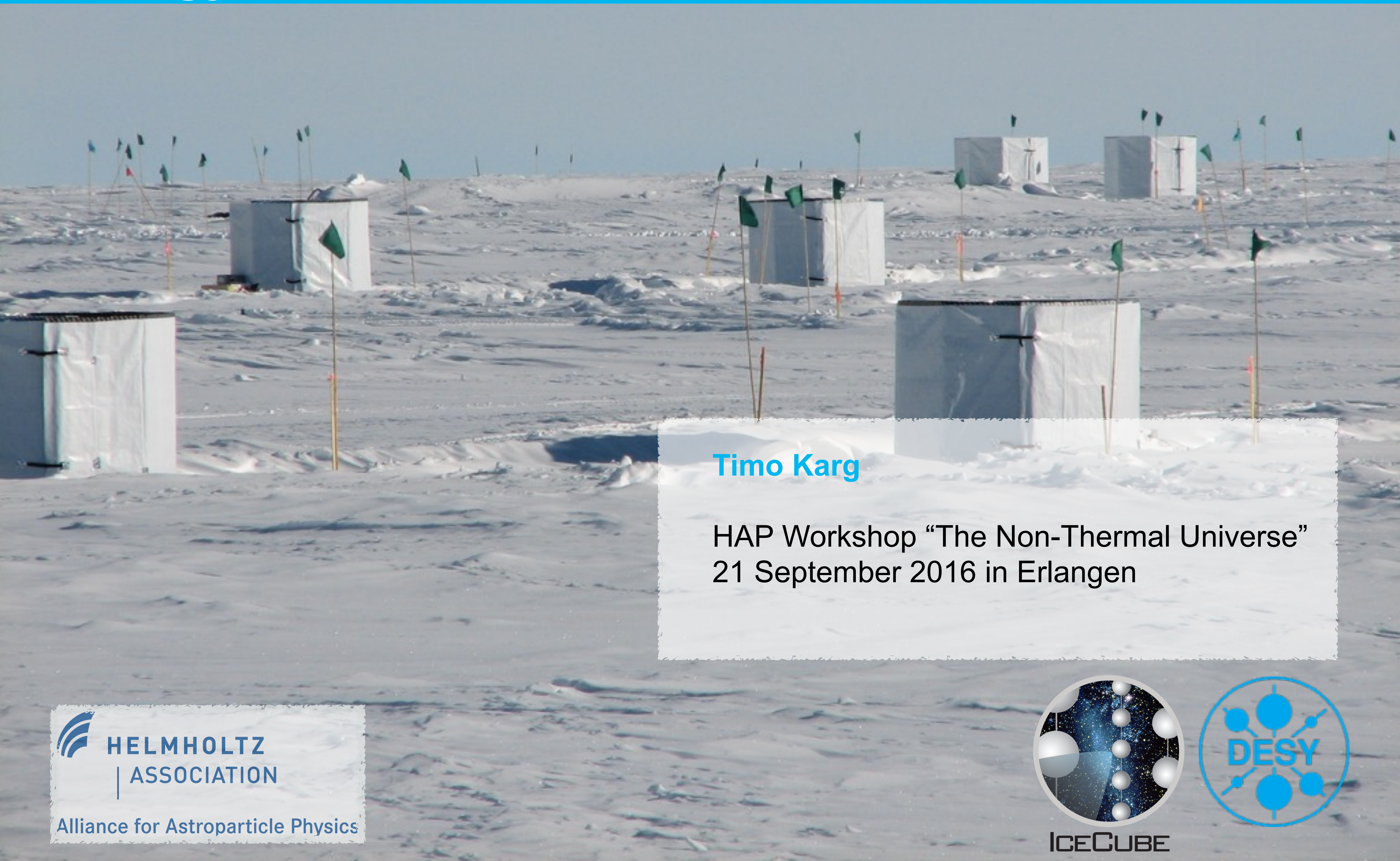
Measurement of the Cosmic Ray Energy Spectrum and Composition with IceCube.



Timo Karg

HAP Workshop “The Non-Thermal Universe”
21 September 2016 in Erlangen

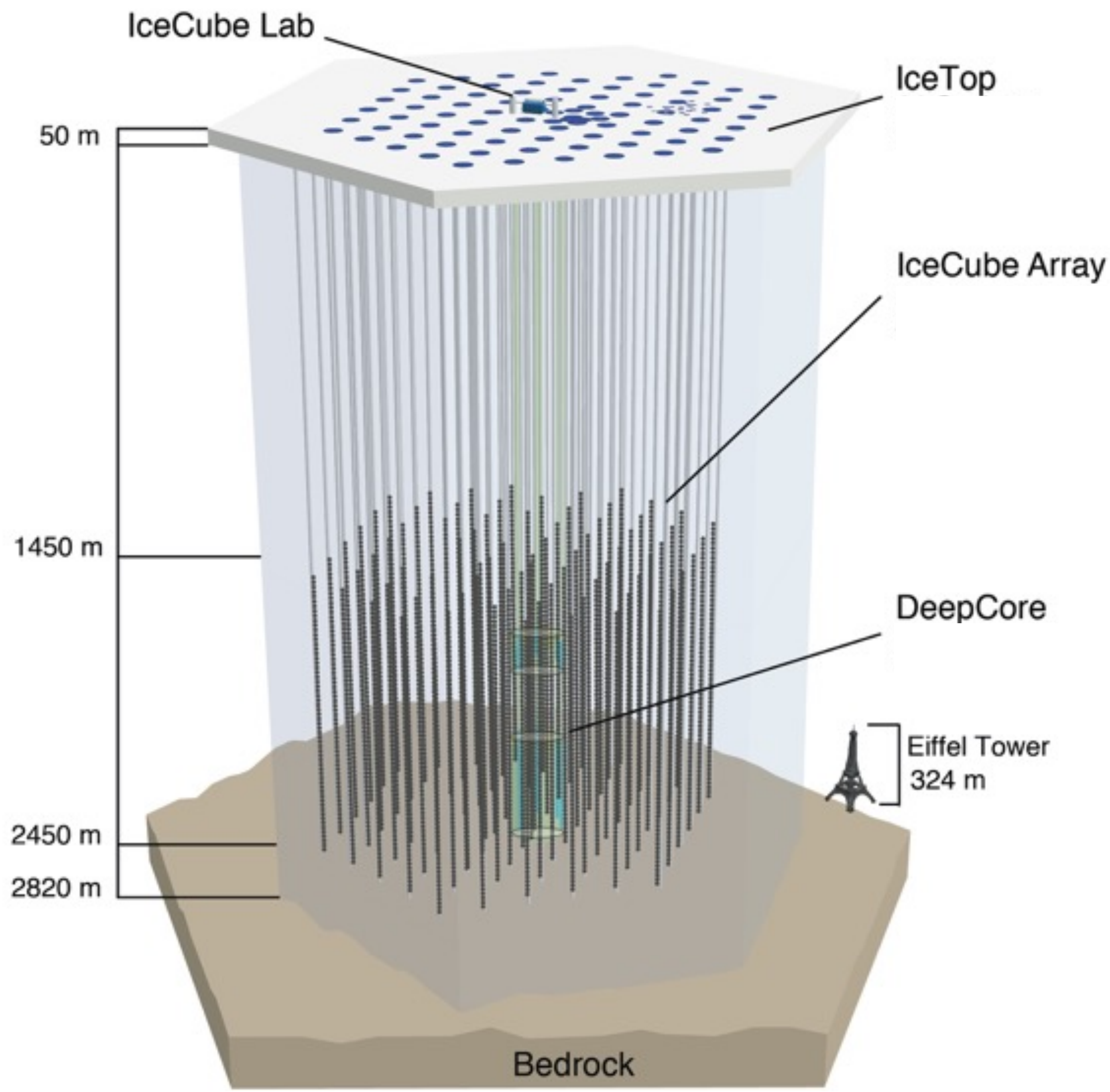
HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

ICECUBE

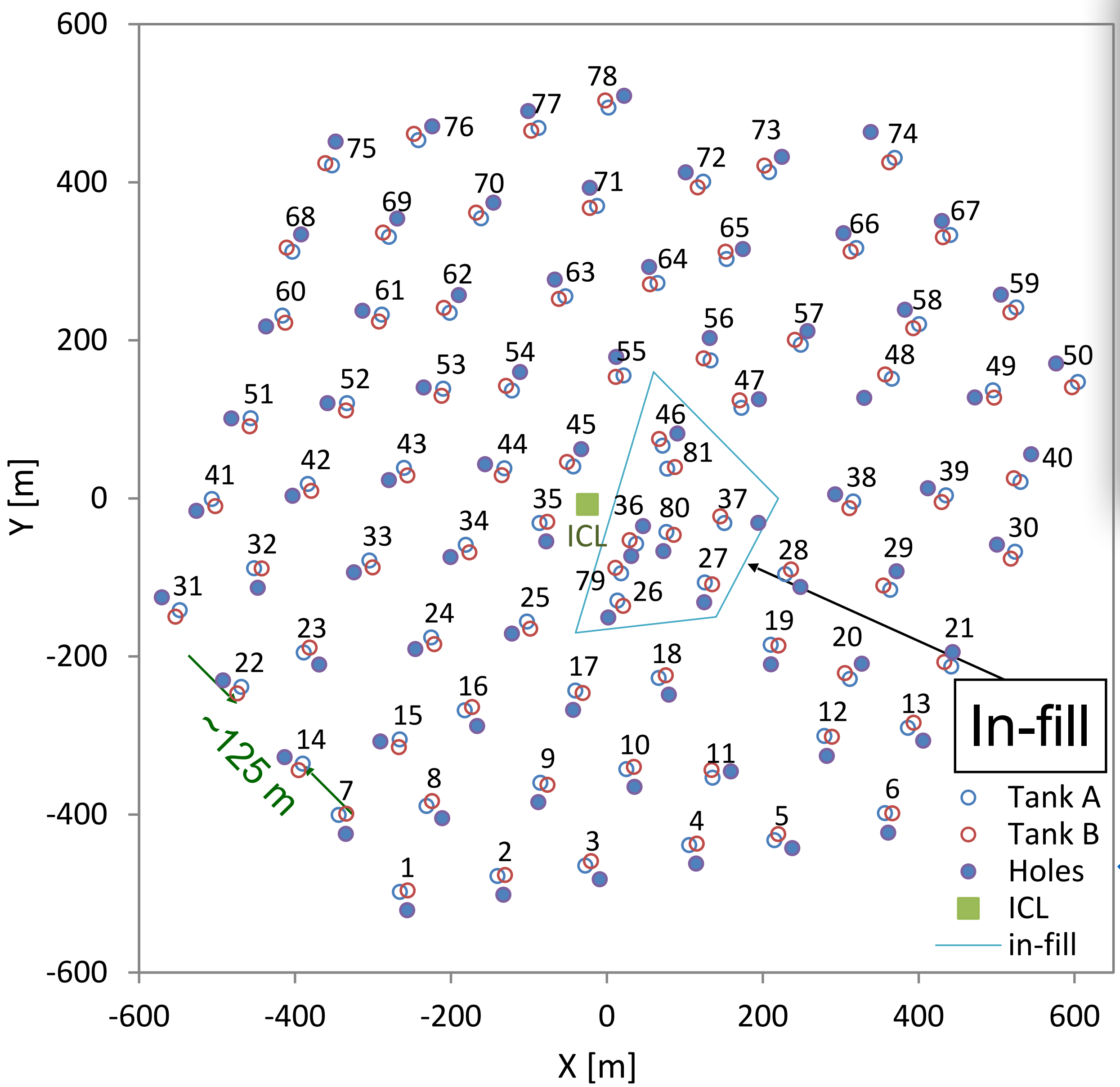
DESY

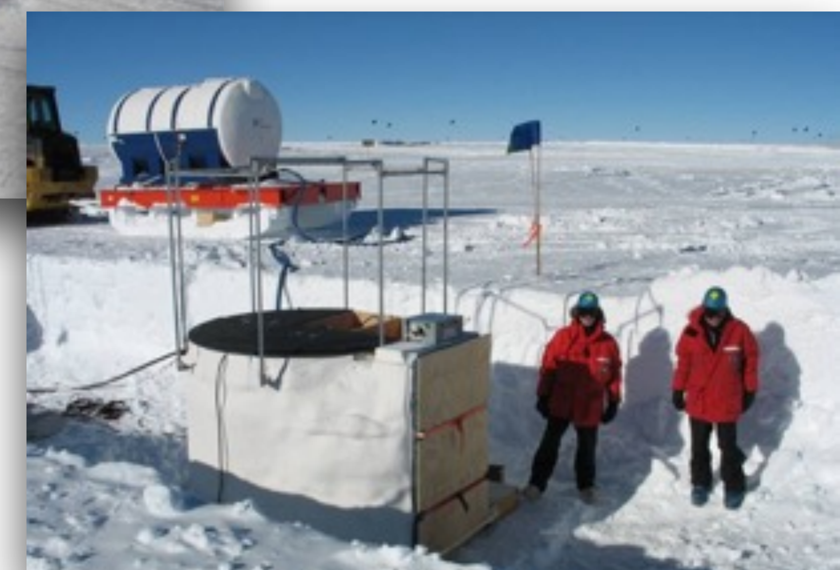
The IceCube Observatory

- Depth: 1450 to 2450 m
- 86 strings
  (60 optical modules each)
- 17 m vertical distance
  btw. optical modules
- 125 m distance btw. strings
- Volume: 1 km³
- More dense instrumentation
  in center (DeepCore)
- **1 km² surface array (IceTop)**
- Completed: 18 Dec. 2010



The IceTop Detector Array (~ 1 km^2)



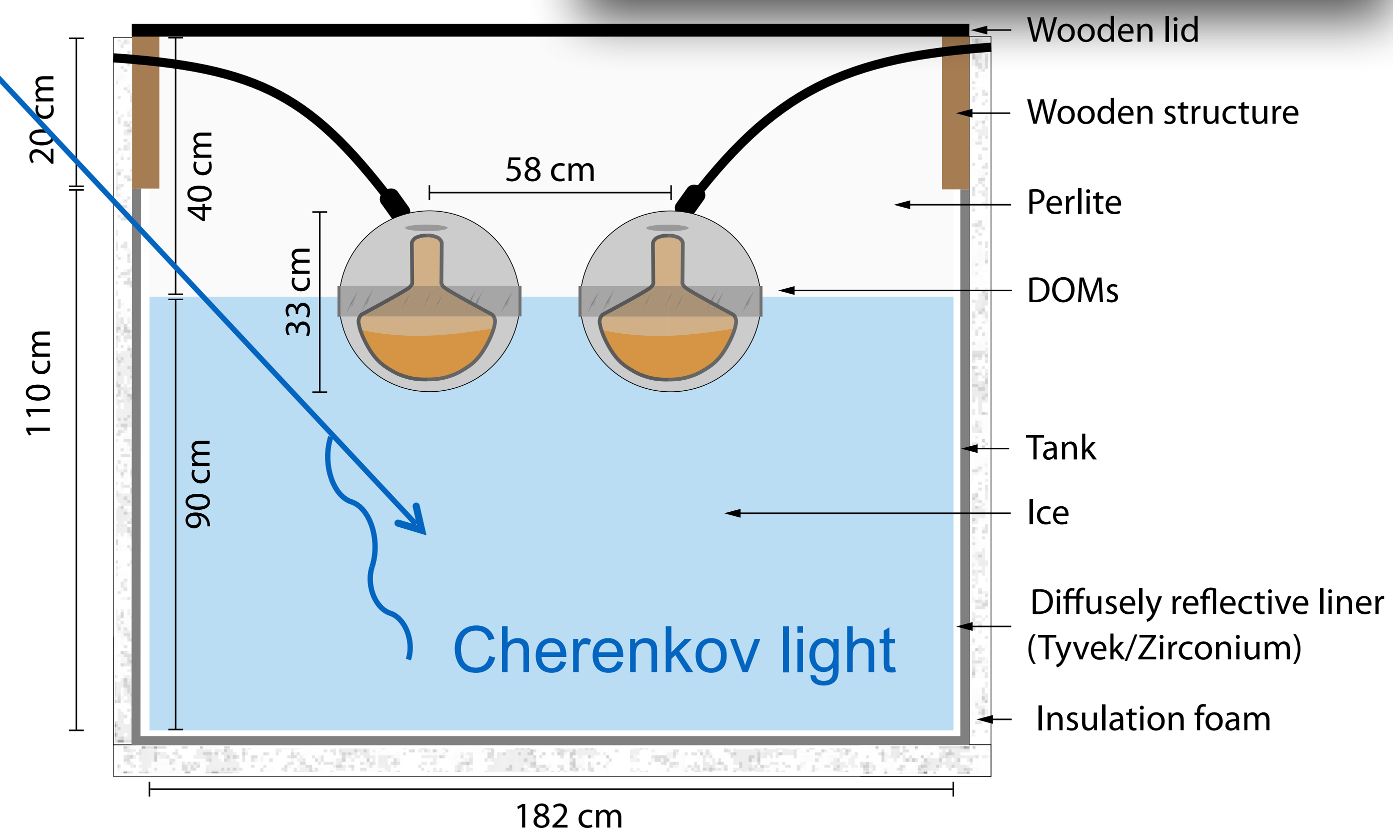


81 stations (162 tanks)

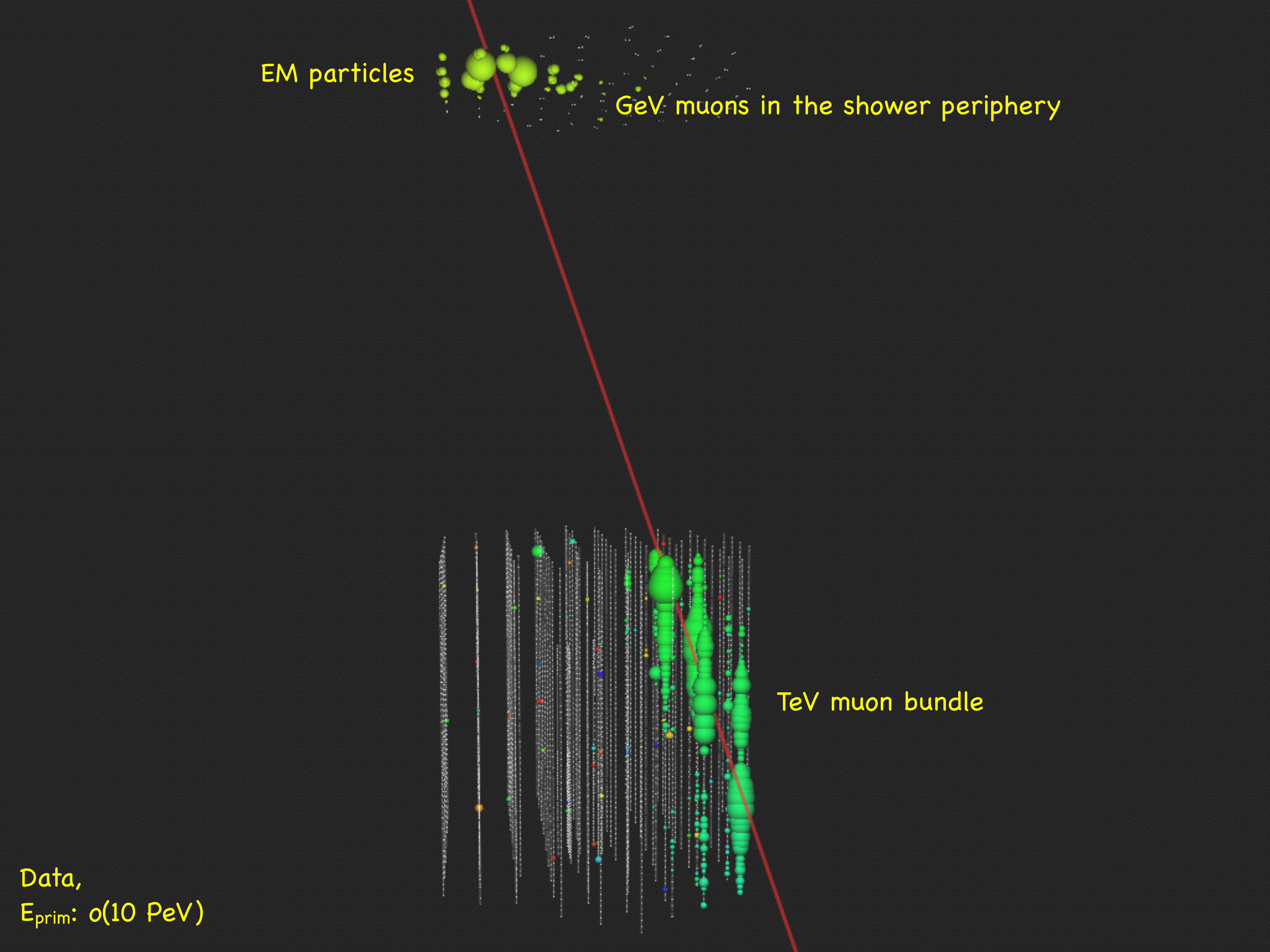
typical spacing: 125 m

fill ratio ~ 4×10^{-4}

altitude: 2835 m (X = 680 g cm^{-2})

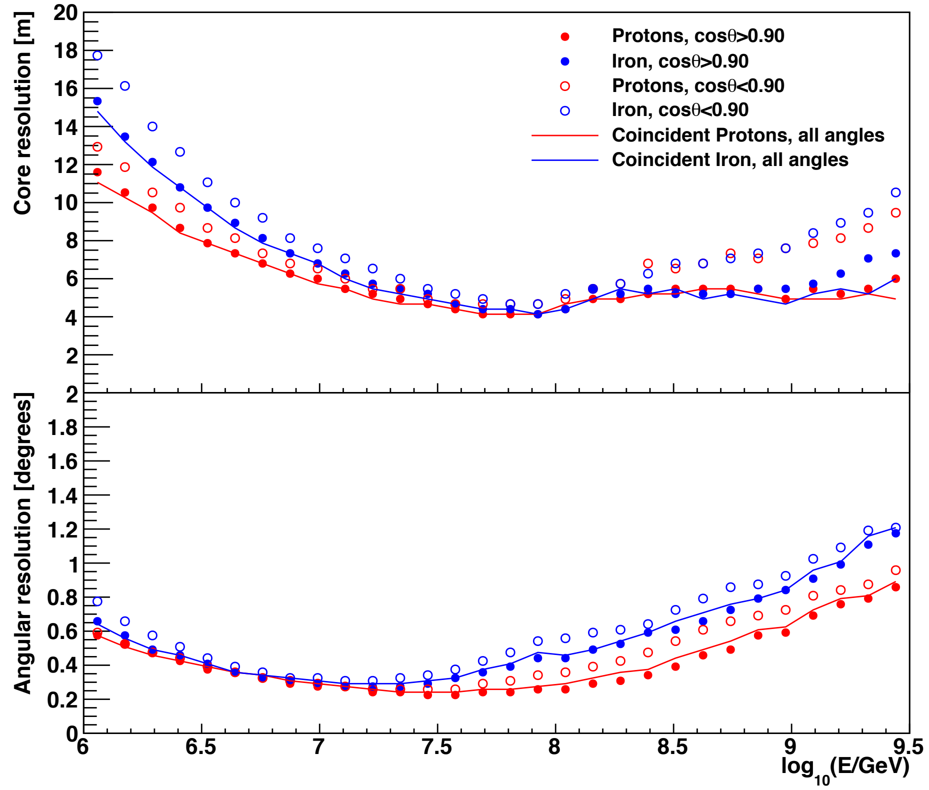


*NIM A **700** (2013) 188*


EM particles
GeV muons in the shower periphery
TeV muon bundle
Data,
E_{prim}: o(10 PeV)

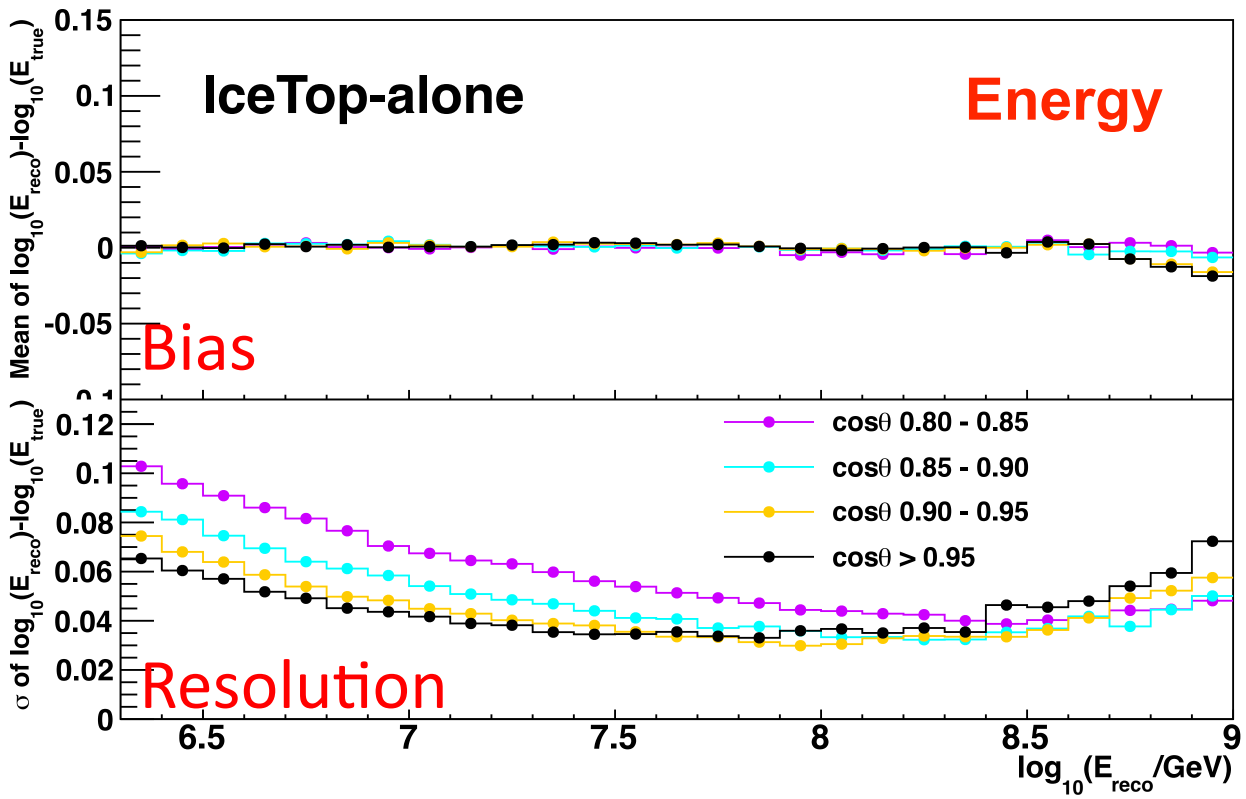
Reconstruction Performance

Typical resolutions; might differ slightly between analyses / event selections



Core position:
between 5 and 10 m

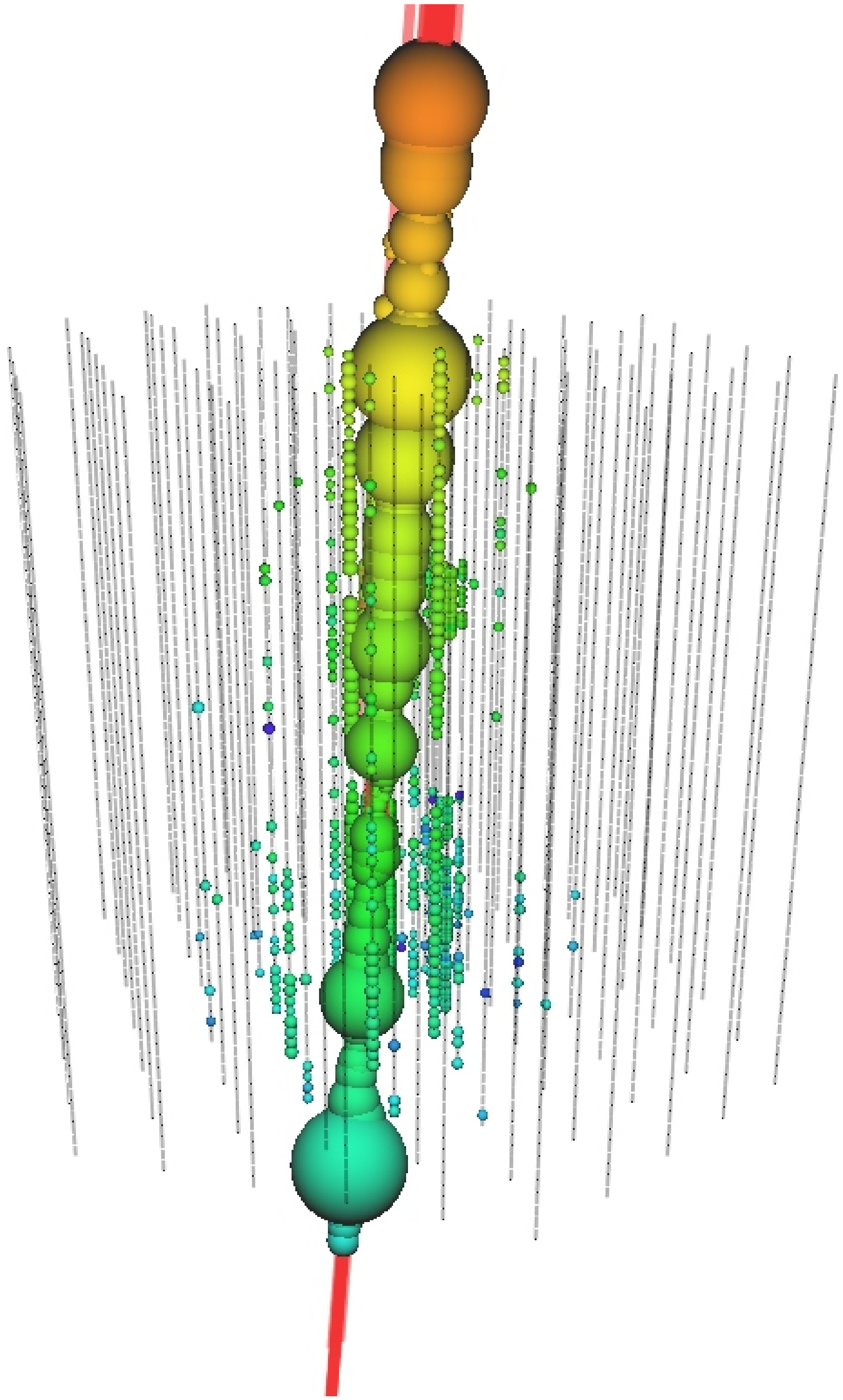
Direction:
better than 1°

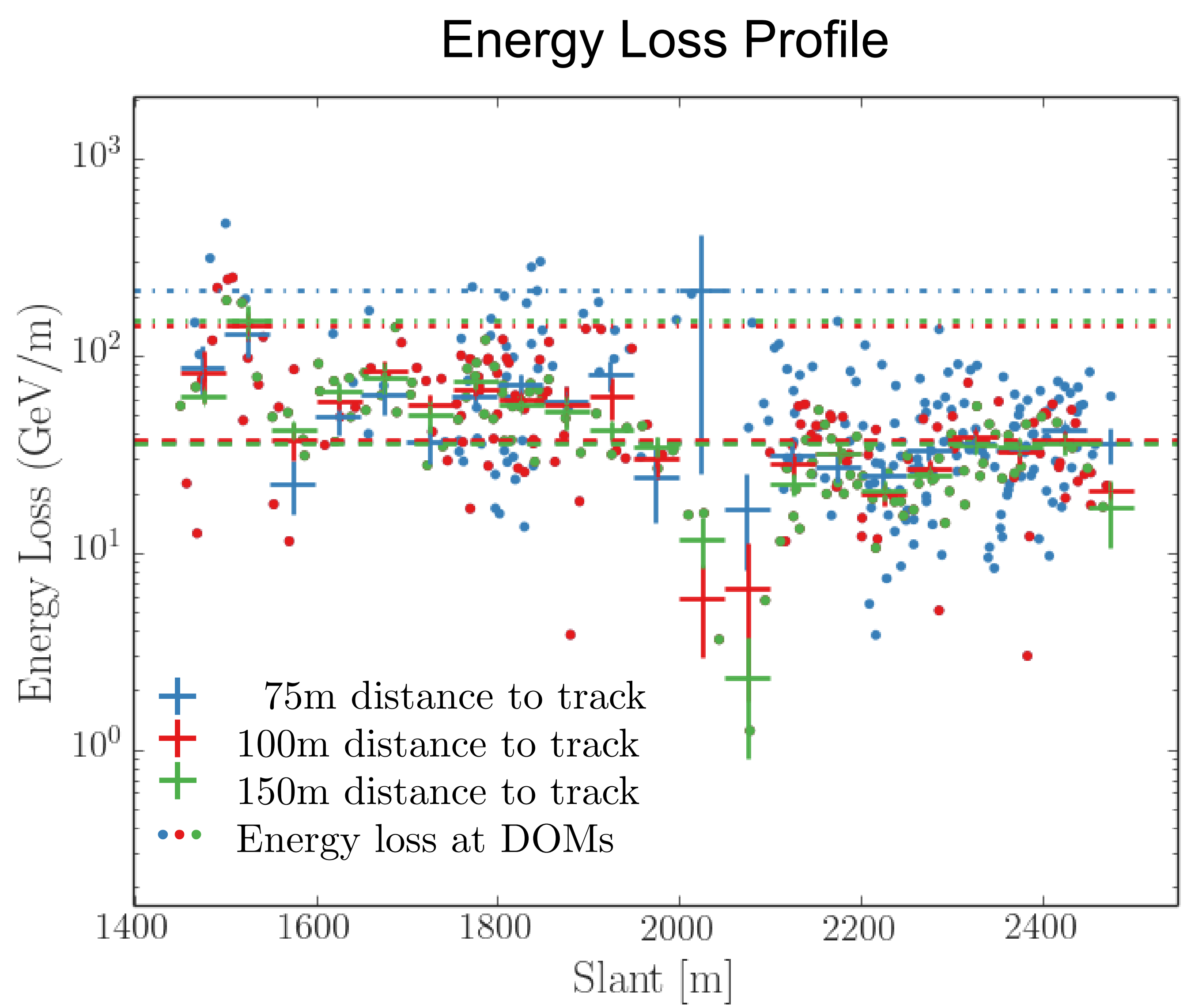


Bias near zero

Resolution best
between 10
and 300 PeV

Muon Bundle Reconstruction





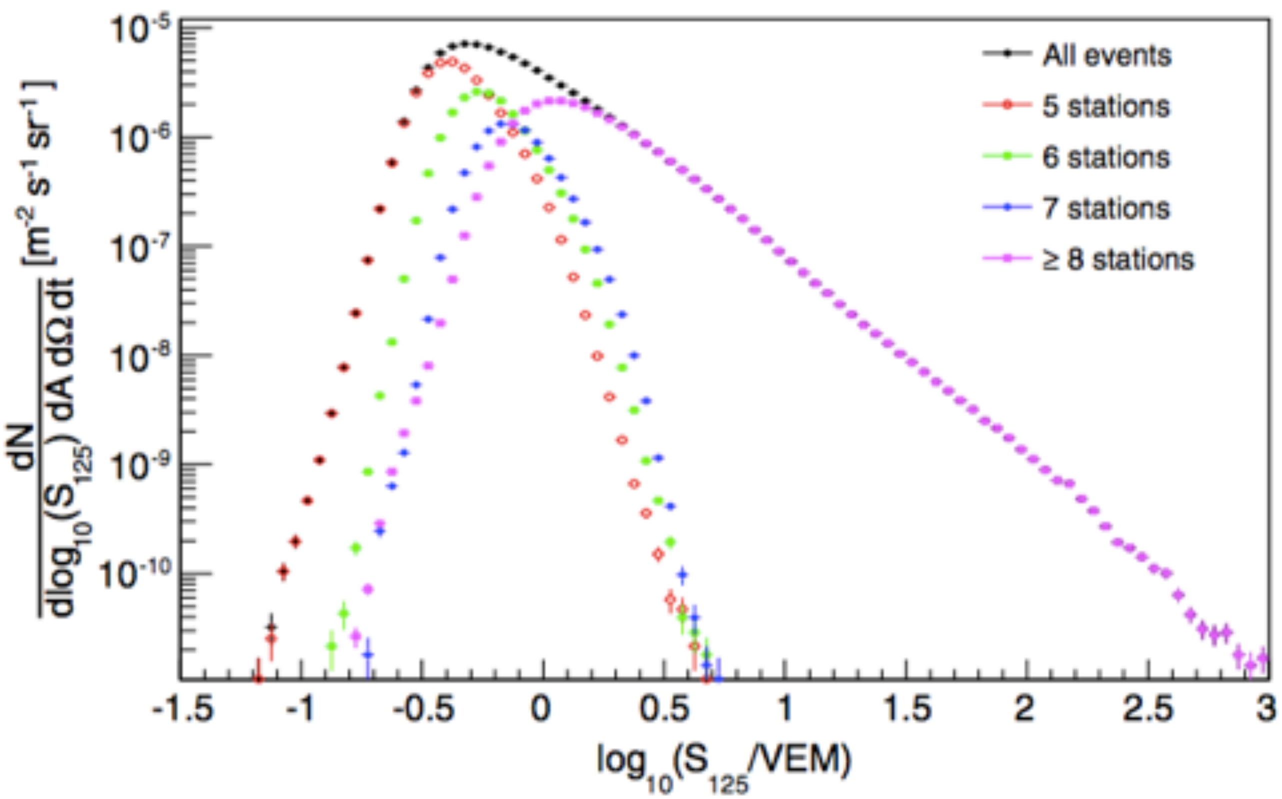
- Reconstruct energy loss as function of slant depth
- Measure for the number of muons in bundle

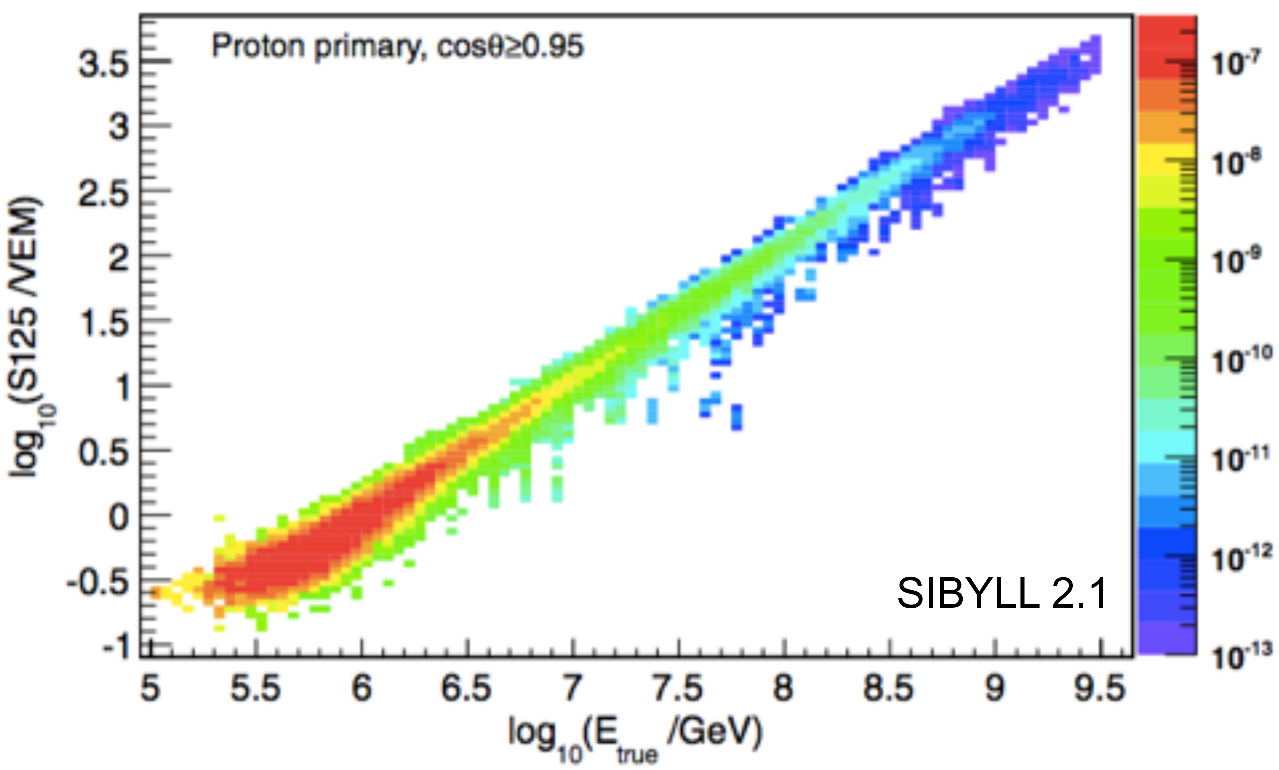
Results

Cosmic Ray Energy Spectrum

IceTop only: primary energy from shower size (number of particles) at ground level

Phys. Rev. D ***88*** *(2013) 042004*





> Conversion from shower size to primary energy depends on zenith angle and composition assumption

> Zenith dependence can be used as cross check for composition assumption

IceTop-only Energy Spectrum

Three years of data (2010 — 2012)

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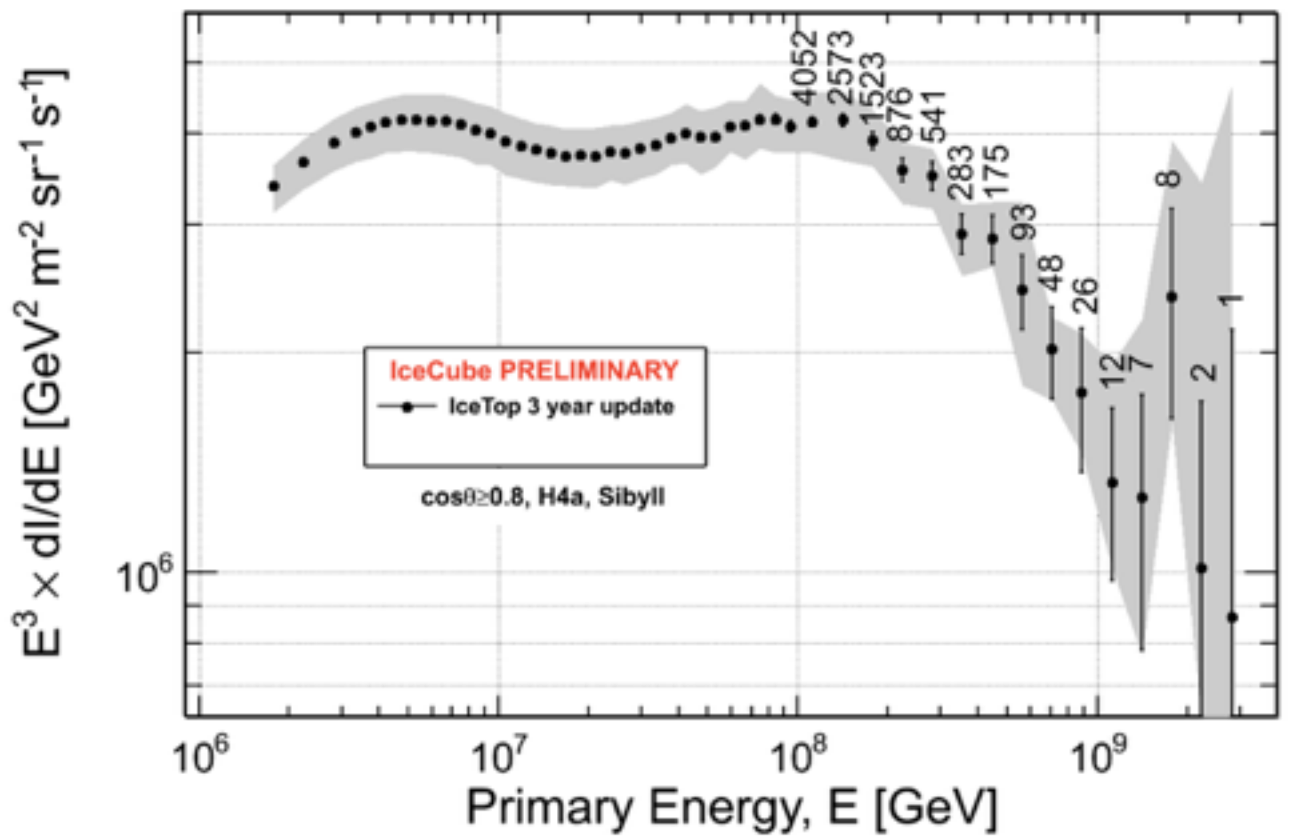

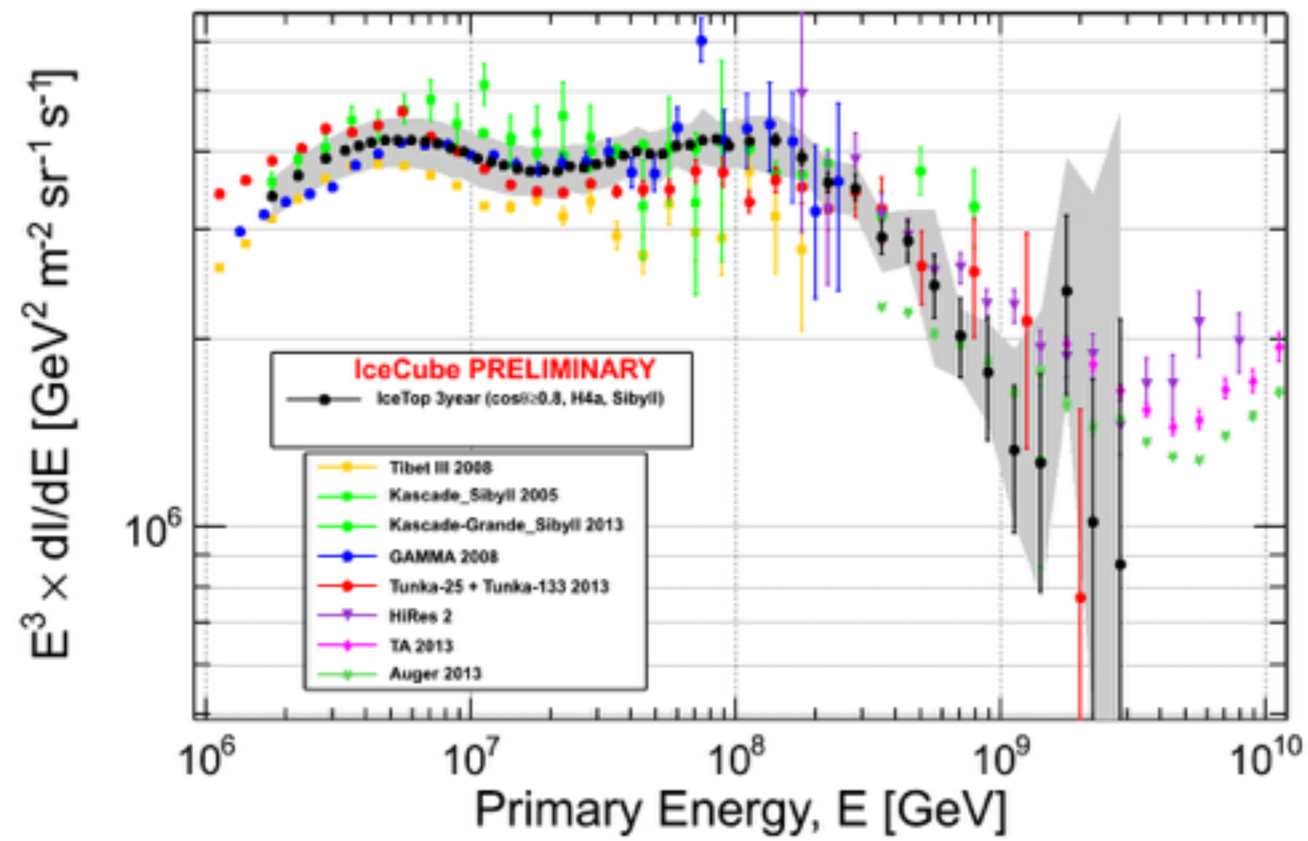

Systematic uncertainties:

	3 PeV	30 PeV
VEM calibration	+4.0% − 4.2%	+5.3% − 5.3%
Snow	+4.6% − 3.6%	+6.3% − 4.9%
Interaction models	−4.4%	−2.0%
Composition[a]	±7.0%	±7.0%
Ground pressure	+2.3% − 2.0%	+0.4% − 1.0%

[a]Composition uncertainty is not constant with energy but the largest value was chosen as a fixed, conservative estimate.

> CR energy spectrum does not follow a single power law

- Hardening at around 20 PeV, softening past 100 PeV
- Contribution of different source populations?

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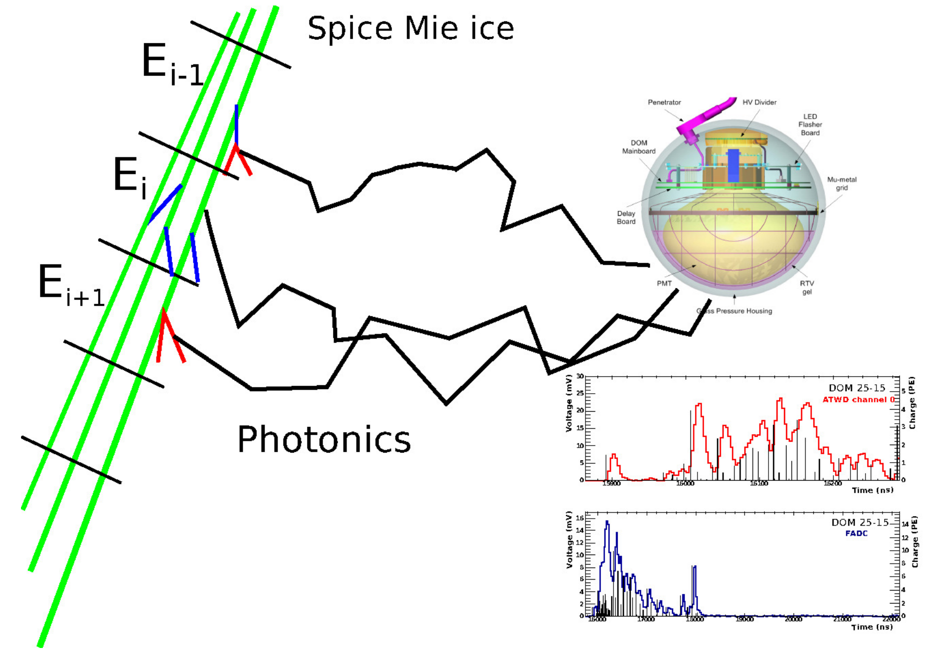
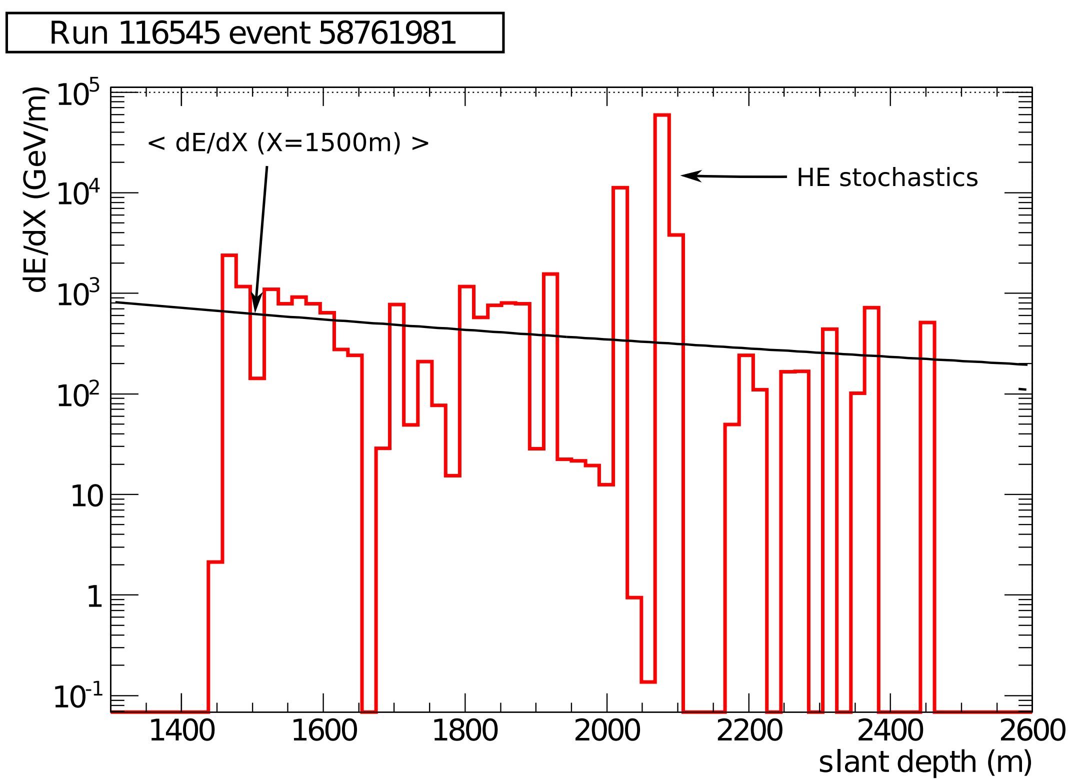
Cosmic Ray Composition

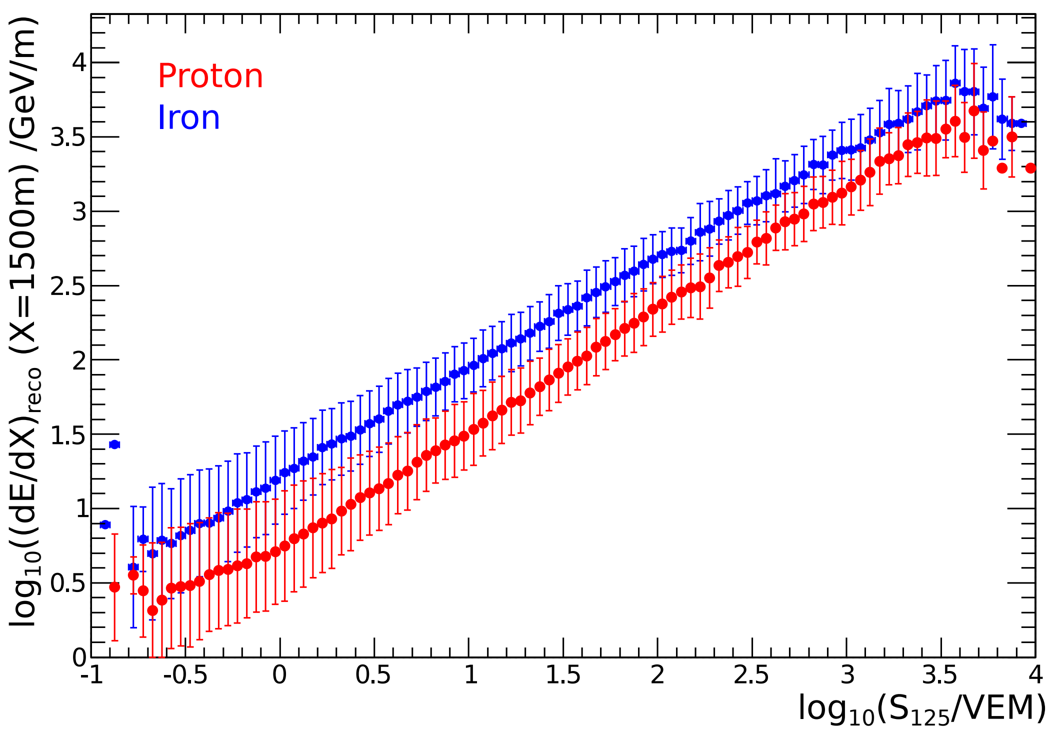
Coincident analysis with deep-ice detector: number of high energy muons as measure for mass number A

> Unfolding the energy loss pattern

- Muon bundle energy loss depends on number of muons
- Stochastic behavior: count number of peaks above some threshold (2 selection procedures)





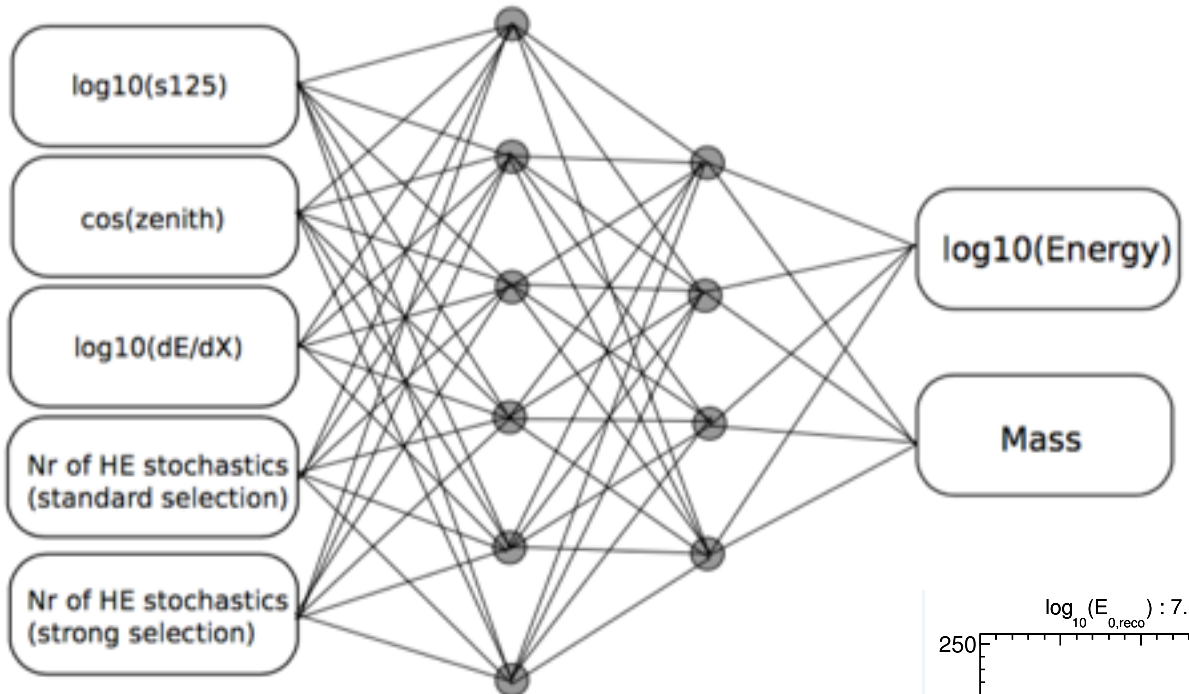


Composition sensitive variable: dE/dx at 1500 m slant depth

Analysis Using a Neural Network

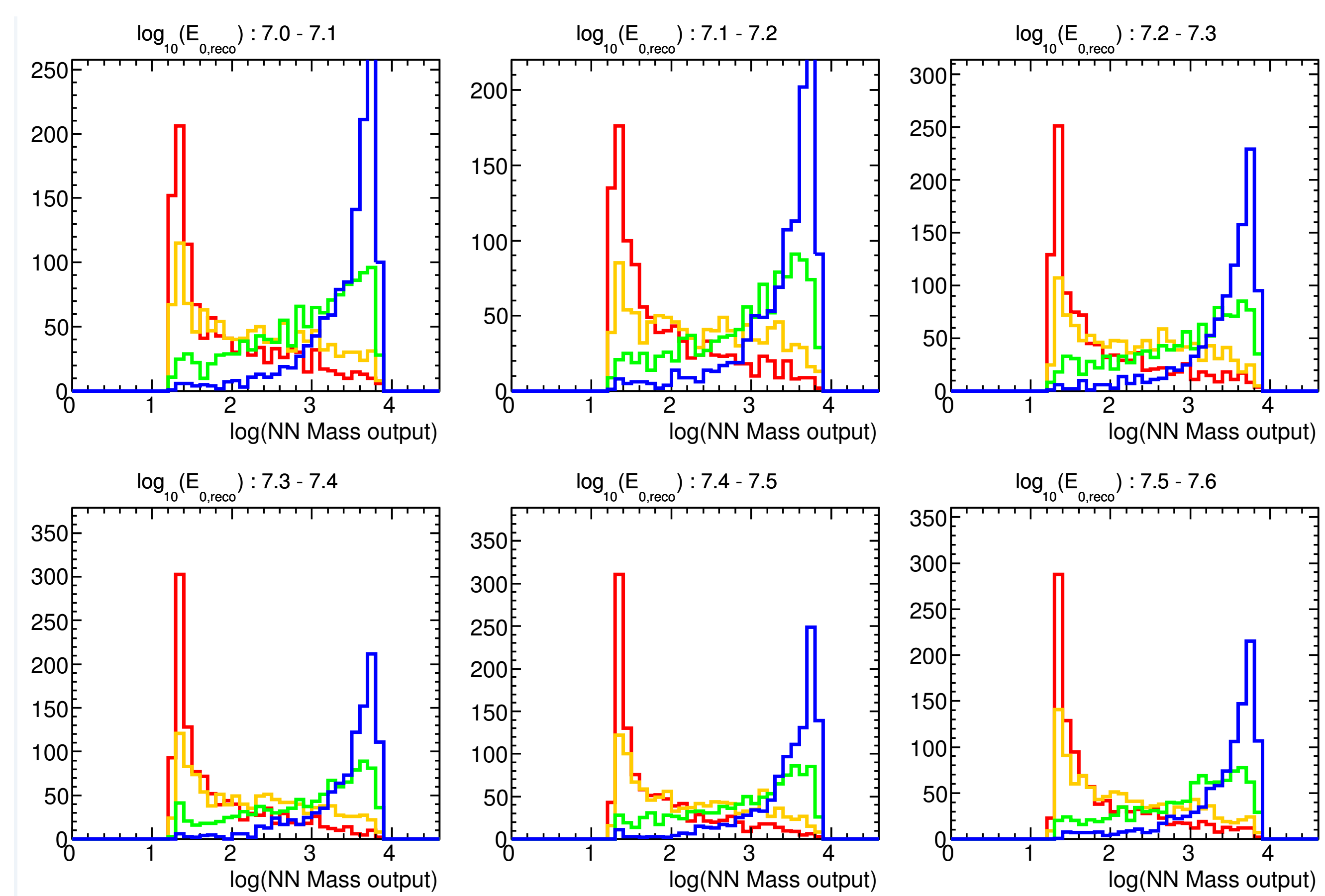
IceTop vars:
primary energy

in-ice vars:
muon number



- Train neural network on Monte Carlo data (four mass groups: p, He, O, Fe)
- Derive MC templates for mass groups in each energy bin
- Process data with same NN, fit templates to data output in each energy bin

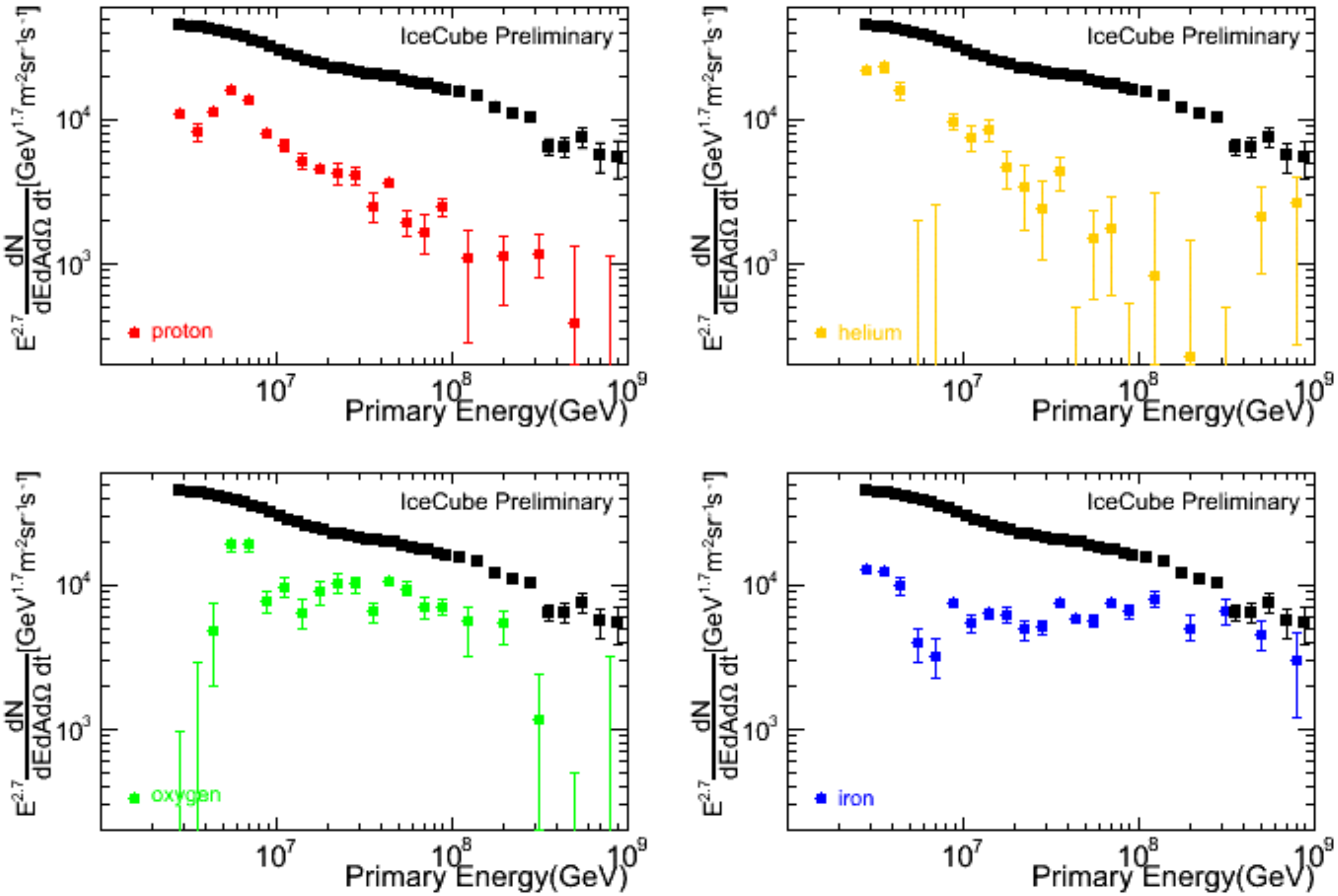
Templates:



Spectra for Individual Mass Groups (p, He, O, Fe)

Three years of data (2010 — 2012)

statistical errors only



- Proton and helium turning down steeply at lower energies
- Oxygen and iron maintain harder spectrum up to higher energies

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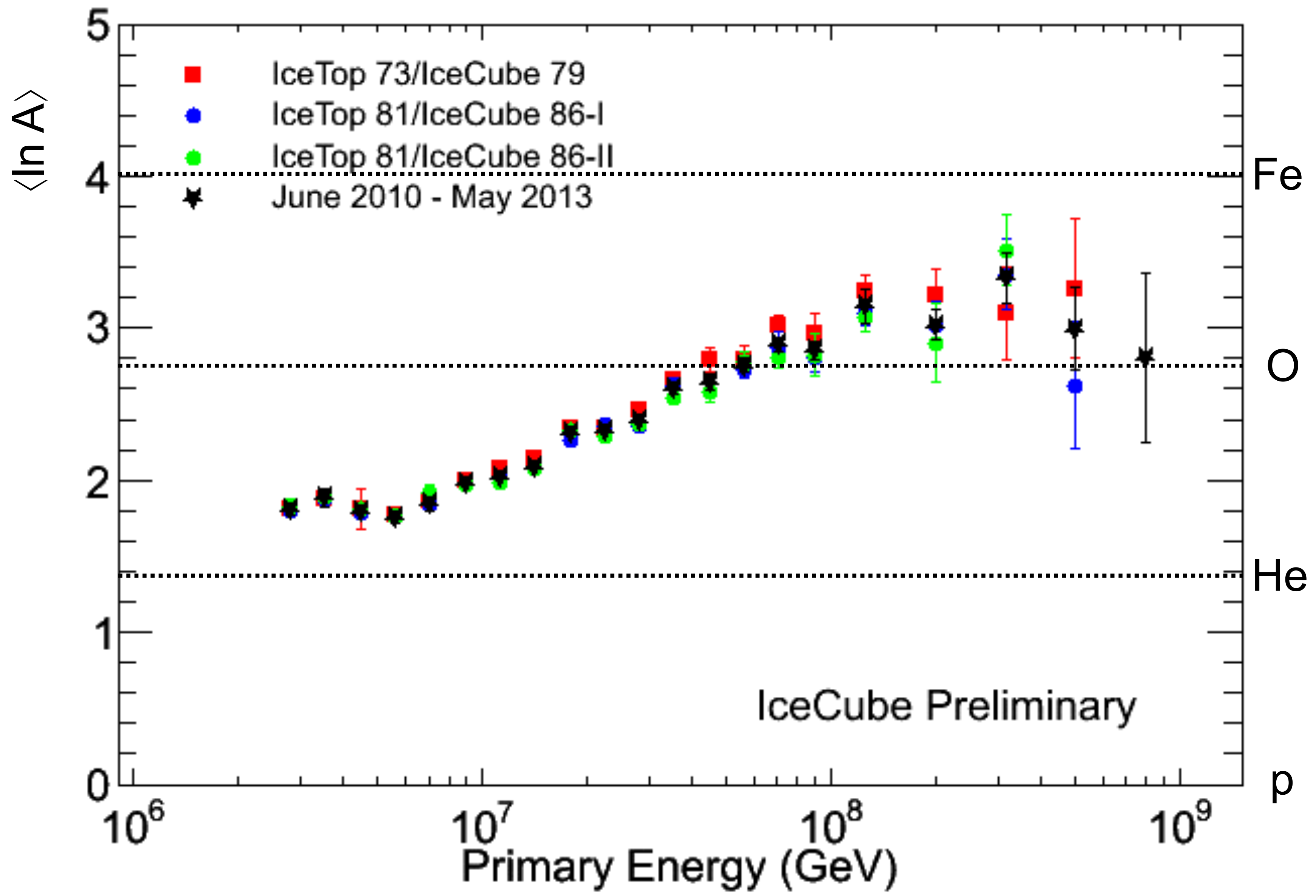
Mean Mass and Systematic Uncertainties

Three years of data (2010 — 2012)

- Consistent results in each year



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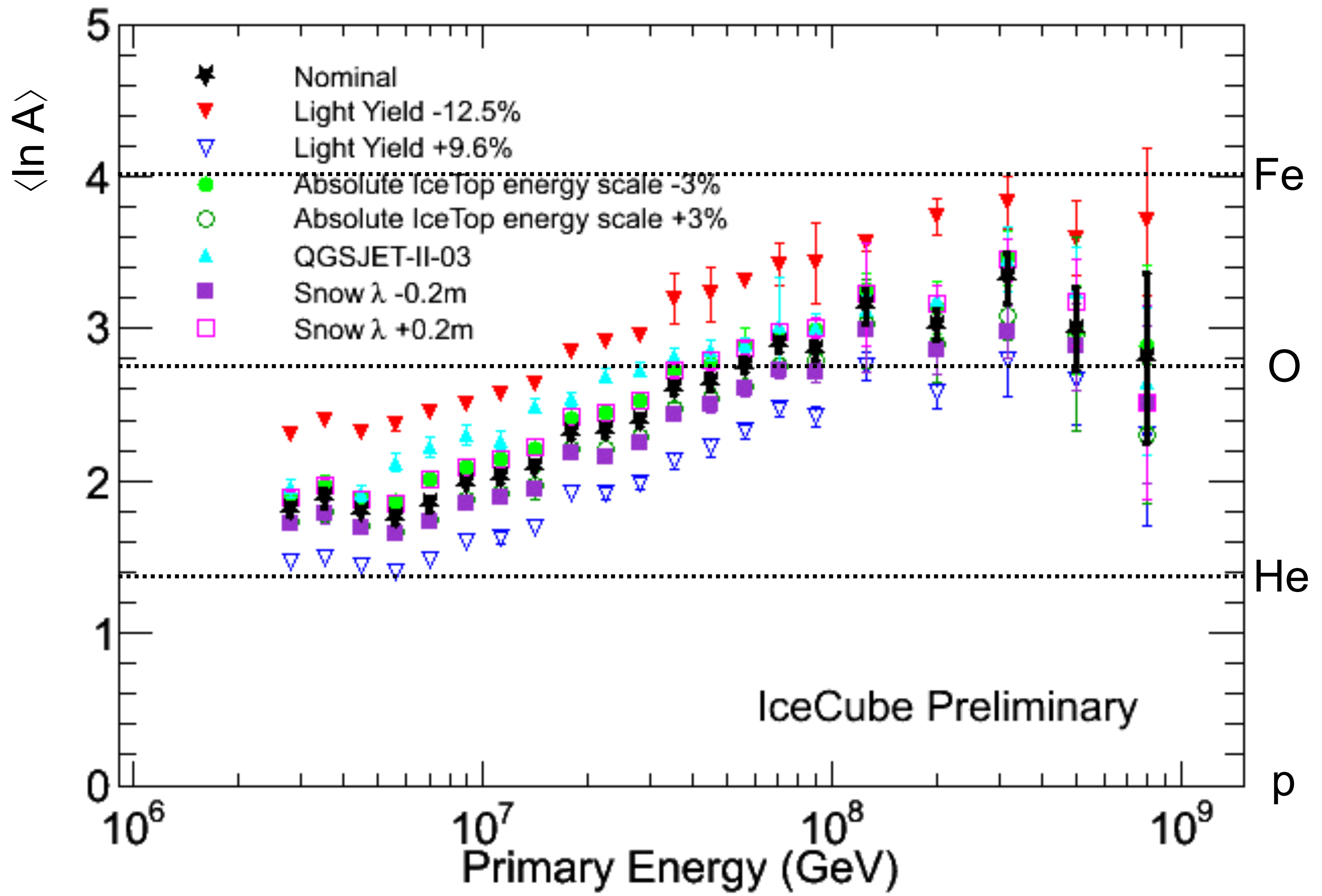
Mean Mass and Systematic Uncertainties

Three years of data (2010 — 2012)

- Consistent results in each year
- Dominant systematic uncertainties:
  - Light yield: optical properties (scattering, absorption) of the Antarctic ice
  - Hadronic interaction model



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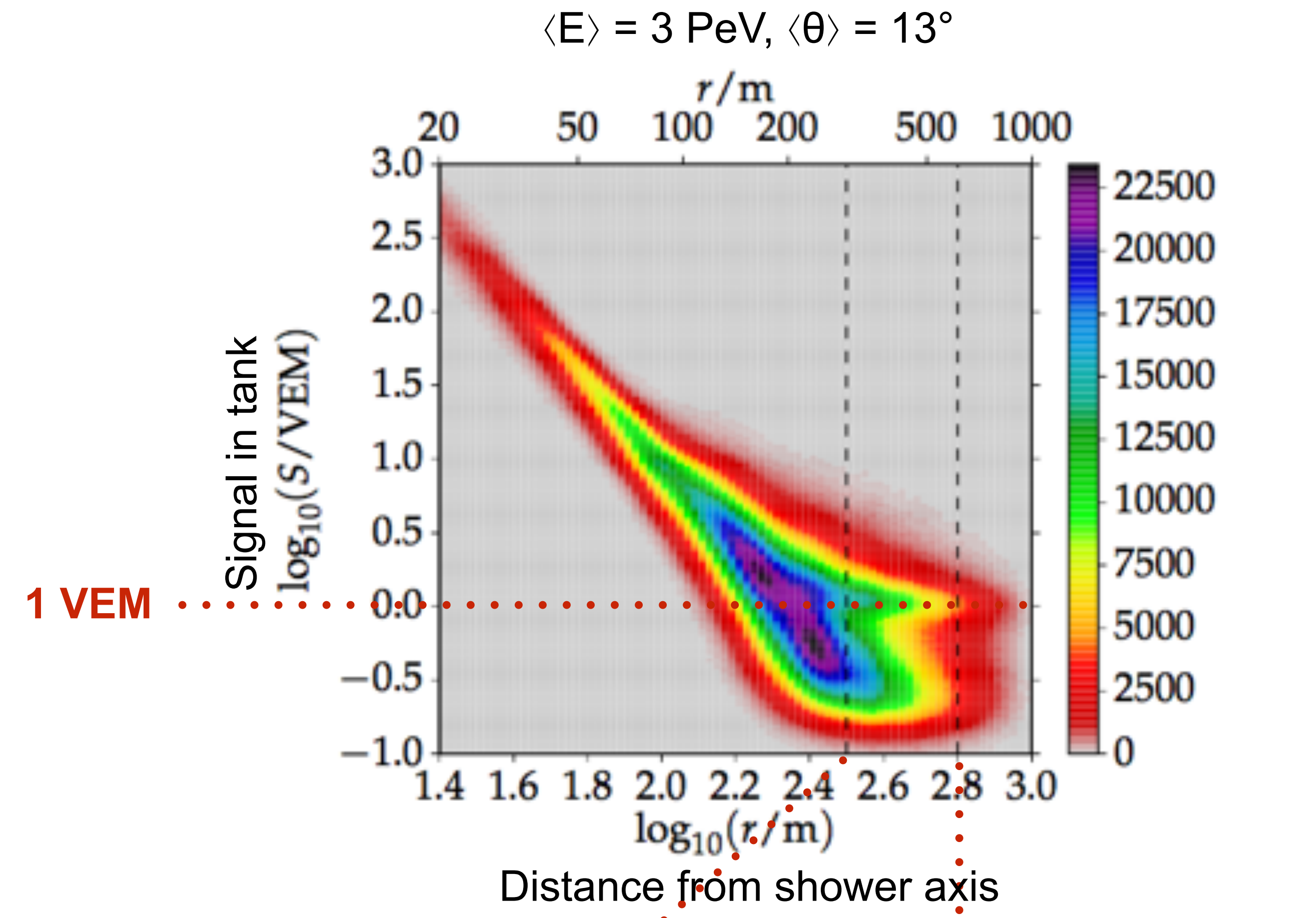
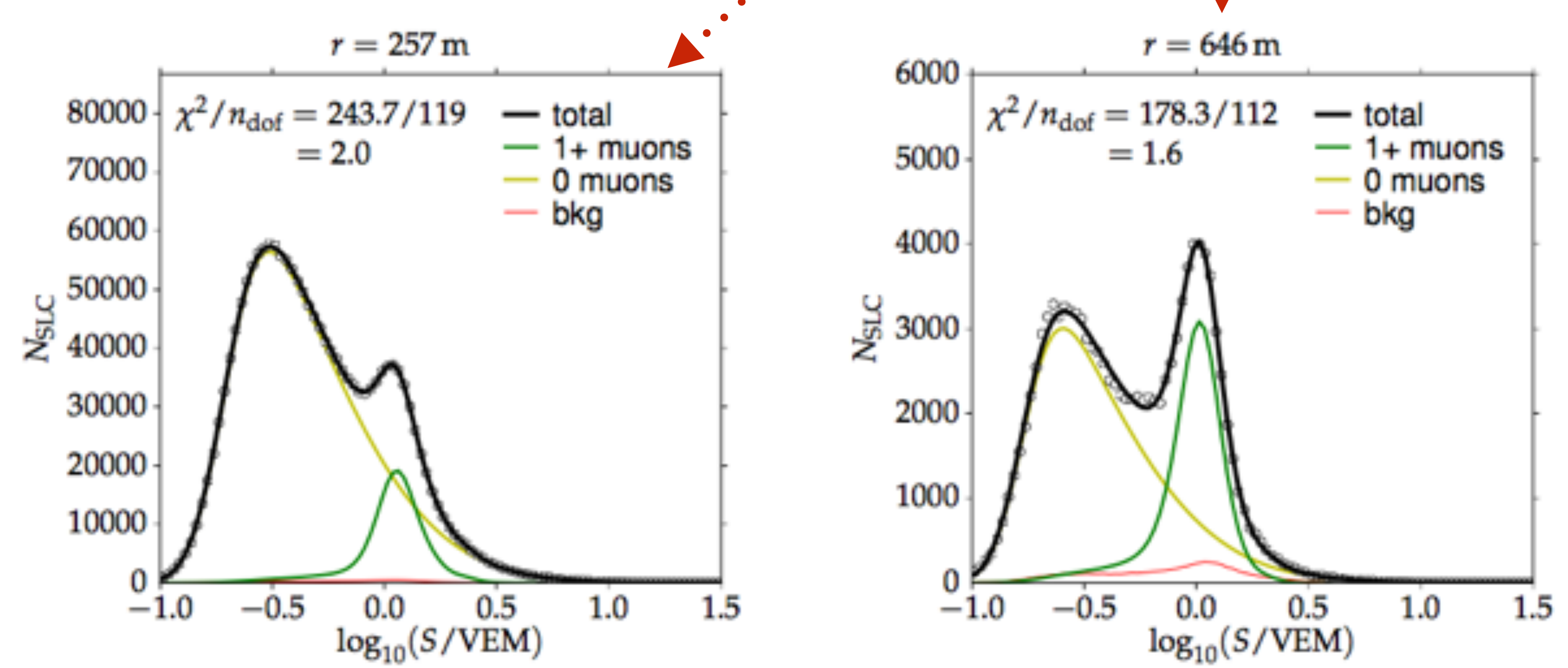
GeV Muons on the Surface

- At large distance from the core muons dominate the tank signal
- Trigger threshold of tanks: ~ 1/6 VEM
- Determine mean muon number from fit to charge distribution (fixed radius, E_{CR}, θ)
- Measurement independent of air shower simulation!





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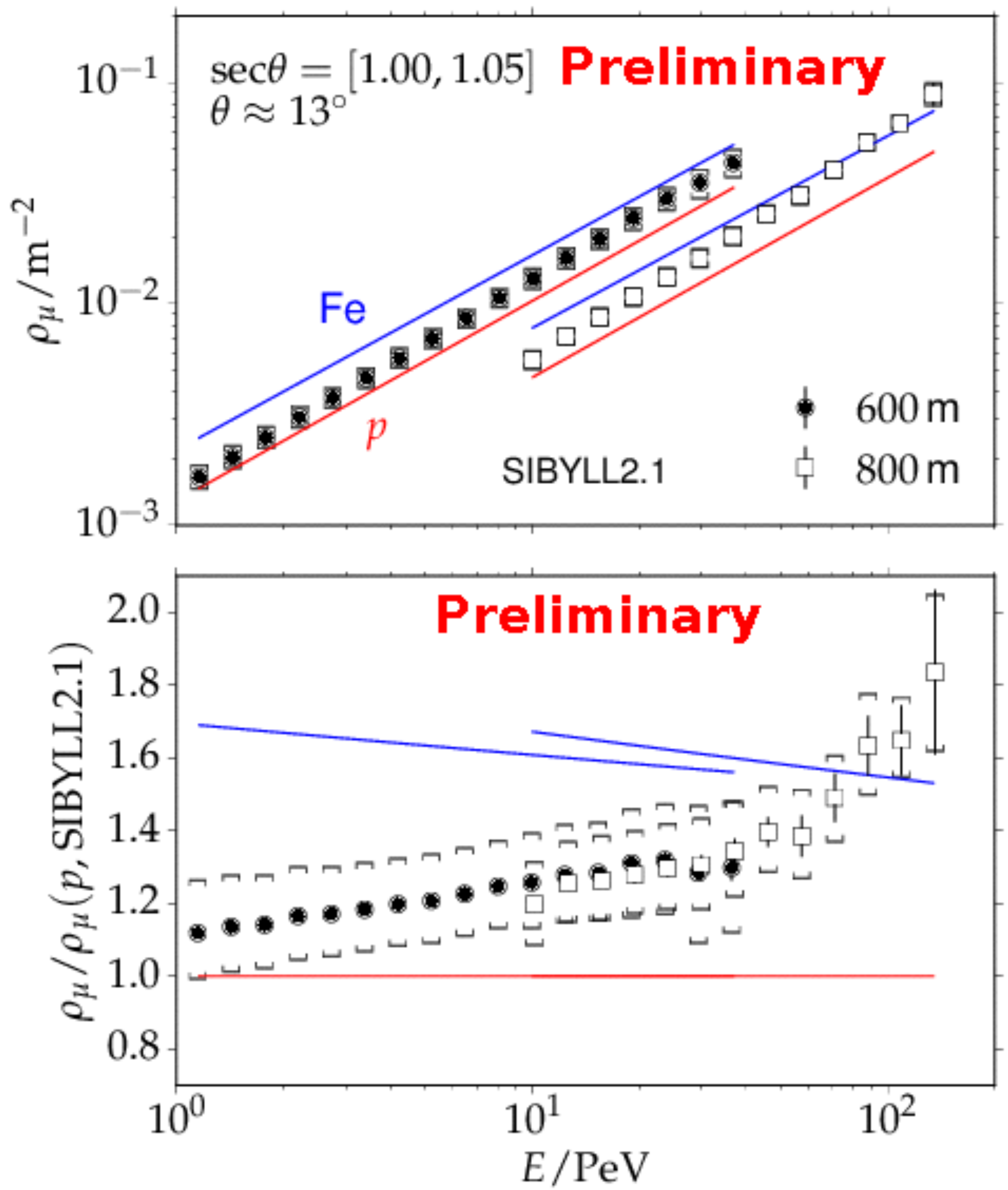
GeV Muons on the Surface

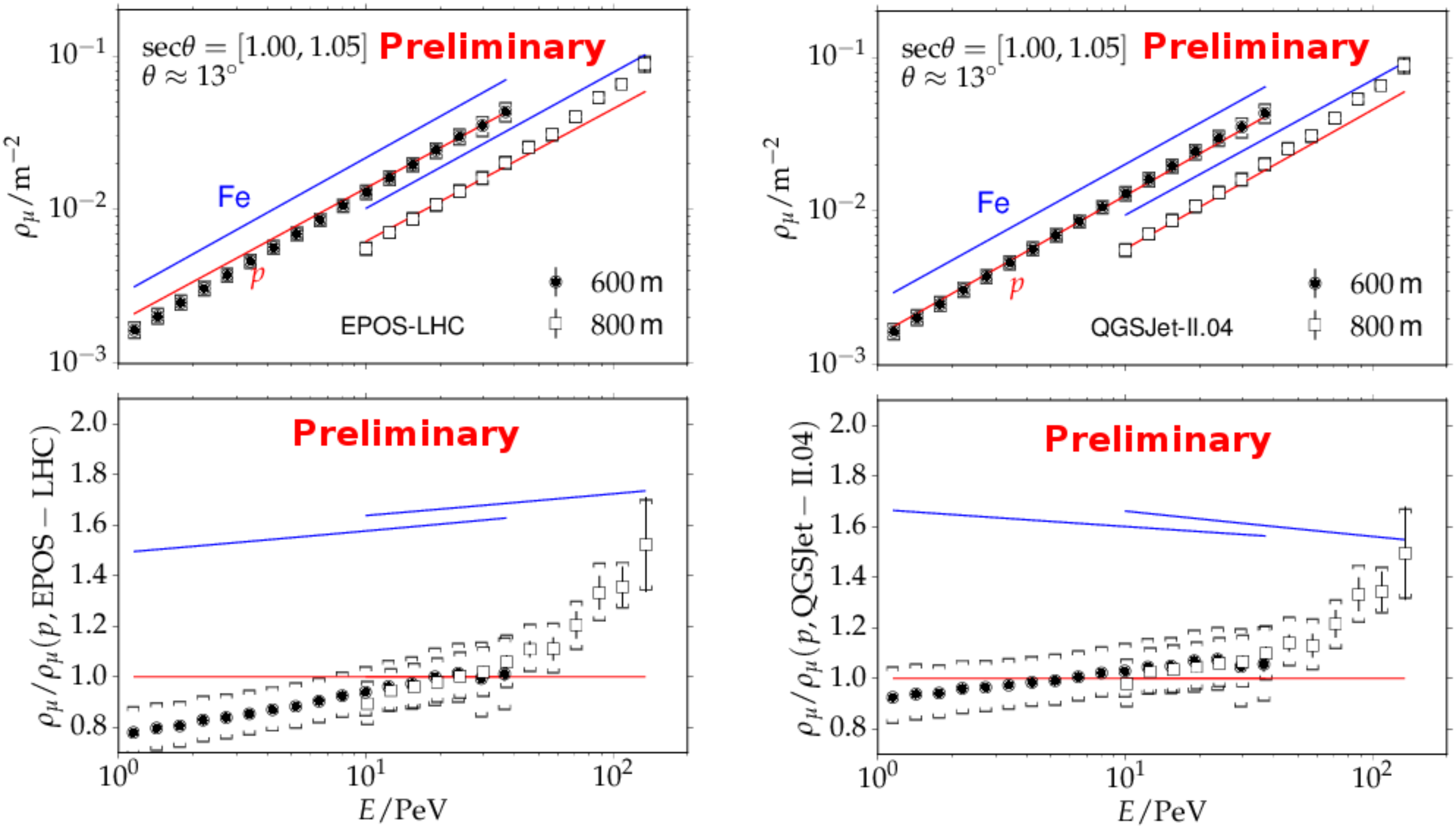
- Muon density at 600 m and 800 m from the shower core
- Air shower simulations for reference
- Will be used in the future
  - to constrain hadronic interaction models
  - to improve composition measurements



IceCube
DESY

GeV Muons: EPOS-LHC & QGSJet-II.04

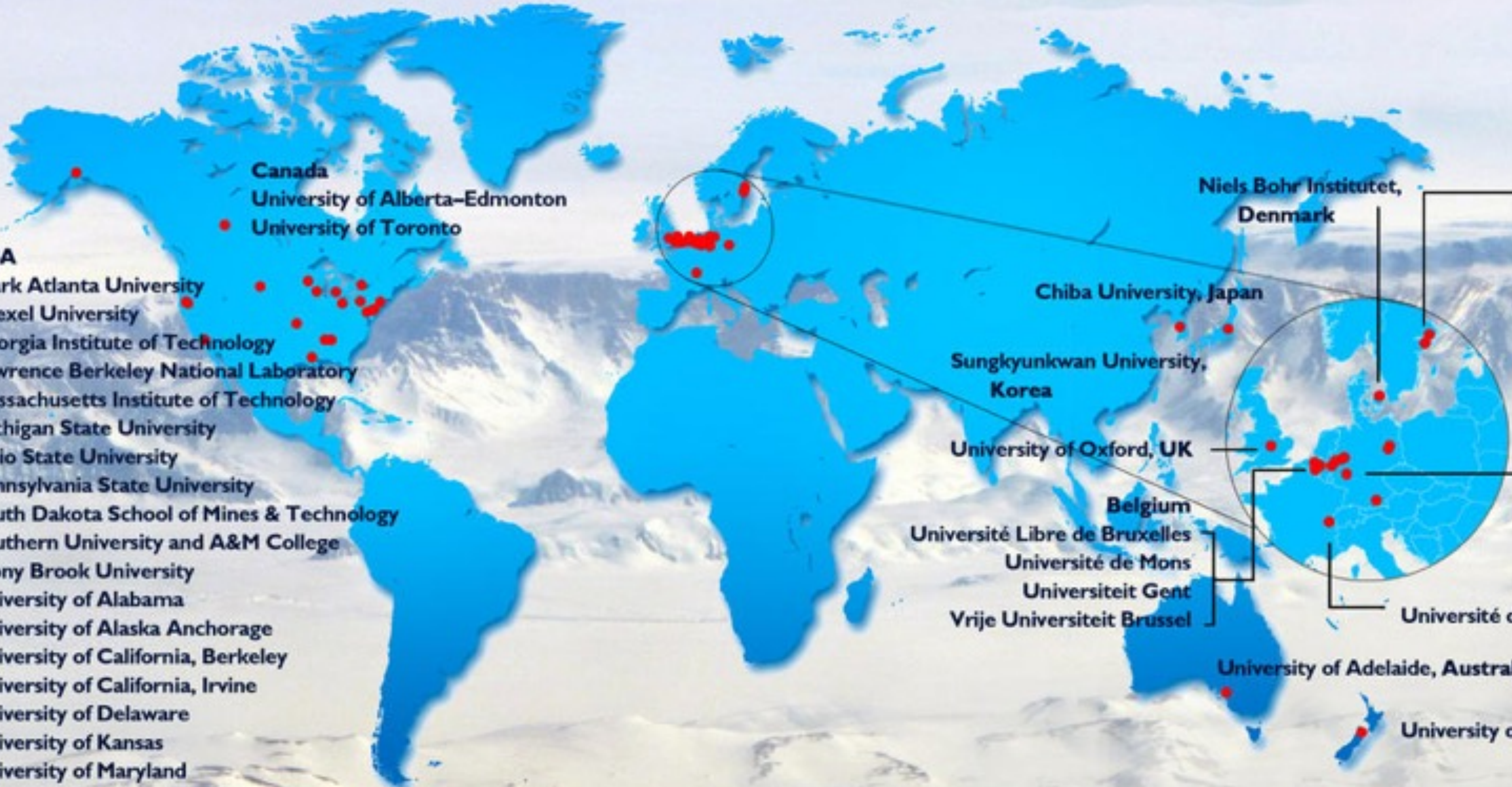
Same data points. Different int. models for reference



Summary and Conclusions

- The IceCube Observatory can simultaneously measure EM component, GeV surface muons, and TeV muon bundle
  - Will help to test cosmic-ray composition **and** hadronic interaction models
- All particle spectrum and composition from the knee to 1 EeV
  - Changes of spectral index at 20 PeV and ~100 PeV
  - Heavy composition at high energies observed
- Muon density at 600 m and 800 m measured
  - Independent test of composition / hadronic interaction models

The IceCube Collaboration

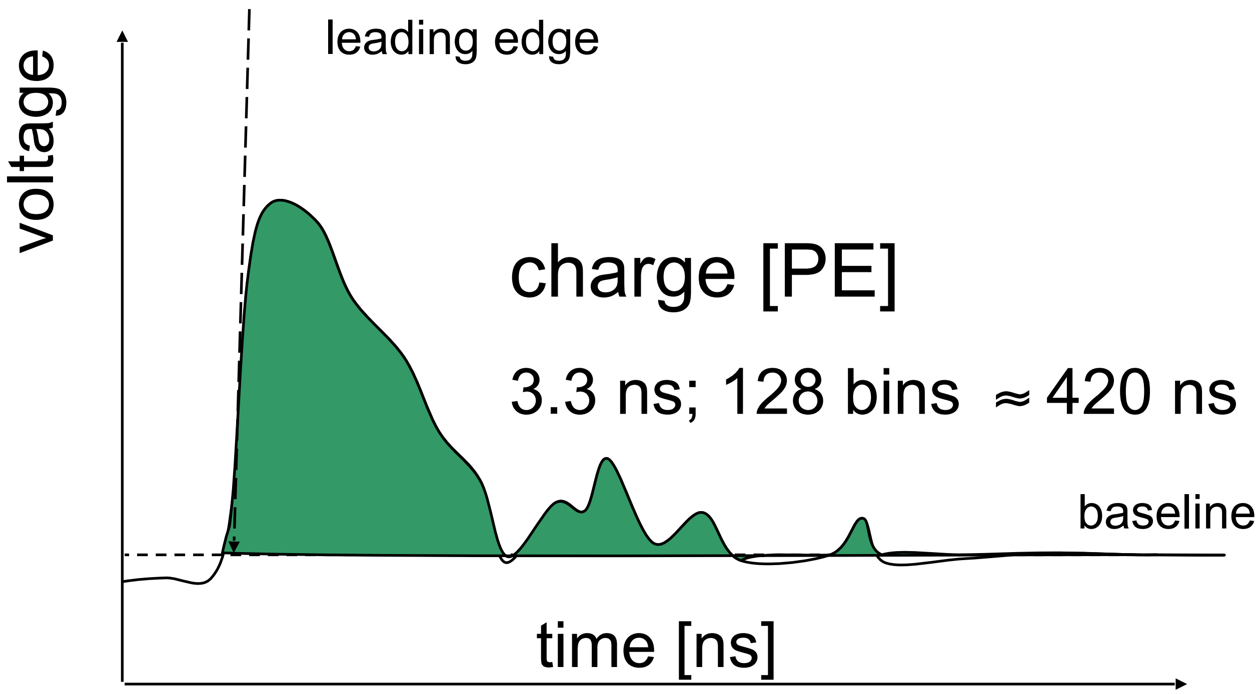


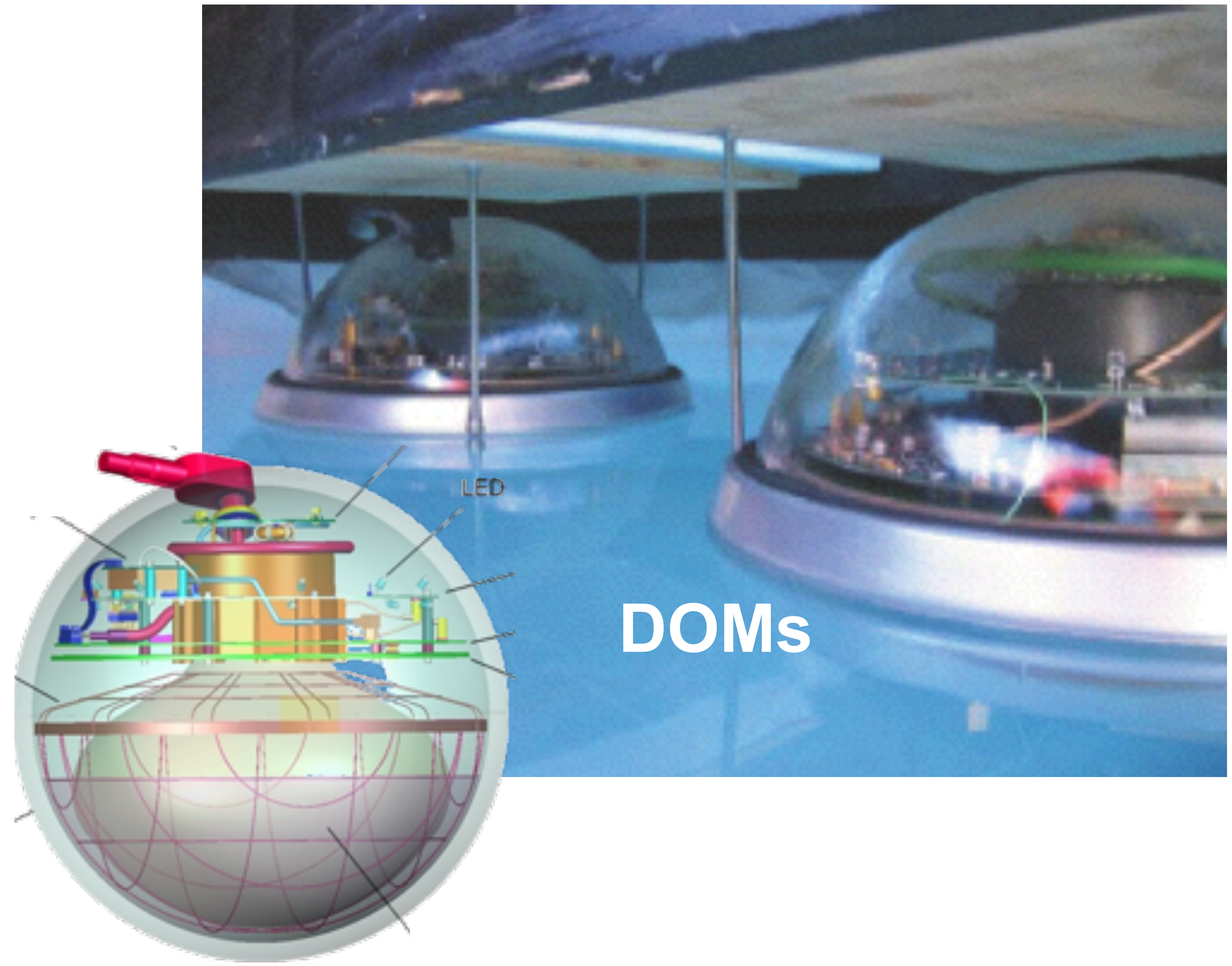
Funding Agencies

- Fonds de la Recherche Scientifique (FRS-FNRS)
- Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
- Federal Ministry of Education & Research (BMBF)
- German Research Foundation (DFG)
- Deutsches Elektronen-Synchrotron (DESY)
- Japan Society for the Promotion of Science (JSPS)
- Knut and Alice Wallenberg Foundation
- Swedish Polar Research Secretariat
- The Swedish Research Council (VR)
- University of Wisconsin Alumni Research Foundation (WARF)
- US National Science Foundation (NSF)

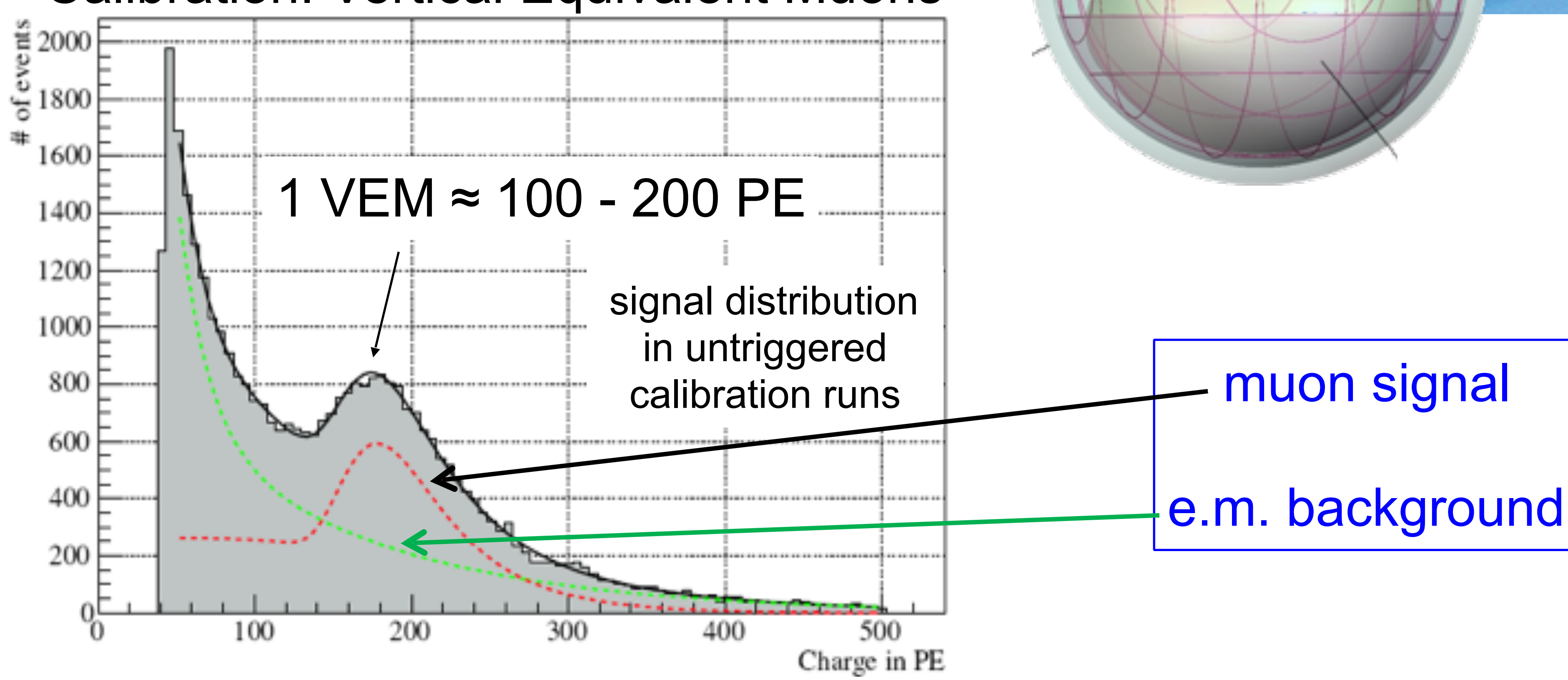
Backup Slides

IceTop Data Acquisition





Calibration: Vertical Equivalent Muons



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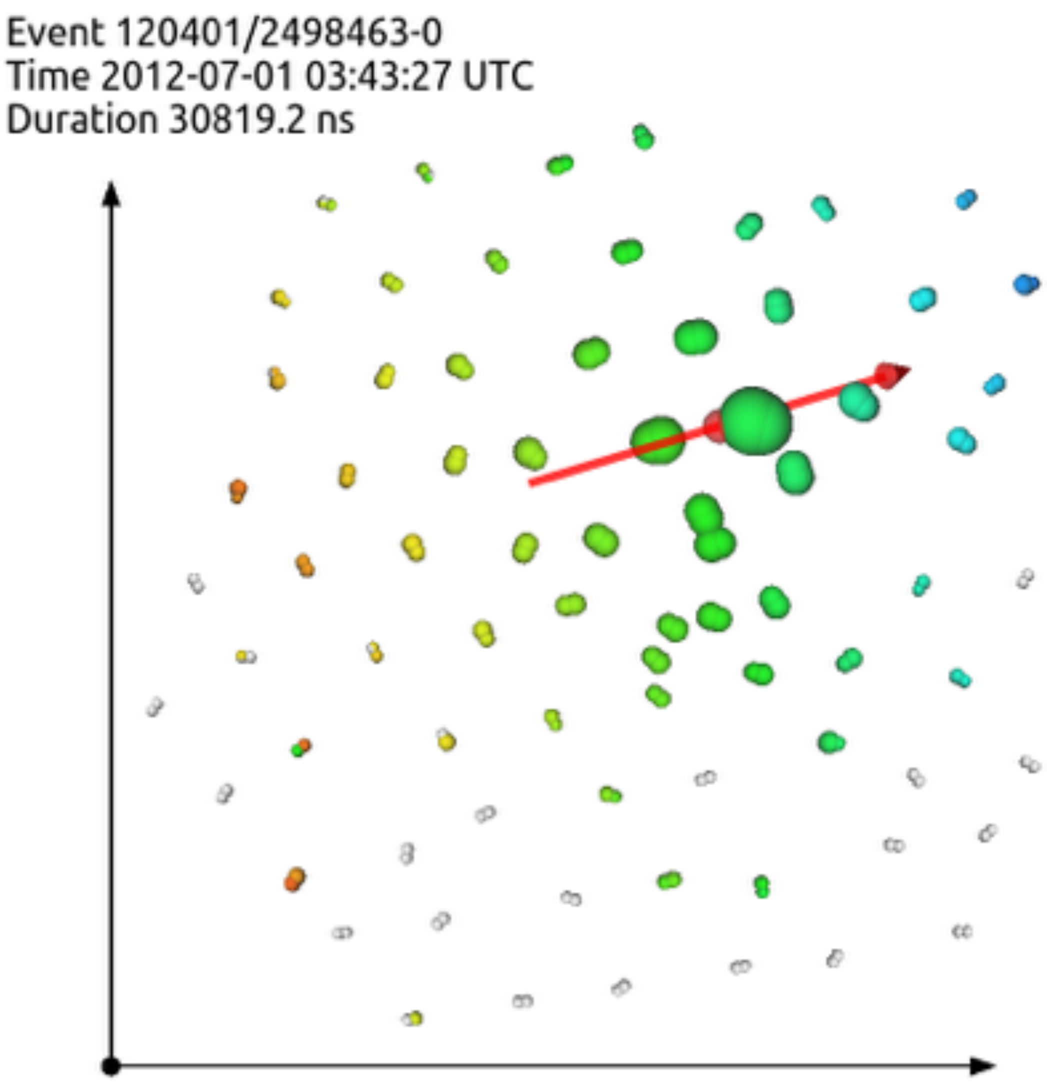
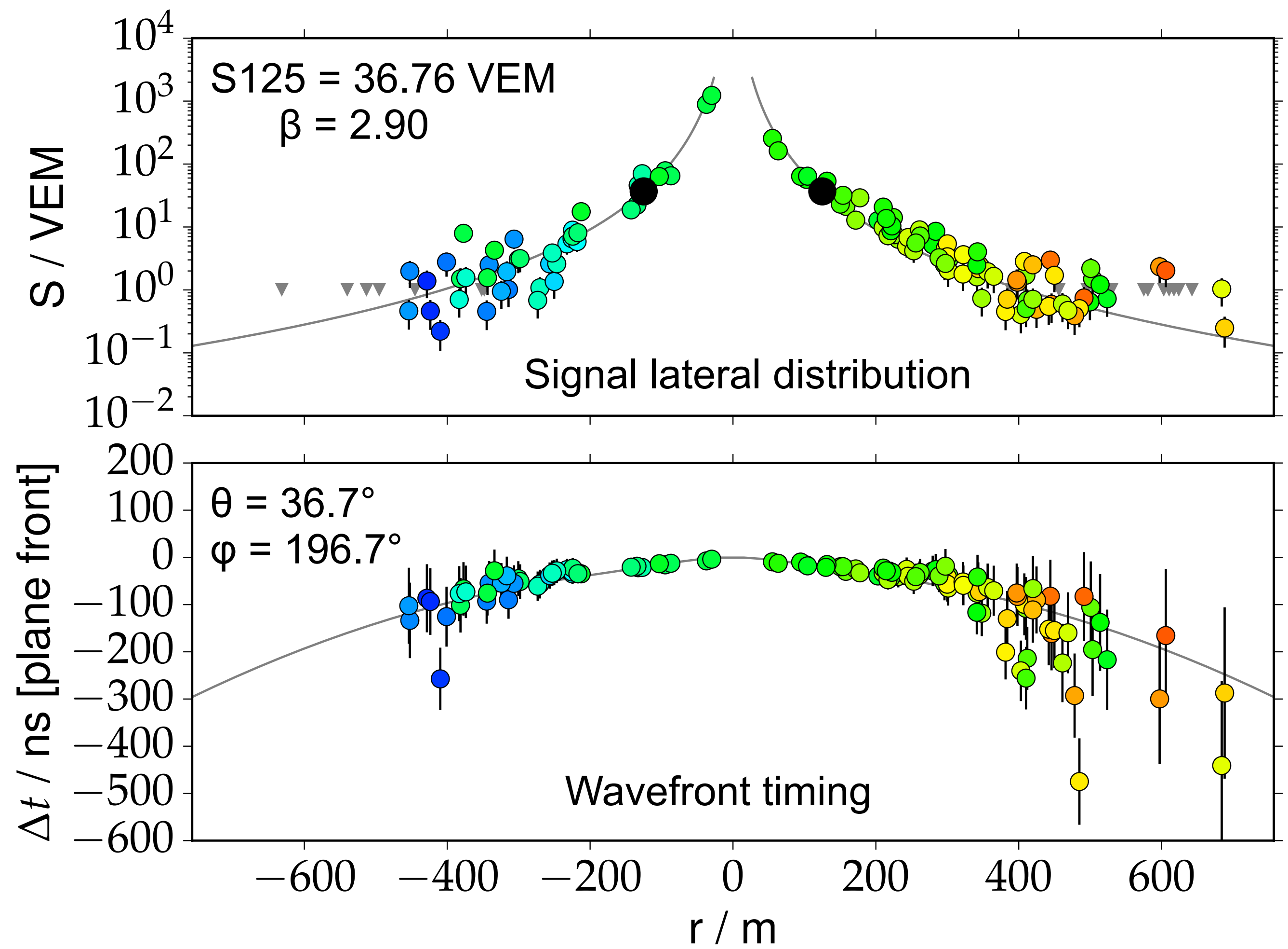
Air Shower Reconstruction





Signal lateral distribution:

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

Correction for attenuation in snow

Wavefront timing:

$$t(\vec{x}) = t_0 + \frac{1}{c}\left(\vec{x} - \vec{x}_c\right) \cdot \vec{n} + \Delta t(r)$$

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

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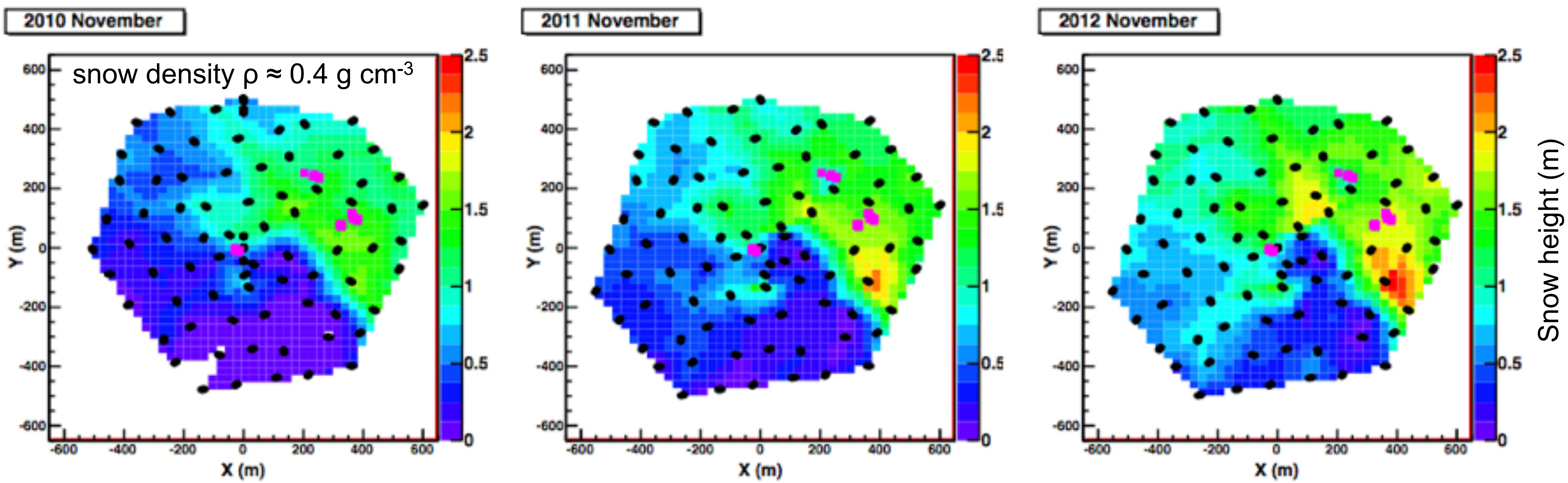
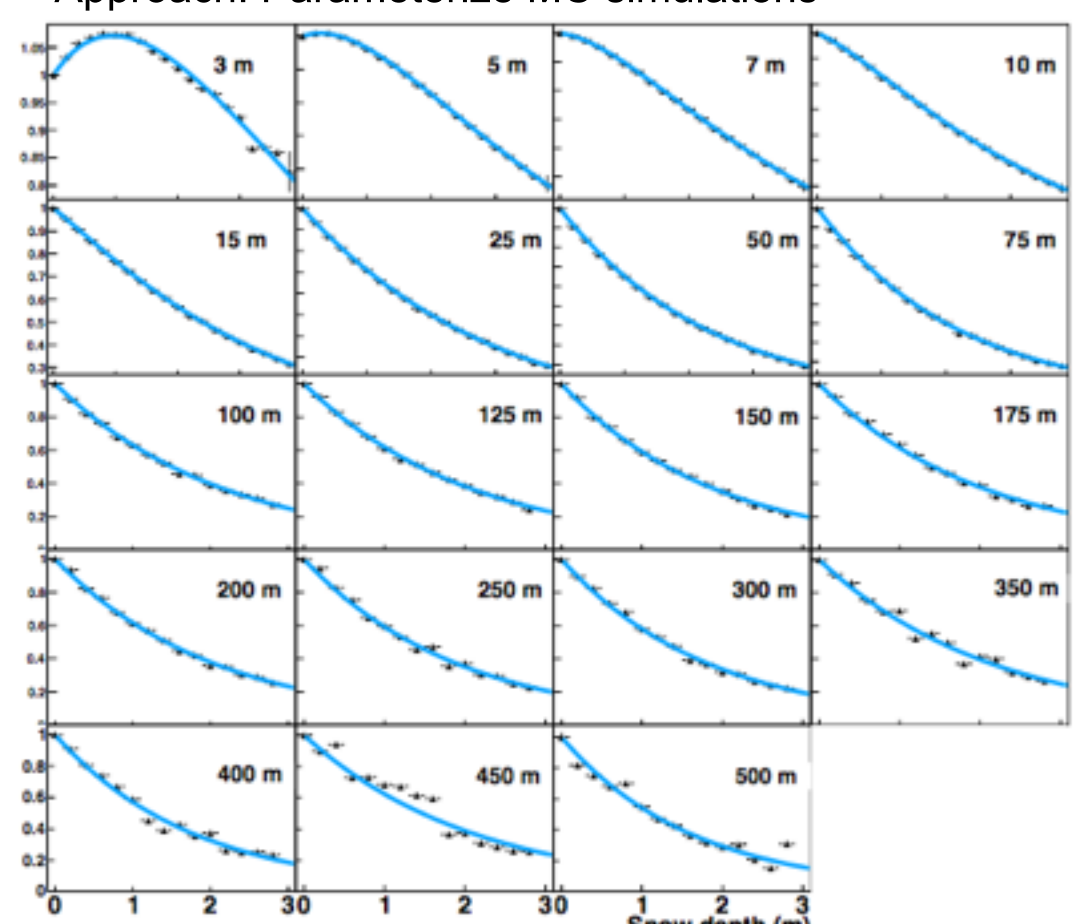
IceTop and the Snow



Approach: Parameterize MC simulations



- Snow is largest detector-related systematic uncertainty in IceTop
- Snow height on each tank measured twice per year
- Signal attenuation different for muons and e.m. particles
  - Signal becomes more muon dominated
  - ➡ Simple exponential snow correction not sufficient

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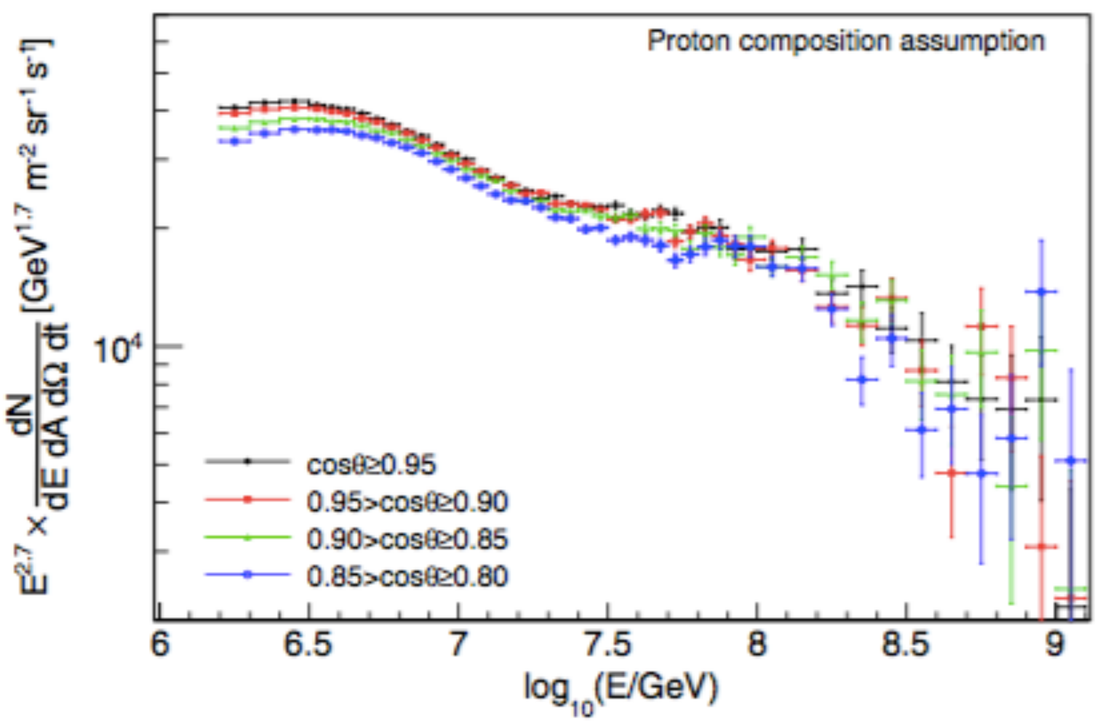
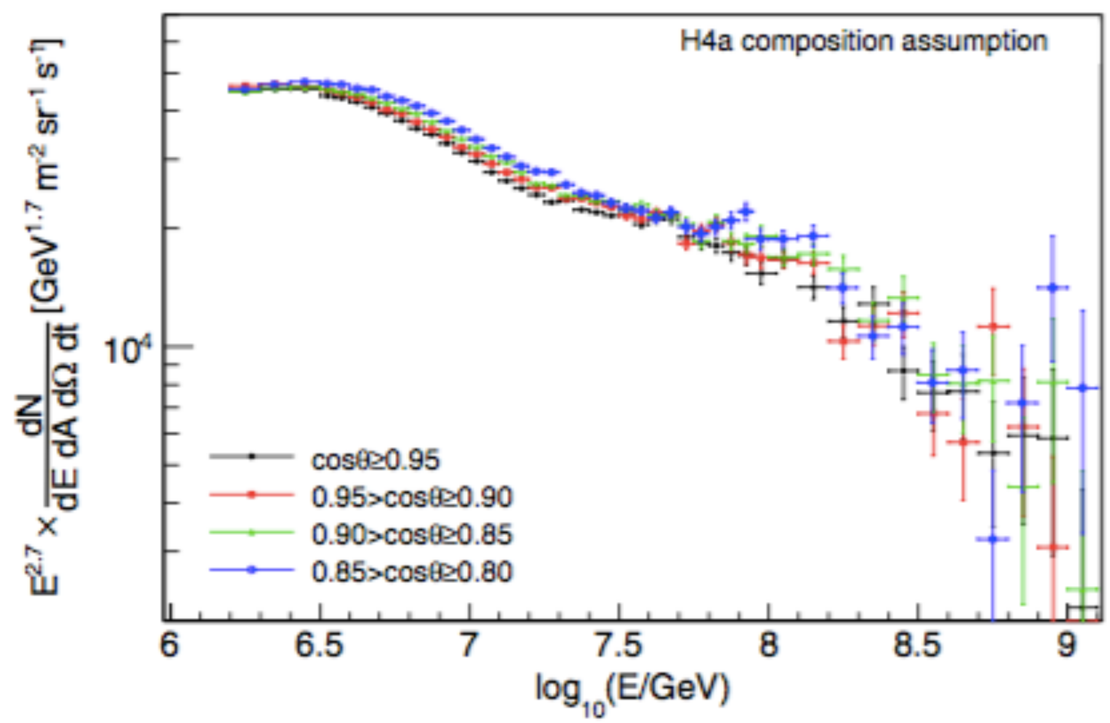
Zenith Dependence as Cross Check for Composition

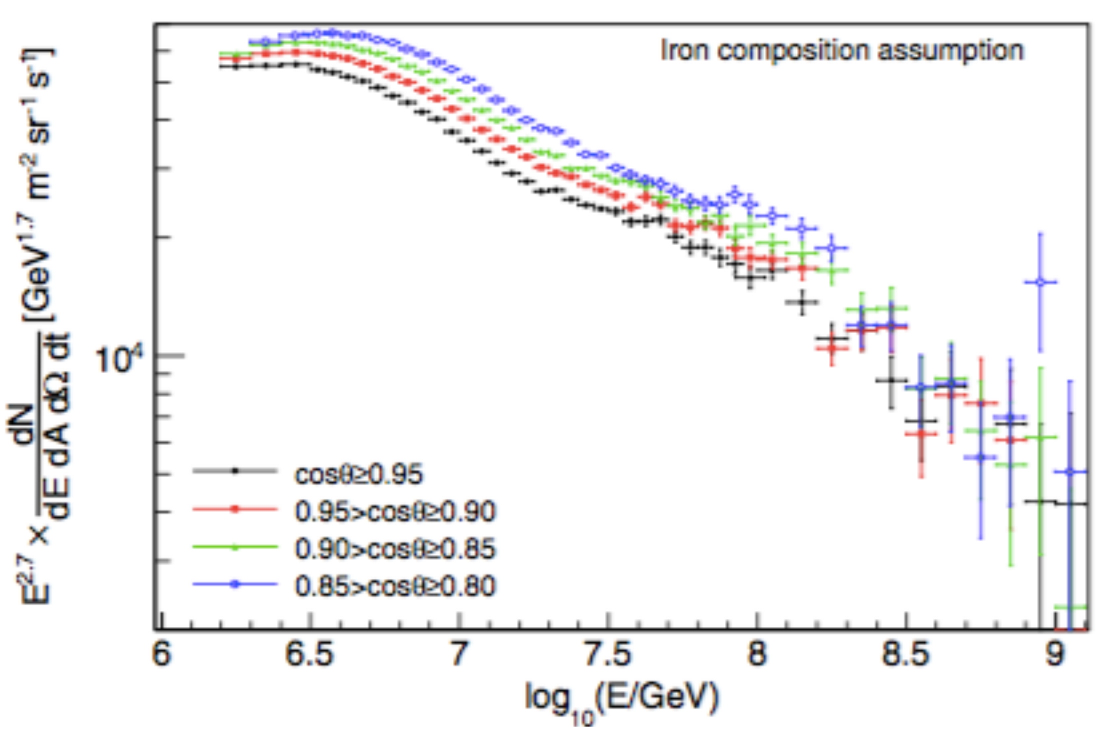
Phys. Rev. D ***88*** *(2013) 042004*



Pure Proton



H4a



Pure Iron

- Energy spectrum expected to be the same for all zenith ranges
- H4a(*) model gives best agreement (of tested models)

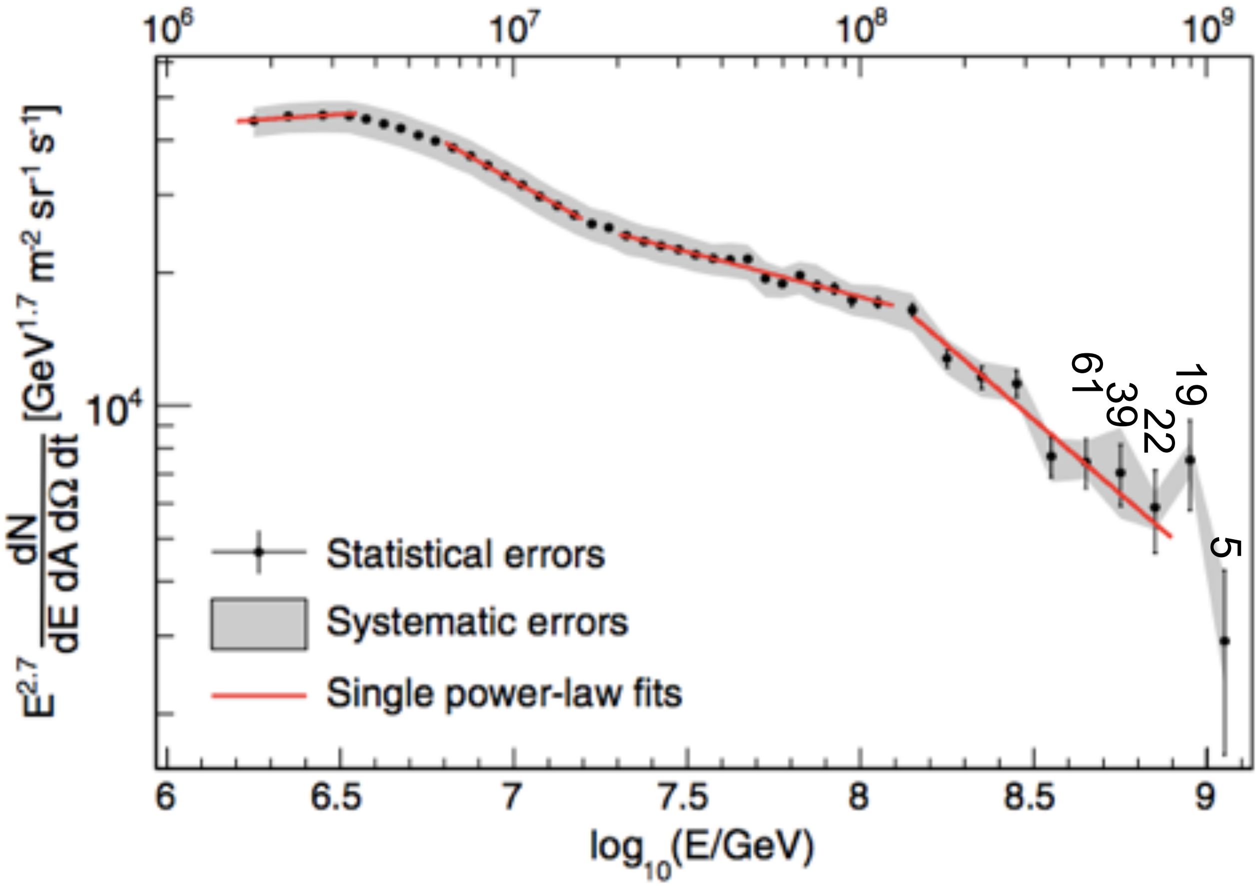
(*) Gaisser: Astropart. Phys. ***35*** *(2012) 801*

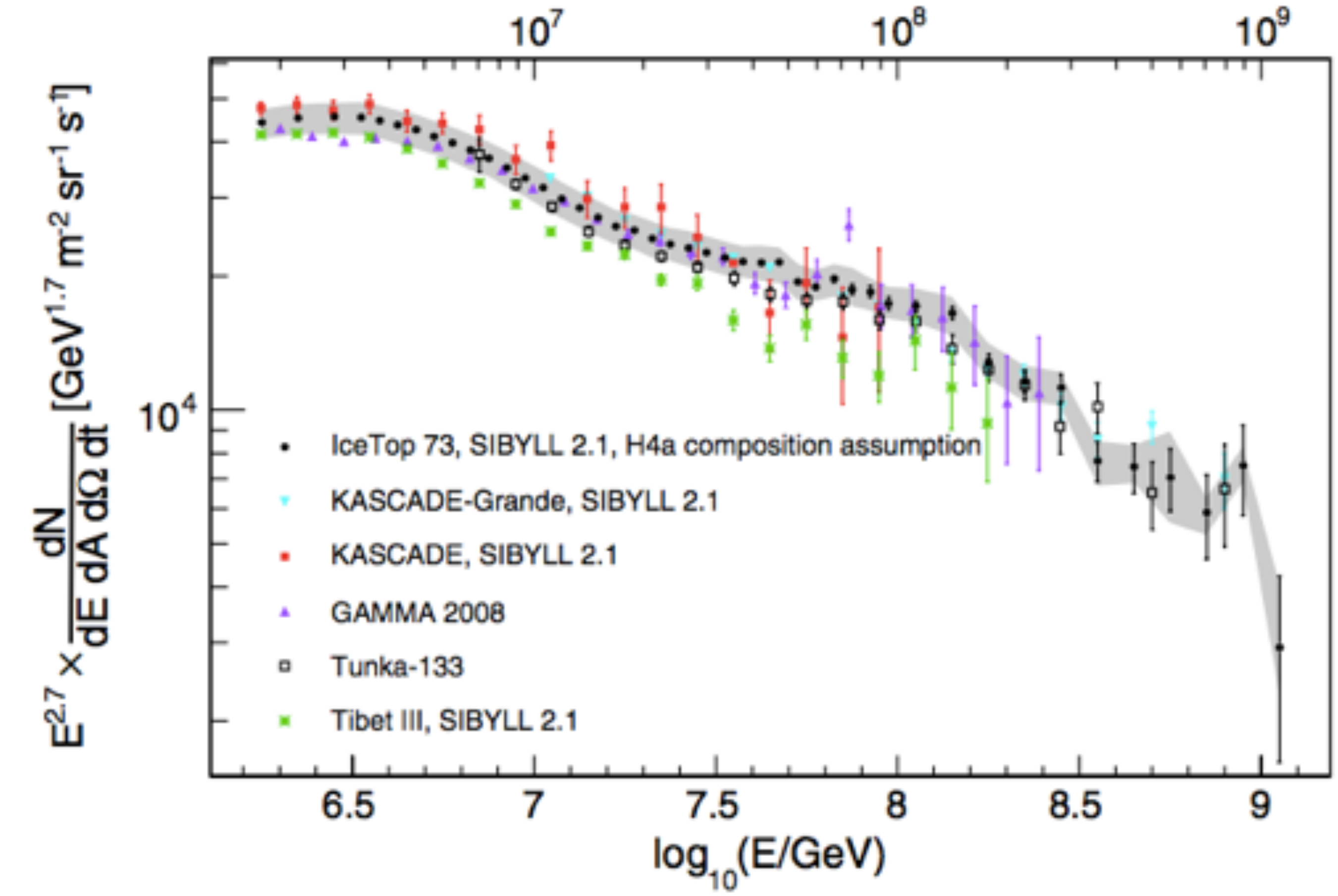
IceCube

IceTop-only Energy Spectrum

One year of data (IT-73)

*Phys. Rev. D **88** (2013) 042004*





Systematic uncertainties:

	3 PeV	30 PeV
VEM calibration	+4.0% − 4.2%	+5.3% − 5.3%
Snow	+4.6% − 3.6%	+6.3% − 4.9%
Interaction models	−4.4%	−2.0%
Composition[a]	±7.0%	±7.0%
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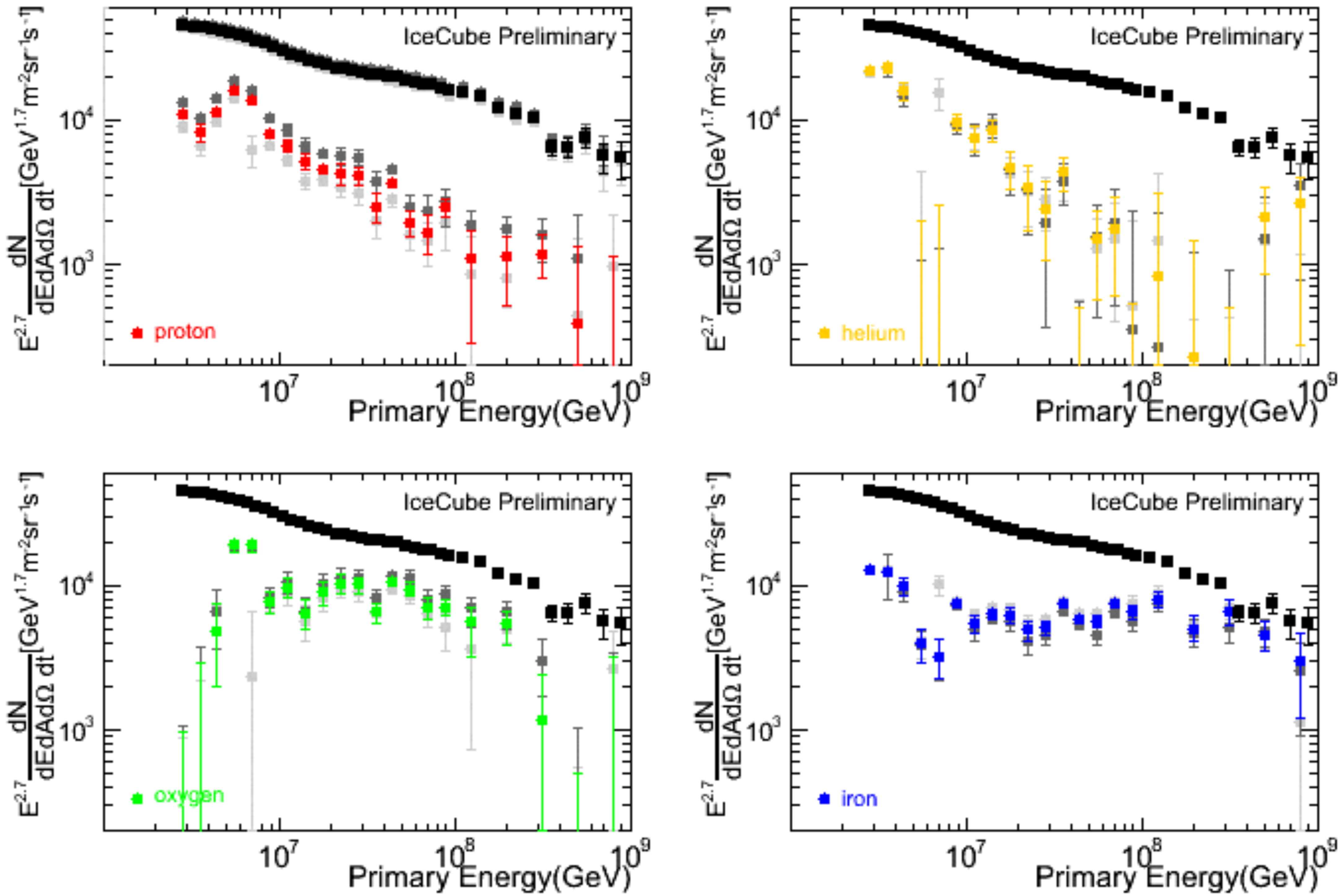
[a]Composition uncertainty is not constant with energy but the largest value was chosen as a fixed, conservative estimate.

> CR energy spectrum does not follow a single power law

- Hardening at around 20 PeV, softening past 100 PeV
- Contribution of different source populations?

Elemental Spectra: Snow Correction Uncertainty

dark gray: −0.2 m, light gray: +0.2 m



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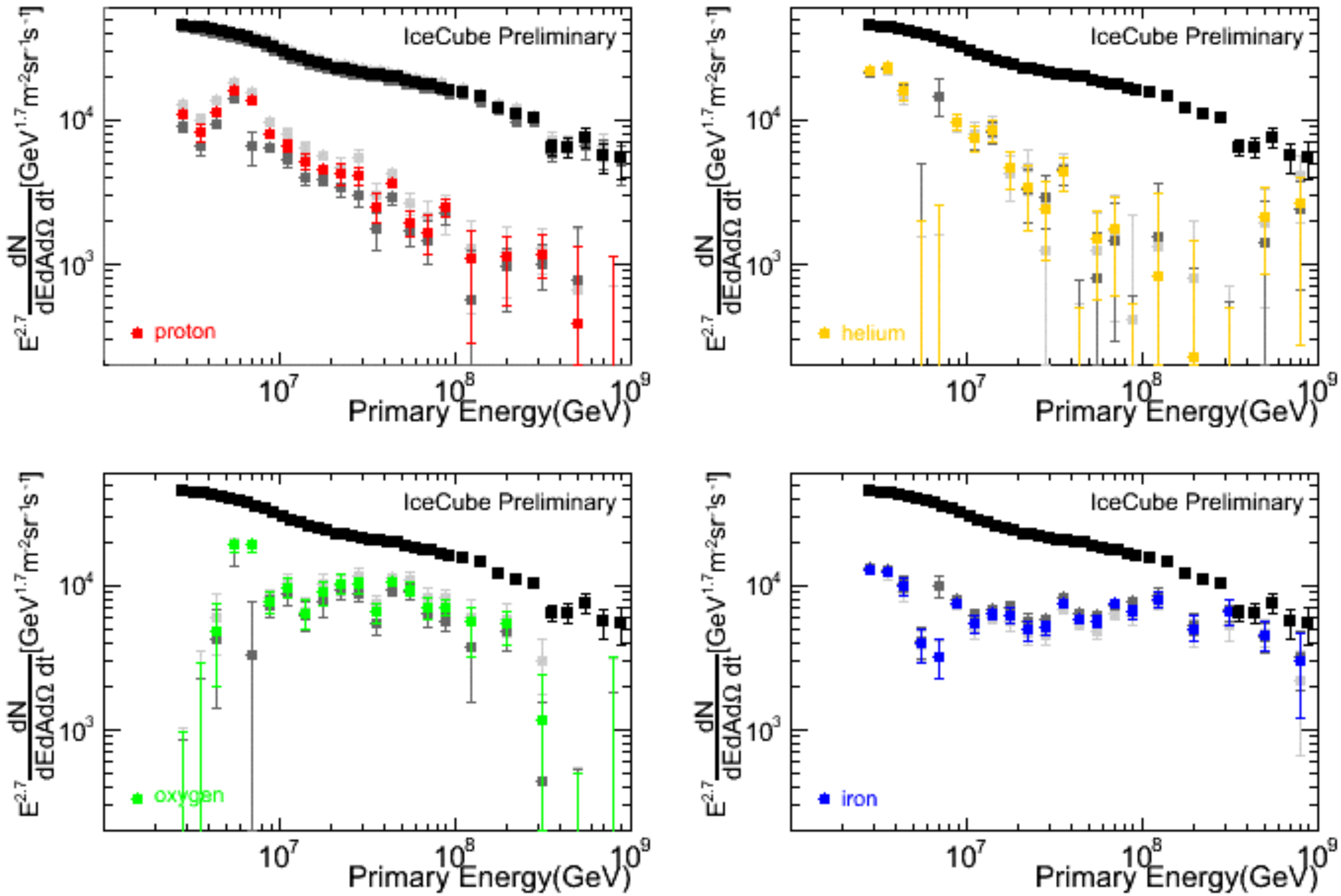
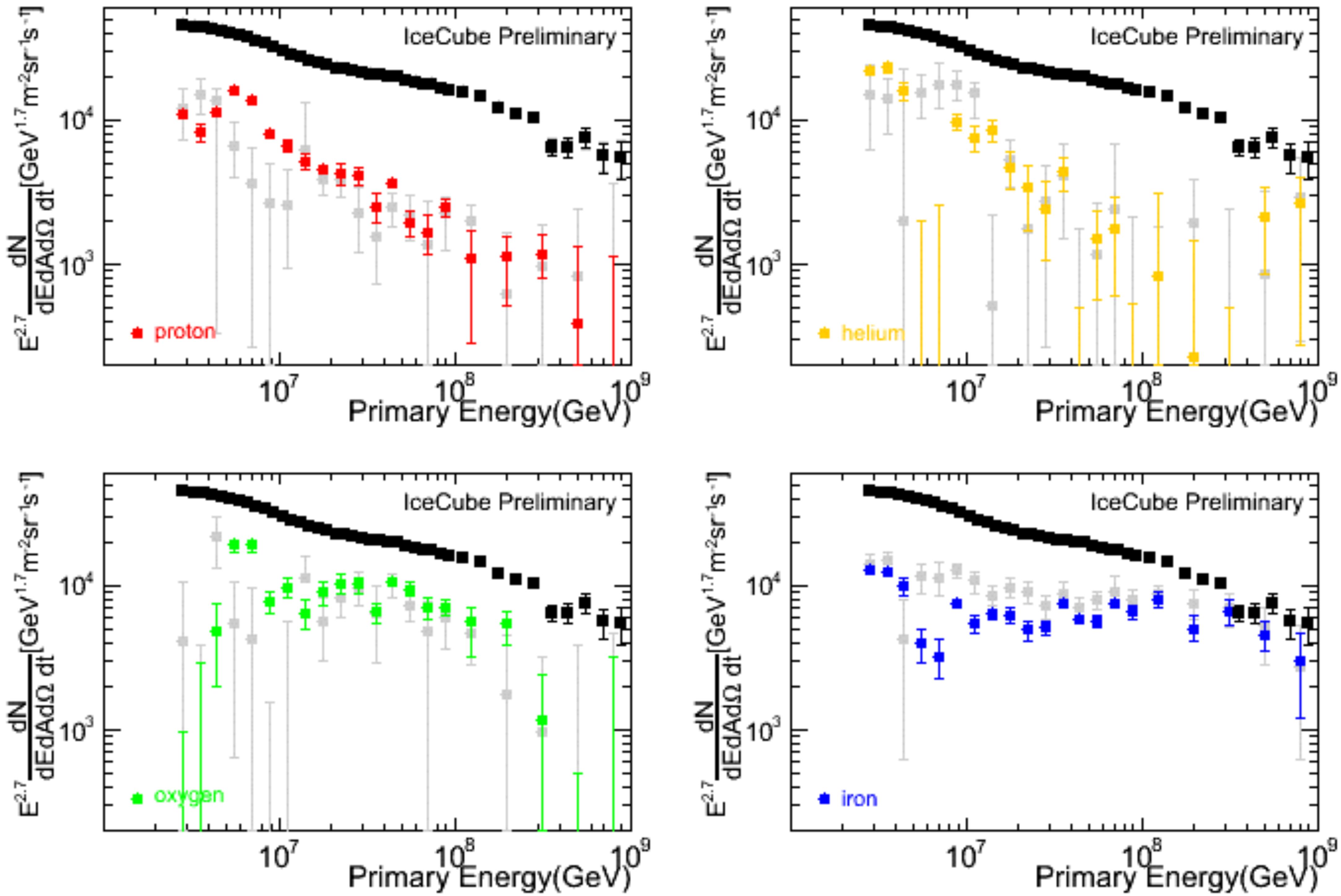
Elemental Spectra: IceTop Energy Scale Uncertainty

dark gray: −3%, light gray: +3%



Elemental Spectra: Hadronic Model Uncertainty

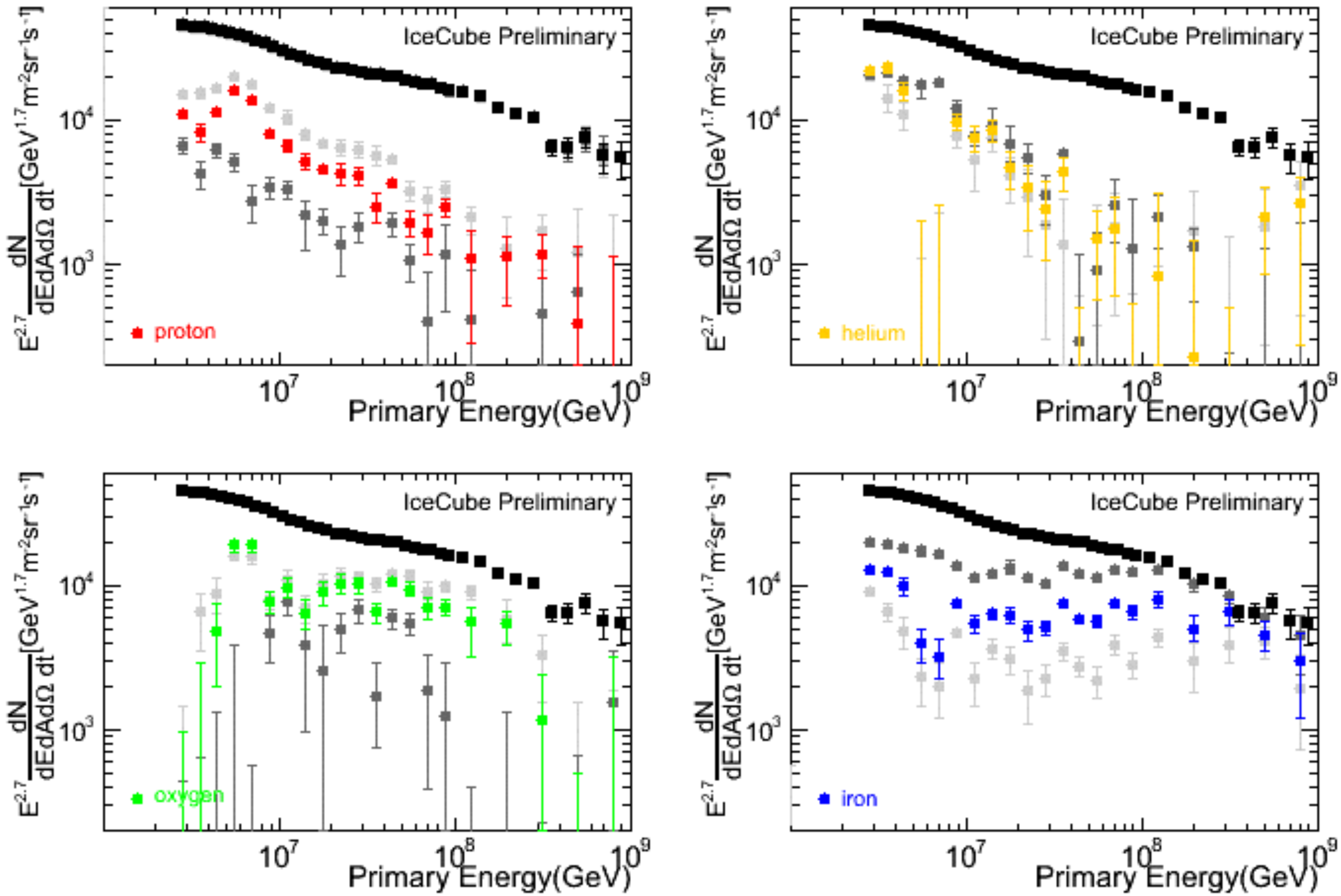
light gray: QGSJet-II.03



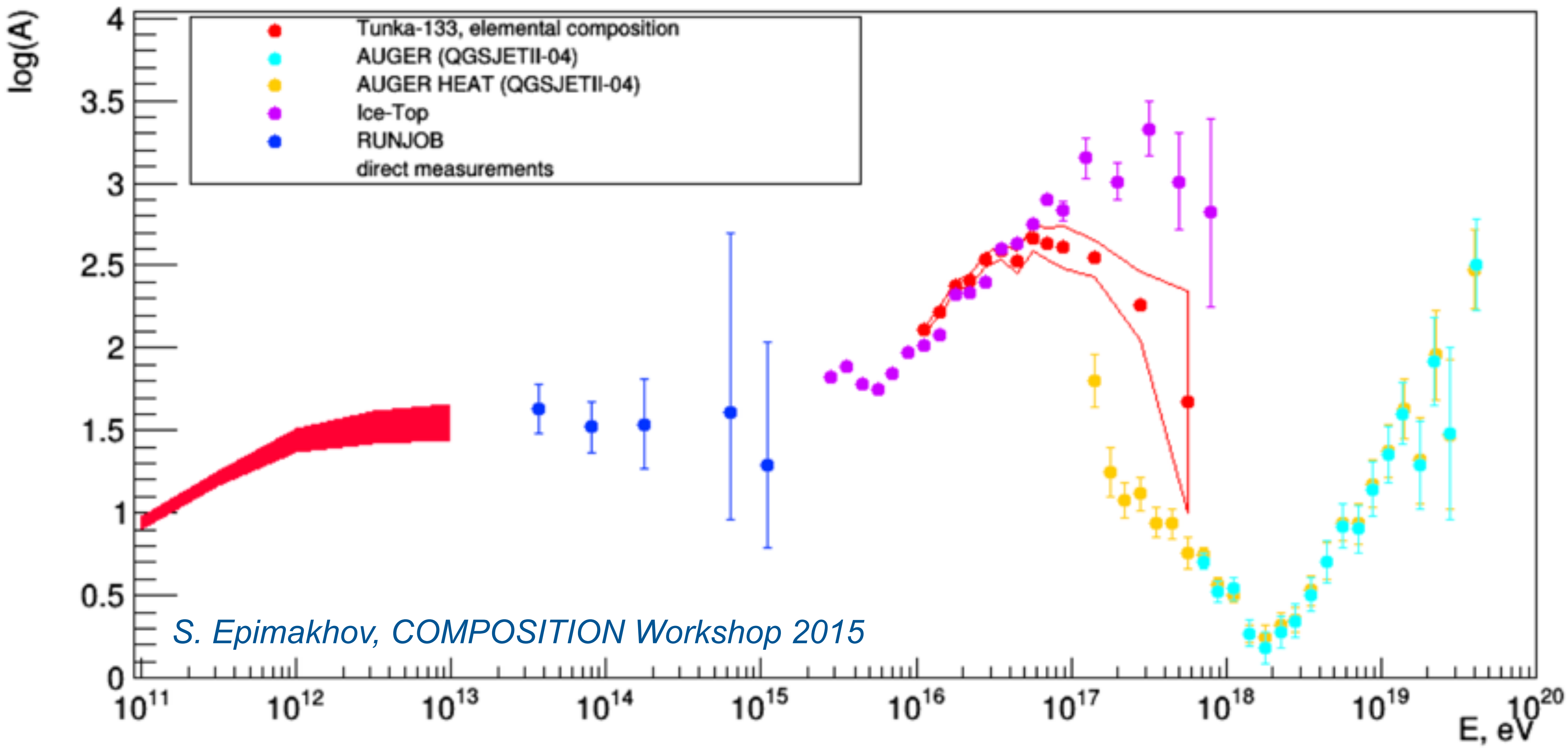
IceCube

Elemental Spectra: In-ice Light Yield Uncertainty

dark gray: −12.5%, light gray: +9.6%



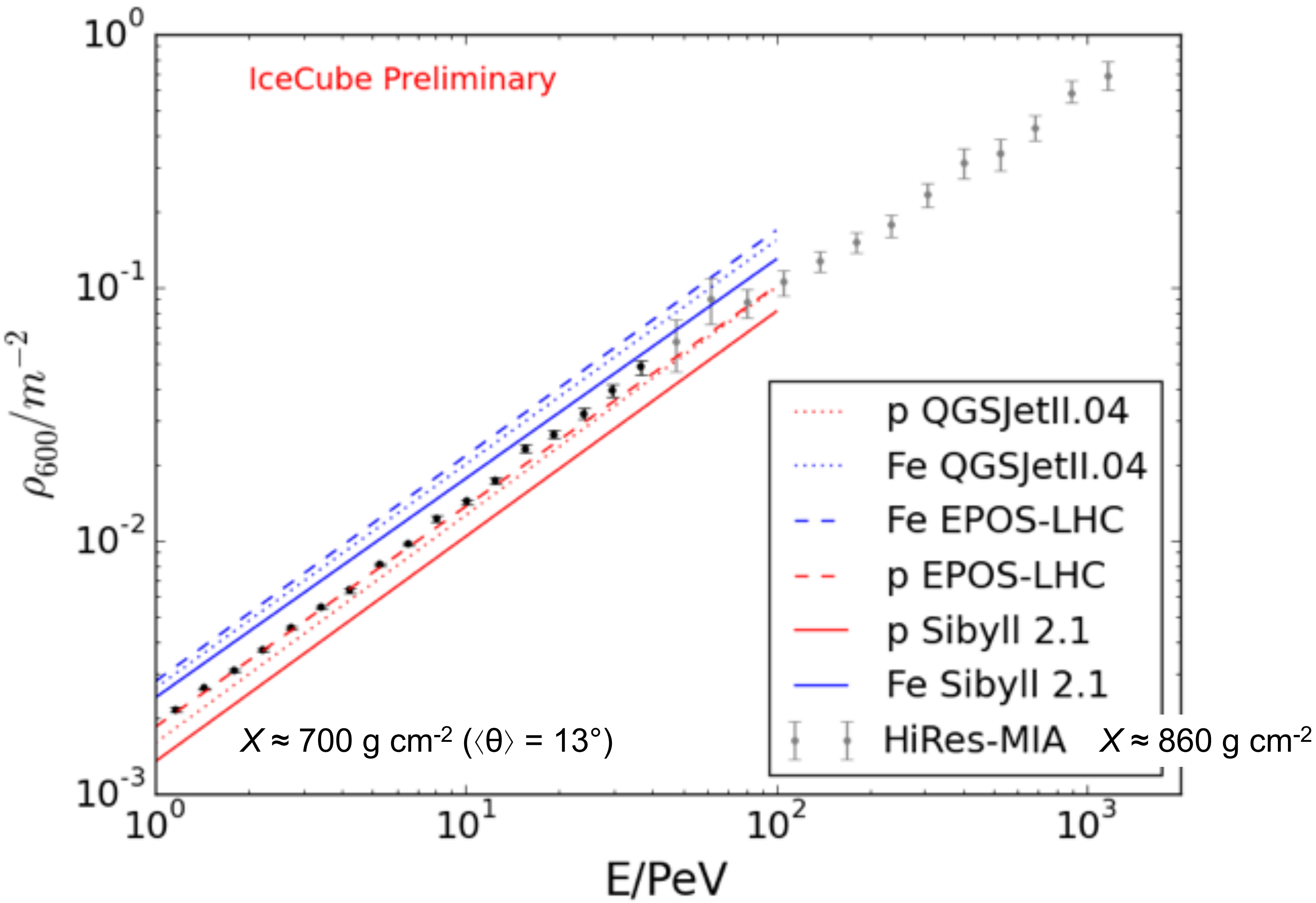
Comparison to Other Experiments



> Tension between different experiments

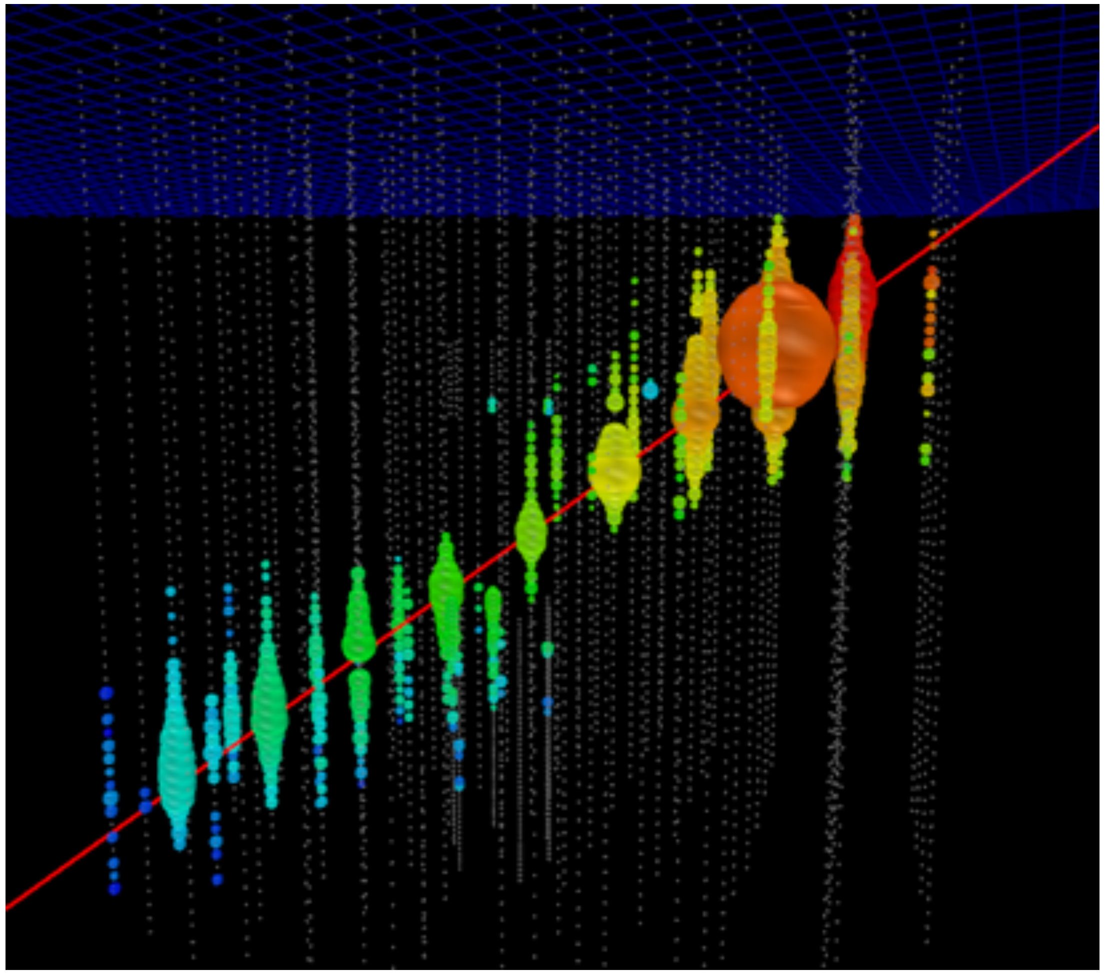
- Different experimental techniques — measurement of: depth of shower maximum (air fluorescence), non-imagaing air-Chrenekov, TeV muon bundles probe different components of the air shower
- Different hadronic interaction models used to describe the data
  Models evolve rapidly thanks to LHC data

GeV Muons on the Surface

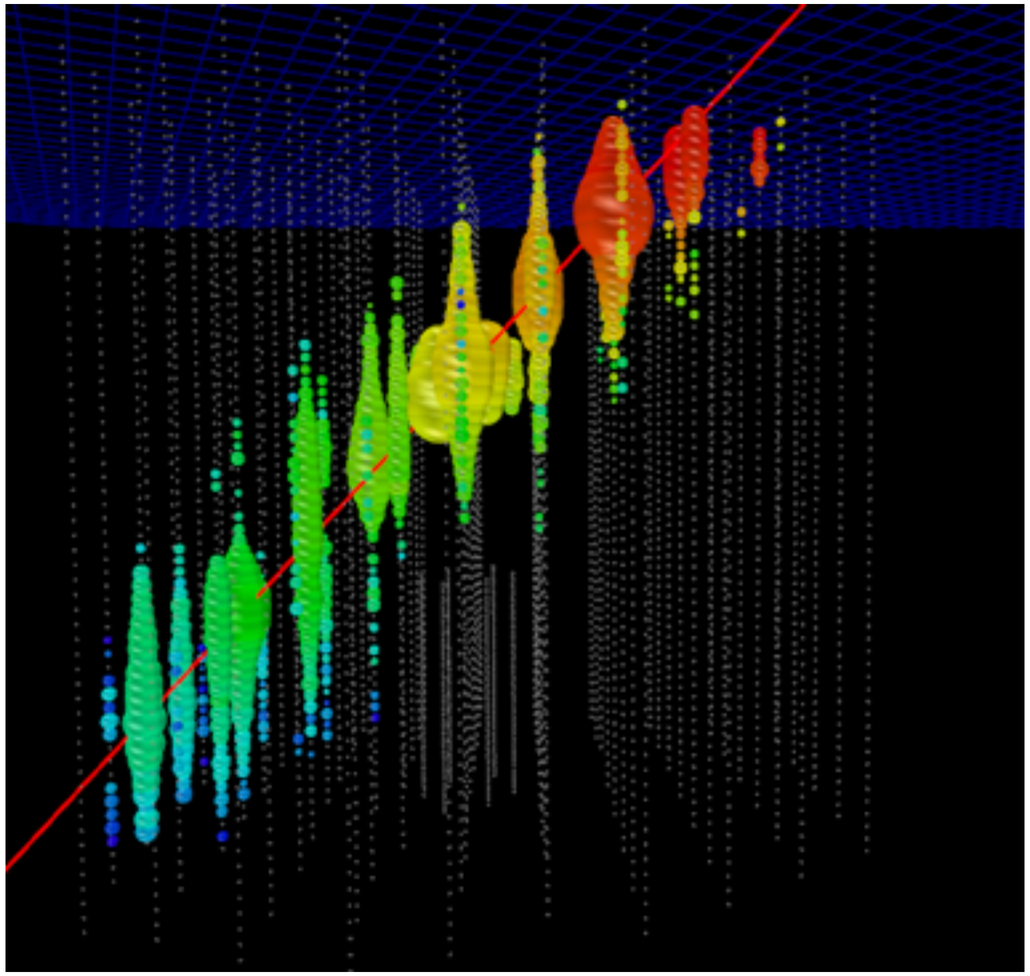


- Muon density 600 m from shower core
- Air shower simulations for reference
- Will improve composition measurements in the future

Atmospheric Muon Bundles



High-energy muon



Muon bundle

- Bundle multiplicity proportional to number of nucleons *A*
- Select events w/o large stochastic losses to suppress high-energy muons
- Energy deposition in deep-ice detector proportional to muon number

$$E_{\mathrm{mult}} := E_{\mathrm{prim}} \cdot (A/56)^{\frac{1-\alpha}{\alpha}} = g_{\mathrm{scale}}(\cos\theta) \cdot N_{\mu,\mathrm{det}}^{1/\alpha}$$

- Unfold E_{mult} spectrum from measured muon bundles

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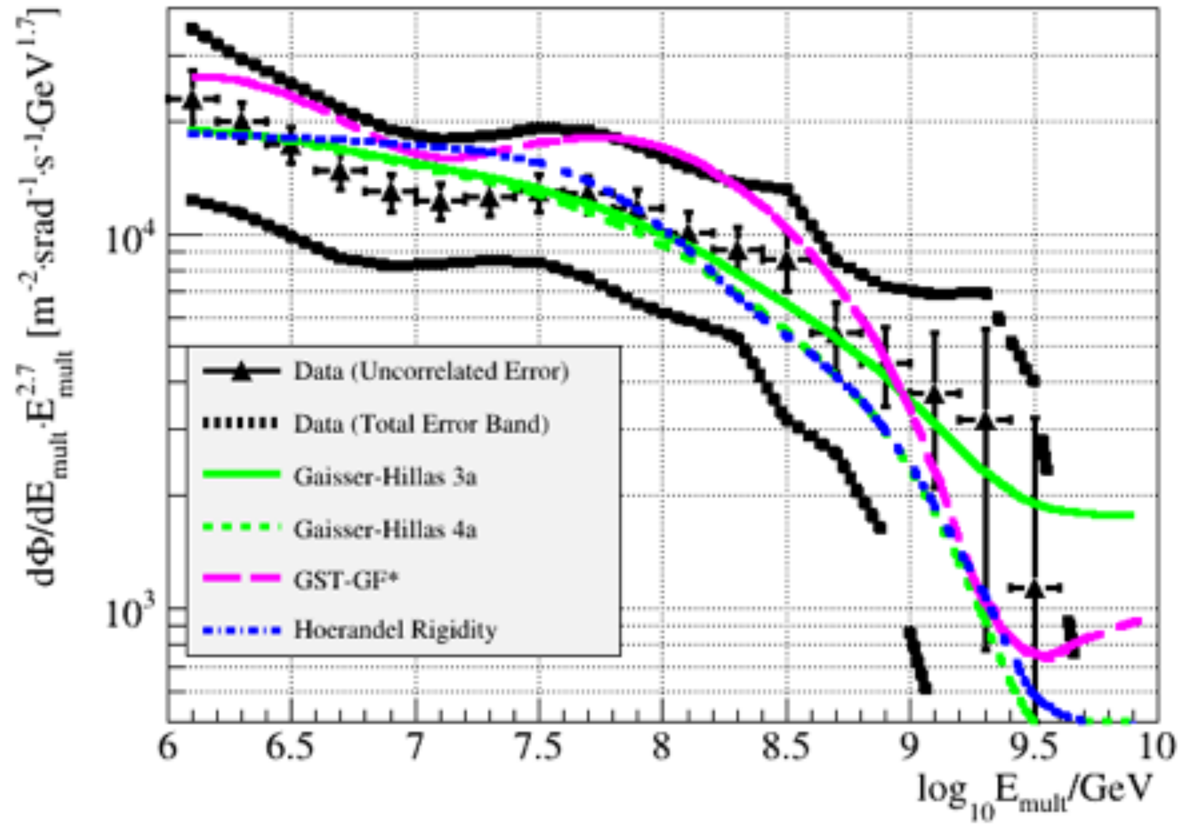
IceCube

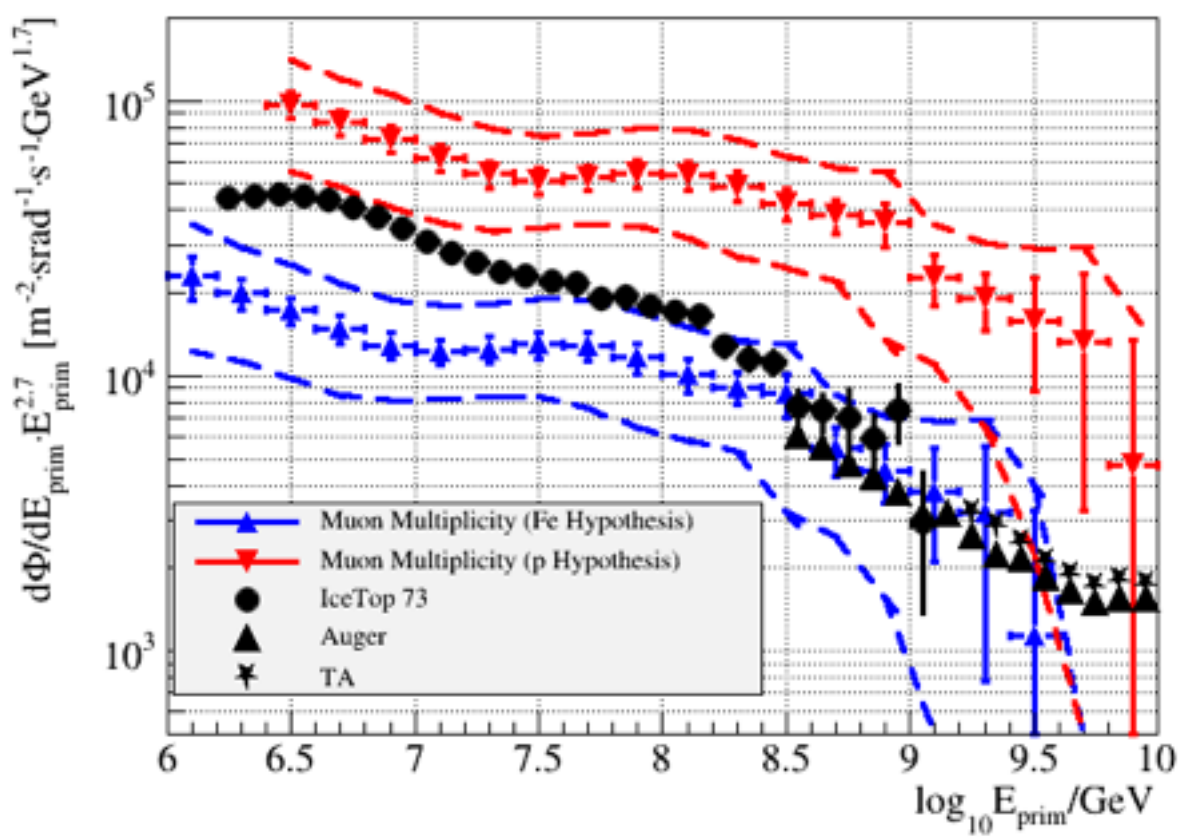
Interpretation of E_{mult} Spectrum

- Comparison to cosmic-ray models converted to E_{mult} via

$$E_{\text{mult}} := E_{\text{prim}} \cdot (A/56)^{\frac{1-\alpha}{\alpha}}$$



- Conversion of E_{mult} spectrum to all-particle flux assuming a composition model



IC-79, 1.2×10^7 muon bundle events

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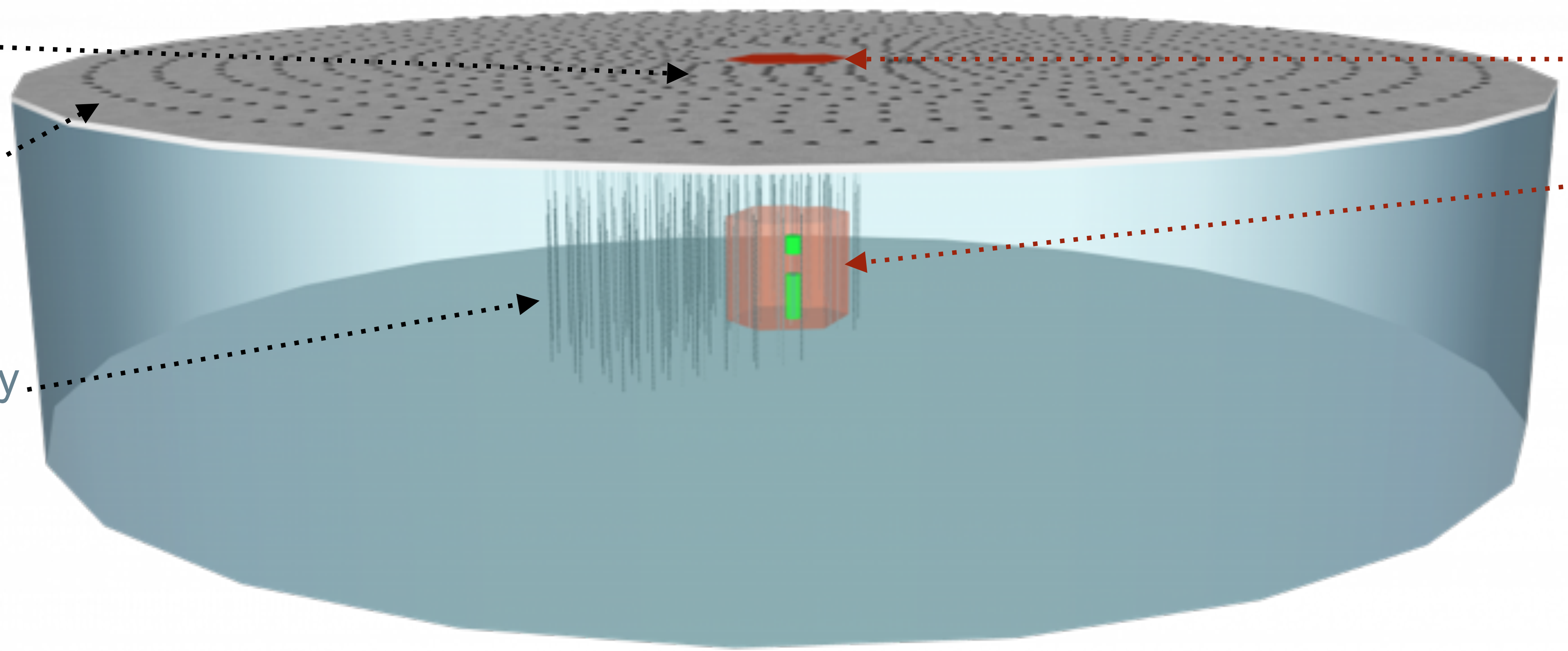
Cosmic Ray Physics with IceCube-Gen2



- 10 km³ in-ice array with 10 km² "IceTop-2" cosmic-ray array on top
  - Increase accessible cosmic-ray energy range by factor 3
  - Increase coincident events by factor 50 (due to increased zenith range)
- Surrounded by ≈ 75 km² veto (less sophisticated air shower detectors)
  - Enable lateral muon distribution measurements for every event

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