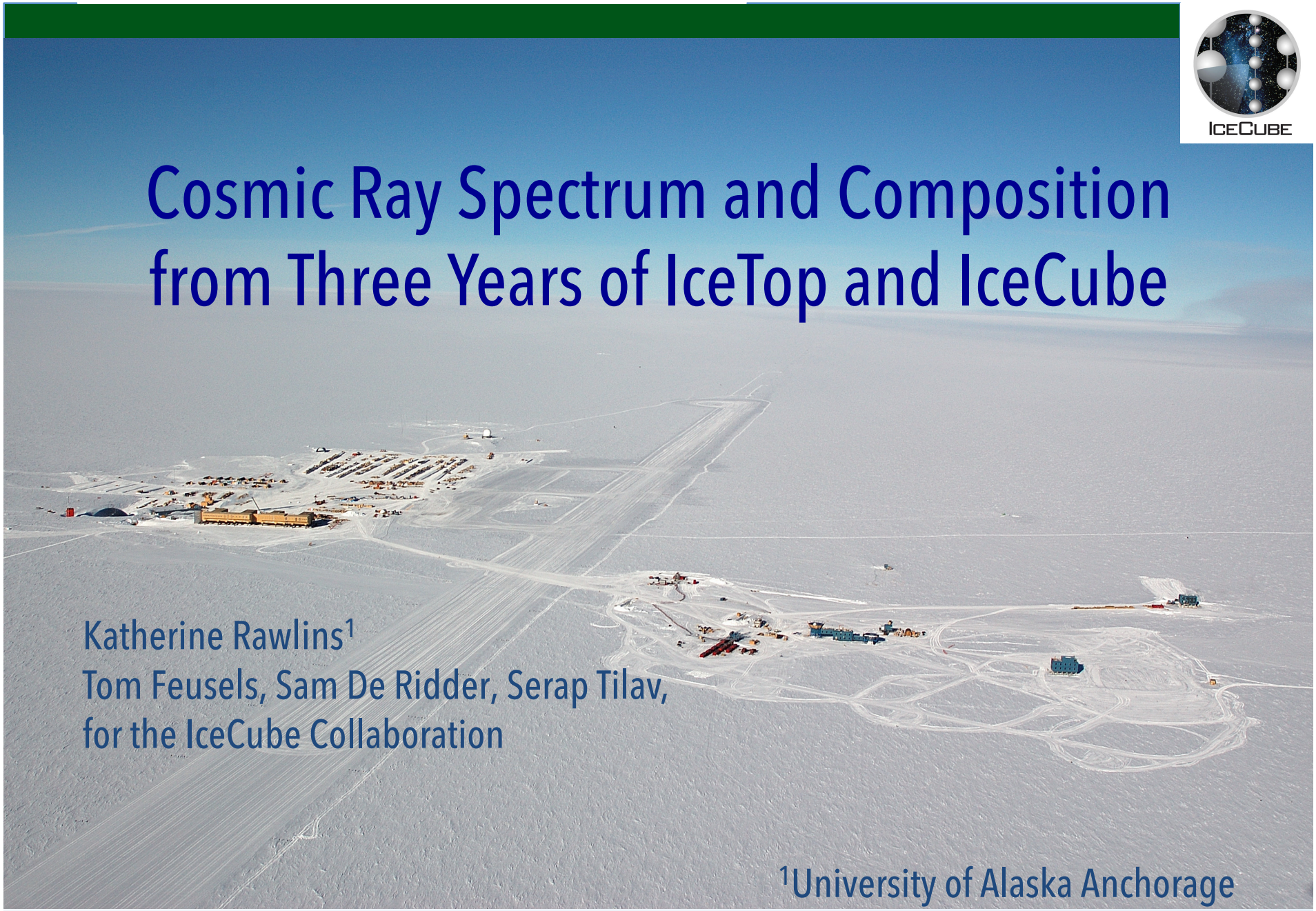
Cosmic Ray Spectrum and Composition from Three Years of IceTop and IceCube

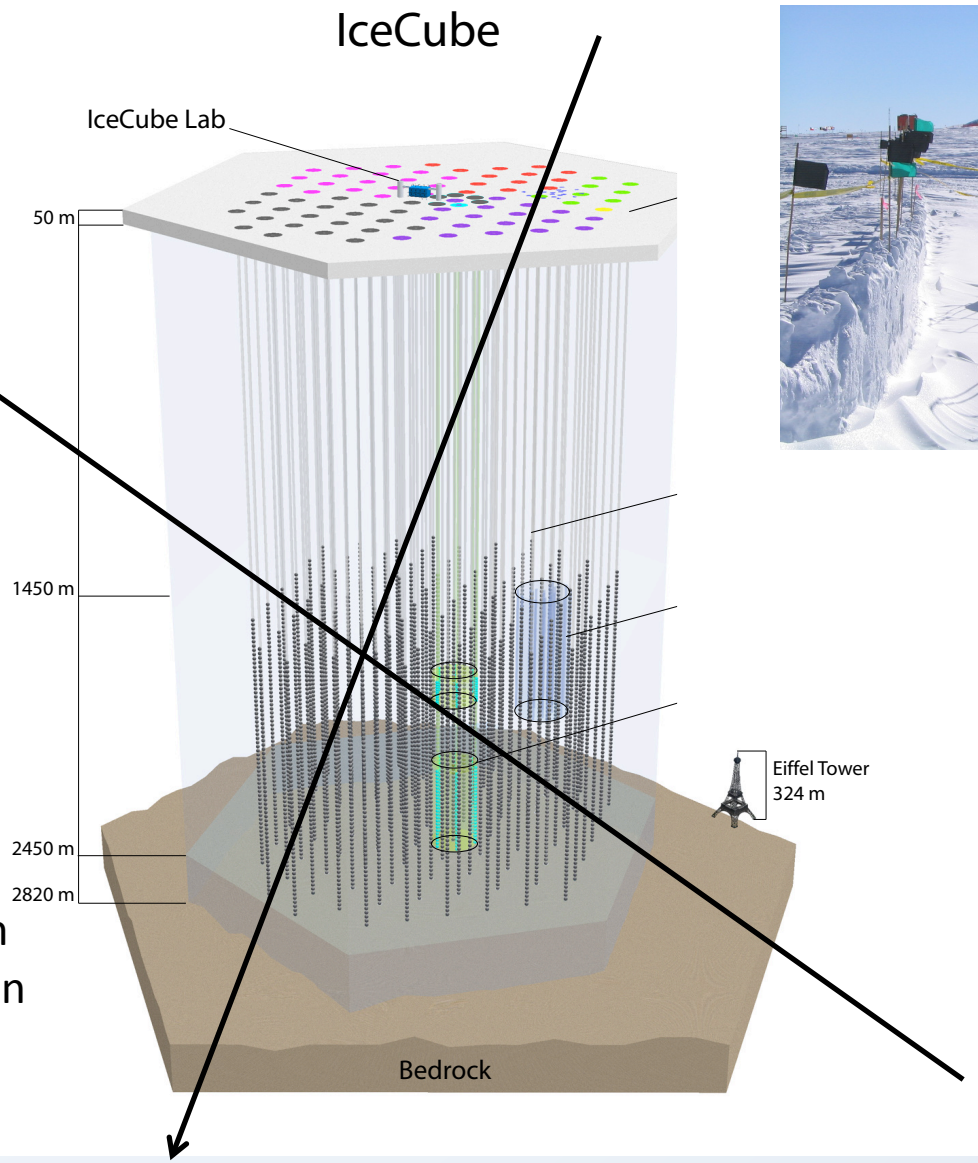


Katherine Rawlins[1]
Tom Feusels, Sam De Ridder, Serap Tilav,
for the IceCube Collaboration

[1]University of Alaska Anchorage

The IceCube Observatory

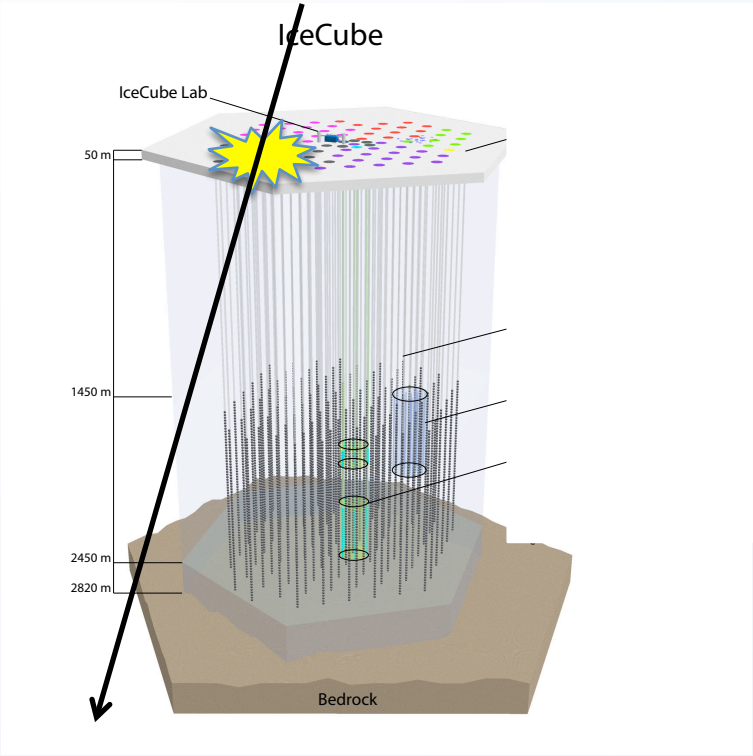
detects Cherenkov light from neutrino-induced leptons…



… and also from cosmic ray muon bundles

IceCube and Cosmic Rays: analysis styles

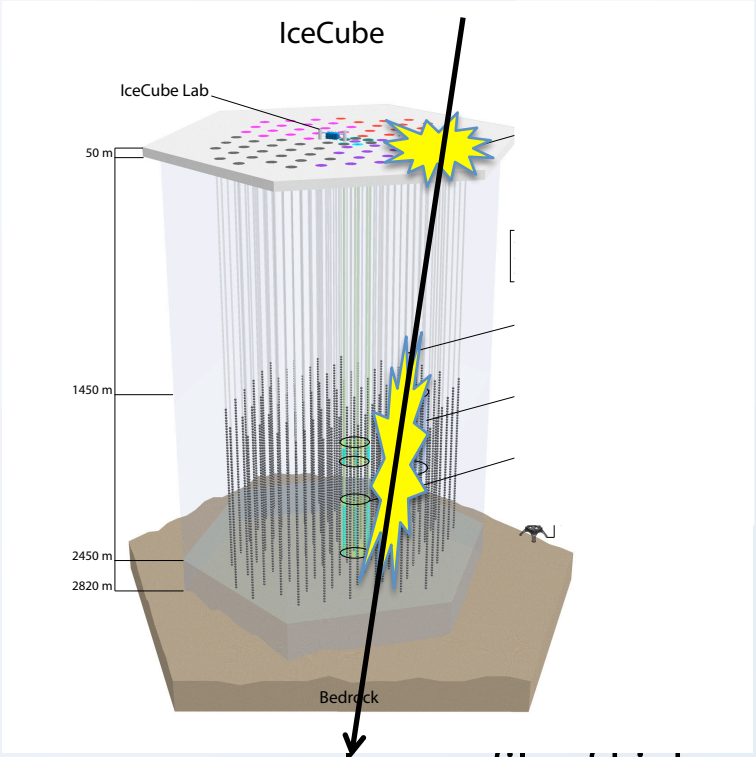
- "IceTop alone"



Greater acceptance, more events

Energy sensitivity from shower size (assuming a composition model)

- "IceTop-IceCube Coincidence"

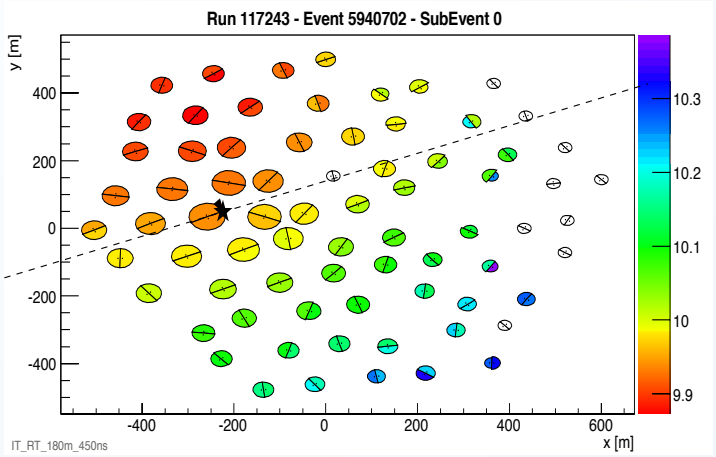


Also measure energy loss profile of high-energy muons that penetrate to depth

Limited number of events, energy and composition sensitivity

Analysis Strategy: IceTop-alone

Reconstruct events:

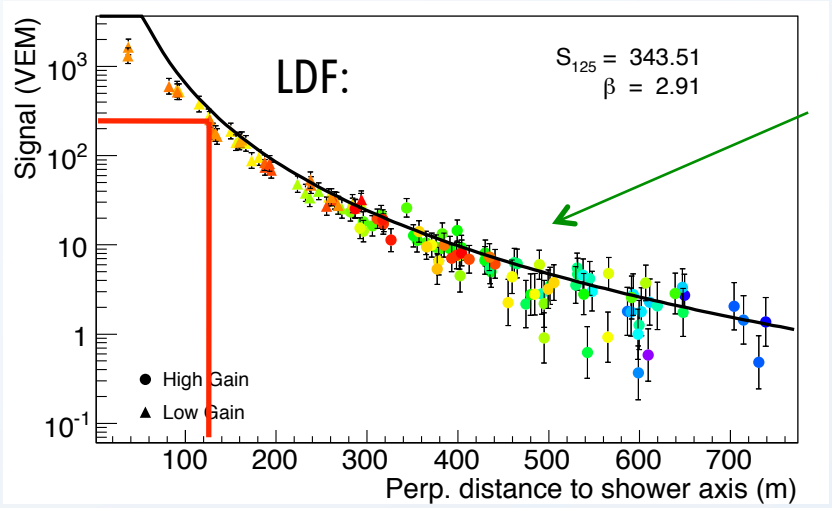


Estimate the shower's core position and direction…

Top view:

colors = timing,

bubble size = charge



Fit a lateral distribution function (LDF)

Use tank charges and arrival times

Find best-fit core position/direction, and LDF:

S125 = signal at 125 meters from the core

beta = a measure of the slope

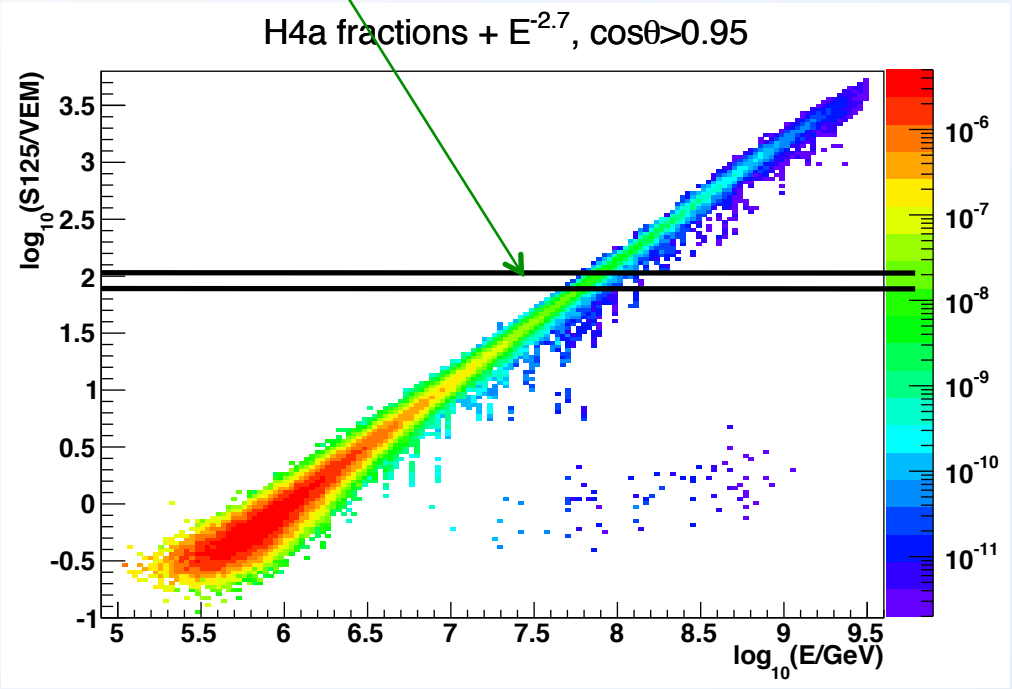
Analysis Strategy: IceTop-alone

Build S125 -> Energy conversion functions:

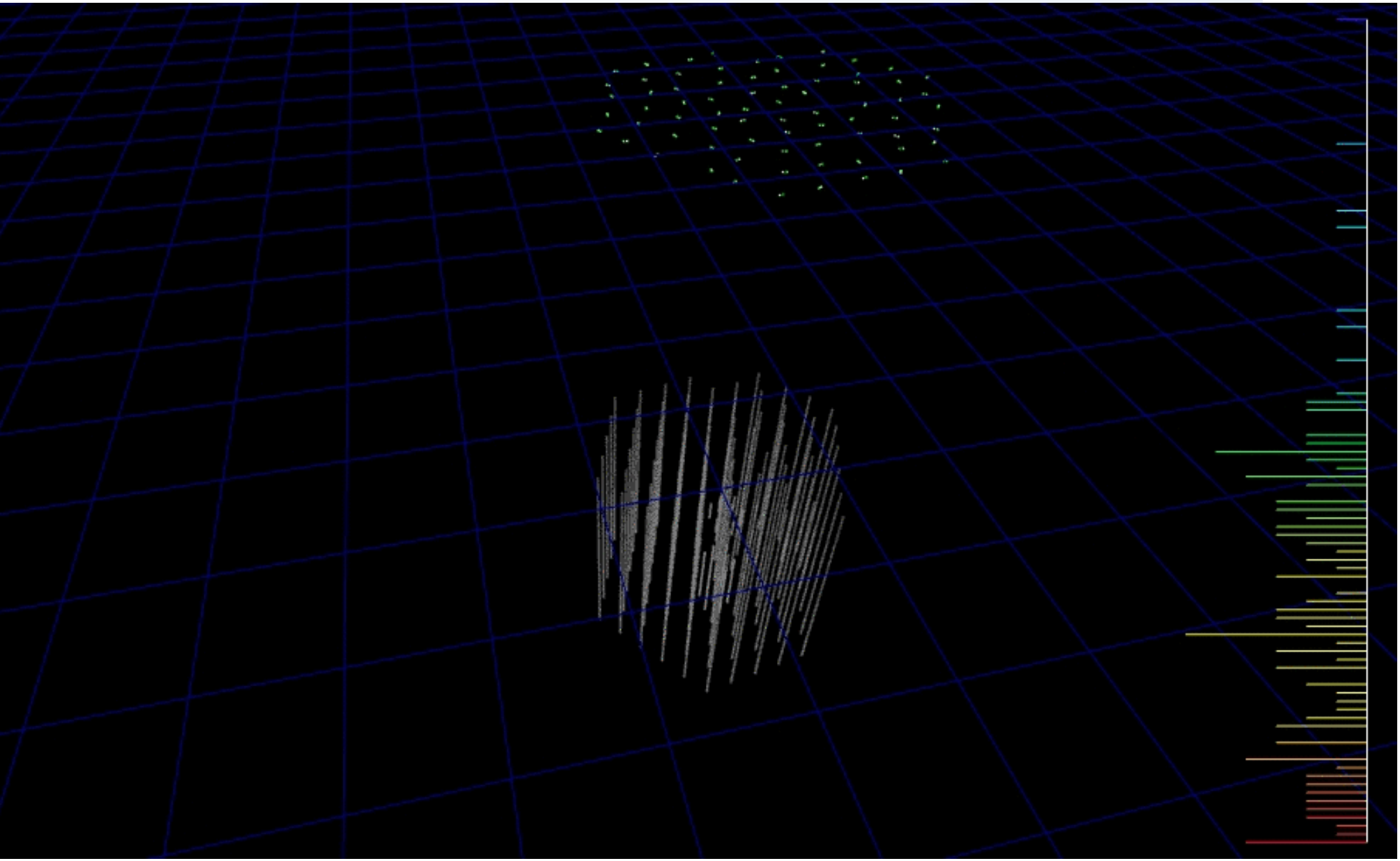
Using Monte Carlo simulations (and assuming a composition model),

Find most likely energy within each slice of S125

Do this separately for 4 zenith angle ranges



Analysis strategy: Coincidence



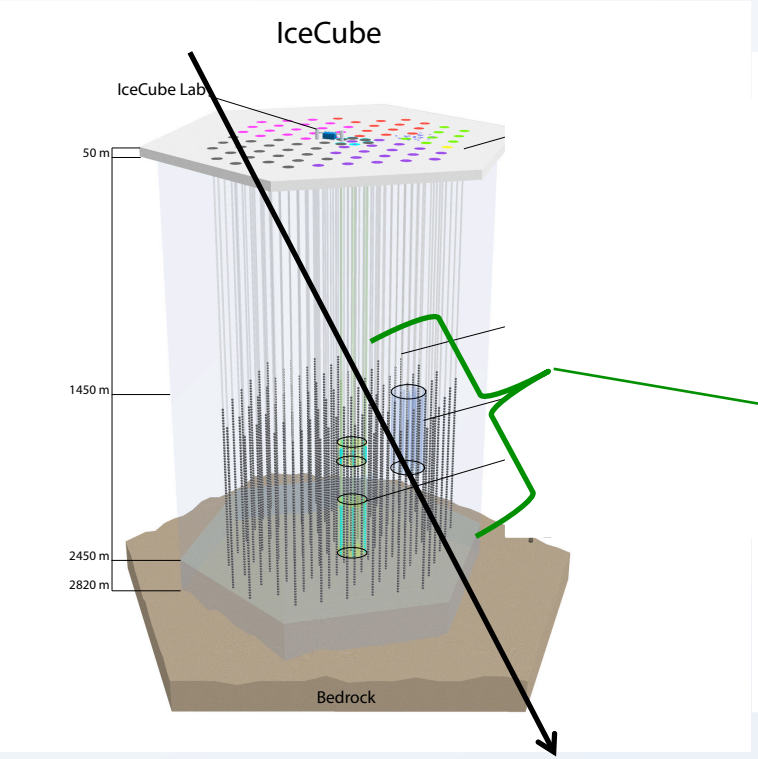
Analysis Strategy: Coincidence

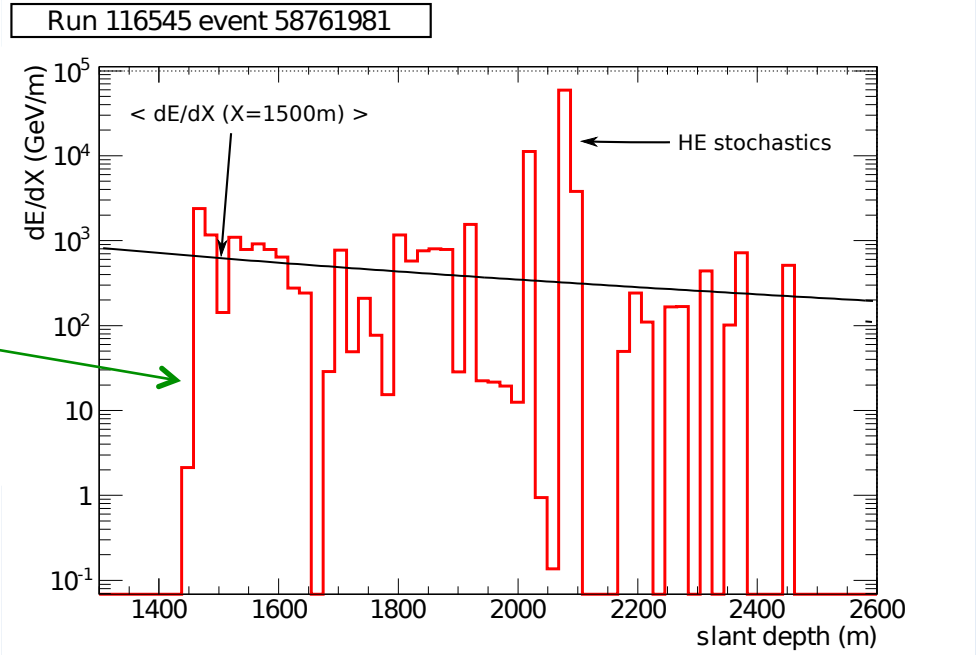
Also reconstruct in deep IceCube:

Construct energy loss profile

Fit the profile to find:

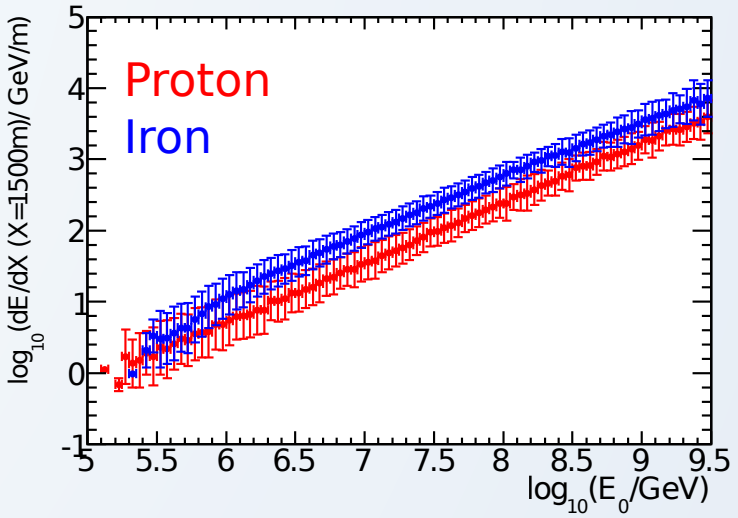
- the mean muon energy loss at 1500 m slant depth, and
- the number of large stochastic losses (2 different thresholds)





Analysis Strategy: Coincidence

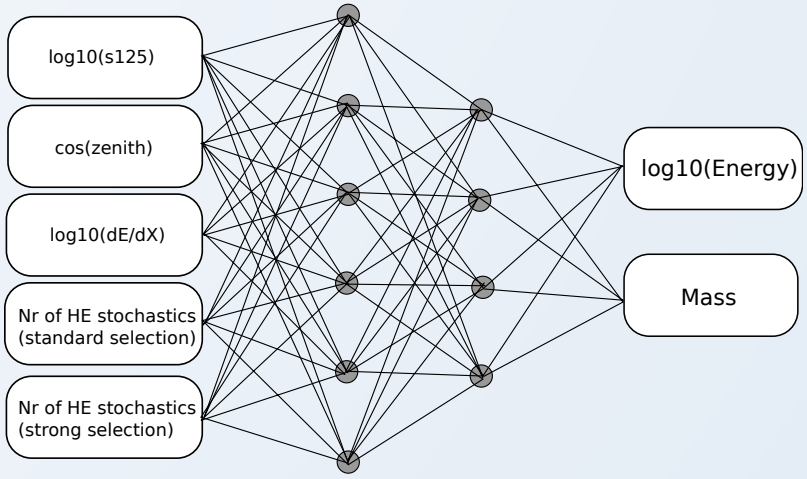
Muon energy loss at 1500 m is highly composition-sensitive:



The two measures of number of stochastics are also sensitive to composition.

Feed five input variables from both IceTop (S125, zenith) and IceCube (dE/dX @ 1500, Nstoch1, Nstoch2) into a neural network…

Outputs of the network: Primary energy, Primary mass.

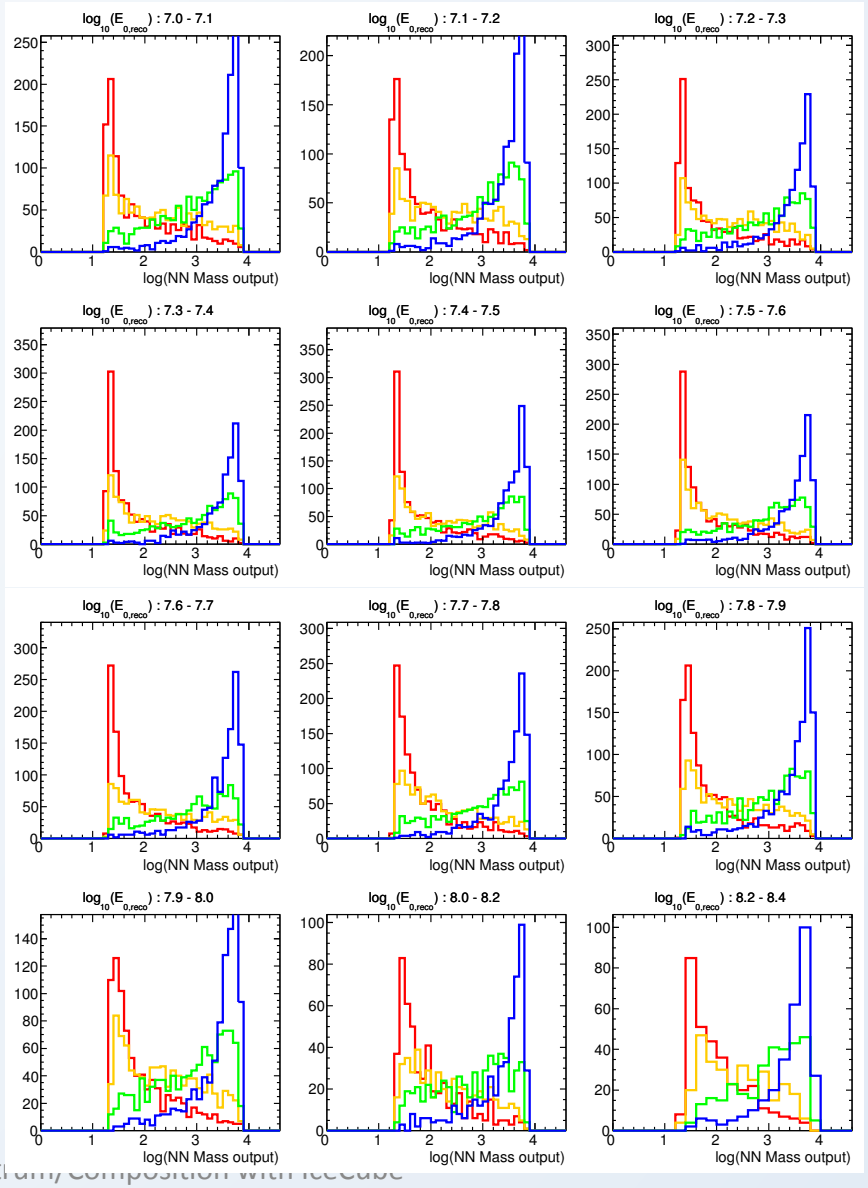


Analysis Strategy: Coincidence

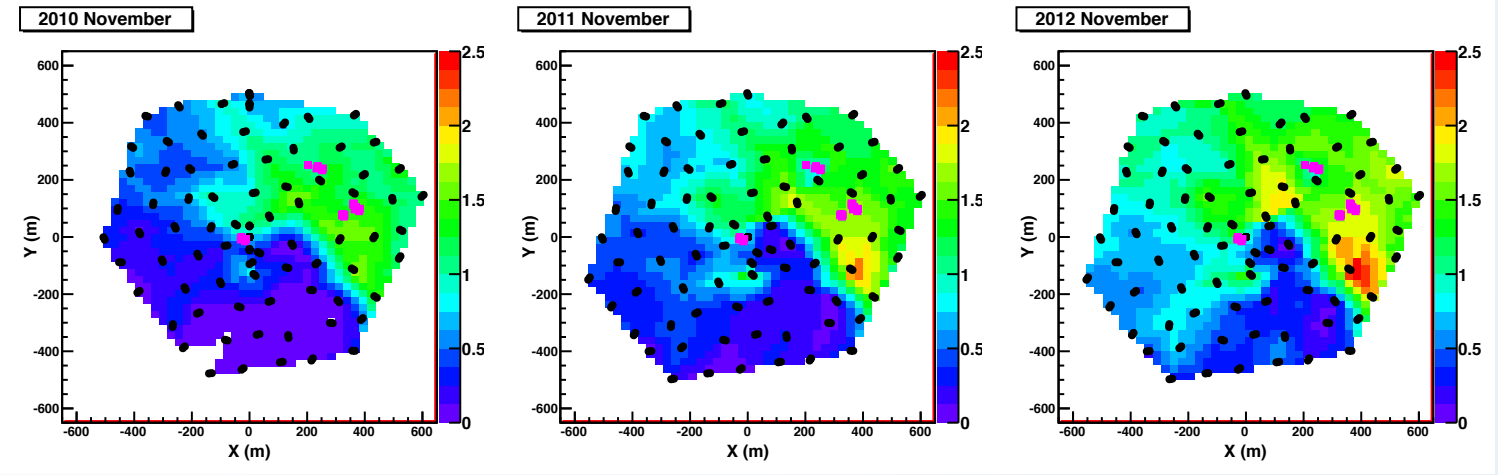
Construct template histograms of NN primary mass

Within each bin of reconstructed energy, compare templates for Monte Carlo (four types: H, He, O, Fe)

Run experimental data through the same NN procedure, and find the fractions of each element that best reproduce the template histogram of the data.



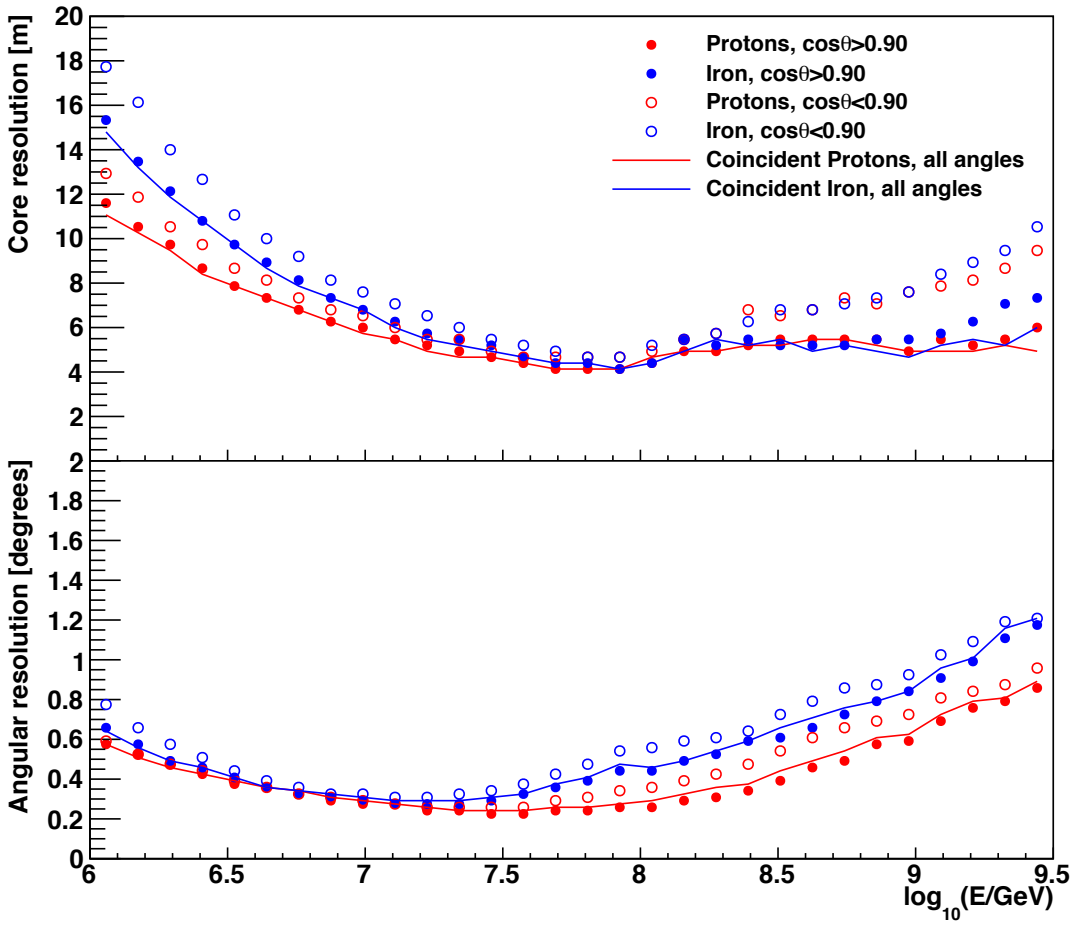
Effects of snow



- As snow accomulates on IceTop, the effect of attenuation on signals taken into account in reconstruction.

- Both analyses extended from 1 year to 3 years of experimental data
  - IT-81/IC-86 data retriggered to IT-73/IC-79
  - Snow reconstruction optimized separately for the three years

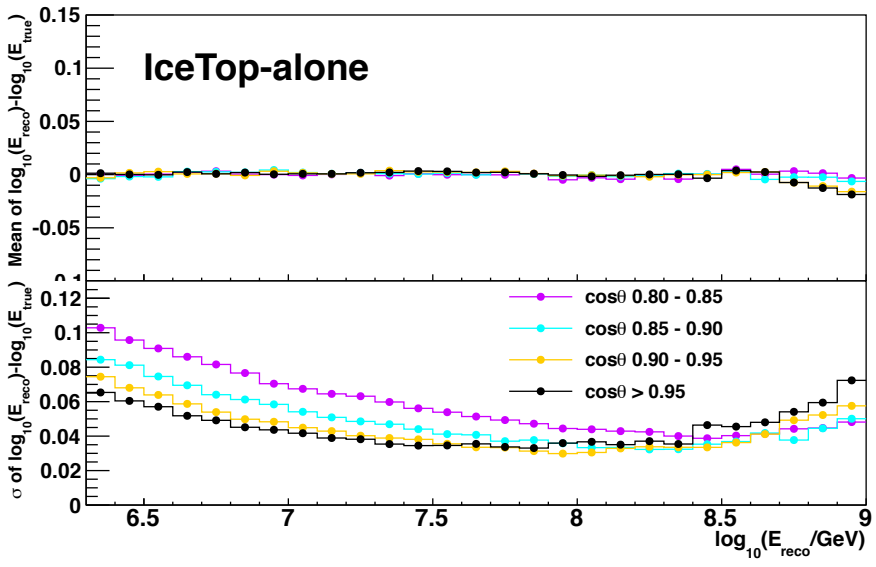
Position/Direction Performance

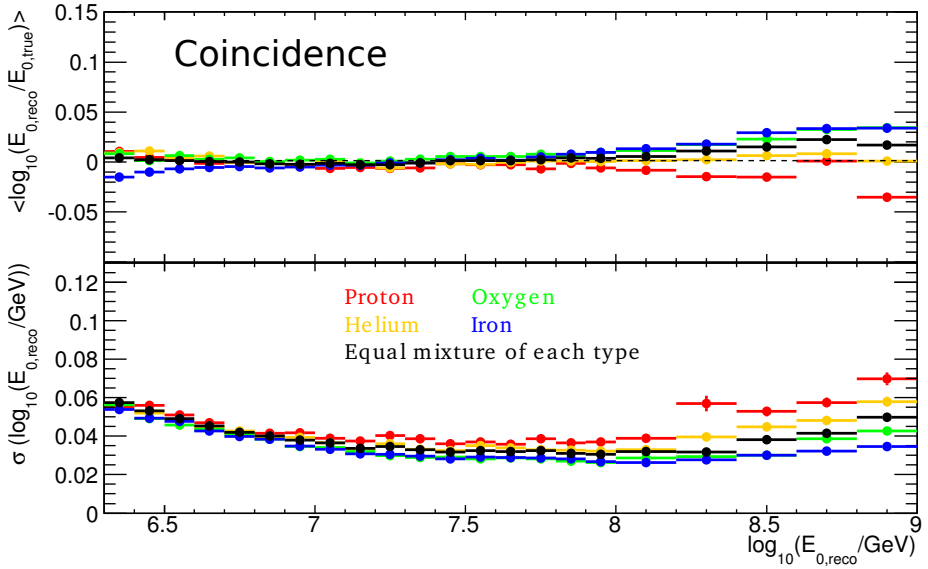


Core position: between 5-10 meters

Direction: less than 1°

Energy Reconstruction Performance





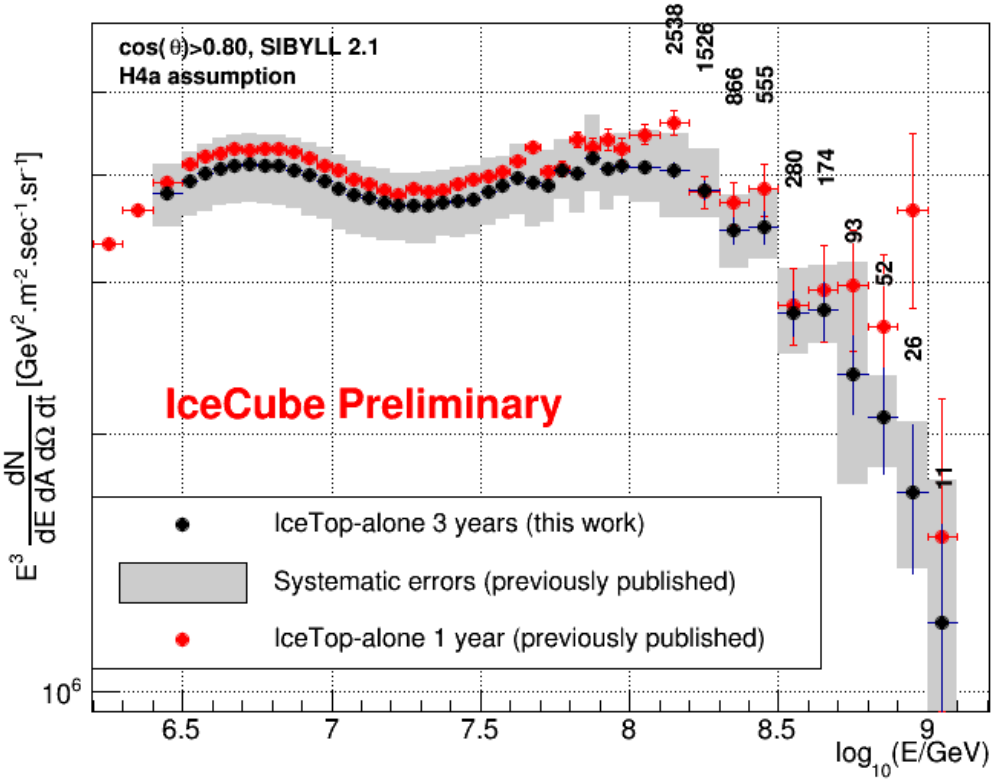
Bias = near zero

Resolution: best between 10 and 300 PeV, worsening in regions where position/ direction resolution suffers (misreconstructions)

Spectrum result: IceTop-alone

- 3-year result compared to previously published (from 1 year)

M.G. Aartsen et al., *Phys. Rev. D* **88**, (2013) 042004. (arXiv:1307.3795)



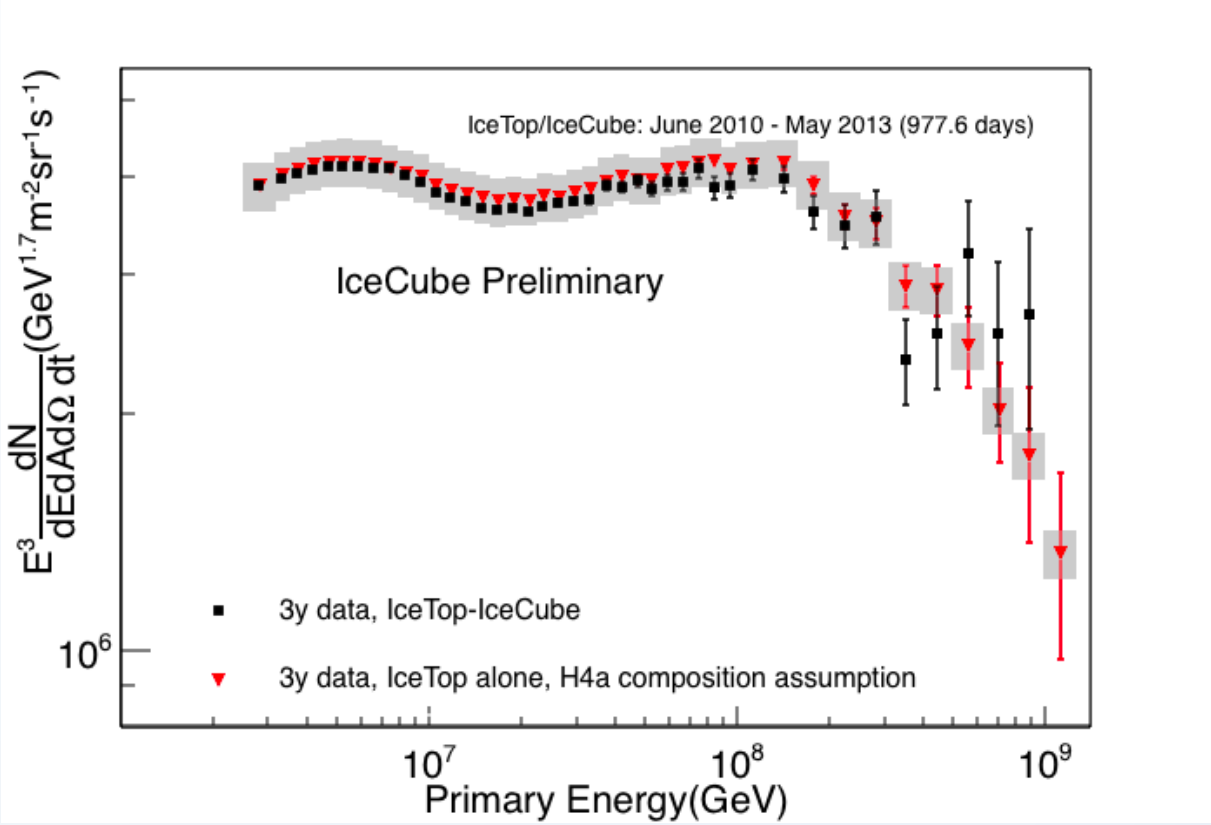
The 5% shift downward:

Problem found in simulation of the northeast corner of the array: under-simulation of snow, leading to overestimation of S125 in Monte Carlo – fixed in both analyses.

- Reconstruction resolution improved
- Overall spectrum moved downward

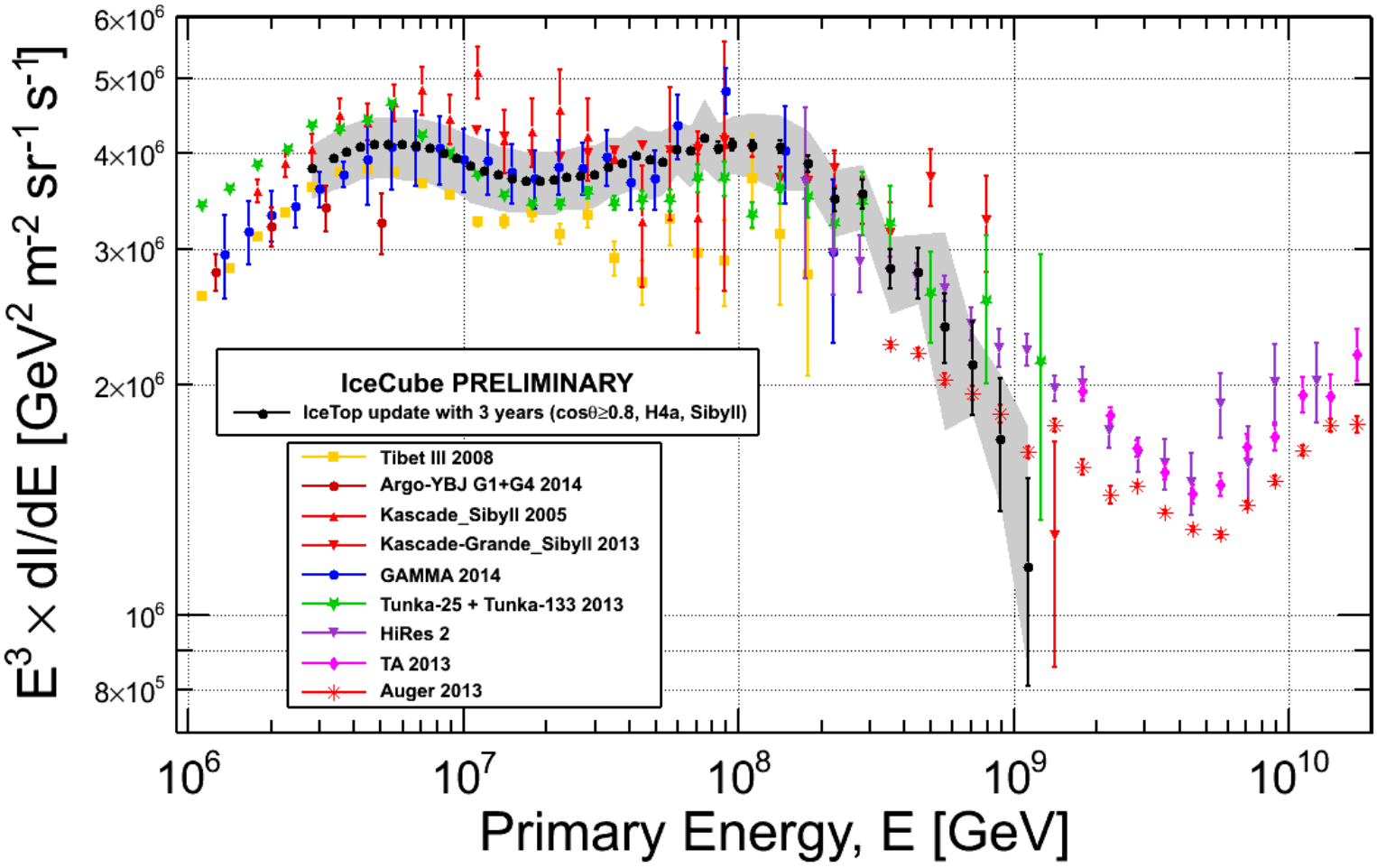
Spectrum Result: Coincidence

- Coincidence result compared to IT-alone result



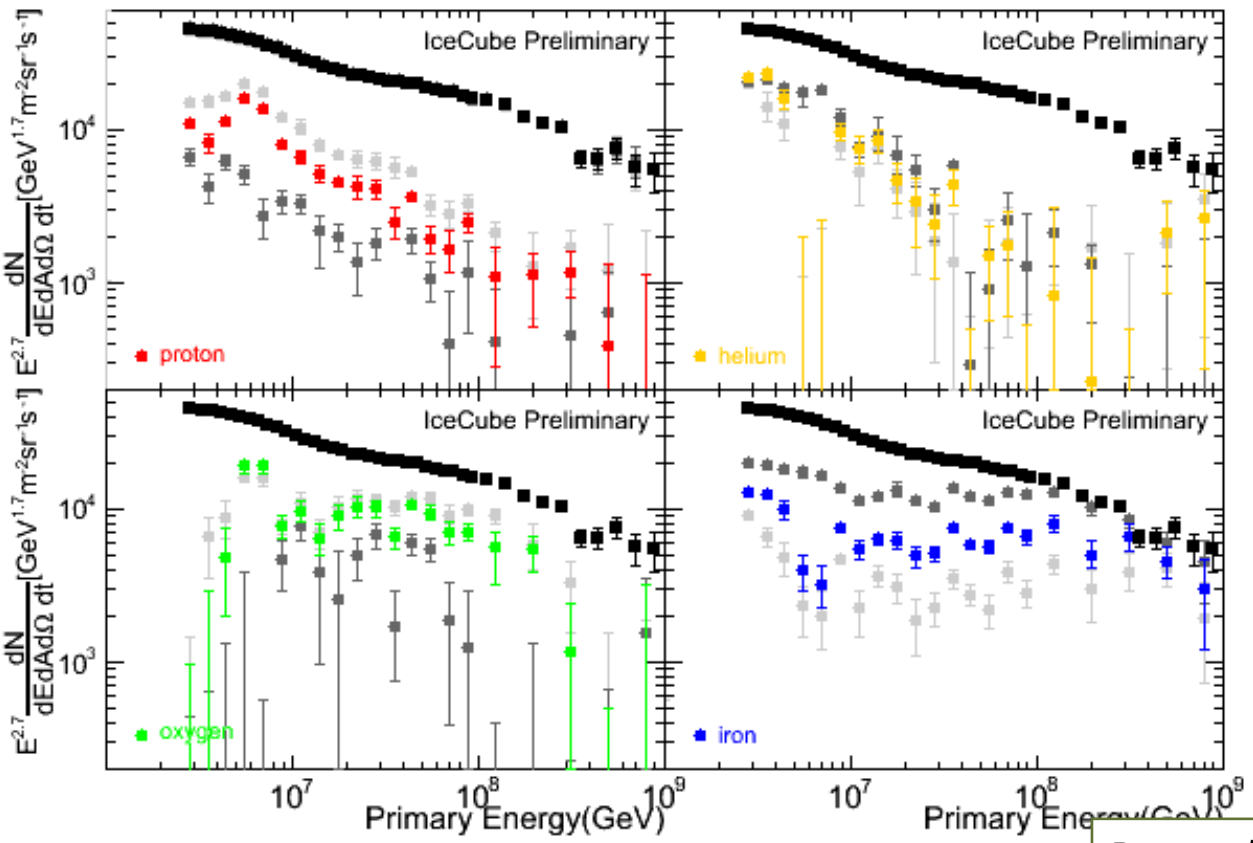
Good agreement between complementary techniques

Spectrum: comparisons



Individual Nuclear Spectra

- … with light yield systematics

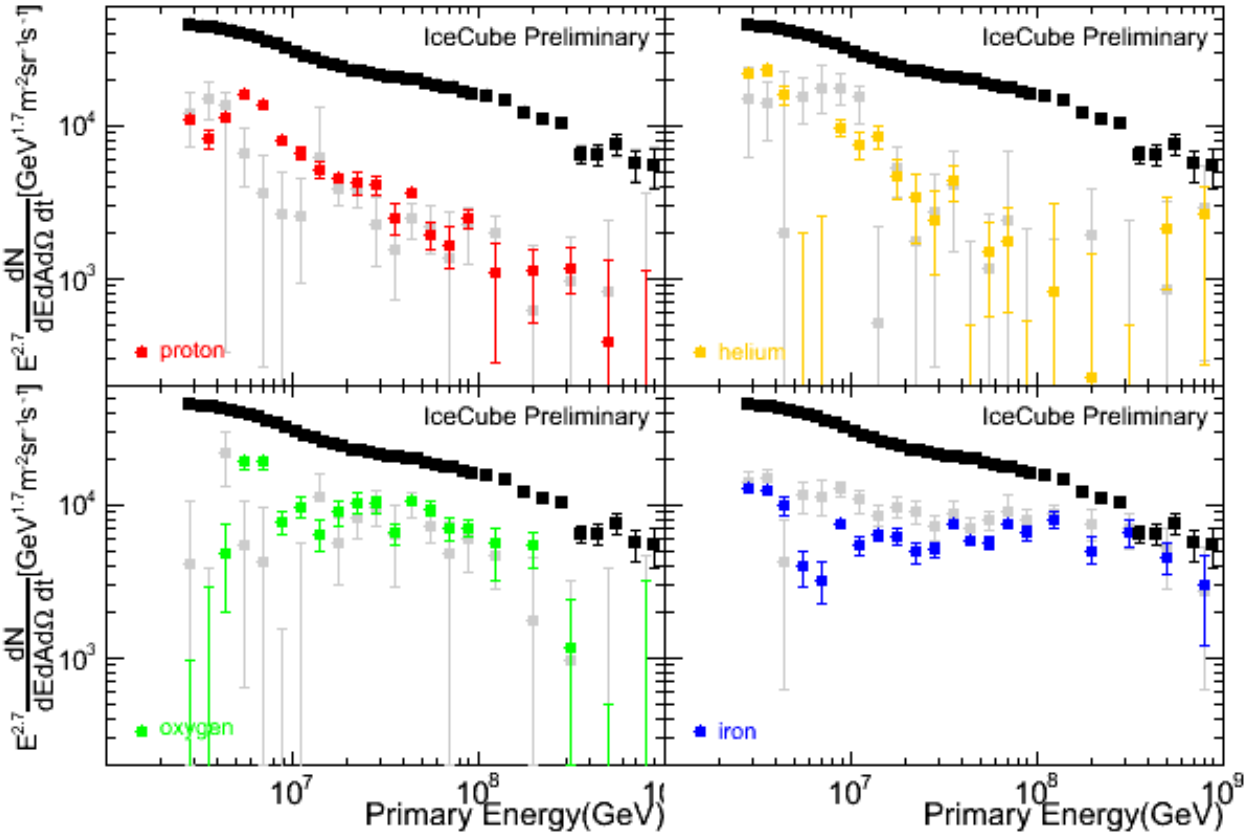


Colors = nominal
Dark Grey = -12.5%
Light Grey = +9.6%

Protons/Helium spectra are steeper.
Oxygen/Iron maintain harder spectrum out to higher energies.

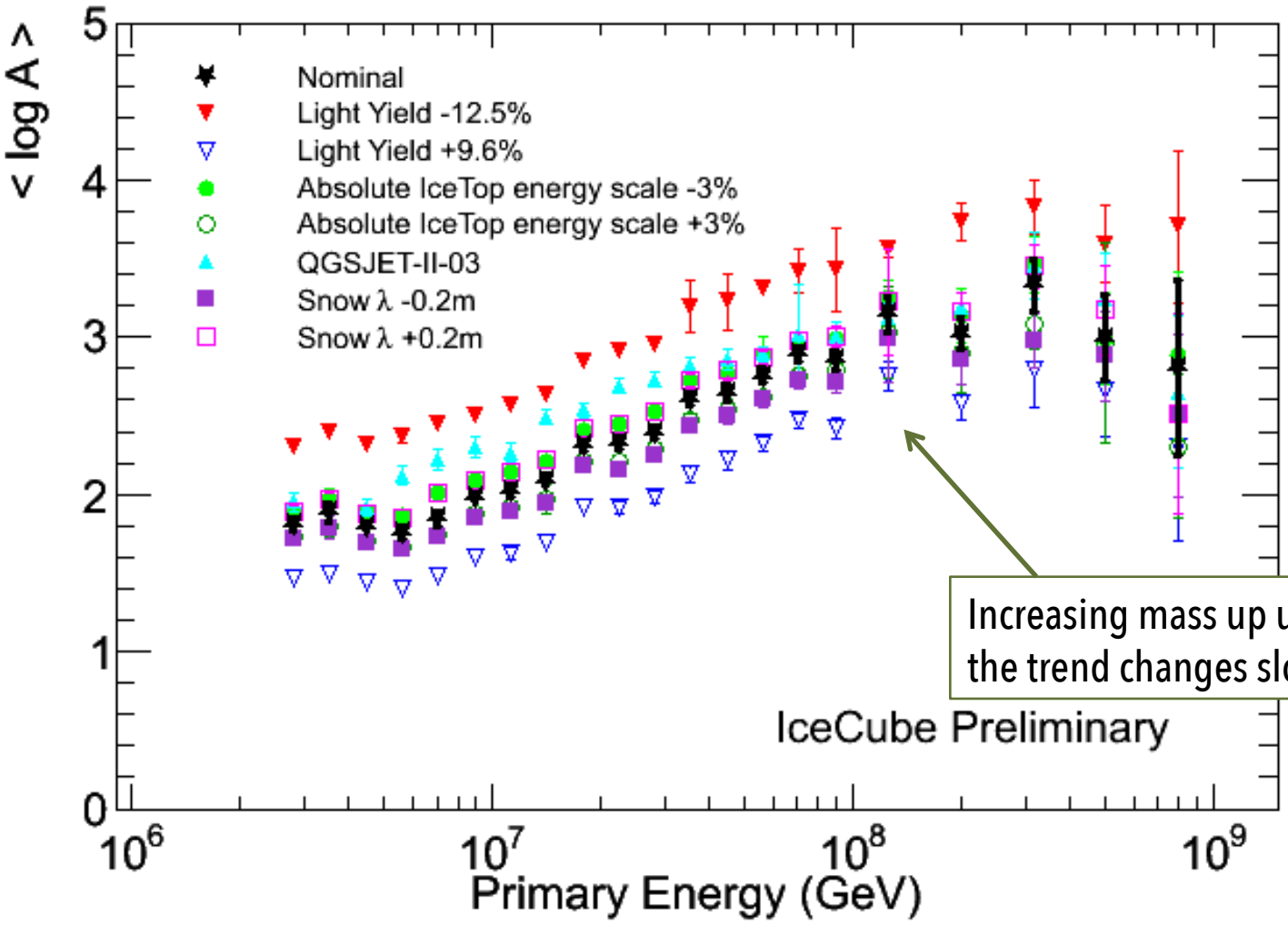
Individual Nuclear Spectra

- … with hadronic interaction model systematics



Colors = SIBYLL 2.1
Grey = QGSJET-II-03

Mean log mass <lnA>



Increasing mass up until ~100 PeV, where the trend changes slope

Conclusions

- IceCube and IceTop can be used in a variety of different ways to analyze cosmic ray air showers, and measure spectrum and composition.

- The spectrum (from both analyses) shows features:
  - Hardening at ~ 20 PeV
  - Turndown again at 100-200 PeV

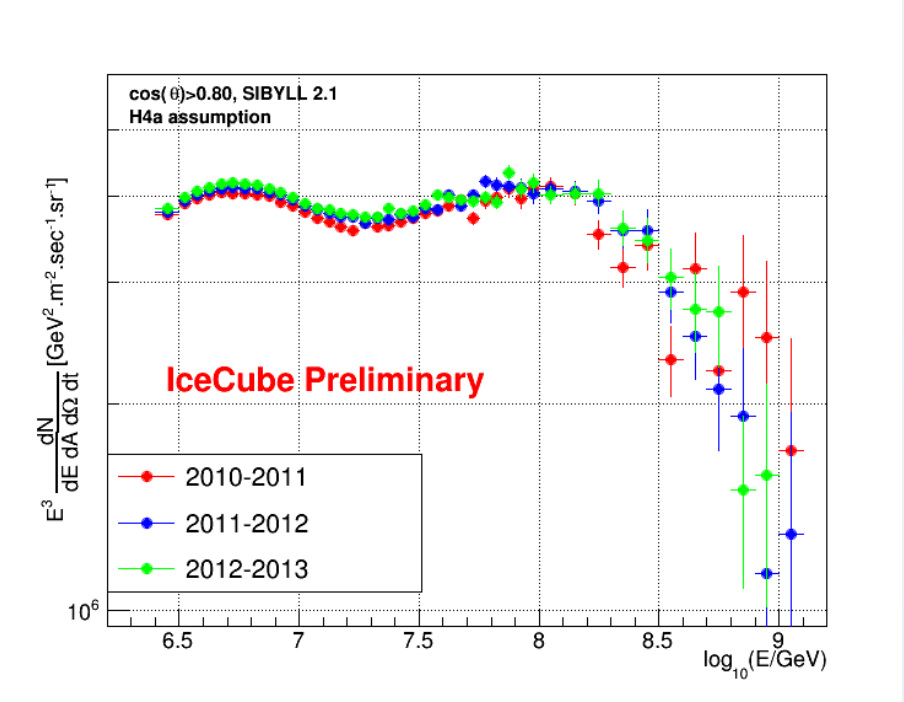
- A composition getting heavier up to ~ 100 PeV
  - Heavy elements (O and Fe) maintain a harder spectrum than lighter elements (H and He)

The end!

(Backup slides…)

Comparing 3 years: IceTop-alone

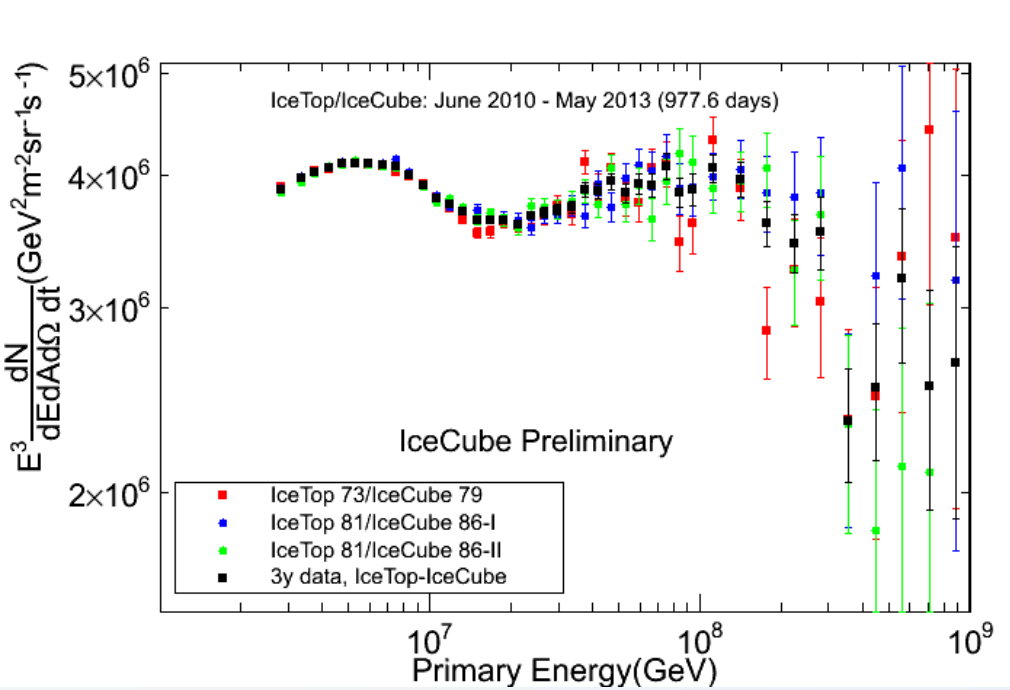
- 3 years compared to each other



Differences due to artifacts of snow reconstruction, which are different from year to year

Comparing 3 years: coincidence

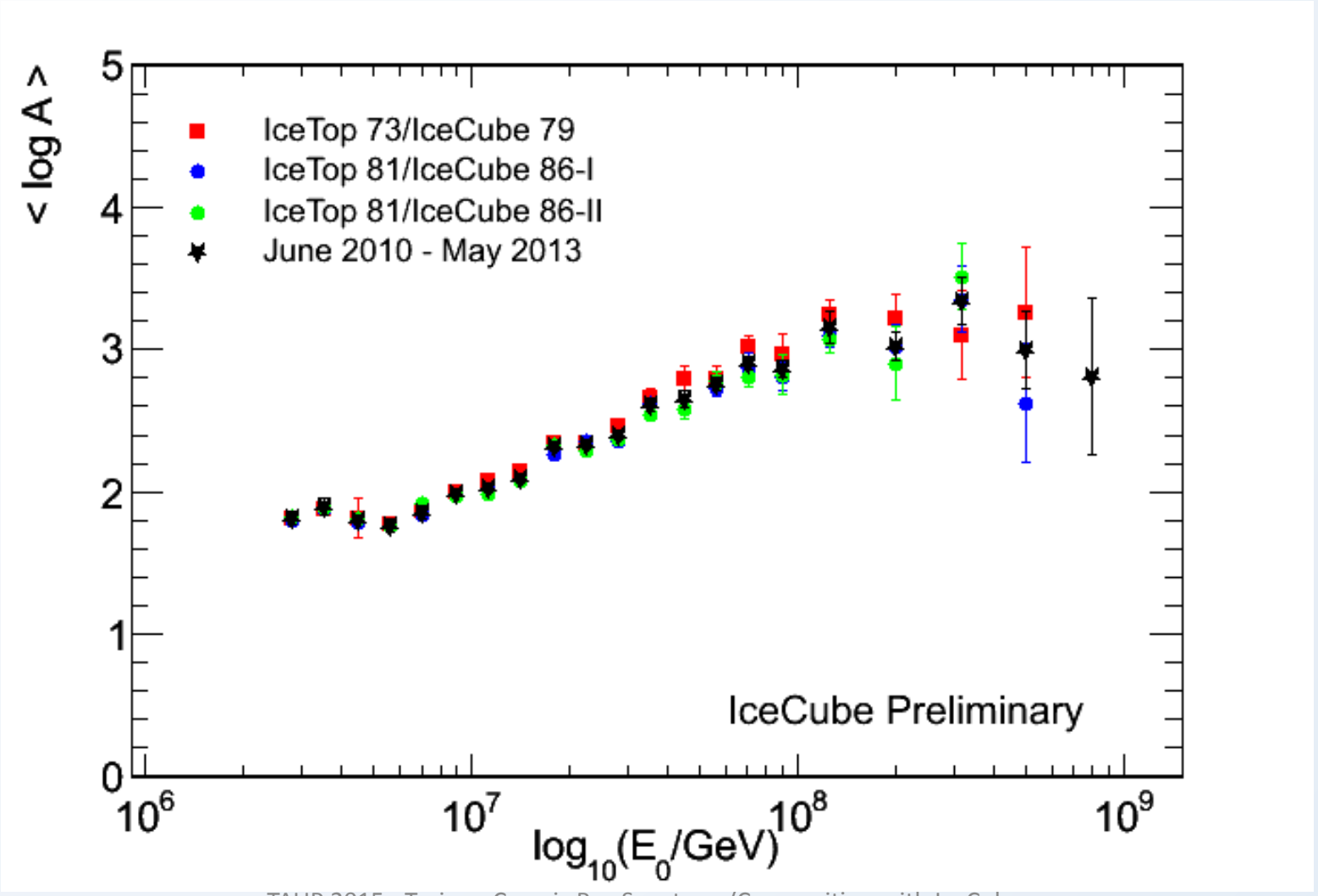
- 3 years compared to each other



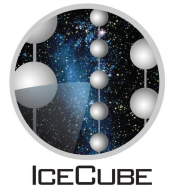
Good agreement between years

Mean log mass <lnA>

- 3 years compared to each other



Coincidence: systematic uncertainties

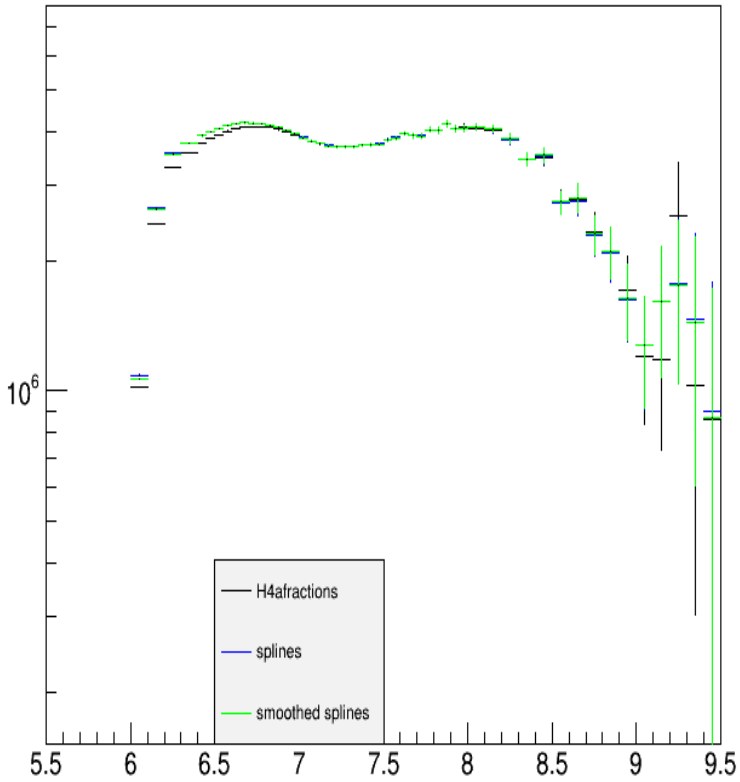


	Systematics Uncertainty
DOM efficiency	±3%
Hole Ice 30cm	+4.5%
Hole Ice 100cm	-2.9%
+10% scattering	+3.6%
+10% absorption	-11.8%
−7% scattering AND absorption	+7%
Total	+9.6% −12.5%

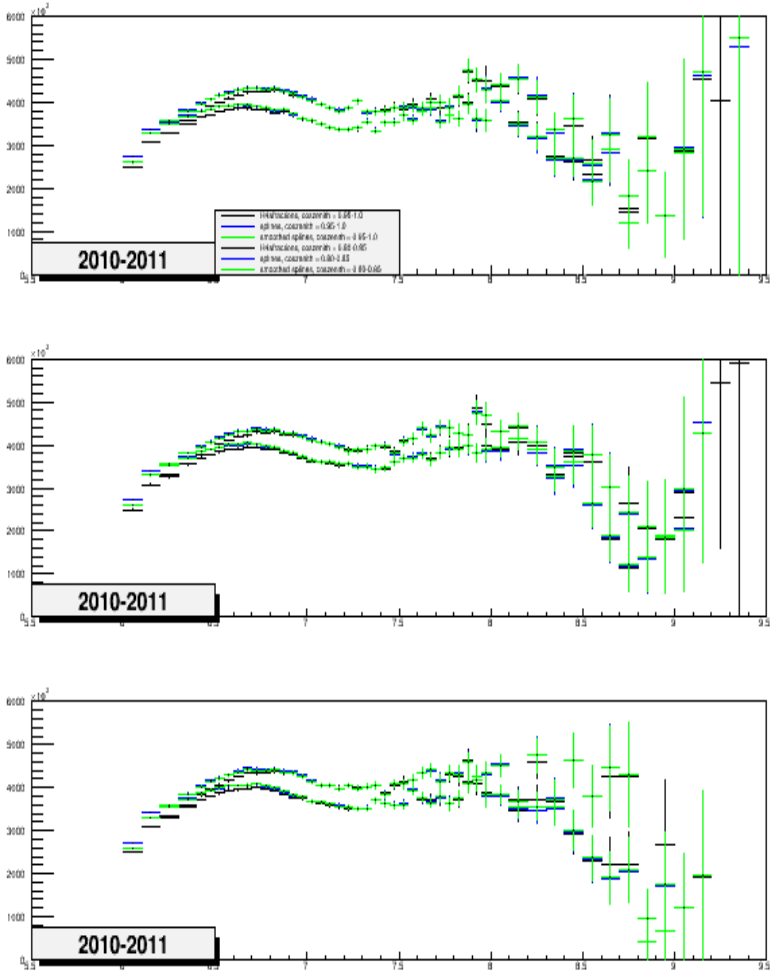
	3.35 PeV	33.5 PeV
VEM calibration/Absolute energy scale	+4.1% -4.4%	+7.0% -4.3%
Snow correction	+5.0% -4.3%	+7.9% -4.7%
QGSJet-II-03	+2.1%	+1.4%
Light yield	+3.1% - 3.0%	+1.1%
Total	+7.5% -6.5%	+10.8% -6.4%

IT-alone: different composition input?

- All 3 years

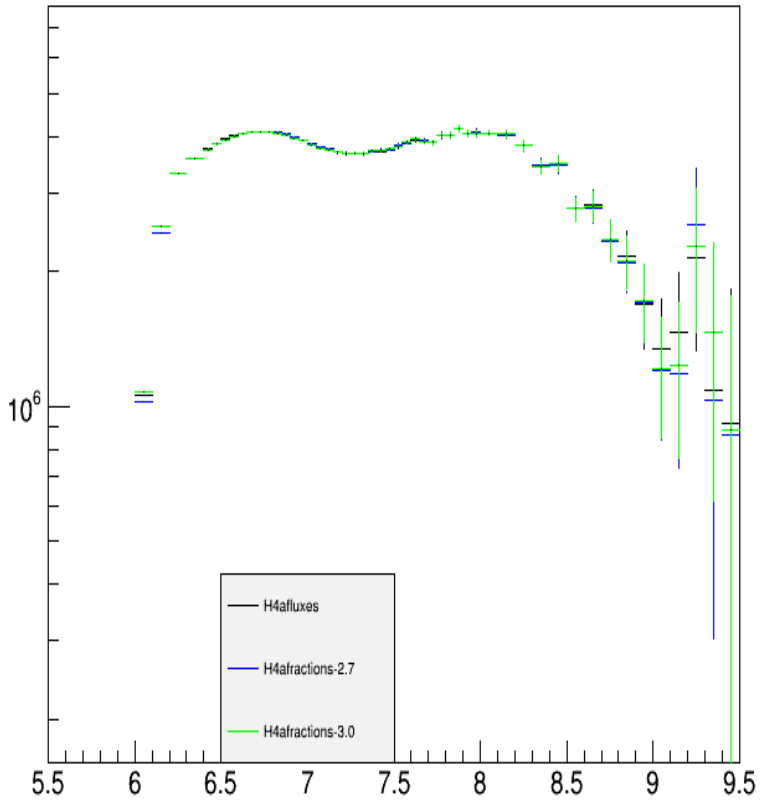


- Individual years

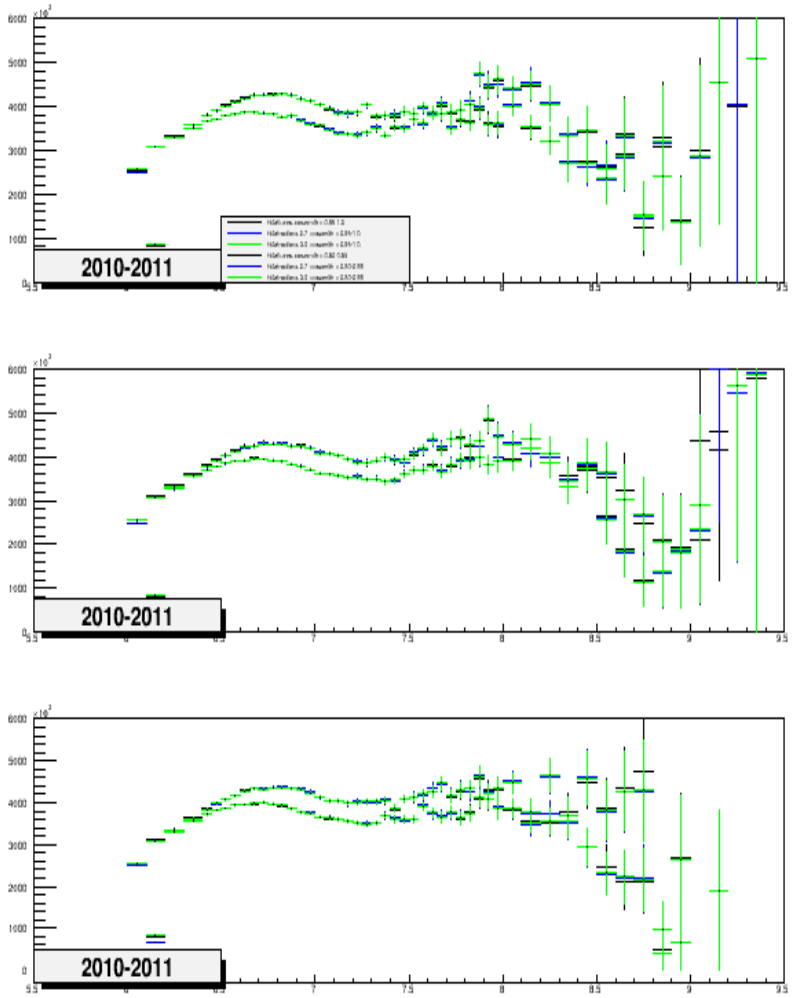


IT-alone: different spectrum input?

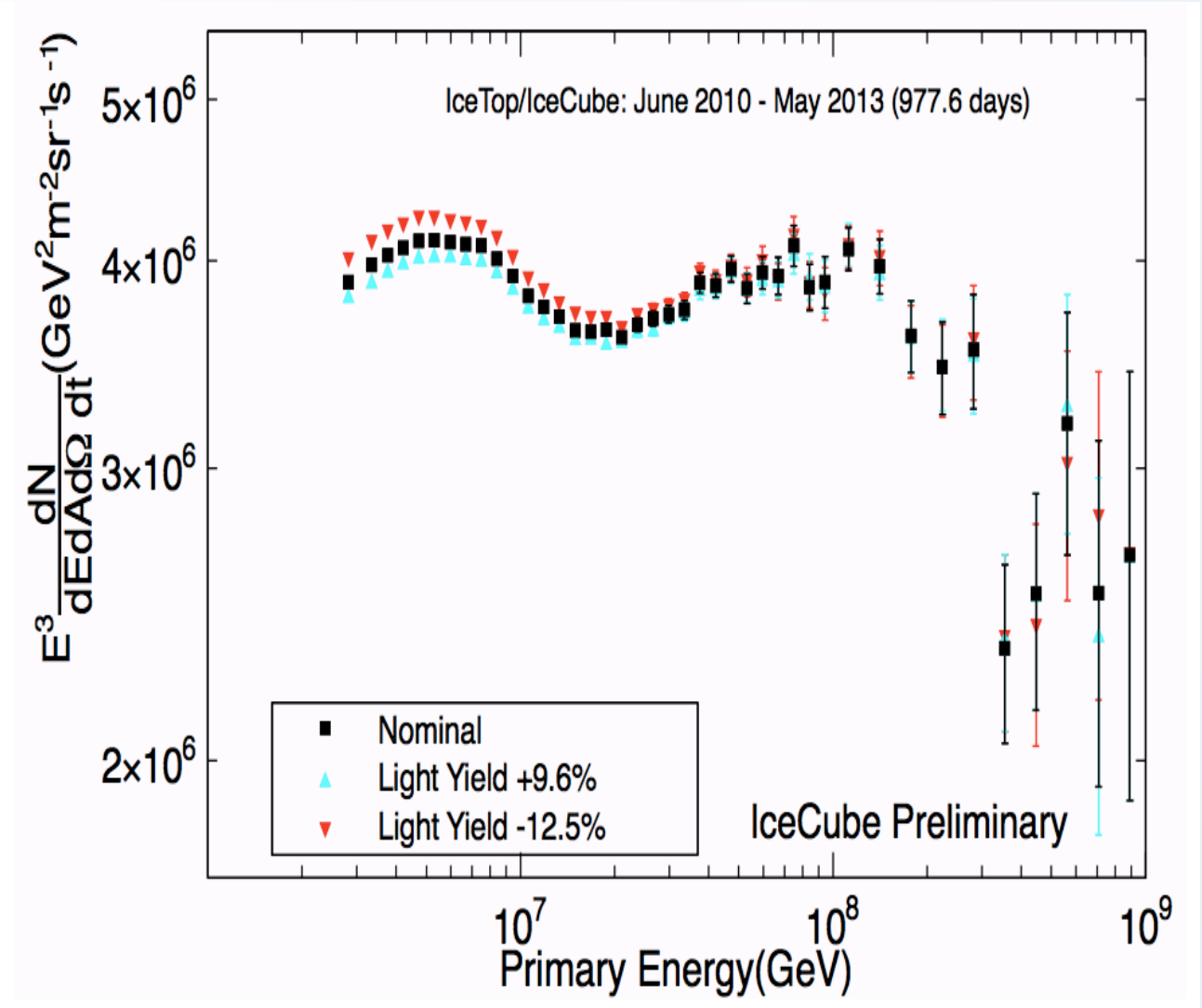
- All 3 years



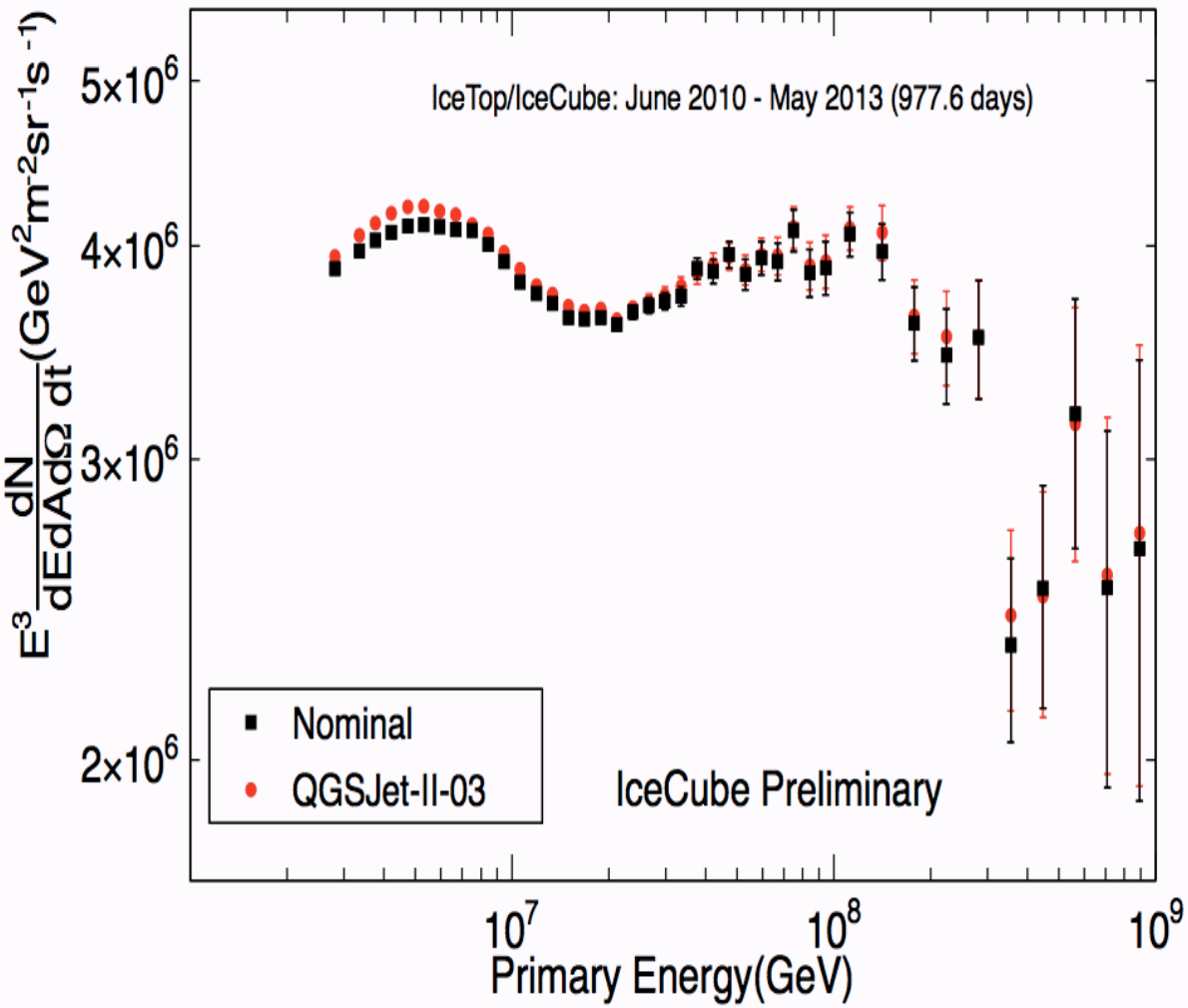
- Individual years



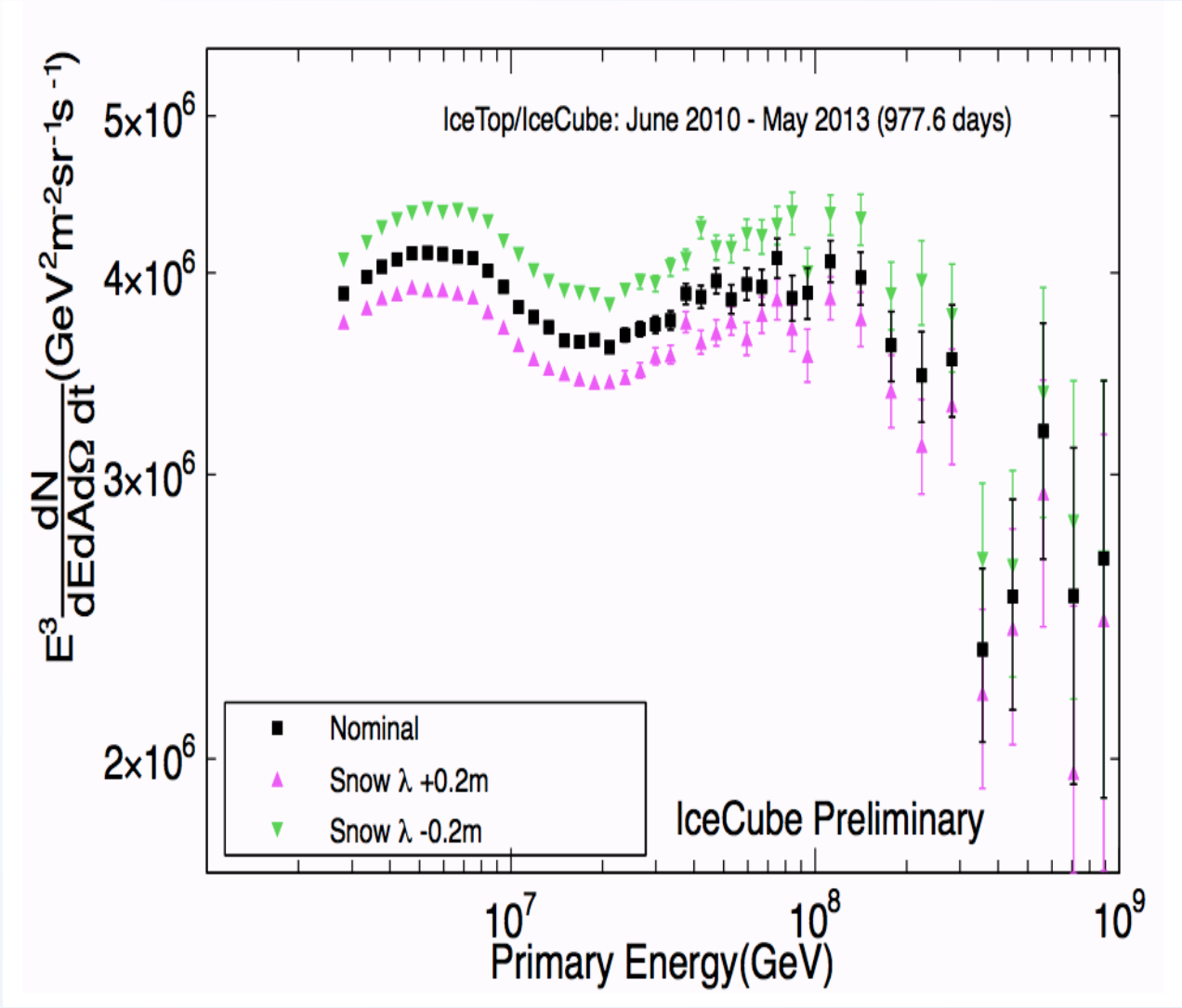
Coincidence: different light yields



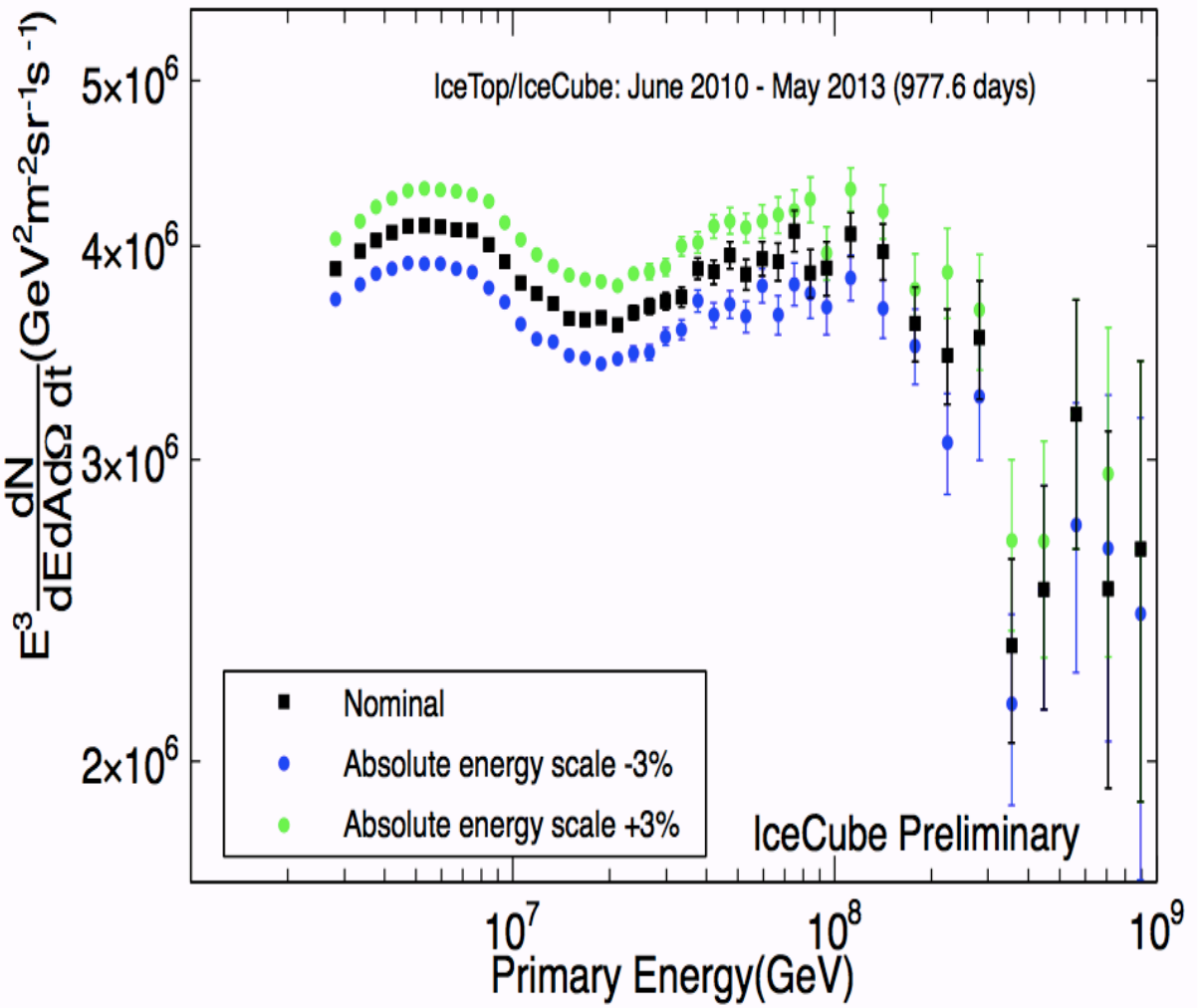
Coincidence: different hadr. int. model



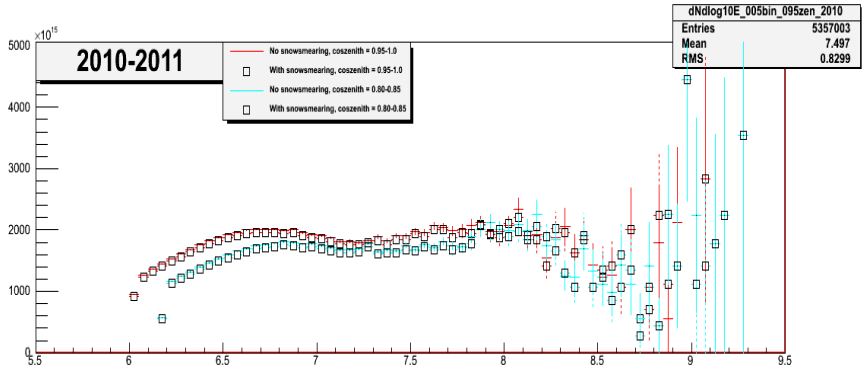
Coincidence: different snow reco

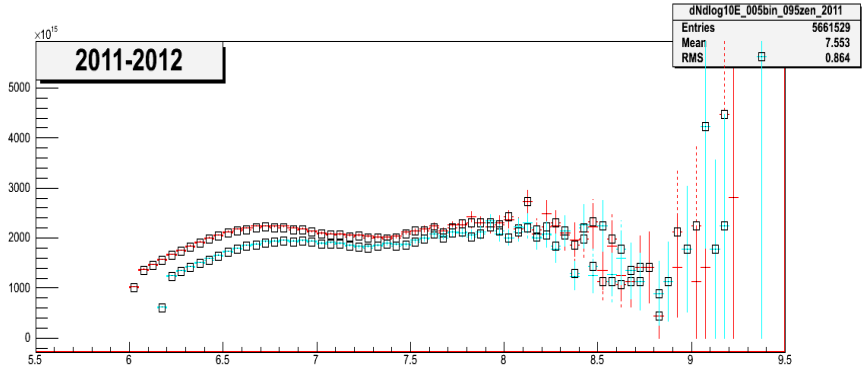


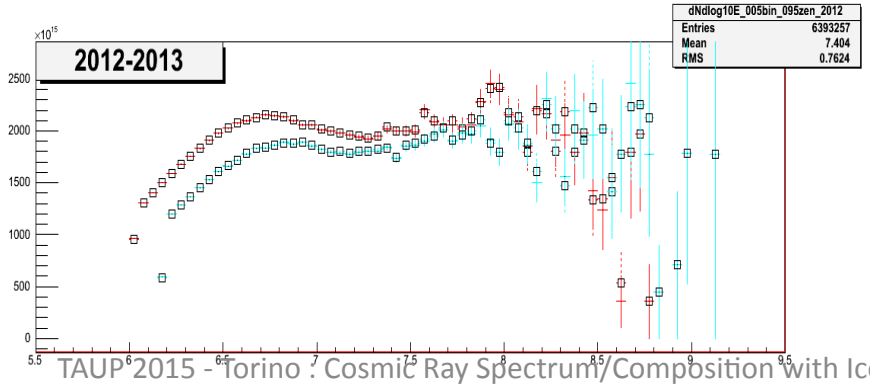
Coincidence: different surface E scale



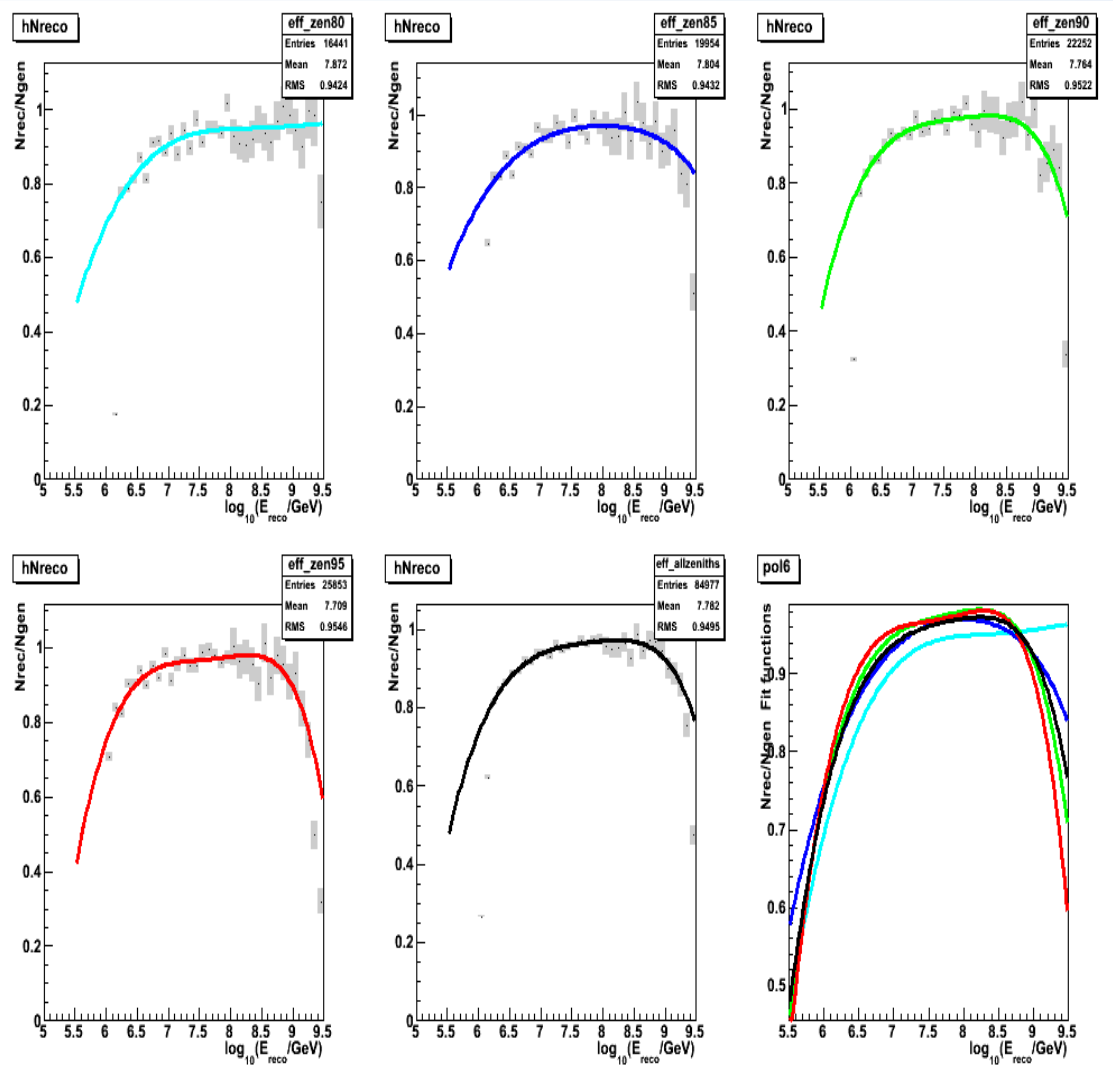
Snow-smearing



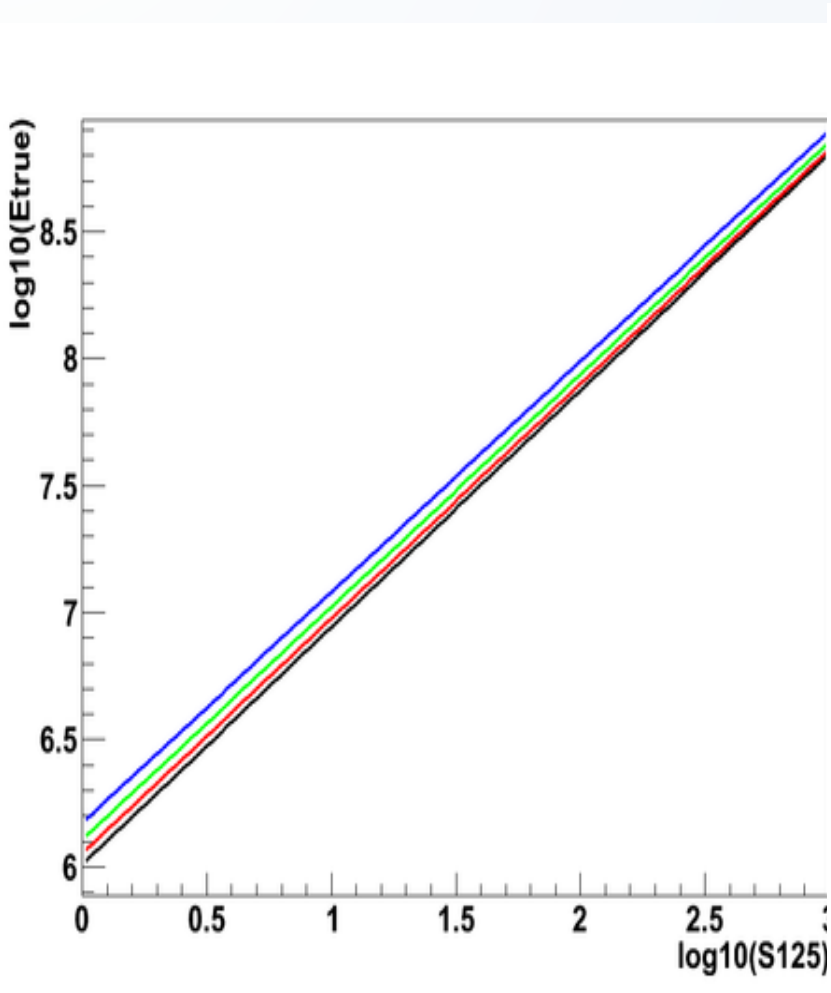


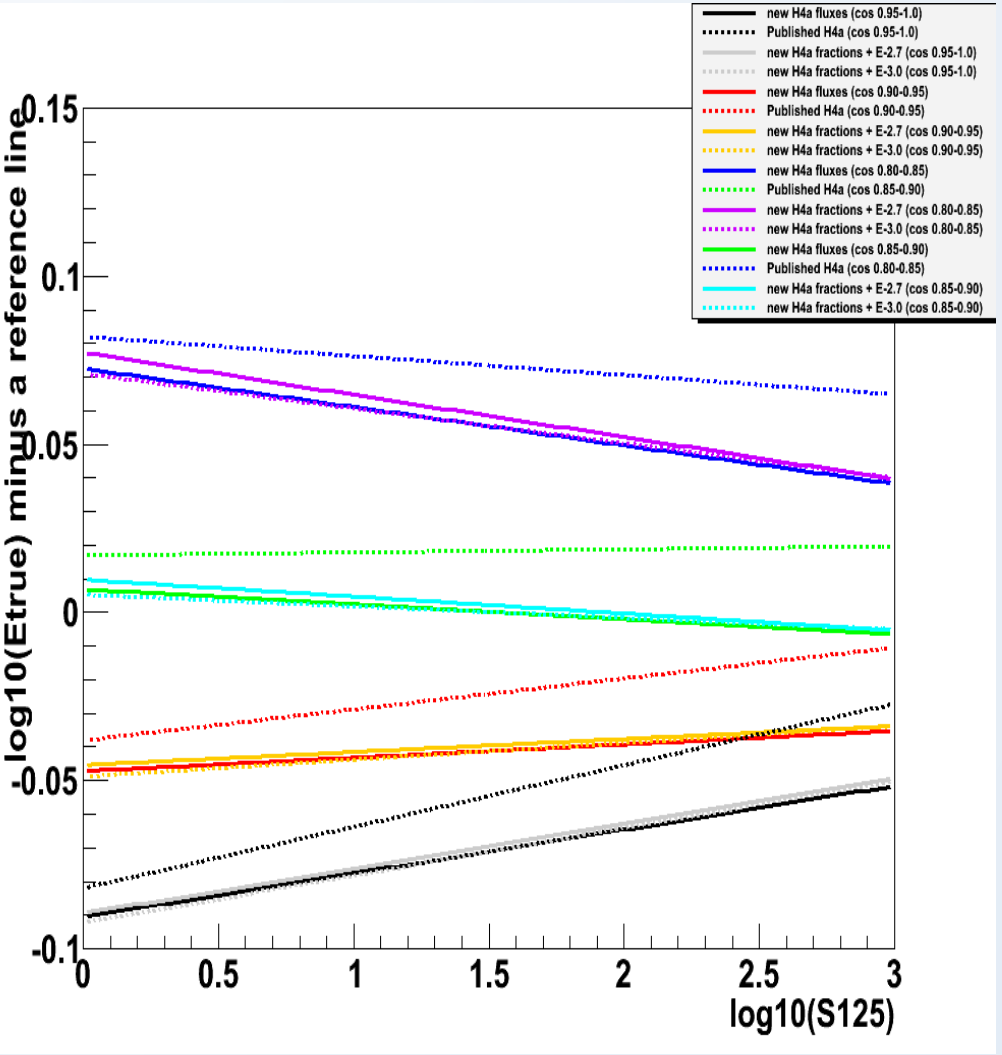


IT-alone: efficiency



IT-alone: S125->E conversion functions





IT-alone: four zenith bins