Statistical Issues in High Energy Neutrino Searches with IceCube

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For PhysStat-Nu Fermilab 2016

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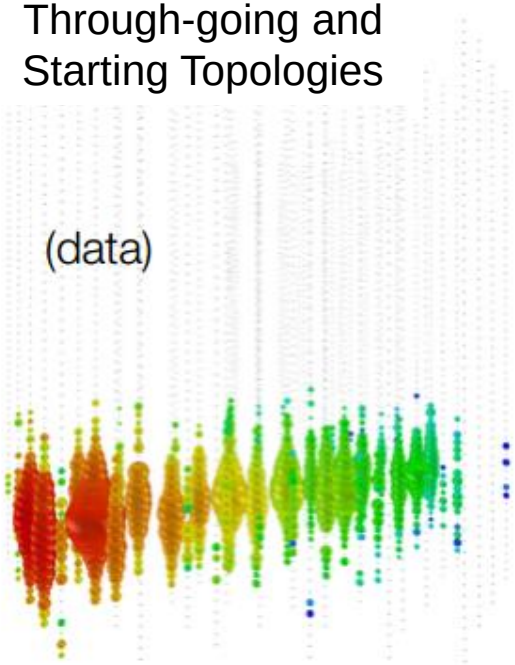
Event Topologies

Charged-current ν_μ

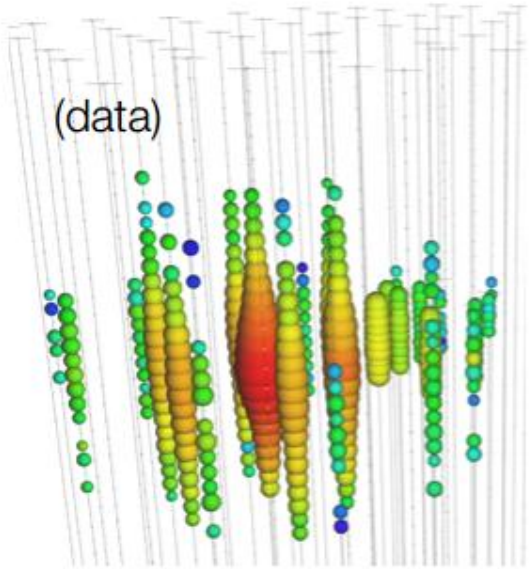
Through-going and
Starting Topologies



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

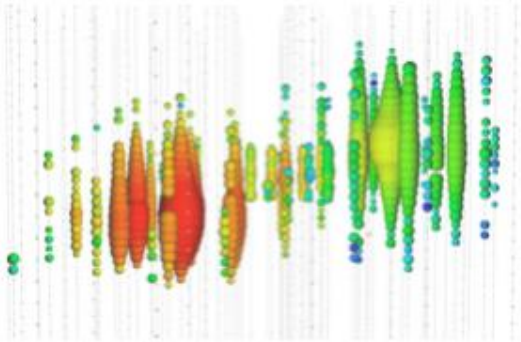
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

Charged-current ν_τ



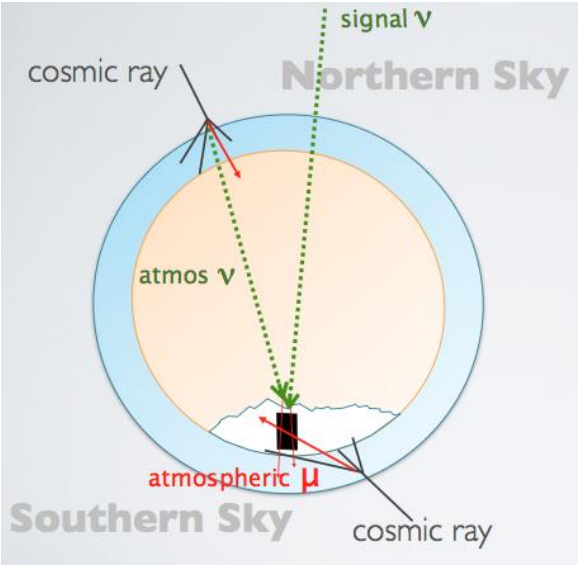
"Double-bang"

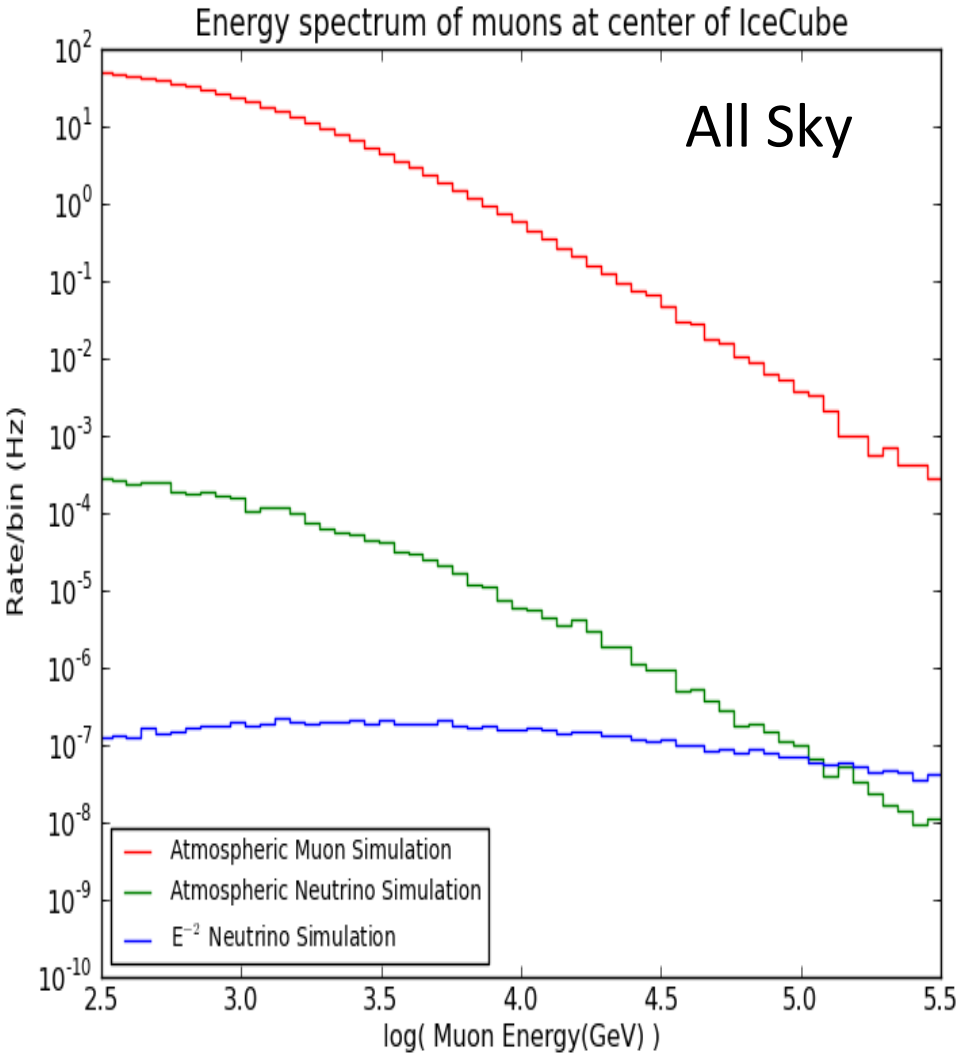
(none observed yet: τ decay length is 50 m/PeV)

Early Late

Using the Earth as a Shield

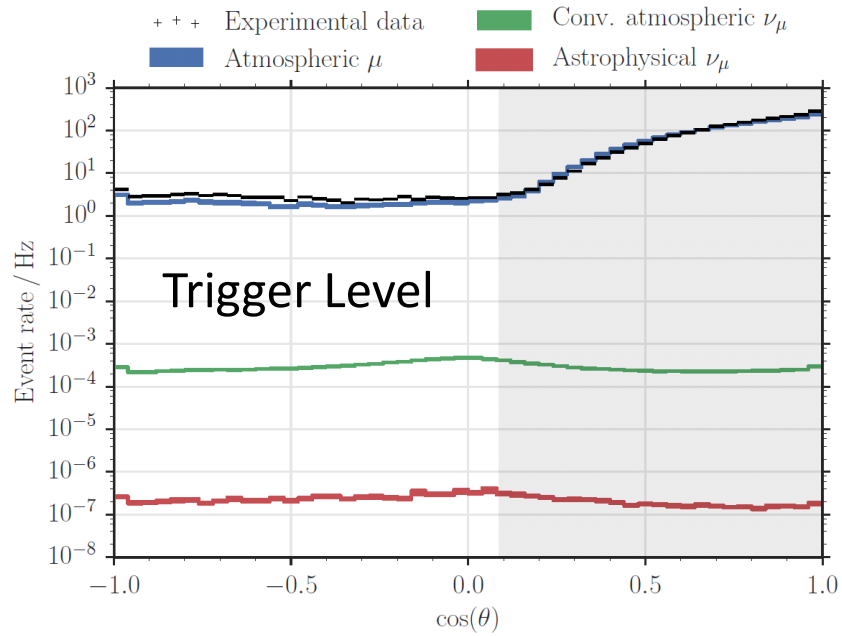
- IceCube is a very good atmospheric muon detector
  - ~200 neutrinos per day vs 10^8 muons per day
- Penetrating muons are stopped by the Earth

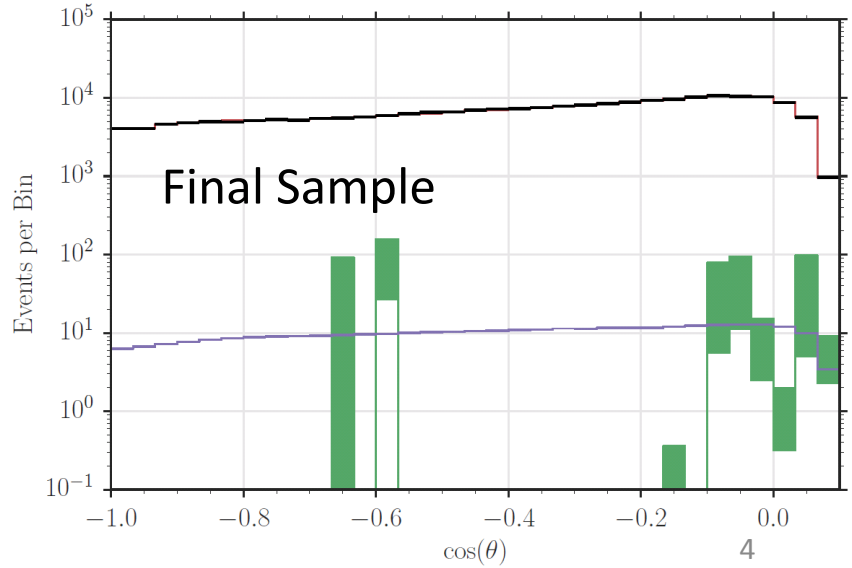




Through-Going Muon Event Selection

- Begin with muon and EHE filters
  - Muon filter: Everything track-like
  - EHE: Everything with > 1000 PE deposited in the detector
- Apply quality cuts on track quantities and reconstructions
- Boosted Decision Tree (Adaboost)
  - Signal: E^{-2} neutrino simulation
  - Background: Atmospheric neutrino simulation
  - Verified with cross validation studies
- Atmospheric muon contribution taken as negligible to the final result
  - Not included in likelihood fit

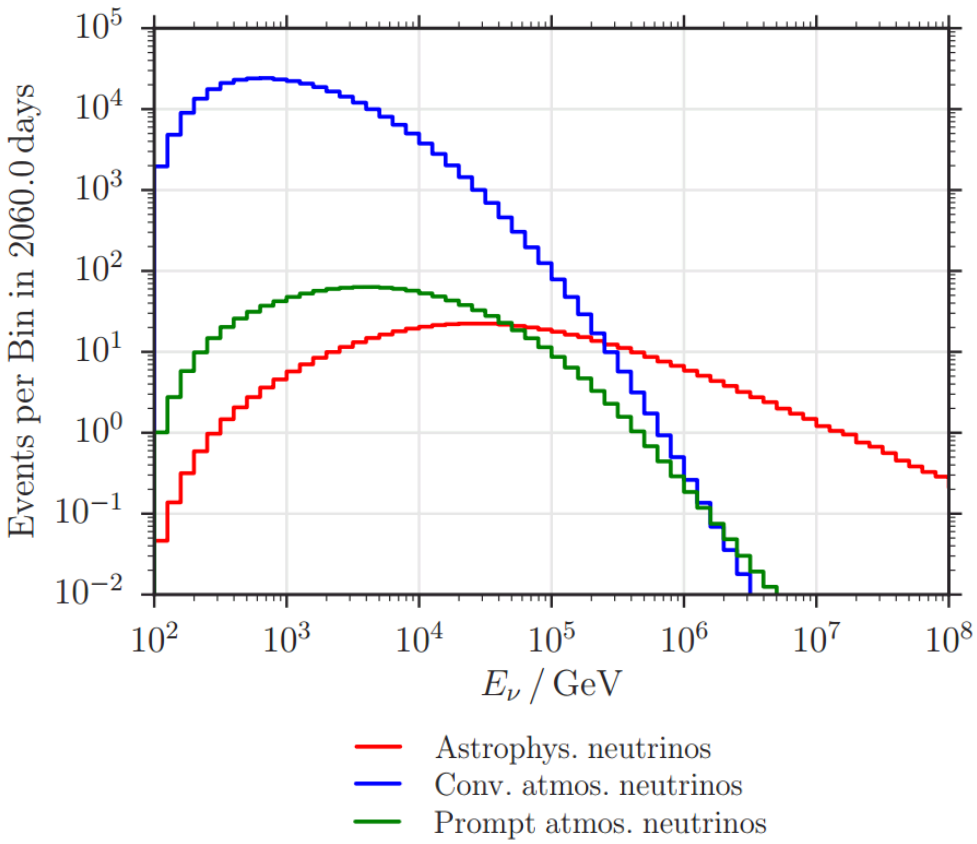


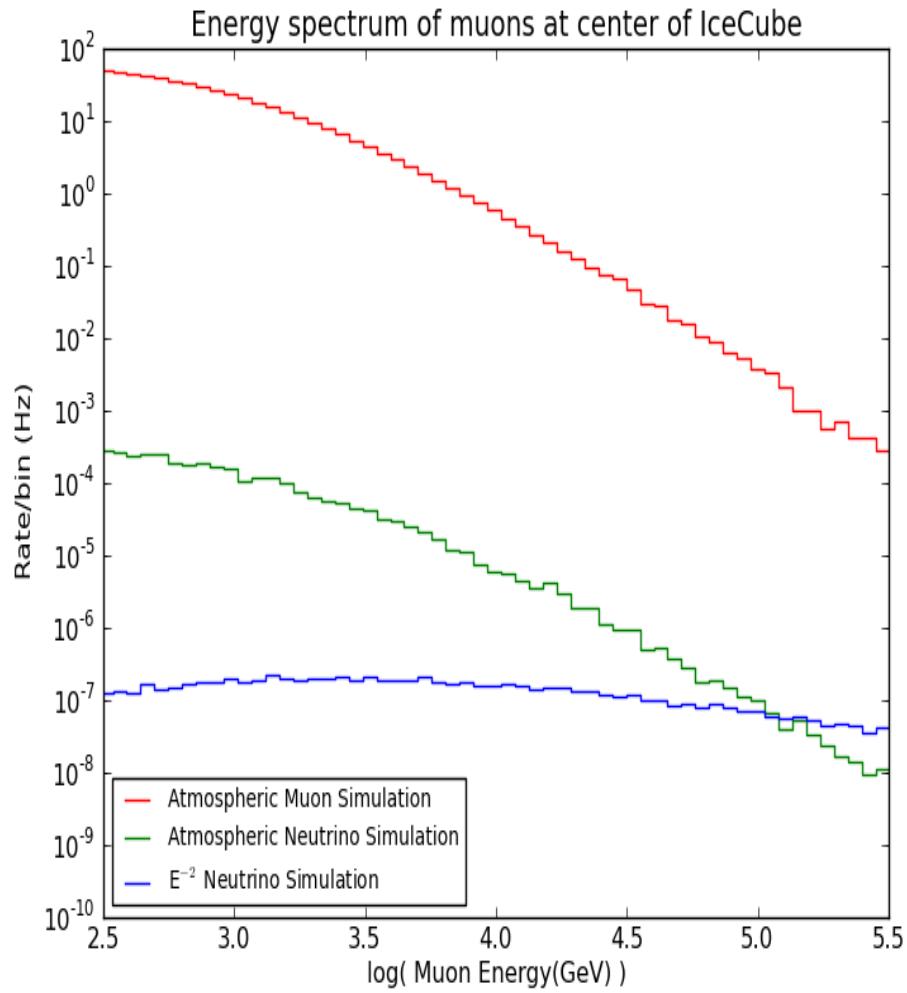


Ref. 1 https://arxiv.org/pdf/1607.08006v1.pdf

Expectations for the Through-Going Muon Event Selection

Monte Carlo Expectations

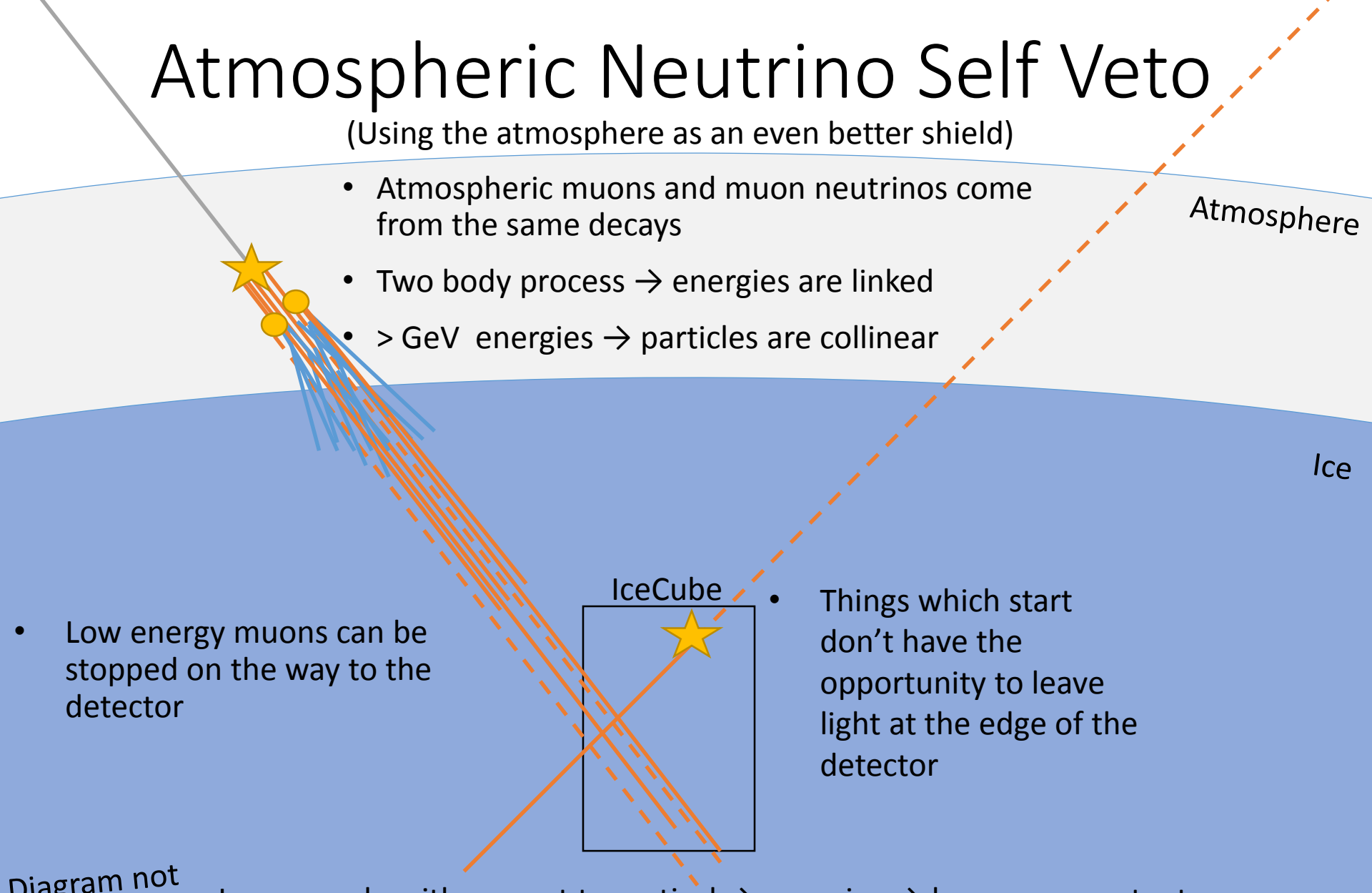




Atmospheric Neutrino Self Veto

(Using the atmosphere as an even better shield)

- Atmospheric muons and muon neutrinos come from the same decays
- Two body process → energies are linked
- > GeV energies → particles are collinear



- Low energy muons can be stopped on the way to the detector
- Things which start don't have the opportunity to leave light at the edge of the detector

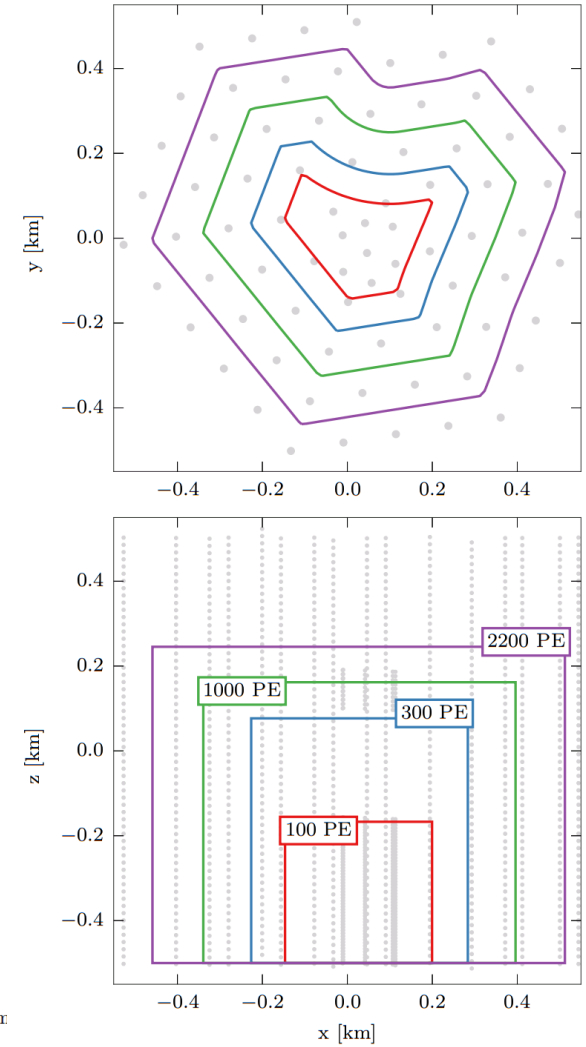
Diagram not to scale

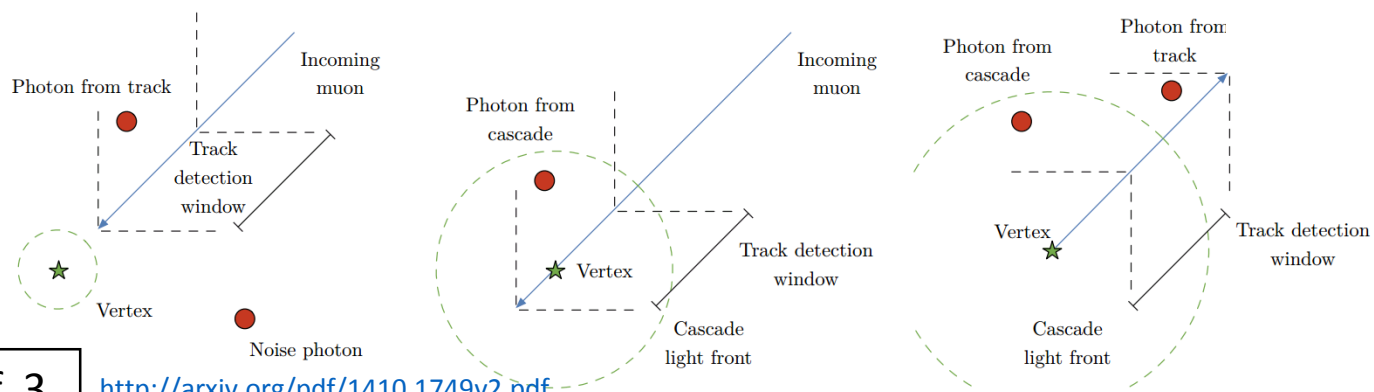
Larger angle with respect to vertical → more ice → less muon content

Ref. 2 http://arxiv.org/pdf/1405.0525v1.pdf

Starting Event Selection

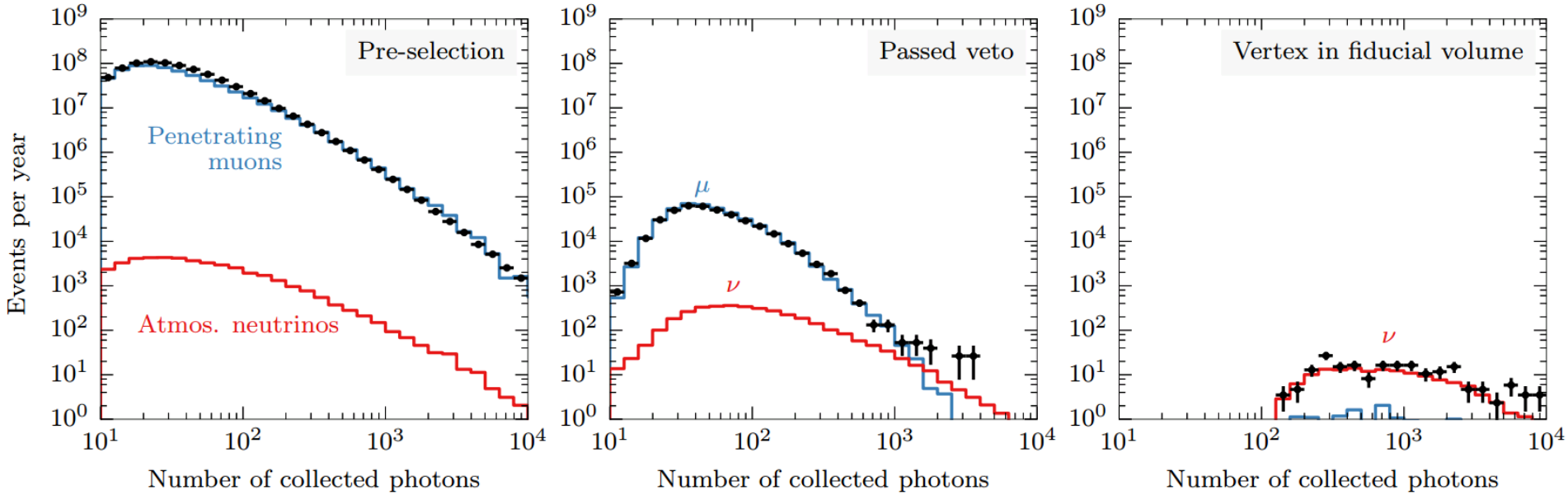
- Incoming events are removed by two veto cuts
  - Incoming track veto
    - < 2 hits coincident with possible muon track
  - HESE veto + layer veto
    - 0 PE allowed in layer veto
    - 2 PE allowed in HESE veto
- Removes all background events but the most persistent atmospheric muons and unaccompanied atmospheric muons



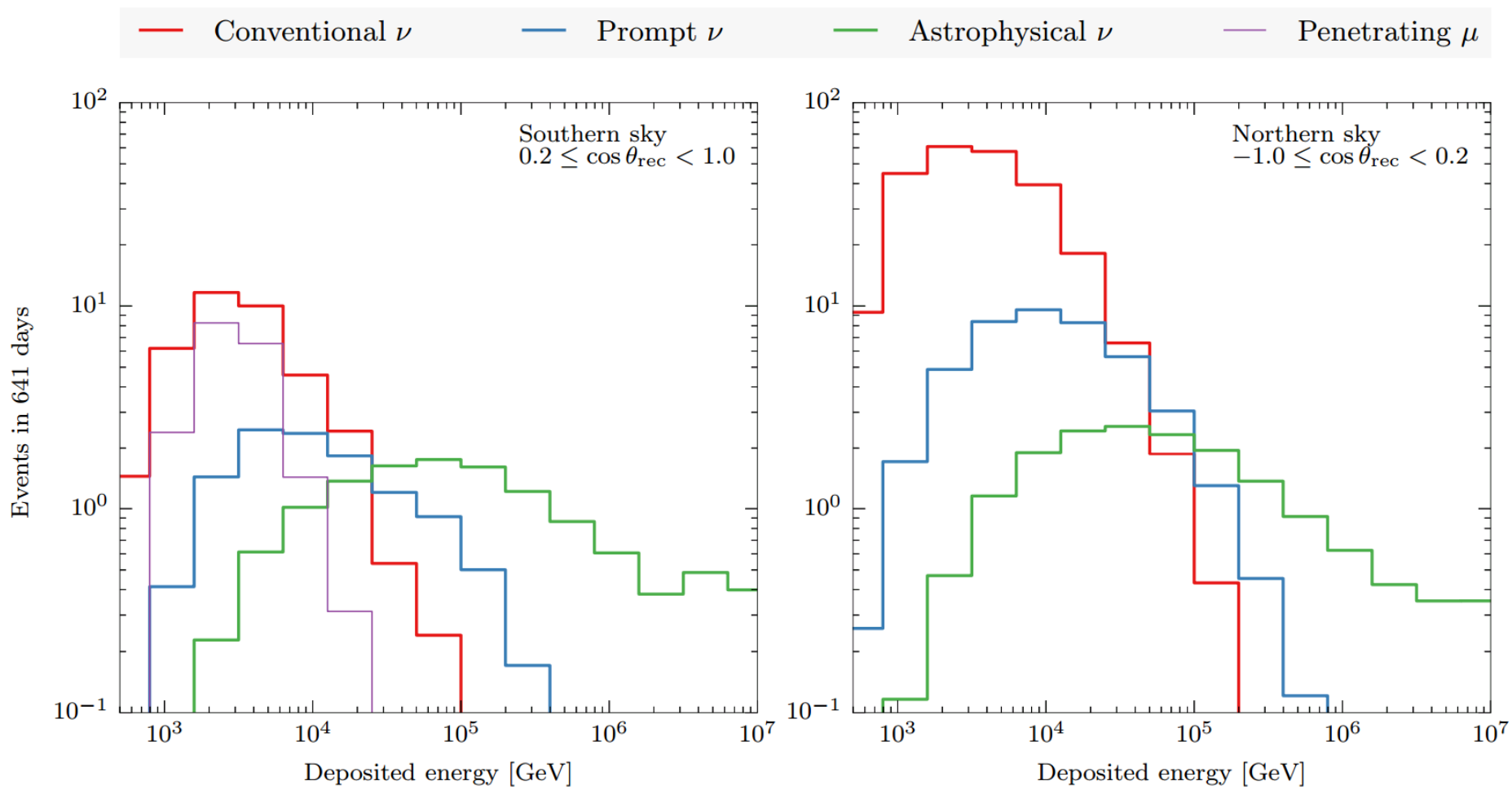


Ref. 3 http://arxiv.org/pdf/1410.1749v2.pdf

Expectation and Observed Events for the Starting Event Selection

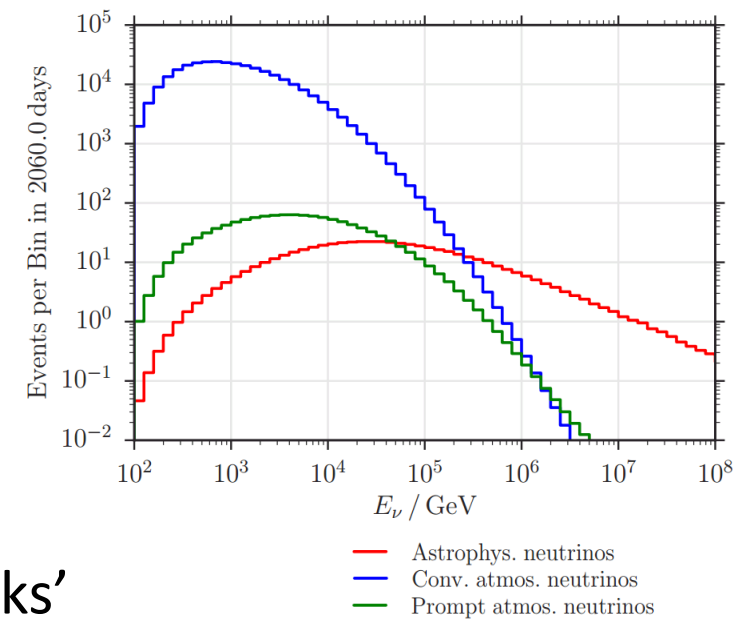


Expectation for the Starting Event Selection



Fitting Procedure

- All analyses are kept blind, except a 10% open (burn) sample for sanity checks, until the analysis procedure is fixed
- Use a binned Poissonian or modified Poissonian likelihood
  - Per bin expectation is taken as the sum of signal and background Monte Carlos
  - Background models are assumed to have a fixed spectral shape and scale only in normalization
  - Astrophysical signal can vary in power law index and normalization
  - Complete coverage of simulation is critical
    - Data where no simulation cannot be assessed



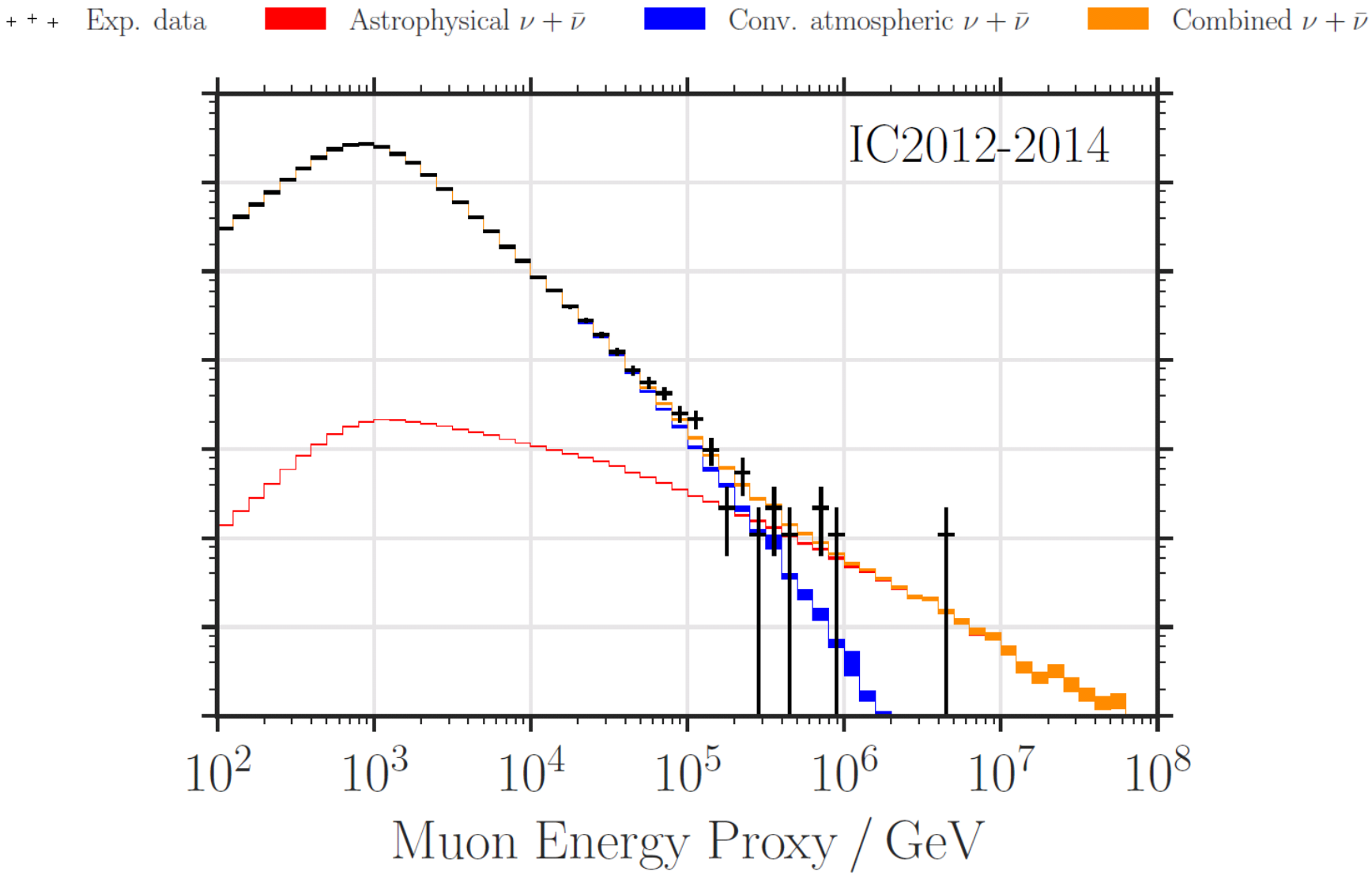
- Confidence intervals assessed with Wilks' Theorem and profile likelihood scans with 1 free parameter
  - Confirmed with ensemble tests when possible
- After assessing the astrophysical flux's properties, the most likely neutrino energy for each data event can be unfolded

Systematics

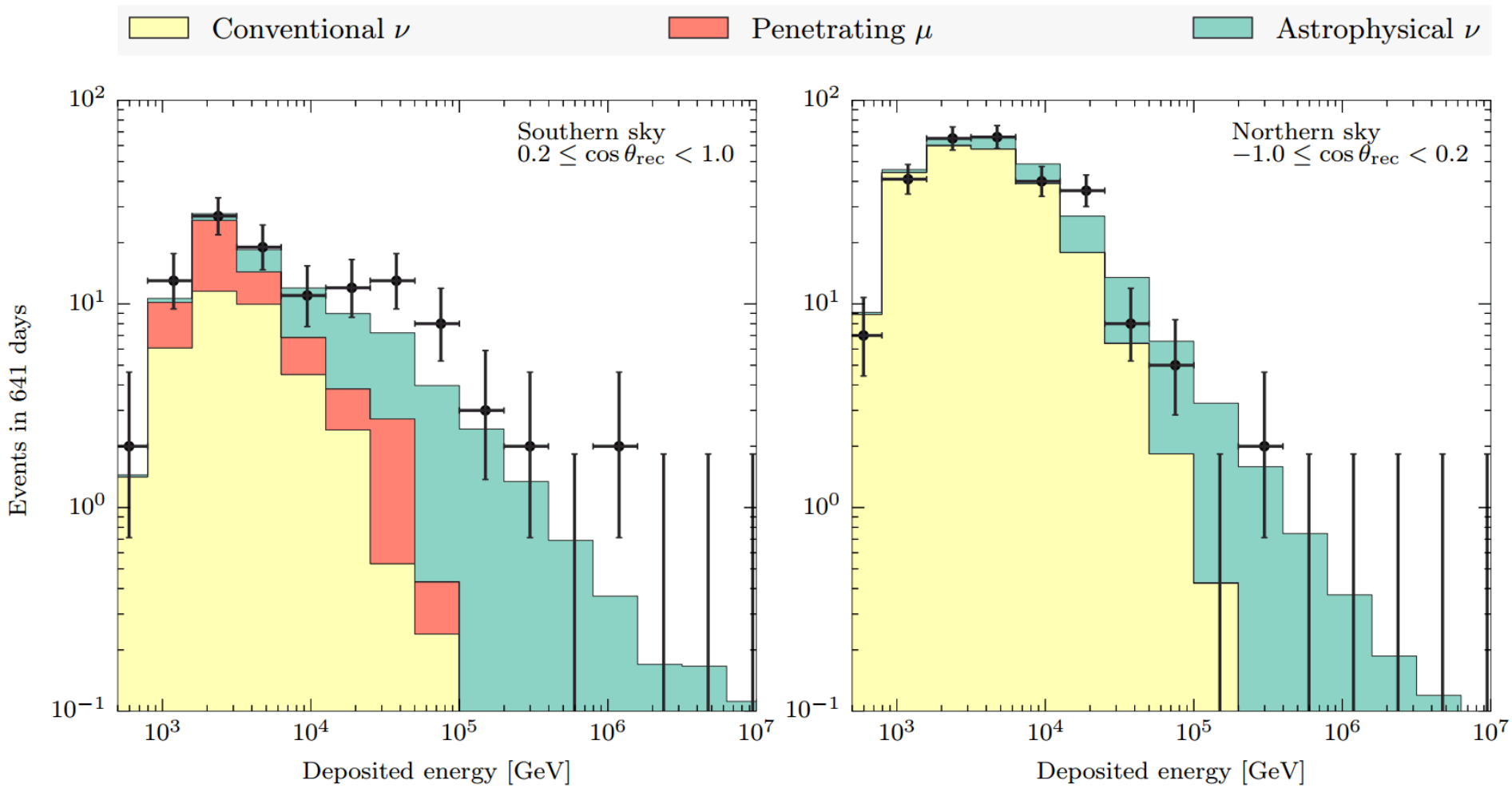
- Taken into account via independent Monte Carlo samples
- Use bin-wise interpolation between discrete systematic Monte Carlo sets

	IC59	IC79	IC2011	IC2012-2014	scaling	Best Fit (68% C.L.)
Flux properties:						
Conventional flux Φ_{conv}	1.028	1.047	1.184	1.194	relative	0.998 ± 0.003
Kaon-pion ratio K/π	1.310	1.514	1.002	1.032	relative	0.977 ± 0.027
Cosmic-ray spectral index $\Delta\gamma_{\mathrm{CR}}$	-0.049	-0.049	-0.061	0.012	absolute	$0.008^{+0.004}_{-0.023}$
Cosmic-ray model λ_{CR}	1.0 (H4a)	1.0 (H4a)	1.0 (H4a)	1.0 (H4a)	absolute	$0.0 - 0.5$
Optical efficiency ϵ_{opt}	1.011	0.974	1.042	1.056	relative	1.002 ± 0.002
Optical ice properties:						
Scattering length λ_{scat}	...	...	1.027	1.014	relative	0.999 ± 0.005
Absorption length λ_{abs}	...	...	1.000	1.047	relative	1.001 ± 0.004
Absorption/scattering length $\lambda_{\mathrm{abs/scat}}$	...	0.991	...	...	relative	1.000 ± 0.004
Ice model λ_{ice1} [SpiceMie,WHAM]	0. (SpiceMie)	SpiceMie (fixed)	...	...	absolute	$0.000 + 0.014$
Ice model λ_{ice2} [SpiceMie,SpiceLea]	...	...	0.551	SpiceLea (fixed)	absolute	0.006 ± 0.057

Fit to the Observed Events for the Through-going Event Selection

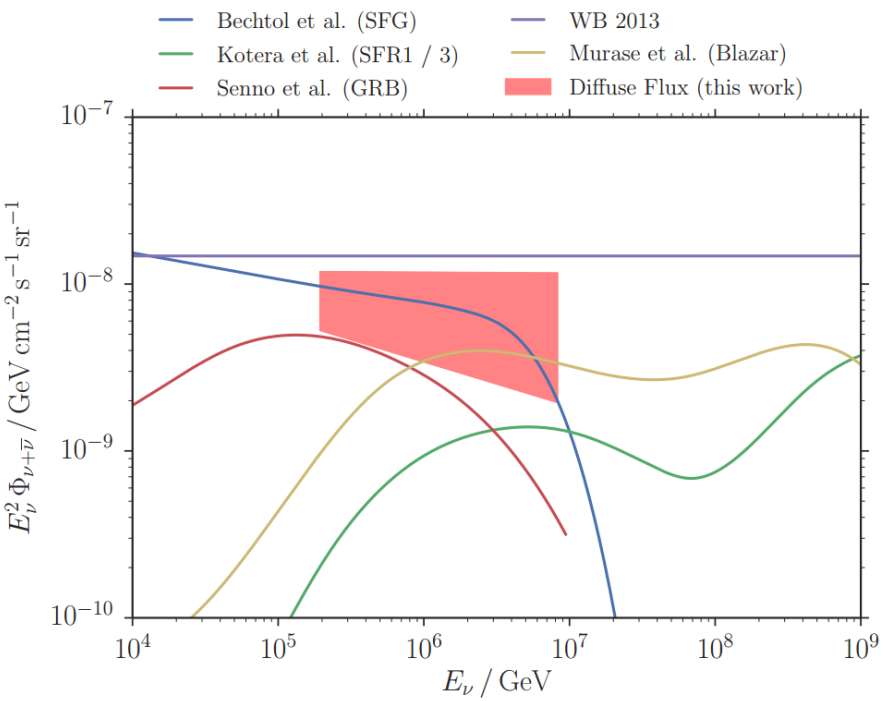


Fit to the Observed Events for the Starting Event Selection

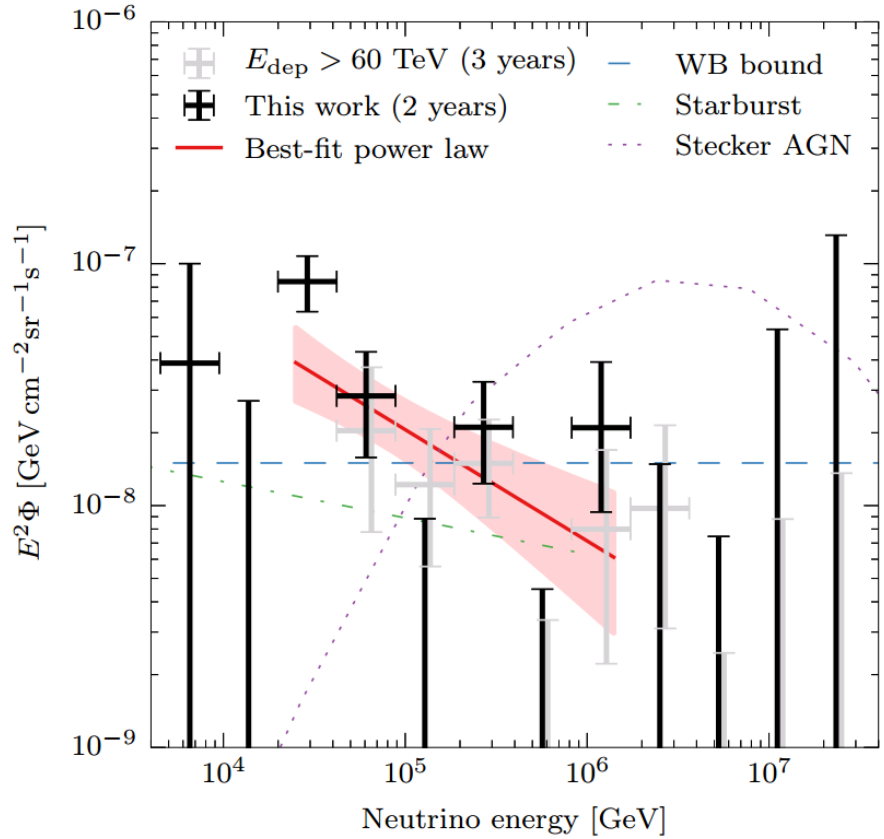


Results

Through-going Muons



Starting Events



- Through-going muons best fit
  - $\Phi_{\nu+\bar{\nu}} = (0.90^{+0.30}_{-0.27} \times 10^{-18}) \left(\frac{E_\nu}{100\,TeV}\right)^{-(-2.13\pm0.13)} \; GeV^{-1}cm^{-2}s^{-1}sr^{-1}$
- Starting Events best fit
  - $\Phi_{\nu+\bar{\nu}} = (2.06^{+0.35}_{-0.26} \times 10^{-18}) \left(\frac{E_\nu}{100\,TeV}\right)^{-(-2.46\pm0.13)} \; GeV^{-1}cm^{-2}s^{-1}sr^{-1}$

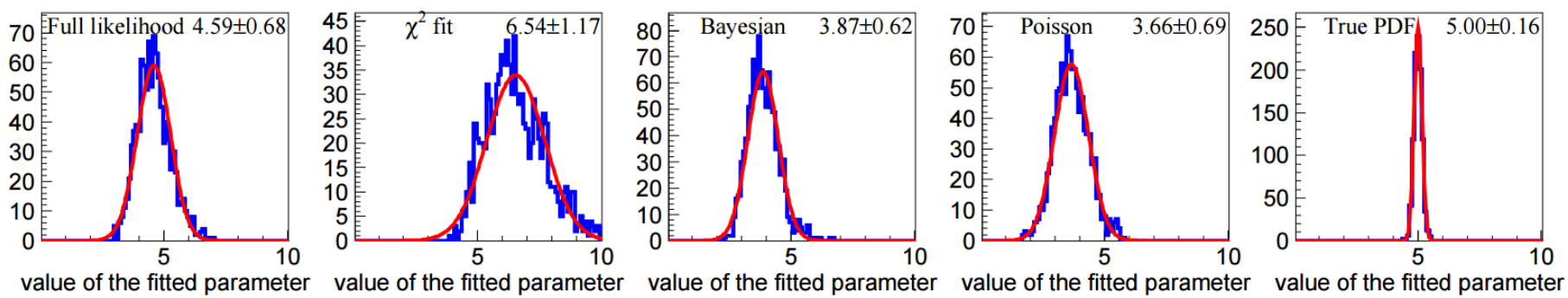
Modified Poissonian Likelihood

- Given a poisson process, we want to test if simulation and data per bin expectations are the same
- If they are independent
  - $s = number\ of\ sim.counts; n_s = number\ of\ sim.trials$
    - $\mu_s = \frac{s}{n_s}$
  - $d = number\ of\ data\ counts; n_d = number\ of\ data\ trials$
    - $\mu_d = \frac{d}{n_d}$
- If they are the same
  - $\mu = \mu_s = \mu_d = \frac{s+d}{n_s+n_d}$
- Forming a likelihood ratio
  - $$\frac{P(same)}{P(indep)} = \frac{\frac{\left(n_s\left(\frac{s+d}{n_s+n_d}\right)\right)^s e^{-n_s\left(\frac{s+d}{n_s+n_d}\right)}}{s!}\frac{\left(n_d\left(\frac{s+d}{n_s+n_d}\right)\right)^d e^{-n_d\left(\frac{s+d}{n_s+n_d}\right)}}{d!}}{\frac{\left(n_s\left(\frac{s}{n_s}\right)\right)^s e^{-n_s\left(\frac{s}{n_s}\right)}}{s!}\frac{\left(n_d\left(\frac{d}{n_d}\right)\right)^d e^{-n_d\left(\frac{d}{n_d}\right)}}{d!}}$$

Ref. 4 http://arxiv.org/pdf/1304.0735v3.pdf

Modified Poissonian Likelihood

- $\frac{P(same)}{P(indep)} = \left(\frac{n_s}{s}\left(\frac{s+d}{n_s+n_d}\right)\right)^s \left(\frac{n_d}{d}\left(\frac{s+d}{n_s+n_d}\right)\right)^d = \left(\frac{n_s}{s}(\mu)\right)^s \left(\frac{n_d}{d}(\mu)\right)^d$
- We only conduct one experiment so n_d = 1
  - $\frac{P(same)}{P(indep)} = \left(\frac{\mu}{s/n_s}\right)^s \left(\frac{\mu}{d}\right)^d$
- This is the single bin version, multi-bin is simply the product of this over all bins
- Example
  - Reconstructing μ with 1000 random data drawings in 100 data trials
  - 200 simulation sets with 10 trials each are sampled log-uniformly from μ/5 to 2 μ



Nu-SQUIDs

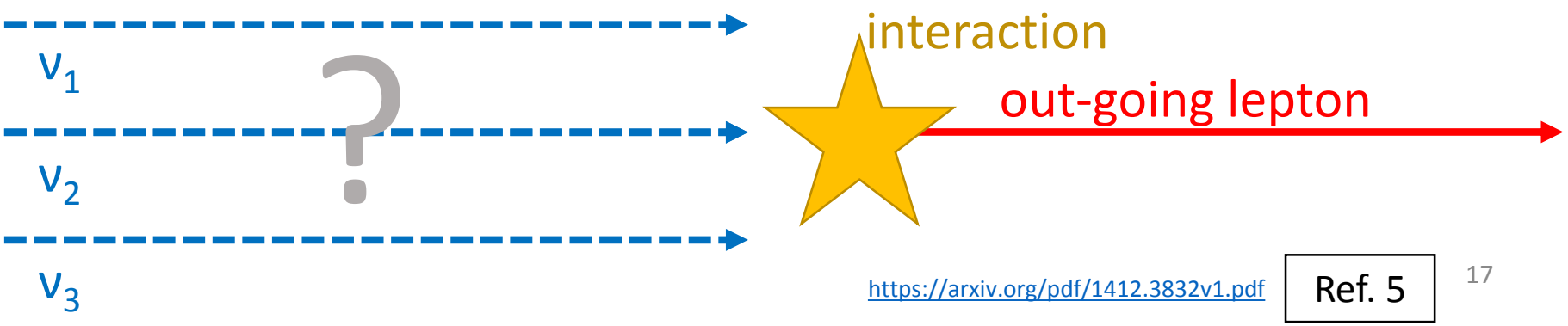
(Simple Quantum Integro-Differential Solver)

$$\frac{dF_\nu(E)}{dx} = -i[H, F_\nu(E)] - \sum_\alpha \frac{1}{2\lambda^\alpha(E)}\{\Pi_\alpha, F_\nu(E)\} + \int_{E'} \frac{1}{\lambda_{\rm NC}(E')} \sum_\alpha \{\Pi_\alpha, F_\nu(E')\} NC(E', E) + \int_{E'} \frac{1}{\lambda^\tau(E')} F_\tau(E') CC_\tau(E', E)\Pi_\tau + {\rm Br}_\mu \int_{E'} \frac{1}{\lambda^\tau(E')} \bar{F}_\tau(E') CC_\tau(E', E)\Pi_\mu + {\rm Br}_e \int_{E'} \frac{1}{\lambda^\tau(E')} \bar{F}_\tau(E') CC_{\bar{\tau}(E',E)}\Pi_e$$

- Neutrino propagation can be solved analytically
  - Decouple neutrino propagation from charged lepton production
  - Faster and more accurate than Monte Carlo propagation

$$\frac{dF_\tau(E)}{dx} = -\frac{1}{\lambda^\tau(E)} F_\tau(E) + \int_{E'} \frac{1}{\lambda^\tau_{\rm CC}(E')} {\rm Tr}[\Pi_\tau, F_\nu(E')] CC_\tau(E_\nu, E_\tau)$$

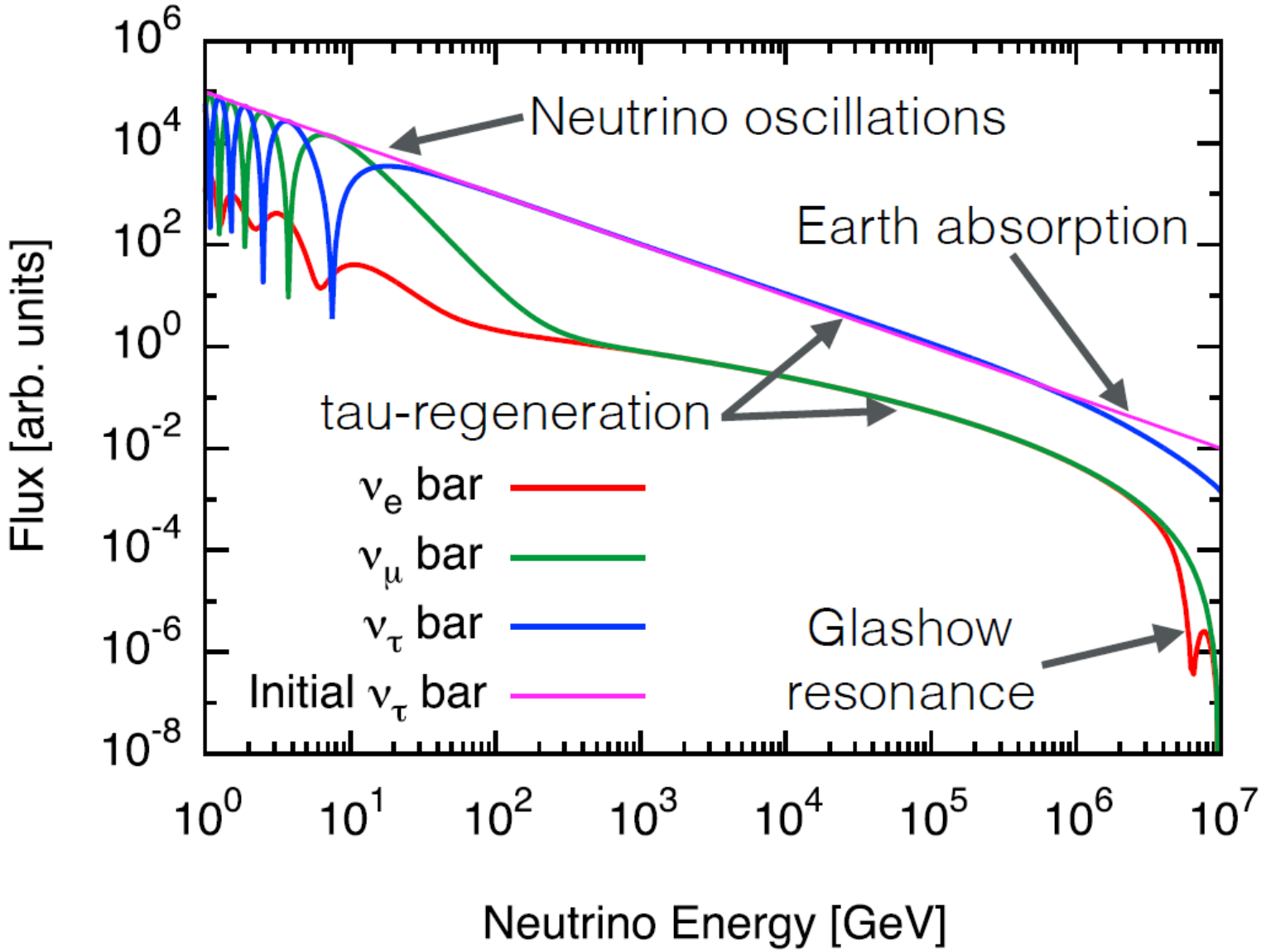
- Can incorporate any modifications to neutrino flux
- One Monte Carlo can be used for a range of neutrino systematics simply by reweighting
  - Cross Sections
  - Earth Models
  - Oscillation Parameters



https://arxiv.org/pdf/1412.3832v1.pdf

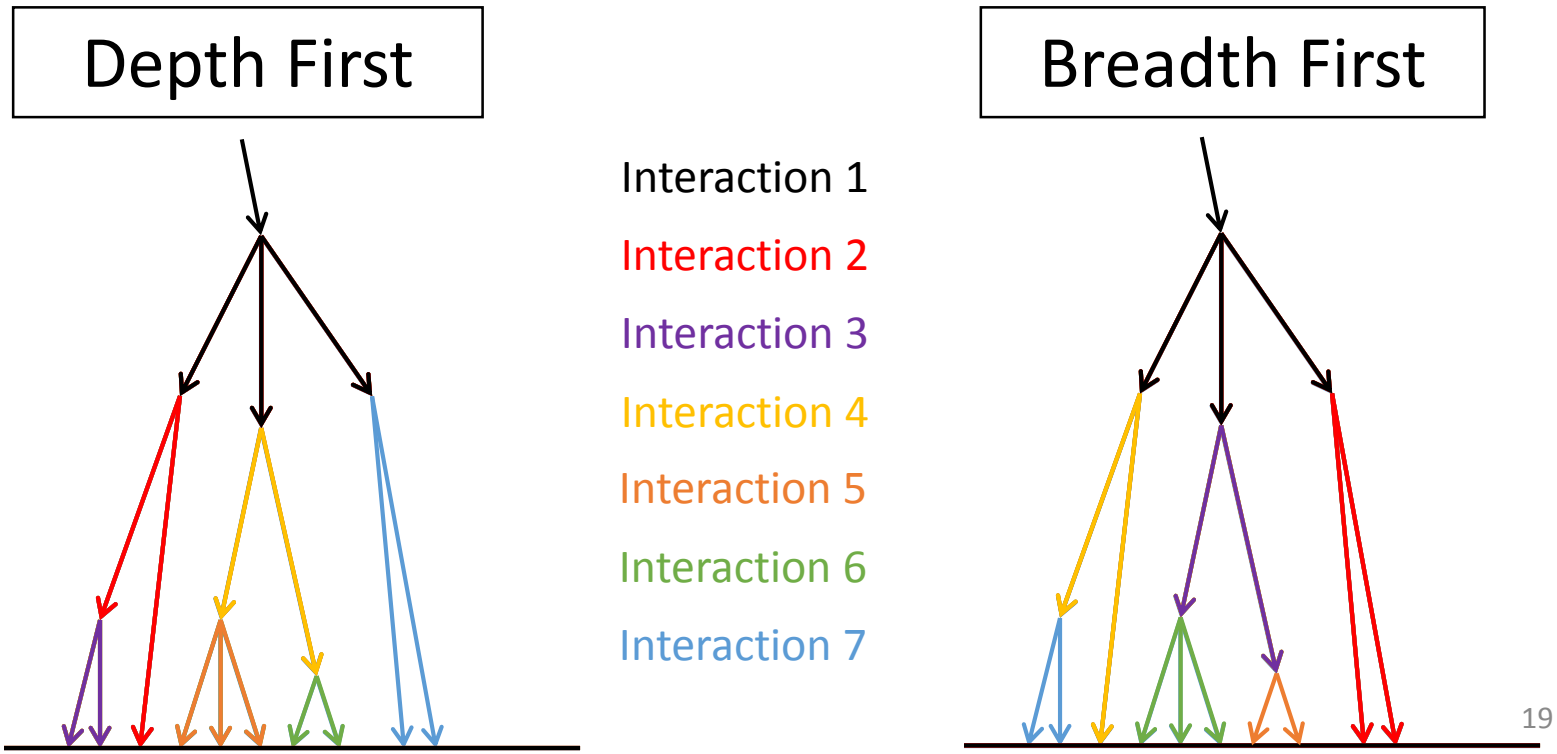
Ref. 5

Nu-SQUIDs Example



CORSIKA Modifications for Improved Atmospheric Neutrino Simulation

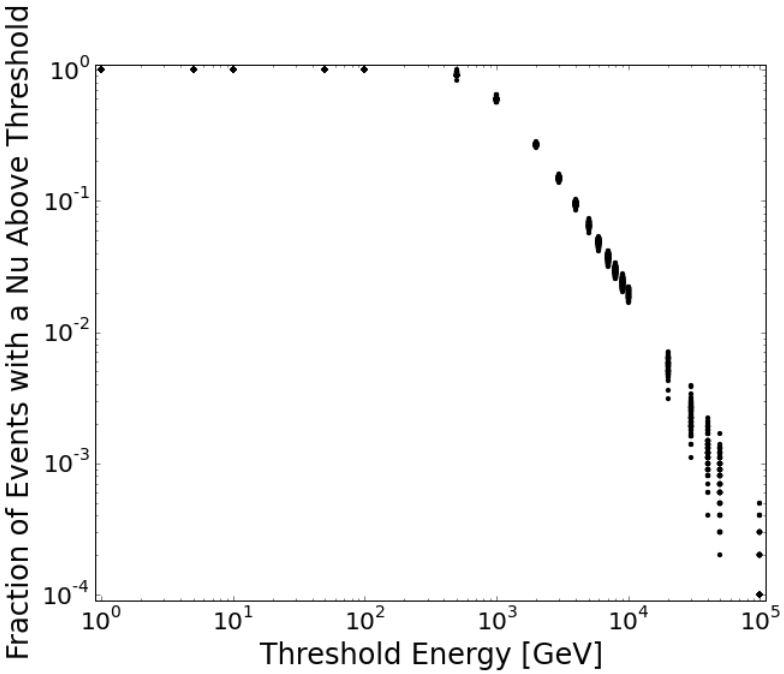
- Background for starting event searches simulated with CORSIKA
- Often searching for a minimum energy neutrino
  - Normal propagation method requires full shower simulation
  - Modified propagation allows detection of relevant neutrino on the fly

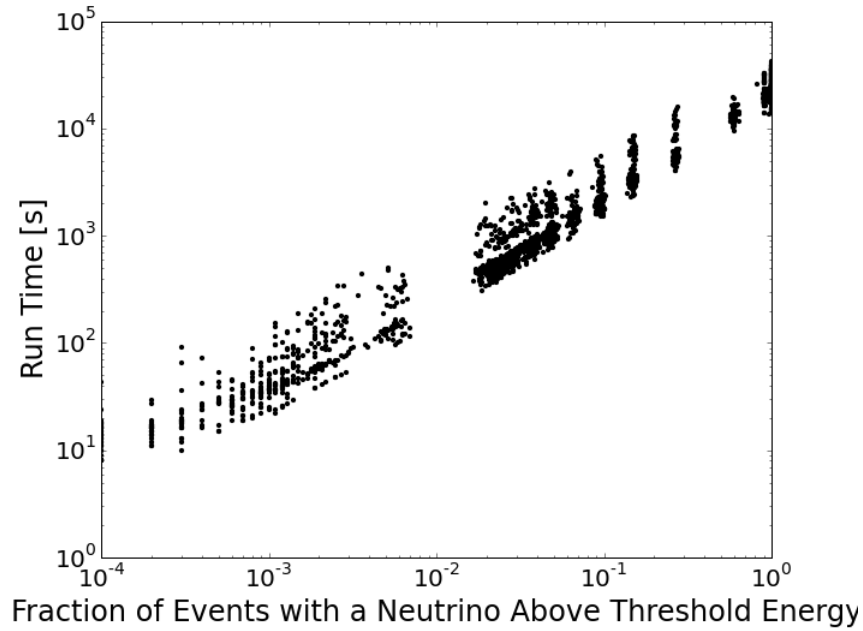


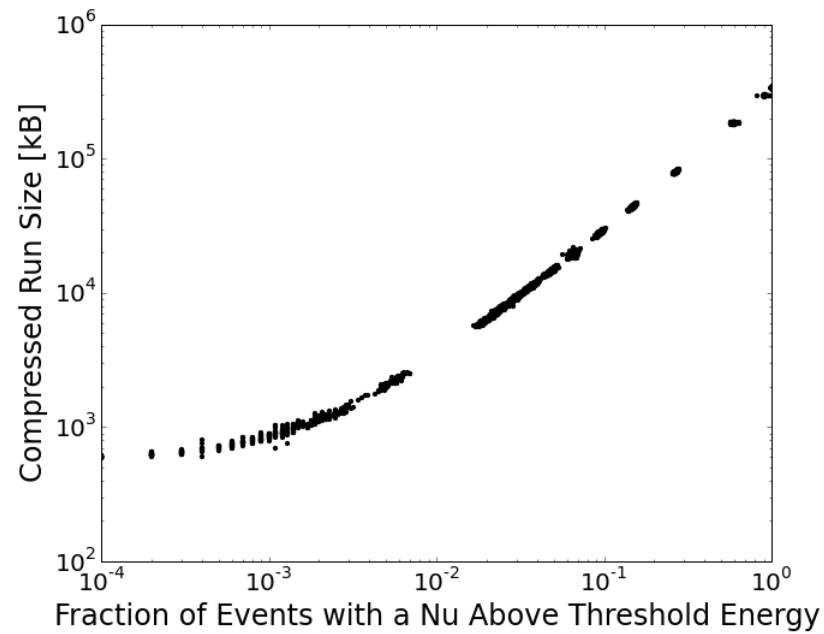
Ref. 6

http://www.epj-conferences.org/articles/epjconf/pdf/2016/11/epjconf-VLVnT2015_02003.pdf

Performance



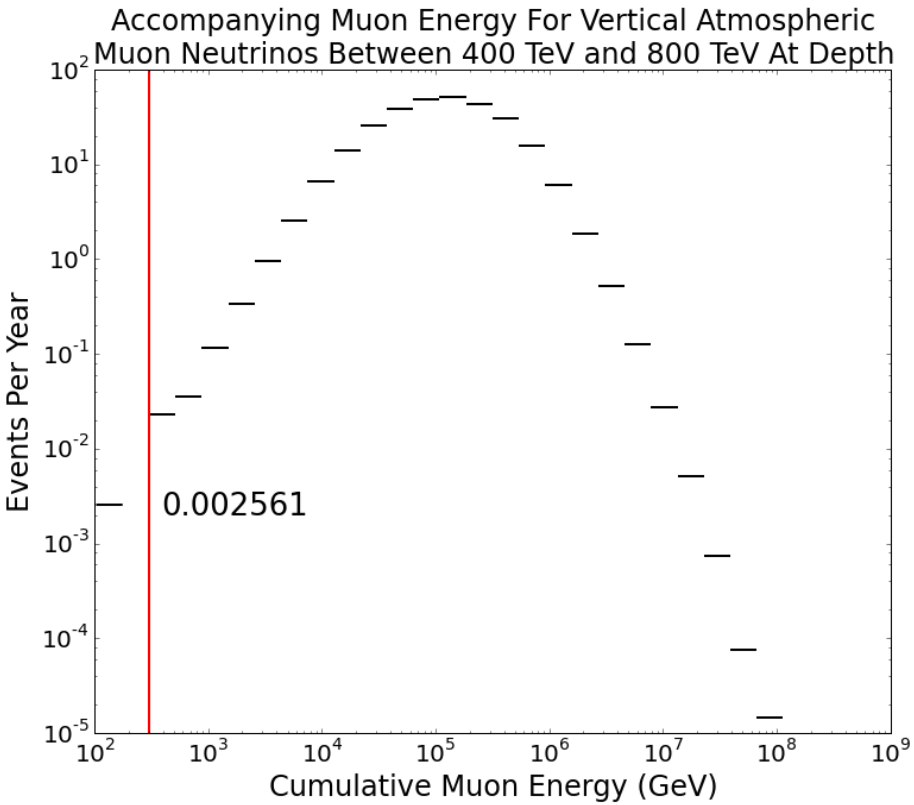


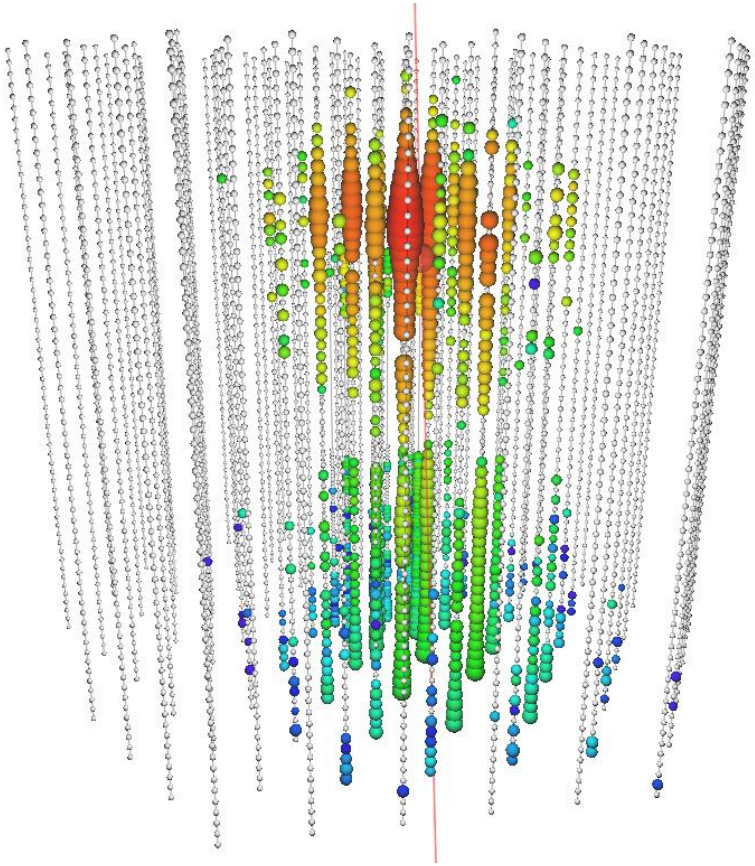


- Improvement linear with fraction of stopped showers
  - Generation and storage of stopped primaries is constant and dominant for low fractions of events

Vertical Event Significance

- Millipede Deposited Energy (Cascade) ~ 400 TeV
- MuEX (Muon+Cascade) ~140000 → ~ 400 TeV
  - Neutrino Energy > Cascade + Muon Energy (400-800 TeV)





- Only production option from charm
  - DPMJET simulation for charm overproduction (~8 times the current IceCube limit on charm)
- Common upper limit for veto-able muon energy of 300 GeV
- Within 4 degrees of vertical
  - 1 event every 390.47 years (3123.76 years)
  - Just over 3 sigma (3.6 sigma)

Conclusions

- Discussed statistical methods used in determining astrophysical neutrino flux from two complimentary samples
  - Use a binned Poissonian likelihood
  - Expectations come from simulation
  - Confidence intervals from Wilks' Theorem
- Showed improvements to standard tools
  - Modified Poissonian likelihood
  - Improved neutrino propagation
  - Improved background simulation

References

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