UNIVERSITY of DELAWARE

Cosmic Ray Energy Spectrum and Composition from IceCube

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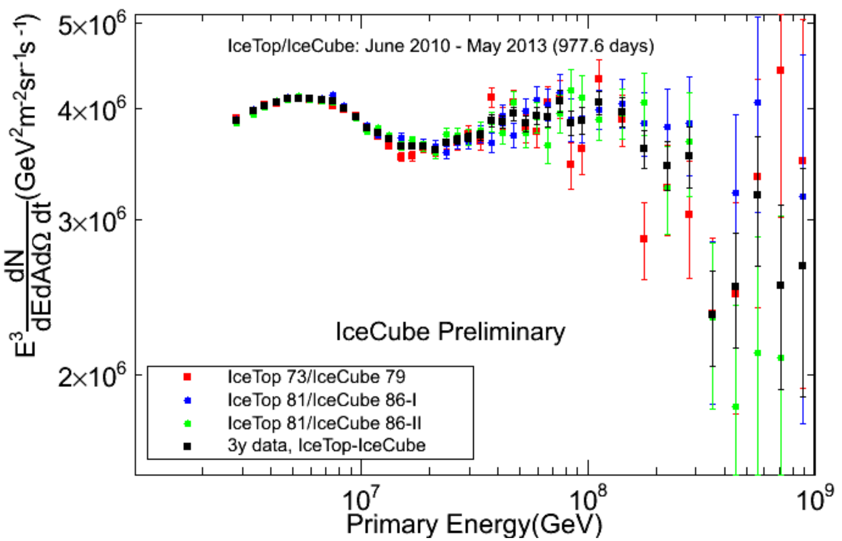
for the IceCube Collaboration

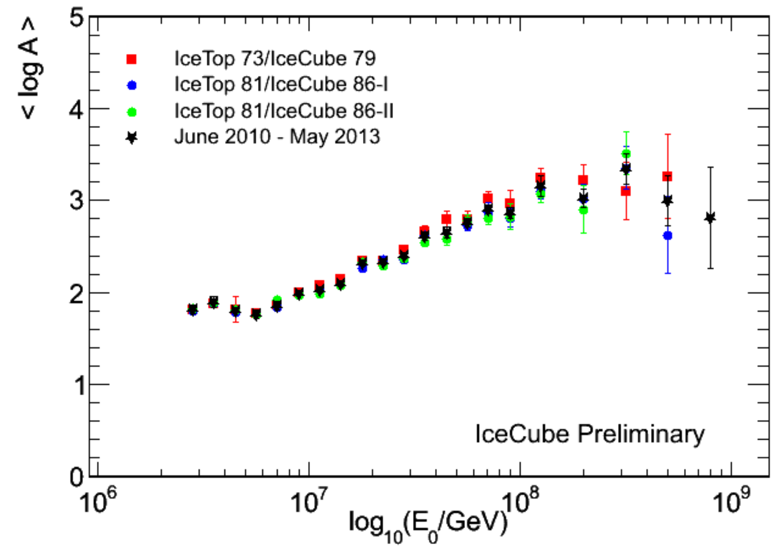
IceCube

- Highlights from IceCube/IceTop:
  - Brief recap of cosmic ray energy spectrum from IceTop
  - Description of how we can determine primary mass from a combined IceTop/IceCube analysis

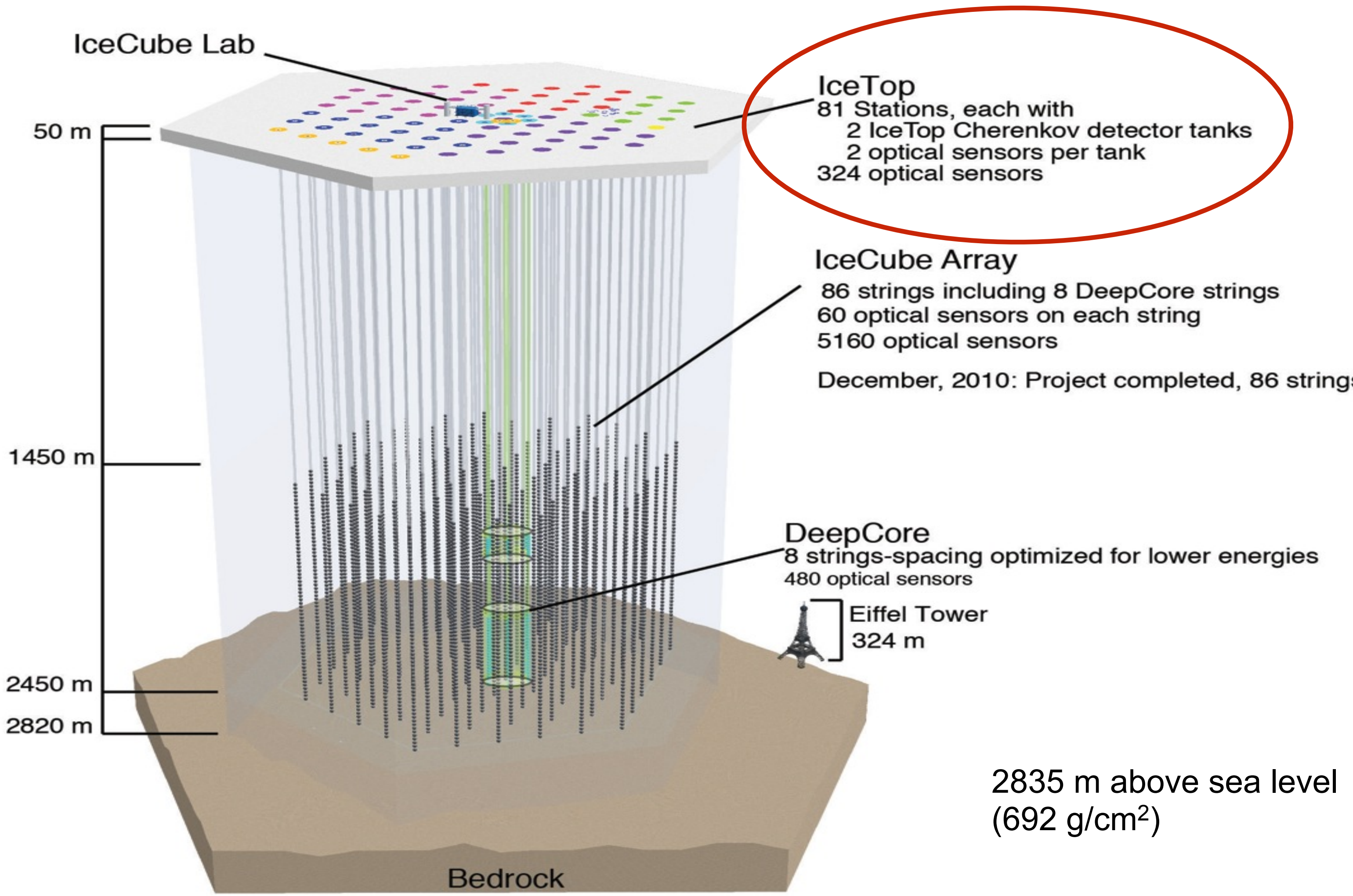
- Update: IceTop spectrum with 3 years of data

- Results on spectrum and mass composition from IceTop/IceCube analysis, including elemental group spectra (for the first time, just out!)



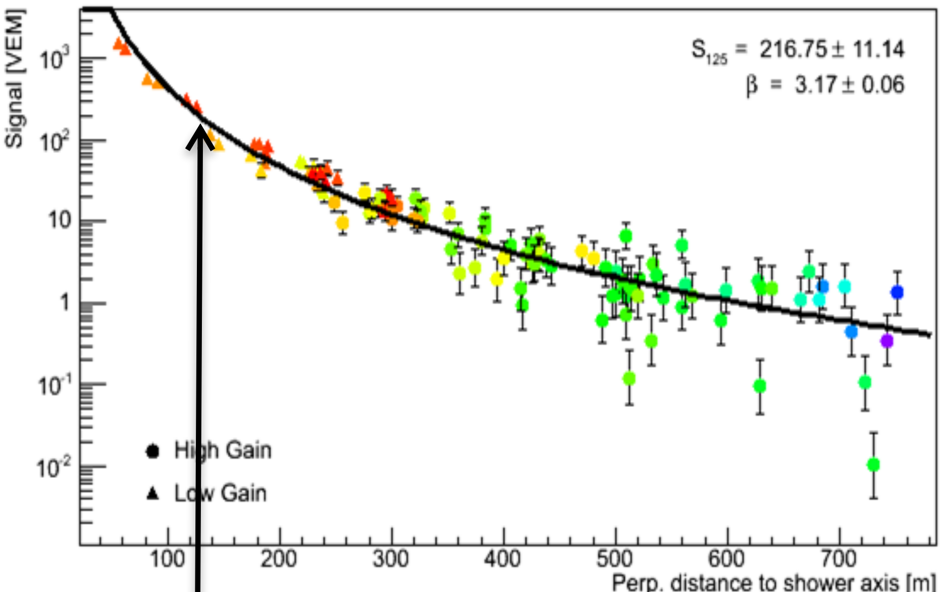


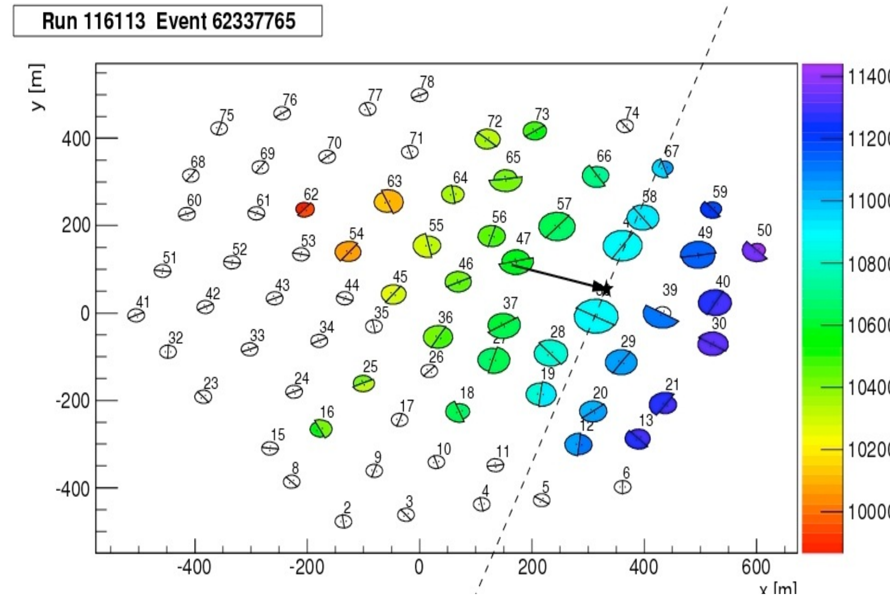
IceCube



2835 m above sea level
(692 g/cm^2)

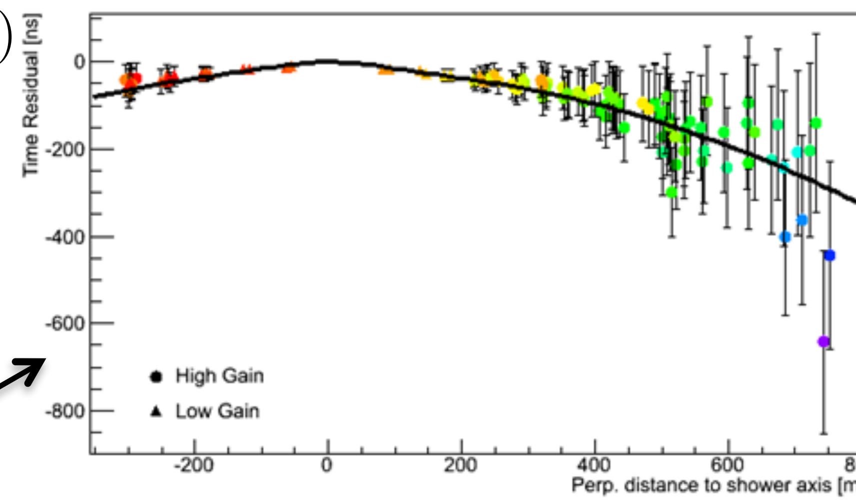
IceTop event
(recap)





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

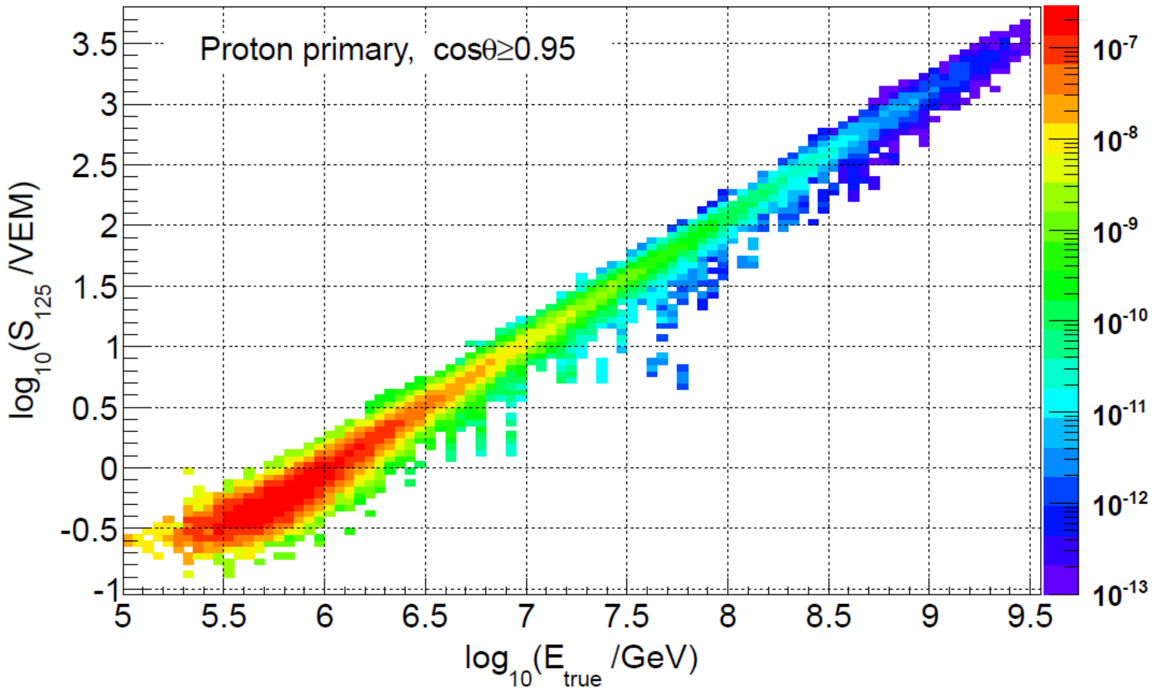
Attenuation due to snow



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

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

S_{125}-Energy Conversion
(recap)



Fit performed in four cosθ bins.
Between 1. and 0.8

$$\log_{10}(E) = p_1 \log_{10}(S125) + p_0$$

<u>Simulation dataset:</u>

- CORSIKA v6990.
- Sibyll 2.1 - FLUKA.
- primaries: H, He, O, Fe.
- South Pole July atmosphere.
- E^{-1} spectrum: 100 TeV - 3 EeV.
- Zenith: 0-40°.
- 42000 showers per primary.
- Detailed detector response.

<u>Assumptions:</u>

- Assumes composition model from:
  T.K. Gaisser, Astropart.Phys. **35** (2012) 801-806
  (from now on called *H4a)*
- Distribution follows the measured energy spectrum

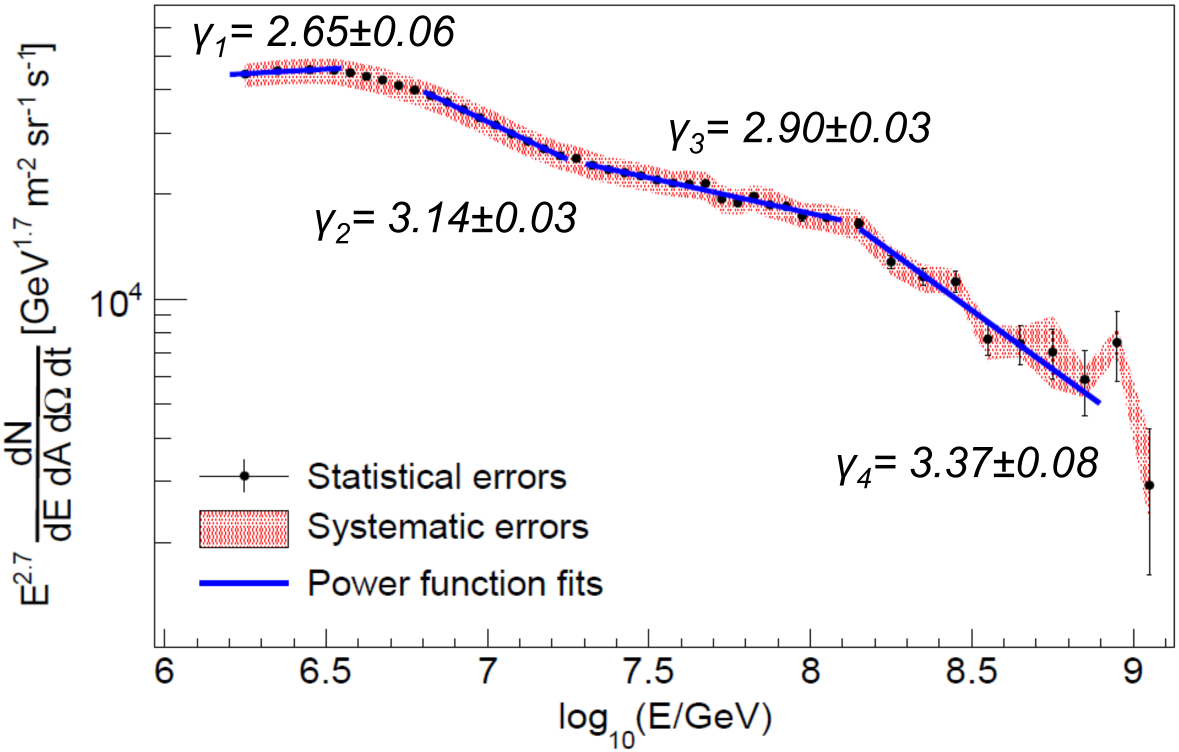
Systematic Uncertainties

	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%

[a] From the difference between QGSJet-II-03 and SYBILL 2.1.
[b] Fixed for all energies. Given by the differences between spectra at different zenith angles.
[c] From difference between high/low pressure sub-samples (690 hPa/670 hPa).

M.G. Aartsen et al, Physical Review D88 (2013) 042004
URL: http://link.aps.org/doi/10.1103/PhysRevD.88.042004

IceTop-73 Spectrum
(recap)



- 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±2 PeV.
  (124800 events expected, 139880 observed)
- The spectrum steepens at 130±30 PeV.
  (4213 events expected, 3673 observed)

M.G. Aartsen et al, Physical Review D88 (2013) 042004
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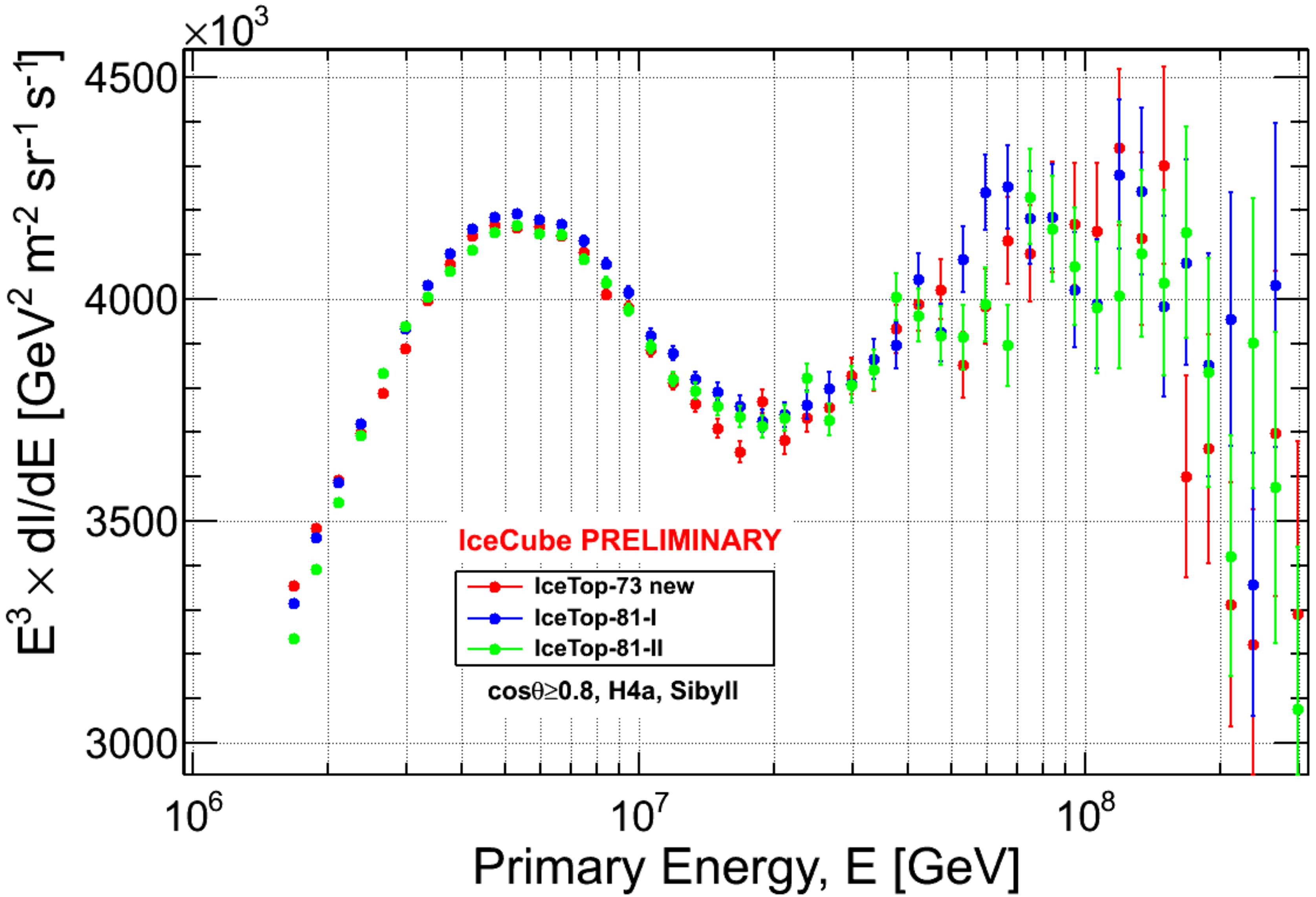
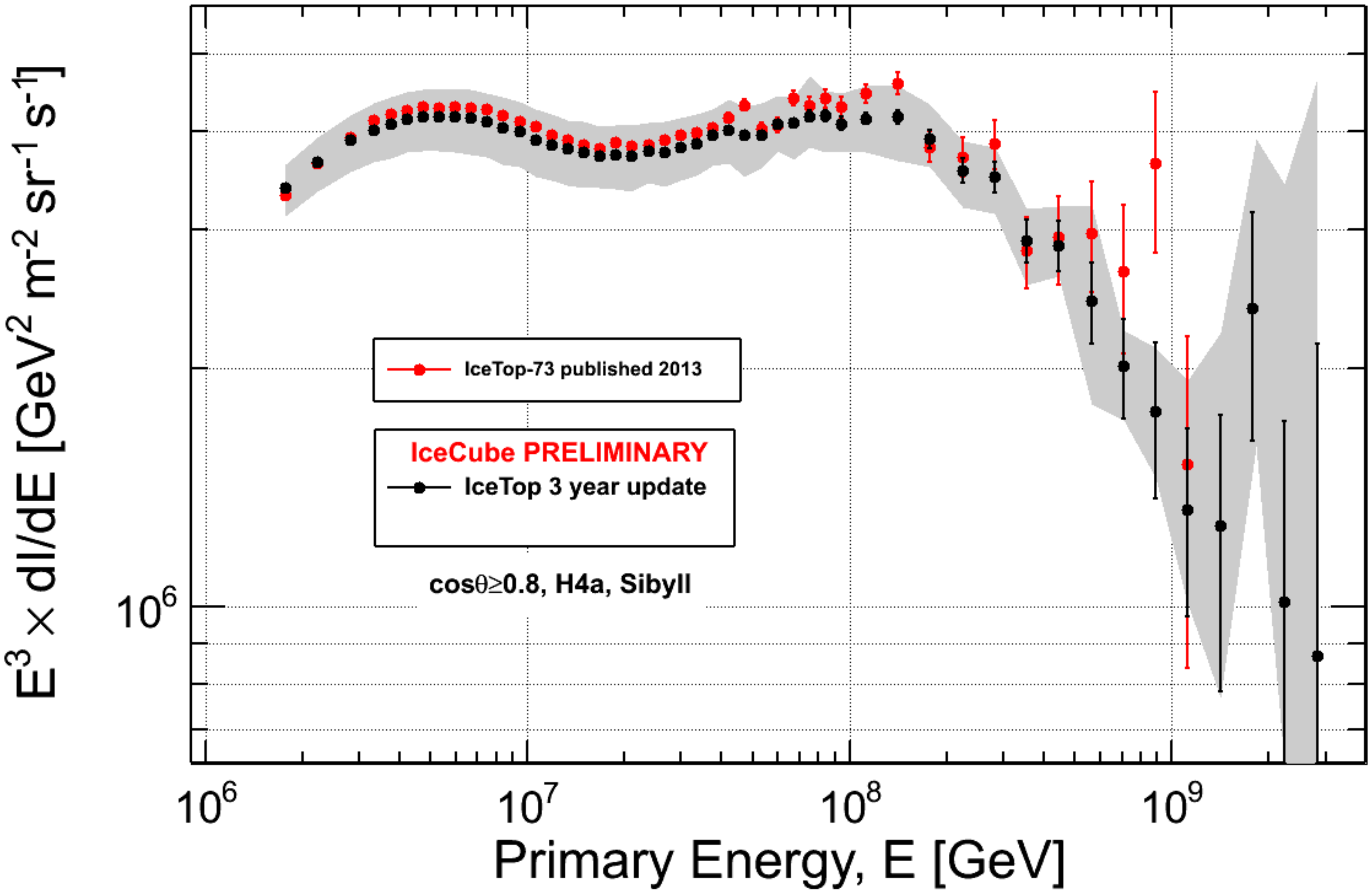
IceTop Spectrum — 3 Years



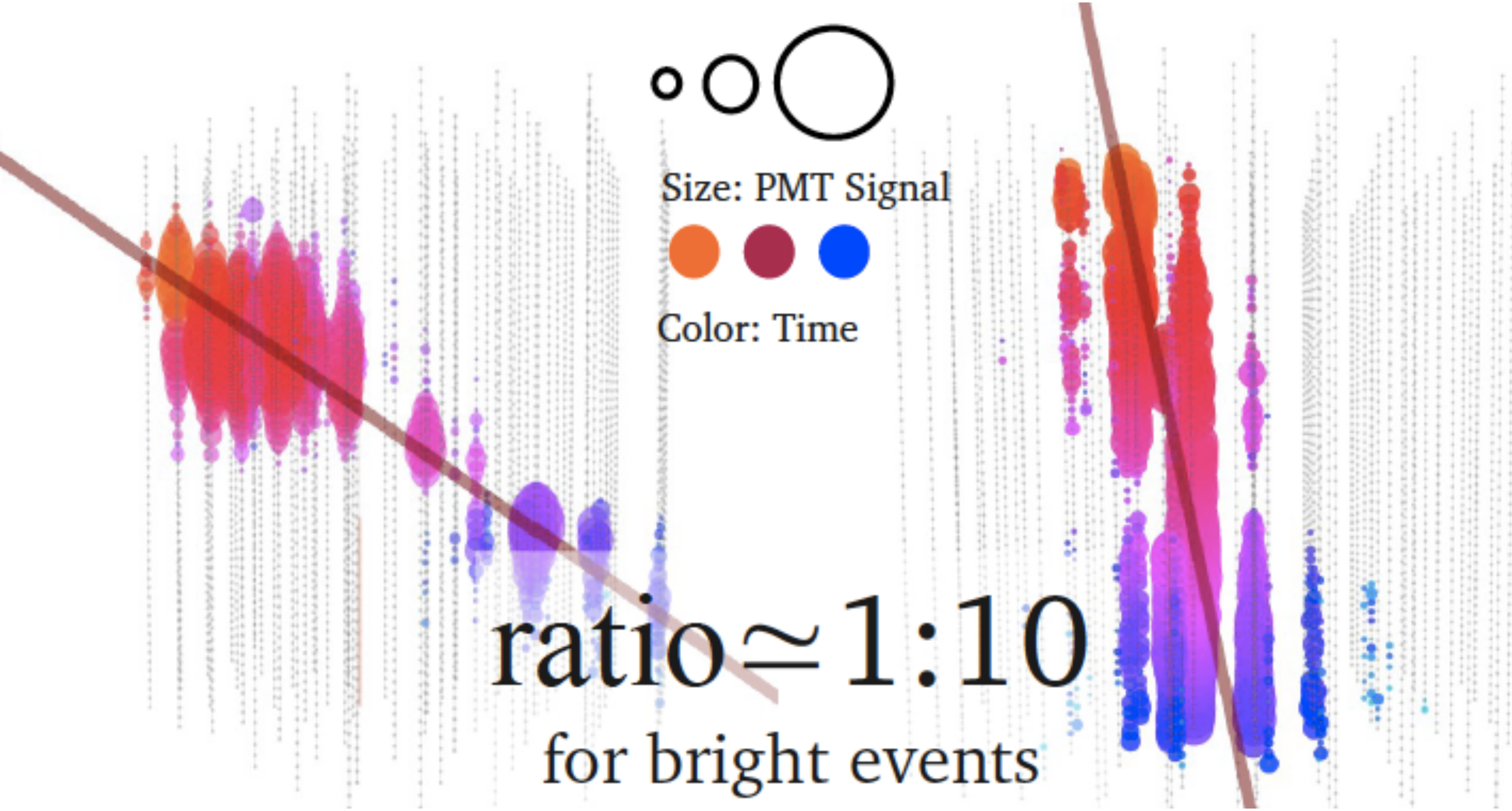
IceTop Spectrum — 3 Years



2% decrease arising from improvement in the treatment of attenuation due to snow

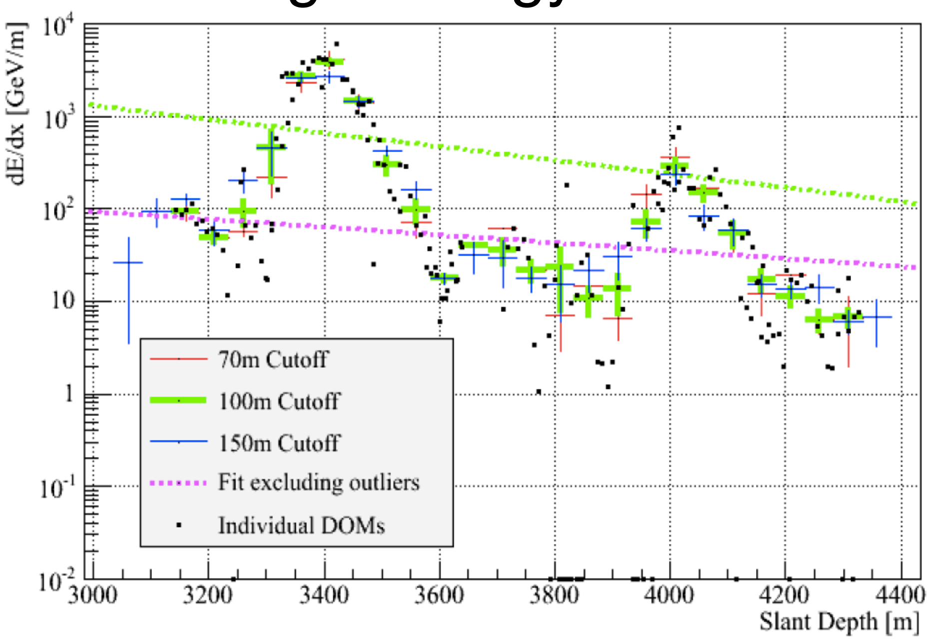
Types of Muon Events in IceCube

High Energy Muon | High Multiplicity Muon Bundle

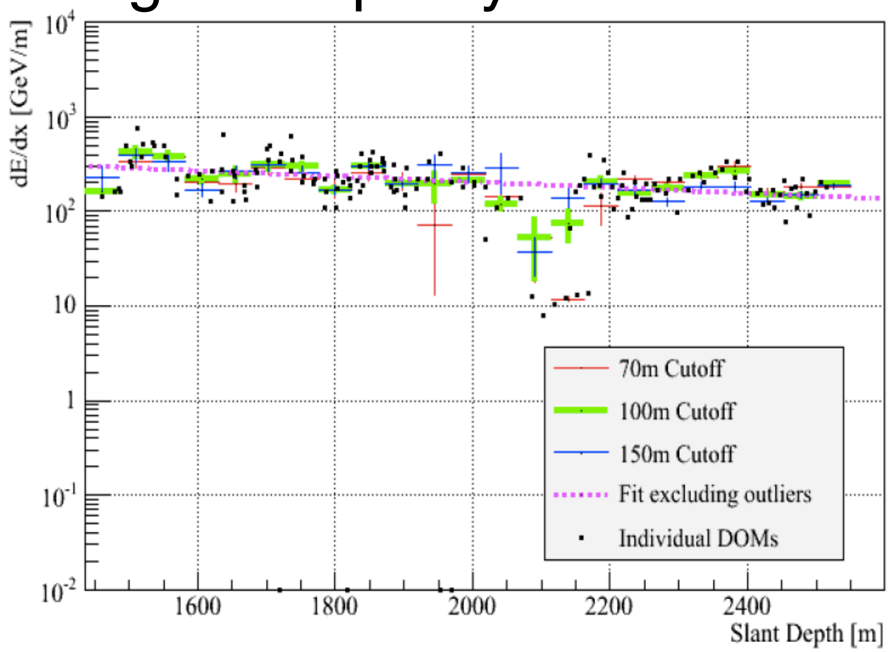


Types of Muon Events in IceCube

High Energy Muon

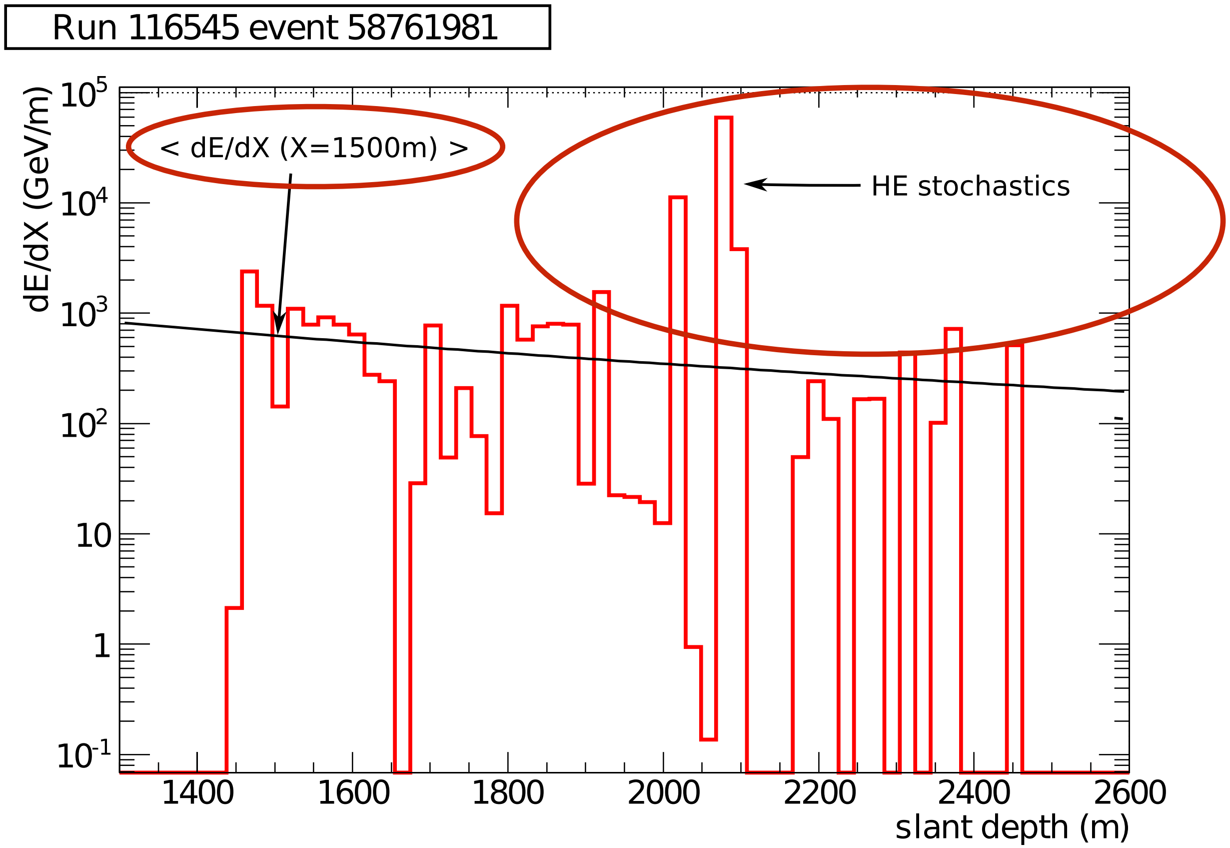


High Multiplicity Muon Bundle



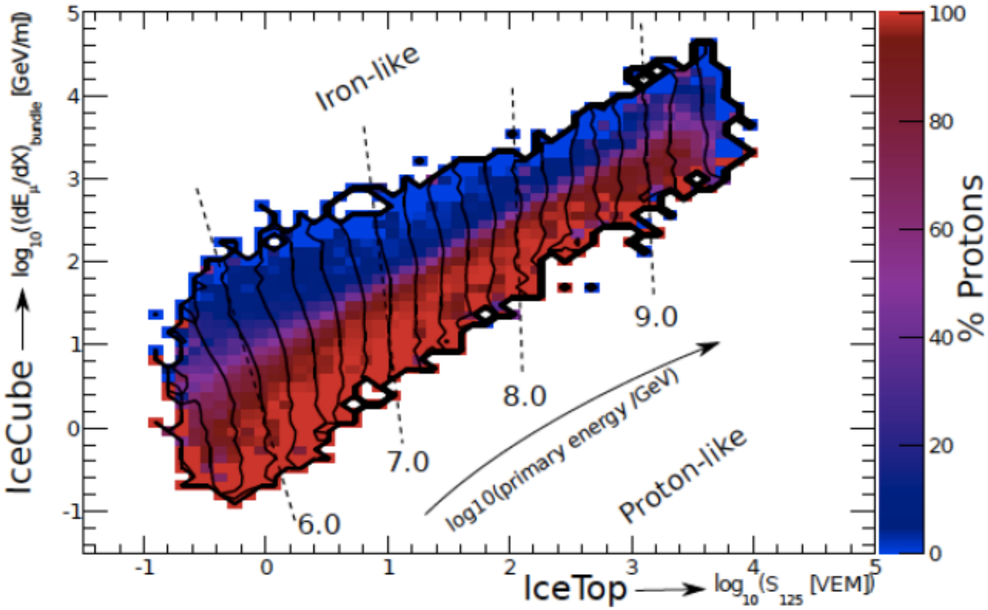
(Plots from talk by P. Berghaus, ISVHECRI 2012)

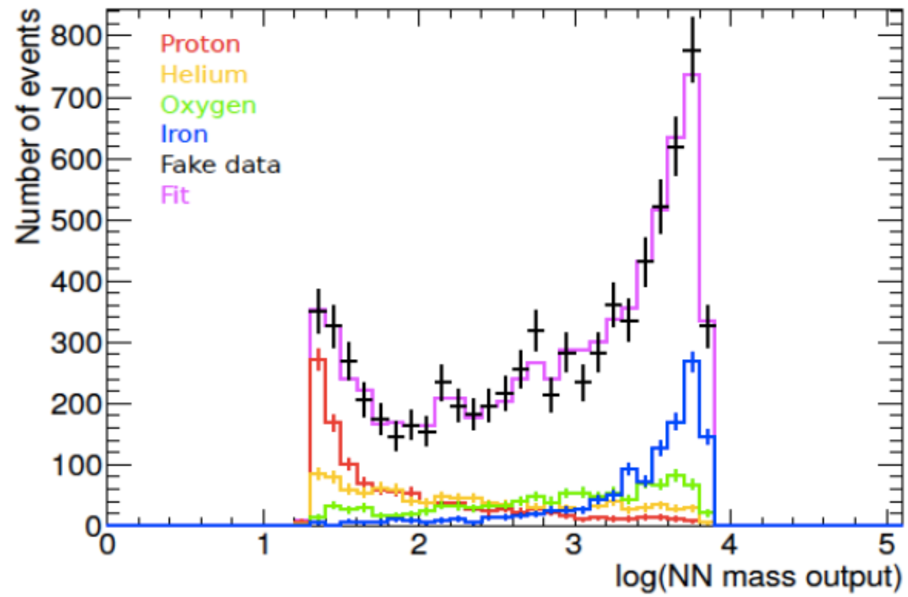
- dE/dX proportional to bundle multiplicity
- “Stochastics:” bremsstrahlung catastrophic energy losses related to leading muons

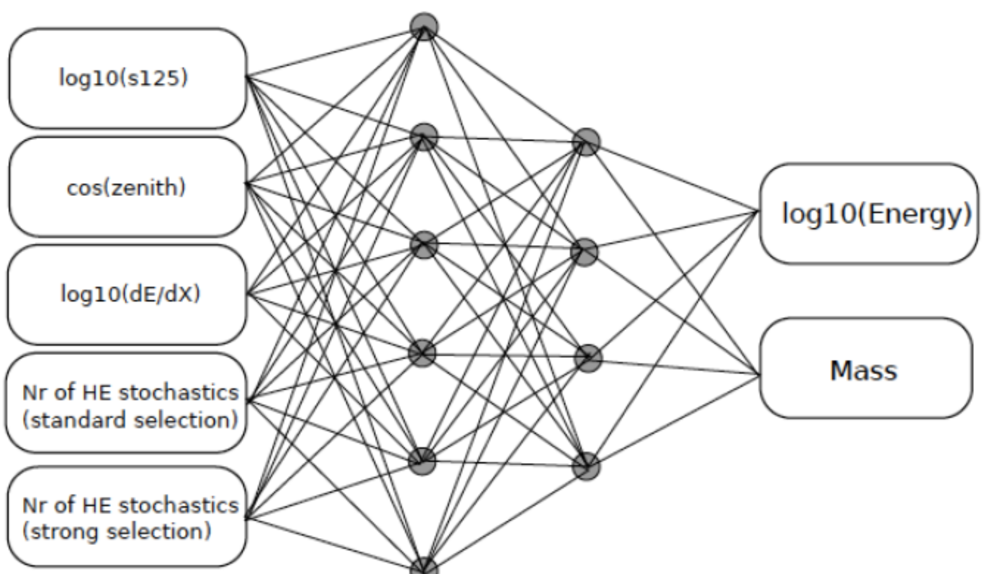


Reconstruction of muon bundle energy loss, including the effect of light propagation in the ice.

IceCube-79/IceTop-73
(recap)







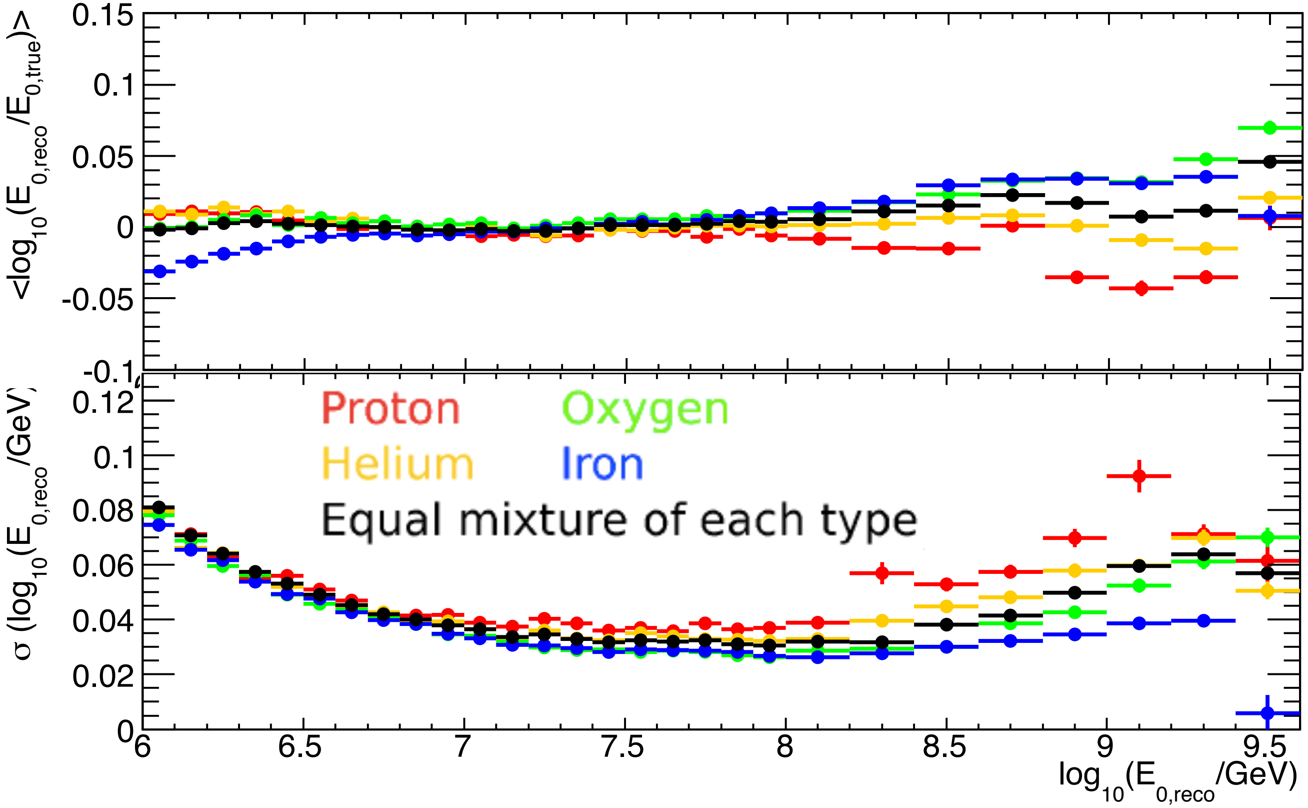
Template histograms for 4 mass groups (H, He, 0, Fe) in one energy bin for a fake MC dataset.

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_{reco} bins to templates just mentioned.

Combined IceTop/IceCube Performance



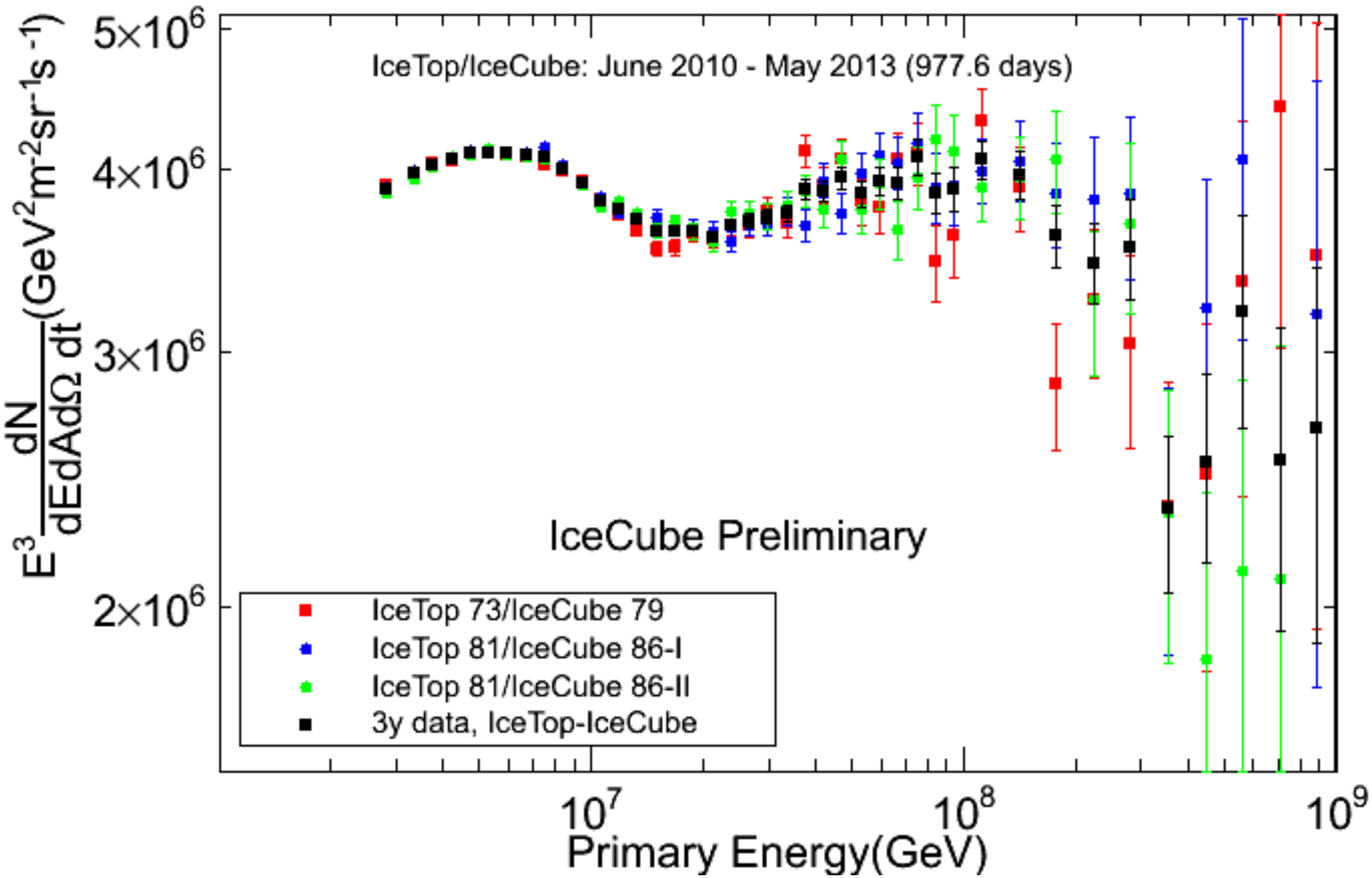
Energy bias

Energy resolution

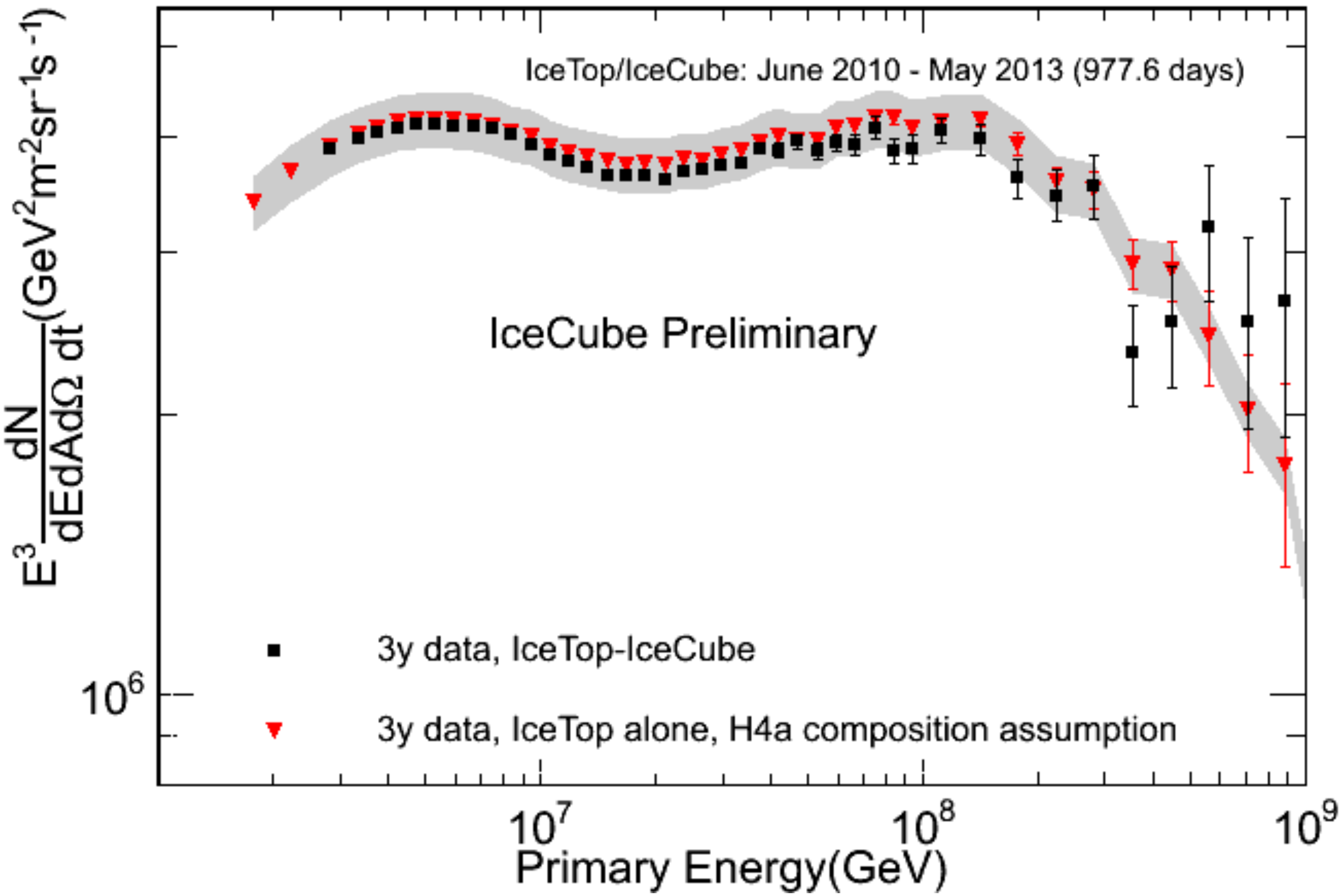
This update includes:

- improvements in snow attenuation calculation,
- improvement in light propagation models,
- New NN architecture (5-6-4-2).

Spectra — 3 Years Compared

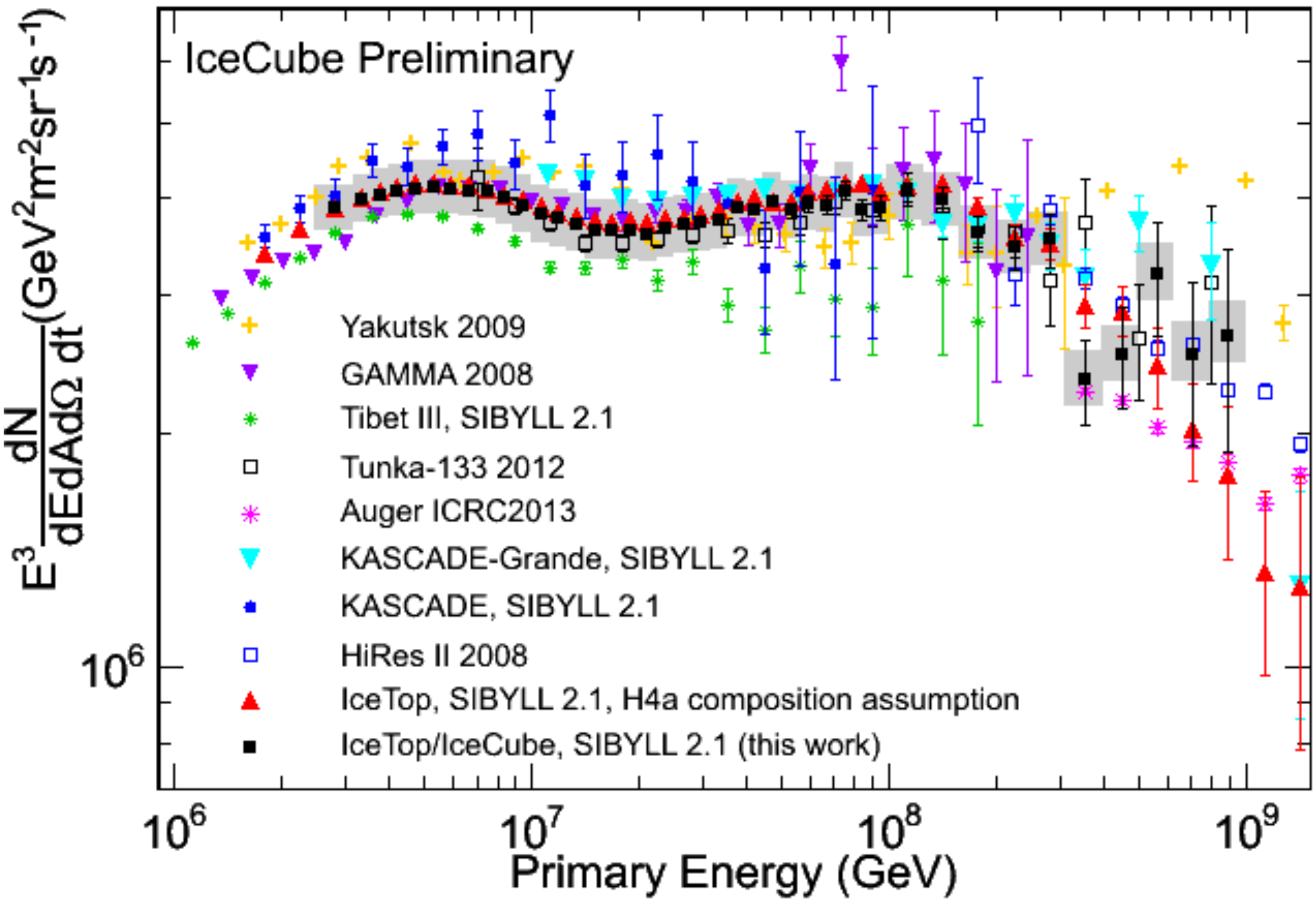


IceTop/IceTop+IceCube Compared



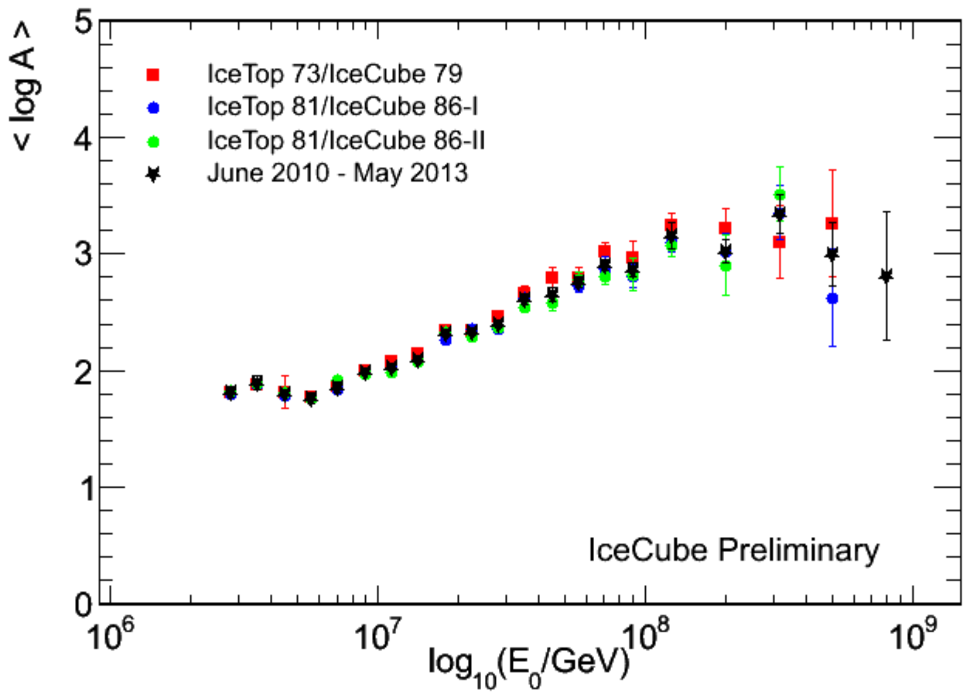
Systematic error band showed corresponds to 7% composition systematic

Compared to Others

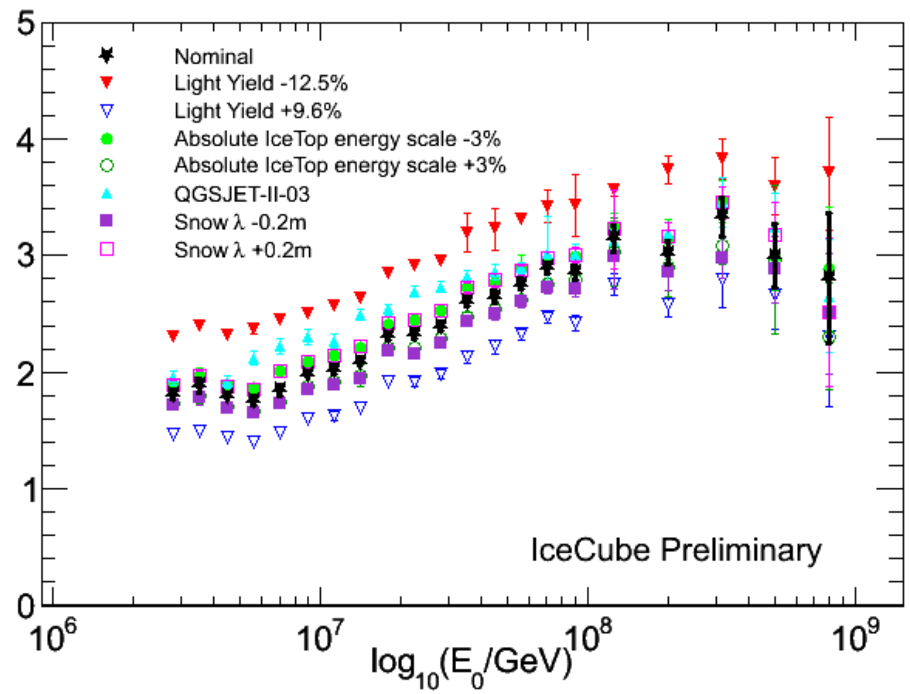


Mean Log Mass

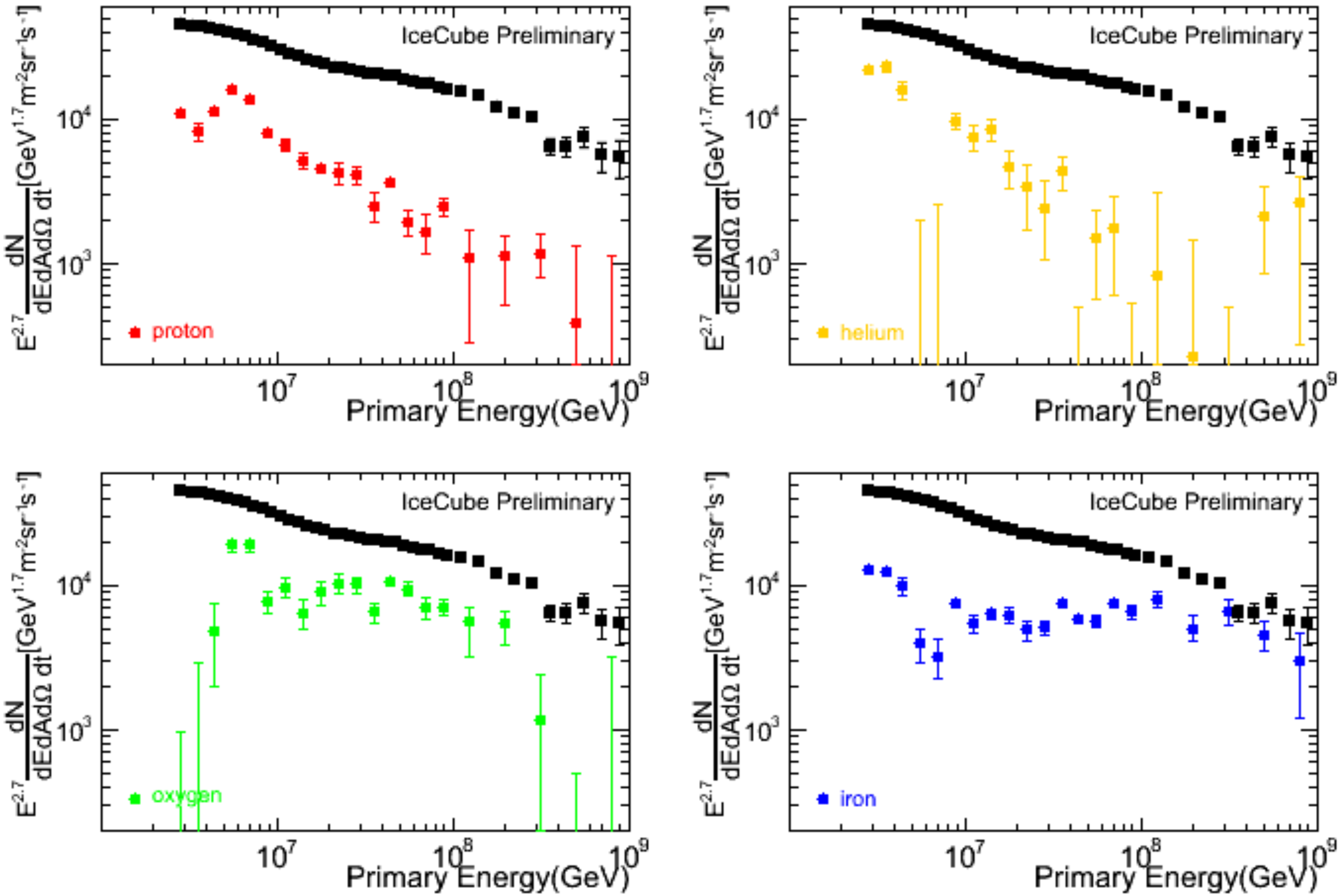
3 Years Compared



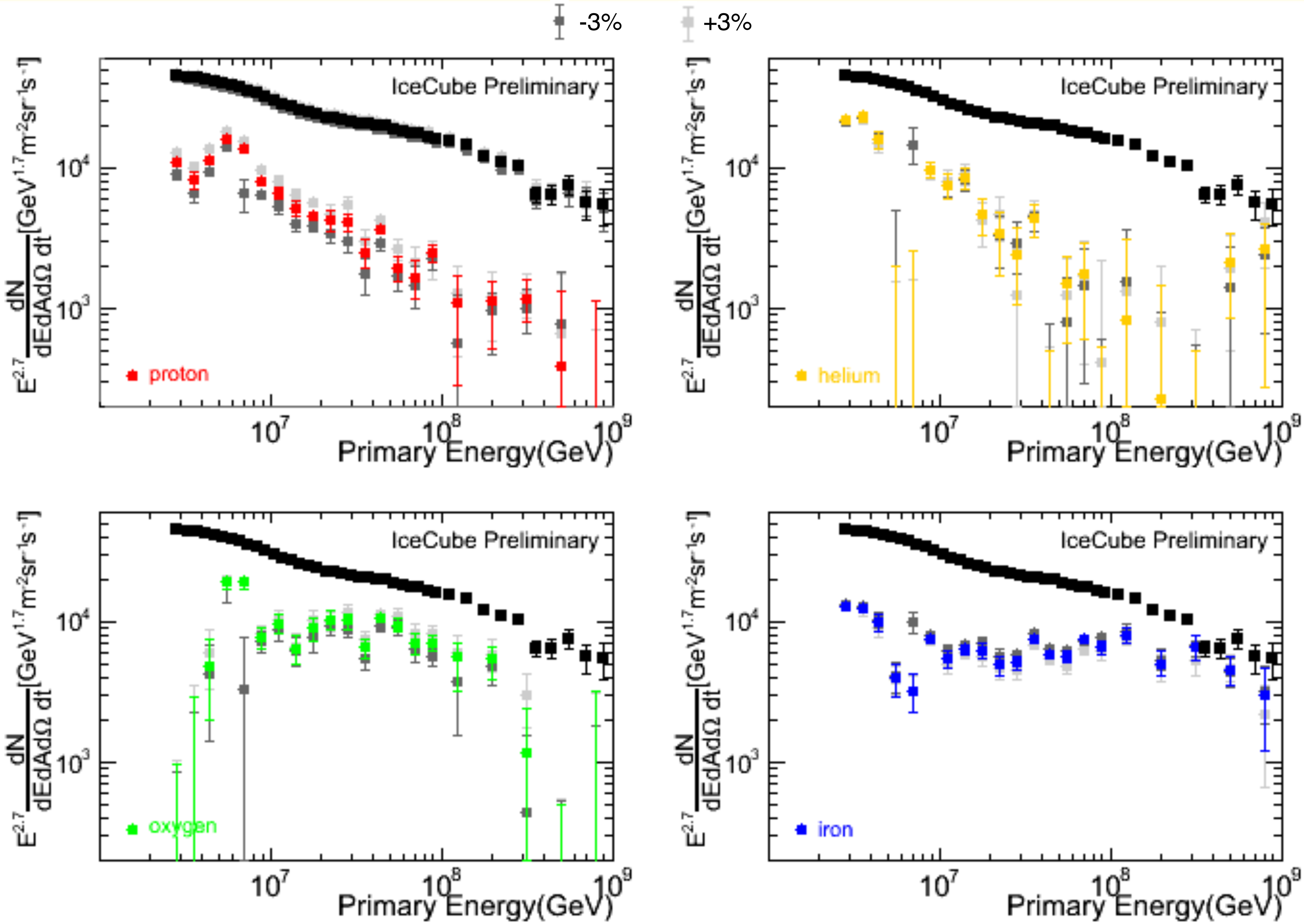
Systematic Effects



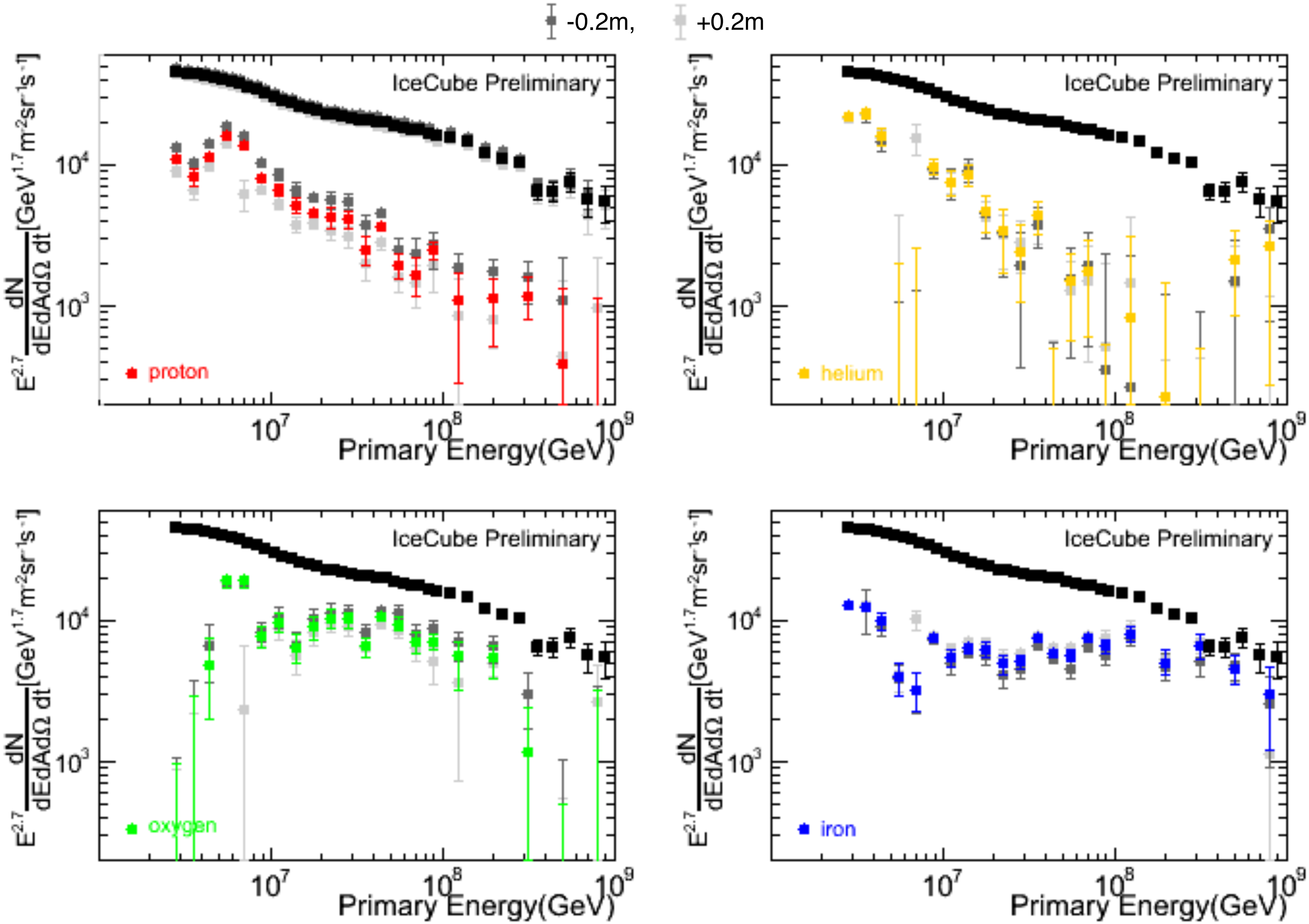
Elemental Group Spectra



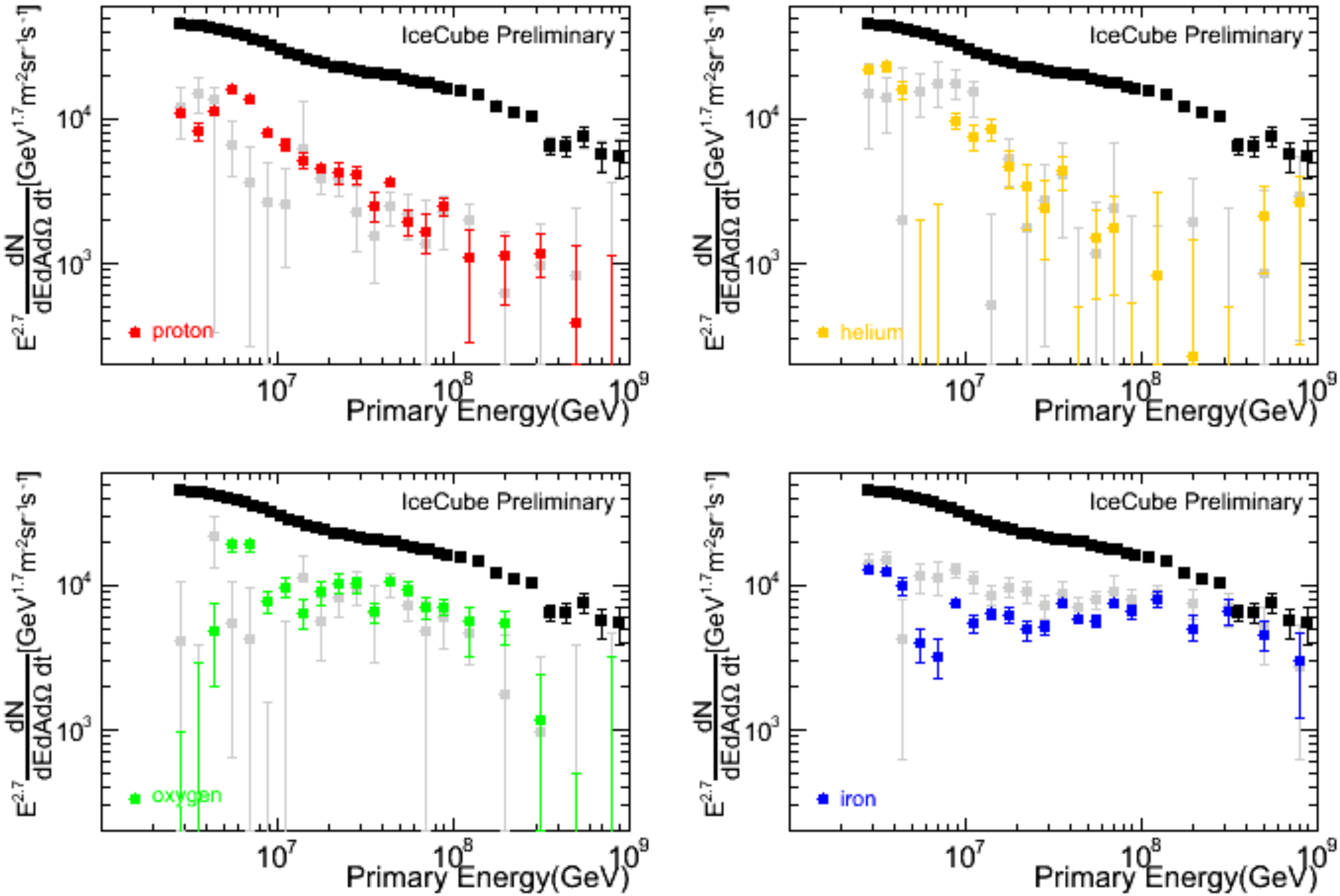
Systematic: IceTop Energy Scale



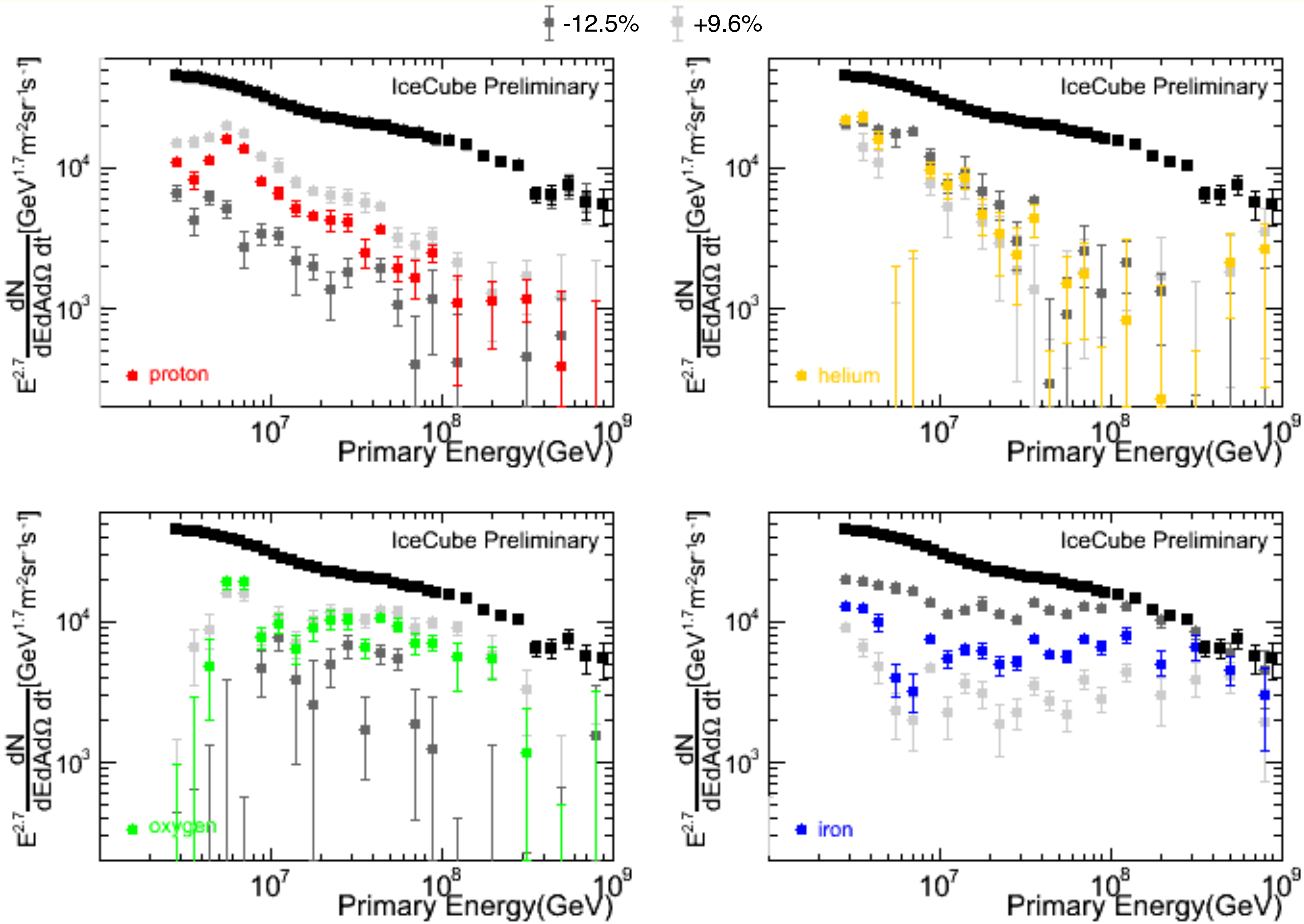
Systematic: Snow Correction



Systematic: QGSJet II.03

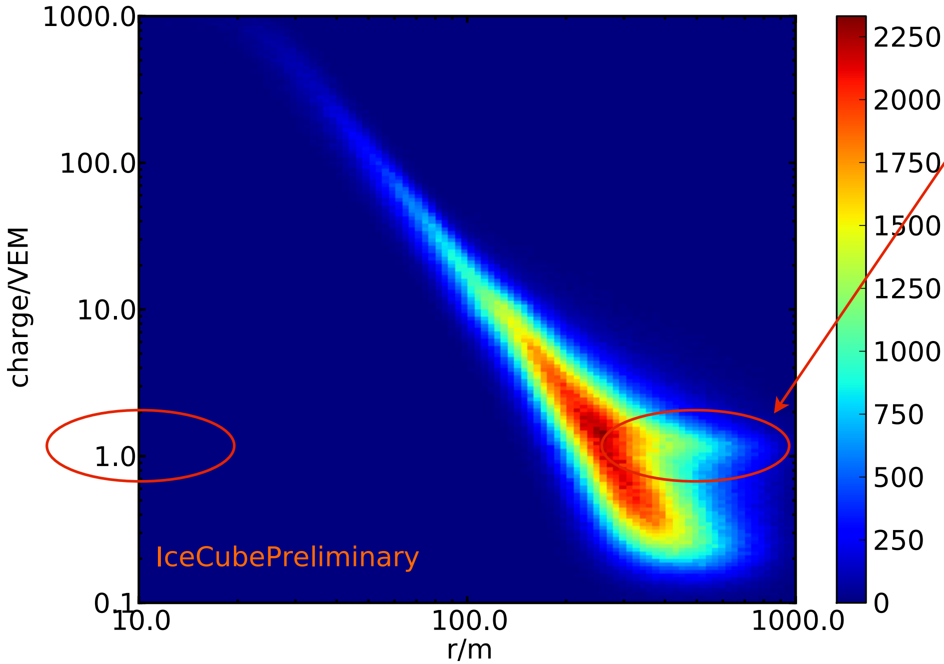


Systematic: Light Yield



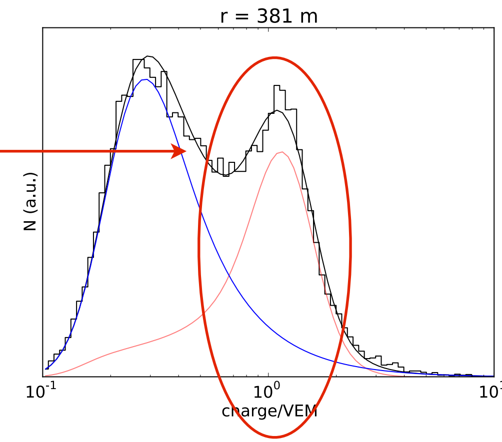
Low-Energy Muons in IceTop

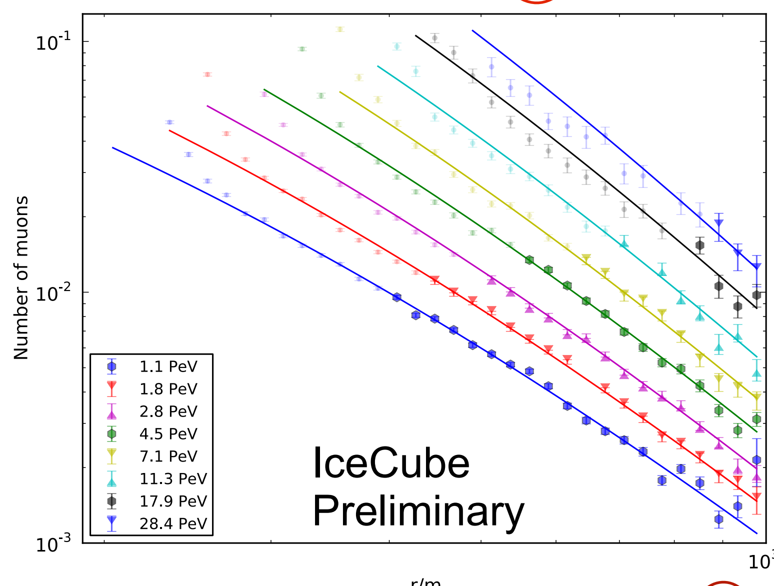
E > 200 MeV



$28^\circ < \theta < 32^\circ$ 10 PeV < E < 12.6 PeV

Muons





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

Conclusions

- We have determined the energy spectrum from 1.58 PeV to 1.26 EeV with unprecedented statistical accuracy. Spectral breaks at 18±2 PeV and 130±30 PeV.
  Both analyses agree well within the composition systemic error.

- The combined IceCube-IceTop analysis shows a clear trend toward heavy primaries in average log(A).

- We have presented elemental group spectra (H, He, O, Fe).
  Please stay tuned for more on this.

- With IceTop we can measure the average number of muons at large distances from the shower axis. In the future this will be included in the reconstruction.

Back up slides

Systematic Uncertainties

	3.35 PeV	33.5 PeV
Energy scale (VEM calibration)	+4.1% - 4.4%	+7% -4.3%
Snow Correction	+5% -4.3%	+7.9% -4.7%
Interaction models (a)	+2.1%	+1.4%
Light Yield	+3.1% -3.0%	+1.1%
Total	+7.5% -6.5%	+10.8% -6.4%

[a] From the difference between QGSJet-II-03 and SYBILL 2.1.
[b] Fixed for all energies. Given by the differences between spectra at different zenith angles.

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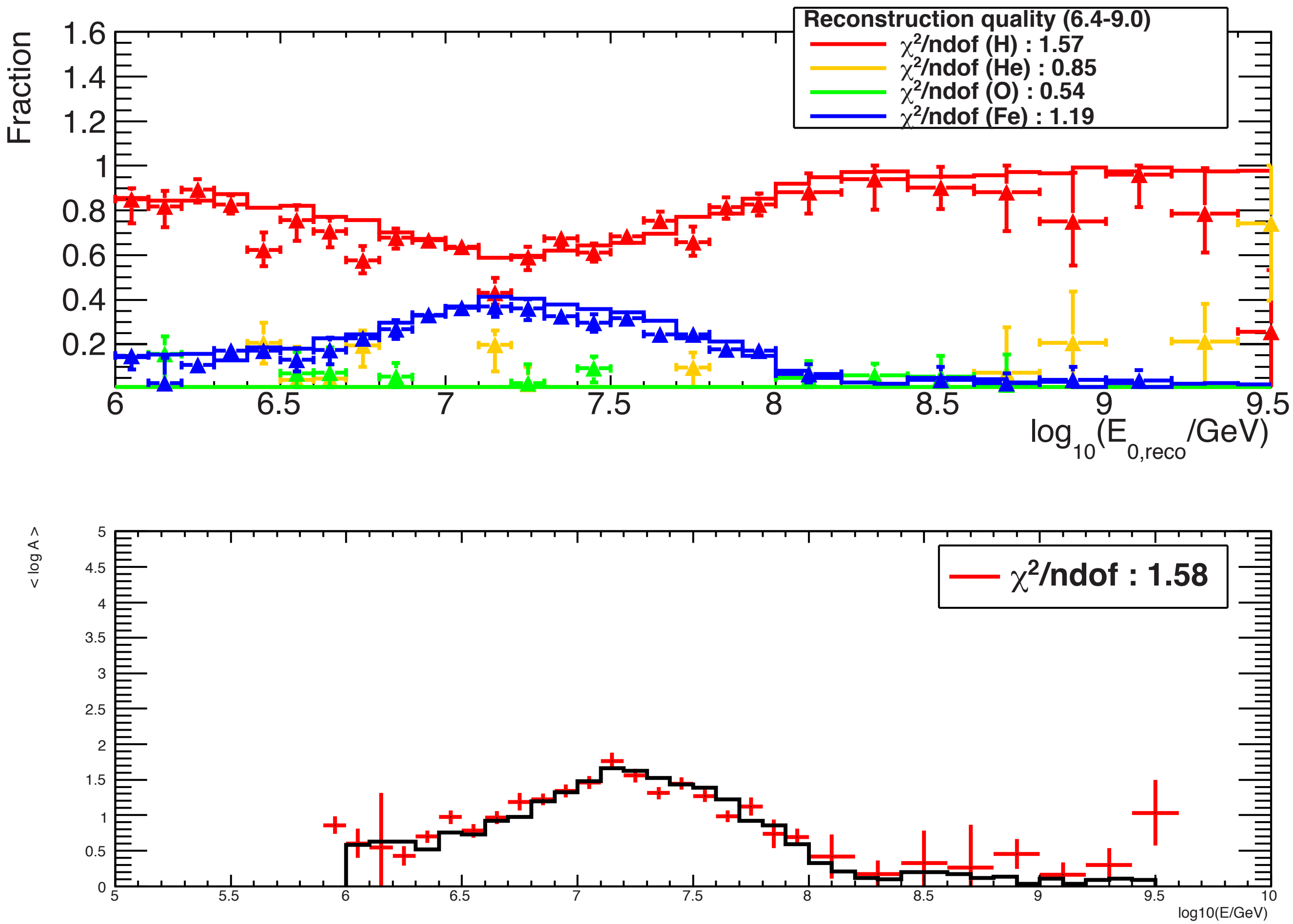
Data Challenge Example



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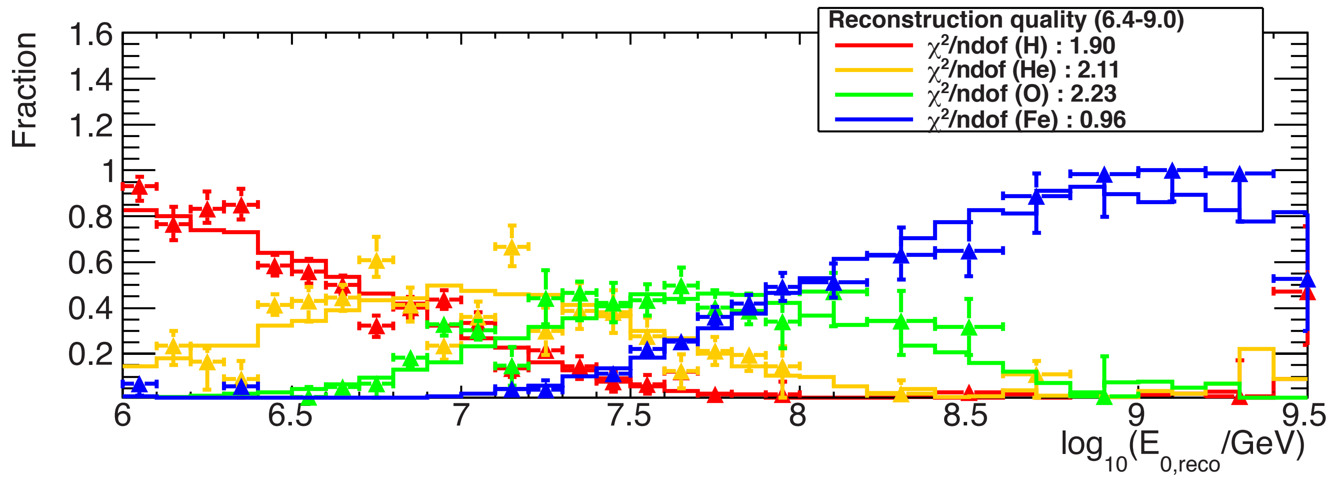
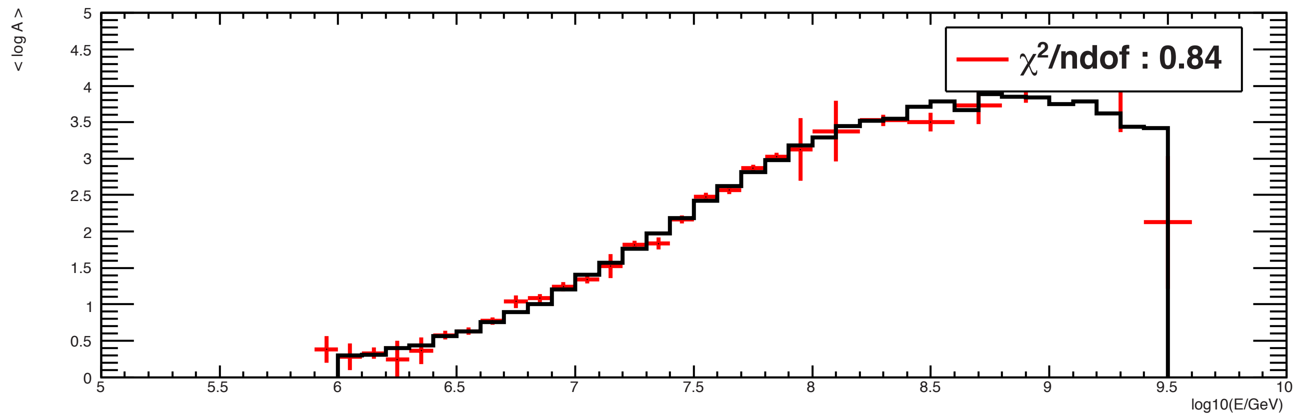
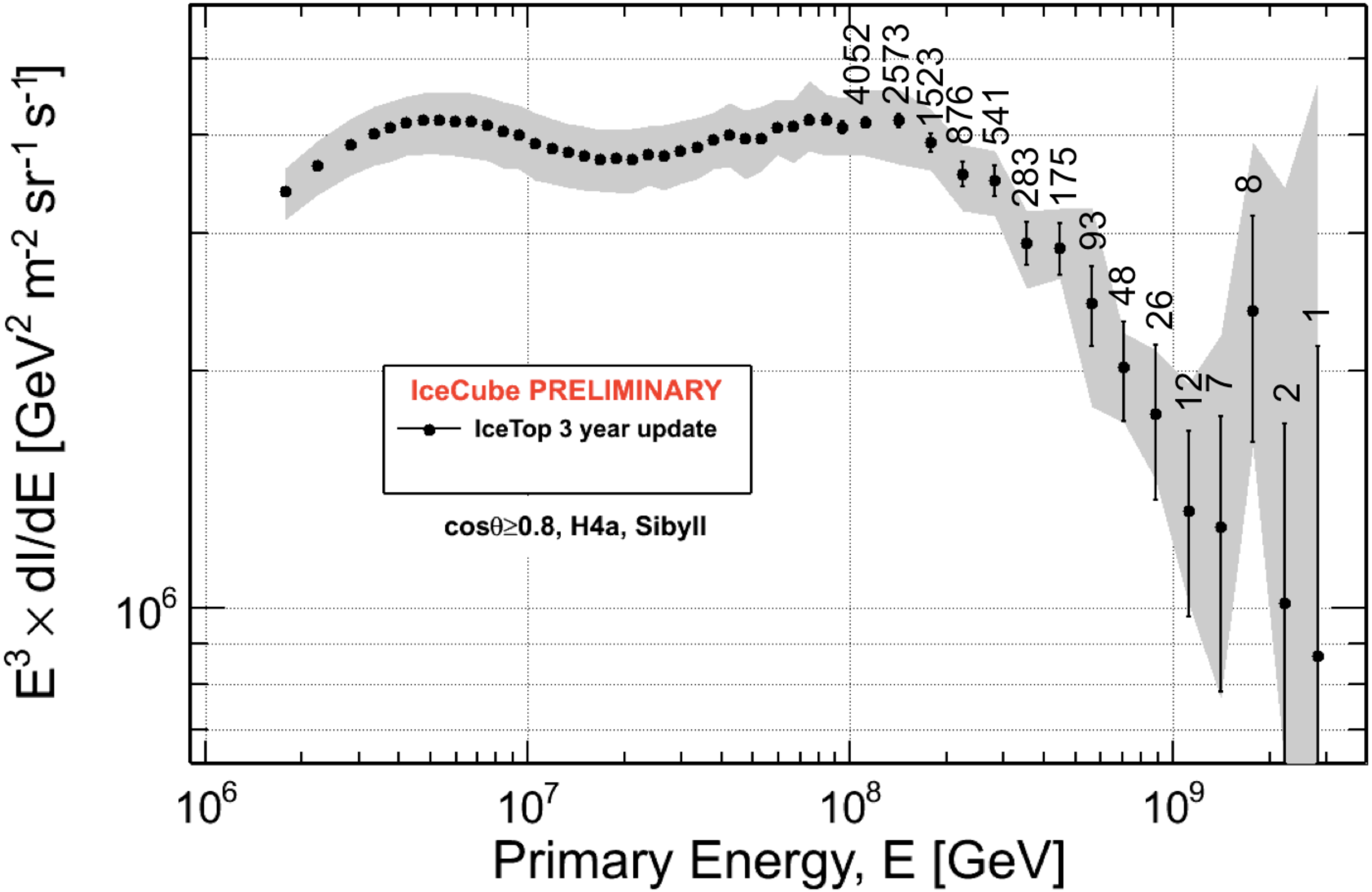
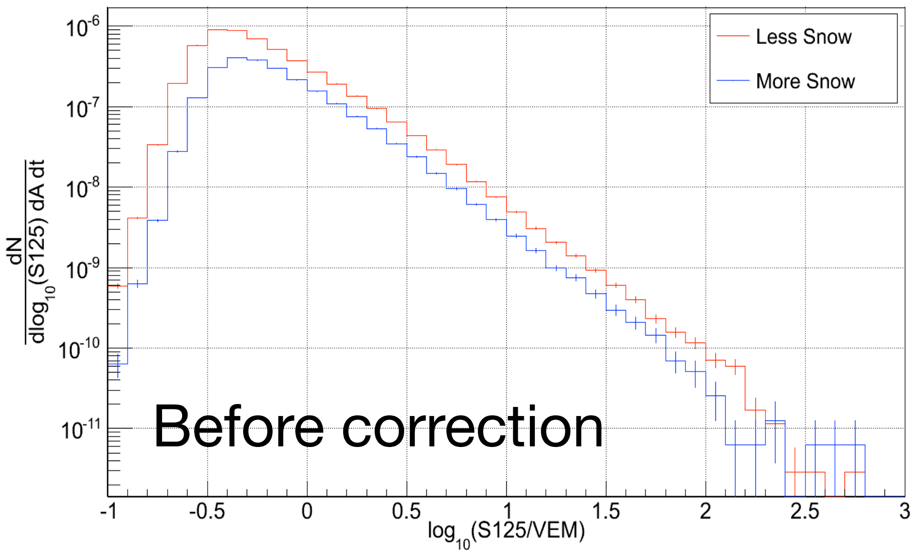


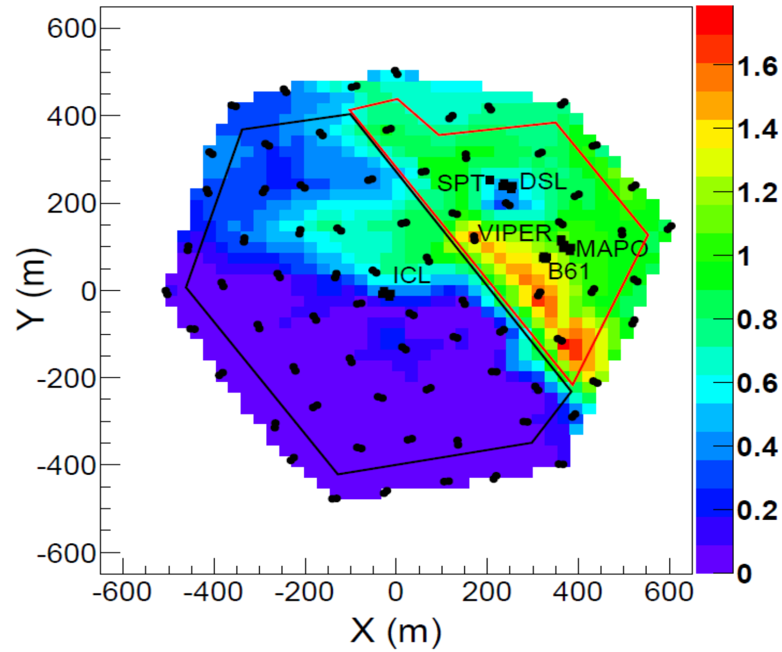


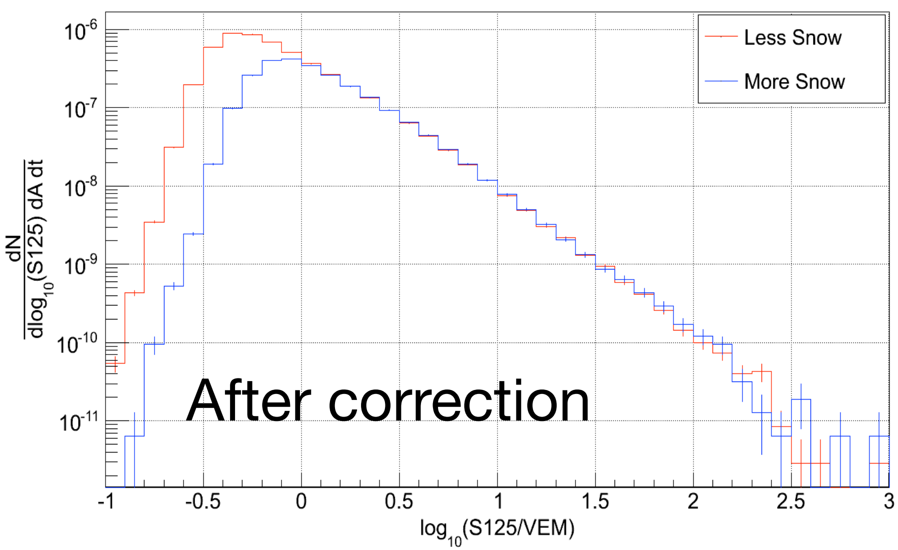
3 Year IceTop Spectrum



Snow correction



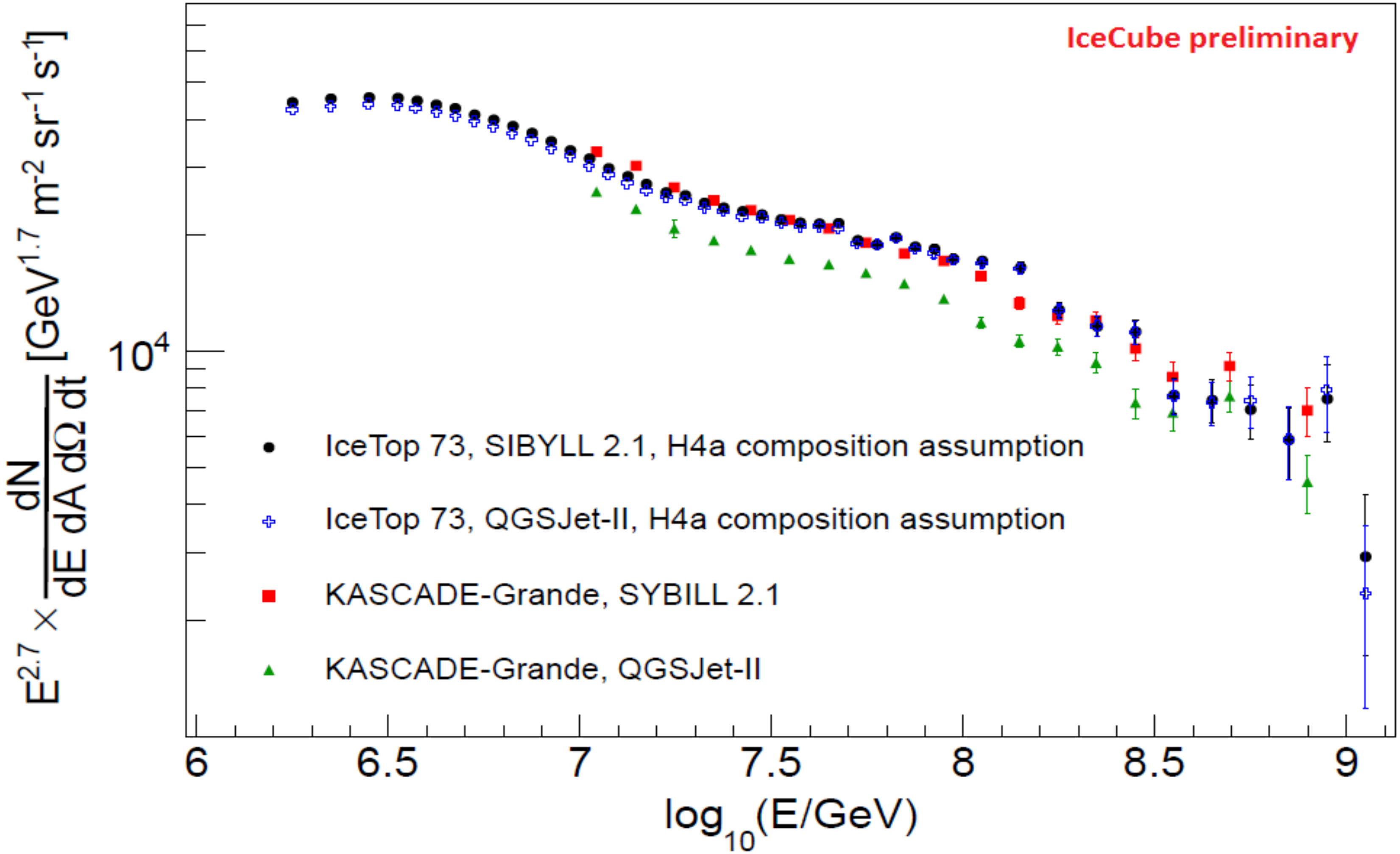




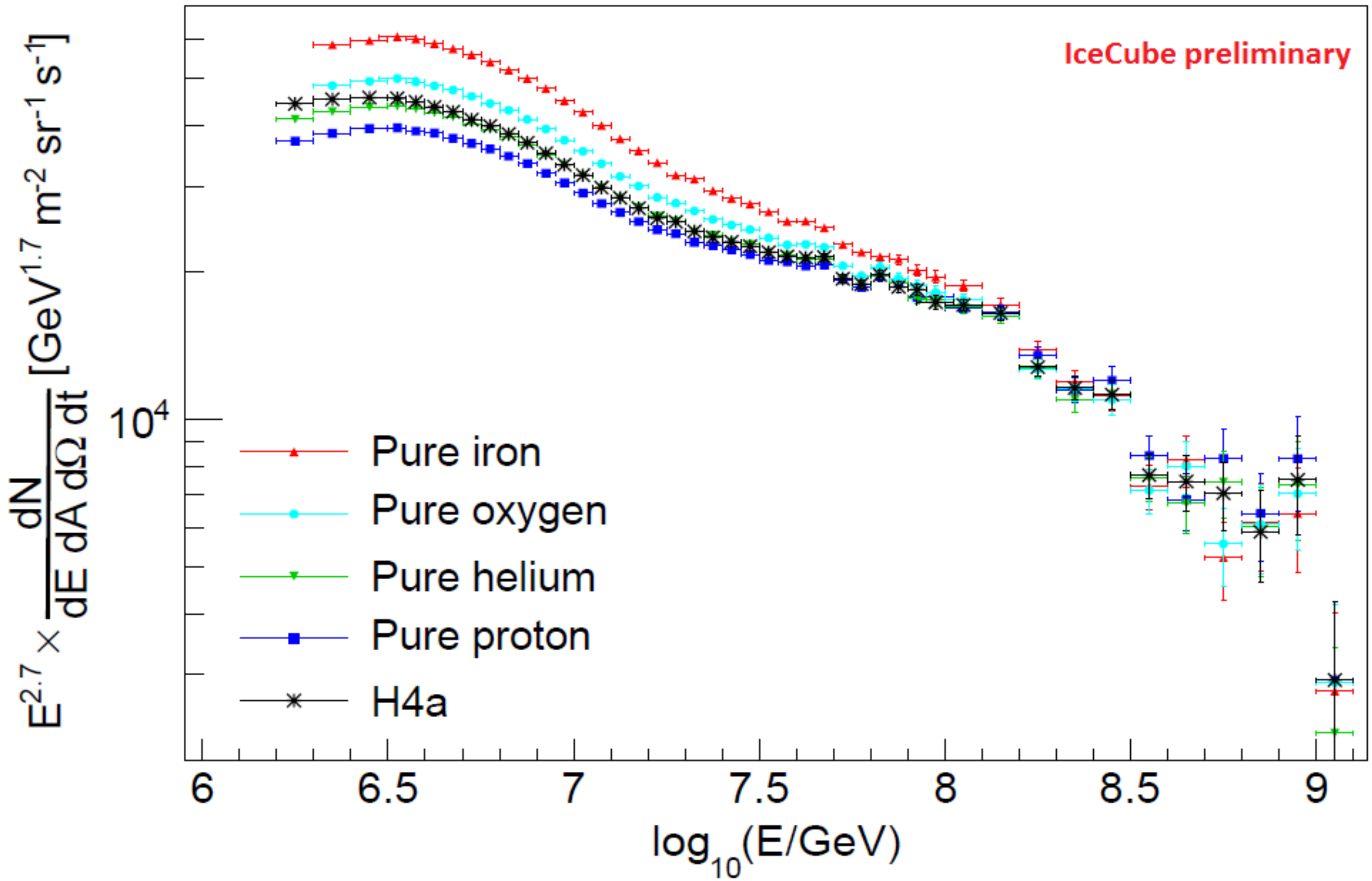
To correct for snow, expected signal for each tank is reduced according to the formula below.

$$S_{corrected} = S_{expected} * exp\left(-\frac{d\ sec\theta}{\lambda}\right)$$

Estimated from the difference between
QGSJET-II and SYBILL 2.1



IceTop Systematics



IceTop Systematics

Isotropic Cosmic ray flux

Same composition in all directions

Correct composition should give the same spectrum in all zenith bins.

Error ~ max. difference between bins (under H4a assumption)