Diffuse Analysis with IceCube

June 24, 2011

Why do a diffuse search?

- It may be hard to resolve point sources
- So, we can try to look for a total signal over the whole sky

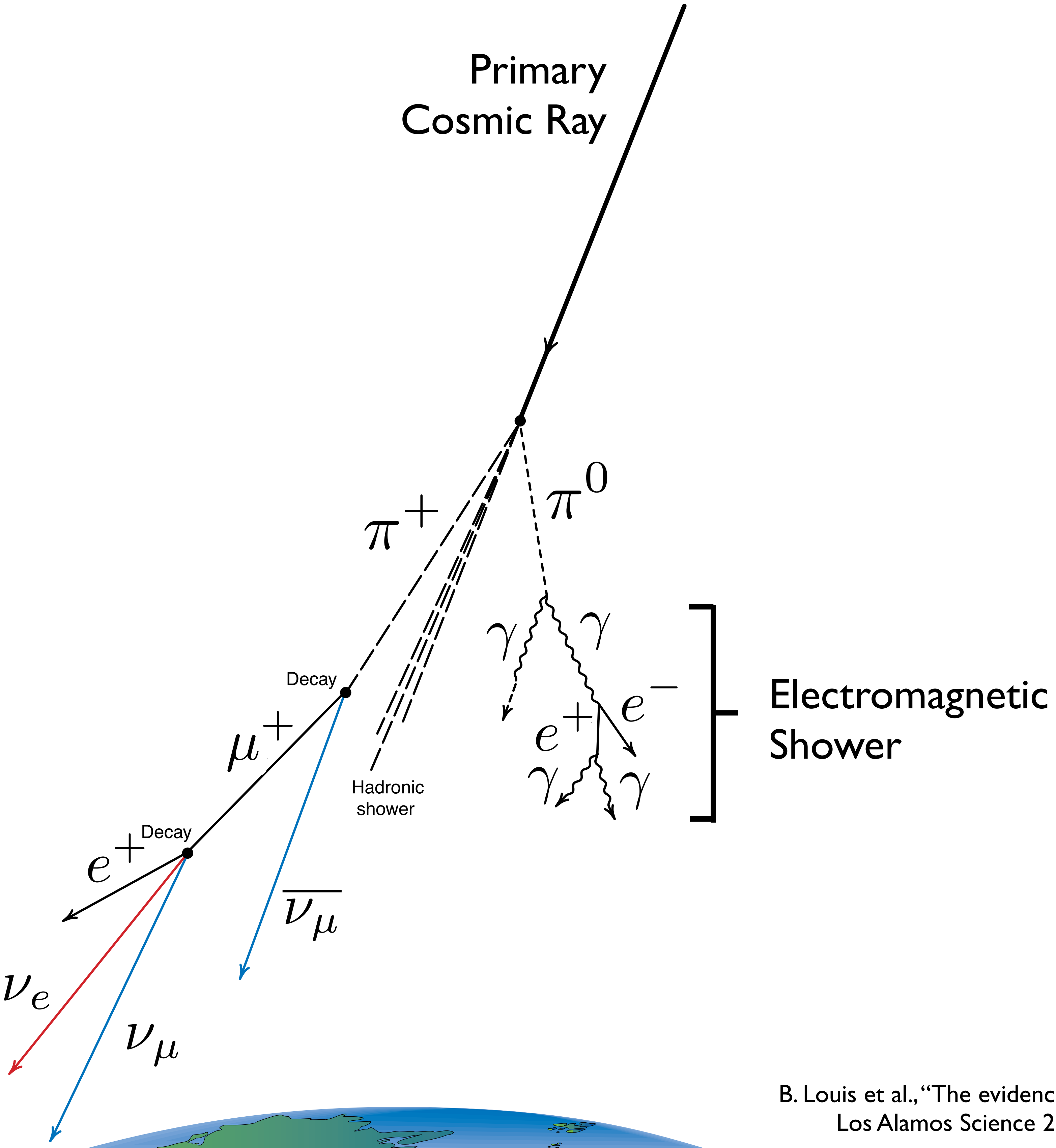
Backgrounds

- **When do you get a neutrino?**

Backgrounds

- **When do you get a neutrino?**
- Any time you create or destroy a charged lepton (including changing one into another)
- Heavy leptons decay into lighter ones
- Any time you have enough energy around, you might be able to make a heavy lepton

Cosmic Ray Air Showers



B. Louis et al., "The evidence for oscillations," Los Alamos Science 25 (1997) 16.

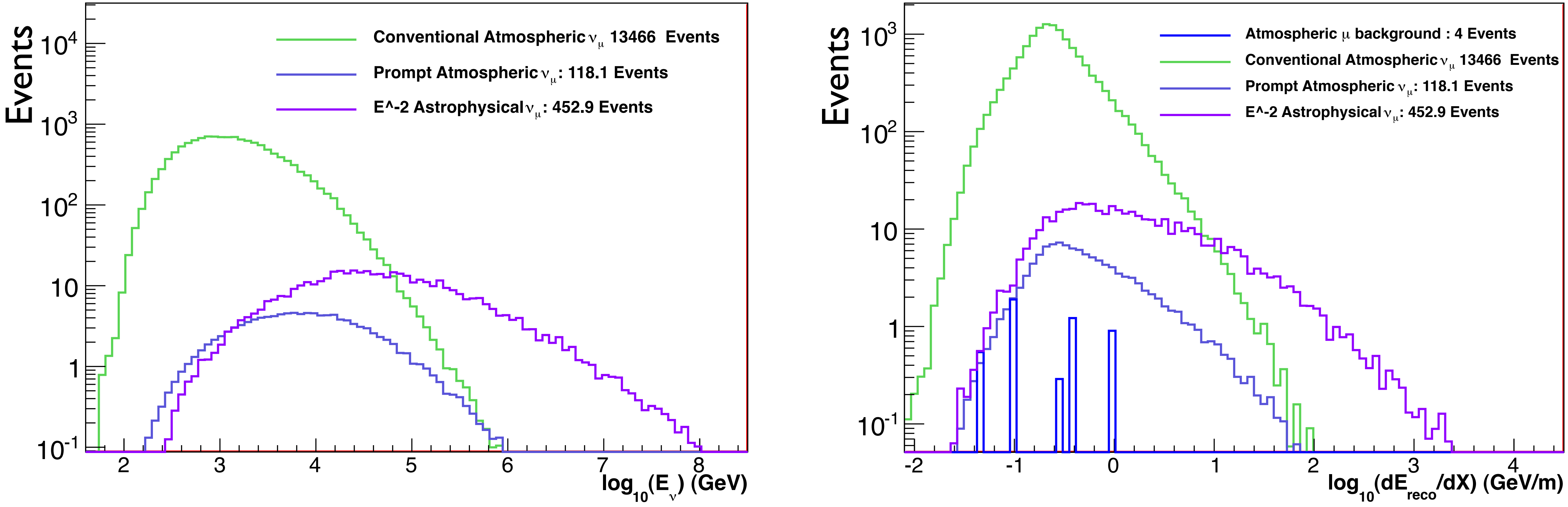
‘Prompt’ Neutrinos

- The ‘usual’ hadronic components of showers only extend to involving the first three kinds of quarks (u,d,s)
- At higher energies heavier quarks can be produced ~1.9 GeV gives access to the lightest charmed mesons:
  - $D^{\pm}$ ($c\bar{d}/\bar{c}d$), D^{0} ($c\bar{u}/\bar{c}u$), $D_s^{\pm}$ ($c\bar{s}/\bar{c}s$)
- The decays of these particles give more ways to arrive at pions, kaons, and eventually heavy leptons, with different energy spectra

Expected Energy Spectra

Spectrum in true energy

Spectrum in energy proxy



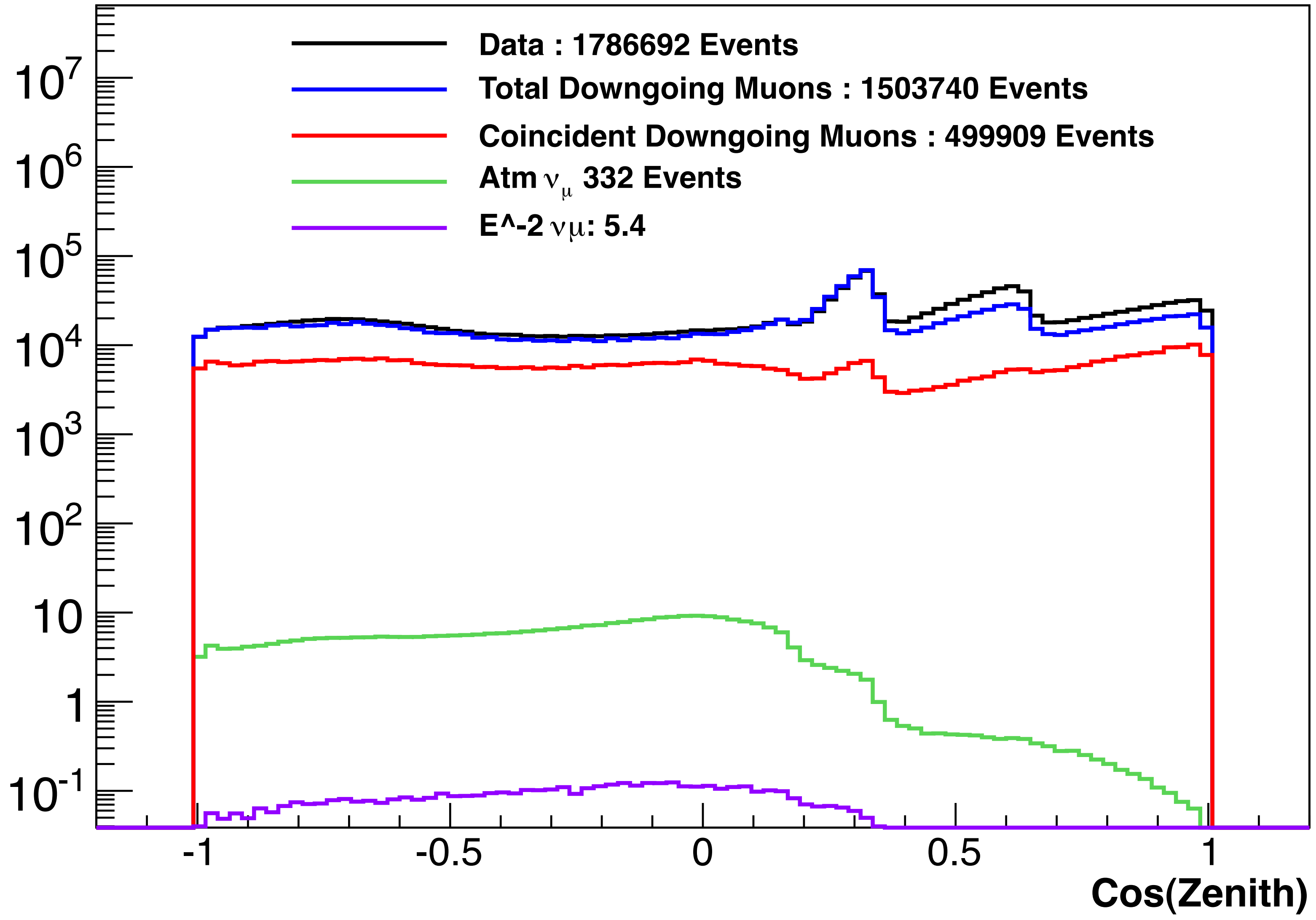
Plots from Sean Grullon

Event Selection

Cut Development Example

- Before we can start inspecting energy spectra, we need a nice, pure sample of neutrinos
- Let's look at the logic behind a series of cuts (developed by Sean)

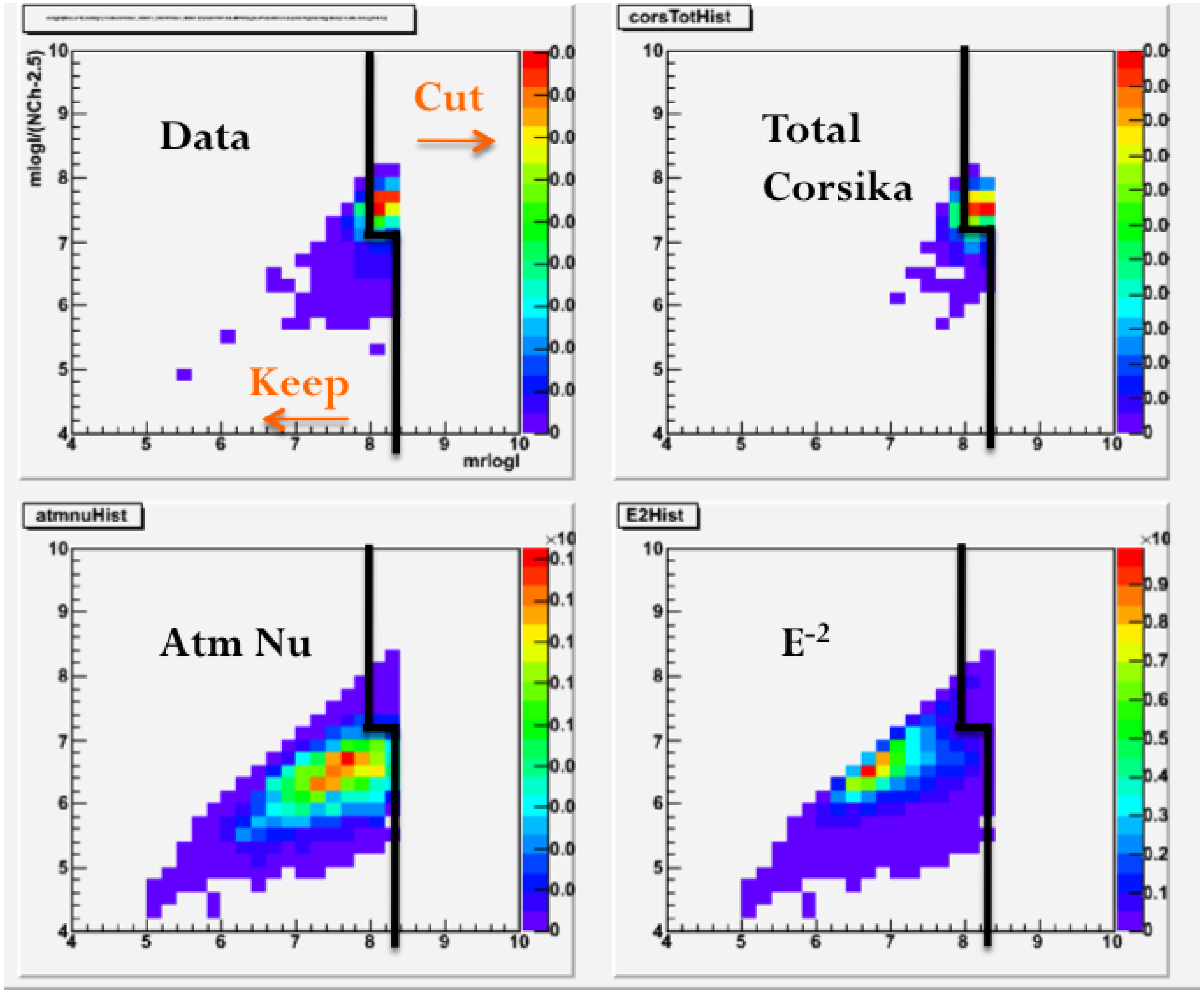
Zenith Angle



- Muons from cosmic ray air-showers disappear rapidly below the horizon
- So, make a cut zen>90°

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
19211340	24557460	14318580	7290	100.0%

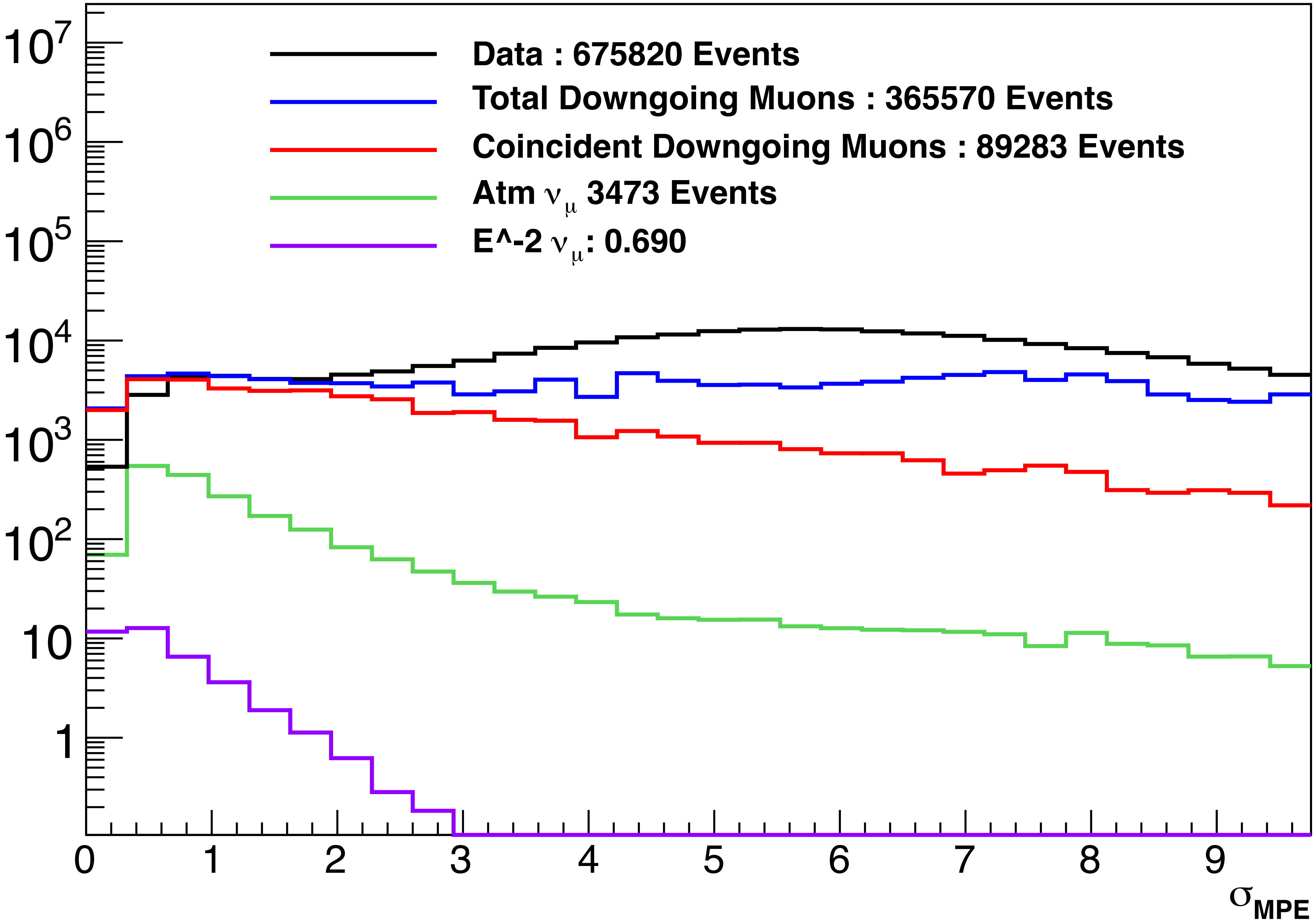
Reconstruction Likelihood



- We want good reconstructions, not bad reconstructions that came out up-going

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
675820	365570	89283	3473	69%

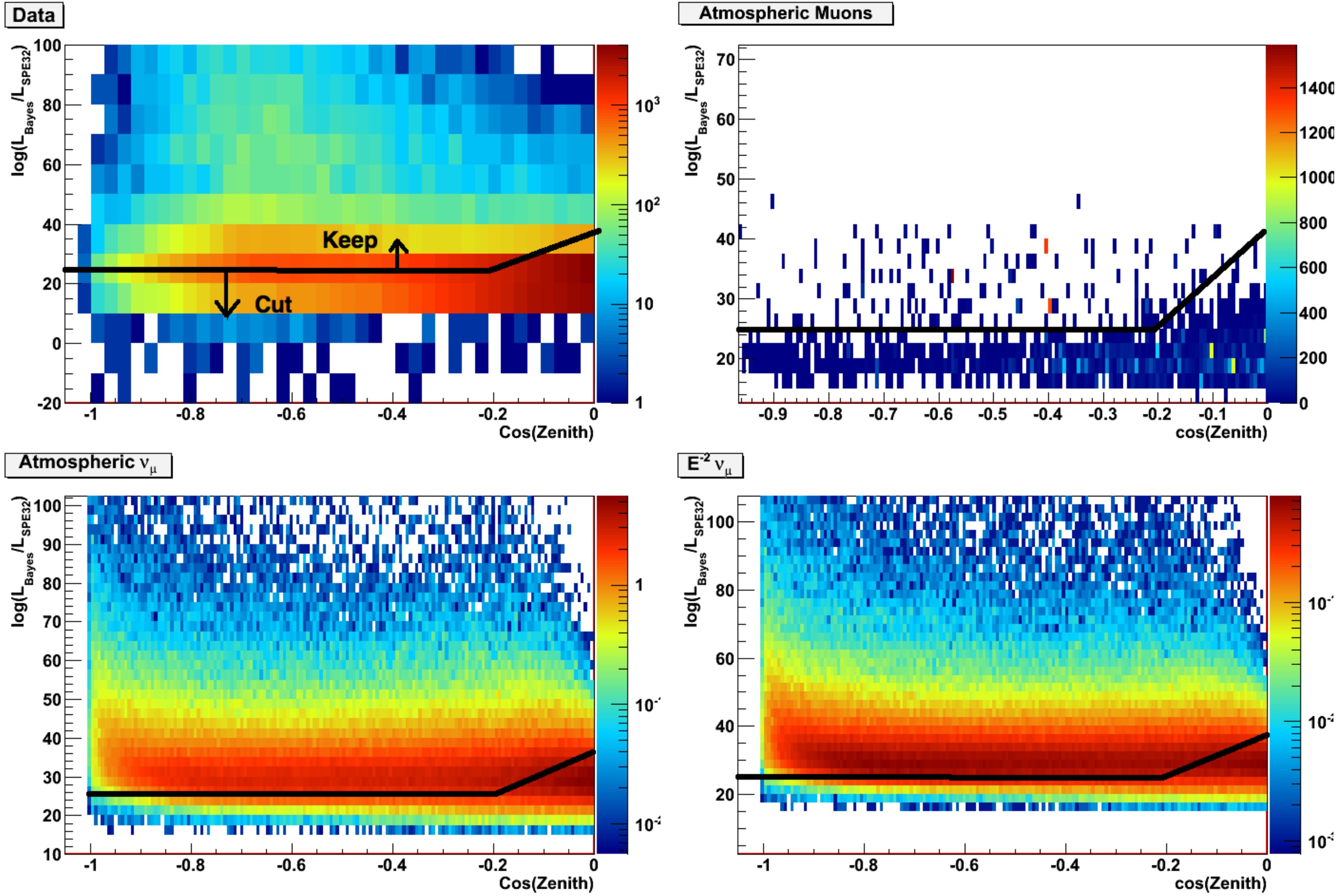
Reconstruction Angular Quality



- Let's also make sure that the reconstruction had reasonable angular resolution, pick $\sigma_{MPE}<3$

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
114305	83913	32615	2985	50%

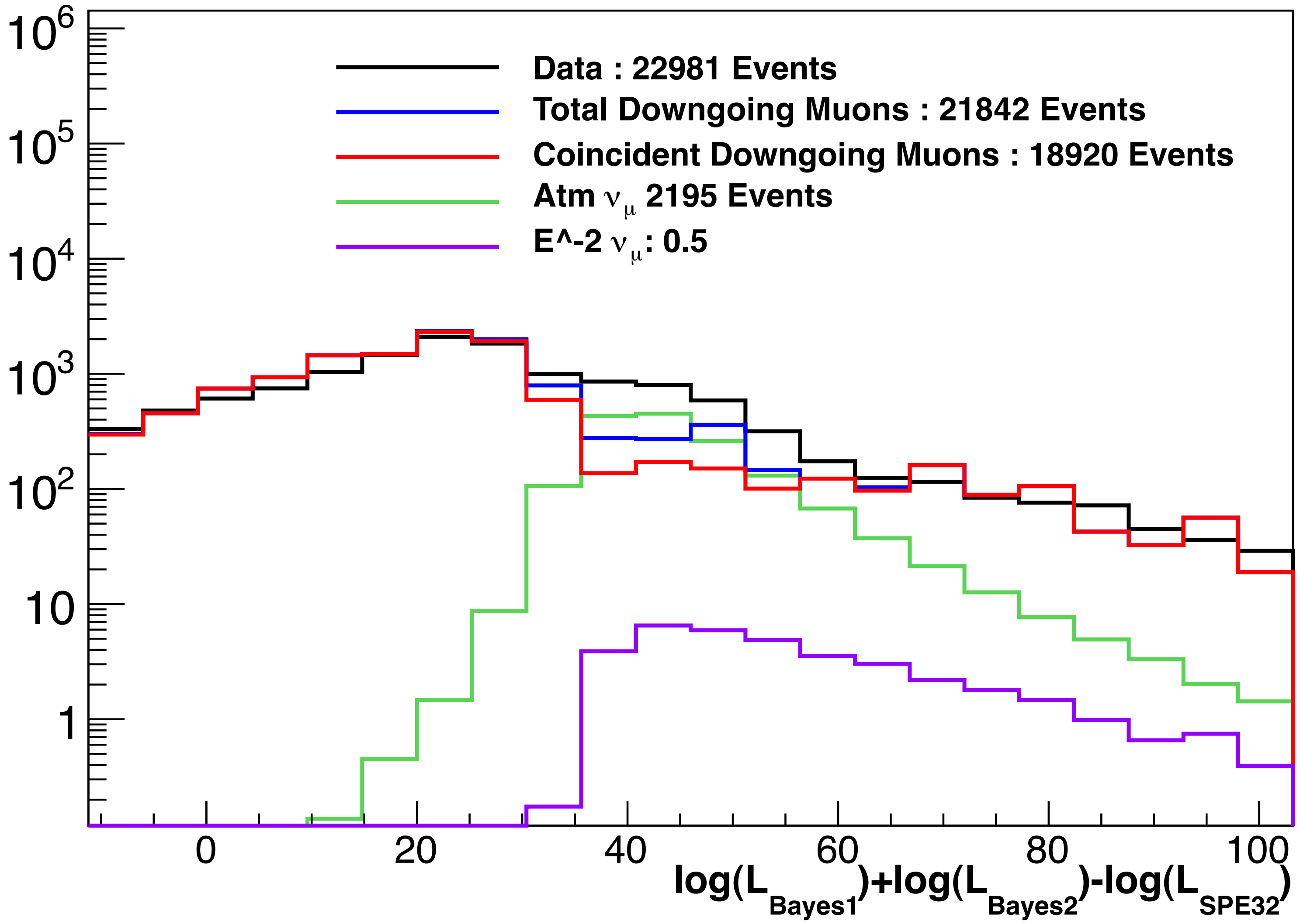
Bayesian Likelihood



- The hypotheses that the event does not come from the angular distribution of down-going muons should be more likely than the hypothesis that it does

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
22981	21842	18920	2195	48.7%

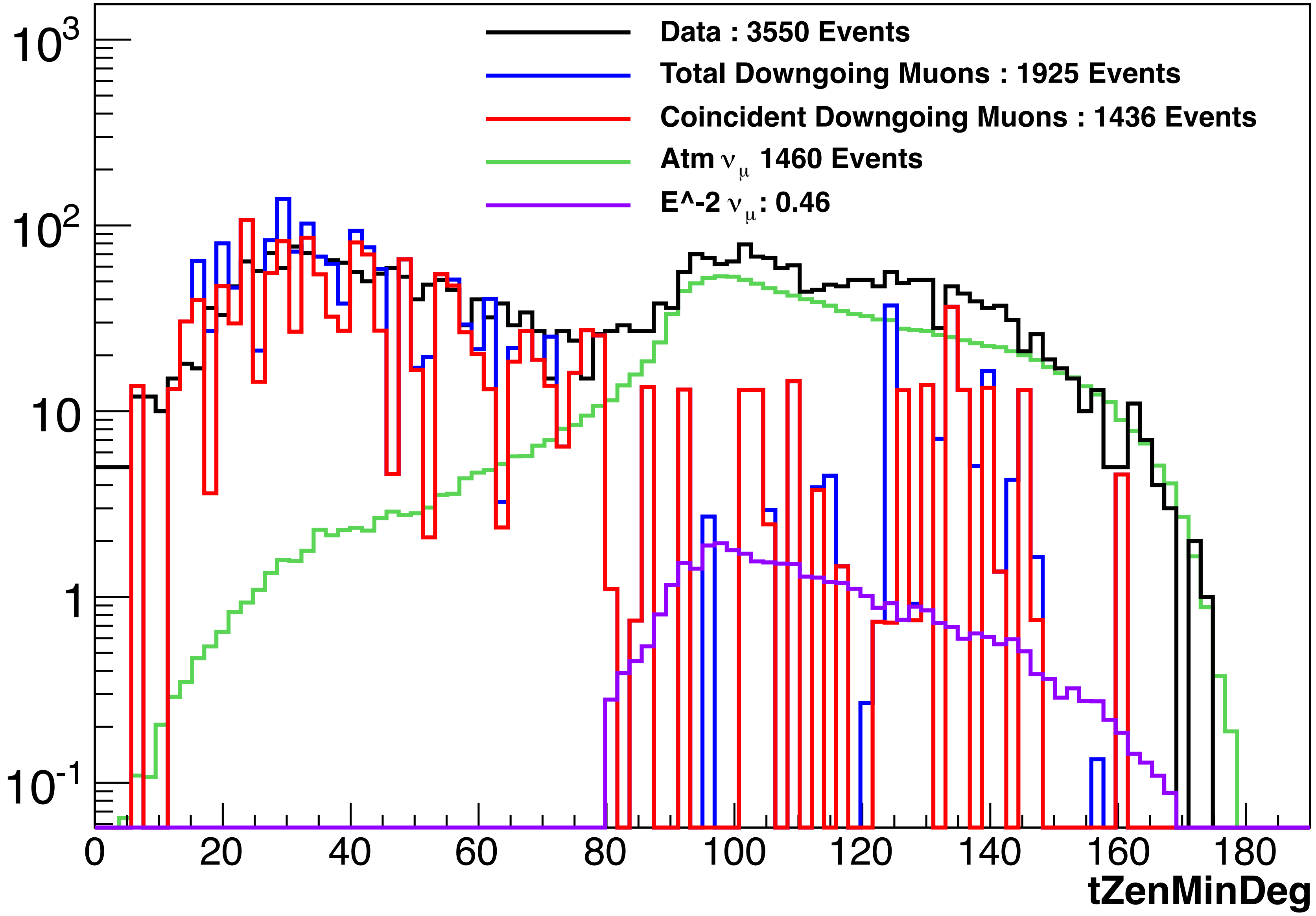
Split Bayesian Likelihood



- The hypothesis that the event is a single track, not drawn from the angular distribution of down-going muons should also be more likely than the hypothesis that it consists of *two* tracks which are

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
3550	1925	1436	1490	46.0%

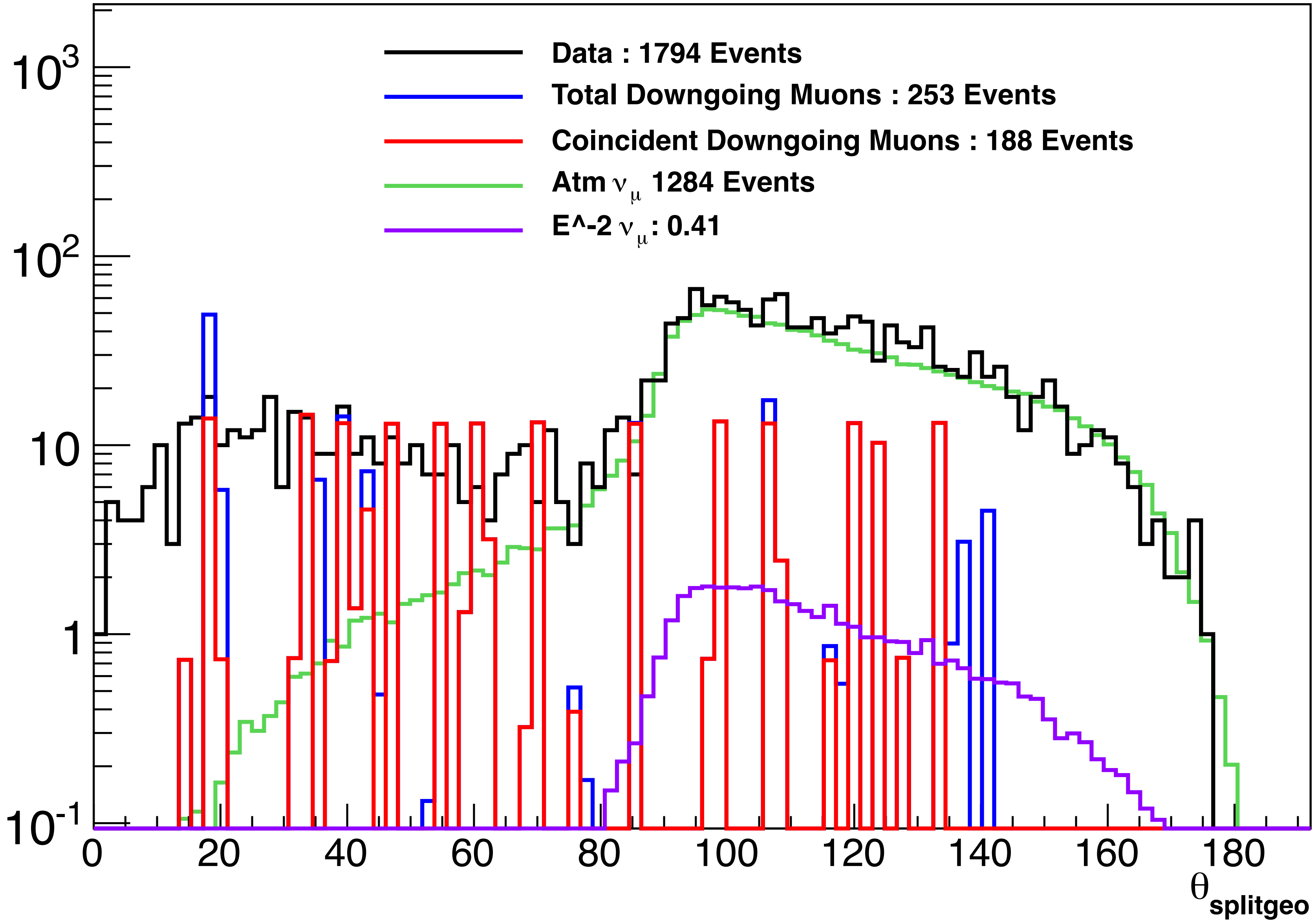
Angle of Time Split Reconstruction



- If we split the event in half in time, neither half should be down-going: min(time split zeniths)>80°

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
1794	253	188	1284	41.1%

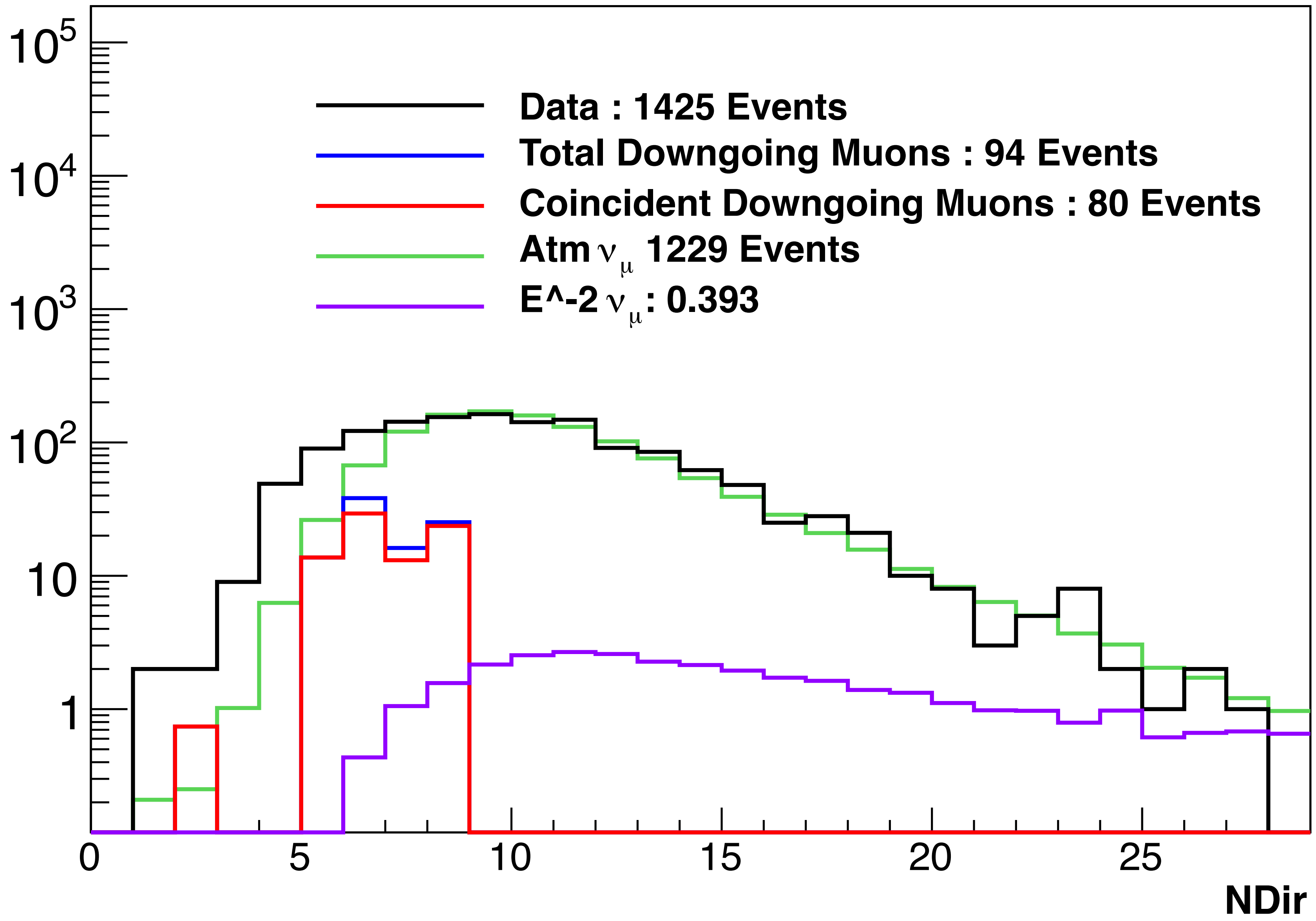
Angle of Geo Split Reconstruction



- If we split the event in half in space, neither half should be down-going: min(time split zeniths)>80°

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
1425	94	80	1229	39.3%

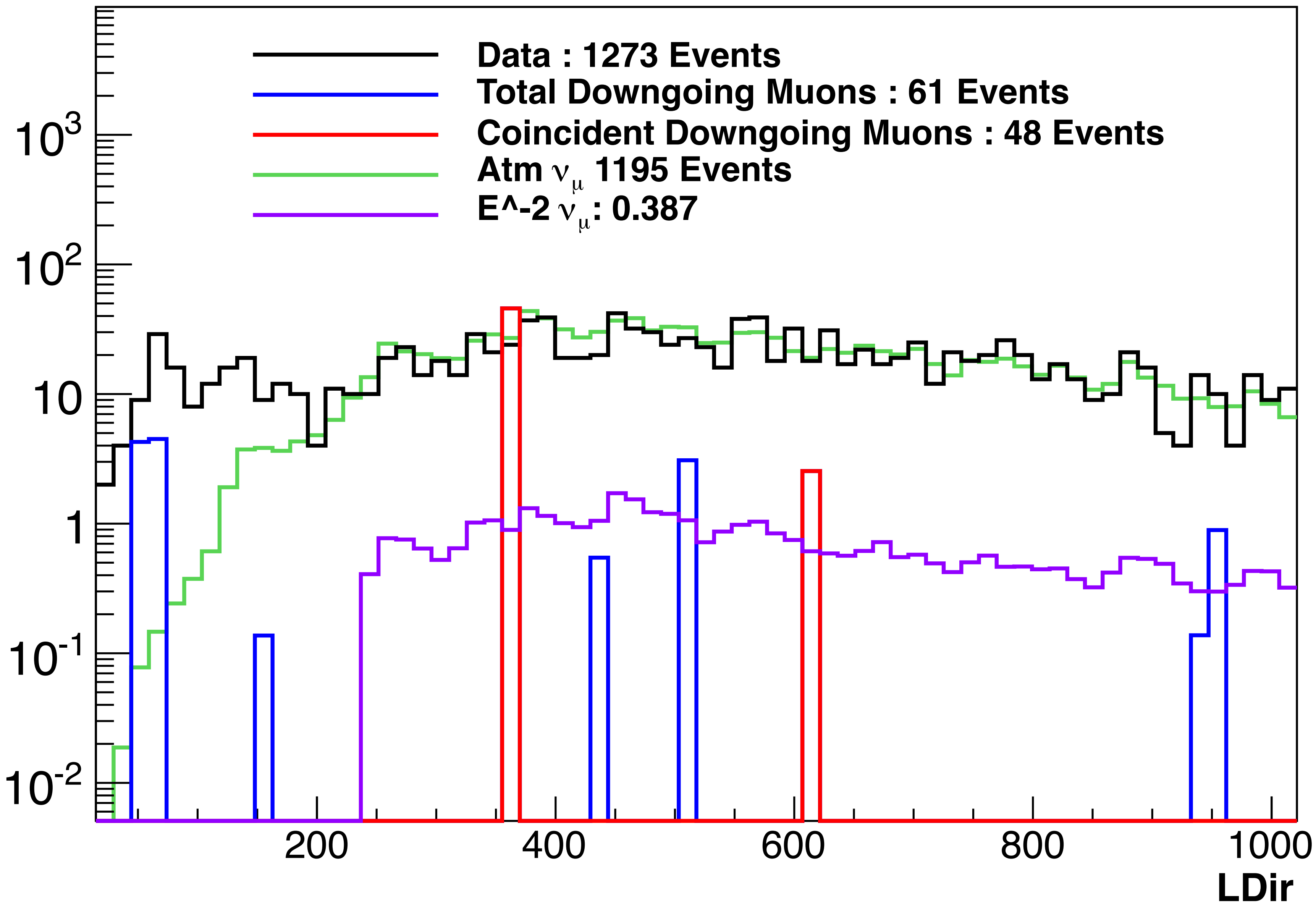
Number of Direct Hits



- Good events should have more direct light from the reconstructed track

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
1273	61	48	1195	38.7%

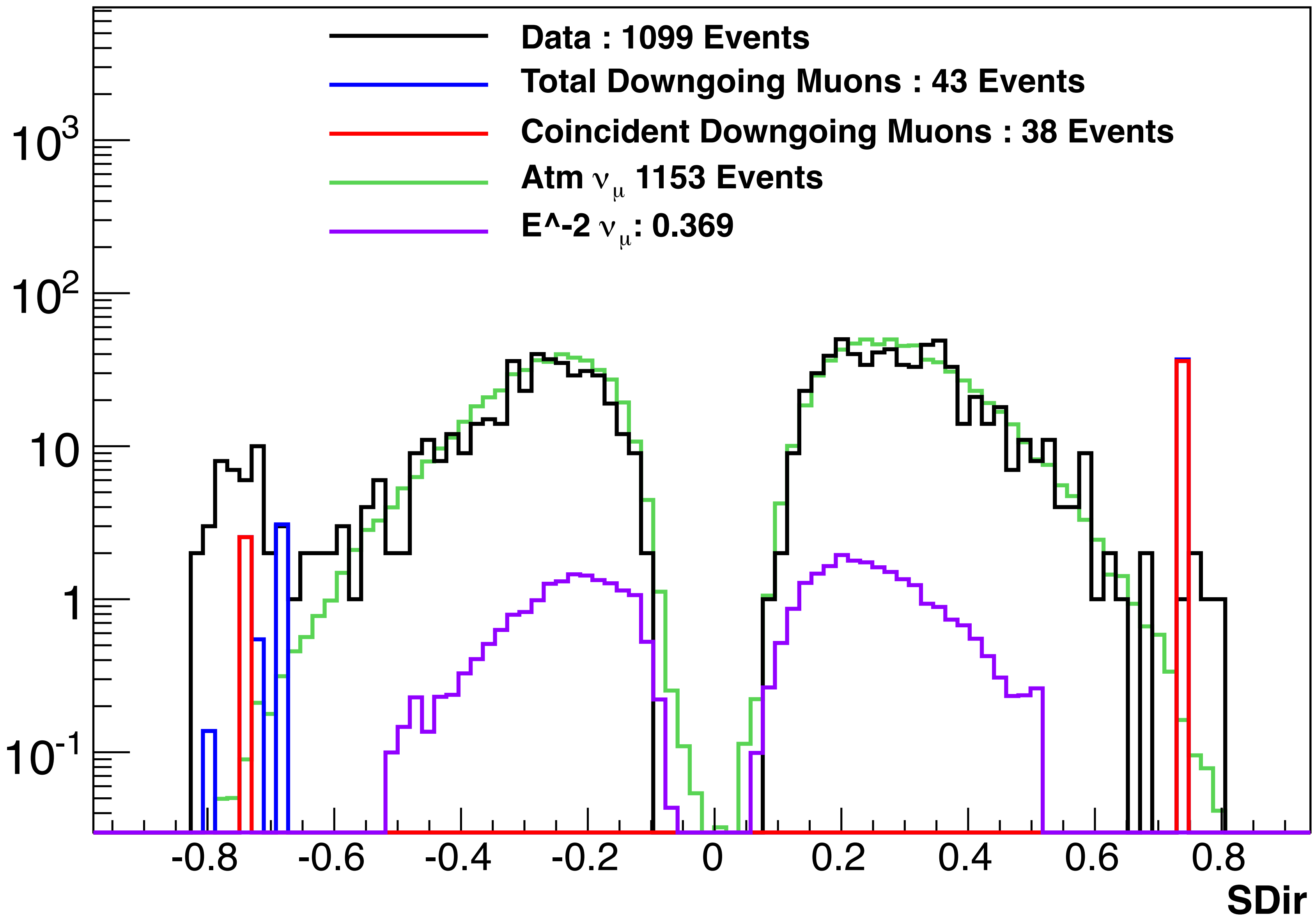
‘Direct Length’



- Good events should have a longer tracks with direct hits distributed more widely along them

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
1099	43	38	1153	36.9%

‘Direct Smoothness’



- Good events should direct hits even distributed along the reconstructed track

Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
1001	0	0	1111	35.1%

Summary of Cuts

Quality Parameter	Data	Total Atm. μ	Coincident μ	Atm. ν_μ	E^{-2} ν_μ
$\theta_{MPE} > 90°$	19211340	24557460	14318580	7290	100.0%
$\log(L_{MPE})$	675820	365570	89283	3473	69%
σ_{MPE}	114305	83913	32615	2985	50%
$\log(L_{Bayes}/L_{SPE32})$	22981	21842	18920	2195	48.7%
$\log(\frac{L_{Bayes1}+L_{Bayes2}}{L_{SPE32}})$	3550	1925	1436	1490	46.0%
$\theta_{splittime}$	1794	253	188	1284	41.1%
$\theta_{splitgeo}$	1425	94	80	1229	39.3%
$NDir$	1273	61	48	1195	38.7%
$LDir$	1099	43	38	1153	36.9%
$SDir$	1001	0	0	1111	35.1%

Spectrum Analysis

Maximum Likelihood

- What we measure is a single energy spectrum, which should be some combination of signal and background spectra
- We need to unpack this, and a good way is to use a *Maximum Likelihood* technique

Maximum Likelihood cont'd

- Basically, we can write down a probability for measuring the observed data, given a particular set of parameters
    - In this case our parameters describe the combination of input spectra
- Since the data is fixed and the values of the parameters are unknown to us, we call this a likelihood for the model parameters
- Vary the parameters until the likelihood is as large as possible—this is the best estimate

Likelihood Function

$$L(\{n_i\}|\{\mu_i(\theta_r)\}) = \prod_{i=1}^{N} \frac{e^{-\mu_i}}{n_i!}\mu_i^{n_i}$$

$$\mu_i = \mu_c p_{c,i} + \mu_p p_{p,i} + \mu_a p_{a,i}$$

$$\mu_c = \int dE_\nu \; d\Omega \; dt \; A_{eff}(E,\theta,\phi) \; (1+\alpha_c) \left(\frac{E}{1.17 \; TeV}\right)^{\Delta\gamma} \Phi_{Honda}(E_\nu,\theta,\phi)$$

$$\mu_p = \int dE_\nu \; d\Omega \; dt \; A_{eff}(E,\theta,\phi) \; (1+\alpha_p) \left(\frac{E}{7.24 \; TeV}\right)^{\Delta\gamma} \Phi_{Sarcevic}(E_\nu,\theta,\phi)$$

$$\mu_a = \int dE_\nu \; d\Omega \; dt \; A_{eff}(E,\theta,\phi) \; N_a E^{-2}$$

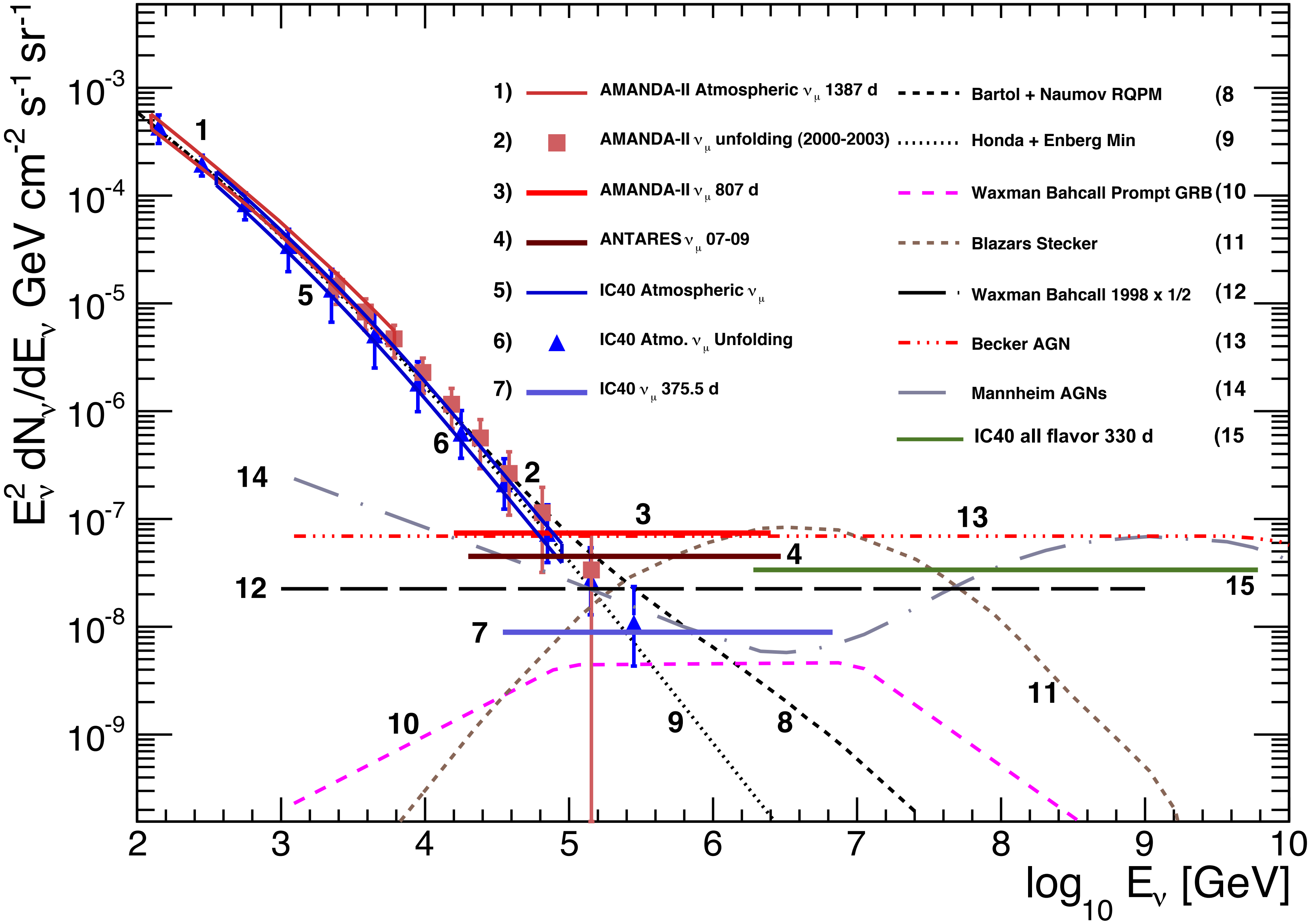
Parameters:

N_a

Astrophysical E^{-2} Normalization

Systematic Uncertainty	Nuisance Parameter	Magnitude
Conventional Atmospheric ν_μ Normalization	$1+\alpha_c$	±25%
Prompt Atmospheric ν_μ Normalization	$1+\alpha_p$	$-44\%, +25\%$
Cosmic Ray Spectral Slope	$\Delta\gamma$	±0.03
Detector Efficiency	ϵ	±8.3%
Scattering Coefficient	$b(405)$	±10%
Absorption Coefficient	$a(405)$	±10%

Recent Results



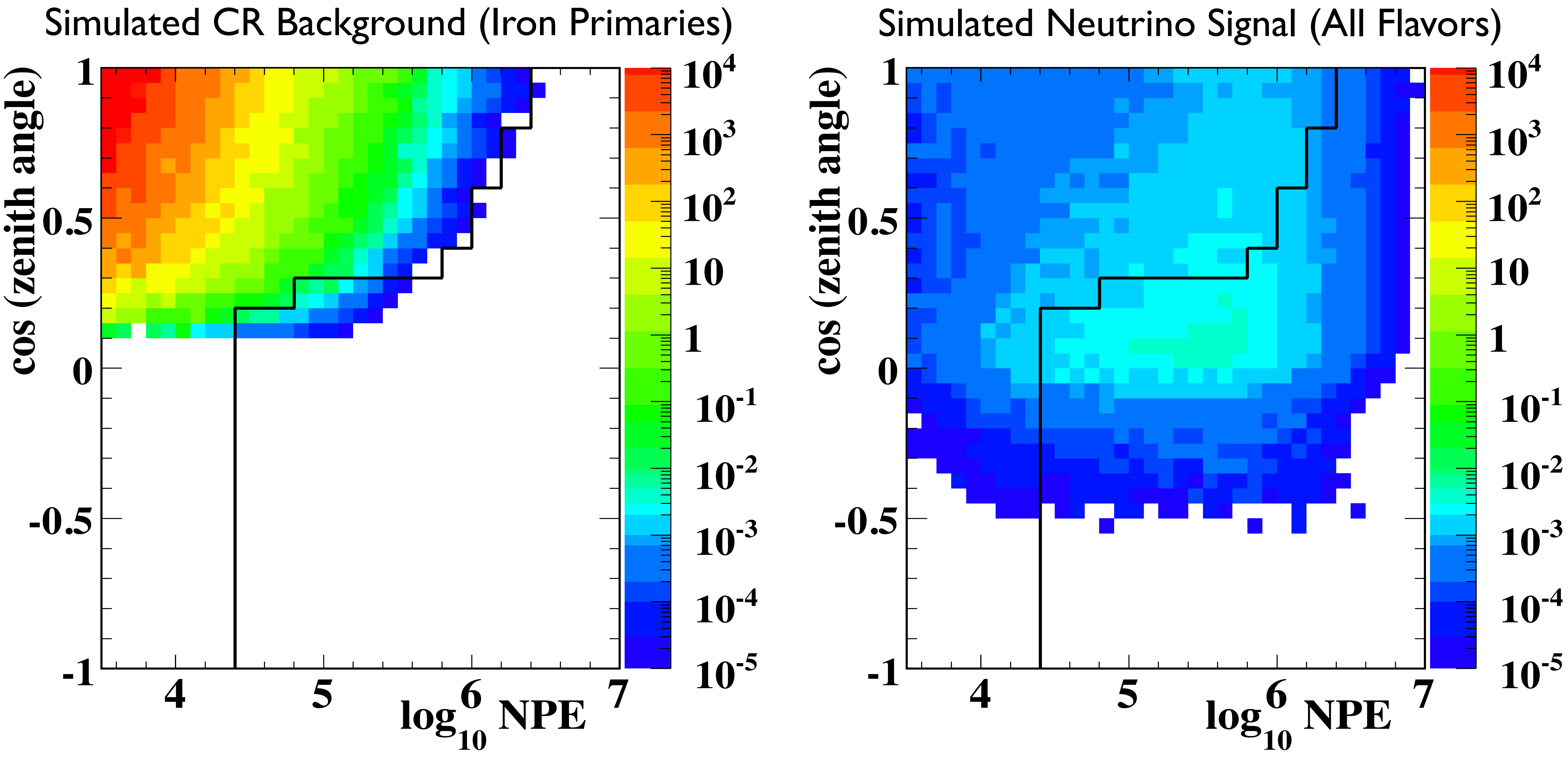
- Diffuse Analysis by Sean Grullon (ν_μ only)
- EHE Analysis by Aya Ishihara (all flavor)

Something New We Want to Use

Including the Whole Sky

- Diffuse and Extremely High Energy Analyses are closely related
- Both would like to look at the whole sky (and so would people doing other analyses)
- For the highest energy neutrinos the Earth becomes opaque, so the horizon region is where the data is
- Unfortunately, the horizon and above is also where the background gets really big

Angular Distribution of Bright Events



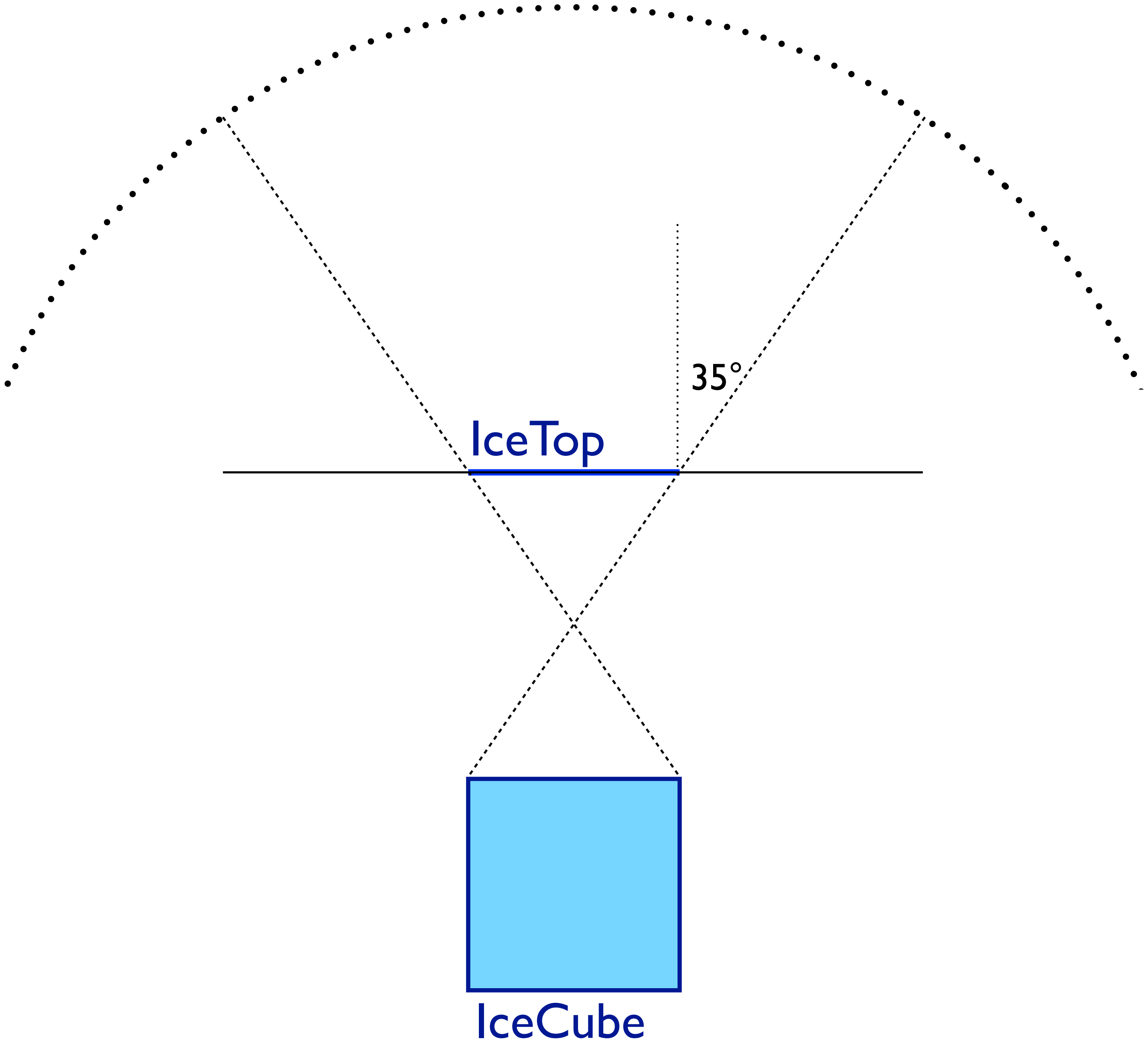
Simulated CR Background (Iron Primaries)

Simulated Neutrino Signal (All Flavors)

Figure from Aya Ishihara

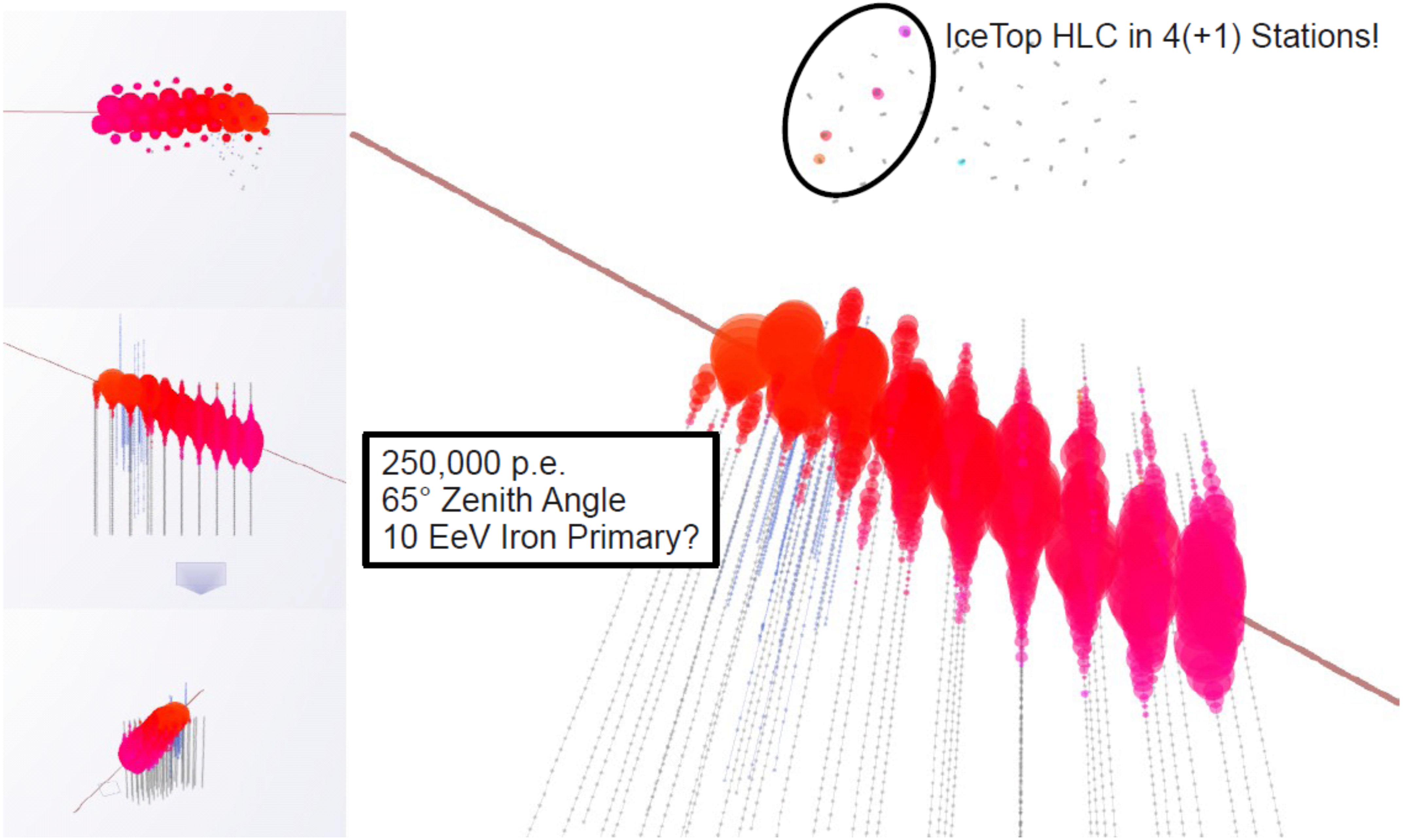
Vetoing with IceTop

- IceTop has been used as a veto before, but mostly in an ad hoc fashion
- IceTop subtends only a small fraction of the angular space above IceCube: ~.2 of the sky
- A more thorough approach is needed to do vetoing with highly inclined events



A Real Event

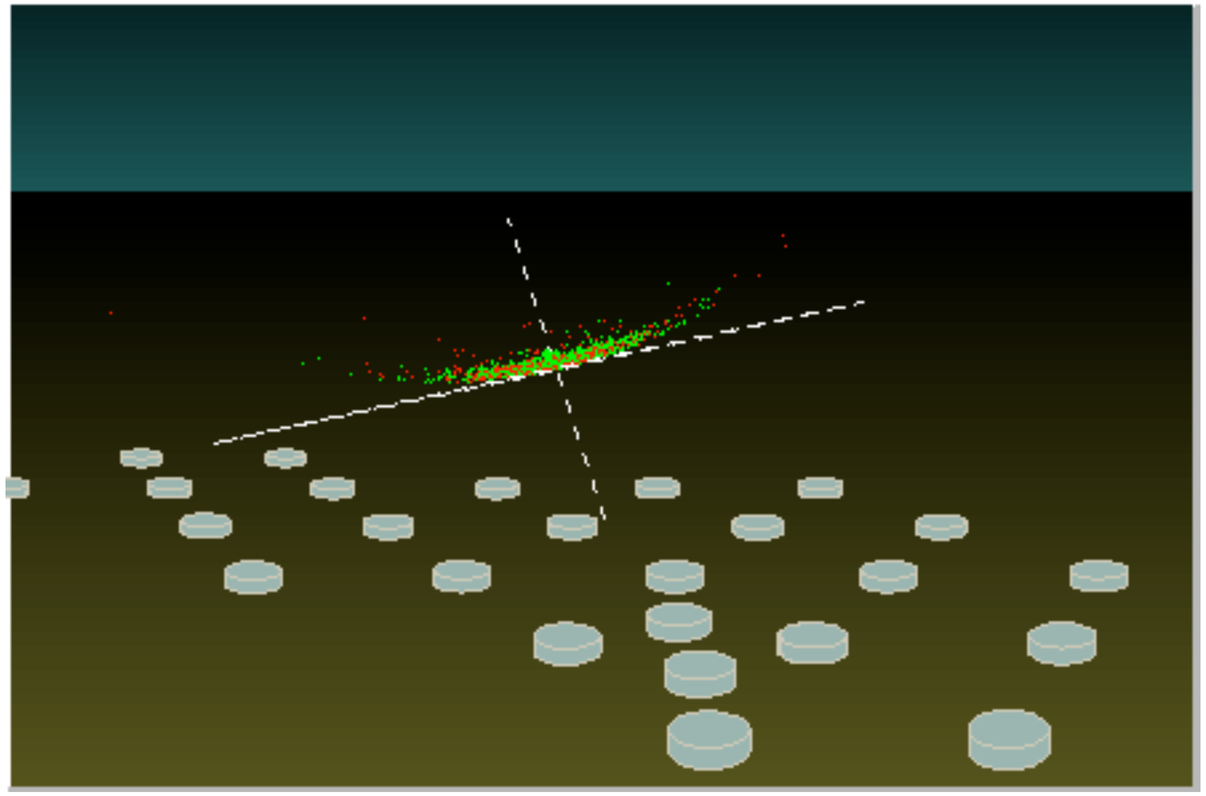
Highest energy event in diffuse GZK neutrino search very close to signal region



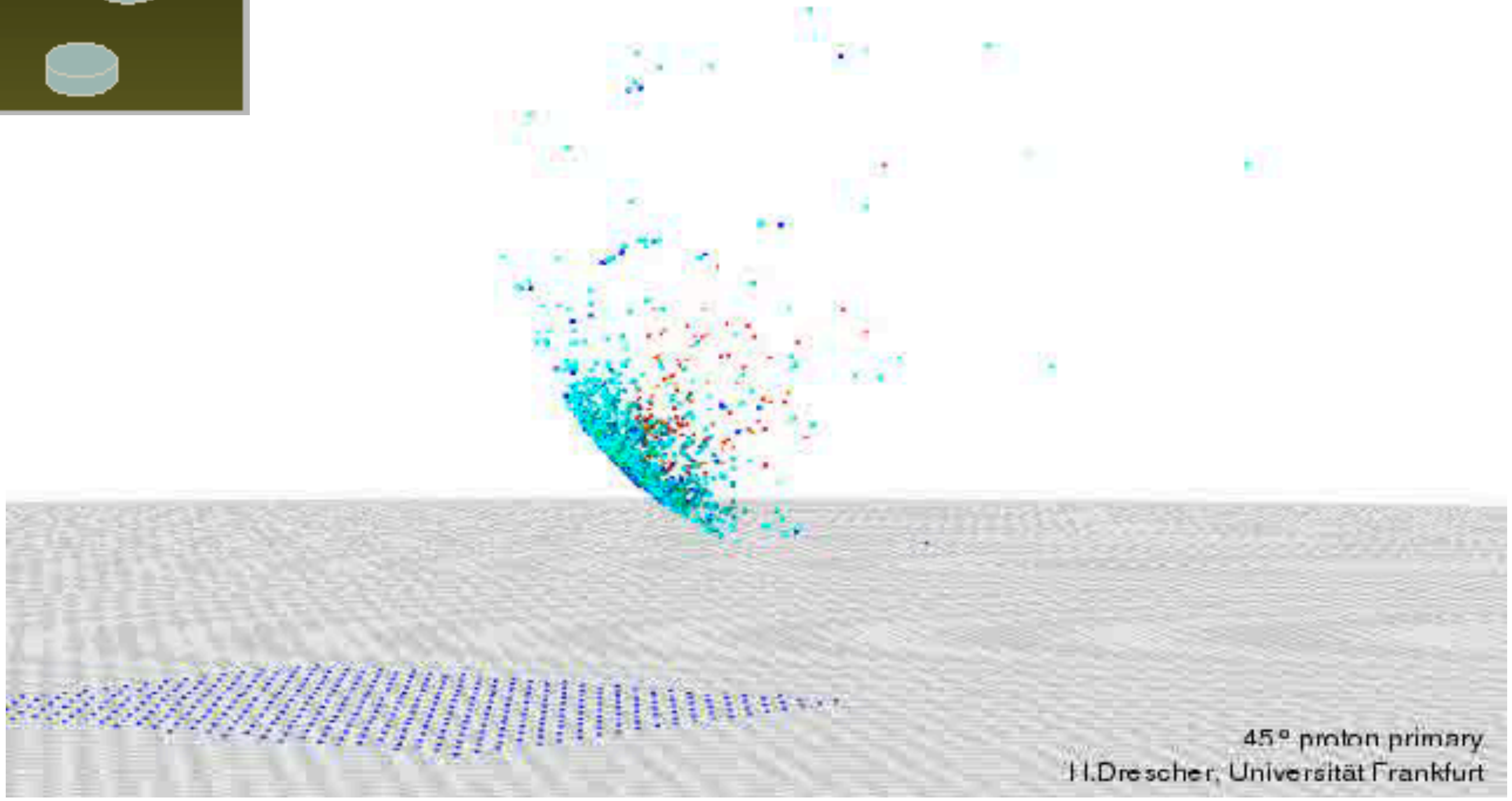
IceTop HLC in 4(+1) Stations!

250,000 p.e.
65° Zenith Angle
10 EeV Iron Primary?

Extensive Air Showers



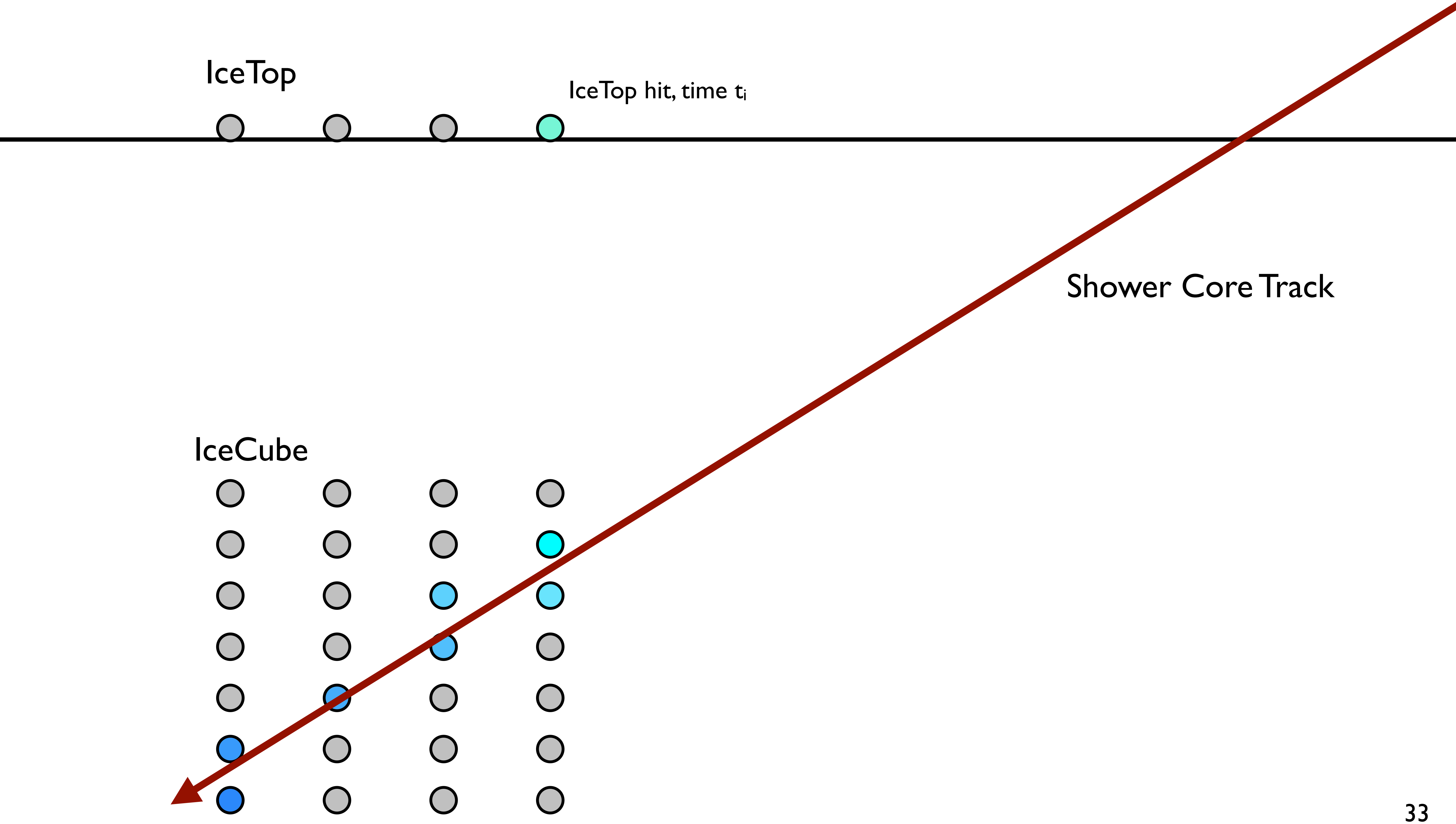
http://www.auger.org/observatory/animation.html



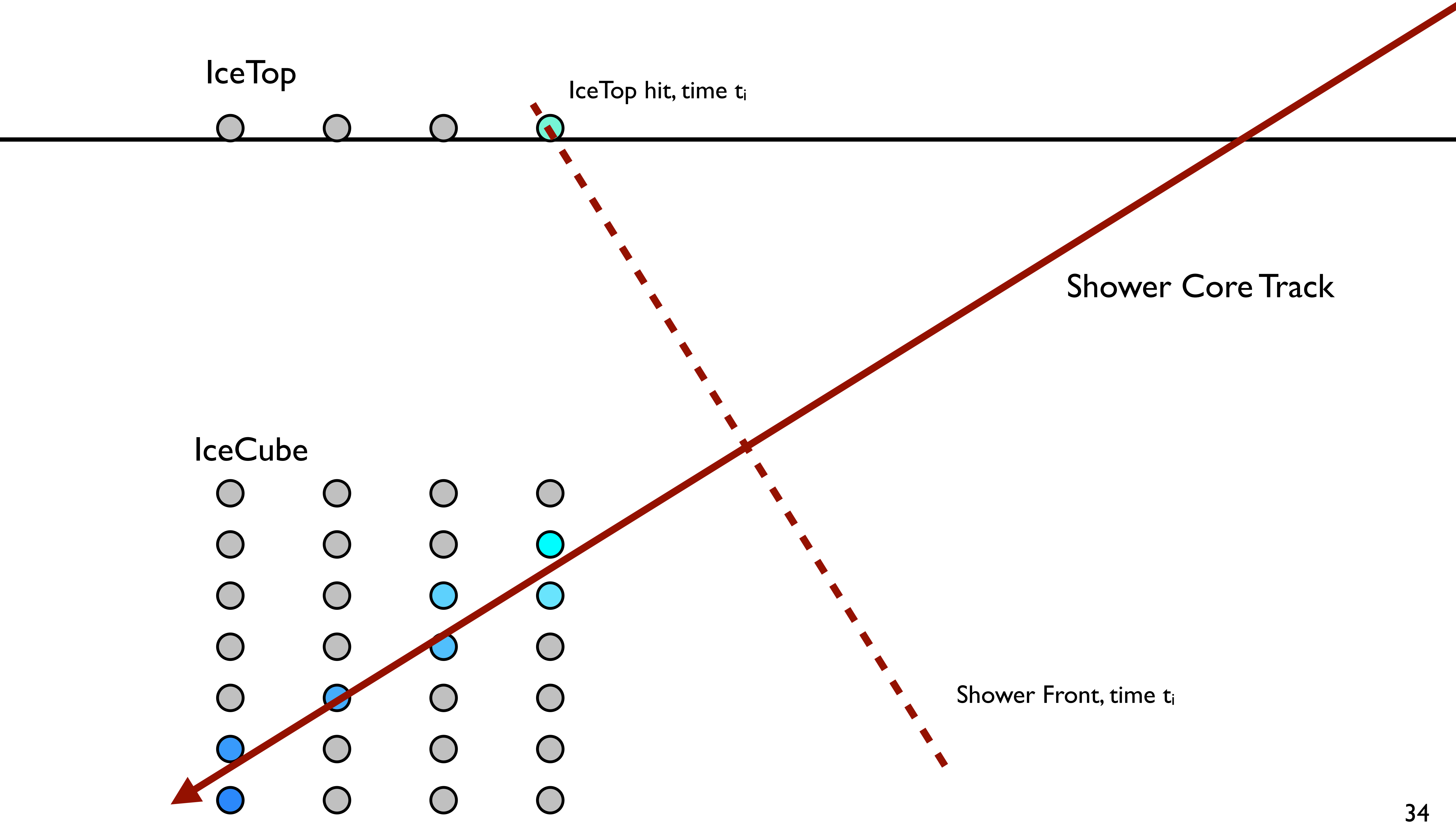
H. Drescher, Universität Frankfurt http://th.physik.uni-frankfurt.de/~drescher/CASSIM/

Veto Cartoon

Veto Cartoon (cont'd)



Veto Cartoon (cont'd)



IceTop

IceTop hit, time t_i

Shower Core Track

IceCube

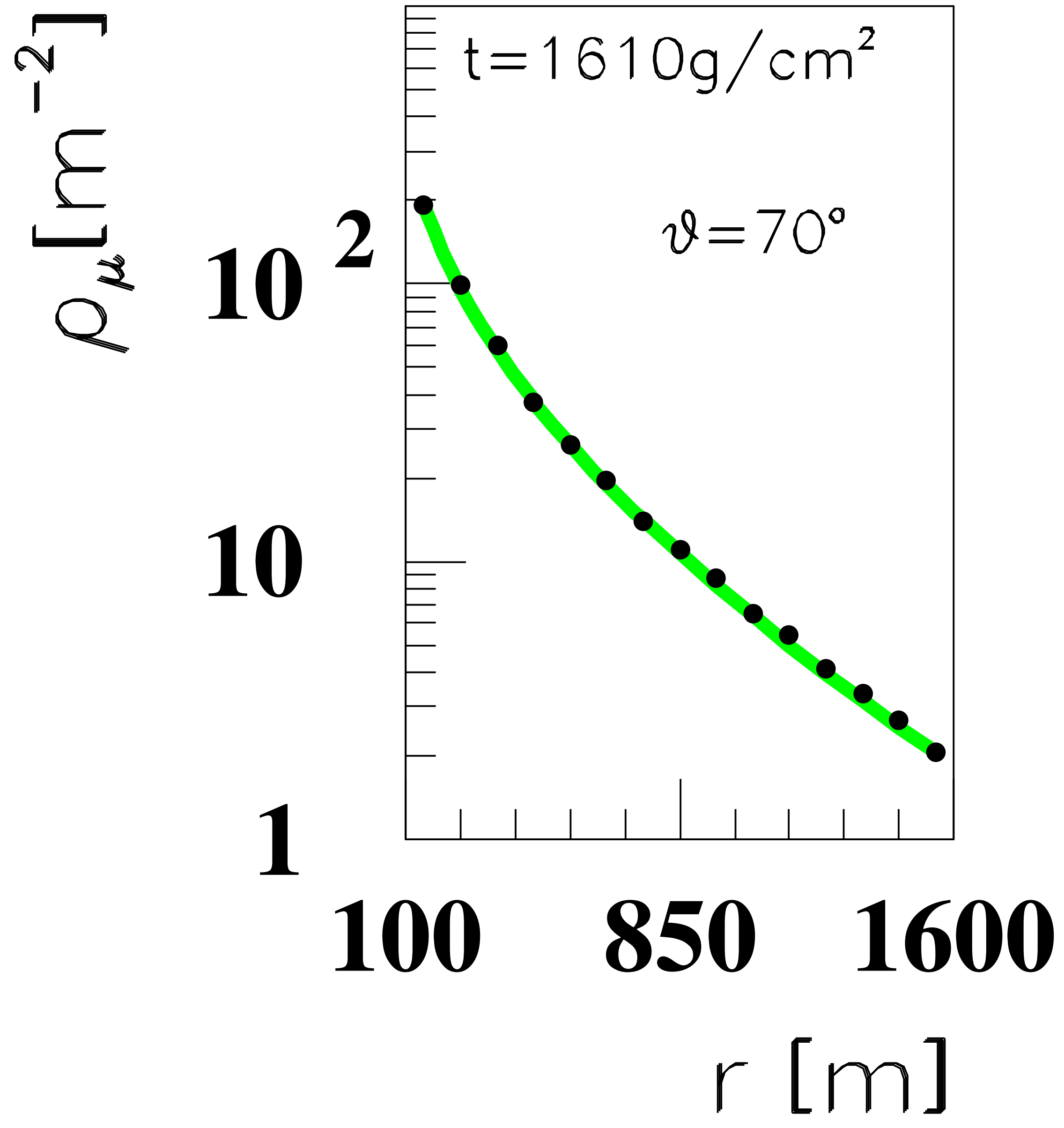
Shower Front, time t_i

Outlying Muon Distributions

- Even highly inclined air showers have substantial numbers of muons at large distances from the core

- Large numbers of muons combined with substantial numbers of IceTop tanks gives a good probability for detection even at high inclination

Radial Distribution of muons from a 10^{19} eV proton shower



M.T. Dova, L.N. Epele, A.G. Mariazzi arXiv:astro-ph/0110237v2