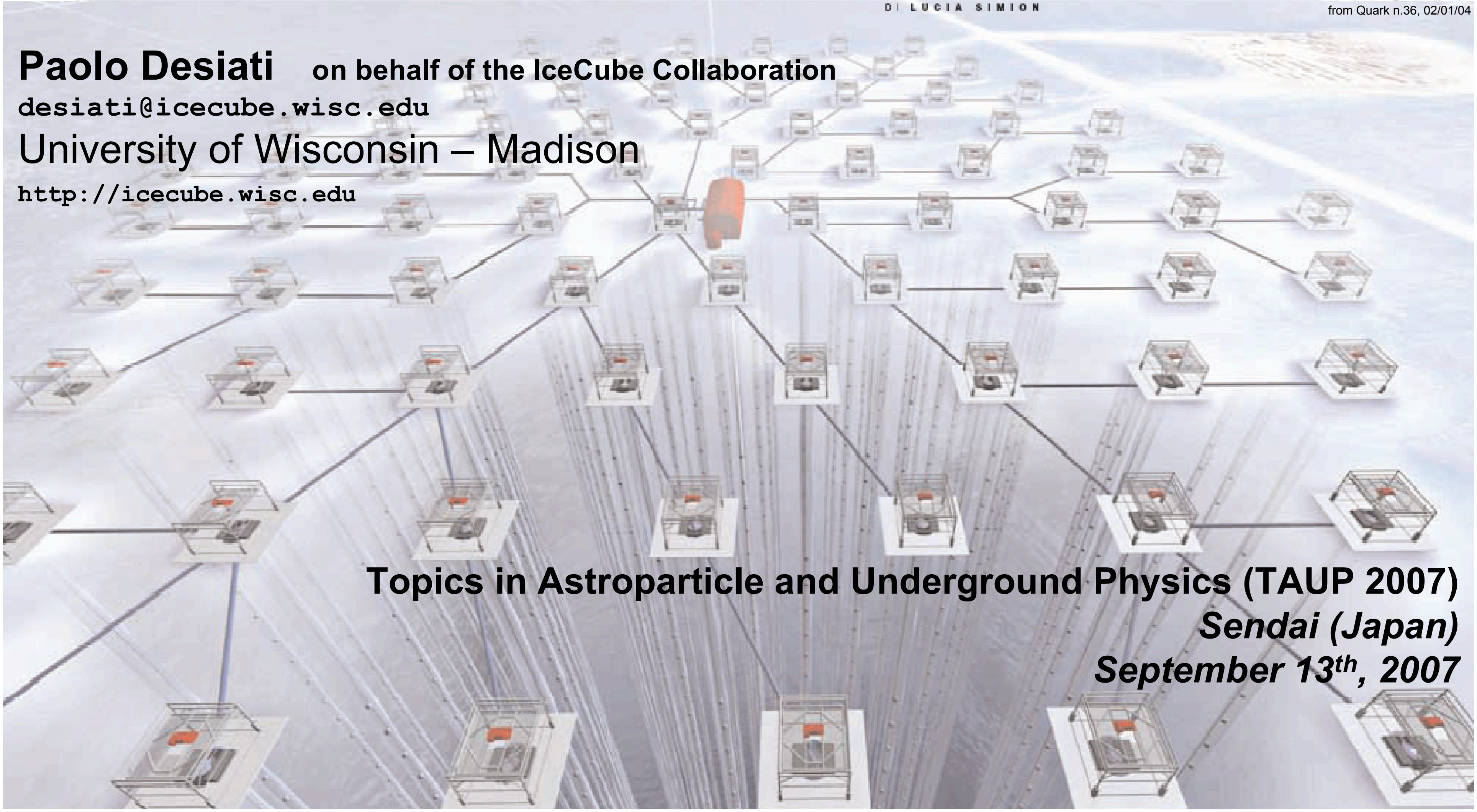
Measurement of the atmospheric neutrino flux with AMANDA-II and IceCube

from Quark n.36, 02/01/04



Paolo Desiati on behalf of the IceCube Collaboration
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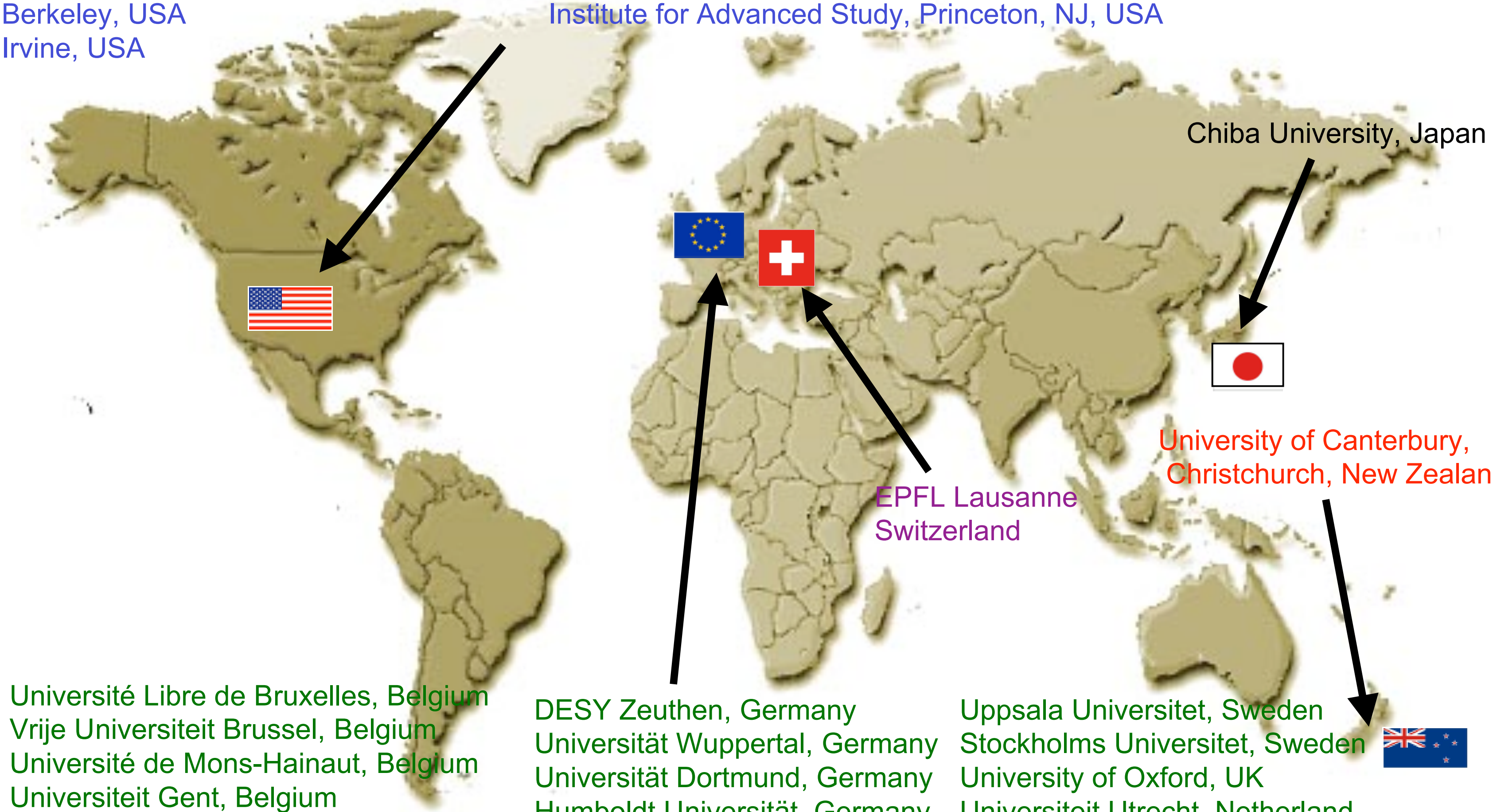
University of Wisconsin – Madison
http://icecube.wisc.edu

Topics in Astroparticle and Underground Physics (TAUP 2007)
Sendai (Japan)
September 13th, 2007

Who is in IceCube ?



Bartol Research Inst, Univ of Delaware, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA

Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA
University of Alaska – Anchorage, USA
Institute for Advanced Study, Princeton, NJ, USA

Chiba University, Japan

University of Canterbury,
Christchurch, New Zealand

EPFL Lausanne
Switzerland

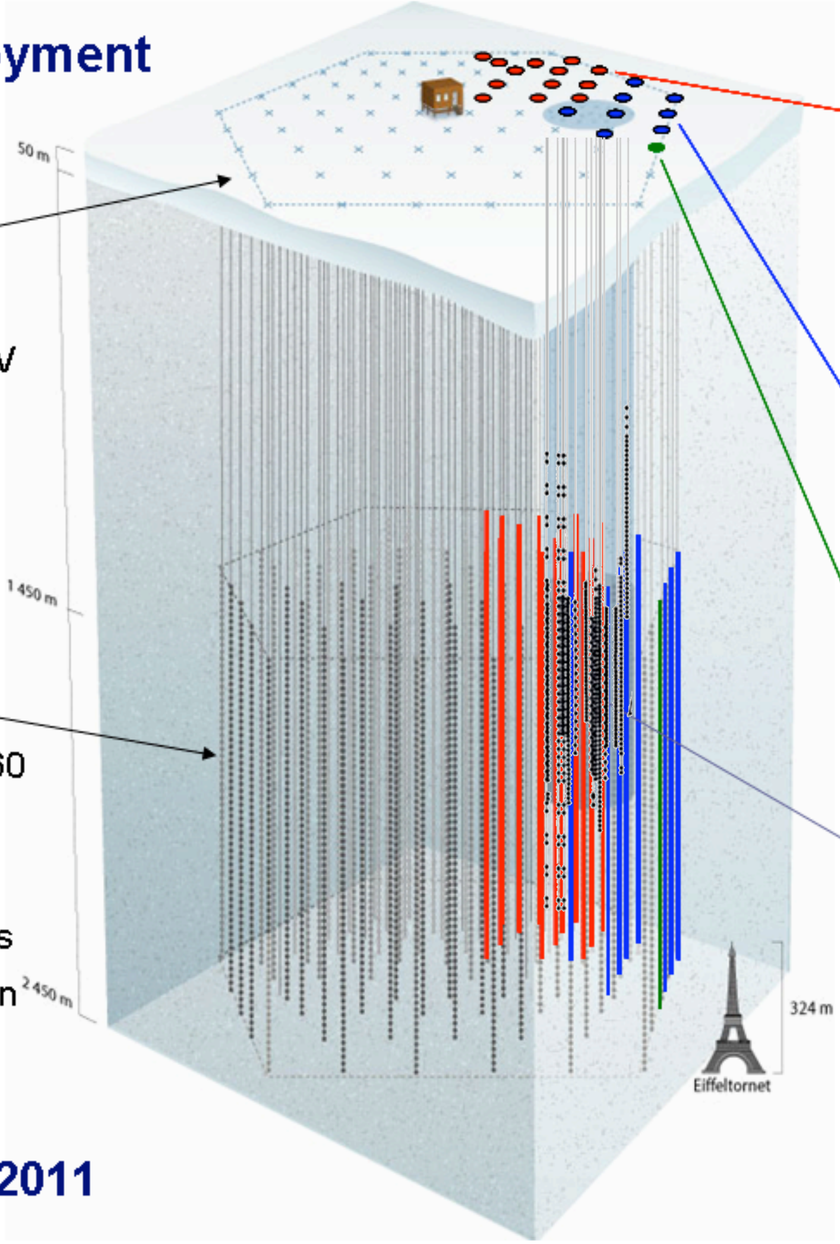
Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium
Universität Mainz, Germany
RWTH Aachen Universität, Germany

DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany
Humboldt Universität, Germany
MPIfK Heidelberg, Germany

Uppsala Universitet, Sweden
Stockholms Universitet, Sweden
University of Oxford, UK
Universiteit Utrecht, Netherland

Amundsen-Scott Station, Antarctica

IceCube Deployment



IceTop

Air shower detector

Threshold ~ 300 TeV

InIce

planned 80 strings of 60 optical modules each

17 m between modules

125 m string separation

2006-2007:

13 strings deployed

Altogether: 22 strings

52 surface tanks

2005-2006: 8 strings

2004-2005 : 1 string

First data in 2005

first upgoing muon:

July 18, 2005

AMANDA

19 strings

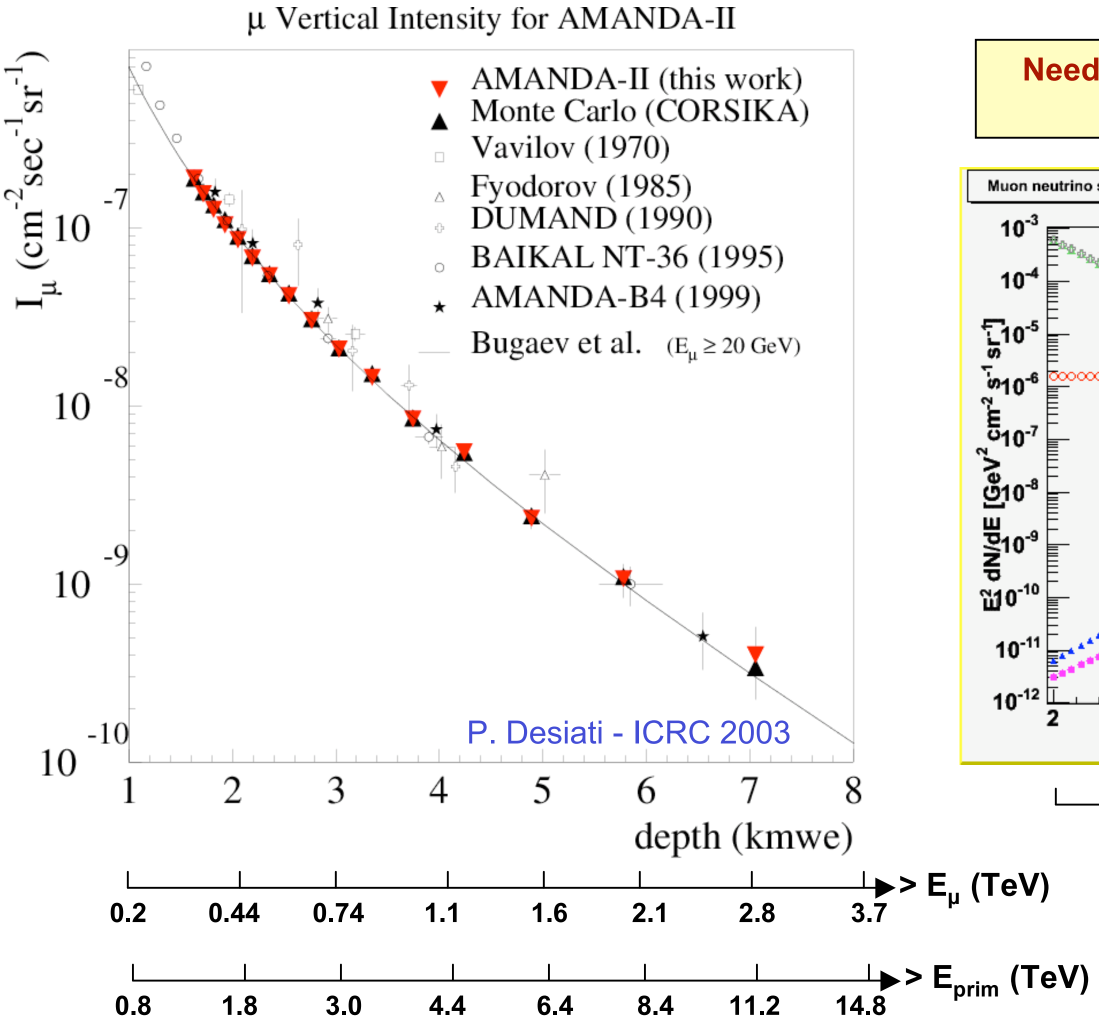
677 modules

17 m between modules

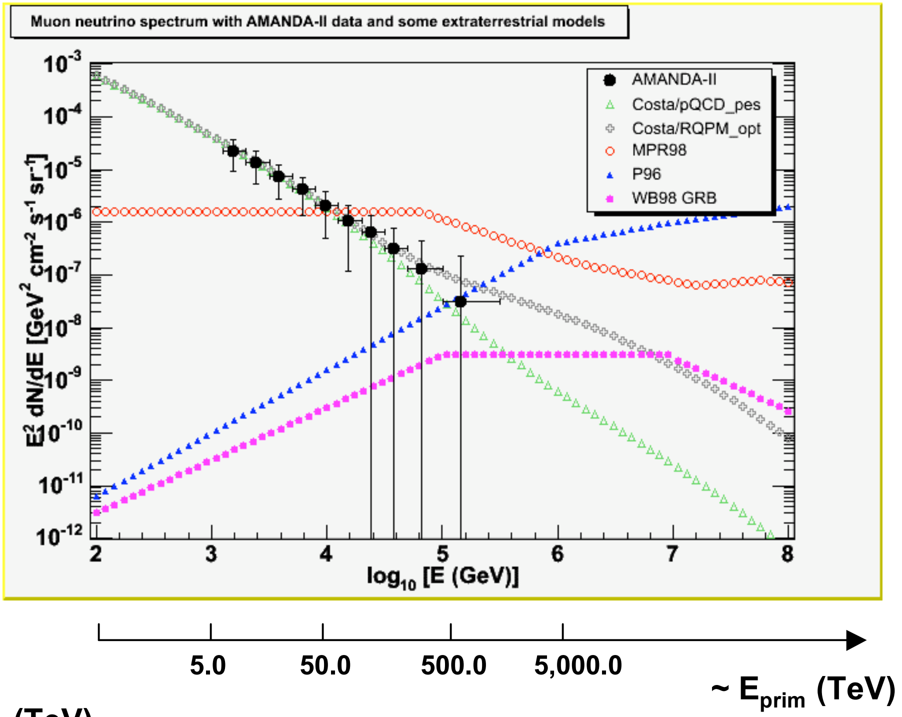
~30 m string separation

Completion by 2011

Understanding the background



Need to understand atmospheric neutrinos where cosmic signal is expected

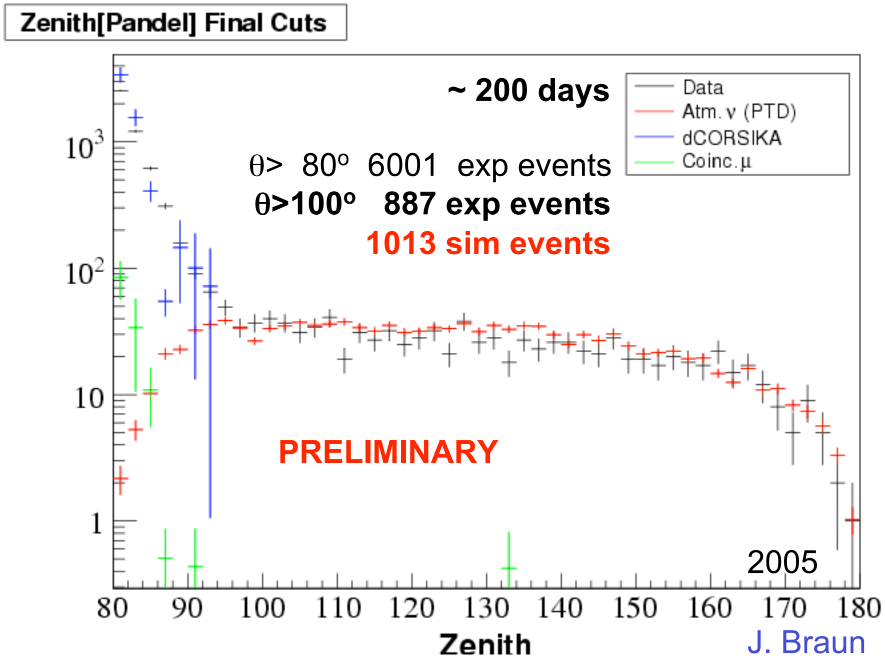


- uncertainties on CR spectrum & composition
- uncertainties on hadronic interaction models
- atmosphere properties
- ice optical properties

- μ background (~10^6 times ν_μ events)
  - mis-reco atmospheric bundles (~10^3 times ν_μ events)
  - coincident events (~10 times ν_μ events)

Constrain measurements at low energy

Rejecting the background : AMANDA-II



~ 200 days

$\theta >$ 80° 6001 exp events

$\theta >$100° 887 exp events

1013 sim events

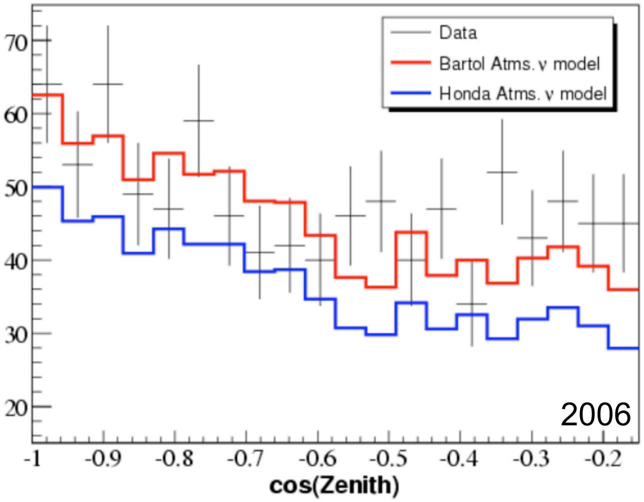
J. Braun

ν_μ event selection:

- high likelihood of up-going tracks
- good angular resolution
- smooth hit distribution along tracks

- background contamination
  - ~10% for $\theta >$100°

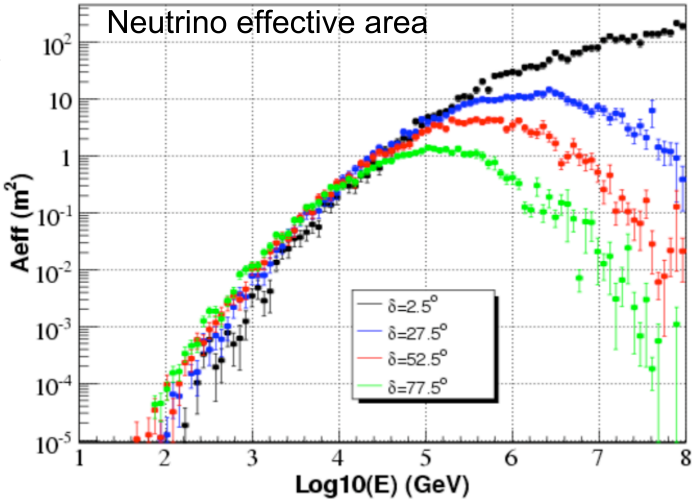
- energy threshold ~50-100 GeV



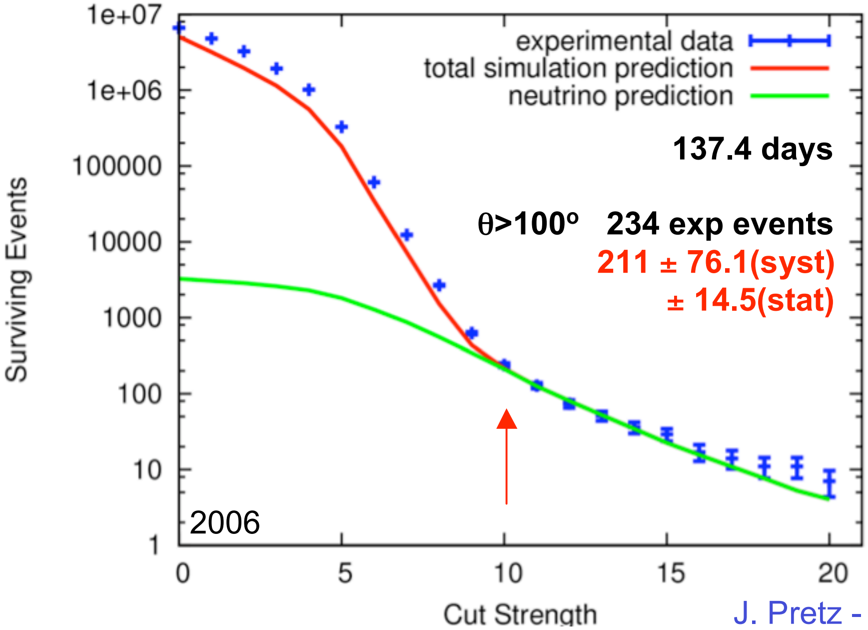
Theoretical uncertainties

~ 30 % in normalization

PRELIMINARY



Rejecting the background : IceCube-9



J. Pretz - ICRC 2007

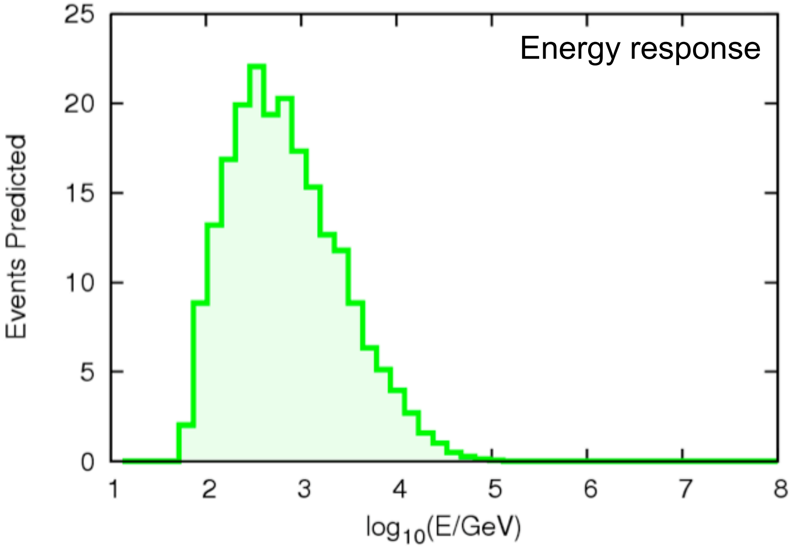
ν_μ event selection:

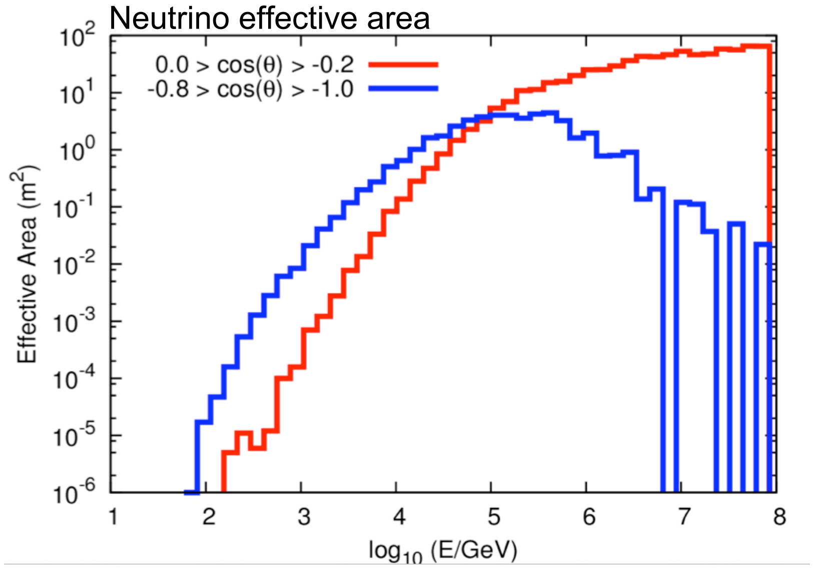
- number of non-scattered photons >= 10
- distance of hits along the track >= 250 m

- cuts designed for 95% neutrino purity
  - ~3% atmospheric neutrino efficiency
  - still ~20-30 background contamination

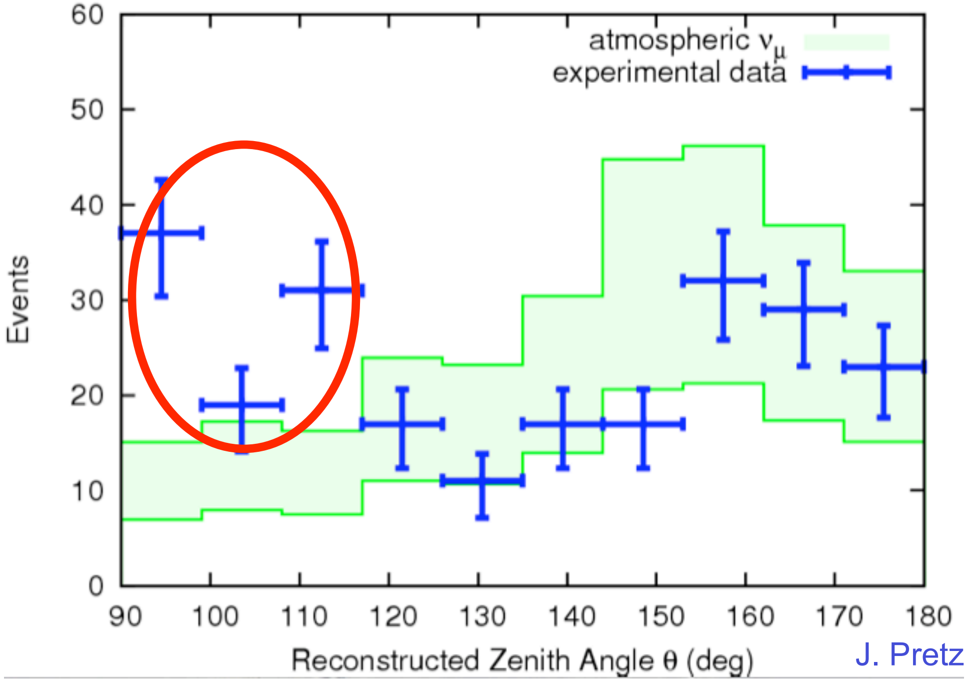
- energy threshold ~100 GeV

Phys.Rev.**D76**:027101,2007

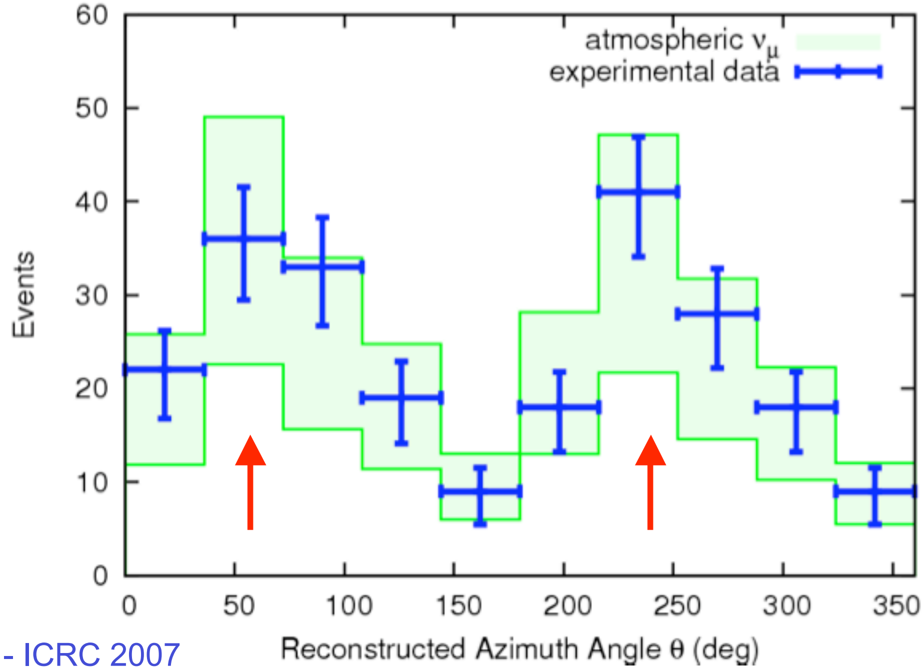




Measuring atmospheric ν_μ in IceCube-9

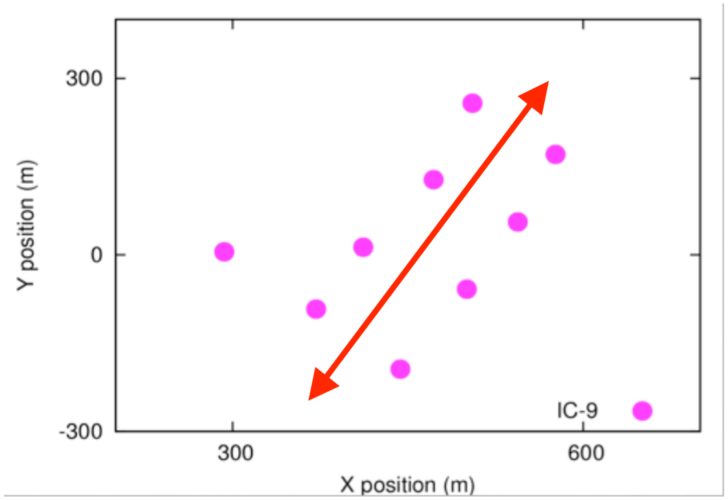


J. Pretz - ICRC 2007

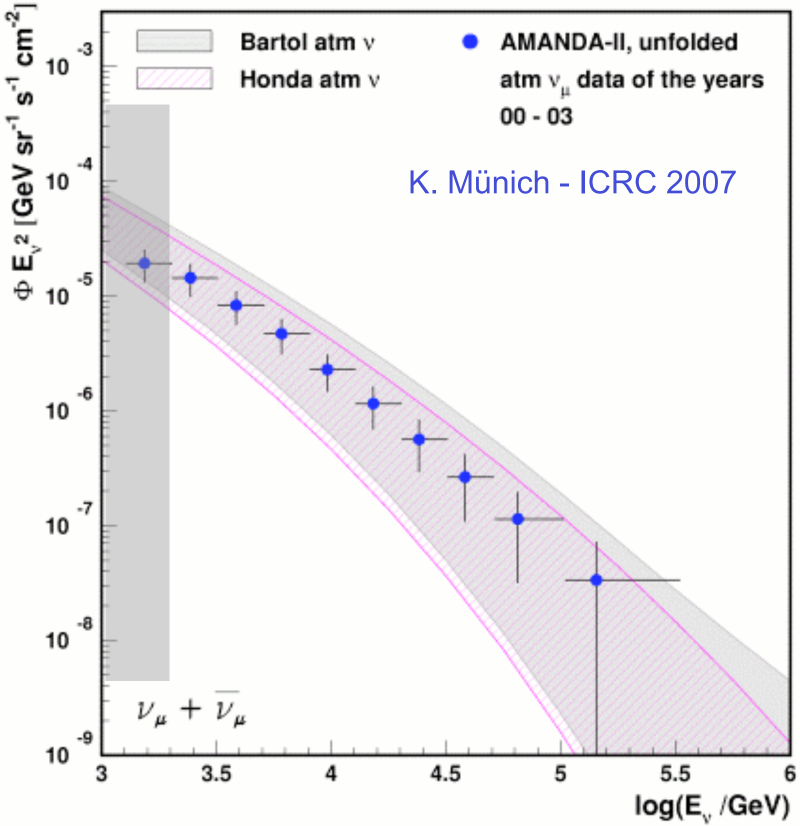


- ~20-30% uncertainties in atmospheric neutrino modeling
- contamination at horizon of lower quality background events

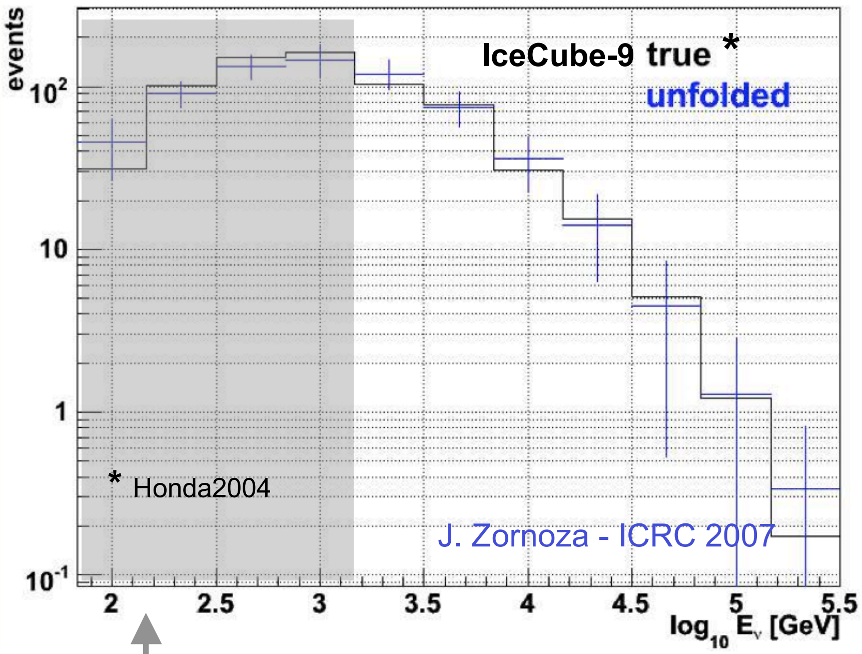
Phys.Rev.**D76**:027101,2007



Measuring the atmospheric ν_μ spectrum



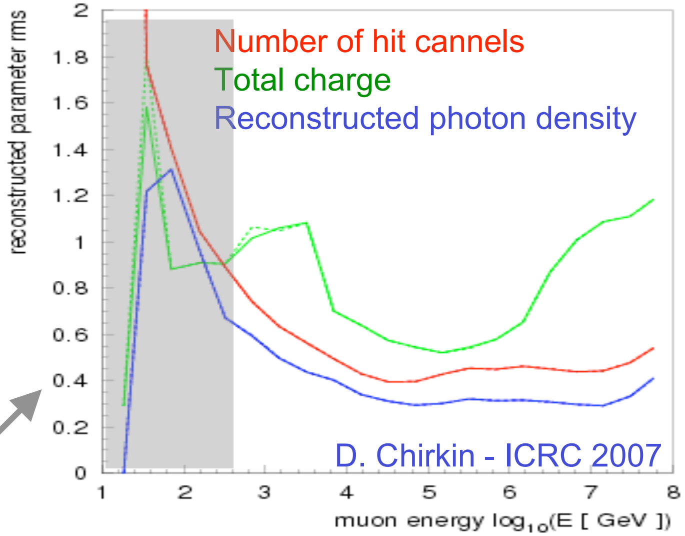
K. Münich - ICRC 2007



J. Zornoza - ICRC 2007

PRELIMINARY

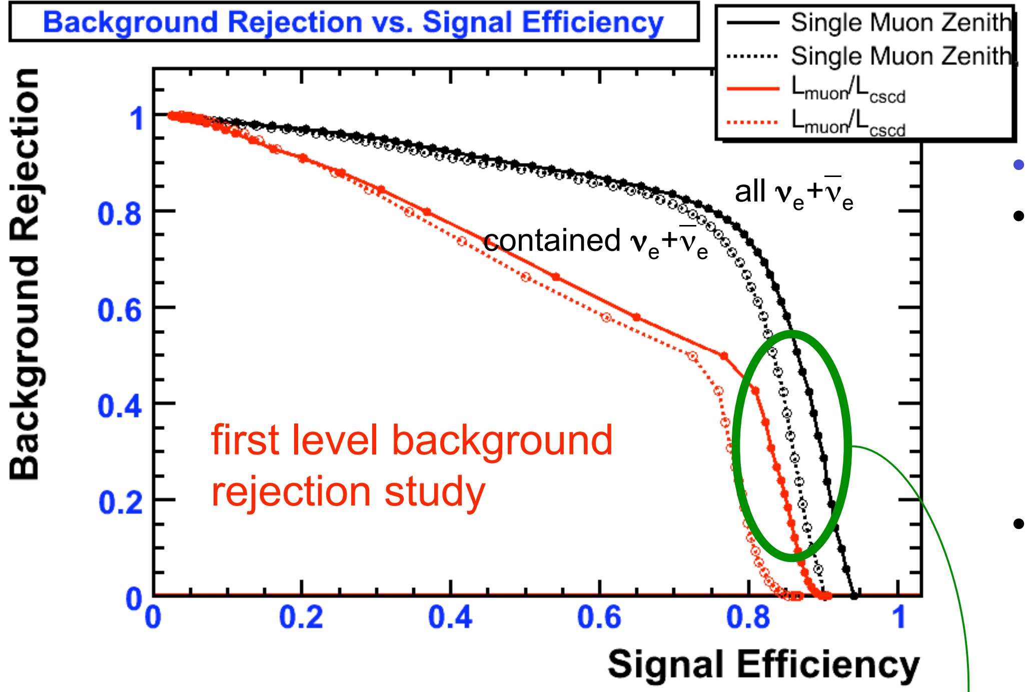
- measure photons from muon stochastic energy loss
- correlate number of photons with muon energy
- correlate photon density with expected PDF



D. Chirkin - ICRC 2007

use μ track length where no stochastic losses

Rejecting the background : IceCube-22



first level background rejection study

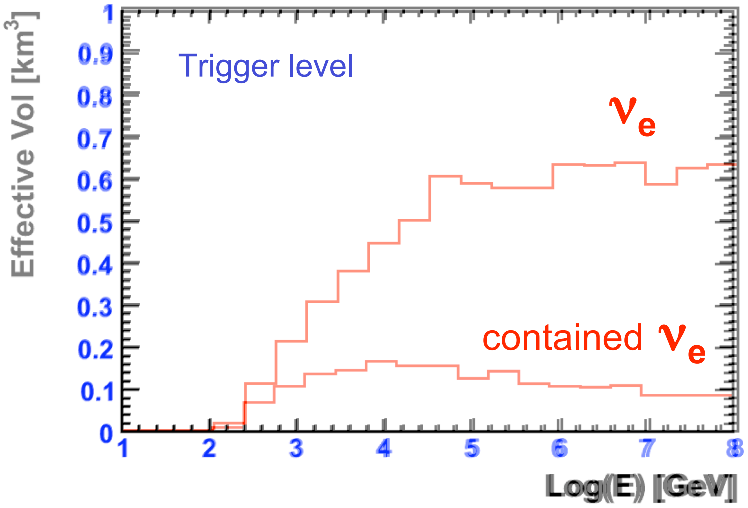
ν_e event selection:

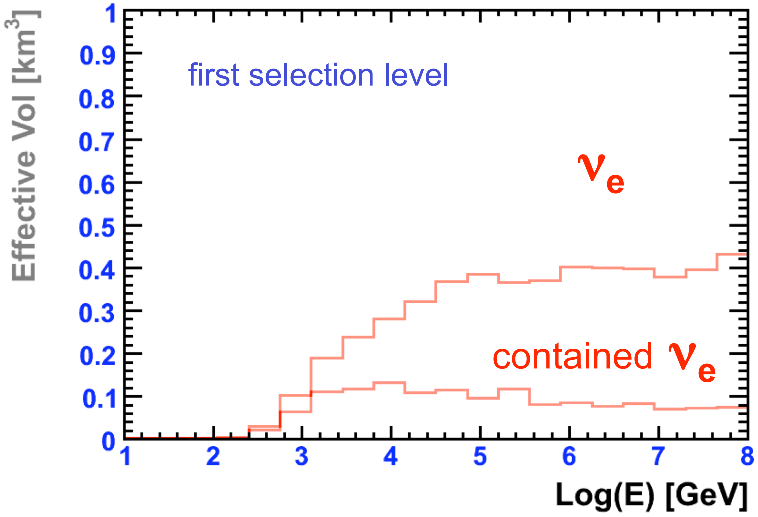
- background rejection more critical
- different signal / background rejection strategies under investigation
  - spherical hit topology
  - high value of L(cascade)/L(track)
  - reconstructed track-like θ on all events

- energy threshold ~100 GeV

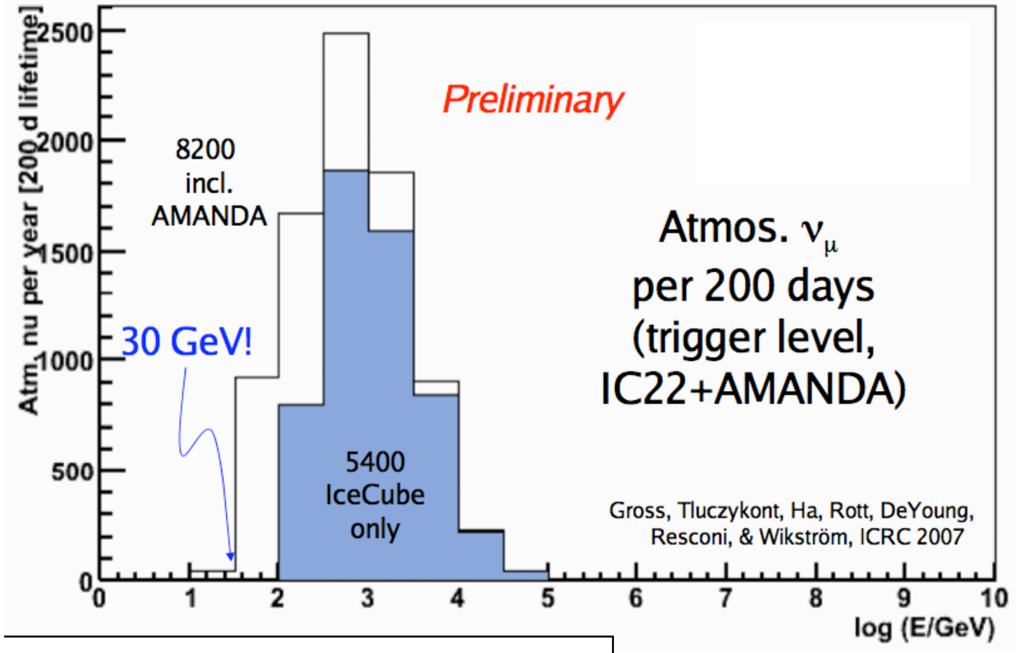
M. D'Agostino

PRELIMINARY STUDY





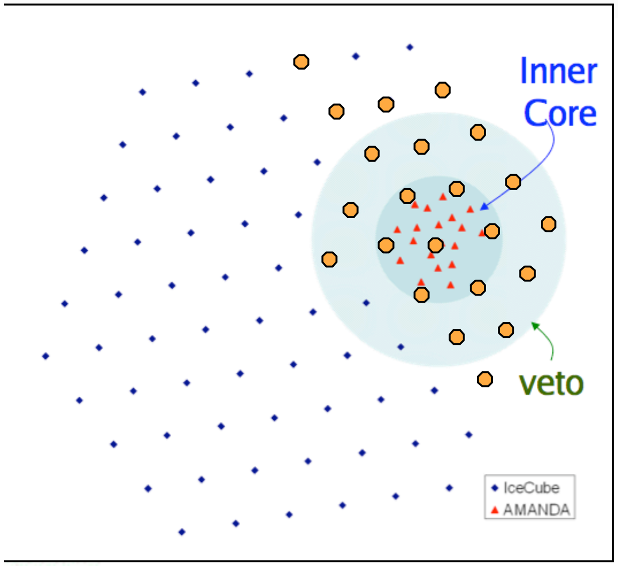
Low energy atmospheric neutrinos

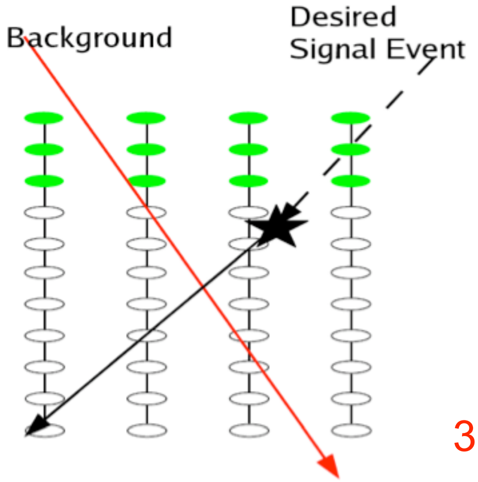


Gross, Tluczykont, Ha, Rott, DeYoung, Resconi, & Wikström, ICRC 2007

Neutrinos < 100 GeV generally better understood : constrain normalization at low energy to reduce systematics at high energy

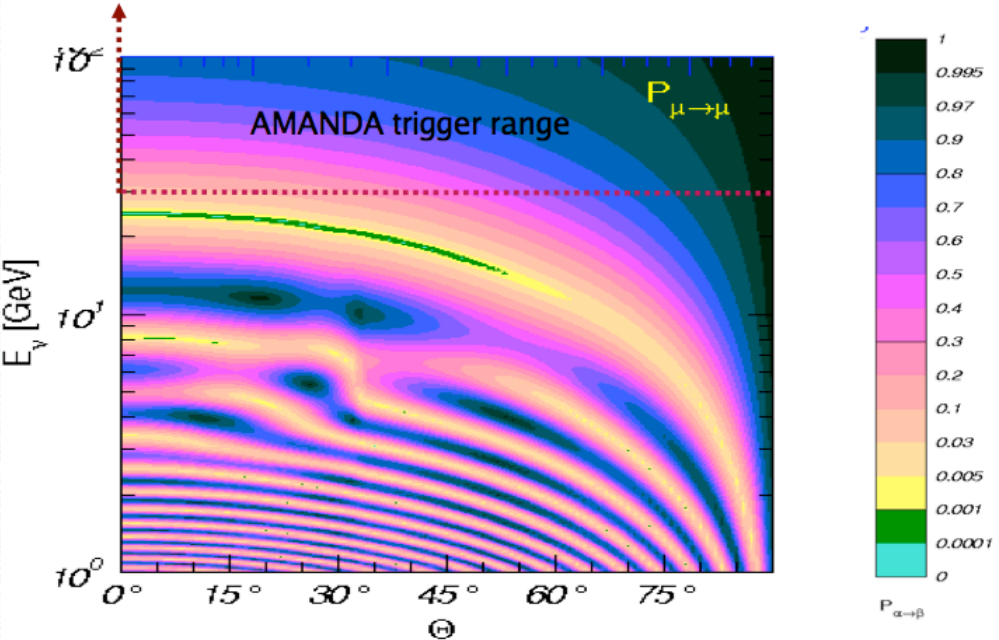
- The denser AMANDA-II array embedded within the coarser IceCube array lowers energy threshold
- contained and partially-contained tracks
- vertical tracks close to 1km-long strings
- “easier” background rejection
    - veto with external IceCube strings
    - veto with upper sensors (down ν)





30 GeV < E_ν < 100 GeV

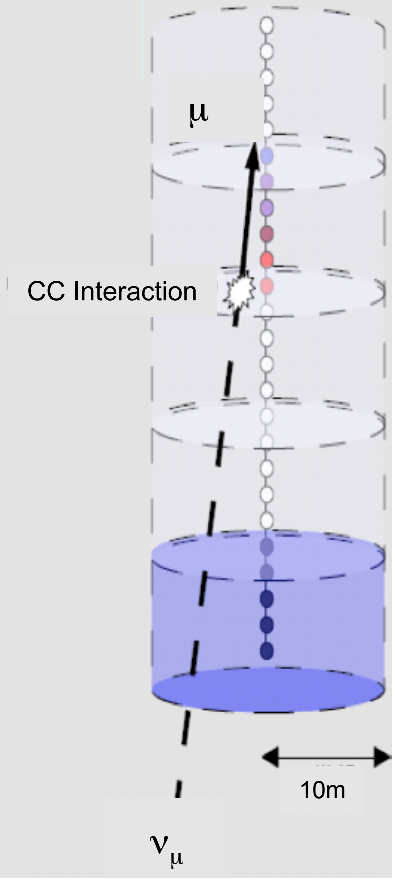
Neutrino oscillations



Akhmedov, Maltoni & Smirnov, hep-ph/0612285

At ~30 GeV ν marginally affected by standard oscillations : systematics

With ~30 GeV threshold only up-ward neutrino tracks have chance to oscillate



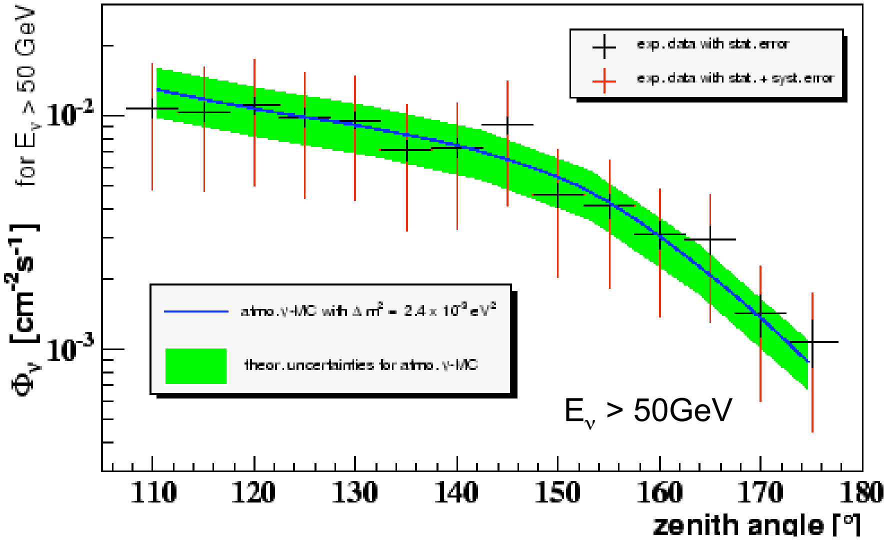
- measure contained events versus cosθ
    - μ angular resolution & ν_μ - μ angle at low energy
    - threshold effects
- measure L/E_ν for vertical tracks
    - ν_μ - μ kinematic issues
    - energy resolution
    - statistical analysis

$$\boxed{\frac{\sigma^2_{L/E_\nu}}{(L/E)^2} = \frac{\sigma^2_{E_\nu}}{E^2_\nu} + \frac{\sigma^2_L}{L^2} \simeq \frac{\sigma^2_{E_\nu}}{E^2_\nu} + \tan^2\theta_Z \sigma_{\theta^2_Z}}$$

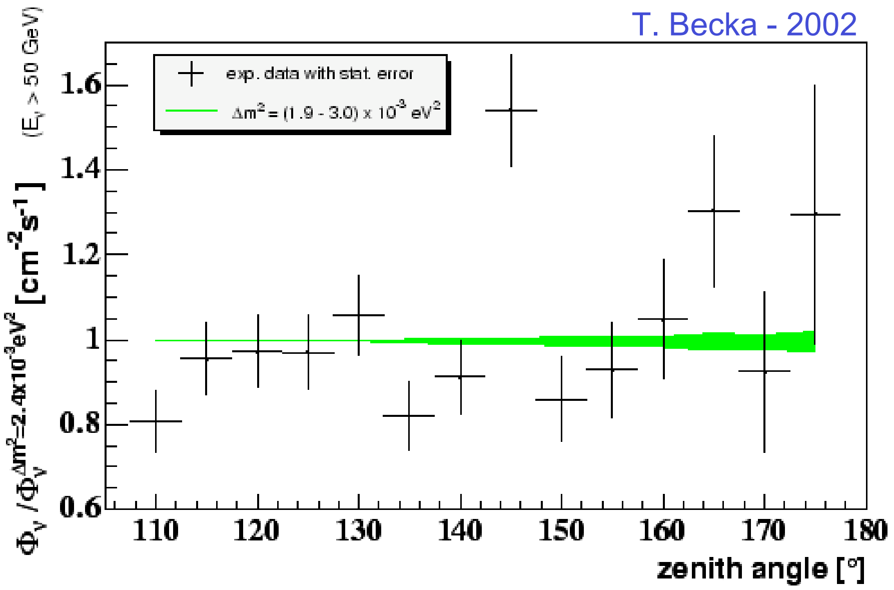
$$\boxed{\frac{\sigma_{E^2_\nu}}{E^2_\nu} = \frac{\sigma^2_{E_\mu}}{E^2_\mu}(1-y)^2 + \frac{\sigma^2_{E_h}}{E^2_h}y^2}$$

(Albuquerque and Smoot, Phys Rev D64, 053008)

Neutrino oscillations in AMANDA-II



T. Becka - 2002

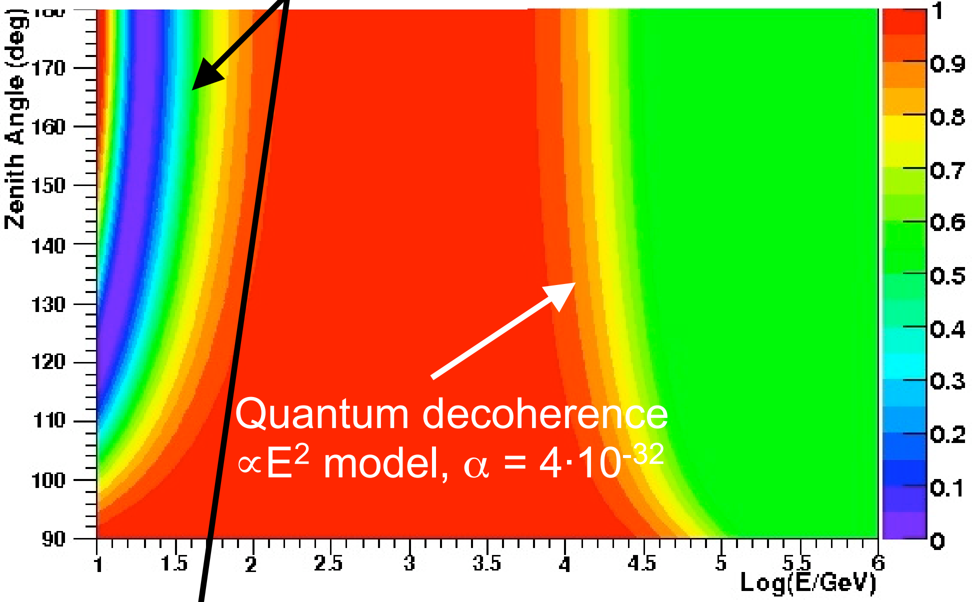


- Oscillations affect marginally our data at the threshold
- need large statistics & lower threshold
- systematics important

Influence of Δm^2 on atmospheric neutrino flux for $E_\nu > 50$ GeV and for maximal mixing angle is very small and dominated by statistics and experimetal resolution

Alternative oscillation scenarios

Standard oscillations



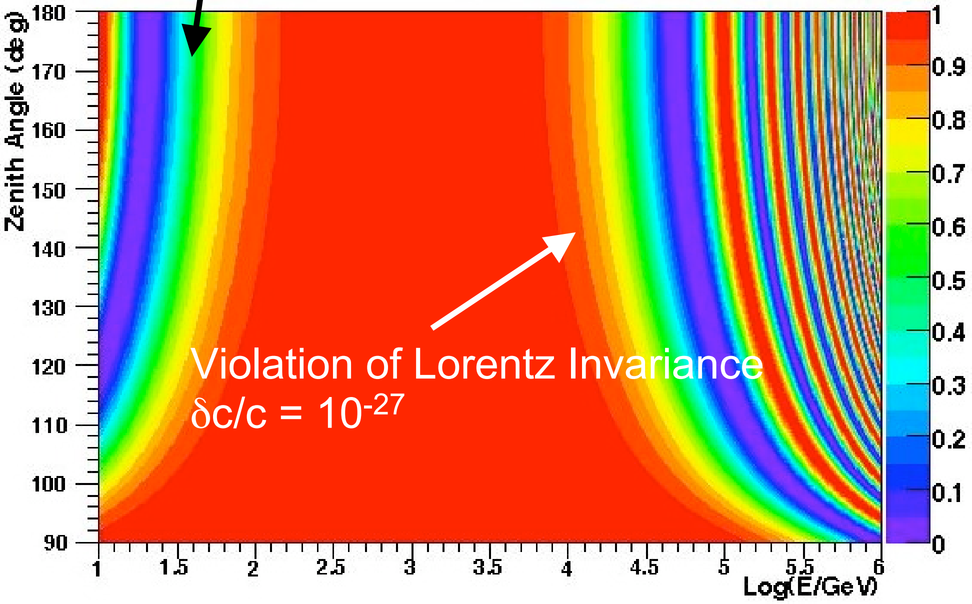
Quantum decoherence

$\propto E^2$ model, $\alpha = 4 \cdot 10^{-32}$

non standard effects :

- Quantum Decoherence
  - flavor eigenstates decohere through interaction with a foamy quantum-gravitational space-time

astro-ph/0412618



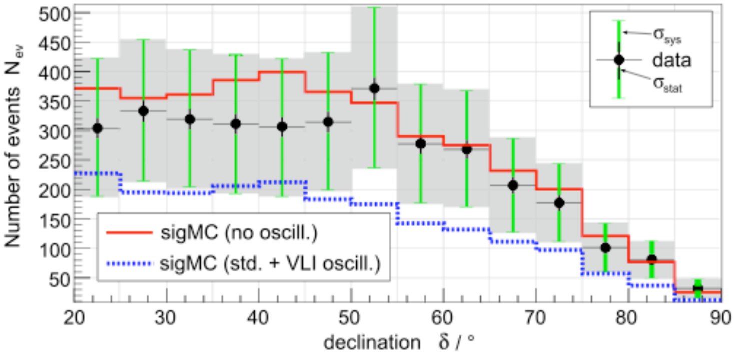
Violation of Lorentz Invariance

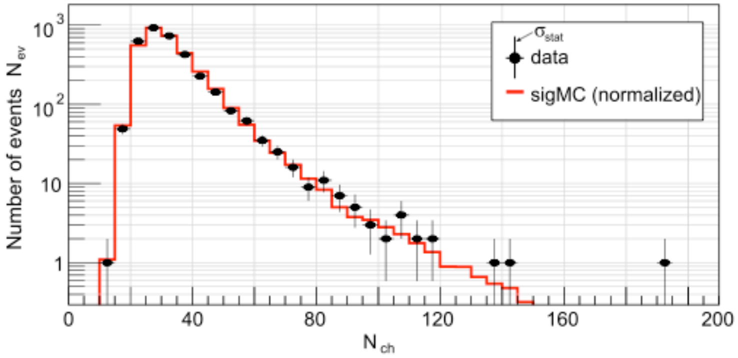
$\delta c/c = 10^{-27}$

- Violation of Lorentz Invariance
  - different speed for different flavors
- Violation of Equivalence Priciple
  - non-universal coupling to gravitational field

hep-ph/0502223

Alternative oscillation scenarios in AMANDA-II





J. Ahrens, J. Kelley - ICRC 2007

No evidence of oscillation :

$\delta c / c < 5.3 \cdot 10^{-27}$ (90% CL)

for $\Theta_c \approx \pm \pi/4$ (max mixing)

Standard + VLI oscillations :

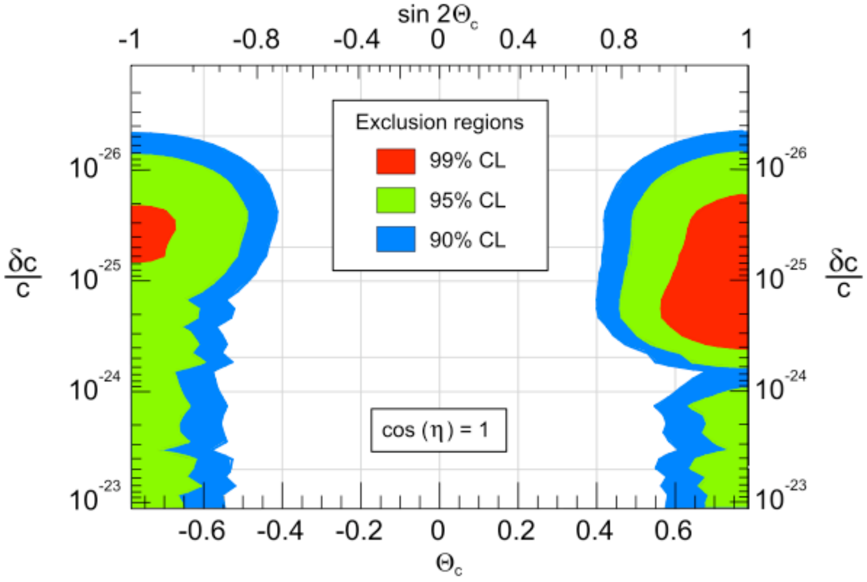
- $\Delta m^2 = 2.3 \cdot 10^{-3}$ eV^2
- $\Theta_m = \pi/4$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - sin^2 2\Theta sin^2(\Omega L)$$

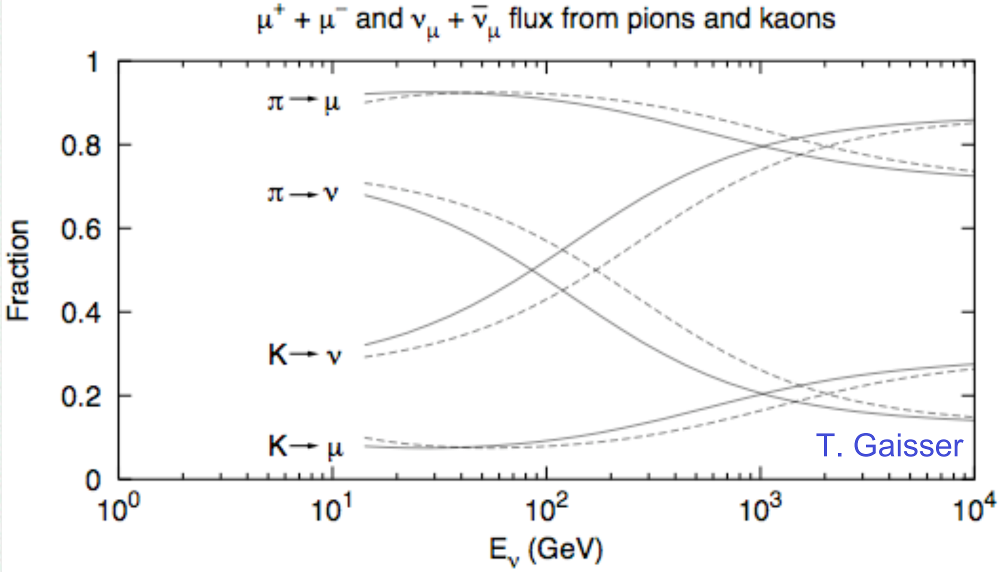
$$2\Theta = arctan(s/t) \qquad \Omega = \sqrt{s^2 + t^2}$$

$$s = 2.92 \cdot 10^{-3} \cdot \left[\frac{1}{E_\nu} + 8.70 \cdot 10^{20} \cdot \frac{\delta c}{c} \cdot sin 2\Theta_c \cdot E_\nu \cdot e^{i\eta} \right]$$

$$t = 2.54 \cdot 10^{18} \cdot \frac{\delta c}{c} \cdot cos 2\Theta_c \cdot E_\nu$$



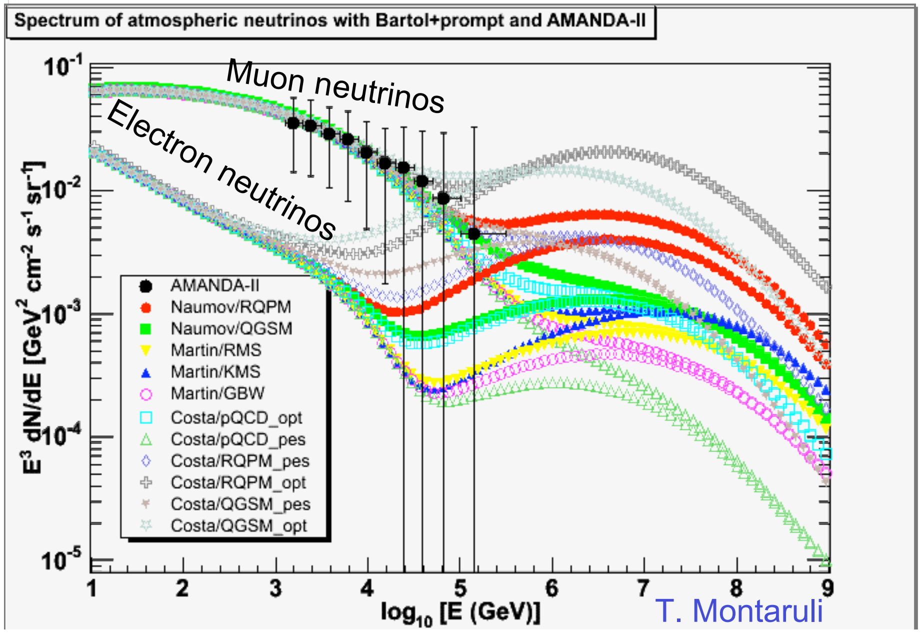
High energy atmospheric neutrinos

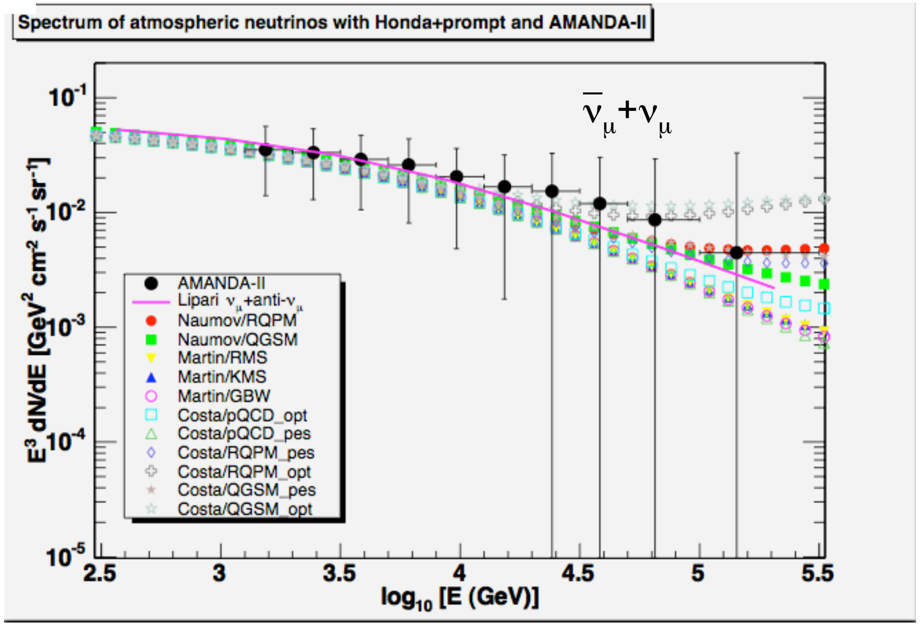


Atmospheric neutrinos depend on

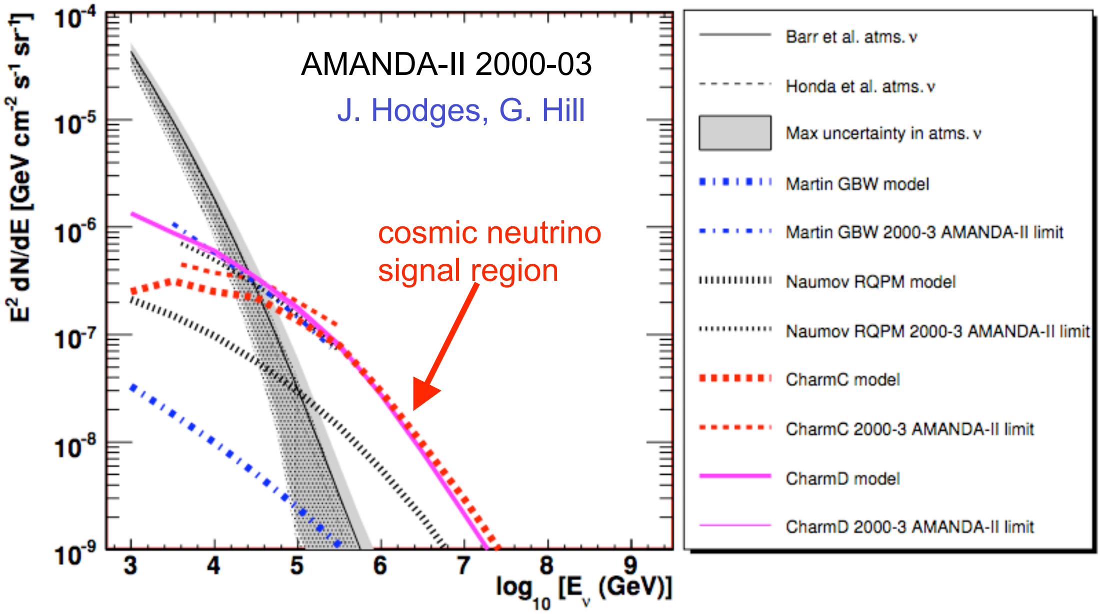
- primary cosmic ray flux
- atmospheric profile
- rigidity cutoff (low energy only)

- hadronic interaction model
  - π/K contribution
  - charm production





Charm production in the atmosphere



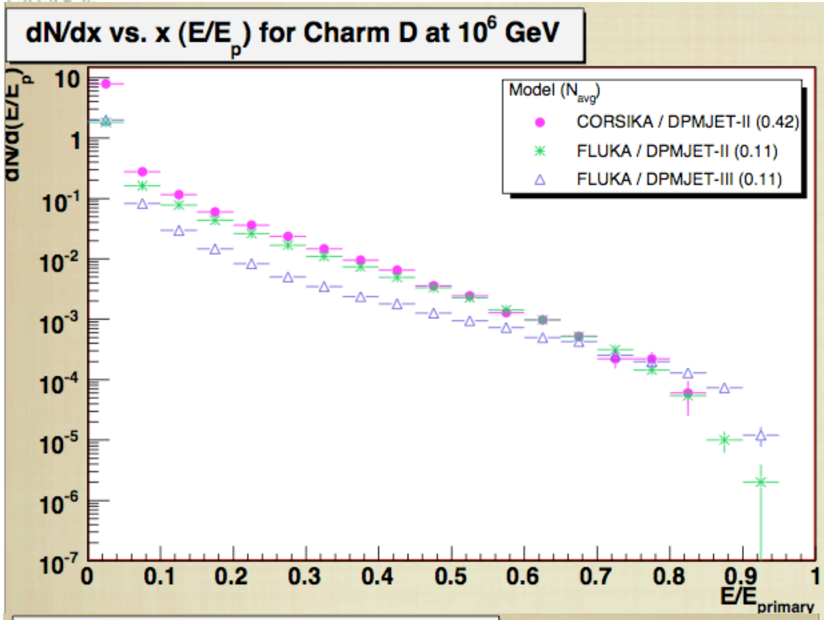
Physical Review D 76, 042008 (2007)

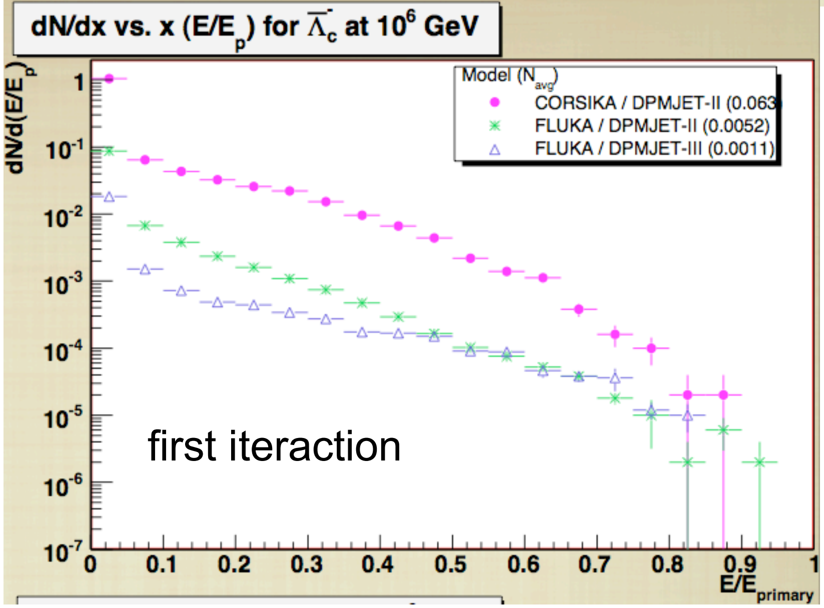
- AMANDA-II highest sensitivity @ 100 TeV
- IceCube will increase significantly event statistics
- able to probe charm production

- charmed mesons in the atmosphere produce flatter prompt spectrum
- big uncertainties due to lack of direct data in forward regime
- AMANDA-II have put limits on various models

- use also huge cosmic μ statistics : issues with multiplicity and lateral distribution

Charm production in the atmosphere


dN/dx vs. x (E/E_p) for Charm D at 10^6 GeV


dN/dx vs. x (E/E_p) for $\overline{\Lambda}_c$ at 10^6 GeV

- cross section very uncertain : lack of direct measurements
- data have harder x_F distribution than DPMJET-II (pQCD prediction)
- better meson D description in DPMJET-III
- improvement in DPMJET-III for asymmetry in target fragmentation region for baryon (P. Berghaus, T. Montaruli, J. Ranft)
- big spread among interaction models, especially for the Λ particles
- charm production to be incorporated in other models
- need more benchmark of existing codes

P. Berghaus, J. Ranft, T. Montaruli

Conclusions and remarks

- IceCube will collect unprecedented atmospheric neutrino statistics

- important high energy irreducible background for neutrino telescopes

- with AMANDA-II dense core and dedicated analysis techniques the energy threshold can be lowered down to ~30 GeV : lower theoretical uncertainties and marginally affected by standard oscillations

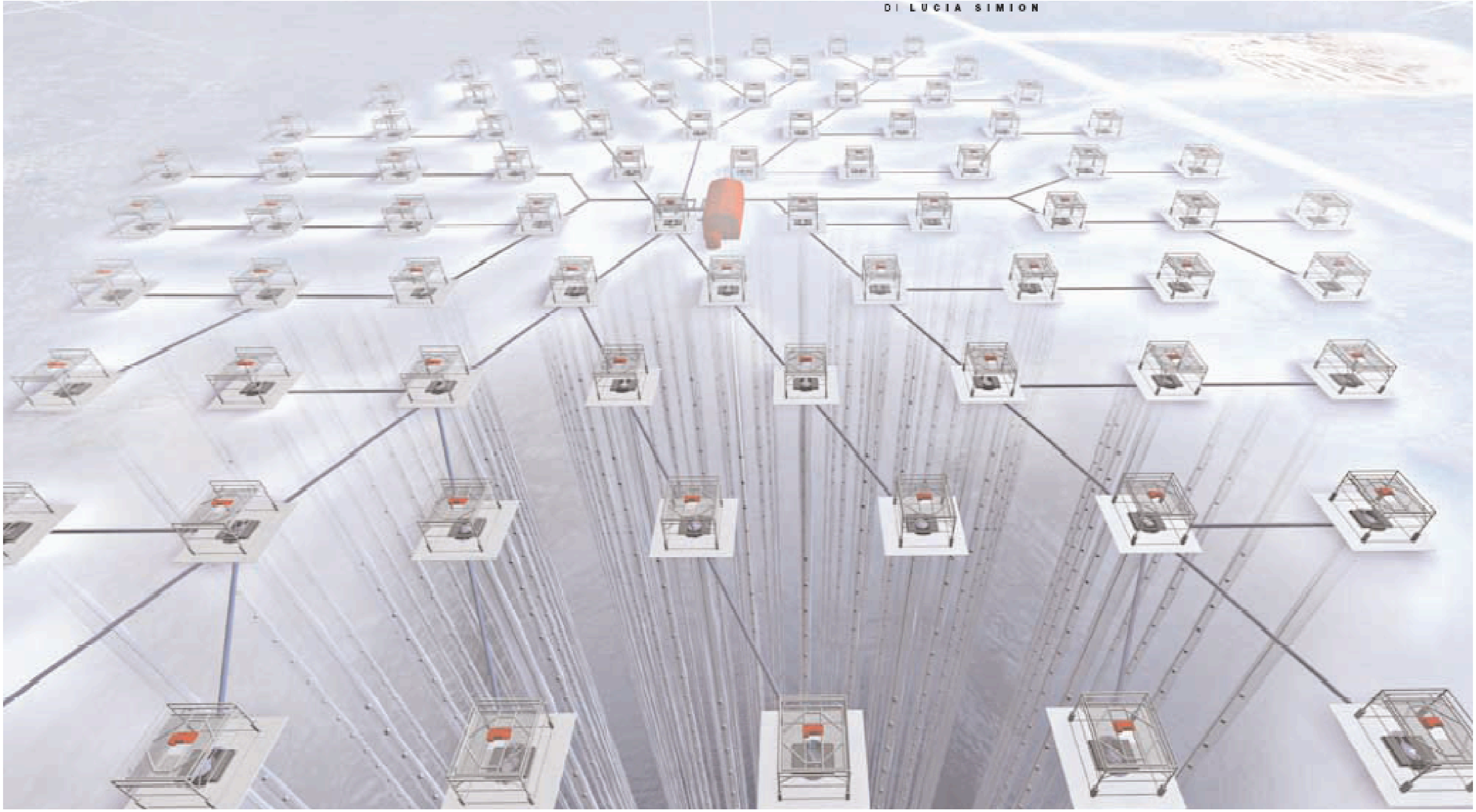
- high energy neutrinos to probe non-standard oscillation scenarios

- possible to probe interaction models and cosmic ray composition

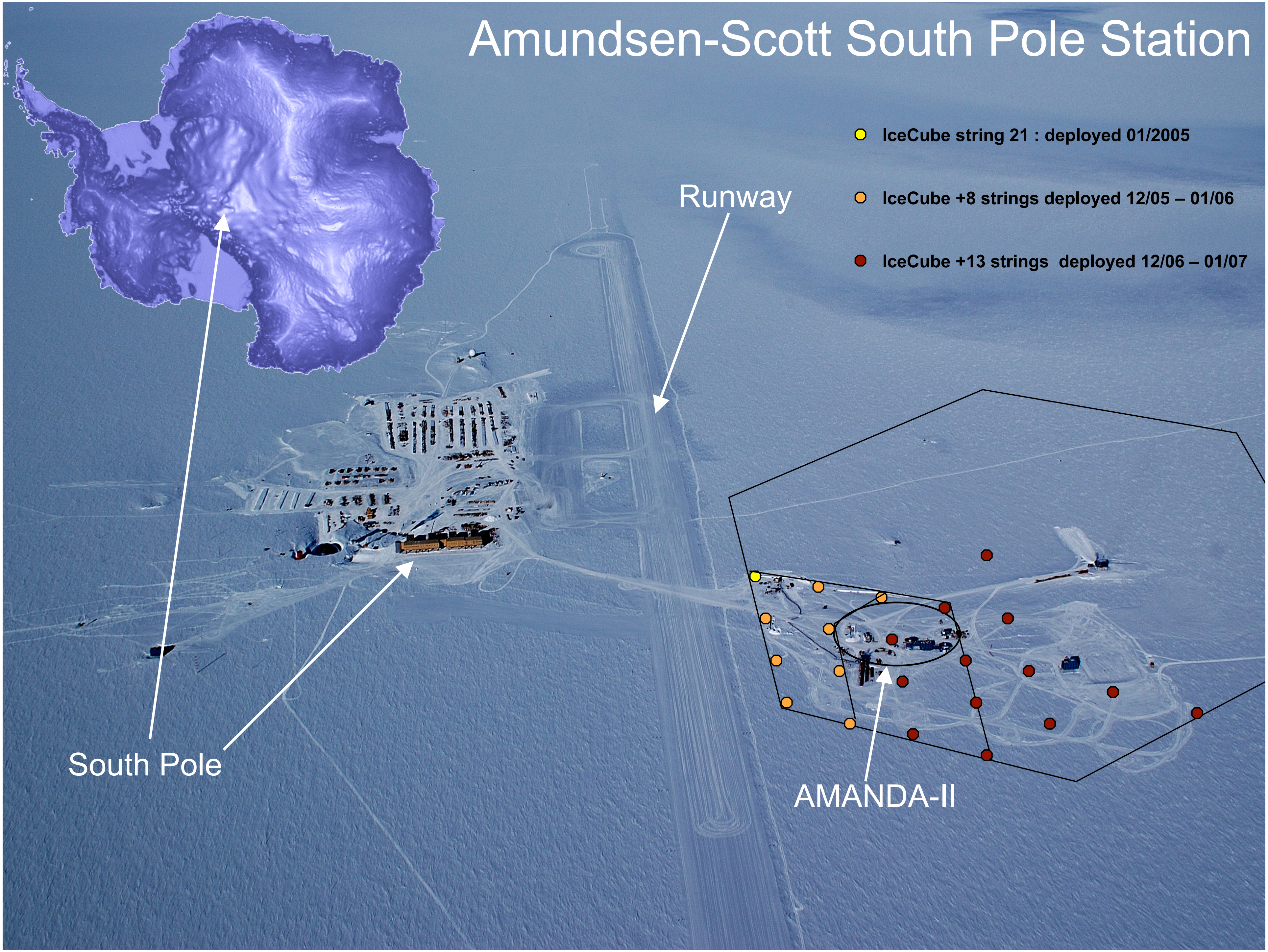
- high energy hadronic models play important role in neutrino telescopes

- charm production suffers large uncertainties. Improvements underway. Need to benchmark models and wait for measurements from dedicated experiments

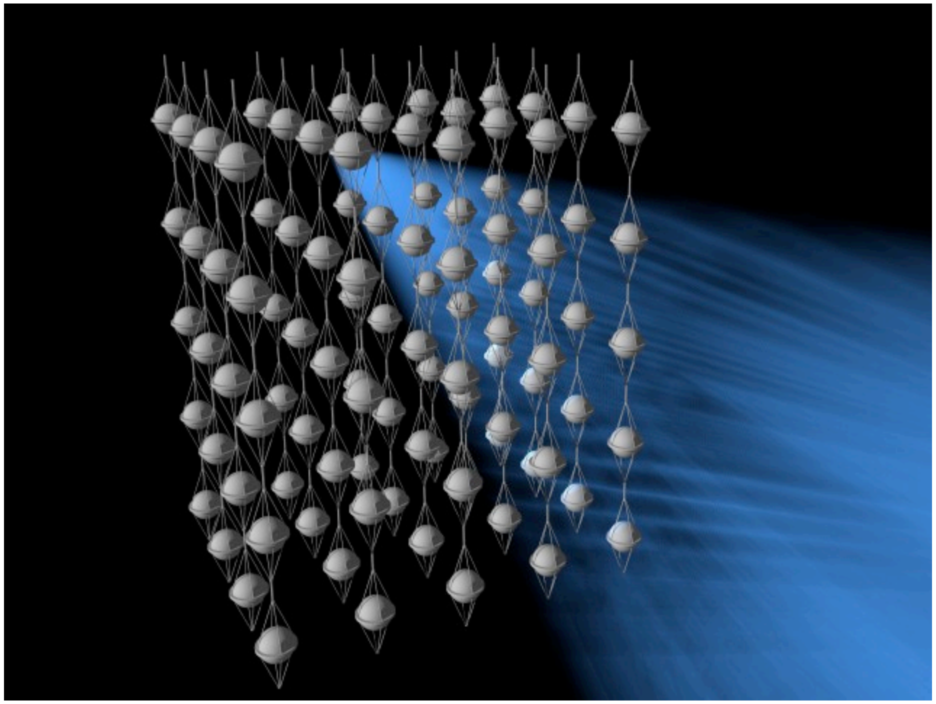
Spare slides

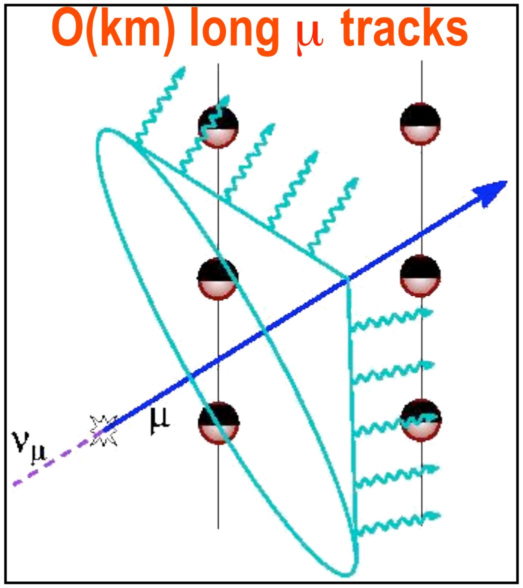


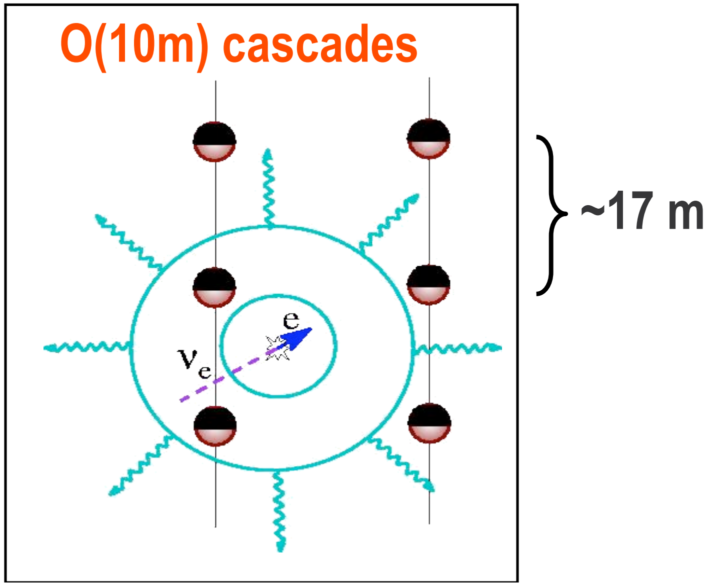
Amundsen-Scott South Pole Station



Detection principle




O(km) long μ tracks


O(10m) cascades

if energy is > few TeV muon points to neutrino direction

neutrino astronomy is possible

ice properties very important

a neutrino telescope

$$\Theta_{\mu\nu} \approx 0.65^{\circ} \cdot (E_\nu/\mathrm{TeV})^{-0.48}$$

$(3\mathrm{TeV} < E_\nu < 100\mathrm{TeV})$

Atmospheric neutrinos in IceCube

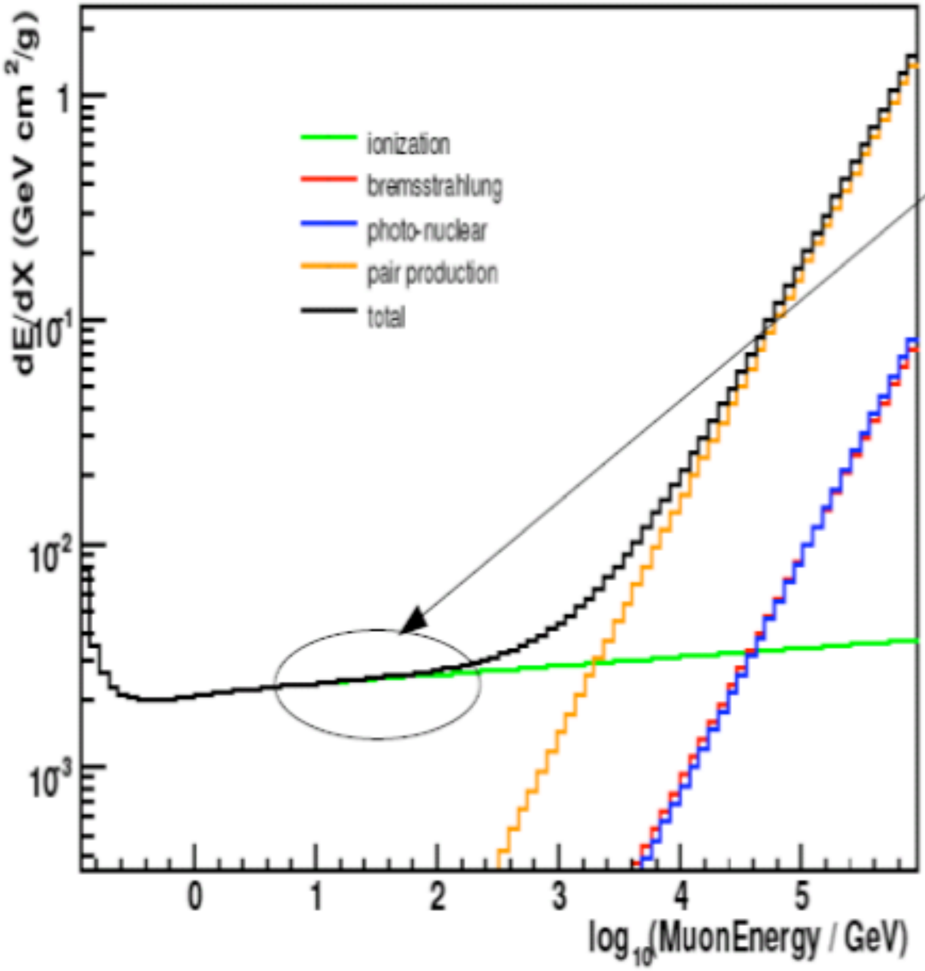
IceCube will detect a large number of atmospheric neutrinos

	AMANDA-II	IC-9	IC-22	IC-80
Atm ν_μ	~1800 /y	~630 /y	~2,000	~40,000 / y
Background	~10%	~10-20%	~20%	??

Notes : A part from AMANDA-II and IC-9 the numbers reported are approximate.
Year is 365 day livetime
Numbers for IC22 and IC80 are preliminary estimations based on IC9 selection

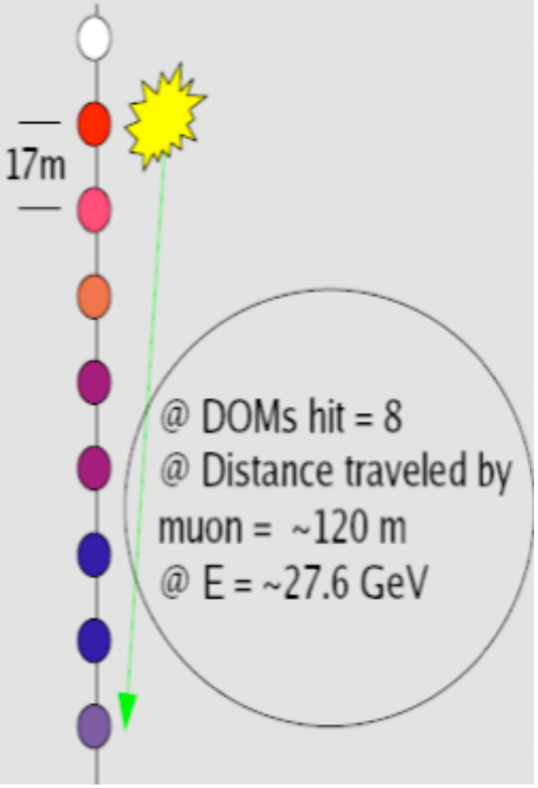
- unprecedented statistics of atmospheric neutrinos able to probe hadronic interaction models
- huge statistics of cosmic muons to probe dependency on cosmic ray composition and on hadronic interaction model
- wide energy range to constrain uncertainties on normalization

Muon energy loss



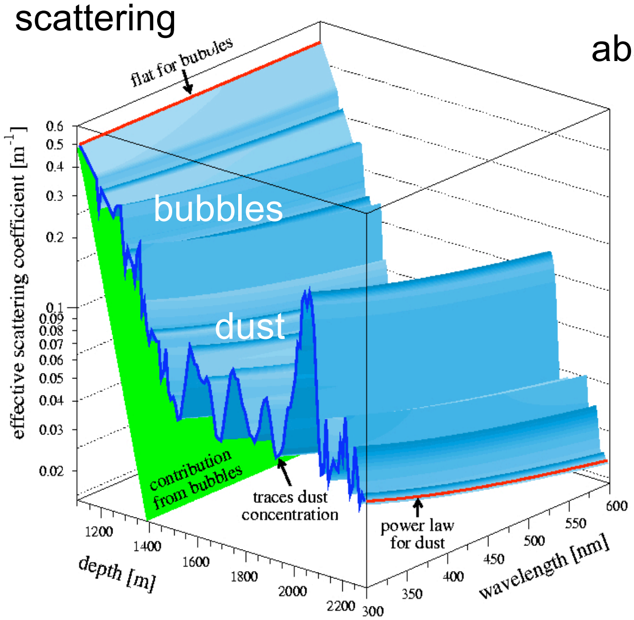
J. Pretz Thesis Figure 4.4

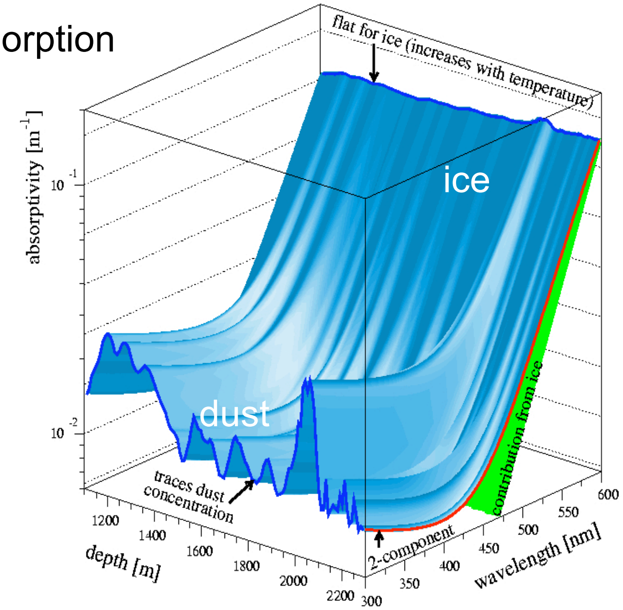
@ dE/dX =
~2.5e-3 GeV cm^2/g
@ Density of ice =
0.92 g/cm^2
@ Approximate Energy Loss =
~0.23 GeV/m



@ DOMs hit = 8
@ Distance traveled by muon = ~120 m
@ E = ~27.6 GeV

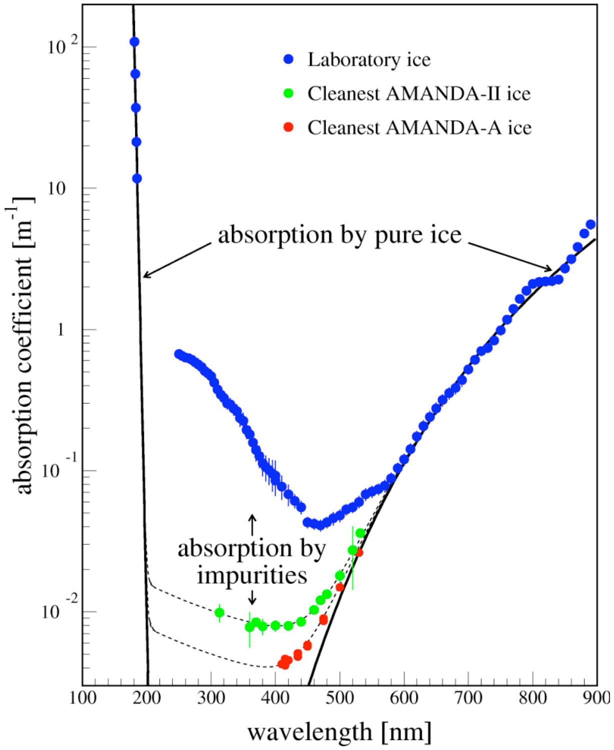
Polar ice optical properties


scattering

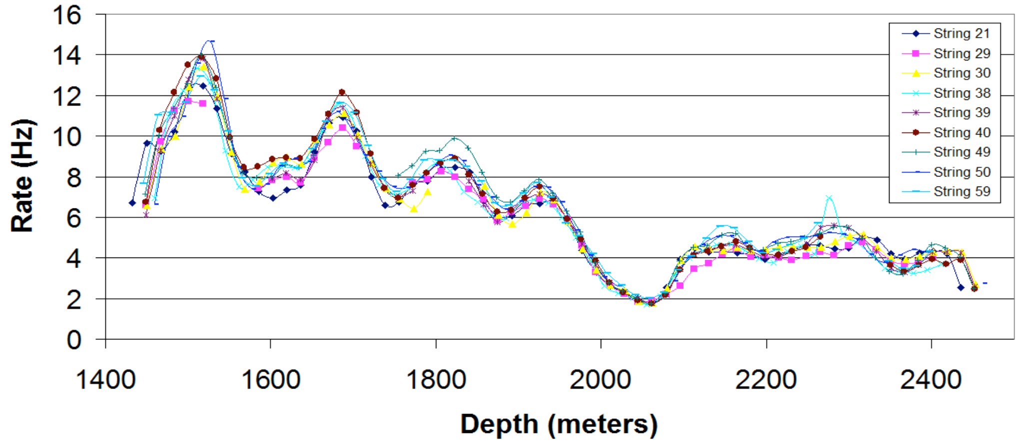

absorption

Measurements:

- in-situ light sources
- atmospheric muons



J. Geophys. Res. 111 (2006) D13203



Average optical ice parameters:

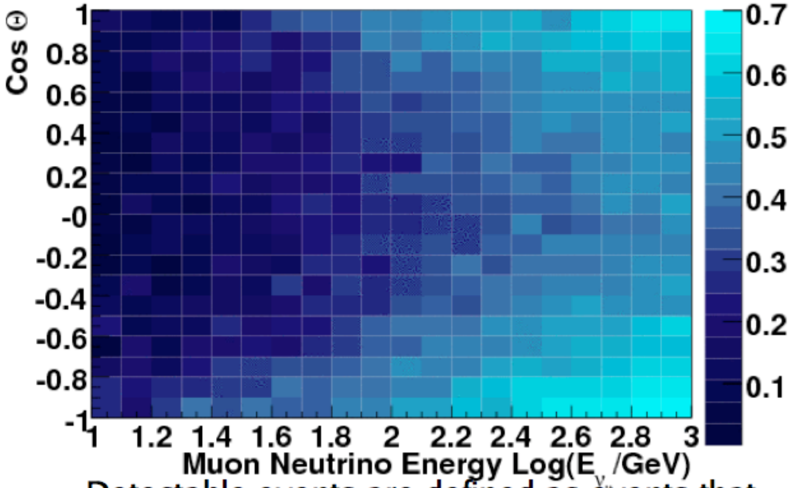
λ_{abs} ~ 110 m @ 400 nm

λ_{sca} ~ 20 m @ 400 nm

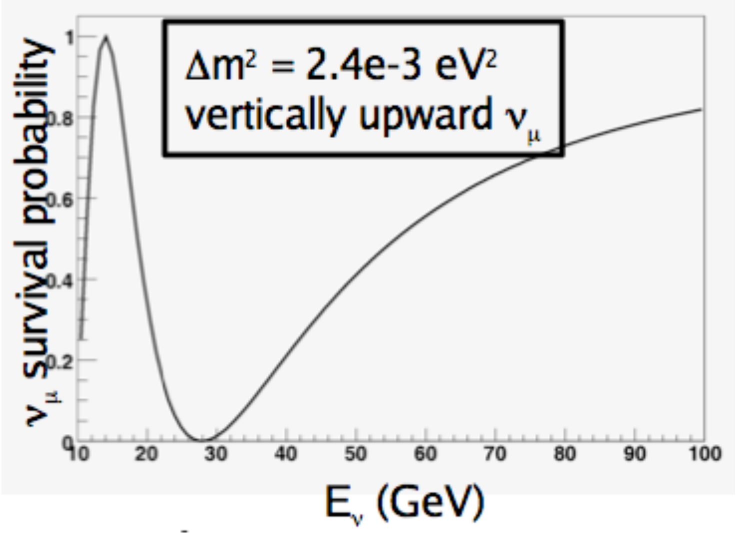
Accessing low energy events

- IceCube and AMANDA-II denser core to measure events down to ~ 30 GeV
- Topological trigger in IceCube based on hit sensor topology
  - starting/stopping tracks
  - contained tracks
- IceCube denser along vertical strings (17 m vs 125 m string distance)
  - at least 5 hit consecutive sensors in a string : E_ν >30 GeV
  - measure neutrino track length
  - Albuquerque and Smoot, Phys Rev D64, 053008

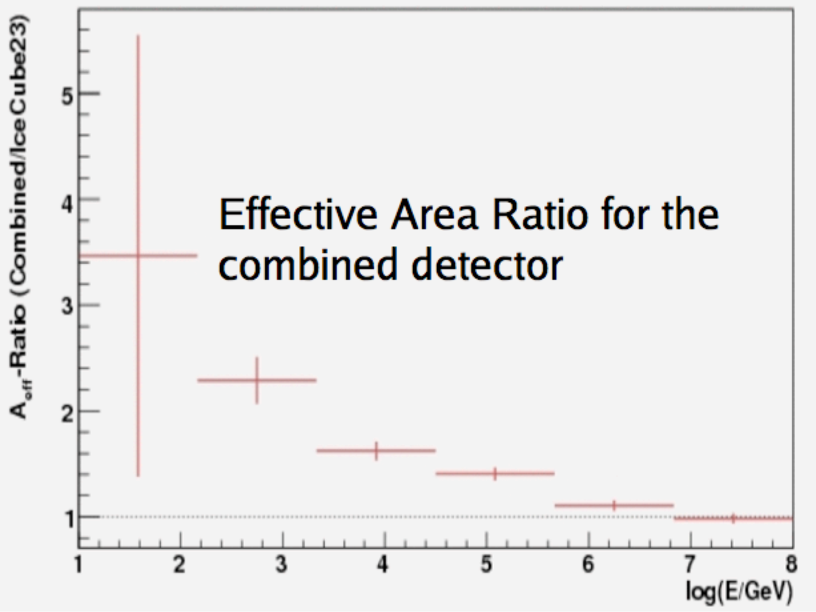
Efficiency for detectable ν_μ signal string trigger (5 out of 7)

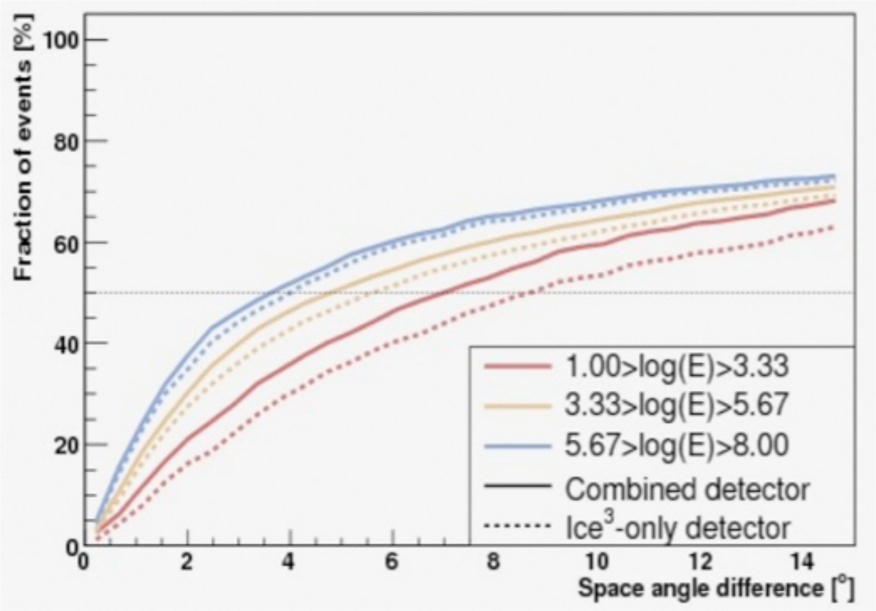


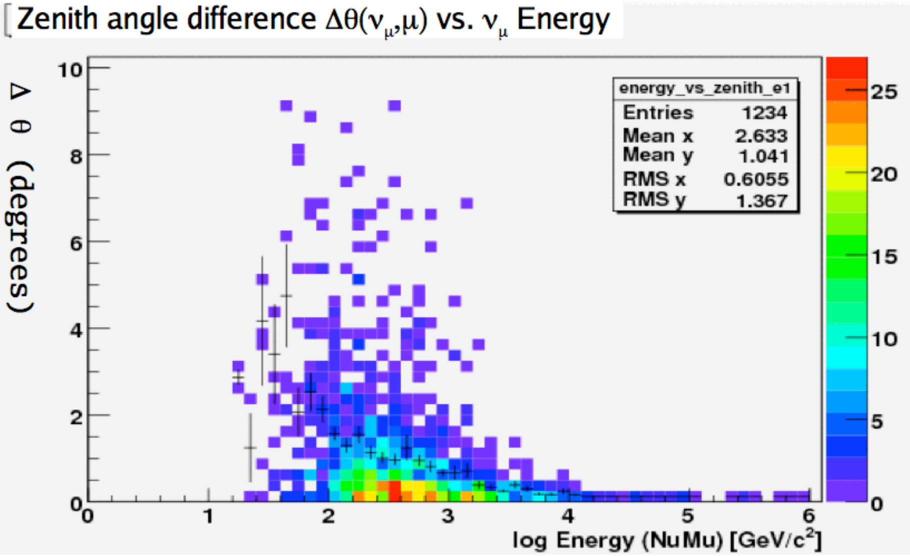
Detectable events are defined as events that have at least one hit in the detector



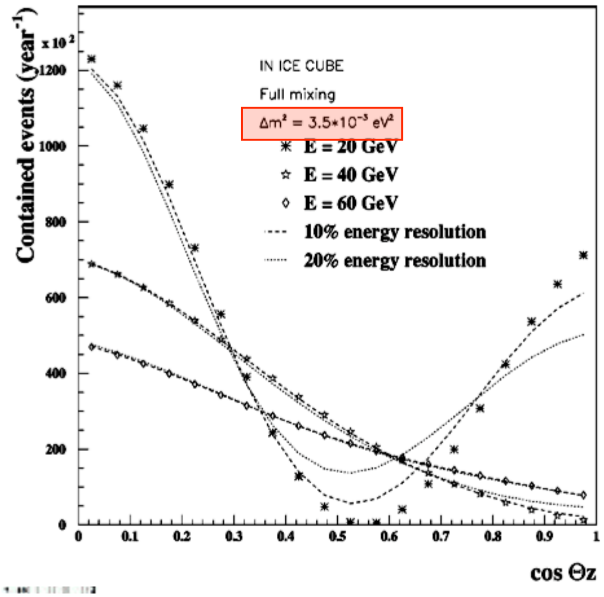
Accessing low energy events (cont.)

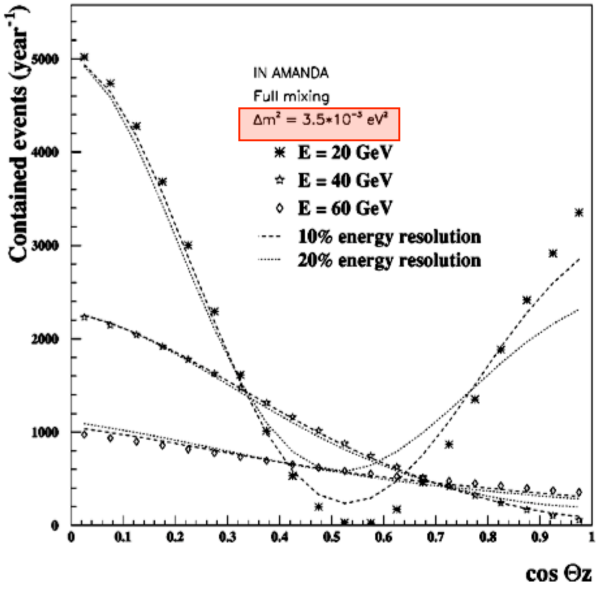




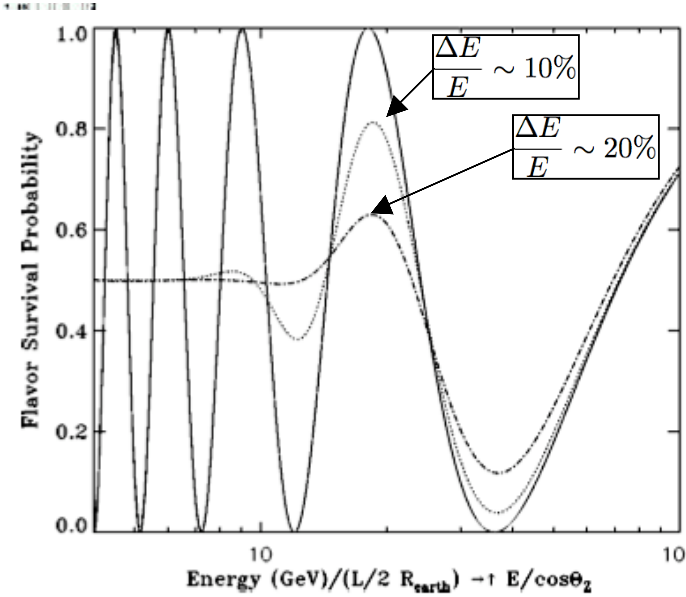


Neutrino oscillations





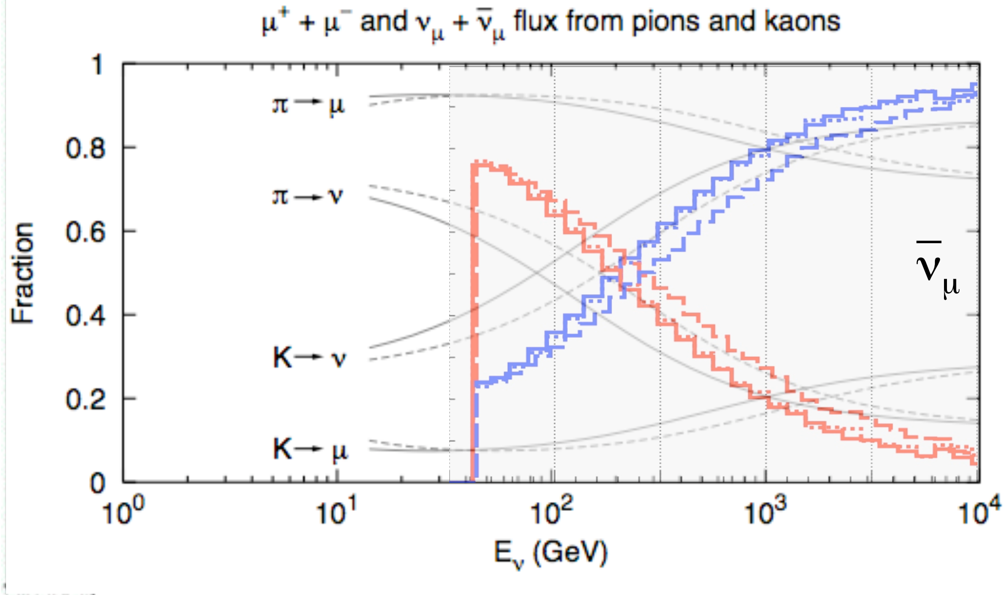
- angular distribution of contained events
    - energy threshold ~ 20 GeV
    - energy resolution < 30 GeV
- effect reduced for $\Delta m^2 < 3 \cdot 10^{-3}$ eV^2

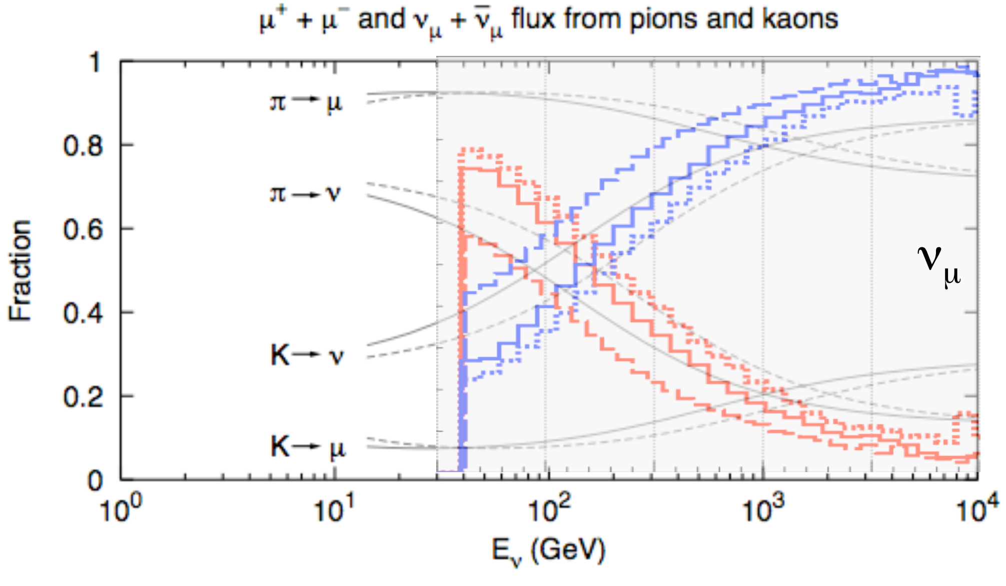


- L/E distribution
    - maximal for up-going tracks

Albuquerque and Smoot, Phys Rev D64, 053008

High energy atmospheric neutrinos





Neutrinos from pions and Kaons

from π decay
from K decay

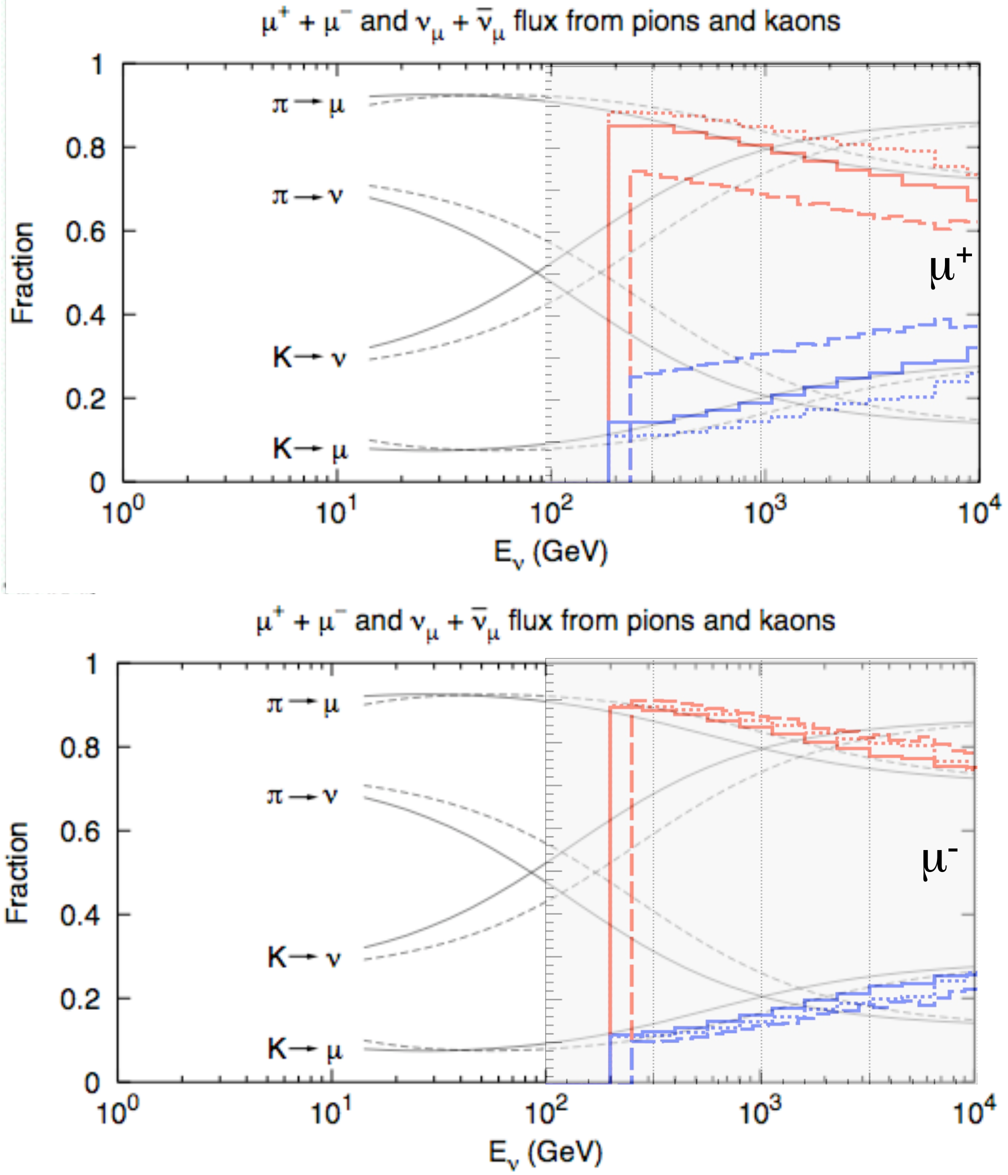
QGSJET01
QGSJET-II
SIBYLL

SIBYLL produces more K^+ than other interaction models, which contributes to μ^+ and ν_μ

R. Birdsall, PD

PRELIMINARY

High energy atmospheric muons



Muons from pions and Kaons

— from π decay
— from K decay

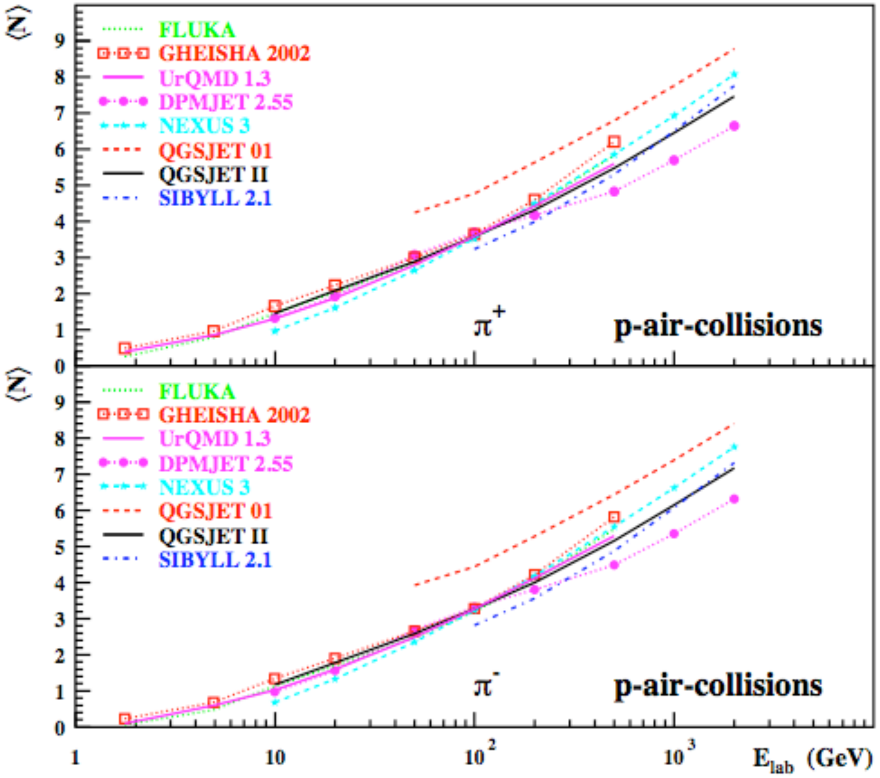
— QGSJET01
········· QGSJET-II
– – – SIBYLL

R. Birdsall, PD

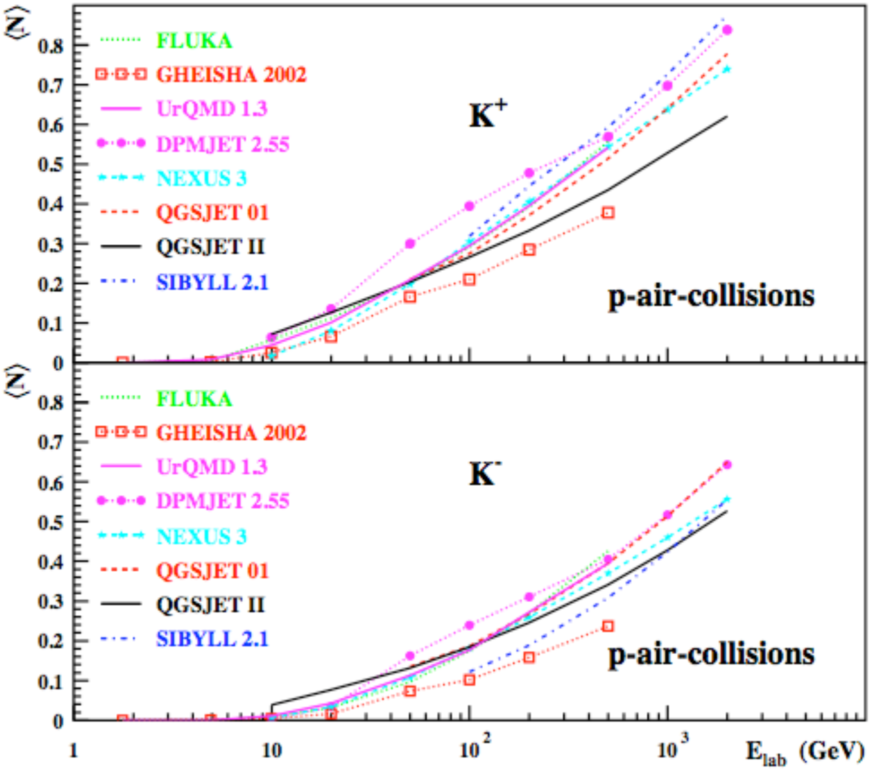
PRELIMINARY

Interaction Models : π/K

p-air Interactions

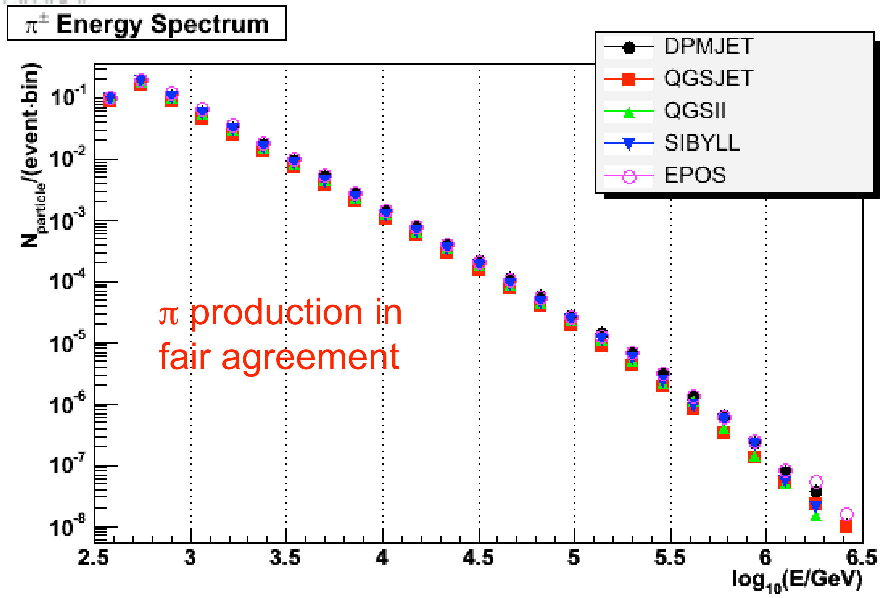


p-air Interactions



D. Heck

Interaction Models : π/K

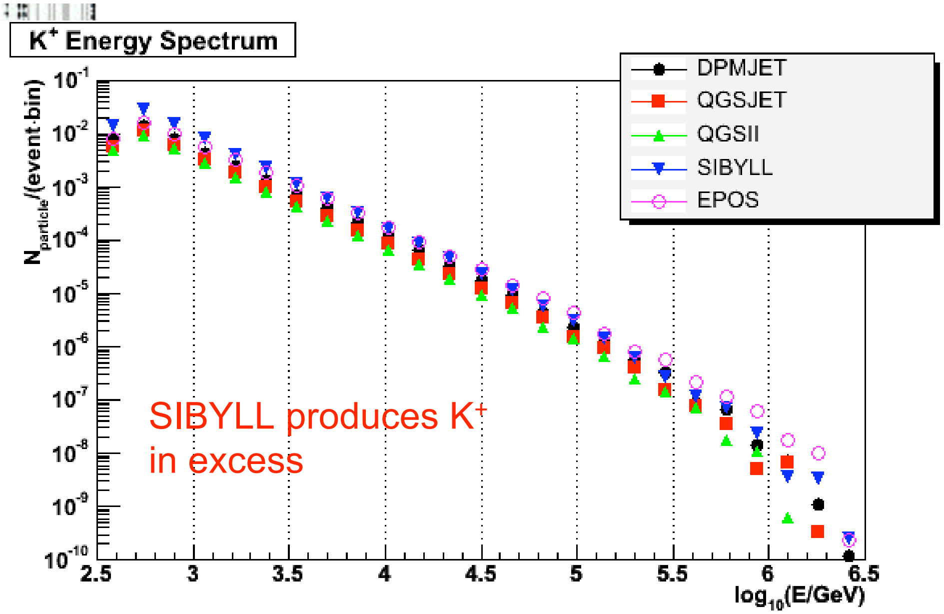

$\pi^{\pm}$ Energy Spectrum

π production in fair agreement

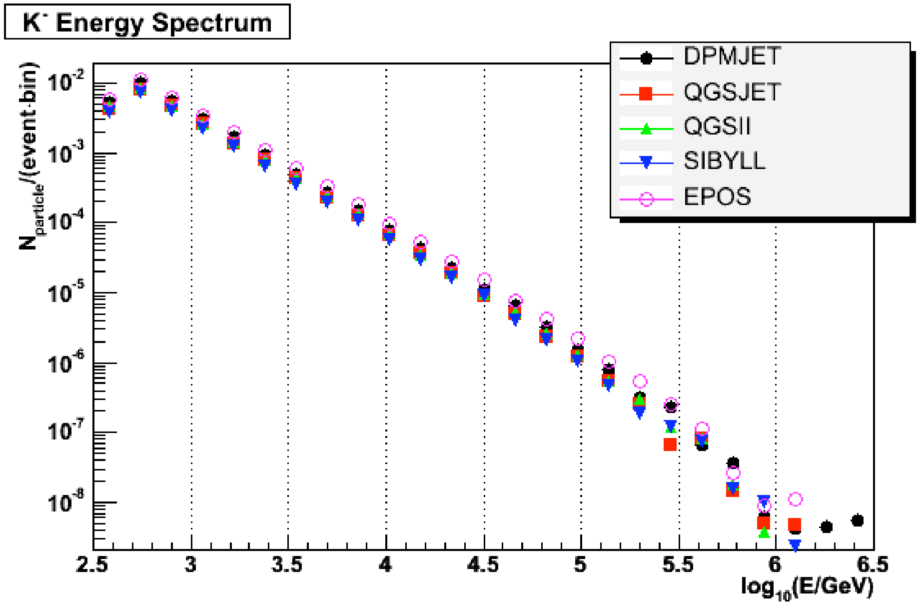
Full shower development with CORSIKA

Hörandel Polygonato Cosmic Ray Spectrum

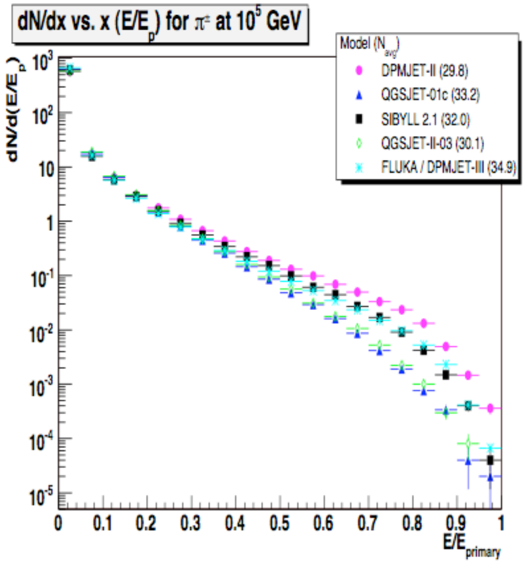
P. Berghaus

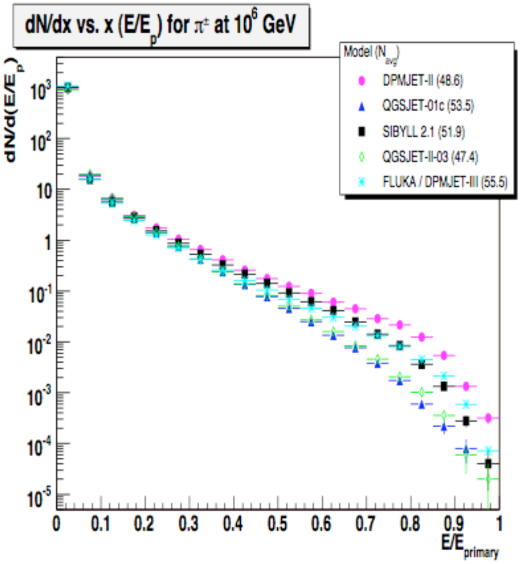

K^{+} Energy Spectrum

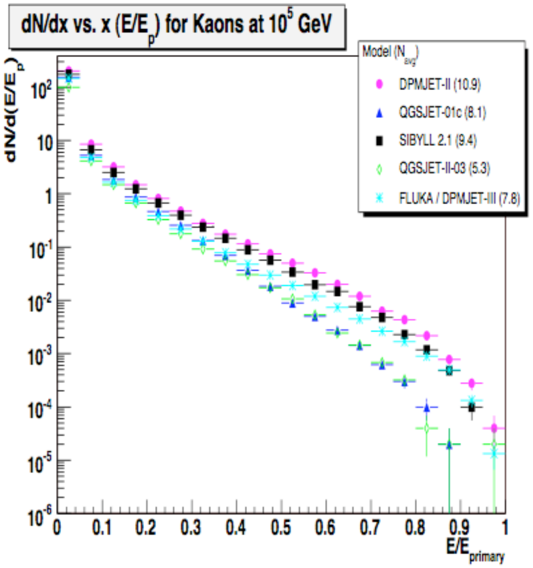
SIBYLL produces K^{+} in excess

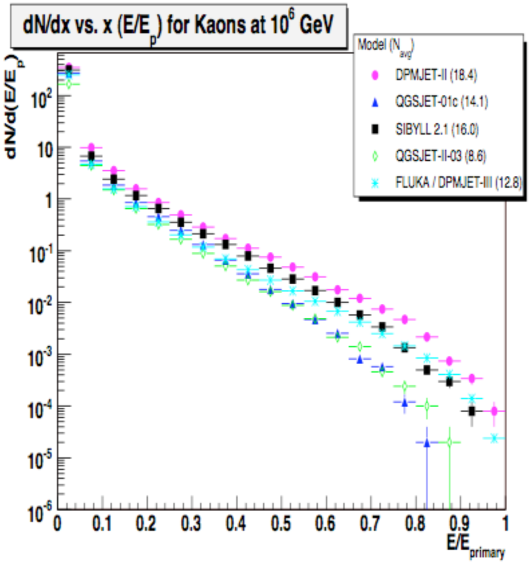

K^{-} Energy Spectrum

π and K production @ first interaction



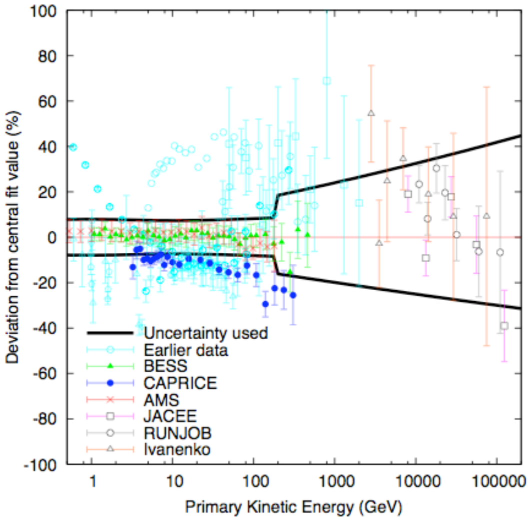


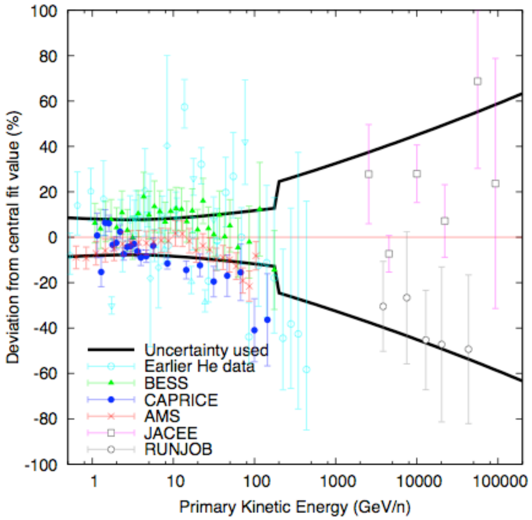


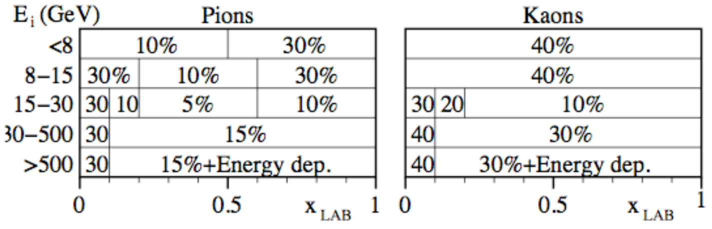


R. Ganugapati, J. Kelley, T. Montaruli

Uncertainties on atmospheric neutrino flux







E_i (GeV)	Pions				Kaons		
<8	10%	30%			40%		
8–15	30%	10%	30%		40%		
15–30	30	10	5%	10%	30	20	10%
30–500	30	15%			40	30%	
>500	30	15%+Energy dep.			40	30%+Energy dep.	

FIG. 2: Uncertainties assigned to the production rate of charged pions (left) and charged kaons (right) as a function of $x_{\rm lab}$. The uncertainties are shown for various ranges of incident particle energy $E_{\rm i}$ for interactions of protons on light nuclei.

G.D. Barr et al., astro-ph/0611266