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IceCube High Energy Neutrinos

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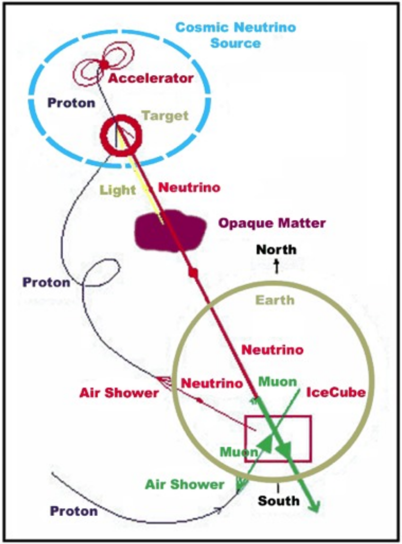
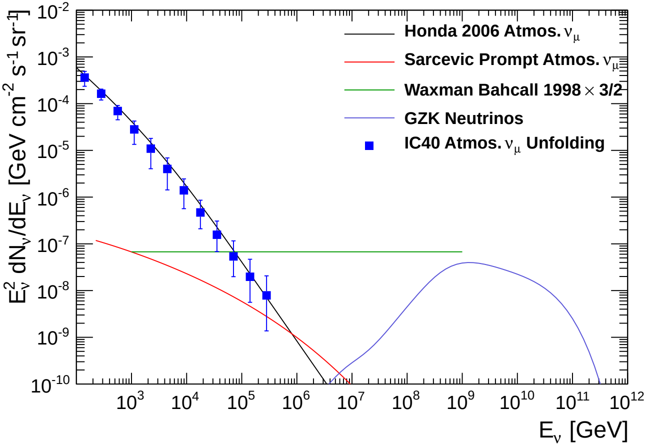
Neutrino Astronomy

Main goal: find cosmic ray accelerators

- Charged particles bend in magnetic fields
- Photons can be blocked, have ambiguous interpretation
- Neutrinos "smoking-gun" hadronic acceleration tracers, fly straight



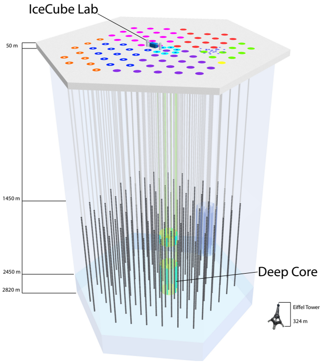
The Neutrino Landscape above 1 TeV

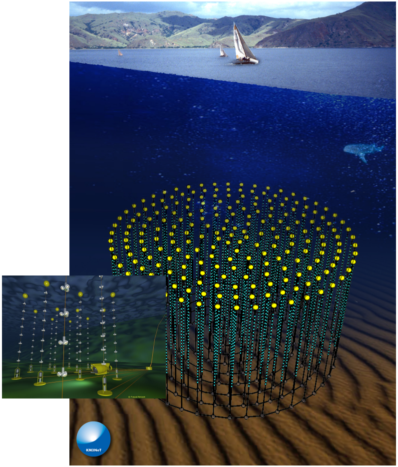


- π/K Atmospheric Neutrinos (dominant < 100 TeV)
- Charm Atmospheric Neutrinos ("prompt", visible ~ 100 TeV)
- Astrophysical Neutrinos (maybe dominant > 100 TeV)
- Cosmogenic Neutrinos ($> 10^6$ TeV)

Gigaton Detectors: the Size Frontier

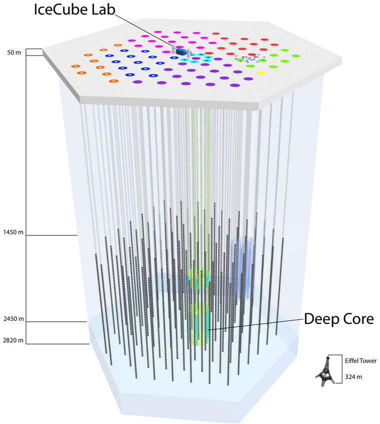
Need natural detectors: IceCube, KM3NET (future), ANTARES, Baikal





IceCube

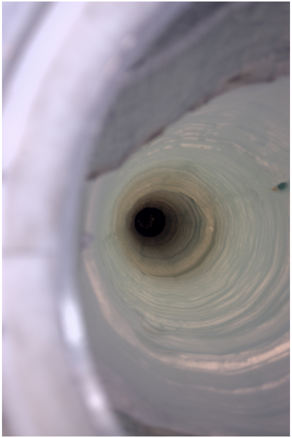
- 5160 PMTs
- 1 km^3 volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 120 m string spacing
- Completed 2010



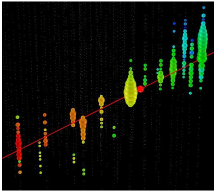
The IceCube Collaboration includes about 250 researchers from 39 institutions around the world. Prof. Francis Halzen, University of Wisconsin – Madison is the principal investigator and Prof. Olga Botner from Uppsala University serves as the collaboration spokesperson.

Physics Reach of IceCube

- Astrophysical ν
  - Understand Cosmic Ray Source Populations
  - Indirect Dark Matter Searches
  - Lorentz Invariance Violation
  - Direct Observation of ν_τ
- Atmospheric ν
  - Measurement of Atmospheric Neutrino Spectrum (100k events/year)
  - Measurement of θ_{23}
  - Cross-sections at ultra-high energies
  - Cosmic Ray Measurements



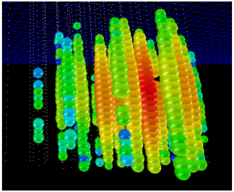
Event Signatures



Muon Neutrino CC (data)

$<$ 1 degree angular resolution

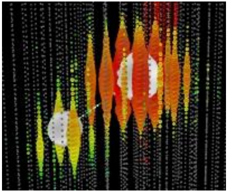
factor of 2 resolution of muon energy



Neutral Current or Electron Neutrino (data)

10 degree angular resolution (high energy)

$\sim$ 15% deposited energy resolution

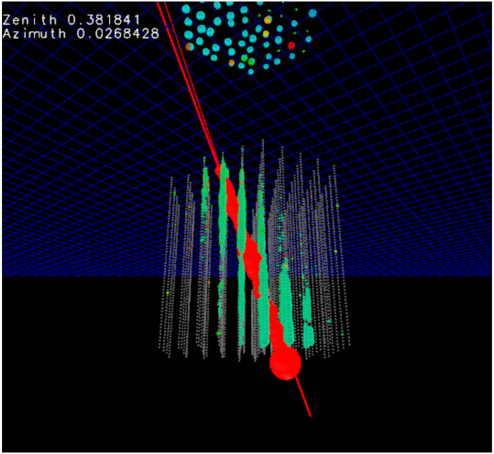


Tau Neutrino CC (simulation)

Backgrounds

Only backgrounds at TeV energies are cosmic ray showers:

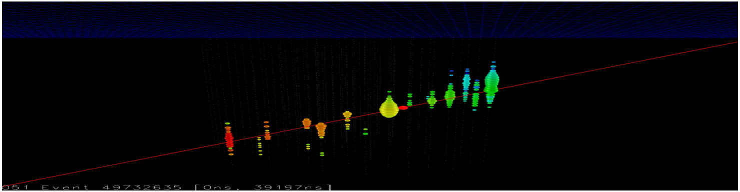
- Muons and neutrinos from southern sky
- Neutrinos from northern sky



Neutrino Identification

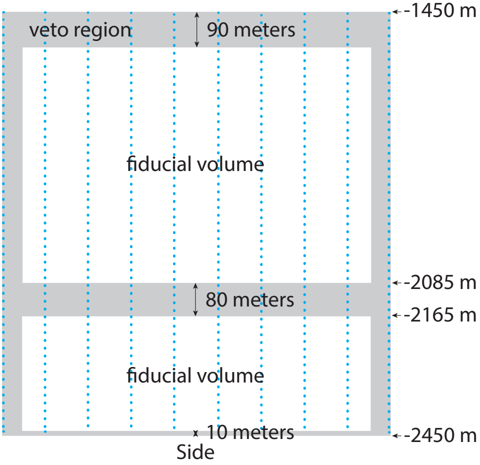
How to identify neutrinos?

1. Upgoing muon tracks
   - Filter out CR muons with bulk of Earth
   - Unknown vertex – hard to measure energy
2. Contained vertex
   - Filter out CR muons using detector edge for anticoincidence
   - All charged particles seen
3. Excess over background
   - Works only for extremely bright/high energy sources

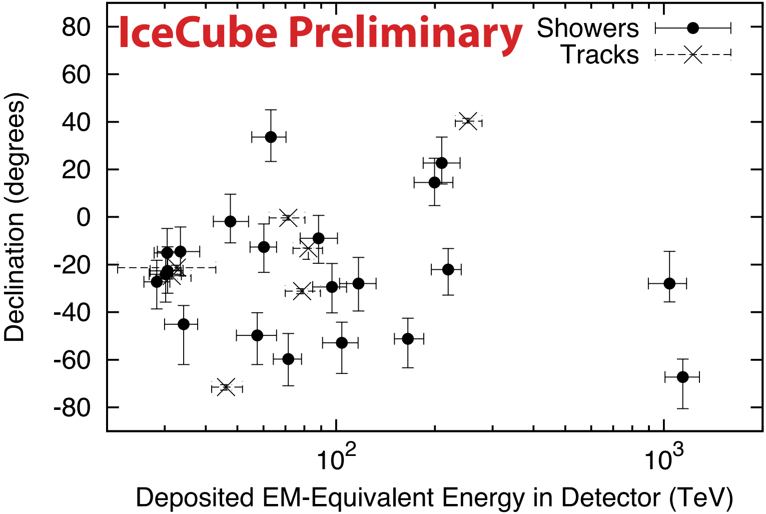


Event Selection For Contained Events

- Define a fiducial volume and a veto region
- Make sure first hits are not on boundary
- Go to high energy (> 6000 PE) to make sure significant numbers of photons expected on boundary
- Topology/direction independent sample
- Becomes efficient at $\sim 50 - 100$ TeV



Results of Contained Vertex Event Search (2010-2012)



28 events (7 with visible muons, 21 without) on background of $10.6^{+5.0}_{-3.6}$

Observables of Interest

Spectral slope Separate extraterrestrial fluxes from atmospheric, probe properties of accelerator

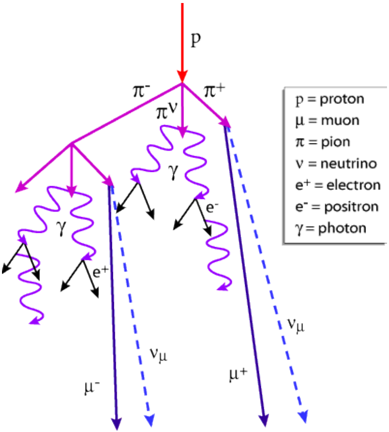
Spectral structure Cutoffs/slope changes may imply population changes

Flavor composition Discrimination against ν_μ dominated backgrounds, probes physics of production process

Zenith distribution Comparison to backgrounds, probes source locations

Vetoing Atmospheric Neutrinos: an Interesting Wrinkle

- Atmospheric neutrinos are made in air showers
- For downgoing neutrinos, the muons from the shower will likely not have ranged out when they arrive at IceCube
- Downgoing events that start in the detector are extremely unlikely to be atmospheric
- Note: optimal use requires *minimal* overburden to have the highest possible rate of cosmic ray muons



Schönert et al. arXiv:0812.4308

Signals and Backgrounds: Why This is Compelling

Signal	Background	Data
✔ Cascade-dominated ($\sim 80\%$) from oscillations	✘ Track-like from CR muons and atmospheric ν_μ	• 21/28 are cascades
✔ High energy? Typically assume E^{-2}	✘ Soft spectrum ($E^{-3.7}$), $\lesssim 1$ event/year $>$ 100 TeV	• Energies to above 1 PeV, 9 above 100 TeV
✔ Mostly (2/3) in southern sky from Earth absorption	✘ Muons in south, atmospheric neutrinos in north	• 24/28 from South, mostly cascades

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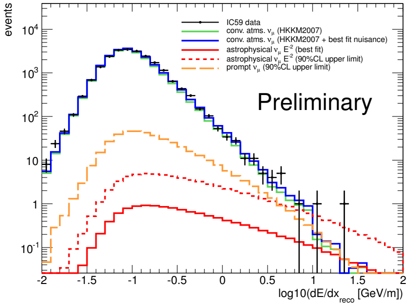
$\rightarrow 4\sigma$ evidence for astrophysical flux

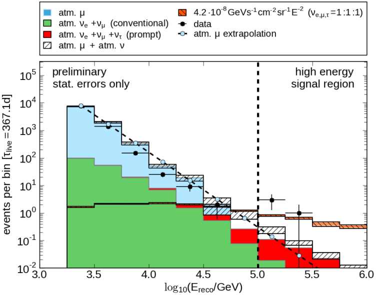
Hints in other channels

IC59 Northern ν_μ arXiv:1302.0127



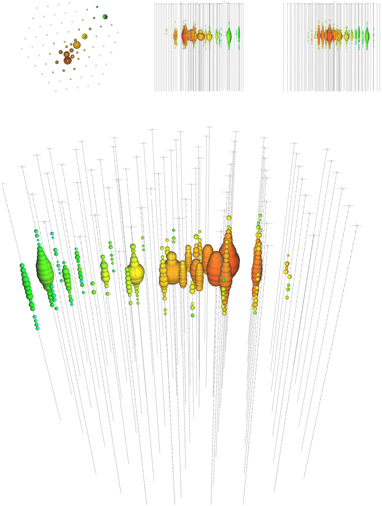
2009, 1.8σ

IC40 Cascades

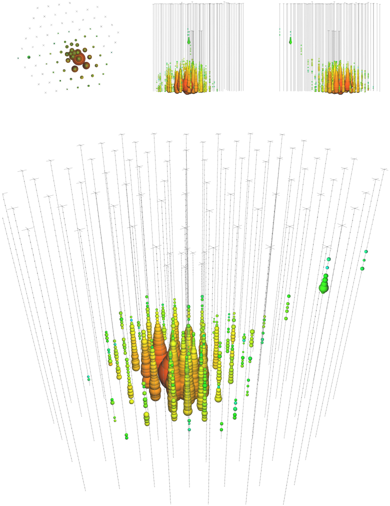


2008, 2.4σ

Some interesting events



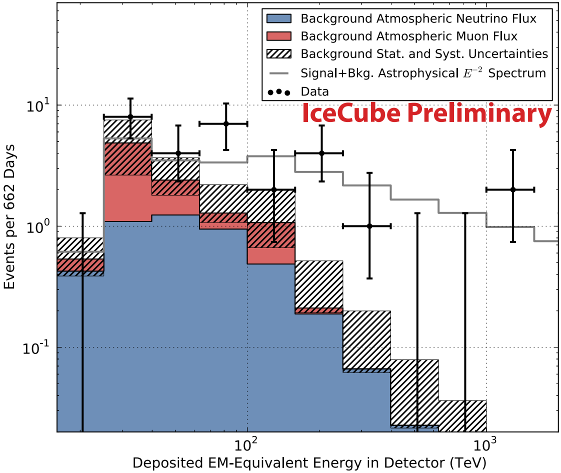
74.1 TeV, -0.4°



252.7 TeV, $+40^\circ$

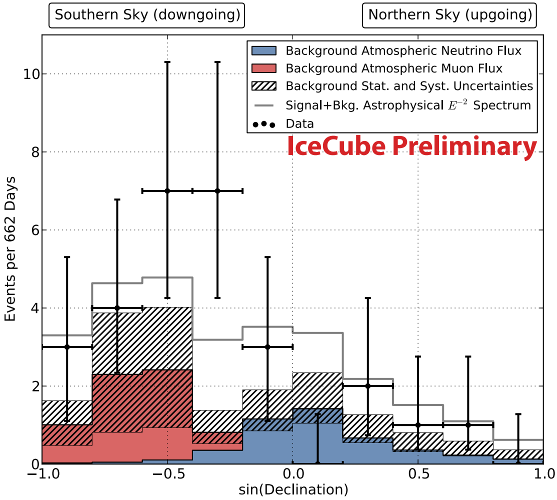
Energy Spectrum

- Harder than any expected atmospheric background
- Merges well into expected backgrounds at low energies
- Potential cutoff around 2 PeV if E^{-2}
- Too few events to measure spectrum well

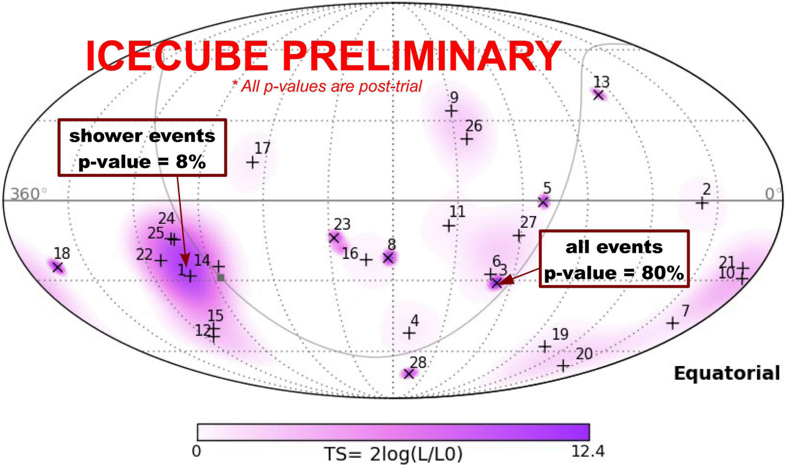


Zenith Distribution

- Compatible with Isotropic Flux
- Events absorbed in Earth from Northern Hemisphere
- Minor excess (1.5σ) in south
- Southern-hemisphere dominance *generically* constrains atmospheric origin



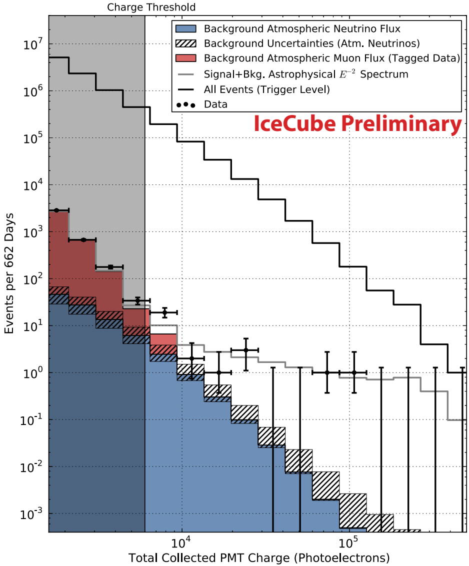
Skymap: Compatible with Isotropy



Too few events to evaluate isotropy or identify sources

Summary

- Energy spectrum seems hard
- Flavor distribution consistent with 1:1:1
- Angular distribution makes atmospheric explanation hard: where are the air showers?
- Matches expectations for astrophysical flux
- Still no evidence for clustering
- Does not continue at E^{-2} past a few PeV
- Hard to characterize without more statistics

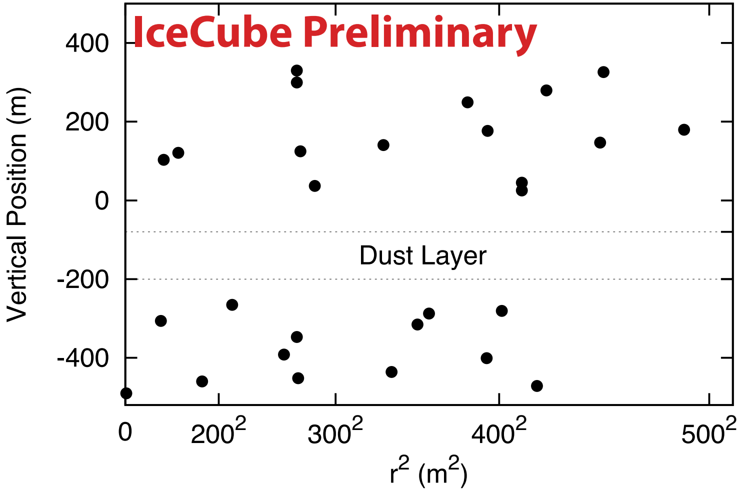


Next Steps

- Atmospheric neutrino veto is a very powerful concept
- Dominant observable channel for astrophysical diffuse flux is 100 TeV - 1 PeV cascade events
- If an astrophysical flux, $\mathcal{O}(20)$ events per year per fiducial gigaton
- Analysis now gives $\mathcal{O}(100)$ events in IceCube in 10 years
- Angular resolution for cascades limited by modelling of light transport and sparse instrumentation
- Need $\mathcal{O}(10)$ events from a source to identify
- Flavor composition probes particle and astrophysics

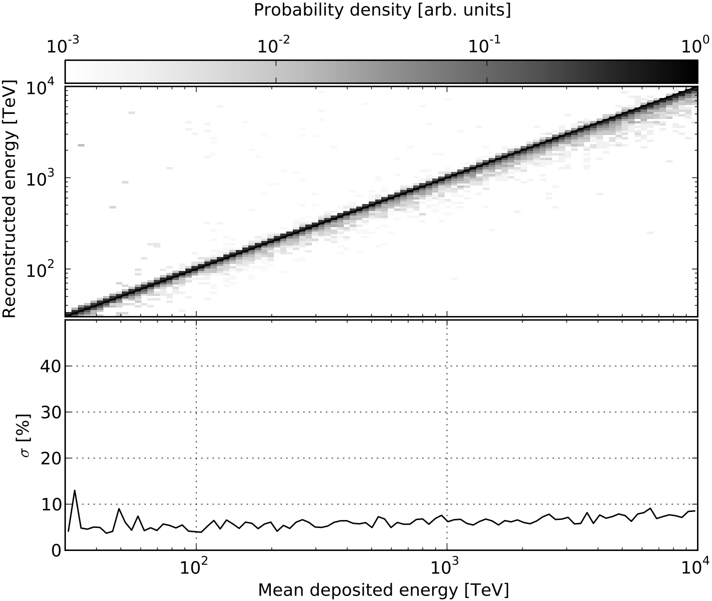
Backup

Event Distribution in Detector

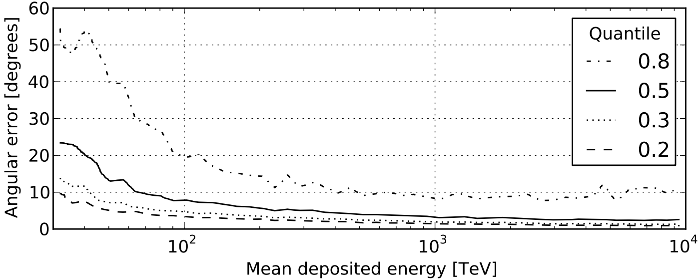


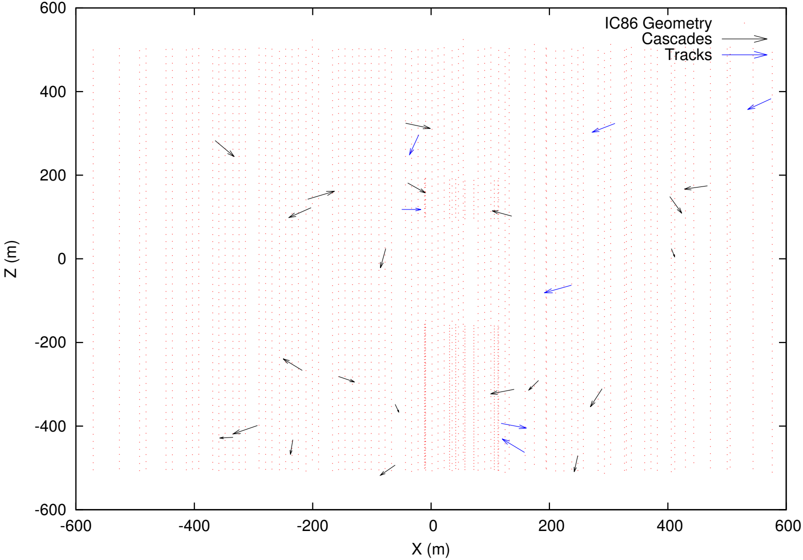
Uniform in fiducial volume

Shower Energy Resolution

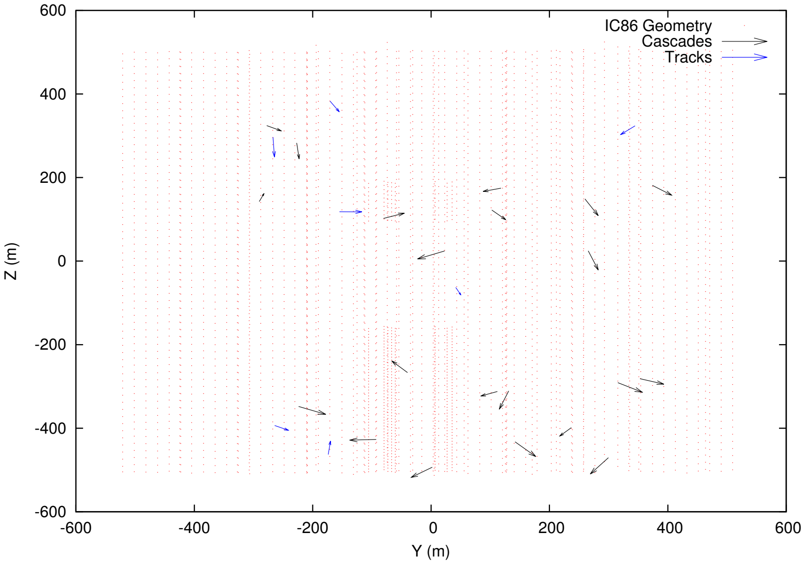


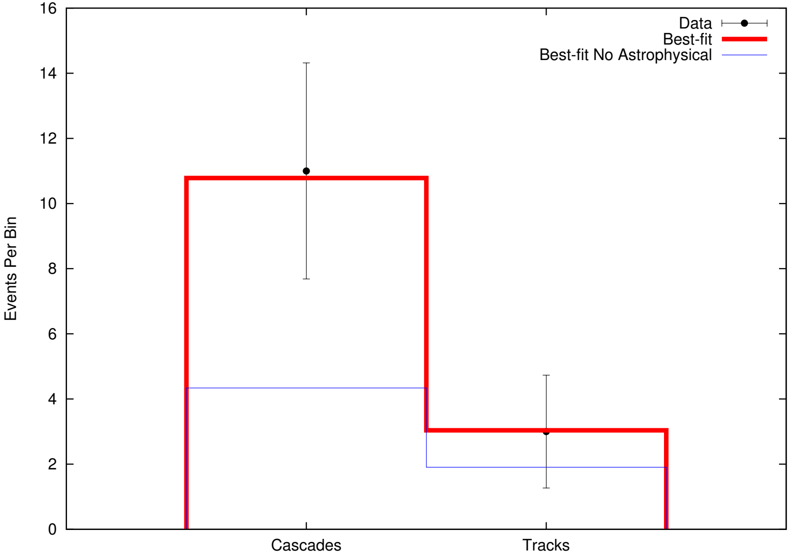
Shower Angular Resolution





IC86 Geometry
Cascades
Tracks
Z (m)
X (m)
600
400
200
0
-200
-400
-600
-600
-400
-200
0
200
400
600


IC86 Geometry
Cascades
Tracks
600
400
200
0
-200
-400
-600
Z (m)
-600
-400
-200
0
200
400
600
Y (m)



Data
Best-fit
Best-fit No Astrophysical
Events Per Bin
0
2
4
6
8
10
12
14
16
Cascades
Tracks