A view on prompt atmospheric neutrinos in IceCube

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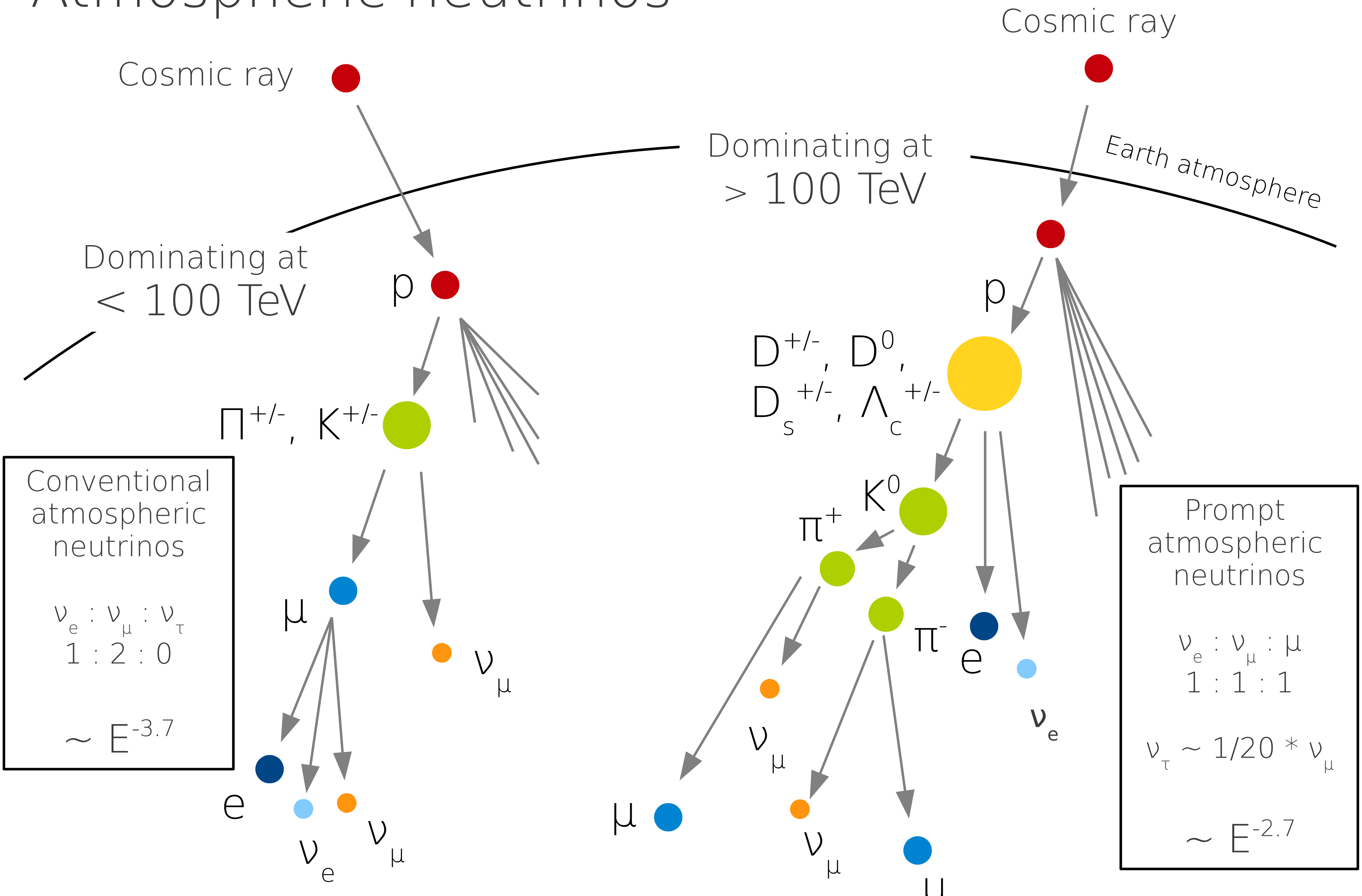
NOW2012, Sept 14, Otranto, Italy

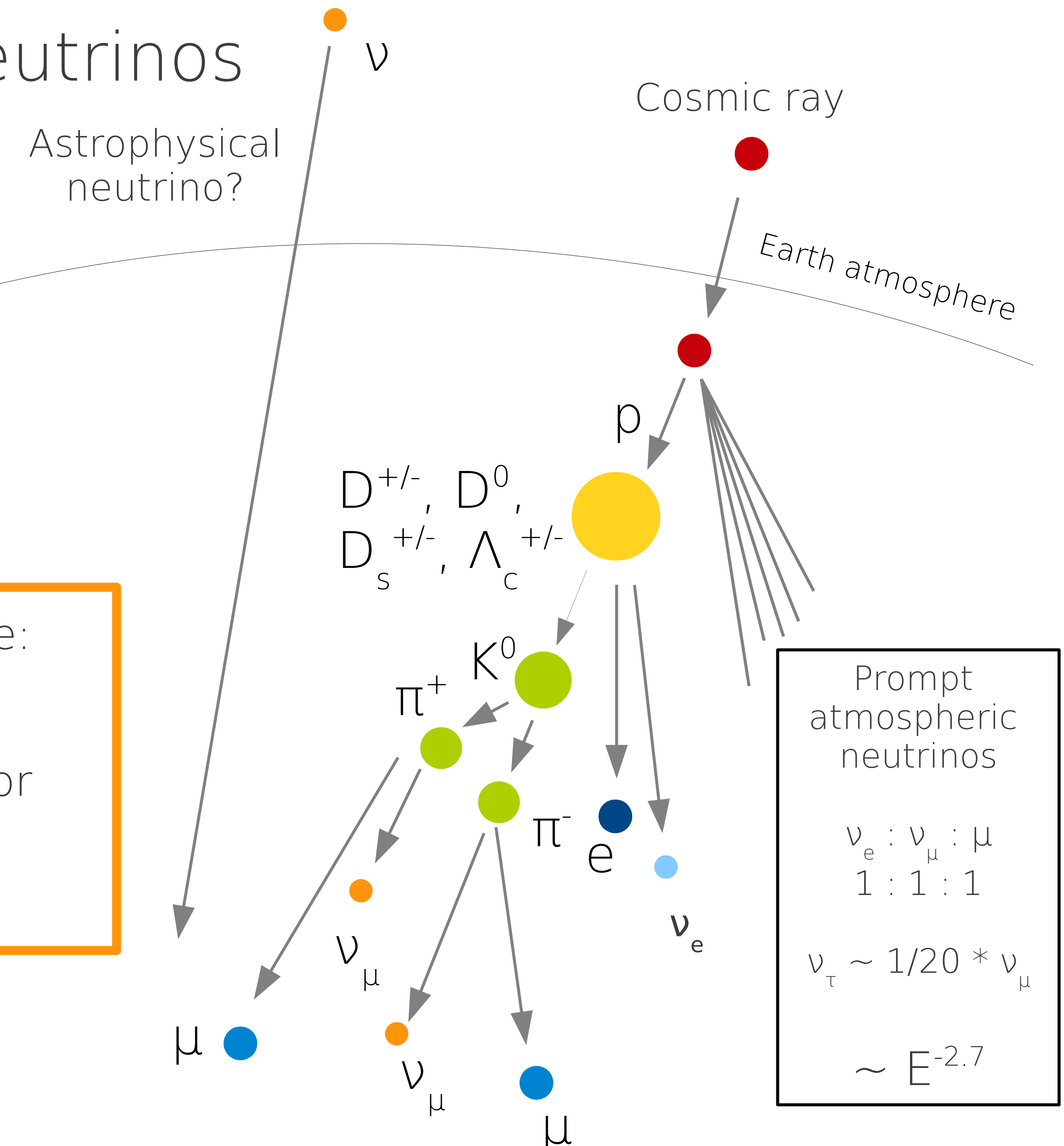
Outlook

- An introduction to prompt atmospheric neutrinos
- The search for prompt neutrinos with IceCube
- Latest results on prompt from IceCube
- Outlook on future searches

Atmospheric neutrinos



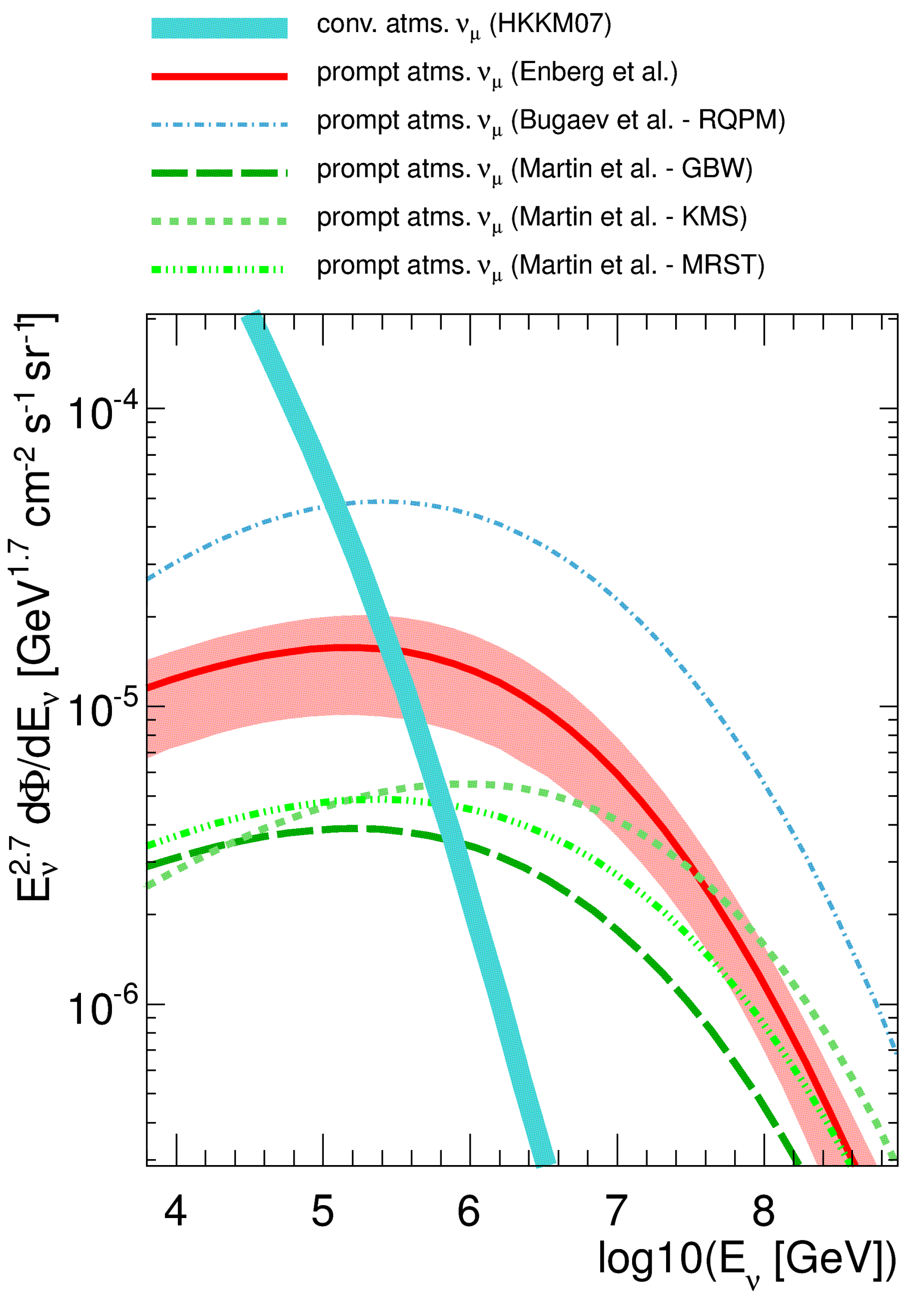
Atmospheric neutrinos



Interesting because:

1. Background at high energies for the search for astrophysical ν

Models for prompt neutrino fluxes



Enberg et al.: Phys.Rev.D78:043005,2008
Martin et al.: Acta Phys.Polon.B34:3273-3304,2003
Bugaev et al.: Phys. Rev. D58:054001, 1998

Ingredients:

- Primary cosmic ray nucleon flux
- Differential cross section for gg → ccbar
- Nucleonic and charm attenuation and interaction lengths in the atmosphere
- Charm semi-leptonic decay spectra

Gluon distribution function

Interesting because:

2. Provides experimental input to nucleon physics at small x, which are hardly accessible for colliders

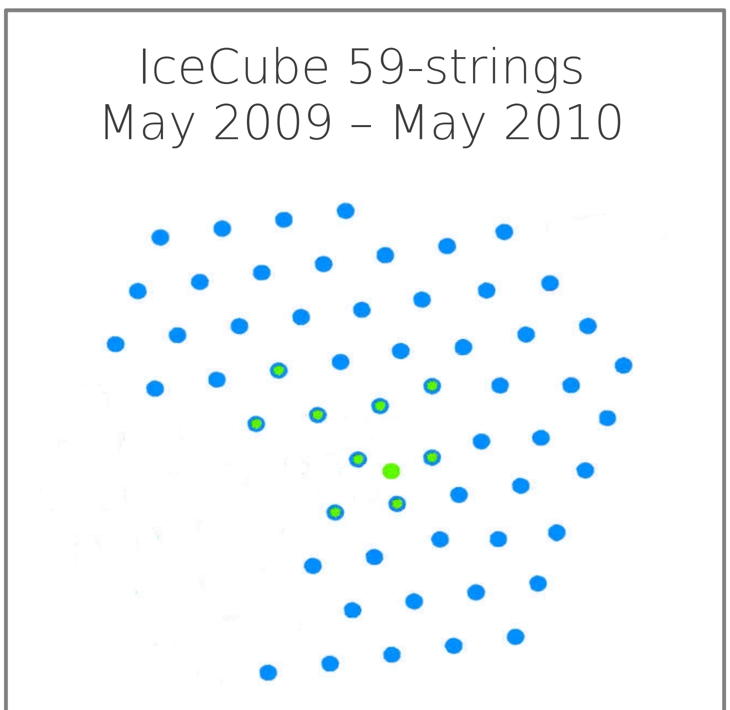
The IceCube Neutrino Observatory

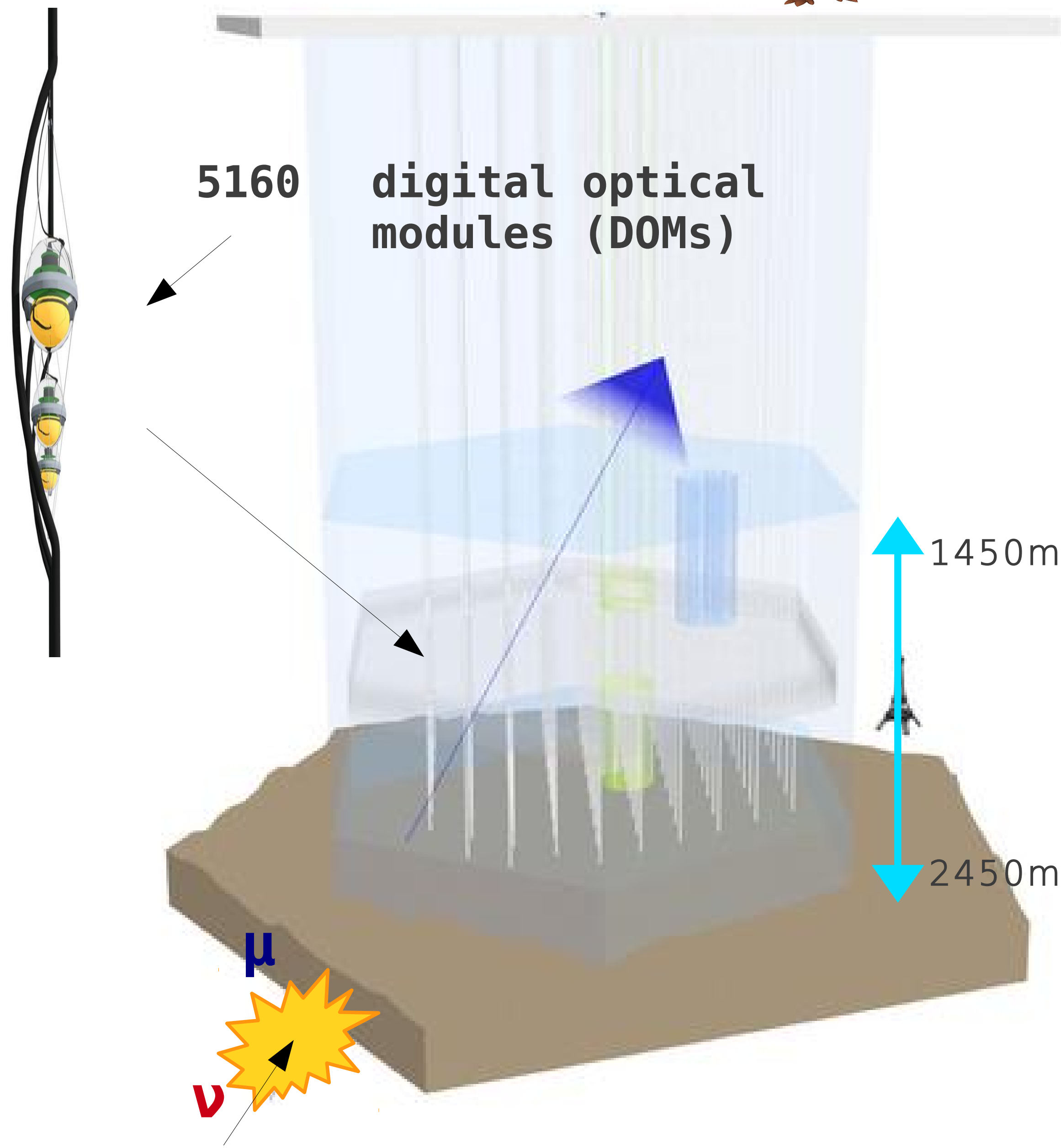
(not to scale)

Detection of high energy neutrinos via Cherenkov light emitted by secondary leptons.

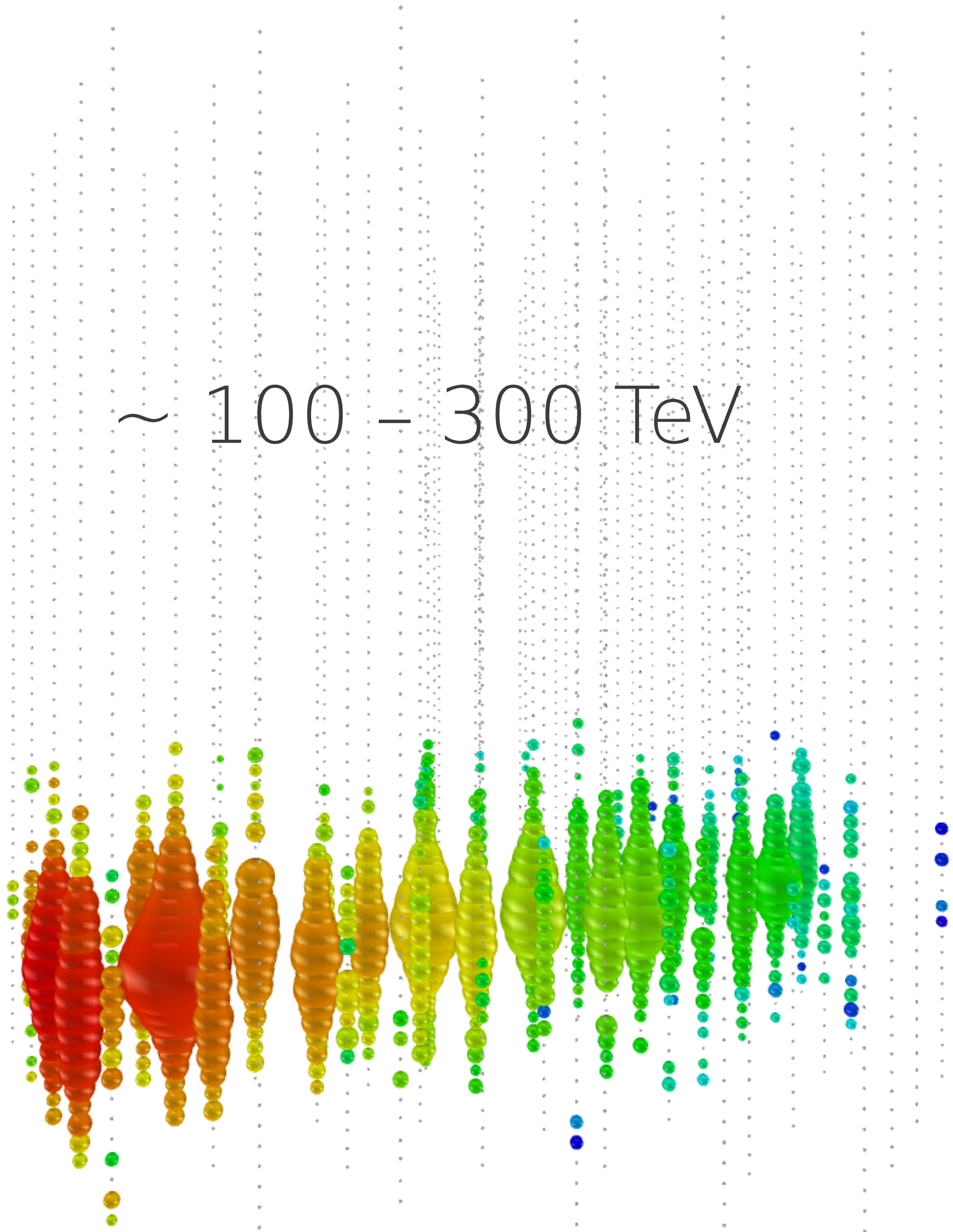
The first km^3 ν detector .

Completed in Dec. 2010!





The highest energy event in the sample



Selection of upgoing, high-energy neutrino induced muon events to remove background from downgoing atmospheric muons.

Expected event numbers

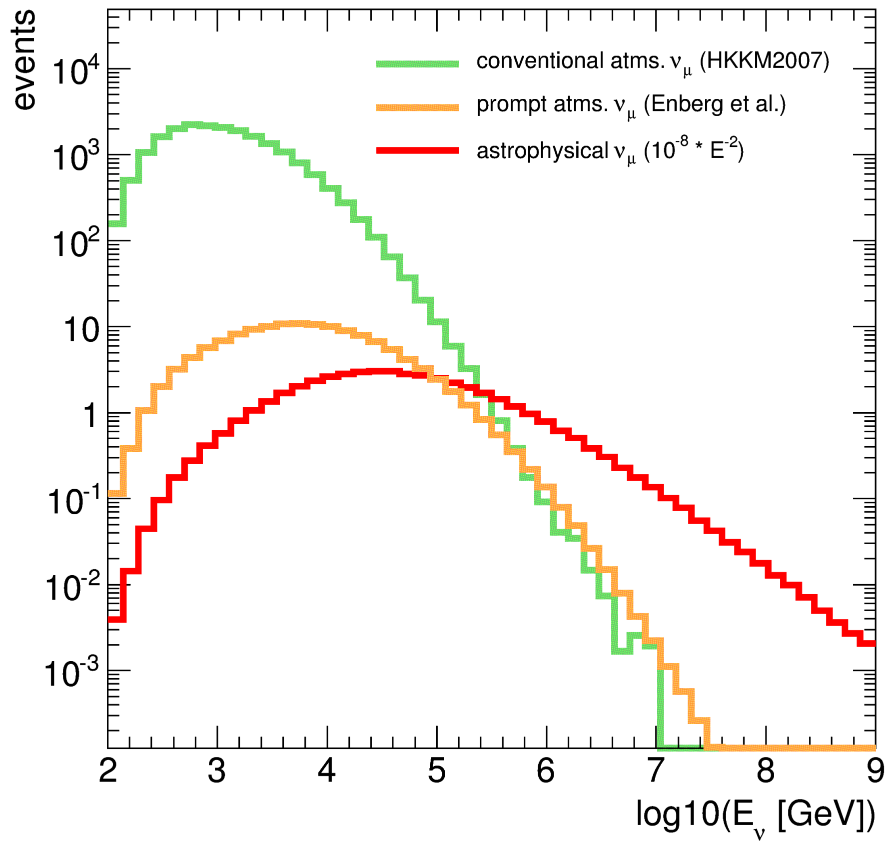
Conventional ν_μ:	~ 21 000
Prompt ν_μ:	~ 150
Astrophysical ν_μ:	< 40

Conv. atms. muon background:

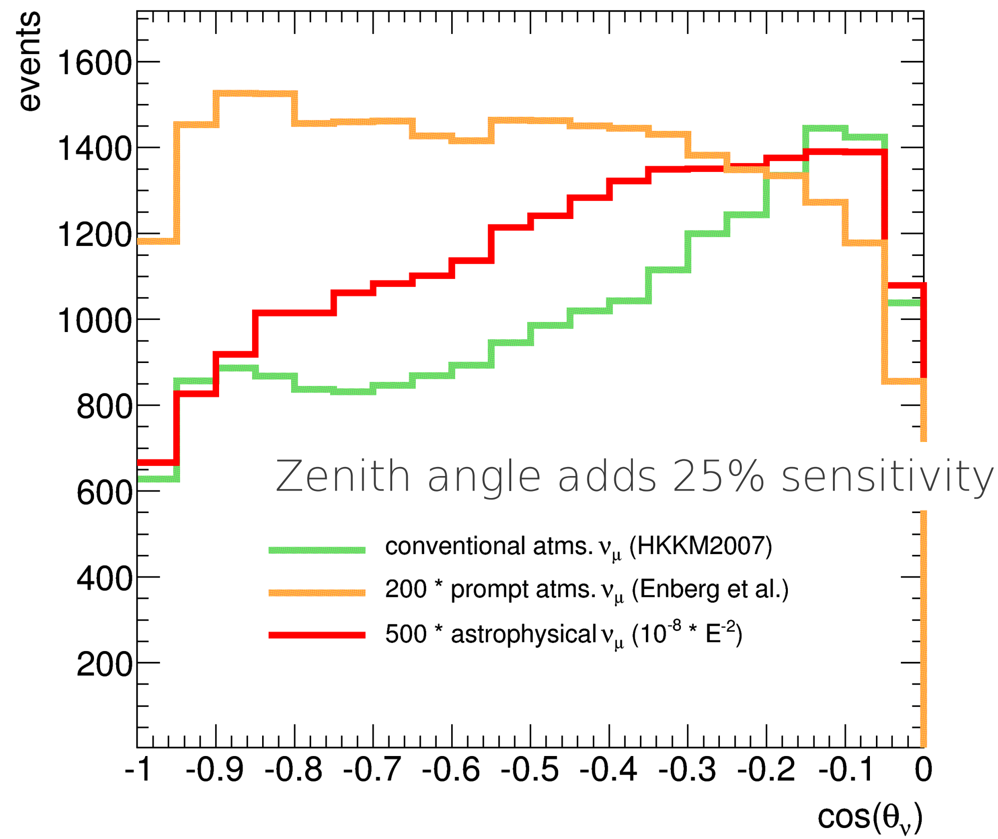
~ 30

Signatures of high energy ν_μ in IceCube

Energy distribution
The three neutrino components have different spectral slopes

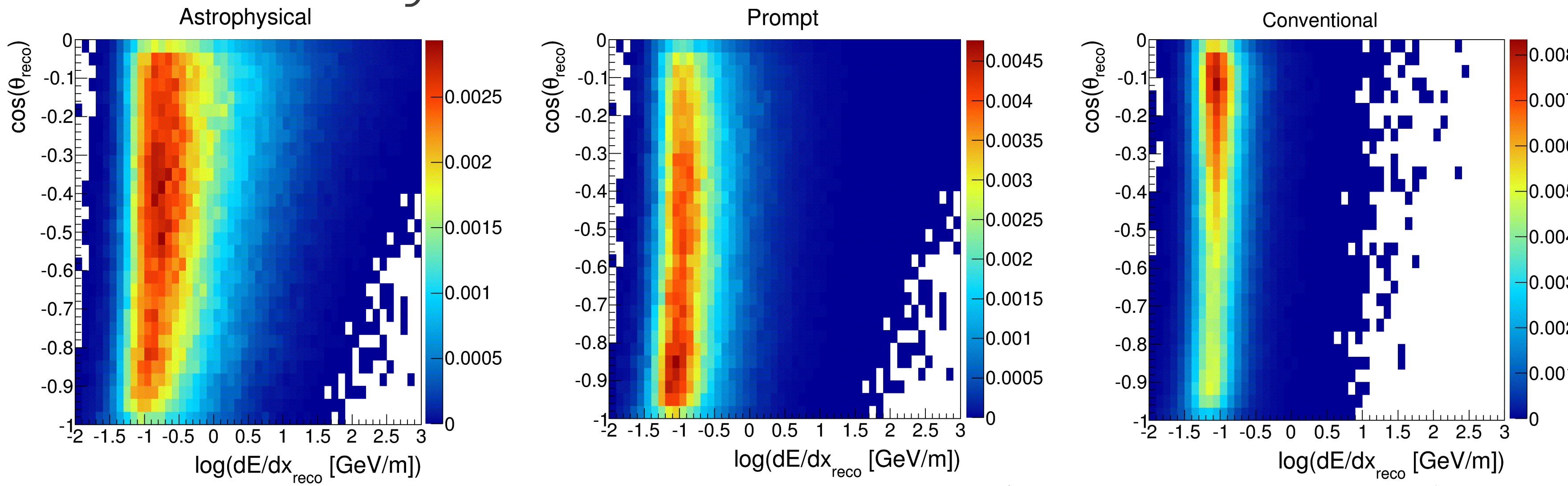


Zenith angle distribution
Additional sensitivity through characteristic angular distributions



Conventional, prompt and astrophysical neutrinos can't be decoupled and need to be looked at together in a HE neutrino analysis.

Likelihood analysis method



2-dim (energy and zenith) global fit for

Signal parameters

N_a = number of astrophysical ν
N_p = number of prompt atmospheric ν

$$\mu_{ij} = N_a \cdot a_{ij} + N_p \cdot p_{ij} + \cdot N_c \cdot c_{ij}$$

Detector uncertainties

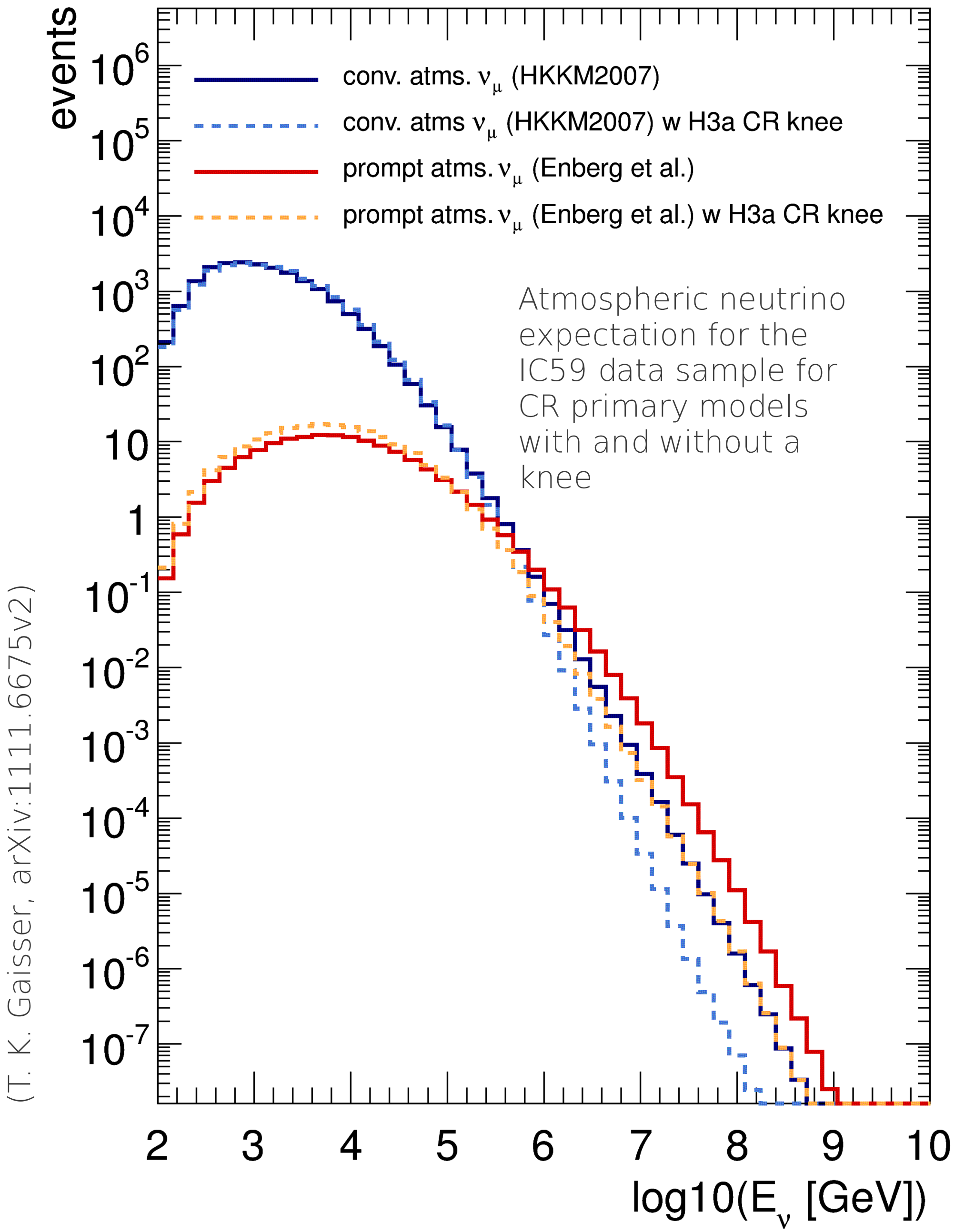
Optical ice properties, relative DOM efficiency

$$\mathcal{L} = \prod_{i,j} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} \cdot e^{-\mu_{ij}}$$

Physics model uncertainties

N_c = number of conventional atmospheric ν
CR flux normalization, spectral slope and composition
Pion-Kaon ratio

The knee in the atmospheric neutrino flux



Standard models for atms. neutrinos:

Conv.: HKKM2007 → assumes a $E^{-2.7}$ power law for the primary flux

Prompt: models assume power law with a simple kink at 5 * 10^6 GeV

Recalculation of neutrino fluxes:

$$\phi_\nu(E_\nu, \theta) = \int dE_0 \quad \phi_N(E_0) \cdot Y_\nu(E_\nu, E_0, \theta)$$

Neutrino energy

Nucleon energy

Nucleon primary flux (from model fits to CR data)

Neutrino yield per nucleon (from simulation)

With a realistic CR primary flux the atmospheric background prediction at high energies decreases

→ increases the chances for a discovery of astrophysical neutrinos

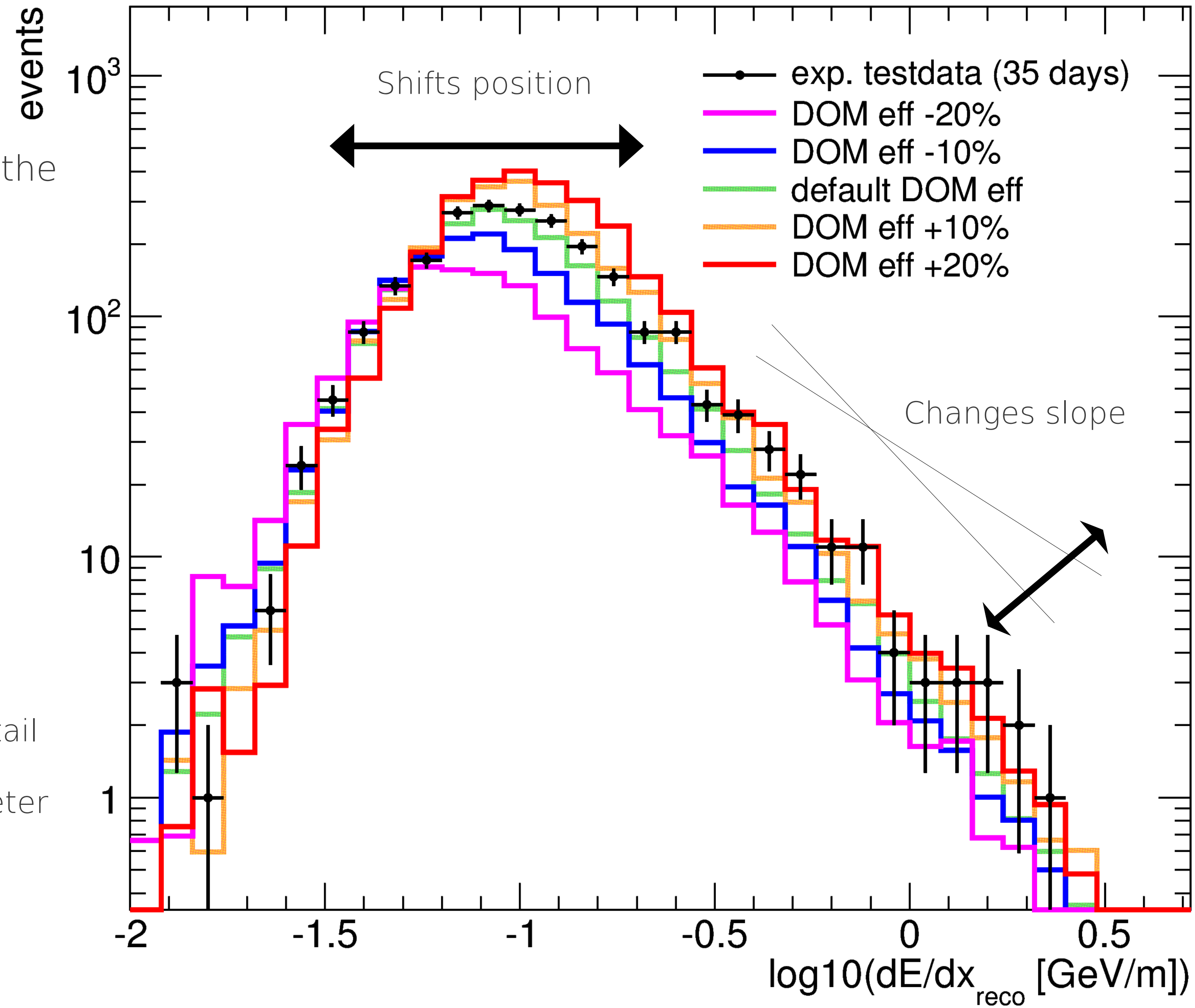
Optical efficiency

Relative uncertainty of the optical efficiency composes of:

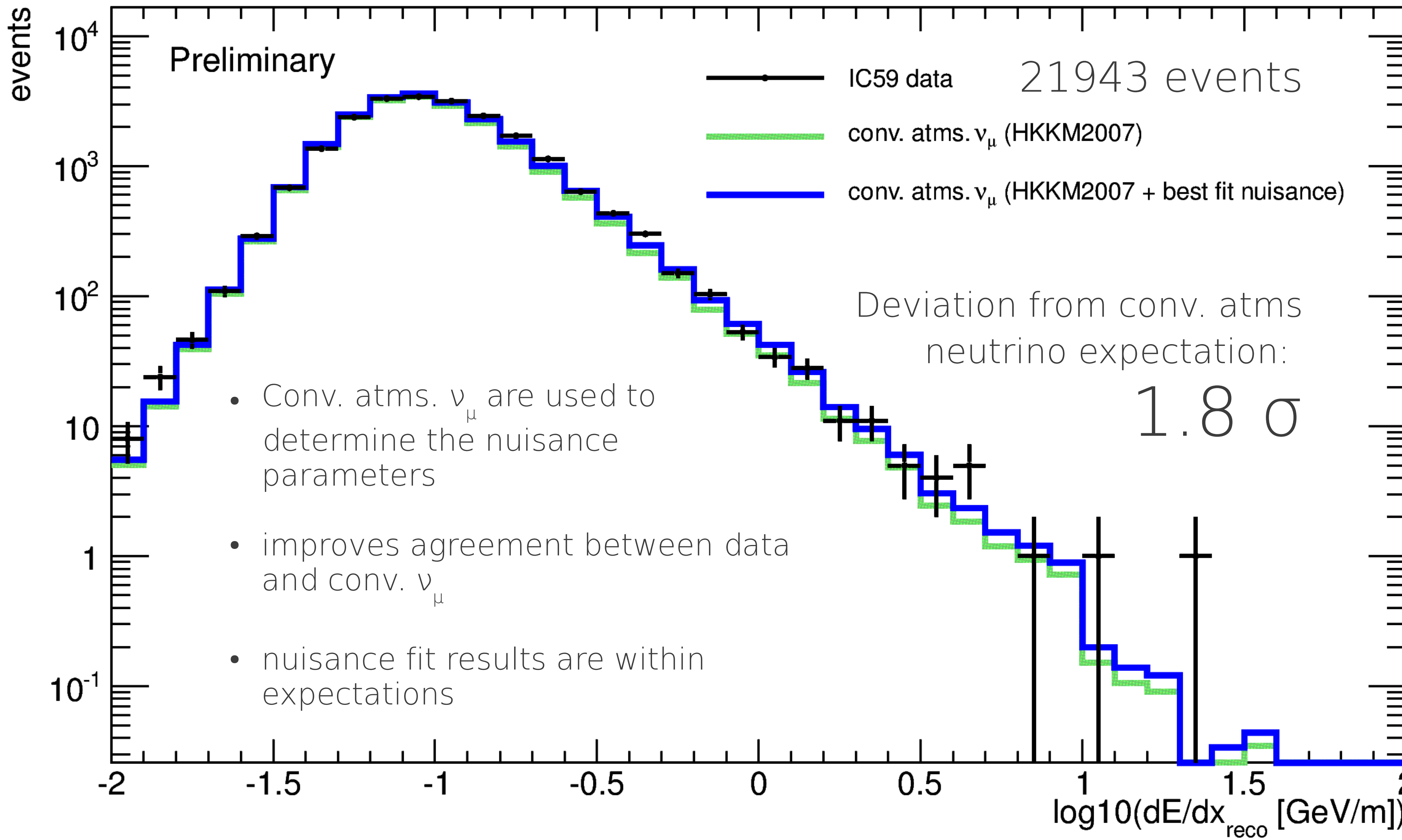
- Photon light yield
- Absolute PMT efficiency
- Cable and metal grid shadowing
- DOM by DOM variations

Total uncertainty: O(15%)

Affects event rates in the tail of the energy distribution
→ free fit nuisance parameter



The final ν_μ energy spectrum



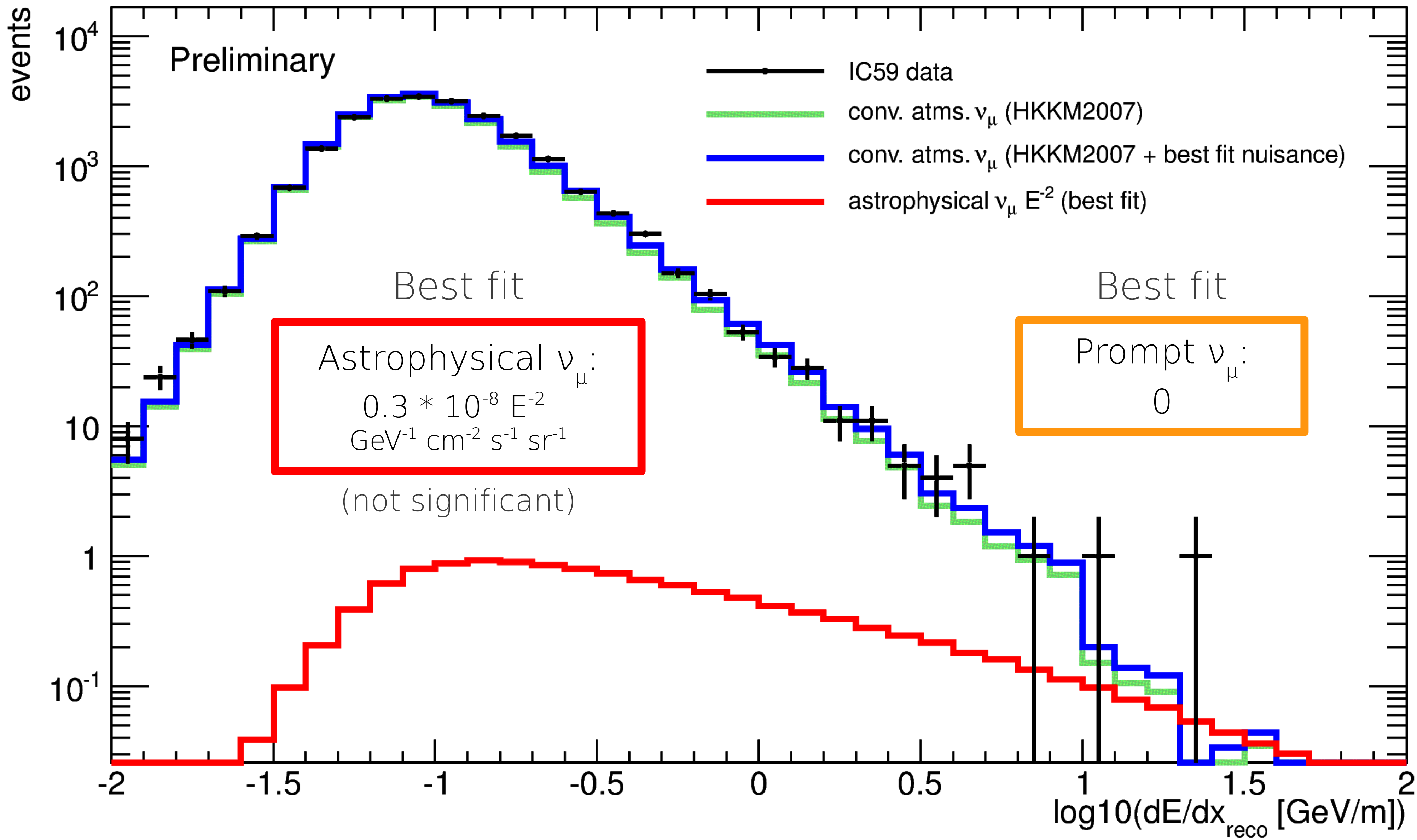
21943 events

Deviation from conv. atms neutrino expectation:

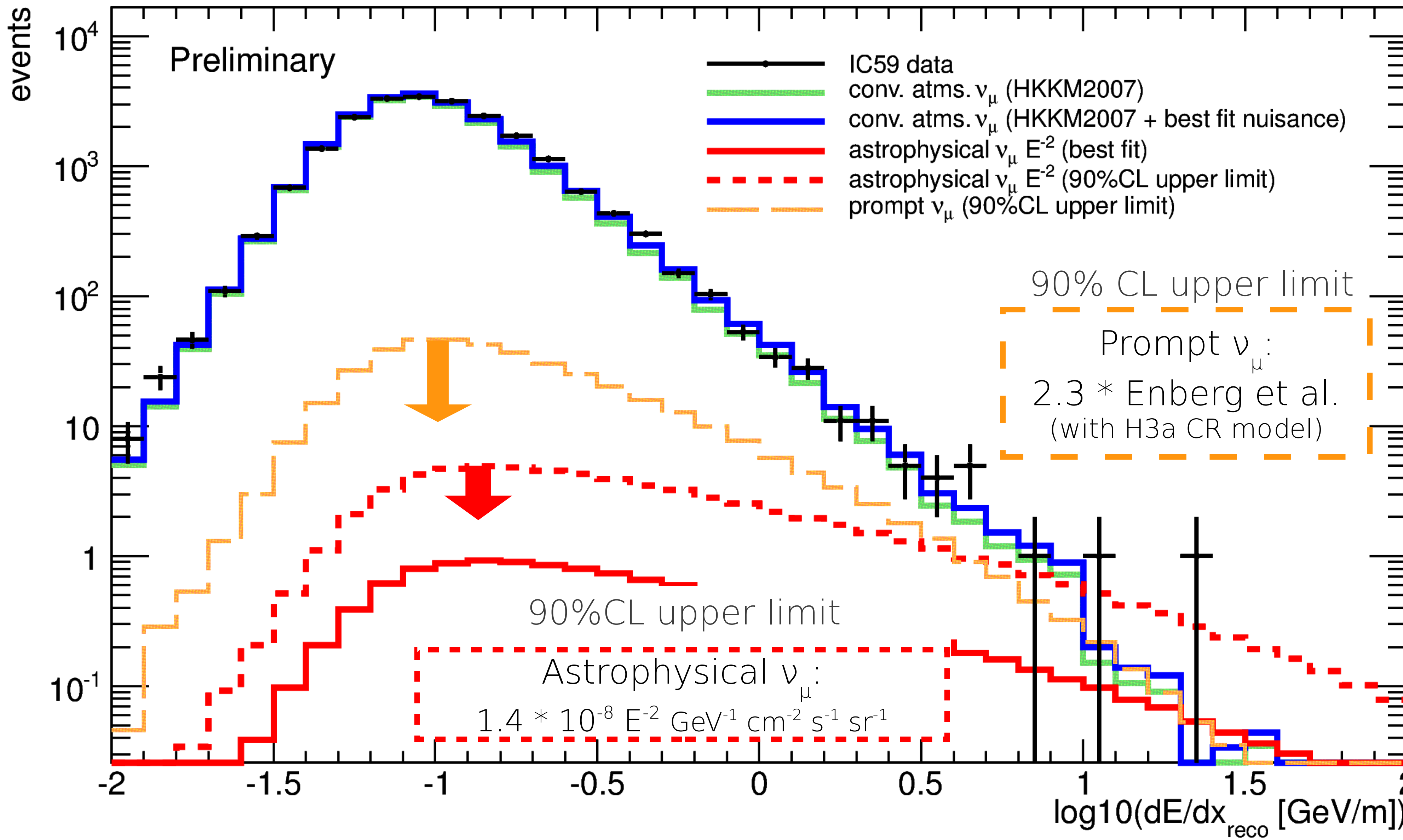
1.8 σ

- Conv. atms. ν_μ are used to determine the nuisance parameters
- improves agreement between data and conv. ν_μ
- nuisance fit results are within expectations

The final ν_μ energy spectrum – Best fit



The final ν_μ energy spectrum – Upper limits



Experimental constraints to prompt models

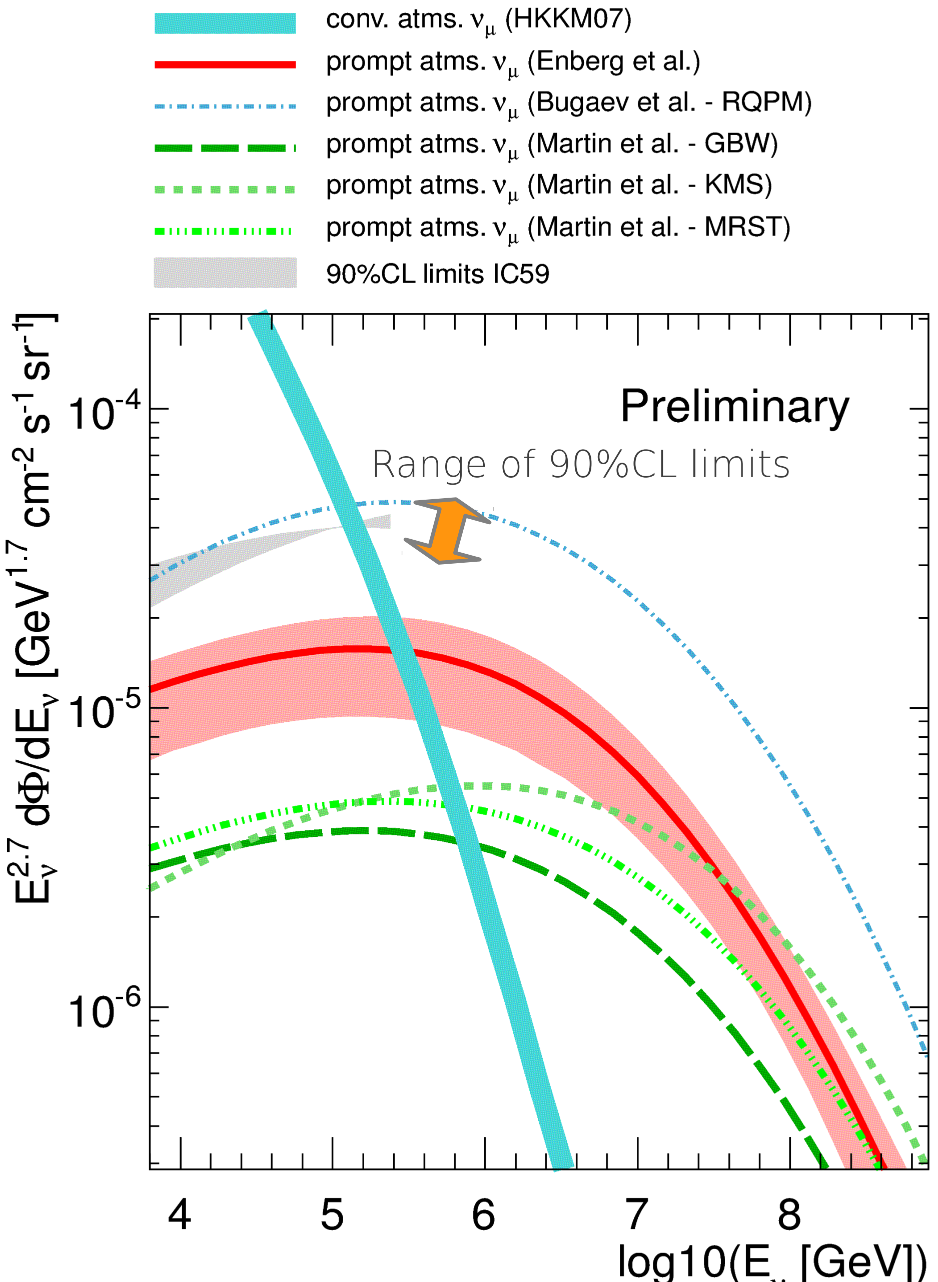
Model rejection factors as a display format of prompt limits:

$$MRF = \frac{\text{90\%CL model flux}}{\text{predicted model flux}}$$

Model	MRF
Enberg et al. std.	2.5
Enberg et al. min	4.3
Enberg et al. max	2.0
Bugaev et al. RQPM	0.9
Martin et al. GBW	10.4
Martin et al. KMS	8.7
Martin et al. MRS	8.4

Preliminary

(Note:
No CR knee systematics included in the models and MRFs/limits)



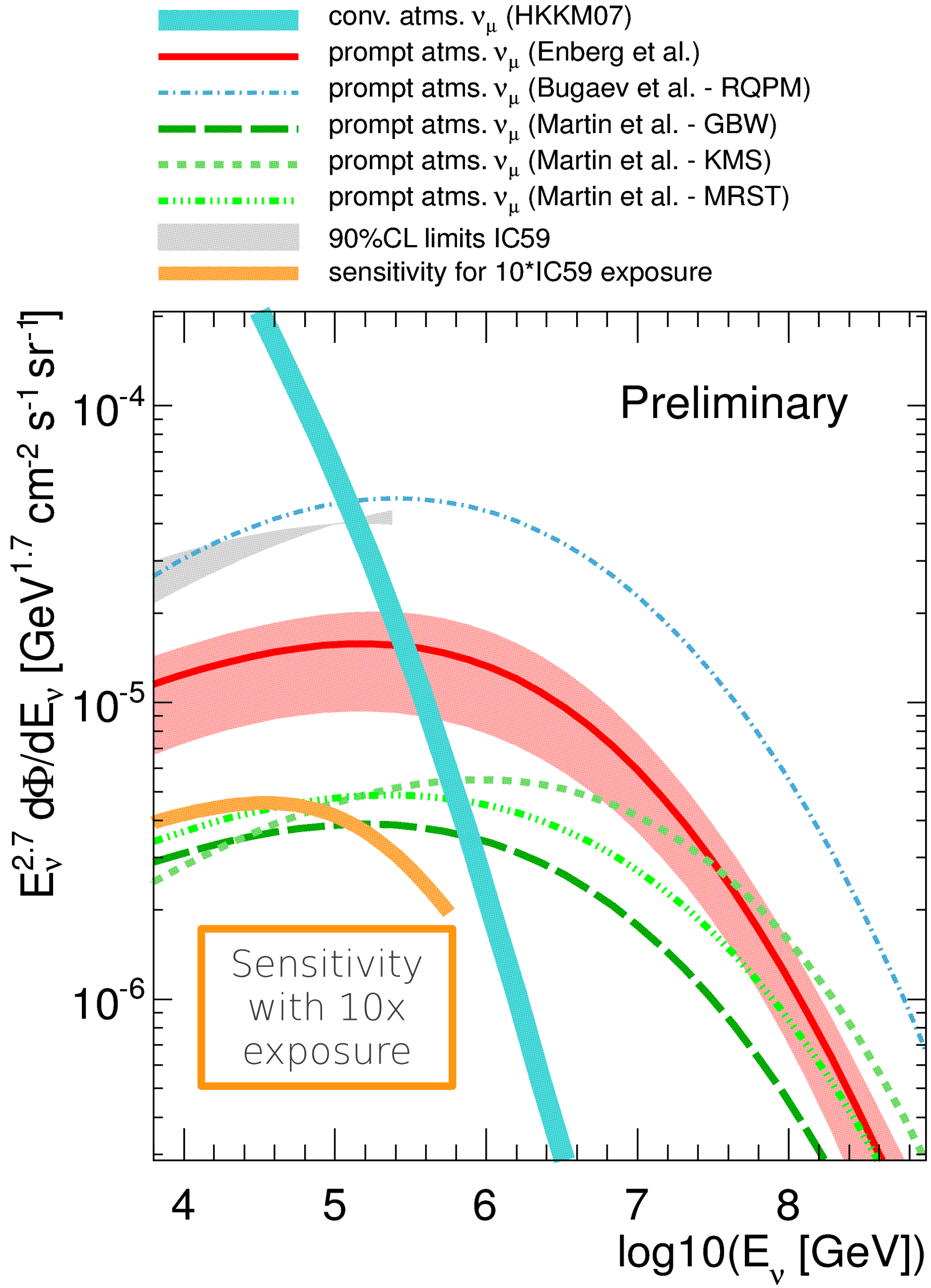
Outlook

With several years of the full detector the sensitivity reaches below current prompt predictions

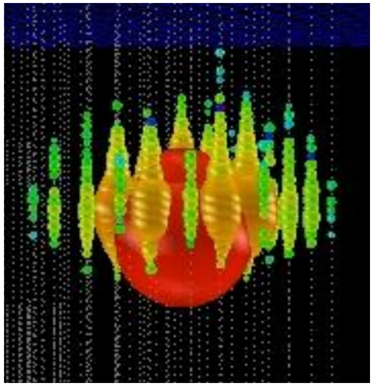
(assuming that no prompt or astrophysical signal is measured)

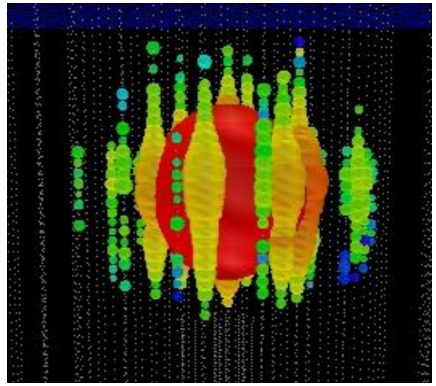
Further improvements:

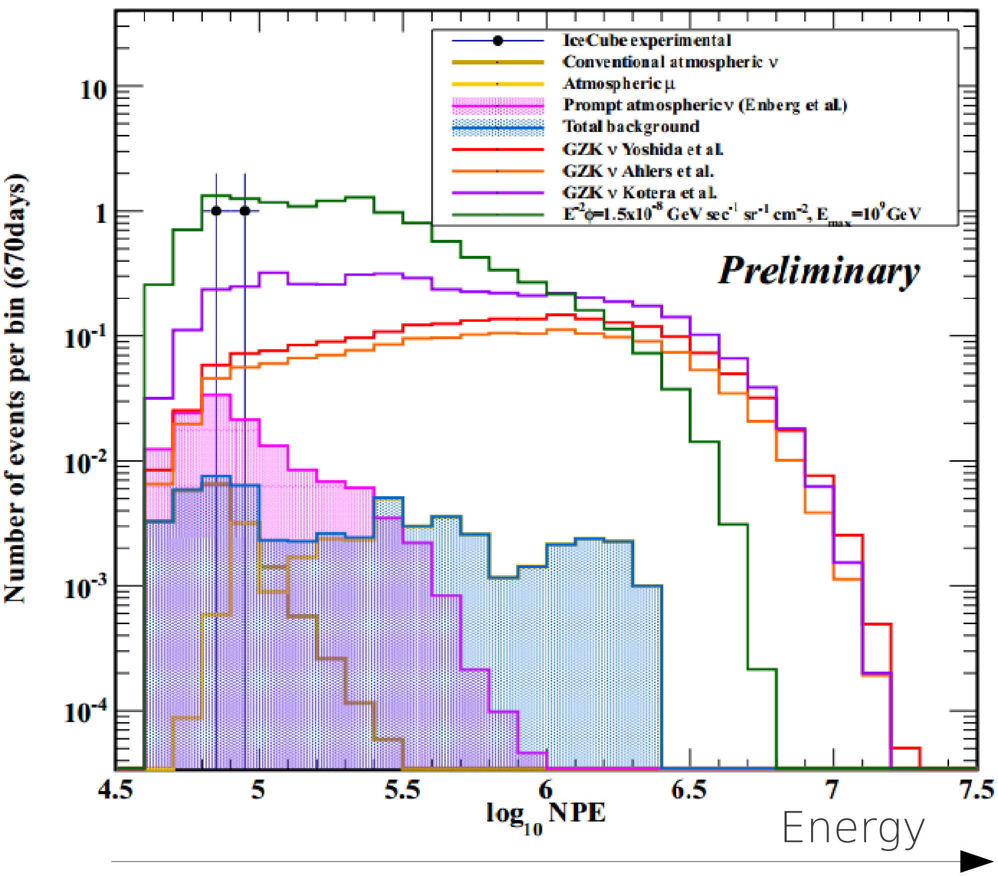
- Full (= larger) detector
  → increases energy range
- Add cascade channel
  → less conv. atmospheric background for ν_e
  → precise energy measurement for contained events



The two EHE events in IC86







Expected event numbers

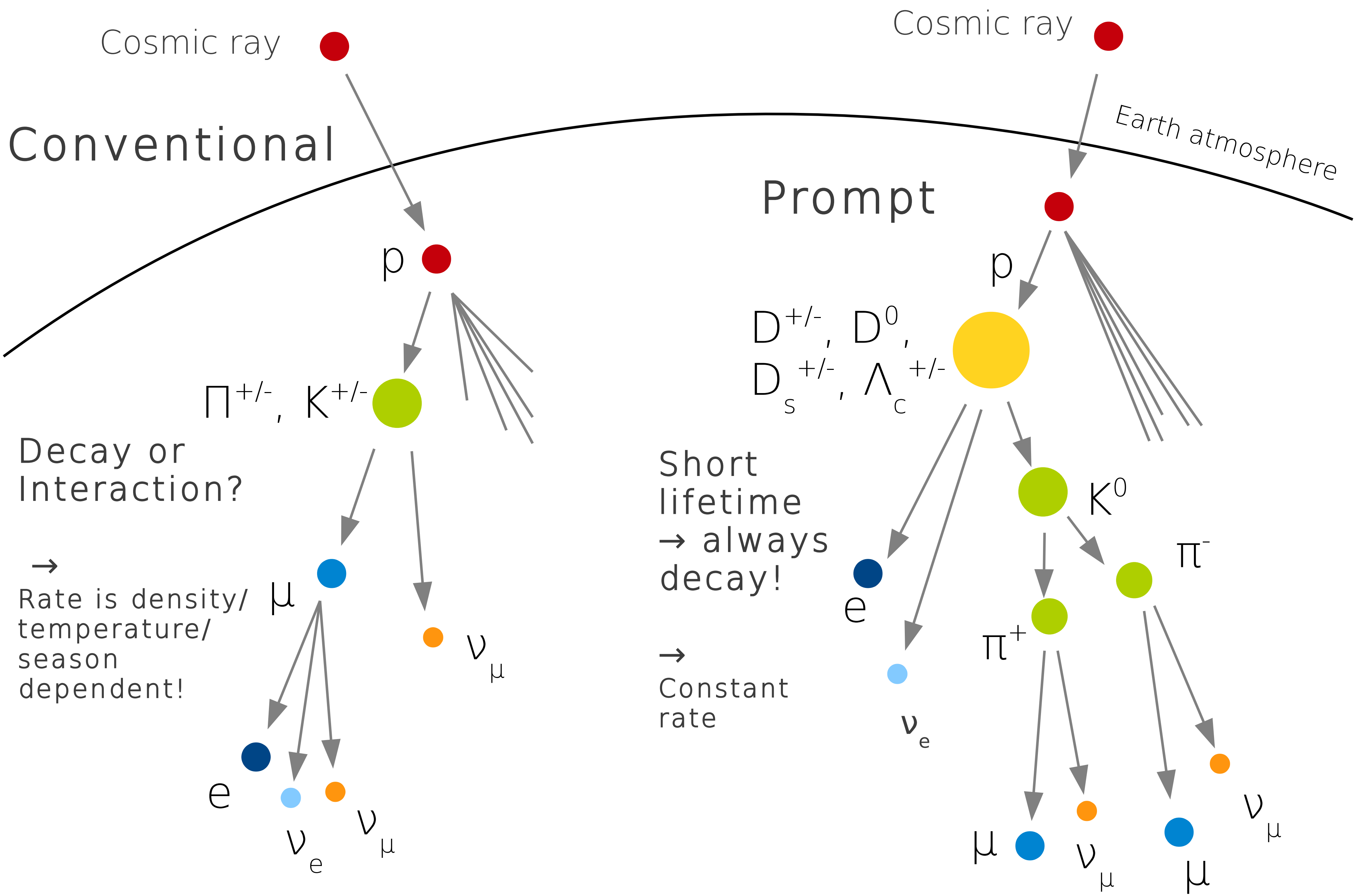
Atms. Background (conv. ν + μ)	0.06
Prompt atms. ν (Enberg et al. + knee)	0.13
Prompt (IC59 limit)	0.30
Astrophysical (IC59 best fit) 0.3×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}	1.7
Astrophysical (IC59 limit) 1.4×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}	9.1
GZK (various models)	0 – 4
Data	2

First PeV-events detected at the low-energy threshold of the IC86 EHE analysis!

Events look like good neutrino cascades.

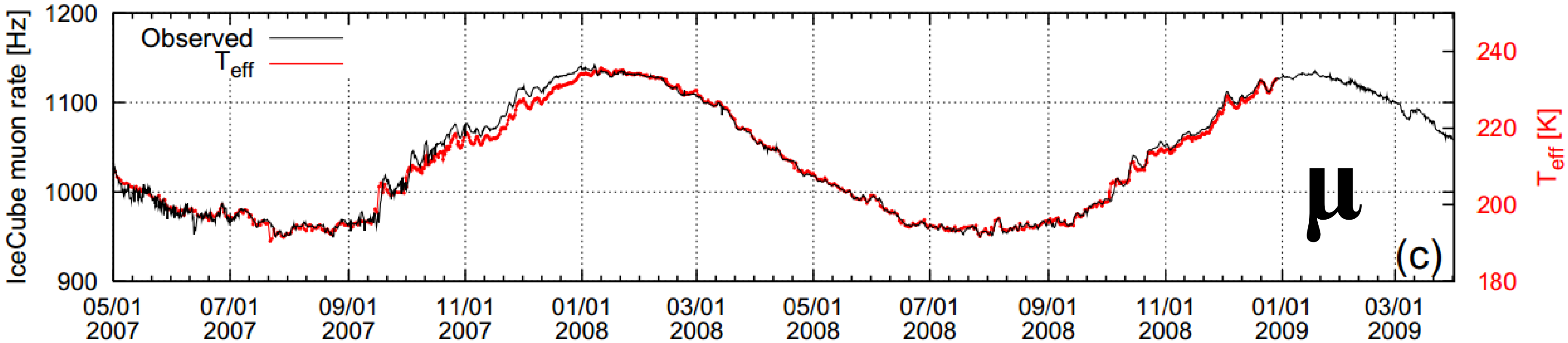
Probability to be consistent with conv. atms. or prompt is very small.

Seasonal variation of atmospheric neutrinos



A prompt limit from seasonal variations

Seasonal variations in the downgoing muon rate
→ very large statistics (150 billion events, medium energy ~ 20 TeV)



IceCube, ICRC2011, arXiv:1111.2735v2
P. Desiati and T. Gaisser, PRL 105, 121102 (2010)

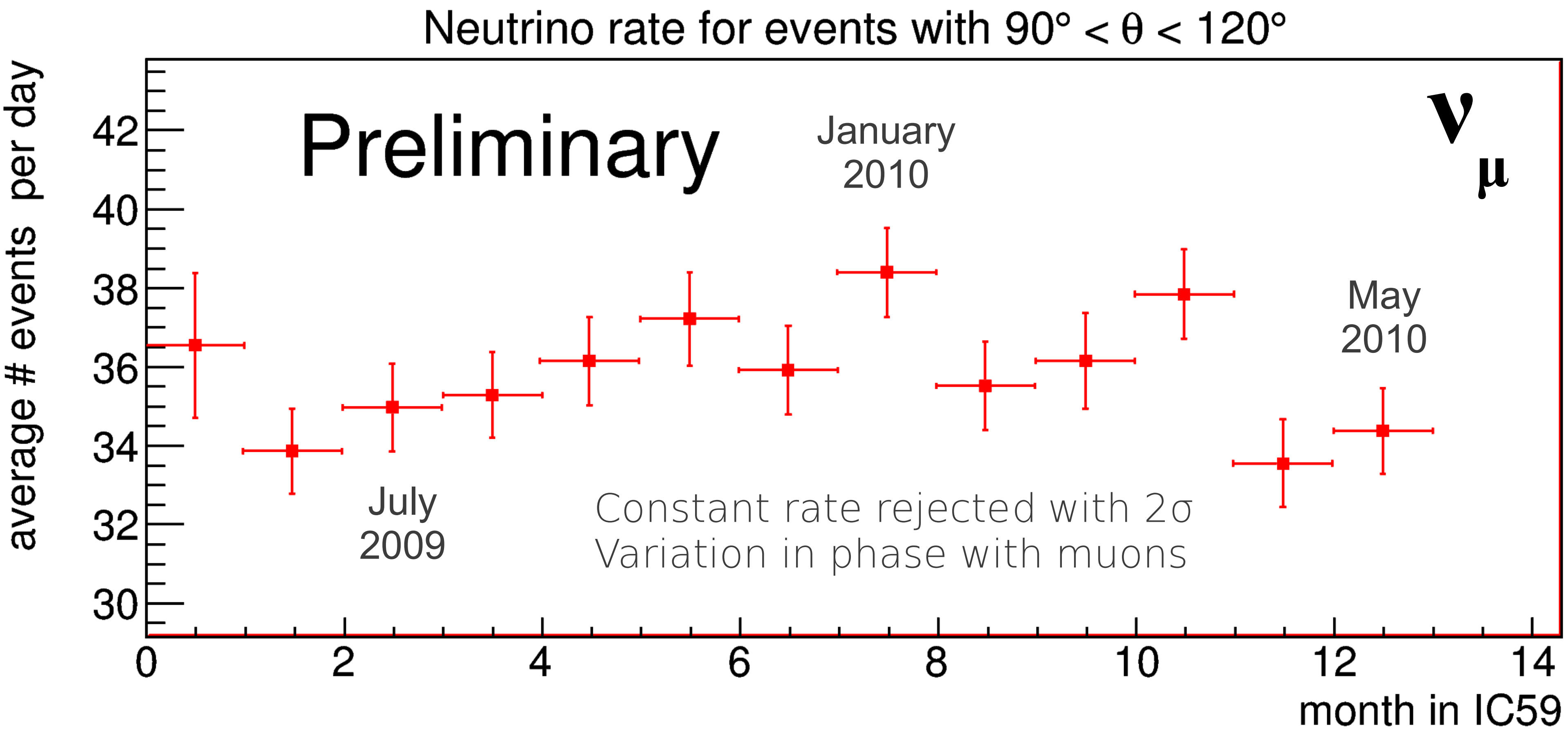
$$\frac{\Delta R_{\mu/\nu}}{\langle R_{\mu/\nu} \rangle} = \alpha_{conv} \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$

$$\alpha_{conv}^{exp} = 0.860 \pm 0.002\ (\mathrm{stat.}) \pm 0.010\ (\mathrm{syst.})$$

Expected:
$\alpha_{prompt}^{exp} = 0$

First hints on neutrino seasonal variations

Seasonal variations in the upgoing neutrino rate

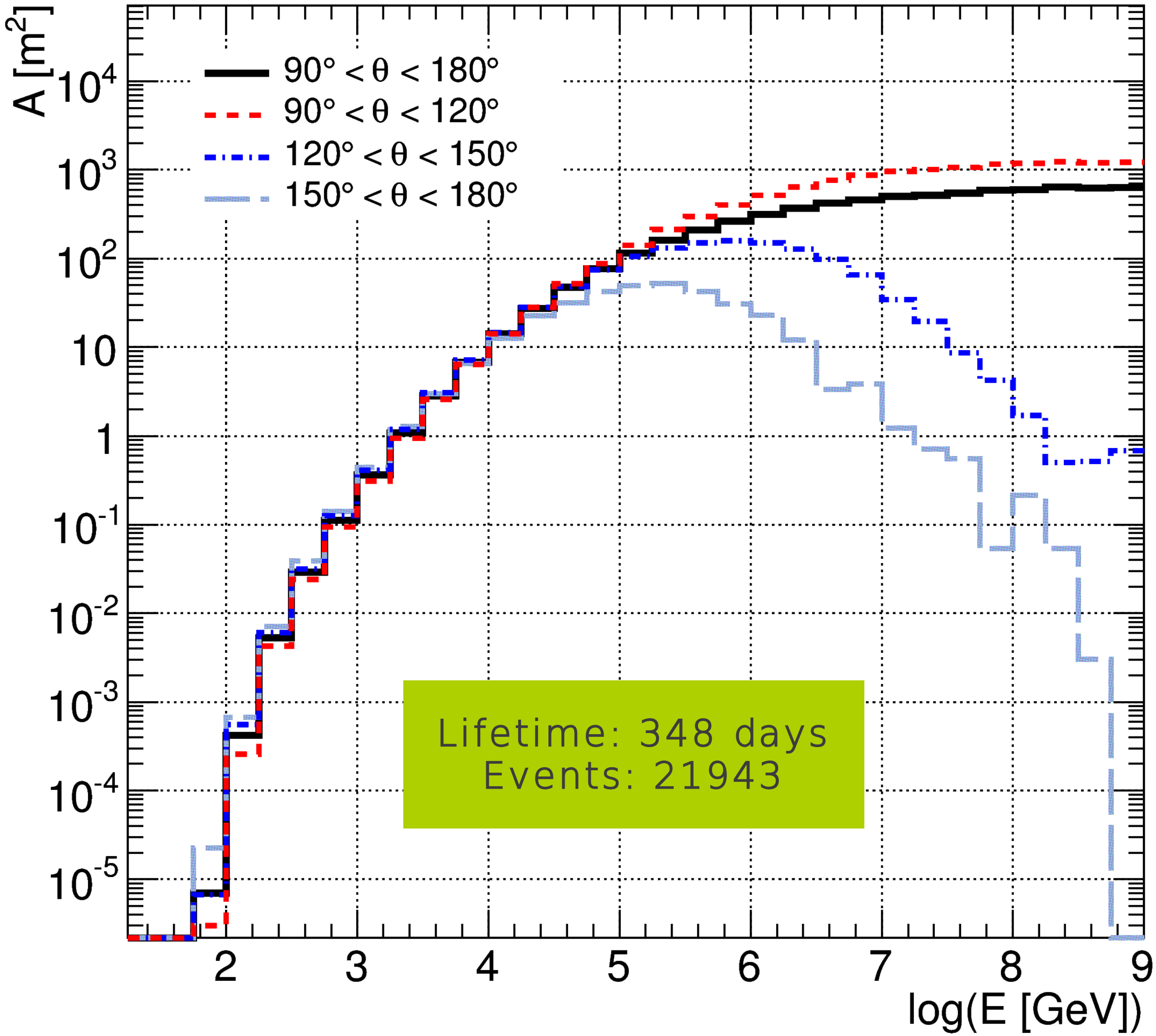


Limit the prompt neutrino flux by searching for the non-oscillating component in the neutrino rate.

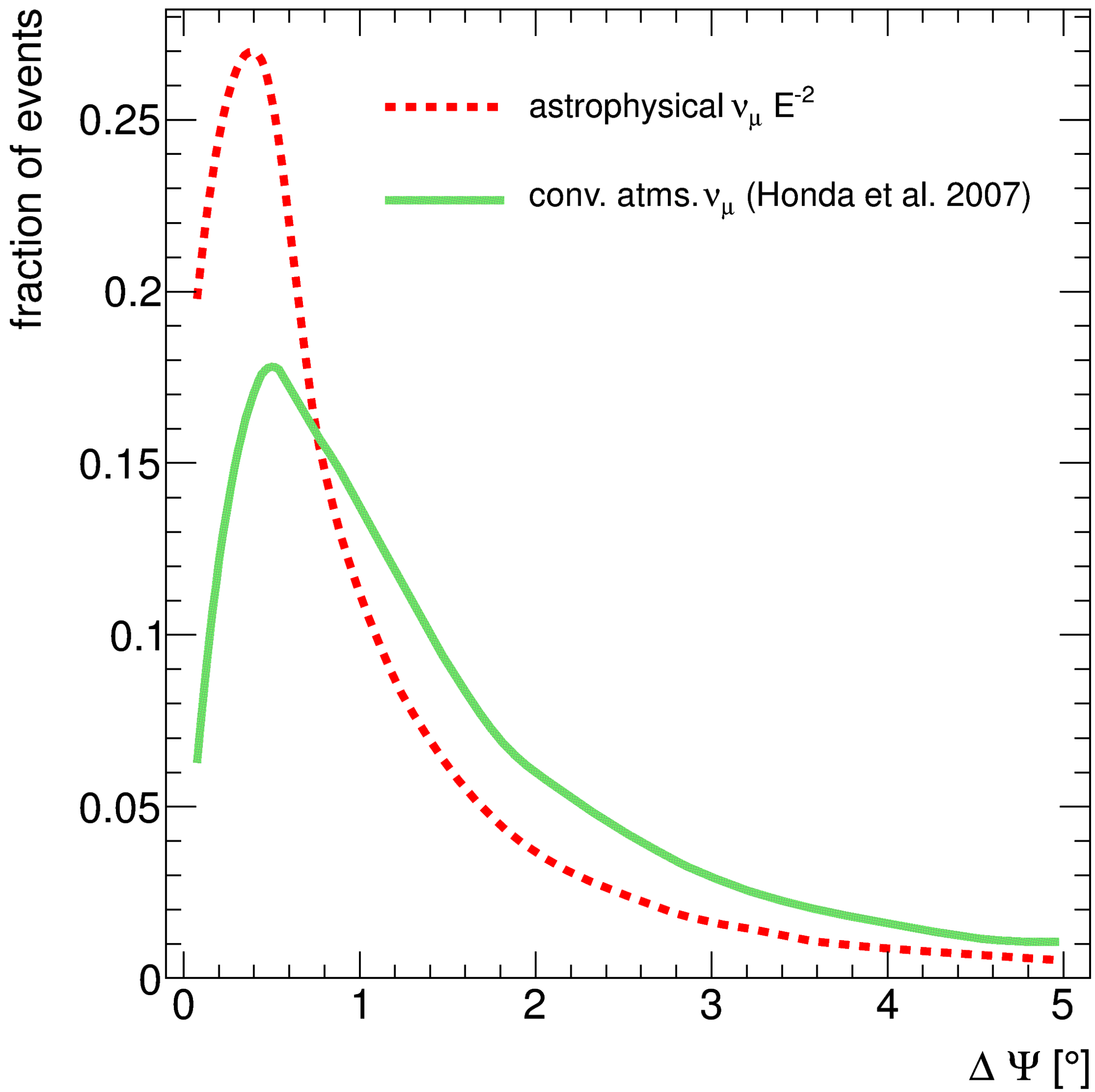
Summary

- Fluxes of conv. atms., prompt atms. and diffuse astrophysical neutrinos are coupled and have to be studied together.
- Diffuse searches are a very active field in IceCube in different channels.
- This talk presented the analysis and results of the IceCube 59-string ν_μ data.
- No astrophysical neutrino flux was found. The limit is in the region of the Waxman-Bahcall upper bound.
- No prompt neutrino flux was found. Limits are a factor of two above theoretical predictions.
- Theoretical predictions are in reach with the exposure of several years of full IceCube detector and improved analysis techniques.

Backup -
The effective area of the 59-string ν_μ sample



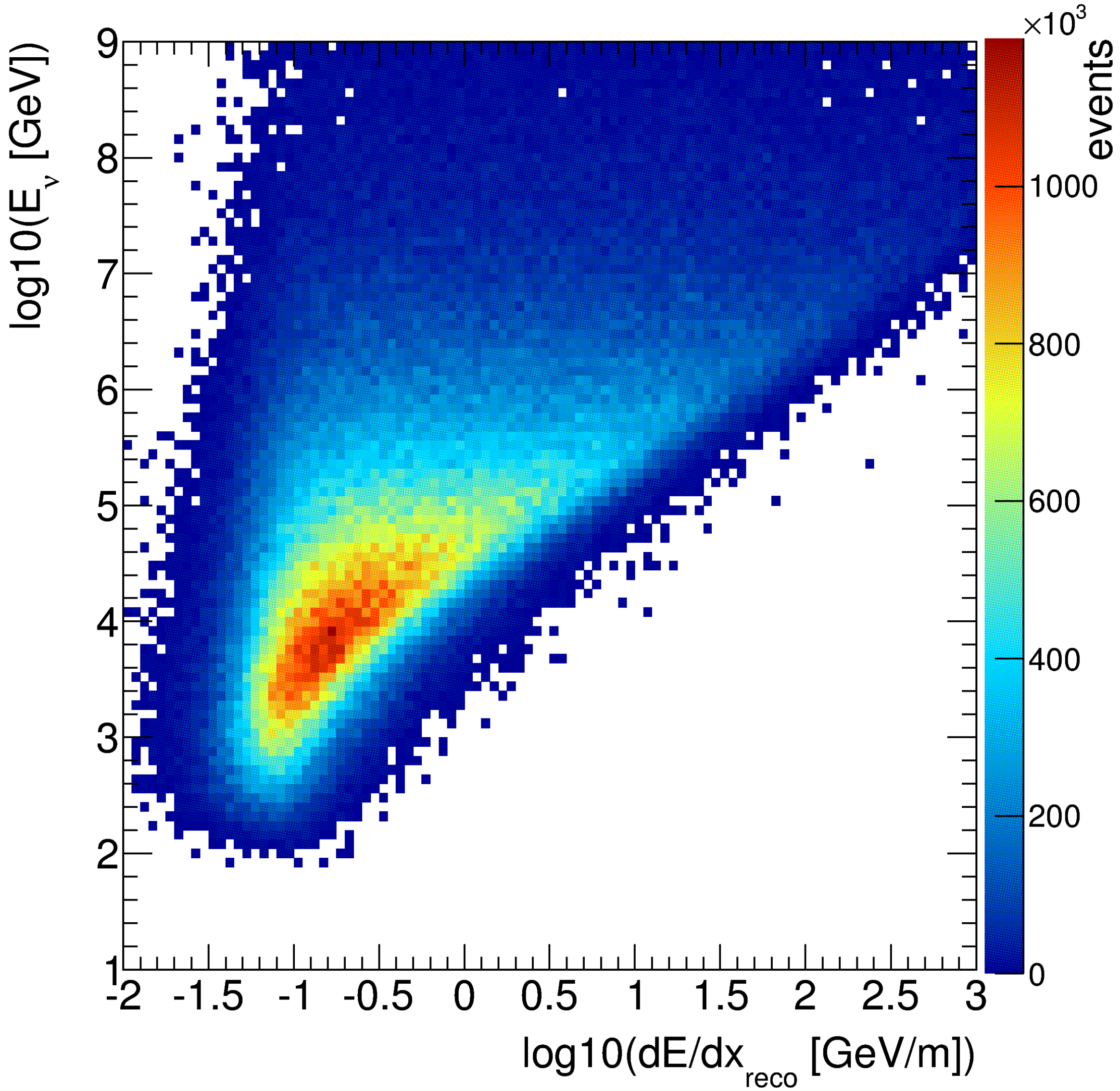
Backup - Angular resolution



Timing information of hit Optical modules allows angular reconstruction.

50% of the events reconstructed better than 1° at final level.

Backup - Energy reconstruction



Event brightness
→ correlated to muon energy loss
→ proportional to muon energy
→ correlated to neutrino energy

Backup - Likelihood fitting with systematics

Systematic uncertainties influence the pdfs and therefore the likelihood fit results

→

Parameterize the effect of different systematic uncertainties on the pdfs and implement systematics parameters as free fit parameters (**nuisance parameters**)

$$\mathcal{L} = \left(\prod_{i,j} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} \cdot e^{-\mu_{ij}} \right) \cdot e^{-\frac{1}{2}\left(\frac{\epsilon-\epsilon_0}{\sigma_\epsilon}\right)^2}$$

Expectation

Gaussian penalty term

Basic likelihood term

Constraint for range of the nuisance parameter

Significance calculation with a profile likelihood as test statistics

$$\mathcal{R} = 2 \ln \frac{\mathcal{L}}{\mathcal{L}_0}$$

All parameters floating

Only nuisance parameters floating

G. Feldman and R. Cousins. Phys. Rev. D., 57:3873 (1998)

Backup –
The calculation of a neutrino knee

$$\phi_\nu (E_\nu, \theta) = \int dE_0 \quad \phi_N (E_0) \cdot Y_\nu (E_\nu, E_0, \theta)$$

Neutrino yield factor

The Elbert formula for the calculation of a muon flux

$$N_\mu(> E_\mu) = \frac{\mathcal{E}_\mu^*}{E_\mu \cos\theta} \left(\frac{E_0}{AE_\mu}\right)^p \left(1 - \frac{AE_\mu}{E_0}\right)^q$$

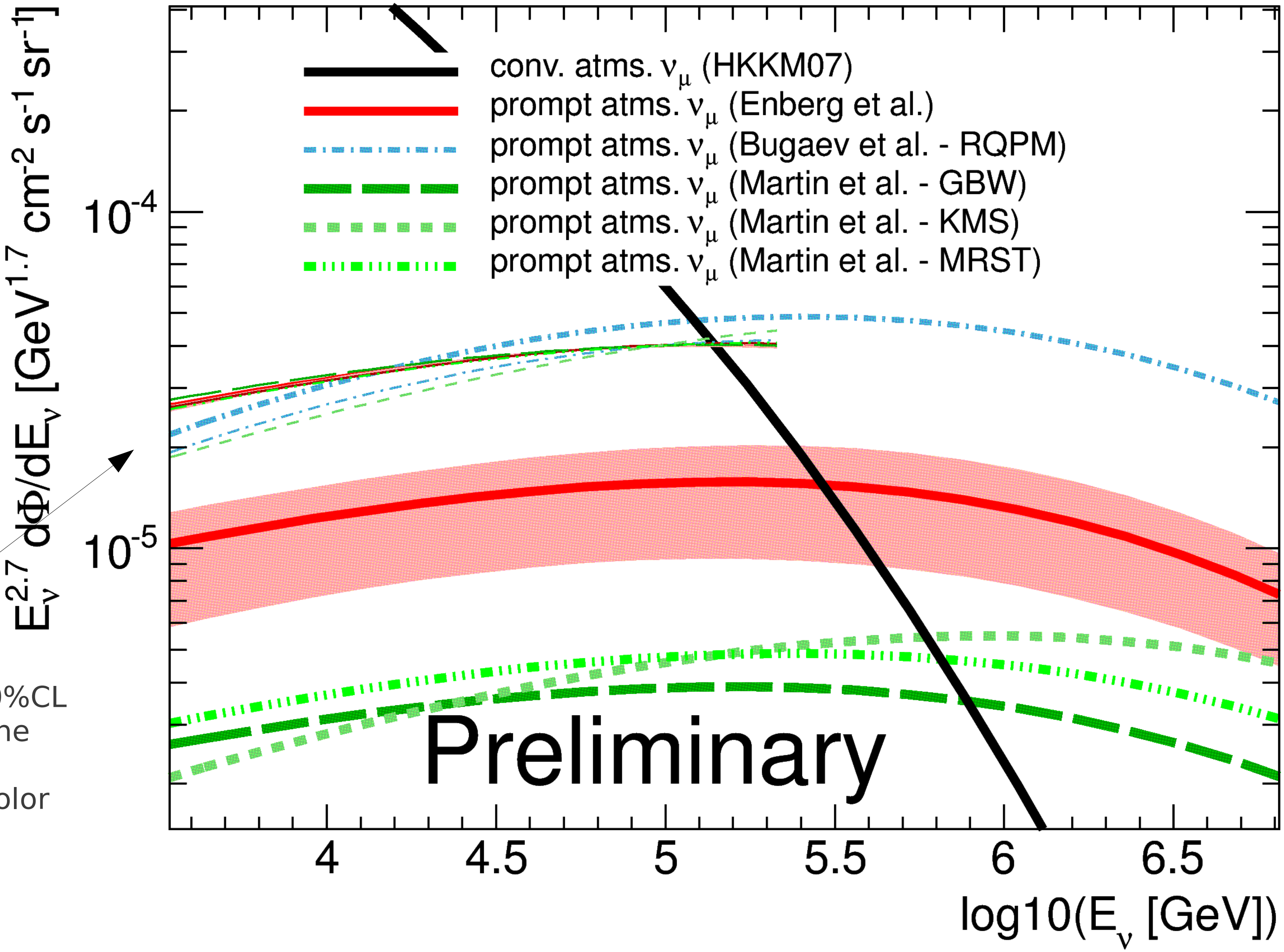
$$\mathcal{E}_\mu^* \approx 14.5\, GeV, \;\; p \approx 0.76 \; and \; q \approx 5.25$$

J.W. Elbert, In Proc. DUMAND Summer Workshop (ed. A. Roberts), 1978, vol. 2, p. 101
P. Lipari, Astropart.'Phys.'1'(1993)'399B415

Replacing the decay kinematics p → m by p → n yields $\mathcal{E}_\nu^* \approx 4.8\, GeV$ and allows calculation of the neutrino yield (T. Gaisser, 2012)

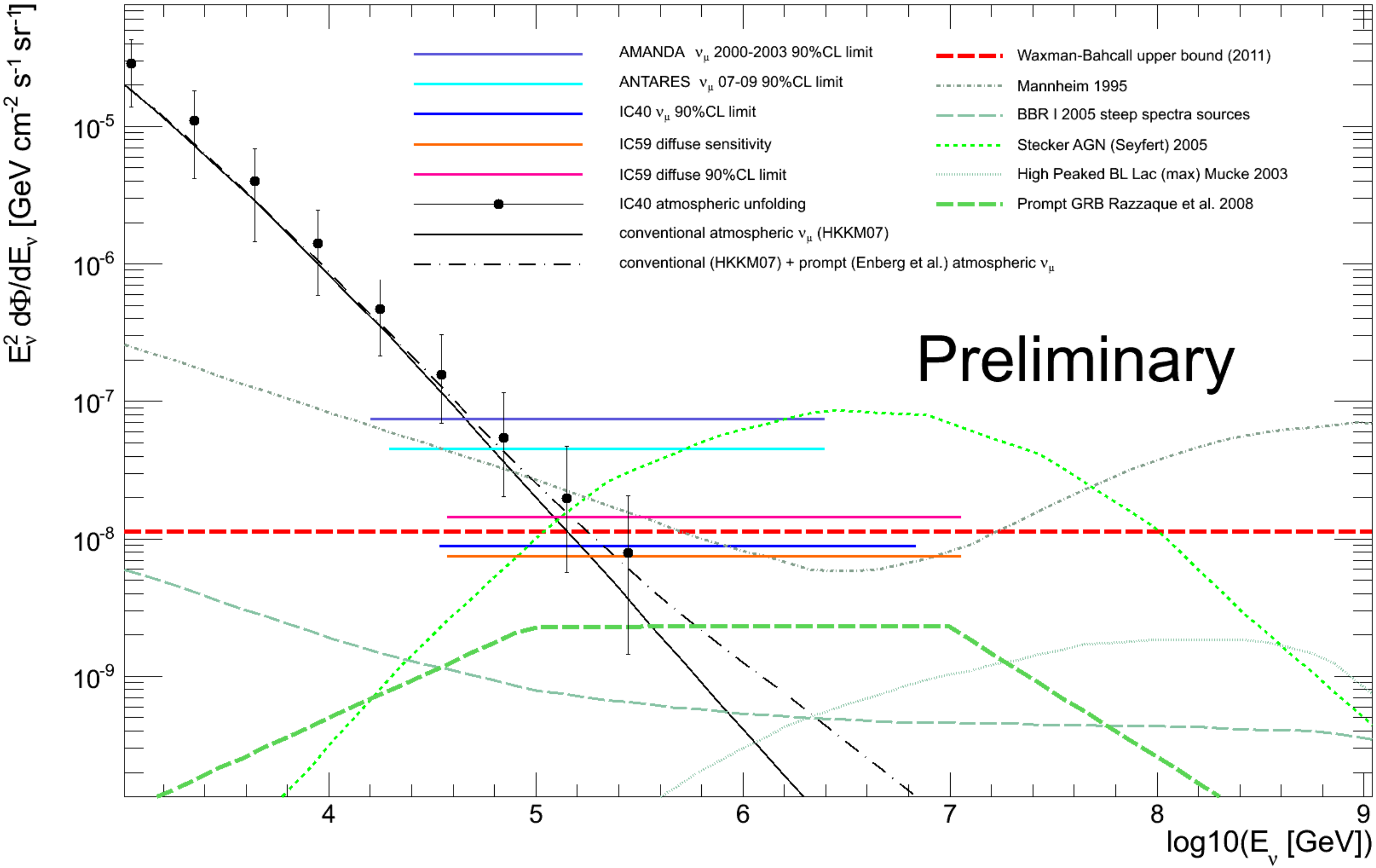
Alternative approach: Get neutrino yield factor from CORSIKA air shower simulation

Backup – Prompt individual limits



Thin lines are 90%CL upper limits to the model in the corresponding color and line style

Backup - Astrophysical limit



Backup - EHE expected event numbers

Background Contributions	Event Rates in 670days
Atmospheric muons	0.036 ± 0.0062
Conventional atmospheric neutrinos	0.021 ± 0.001
Total background	0.0573 ± 0.0063
Total background with prompt ν	0.190 ± 0.0063

Table 1: Expected number of events in 670.1 days of effective livetime. Errors includes statistical only.

Signal Models	Event Rates	Event Rates $E_\nu \geq$100 PeV
cosmogenic Yoshida et al. [9]	2.1	1.7
cosmogenic Kotera et al. (FRII) [11]	4.1	2.4
cosmogenic Ahlers et al. (maximal) [12]	3.2	2.7
cosmogenic Ahlers et al. (the best fit) [12]	1.6	1.3
$E^2\phi = 1.5\text{x}10^{-8}$ GeVsec^{-1}cm^{-2}sr^{-1} [1]	11.7	1.2
Prompt atmospheric neutrinos Enberg et al. [2]	0.13	1.0 x 10^{-4}

IceCube Experimental	Event Rates	Event Rates $E_\nu \geq 100 PeV$
2010-2011	2	0

Table 2: Expected number of events in 670.1 days of effective livetime.