Cosmic ray composition with IceTop and IceCube

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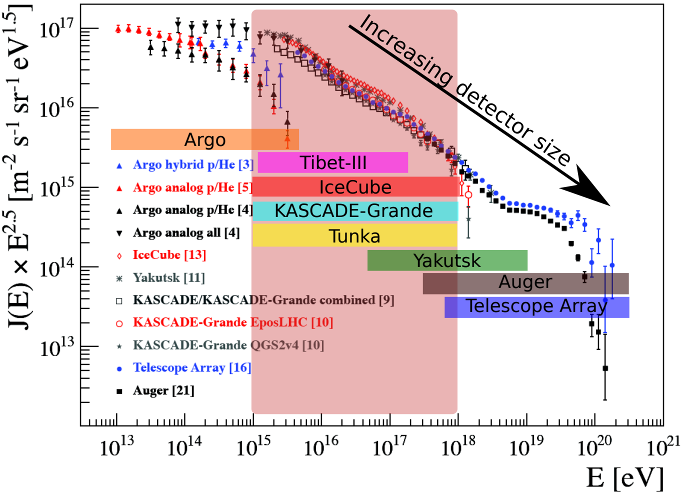
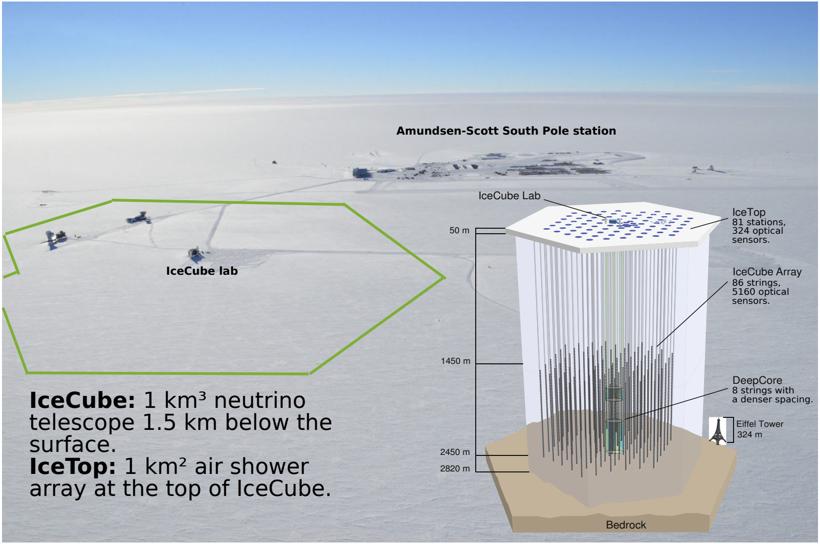
IceCube energy range for CR detection

From ∼1 PeV to ∼1 EeV
knee to **ankle**



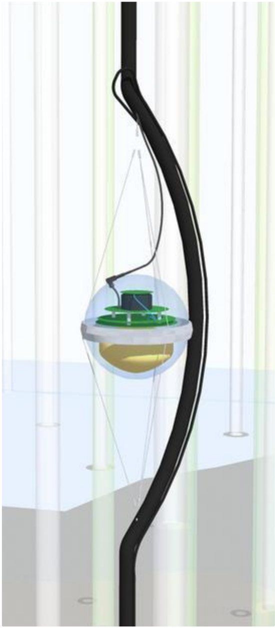
Outline

The IceCube Neutrino Observatory

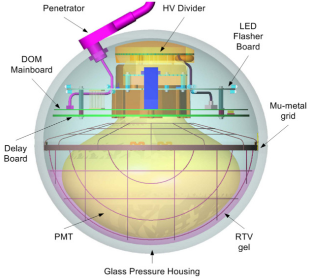


IceCube: 1 km³ neutrino telescope 1.5 km below the surface.
IceTop: 1 km² air shower array at the top of IceCube.

The IceCube Neutrino Observatory: DOM

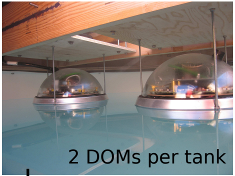


- Digital optical module (DOM)



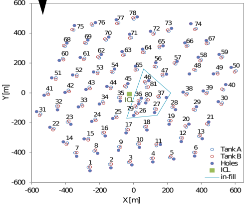
- 5160 in IceCube and 324 in IceTop
- Photomultiplier tube + digitization system
- Sensitive to photons from Cherenkov emission

The IceCube Neutrino Observatory: IceTop

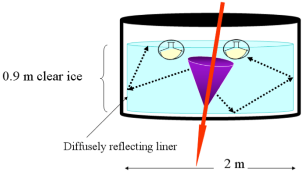


2 tanks per station
(~10 m separation)

81 stations spread
over 1 km^2

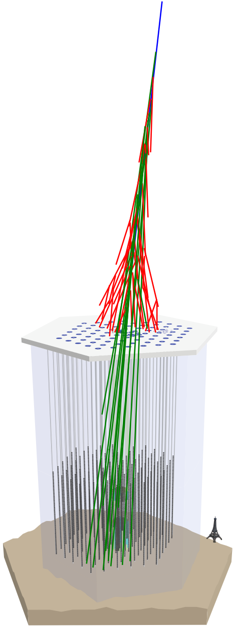


- 2 DOMs per IceTop tank: large charge dynamic range
- Detect Cherenkov light



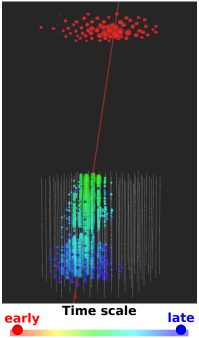
- 2 tanks operate in coincidence in 1 station
- 78 stations next to IceCube strings (1 km^2) + 3 Infill stations
- Atmospheric depth ~690 g/cm^2
- Calibrated with muons (VEM)

Cosmic ray physics with the IceCube ν Observatory



- IceTop stations detect:
  - **electromagnetic** component
  - low energy **muons**

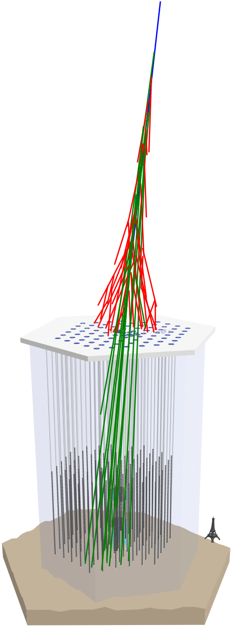
IceTop: energy and age/mass (μ/EM).



- High-energy **muon bundles** travel down to IceCube:
  - $E_\mu > 300$ GeV
  - Multiplicity: 1 - 1000s
  - Ionization + radiative, stochastic energy loss

IceCube: mass from μ from first interactions

Coincident analysis: air shower reconstruction



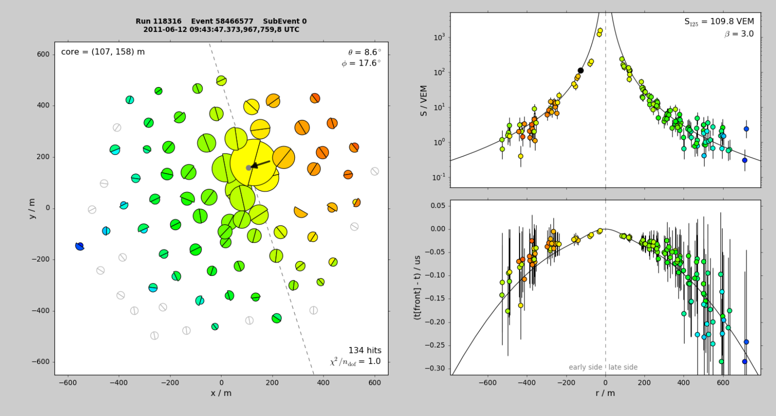
IceTop part:

- Require 5 hit stations
- Calibrate and clean IceTop pulses (ex: remove random coincidences)
- Reconstruct core, direction, time, and other useful variables using minimization
- Correct measured charge for snow on top of tanks

InIce part:

- Look for in-ice hits correlated to the IceTop track
- Perform extra cleaning/hit-selection
- Reconstruct the energy loss profile of the muon bundle
- Extract more composition-sensitive variables
- Add seasonal corrections

Air shower reconstruction with IceTop



Lateral distribution function (LDF):

$$S(r) = S_{125} \cdot \left(\frac{r}{125\ \mathrm{m}}\right)^{-\beta-\kappa \log\left(\frac{r}{125\ \mathrm{m}}\right)}$$

Time residuals:

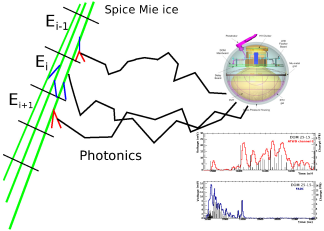
$$\Delta t(r) = ar^2 + b\left(1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right)$$

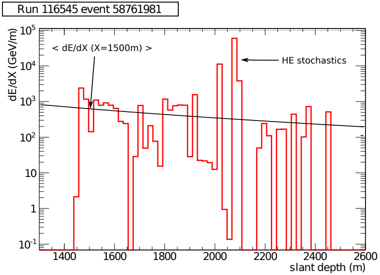
$\rightarrow$ x, y, z, θ, ϕ, β, S_{125} (slope and signal at 125 m from core)

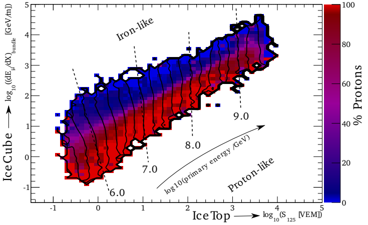
Air shower reconstruction with IceCube

Unfolding the energy loss pattern + maximum loglikelihood

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







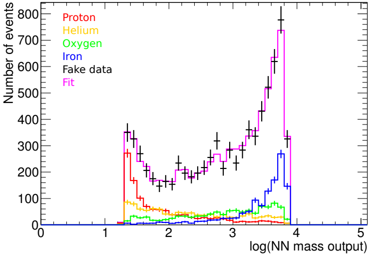
$\rightarrow$ dE/dX_{1500}, # HE stochastics 1, # HE stochastics 2

Coincident analysis: Neural network + template

Neural network

- Inputs:
  - S_{125}
  - zenith angle
  - $\frac{dE}{dX}(X)$
  - # HE stochastics 1
  - # HE stochastics 2
- Outputs: $\log_{10}(\text{Energy})$, mass A.
- Relation between inputs and outputs is unknown, non-linear mapping.
- Energy spectrum directly from NN output.
- Mass shows broad distributions in NN output.

Template fitting



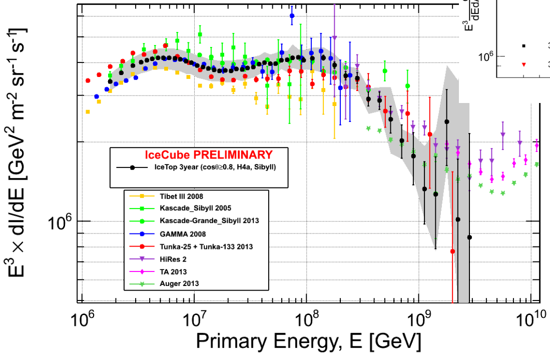
- For each energy bin: $(\text{Data})_i = f_H \cdot H_i + f_{He} \cdot He_i + f_O \cdot O_i + f_{Fe} \cdot Fe_i$.
- Binned likelihood fit which takes into account Poisson fluctuations on both data and MC.

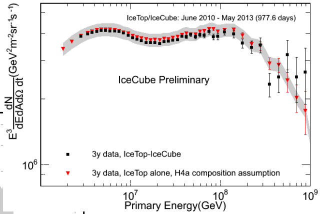
Systematics (coincident analysis)

- **Snow** correction uncertainty: $\lambda \pm 0.2$ m.
- Absolute **IceTop energy scale**: $\pm 3\%$ on the data/MC calibration.
- **Hadronic Interaction Model**: SYBILL 2.1 vs QGSJet-II-03. (update ongoing)
- **In-ice light yield** systematics:

	uncertainty
DOM efficiency	$\pm$ 3%
Hole ice 30 cm	+ 4.5%
Hole ice 100 cm	- 2.9%
+ 10 % scattering	+ 3.6 %
- 10 % scattering	-11.8 %
-7 % scattering and absorption	+ 7%
Total	+9.6%,-12.5%

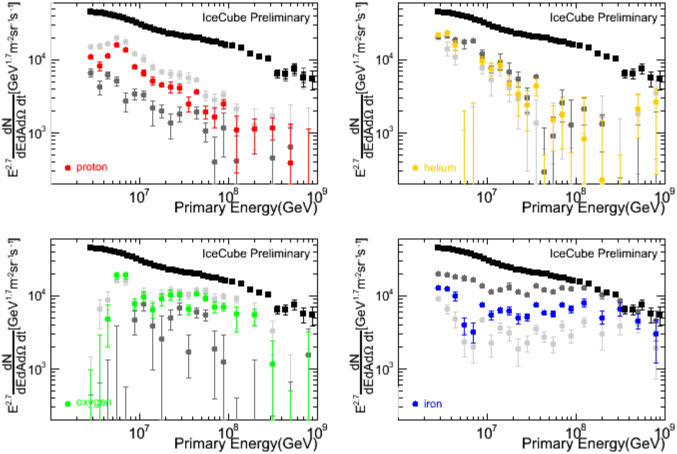
Energy spectrum





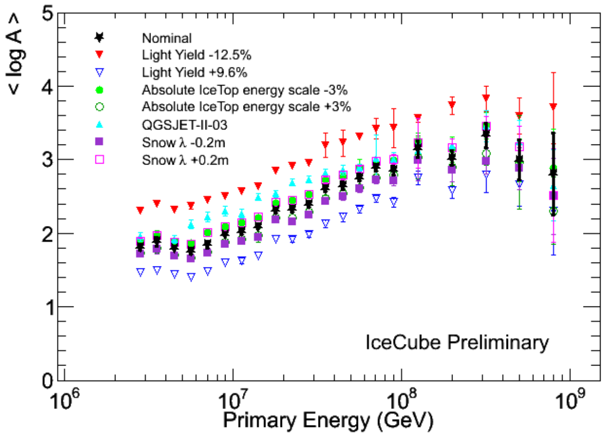
- Agreement between IceTop-only and IceTop-IceCube analyses
- Most detailed energy spectrum measurement in this energy range
- Clear features visible: 2nd knee around 100 PeV

IT-IC composition: individual elements



- Only in-ice light yield systematic shown (grey)
- Clear heavy 2nd knee, no proton at highest energies.
- New versions hopefully available soon: non-statistical fluctuations around 0.5 10^{7} GeV $\rightarrow$ fit problem due to low MC statistics; energy dependence of results not much affected.

IT-IC composition: lnA

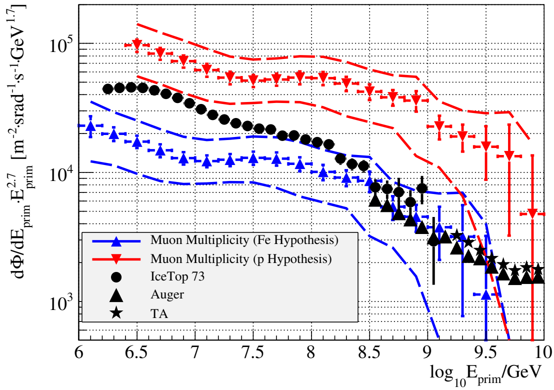


Ref: "Latest Results on Cosmic Ray Spectrum and Composition from Three Years of IceTop and IceCube", 1510.05225, p.37

- Rising average mass up to 100 PeV, stabilization at higher energies but heavy
- In-Ice light yield dominating systematic

Muon multiplicity measurement with deep IceCube

Measurement of TeV muon multiplicity converted to energy spectrum using certain composition assumption. Ex: pure proton and pure iron.
Overlay with energy spectrum measurements:

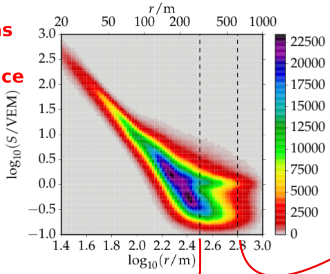


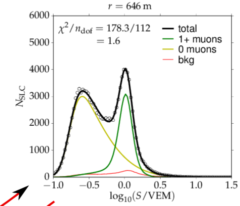
Ref: IceCube, Astropart. Phys. 78, 1 (2016)

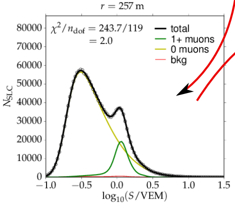
- Qualitative same conclusion about composition as above!
  High-energy (TeV) muons result in a different composition compared to surface/fluorescence detectors.

IceTop composition with GeV μ density: method

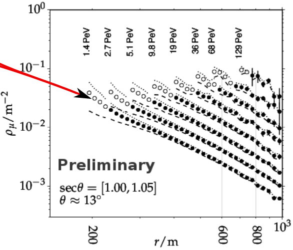
Charge as function of distance



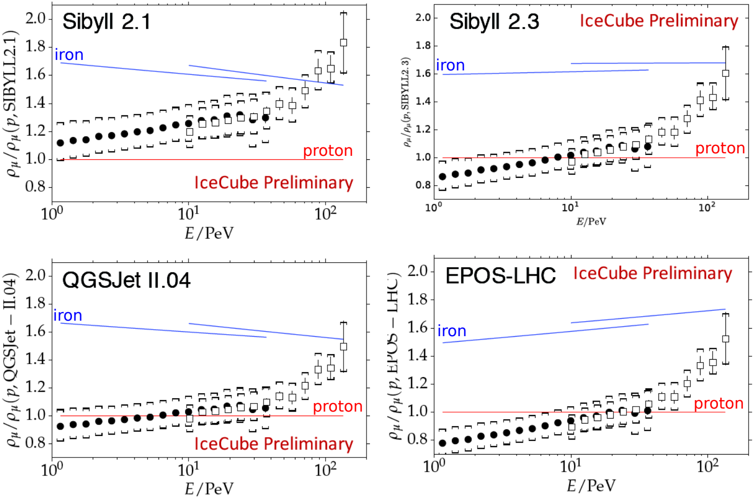




Bin in distance bins and fit EM and µ component per primary energy bin



IceTop composition with GeV μ density: results



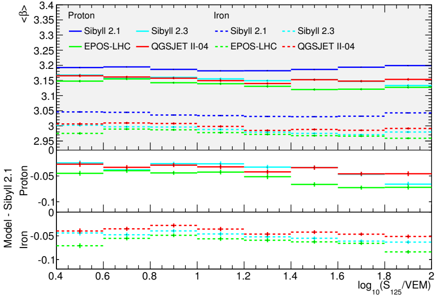
Ref: "Surface muons in IceTop", 1510.05225, p. 21

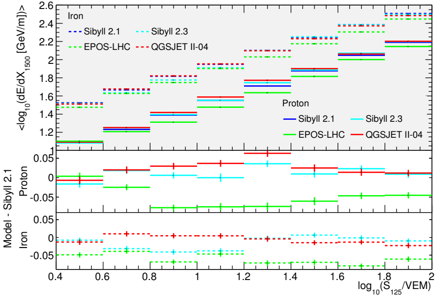
- Muon density (relative to proton) measured up to 100 PeV
- Sibyll 2.1, Sibyll 2.3, QGSJet II.04, EPOS-LHC

Hadronic models with IceTop and IceCube: method

Reason for composition disagreement?

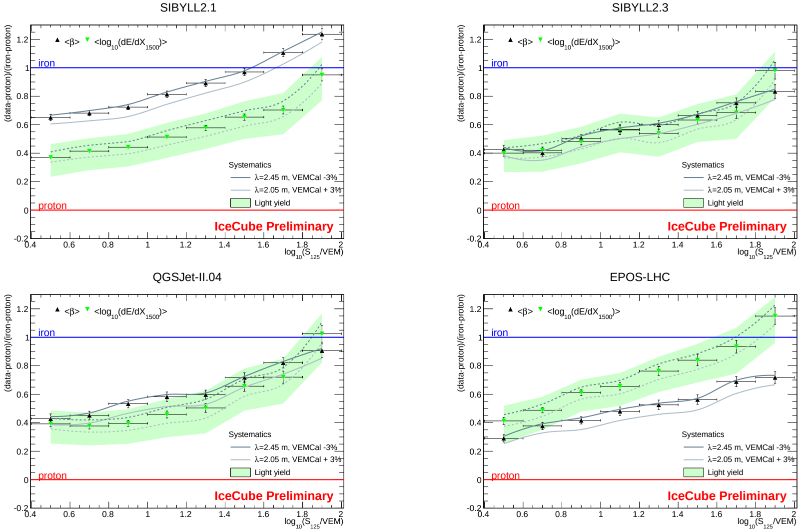
- Energy estimate with S_{125} (IceTop)
- IceTop composition sensitivity through slope of LDF (β): age of shower and low-energy (GeV) muon number
- IceCube composition sensitivity with TeV muon bundle energy loss
- Sibyll 2.1, Sibyll 2.3, QGSJet II.04, EPOS-LHC
- Up to 100 PeV





Ref: PoS(ICRC2017)319

Hadronic models with IceTop and IceCube: results



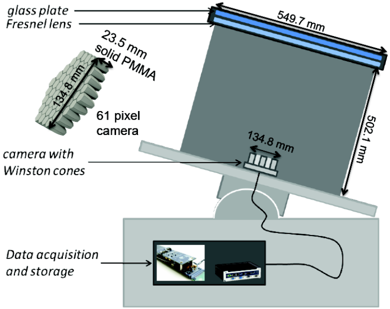
- Consistent composition interpretation with IceTop and IceCube for QGSJet II.04 and Sibyll 2.3
- Low number of low-energy muons for Sibyll 2.1; opposite inconsistency for EPOS-LHC

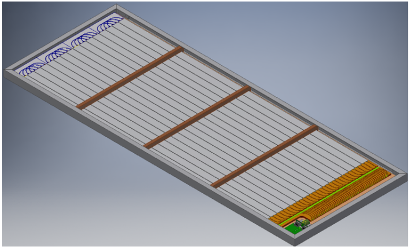
Conclusions

- The cosmic ray energy spectrum is measured in detail between 4 PeV and 1 EeV. A clear 2nd knee is observed.
- Using HE muon bundles, the average mass rises up to 100 PeV and seems constant above this energy.
- IceTop-only composition: rise in average mass up to 100 PeV, investigation of hadronic models.
- The hadronic interaction models are under study: disagreement for EPOS-LHC and Sibyll 2.1 between IceTop and IceCube composition measurement; consistency for Sibyll 2.3 and QGSJet II.04.

Outlook and possible upgrades

- More data to be added at highest energies
- Extend studies of composition with IceTop > 100 PeV
- Cherenkov telescope and scintillator panels prototypes installed.

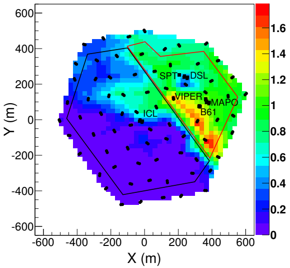




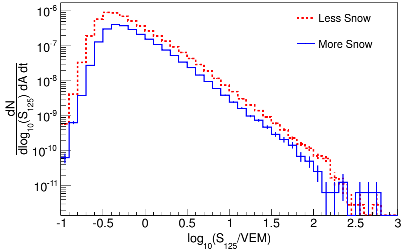
Thanks!

Effect of snow on data

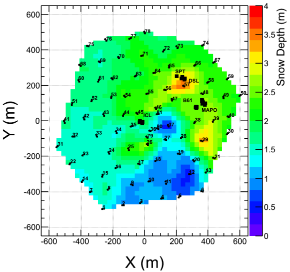
Snow height map [m] (11/2010)



Before correction (11/2010)



Snow height map 10/2016

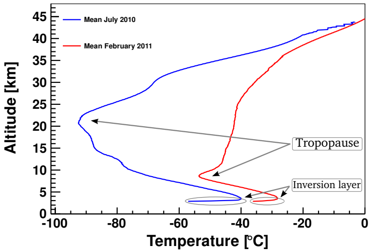


- Electromagnetic particles are attenuated
  $\Rightarrow$ rates reduce.
  $\Rightarrow$ relation between primary energy and detector response changes.

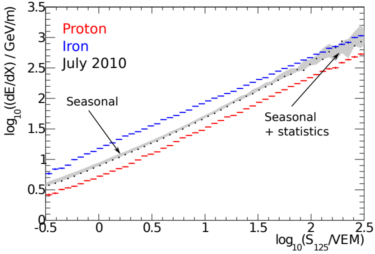
$$S_{corr,tank} = S_{meas,tank} \cdot exp(\frac{d \sec\theta}{\lambda}).$$

- Most significant systematic on energy spectrum.

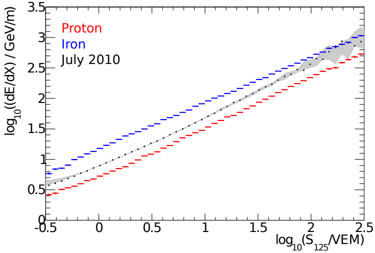
Seasonal variations



Before correction



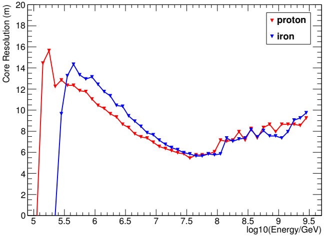
After correction



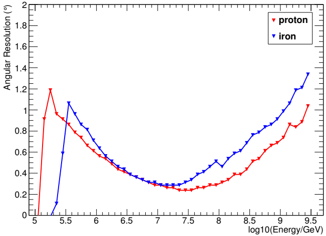
- Denser atmosphere means pions and kaons interact instead of decaying ⇒ less HE muons.
- Affects composition measurement.
- No more shift visible in each month after correction.

Quality

Core resolution

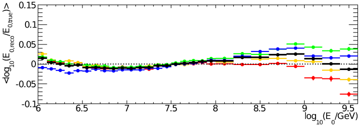


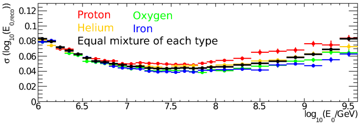
Angluar resolution



For contained, coincident events:

- Core resolution: 6 - 11 m.
- Angular resolution: 0.2° - 1.0°.
- Very good energy resolution (10-15%), small bias.





Results: Individual energy spectra

QGSJET