Atmospheric Muon and Neutrino Energy Spectra measured with the AMANDA-II Detector

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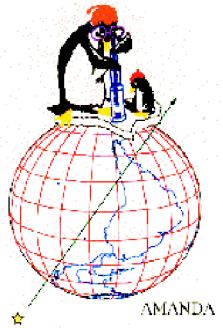
For the
AMANDA Collaboration

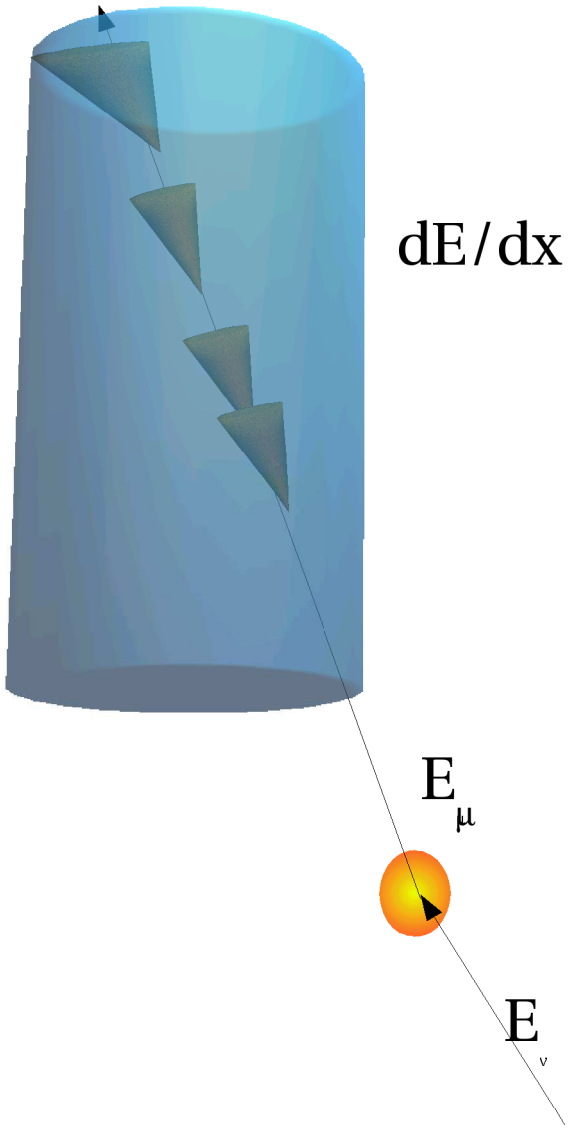
Contents

- Muon energy reconstruction (NN techniques)
- Spectral Unfolding (Method of regularized unfolding)
- Measured down-going muon spectra
- Measured atmospheric neutrino energy spectrum

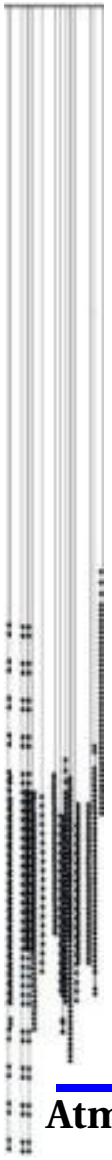
The Problem of Energy Reconstruction in AMANDA



- AMANDA detecting cherenkov radiation of muons passing through the detector (http://www.amanda.uci.edu/)
- Observables are correlated to stochastic energy loss inside the detector
- Initial muon energy can only be derived in a statistical context
- Muon, neutrino, primary hadron energy spectra are a convolution of the energy losses in the detector

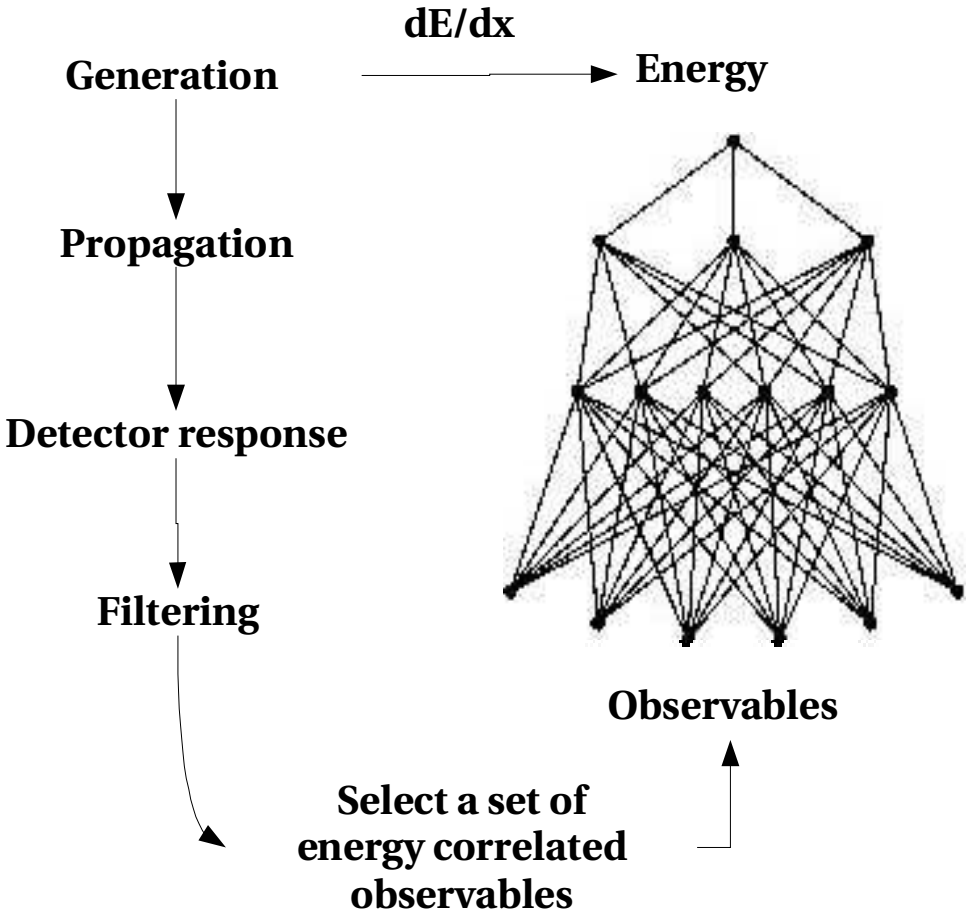


Single Muon Energy Reconstruction



Monte Carlo Simulation

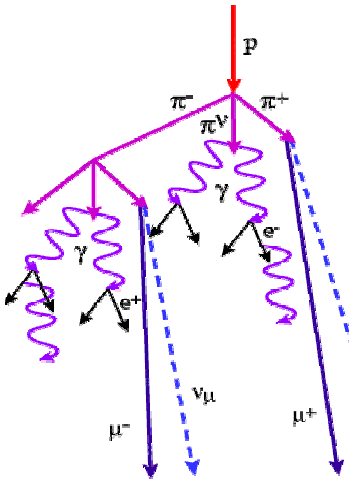
Training Neural Network on energy



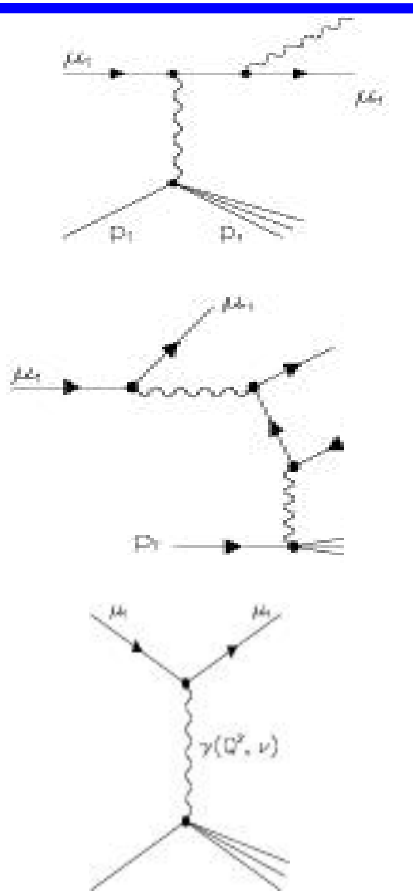
Neural network energy estimator:

- Good choice of independent energy correlated variables: six direct observables (e.g. number of hits)
- Layout: 6-6-3-1
- Standard back propagating Multi-Layer Perceptron

The Monte Carlo chain



Generation:
CORSIKA,
nusim,
muo0



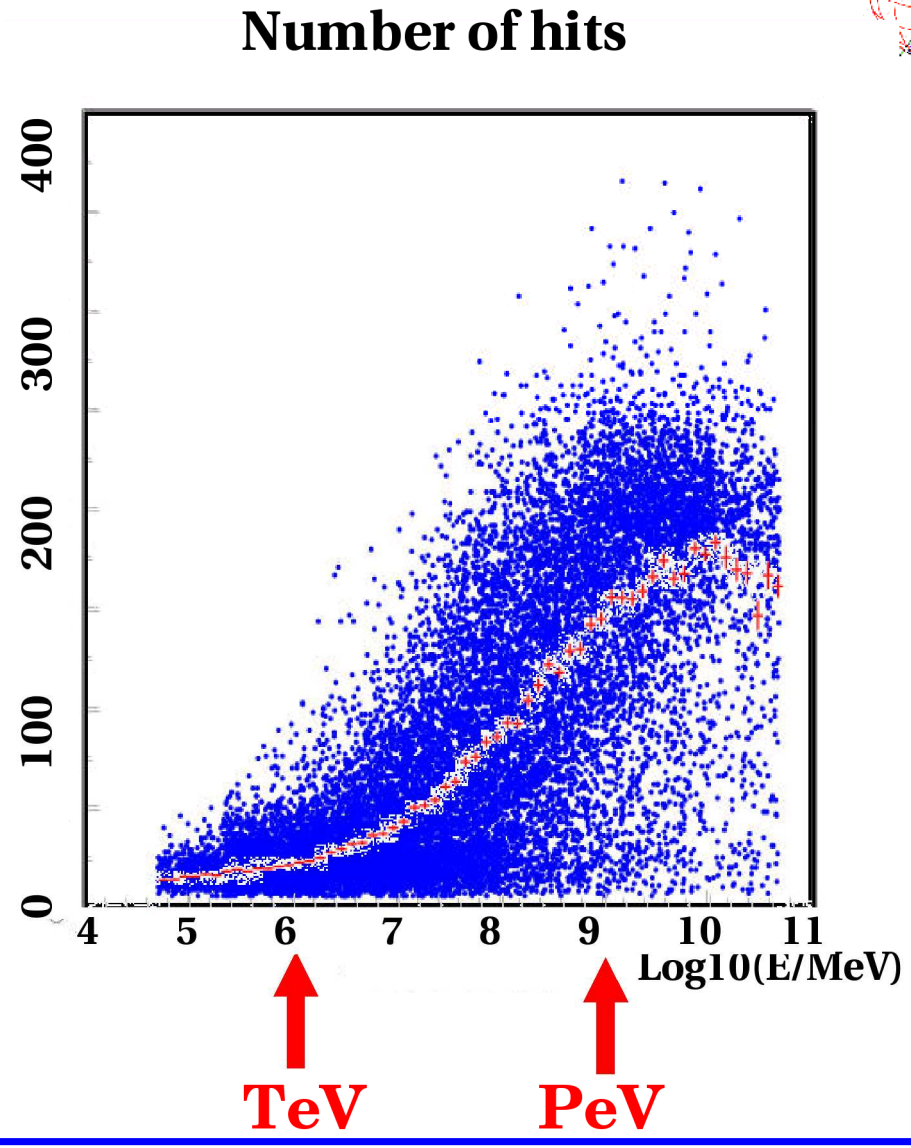
Propagation:
mmc

Detector-response/
Filtering reconstruction:
amasim,
dead OM, hit cleaning

Neural network input

Final set of input variables
conservative choice:
no track reconstruction informations used
->aim: robustness

- mean ADC
- mean LET
- rmsq LET
- nhits
- nch
- nch with one hit



Neural network training

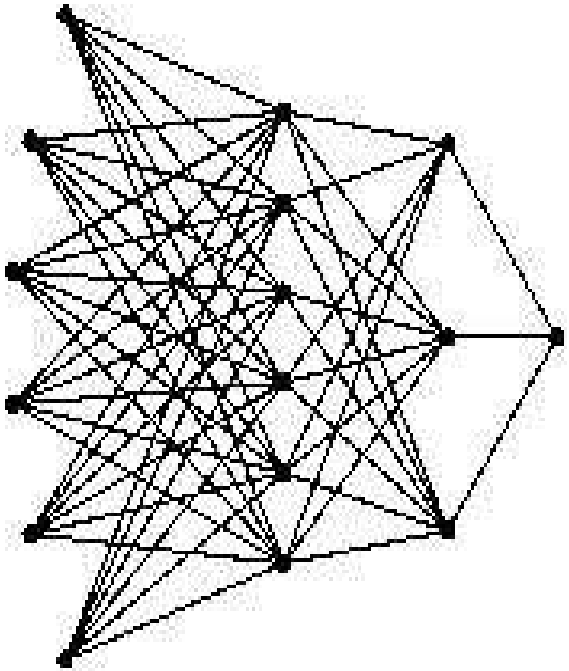
- Reasonable number of patterns:
  #number of training patterns/#nodes > 10

- Minimizing algorithm:
  back propagation mlp (standard for FF-NN)

- Activation
  sigmoidal: 1/[1+exp(-x)]

- Using test patterns
  (stop training if test pattern is minimal
  ->avoid over training)

- Check performance as function of the architectures
  (Result: two hidden layers more effective,
  performance depends mostly on #knots,
  final architecture 6-6-3-1 back propagation mlp)



The Neural Network: Performance Test

Response (MC) for mono-energetic muons (fixed distance 600m)

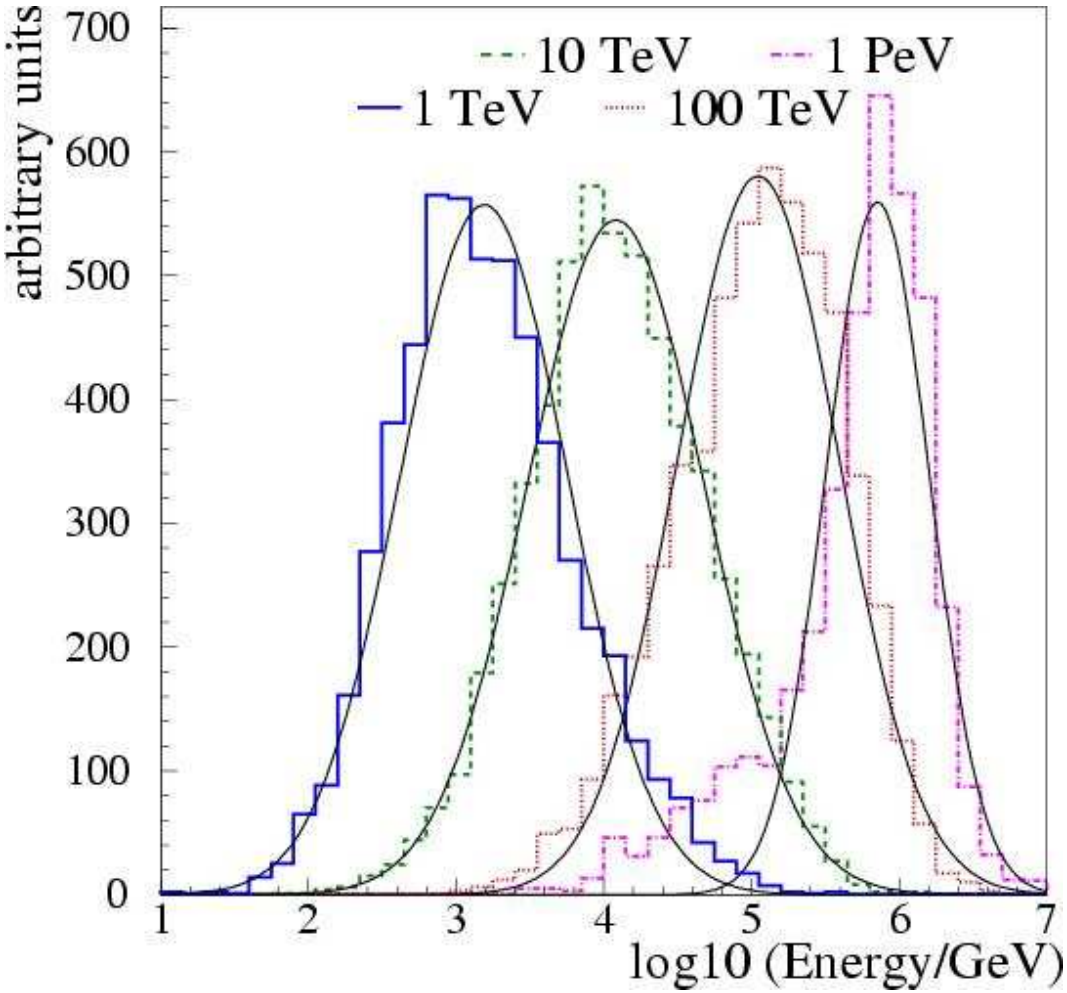
- Energy shift:

$$log_{10}(\frac{E_{rec}}{E_{true}}) < 0.05$$

- Resolution:

$$\sigma\left[\log_{10}(\frac{E_{rec}}{E_{true}})\right] \simeq 0.5$$

- Dynamic range: 500 GeV – 5 PeV
  - <500 GeV radiative processes do not dominate
  - >5 PeV detector saturates (all modules hit)

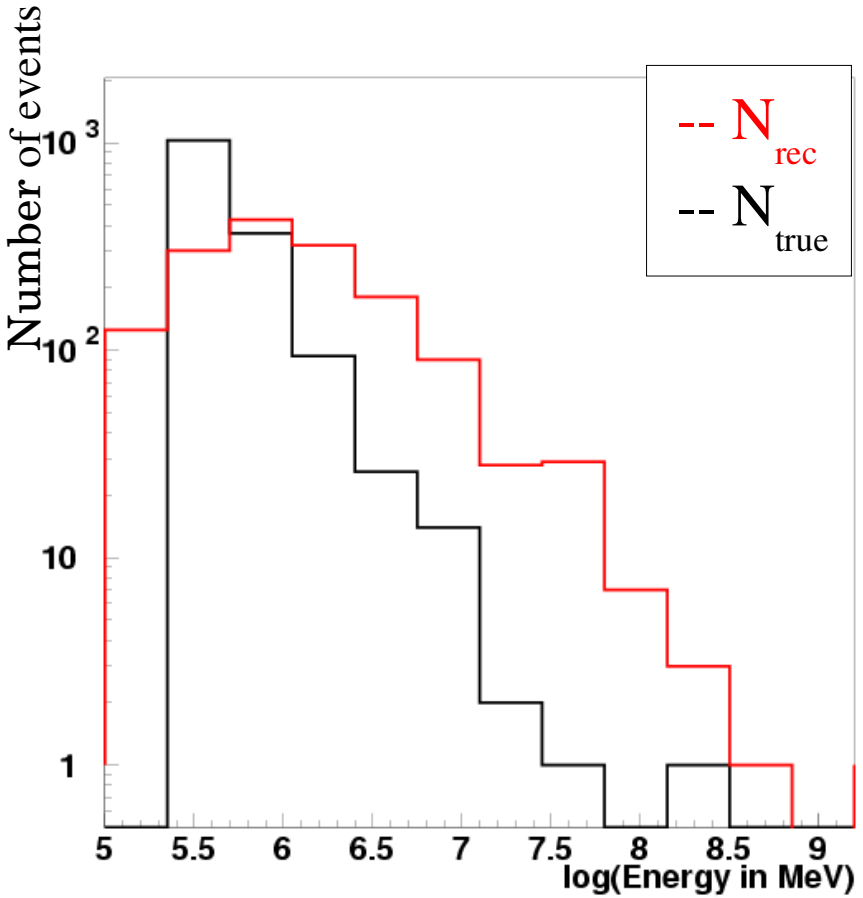


Effects of limited resolution:

$$P(x,y) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left(\frac{-(x-y)^2}{2\sigma^2}\right)$$

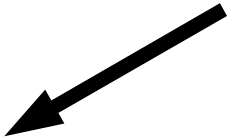
$$N_{rec}(E) = \int_0^\infty dy\, N_{true}(y) P(y,E)$$
$$= N_{true}\left(x + \frac{\gamma\,\sigma^2}{2} \ln 10\right)$$

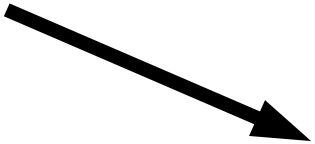
$$N_{true}(E) = N_0 \cdot E^{-\gamma}$$



Experimental Uncertainties

Distribution of reconstructed muon energy losses is not the true neutrino energy spectrum





Finite resolution

causing substantial migration from low to high energy bins (steeply falling spectrum)

mathematically:

$$g(y) = \int A(x,y) f(x) dx$$

use: regularized unfolding

Limited acceptance

caused by energy dependent detector sensitivity

mathematically:

$$g(y) = Acc(y) f(y)$$

use: bin-wise correction

Regularized unfolding à la Blobel

reconstructed energies **true spectrum**

$$g(y) = \int A(x,y) f(x)\, dx$$

$$f(x) = \sum_i a_i B_i(x)$$

B-splines as base functions

$$g(y) = \sum_i a_i \underbrace{\int A(x,y) B_i(x)\, dx}_{A_i(y)} = \sum_i a_i A_i(y)$$

$$L = P(g \mid g_a)$$

Likelihood with regularized minimizer

$$a_1, \ldots, a_n$$

Regularization: Cutoff with well defined conditions
(Blobel, CERN report 85-09)

Performance checks of unfolding

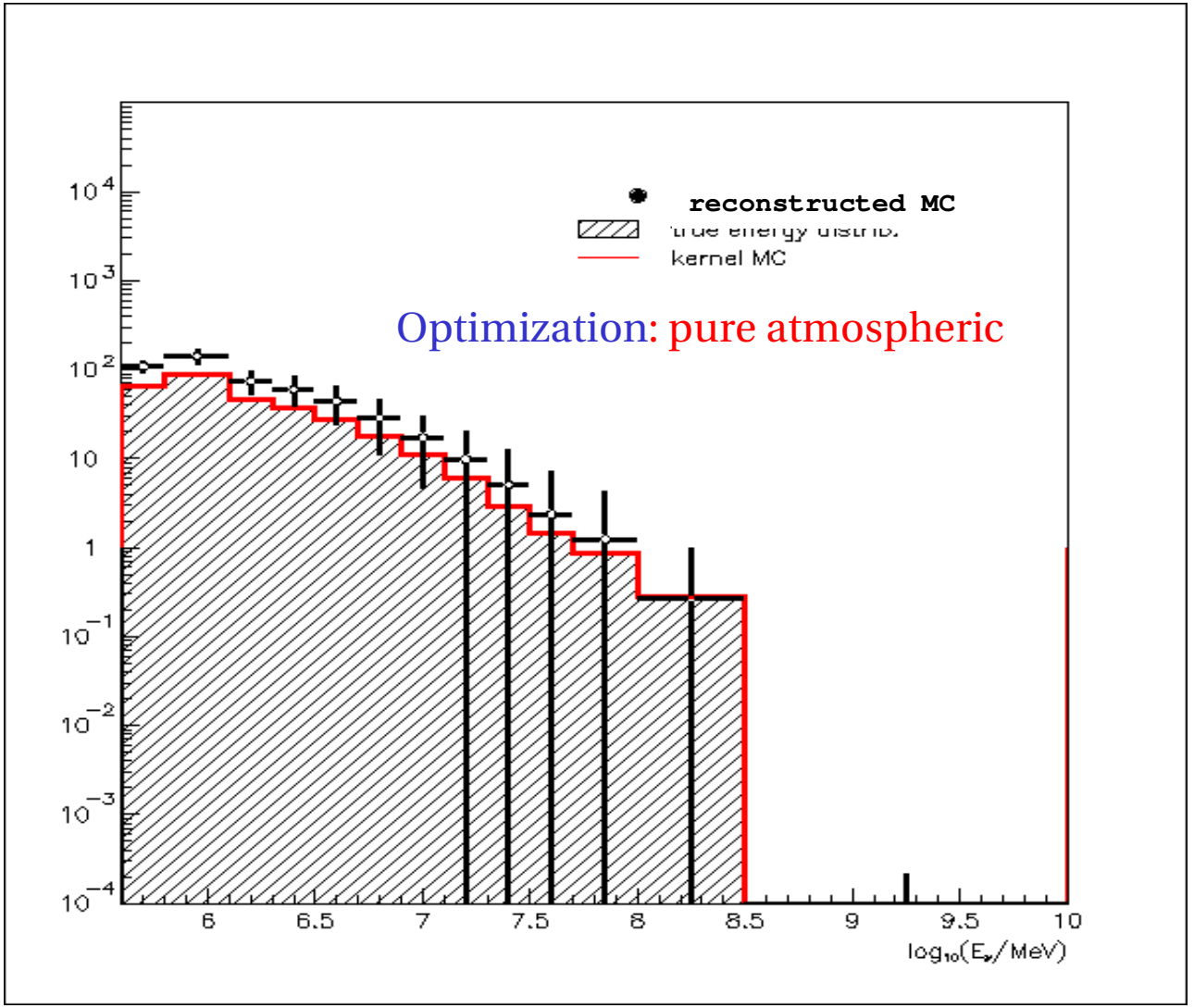
How sensitive is the kernel on the mixture of the MC ?

Monte-Carlo Test

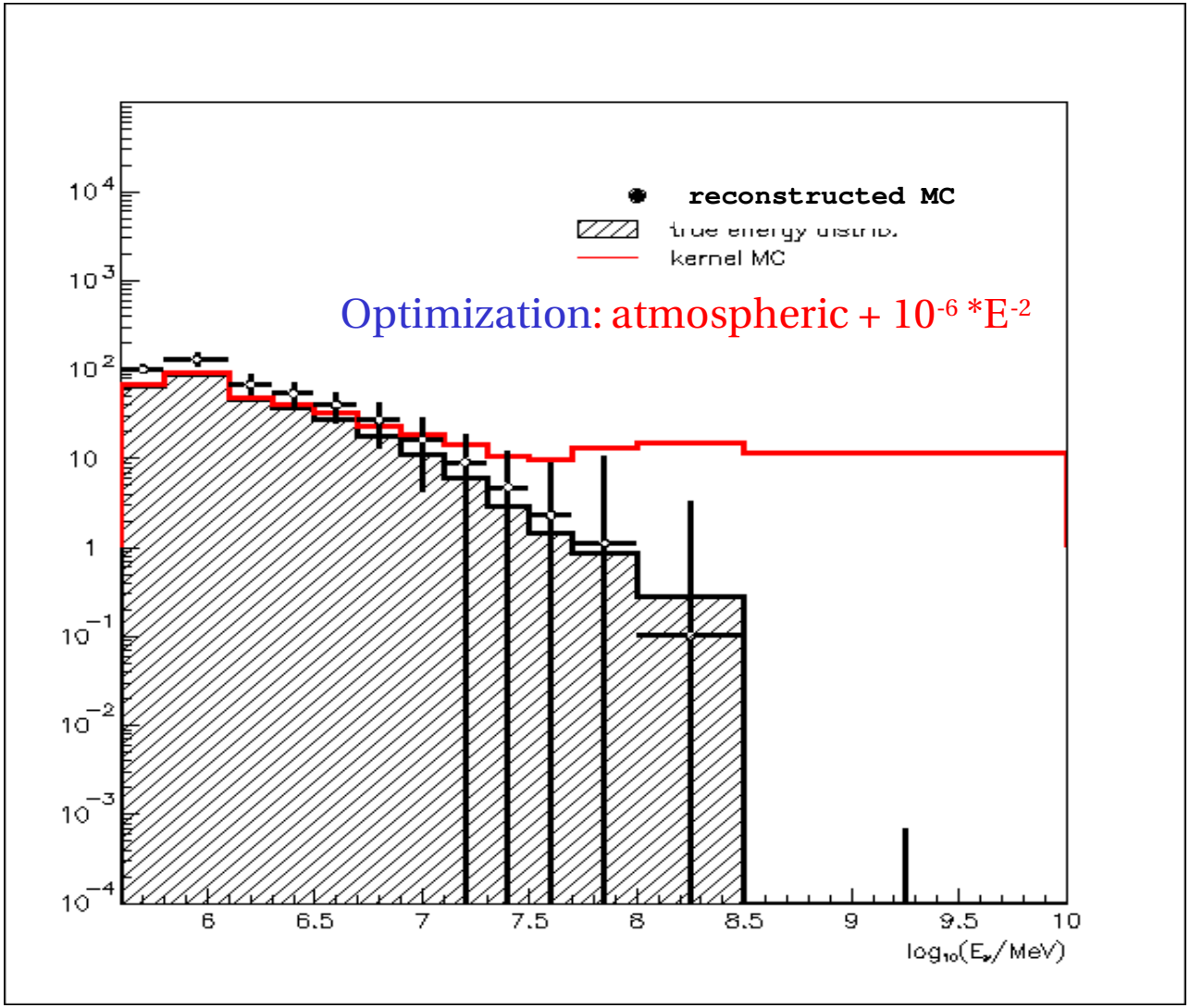
Unfold atmospheric MC, using a kernel that was trained on...

- atmospheric MC
- atmospheric MC + $10^{-6} * E^{-2}$ spectrum
- pure E^{-2} spectrum
- pure E^{-1} spectrum

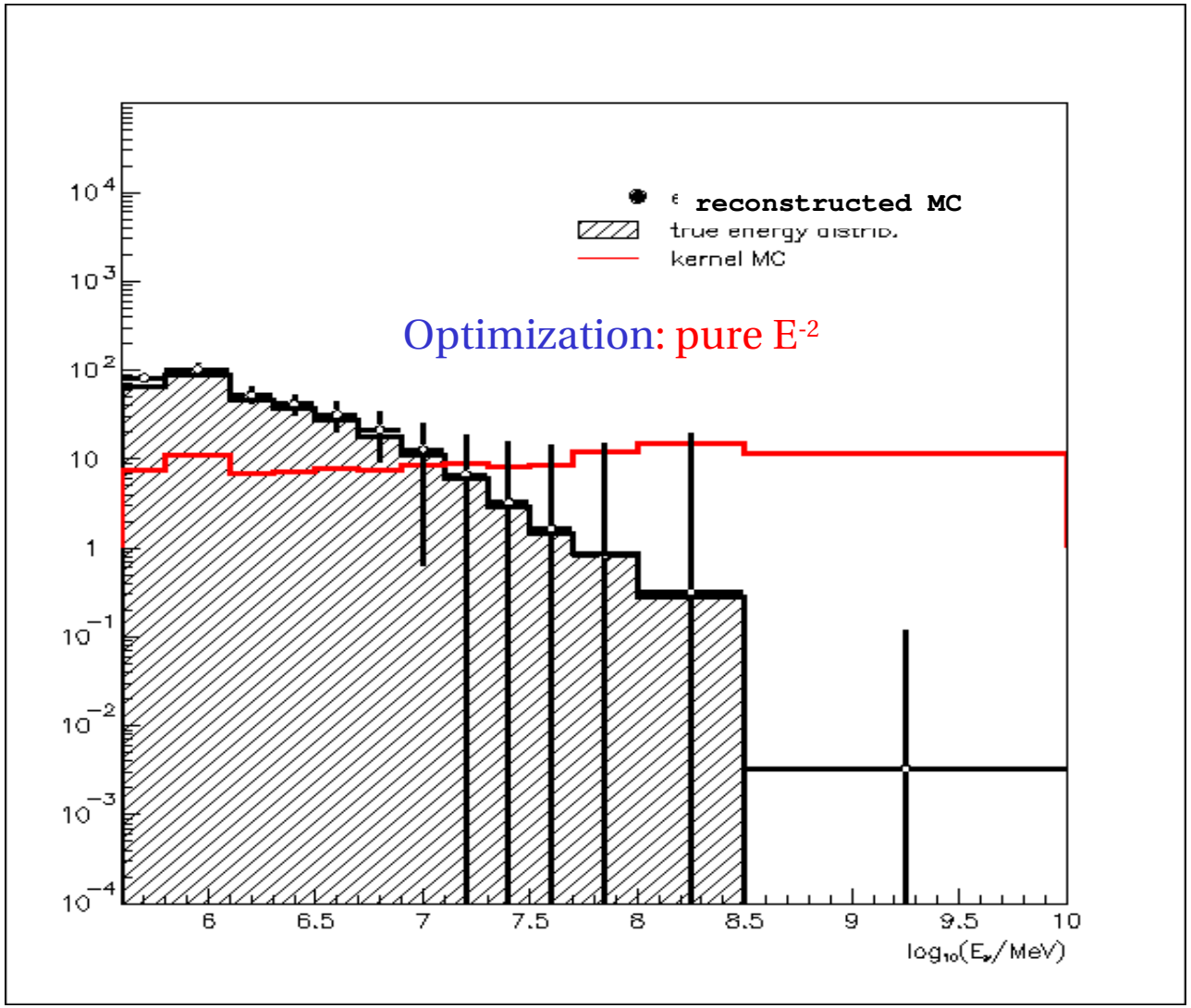
Performance checks of unfolding



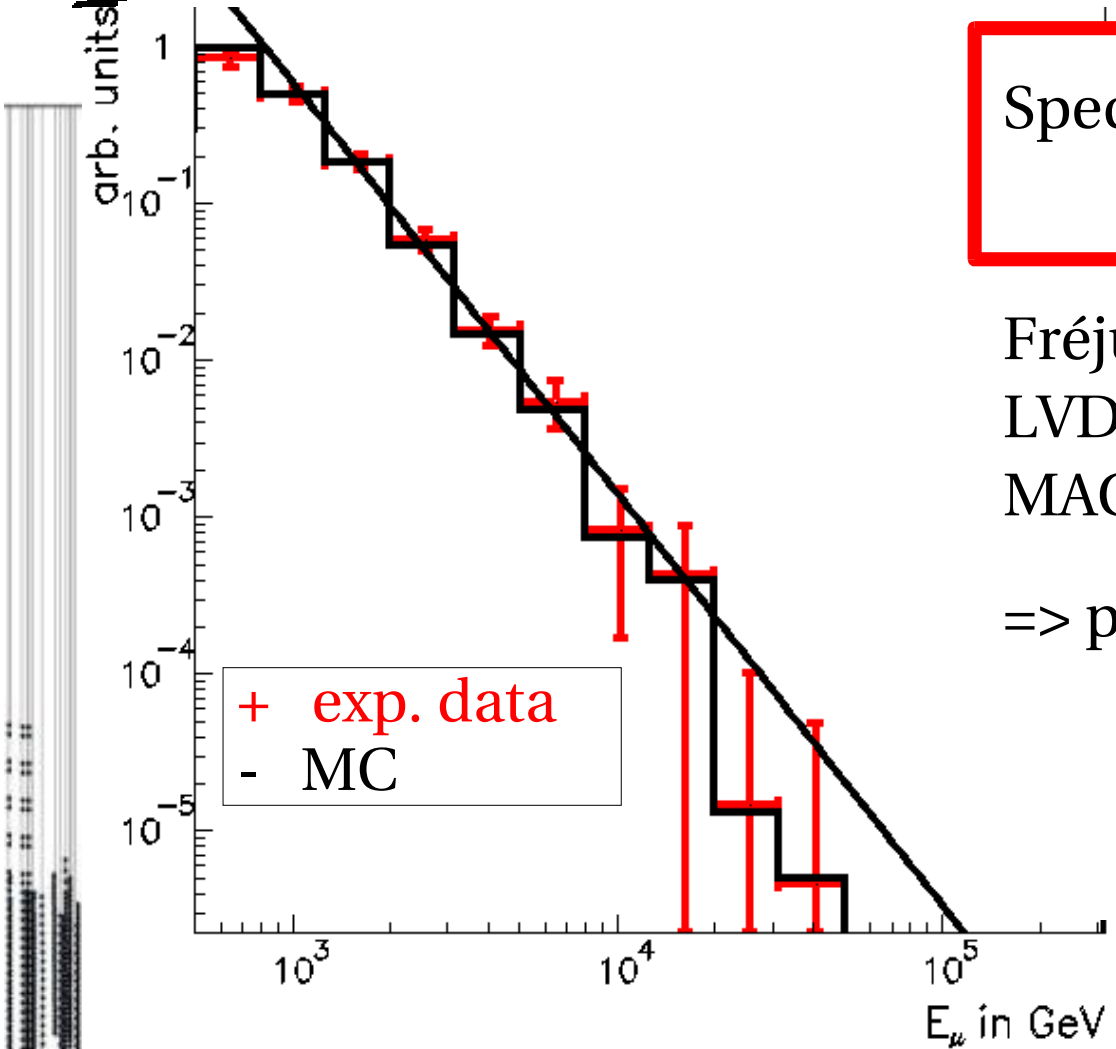
Performance checks of unfolding



Performance checks of unfolding



Cross-check down-going muons
The atmospheric muon spectrum



Spectral index:

$\gamma = 3.62 \pm 0.17$ (stat.)

Fréjus: $\gamma = 3.78 \pm 0.07$ (stat.)

LVD: $\gamma = 3.78 \pm 0.05$ (stat.)

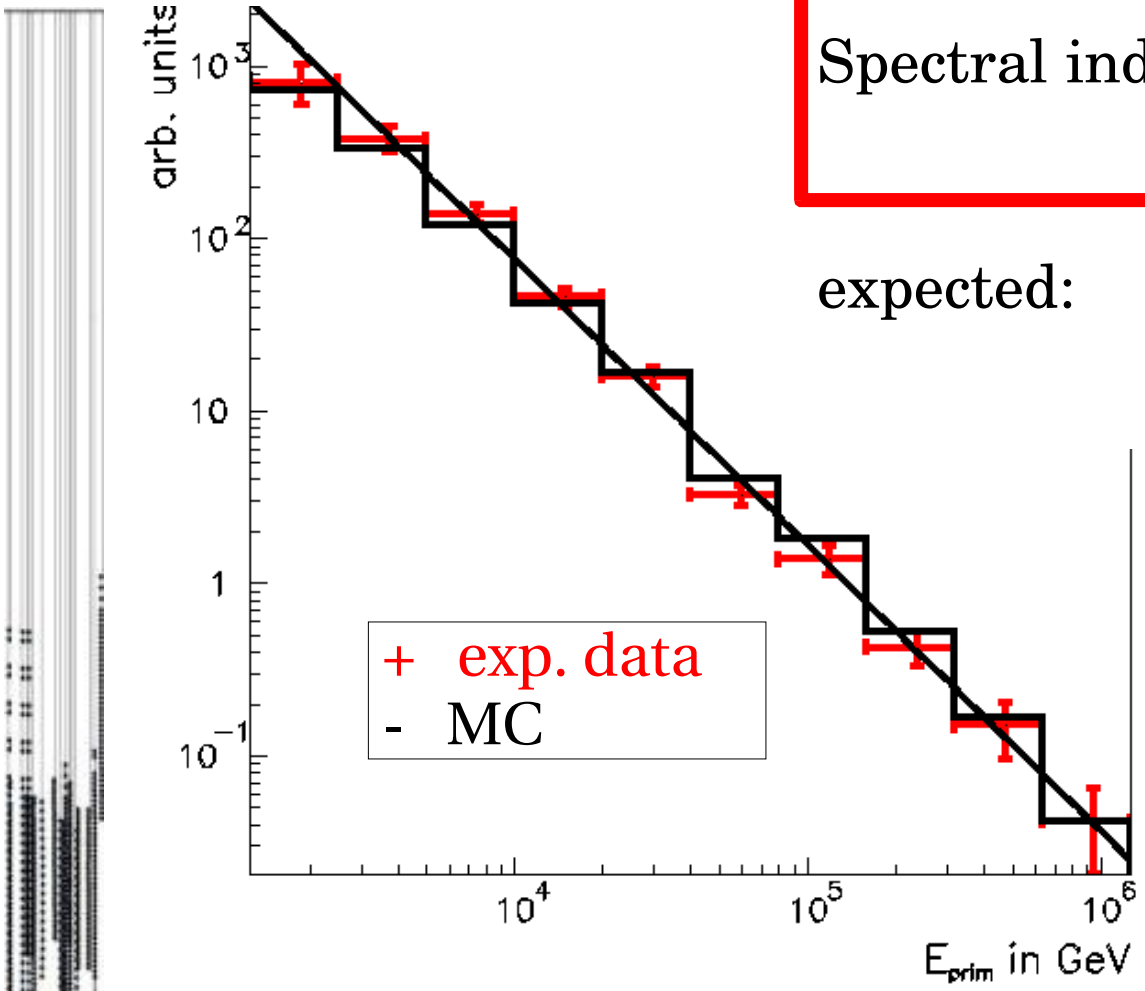
MACRO: $\gamma = 3.74 \pm 0.01$ (stat.)

=> proof of method

$$\frac{d^2\phi}{dE_\mu d\Omega} = 0.185 E_\mu^{-2.78 \pm 0.05} \left(\frac{115GeV}{115GeV + 1.1 E_\mu \cos\theta} + \frac{46GeV}{850GeV + 1.1 E_\mu \cos\theta} \right)$$

Atmospheric Neutrino and Muon Spectra Measured with the AMANDA-II Detector

Cross-check down-going muons
The primary hadron spectrum



Spectral index:

$\gamma = 2.70 \pm 0.05$ (stat.)

expected: $\gamma_H = 2.76 \pm 0.02$ (stat.)

$\gamma_{H\varepsilon} = 2.63 \pm 0.02$ (stat.)

(**Wiebel-Sooth '98**)

The neutrino sample

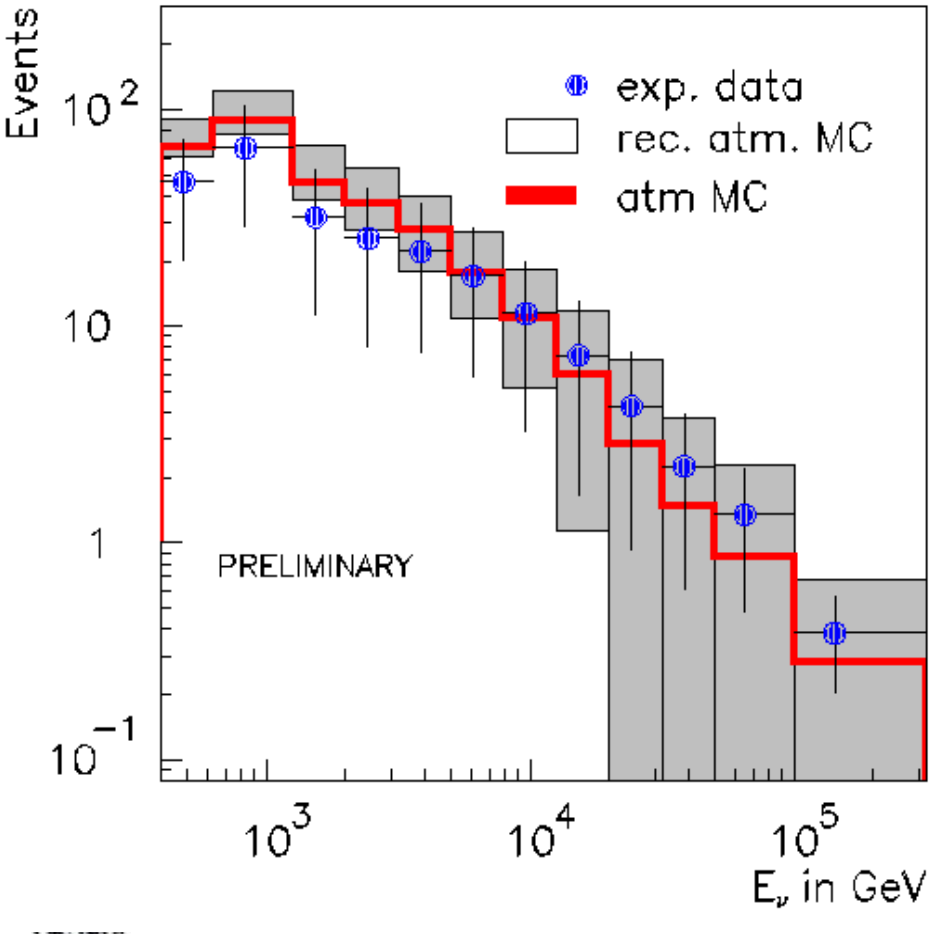
based on the AMANDA (2000) point source neutrino sample, zenith>100°

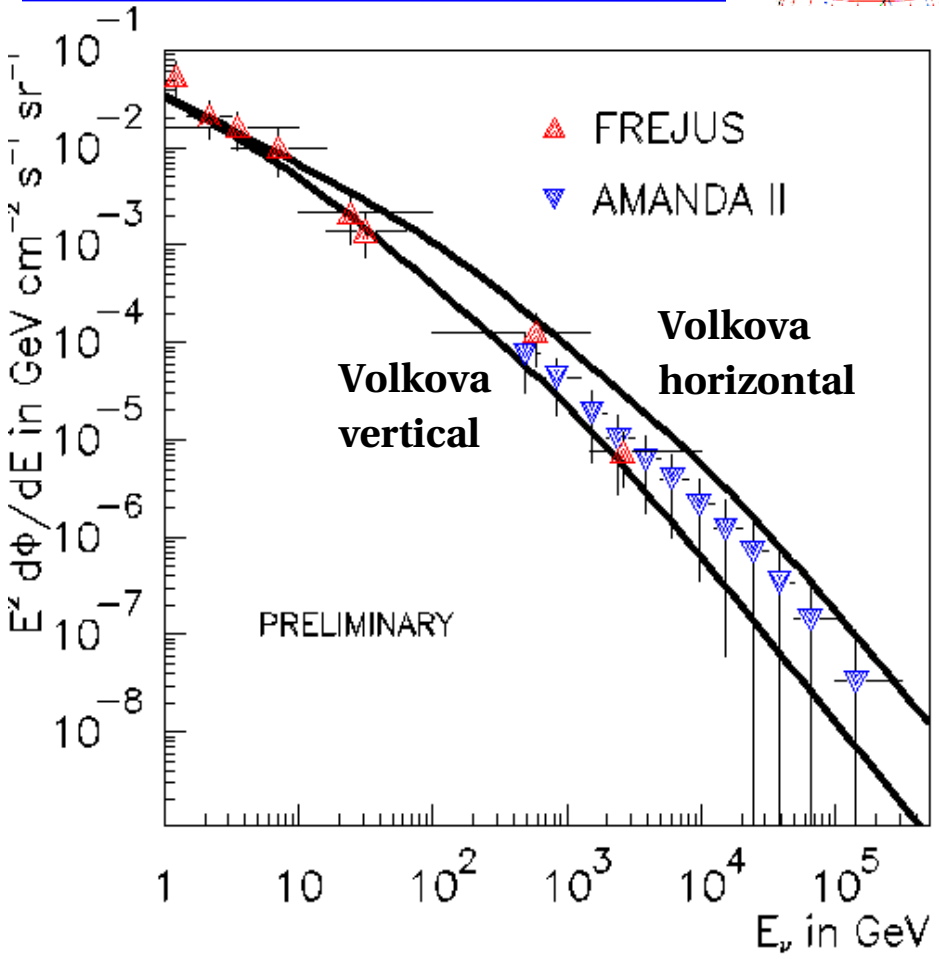
(ICRC-Presentation: D.Steele and T. Hauschildt, HE 2.3)

=> 570 events

Background:
misreconstructed down-going muons <5%

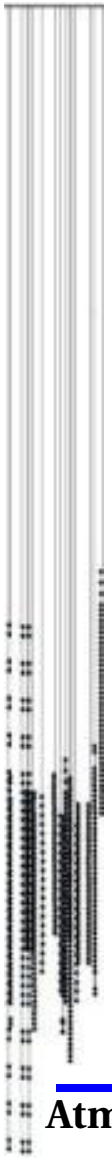
The unfolded atmospheric neutrino spectrum





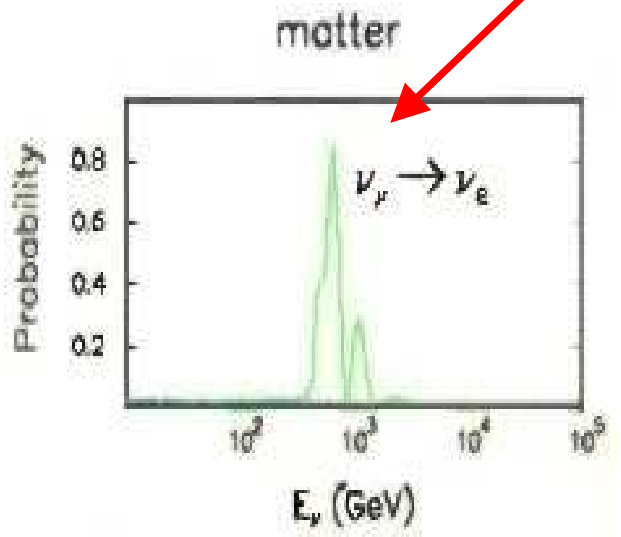
- Statistical **(unfolding)**
- Systematics **(primary hadron flux, pion/kaon cross-section, muon range, ice properties, PMT efficiencies)**

Sensitivity on LSND/Nunokawa predictions



3 dip structure: flux suppression between 400 GeV and 3TeV

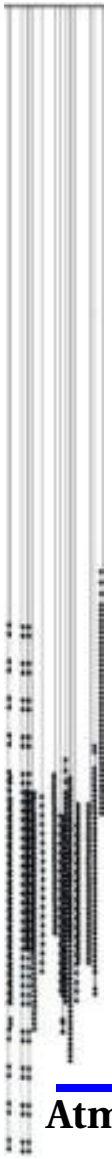
max 80% flux suppression of either nu or resp. nubar (for normal or resp. inverted mass hierarchy)

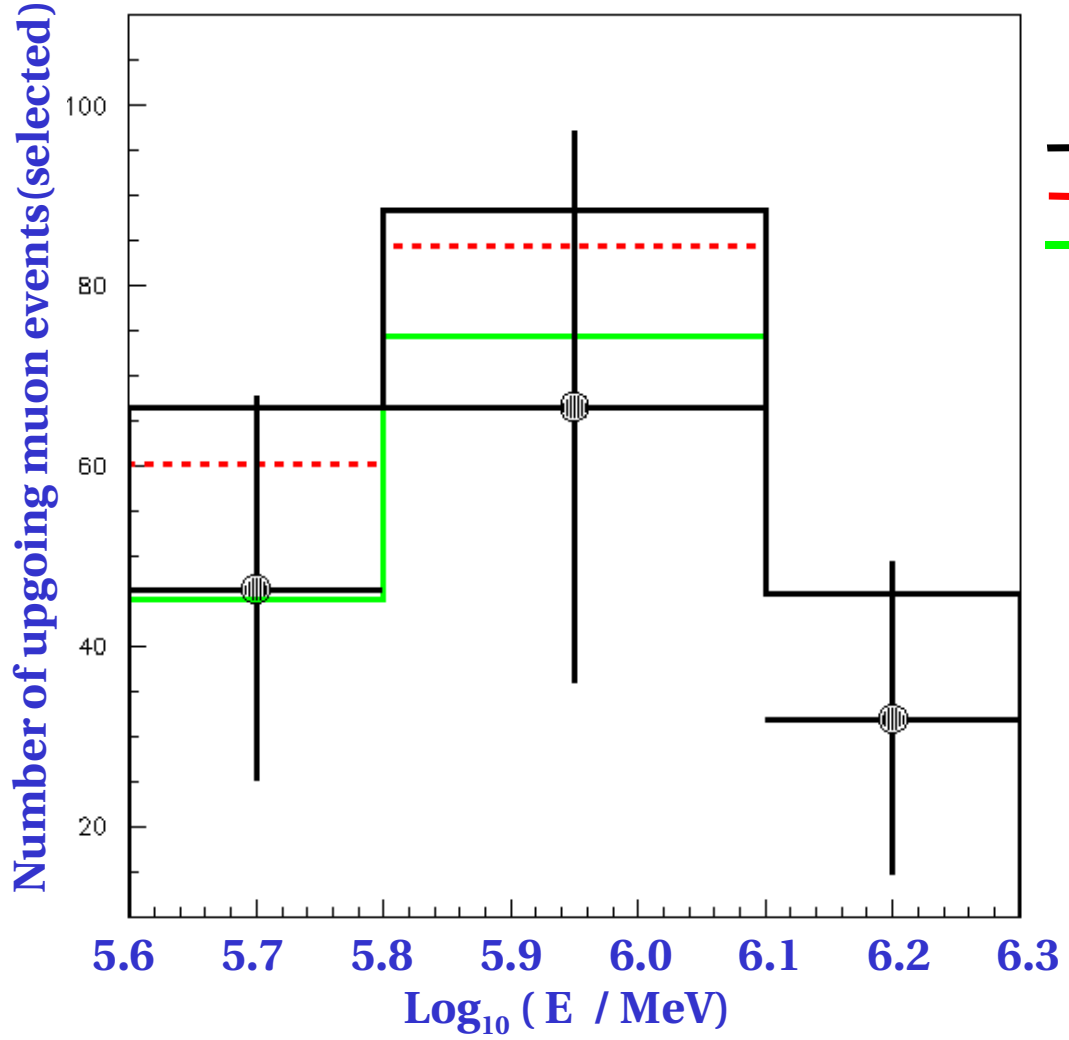


Nunokawa, et al.;
Phys.Lett. B562 (2003) 279-290

- **The LSND experiment observes an oscillation signal**
  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **(PRL 75, 1995)**
  $\nu_\mu \rightarrow \nu_e$ **(PRL 81, 1998)**
- **Nunokawa, et al., hep-ph/0302039 model this in a 2+2 neutrino scenario**
- **predict a resonant** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $(\nu_\mu \rightarrow \nu_e)$ **oscillation for a normal (or inverted) mass hierarchy solution**

Sensitivity on LSND/Nunokawa predictions





Pure atmospheric expectation
2+2 normal mass hierarchy
2+2 inverted mass hierarchy

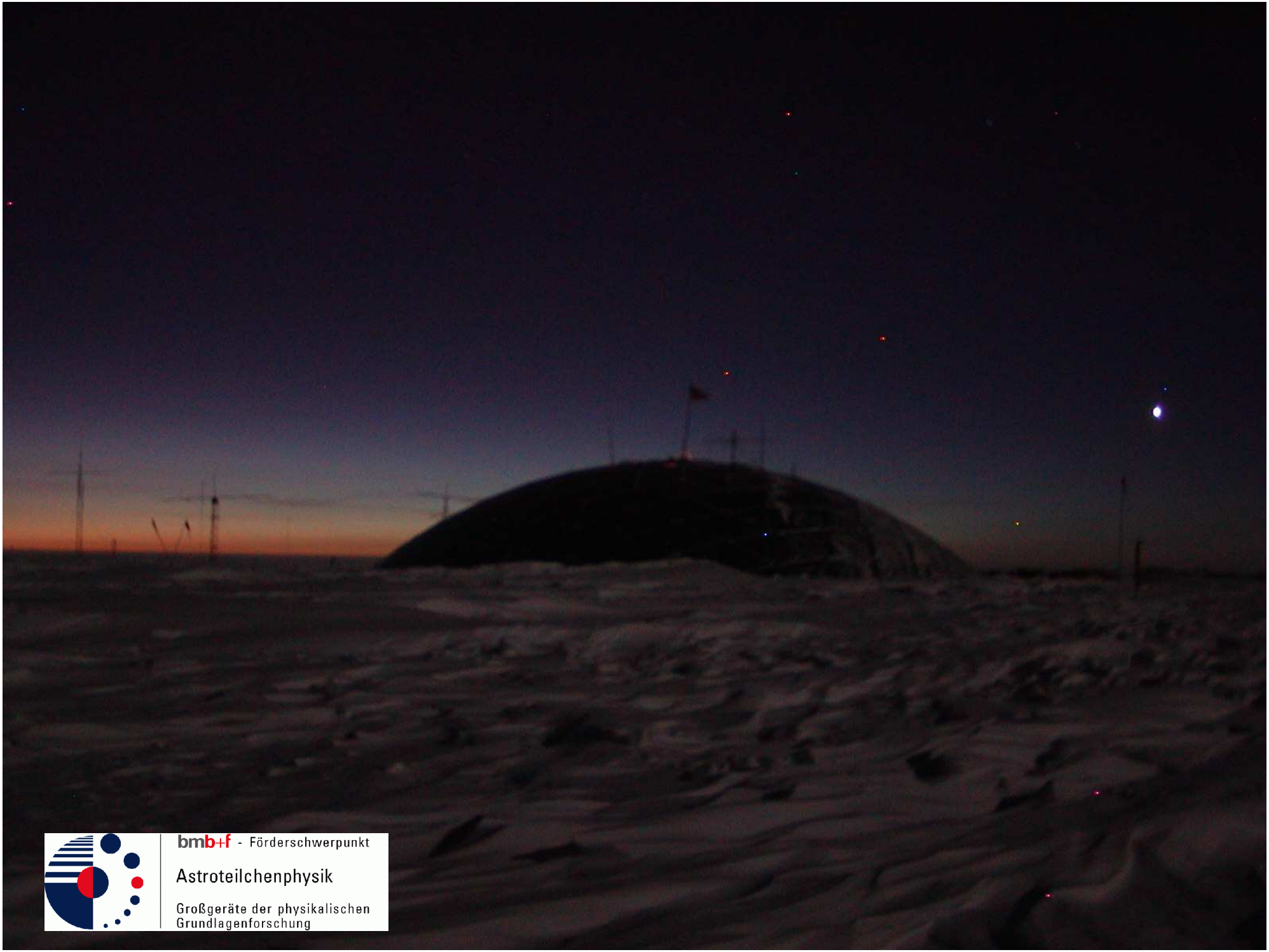
\+ **reconstructed**

=>Presently no sensitivity, limited by statistical and systematic errors and resolution

Summary

- NN energy reconstruction is robust and provides necessary resolution
- Unfolding is necessary to obtain the physical spectra
  Regularized unfolding shows good performance

- Atmospheric muons $\gamma = 3.62 \pm 0.17$ (stat.)
  CORSIKA $\gamma = 3.72 \pm 0.08$
- Primary hadrons $\gamma = 2.70 \pm 0.05$ (stat.)$\pm$ systematics
  Wiebel-Sooth: $\gamma = 2.63$-2.76
- Atmospheric neutrinos $\gamma = 3.56 \pm 0.20$ (stat.)
  Fréjus: $\gamma = 3.66 \pm 0.05$ (stat.)
- Neutrino energy spectrum unfolded up to 100 TeV
- Neutrino spectrum in agreement with atmospheric prediction and Fréjus measurement
- Presently, no sensitivity for Nunokawa prediction



bmb+f - Förderschwerpunkt

Astroteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

What needs to be done to obtain a limit?

- Produce a large set of MC samples statistically equivalent to the experimental measurement (vary also signal contributions)
- Unfold the energy spectra for each MC-experiment
- Evaluate the average upper limit and model rejection potential for different signal contribution and different energy cuts
- Decide where to place the optimum energy cut to obtain best average limit including systematic effects
- Apply cut on data and obtain limit