Composition Sensitivity through Muon Content and Shower Size

Study of Cosmic Ray Composition through Muon Bundle Properties using Coincident IceTop/IceCube Measurements

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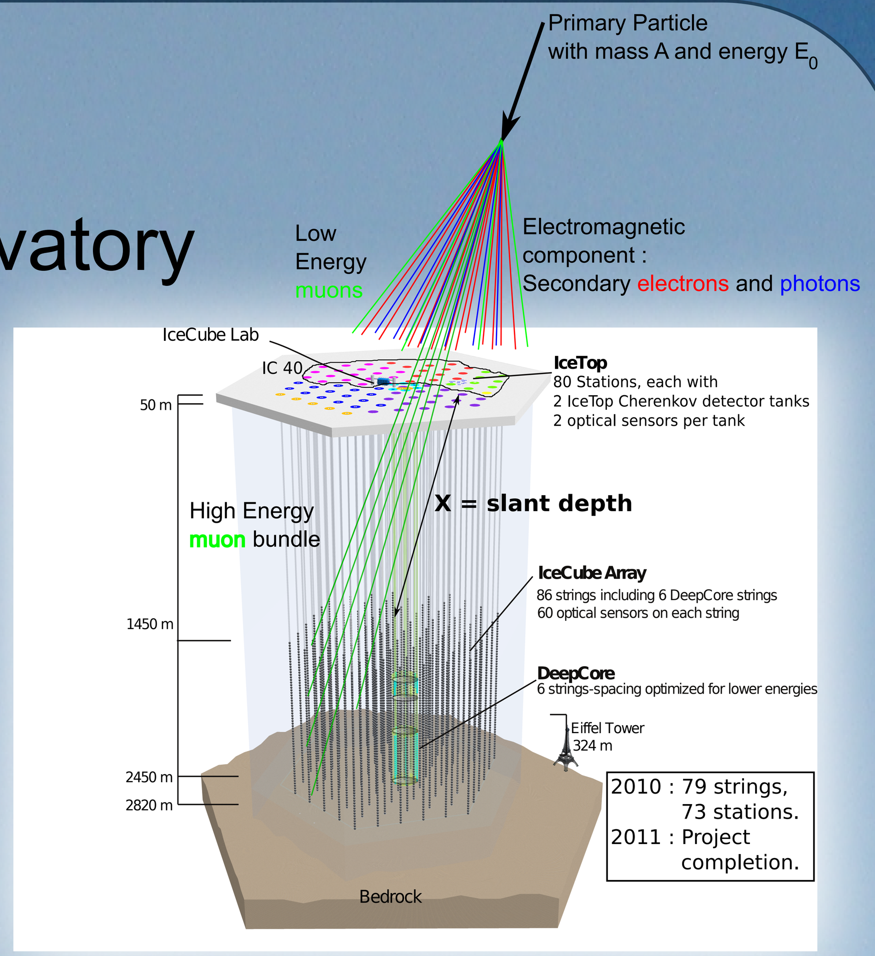
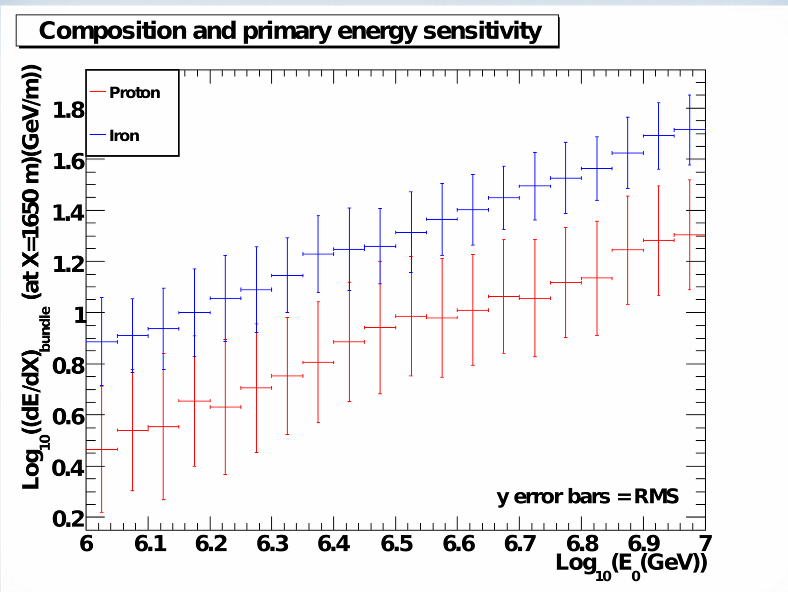
Muon Bundle Detection with the IceCube Neutrino Observatory

The IceTop air shower array, the surface part of the IceCube Neutrino Observatory, probes the electromagnetic component of cosmic ray air showers in the energy region between 300 TeV and 1 EeV. The high energy muon component, a collimated beam of high energy muons created in the first interactions in the upper atmosphere, penetrates deep in the Antarctic Ice. These muon bundles generate Cherenkov light mainly through radiative energy loss processes. After propagation through the ice the Cherenkov light is detected by the deep IceCube detector.



The signal strength in IceTop at 125m from the core position (S125), or shower size, reconstructed using a fit to the lateral distribution, is mainly sensitive to the primary energy of cosmic ray air showers.
The primary mass of cosmic ray air showers can be characterized by their muon multiplicity, which cannot be directly measured by either the IceTop or IceCube detector. The muon bundle energy loss, which is a convolution of the muon energy distribution and the energy loss of a single muon, is the primary mass sensitive observable which can be reconstructed in IceCube.

MC_{true} Muon bundle energy loss



MC_{true} Primary Energy

Muon Bundle Energy Loss Reconstruction

- Likelihood reconstruction that uses the Cherenkov photon arrival times and charges measured by the IceCube sensor modules.

$$\mathcal{L} = \prod^{\text{modules}} \prod^{\text{pulses}} P(\{\mathrm{N_{PE}(t)_{measured}}\} \mid \{\mathrm{N_{PE}(t)_{expected}}\})$$

- Photon propagation and ice properties are taken into account by treating single muons as infinite tracks of electromagnetic cascades.

- Cherenkov light is mainly caused by radiative energy loss processes.
→ Measured charge is proportional to the muon bundle energy loss.

$$\mathrm{N_{PE}(t)_{measured}} \propto \left(\frac{dE_\mu}{dX}\right)_{\mathrm{Bundle}} (X) = \int_{E_{min}}^{E_{max}} \frac{dN_\mu}{dE_\mu} \frac{dE_\mu}{dX} dE_\mu$$

→ Muon bundle energy loss is integral of the muon energy distribution and the single muon energy loss over the muon energies that can reach slant depth X.

- To calculate the muon energy distribution, a simple power law is used as approximation for the Elbert formula which describes the muon multiplicity of cosmic ray air showers.

$$N_\mu(E_\mu > E_{\mu_{thr}}) = \kappa(A) \left(\frac{E_0}{A}\right)^{\gamma_\mu - 1} E_\mu^{-\gamma_\mu} \text{ where } \kappa(A) = \frac{14.5\text{GeV } A}{\cos(\theta)}, \gamma_\mu = 1.757$$

- Expected charge is corrected for the loss of photons by electronics effects and calibration of the measured signals.

Data and Monte Carlo Simulation Sample

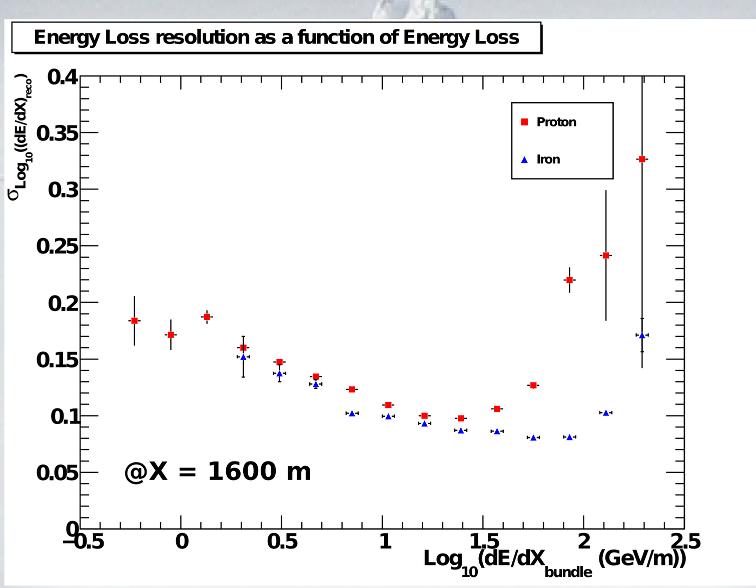
- Coincident data from Sept. 2008 (IC40, 40 IceTop stations and 40 IceCube strings).
- Proton and Fe showers were simulated between 10 TeV and 22 PeV with CORSIKA v6.735 (Sibyll-Fluka).
- The Monte Carlo (MC) is weighted to an $E^{-2.7}$ spectrum before the knee (at 3 PeV) and an $E^{-3.0}$ spectrum after the knee.
- Analysis requirements : 5 triggered IceTop stations and 8 triggered IceCube sensors.

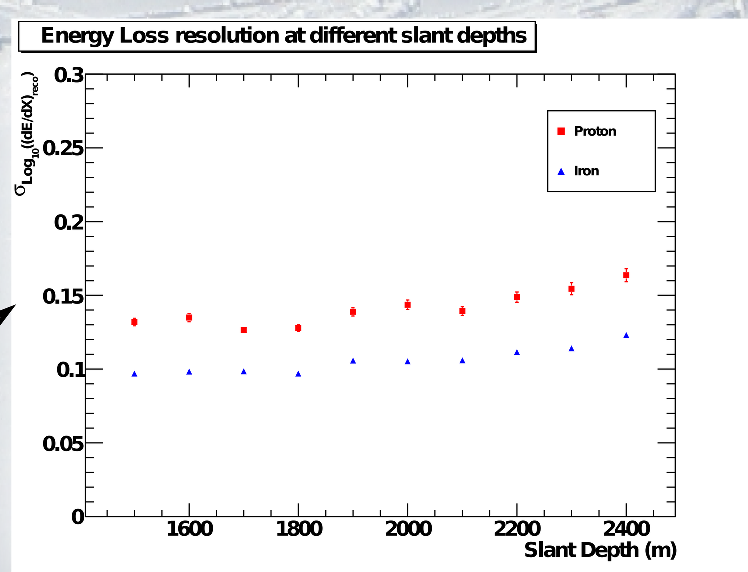
Performance

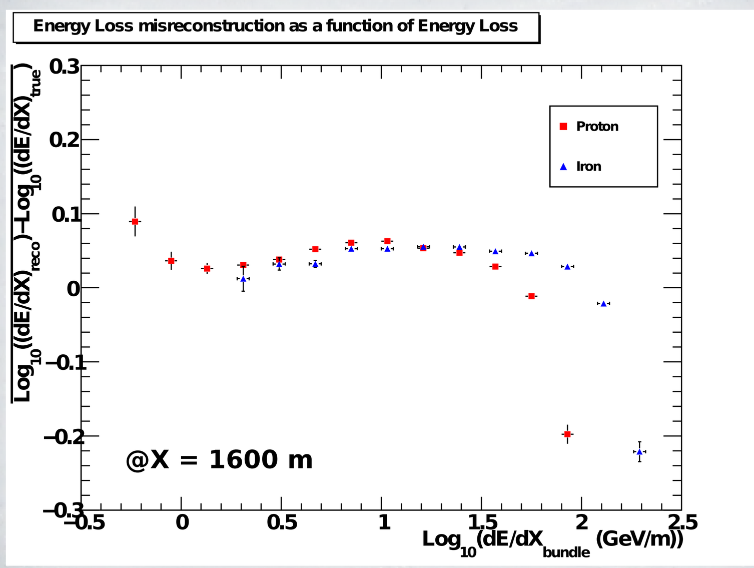
Energy Loss Behavior :
- Resolution < 0.2 in $\log_{10}$(dE/dX) and improves for higher energy losses
- Offset is very small (0.05 in $\log_{10}$(dE/dX)) and constant between 1 and 80 GeV/m.
- Worse resolution and larger shift at highest and lowest energy losses because of statistics, average description of energy loss, and approximation of Elbert formula.

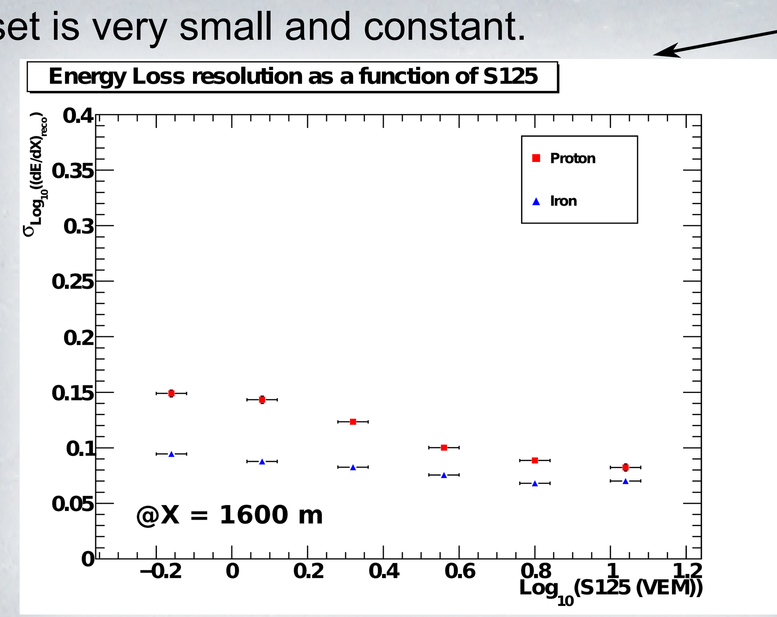
Slant Depth Behavior :
- Resolution relatively constant as function of slant depth. It is larger for proton induced muon bundles because there are on average fewer muons than for iron bundles and the average muon energies are larger.
- Offset is very small and constant.

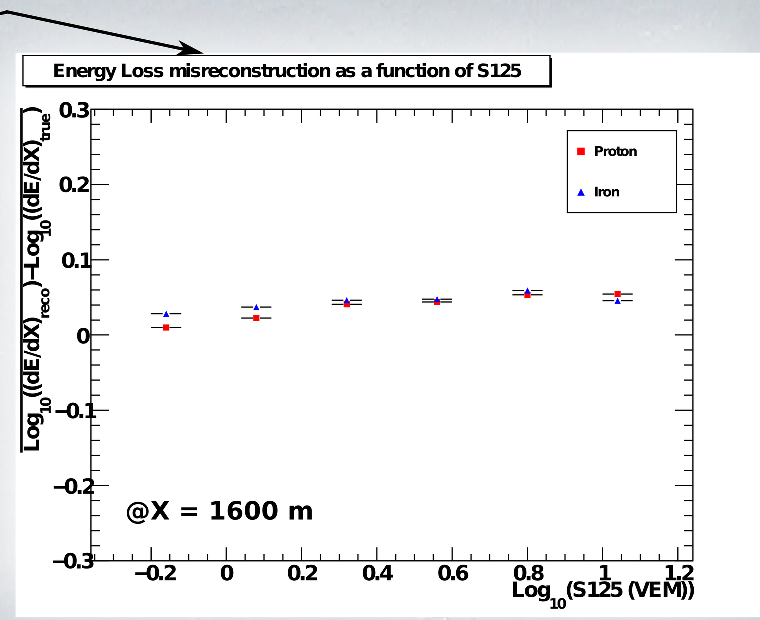
S125 Behavior :
For well reconstructed events contained by both IceTop and IceCube (same cuts as applied to data) :
- Resolution < 0.2 and improves with larger shower sizes.
- Offset is very small and constant.

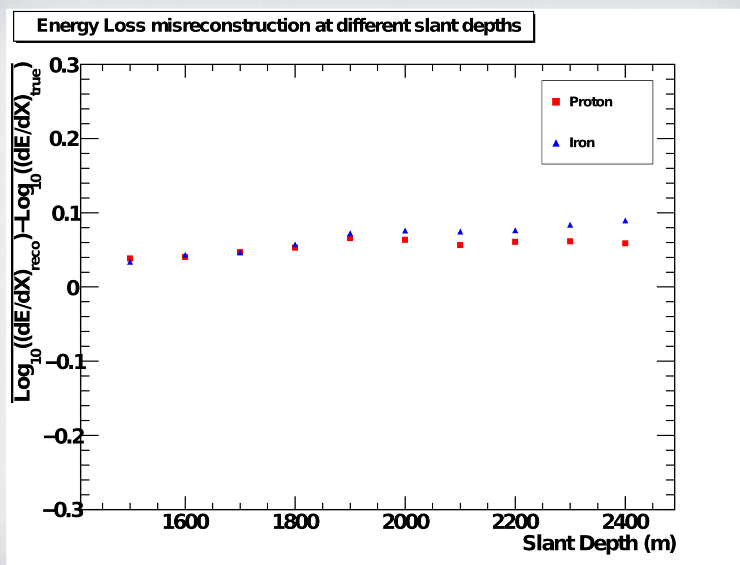








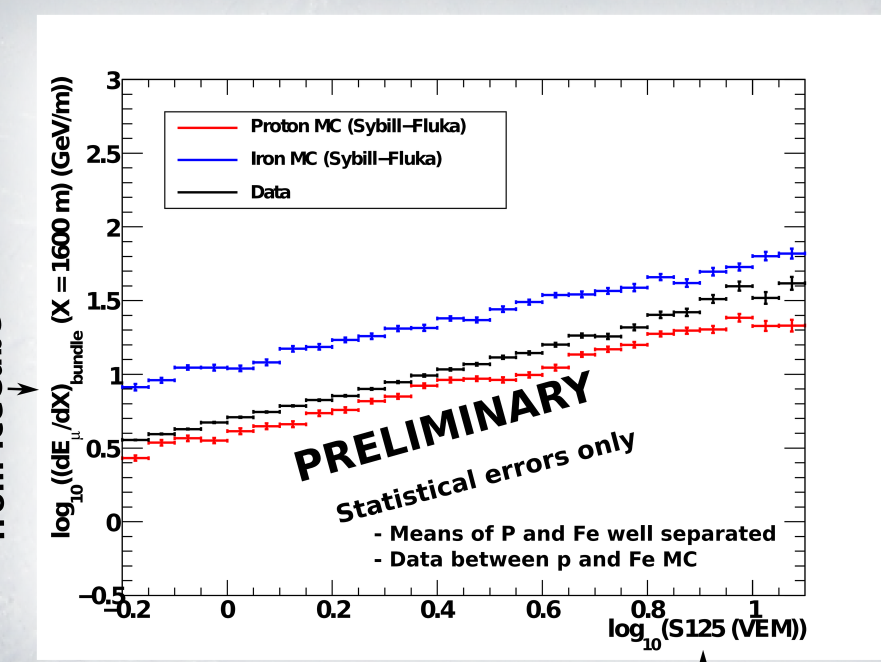




Results

Combining the reconstructed energy loss at a slant depth of 1600 m with the IceTop shower size (S125) :
- The means are well separated for iron and proton showers.
- With loose quality cuts, data lies between proton and Fe MC.
- Only statistical error bars are included.

Muon Bundle Energy Loss from IceCube



Shower Size from IceTop

Conclusions and Outlook

- The muon bundle energy loss can be well reconstructed with a resolution of 0.15 in $\log_{10}$ (dE/dX) and very small offset of 0.05.
- Both the energy loss and the IceTop shower size are sensitive to primary energy and primary mass and will be combined to measure the composition in the PeV - EeV range.

Acknowledgements

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References

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