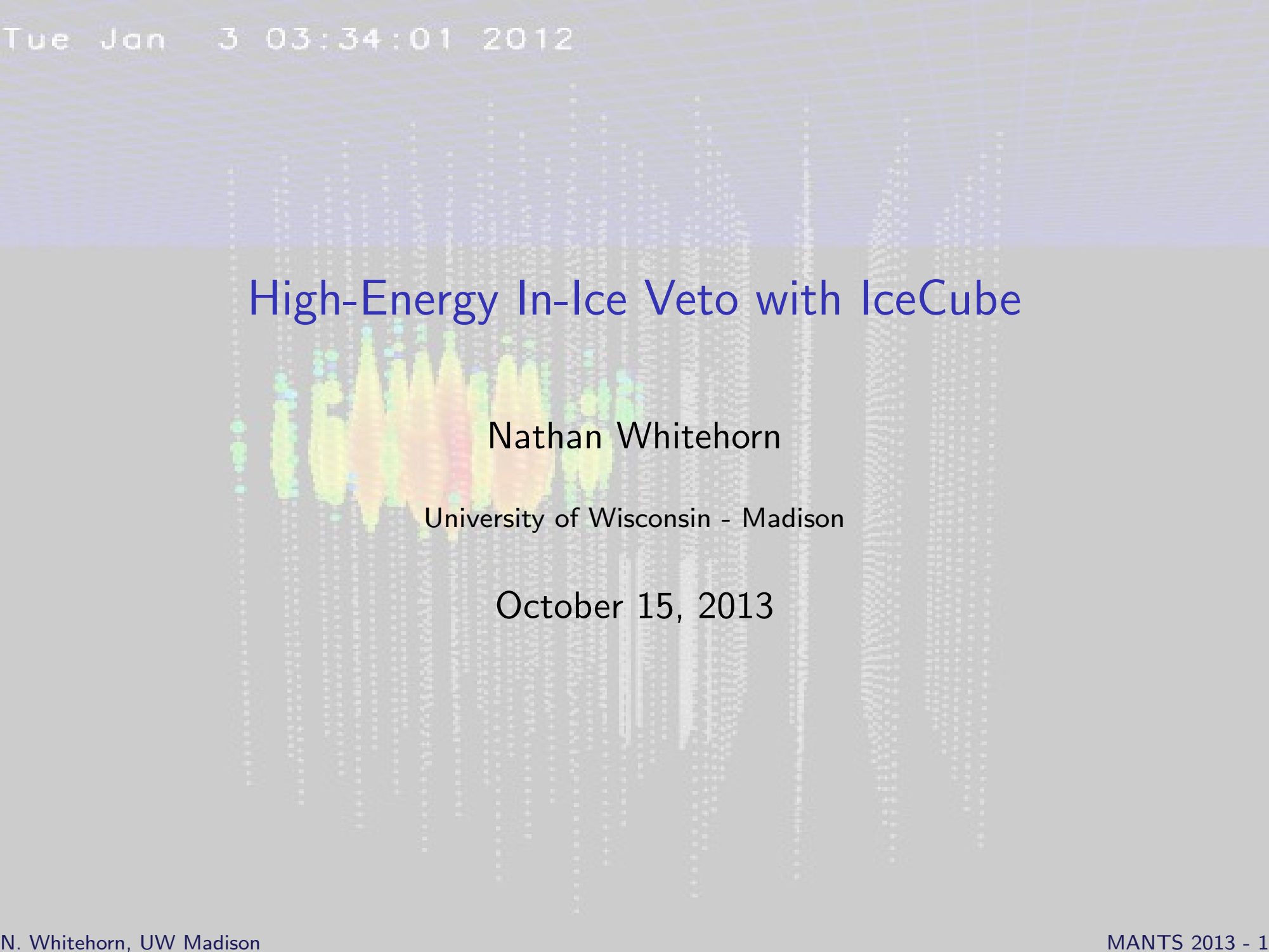


High-Energy In-Ice Veto with IceCube

Nathan Whitehorn

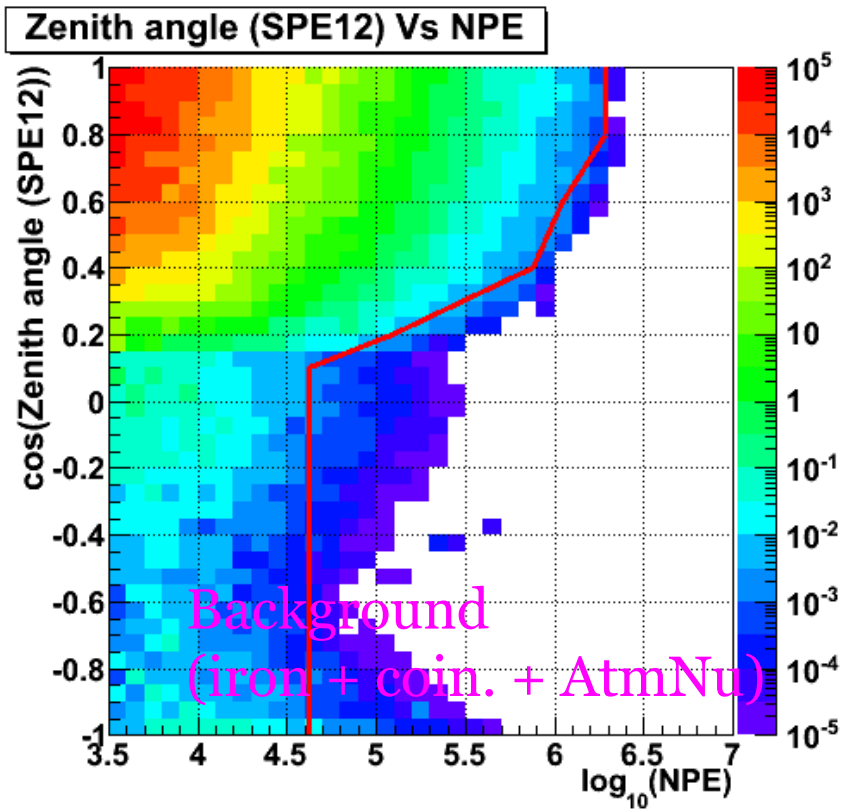
University of Wisconsin - Madison

October 15, 2013

Things Become Interesting: GZK Neutrino Analysis

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

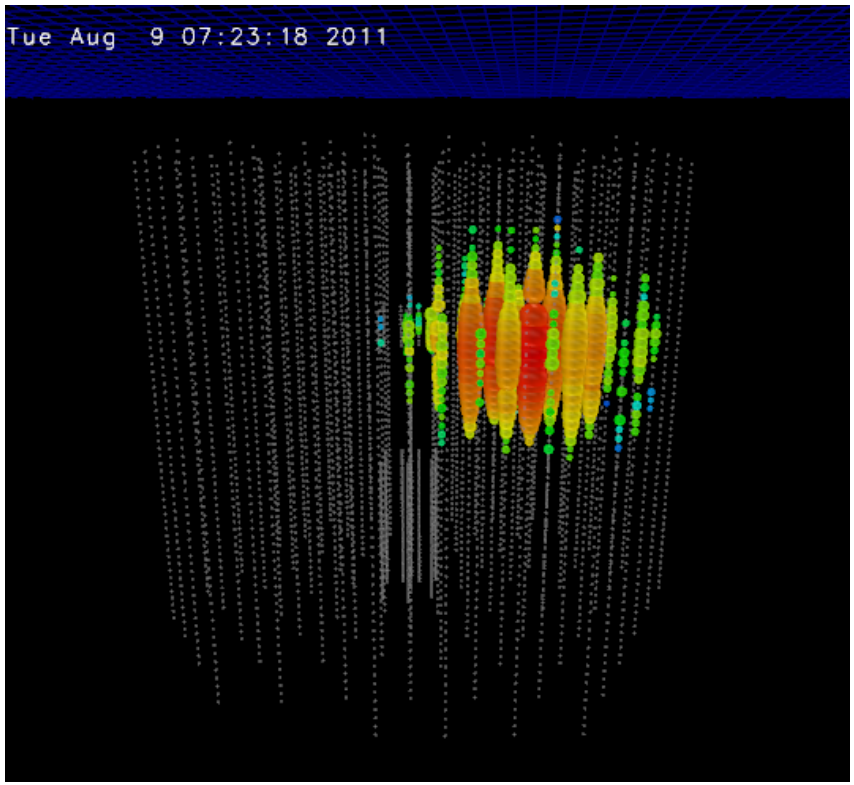
- Upgoing muons
  - Always neutrinos
  - Atmospheric neutrino background
  - High threshold (1 PeV)
- Very highest energy downgoing muons
  - Cosmic Ray muon background
  - Very high energy threshold (100 PeV)
  - Only sensitive to GZK-type events ($E_\nu \gtrsim 10^{18}$ eV)



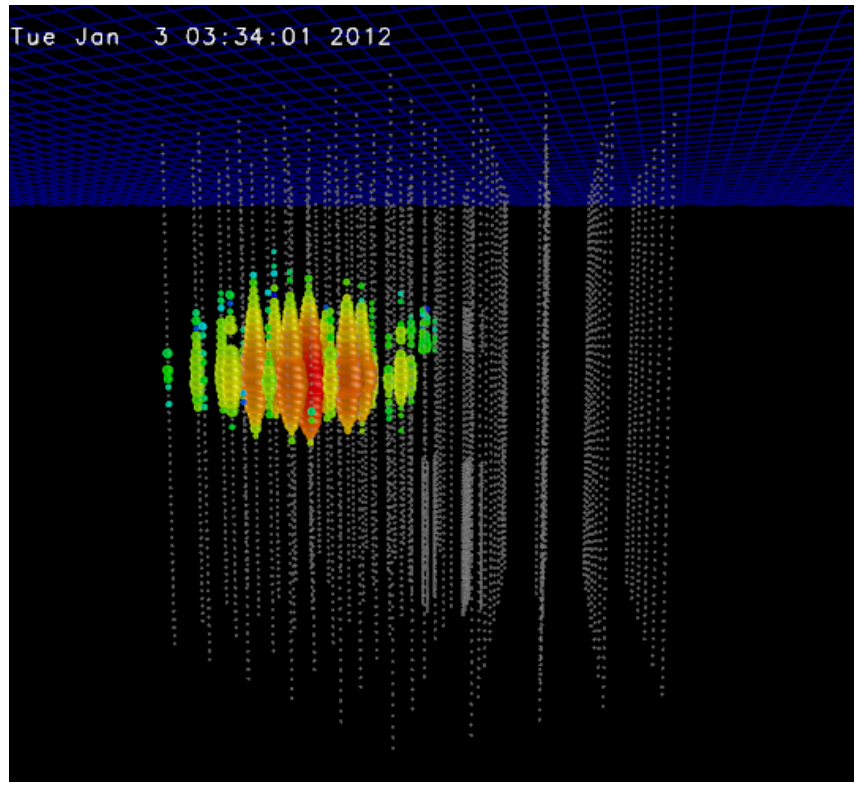
arXiv:1304.5356

Results (2.8σ, 2012)

Appearance of ~ 1 PeV neutrinos at lower energy threshold



"Bert"
~ 1050 TeV

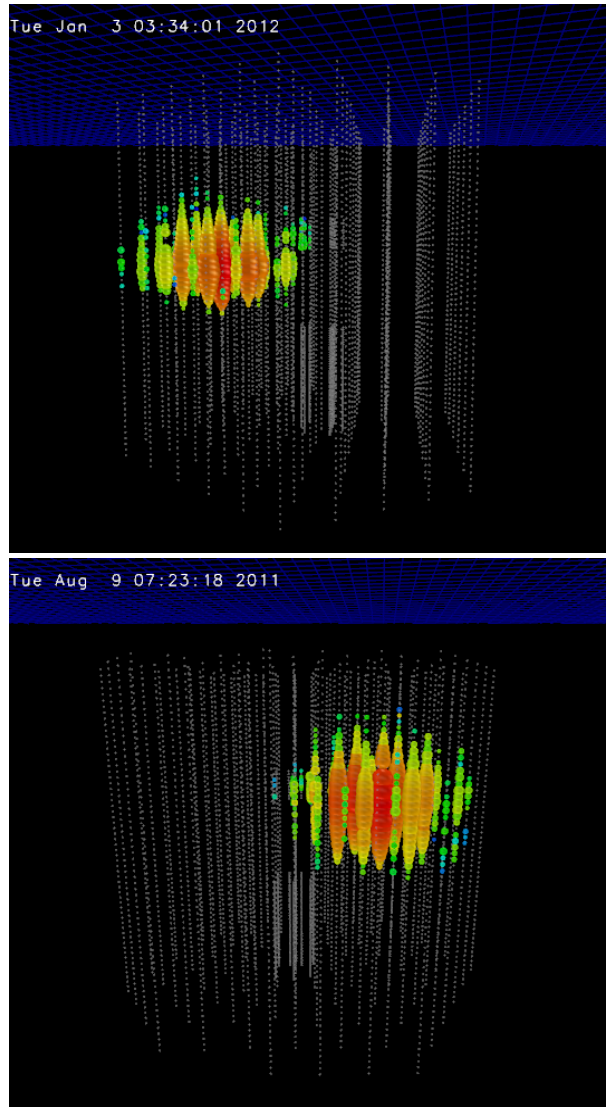


"Ernie"
~ 1150 TeV

Too low in energy for GZK; seems too high in energy for atmospheric

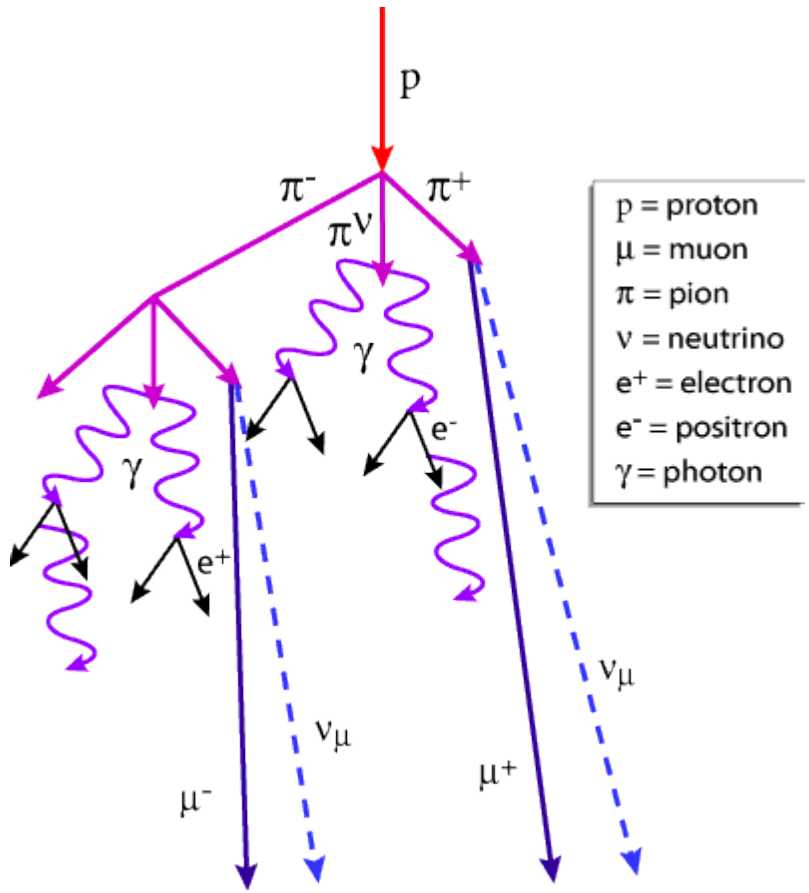
Things We Wanted to Learn

- 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



Vetoing Atmospheric Neutrinos: an Interesting Wrinkle

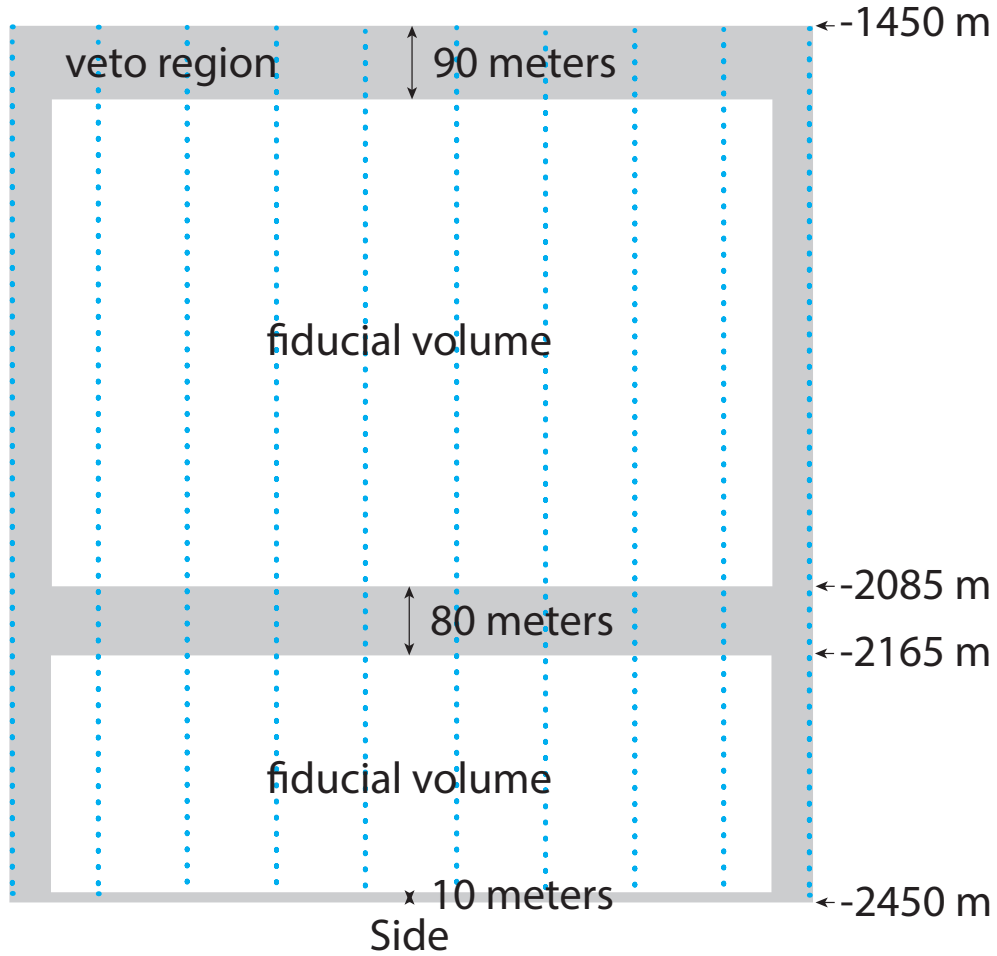
- Atmospheric neutrinos are made in air showers
- For downgoing neutrinos, the muons from the shower will likely not have ranged out when they arrive at IceCube
- Downgoing events that start in the detector are extremely unlikely to be atmospheric
- Note: optimal use requires *minimal* overburden to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



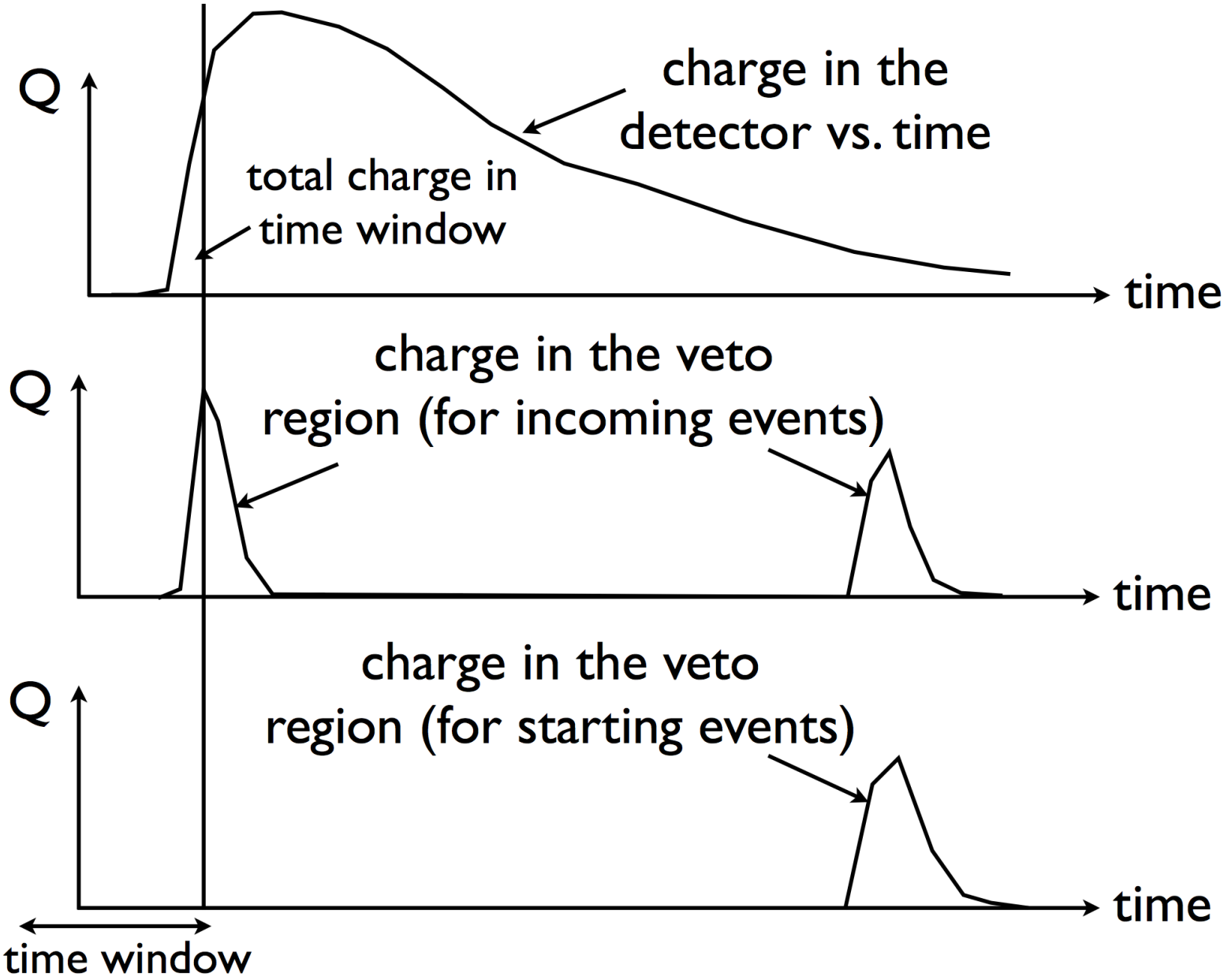
Schönert, Gaisser, Resconi, Schulz arXiv:0812.4308

Event Selection For Contained Events

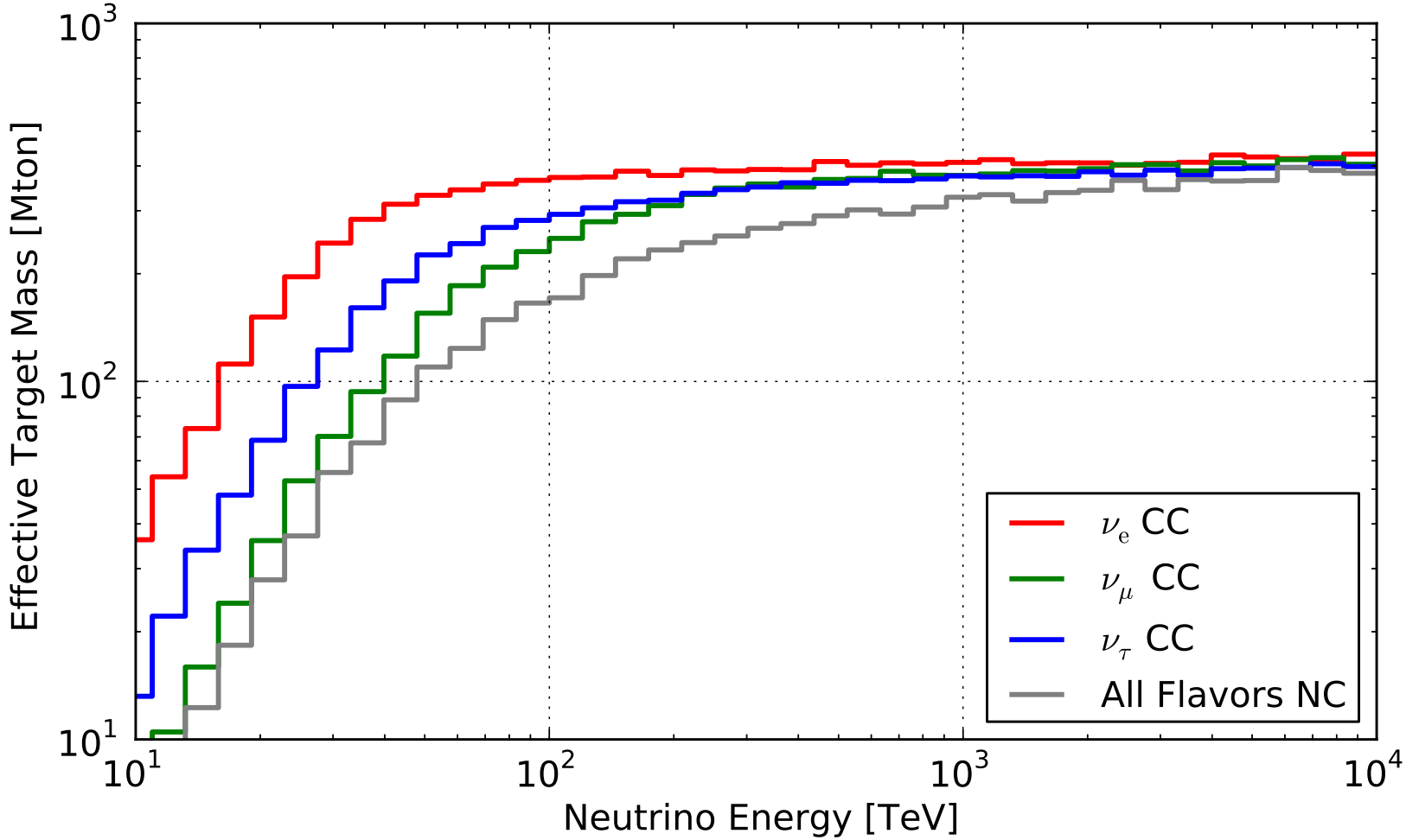
- Define a fiducial volume and a veto region
- Make sure first 3/250 hits are not on boundary
- Go to high energy (> 6000 PE) to make sure significant numbers of photons expected on boundary
- Topology/direction independent sample
- Becomes fully efficient at $\sim 50 - 100$ TeV



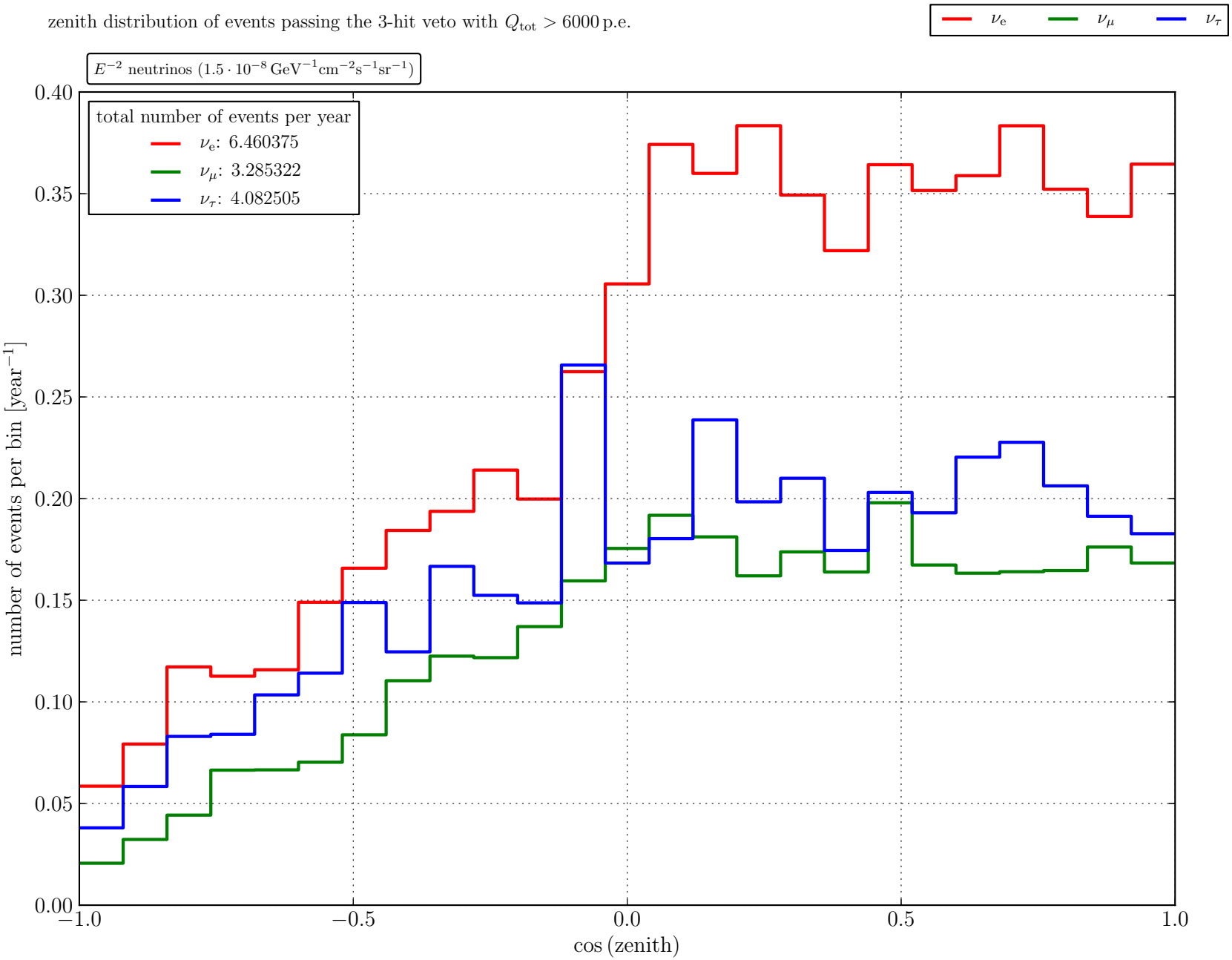
Illustration



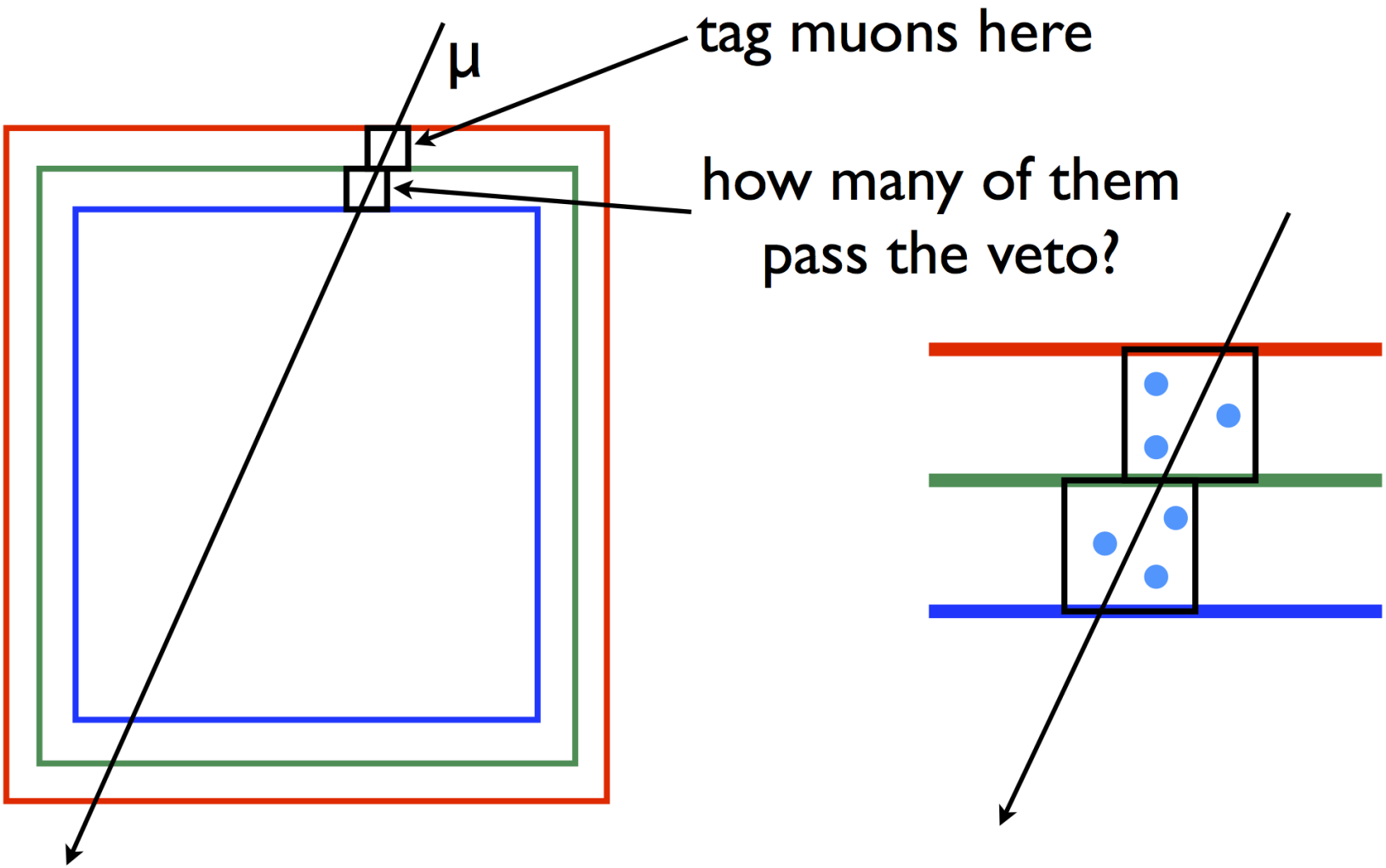
Effective Volume



Isotropic Acceptance

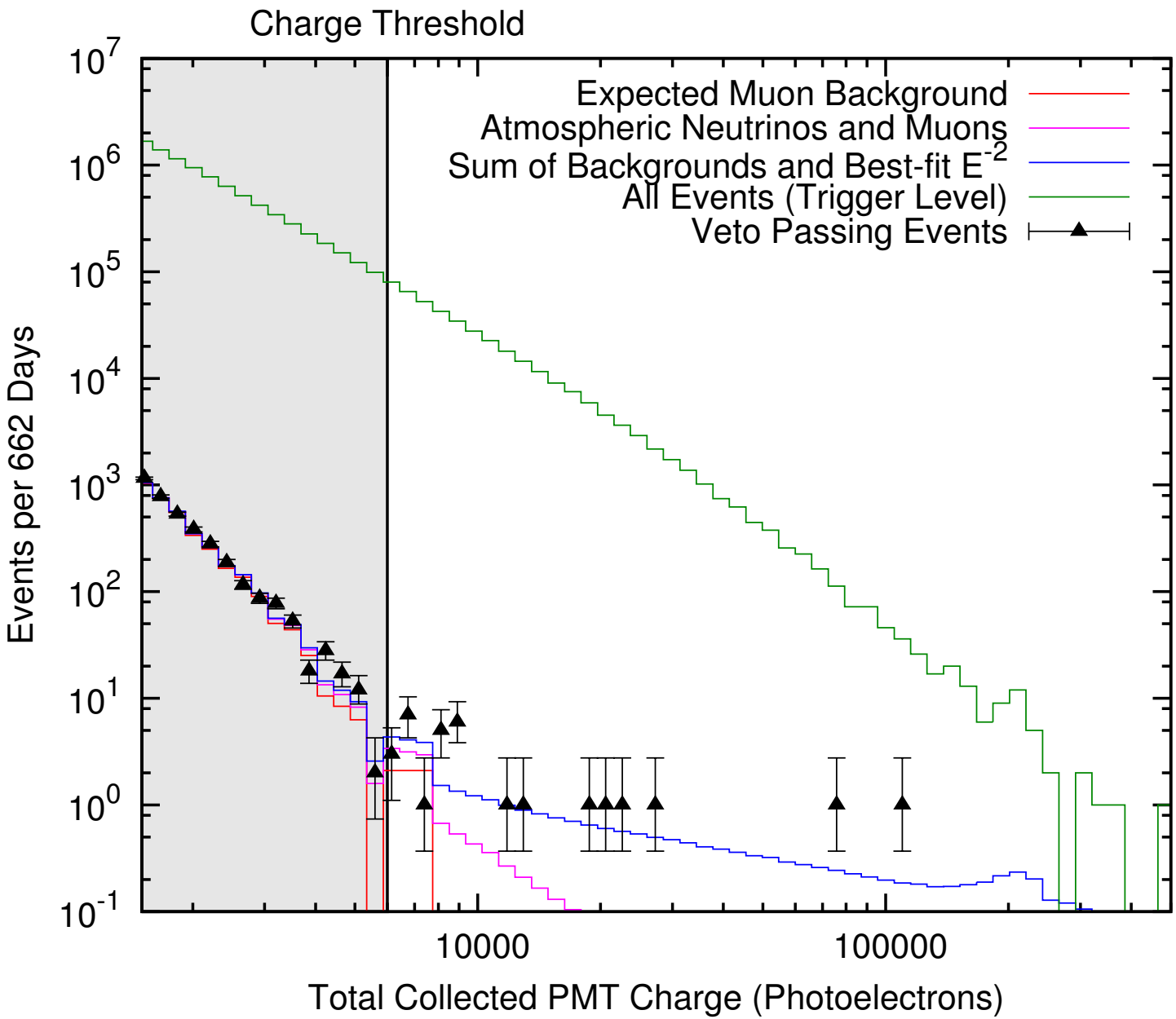


Background 1: Muon Background

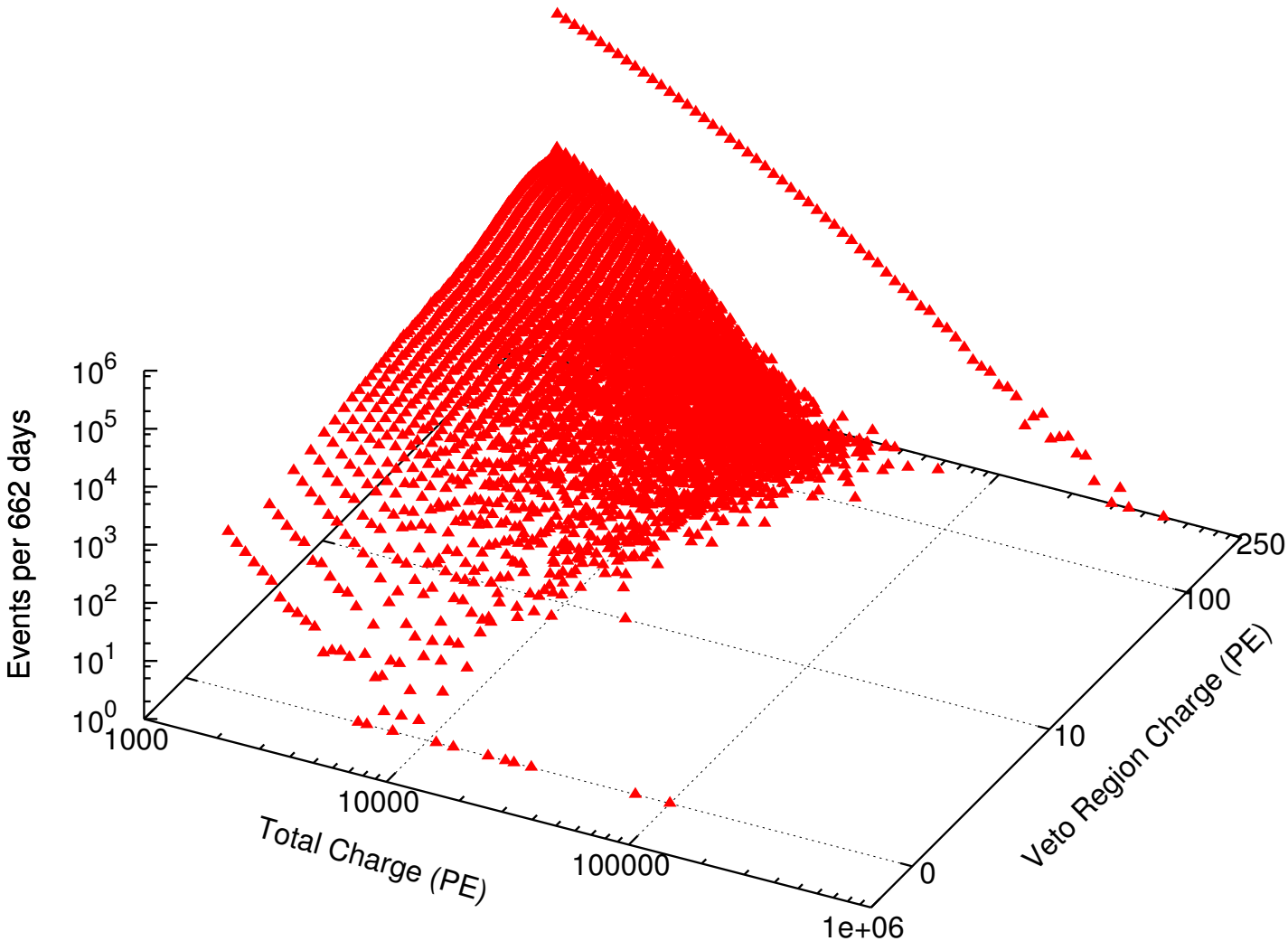


- Estimate Muon Background from Data
- Use outer tagging layer, see how many miss
- 3 ± 1.5 background events per year

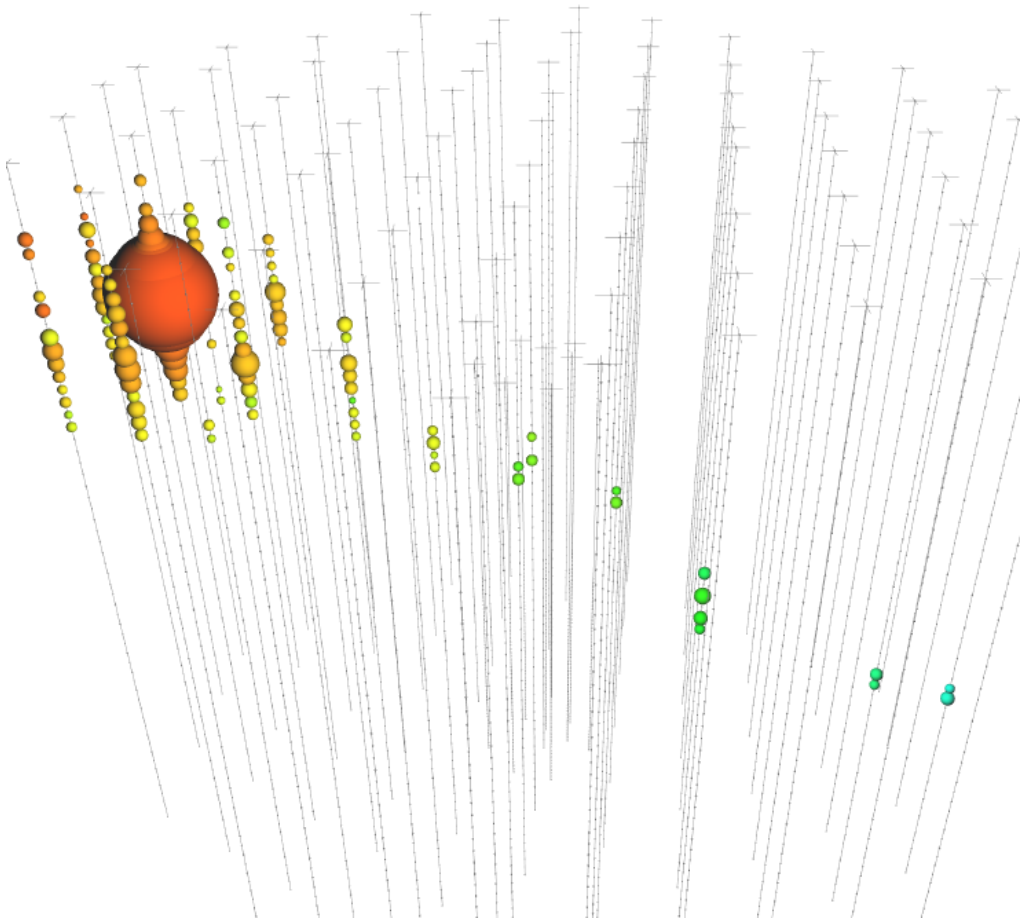
Muon Rate – 10^5 background rejection



More dimensions



A background event



Things to note:

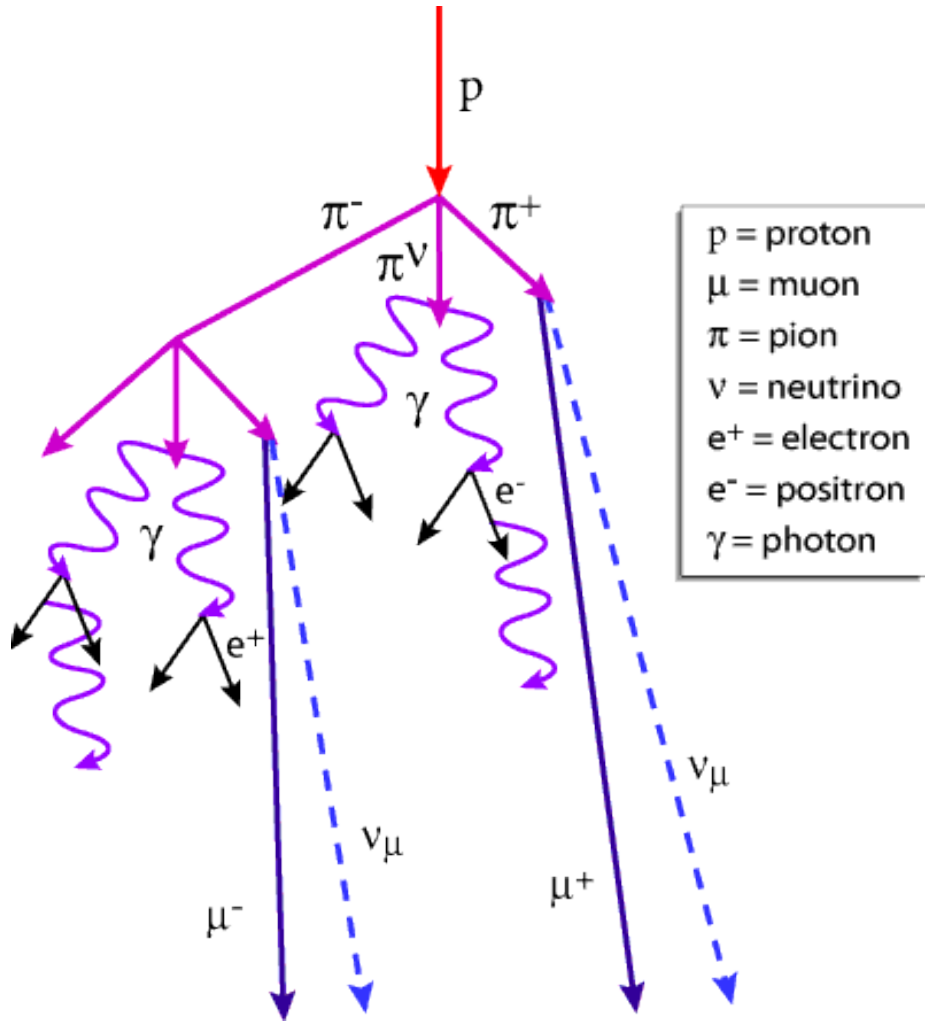
- This is a typical event
- Muon track clearly visible
- Enters on the side or top after a brief underfluctuation
- Large stochastic lets low-energy muons pass deposited energy cut
- One additional subdominant class: coincident muon background (not shown)

Notes on the Muon Background

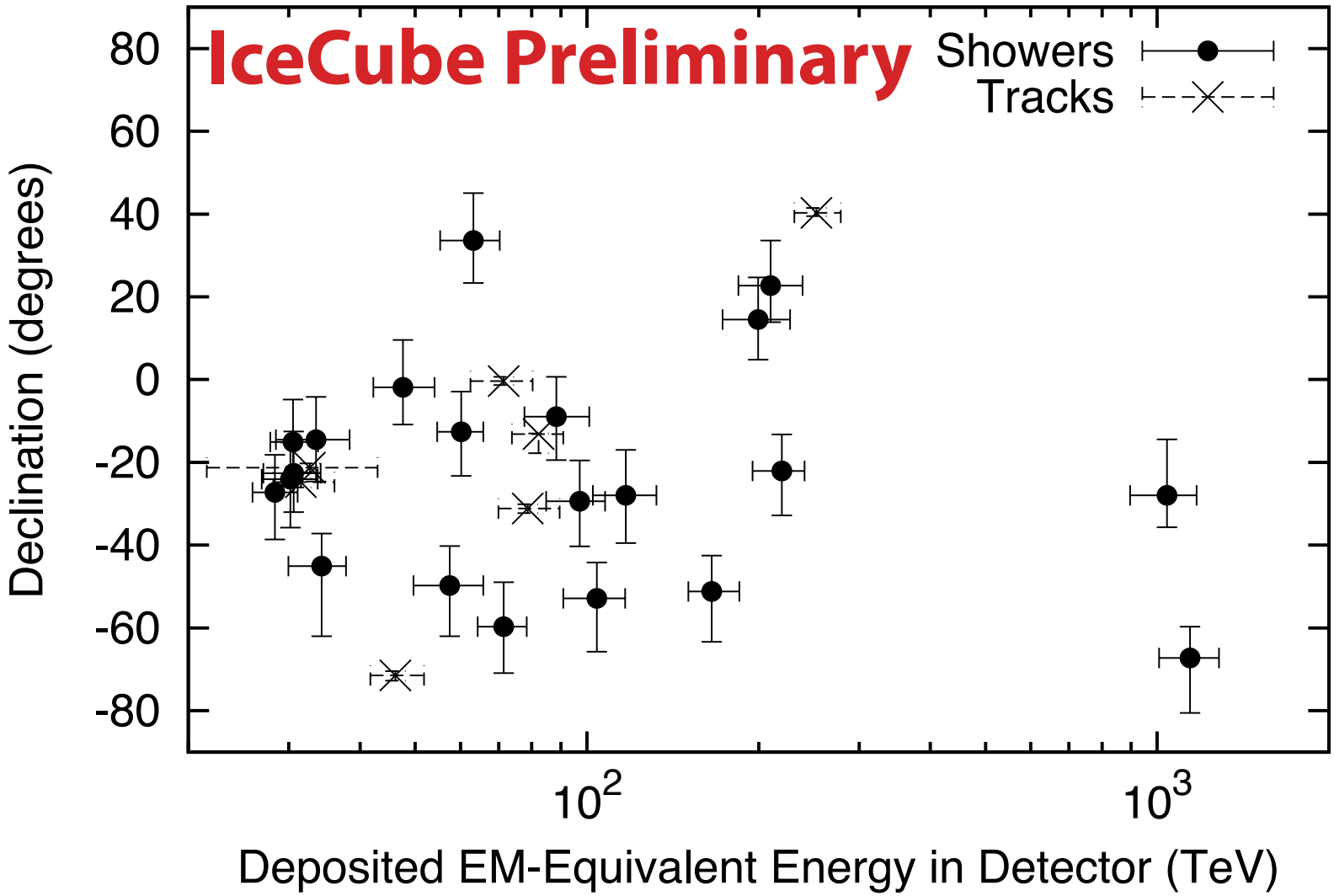
- Far in the tails of the CR background
- Tagging procedure really gives only information on charge, as used here
- Nonetheless provides strong constraint on background and allows validation of Monte Carlo without signal contamination
- Most remaining muons from very low multiplicity bundles
- No evidence for any population of "tricky" muons: to first (and second) order, they all look like the event on the last slide
- Background has $E^{-5.1}$ energy spectrum
- *Conclusion*: At high enough energies, even something very simple-minded can work well

Background 2: Atmospheric Neutrinos

- In-ice veto tags accompanying muons – directly probes lepton detection vertex (see Tom Gaisser's talk)
- π/K rate well constrained: 2.3 ± 0.6 events per year
- Charm rate not well constrained: upper limit (1σ) of 1.7 events per year
- Total: $2.3^{+1.9}_{-0.6}$ events per year

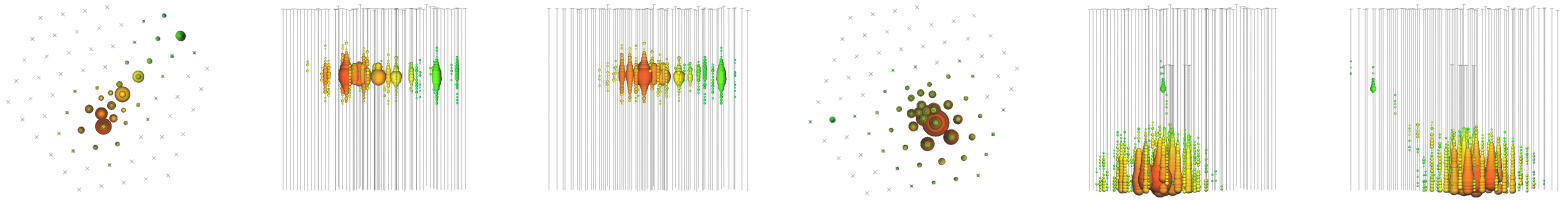


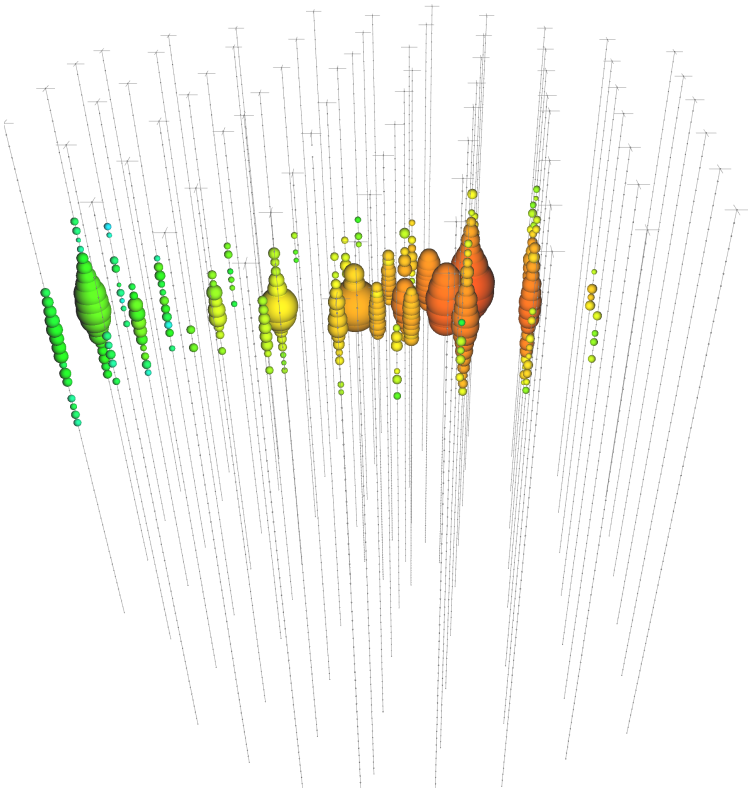
Results of Contained Vertex Event Search (2010-2012)



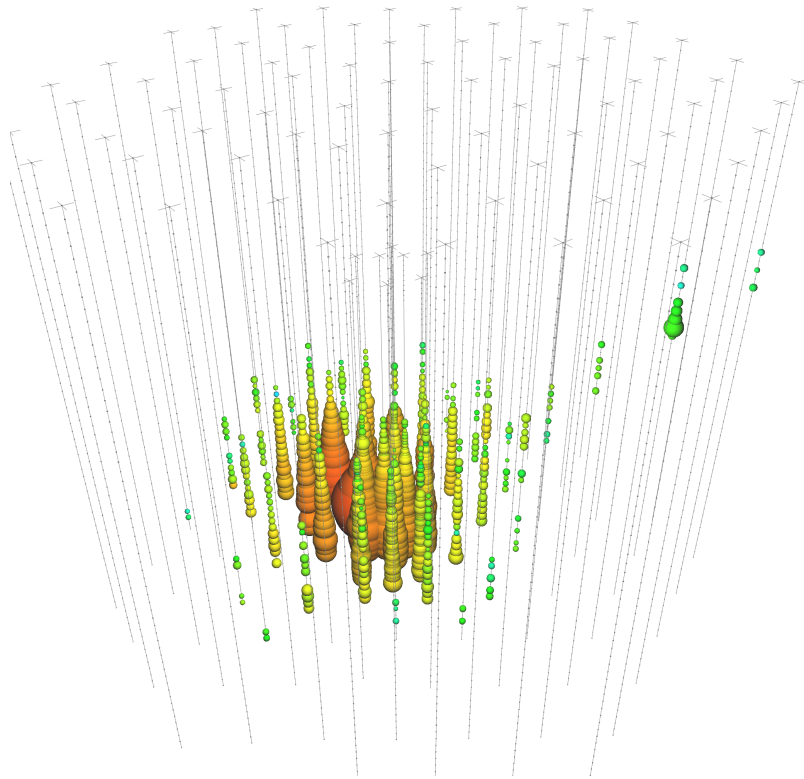
28 events (7 with visible muons, 21 without) on background of $10.6^{+5.0}_{-3.6}$

Some interesting events



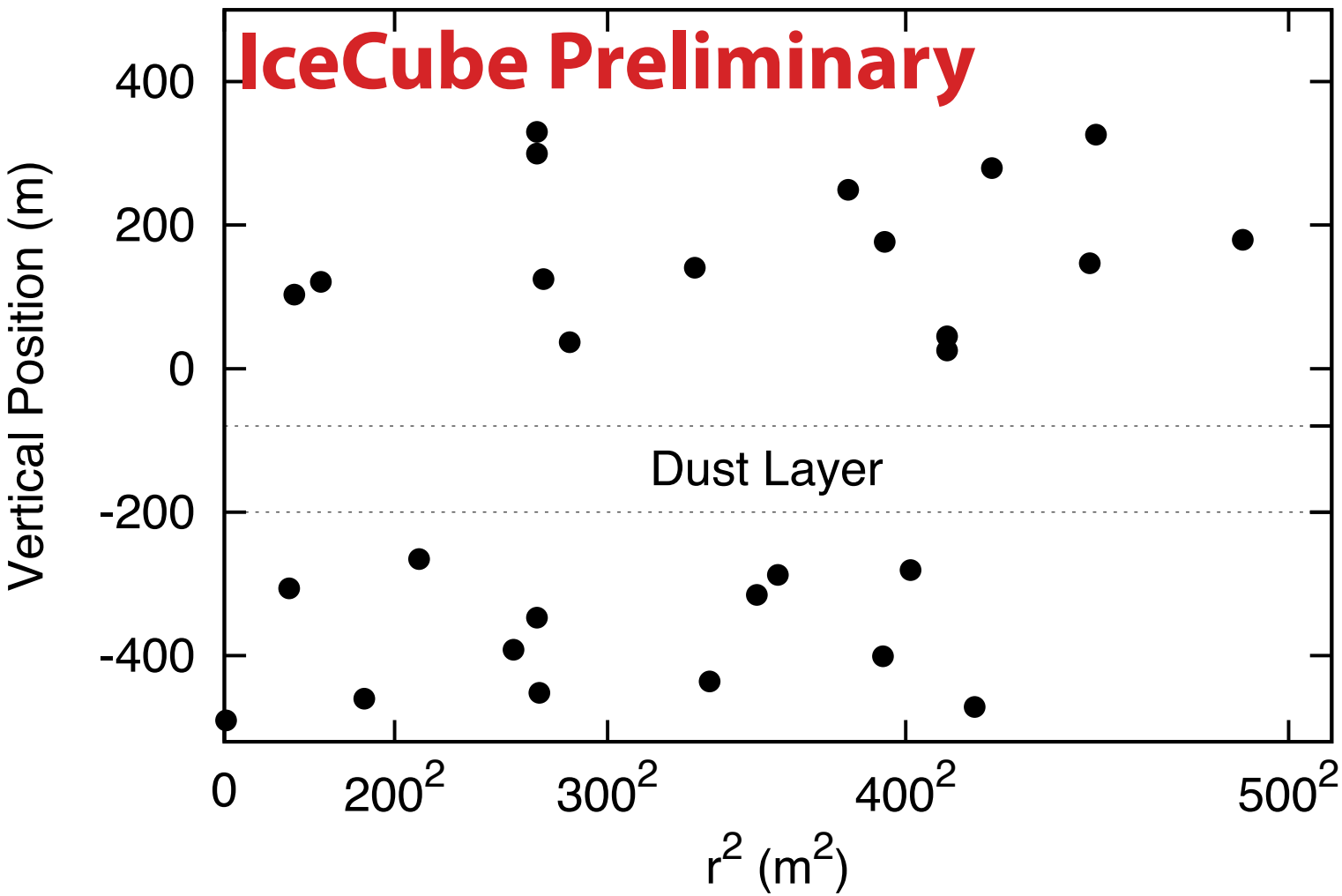


74.1 TeV, -0.4°
Dr. Strangepork



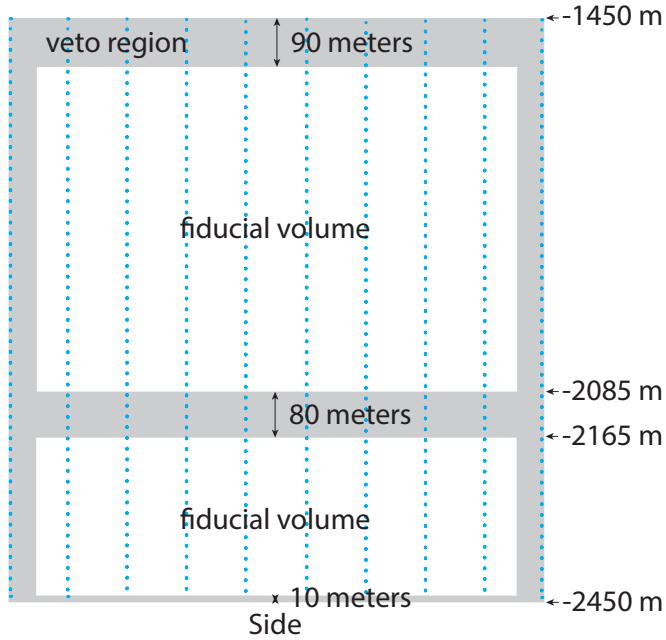
252.7 TeV, $+40^\circ$
Mr. Snuffleupagus

Event Detection Points



Final Thoughts

- In-Ice Vetos work very well, at the cost of volume, but we still get a solid flux measurement and win in solid angle, flavor sensitivity, event quality, and disambiguation
- IceCube now approaching maximal sensitivity to high-energy cascades
- A neutrino telescope can point anywhere
- Highest signal-to-noise for IceCube now, for high-energy searches, is in downgoing cascades!

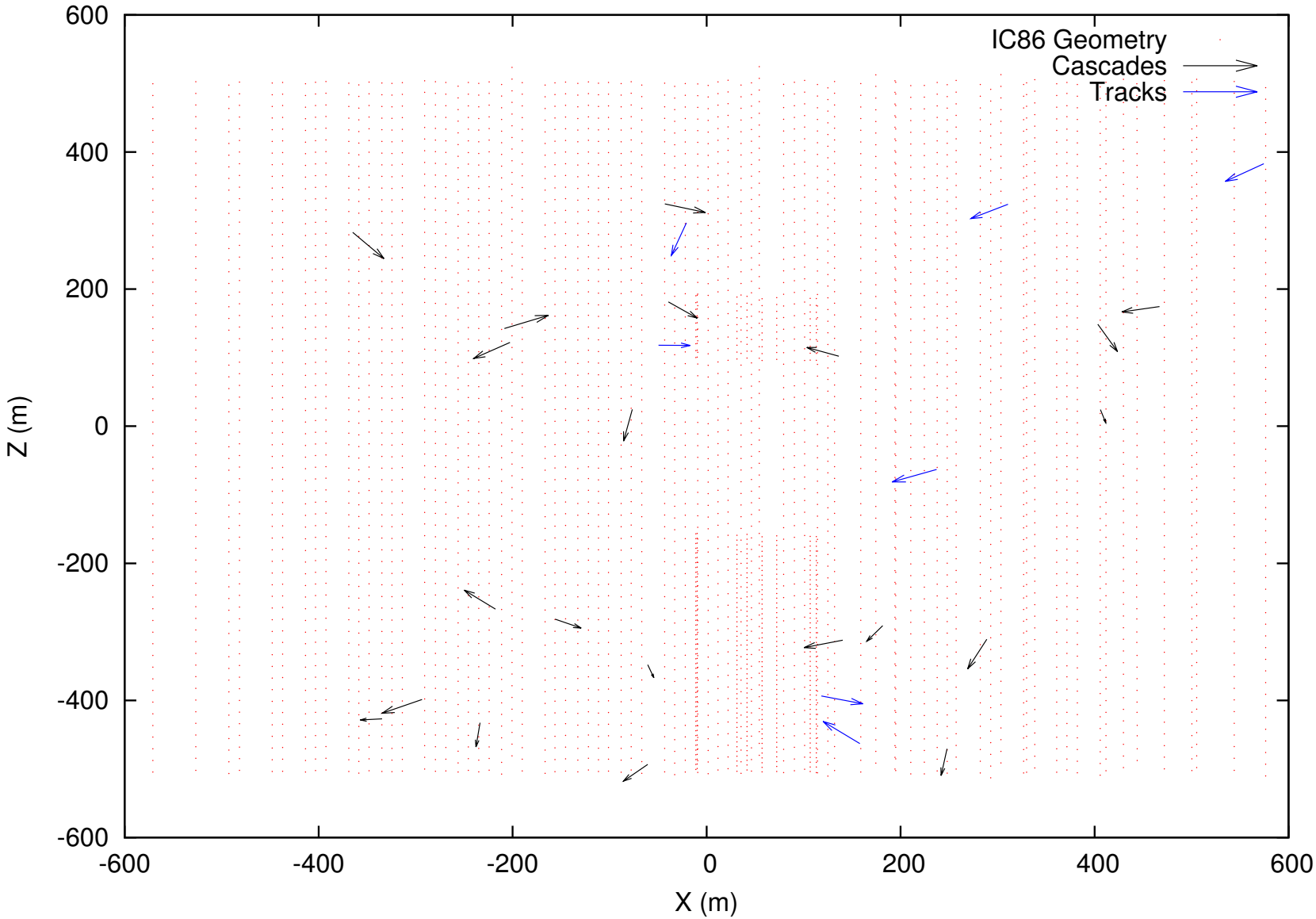


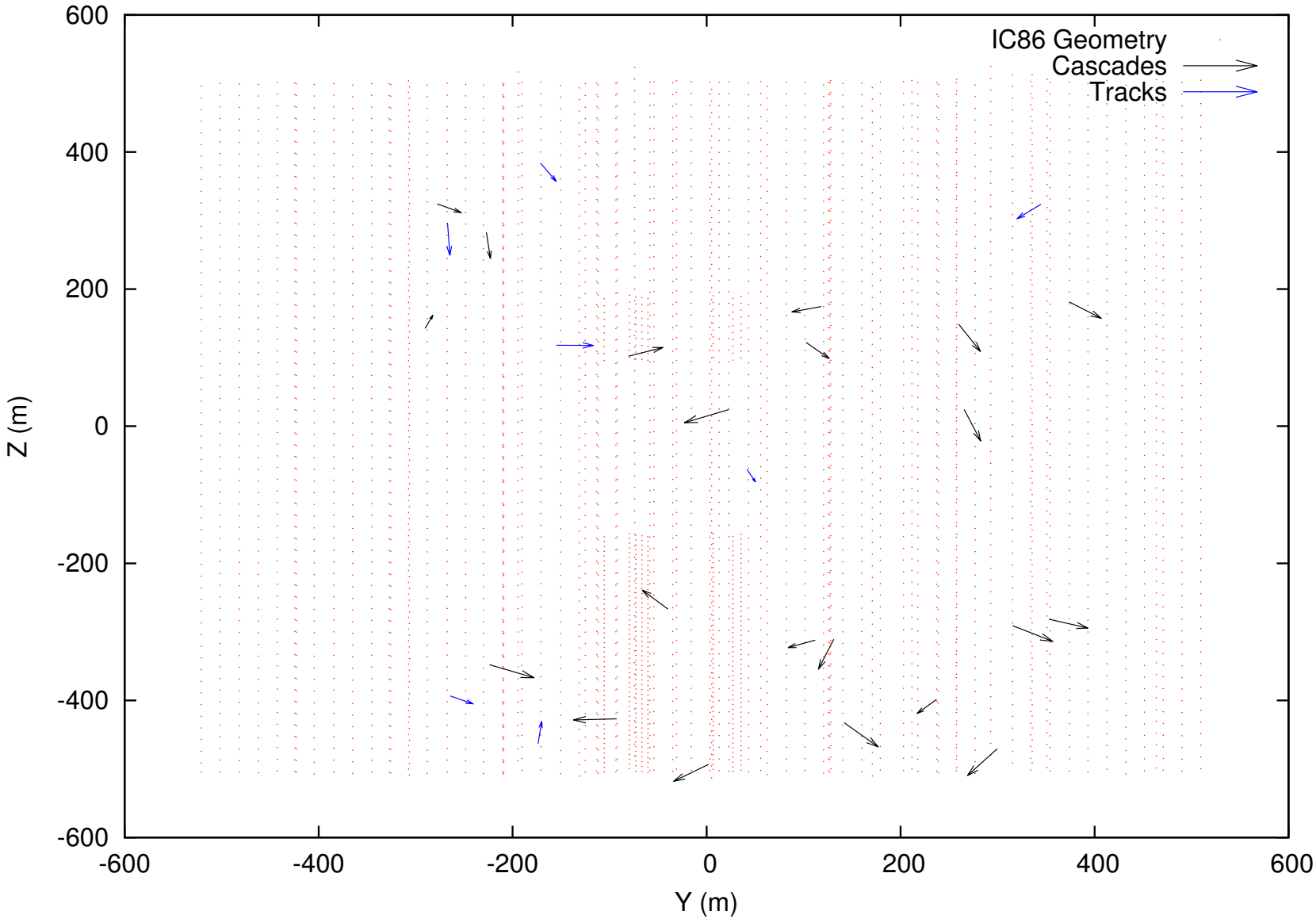
Backup

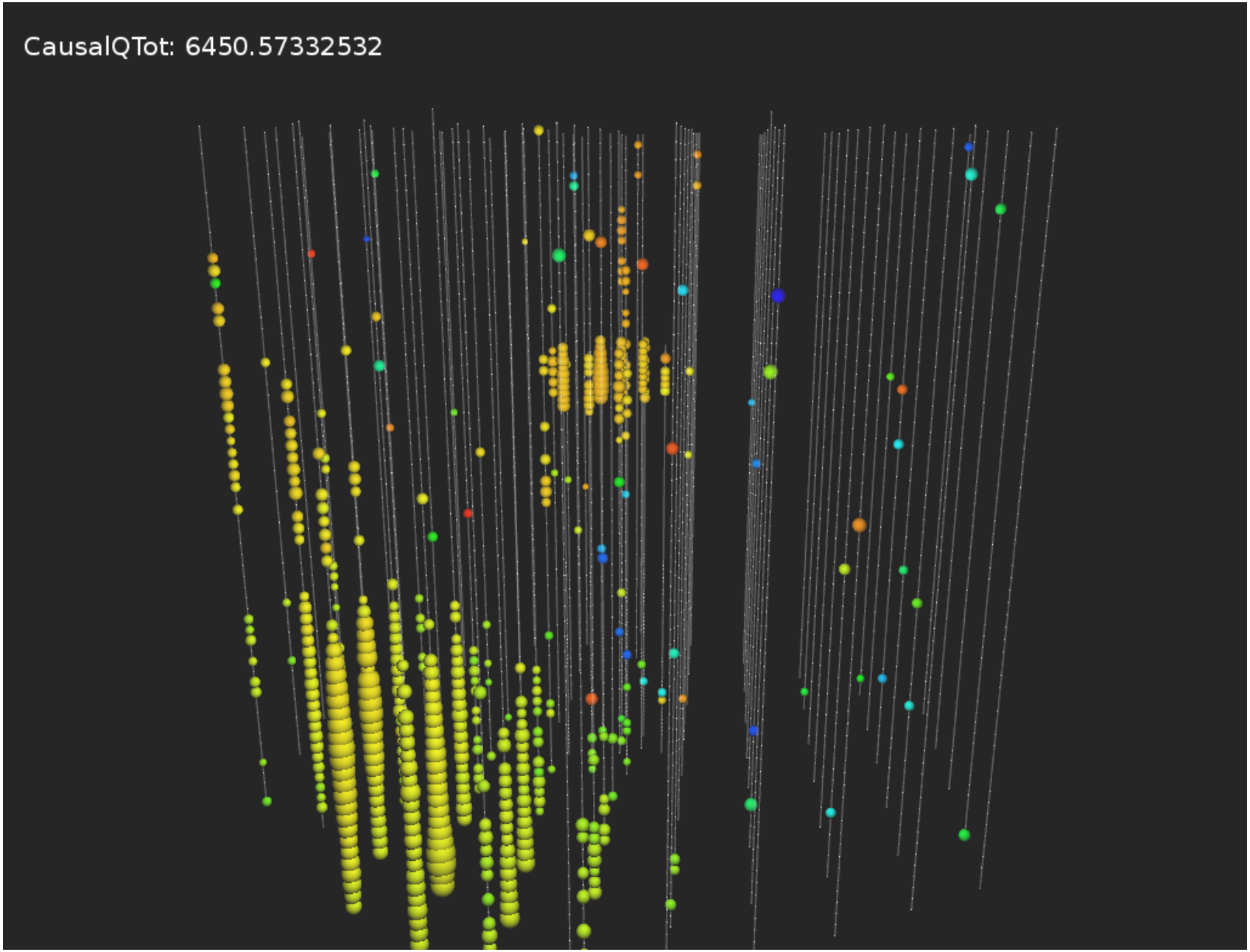
Signals and Backgrounds

	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

$\rightarrow 4\sigma$ evidence for astrophysical flux


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


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


CausalQTot: 6450.57332532

Zenith Distribution (> 60 TeV dep)