Event selections and veto for Diffuse analysis

Select topics

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Bootcamp 2016

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

NSF

Fluxes

Cosmic Rays and Neutrino Sources

Can neutrinos reveal origins of cosmic rays?

$$p\gamma \rightarrow p\pi^0, n\pi^+$$

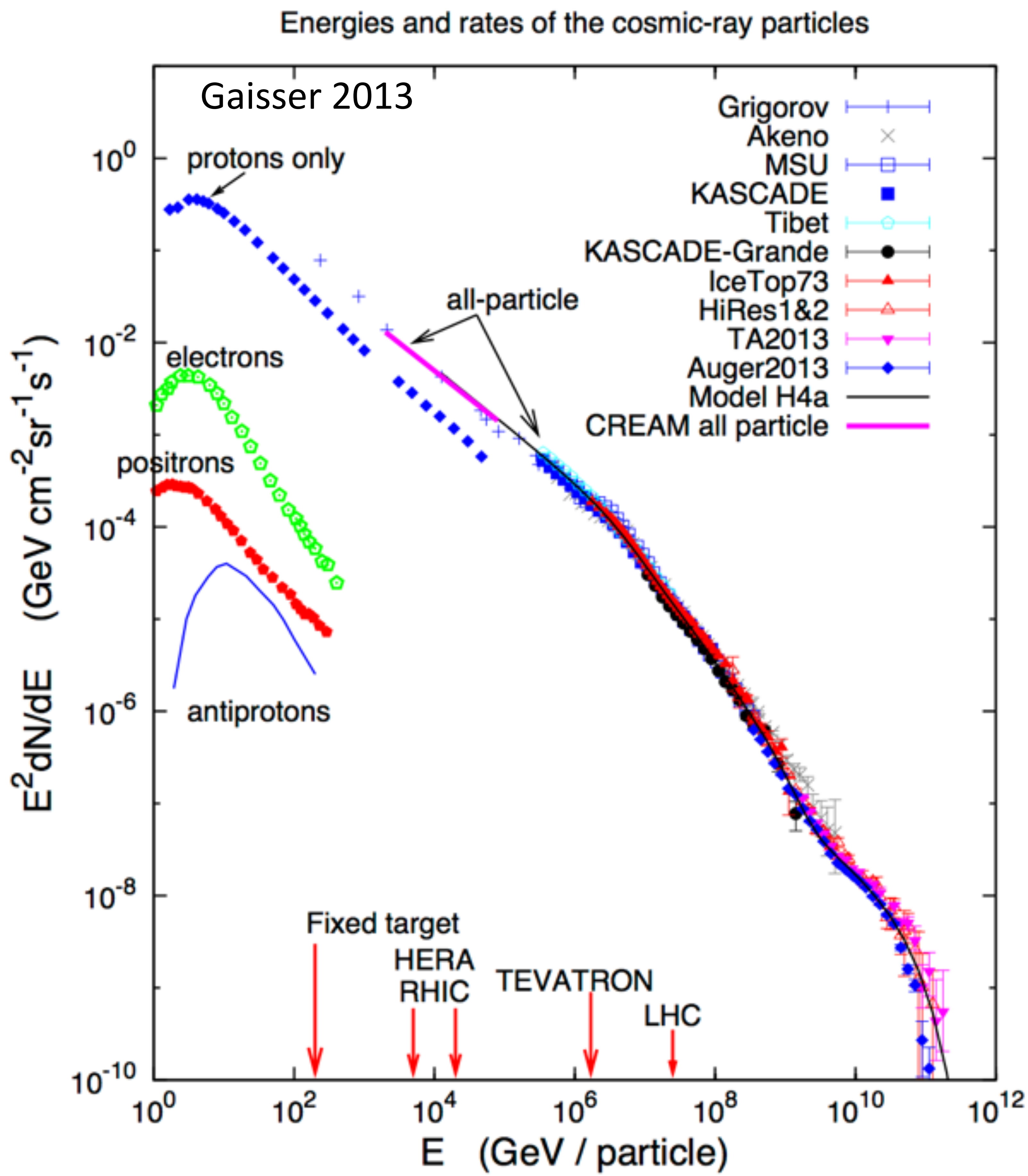
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Cosmic ray interaction in accelerator region

Prime Candidates

- SN remnants
- Active Galactic Nuclei



Neutrino production from cosmic rays on known targets.

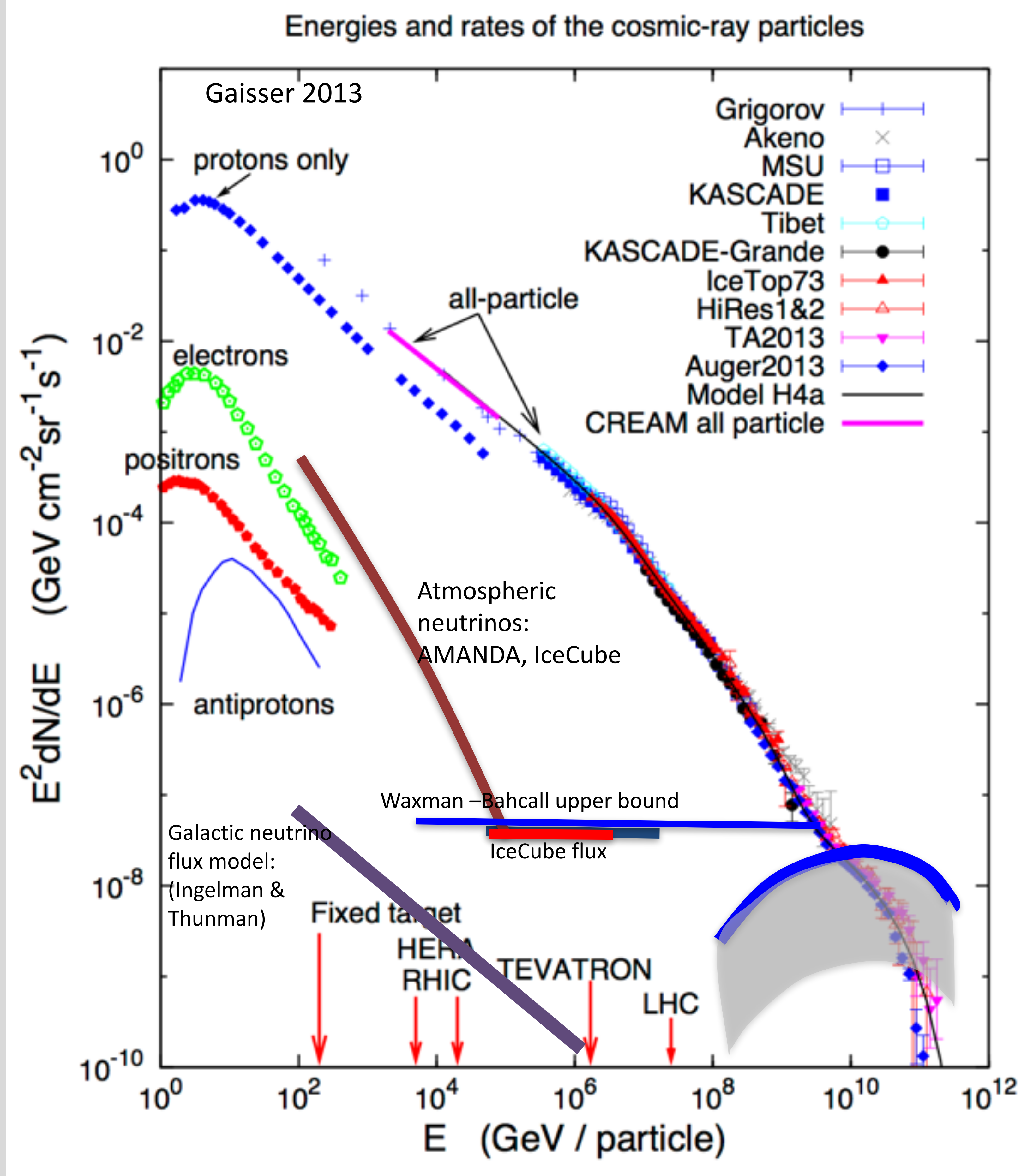
$$pp \to NN + pions; \qquad p\gamma \to p\pi^0, n\pi^+$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

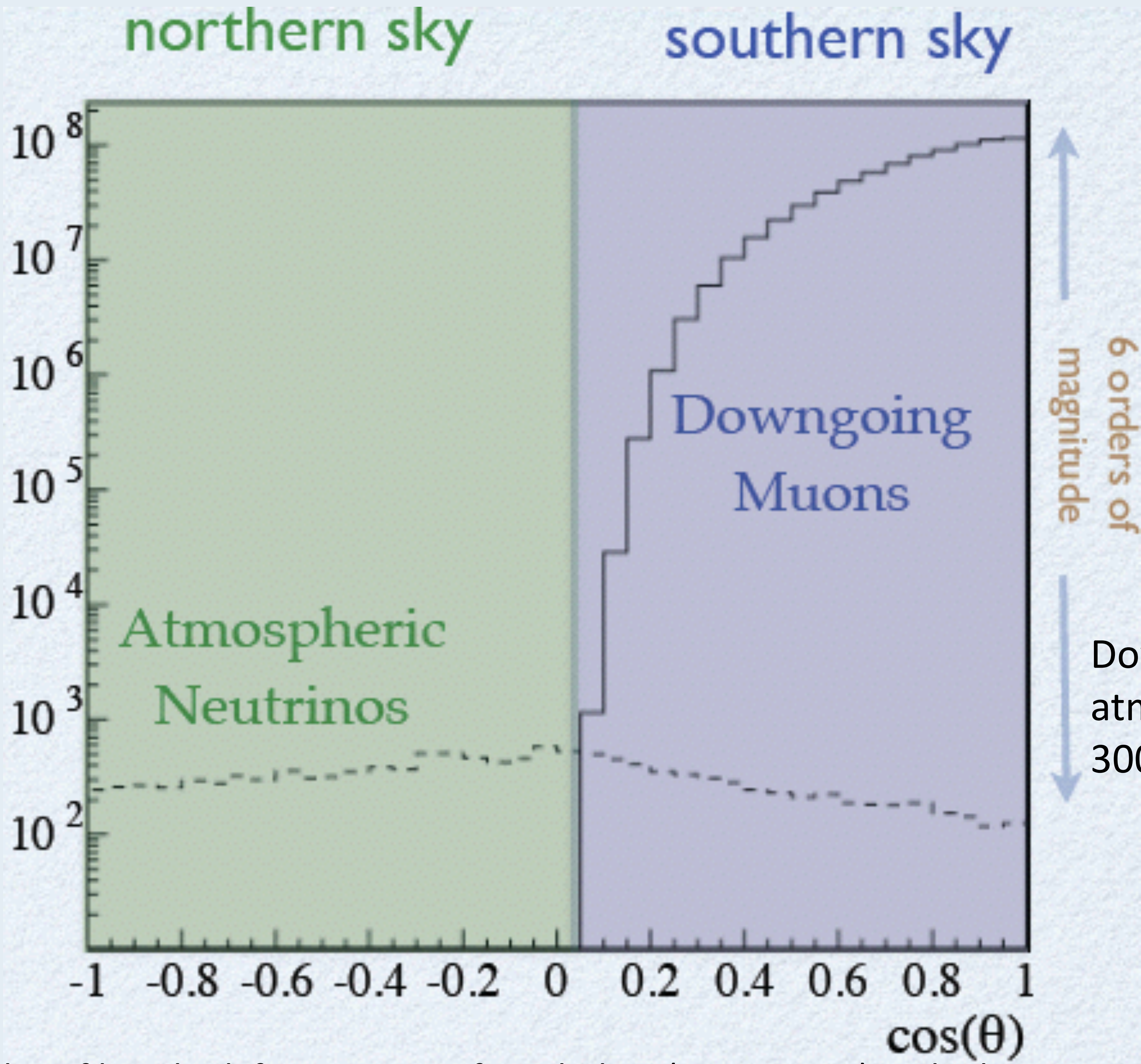
Known targets:

- Earth's atmosphere: Atmospheric neutrinos (from π and K decay)
- Interstellar matter in Galactic plane: Cosmic rays interacting with Interstellar matter, concentrated in the disk
- Cosmic Microwave background: UHE cosmic rays interact with photons in intergalactic photon fields.



Muons and neutrinos at depth

Neutrino-induced muons from all directions
50000 / day



Downward atmospheric muons
300 million / day

àNeutrinos: Use Earth as filter; look for neutrinos from below (GeV to PeV), at high energies from above
àCosmic ray muons:

Cosmic rays and atmosphere

- Cosmic rays bombarding Earth's atmosphere produce energetic secondary particles.
- Important for underground detectors: Muons and neutrinos

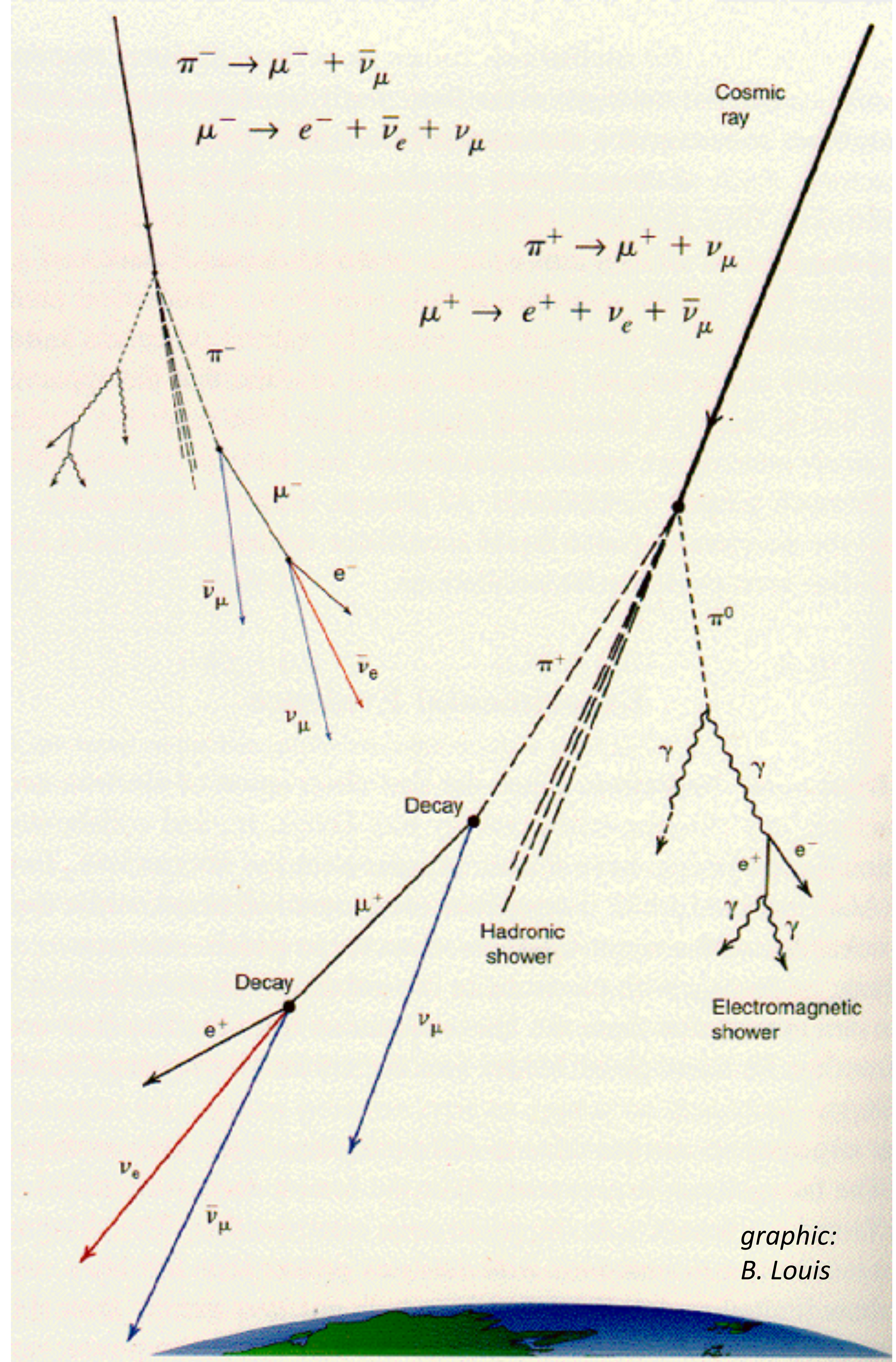
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

and the same for π^-

- Why are there fewer ν_e than ν_μ?
  - Electron neutrinos have lower energy
  - Muon decay is increasingly suppressed at high energies. Life time of 2.2µsec much longer due to time dilatation (Lorentzfactors of > 1000).

- For completeness: $\pi^0 \rightarrow \gamma + \gamma$
  make e.m. showers, which are responsible for most background for ground based detectors (Cherenkov telescopes, scintillator arrays, or HAWC.)



graphic: B. Louis

15 years of neutrino skymaps

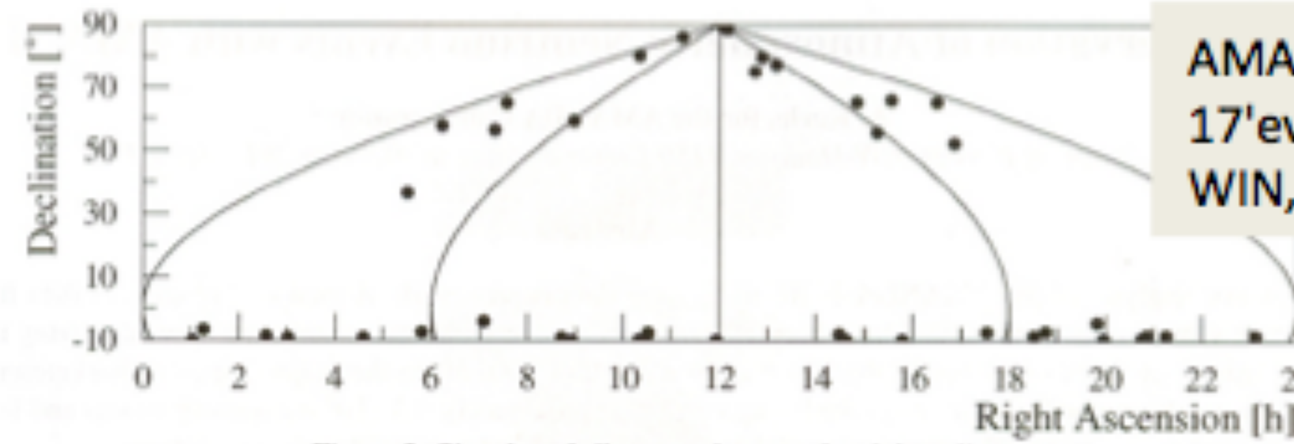
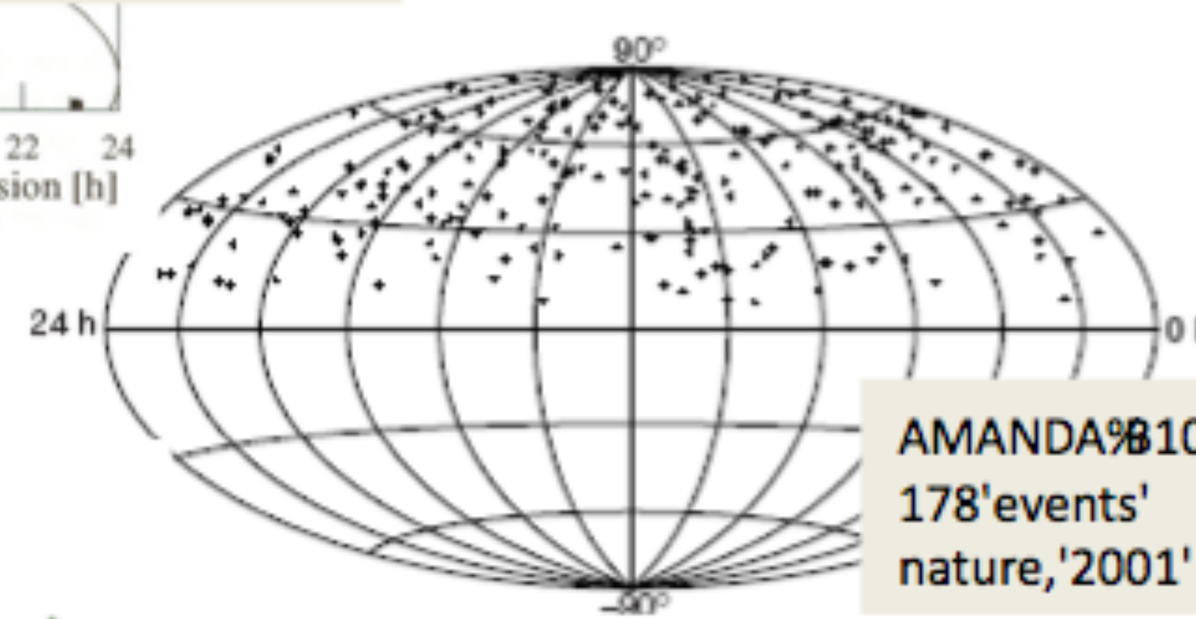
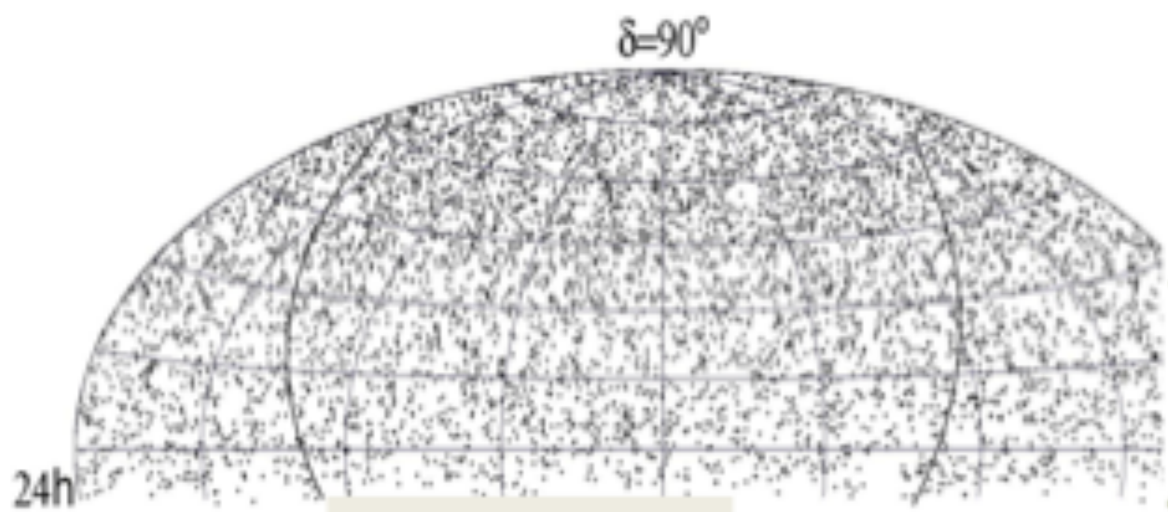


Figure 2: Sky plot of all events that pass level 4 quality cuts.

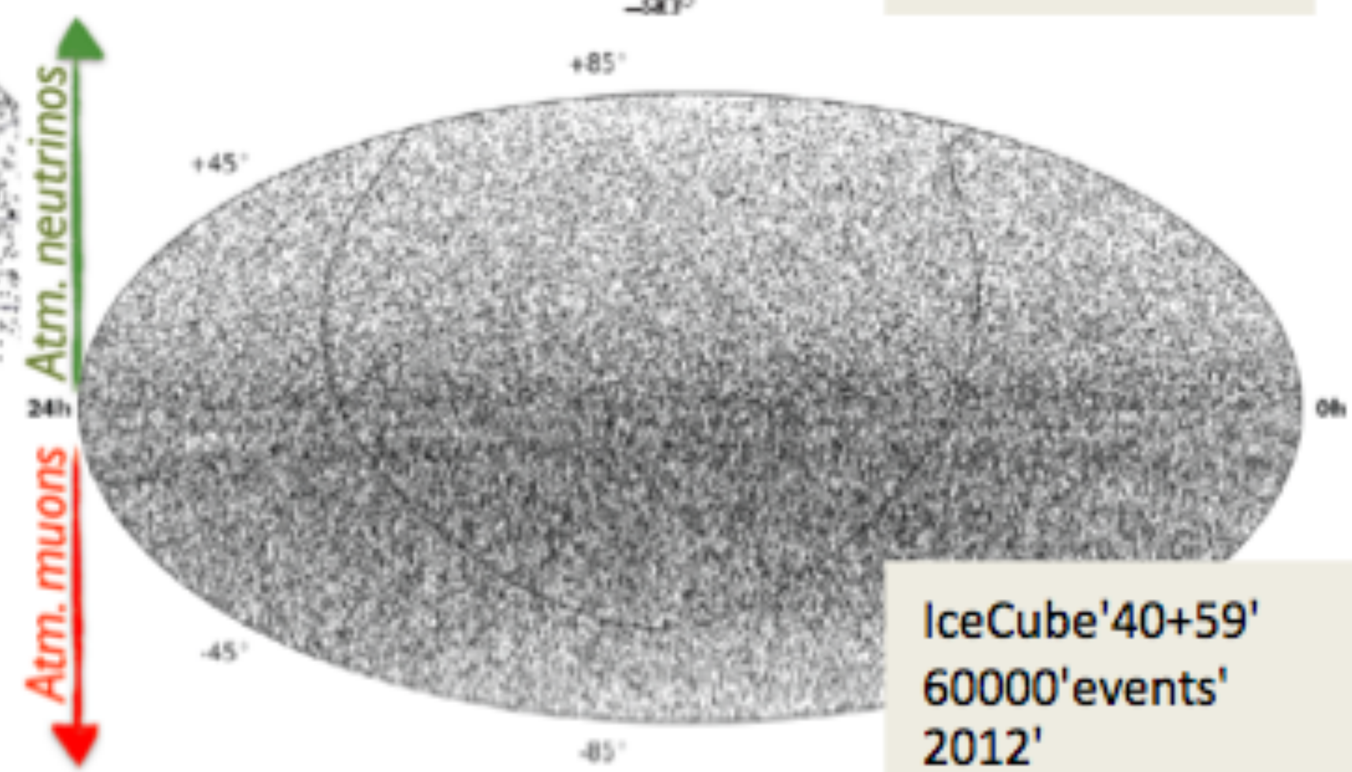
AMANDA%B10'
17'events'
WIN,'1999'



AMANDA%B10'
178'events'
nature,'2001'

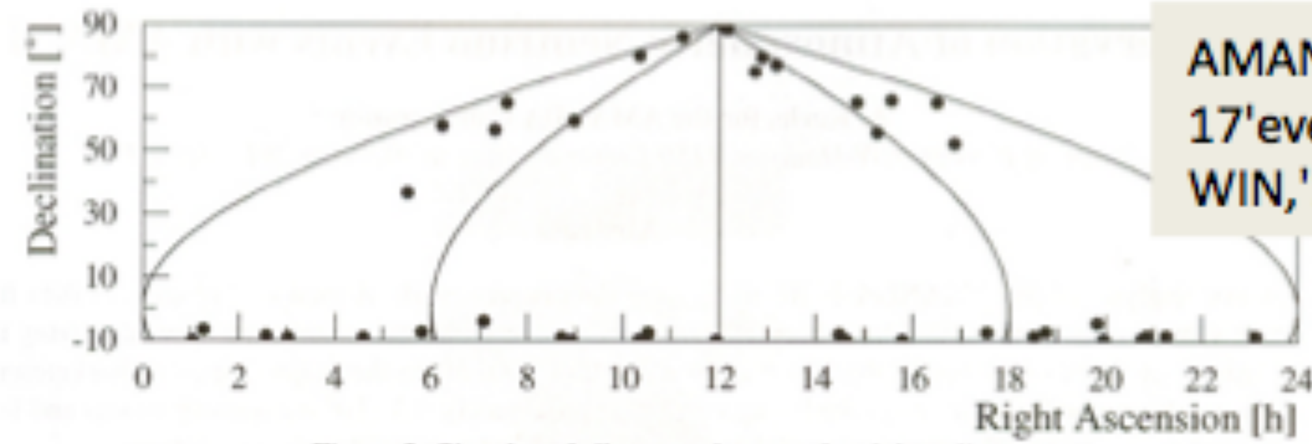


AMANDA%II'
7'years''
6995'events'
2006'



IceCube'40+59'
60000'events'
2012'

15 years of neutrino skymaps



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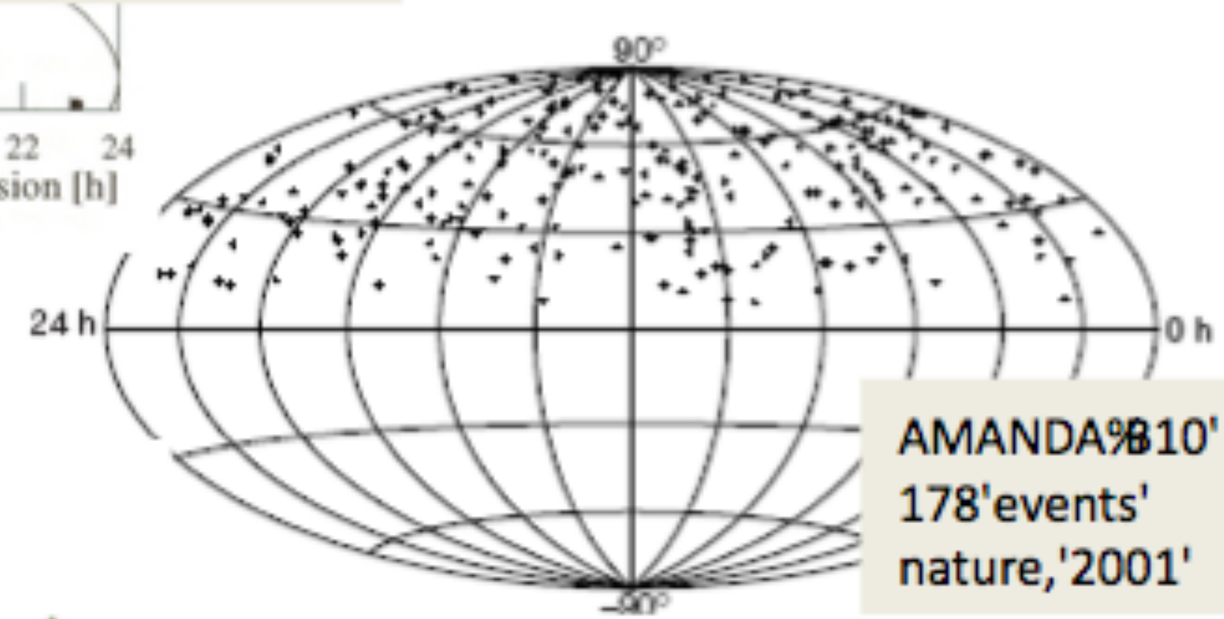

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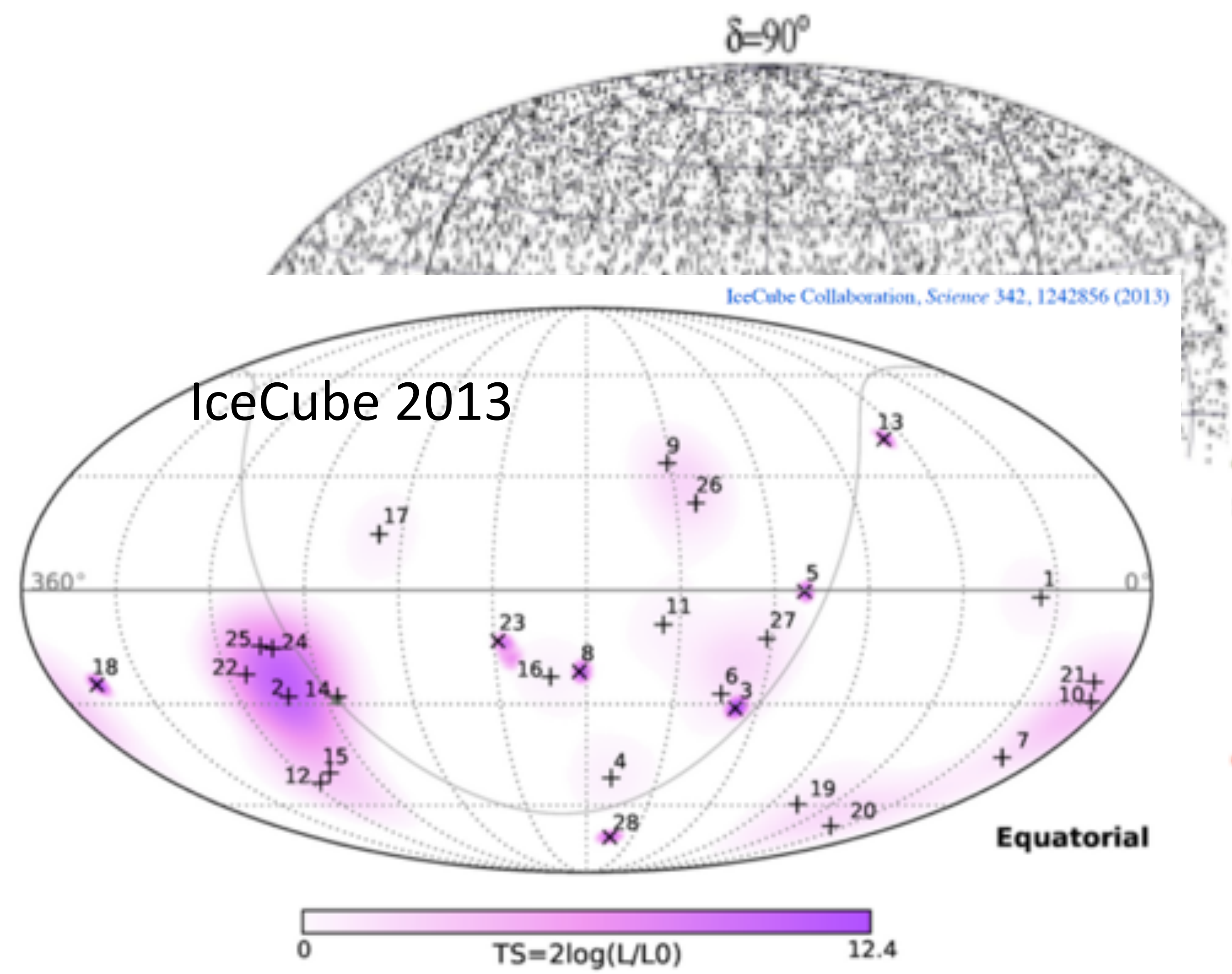
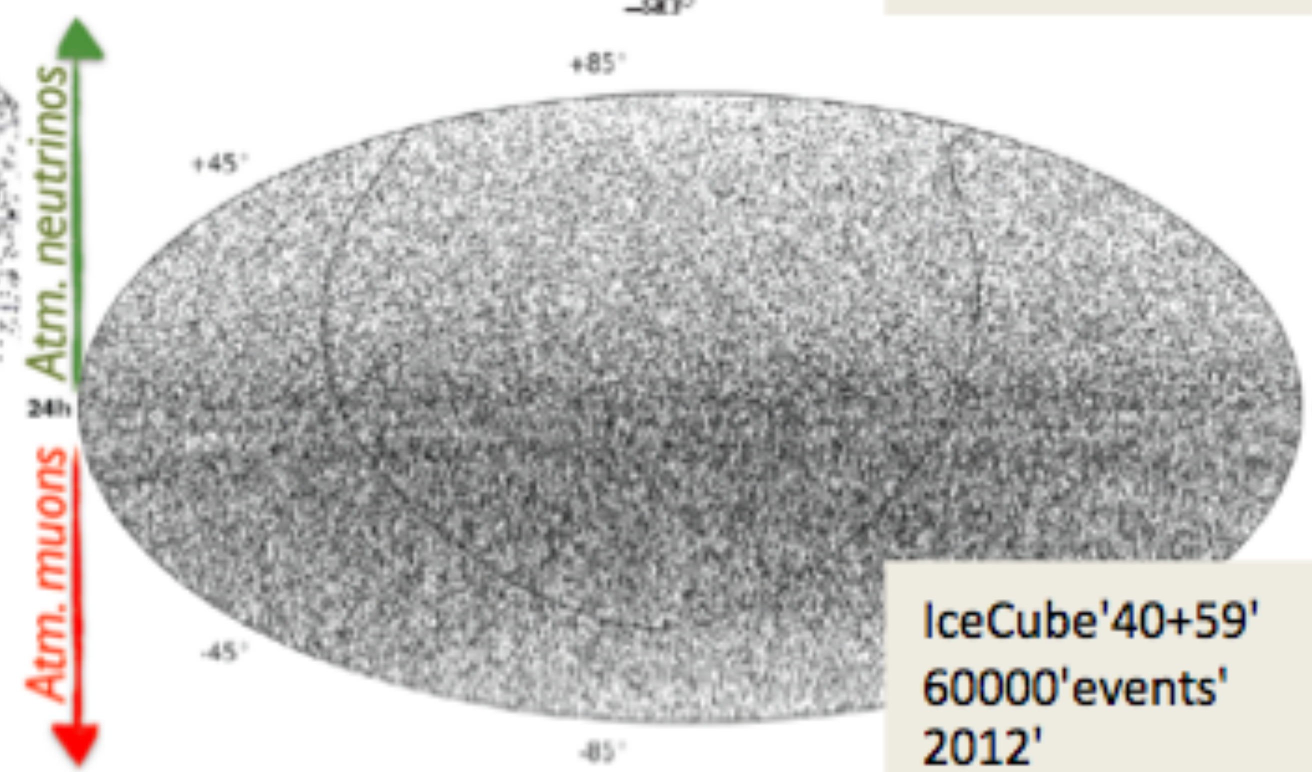
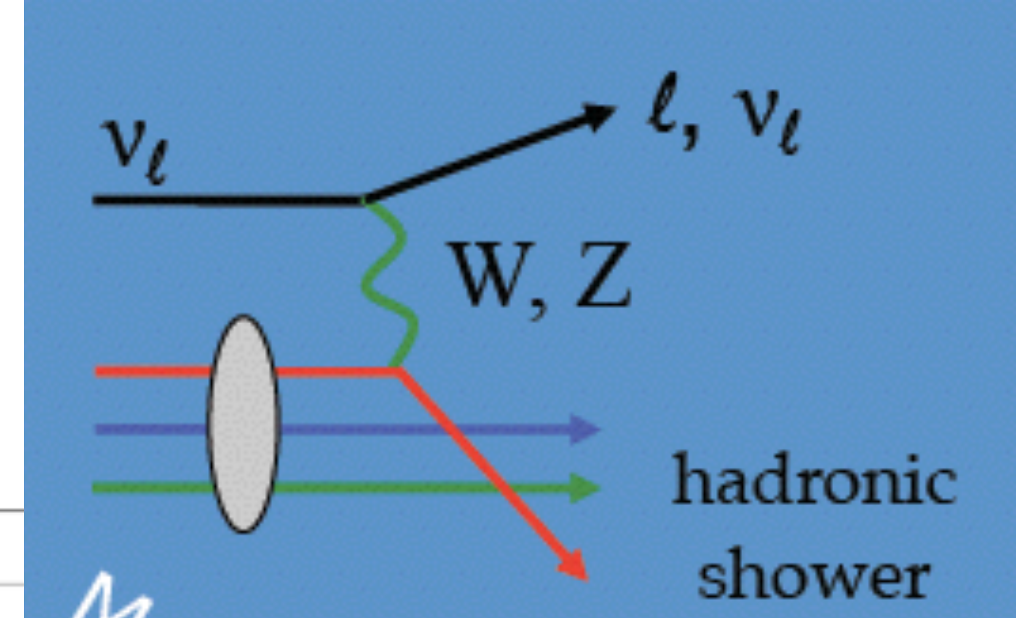


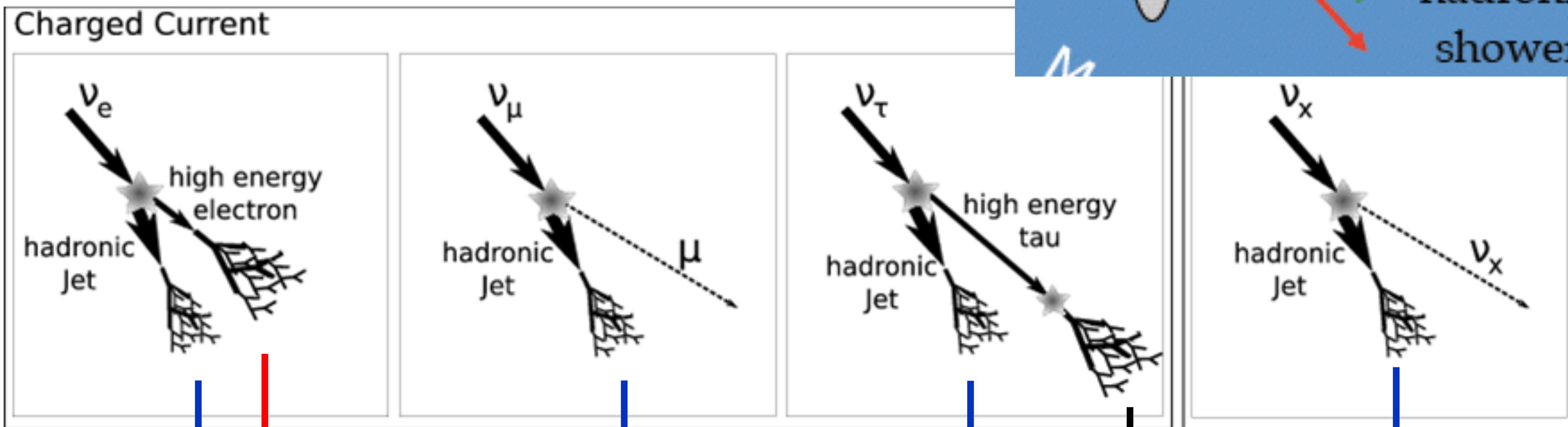


IceCube'40+59'
60000'events'
2012'

Events

Topology of neutrino interactions
neutrino-induced showers





"Mixed" showers

$<E_{electromagnetic}> \approx 80\% \ E_{\nu\upsilon}$

$<E_{hadronic}> \approx 20\% \ E_{nu}$

Hadronic showers

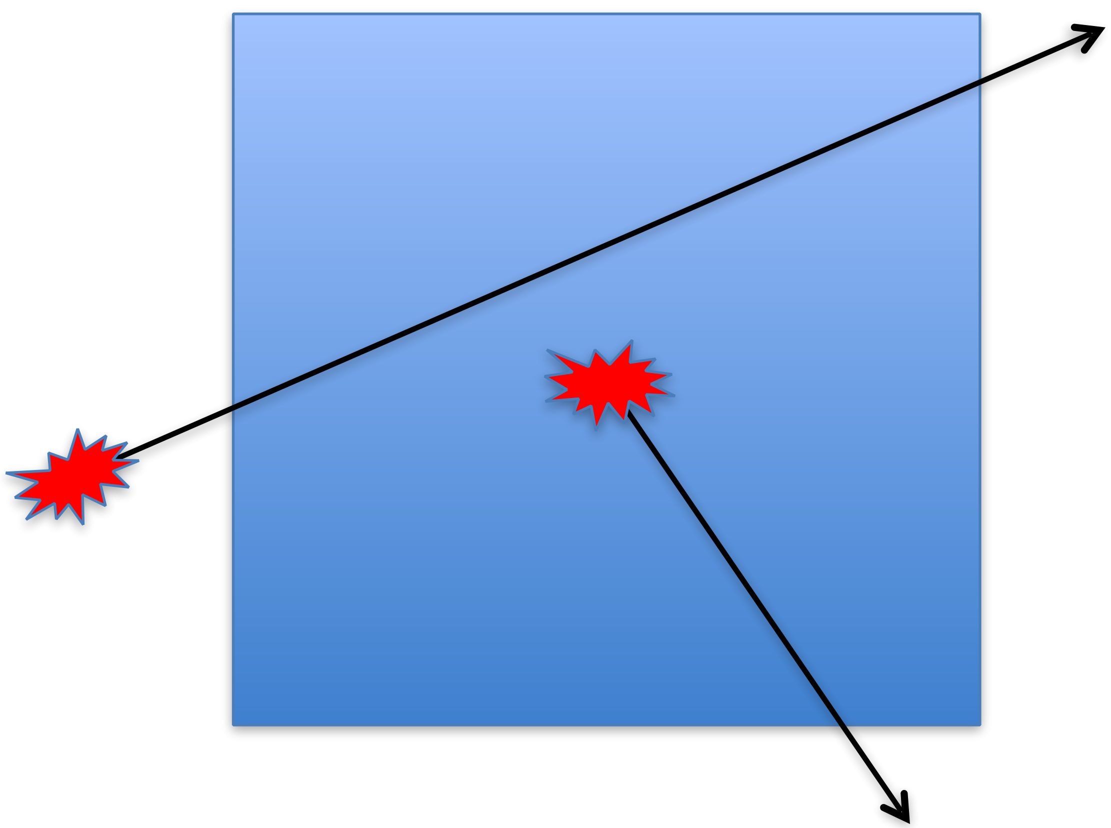
$<E> \approx 20\% \ E_{\nu\upsilon}$

EM or Hadronic

graphics: Jaime Alvarez

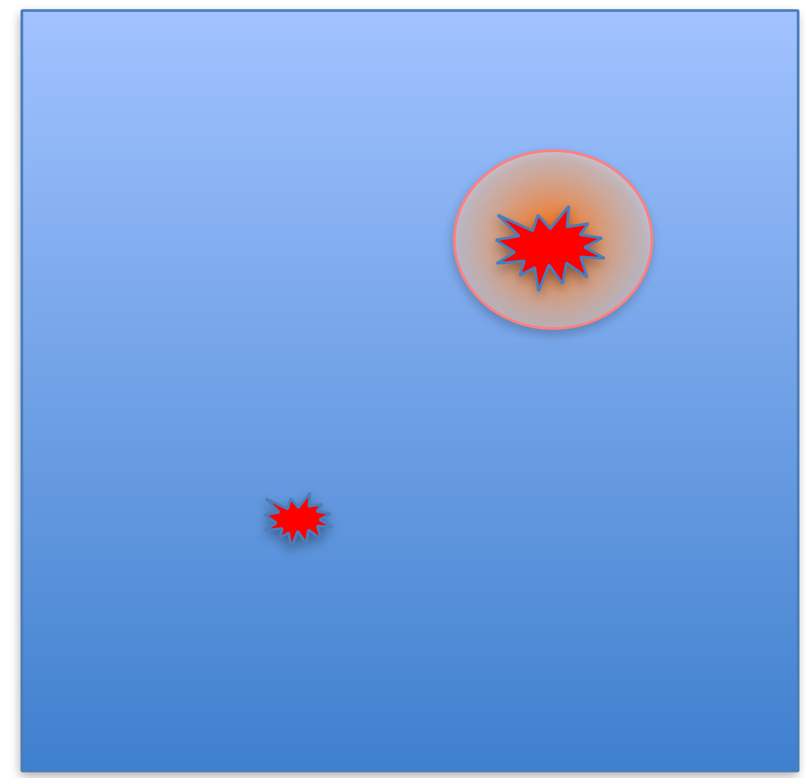
Event types

- **Throughgoing muons** – the workhorse for neutrino astronomy.
  - Vertex can be far outside the detector. Increased effective volume!



- Starting tracks: downgoing neutrino astronomy (reject background of throughgoing cosmic ray muons)

- **Cascade events:**
  - ν_e, ν_τ **and neutral current**
  - High energy resolution (fully active calorimeter, all energy gets depositied in the detection volume)



Rare and complex event types: ν_τ

- Tau events

$$\nu_\tau + N \rightarrow \tau + X$$

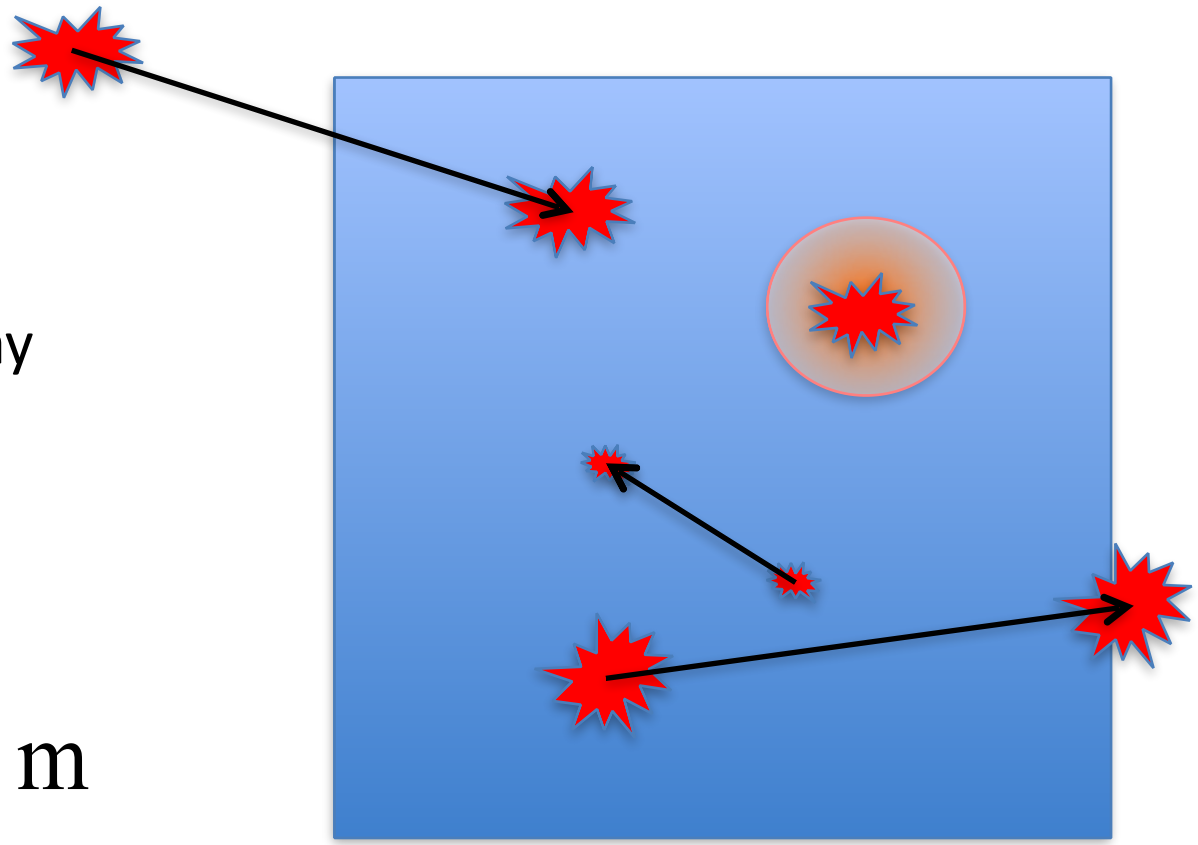
- The tau will decay

$$\tau \xrightarrow[\gamma c t_\tau]{Tau\_decay} \nu_\tau + X$$

- At low energies (<1TeV), the tau will decay "instantly"
- At high energies the decay length is long enough for a the second interaction to become detectable

$$l_\tau = \gamma c t_\tau \sim 50\,(E_\tau\ /\mathrm{PeV})\ \mathrm{m}$$

- "Double bang" signature
- Also possible, partially contained first or second interaction only.
- Energy loss of tau is smaller than that of a muon.



Event types

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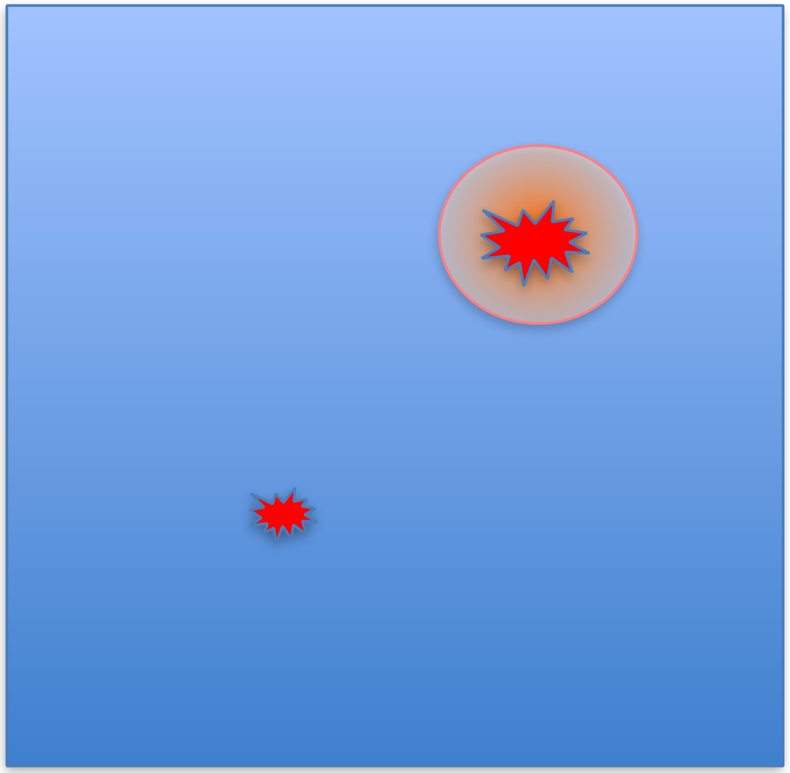
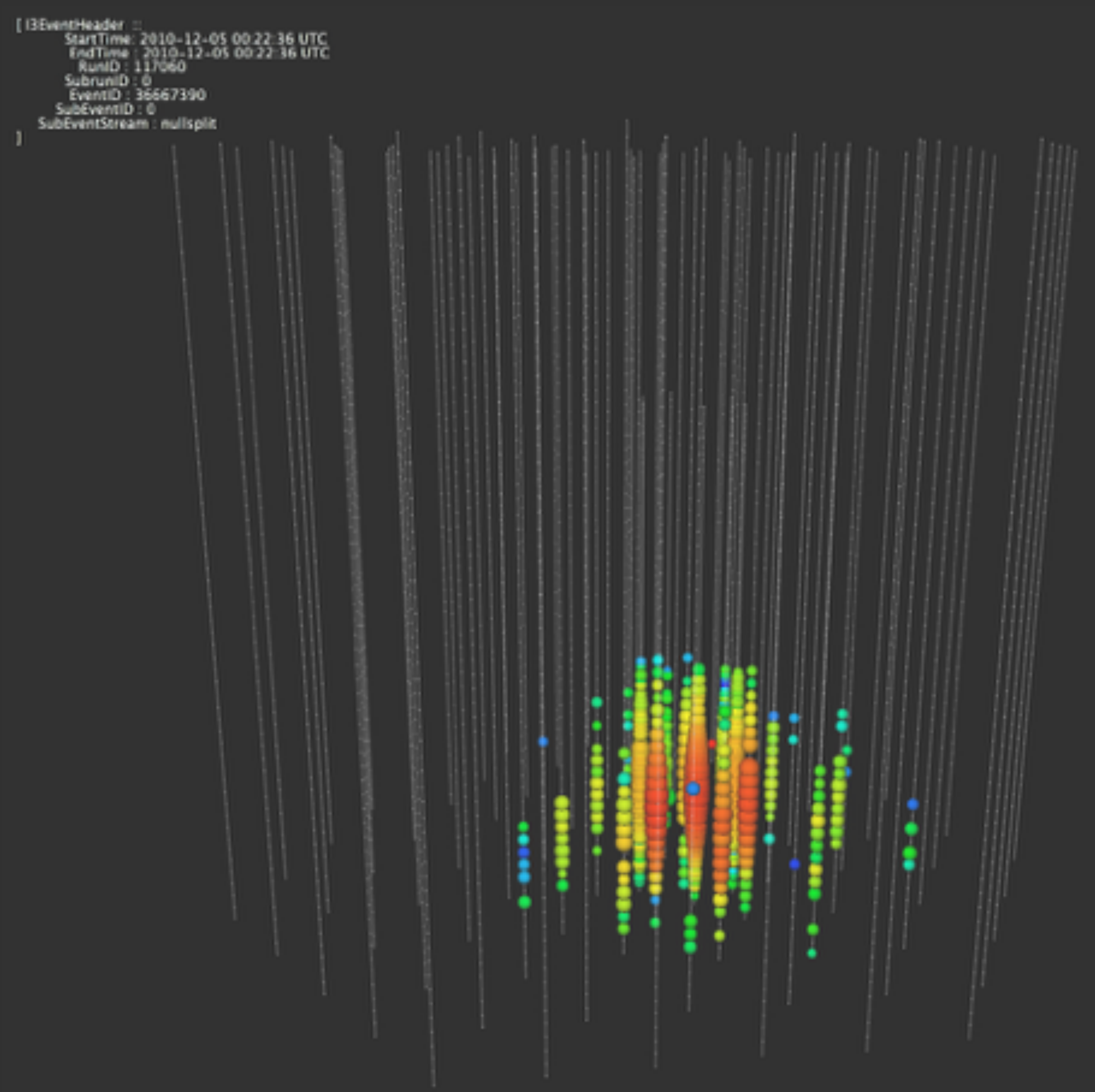
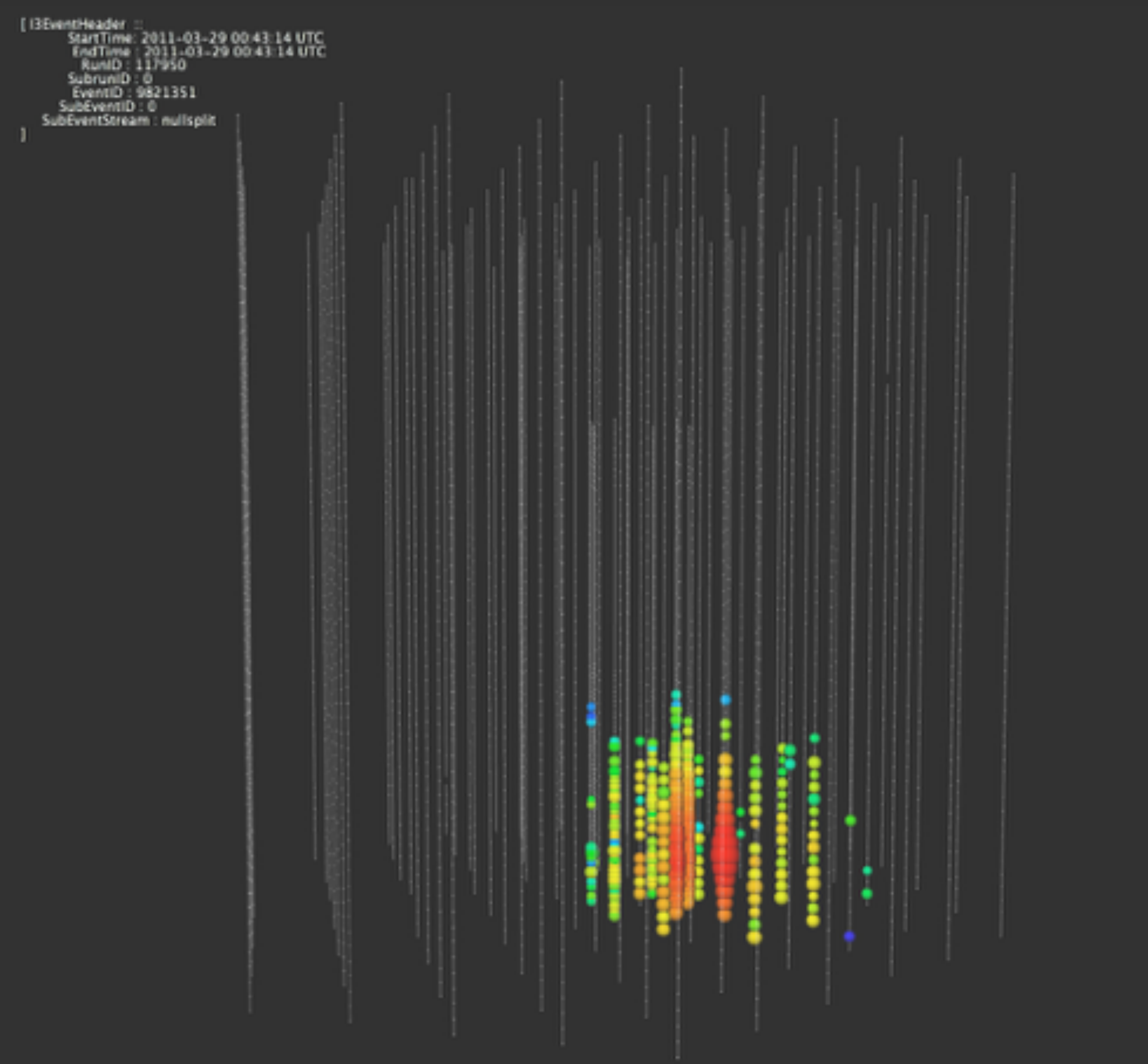


Cascades



~ 20 TeV deposited

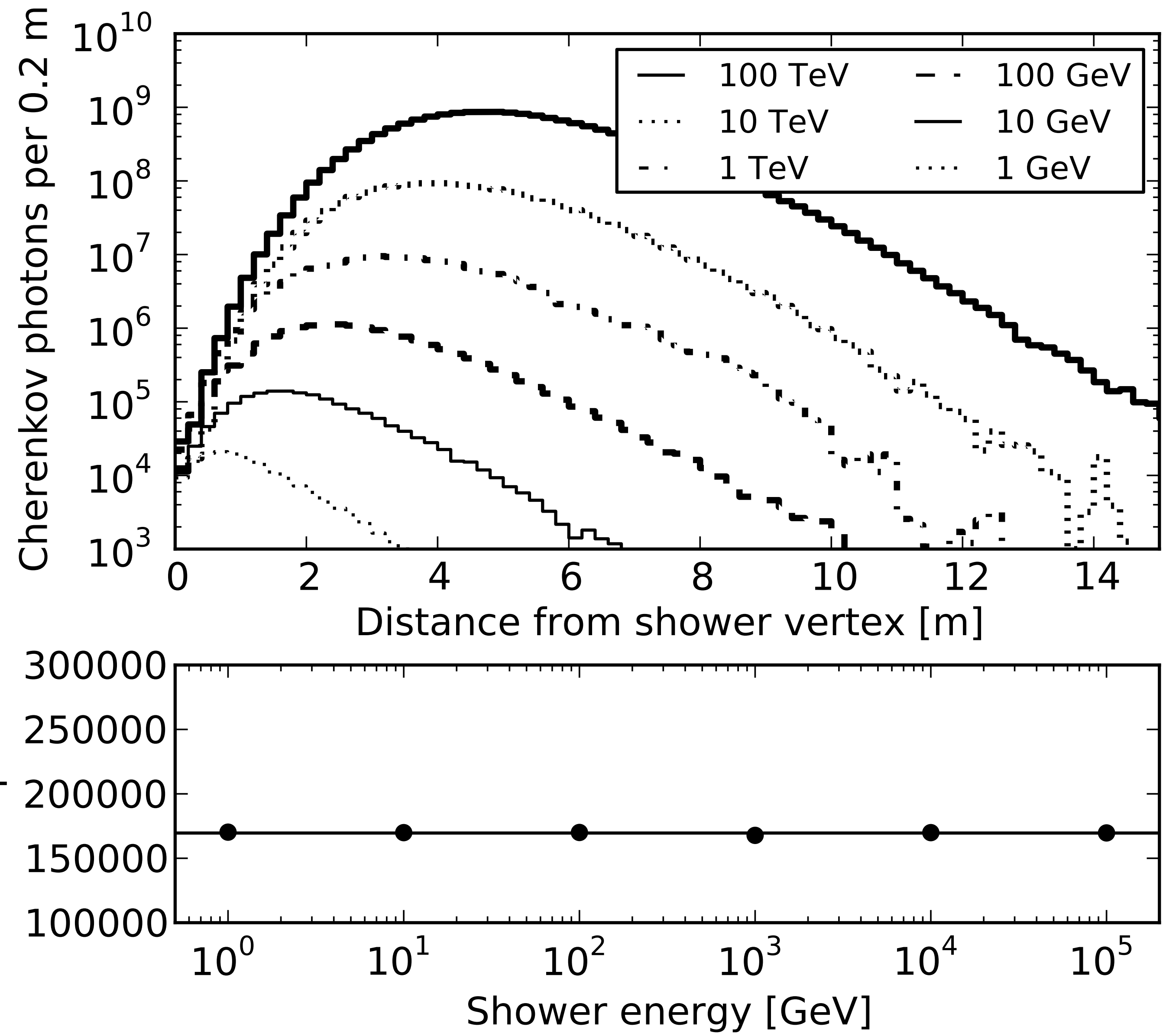


~ 13 TeV deposited

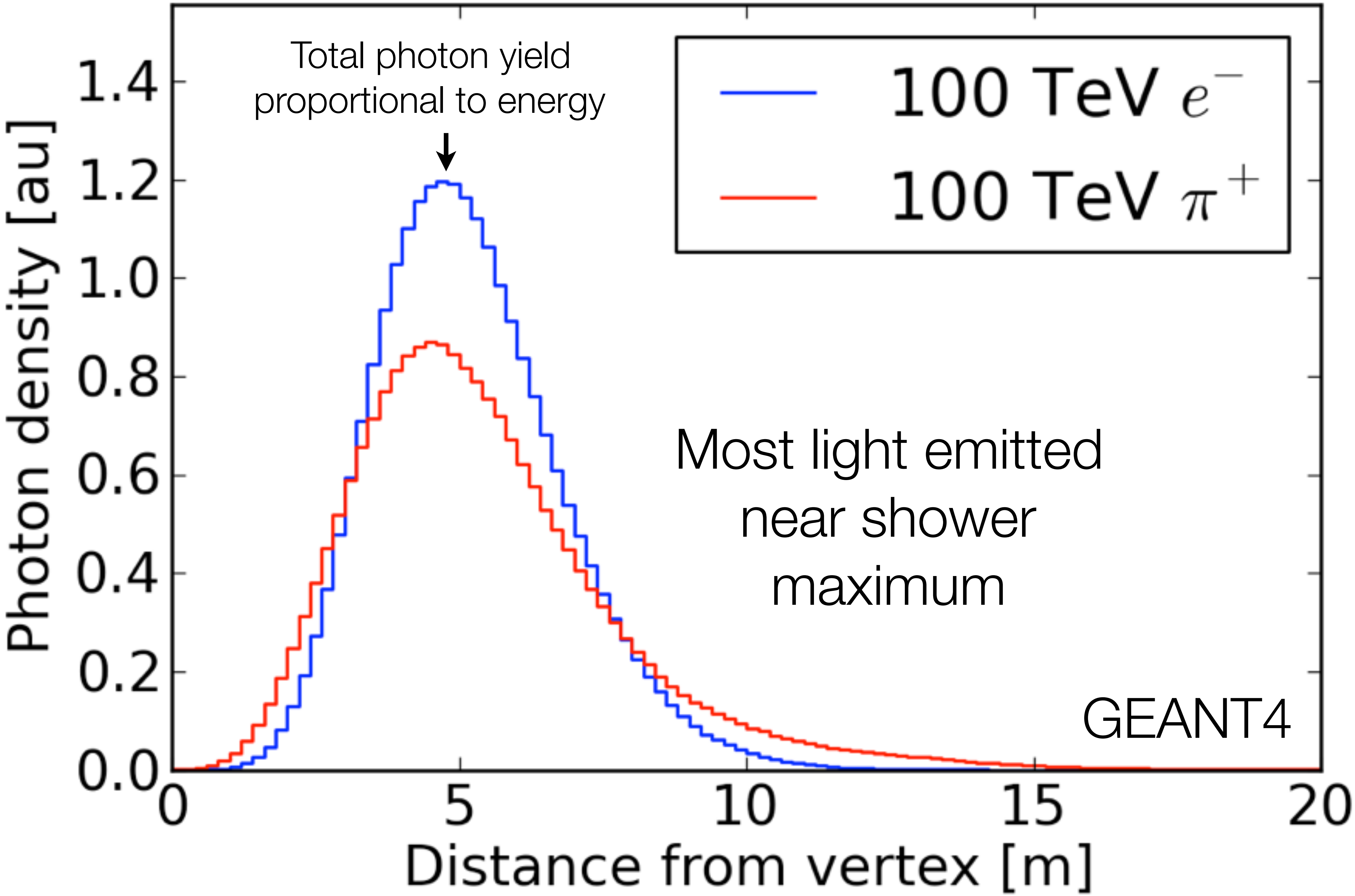
Cherenkov yield from showers

- Ice is a "fully active calorimeter" for energy deposited inside.
  - Charged particles produce Cherenkov light proportional to energy loss.
- Cherenkov yield (300-600nm):
  - 1.7E8 photons/TeV
  - ~0.05% of energy is converted into photons.

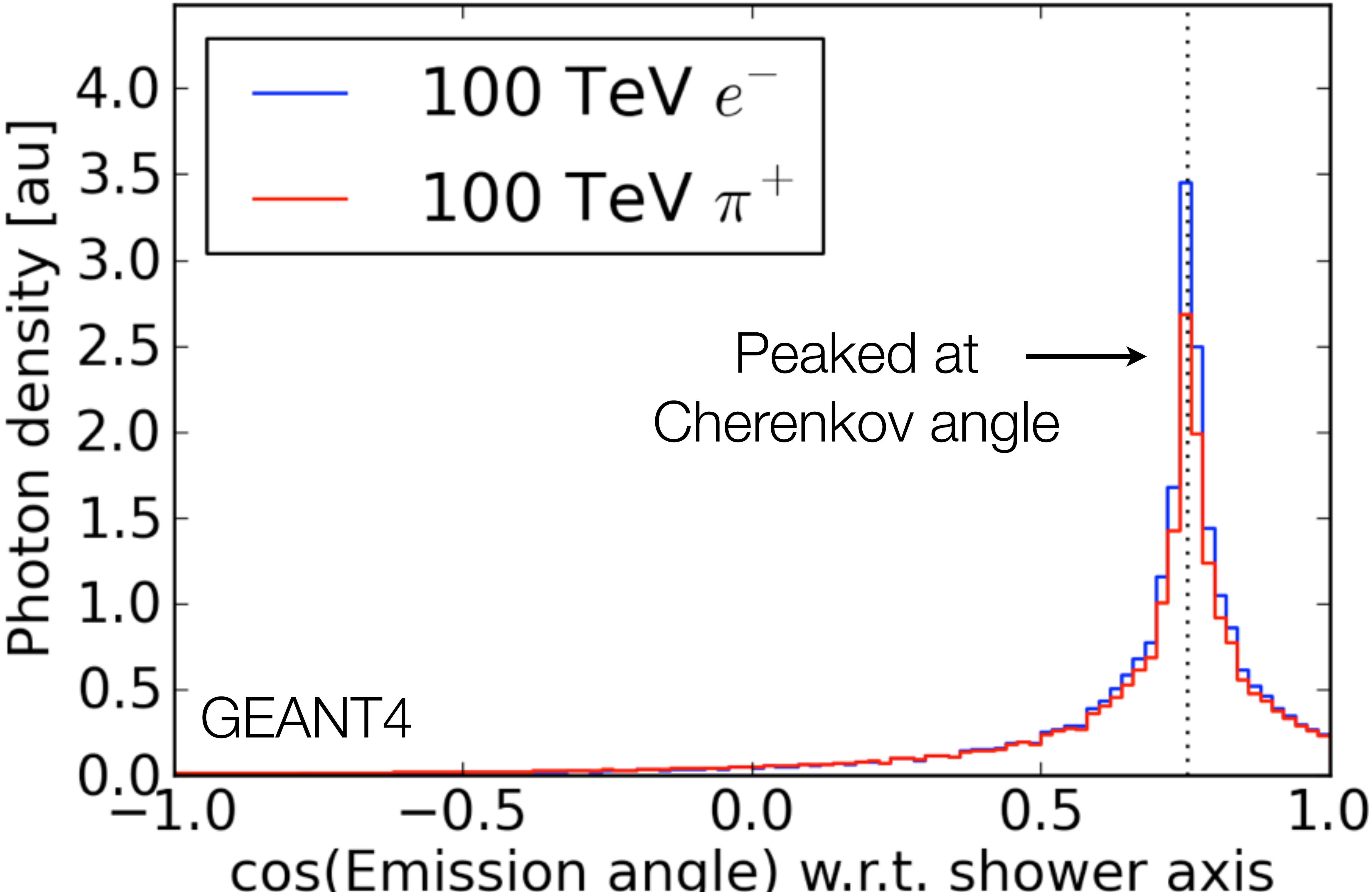
e.m. cascades



Longitudinal development

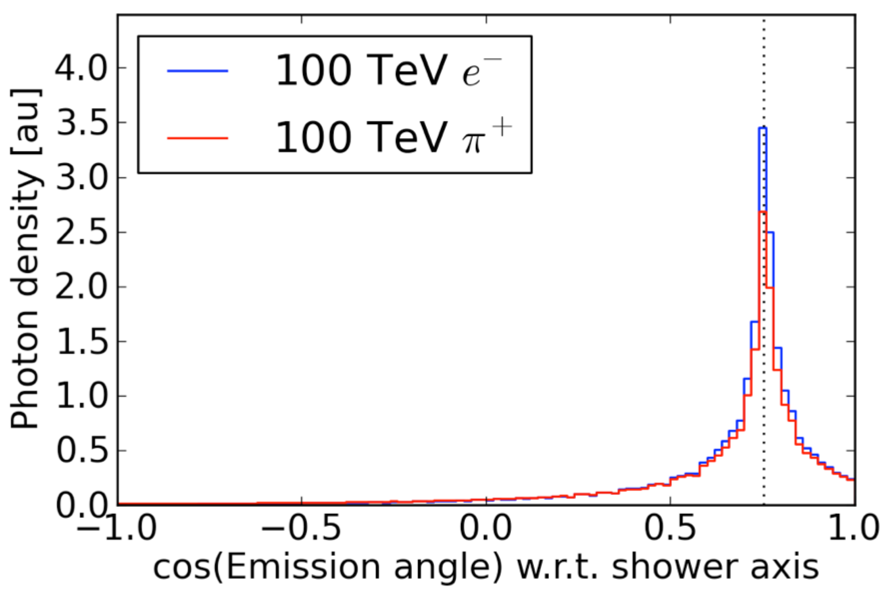


Angular profile

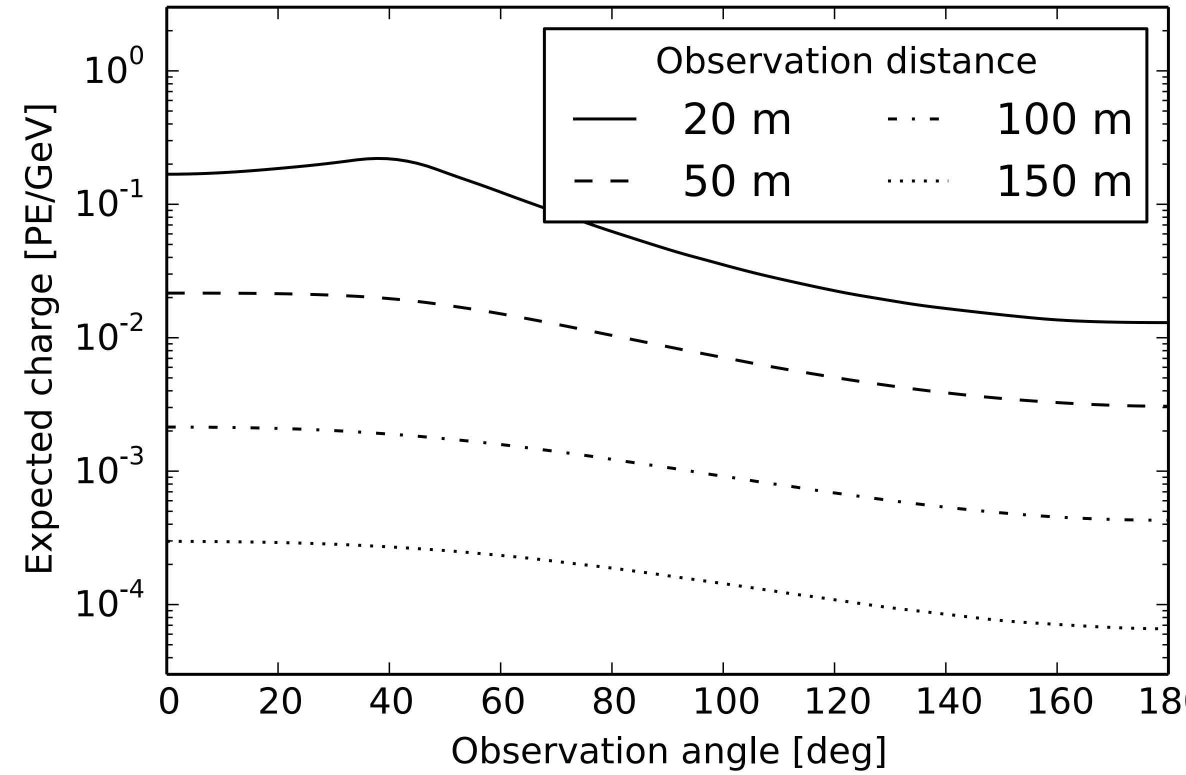


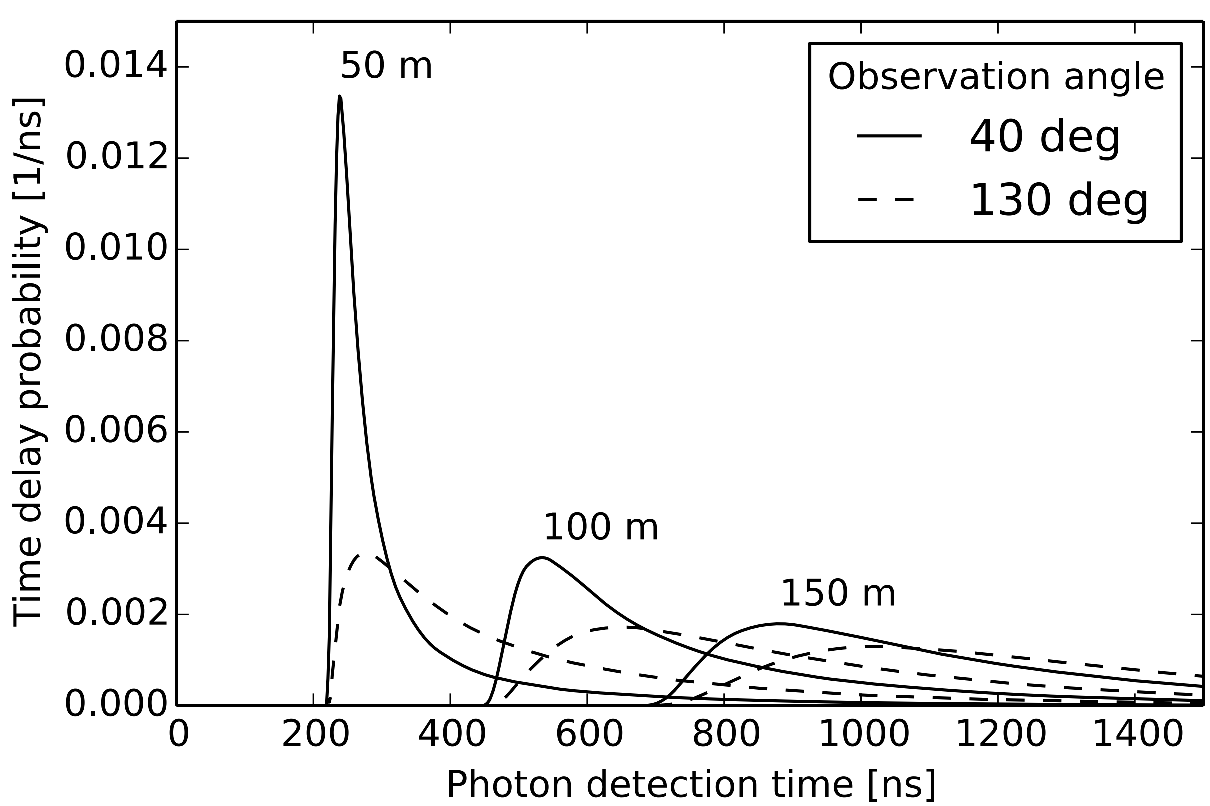
Angular profile

at source



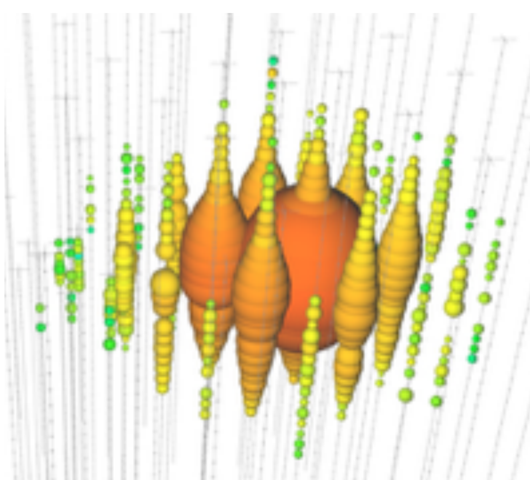
at distance



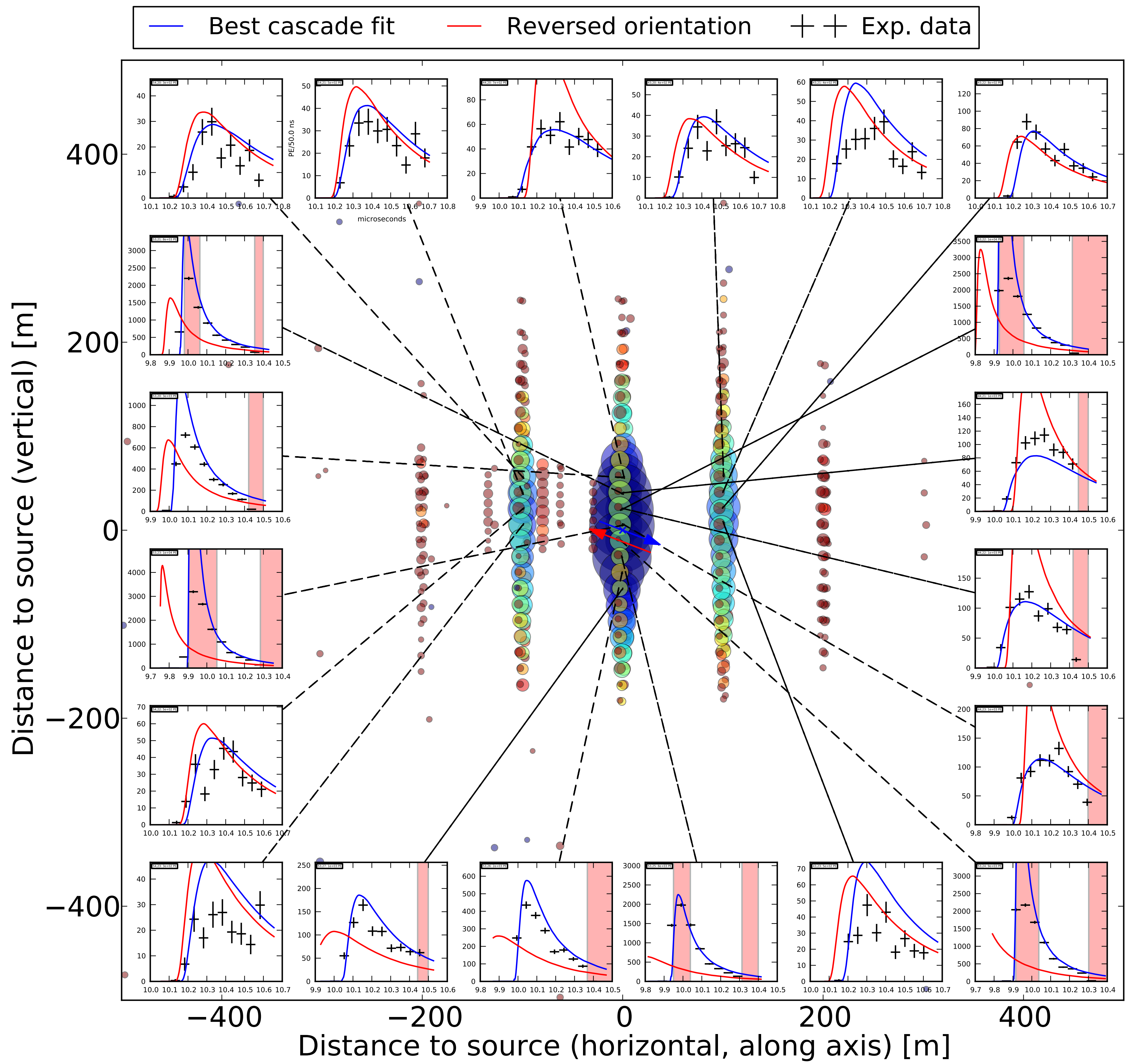


Orientation of sensor matters even at large distances. Modeling important.

Likelihood fit: Millipede/Monopod



Example: a 1 PeV cascade from 2012



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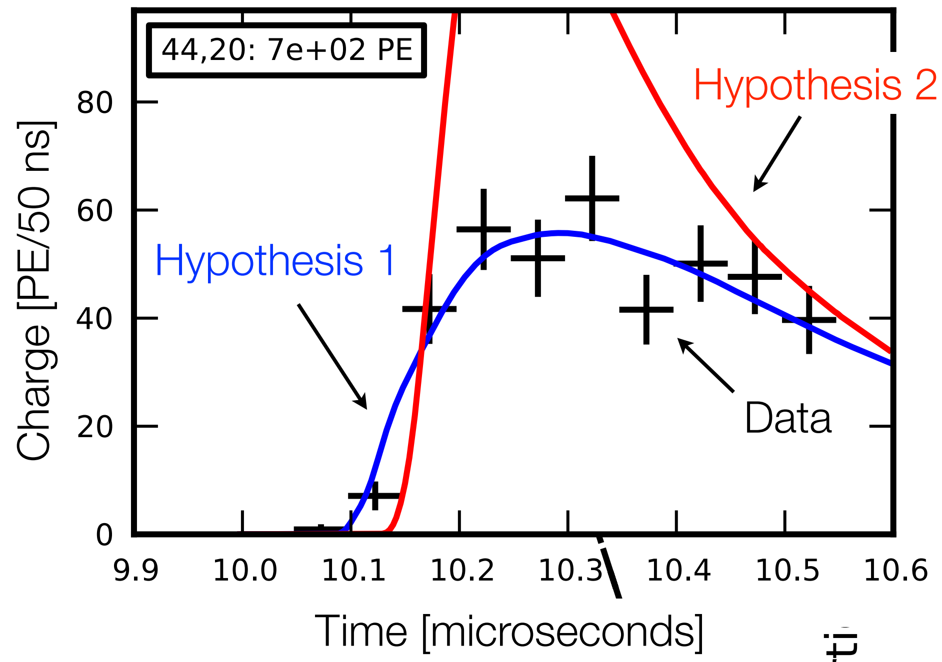

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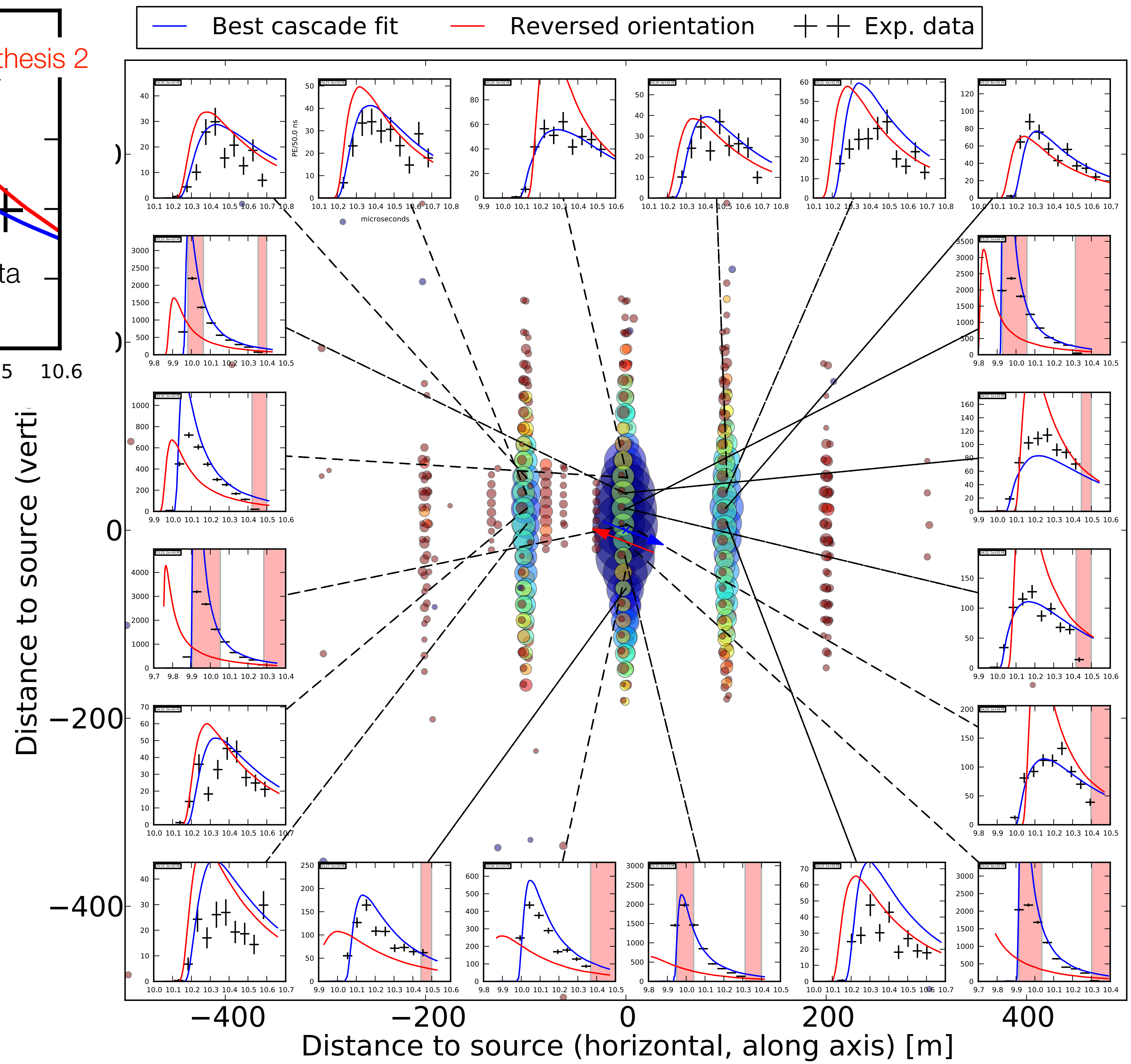

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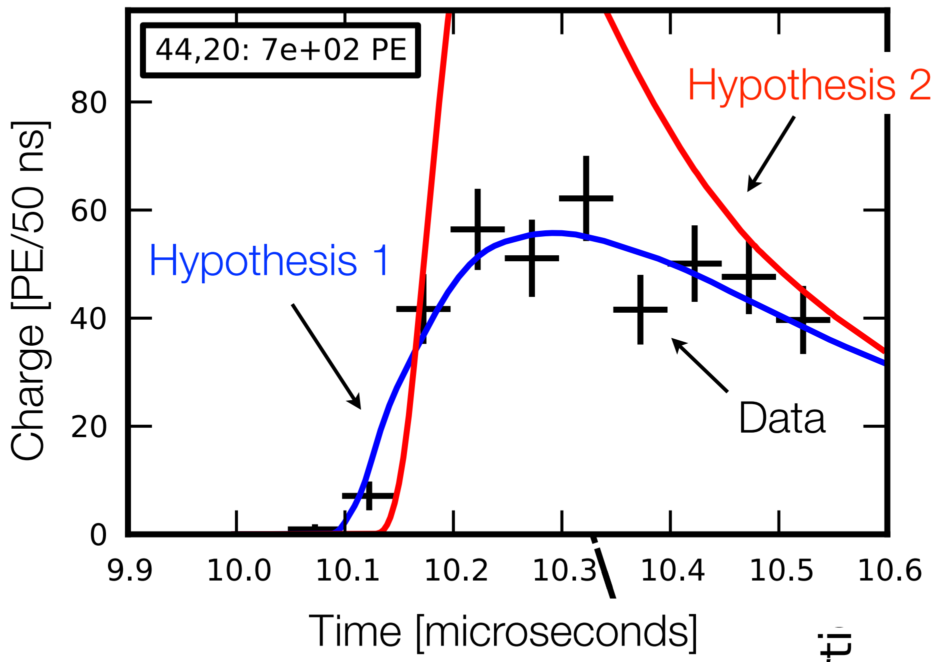
Likelihood fit: Millipede/Monopod



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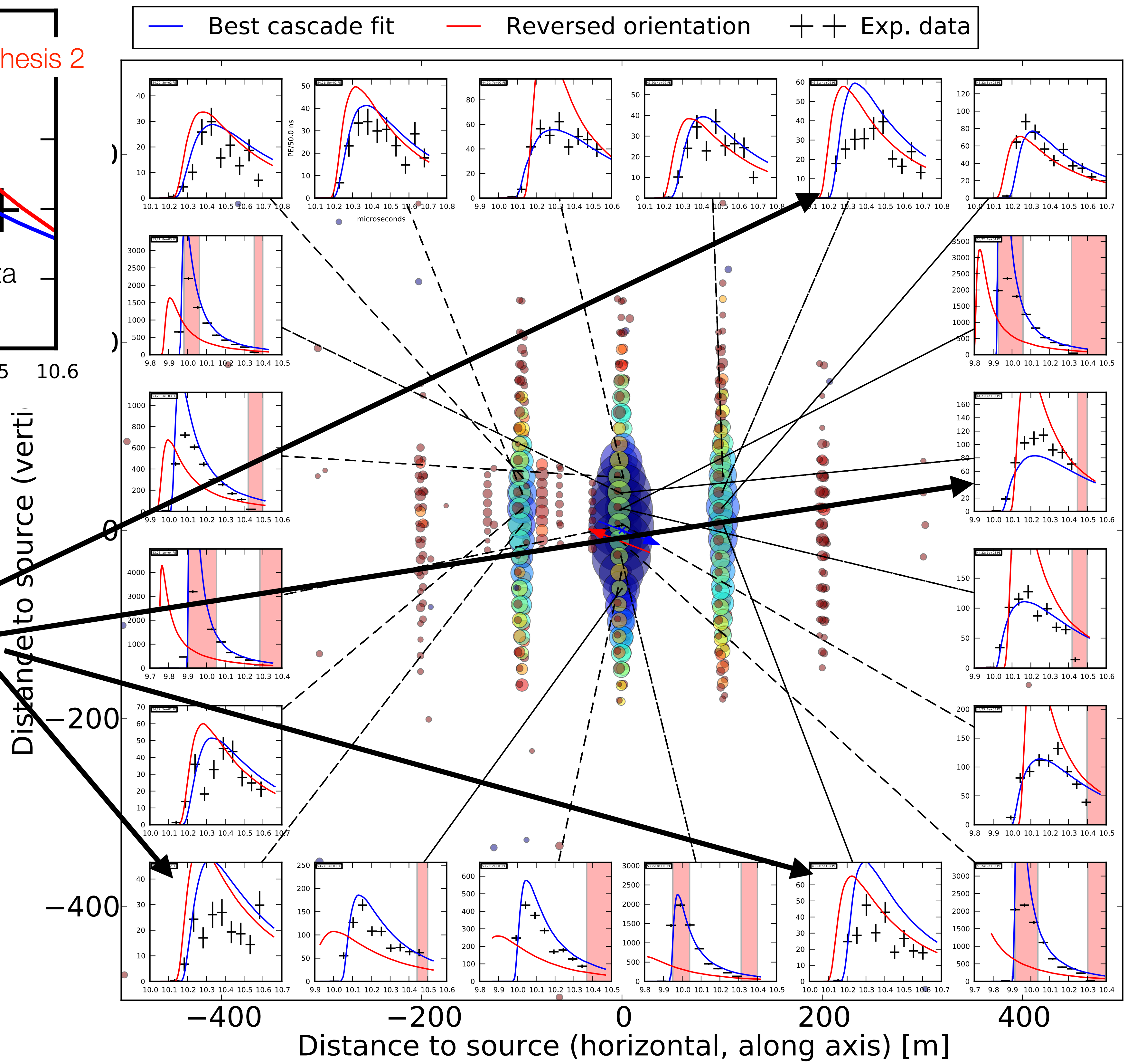
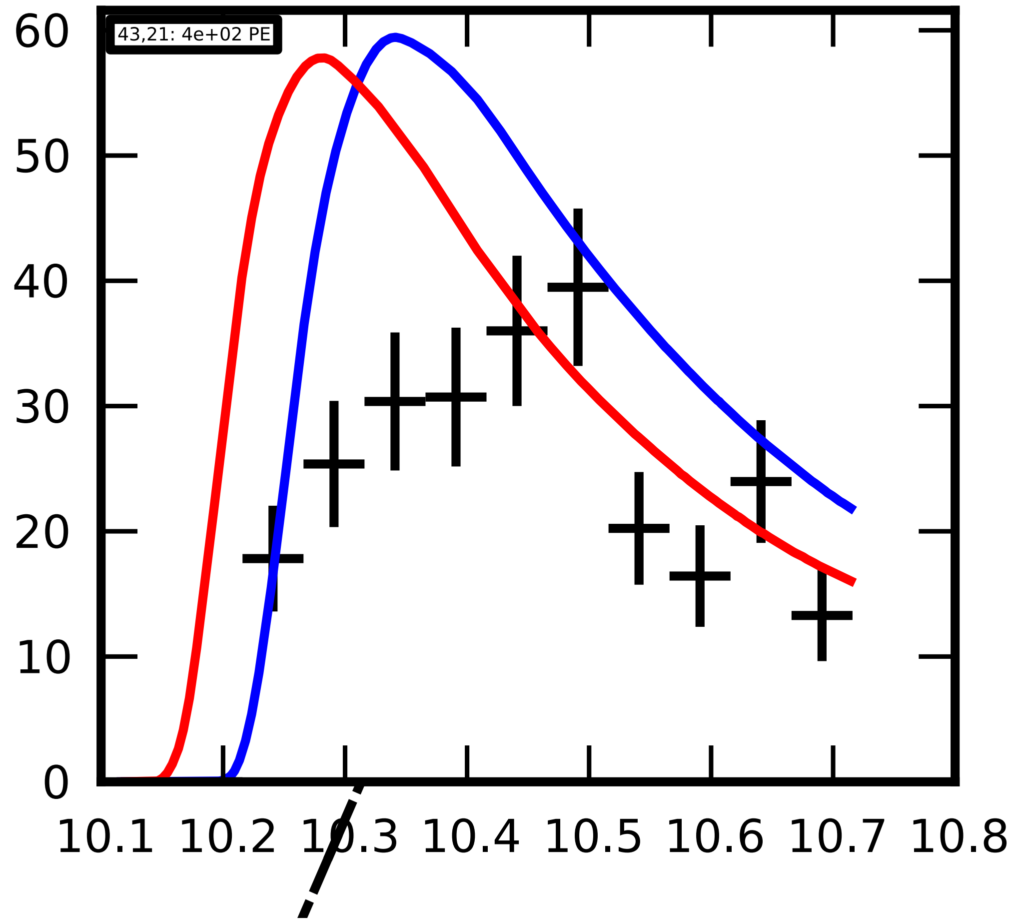
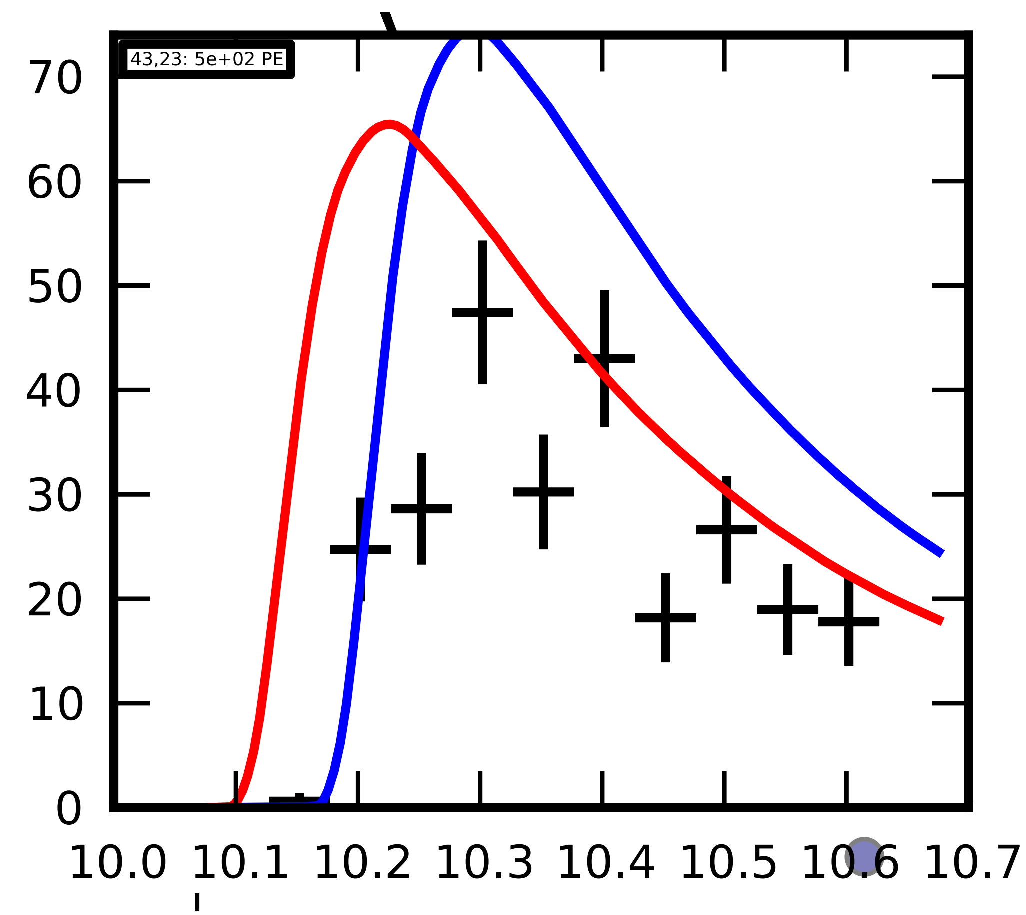


Waveforms do not always fit well! Why?

Likelihood fit: Millipede/Monopod

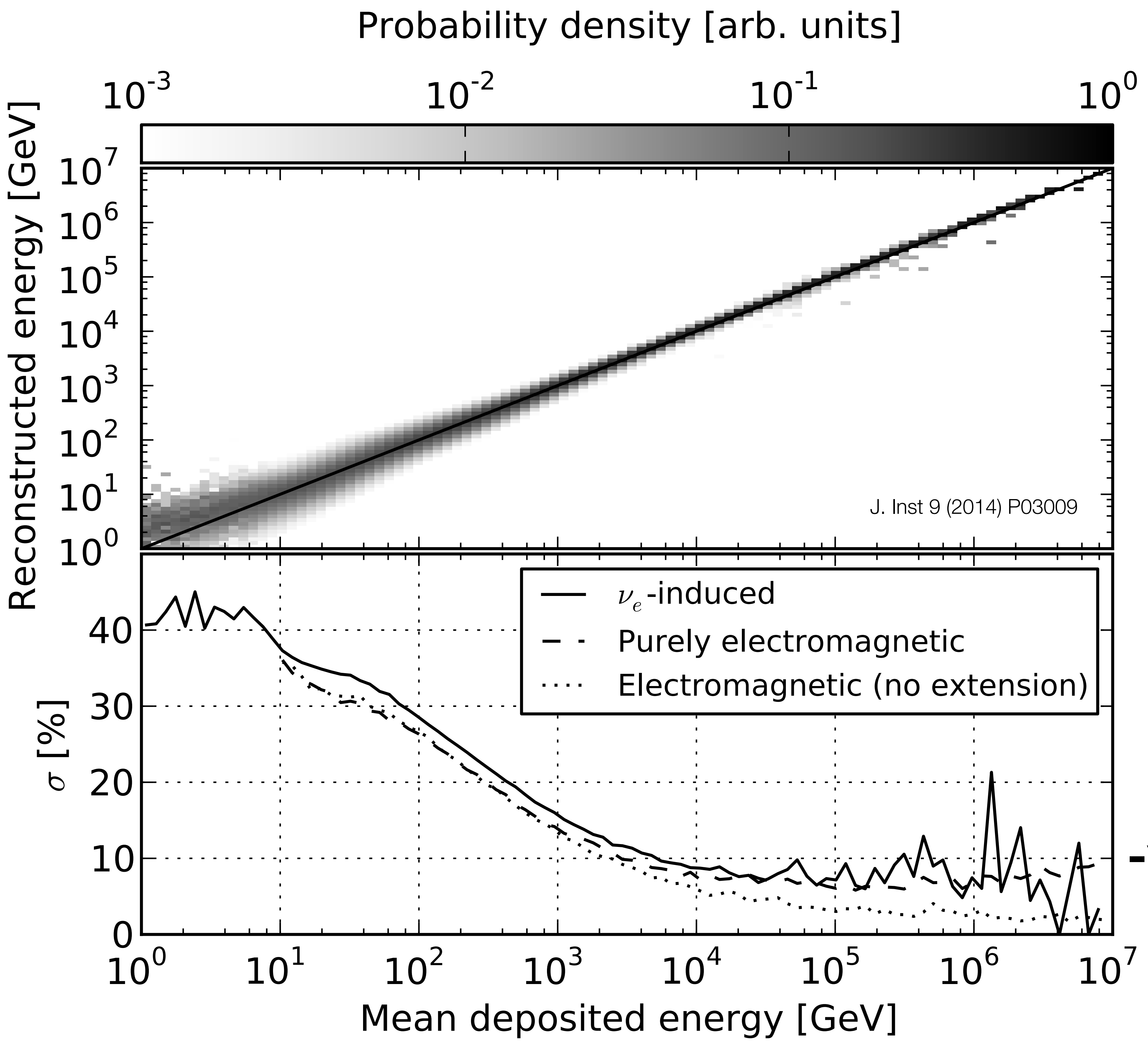




Still some work to do!

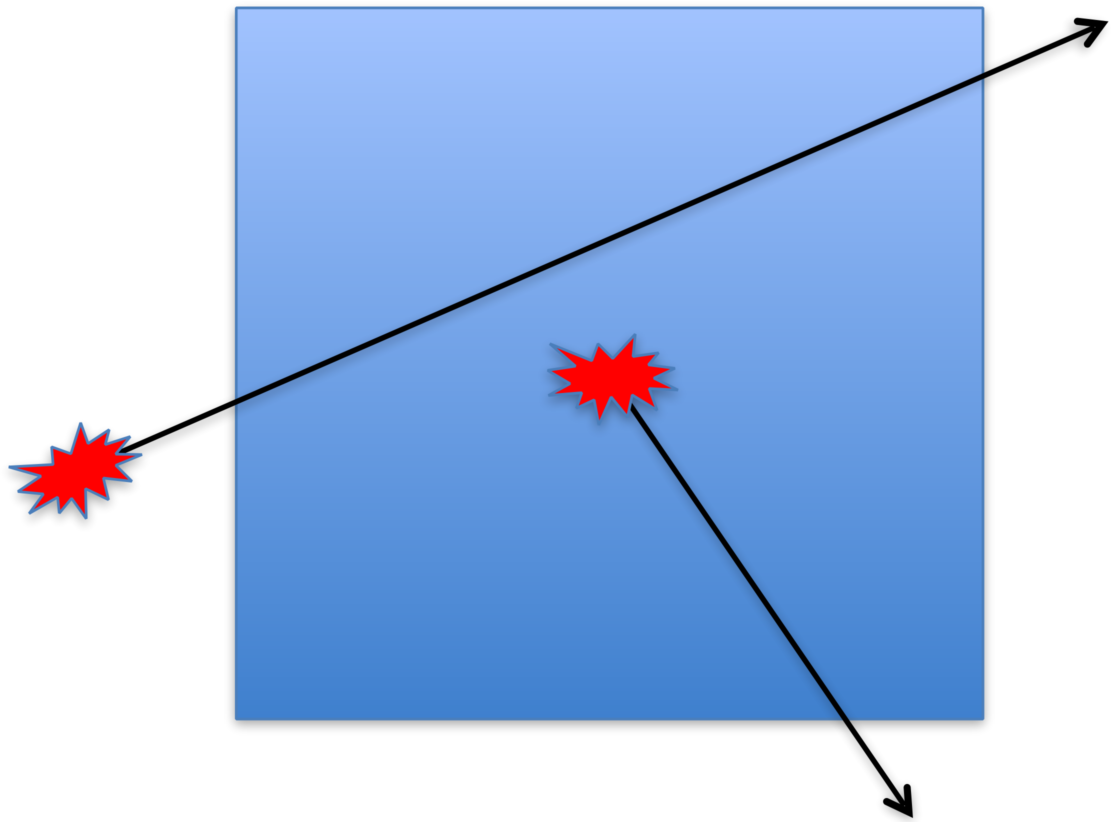
Estimated effect of modeling uncertainties, at least a factor to in angular resolution.

Deposited-energy resolution for showers in IceCube



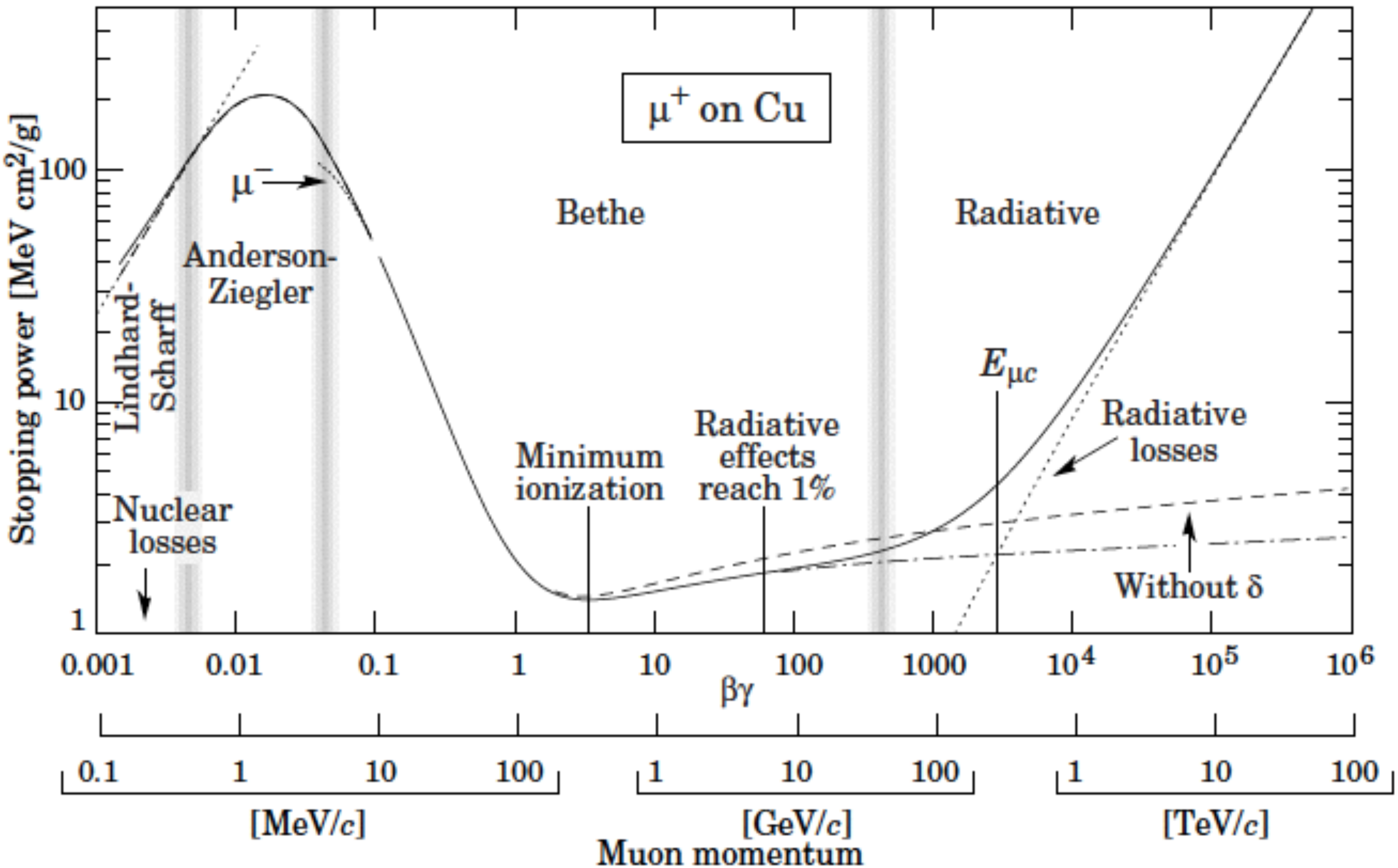
less than 10% -very good!

Muons



Muon energy loss, range

http://pdg.lbl.gov/2011/reviews/rpp2011-rev-passage-particles-matter.pdf



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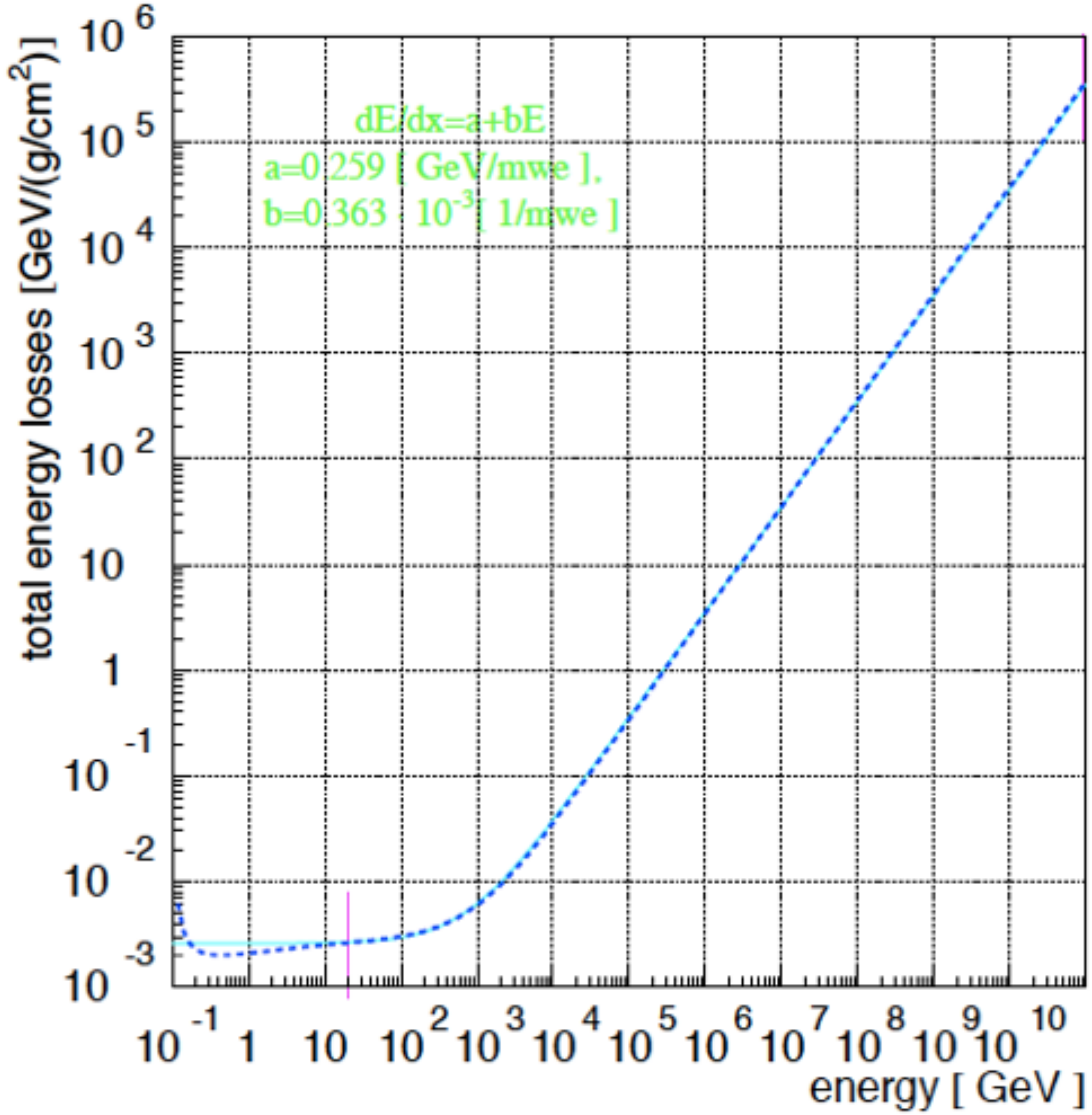

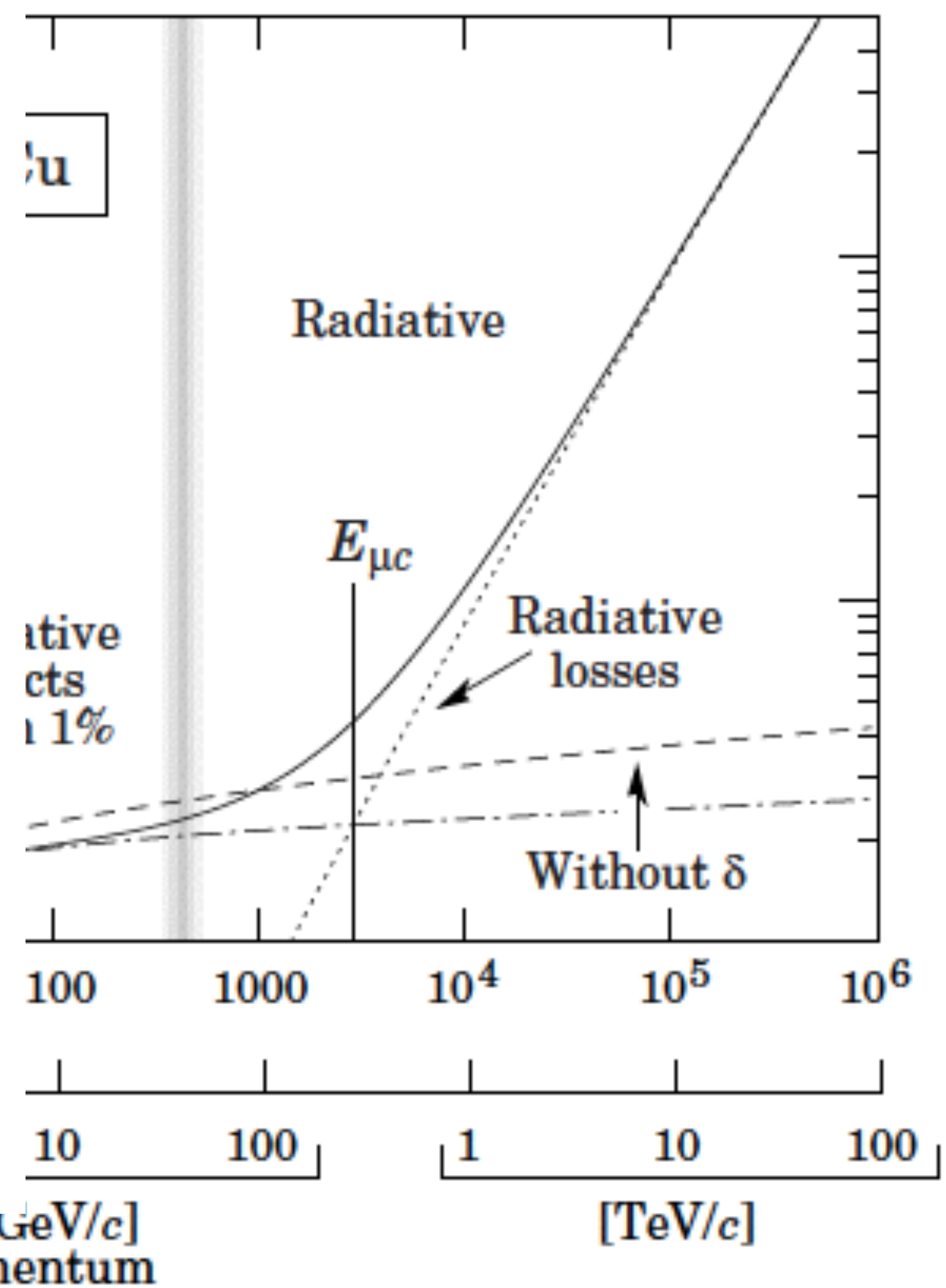

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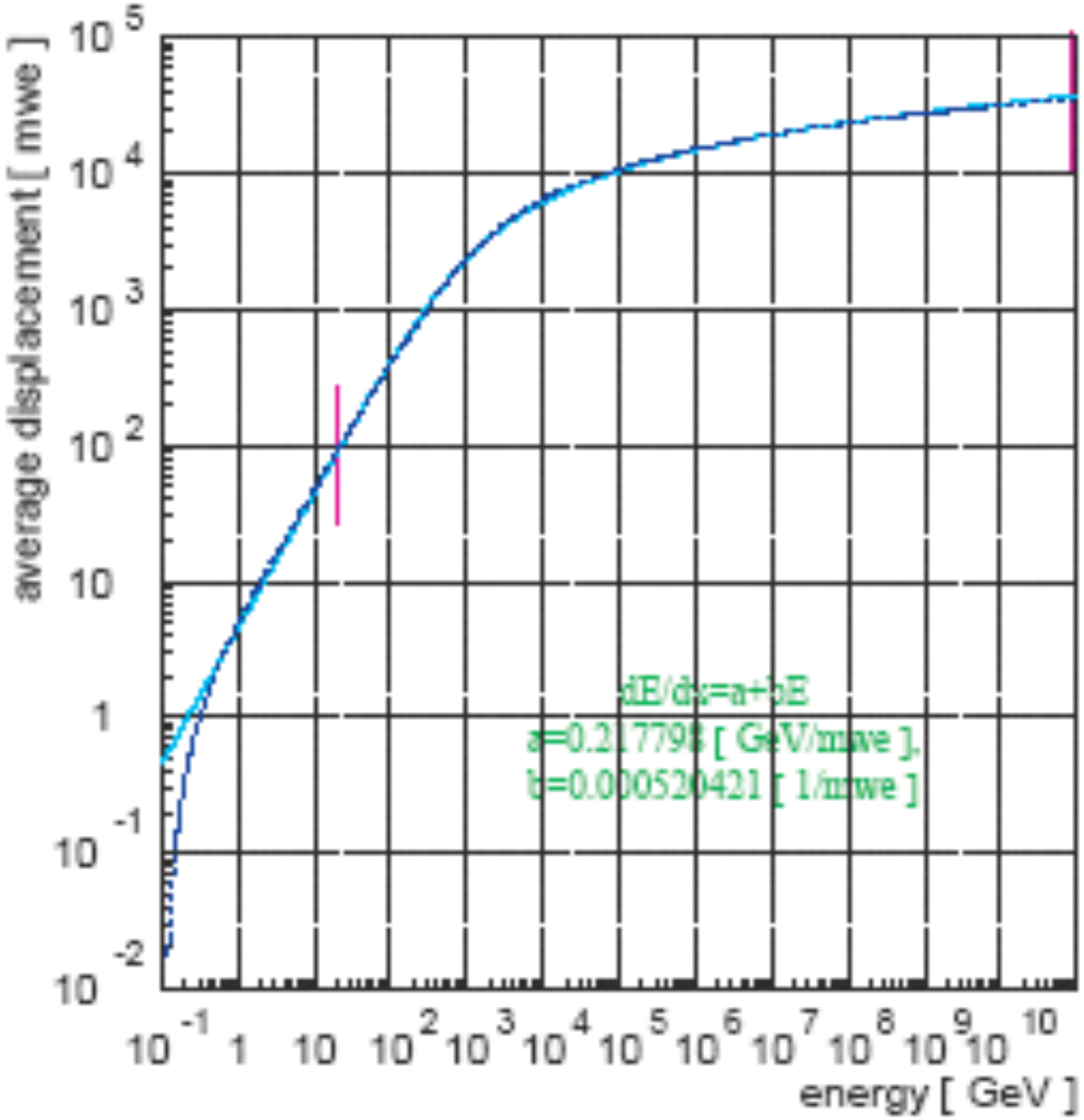
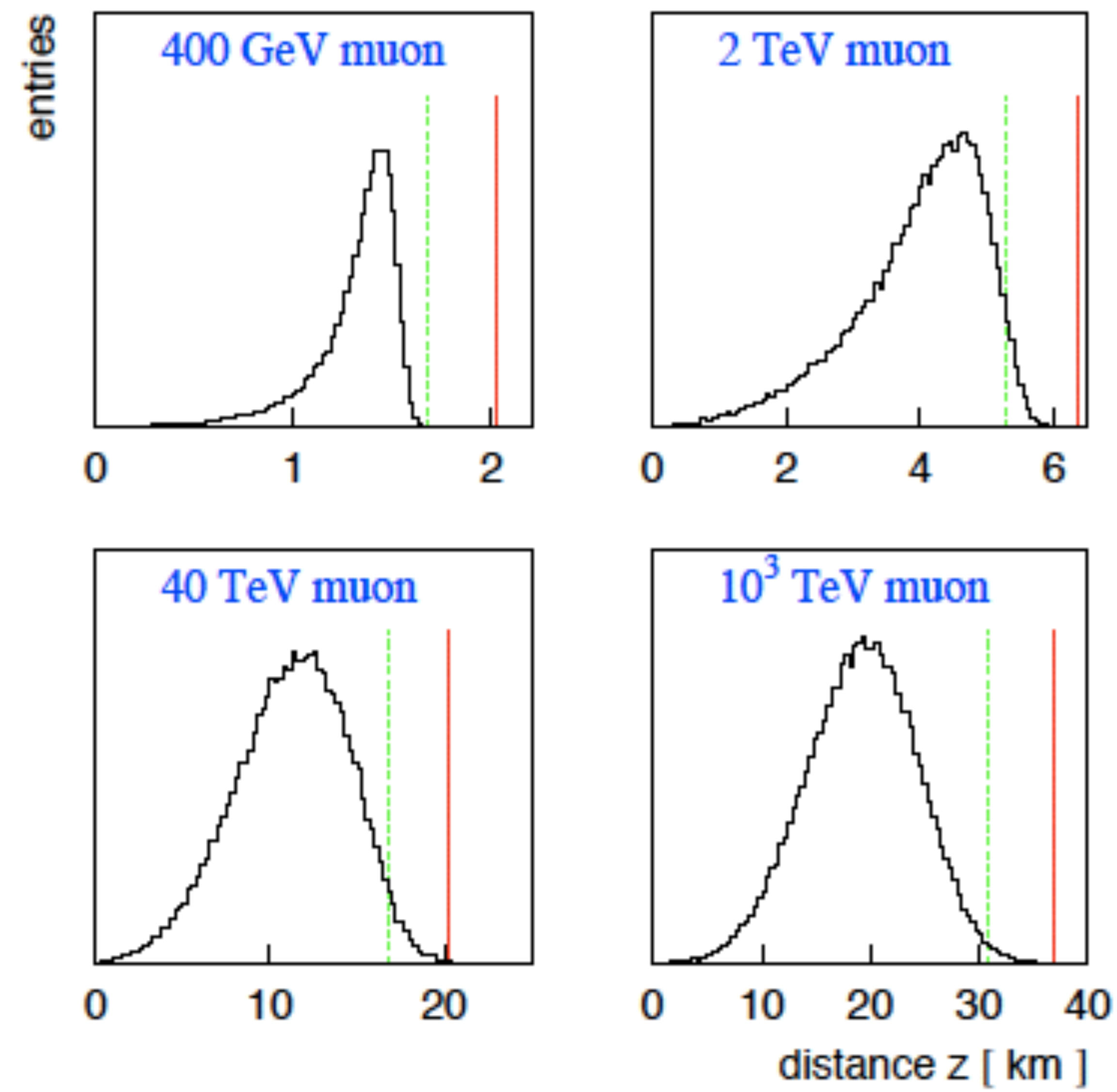




Energy Reconstruction of Muons

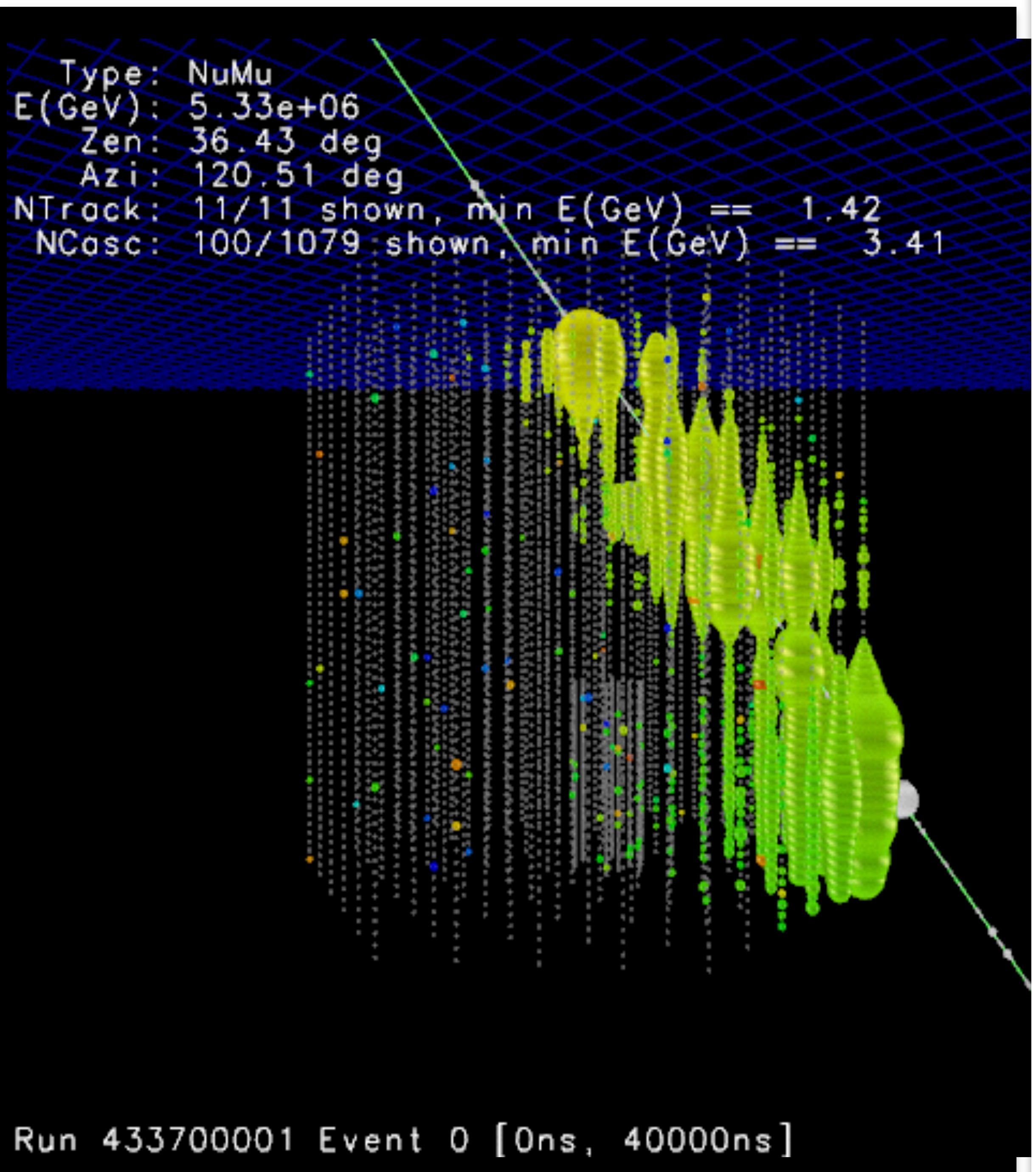
- Measurement/reconstruction of the deposited energy
- Infer the energy of the muon from observed deposited energy
  - Case 1: vertex outside the detector (how far outside is not known)
  - Case 2: vertex inside the detector
- Infer energy of the neutrino

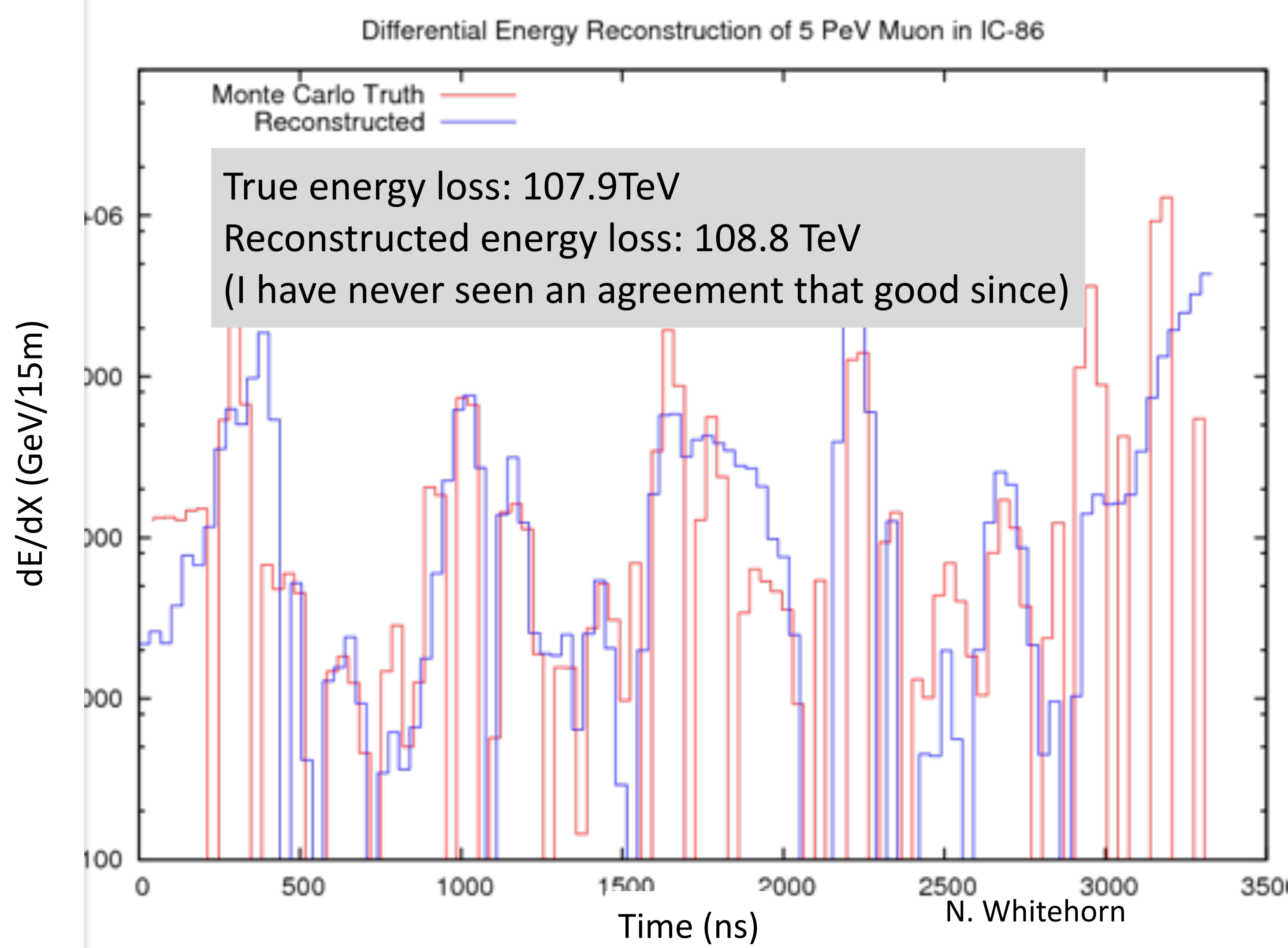
Reconstrucing the deposited energy

Simulated Muon of   5 PeV energy
Many stochastic energy losses complicate energy loss reconstruction.
Current best methods: ~0.2 in log(dE/dx)

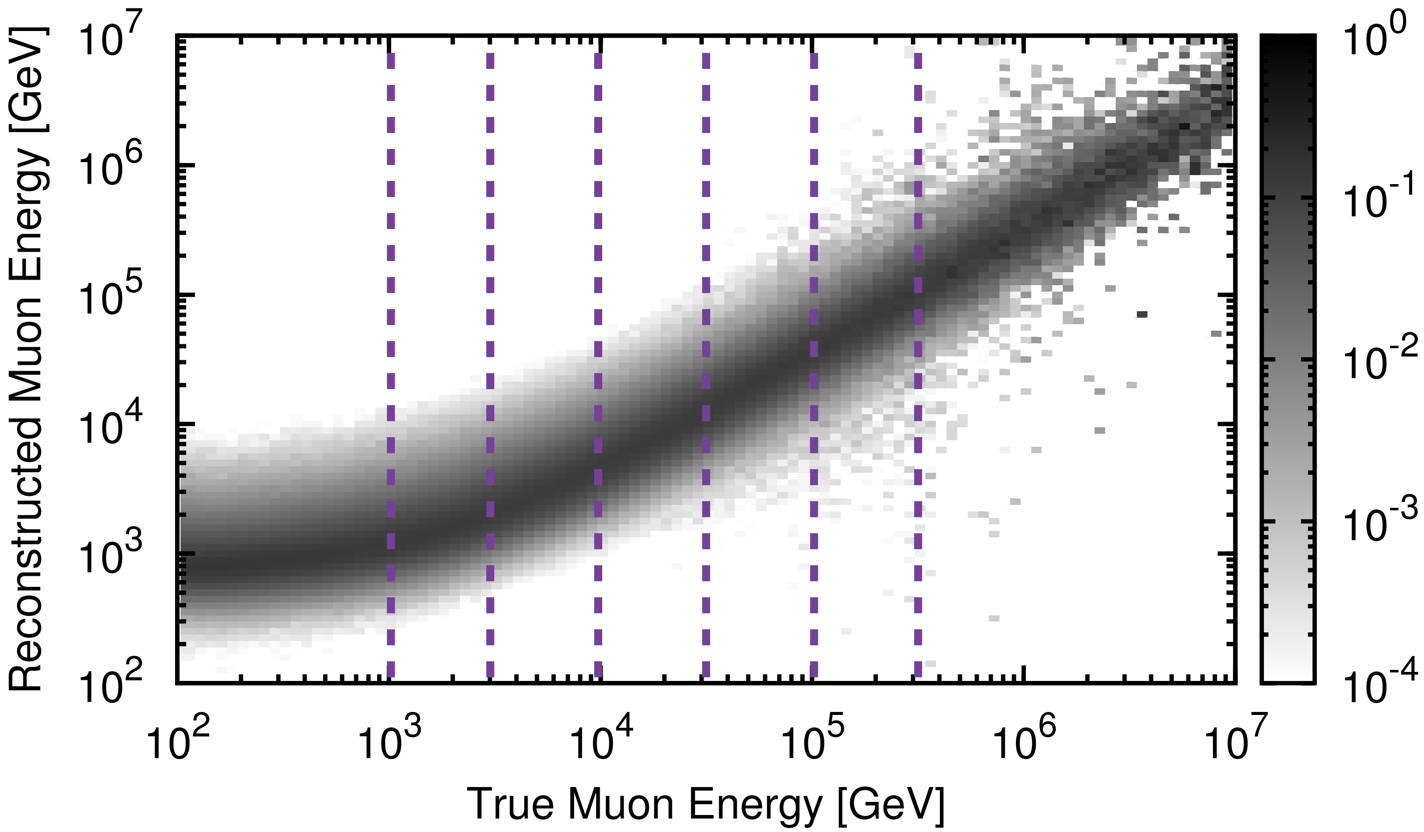
Improved differential energy loss reconstruction determines individual energy losses along the track.

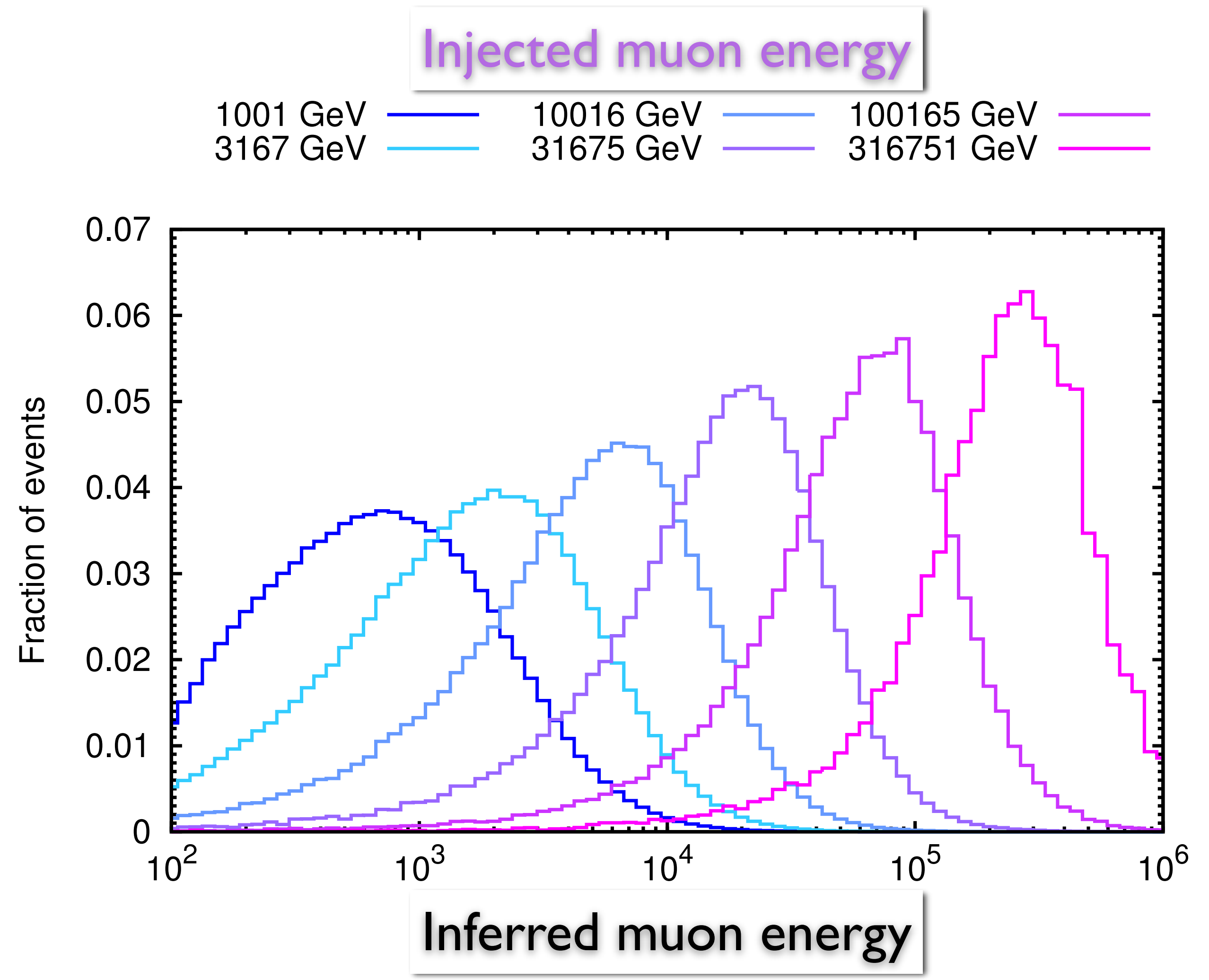
Possible impacts/applications:
- Distinguish single muons from multiple muons
- Basis for substantially improved angular reconstruction much more accurate light emission hypothesis (PDFs) that can be fed to the arrival time fitting algorithm

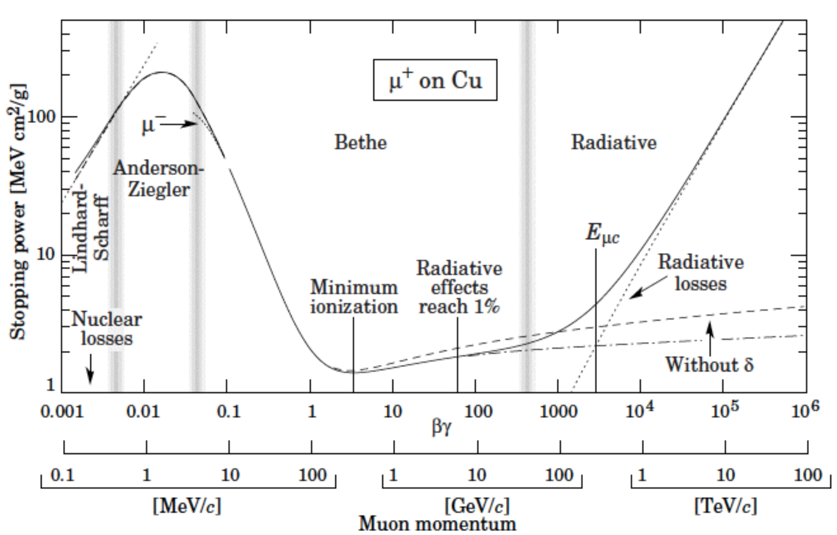


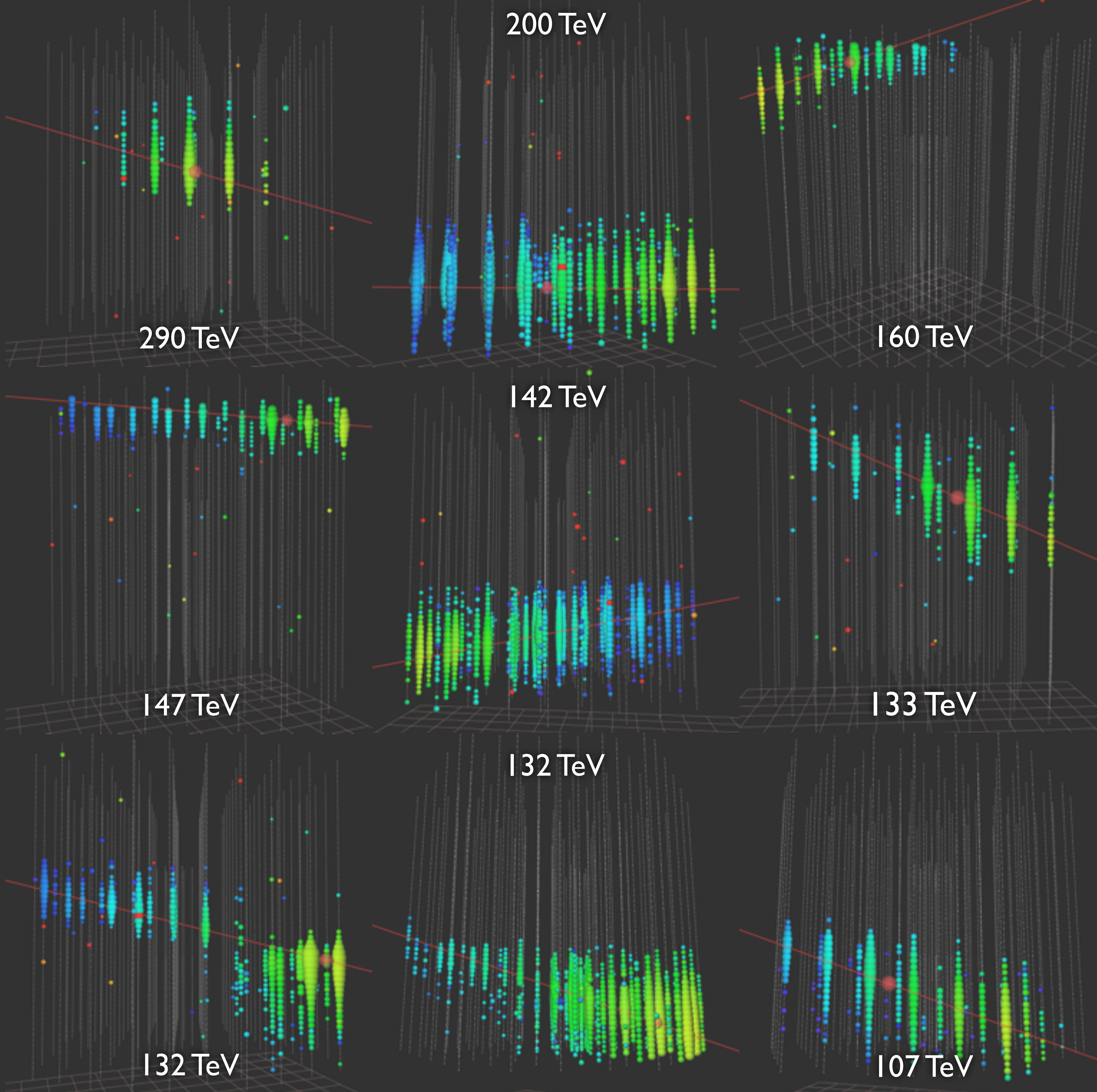


Energy Resolution for Muons








290 TeV
200 TeV
160 TeV
147 TeV
142 TeV
133 TeV
132 TeV
132 TeV
107 TeV

Diffuse Astrophysical Flux

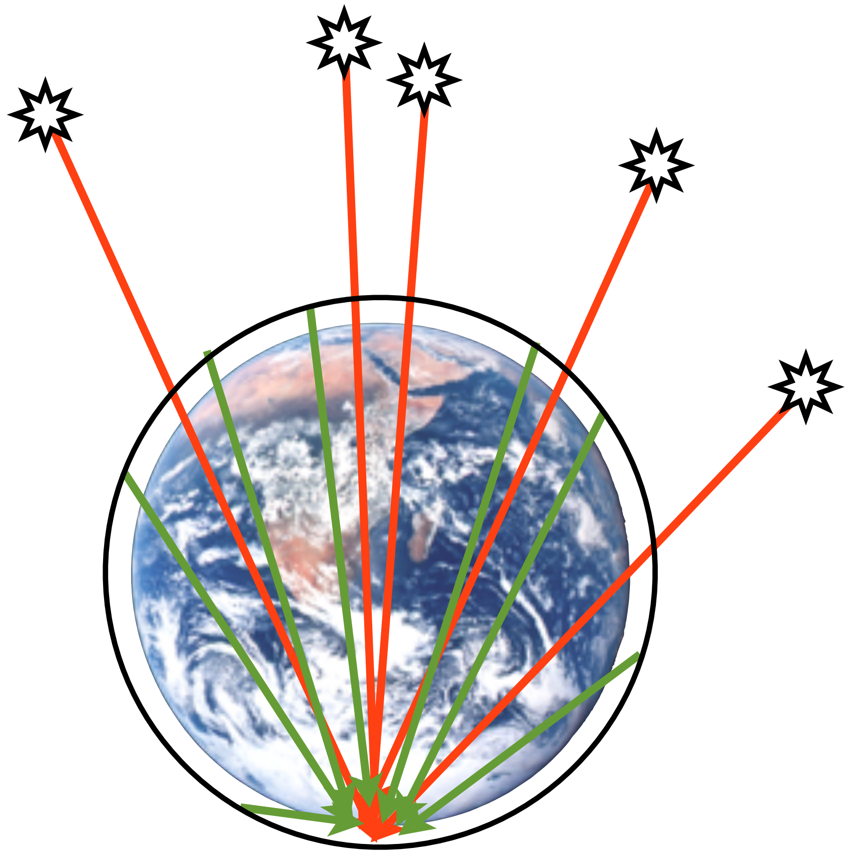
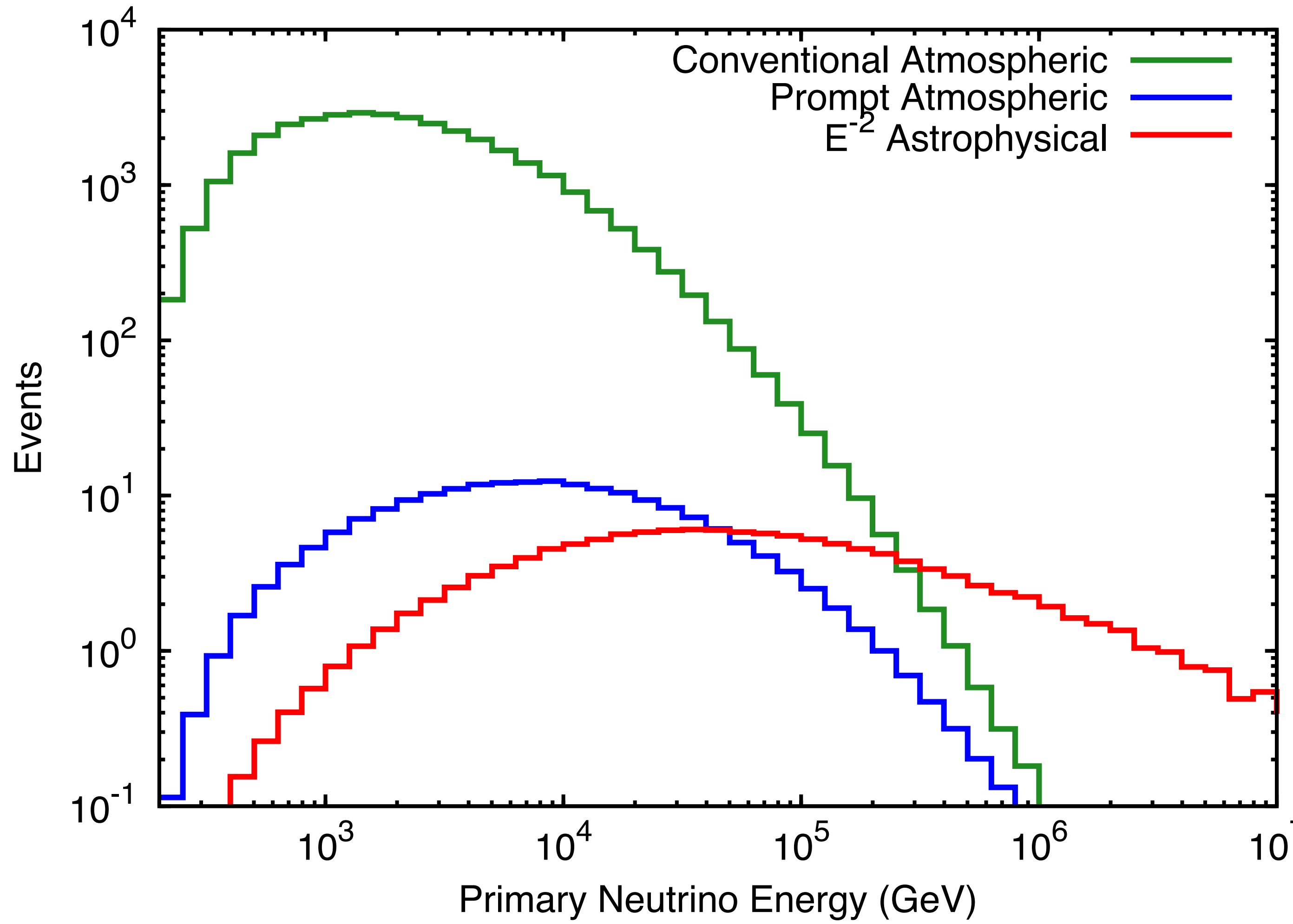
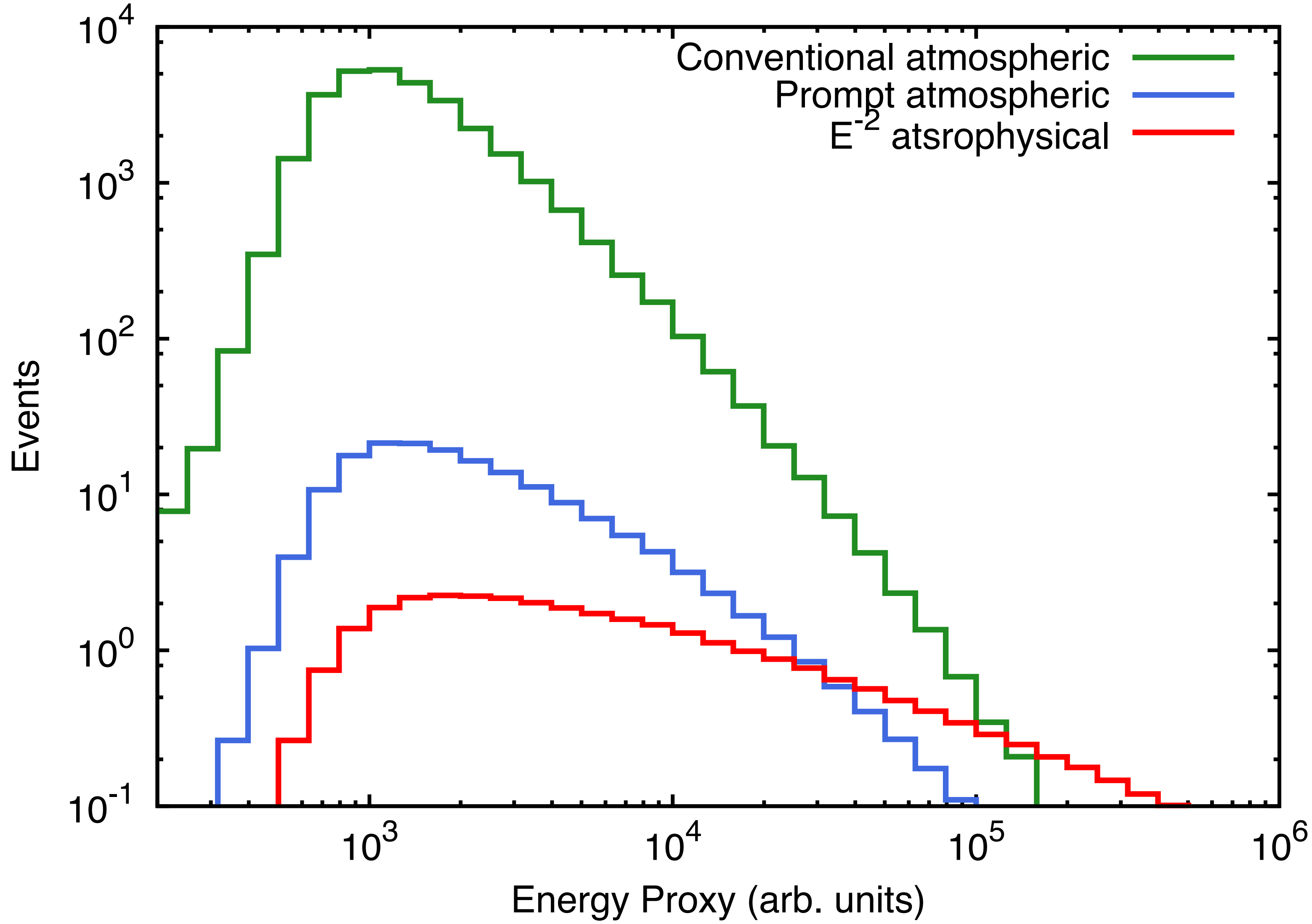


Image courtesy NASA Johnson Space Center

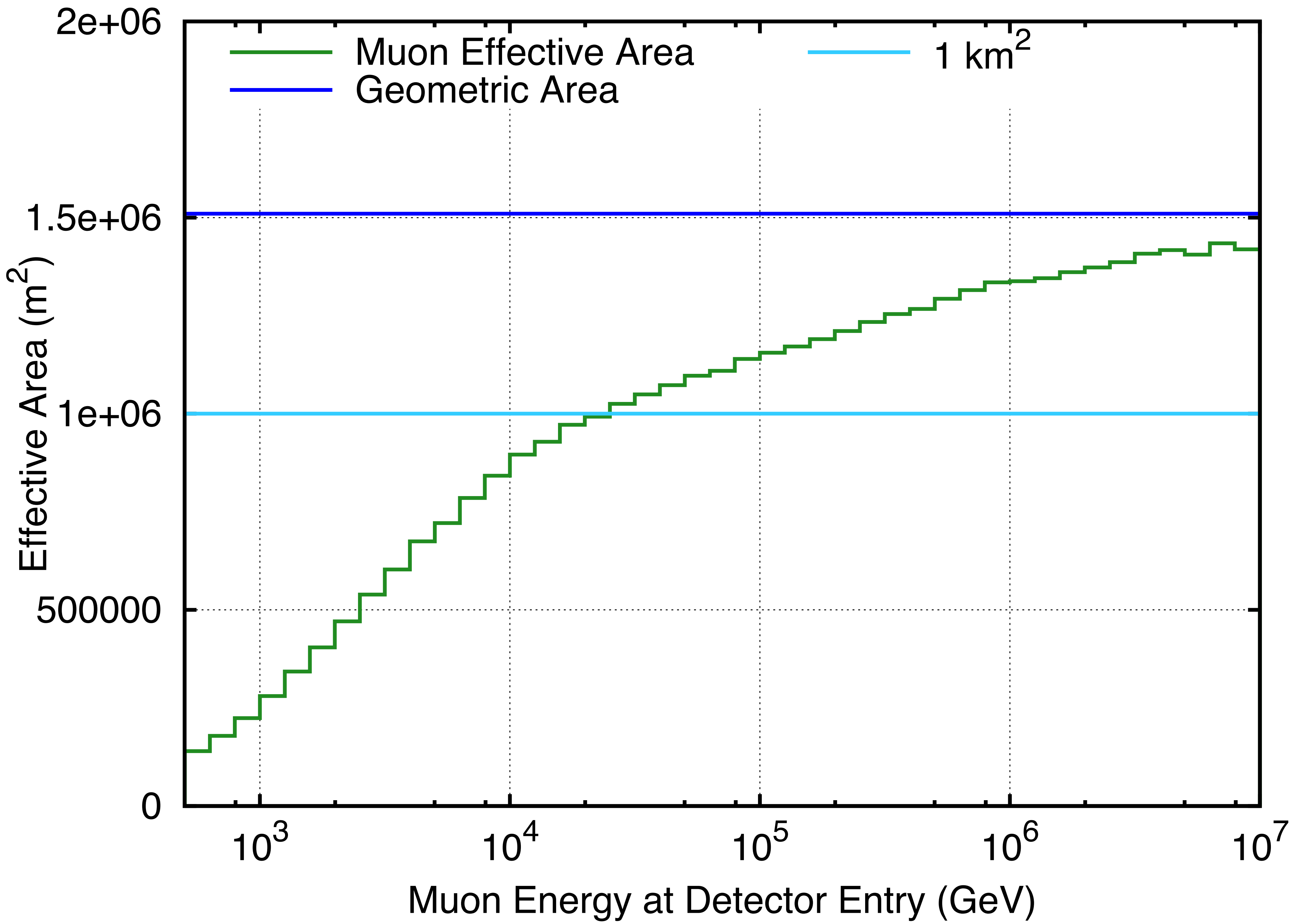


Fitting data as superposition of defined spectra



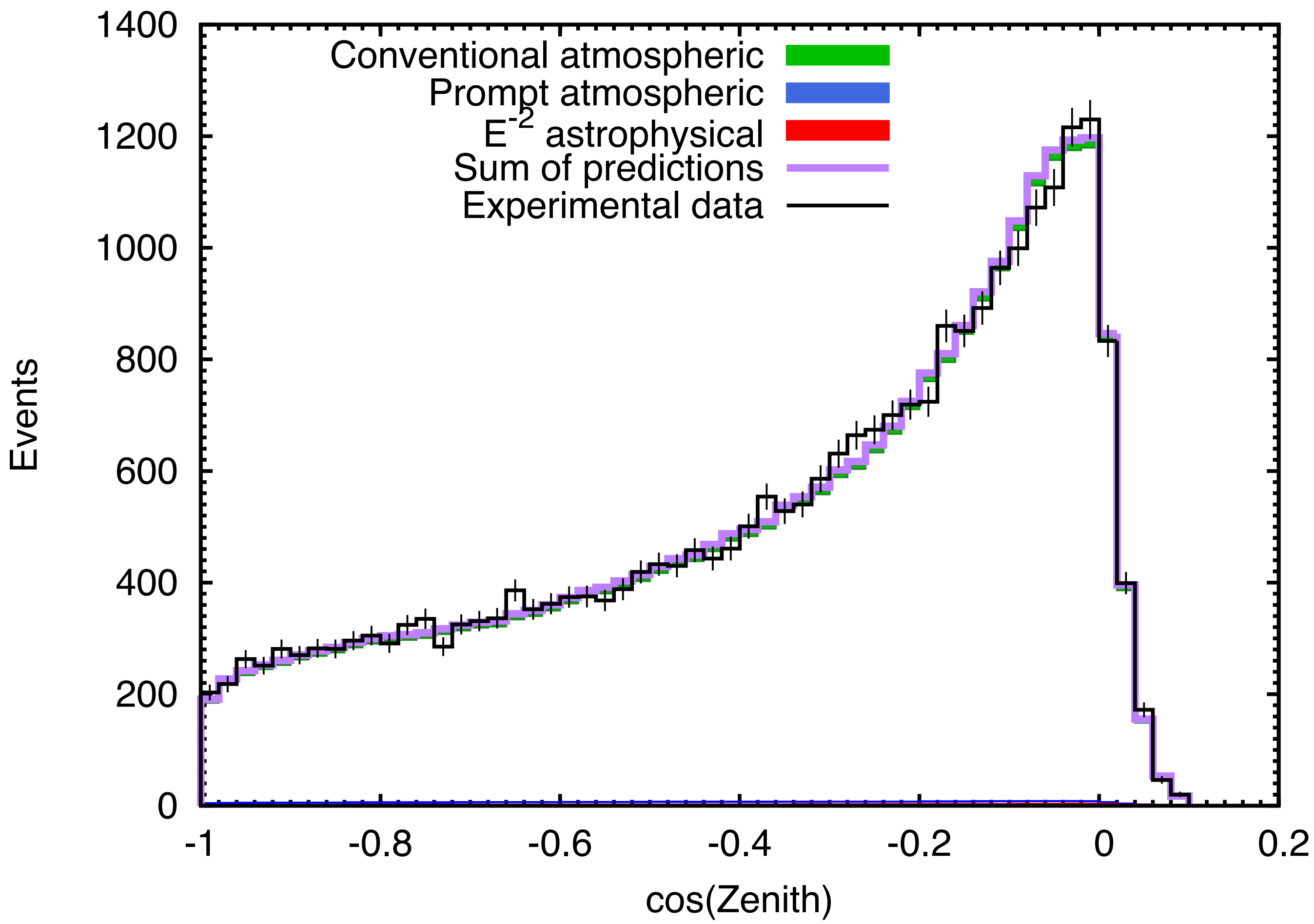
- Try to treat diffuse neutrino data as a superposition of
  - Conventional atmospheric neutrinos
  - Prompt atmospheric neutrinos
  - Astrophysical neutrinos (isotropic with a spectrum of E^{-2})

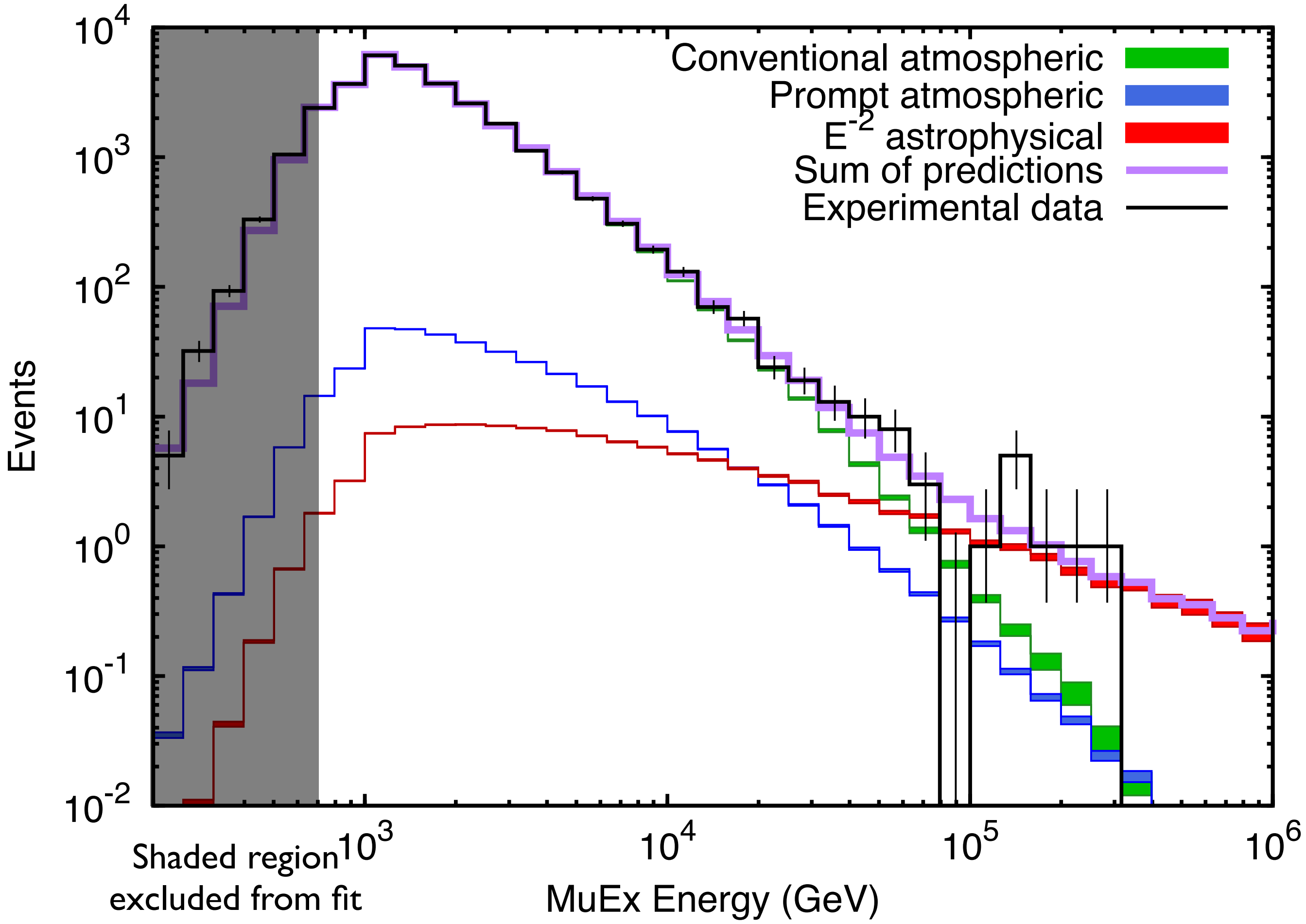
Muon Effective Area



- This event selection is efficient for muon energies at or above 10^5 GeV

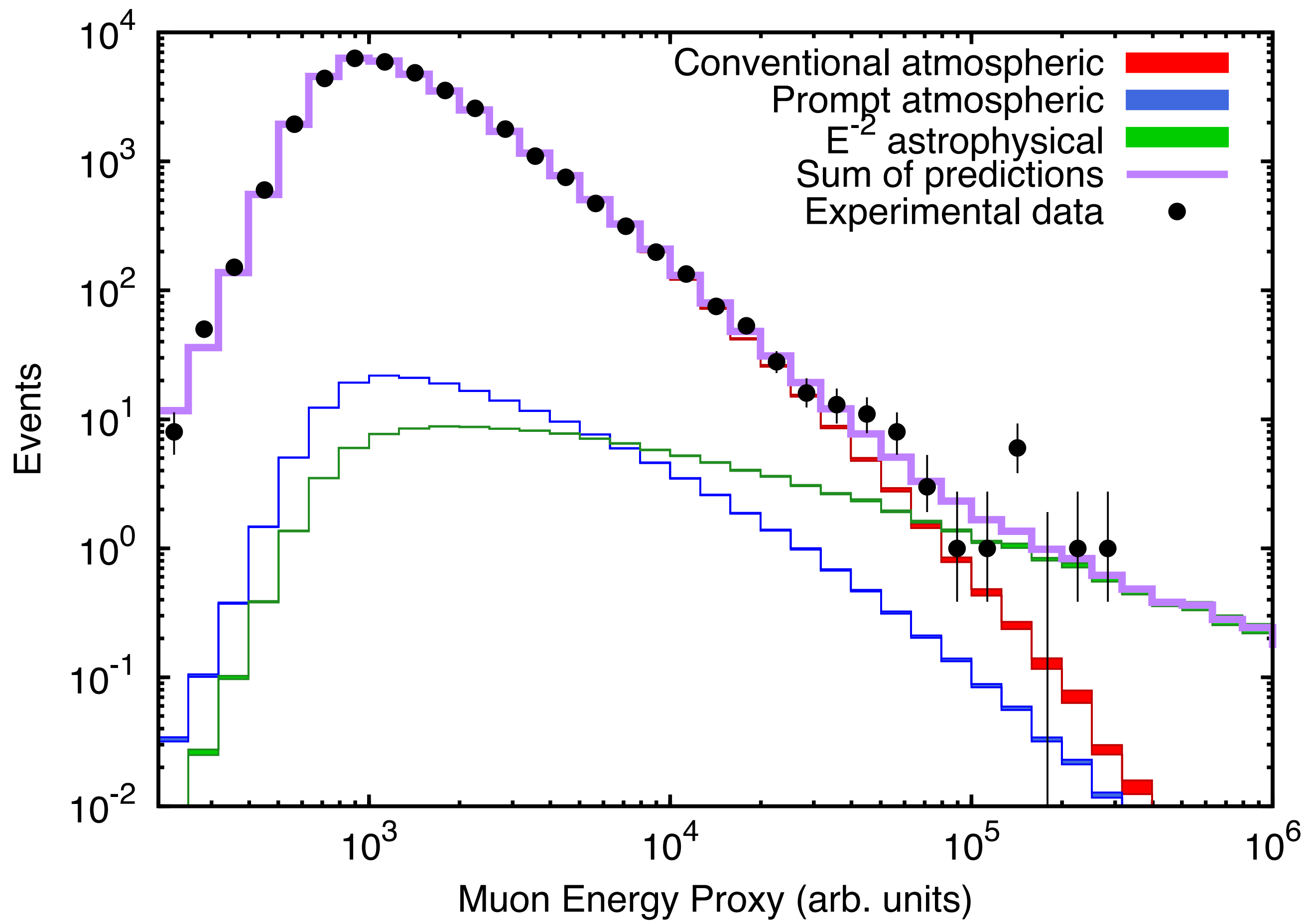
zenith and energy

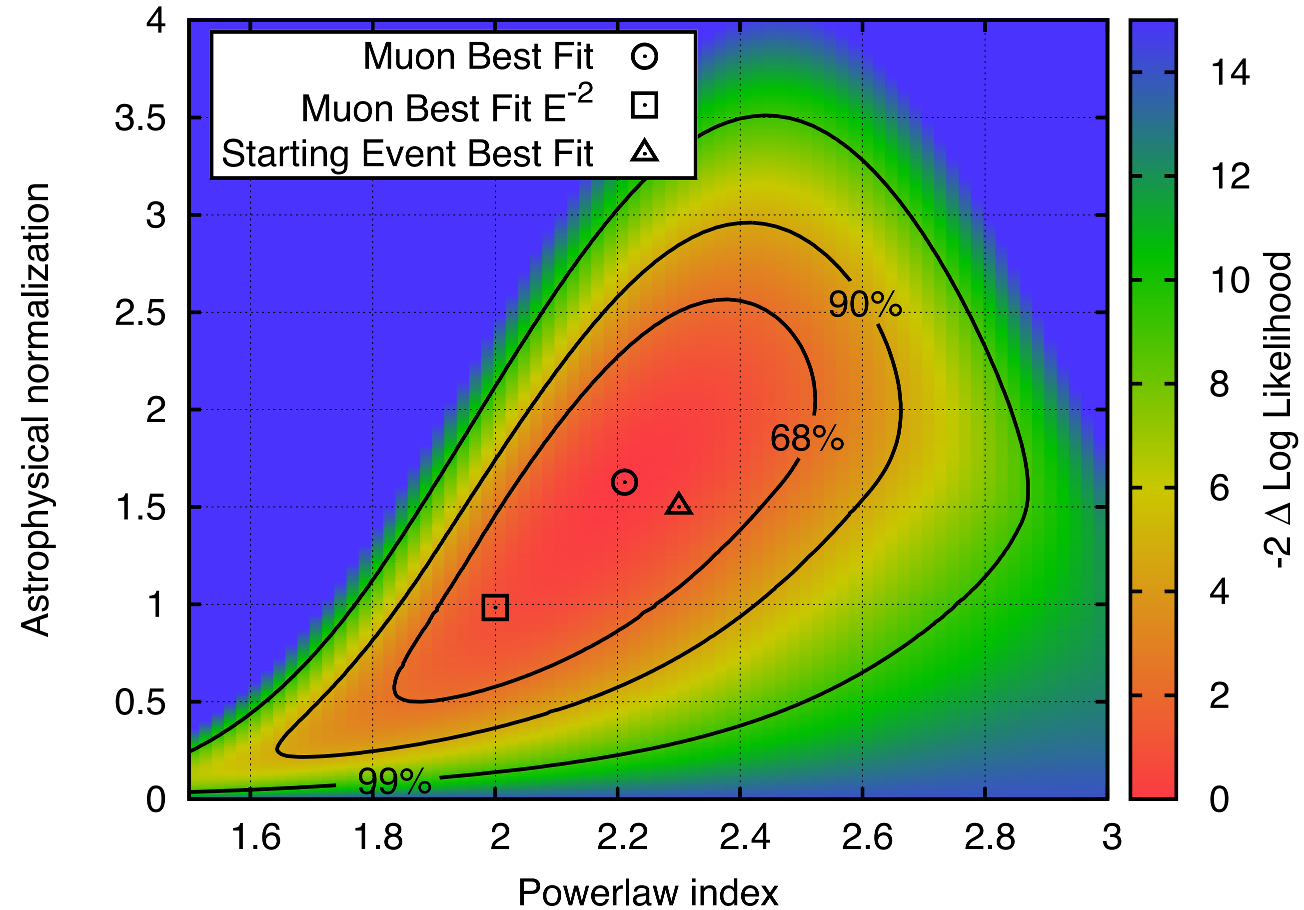




Conventional Normalization	1.20±0.05
Prompt Normalization	1.27 [0,2.8]
Astrophysical Normalization	1.03×10^{-8} [.65,1.45], 0 excluded at ~3.5σ

Northern Sky Through-going Events

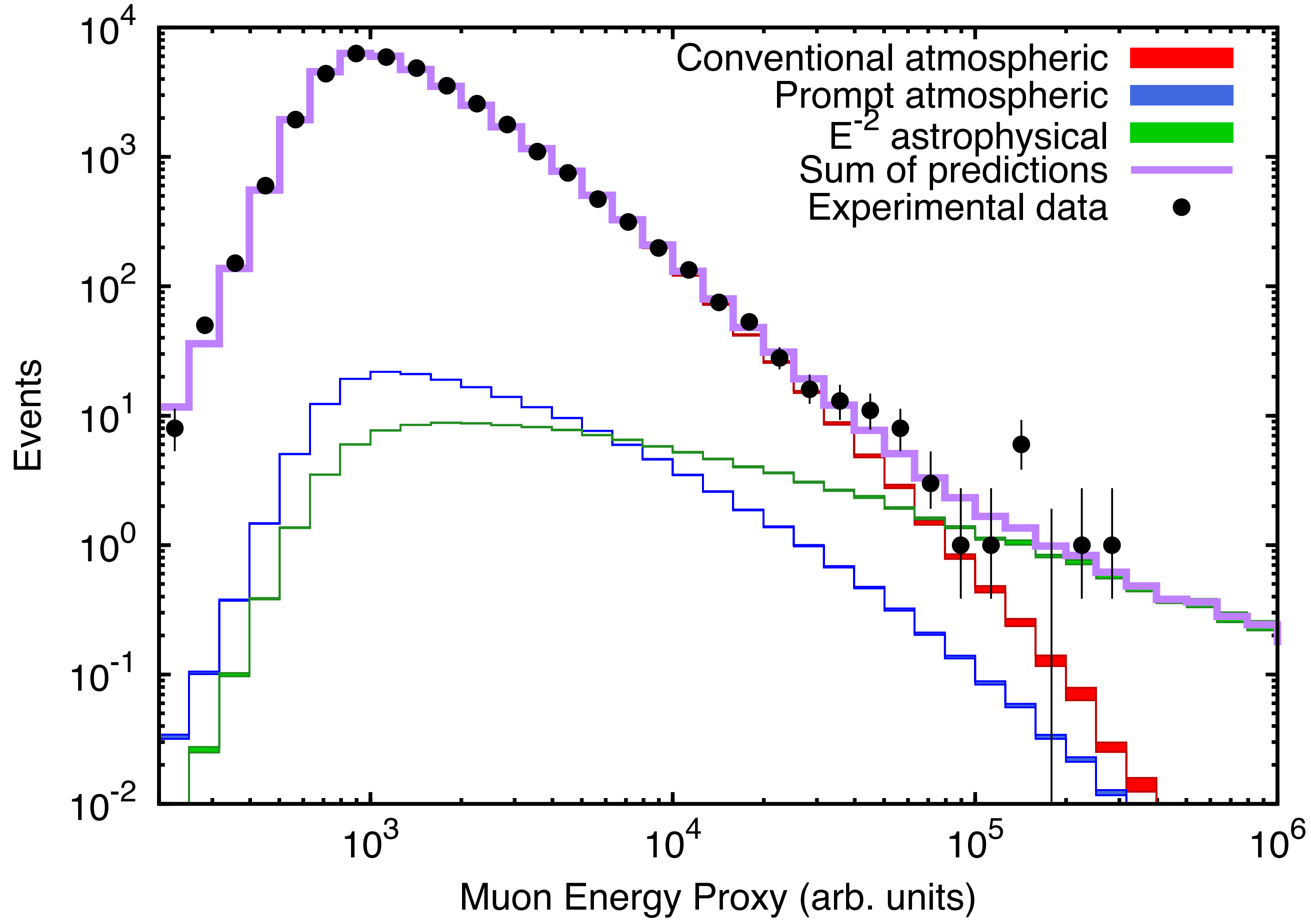


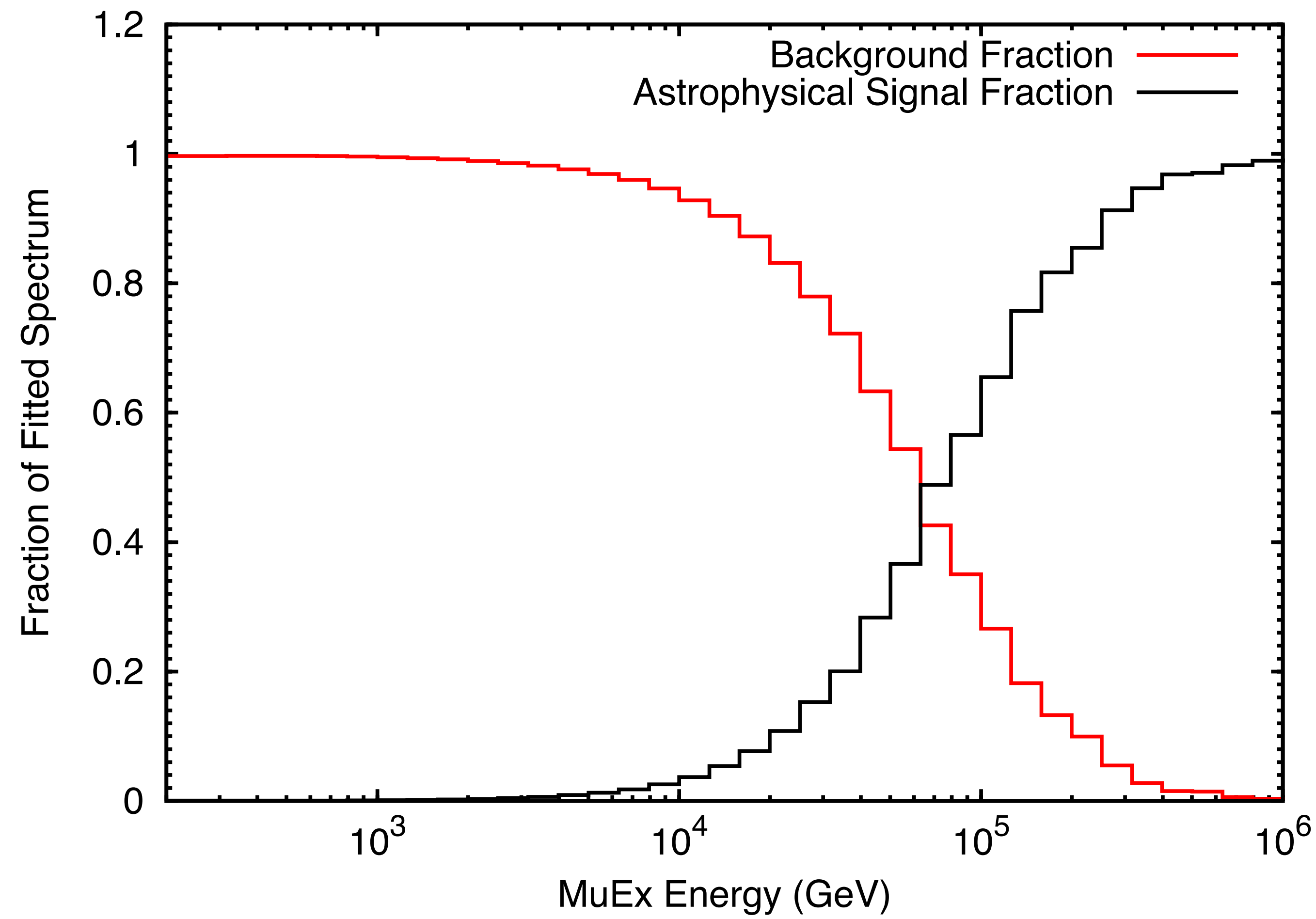


Can also add power index as free parameter to fit.

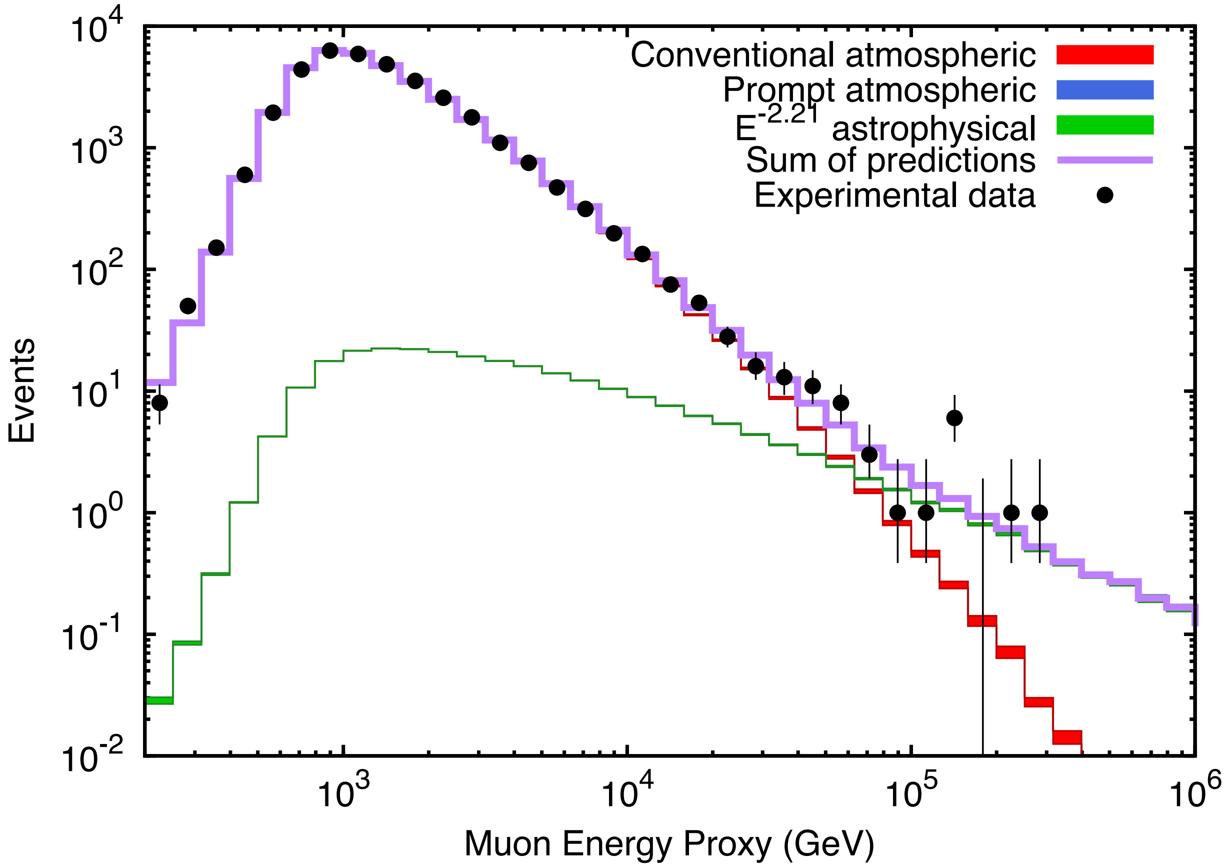
- Analysis of through-going events from the northern sky using 2 years of data—ν_μ charged current only, >1 TeV
- Excess over atmospheric background of 3.7σ
- Signal looks similar in different channels and different parts of the sky

energy tells probability of astro origin on event by event basis



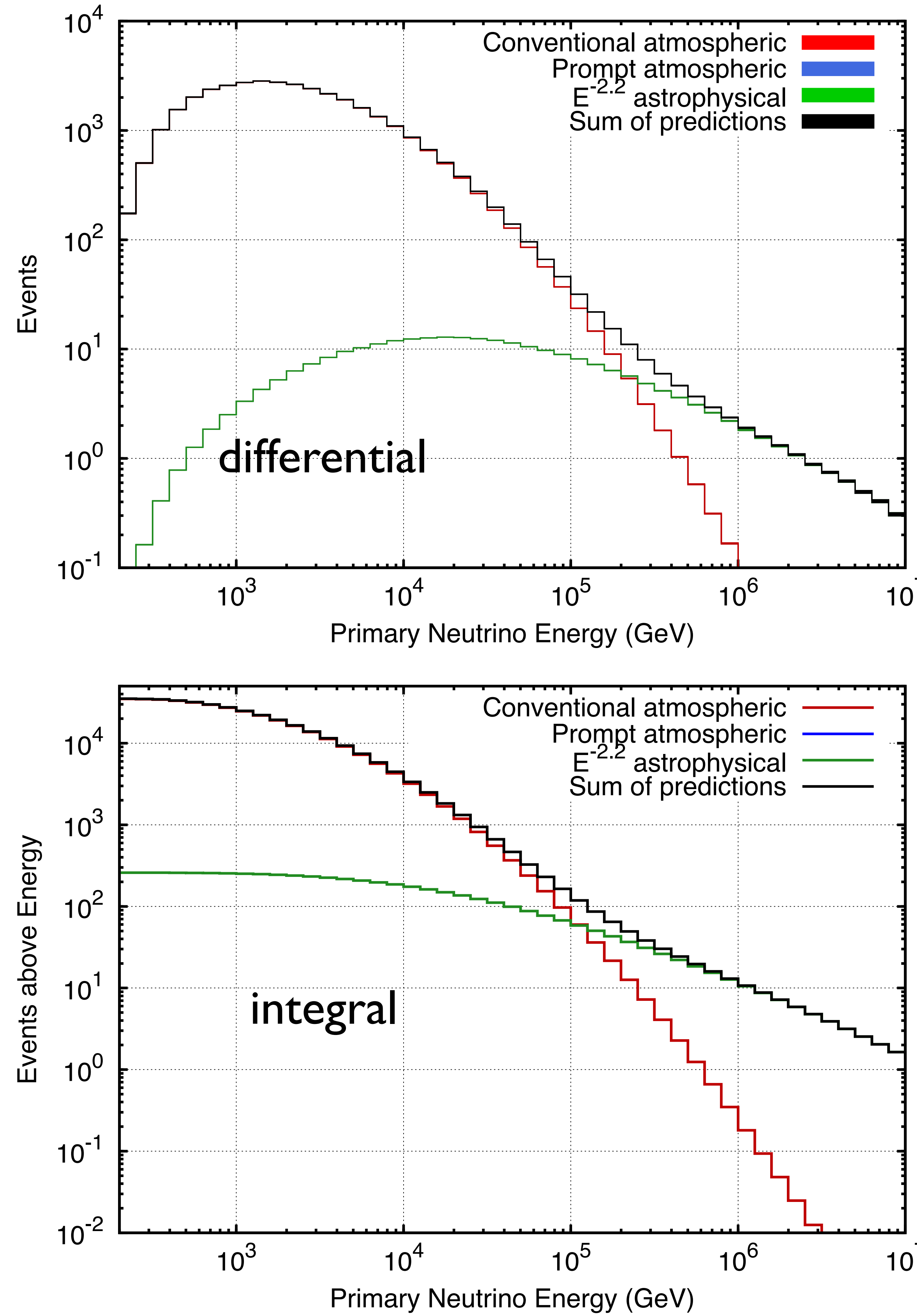


From muEx energy proxy to best fit neutrino spectrum

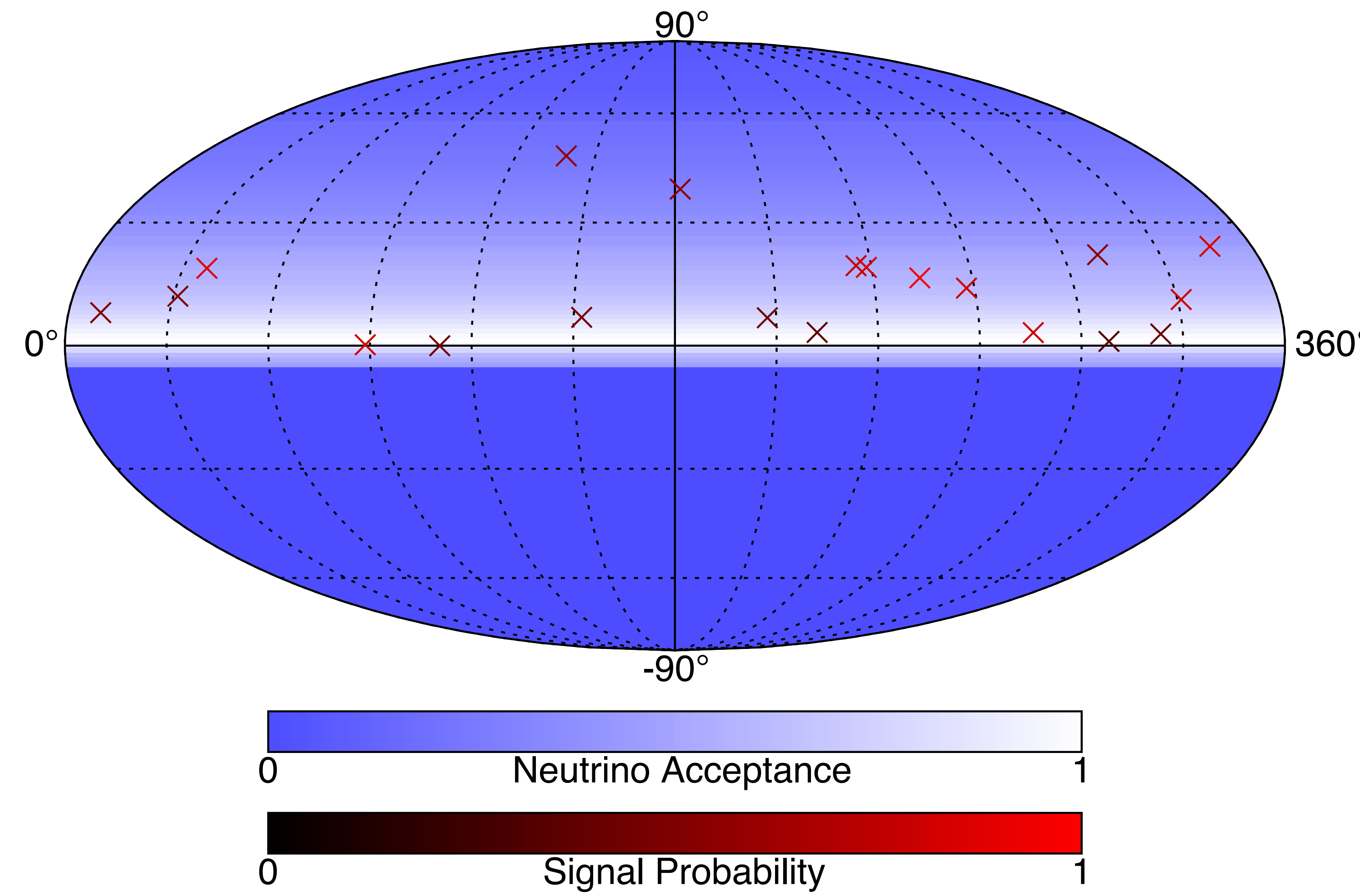


Analysis was done in observable space (MuEx, energy proxy)

best fit neutrino energy distribution

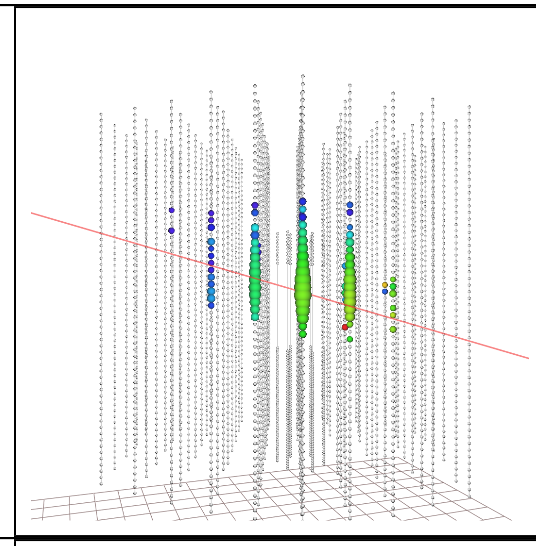
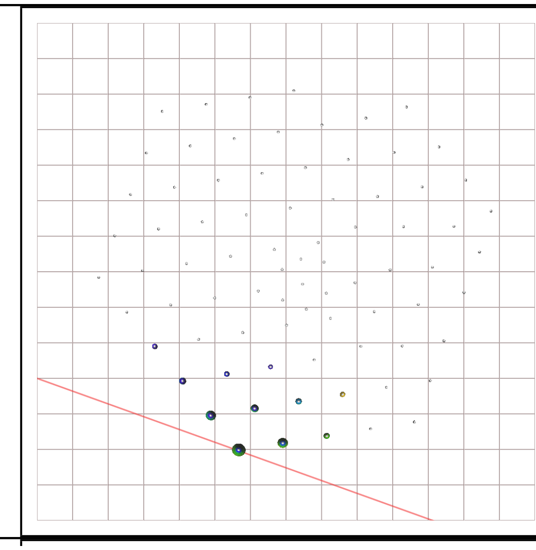


From muEx energy proxy to best fit neutrino spectrum

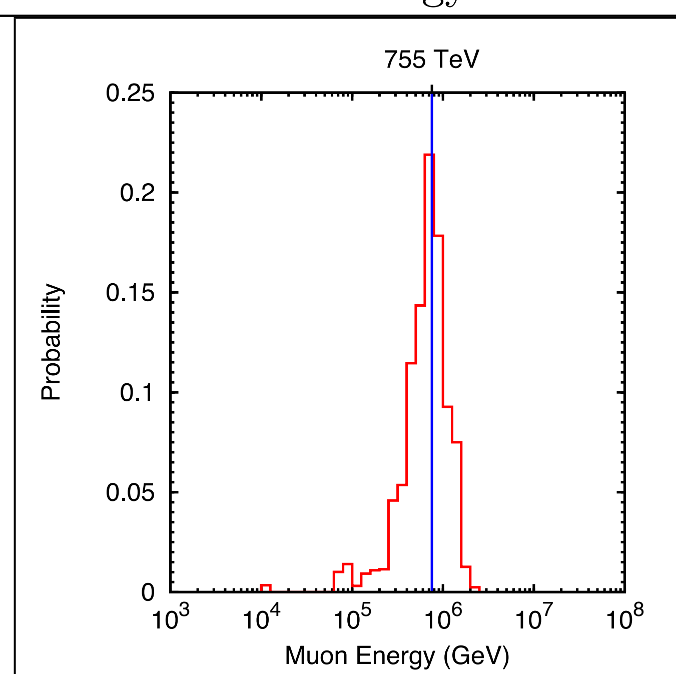
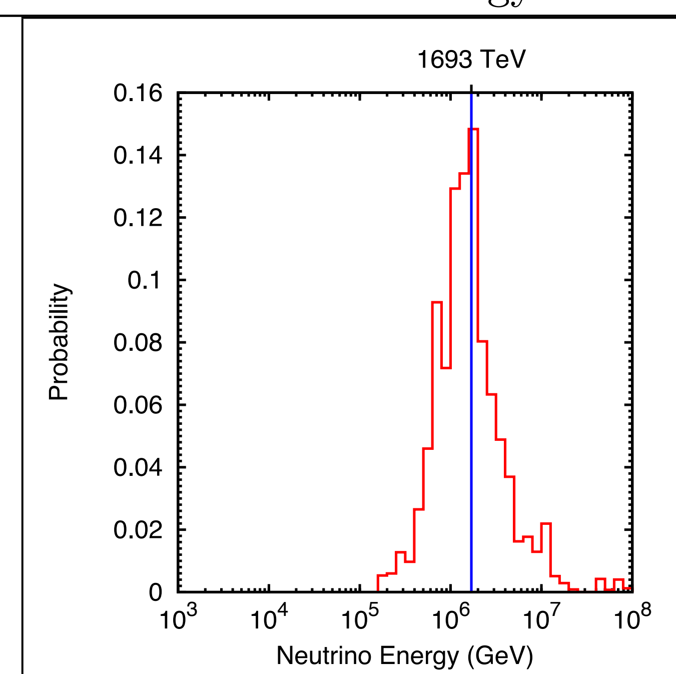


Point source analyses uses the
energy term/weight routinely
when constructing the likelihood function:
A coincidence of 2 events of 100 TeV is a signal.
A coincidence of 20 1 TeV events is still background

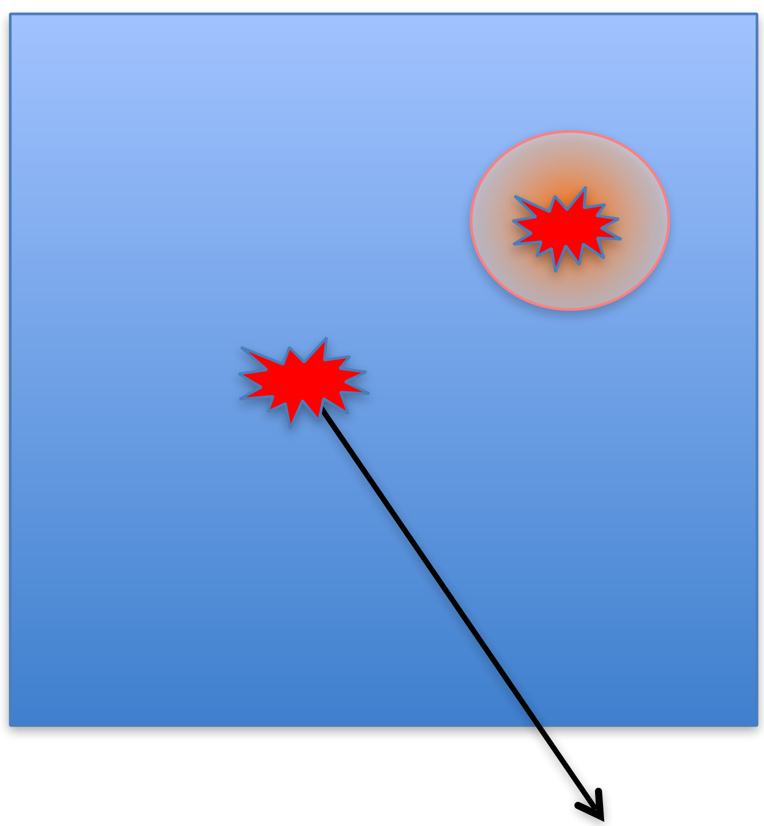
From muEx energy proxy to best fit neutrino spectrum

Name	Side view	Top View	Energy Proxy Zenith Angle (Comments)
Dr. Heinrich Faust			290.1 TeV 106.3°

The inferred energy of the muon and the neutrino depends on the assumed (best fit) neutrino spectrum
Can only make a probabilistic statement about neutrino energy of muon.

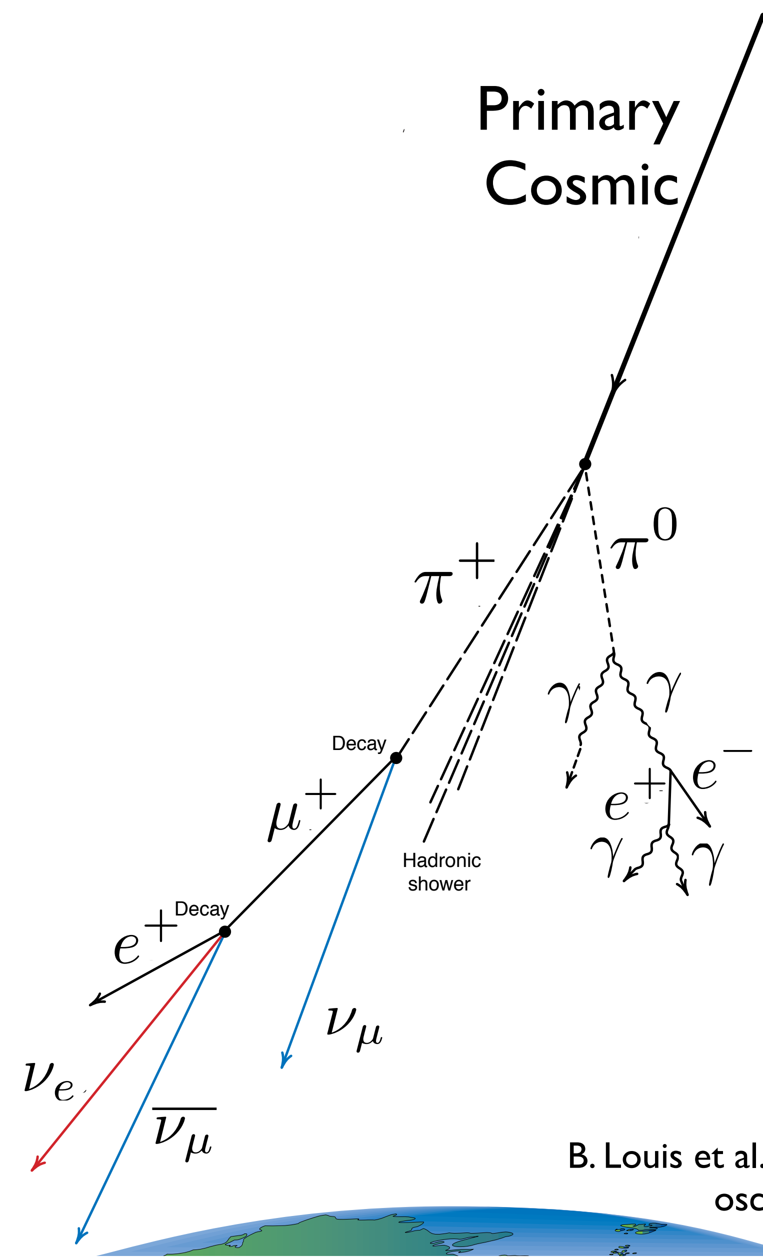
Name	Probable muon energy	Probable neutrino energy
Dr. Heinrich Faust		

Events with contained vertex - starting muons and showers



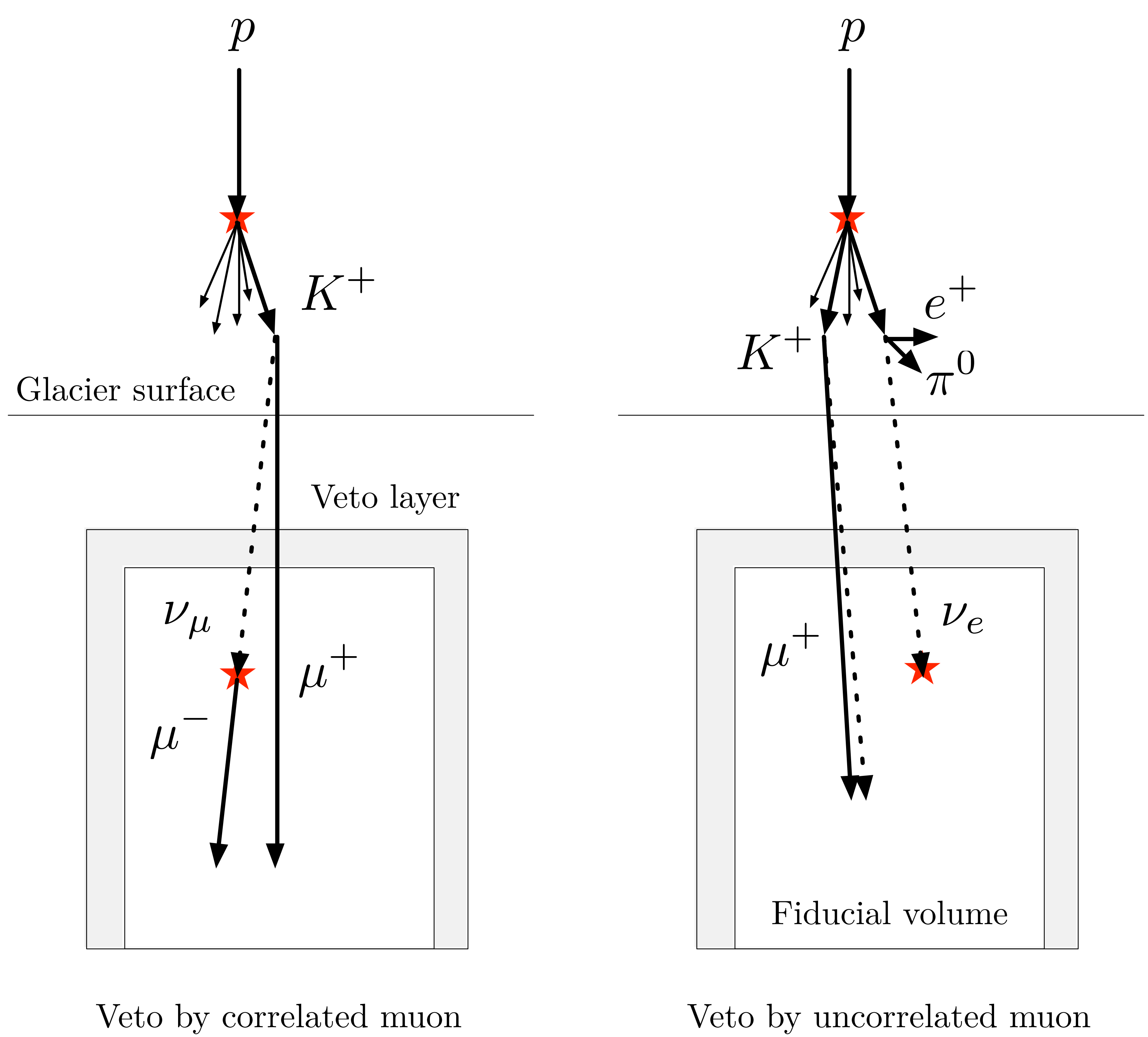
Neutrino self veto –
Background free neutrino astronomy?

- “Atmospheric neutrinos” are generated in cosmic ray air showers.
- Above some neutrino energy, ~100 TeV, these neutrinos will likely be accompanied by one or more muons from parent air shower.
- Those muons can be used to veto atmospheric neutrino background.



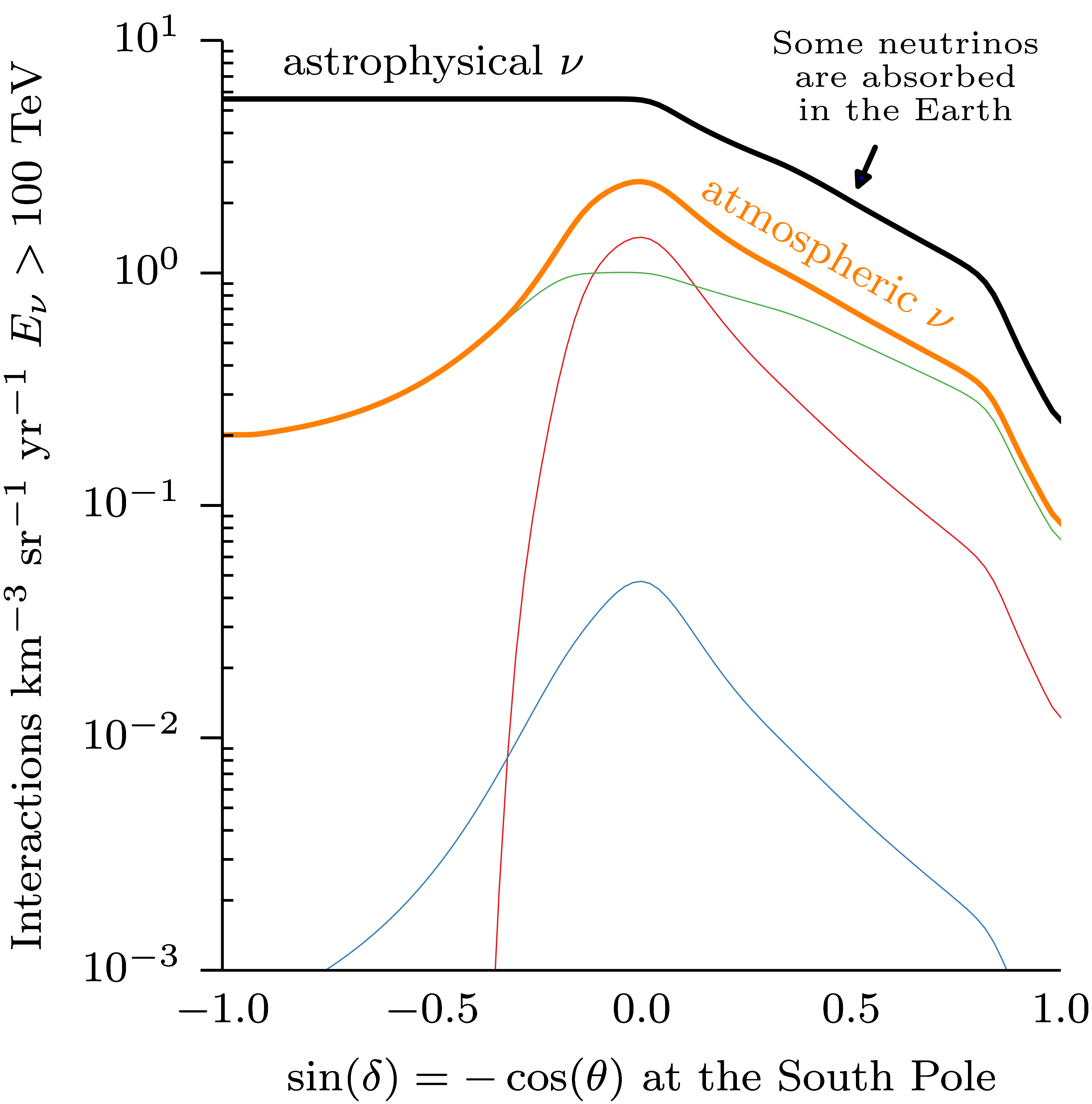
B. Louis et al.,“The evidence for oscillations,”

The atmospheric neutrino self-veto



Muons and any energetic neutrinos travel close to each other, typically within <10 m.

Atmospheric neutrino self-veto



The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

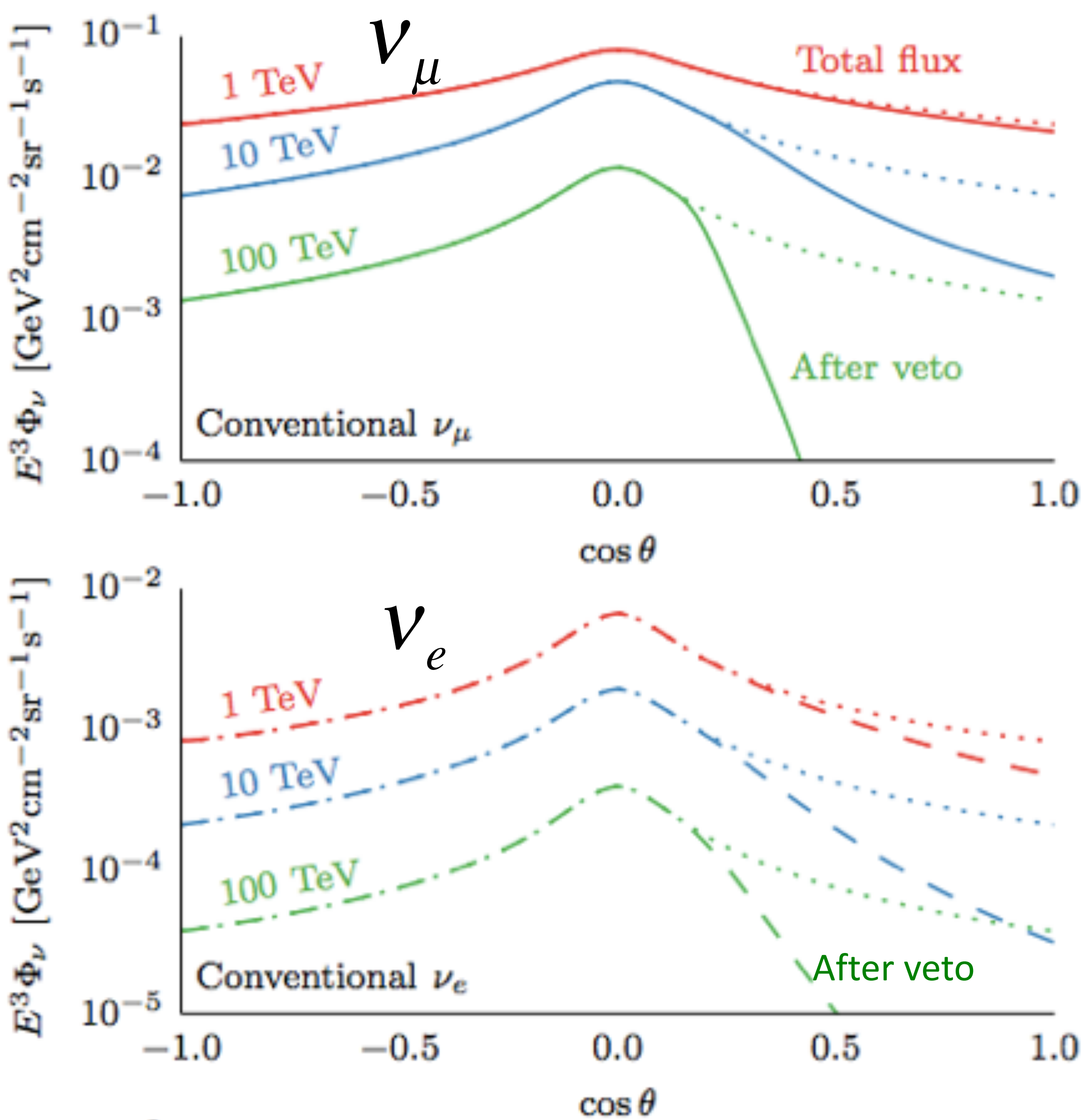
Schönert, Resconi, Schulz, Phys. Rev. D, **79**:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, **90**:023009 (2014)

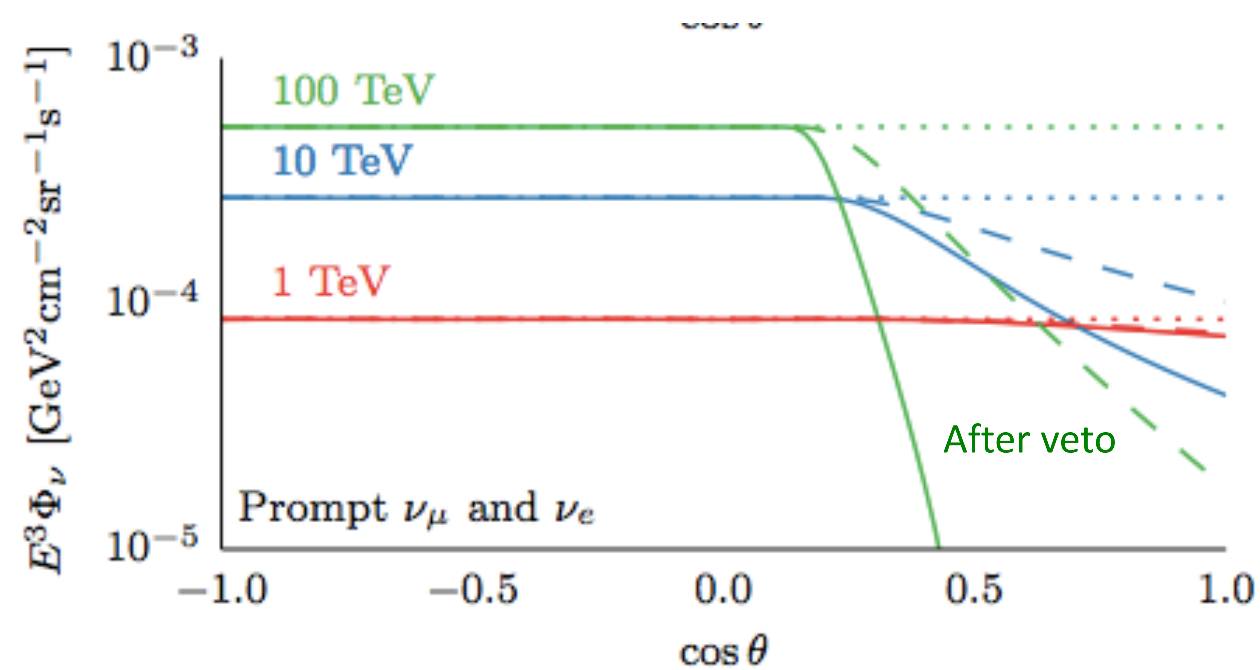
Neutrino self-veto

Based on full simulation

Conventional

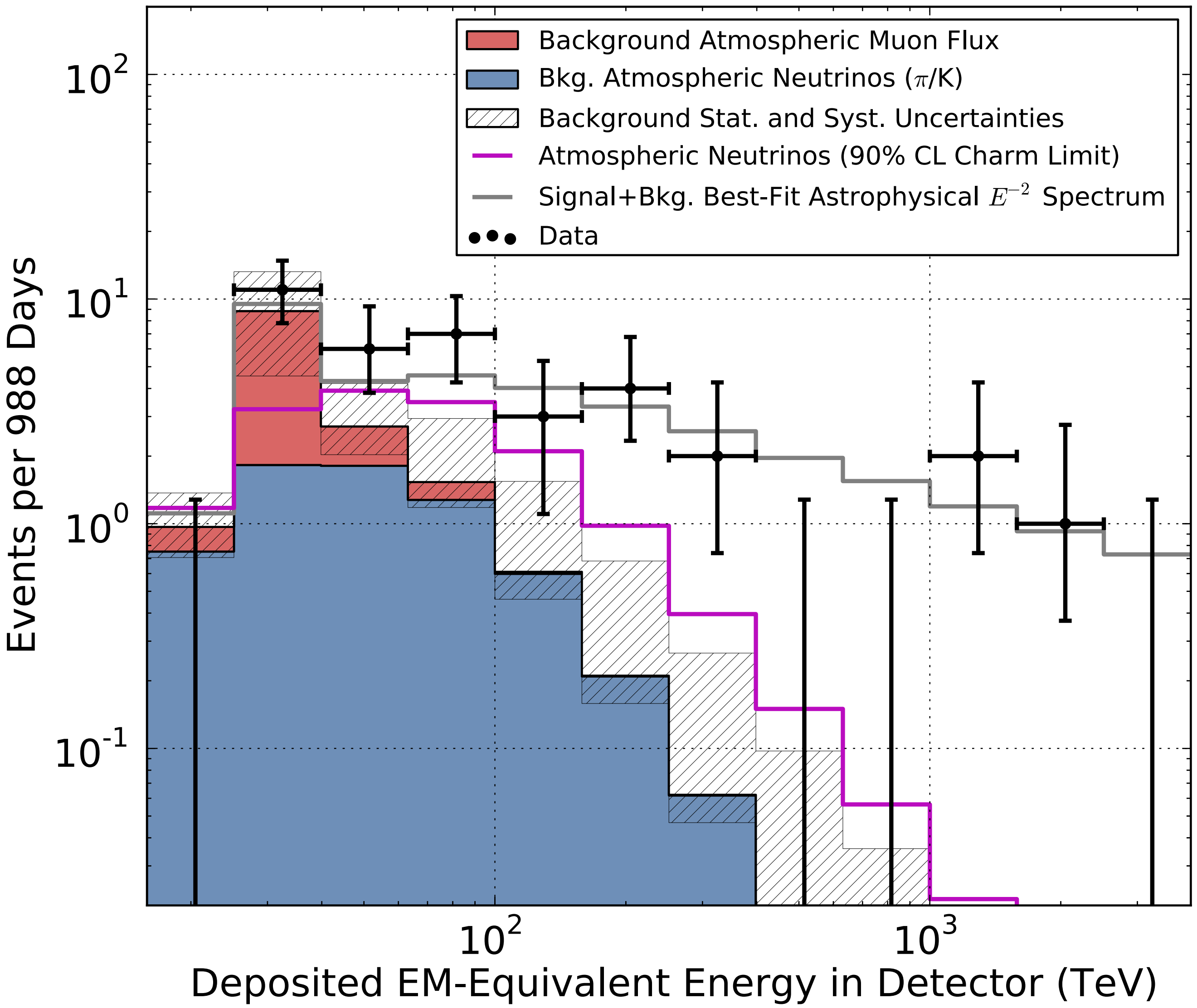


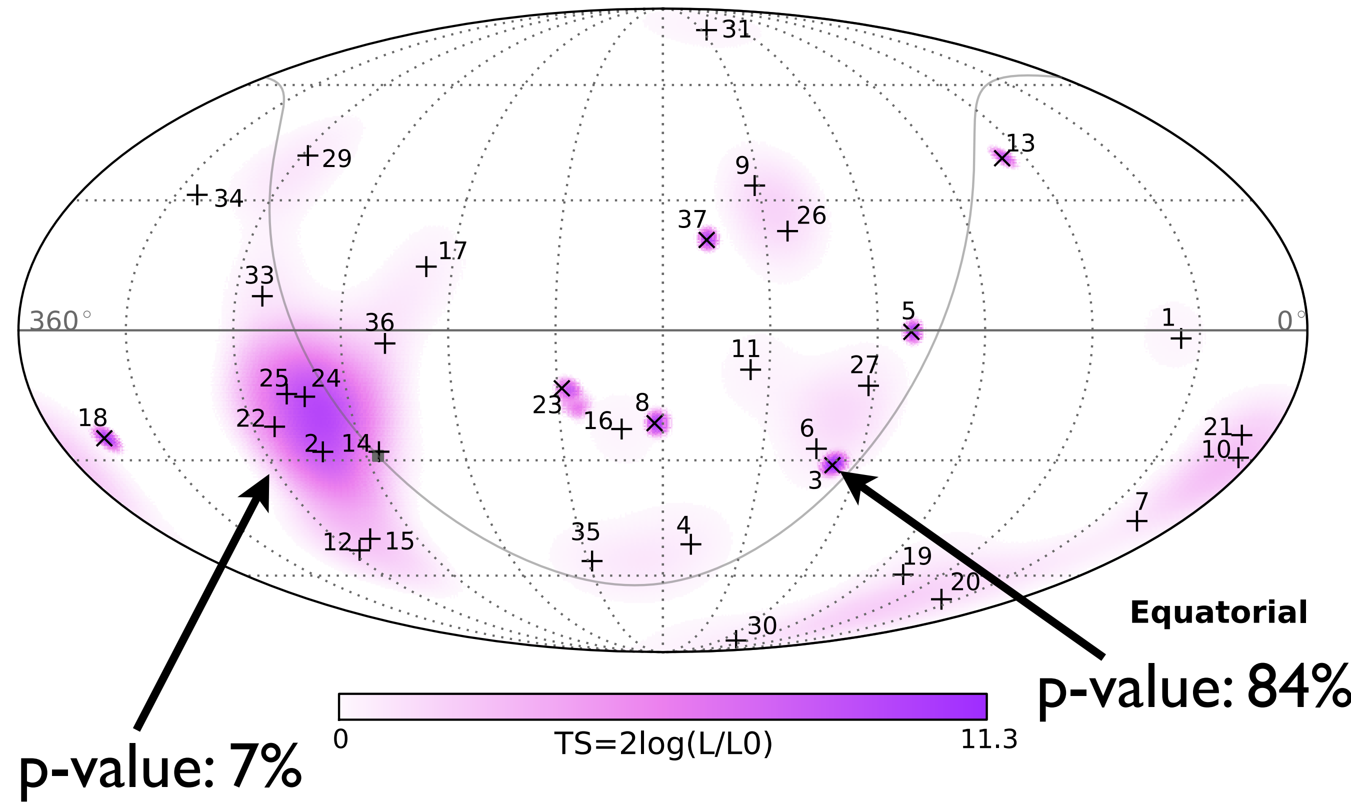
Prompt ν_μ and ν_e



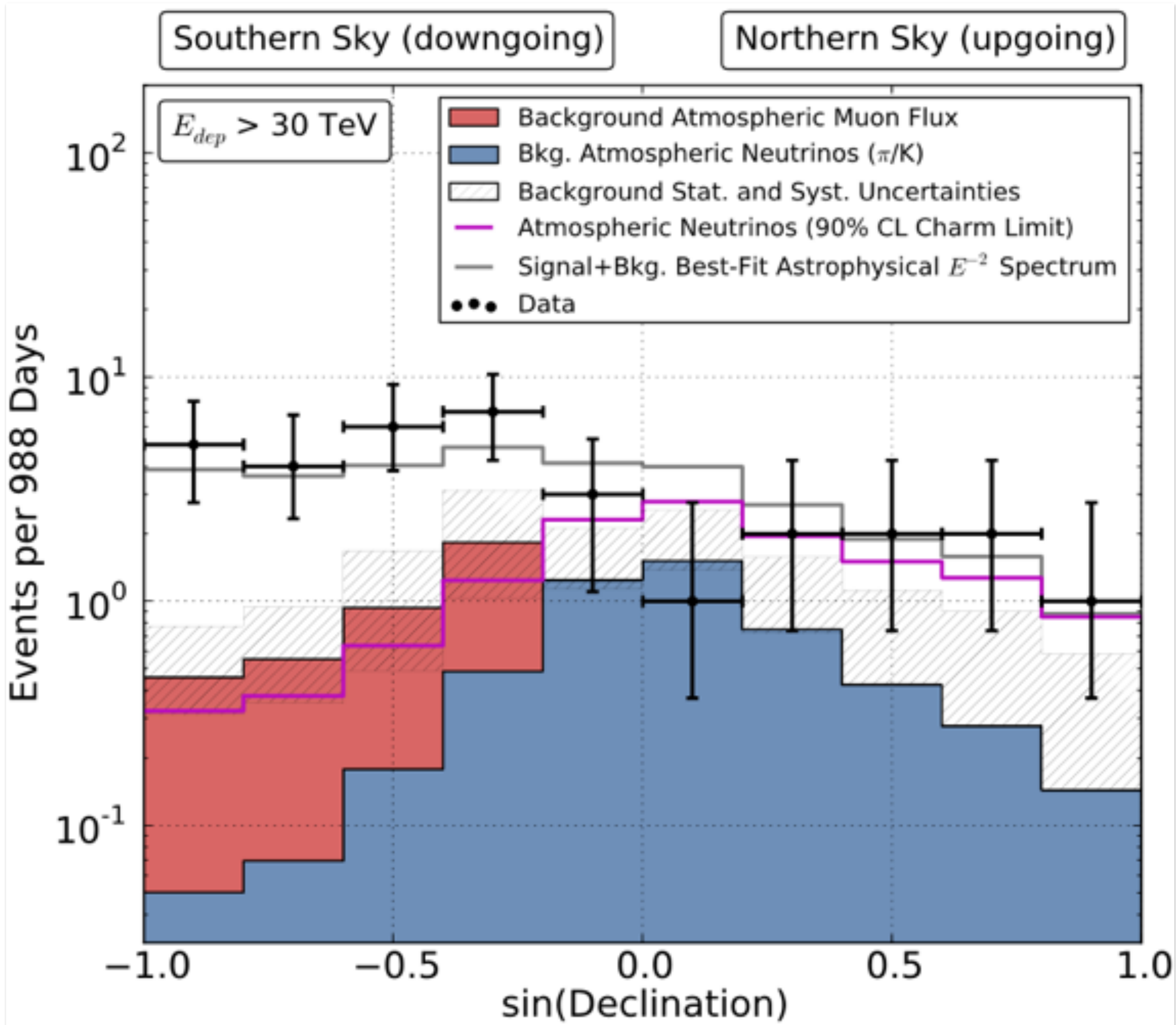
Atmospheric neutrino flux obtained by applying full atmospheric veto to the atmospheric neutrino flux.
(Earth attenuation above 100 TeV is not shown)

All-Flavor, All-Sky with Starting Events

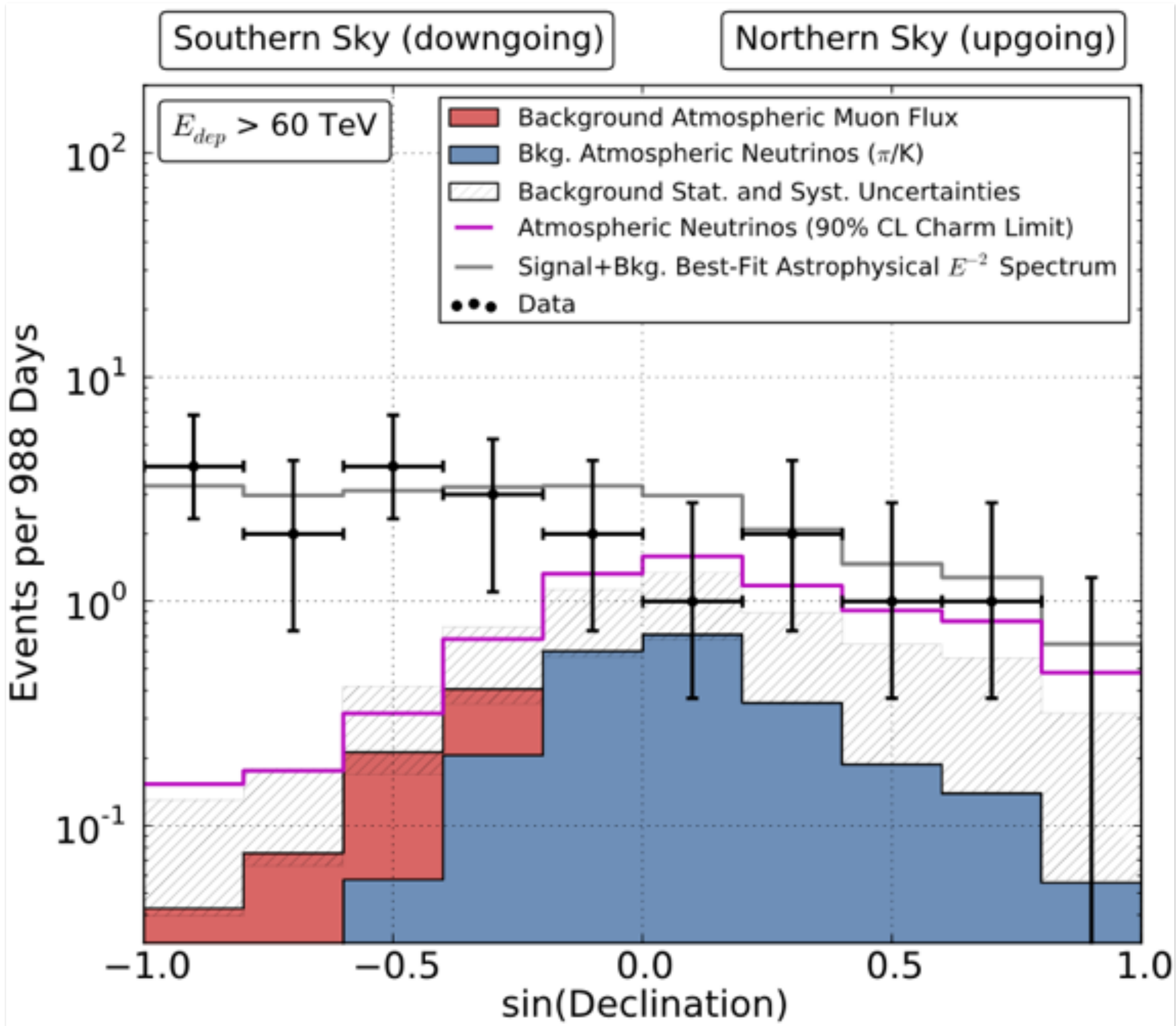




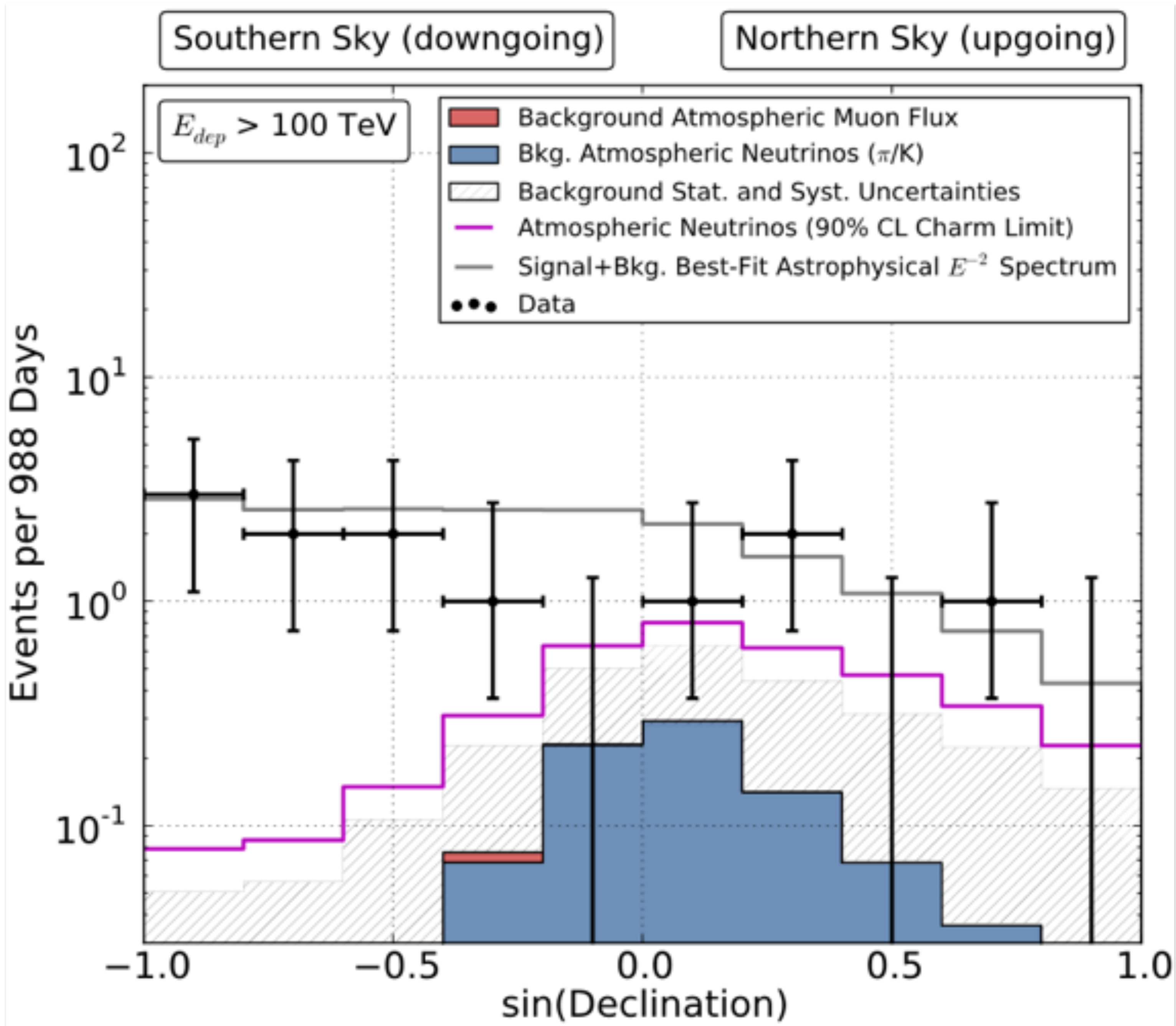
- Phys. Rev. Lett. 113, 101101: Analysis of starting events depositing >60 TeV or more using 3 years of data, observes events up to ~2 PeV
- Mostly ν_e charged current and neutral current interactions, mostly sensitive in the southern sky
- Clear excess over background (5.7σ), no clear clustering on the sky



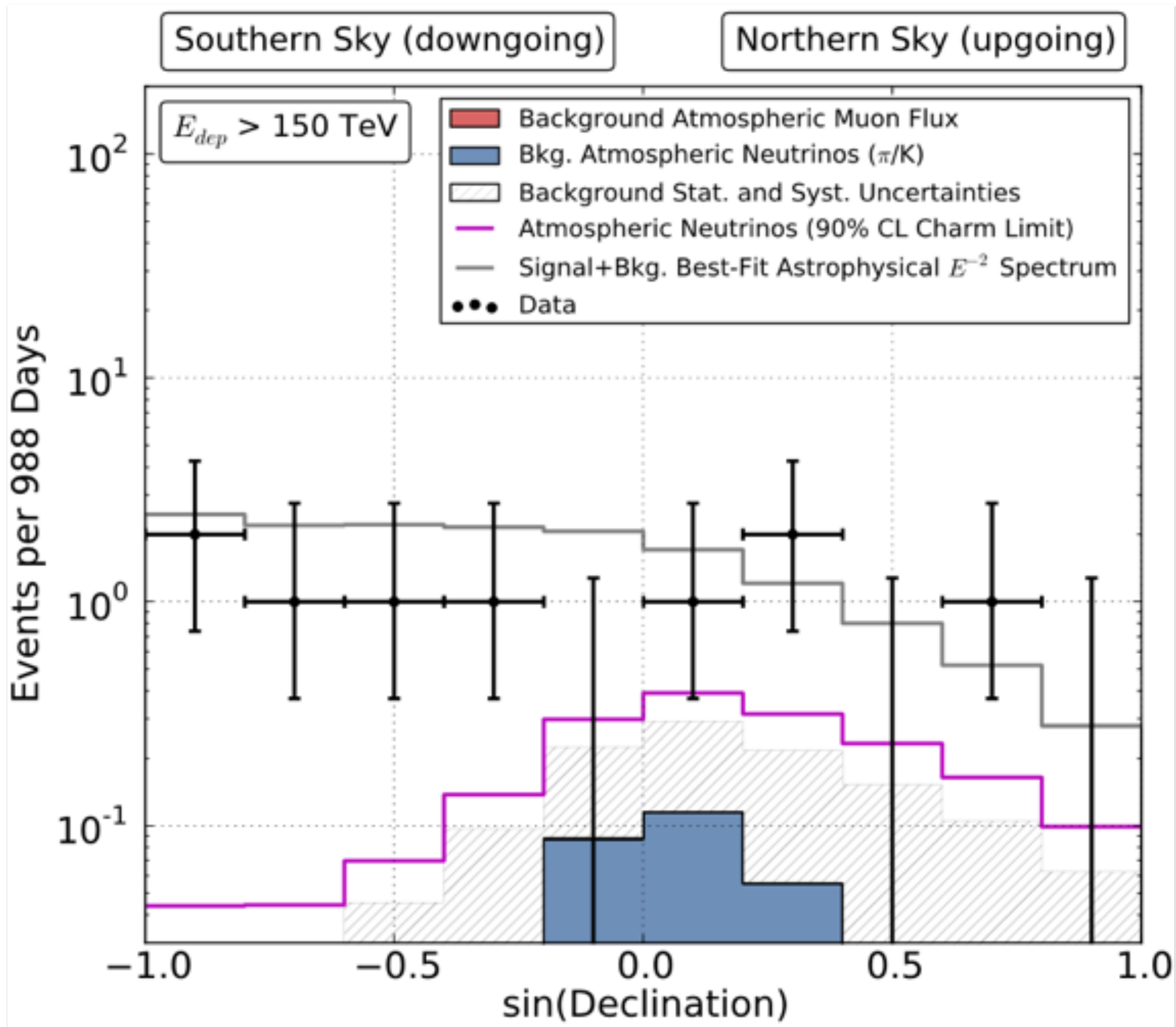
Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 30 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
sin(Declination)



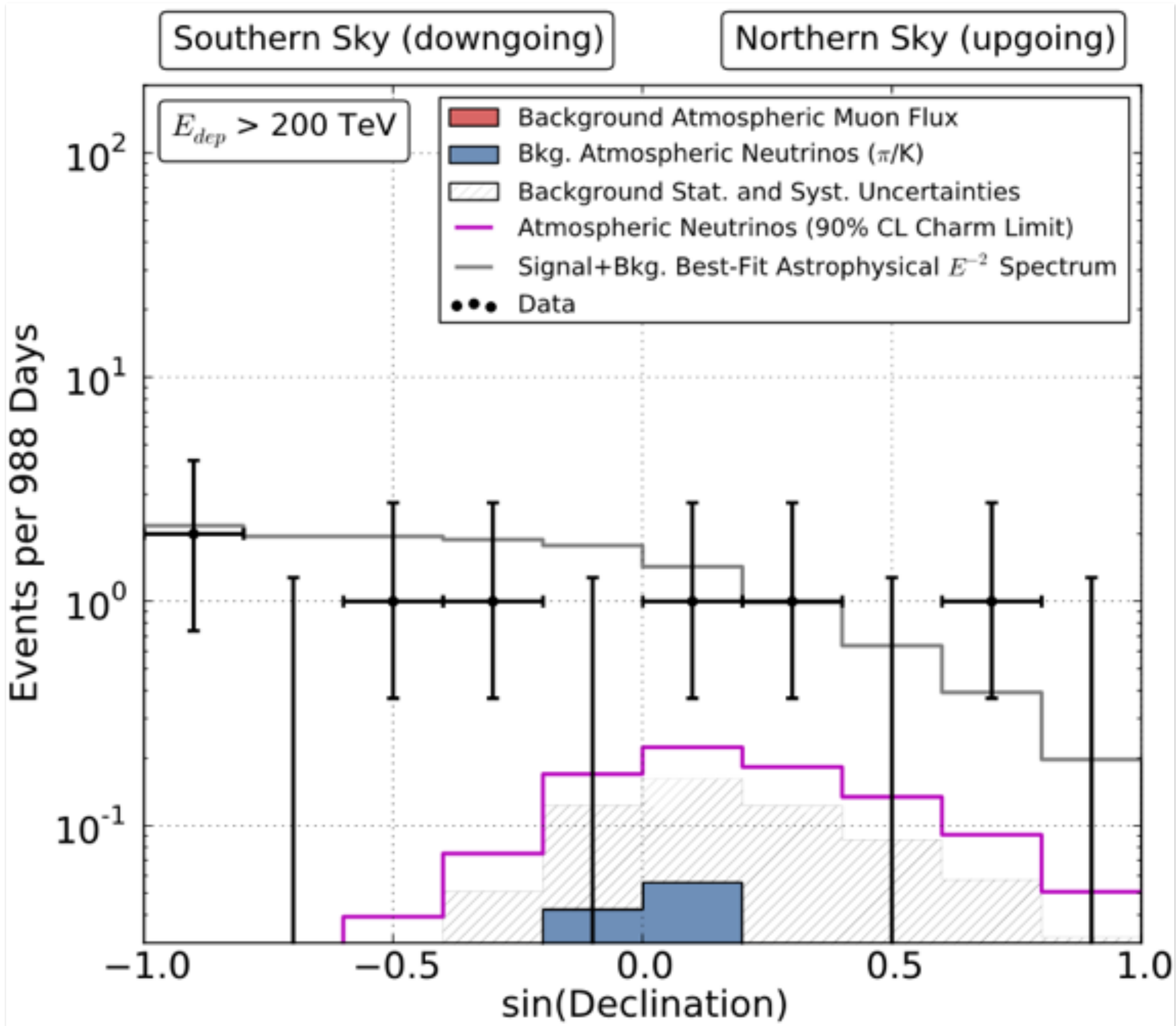
Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 60 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)



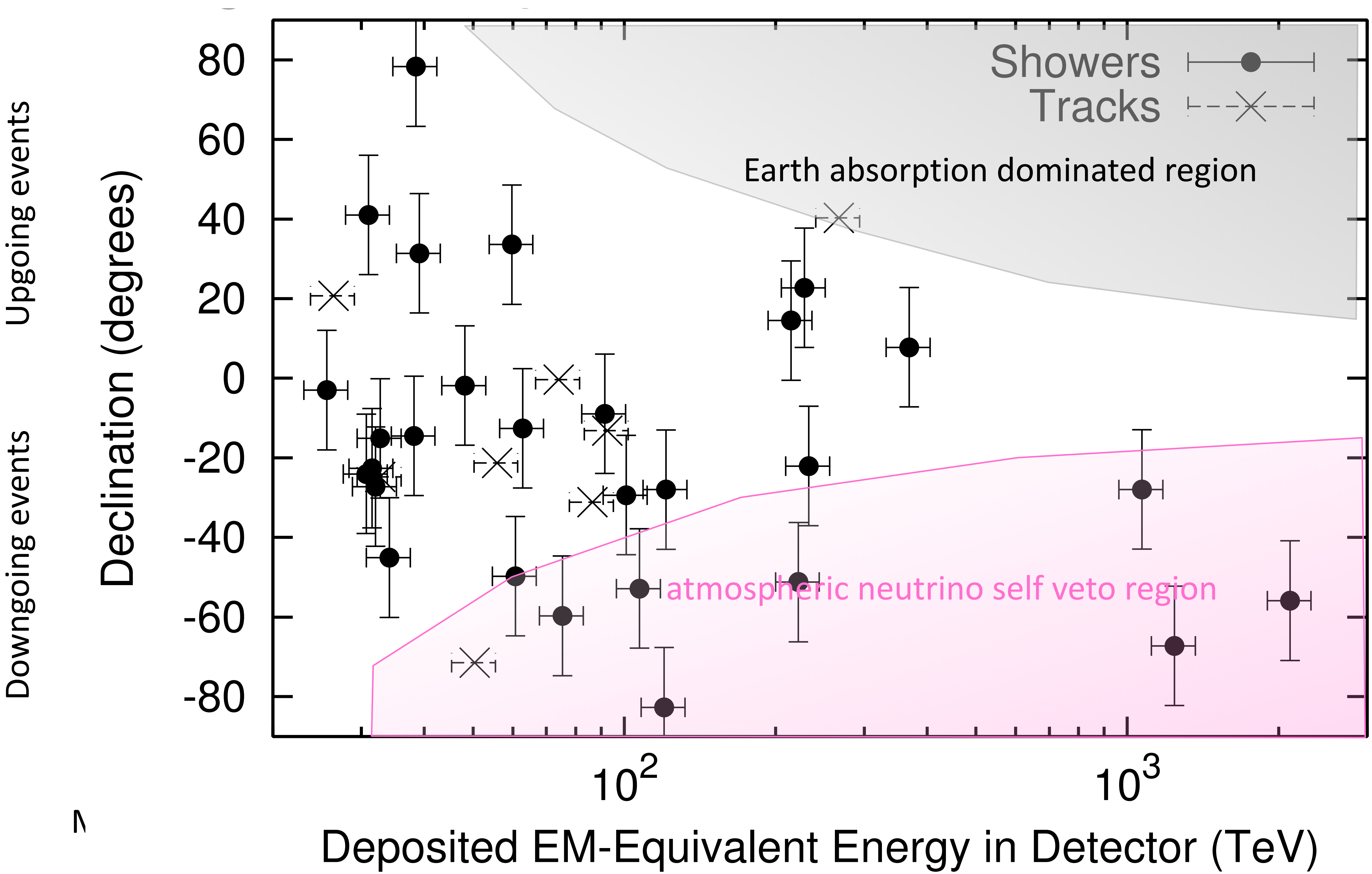
Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 100 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)



Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 150 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

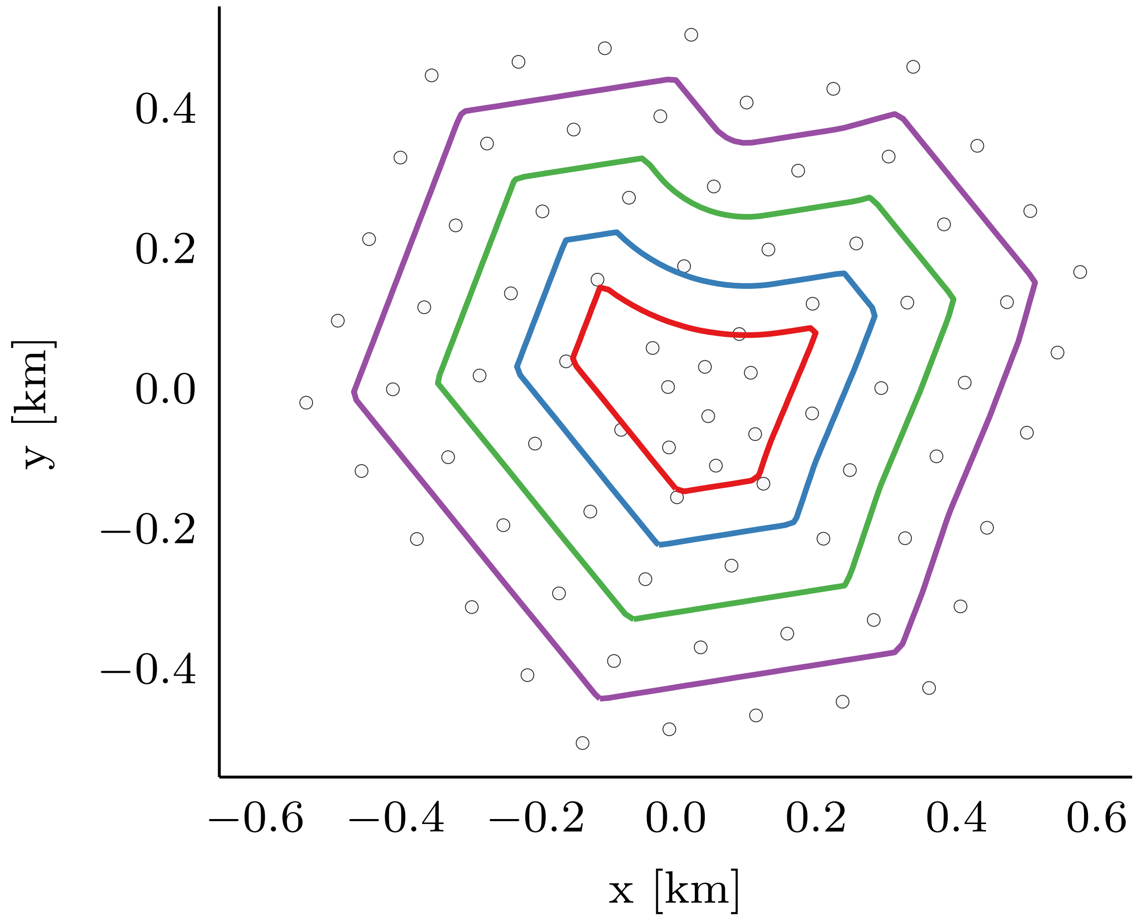

Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 200 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

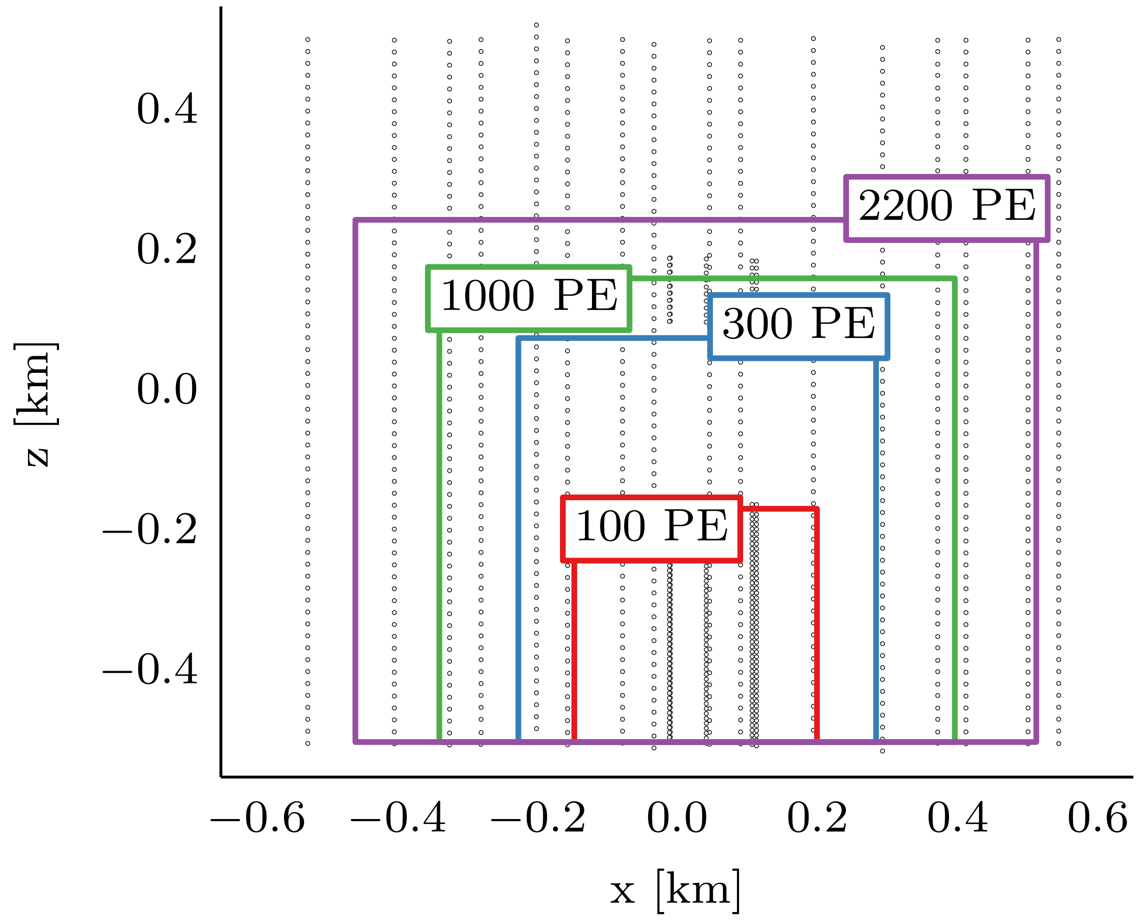
Back to IceCube HESE (High enrgy starting events): Declination vs energy



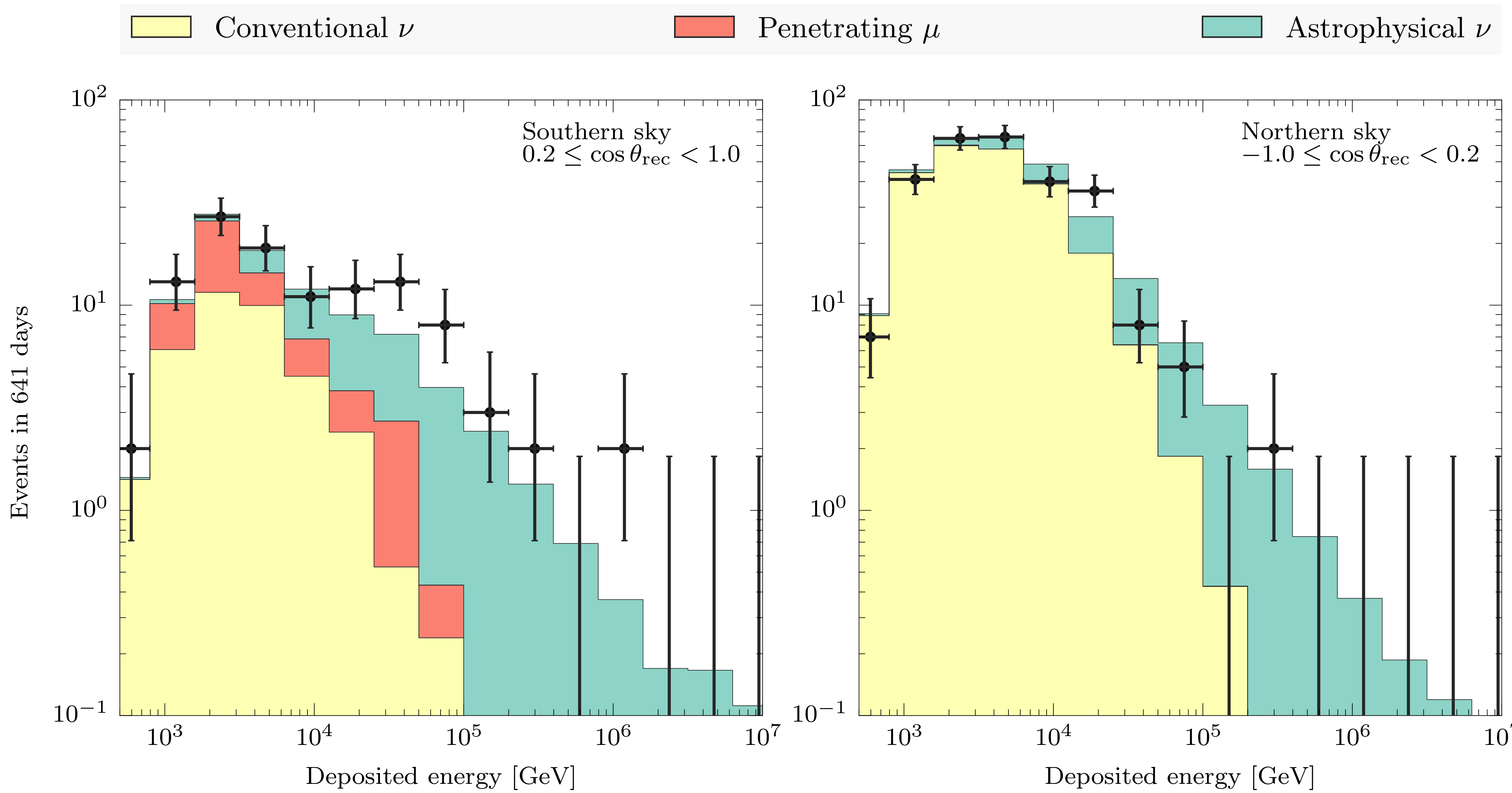
Most events in Southern hemisphere (downgoing).

Energy dependent veto-layers



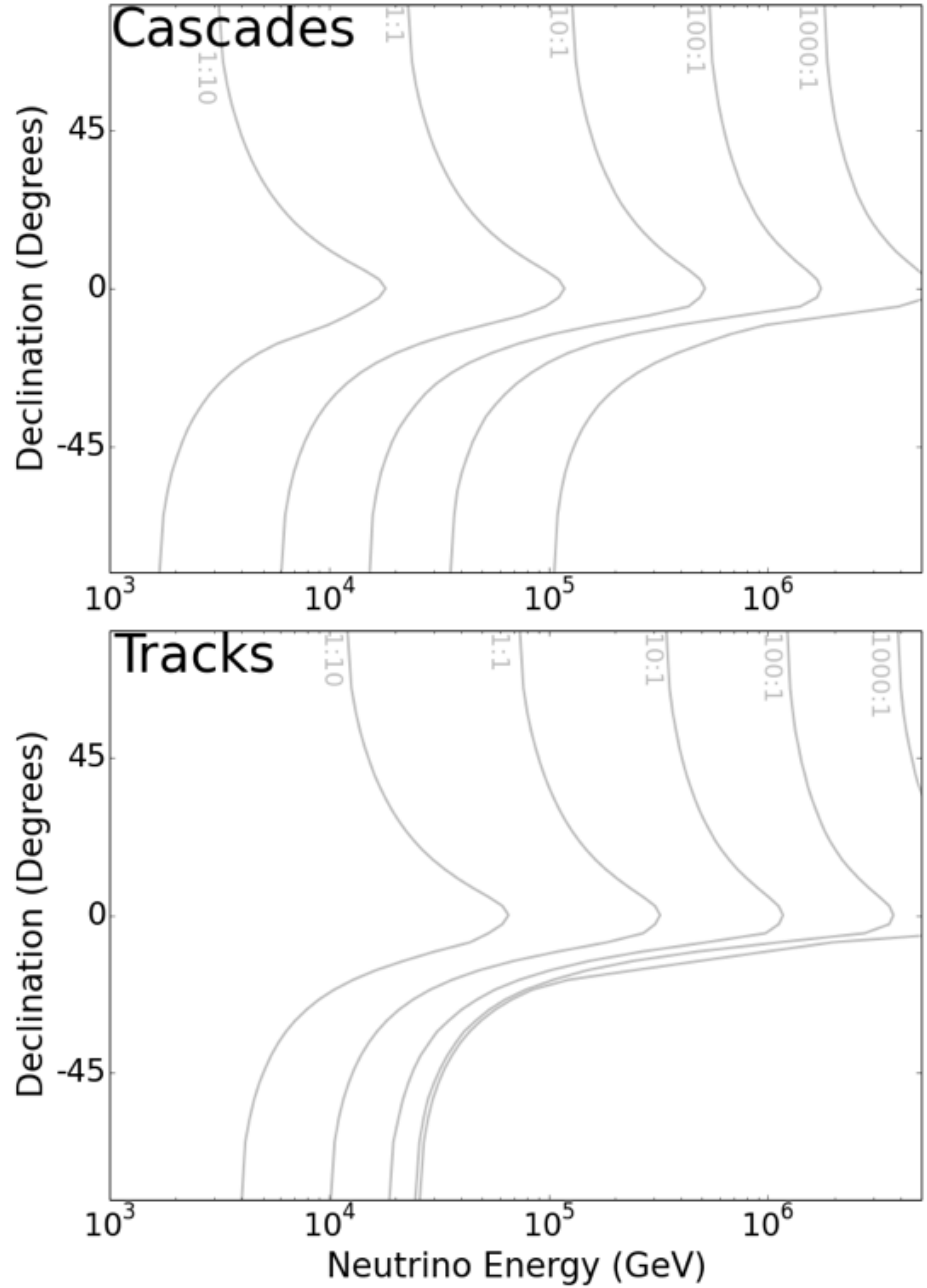


All-Flavor, All-Sky with Starting Events



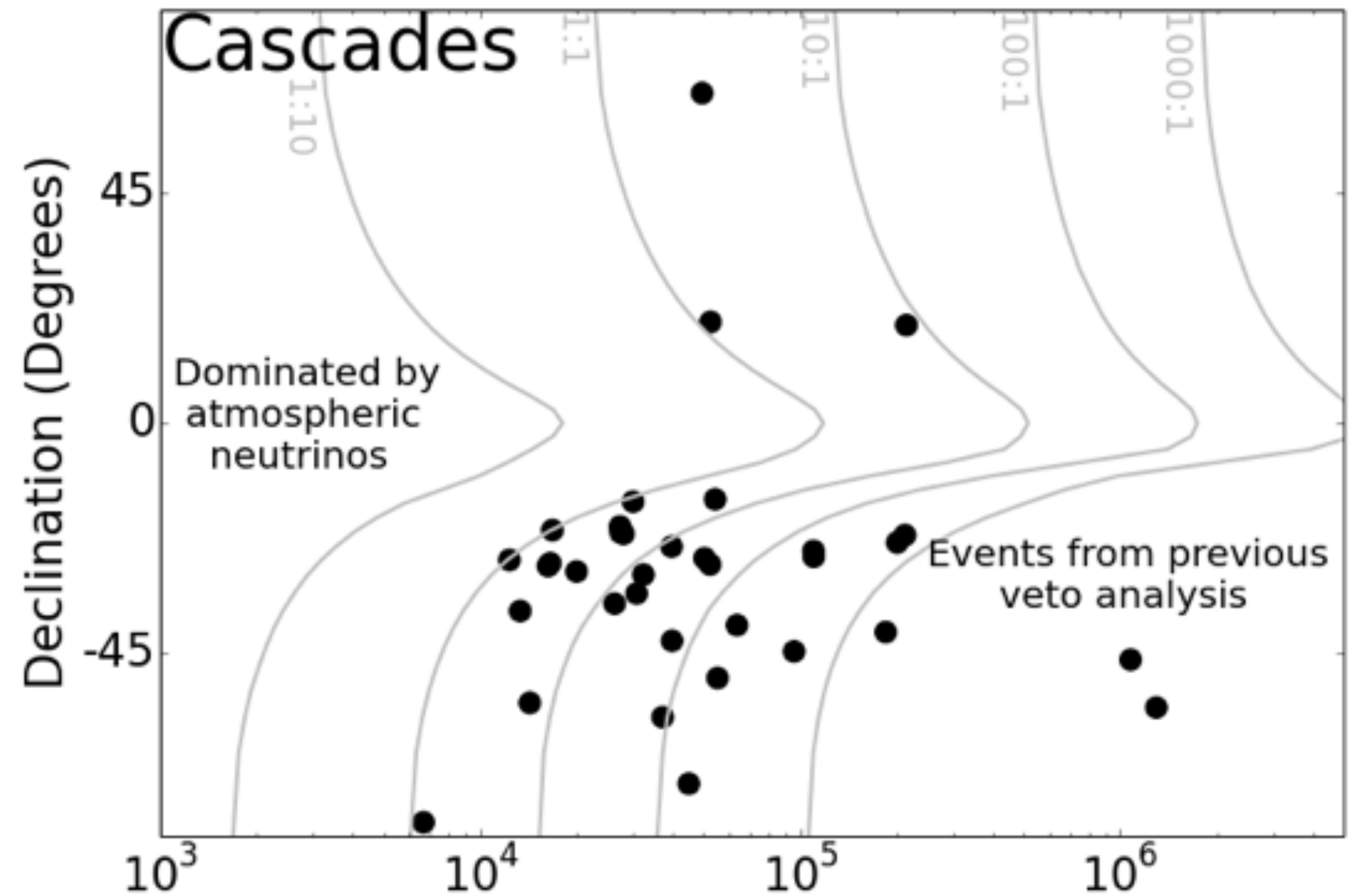
- Phys. Rev. D 91, 022001: Extends analysis of starting events down to ~1 TeV, using 2 years of data
- Astrophysical spectrum seems to continue down to a few TeV

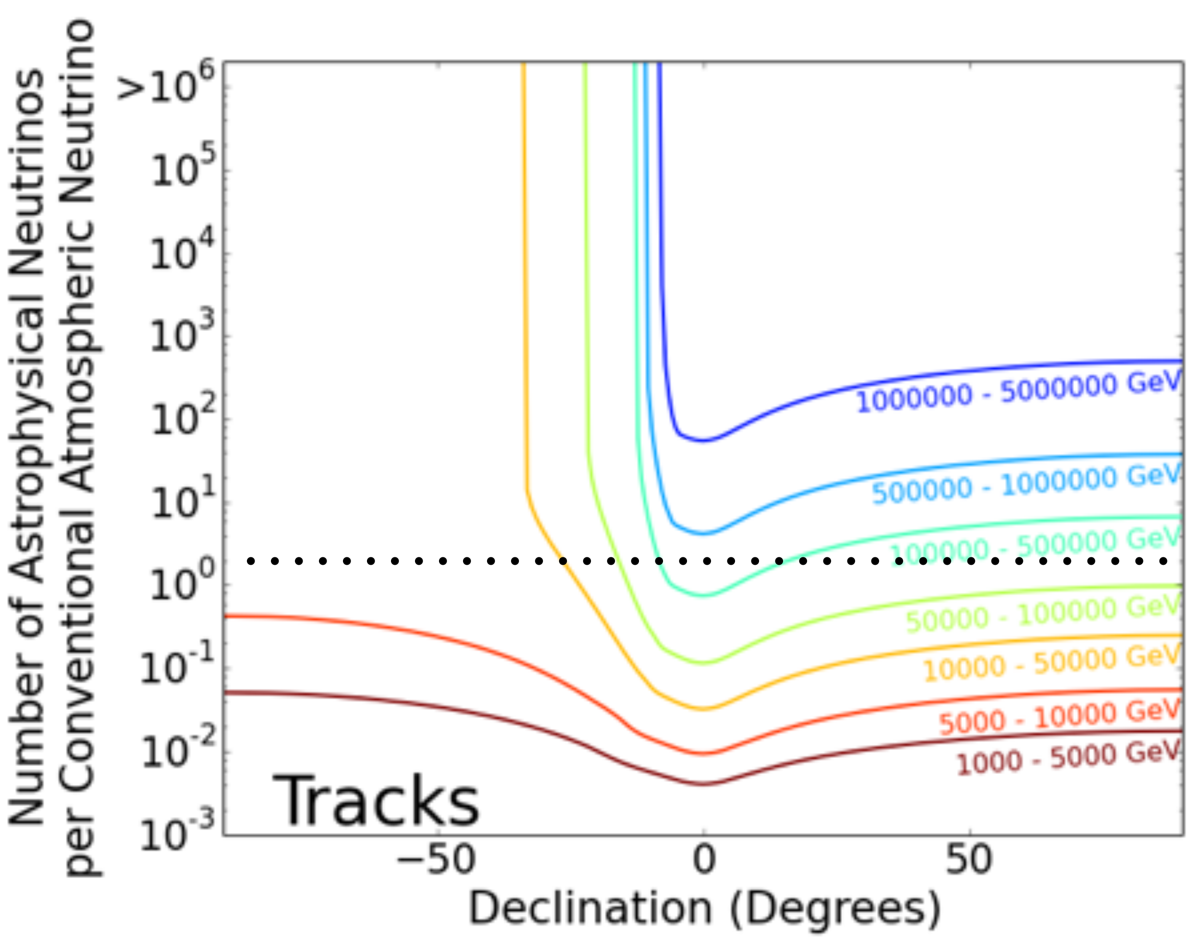
Neutrino self-veto

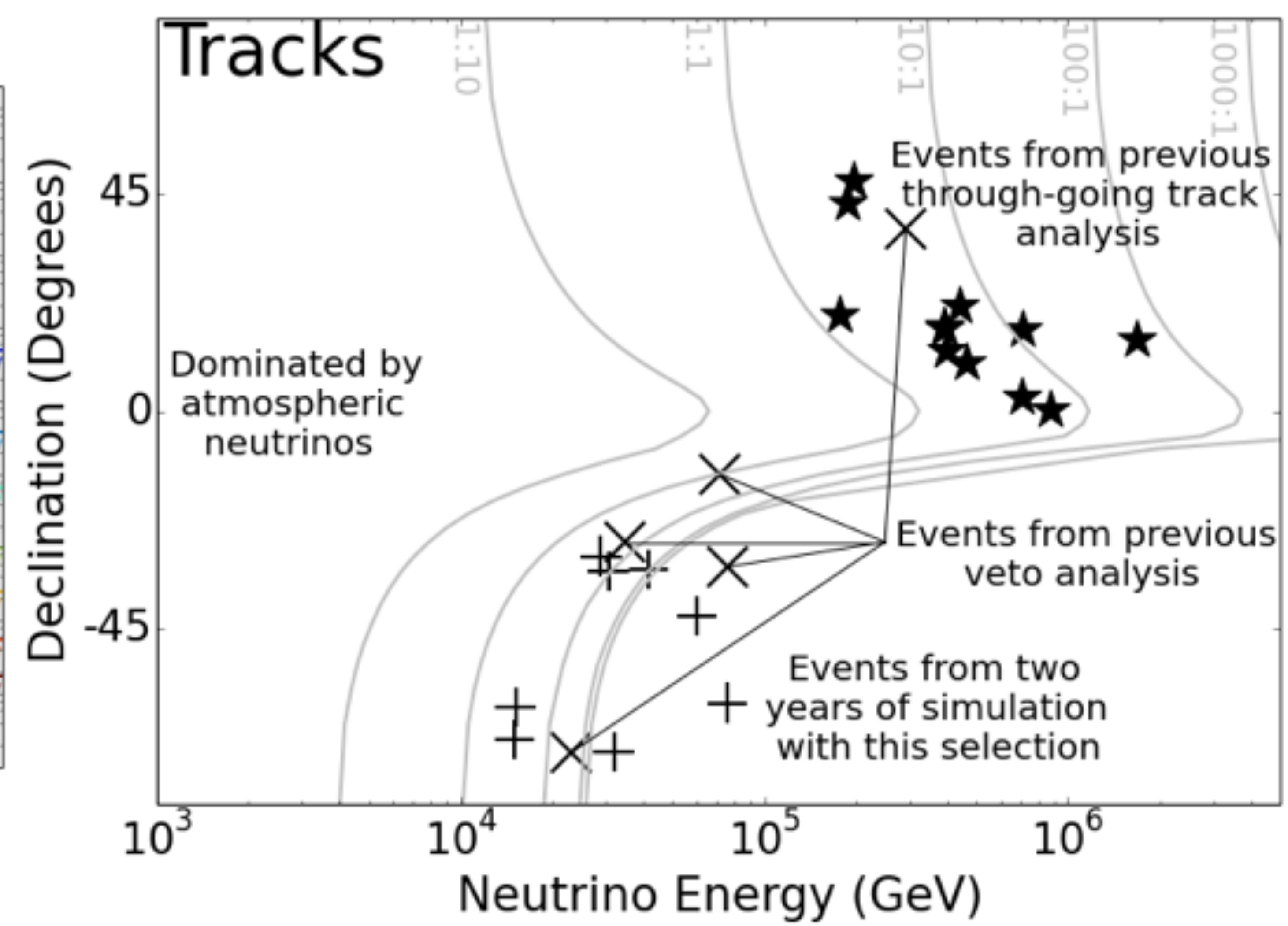


Neutrino self-veto

Kyle Jero -> Neutrino conference poster



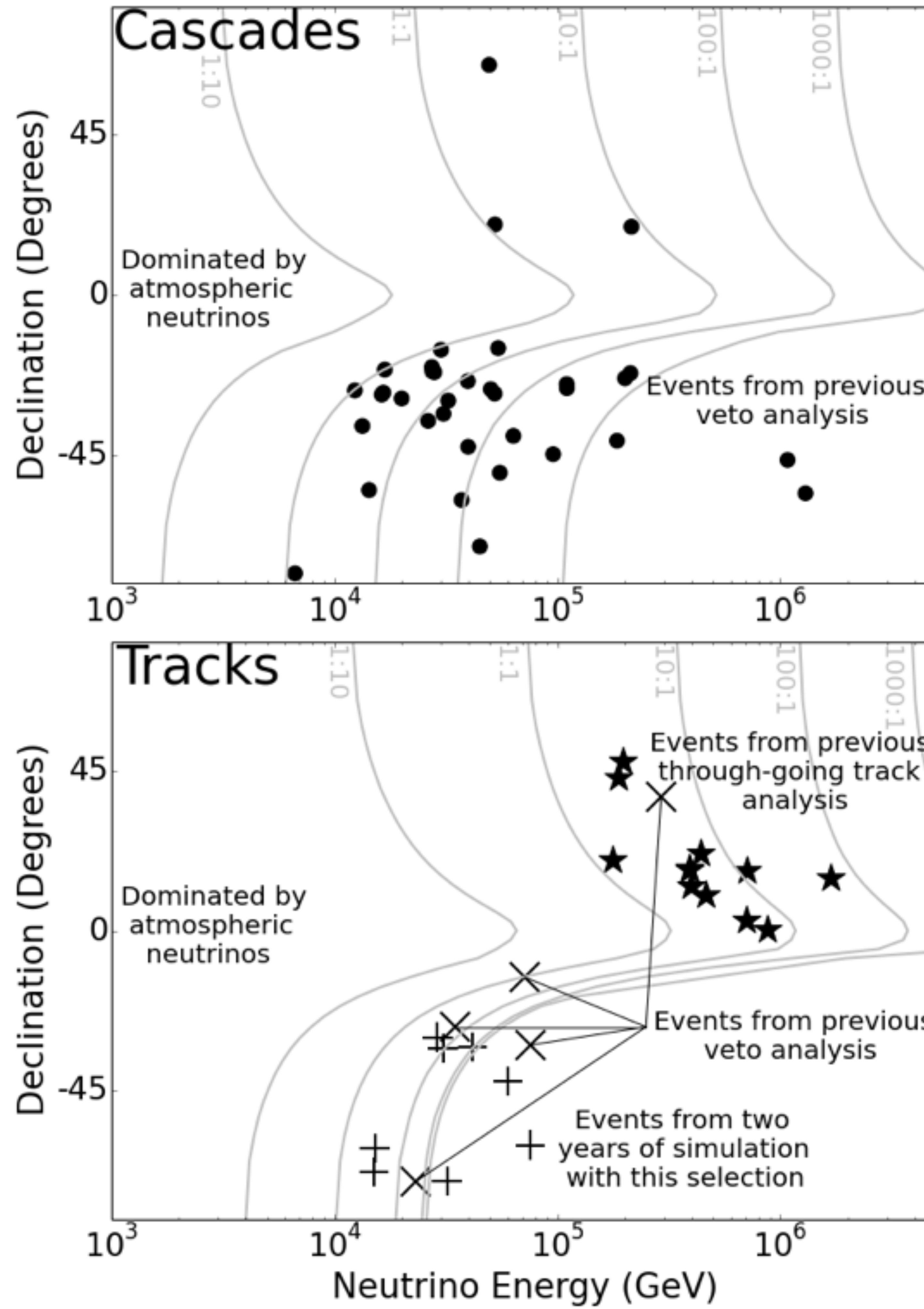




Neutrino self-veto

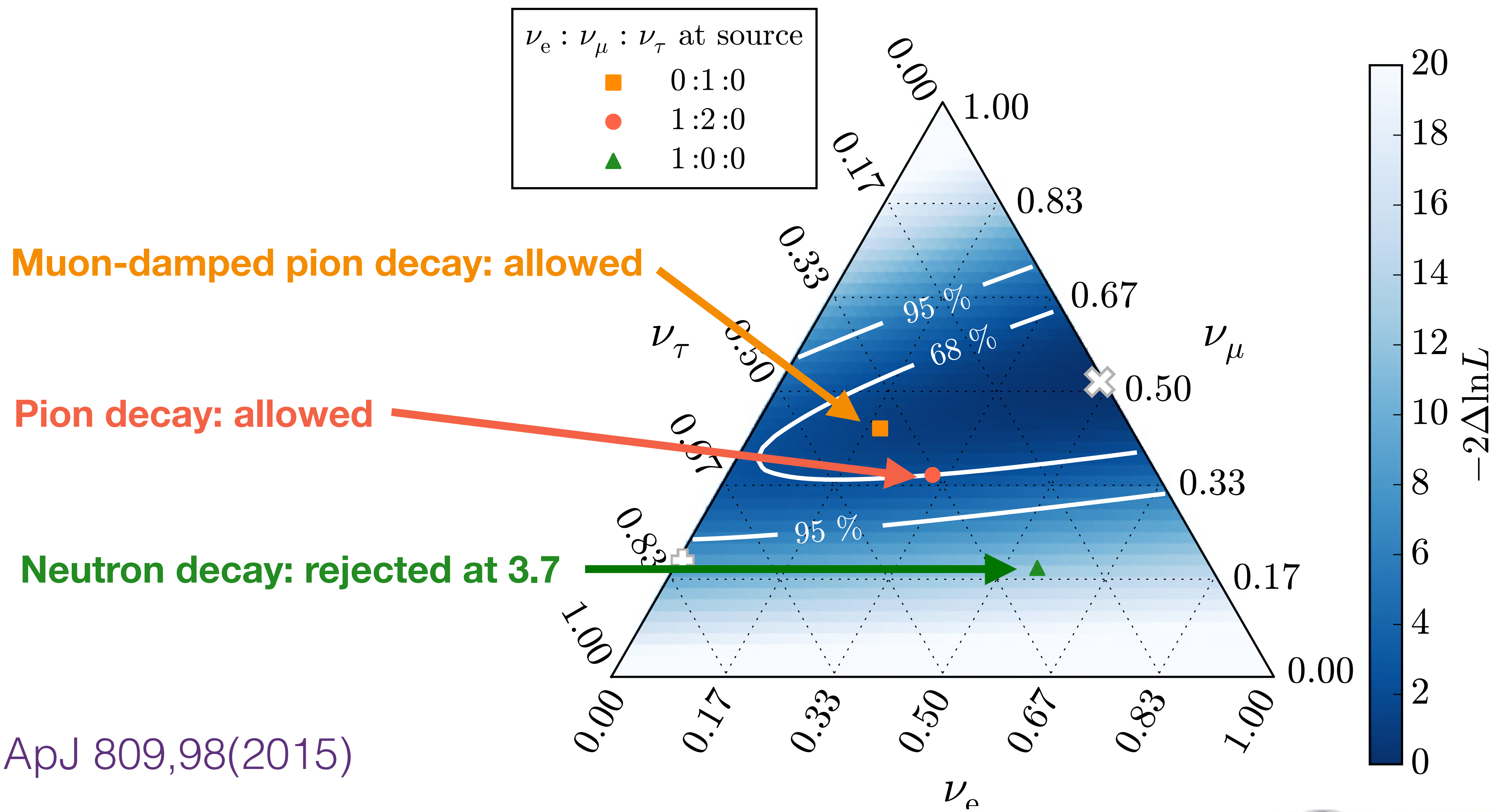
Astronomy in Southern sky increasingly competitive:

- Galactic plane, stacking
- lower energy
- access to flavor ratio at the same energy range



Questions?

Improved muon selections will allow for more precise measurement of astrophysical only muon flux and cascade flux in the same energy range.



ApJ 809,98(2015)