Tue Jan 3 03:34:01 2012

Results from IceCube

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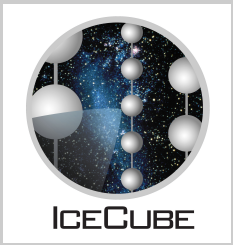
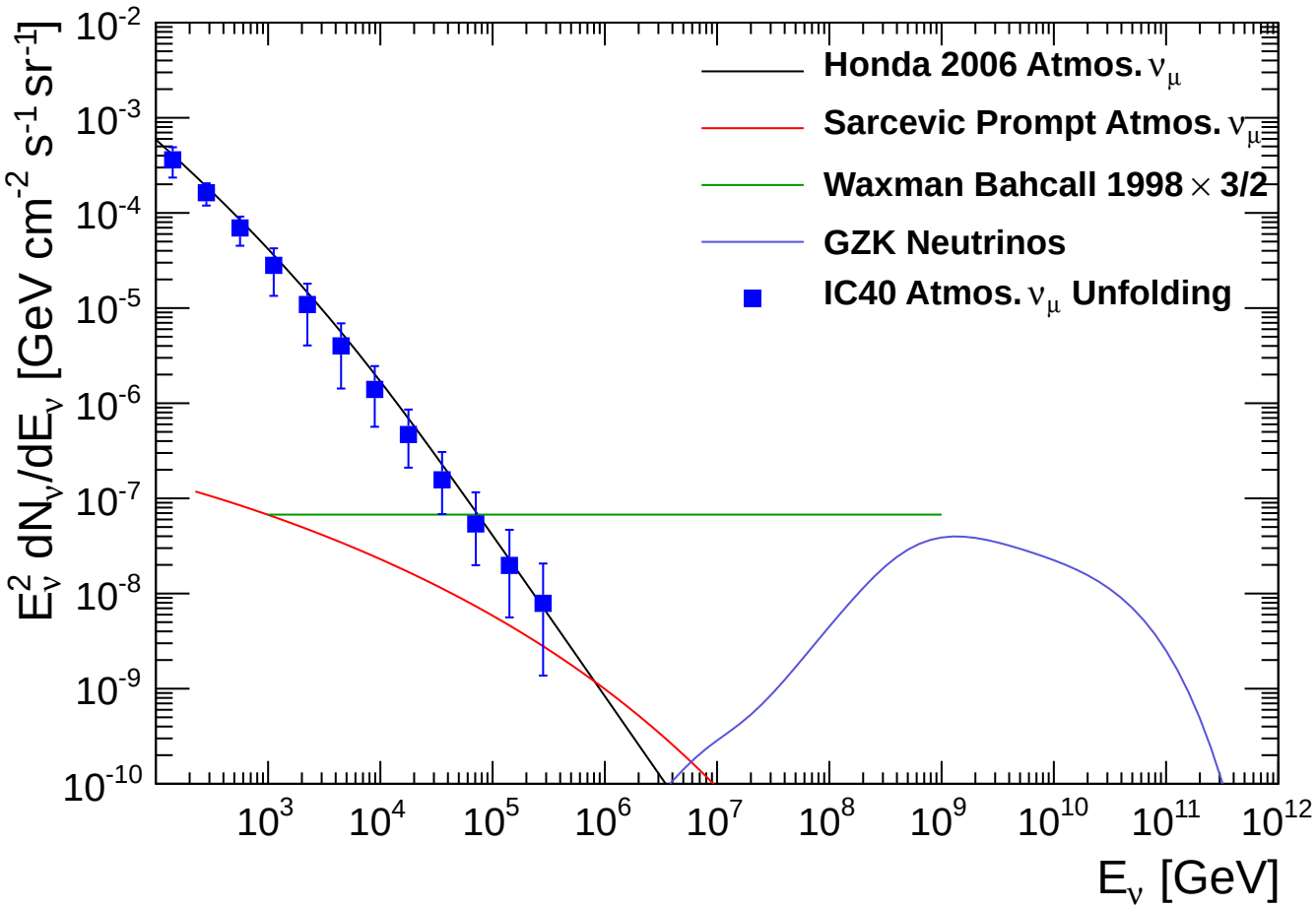
For the IceCube Collaboration

University of Wisconsin - Madison

May 15, 2013



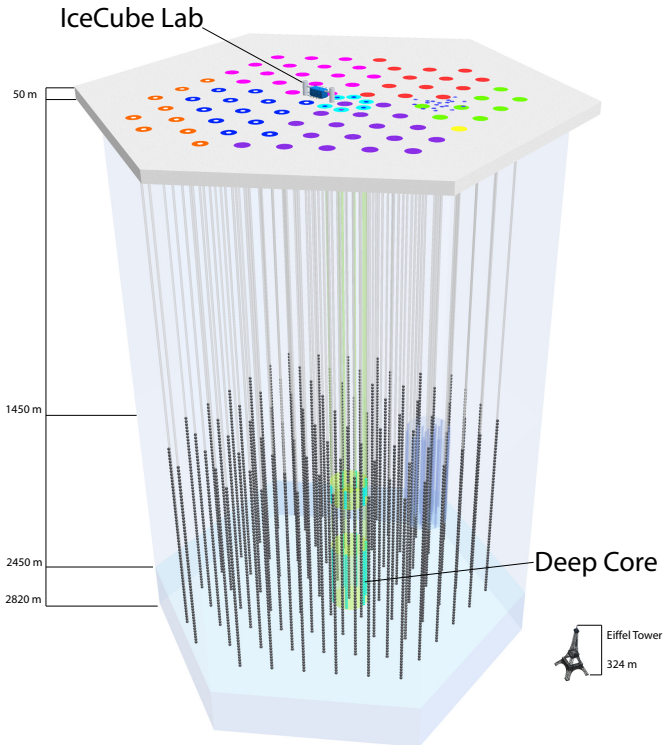
Interesting Neutrinos above 1 TeV

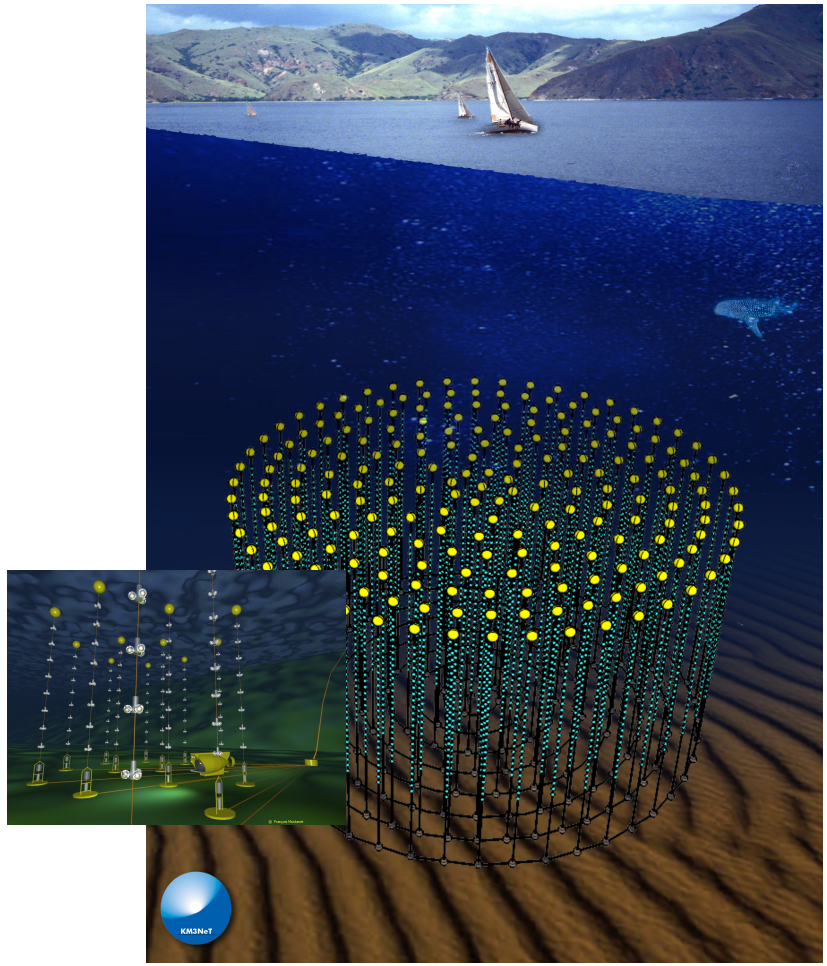


- π/K Atmospheric Neutrinos (dominant < 100 TeV)
- Charm Atmospheric Neutrinos ("prompt", ~ 100 TeV)
- Astrophysical Neutrinos (maybe dominant > 100 TeV)
- Cosmogenic Neutrinos ($> 10^6$ TeV)

Gigaton Detectors To See High-Energy Component

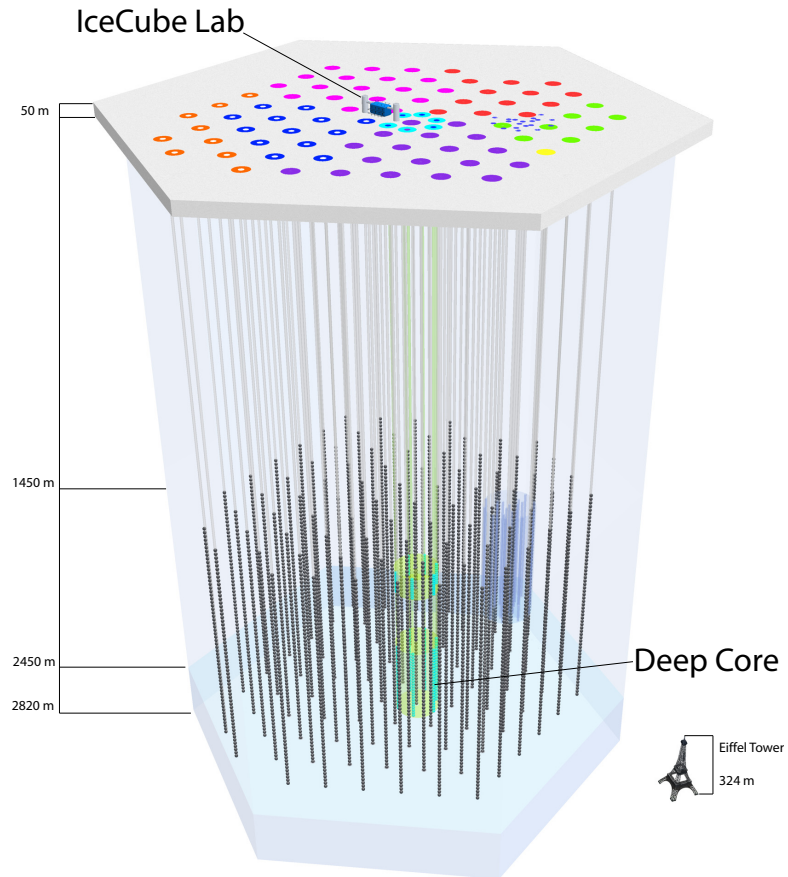
Need natural detectors: IceCube, KM3NET (future), ANTARES, Baikal





IceCube

- 5160 PMTs
- 1 km^3 volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 120 m string spacing
- Angular resolution $\sim 1^o$
- Completed 2010



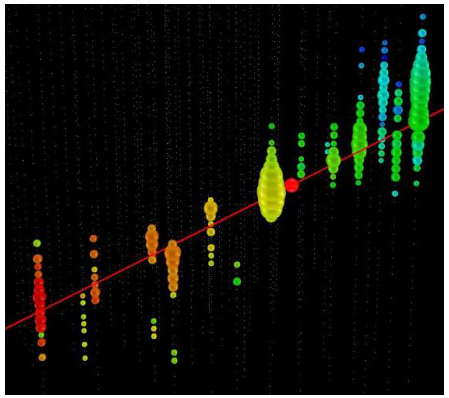
The IceCube Collaboration includes about 250 researchers from 39 institutions around the world. Prof. Francis Halzen, University of Wisconsin – Madison is the principal investigator and Prof. Olga Botner from Uppsala University serves as the collaboration spokesperson.

Event Signatures

Muon Neutrino CC (data)

$<$ 1 degree angular resolution

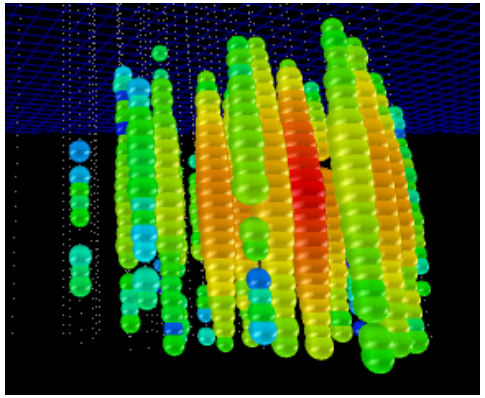
factor of 2 resolution of muon energy



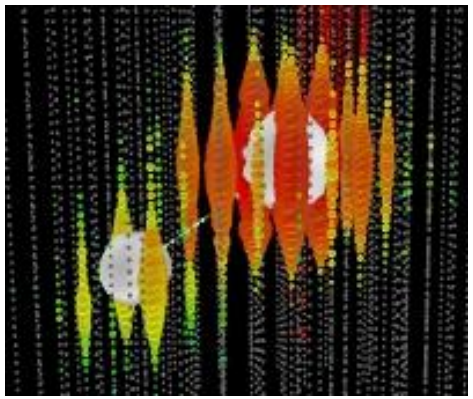
Neutral Current or Electron Neutrino (data)

10 degree angular resolution (high energy)

$\sim$ 15% deposited energy resolution



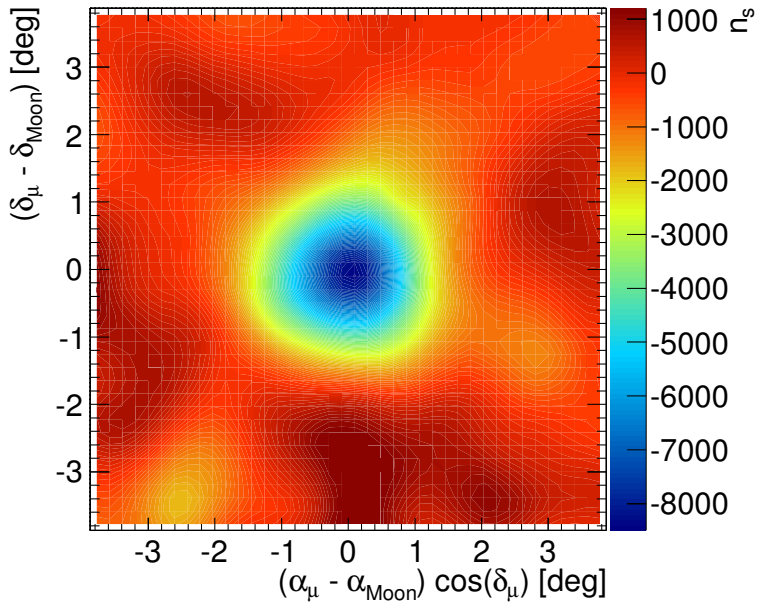
Tau Neutrino CC (simulation)



Calibration

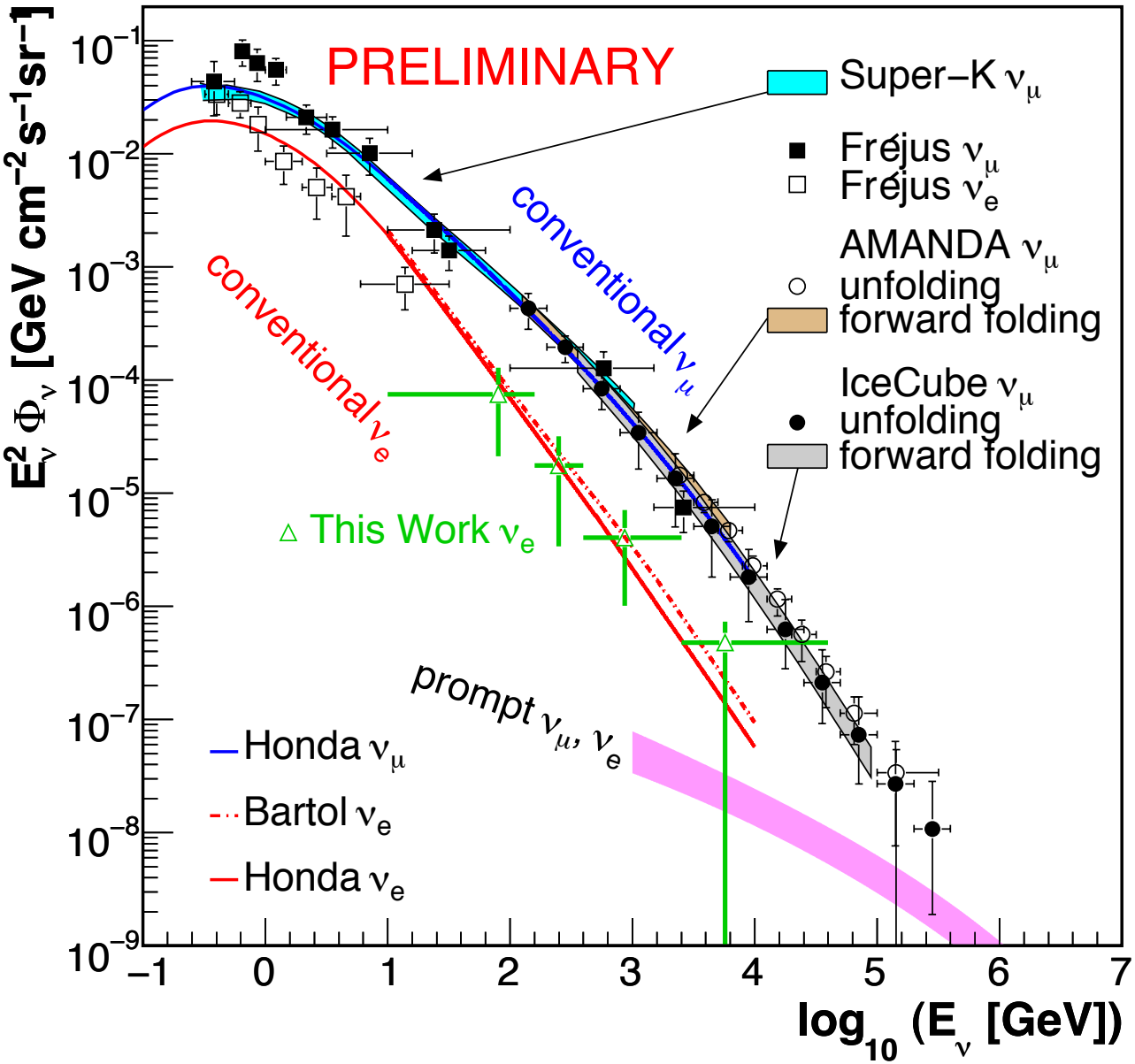
Calibration Sources:

- LED Flashers on each DOM
- In-Ice Calibration Laser
- Cosmic Ray Energy Spectrum
- Moon Shadow
- Atmospheric Neutrino Energy Spectrum
- Minimum-Ionizing Muons



Moon Shadow in Cosmic Ray Muons in IceCube (59 strings)

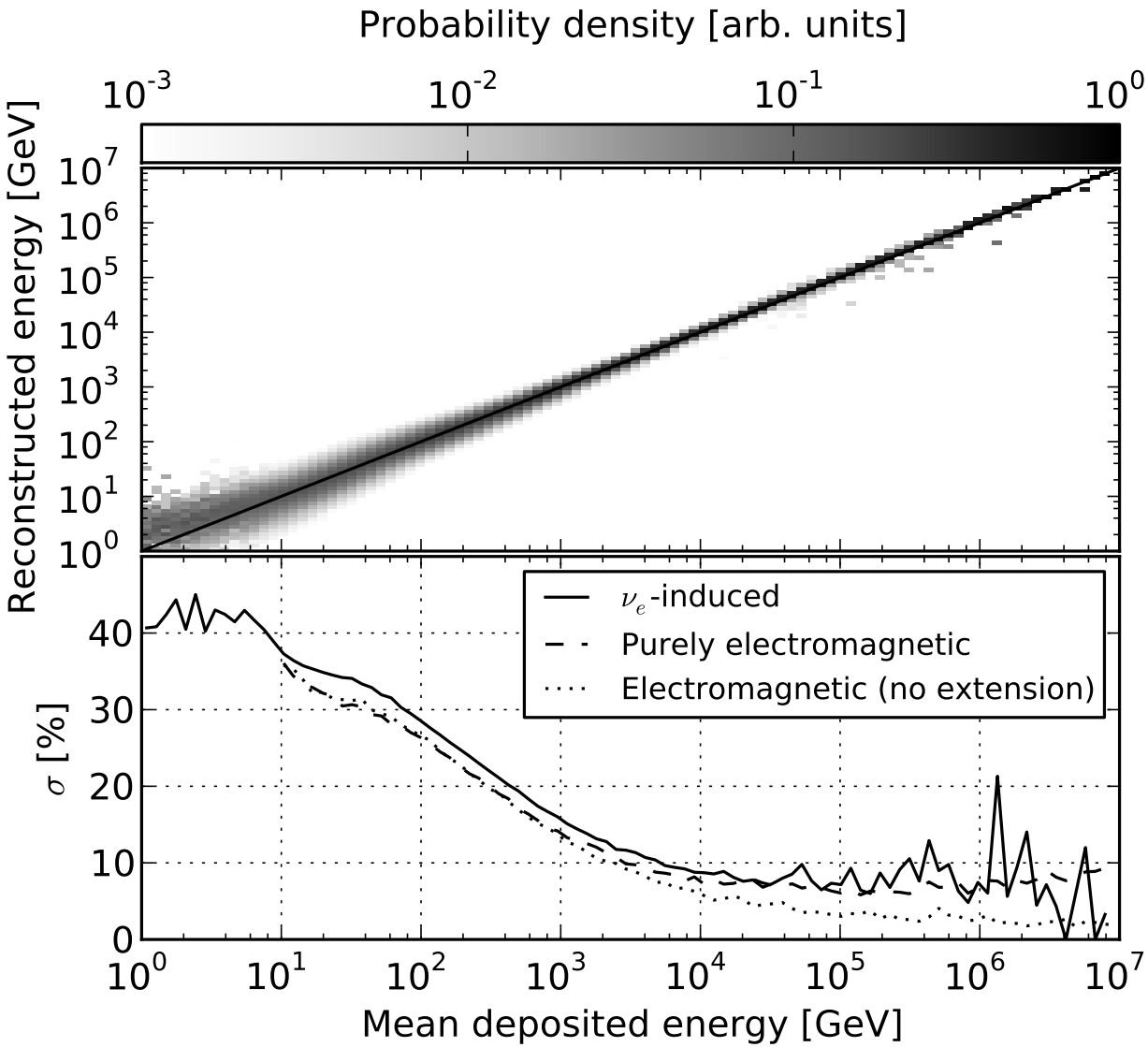
Atmospheric Spectrum

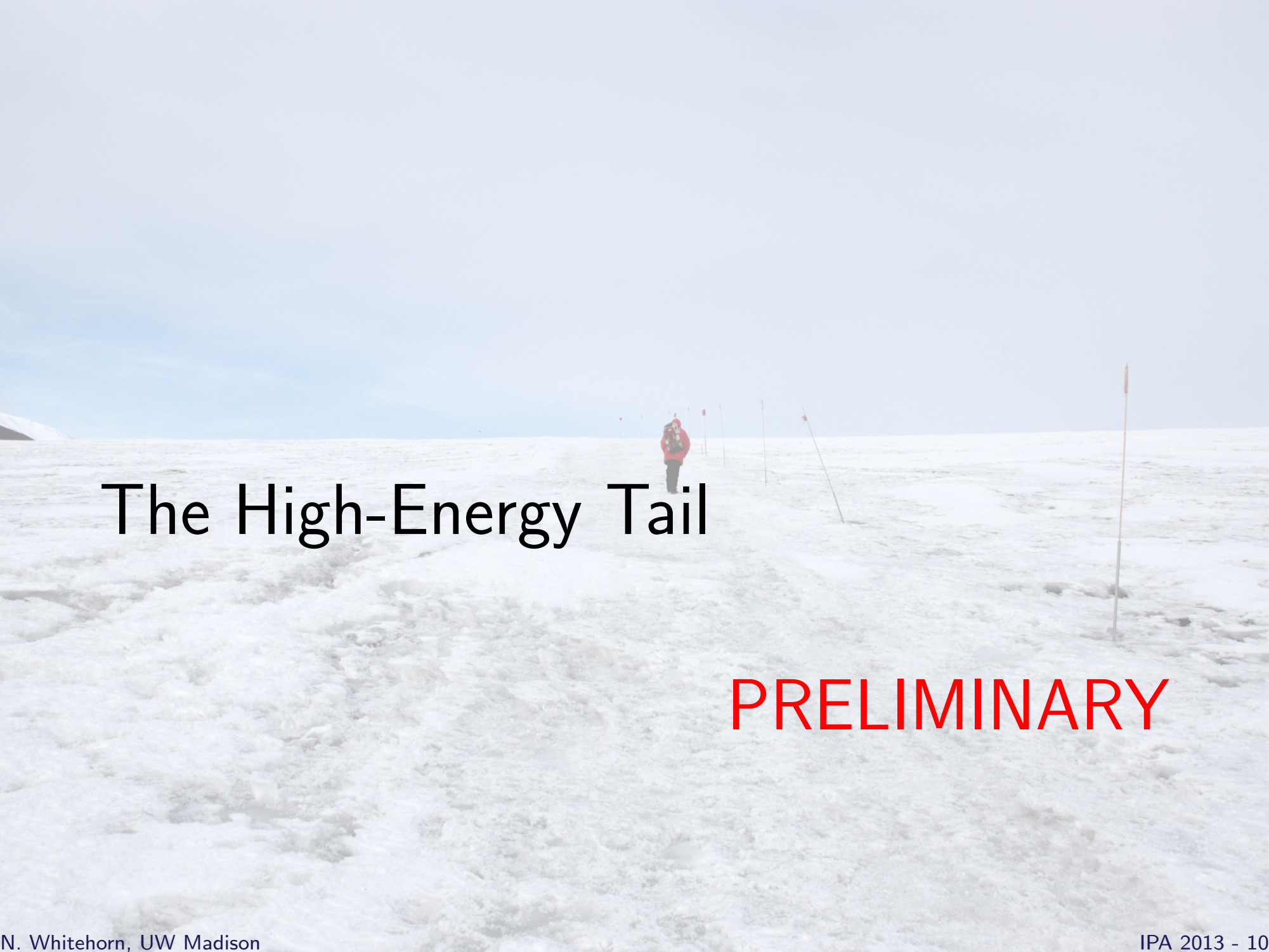


PRL 110 (2013) 151105

Energy Reconstruction

Good energy resolution for showers, systematics limited > 10 TeV





The High-Energy Tail

PRELIMINARY

Signals and Backgrounds

Signal:

- Cascade-dominated ($\sim 80\%$ per volume) from oscillations
- High energy? Typically assume E^{-2}
- Mostly in southern sky from Earth absorption

Background:

- Track-like from CR muons and atmospheric ν_μ
- Soft spectrum ($E^{-3.7} - E^{-2.7}$)
- Muons in south, neutrinos in north

Observables of Interest

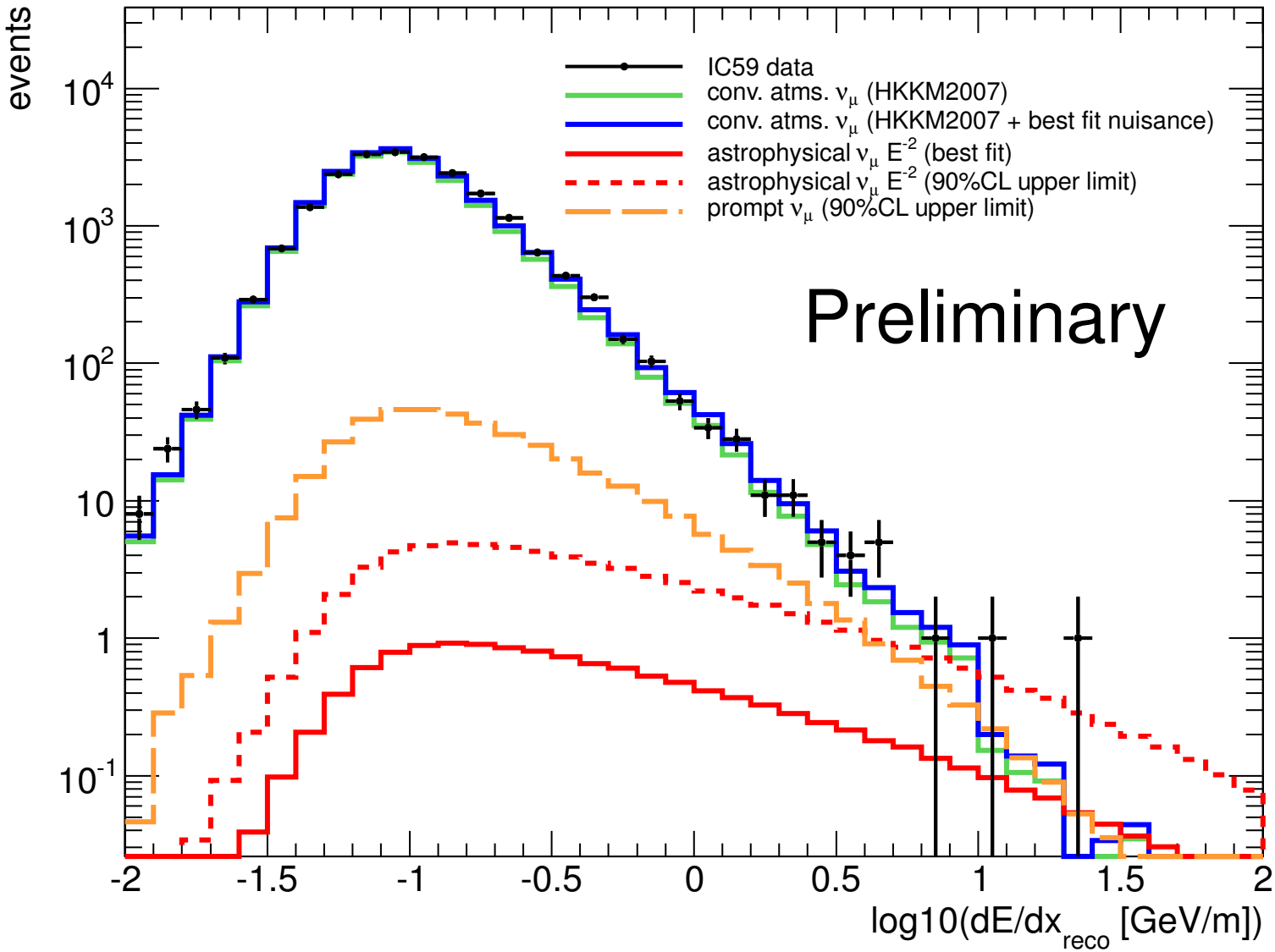
Spectral slope Separate extraterrestrial fluxes from atmospheric, probe properties of accelerator

Position of possible cutoff Maximum energy reach of accelerator – different objects below/above knee?

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

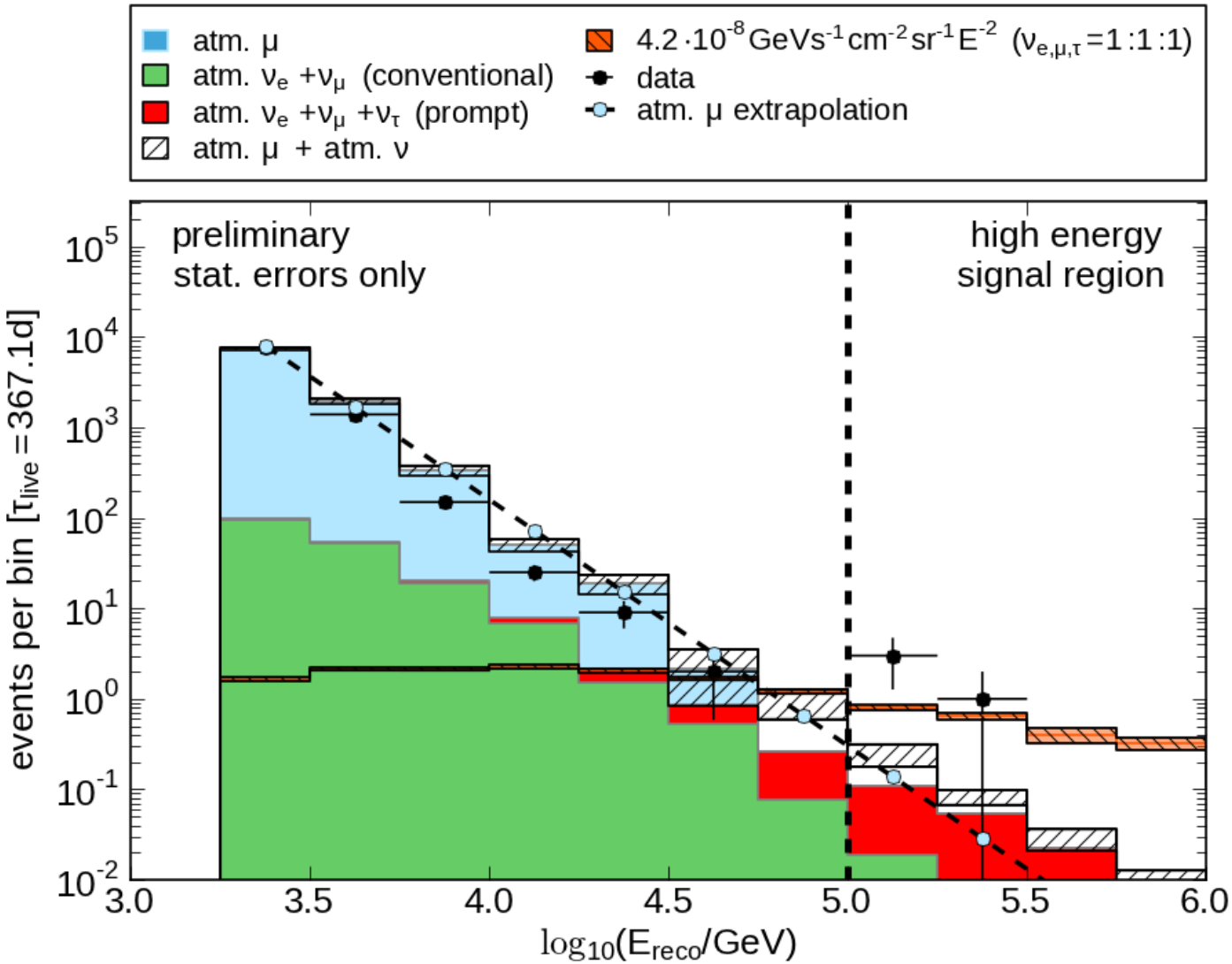
Zenith distribution Comparison to backgrounds, probes source locations

First Hint in IC59 Upgoing Muons (2.1σ)



arXiv:1302.0127

Second Hint in IC40 Showers (2.4σ)

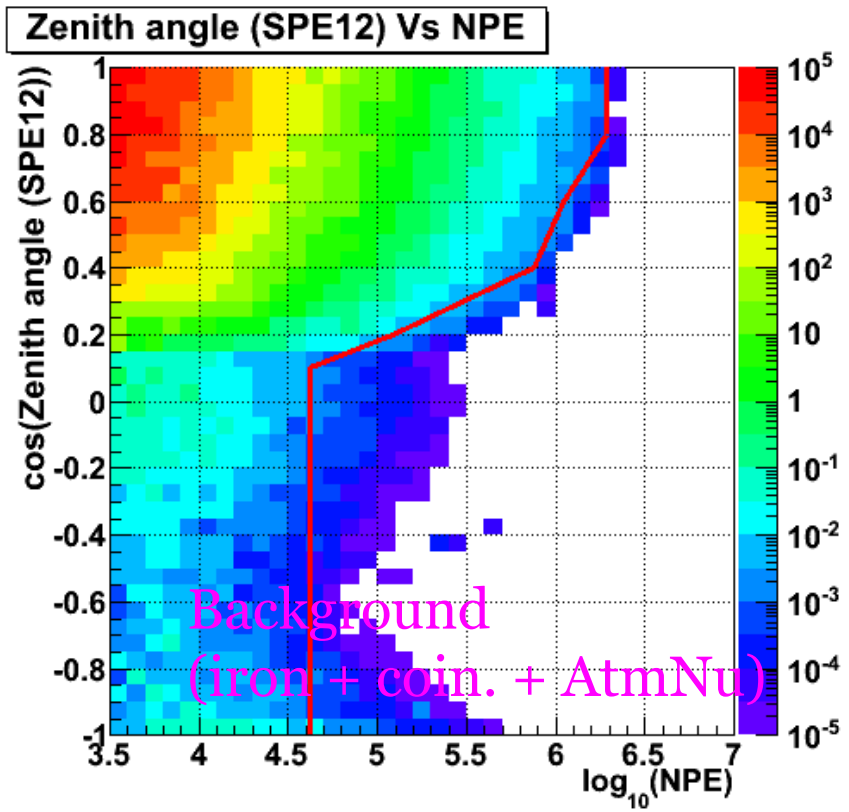


E. Middell, DESY Zeuthen

Things Become Interesting: GZK Neutrino Analysis

Simple search to look for extremely high energy (10^9 GeV) neutrinos from proton interactions on the CMB:

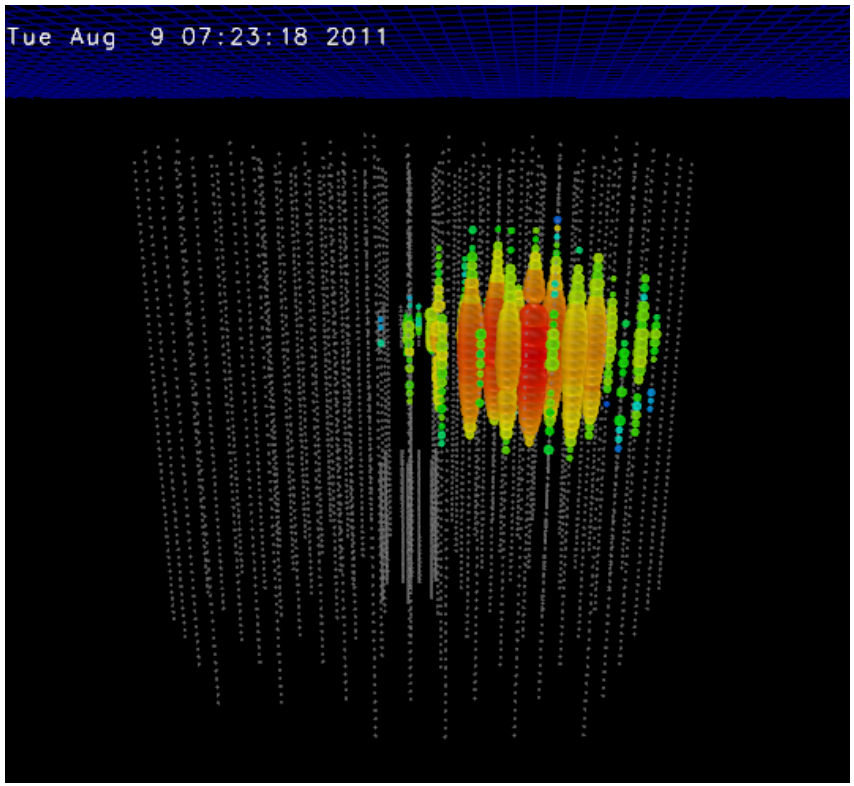
- Upgoing muons
  - Always neutrinos
  - Atmospheric neutrino background
  - High threshold (1 PeV)
- Very highest energy downgoing muons
  - Cosmic Ray muon background
  - Very high energy threshold (100 PeV)
  - Only sensitive to GZK-type events ($E_\nu \gtrsim 10^{18}$ eV)



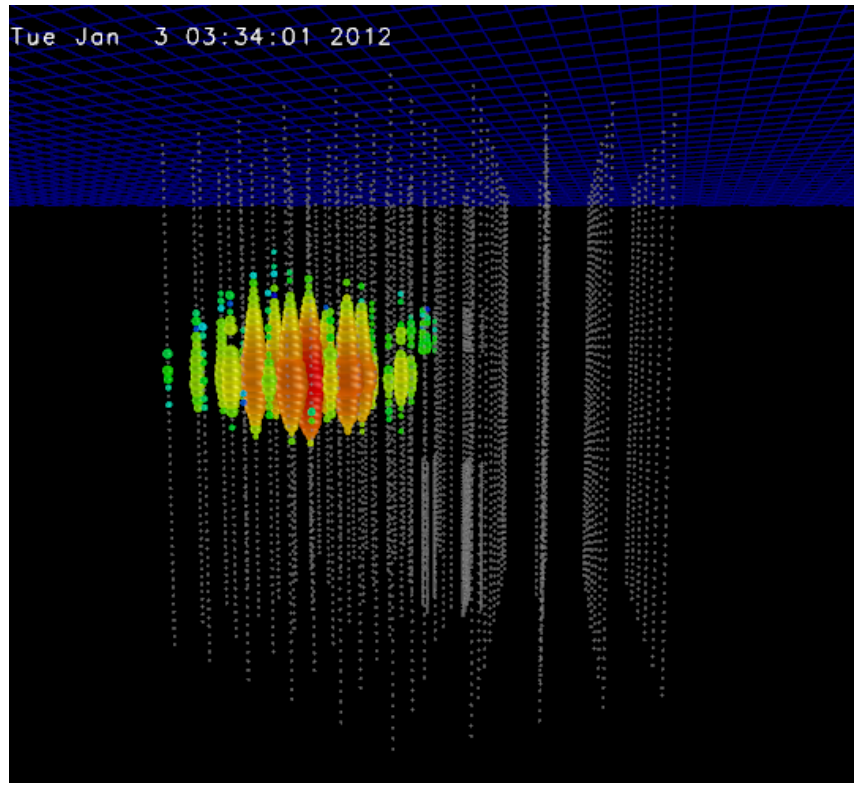
arXiv:1304.5356

Results (2.8σ)

Appearance of ~ 1 PeV neutrinos at lower energy threshold

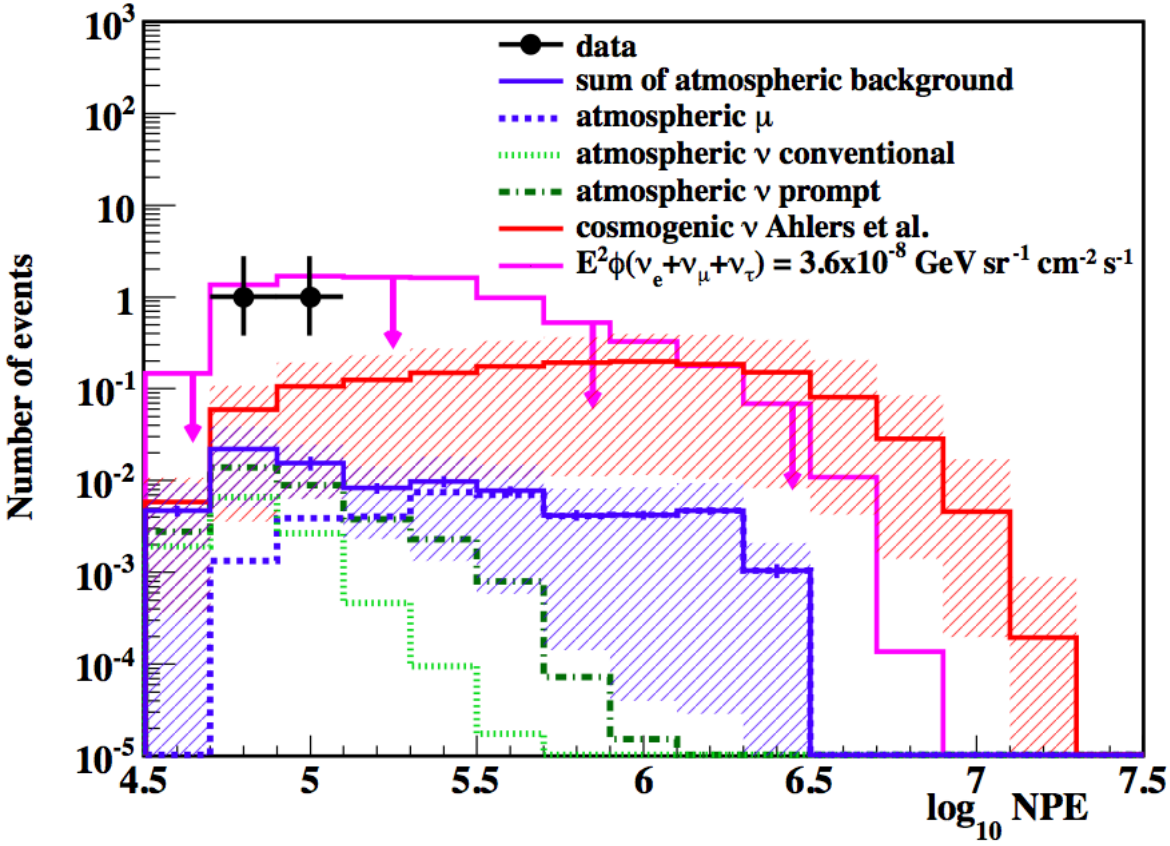


"Bert"
~ 1050 TeV



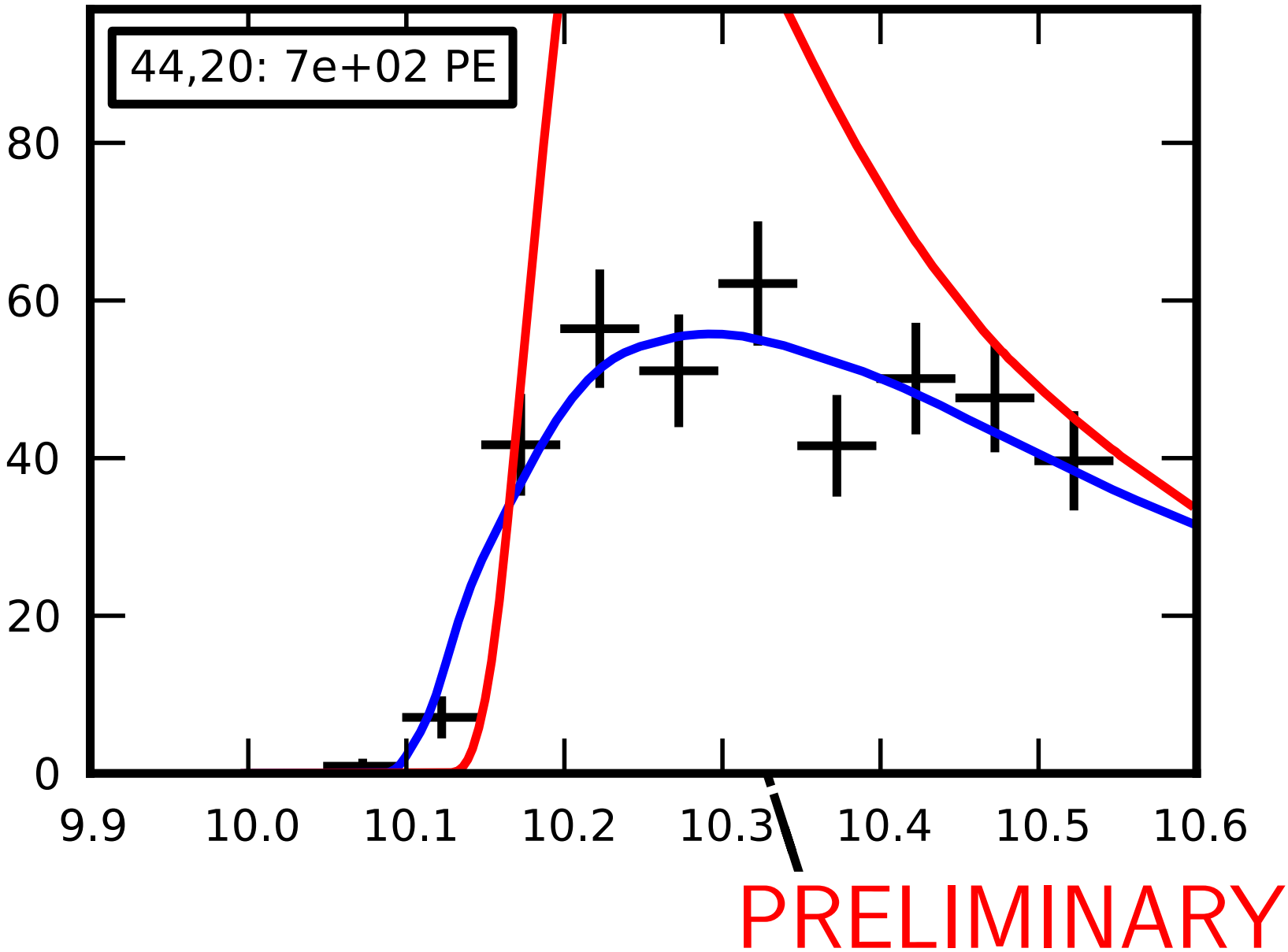
"Ernie"
~ 1150 TeV
arXiv:1304.5356

Comparison to Expectations

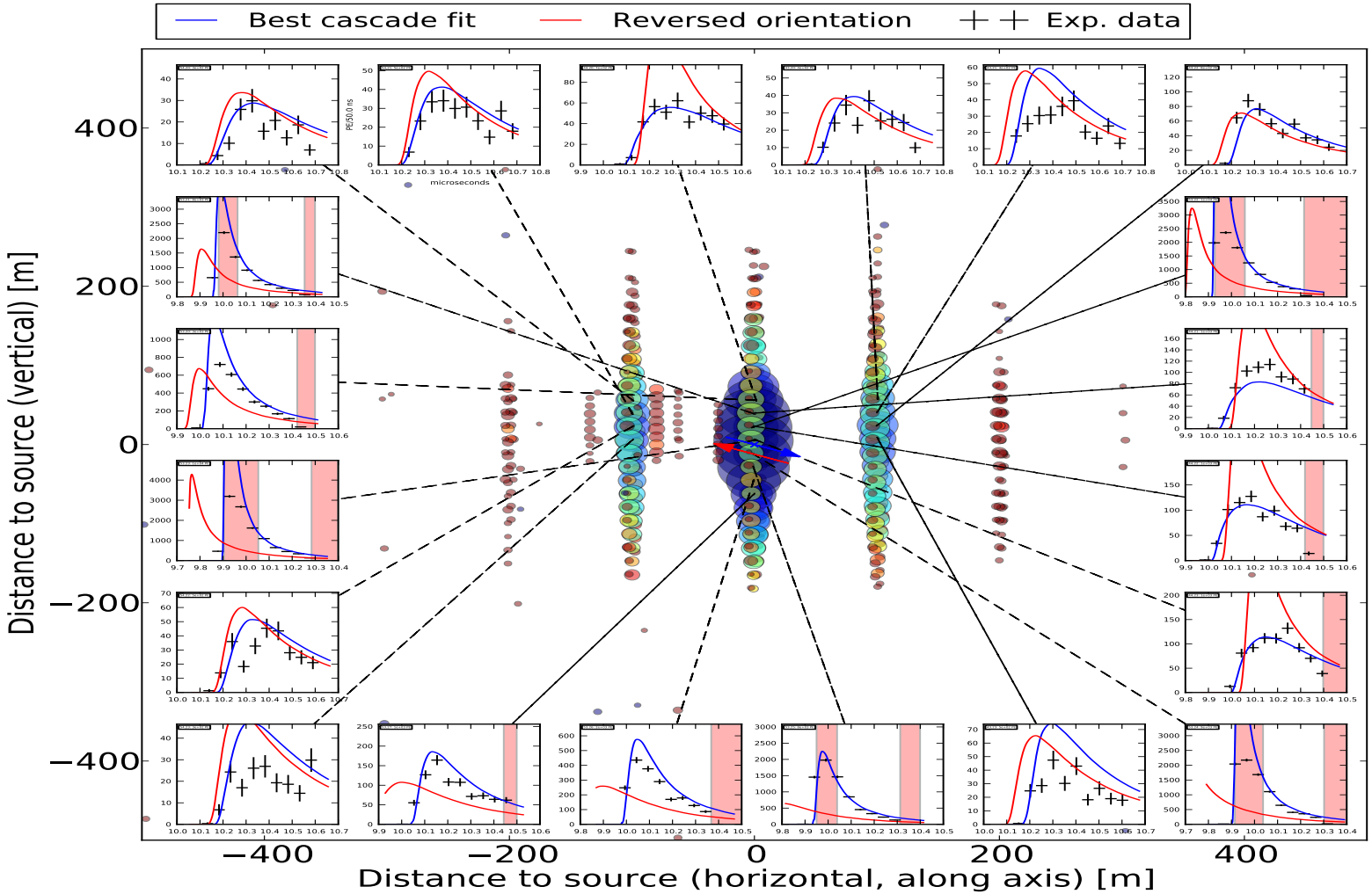


- Too low in energy for GZK
- Seems too high in energy for atmospheric

What are they?



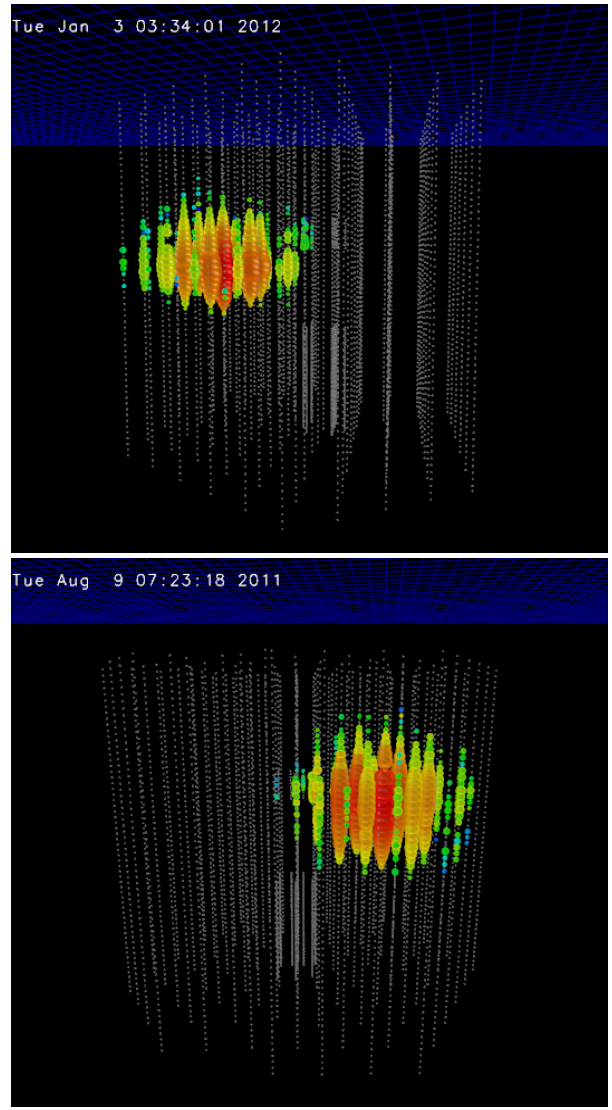
What are they?



PRELIMINARY

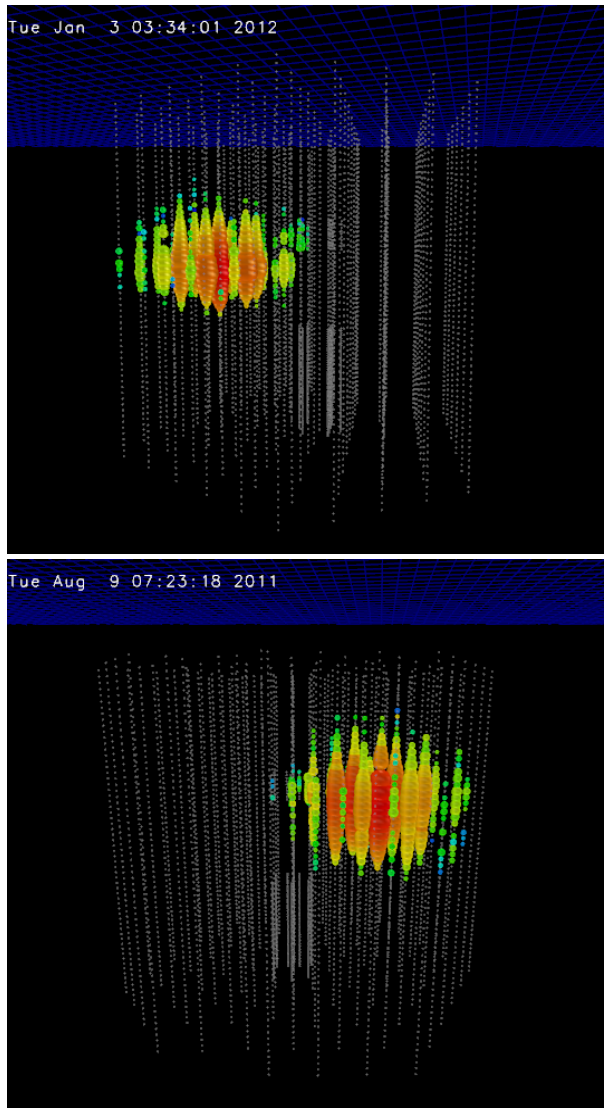
Things We Learned

- At least two PeV neutrinos in 2010-2012 data
- Events downgoing – angular resolution not enough for statistical significance from 2 events
- Seem not to be GZK events (too low in energy)
- Higher than expected for atmospheric background
- Spectrum seems not to extend to much higher energies (unbroken E^{-2} would have made 8-9 more above 1 PeV)



Things We Wanted to Learn

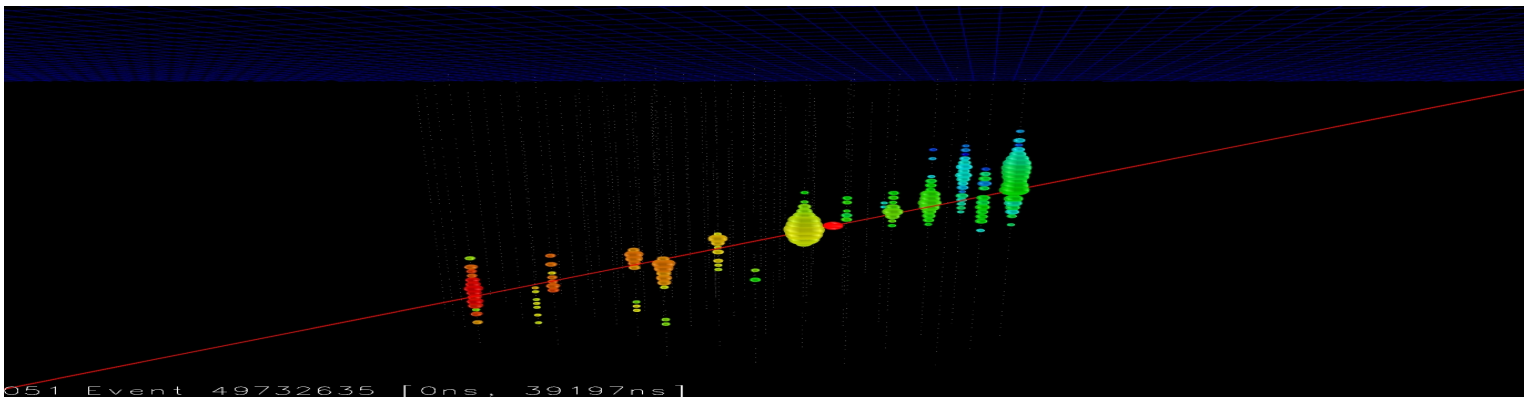
- Isolated events or tail of spectrum?
- Spectral slope/cutoff
- Flavor composition
- Where do they come from?
- Astrophysical or air shower physics (e.g. charm)?
- Needed more statistics to answer all of these



Neutrino Identification

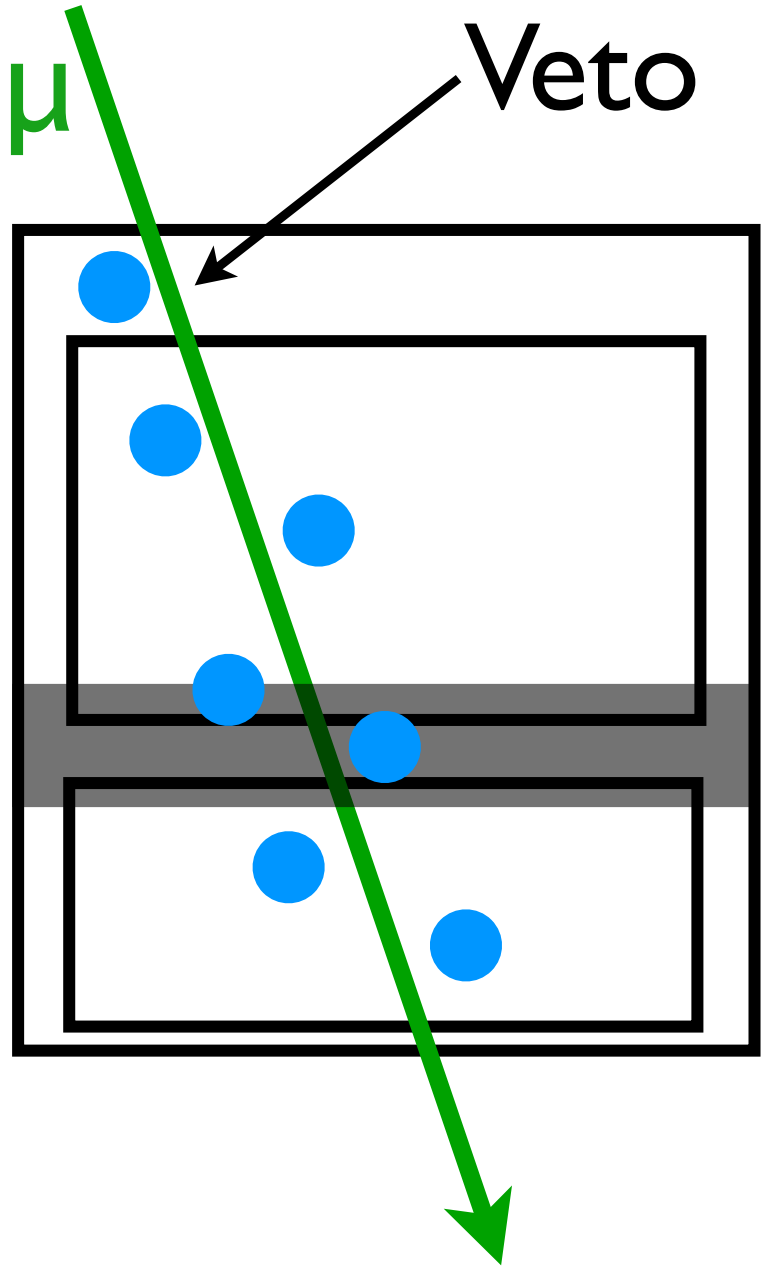
How to identify neutrinos?

1. Upgoing muon tracks
   - Filter out CR muons with bulk of Earth
   - Unknown vertex – hard to measure energy
2. Excess over background
   - Works only for extremely bright/high energy sources
3. Contained vertex
   - Filter out CR muons using detector edge for anticoincidence
   - Neutrino Vertex Observed $\rightarrow$ Good energy estimation



High-energy contained vertex search

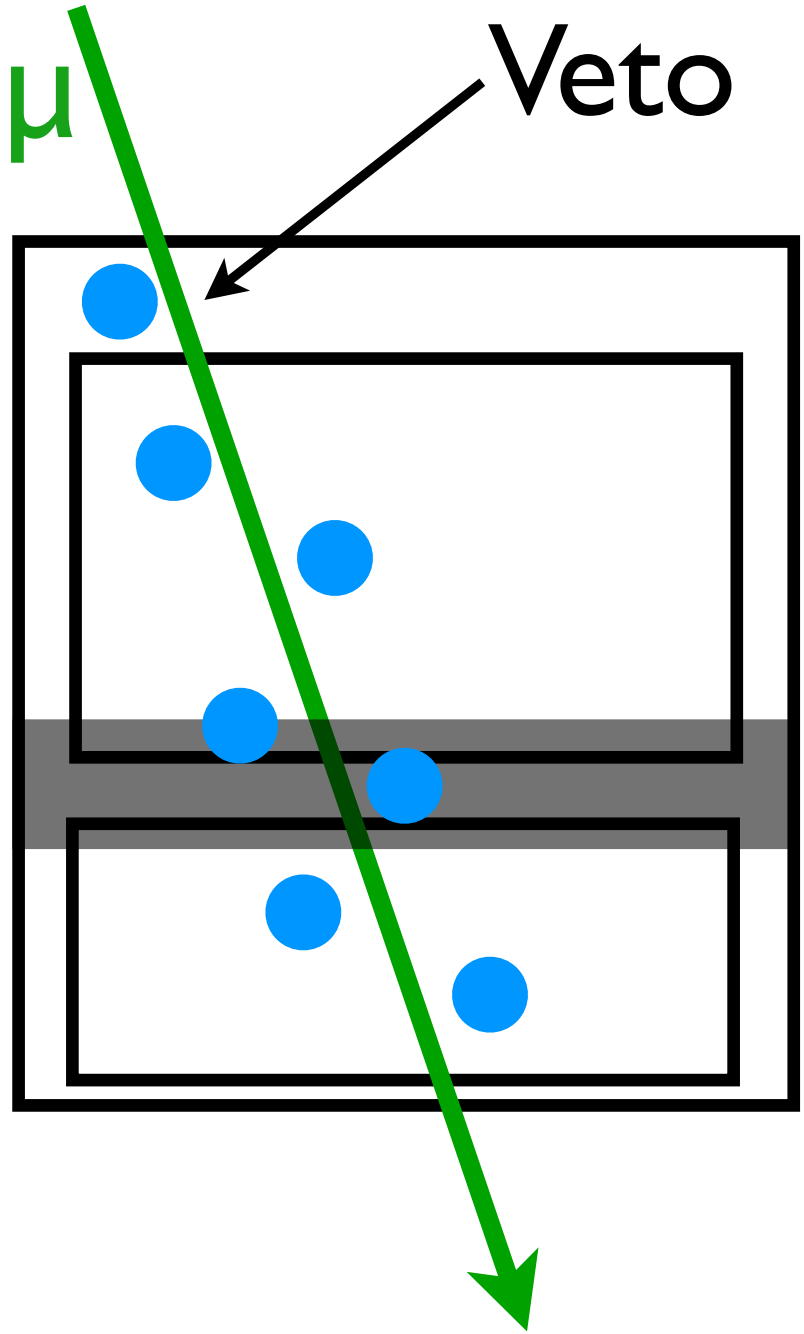
- Contained event search
- 420 megaton fiducial mass
- Sensitive to all flavors in region above 50 TeV
- Neutrinos from 4π
- Three times as sensitive at 1 PeV as GZK search
- Estimate backgrounds from data
- May 2010 - May 2012



See: talk by Claudio Kopper

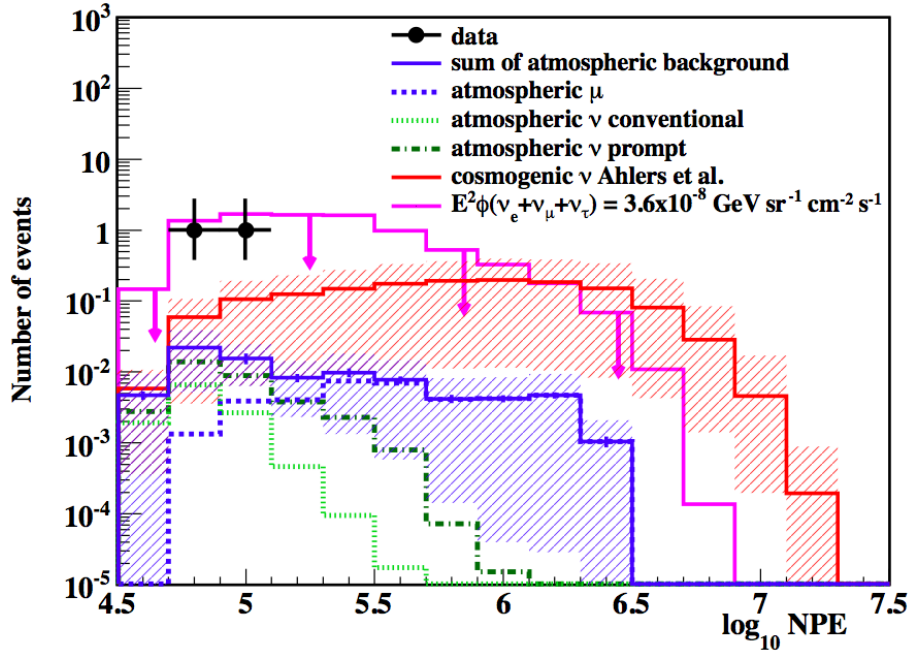
Background 1: Muon Background

- Muons can (rarely) penetrate veto region
- Control sample available: tag muons with part of detector and see what fraction vetoed by another
- 6 ± 3.4 muons per 2 years



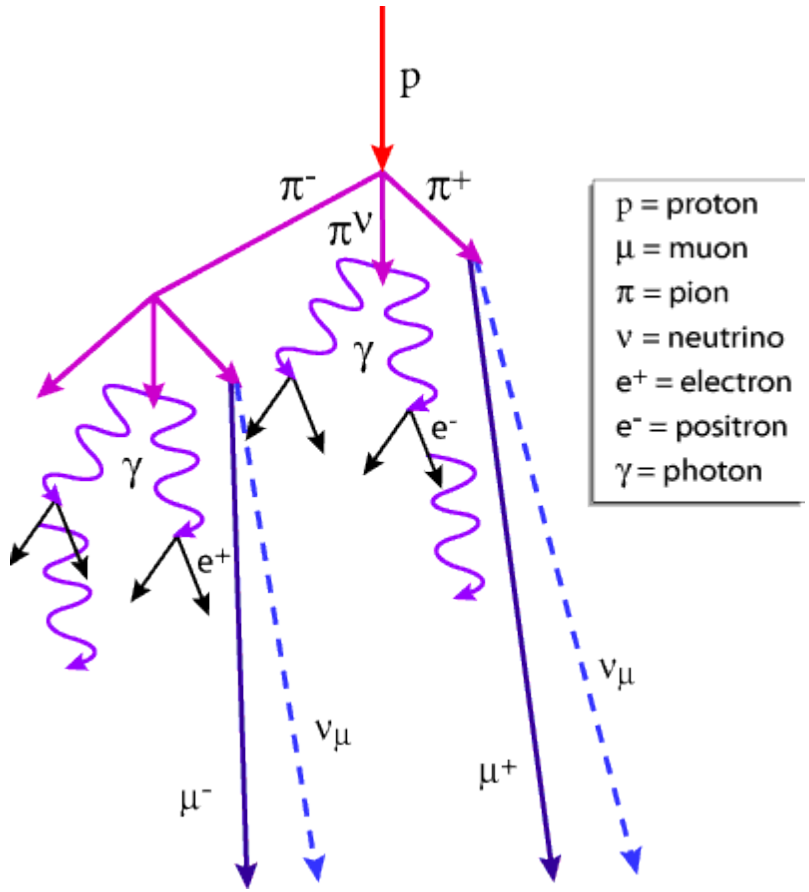
Background 2: Atmospheric Neutrinos

- Typically separated by energy
- Very low background (0.1 event/year) at PeV energies
- Large uncertainties in atmospheric spectrum at high energies

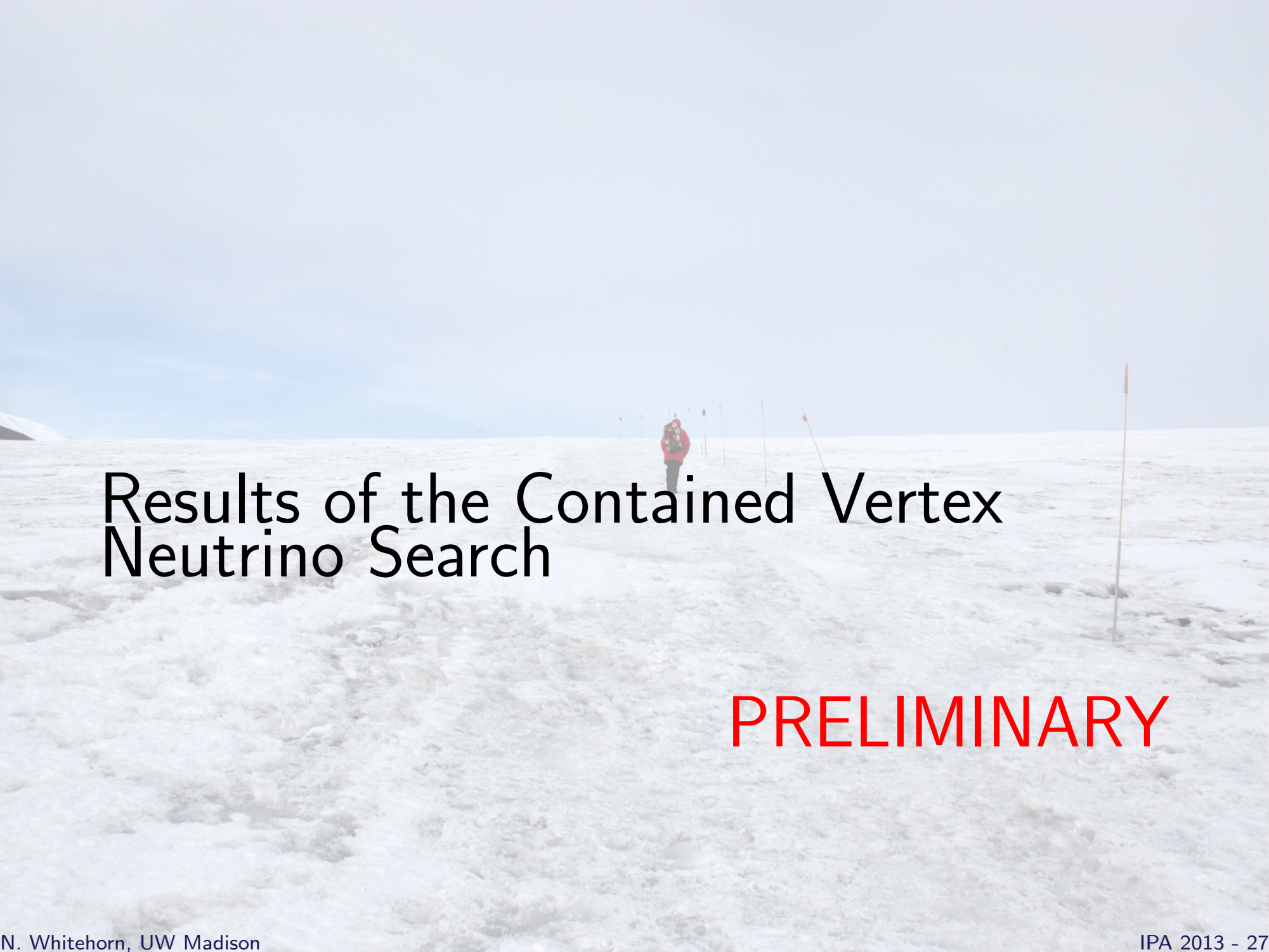


Another approach: vetoing Atmospheric Neutrinos

- 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
- $4.6^{+2.9}_{-1.9}$ events in two years



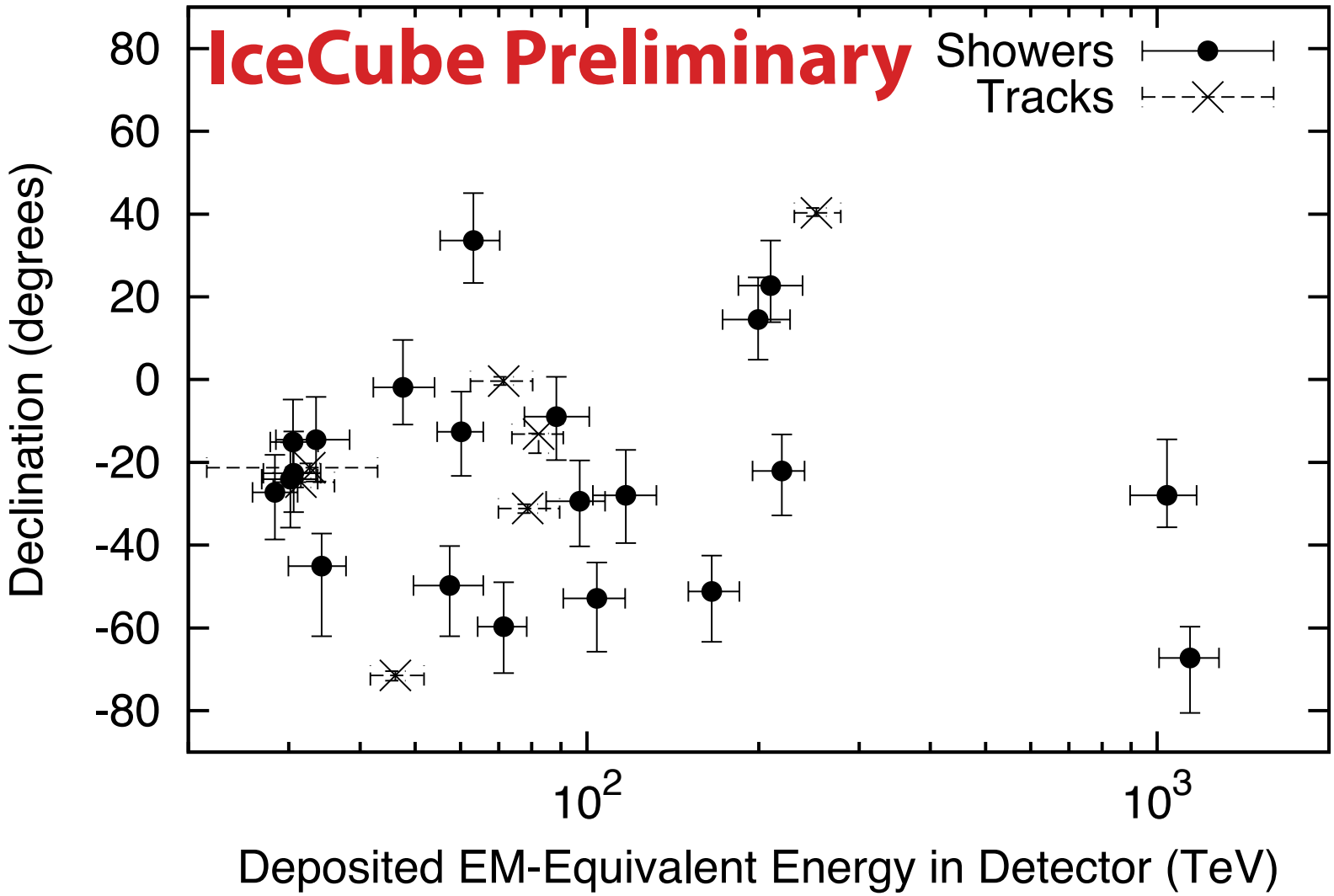
Schönert et al. arXiv:0812.4308



Results of the Contained Vertex Neutrino Search

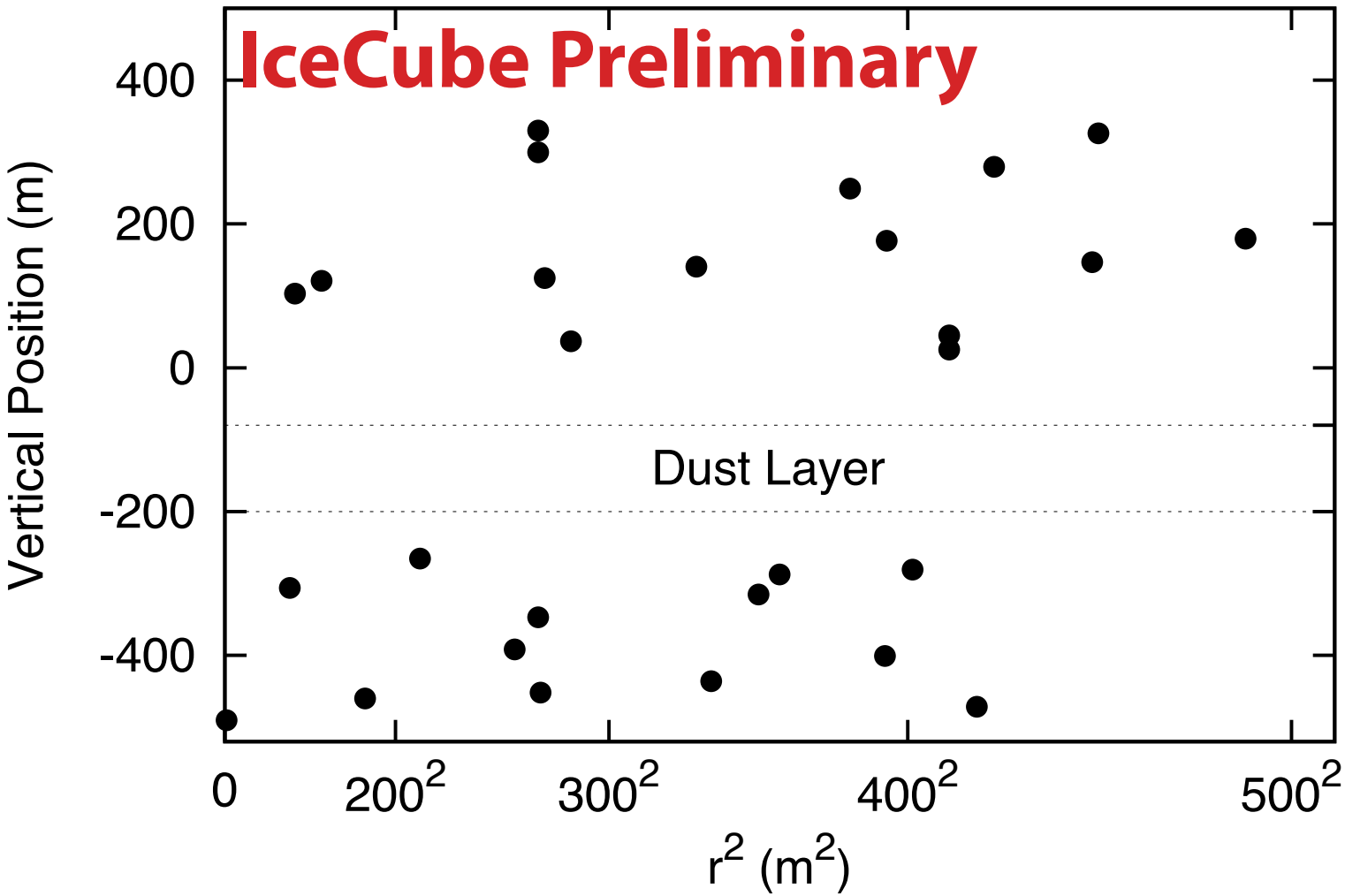
PRELIMINARY

Results of Contained Vertex Event Search (4.3σ)



28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9}$ (12.1 ± 3.4 with reference charm model)

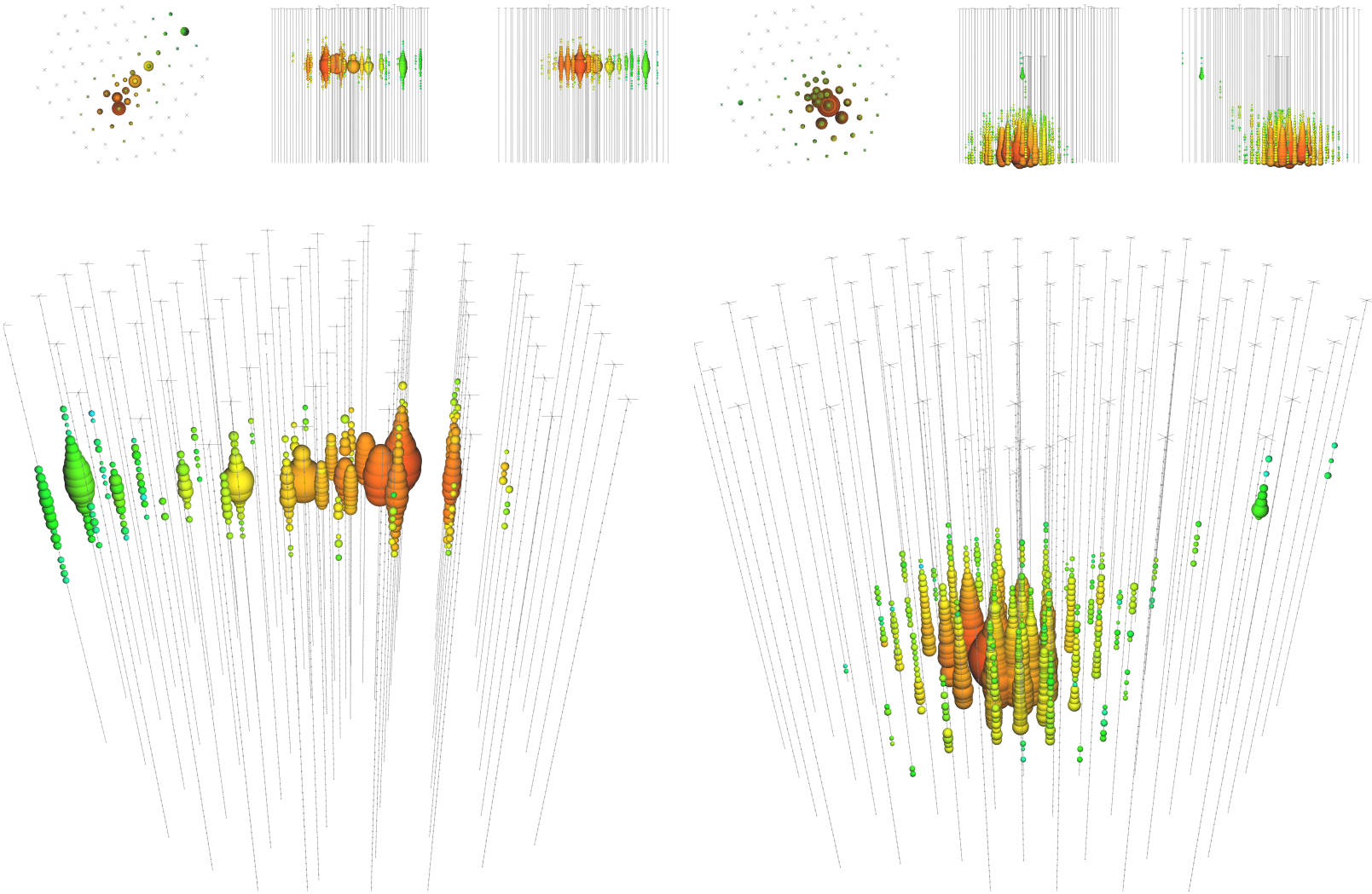
Event Distribution in Detector



Uniform in fiducial volume

PRELIMINARY

Some interesting new events

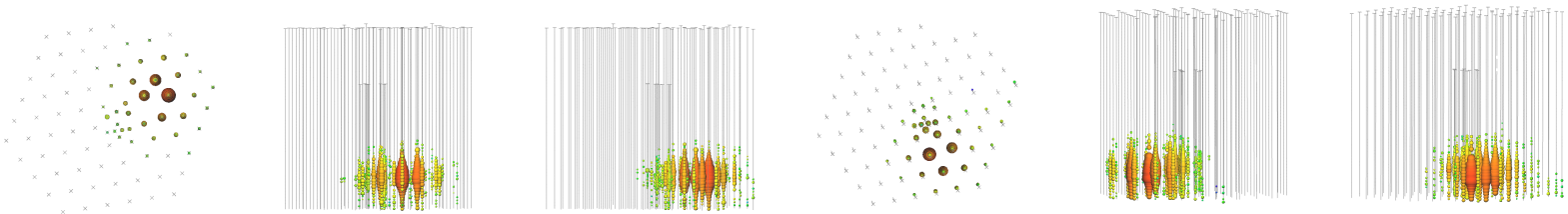


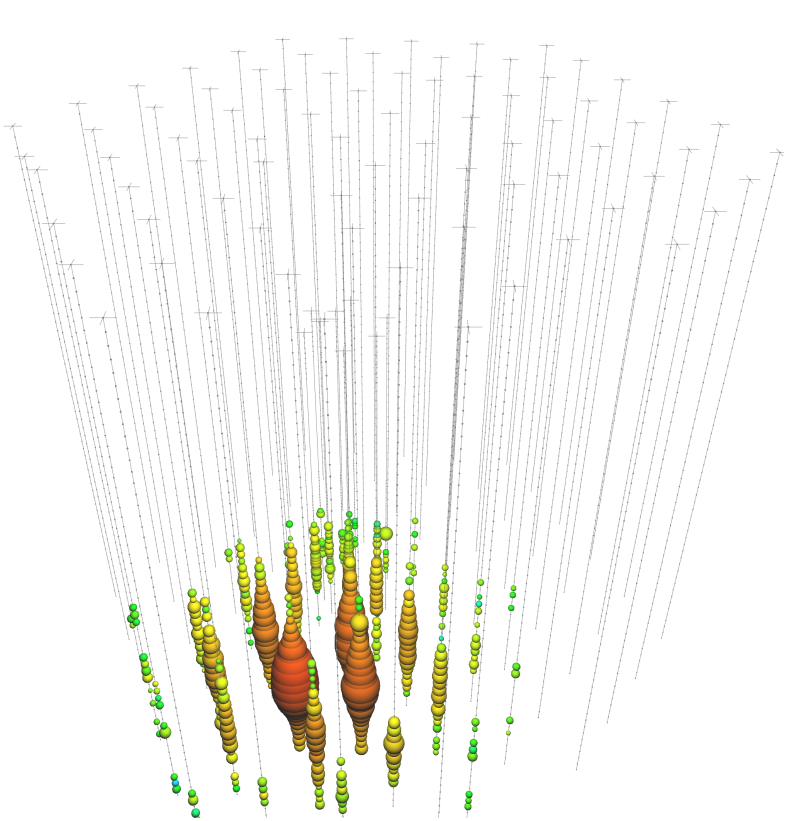
74.1 TeV, -0.4°

252.7 TeV, $+40^\circ$

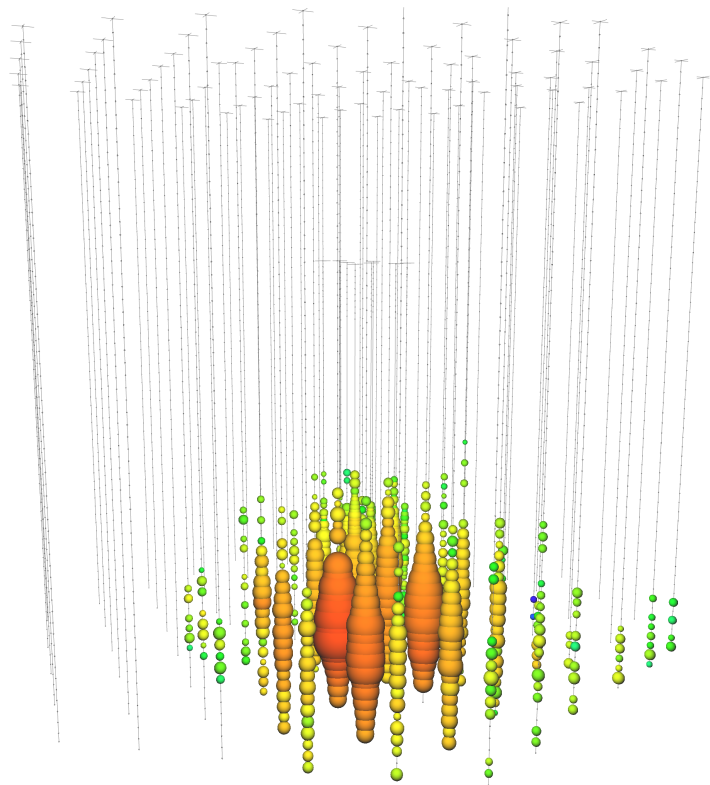
PRELIMINARY

Some interesting new events





71.5 TeV, -60°

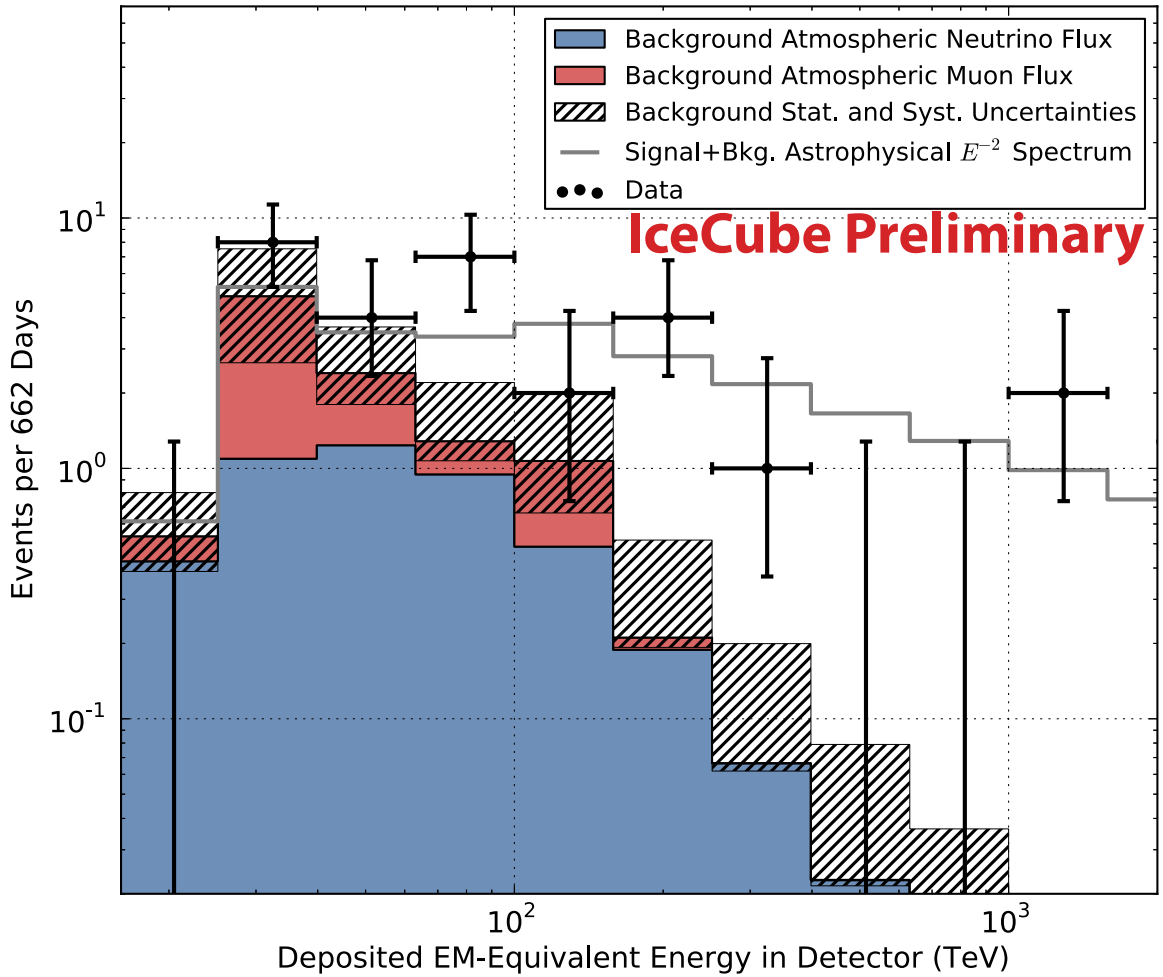


82.2 TeV, -13°

PRELIMINARY

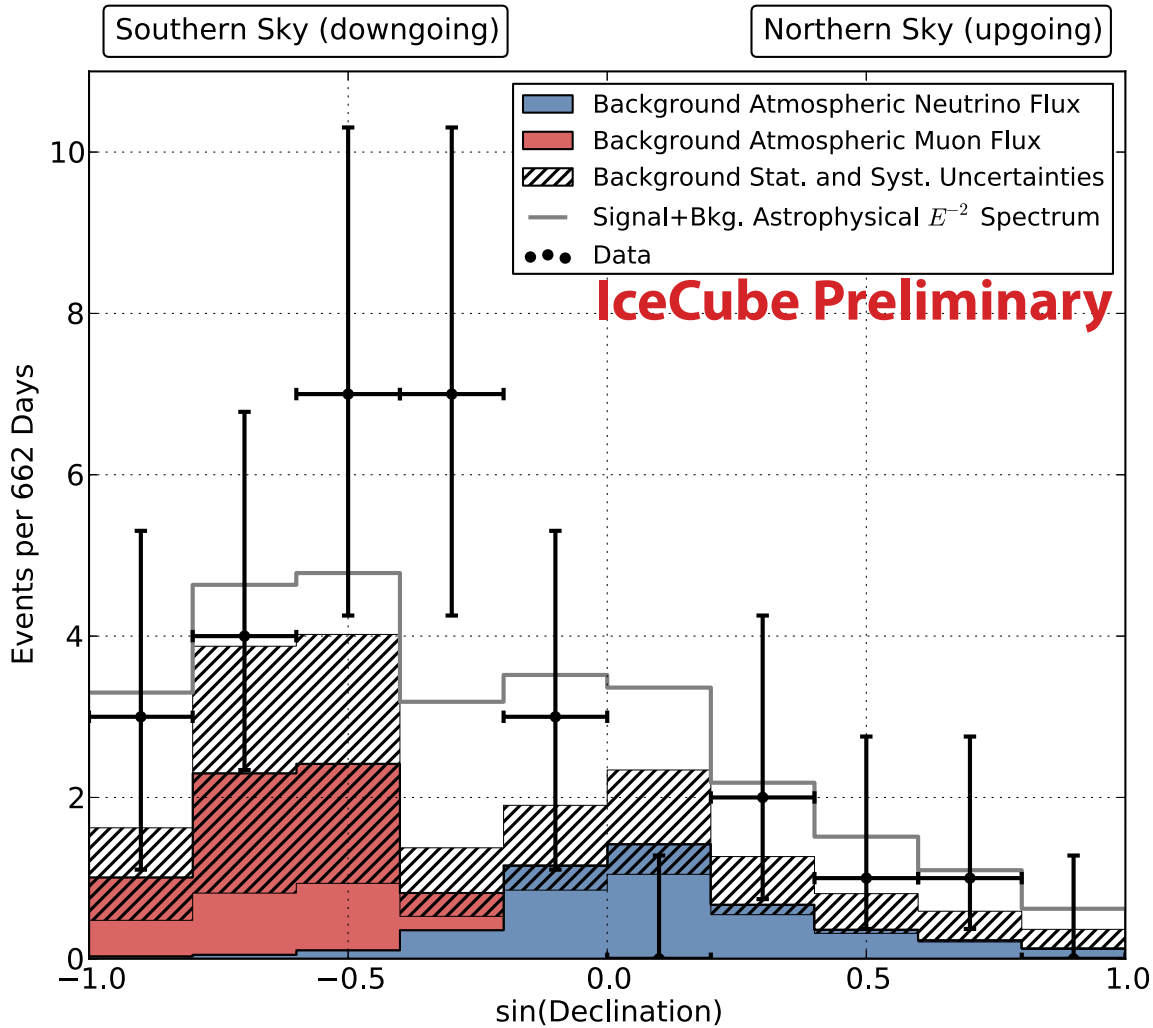
Energy Spectrum

- Harder than any expected atmospheric background
- Merges well into expected backgrounds at low energies
- Potential cutoff at $1.6^{+1.5}_{-0.4}$ PeV

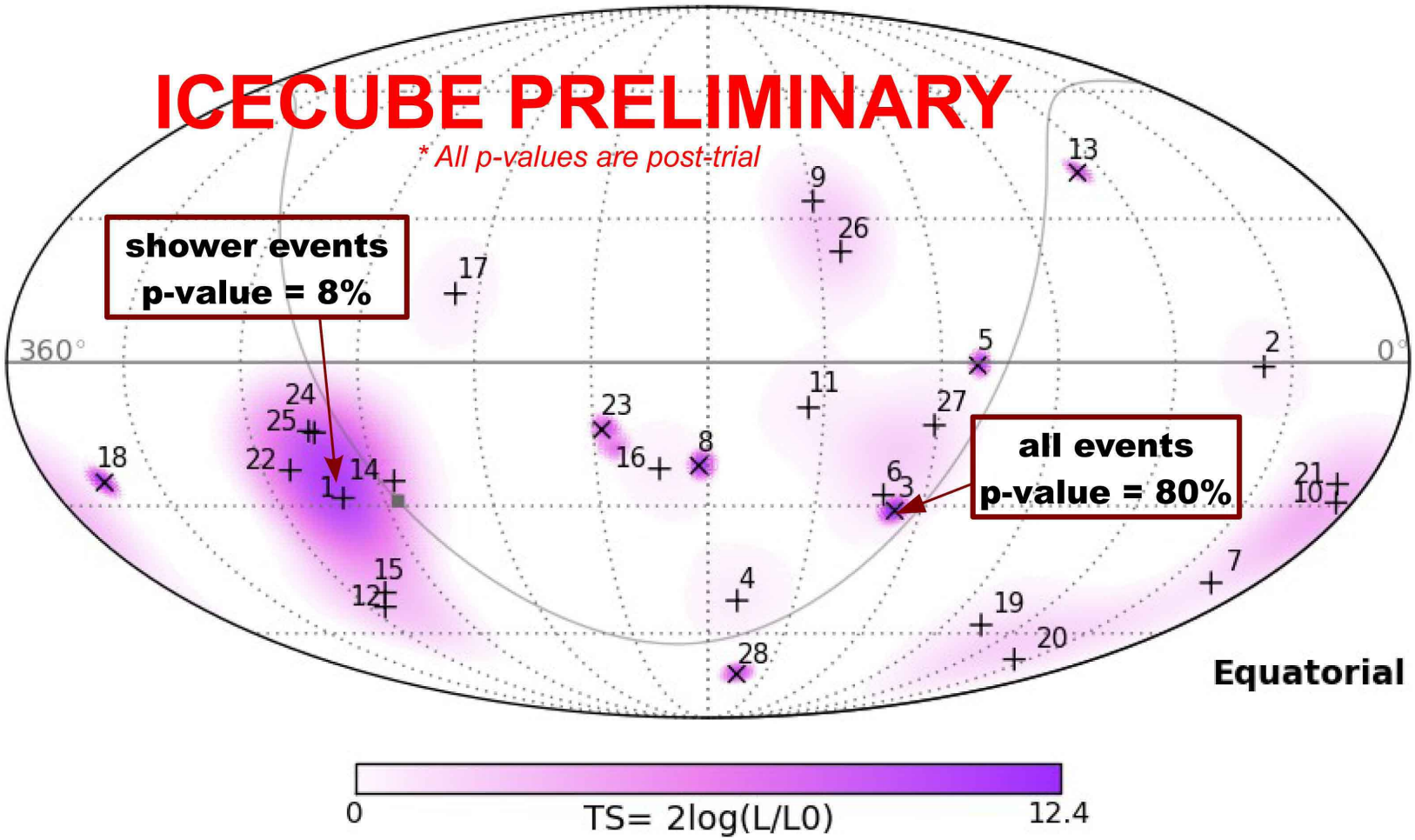


Zenith Distribution

- Compatible with Isotropic Flux
- Events from North absorbed in Earth
- Minor excess in south compared to isotropic, but not significant



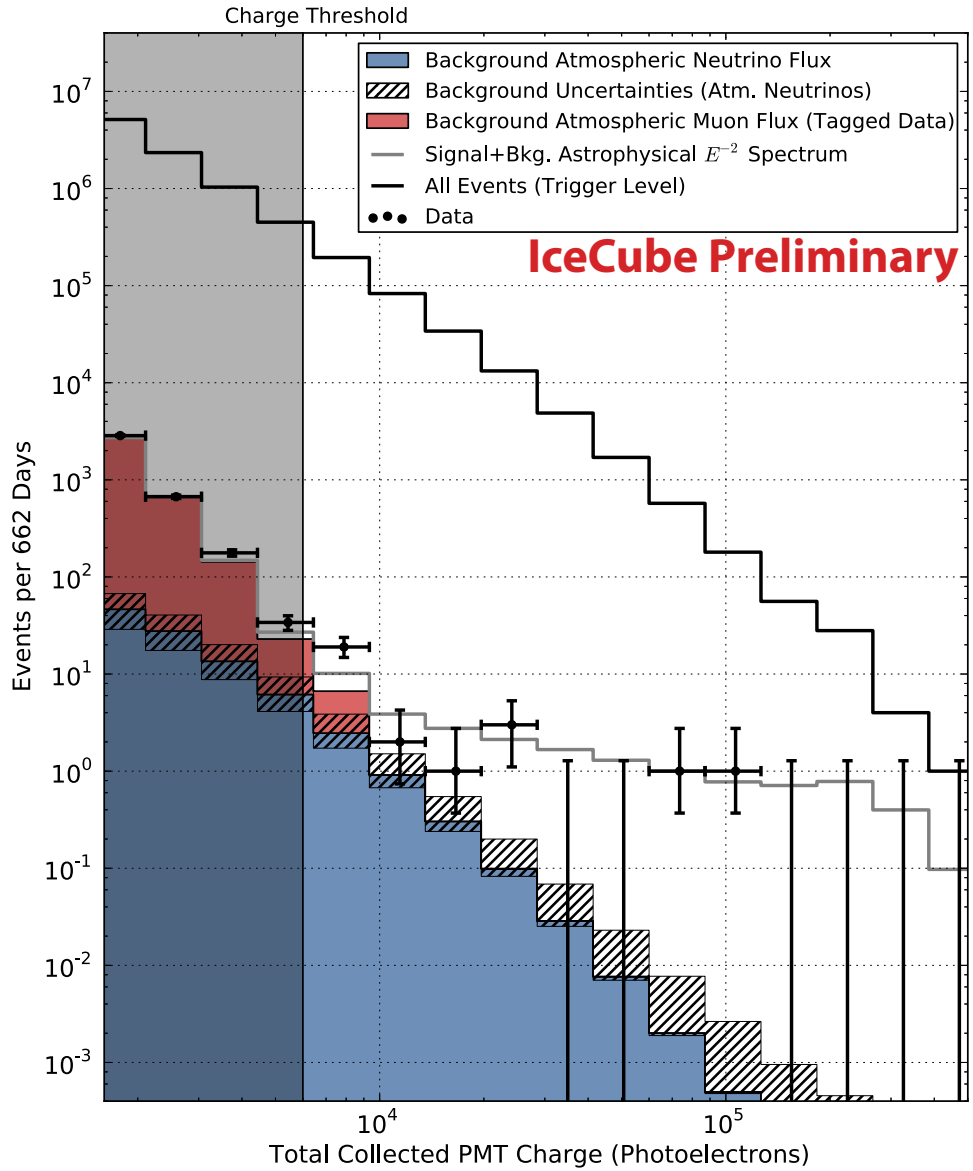
Skymap: No Significant Clustering



See: talk by Naoko Kurahashi Neilson

What are these?

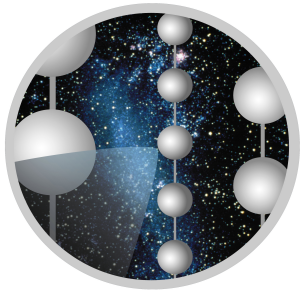
- Events seem to be neutrinos
- Energy spectrum very hard, but stops
- Flavor distribution consistent with 1:1:1
- Angular distribution makes atmospheric explanation hard: where are the air showers?
- Compatible with isotropic flux
- Still no evidence for clustering: definitive answers missing



Conclusions

- Two 1 PeV neutrinos observed at threshold of GZK searches (2.8σ)
- Follow-up analysis finds 26 more at lower energy (3.6σ)
- Increasing evidence for high-energy component beyond the atmospheric spectrum
- Inconsistent at 4.3σ with standard atmospheric backgrounds
- What it is less clear – compatible with astrophysical explanations
- Publication and more data coming soon

IceCube Neutrino Observatory

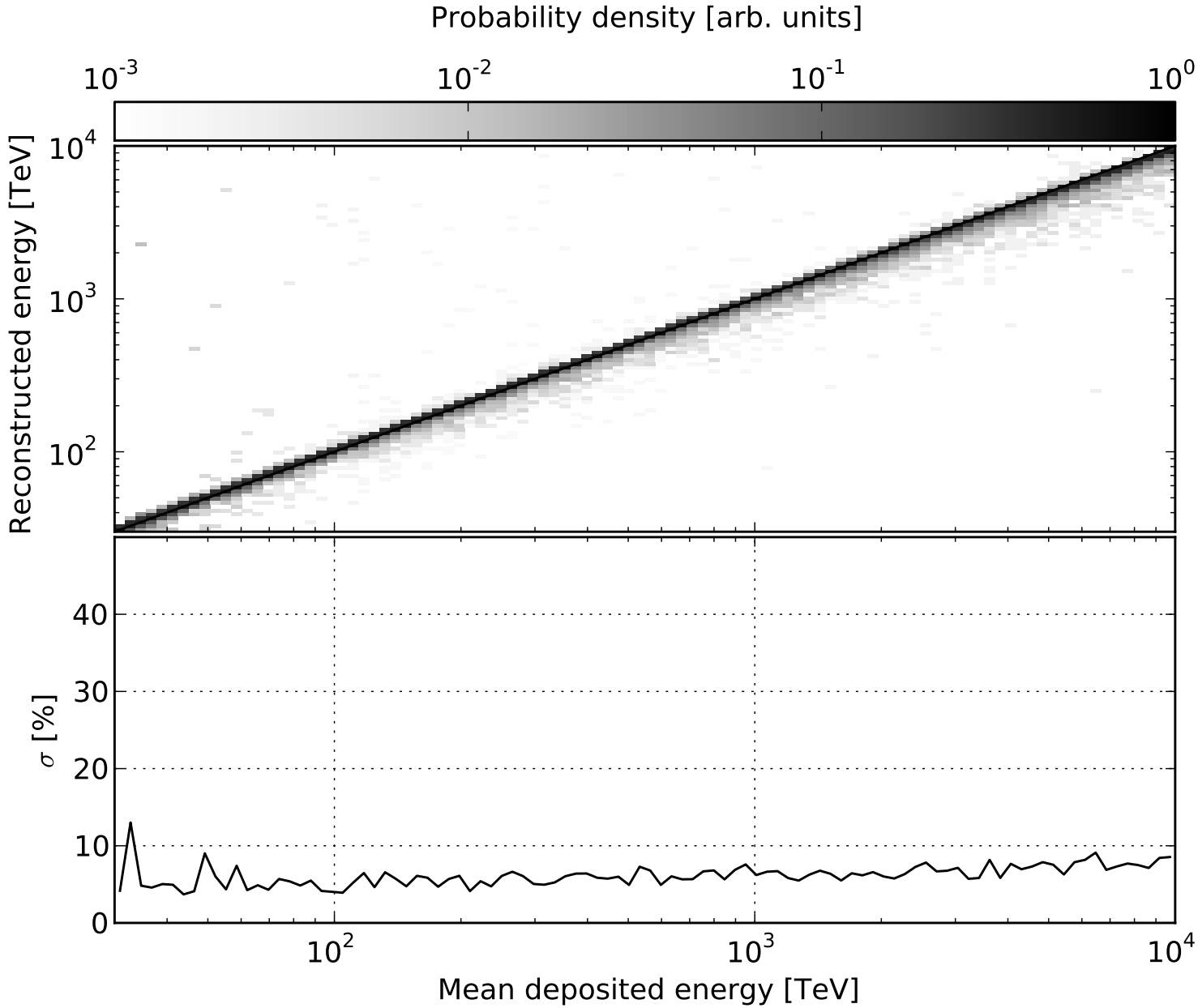


Built under a National Science Foundation (NSF) Major Research and Facilities Construction grant with contributions from national funding agencies and private foundations in Germany, Sweden and Belgium.

Operated with support from the NSF Polar Programs and funding agencies in Germany, Sweden, Belgium, UK, Switzerland, Japan, Canada, New Zealand and Australia.

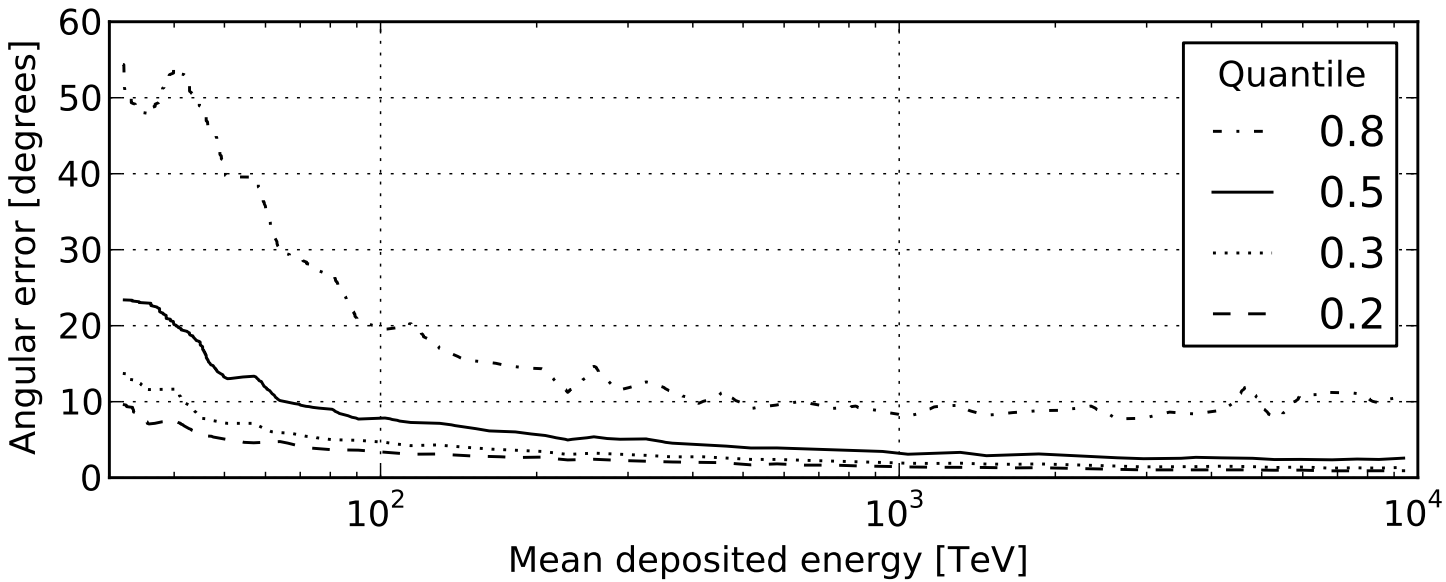
Backup

Shower Energy Resolution



PRELIMINARY

Shower Angular Resolution



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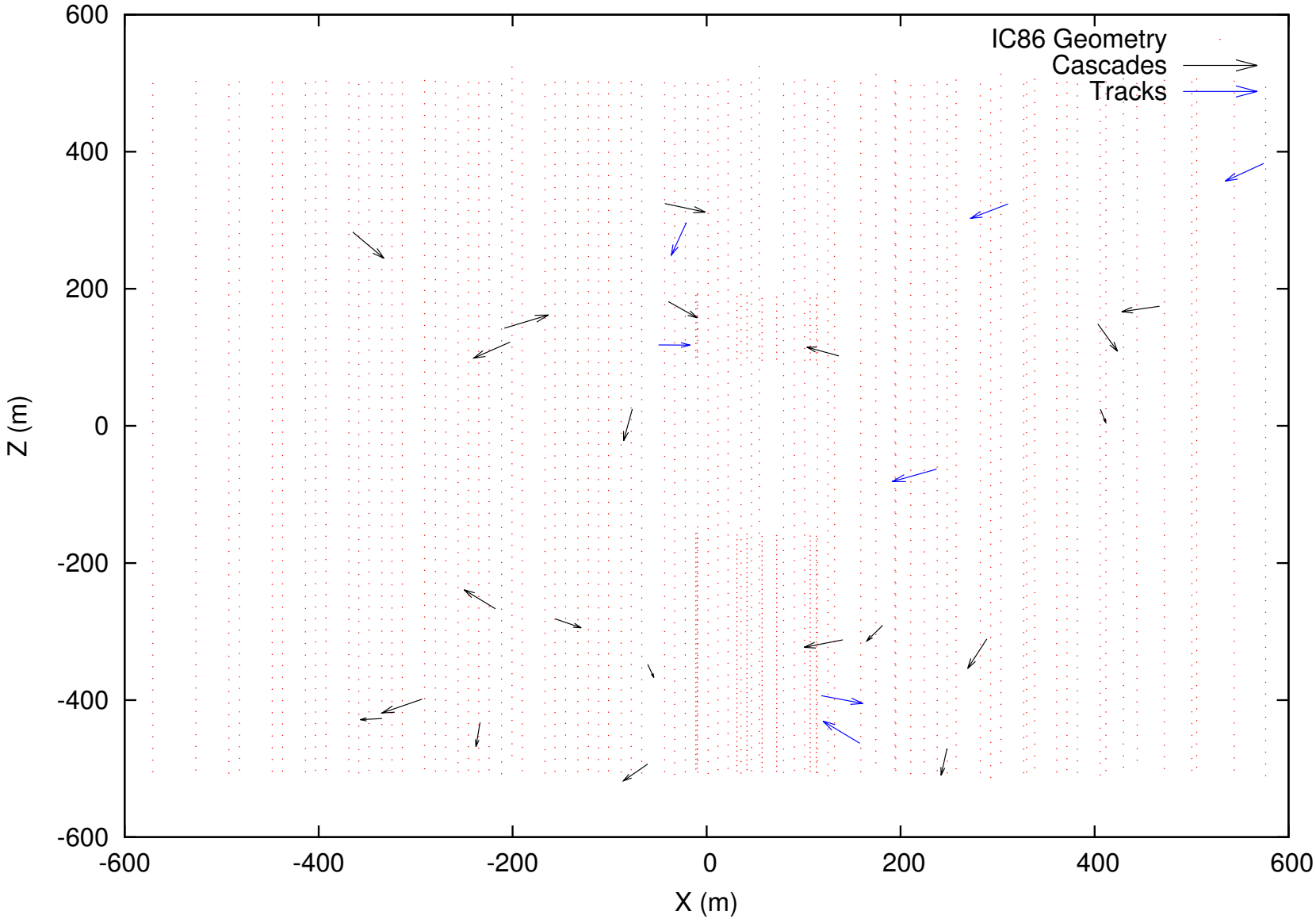

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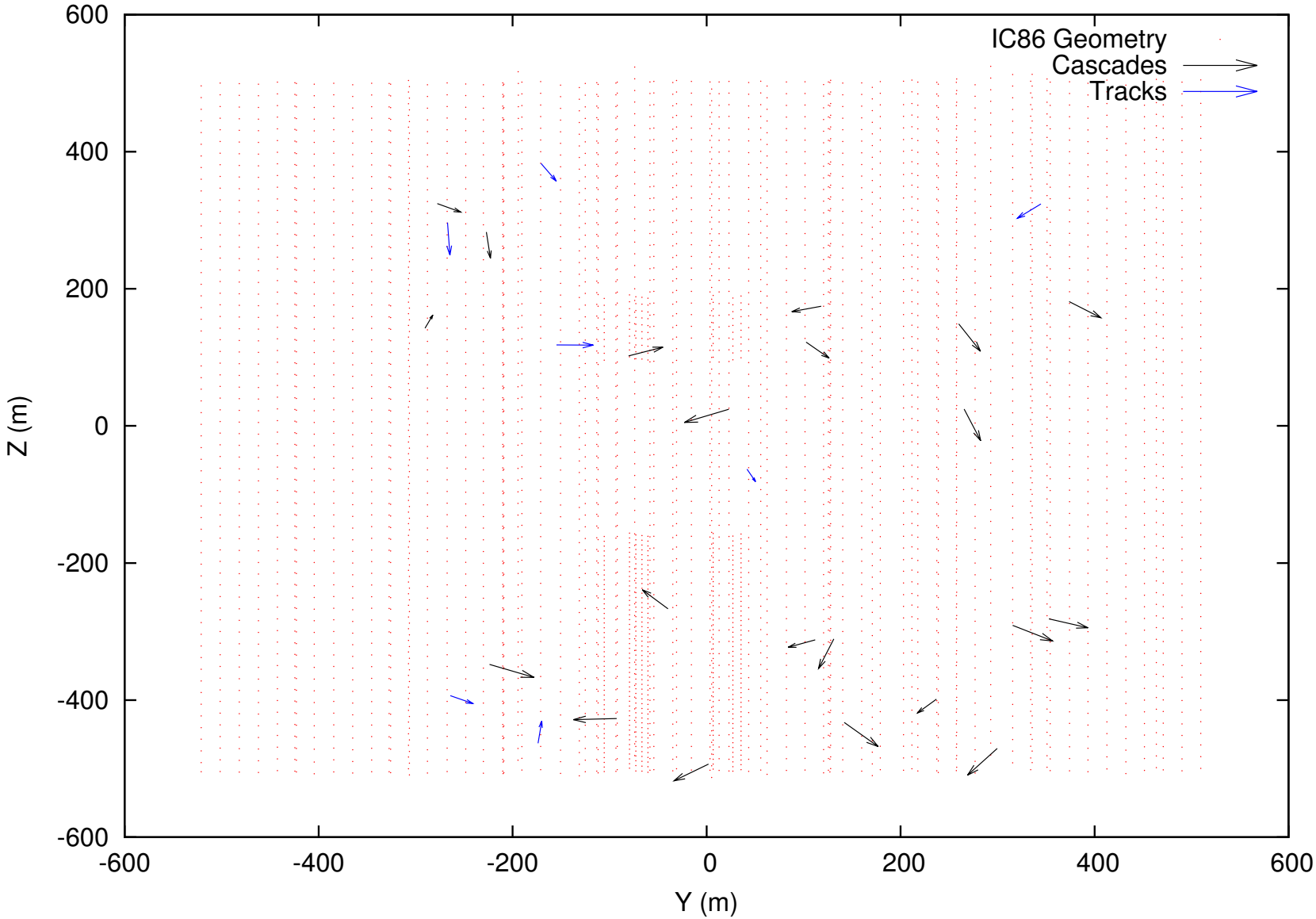

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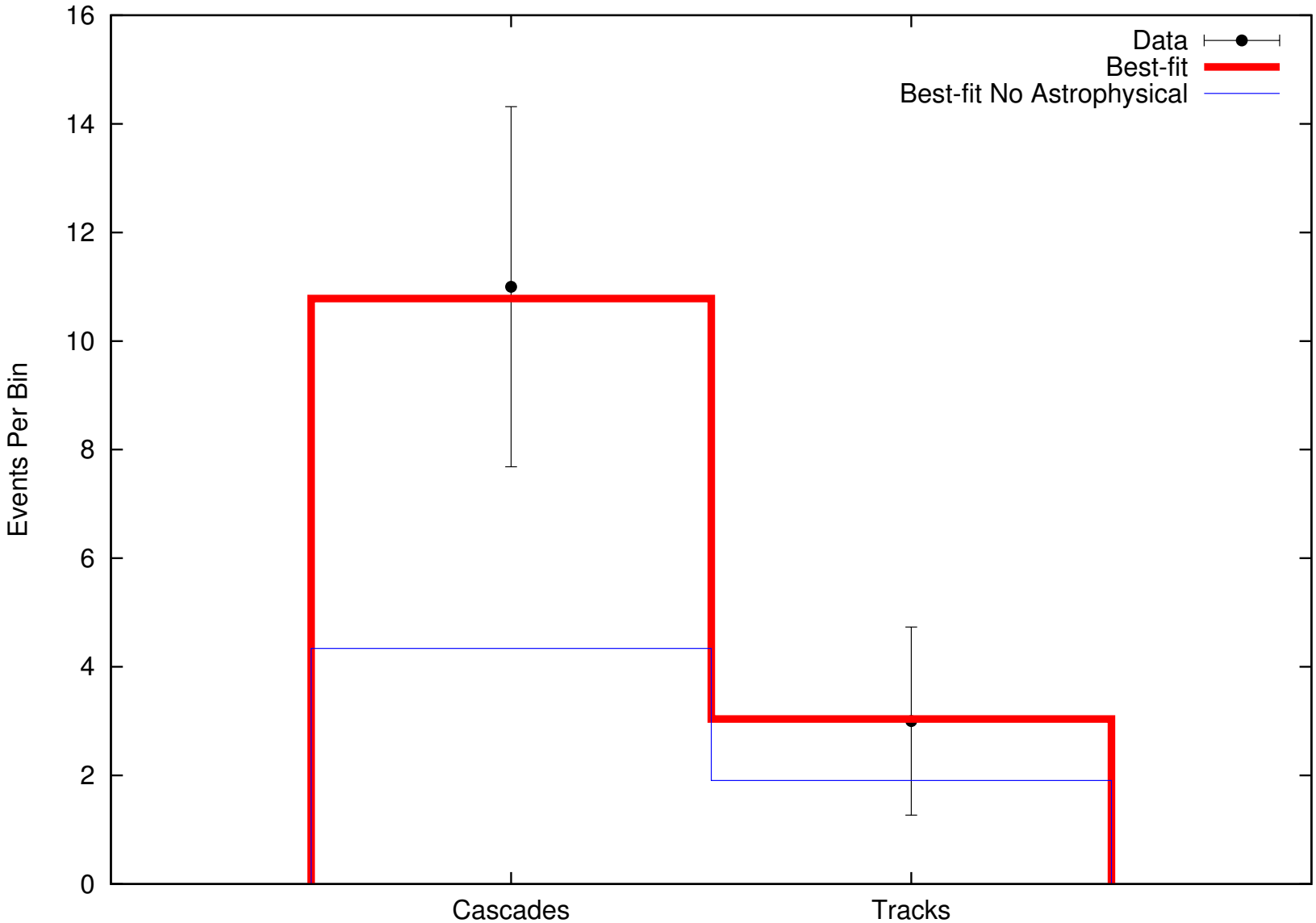

PRELIMINARY