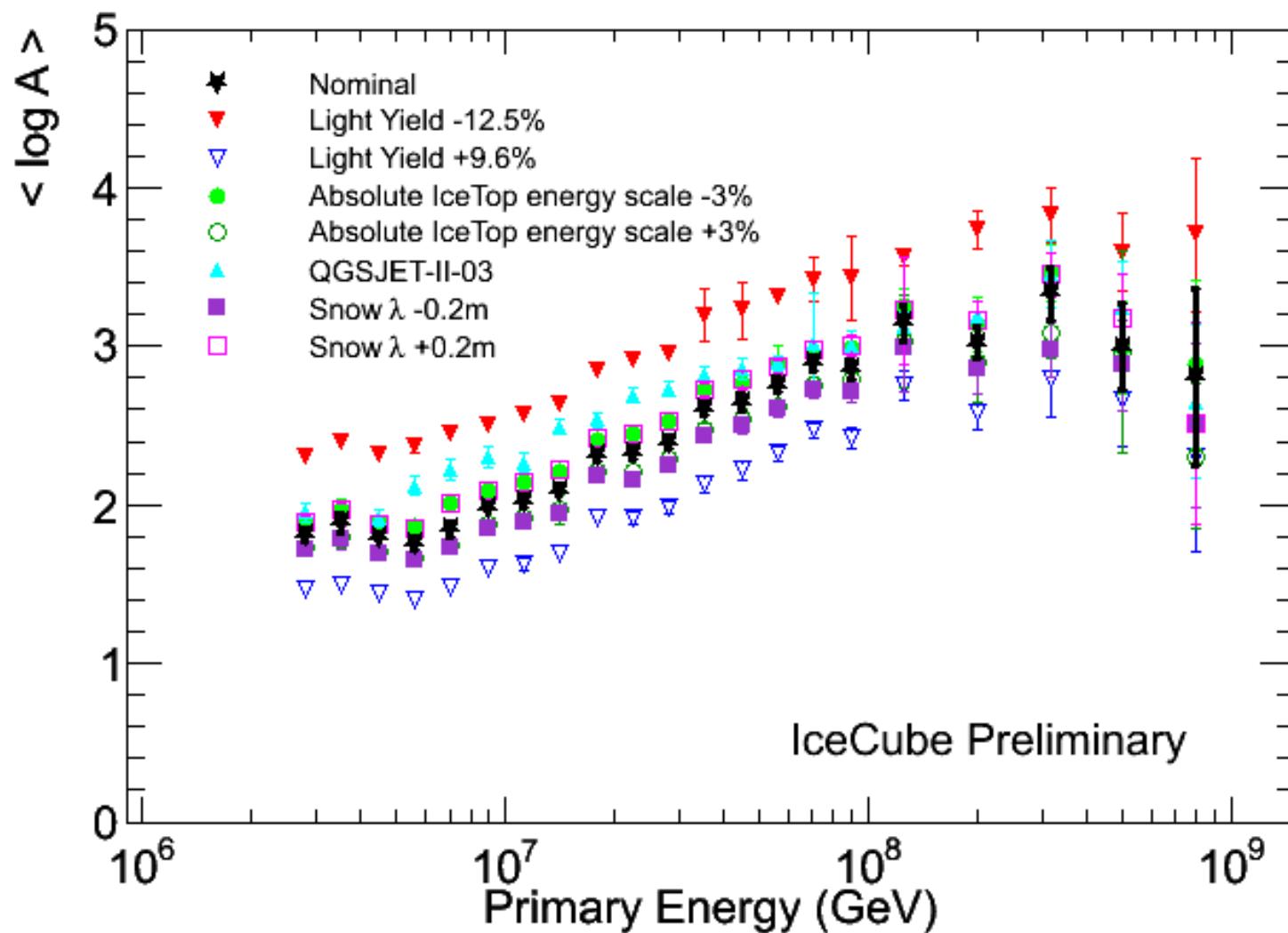
QGSJetII-03 energy spectra in light gray.

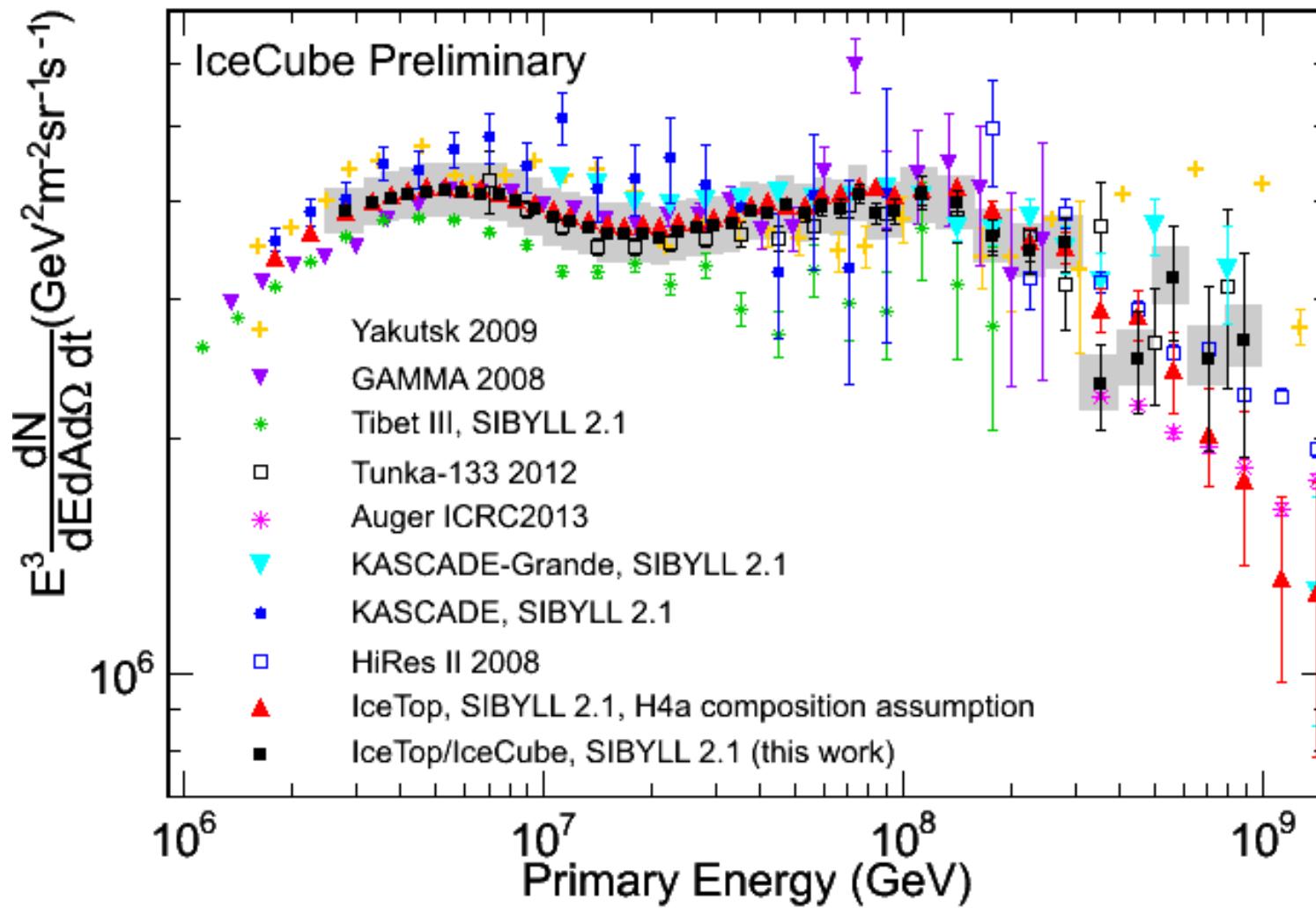


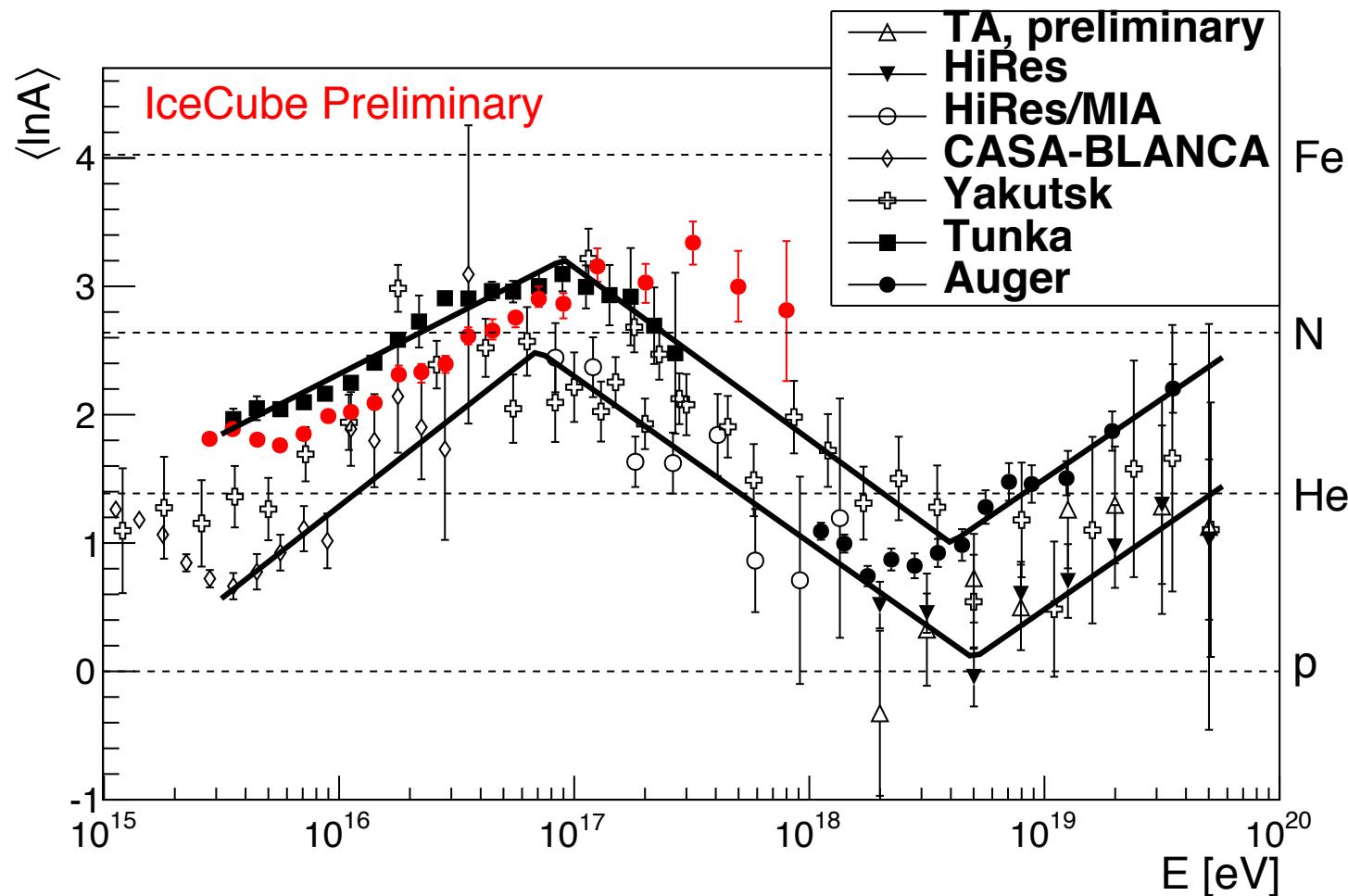
snow correction uncertainty (dark gray: -0.2m, light gray: +0.2m)



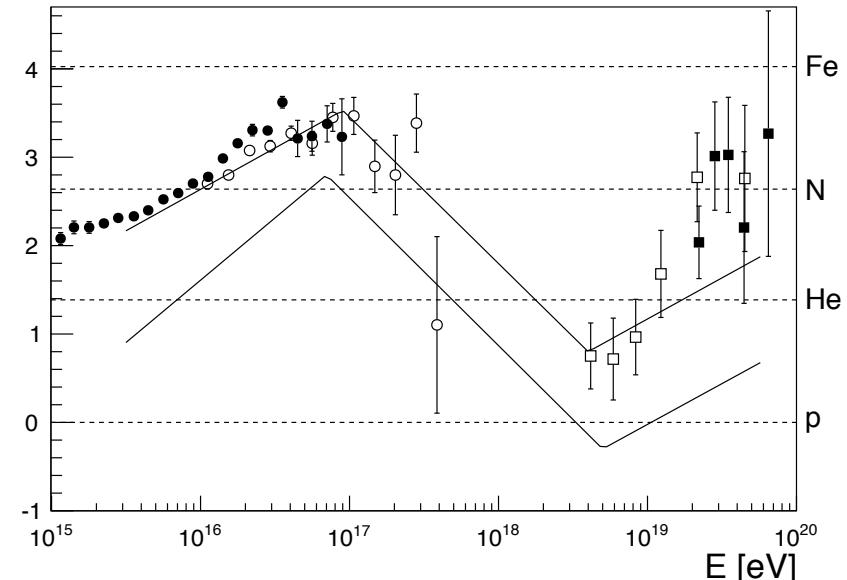
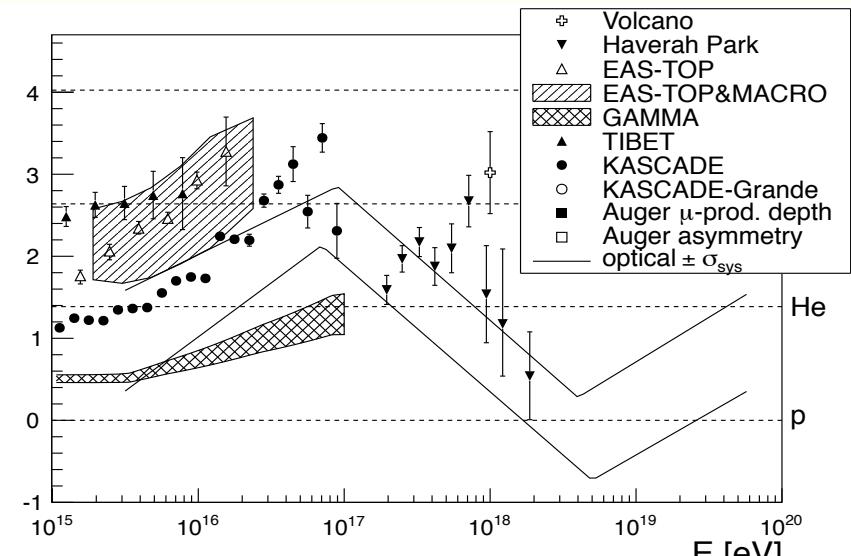
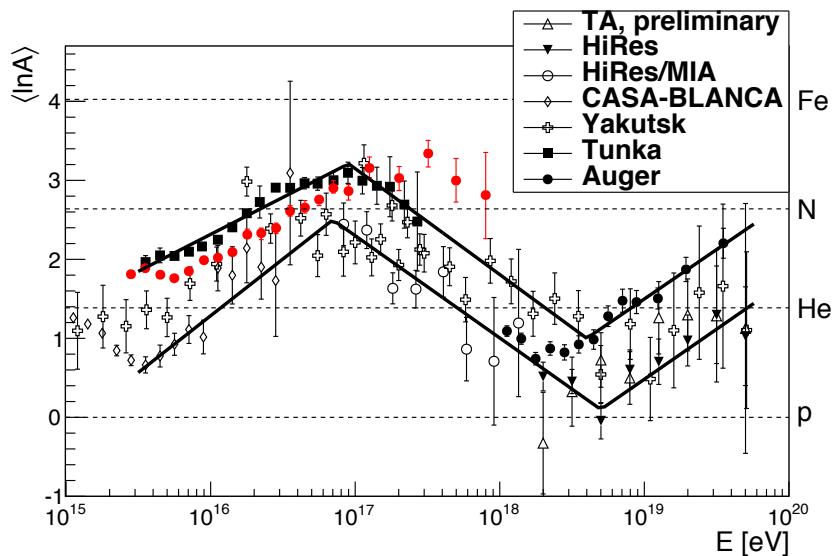
IceTop energy scale uncertainty (dark gray: -3%, light gray: +3%) 17



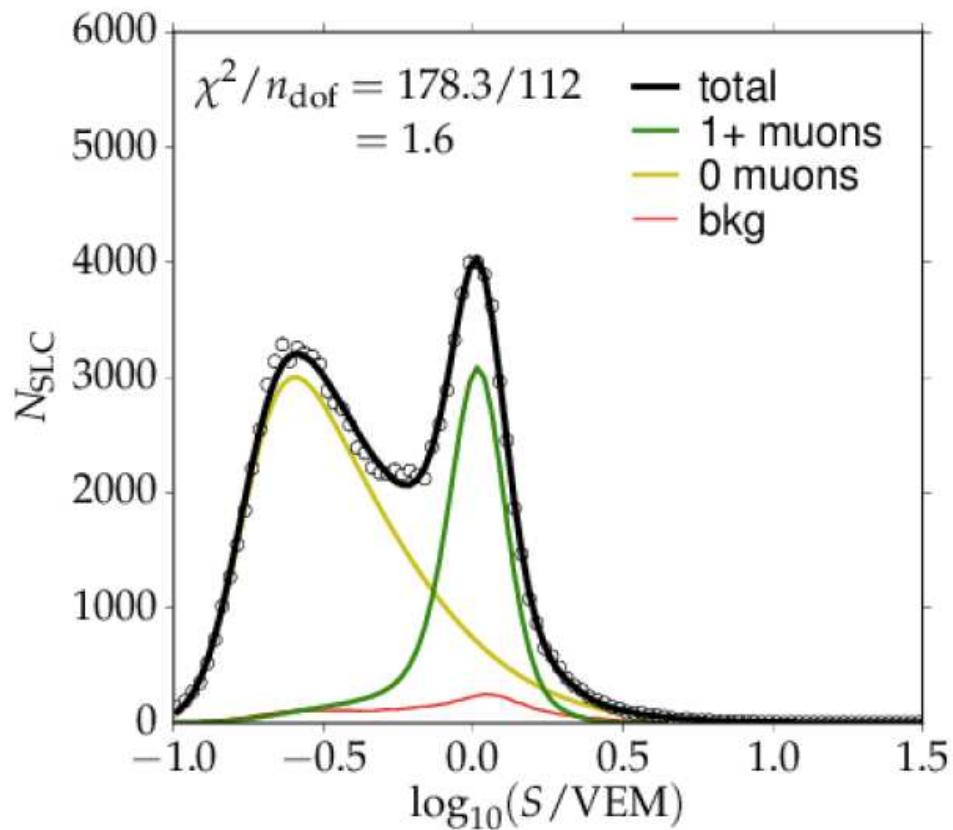
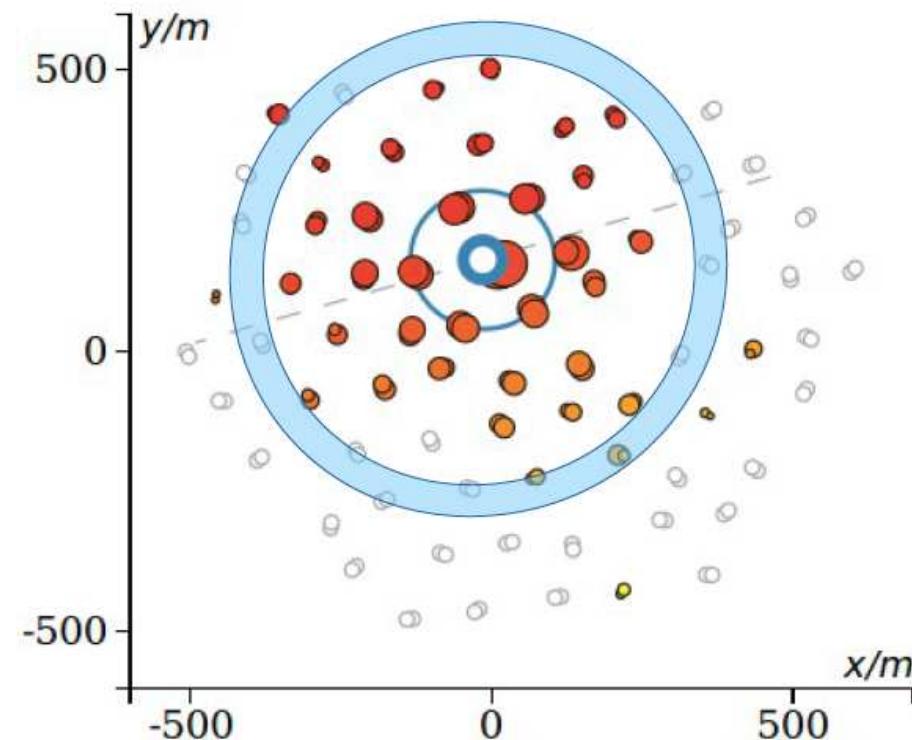




Compared to Figure 13 from Kampert & Unger,  
Astropart.Phys. 35 (2012) 660-678  
(Sibyll 2.1)



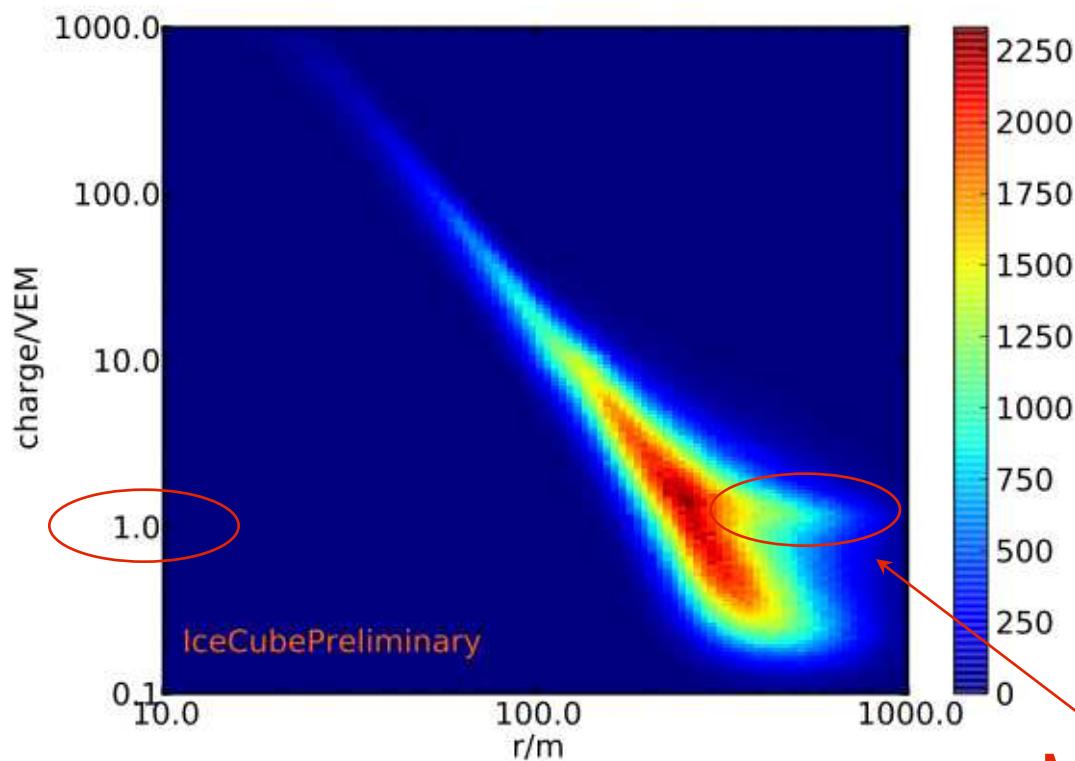
Sibyll 2.1



$$p_{\mu \text{ hit}} = \frac{N_{\mu \geq 1}}{N_{\text{tanks}}} = 1 - e^{-\langle N_\mu \rangle}$$



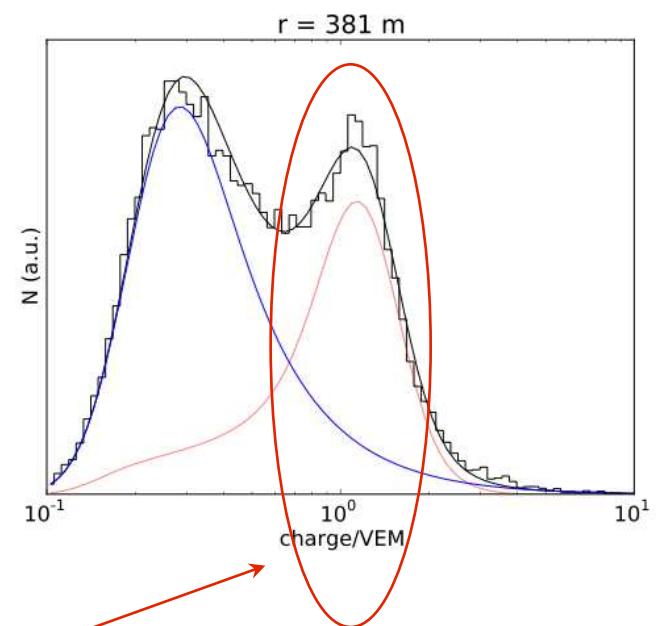
# Charge-Distance to Axis Distribution

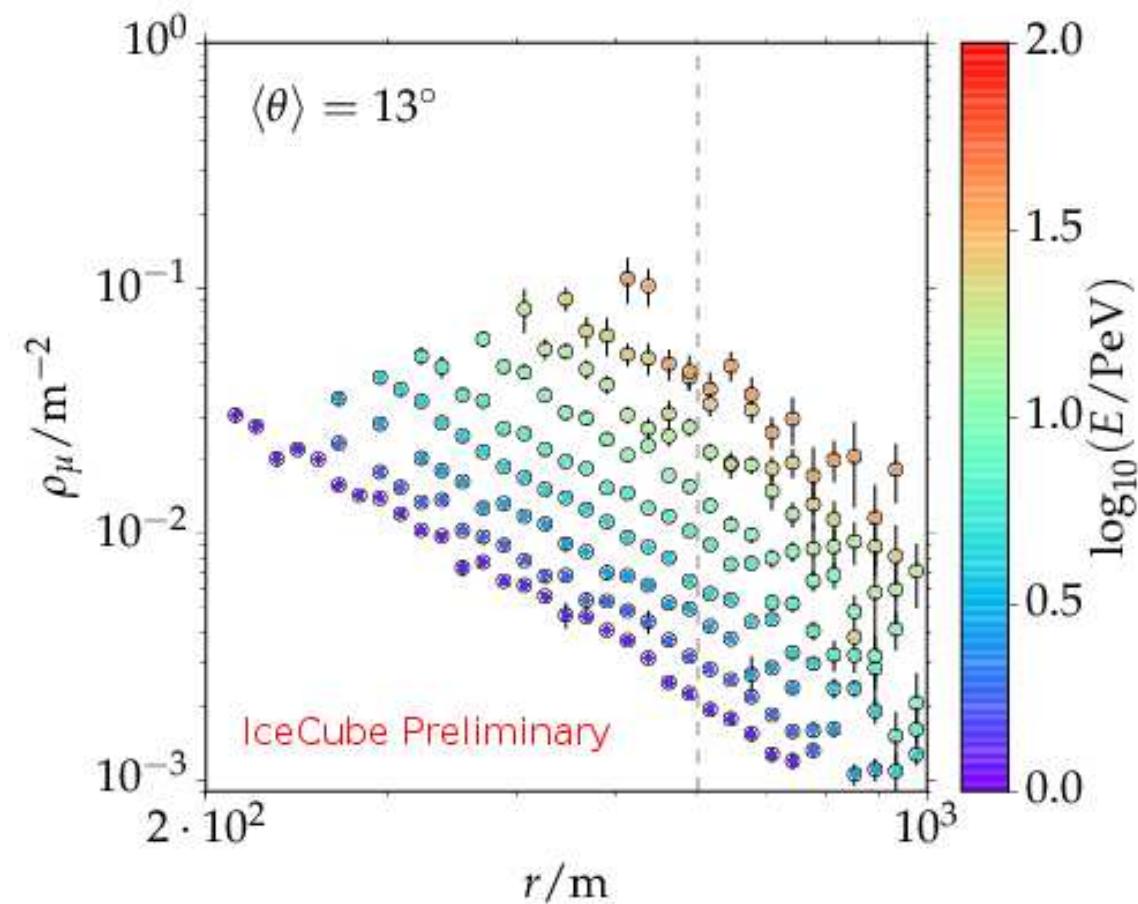
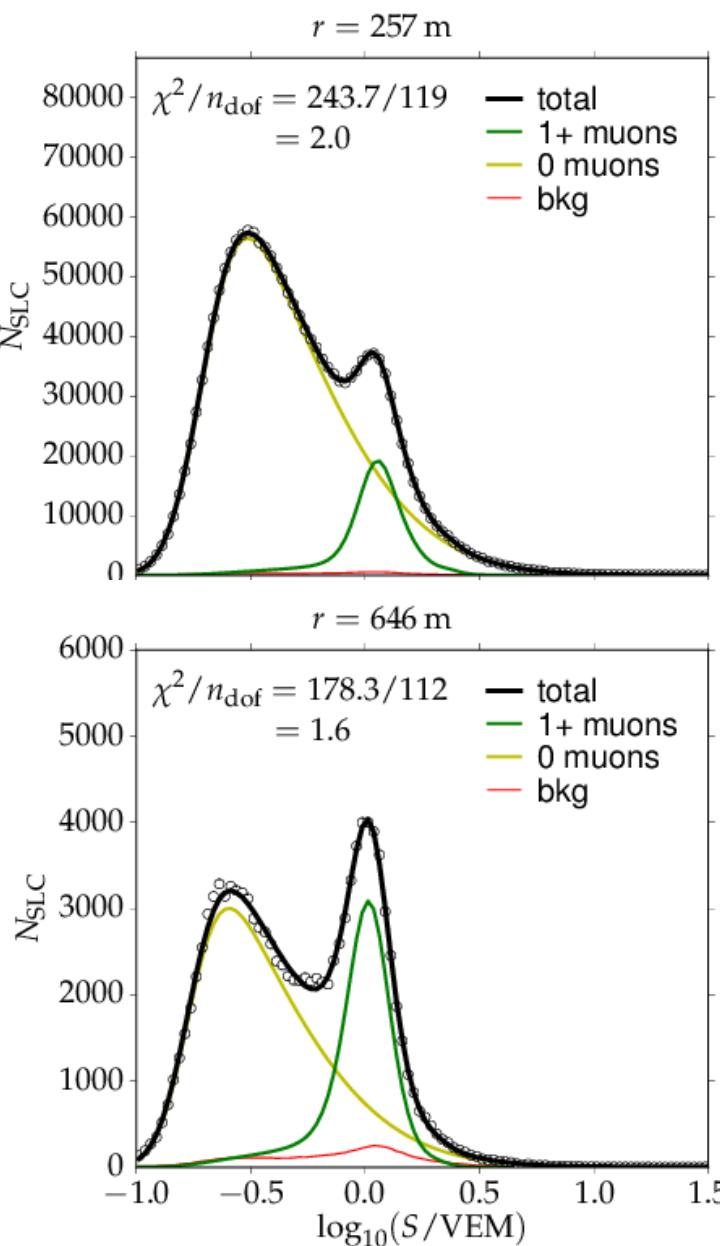


$28^\circ < \theta < 32^\circ$

Muons

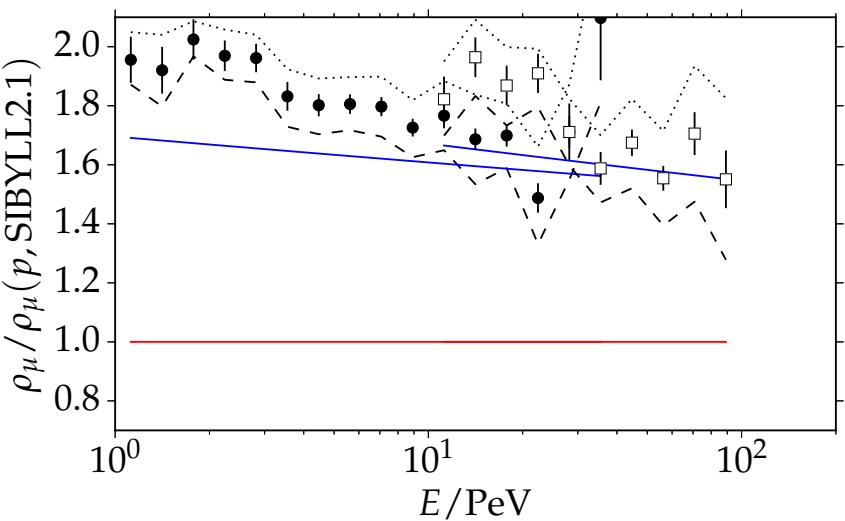
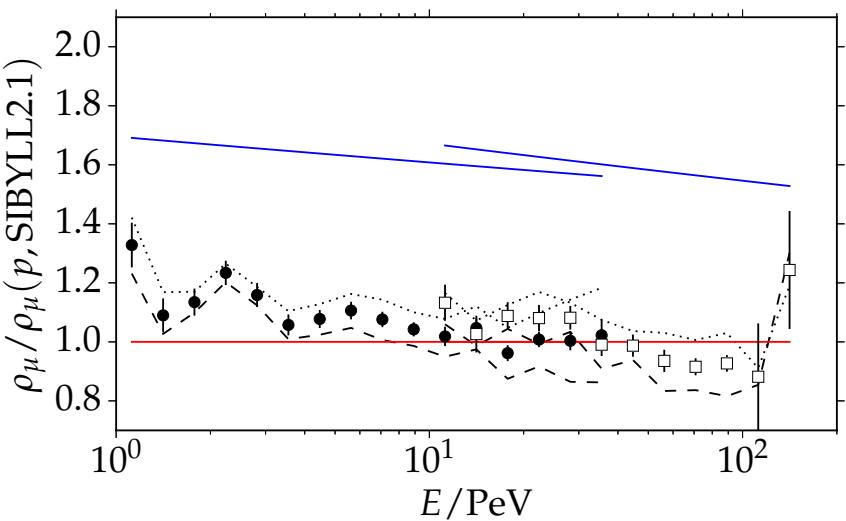
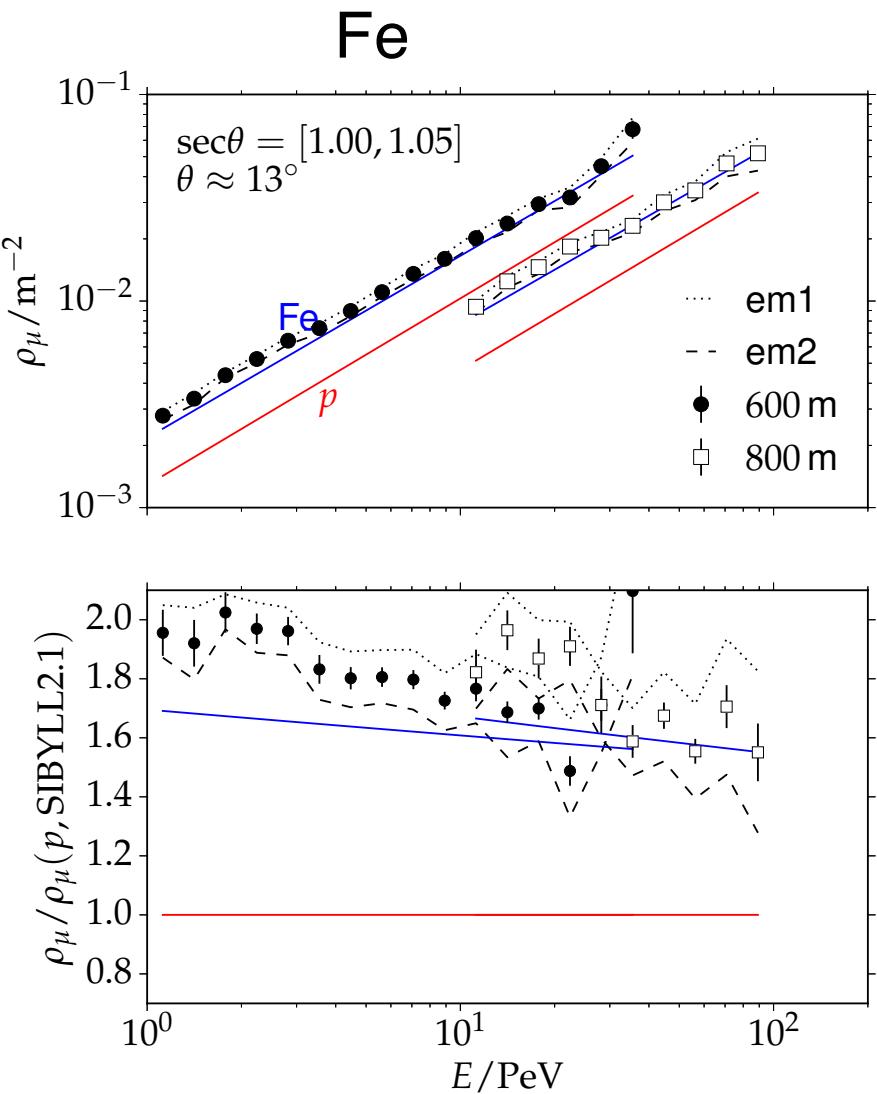
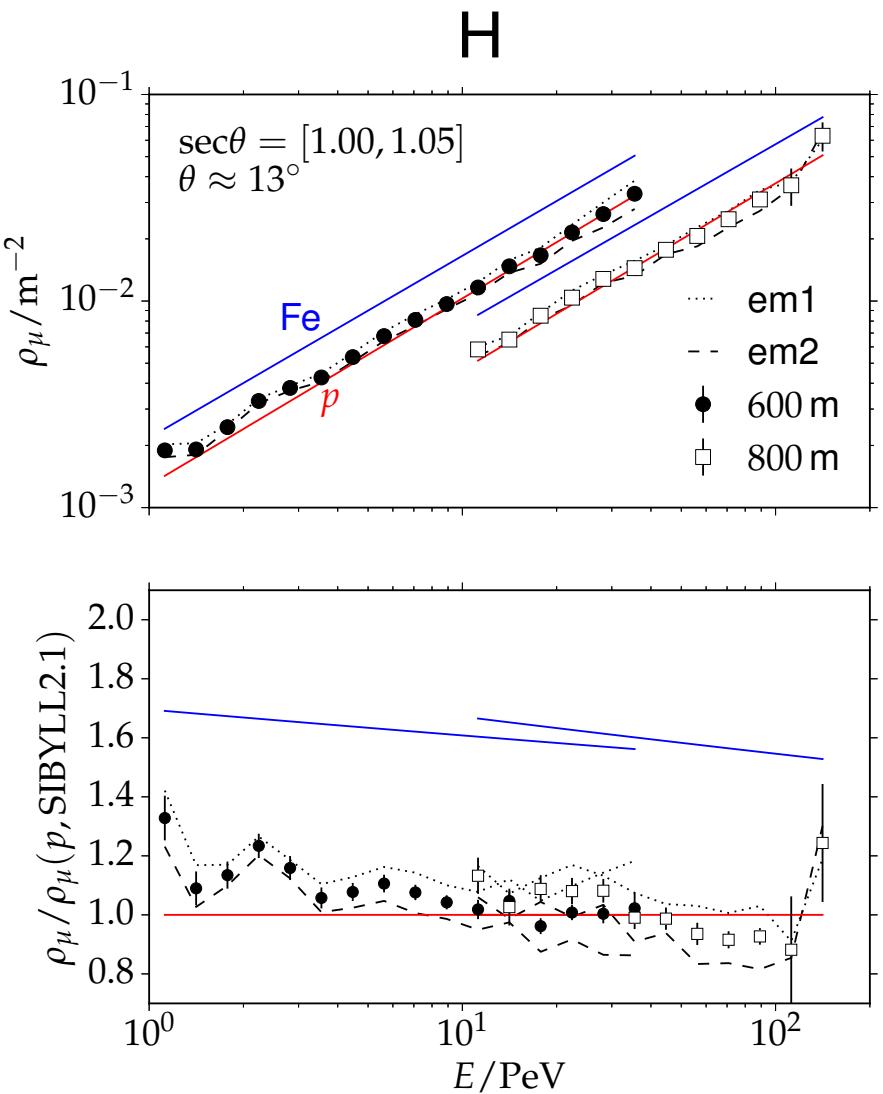
$10 \text{ PeV} < E < 12.6 \text{ PeV}$

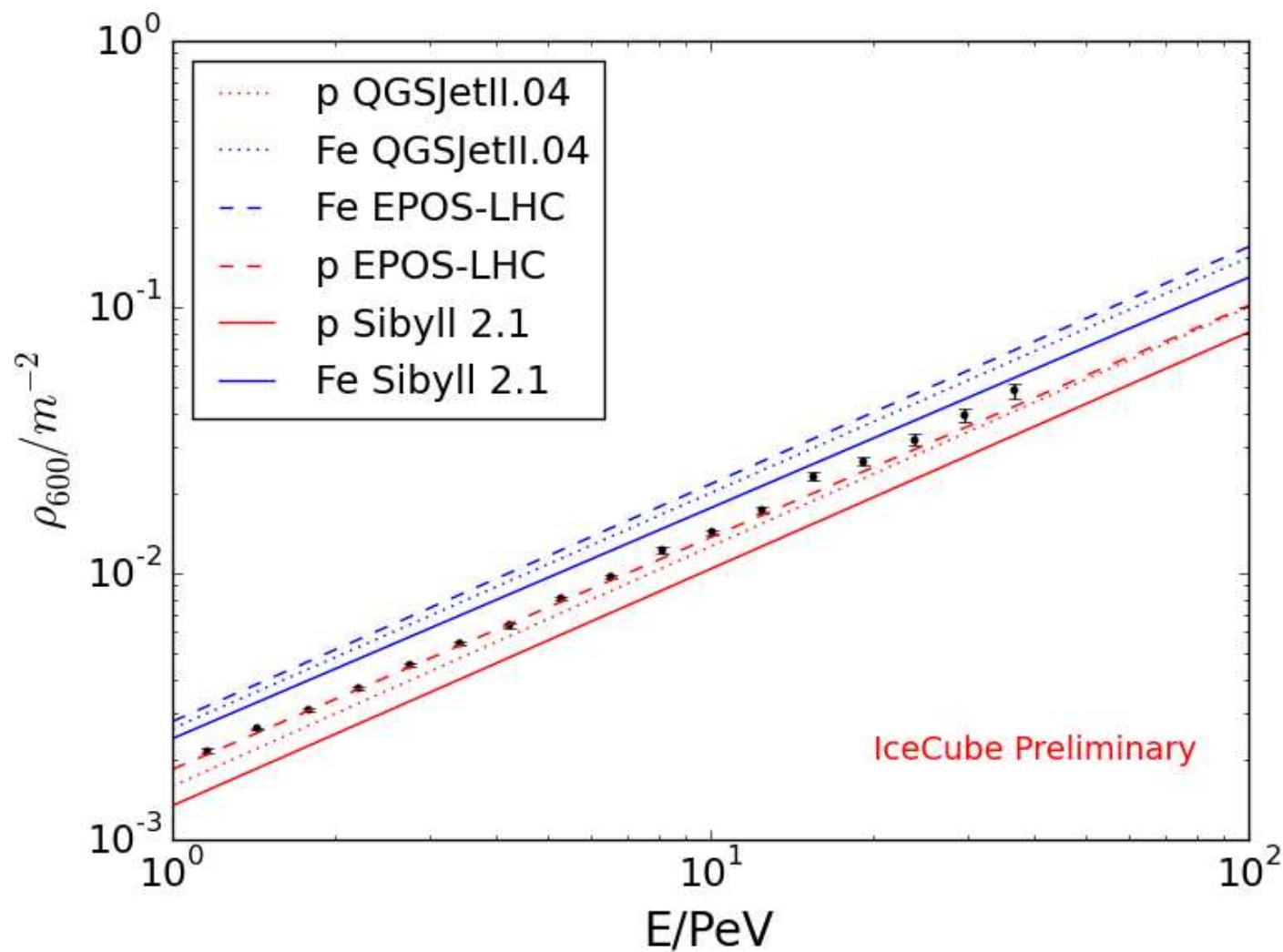




$$N_\mu(r) = N_{r_0} r^{-0.75} \left( \frac{320 \text{ m} + r}{320 \text{ m} + r_0} \right)^{-\gamma}$$

Update by H. Dembinski

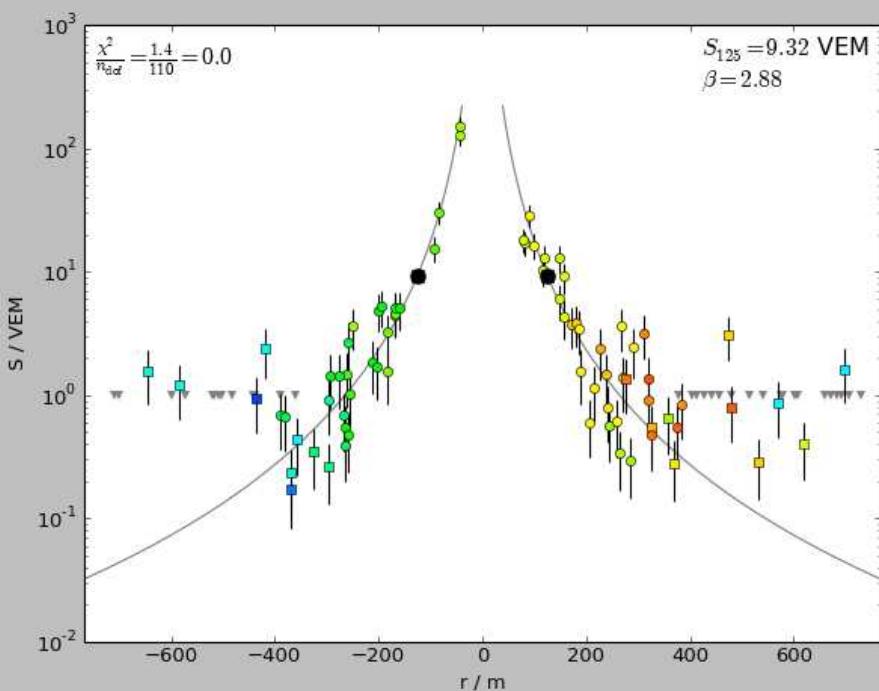




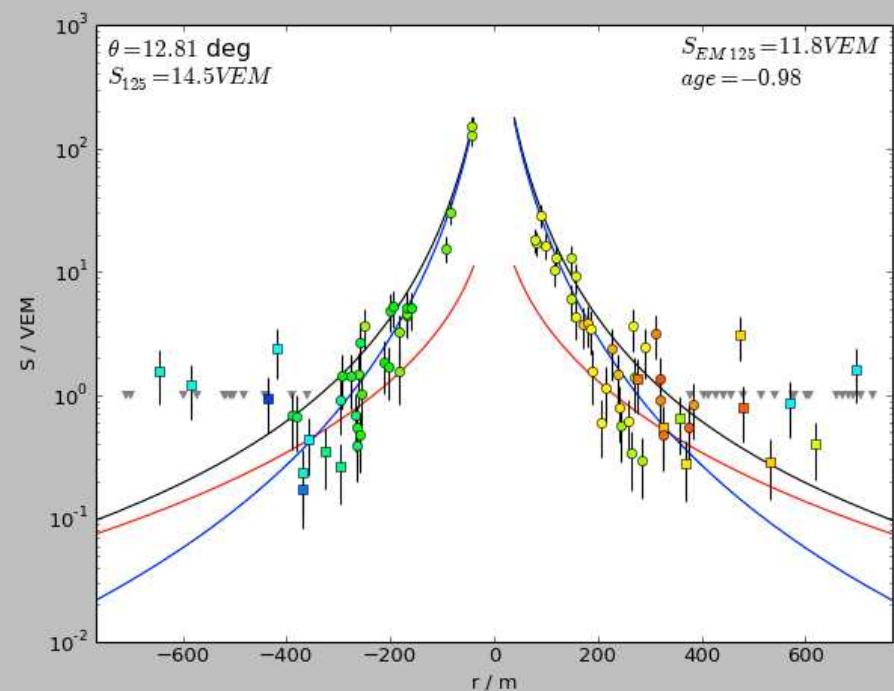
$$N_\mu \propto A \left( \frac{E_0}{A \varepsilon_\pi} \right)^\alpha \rightarrow \rho_{600} \propto A^\beta \rightarrow \ln(\rho_{600}) = a + \beta \ln(A)$$



## Current Reconstruction



## 2-LDF

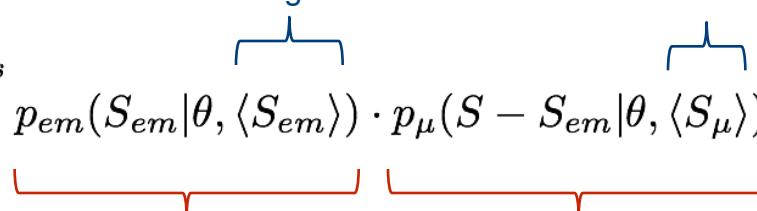


Likelihood term for one tank:

$$p(S|\theta, \langle S_{em} \rangle, \langle S_\mu \rangle) = \int_0^S p_{em}(S_{em}|\theta, \langle S_{em} \rangle) \cdot p_\mu(S - S_{em}|\theta, \langle S_\mu \rangle) dS_{em}$$

Electromagnetic LDF

Muon LDF



Detector response to  
electrons and gamma

Detector response to  
muons



- We have determined the energy spectrum from 1.58 PeV to 1.26 EeV with unprecedented statistical accuracy. Spectral breaks at  $18 \pm 2$  PeV and  $130 \pm 30$  PeV.
  - The combined IceCube-IceTop analysis shows a clear trend toward heavy primaries.
- 
- With IceTop we can measure the average number of low-energy muons at large distances from the shower axis.  
We use 600 m as reference distance at this time. 800 m will be used in near future.
  - Measuring the differences between low-energy and high-energy muons in air showers can help constrain hadronic models.
- 
- New possibilities for inferring primary mass: 2 LDF.
  - The extent to which we can estimate the number of muons event by event is under study.