

The background of the slide is a visualization of the IceCube detector. It shows a dark blue grid representing the detector's structure. A red line, representing a cosmic ray path, enters from the top and passes through a cluster of colorful points (yellow, green, and red) in the upper center. Below this, a large, dense, multi-colored (yellow, orange, and red) structure is visible, representing a particle shower or interaction. The overall scene is set against a dark blue background with a grid pattern.

PeV Cosmic Rays with IceCube/IceTop

Serap Tilav (University of Delaware) for the IceCube Collaboration

Run 116545 Event 58761981 top hlc clusters/0 [0ns, 39197ns]

IceCube

Neutrino Telescope & 3D Cosmic Ray Detector

Air shower detection
@ 2835m altitude (680 g/cm^2)

IceTop

EM component near shower max
shower size & arrival times over 1km^2

IceTop surface air shower array
81 Stations on the surface
2 Ice Cherenkov Tanks per Station
2 Digital Optical Modules per Tank

IceCube

Muonic component @ 1450m-2450m depth in ice
muon bundle energy over 1km

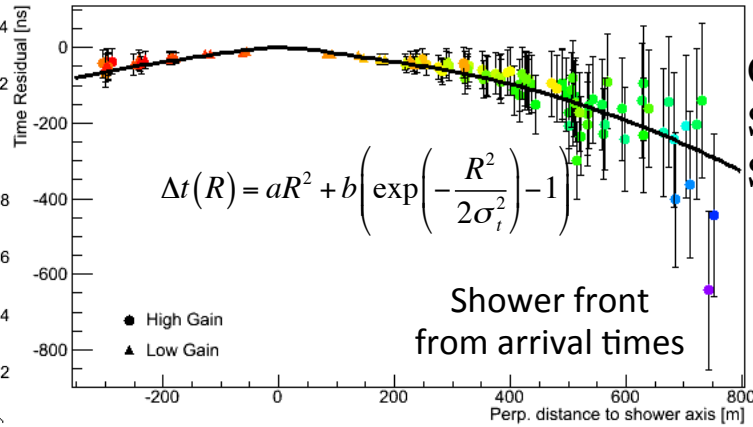
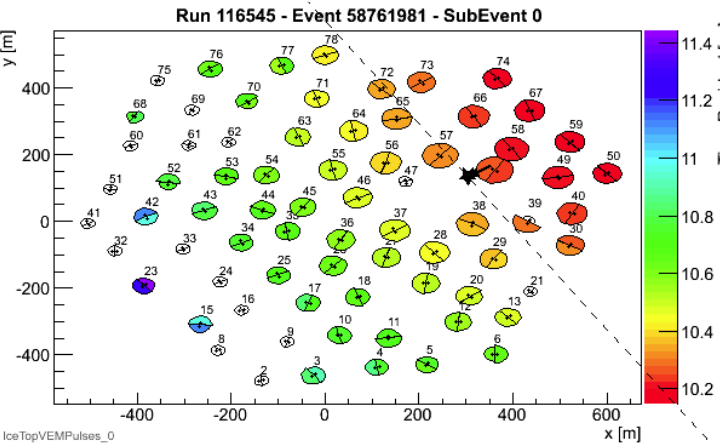
IceCube Array
86 Strings @1450-2450 m depth in ice
60 Digital Optical Modules per String

Run 116545 Event 58761981 top hlc clusters/0 [0ns, 39197ns]

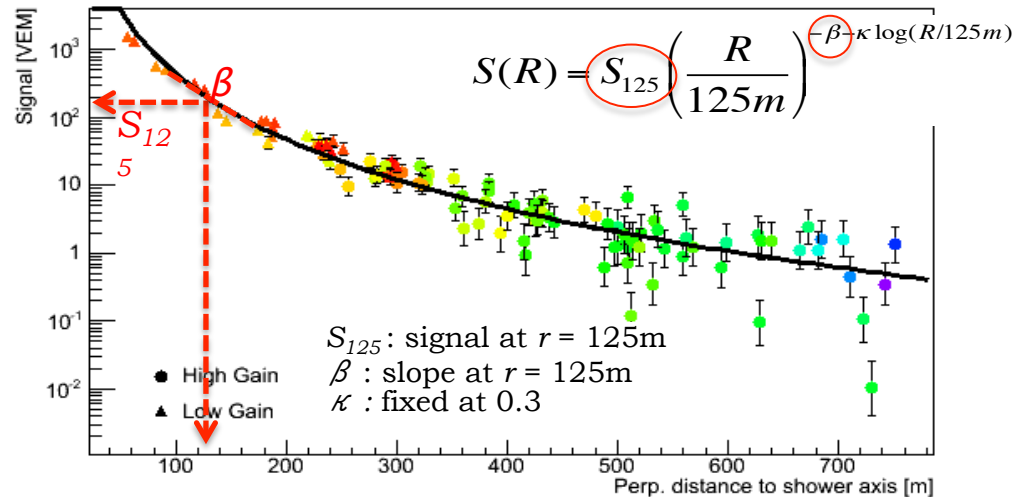
IceTop: Calibration device for IceCube

➔ measure cosmic ray spectrum and composition as input to neutrino calculations

Air Shower Reconstruction

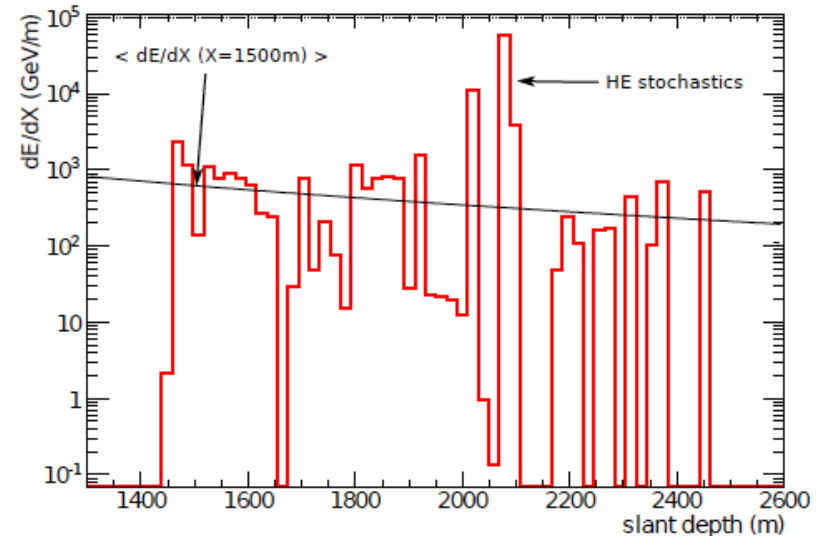


On the surface:
Shower core: x, y, z
Shower direction: ϑ, φ



On the surface:
IceTop shower size S_{125} and β

Run 116545 event 58761981



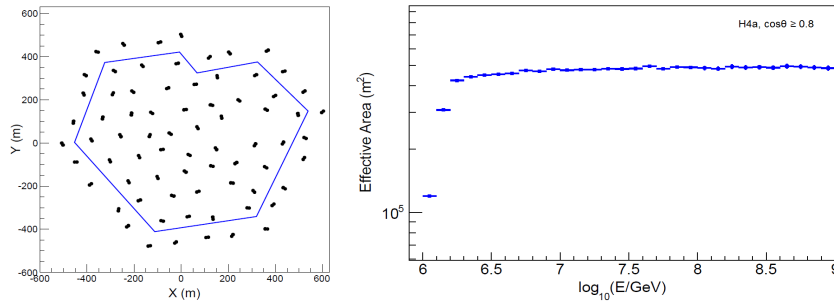
In deep ice:
Muon bundle energy loss
 dE/dX (GeV/m) and stochastic
behavior

IceCube-79 / IceTop-73 Analysis

June 2010 – May 2011

Surface Only: IT73

327 days of live time
12M events after quality cuts



Effective area=Geometric area= $5.77 \cdot 10^5 \text{ m}^2$
above $\sim 2.5 \text{ PeV}$

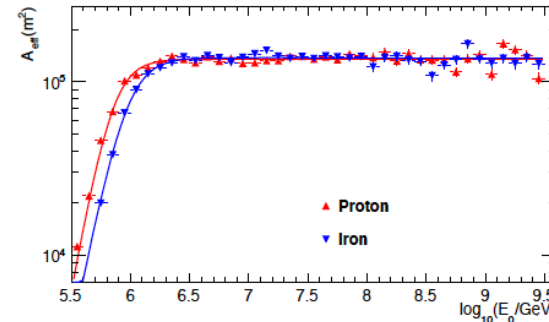
- Assumes composition to derive energy spectrum

Default model: H4a from
T.K. Gaisser, Astropart.Phys. 35 (2012) 801-806

Several different models tried and reported as composition related systematics

Surface and In Ice: IC79/IT73

310 days of live time
1.56M events after quality cuts



Effective area= $1.36 \cdot 10^5 \text{ m}^2$ above $\sim 2.5 \text{ PeV}$

- Multivariate Neural Network Analysis
- Measures Composition
- Measures composition independent energy spectrum

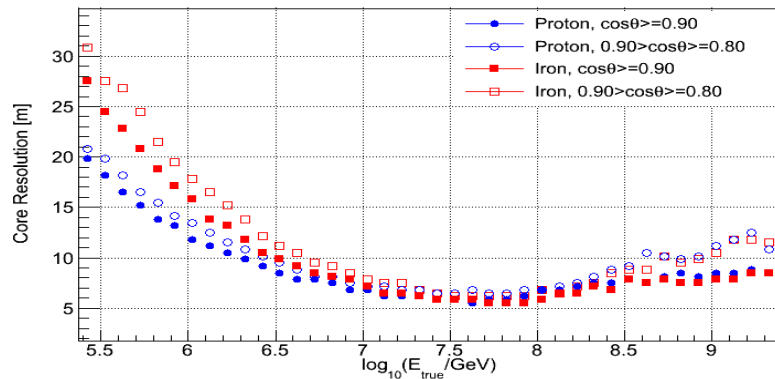
IceCube-79 / IceTop-73 Analysis

June 2010 – May 2011

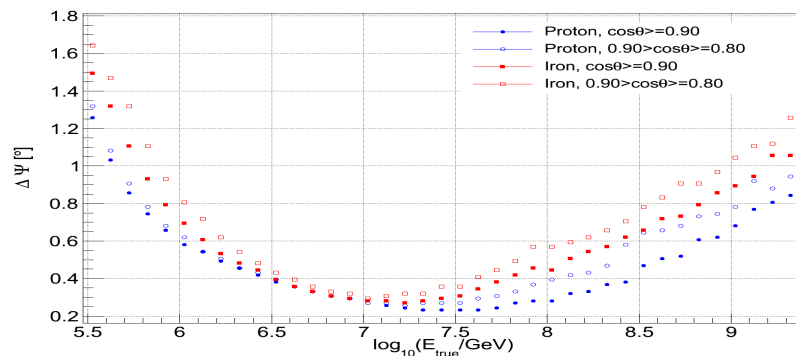
Surface Only: IT73

Surface and In Ice: IC79/IT73

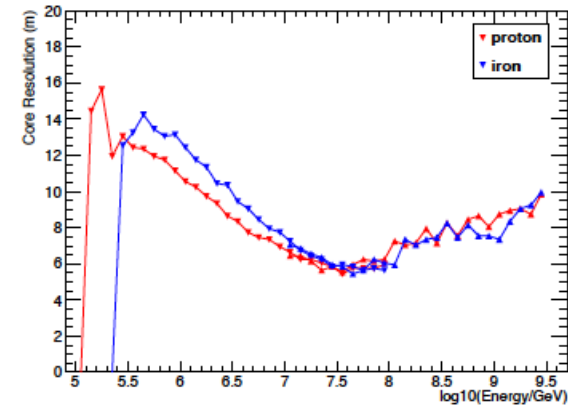
Performance



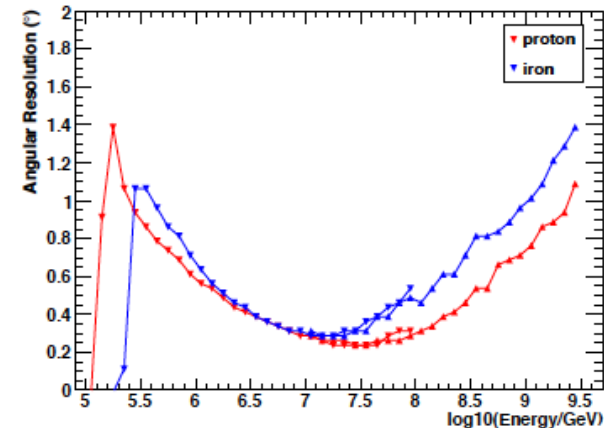
Core resolution : 6-13 m



Angular resolution: $0.2^\circ - 0.8^\circ$



Core resolution : 6-10 m

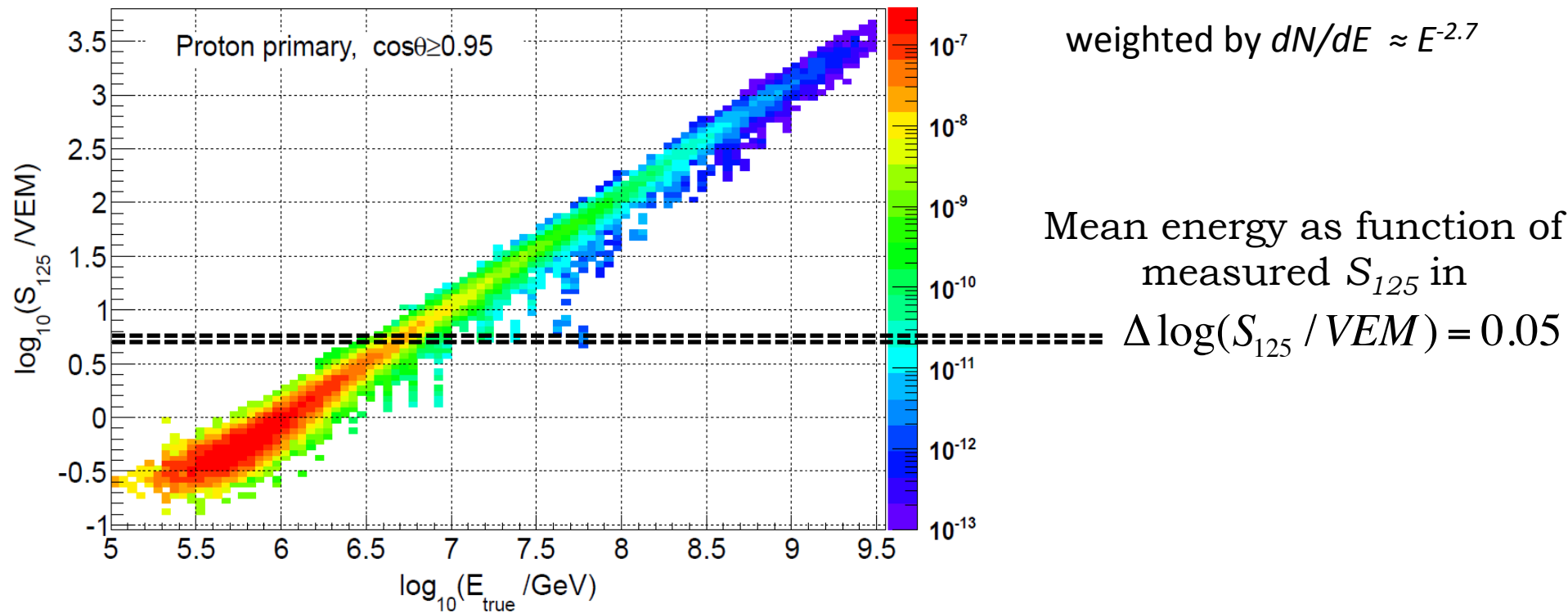


Angular resolution: $0.4^\circ - 1.0^\circ$

IceTop-73 Analysis

S_{125} - Energy Conversion

CORSIKA Sibyll 2.1 – FLUKA Primaries: H, He, O, Fe South Pole July atmosphere.
 E^{-1} spectrum: 100 TeV - 3 EeV Zenith: 0-40° 42000 showers per primary

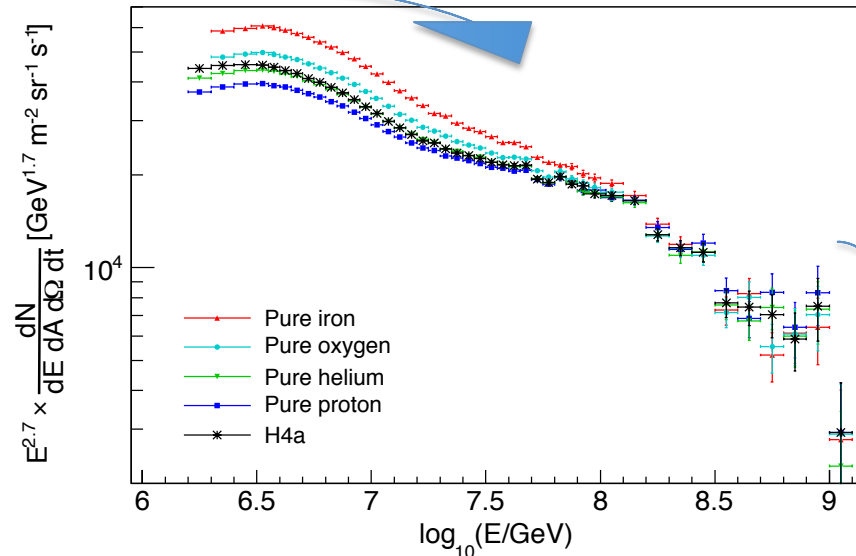
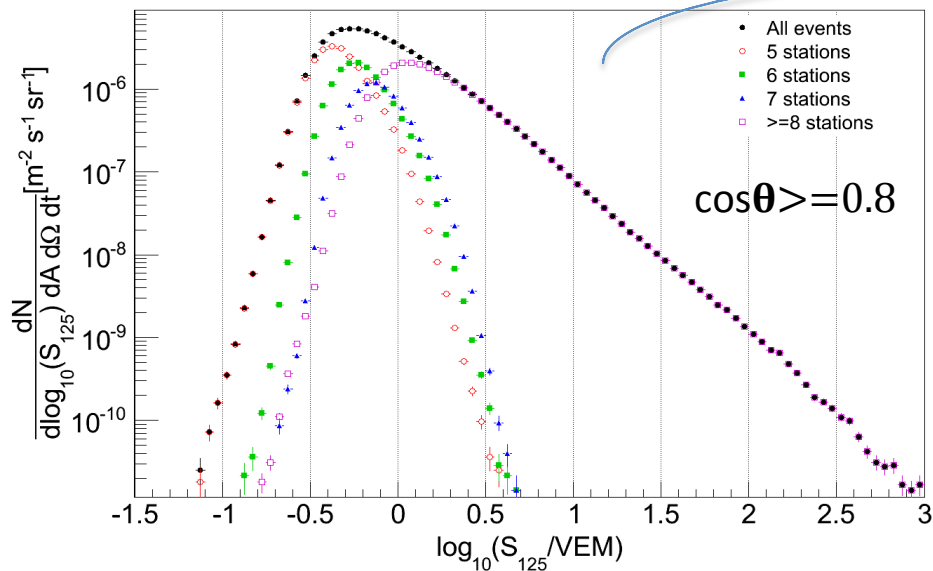


Fit performed in four $\cos\theta$ bins between 1.0 and 0.8

$$\log_{10}(E) = p_1 \log_{10}(S_{125}) + p_0$$

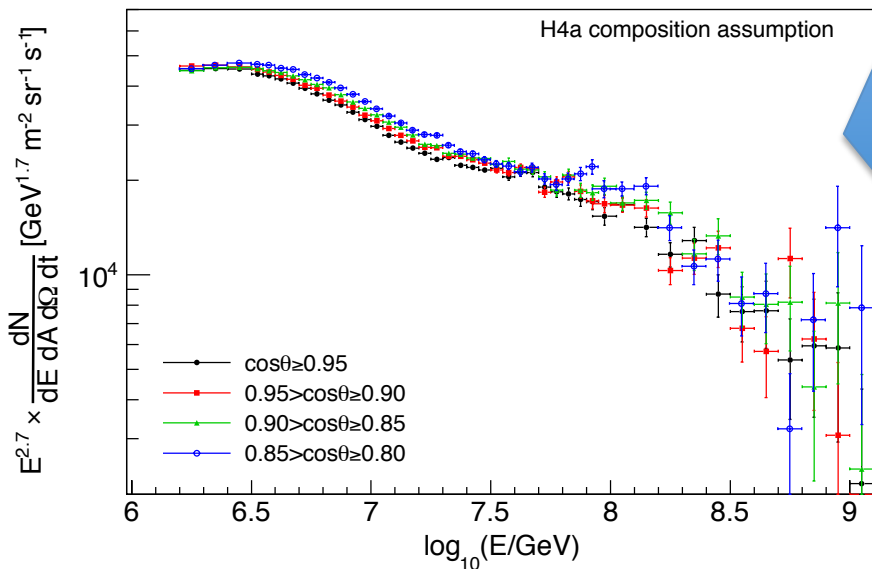
IceTop-73 Analysis

S_{125} - Energy Conversion

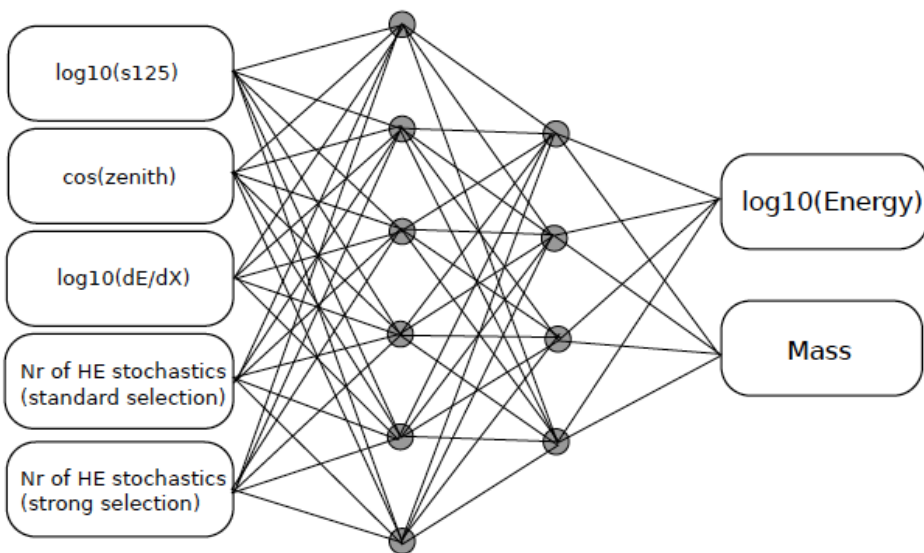
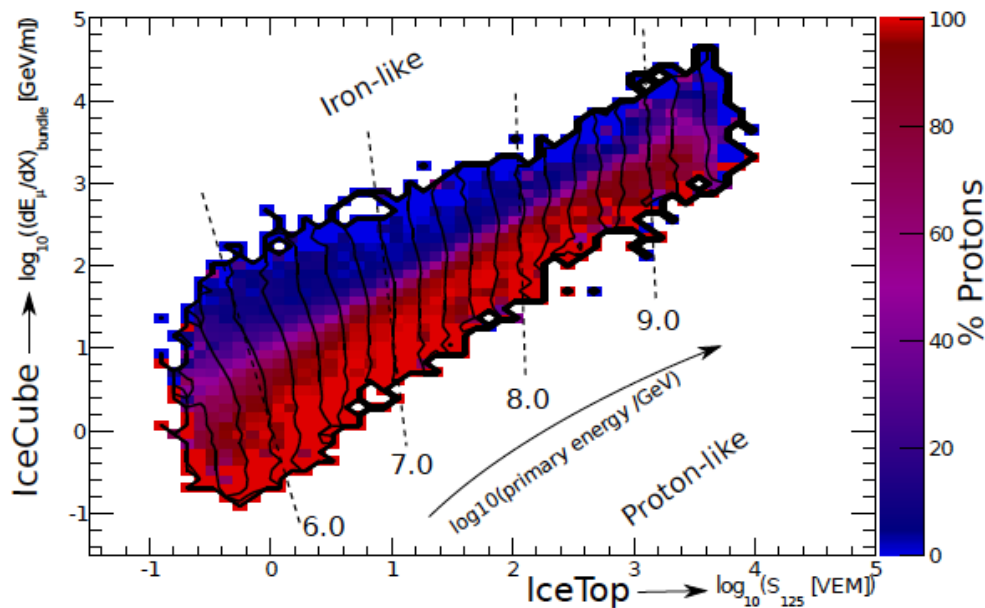


Systematic Uncertainties

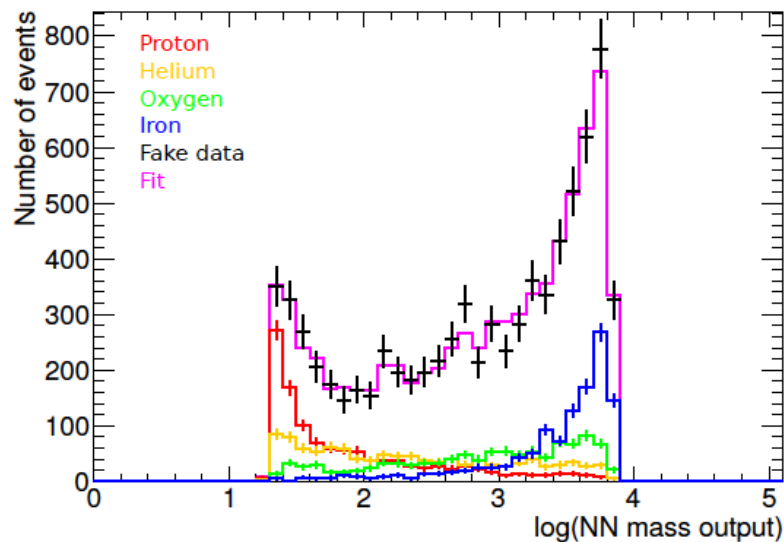
	3 PeV	30 PeV
Energy scale (VEM calibration)	$\pm 4\%$	$\pm 5\%$
Snow Correction	$\pm 5\%$	$\pm 6\%$
Interaction models QGSJet-II-03 and SYBILL 2.1	-2%	-4%
Composition	$\pm 7\%$	$\pm 7\%$
Ground pressure (690 hPa/670 hPa)	$\pm 2\%$	$\pm 0.5\%$



IceCube-79 / IceTop-73 Coincidence Analysis



- 5-6-4-2 Neural Network to map 5 observables to Primary Energy and Mass
- Energy spectrum directly from NN output
- Composition from fitting data in E_{reco} bins to template histograms (H, He, O, Fe) from NN mass output



e.g. Template histograms for 4 mass groups in one energy bin for a fake dataset scrambled from MC

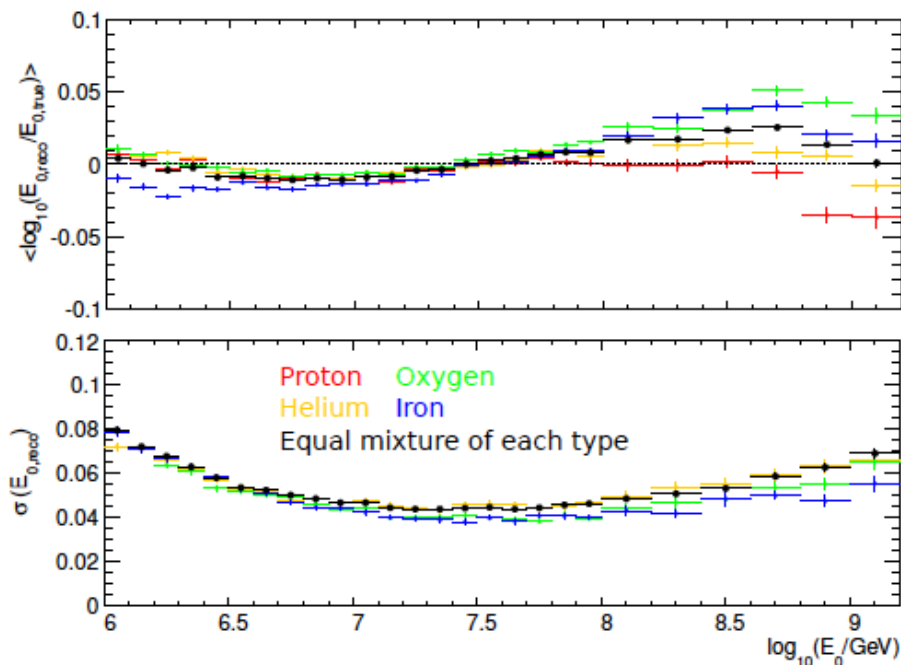
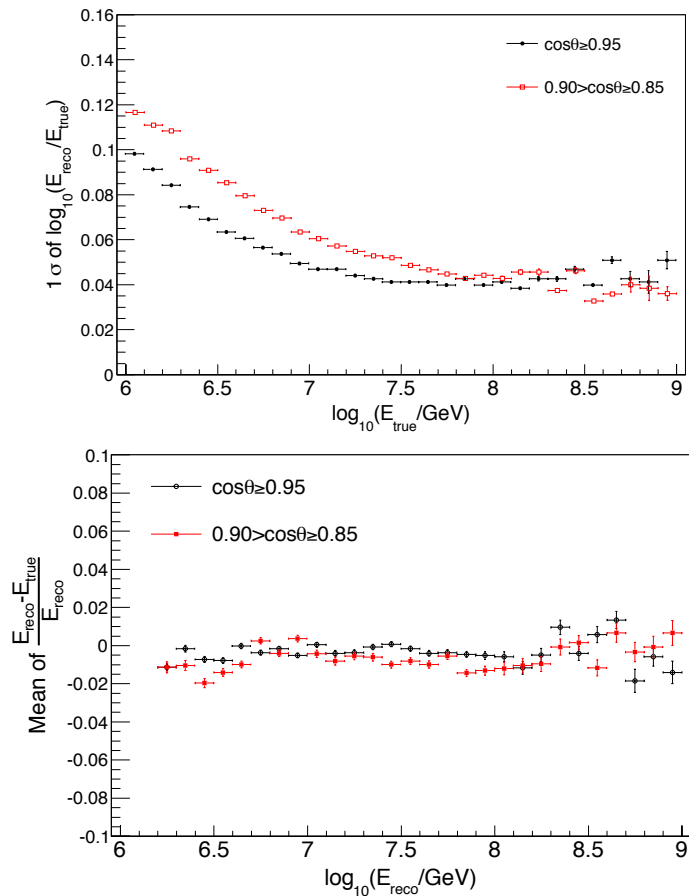
IceCube-79 / IceTop-73 Analysis

June 2010 – May 2011

Surface Only: IT73

Surface and In Ice: IC79/IT73

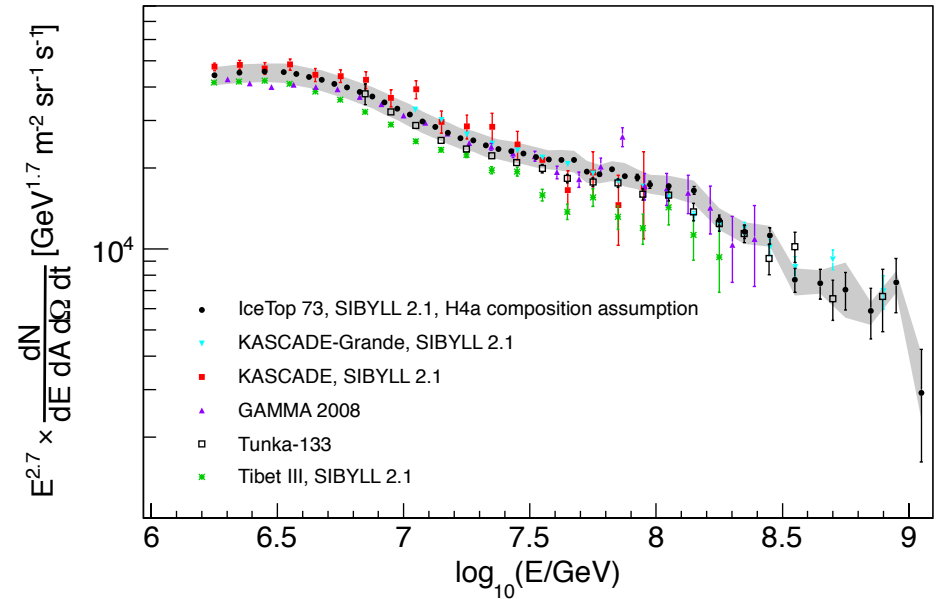
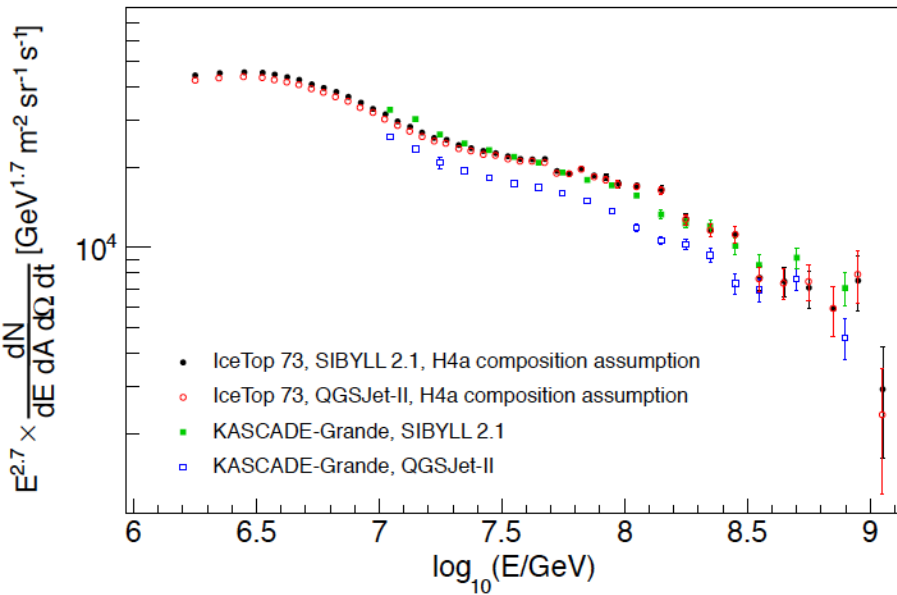
Energy Resolution



use variable bin sizes: $\Delta \log_{10}(E) = 0.05$ for $6.5 < \log_{10}(E/\text{GeV}) < 8$
 $\Delta \log_{10}(E) = 0.1$ for $6.2 < \log_{10}(E/\text{GeV}) < 6.5$ and $8 < \log_{10}(E/\text{GeV}) < 9$

IceTop-73 Analysis

Energy Spectrum



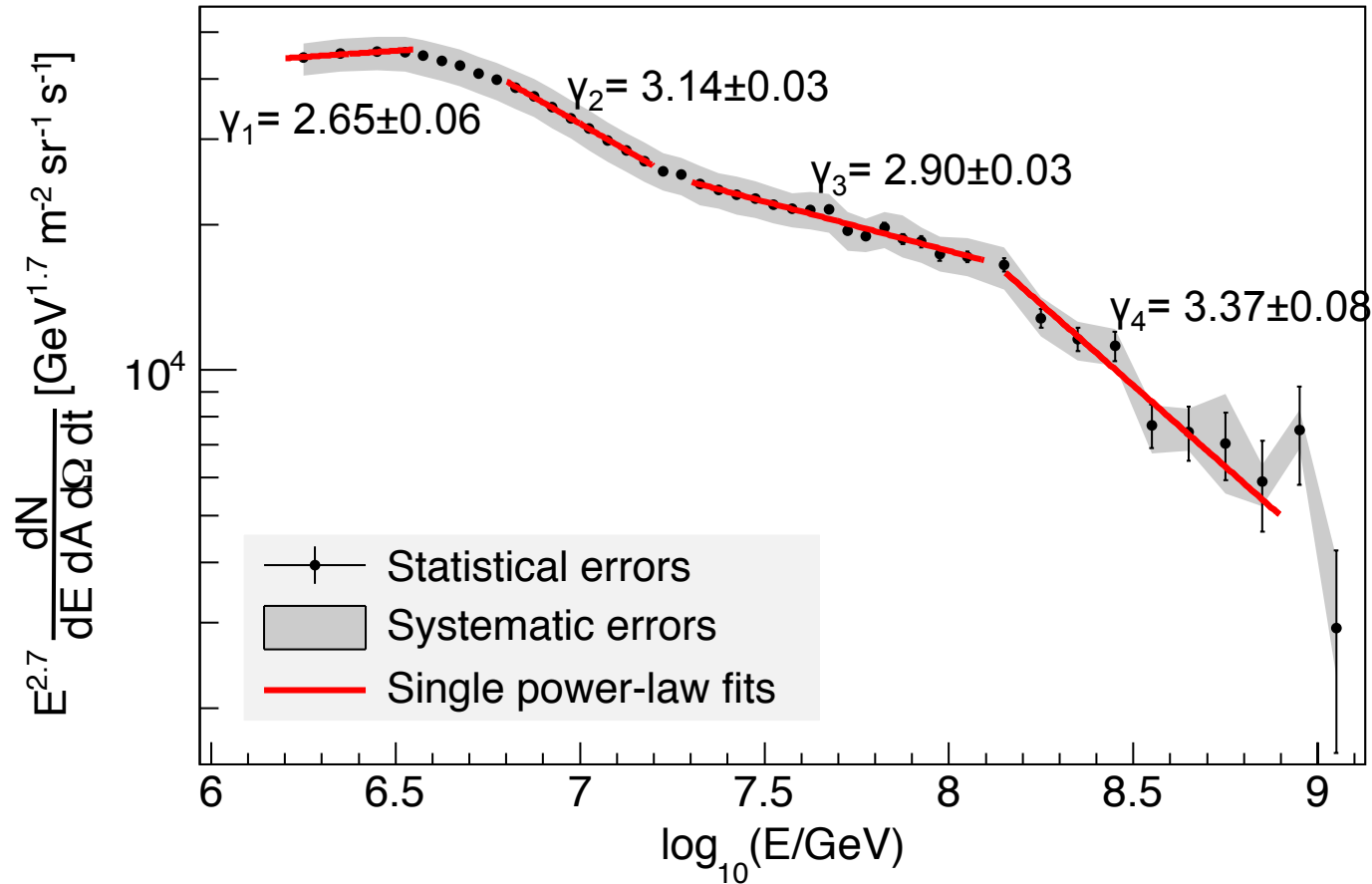
- IceTop: high altitude, near X_{max}
dominated by EM
- KASCADE-Grande: sea level
EM + GeV muons

sea level is better probe to see
interaction model differences

Good agreement between
experiments

IceTop-73 Analysis

Energy spectrum 1.58 PeV to 1.26 EeV



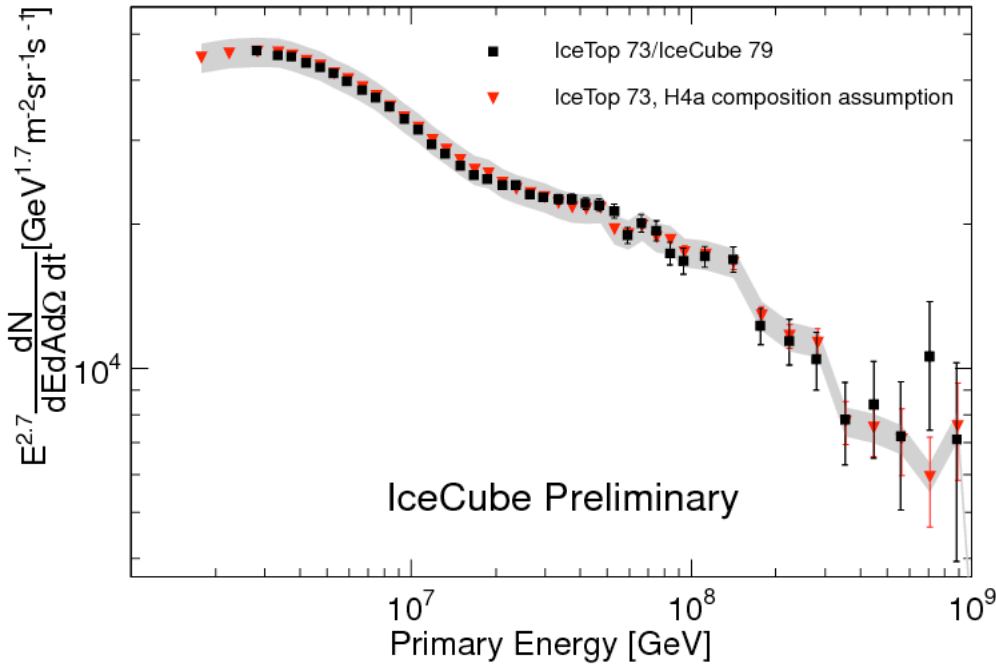
Large scale structure
in spectrum

- Spectrum does not follow a simple power law above the knee up to 1 EeV.
- Spectral hardening at 18 ± 2 PeV (124800 events expected, 139880 observed)
- Spectrum steepens at 130 ± 30 PeV (4213 events expected, 3673 observed)

accepted for publication in Phys. Rev. D

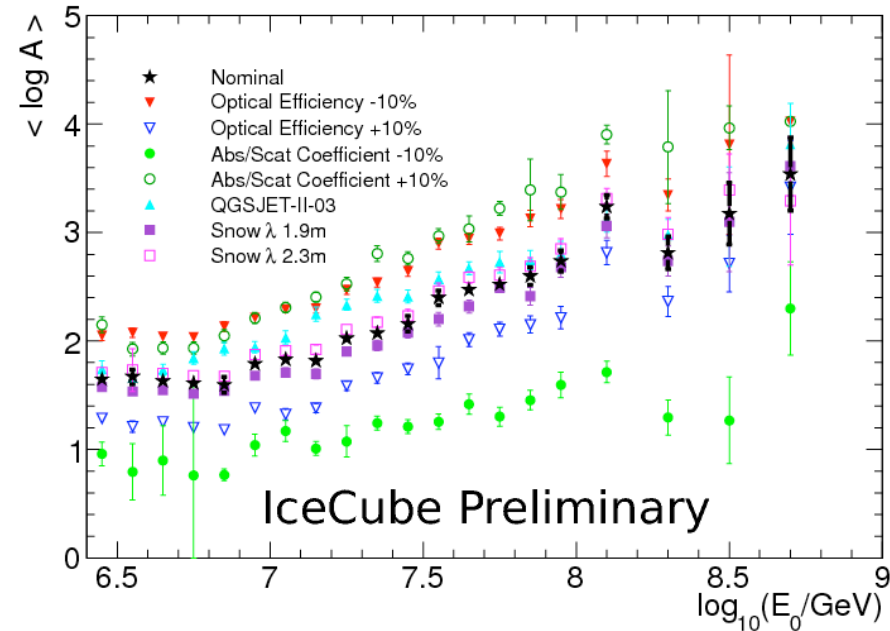
IceCube-79 / IceTop-73 Coincidence Analysis

Systematics under study – will finalize soon



gray band is ± 7 composition systematics of IceTop-73 analysis

Excellent agreement between
two independent analyses



clear trend towards heavier
composition up to ~ 100 PeV

Large Scale Anisotropy with IceCube / IceTop

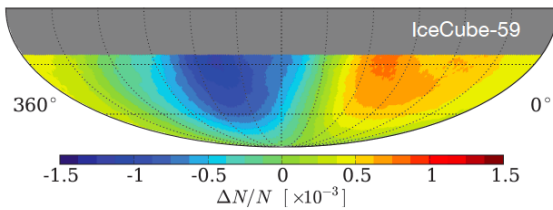
IceCube

muon bundles > 1 TeV

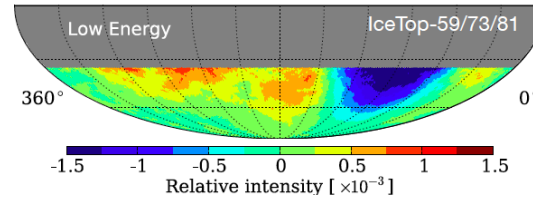
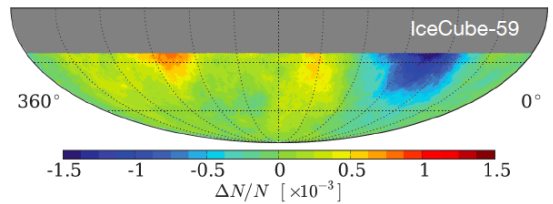
IceTop

CR showers > 100 TeV

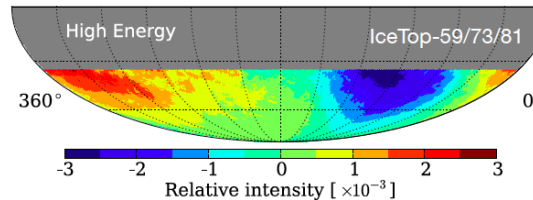
20 TeV



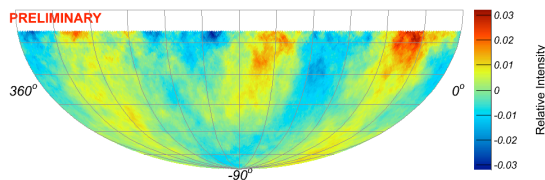
400 TeV



2 PeV



10 PeV



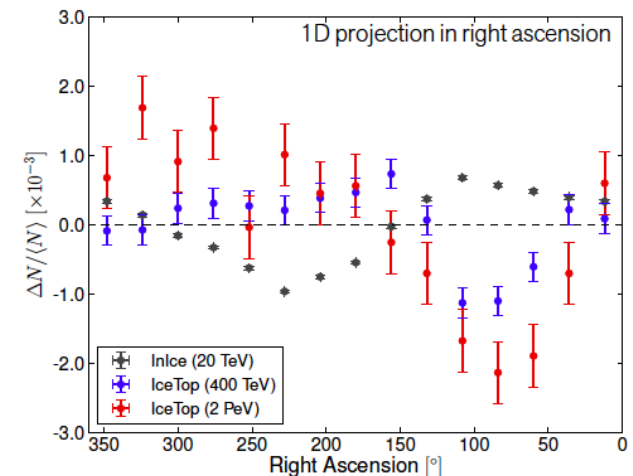
IceCube, ApJ 746, 33 (2012)

IceCube, ApJ 765, 55 (2013)

topology changes
between 20 - 400 TeV

anisotropy is not dipole

amplitude increases
with energy



PeV Gamma Astronomy with IceCube / IceTop

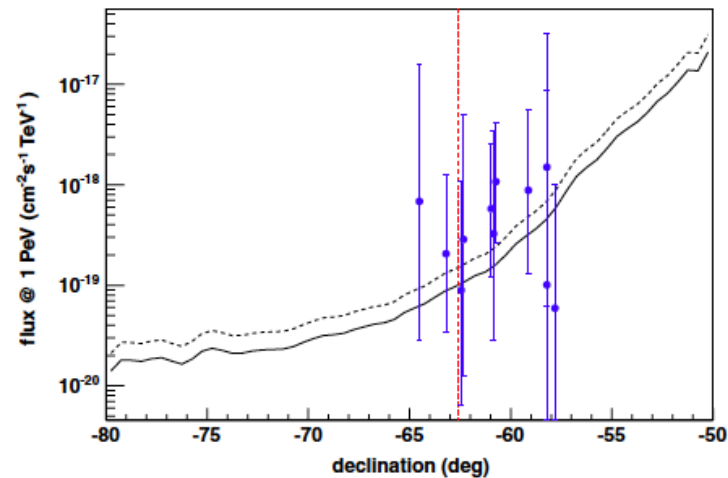
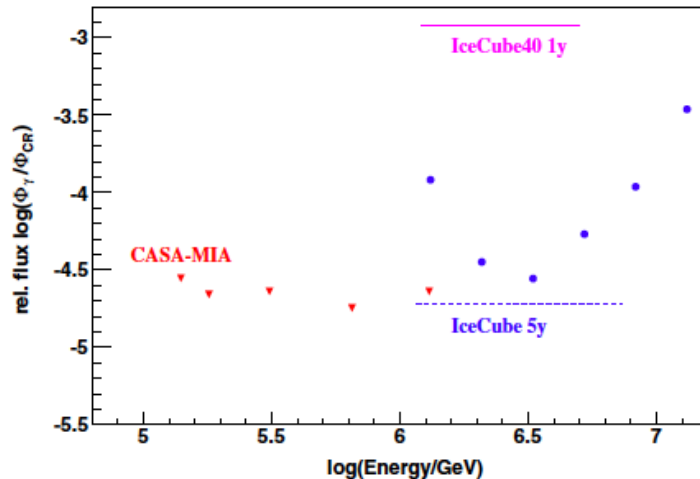
Look for muon poor showers:

- Select IceTop showers with cores going through IceCube
- No activity in IceCube around the shower axis
 - ➔ threshold ~ 1 PeV
 - ➔ event topology restricts field of view to declination range -60° to -90°

268 candidate events found in IceCube-40/IceTop-40 detector configuration (2008/2009)

Search for correlation with the Galactic plane and scan for point sources performed

IceCube, Phys. Rev. D87, 062002 (2013)



- 90% C.L. sensitivity to a diffuse flux from the Galactic plane.
- 5yr sensitivity of IceCube-86 is compatible to existing limits from different regions of the plane.
- 5yr sensitivity of IceCube-86 to point sources near the Galactic plane.
Assume sources do cut off between TeV and PeV
- Several hard gamma-ray sources are in FOV
- IceCube will study these systems

Summary

- High resolution measurement of cosmic ray all particle spectrum and composition in 1.58 PeV – 1.26 PeV region with one year of data from 2010-2011
- Good agreement between recent measurements of other experiments
- Overlap with UHE measurements around EeV
- Spectrum shows large structures hinting to a different mechanism above the knee
- Composition gets heavier up to at least 100 PeV
- Anisotropy changes topology between 20 - 400 TeV, its amplitude increases between 400 TeV and 2 PeV
- ➔ CR modelers of acceleration/propagation need to reproduce these features
- Interesting prospect to search for PeV gamma-rays in correlation with PeV neutrinos