UNIVERSITEIT GENT

FACULTY OF **SCIENCES**

Cosmic ray composition between 1 PeV and 1 EeV

using high-energy muon bundles

with 3 years of IceTop and IceCube data

Sam De Ridder

ICECUBE

HAP workshop
KIT
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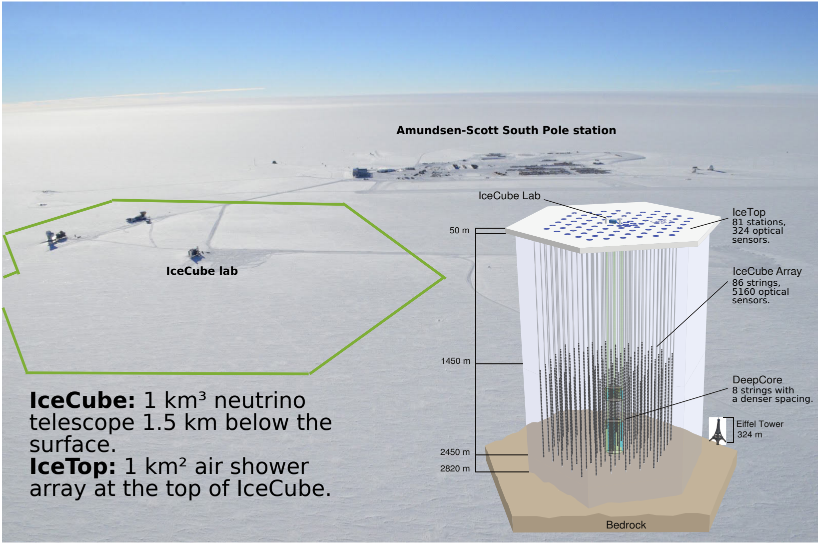
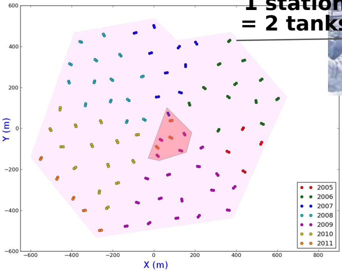
The IceCube Neutrino Observatory



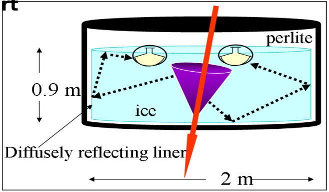
IceTop



Stations 125 m apart

1 station = 2 tanks

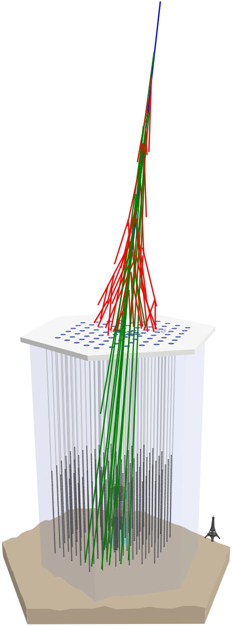
1 tank = 2 DOMs



DOMs collect the Cherenkov light emitted by the particle in the tank

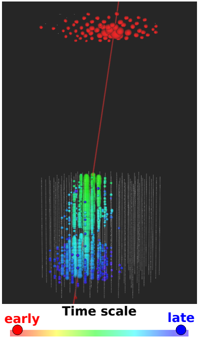
IceTop is at an altitude of $\sim$2835 m $\approx$ 692 g/cm^2

Cosmic ray physics with the IceCube Neutrino Observatory



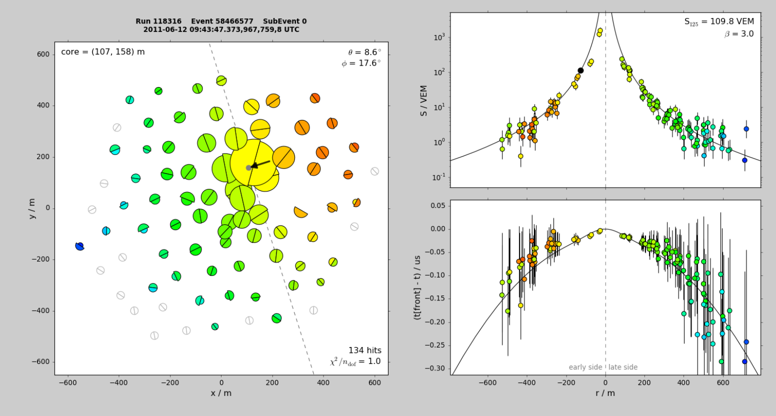
Coincident analysis:

- IceTop stations detect the **electromagnetic** component (and low-energy muons): sensitive to the energy of the shower.
- High-energy **muon bundles** travel down to the IceCube detector:



- Minimal muon energy: ~ 275 GeV.
- Multiplicity: 1 - 1000s.
- Created high in the atmosphere.
- Typical radius: $\sim 20 - 50$ m
- Ionization + radiative, stochastic energy loss.

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:

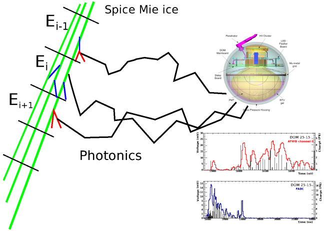
$$\Delta t(r) = ar^2 + b\left(\exp\left(-\frac{r^2}{2\sigma^2}\right) - 1\right)$$

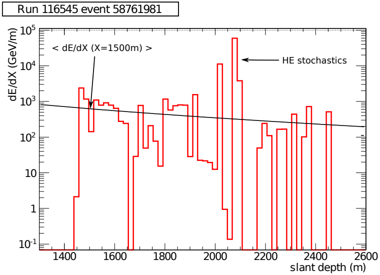
$\rightarrow$ **x, y, z, θ, ϕ, β, $\mathbf{S}_{125}$ (signal at 125 m from core)**

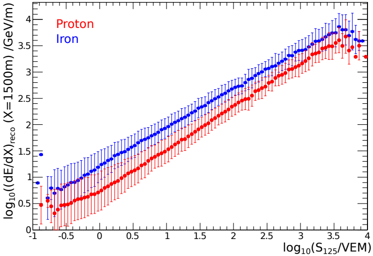
Air shower reconstruction with IceCube

Unfolding the energy loss pattern + maximum loglikelihood

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



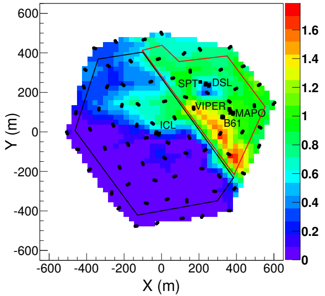




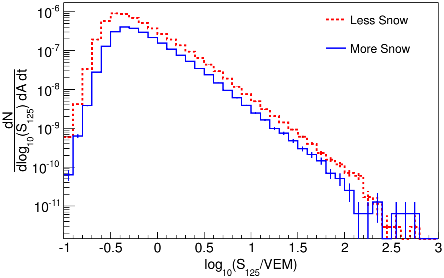
$\rightarrow dE/dX_{1500}$, # HE stochastics 1, # HE stochastics 2

Effect of snow on data

Snow heights in meters

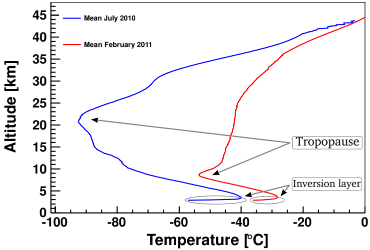


Before correction

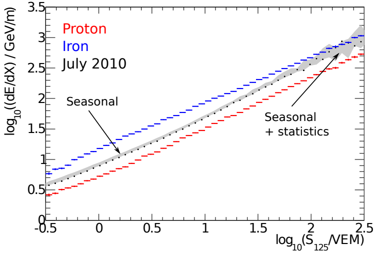


- Electromagnetic particles are attenuated
  $\Rightarrow$ rates reduce.
  $\Rightarrow$ relation between primary energy and detector response changes.
  $S_{corr,tank} = S_{meas,tank} \cdot exp(\frac{d \sec \theta}{\lambda})$.
- Most significant systematic on energy spectrum.

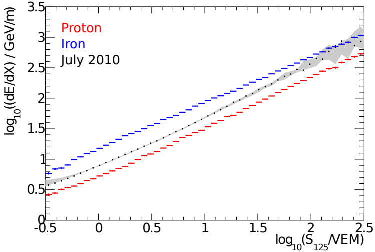
Seasonal variations



Before correction



After correction



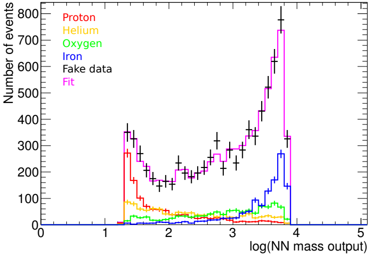
- Denser atmosphere means pions and kaons interact instead of decaying ⇒ less HE muons.
- Affects composition measurement.
- No more shift visible in each month after correction.

Neural network (NN) + template fitting

Neural network

- Inputs:
  - S_{125}
  - zenith angle
  - $\frac{dE}{dX}(X)$
  - # HE stochastics 1
  - # HE stochastics 2
- Outputs: $\log_{10}$(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.

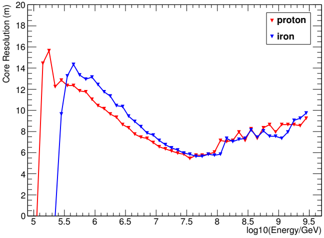
Template fitting



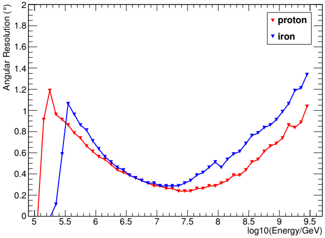
- For each energy bin: $(\text{Data})_i = f_H \cdot H_i + f_{He} \cdot He_i + f_O \cdot O_i + f_{Fe} \cdot Fe_i$.
- Binned likelihood fit which takes into account Poisson fluctuations on both data and MC.

Quality

Core resolution

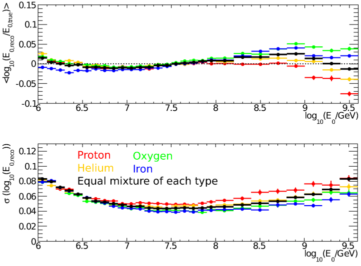


Angluar resolution



For contained, coincident events:

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

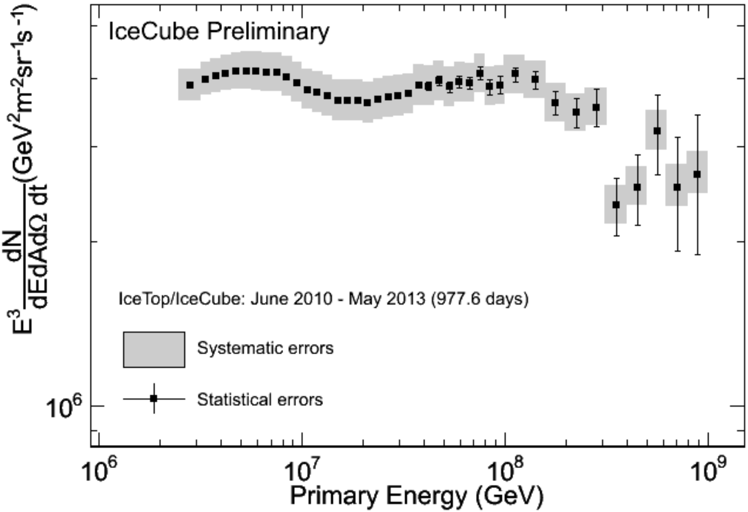


Systematics

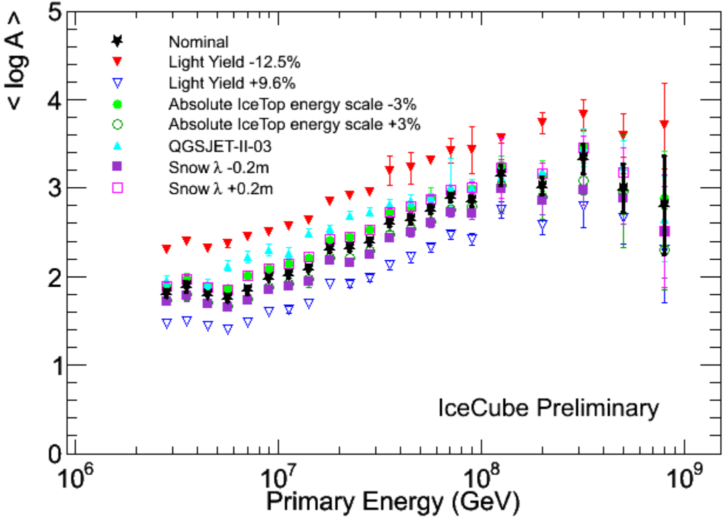
- Absolute IceTop energy scale: $\pm3\%$ on the data/MC calibration.
- Snow correction uncertainty: $\lambda\pm0.2$ m.
- Hadronic Interaction Model: SYBILL 2.1 vs QGSJet-II-03.
- In-ice light yield systematics:

	Systematics uncertainty
DOM eff	$\pm$ 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%

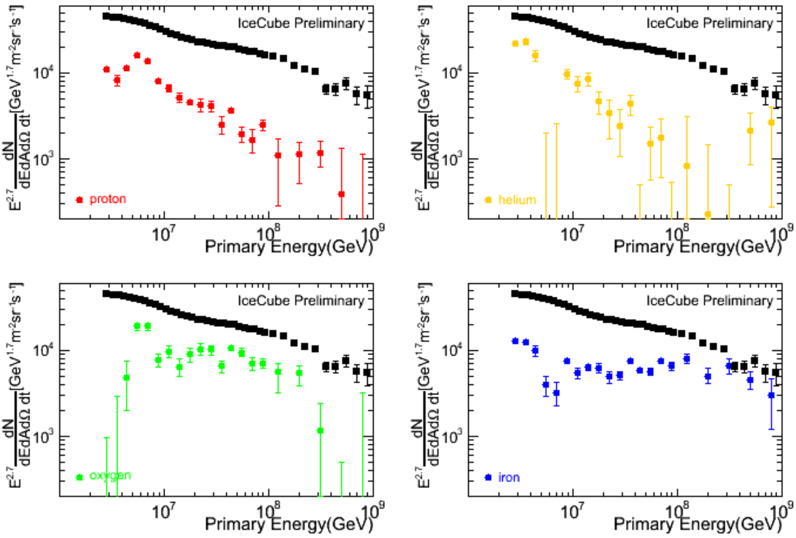
Results: Energy spectrum



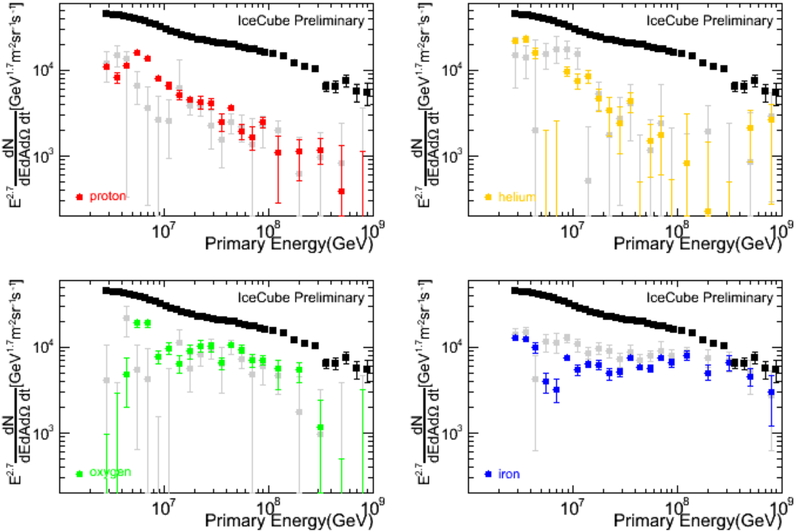
Results: Composition



Results: Individual energy spectra

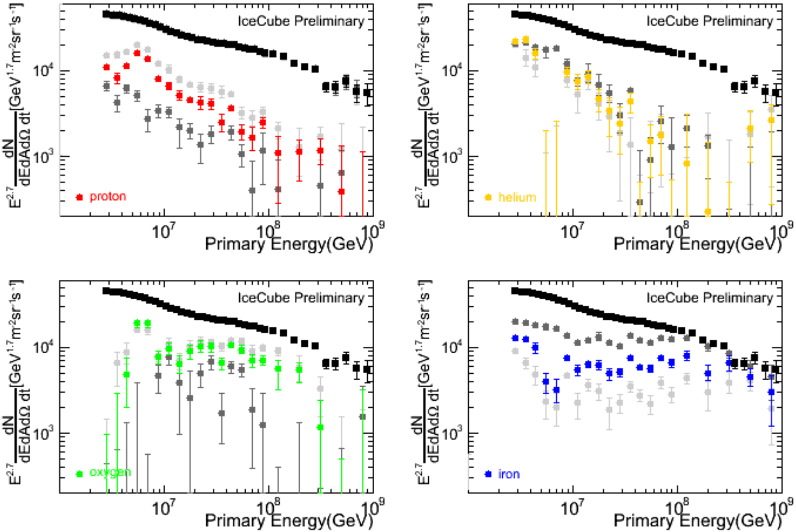


Systematics: Individual energy spectra, QGSJET



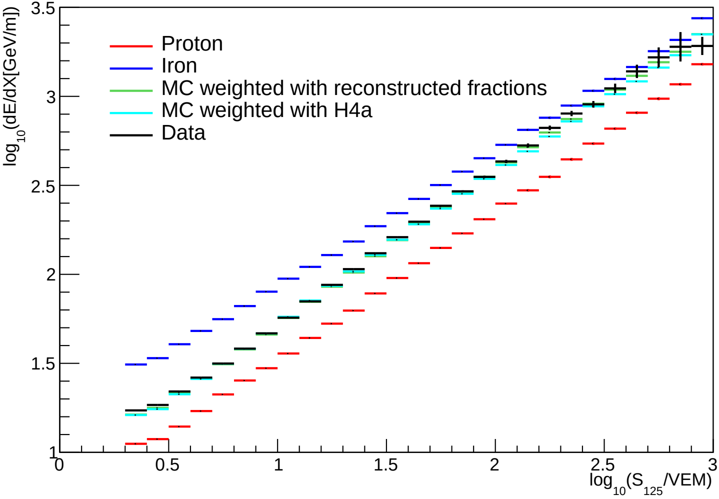
Systematics: Individual energy spectra, In-ice light yield

dark gray: -12.5%, light gray: +9.6%



post-NN evaluation of variables

Comparison of data with MC weighted with reconstructed fractions, together with H4a composition assumption and pure proton and iron.



Summary

Discussed in this presentation:

- Features are seen in the energy spectrum.
- Composition measurement using high-energy muon bundles increases between $\sim$ PeV and 100 PeV due to decrease of light component, then shows a flattening.
  More statistics are needed in this high-energy region.
- Major systematic on composition measurement are the in-ice light yield uncertainties.

Not shown, but important as well:

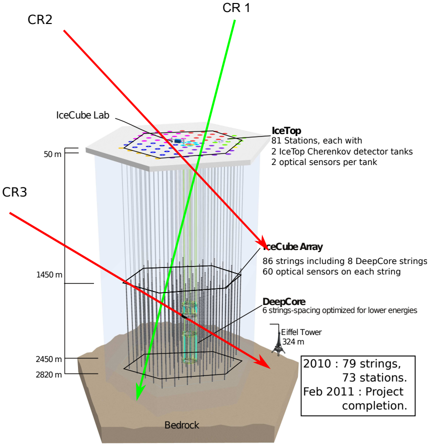
- Individual energy spectra, total energy spectrum and composition reconstruction of 3 separate years agree very well.
- Energy spectrum measured by the coincidence and the IceTop-alone analyses agree well within systematics.

Thanks!

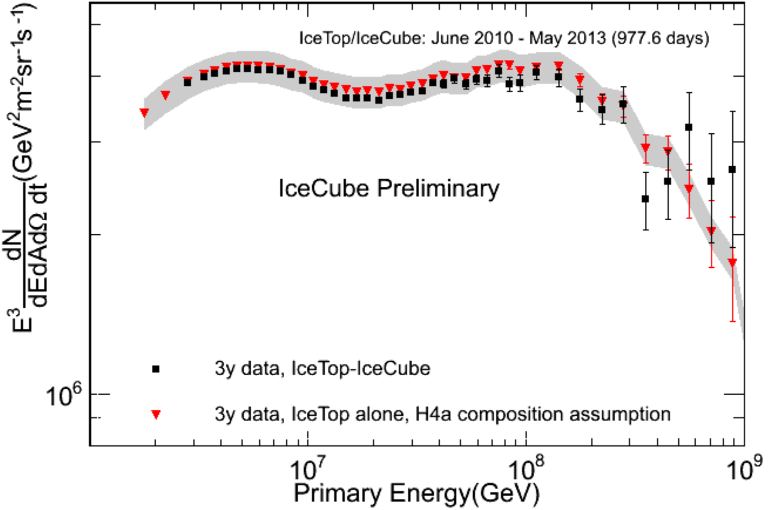
Back-up

Event selection

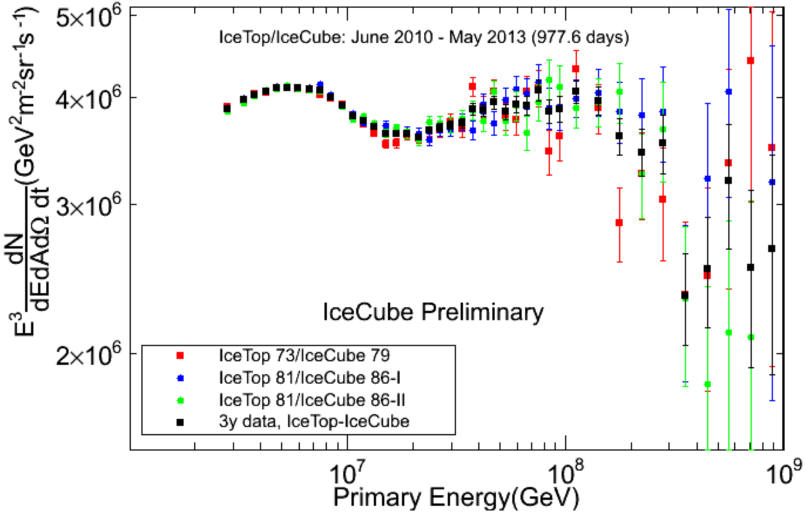
1. Coincident filter, Nstation ≥ 5, NCh ≥ 8.
2. Removal of random coincidences: CR2 with CR3.
3. Removal of extra events at the same time: CR1 and CR2, CR1 and CR3.
4. Containment in IceTop and passing through the IceCube volume.
5. Reconstruction quality cuts.



Results: Comparison IT-alone vs coincident



Results: Energy spectra 3 years



Results: Composition 3 years