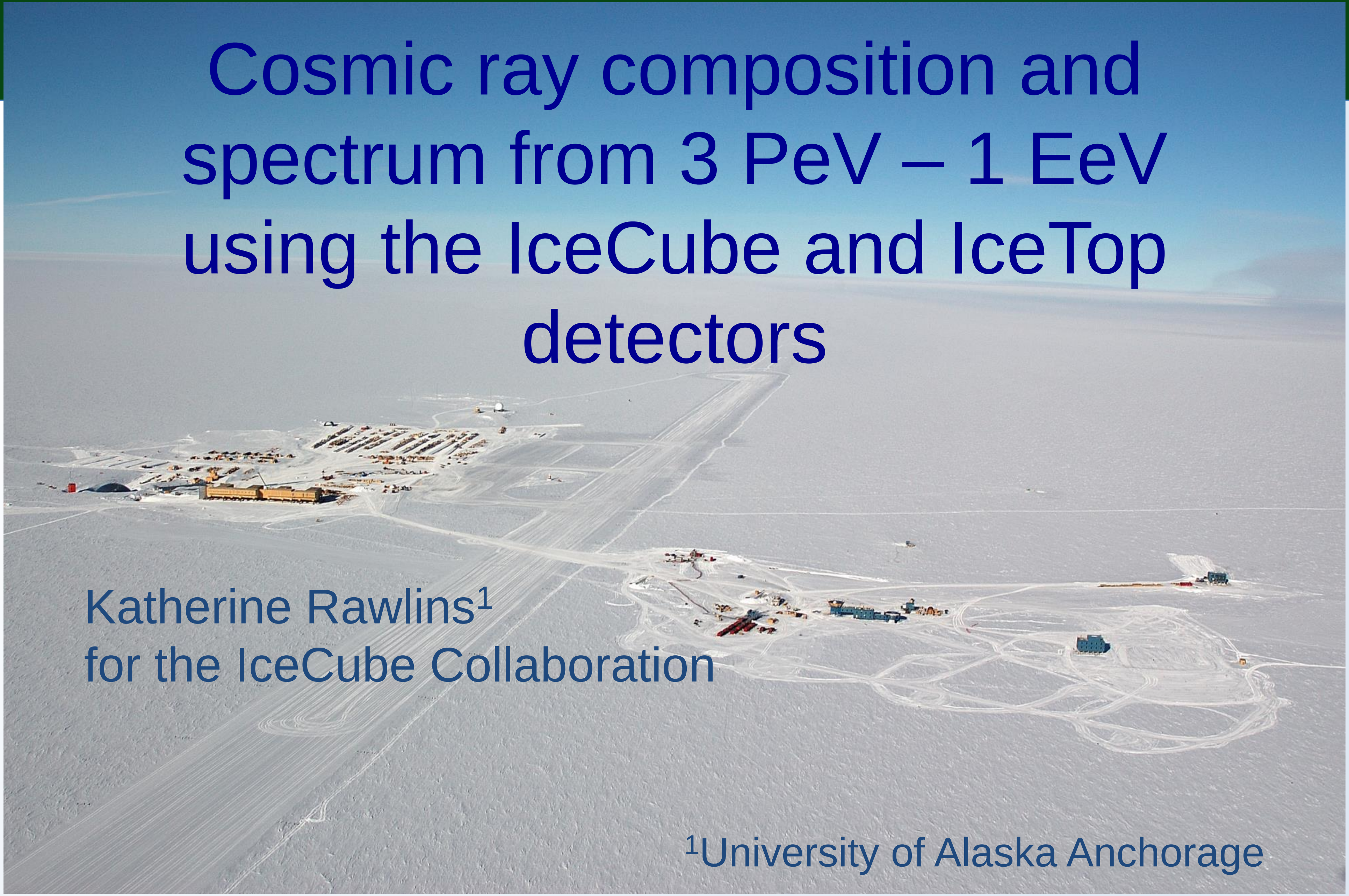

Cosmic ray composition and spectrum from 3 PeV – 1 EeV using the IceCube and IceTop detectors

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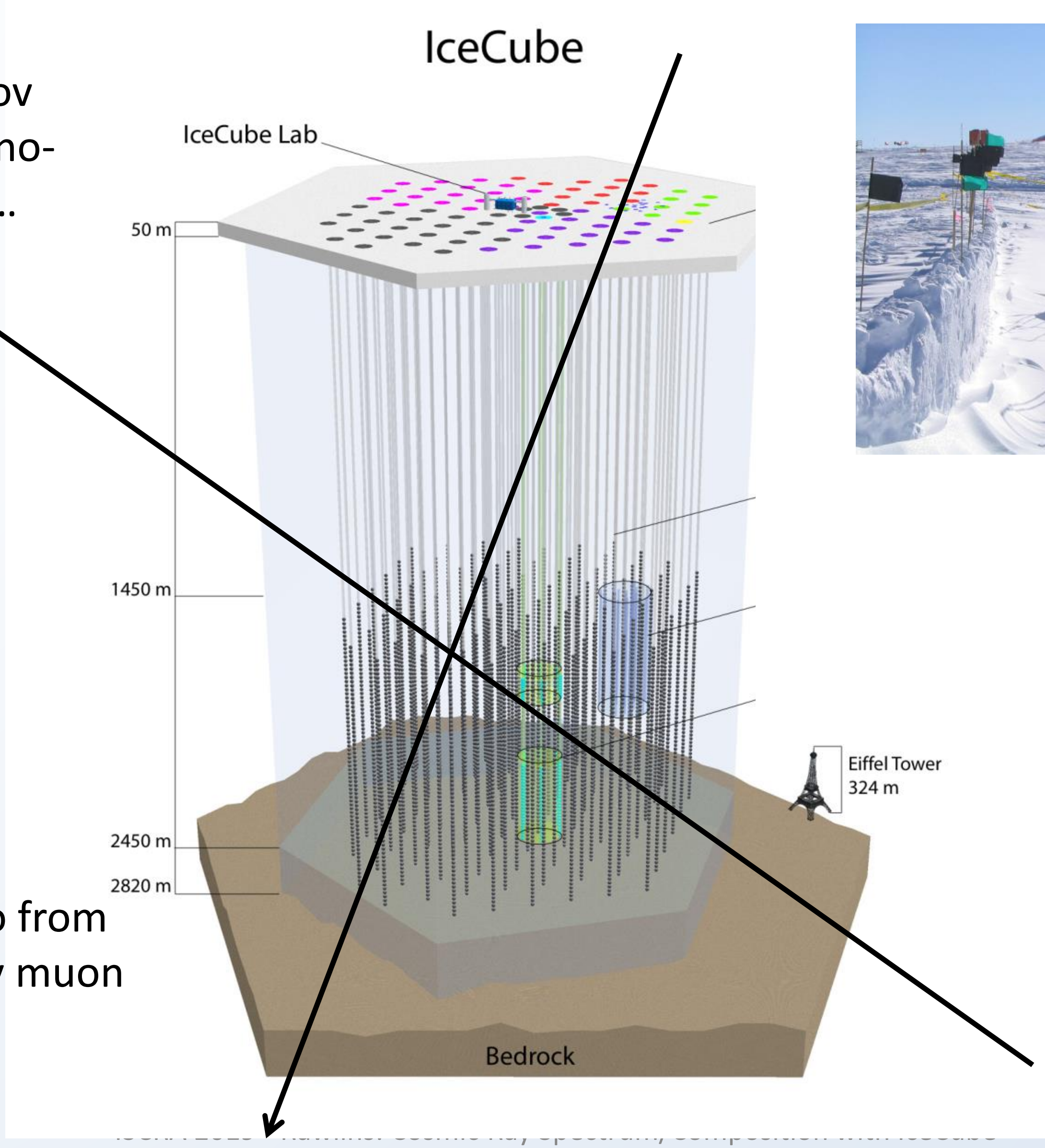
for the IceCube Collaboration

[1]University of Alaska Anchorage

The IceCube Observatory

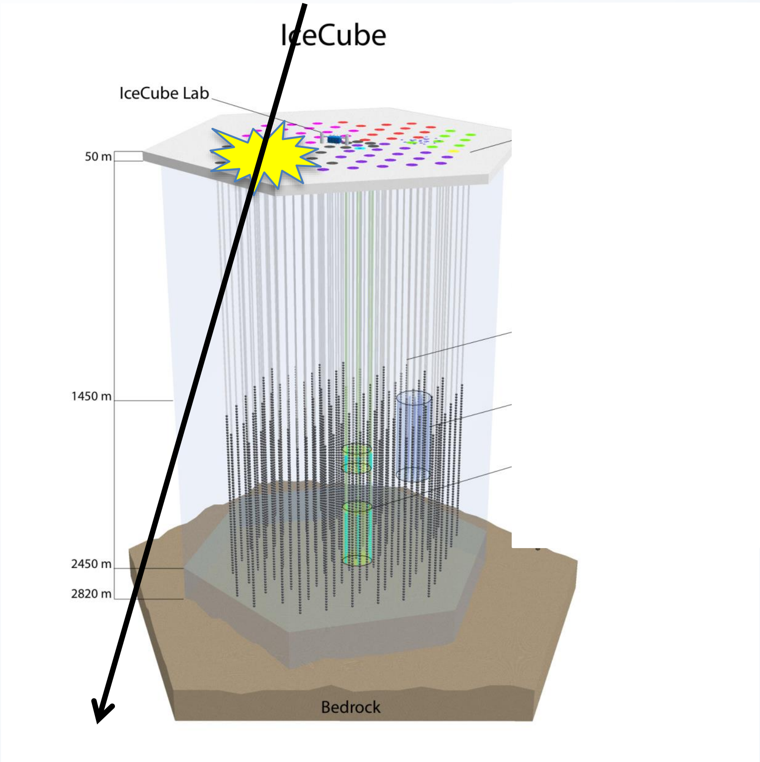
detects Cherenkov light from neutrino-induced leptons…



… and also from cosmic ray muon bundles

IceCube and Cosmic Rays: analysis styles

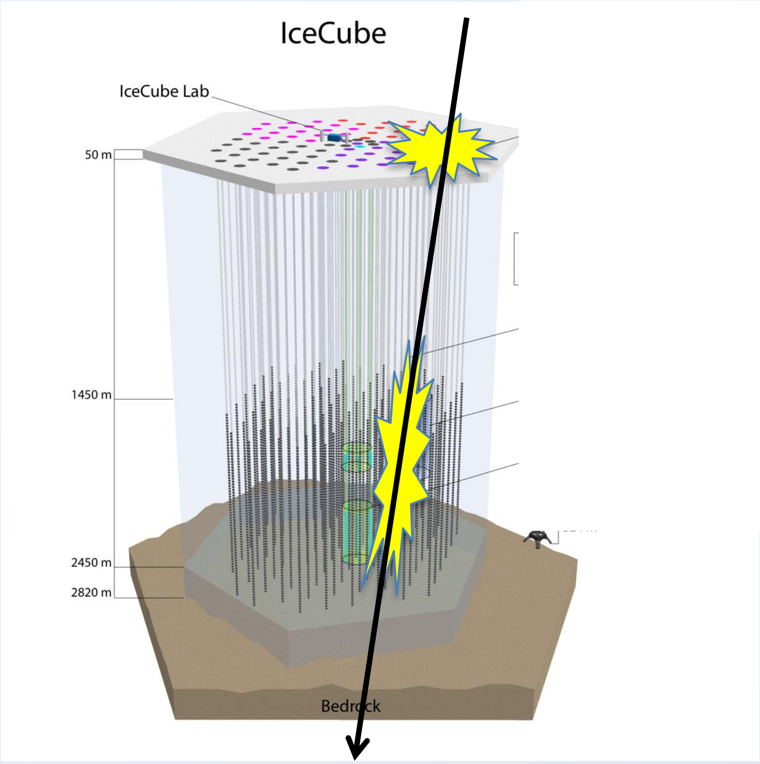
- “IceTop alone”



Greater acceptance, more events

Energy sensitivity from shower size (assuming a composition model)

- “IceTop-IceCube Coincidence”

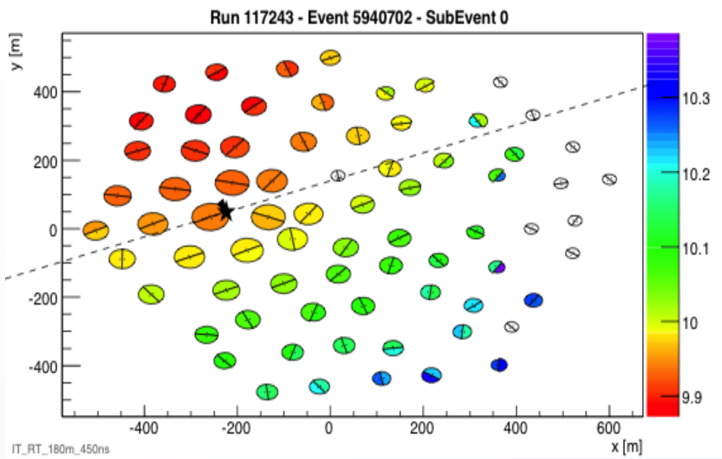


Also measure energy loss profile of high-energy muons that penetrate to depth

Limited number of events, energy and composition sensitivity

Analysis Strategy: IceTop-alone

Reconstruct events:

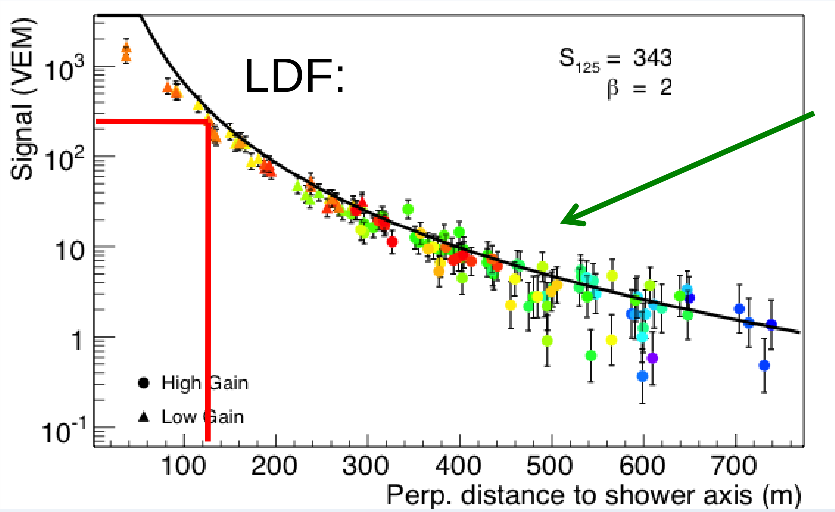


Estimate the shower's core position and direction…

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

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

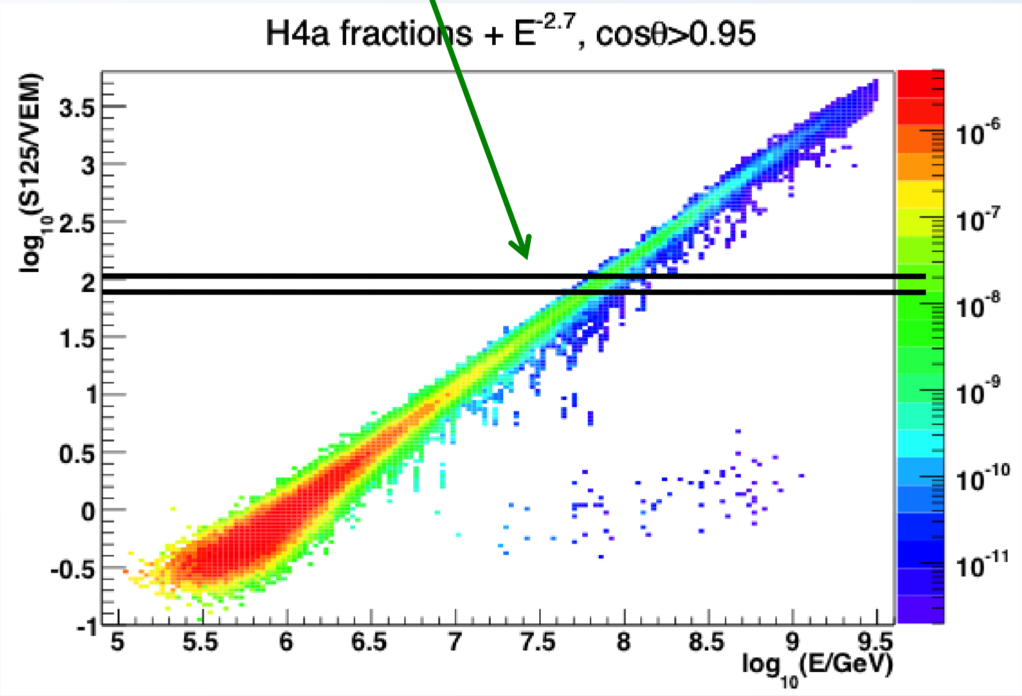
Analysis Strategy: IceTop-alone

Build S125 -> Energy conversion functions:

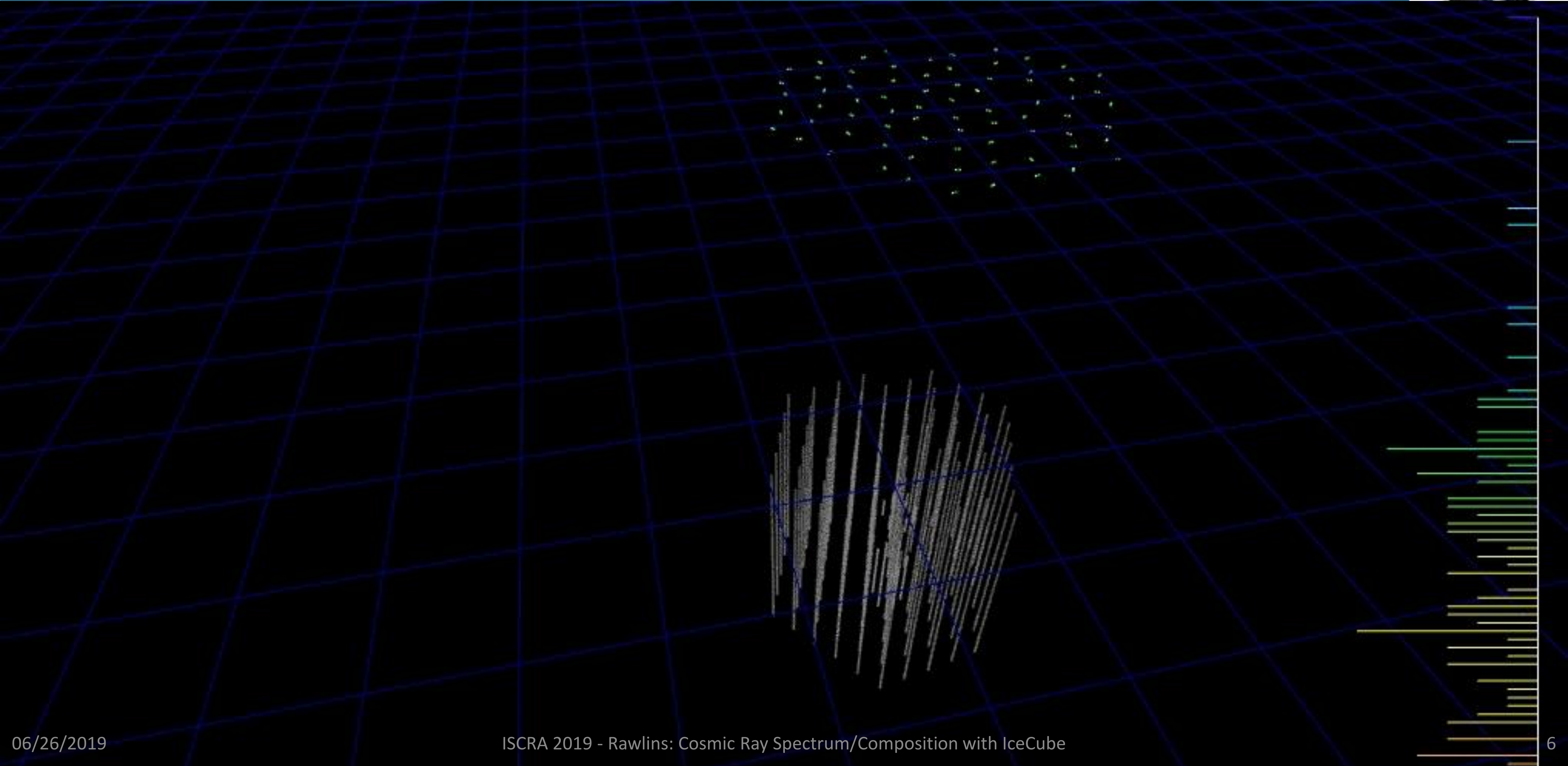
Using Monte Carlo simulations (and assuming a composition model),

Find most likely energy within each slice of S125

Do this separately for 4 zenith angle ranges



Analysis strategy: Coincidence



Analysis Strategy: Coincidence

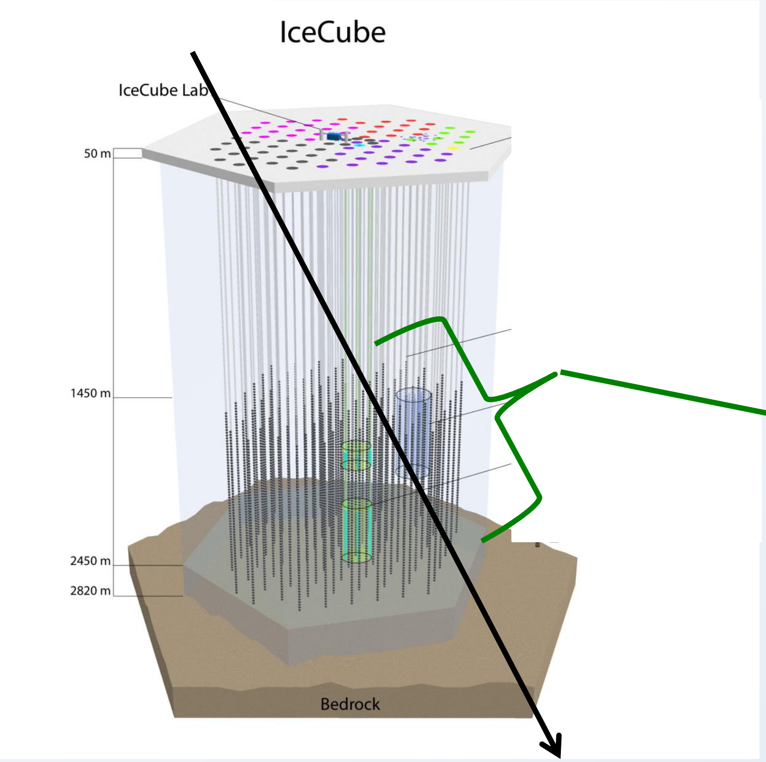
ICECUBE

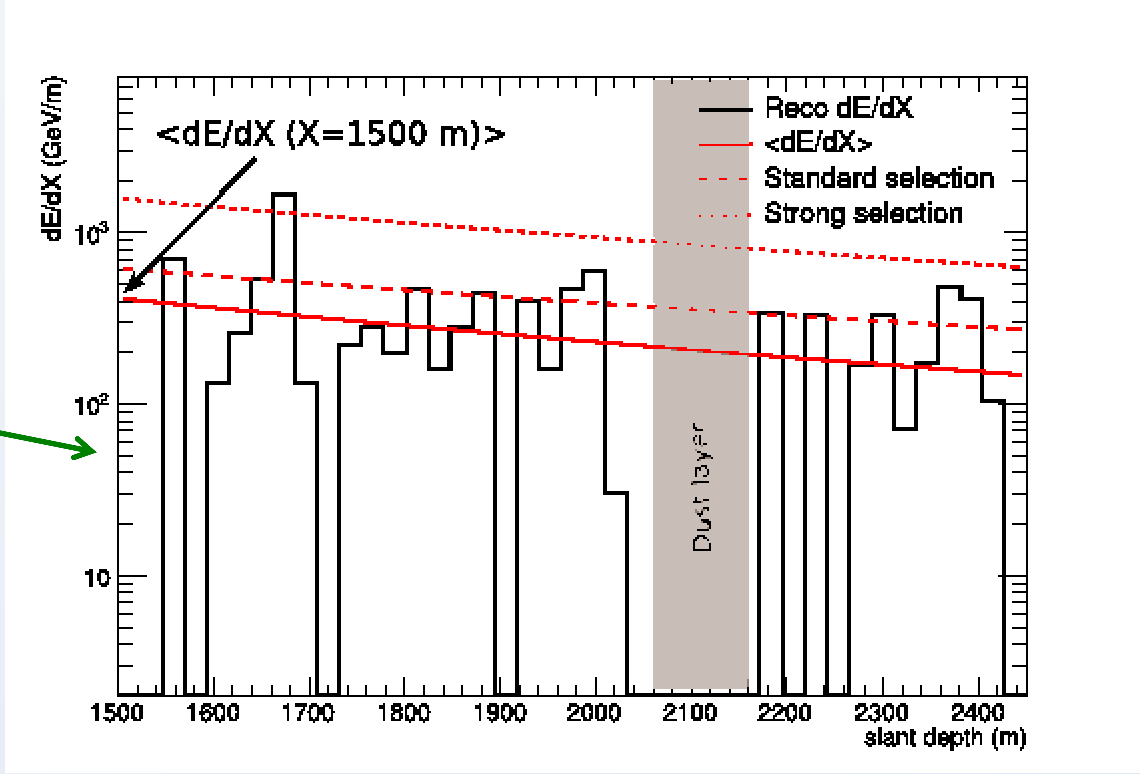
<u>Also reconstruct in deep IceCube:</u>

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)

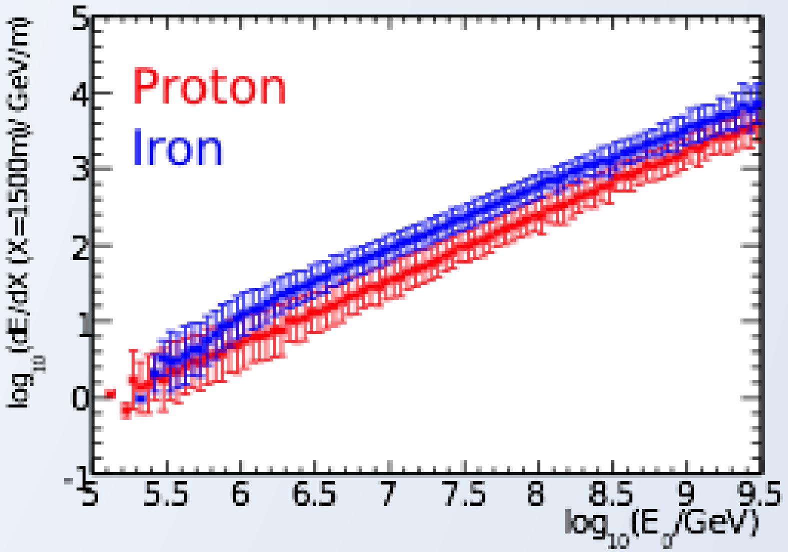




Analysis Strategy: Coincidence

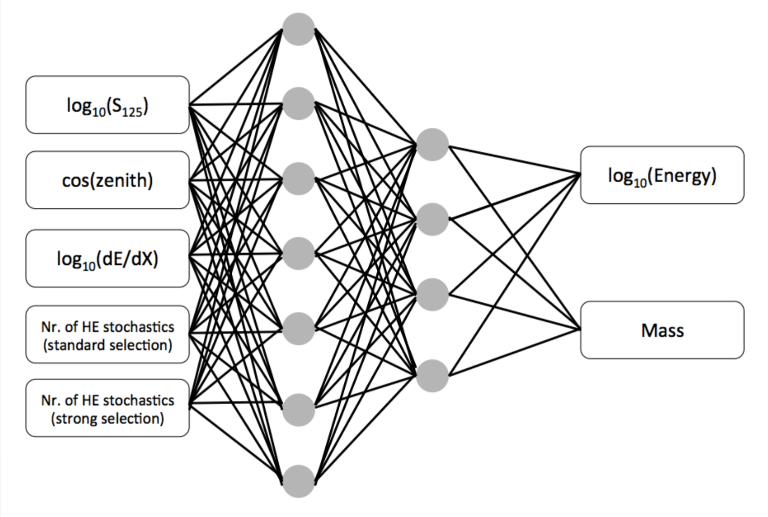
Muon energy loss at 1500 m is highly composition-sensitive:

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.

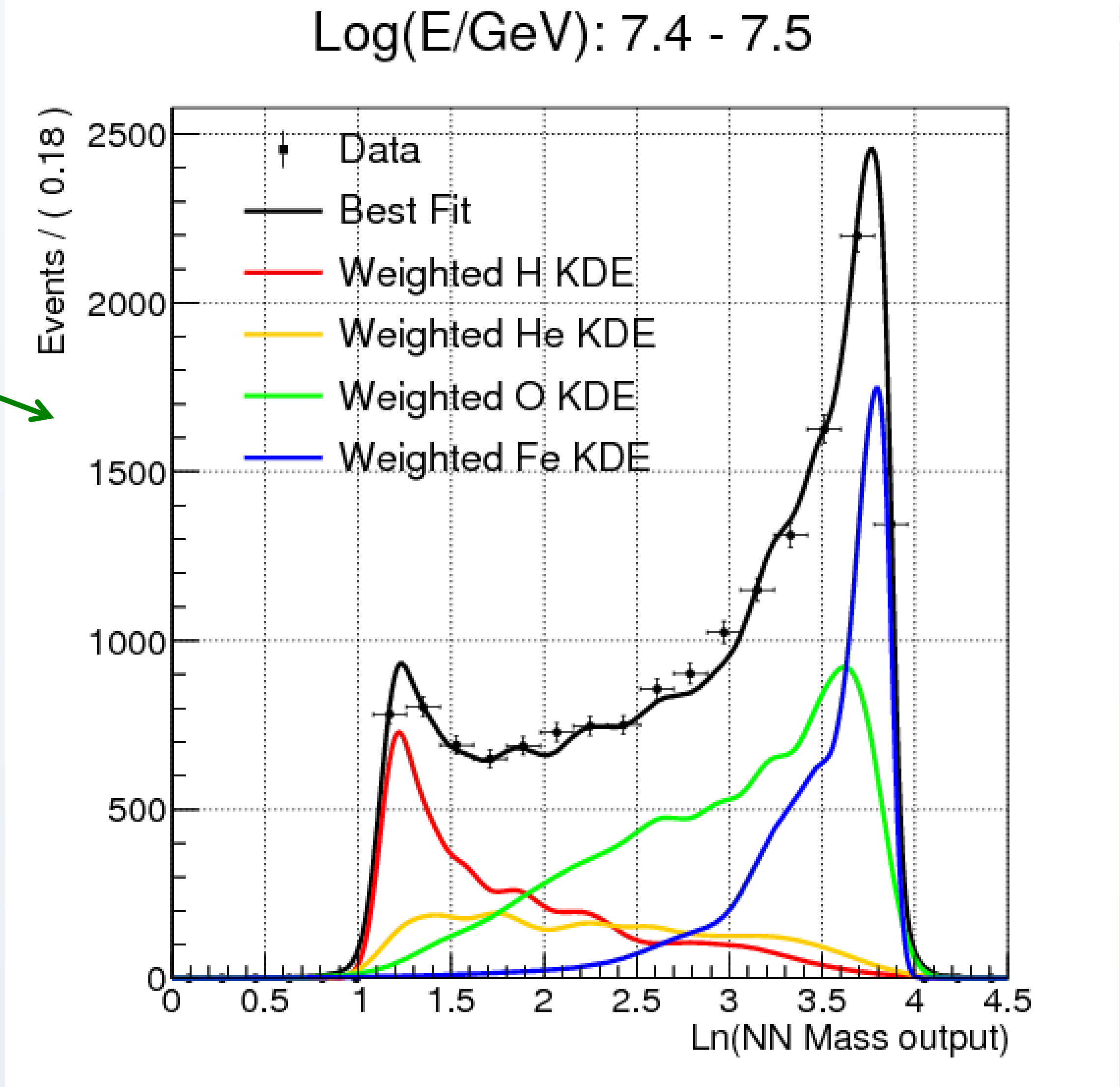


Analysis Strategy: Coincidence

Construct template PDF's of NN primary mass

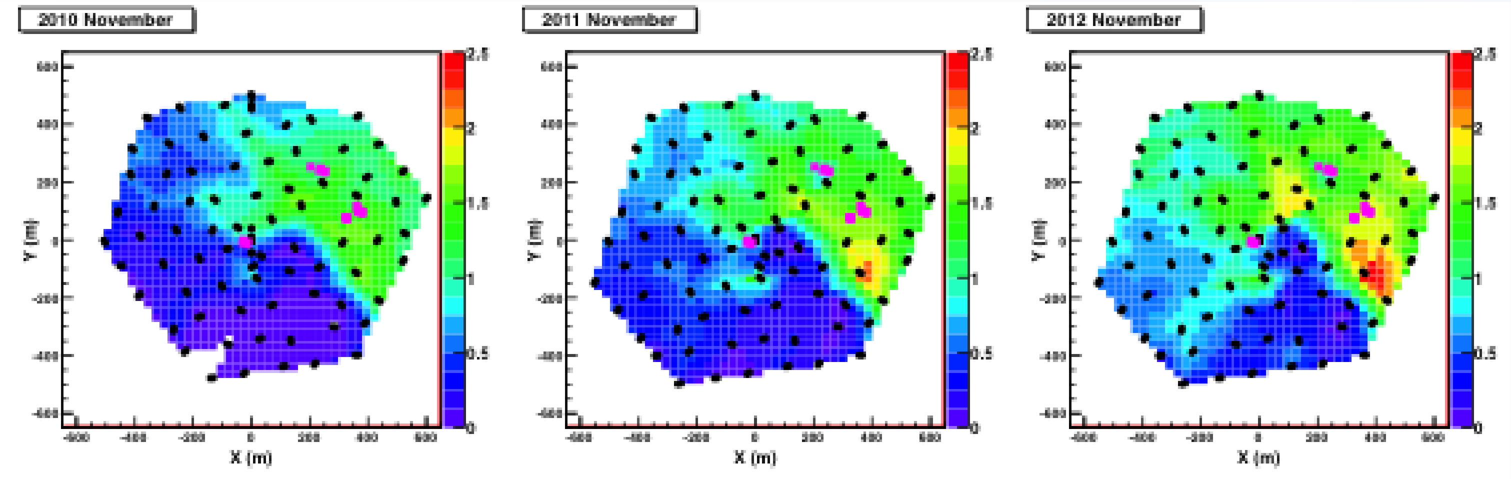
Within each bin of reconstructed energy, compare templates for Monte Carlo (four types: H, He, O, Fe)

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



This and following plots, from: arXiv:1906.04317 [astro-ph.HE]

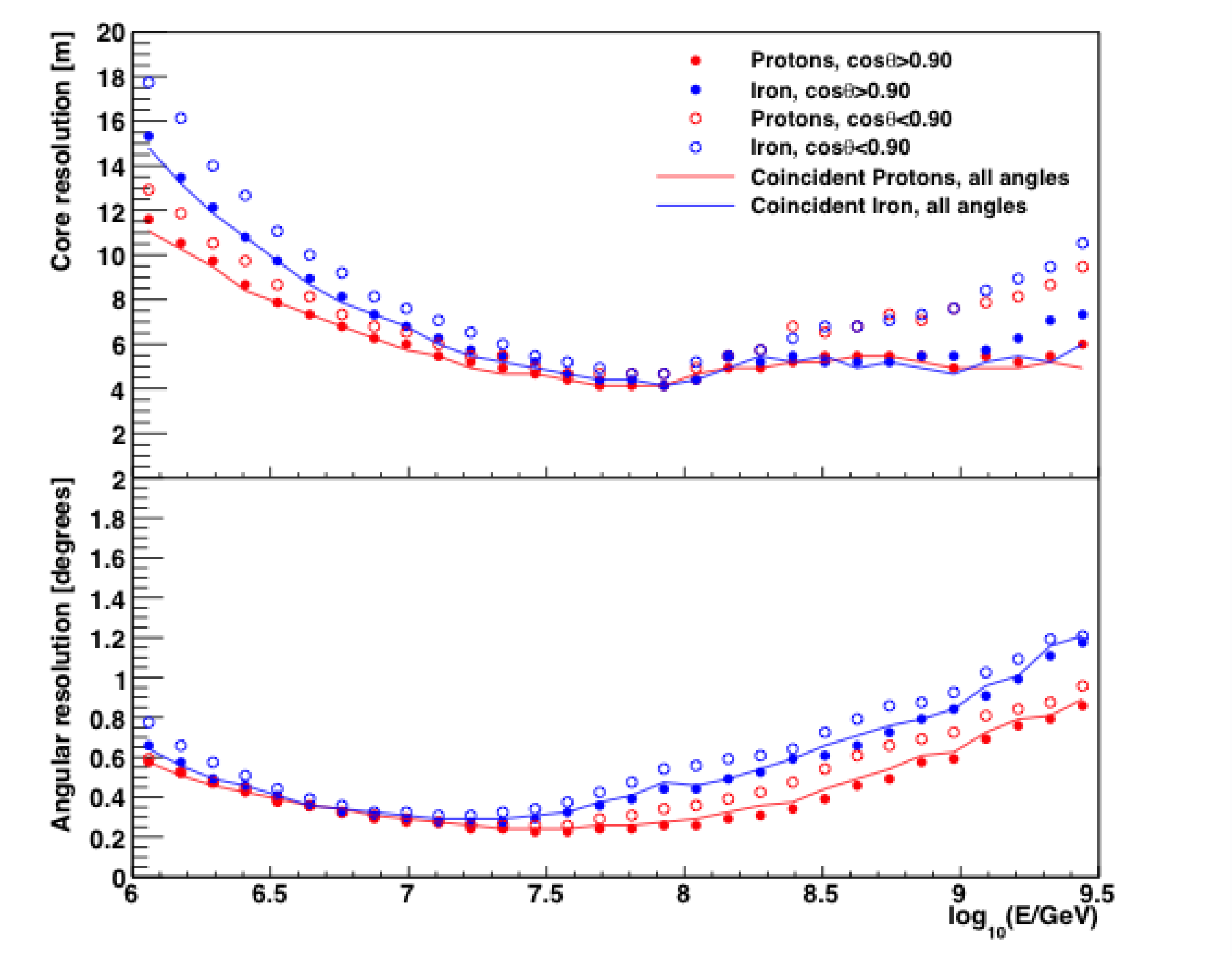
Effects of snow



- 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

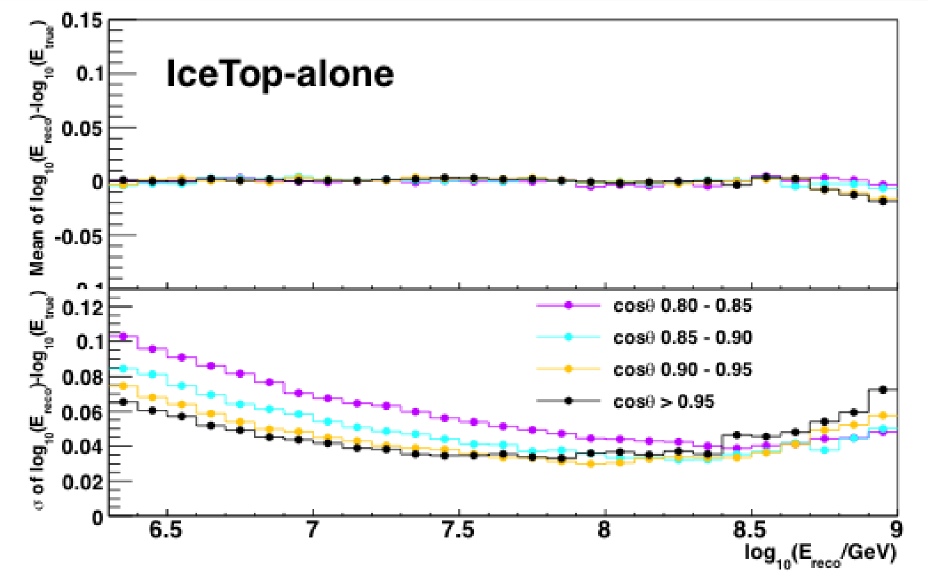
Position/Direction Performance

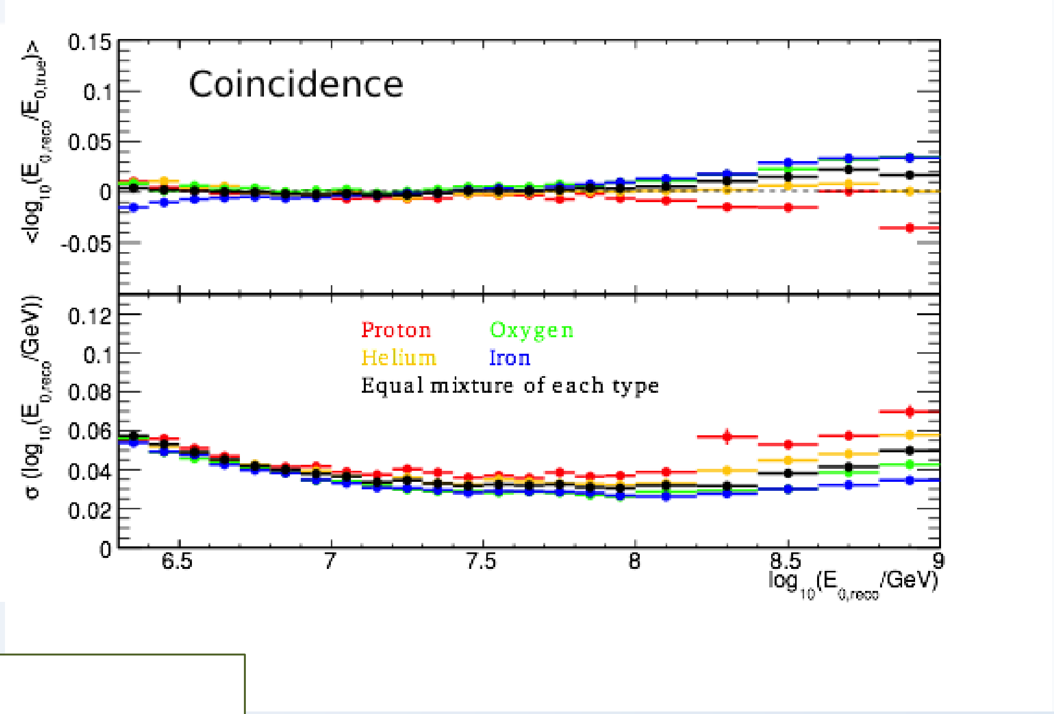


Core position: between 5-10 meters

Direction: less than 1^{o}

Energy Reconstruction Performance



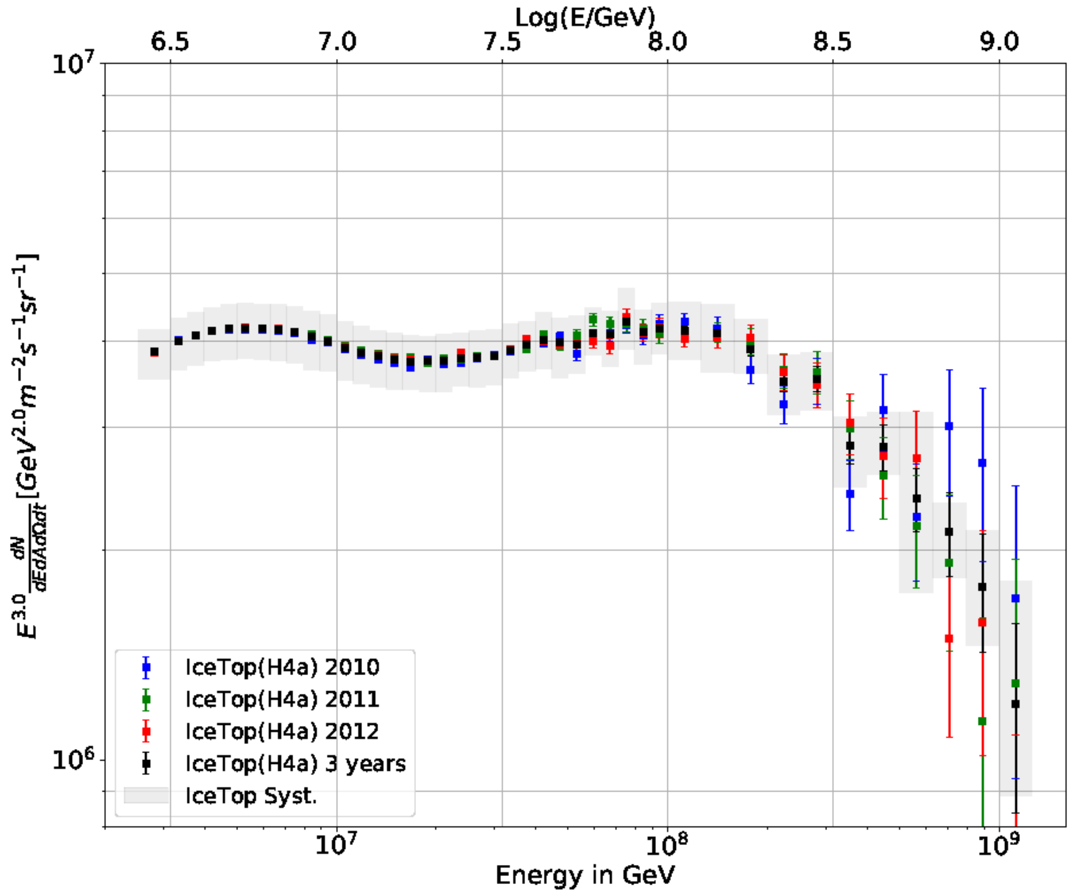


Bias = near zero

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

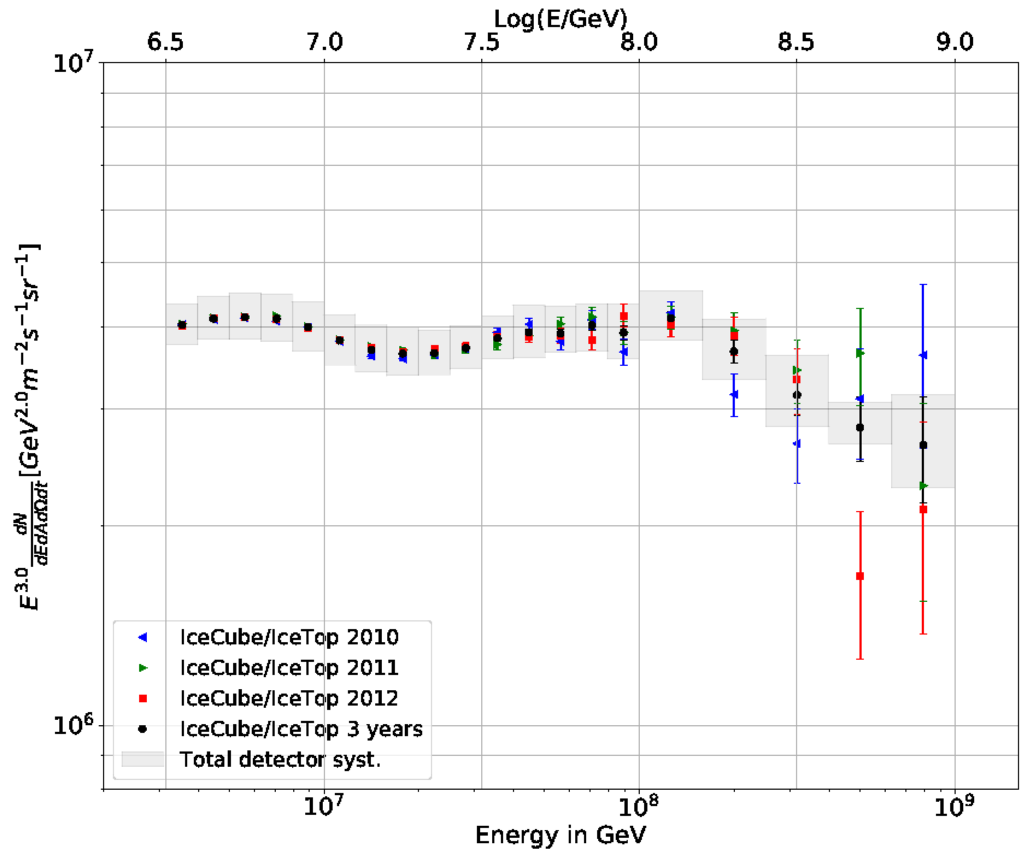
Spectrum result: IceTop-alone

- Results from 3 individual years consistent with each other
- This assumes fractions of nuclei (p, He, O, Fe) drawn from the H4a composition model
- Main systematic effects:
  - Snow attenuation effects
  - Absolute scale of IceTop energy



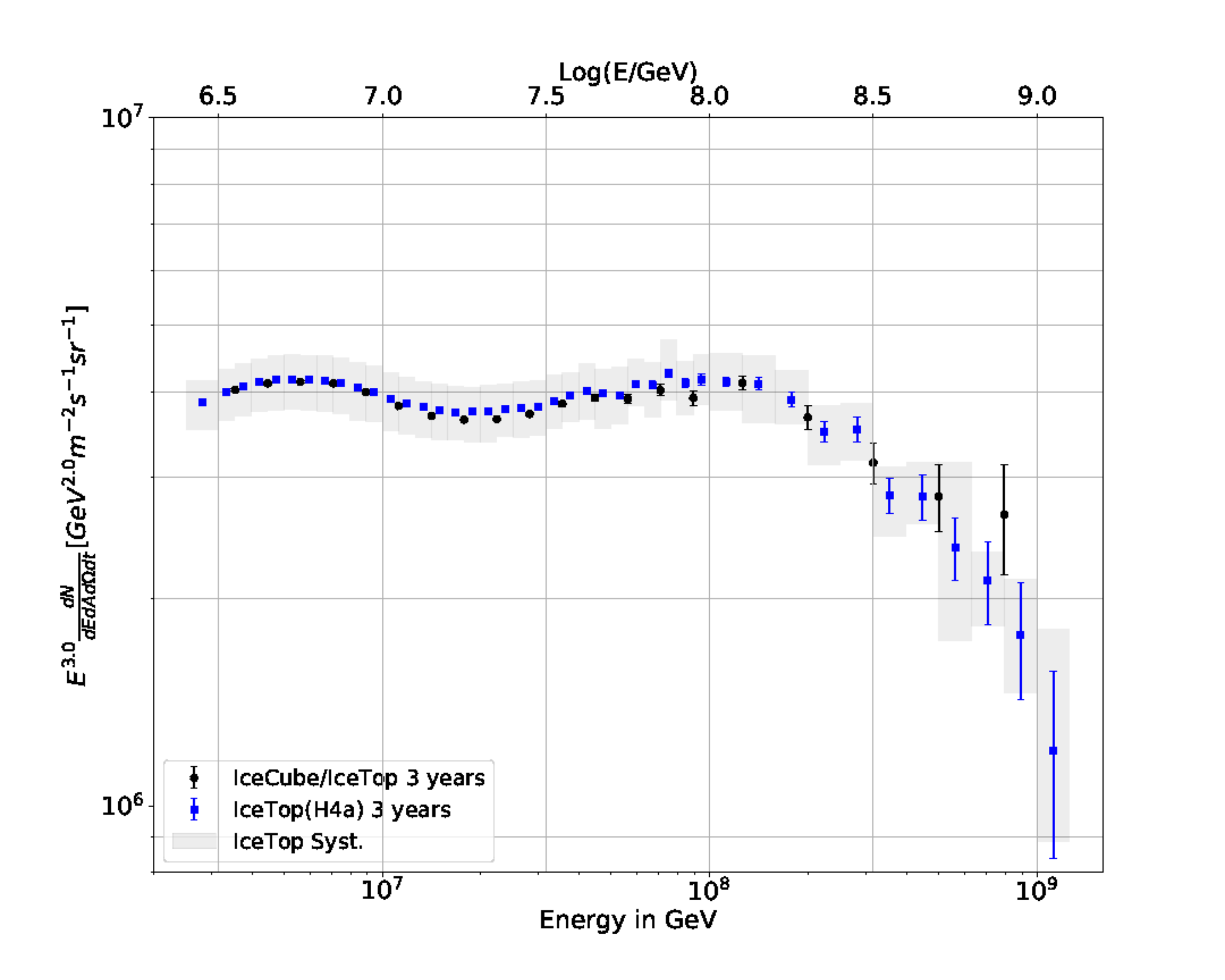
Spectrum result: Coincidence

- Results from 3 individual years (again) consistent with each other



- Main systematic effects similar to the IceTop-alone analysis

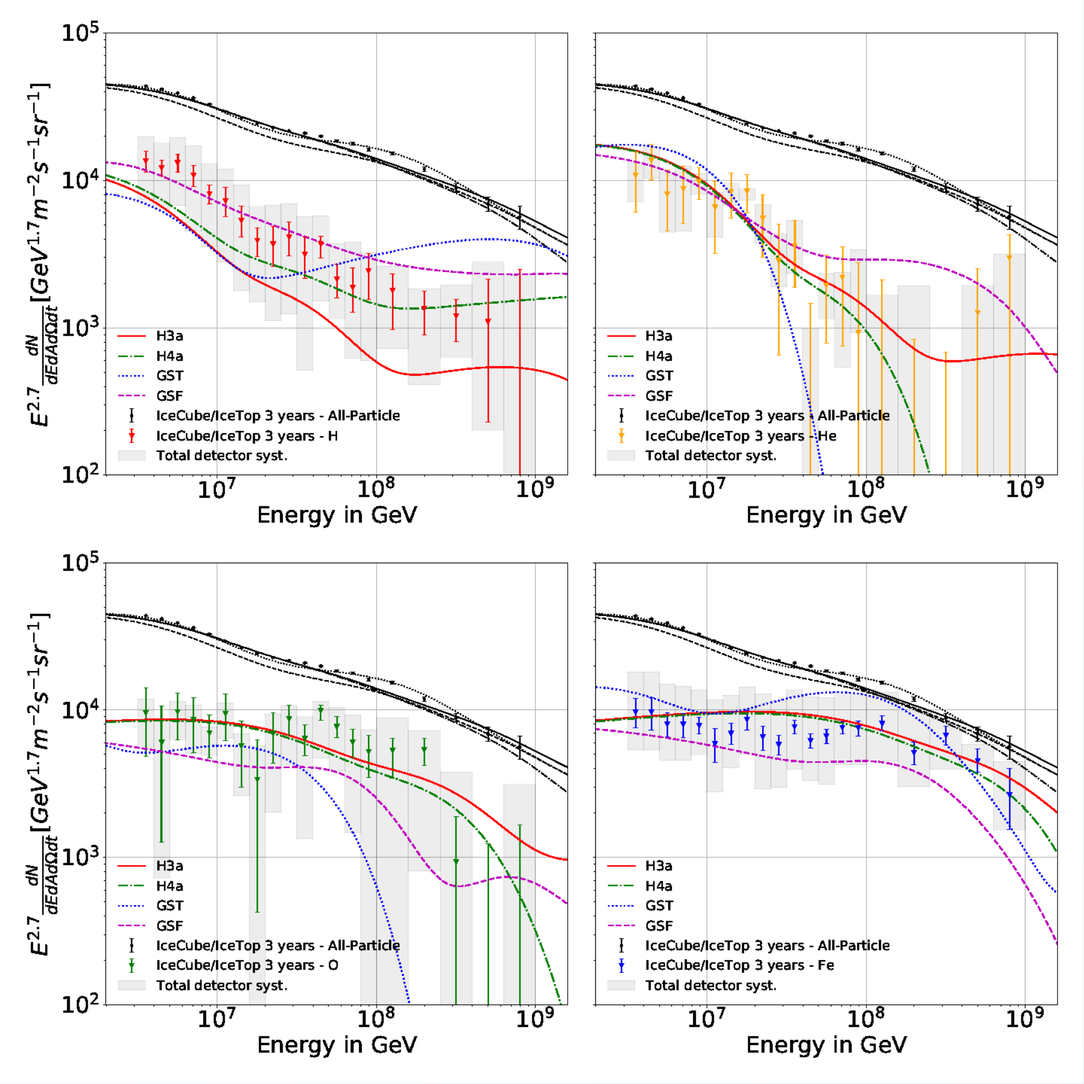
Spectrum Result: comparing the two



Good agreement between complementary techniques

Individual Nuclear Spectra

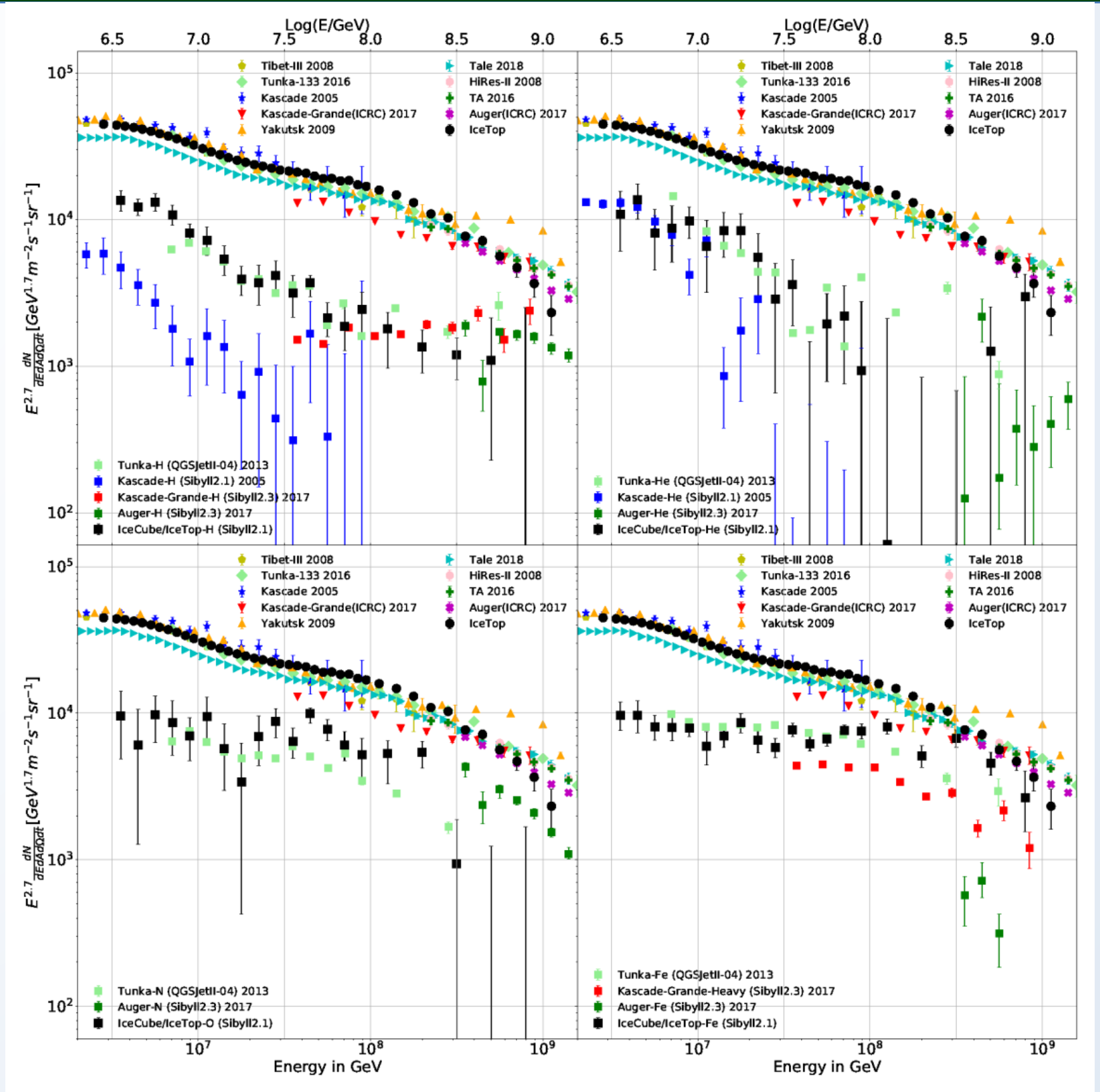
- … with detector systematics
- … compared to composition models



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

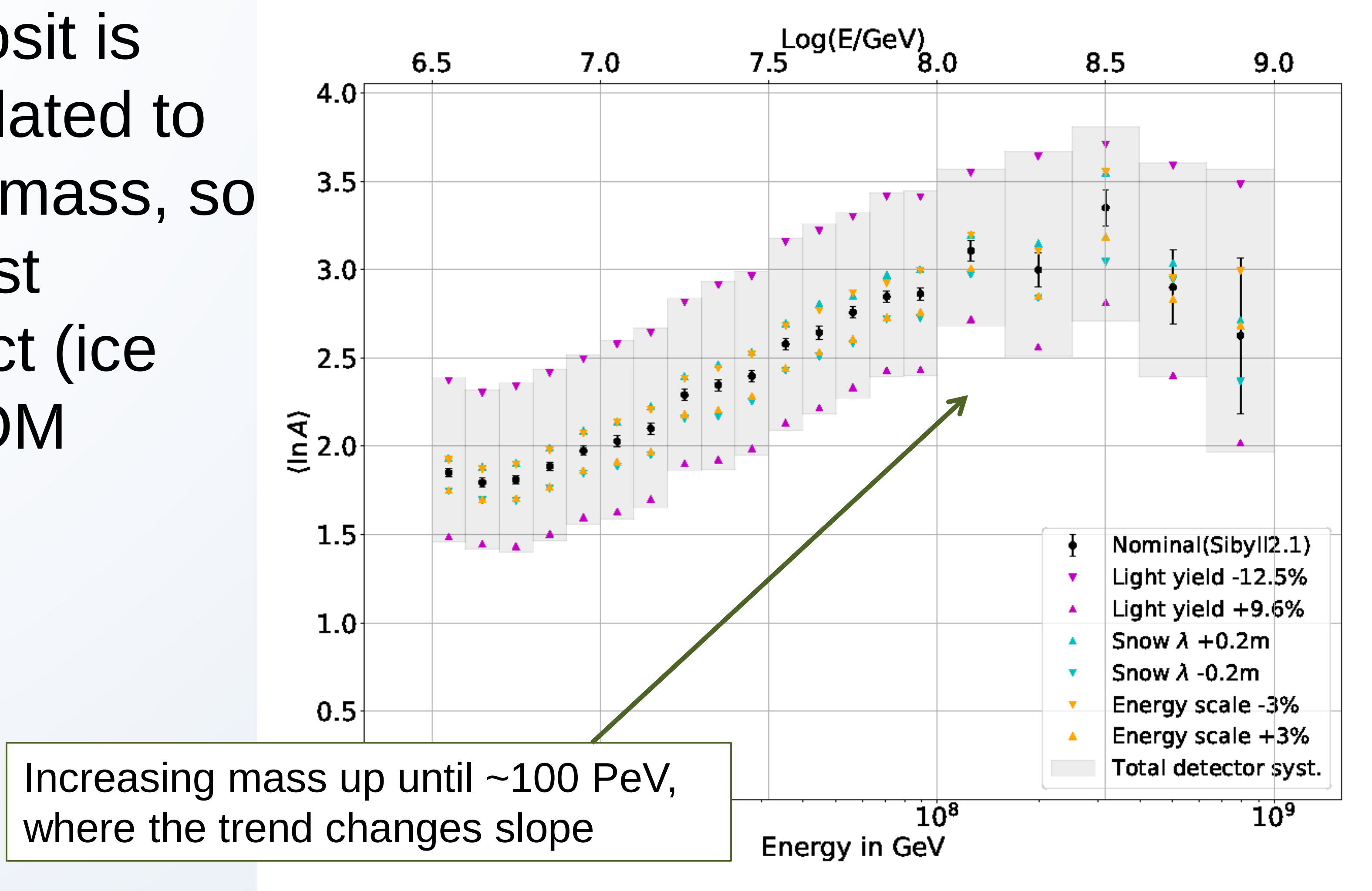
Good match to H4a composition model.

Individual nuclear spectra: comparisons



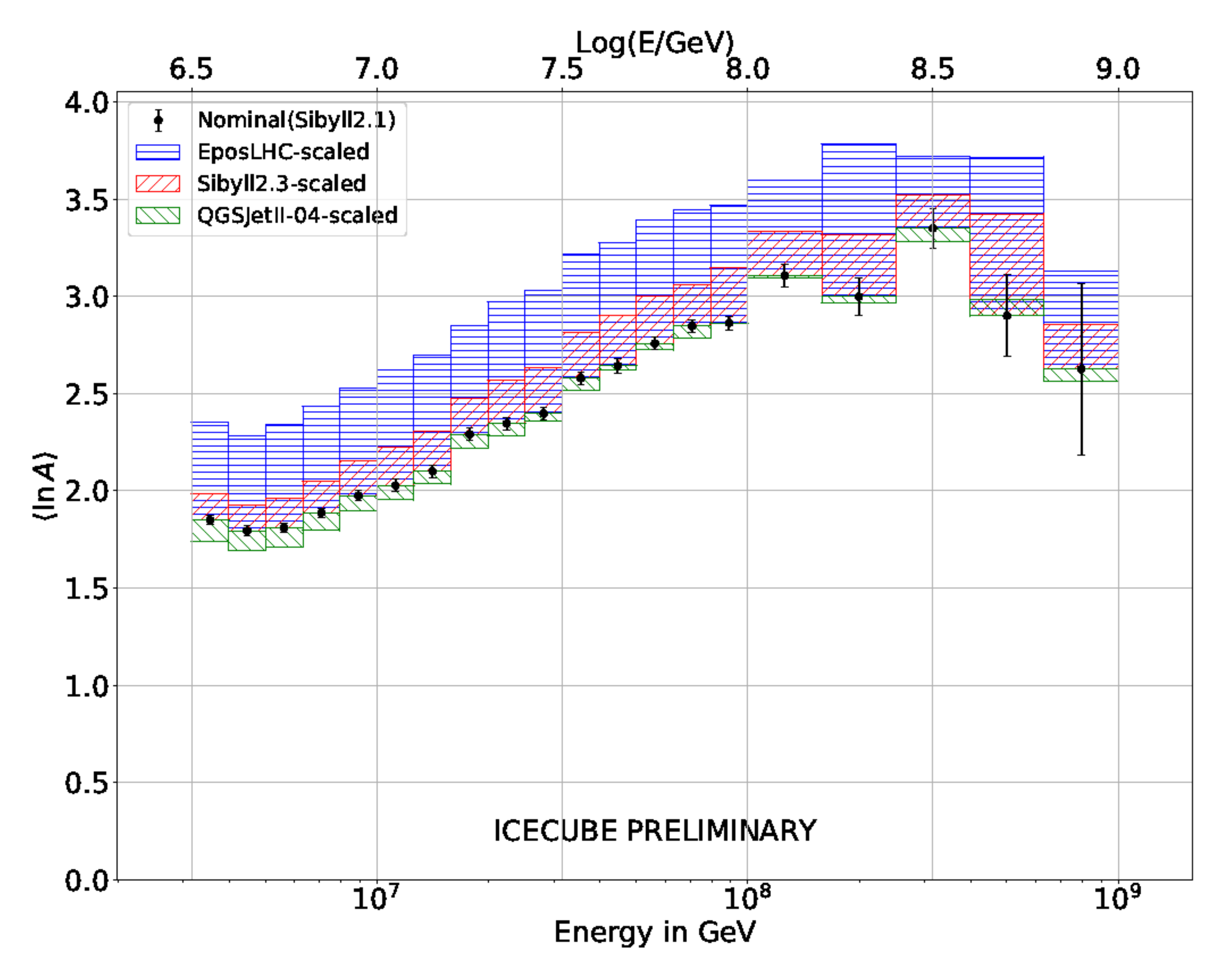
Mass trend

- In-ice light deposit is most directly related to the estimate of mass, so this is the largest systematic effect (ice properties + DOM efficiency)



Hadronic Interaction Model effects

- Models that underpredict high-energy muons: by comparison, the data seems more “iron-like”.
- Affects the absolute scale of the measurement of mass, but not the overall trend



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)

Thank you for your attention!

(Backup slides…)

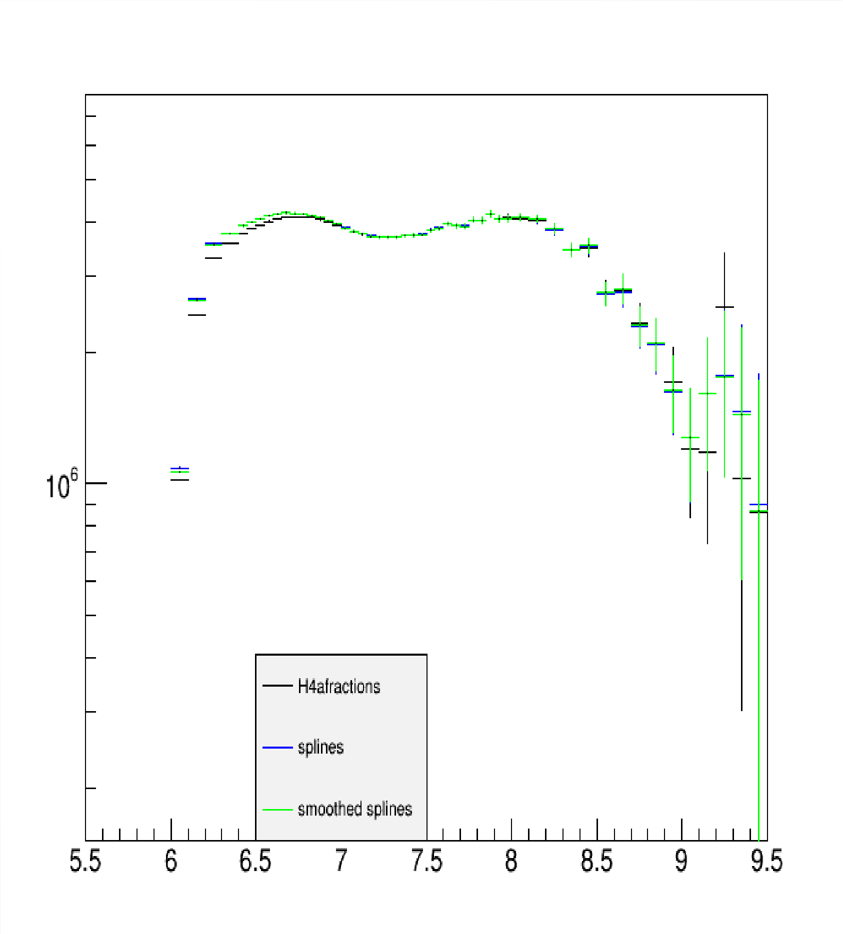
Coincidence: systematic uncertainties

	Systematics Uncertainty
DOM efficiency	$\pm 3\%$
Hole Ice 30cm	$+4.5\%$
Hole Ice 100cm	-2.9%
$+10\%$ scattering	$+3.6\%$
$+10\%$ absorption	-11.8%
-7% scattering AND absorption	$+7\%$
Total	$^{+9.6\%}_{-12.5\%}$

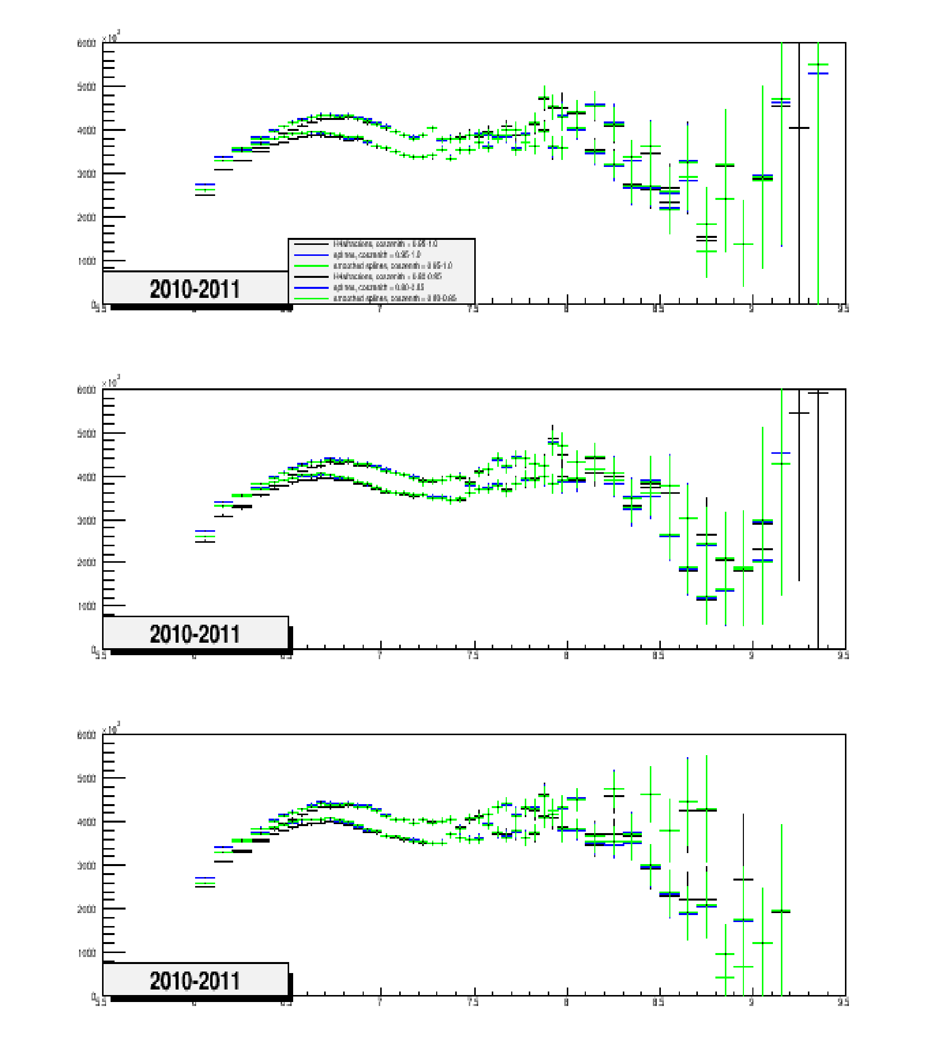
	3.35 PeV	33.5 PeV
VEM calibration/Absolute energy scale	+4.1% -4.4%	+7.0% -4.3%
Snow correction	+5.0% -4.3%	+7.9% -4.7%
QGSJet-II-03	+2.1%	+1.4%
Light yield	+3.1% - 3.0%	+1.1%
Total	+7.5% -6.5%	+10.8% -6.4%

IT-alone: different composition input?

- All 3 years

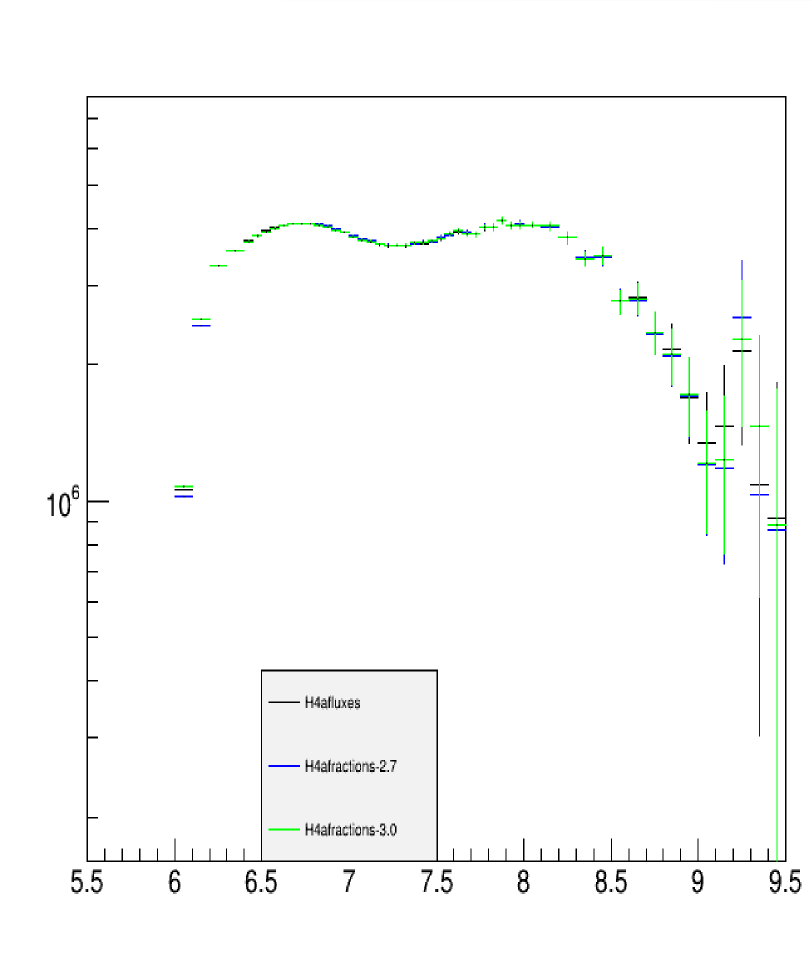


- Individual years

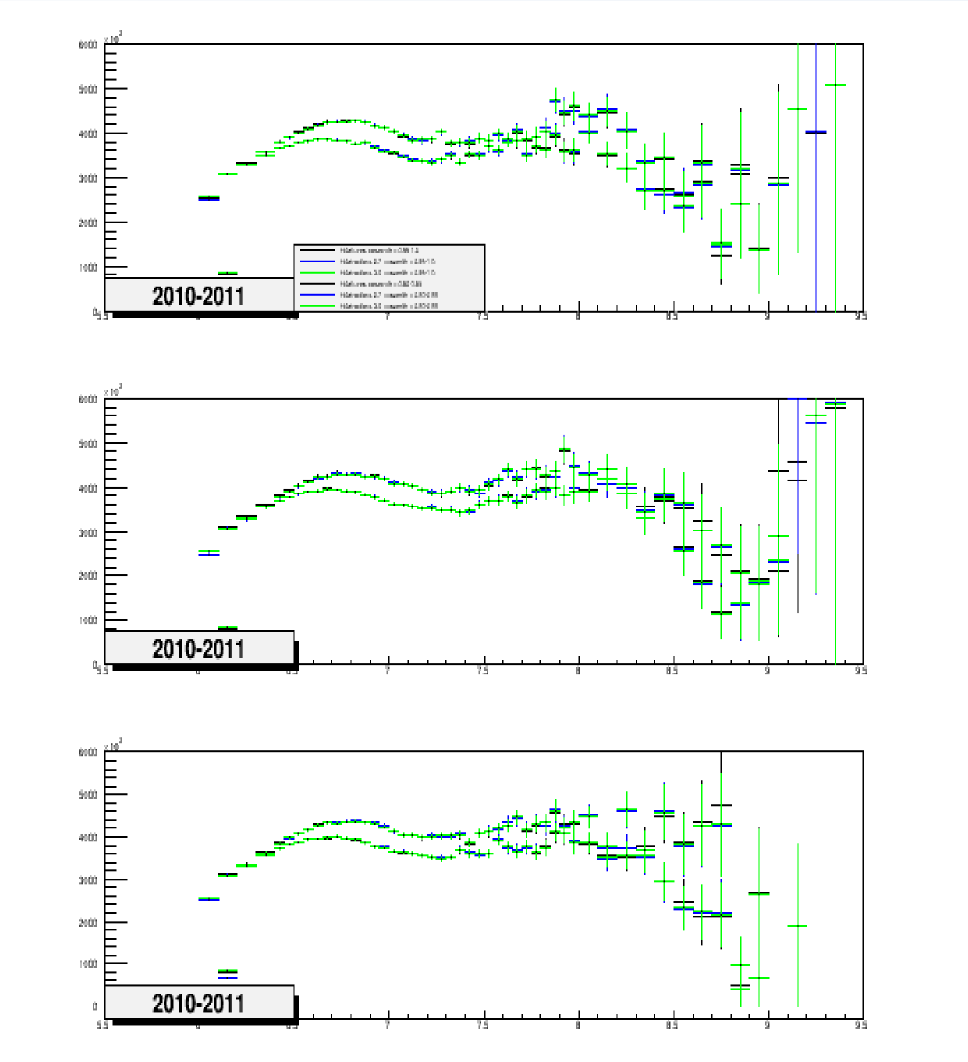


IT-alone: different spectrum input?

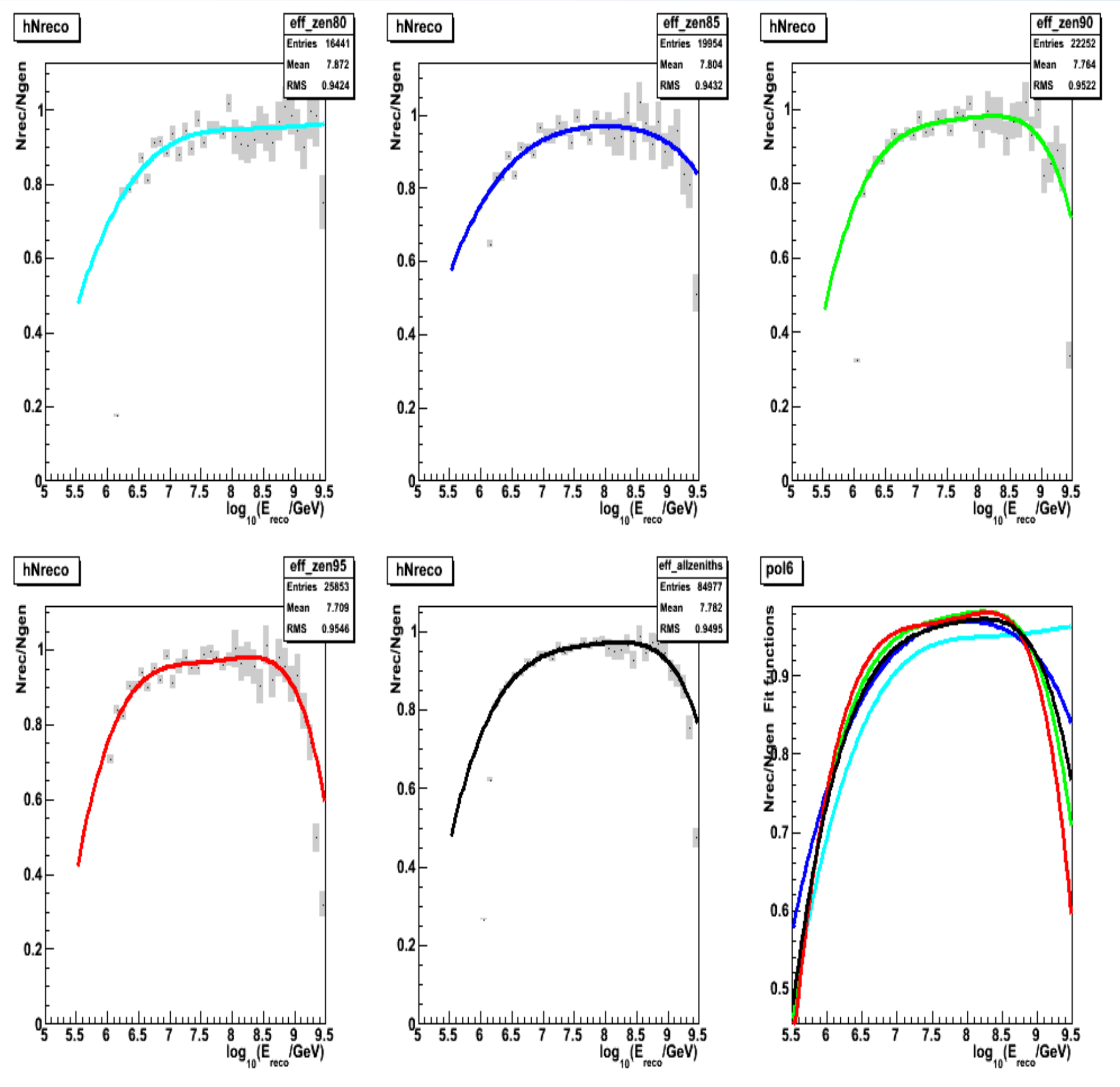
- All 3 years



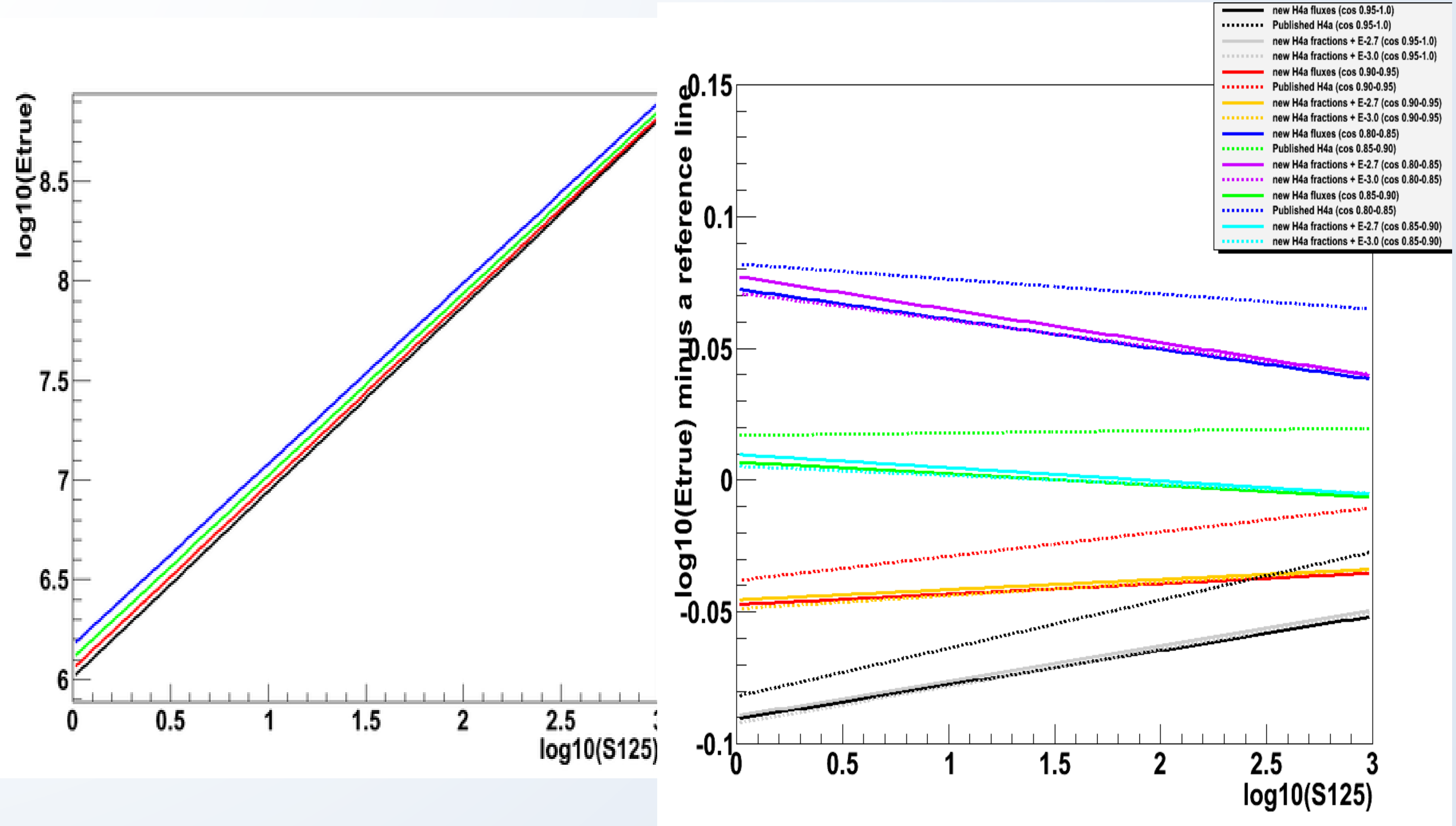
- Individual years



IT-alone: efficiency

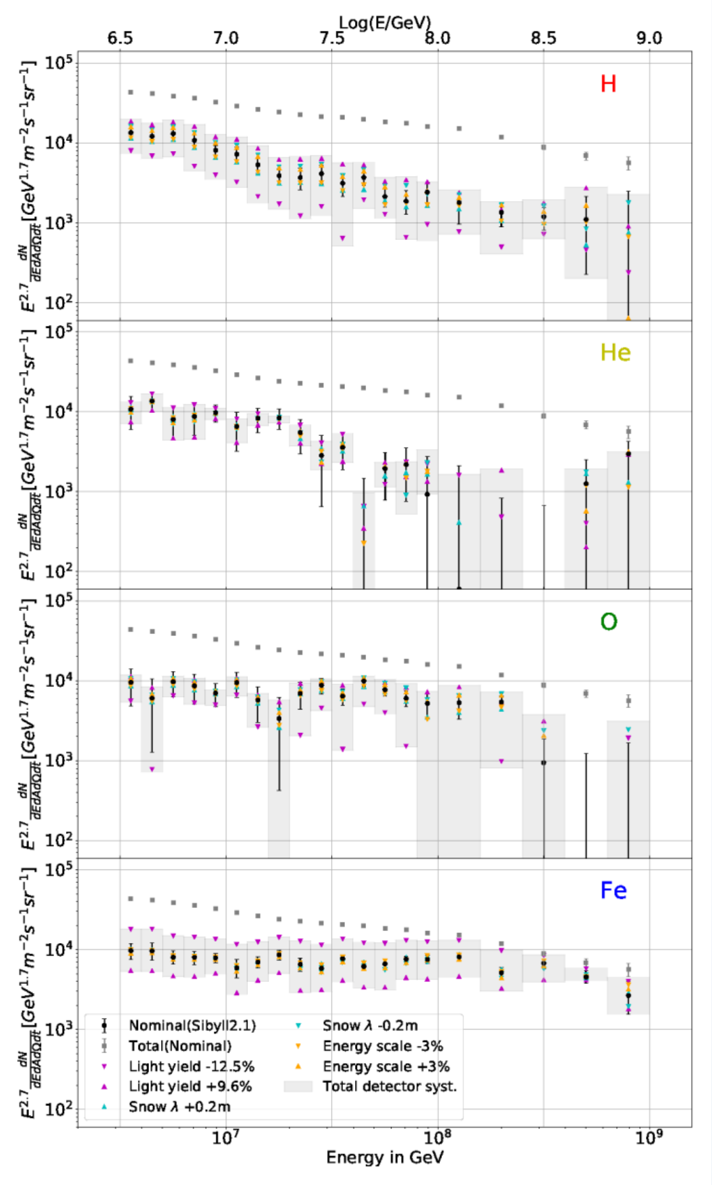


IT-alone: S125->E conversion functions

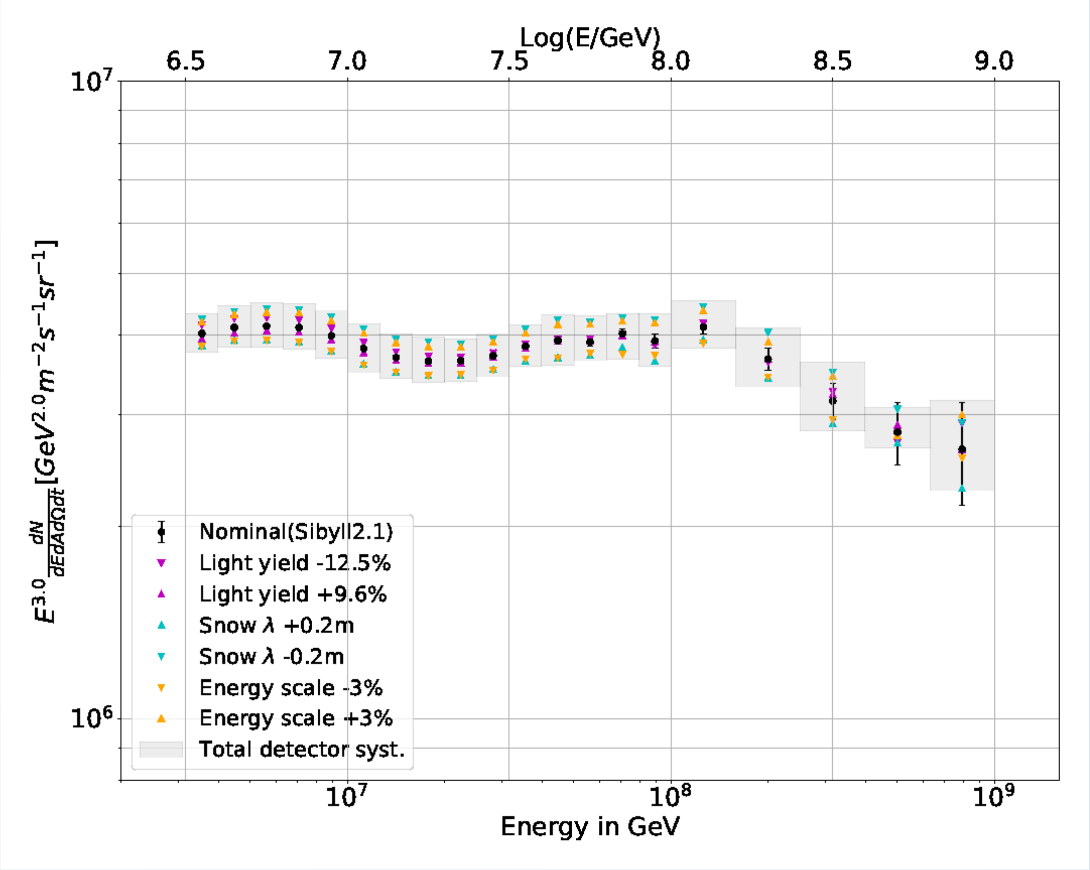


More effects of detector systematics

On nuclear spectra:

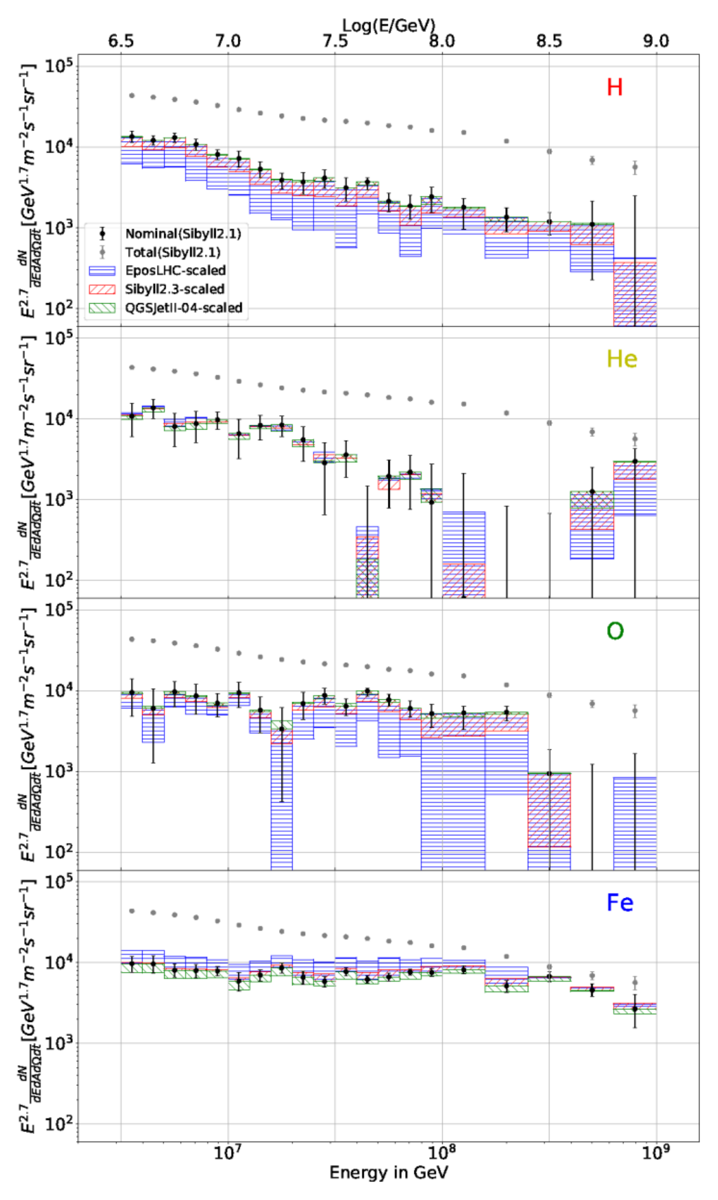


On the all-particle spectrum:

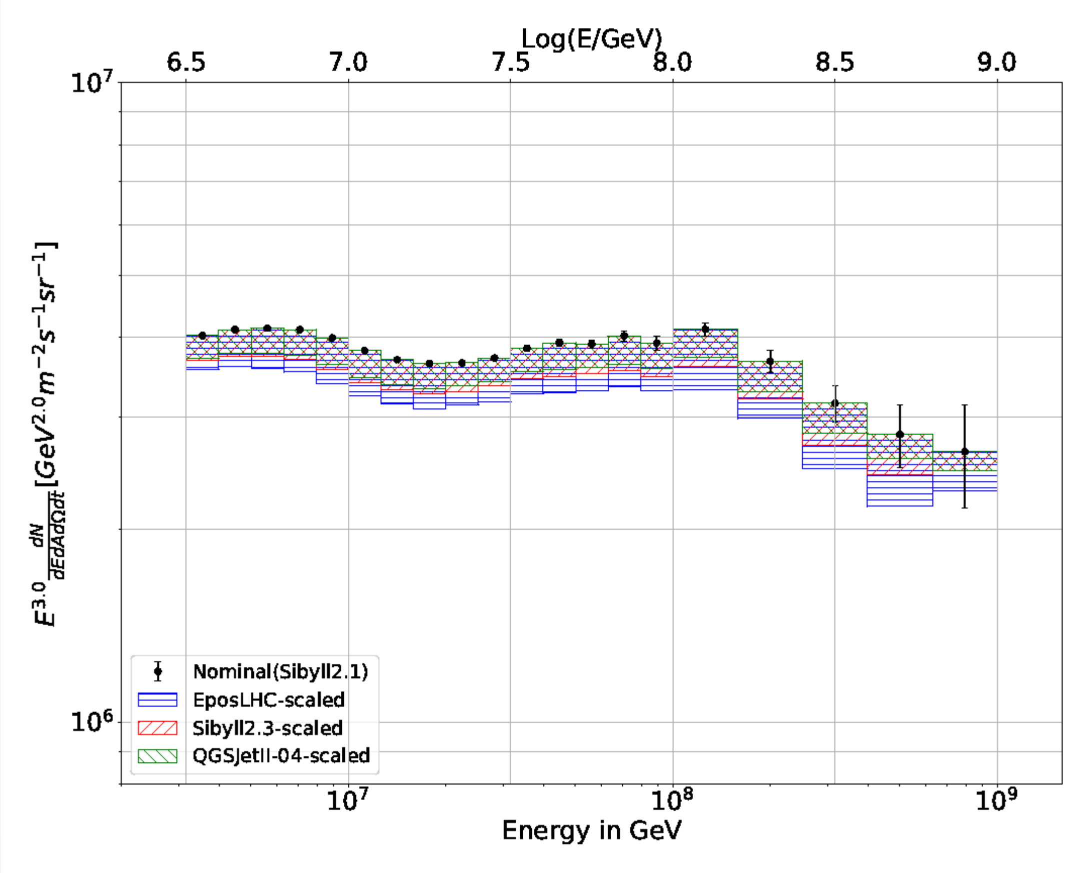


More effects of hadronic interaction model

On nuclear spectra:



On the all-particle spectrum:



dE/dX and the two stochastics