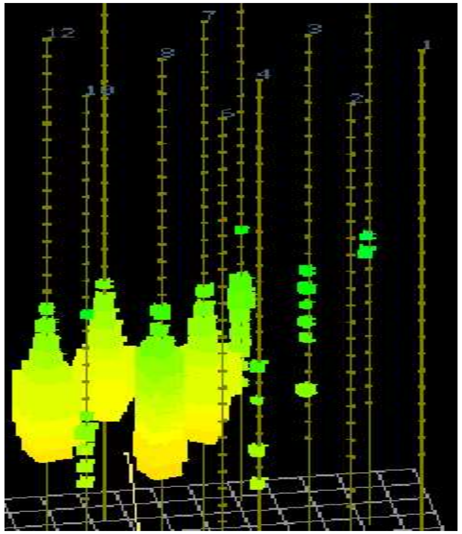
Roma, 4 May 2005

Shower Reconstruction for the ANTARES Neutrino Telescope



- Cosmic Radiation
- Cosmic Neutrinos
- The ANTARES Neutrino Telescope
- Reconstruction of Showers

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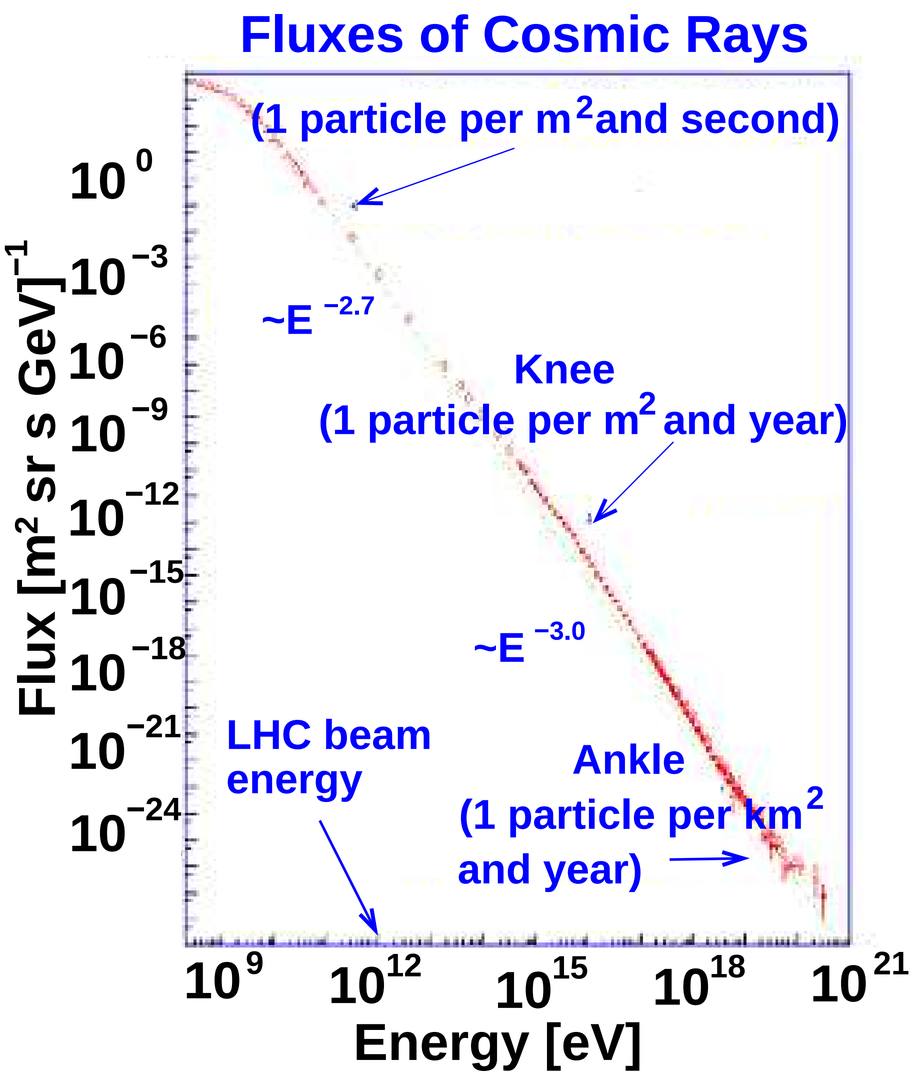
Cosmic Radiation I

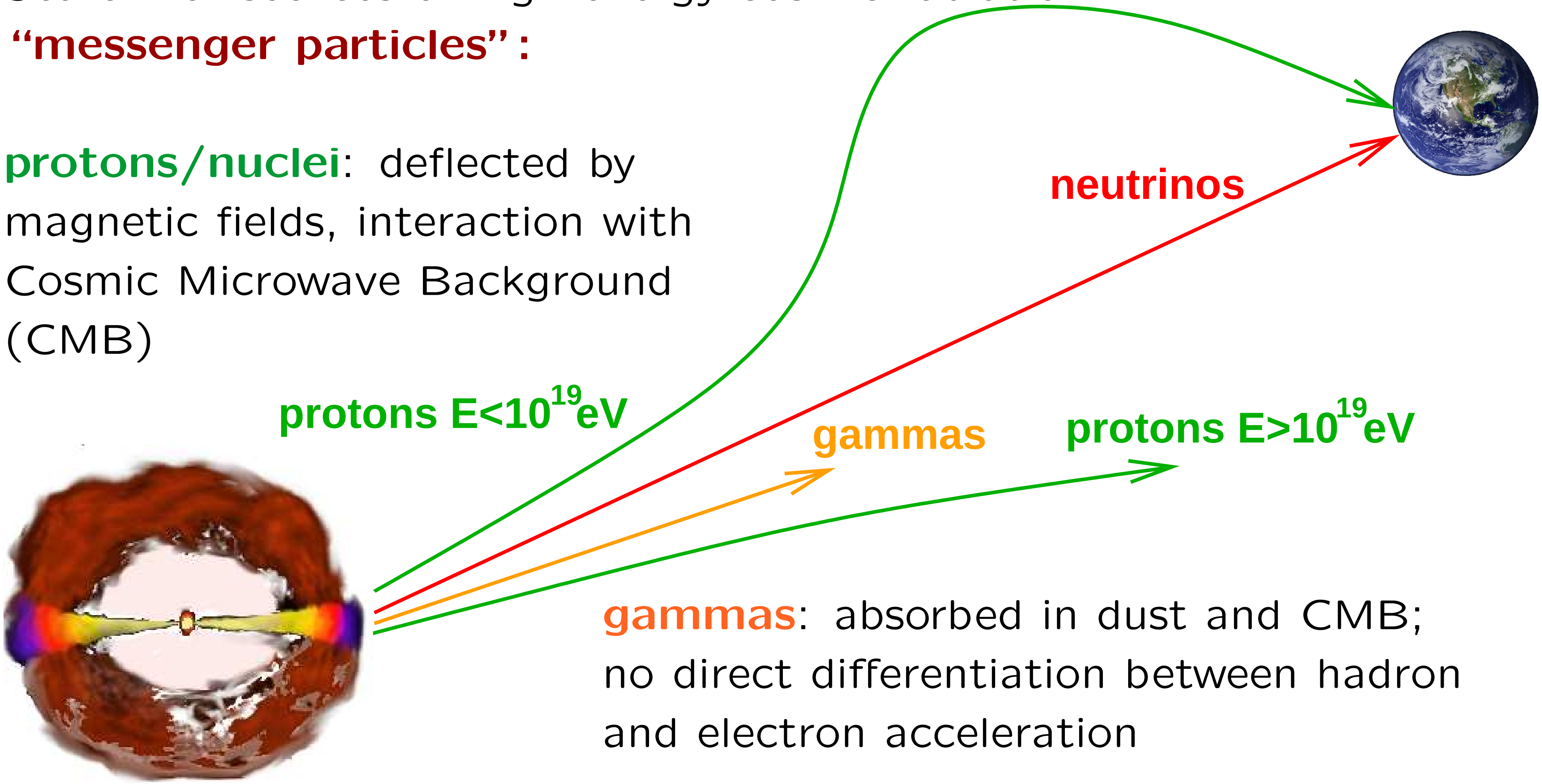
- first discovered in 1912:
  balloon experiment by V. Hess
- for high energies:
  mainly p, α
- $E < 1$ TeV: detected
  by satellites / balloons
- $E > 1$ TeV: air shower arrays
  (e.g. KASCADE, AGASA, Pierre-Auger)



Cosmic Radiation II

Search for sources of high energy cosmic radiation
"messenger particles":

protons/nuclei: deflected by magnetic fields, interaction with Cosmic Microwave Background (CMB)



gammas: absorbed in dust and CMB; no direct differentiation between hadron and electron acceleration

Cosmic High Energy Neutrinos

Production:

accelerated protons interact with interstellar matter, CMB or synchrotron radiation

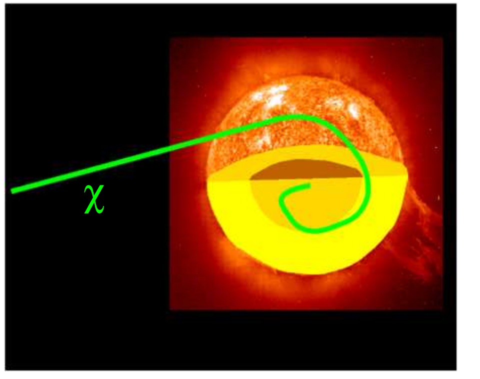
$$
\begin{aligned}
p + p/\gamma \rightarrow \ & \pi^{\pm} \ + \ X \\
& \hookrightarrow \ \mu + \nu_\mu \\
& \qquad \hookrightarrow e + \nu_e + \nu_\mu
\end{aligned}
$$

$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$; neutrino oscillations $\rightsquigarrow \nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

- $+$ not deflected in magnetic fields $\Rightarrow$ identification of source
- $+$ proof for hadron acceleration
- hardly interacts with matter
  - $+$ large range
  - $-$ hard to detect $\Rightarrow$ need to instrument huge target mass

Physics with Neutrino Telescopes

- **neutrino astronomy:** identification of neutrino point sources: SN remnants, GRBs, AGNs, ...
- diffuse cosmic neutrino flux
- search for Cold Dark Matter: WIMPs
- search for exotics, discovery of unknown physics...



Background: Atmospheric Neutrinos

- produced when high energy cosmic particles interact with atmosphere
- from all directions
- irreducible background, but flux approximately known

⇒ **signature of cosmic neutrinos:**
direction (point sources) or energy spectrum (diffuse flux)

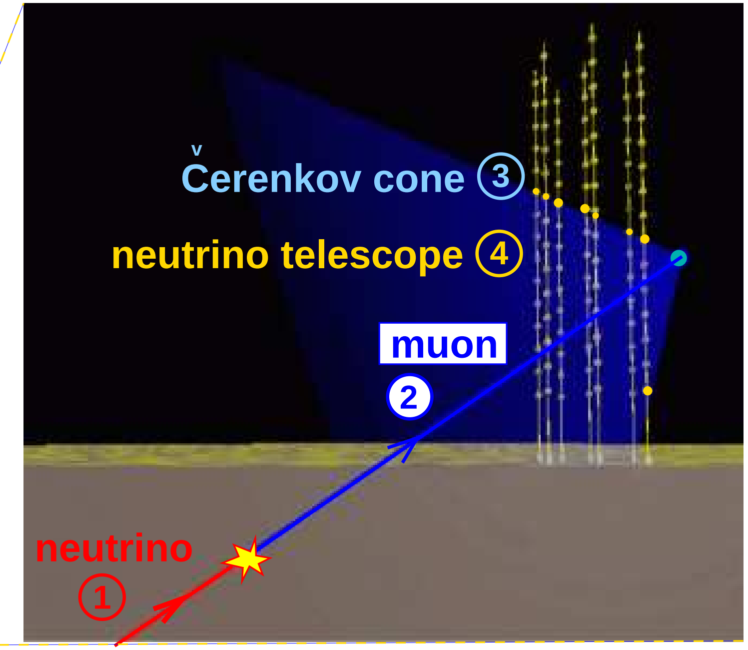
Detection Principle

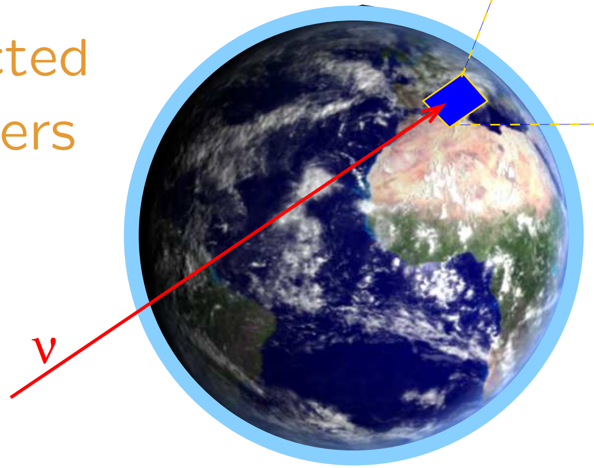
① neutrino interacts with matter (rock/water/ice)

② production of charged particles (muons, hadrons, electrons, taus)

③ charged particles radiate Čerenkov photons in the water/ice

④ photons detected in photo multipliers





Čerenkov angle

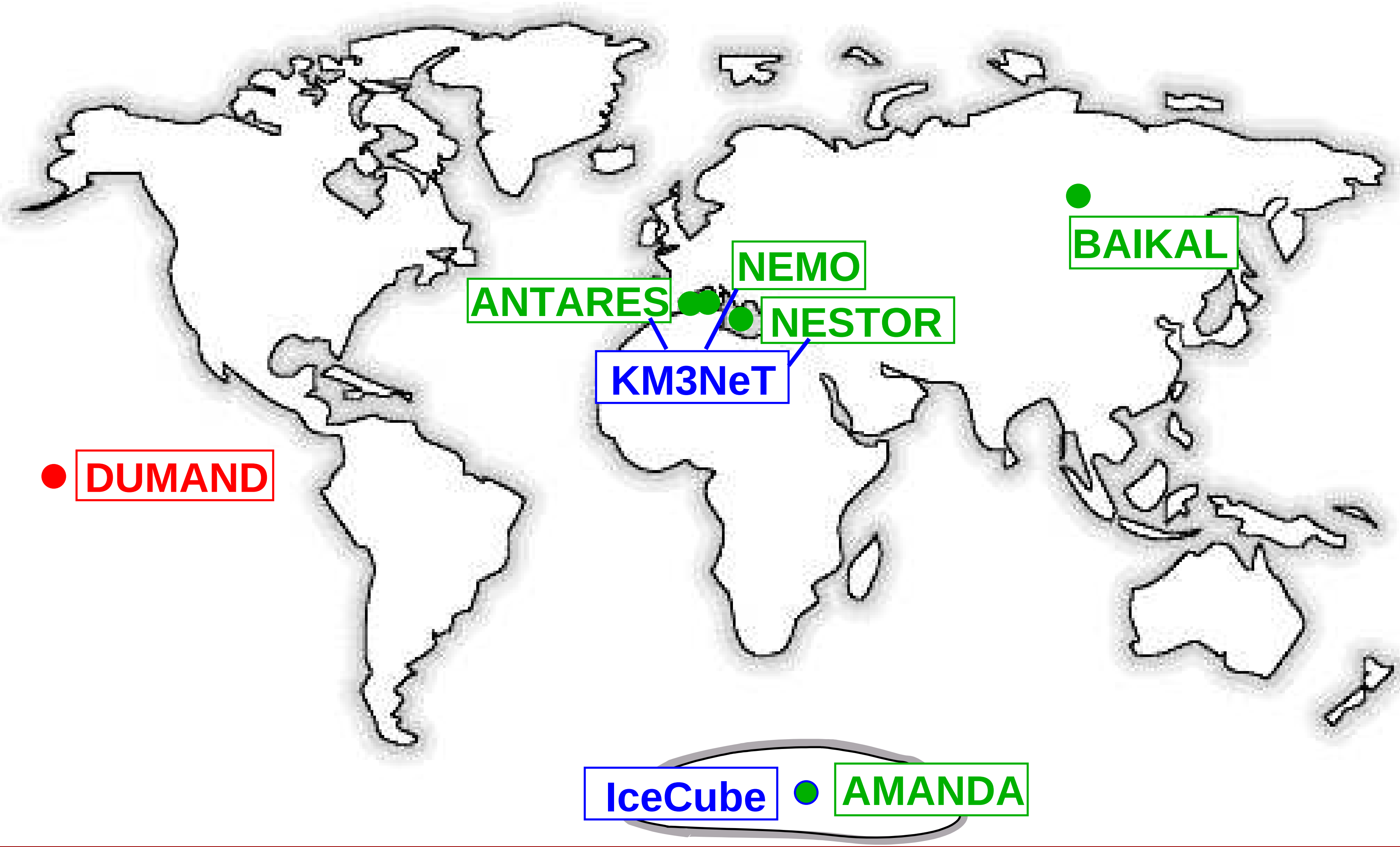
$\Theta_C = \arccos(1/\beta n)$

in seawater:

$\Theta_C \approx 42^\circ$

use large transparent masses in nature
⇒ lakes, ocean, antarctic ice
earth shields all particles except neutrinos

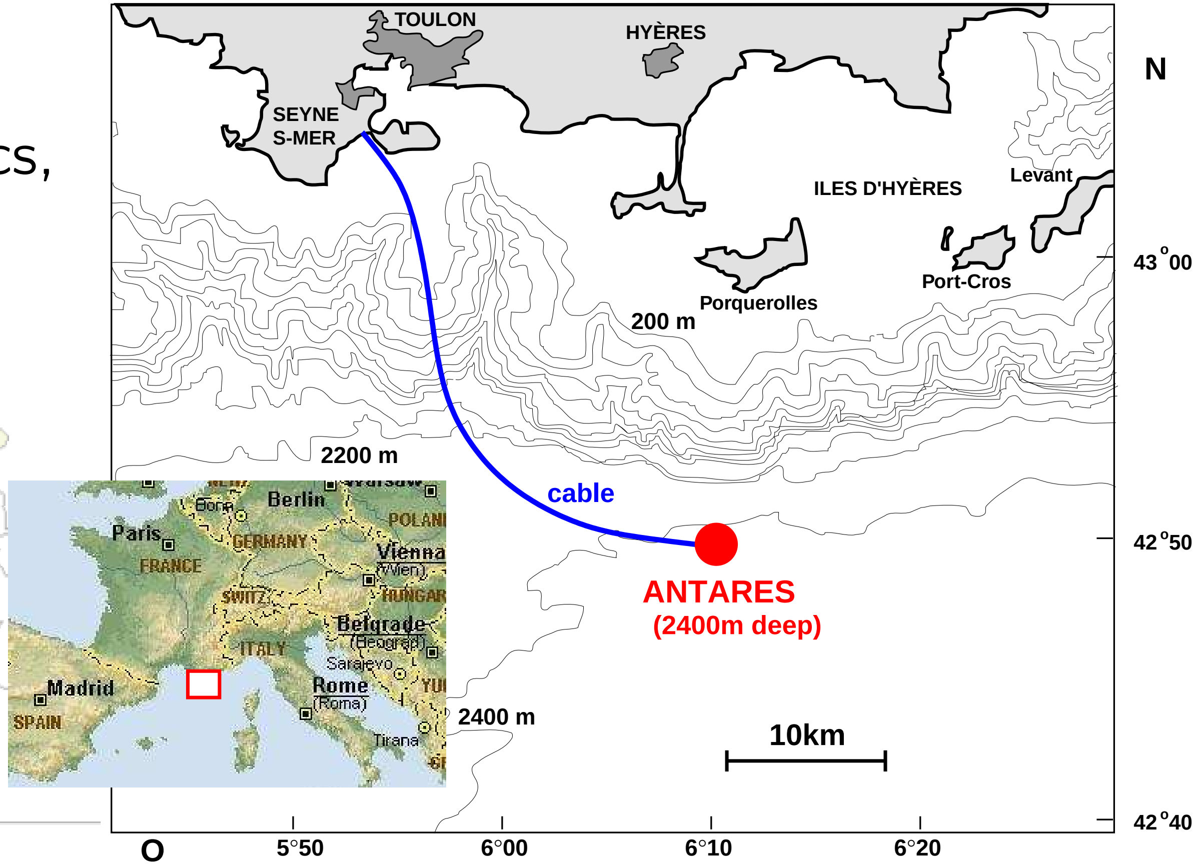
Neutrino Telescopes world wide



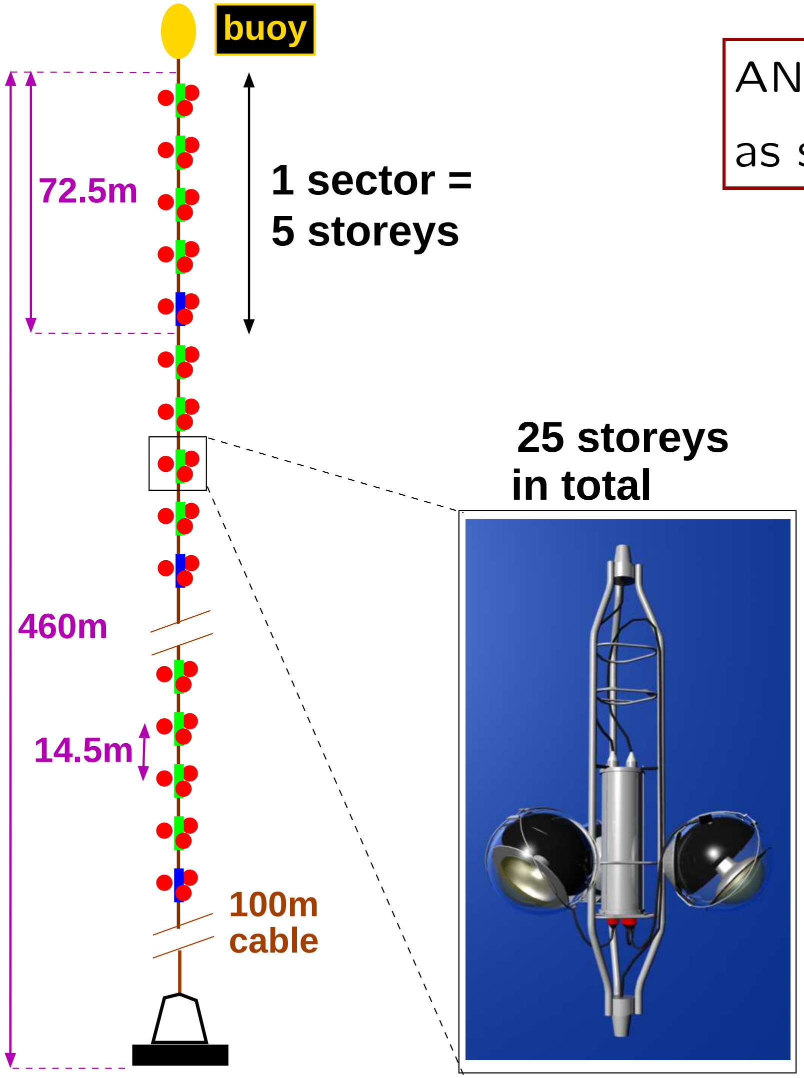
ANTARES

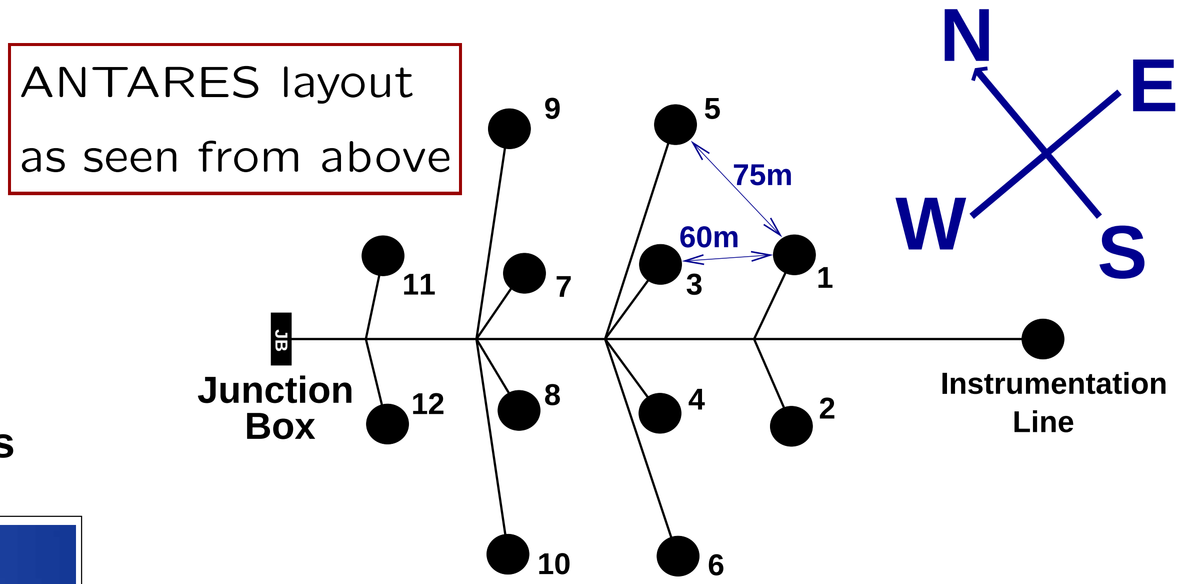
ANTARES: **A**stronomy with a **N**eutrino **T**elescope and **A**byss environmental **RES**earch

- collaboration of 20 institutes from 6 European countries
- members from particle physics, astronomy, oceanology



ANTARES Layout





- in 2400 m depth
- 12 lines with 900 Optical Modules (OMs) in total
- each line has 25 storeys with 3 OMs
- total height 460 m

The ANTARES Optical Modules

glass spheres ⌀ 43 cm,
pressure resistant
up to 600 bar

geomagnetic field shielded
by μ-metal cage

10″ Hamamatsu photo multipliers
quantum efficiency: $> 20\%$ $(360 < \lambda < 460$ nm$)$
looking downward at 45° from horizontal

ANTARES Construction: Milestones

- October 2001: deployment of deep sea cable
- December 2002: deployment of Junction Box

- March - July 2003:
  Prototype Sector Line and
  Mini Instrumentation Line

Current Status of ANTARES

Two test lines deployed March 2005 and connected April 2005

MILOM:

- Mini Instrumentation Line + (3+1) Optical Modules
- Calibration and Monitoring, e.g.
  - light attenuation
  - sea current
  - seismometer
- taking data in ns resolution!

Line 0:

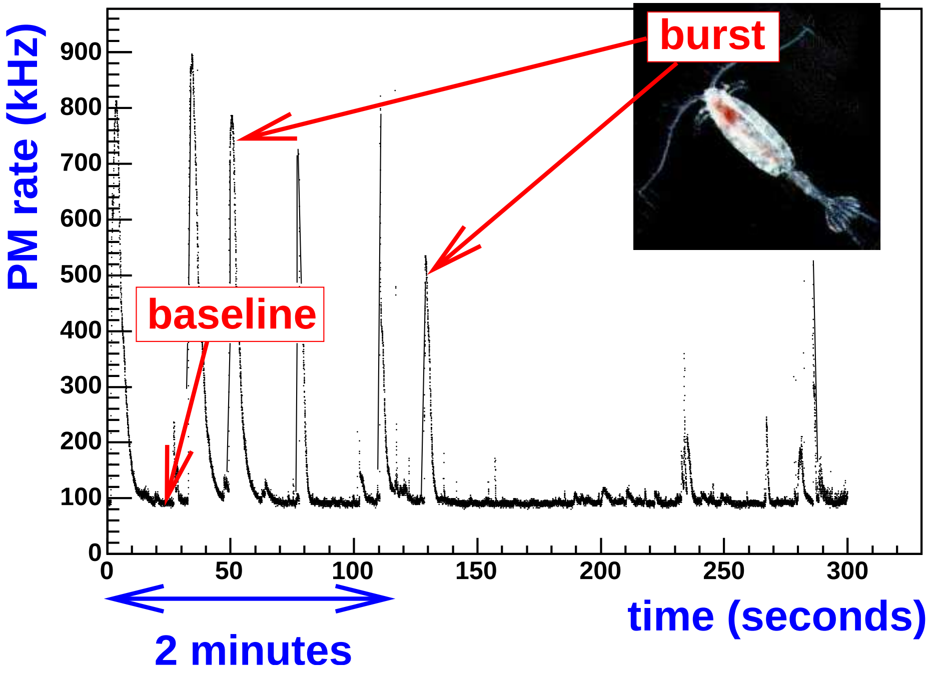
- (almost) full length line, 23 storeys with 3 glass spheres each
- no electronics
- used for structural and cable tests

$\Rightarrow$ to be recovered soon

Deep Sea Optical Background

Rates measured with Prototype Sector Line March - July 2003

Two components:



1. baseline:

- isotropic background
- caused by ^{40}K decays and bacteria bioluminescence
- mainly single photons
- rate $\sim$ 60 kHz to $\approx$ 200 kHz per OM

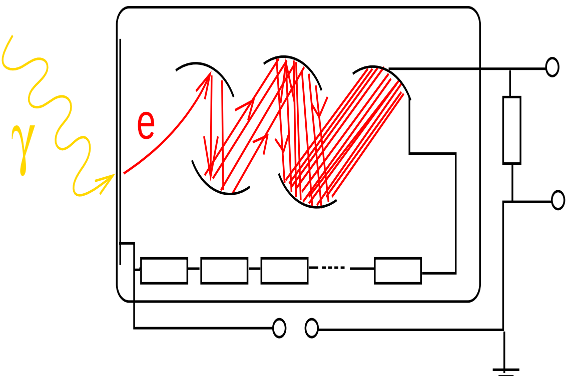
2. bursts:

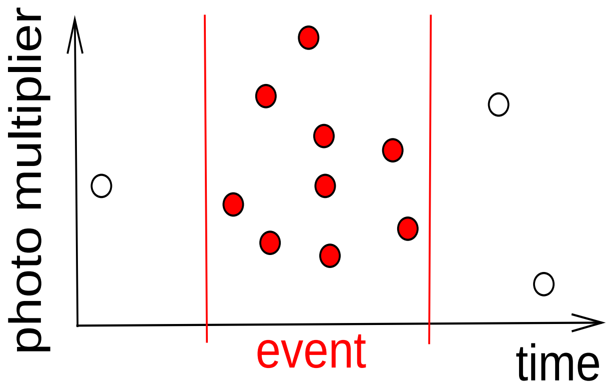
- caused by larger sea organisms
- aperiodic, localised
- MHz rates in nearby OMs
- affected OMs not usable for reconstruction

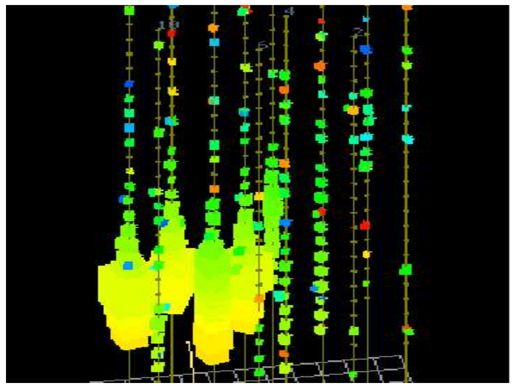
From Signal to Event

Photo multiplier Signal → Trigger (on shore) → Event

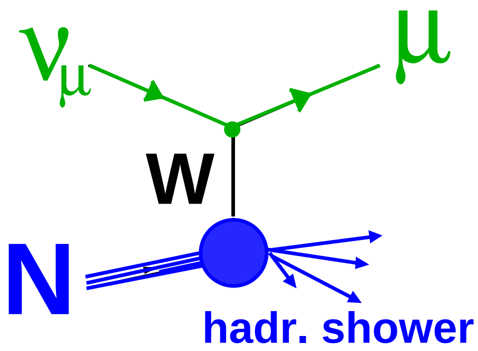
Photo multiplier Signal	Trigger (on shore)	Event
photons produce signal in photo multipliers signal is transmitted to shore station	within time window: signal in several OMs signal large enough $\Rightarrow$ build event	contains hit information: position of OM hit time hit amplitude

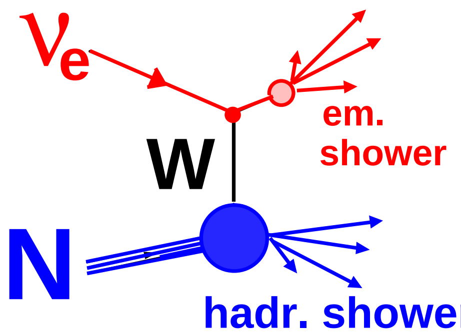


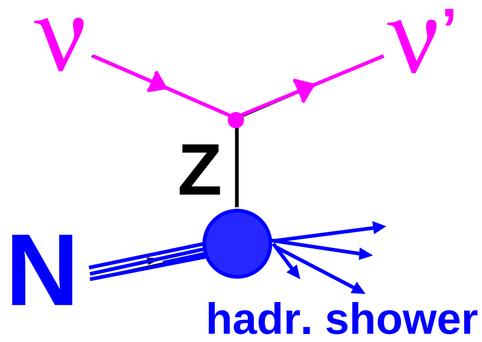




Event Types in ANTARES







ν_μ Charged Current reaction

signature:
long muon track and
hadronic shower

ν_e Charged Current reaction

signature:
electromagnetic and
hadronic shower

Neutral Current reaction

signature:
hadronic shower

Other possible event types:

- $\nu_\tau + N \rightarrow \tau +$ shower $\rightarrow \nu_\tau +$ shower $\Rightarrow$ "Double Bang"
  efficiency small for this event type
- Glashow resonance: $\bar{\nu}_e + e^- \rightarrow l + \nu_l$ at $\bar{\nu}_e \approx 6$ PeV

Reconstruction of Showers

Difficulty:

- ANTARES optimised for the detection of muon tracks
- distance between lines 60 - 75 m, between storeys 14.5 m;
  hadronic showers: length ≈ 10 m
  ⇒ "point-like" events in the detector

Benefits:

- Detection of NC processes only possible with shower reconstruction
- additional event class! ⇒enhanced sensitivity of detector
- chance to look upwards
- improvement of reconstruction of contained CC ν_μ events – hadronic shower can be taken into account as well

Event Sample and Reconstruction Scheme

generated events (Monte Carlo Simulation):

- 5000 NC events inside detector volume
- primary energy between 100 GeV and 10 PeV, energy spectrum E^{-1}
- background: 60 kHz noise per OM

Reconstruction Scheme:

Hit selection ⇒ noise suppression

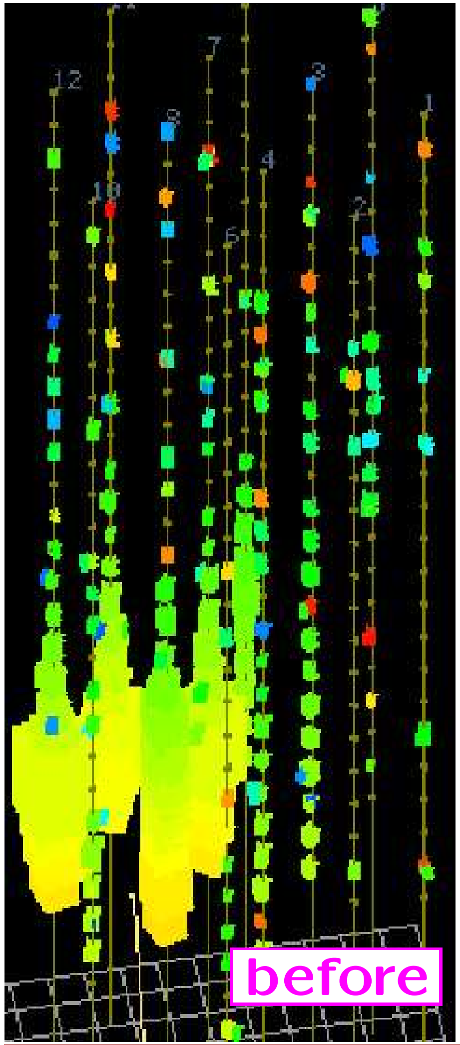
Reconstruction of position

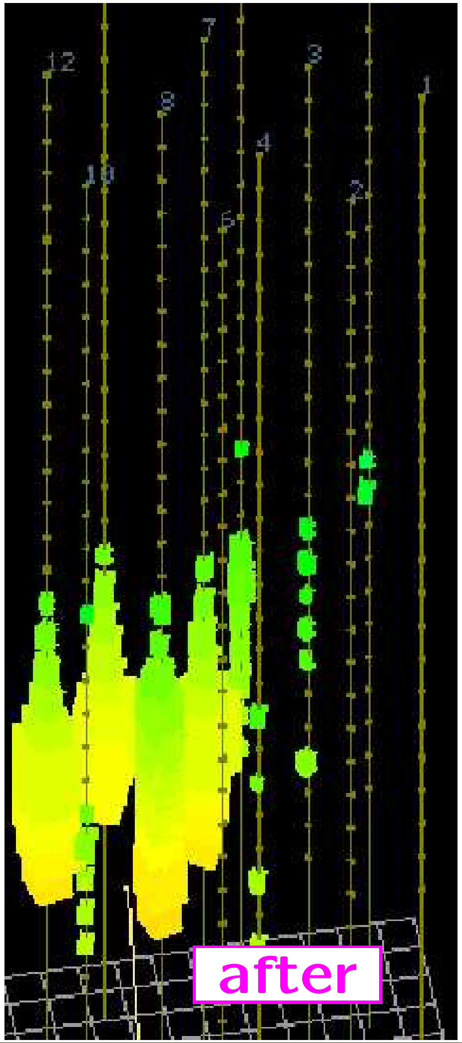
Prefit of direction and energy

Fit of direction and energy

Cut away badly reconstructed events

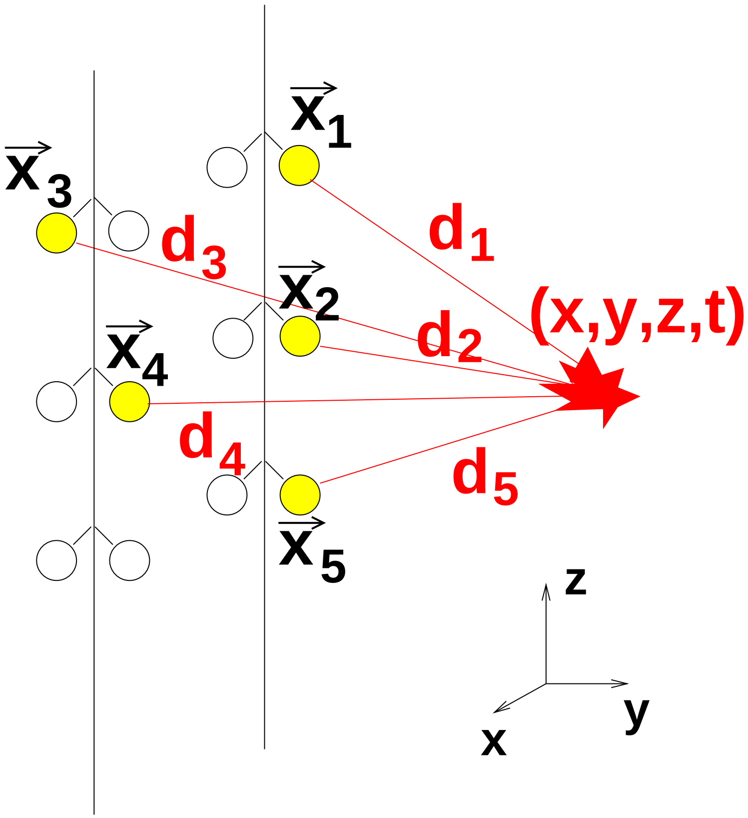
Noise Suppression





- **global condition:**
  causal connection to the largest hit in the event
- **local condition:**
  another hit on same storey within 20 ns
  or amplitude $\geq$ 3 photo-electrons (p.e.)
- avoid accidental **background coincidences:**
  another hit on same line
  or amplitude $\geq$ 1.5 p.e.

Reconstruction of Position: Reconstruction Principle



Triangulation
from position and timing of hits:

- consider shower as point like
- require hits in 5 OMs in 3 lines
- distance shower - OM$_i$:

$$\begin{aligned} d_i^2 &= (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \\ &= c^2/n^2(t - t_i)^2 \end{aligned}$$

- for all N hits: compare i and $i+1$

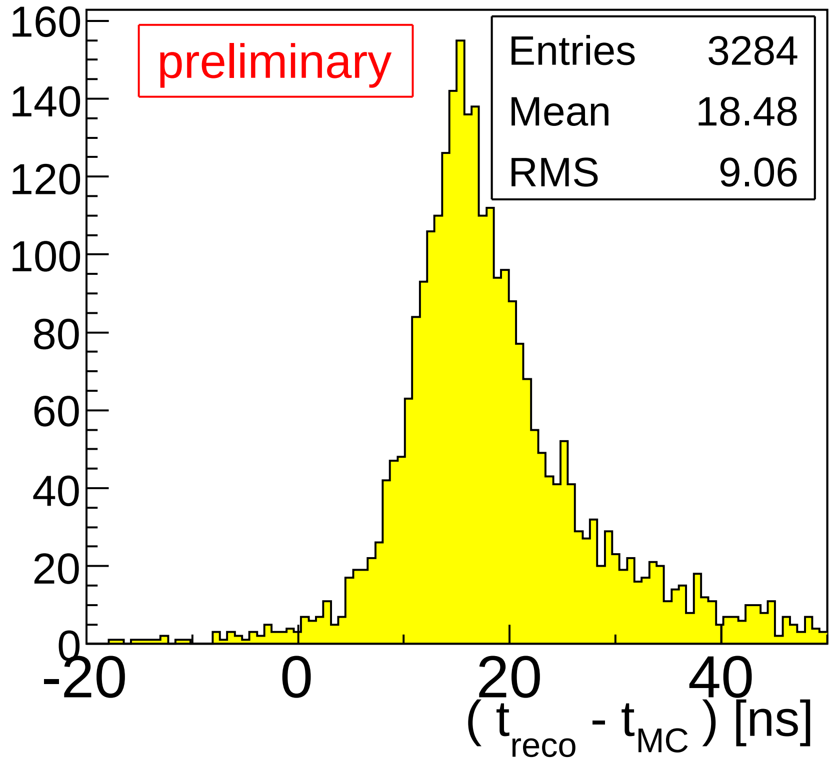
$\Rightarrow$ $N-1$ linear equations in $\vec{x} = (x, y, z, t)$

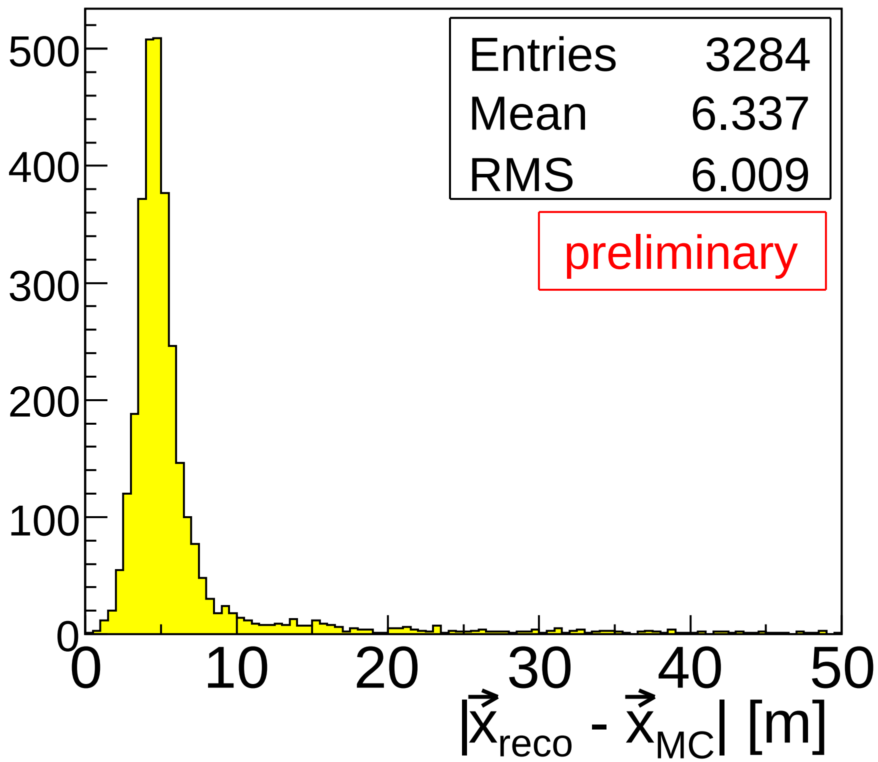
$\Rightarrow$ solve algebraically

Reconstruction of Position: Results

resolution of 9 ns in time, 4 m in space ⇒ size of shower sufficient for use in energy, direction reconstruction

events at detector edge sometimes not reconstructed well





Prefit of Direction and Energy

Direction:

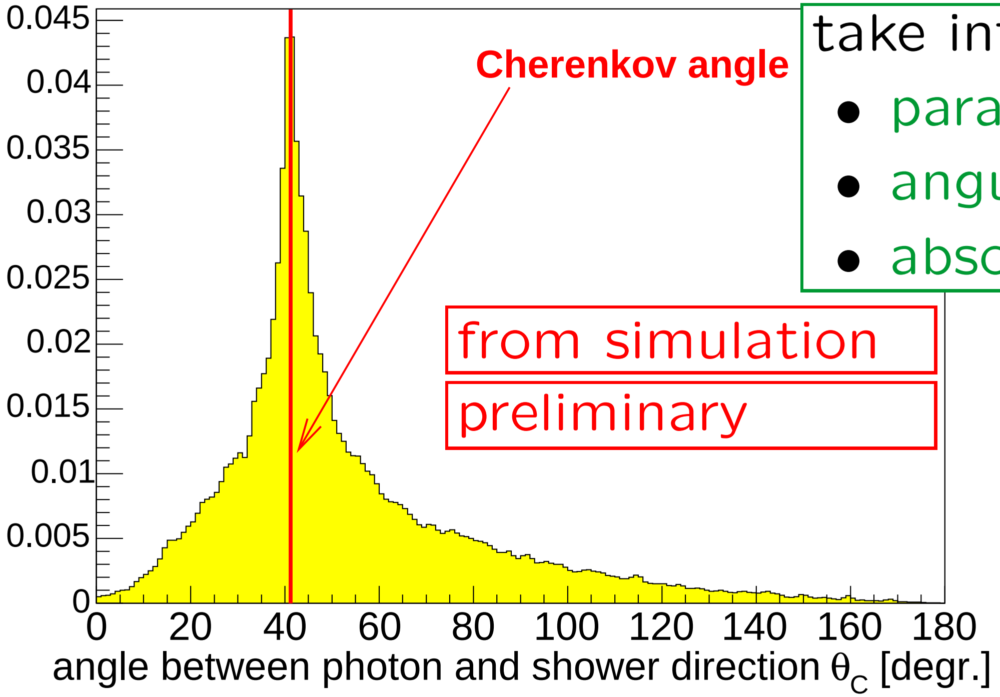
- muons: $\theta_C = \arccos(1/n) \approx 42^\circ$
- showers: transverse momenta of secondaries $\Rightarrow$ broad distribution
- assume 42° as photon radiation angle for prefit
- calculate direction algebraically (as for position)

Energy:

- total photon number of shower $\propto$ shower energy
- in the following: photon number as measure for energy
- from hit amplitude n_i in OM_i, estimate photon number N_i of event
- take median as prefit value

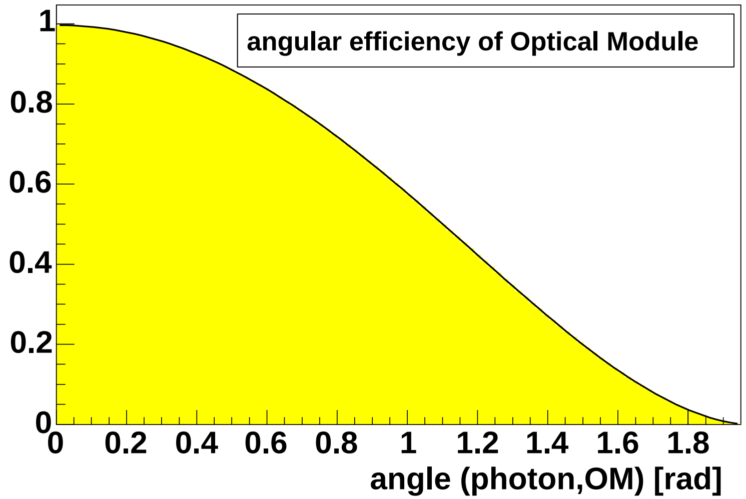
$\Rightarrow$ **start fit!**

Reconstruction of Direction and Energy



take into account:

- parameterised angular distribution $D(\theta)$
- angular efficiency $a(\theta, \phi)$
- absorption $e^{-d/\tau}$

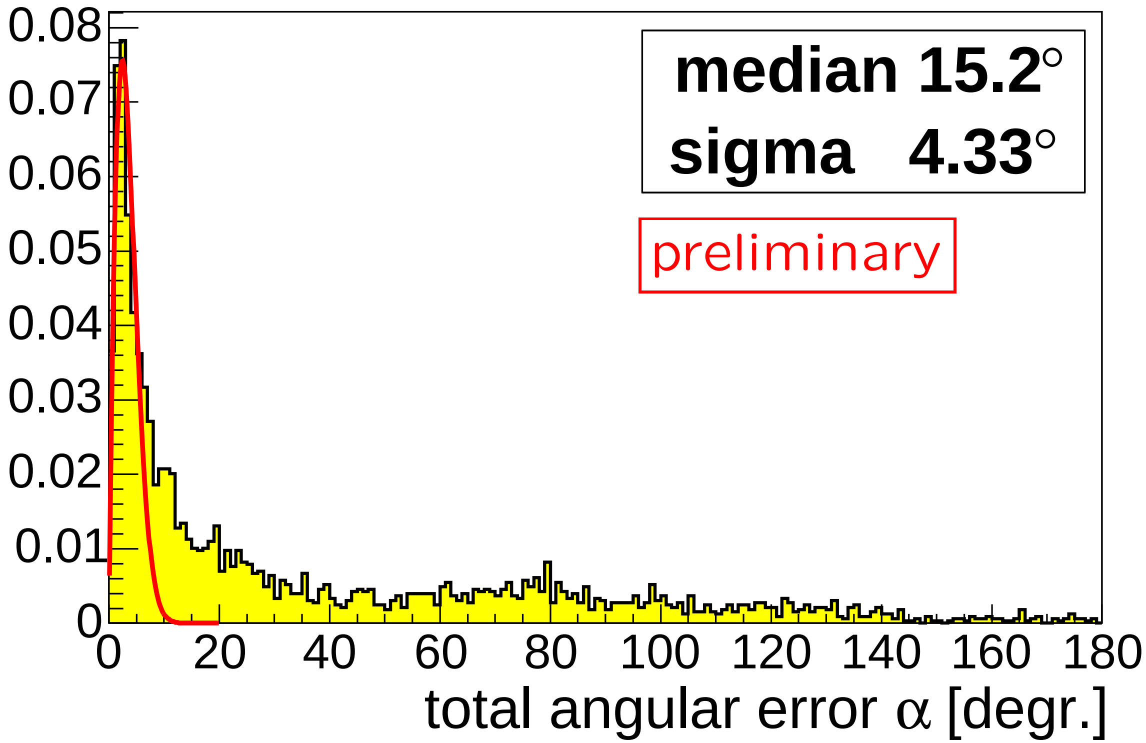


- expected hit amplitude n_i in OM$_i$ from overall photon number N in the event: $n_i \propto N \cdot D(\theta) \cdot a(\theta, \phi) \cdot e^{-d_i/\tau}$
- compare with measured hit amplitude in each PM
- loop over all OMs (hit or not) $\Rightarrow$ maximum likelihood fit for N, θ, ϕ

Results for Direction

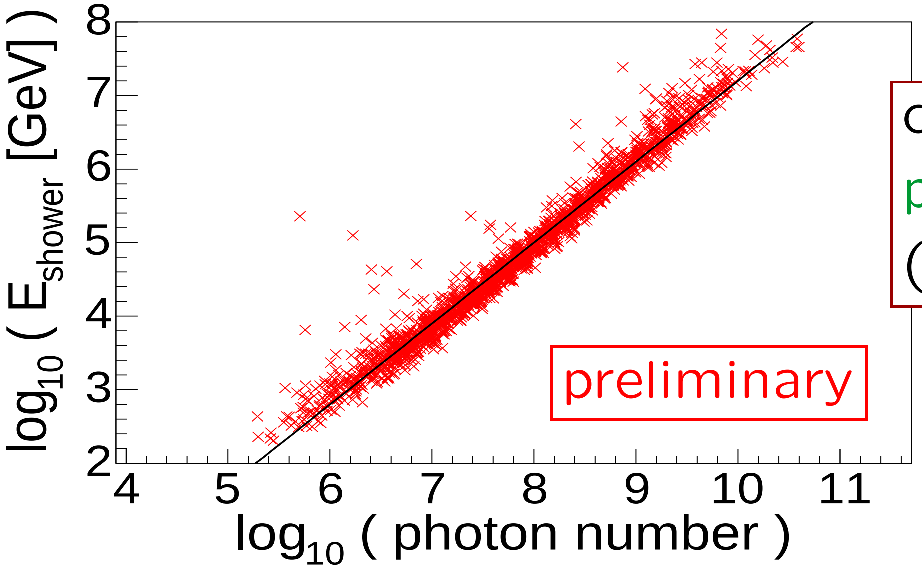
total angular error α:

$$\alpha = \arccos\left(\frac{\vec{d}_{\text{Neutrino}} \cdot \vec{d}_{\text{reco}}}{|\vec{d}_{\text{Neutrino}}| \cdot |\vec{d}_{\text{reco}}|}\right)$$

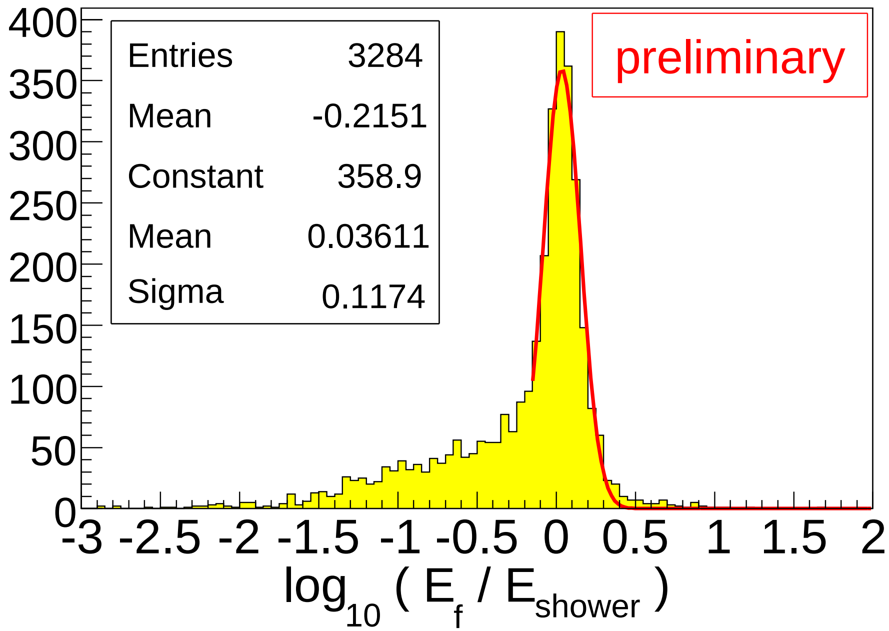


- narrow peak of well reconstructed events!
- but also some misreconstructed events
- identify and discard with cuts **or** improve minimisation!

Results for Energy



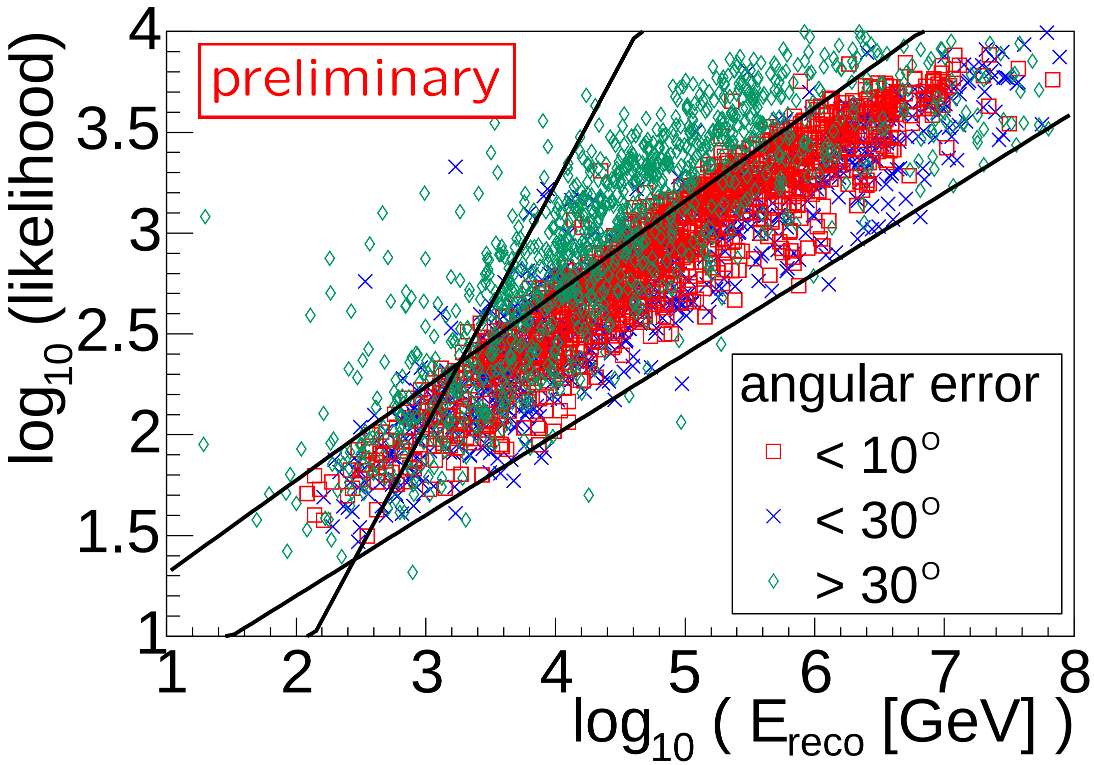
calculate shower energy from photon number
(see plot, for events with $\alpha < 20°$)



- narrow peak around $E_{\text{reco}} = E_{\text{shower}}$, width $\Leftrightarrow$ factor 1.3 in energy
- but again some badly reconstructed events
- correlation direction - energy

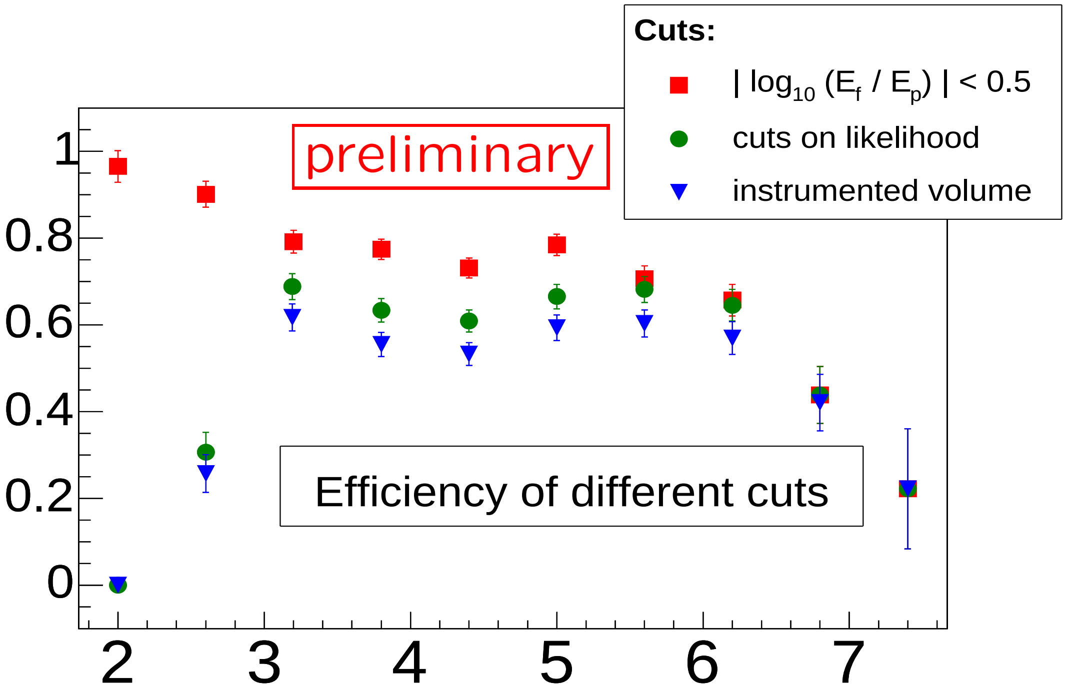
Description of the Cuts

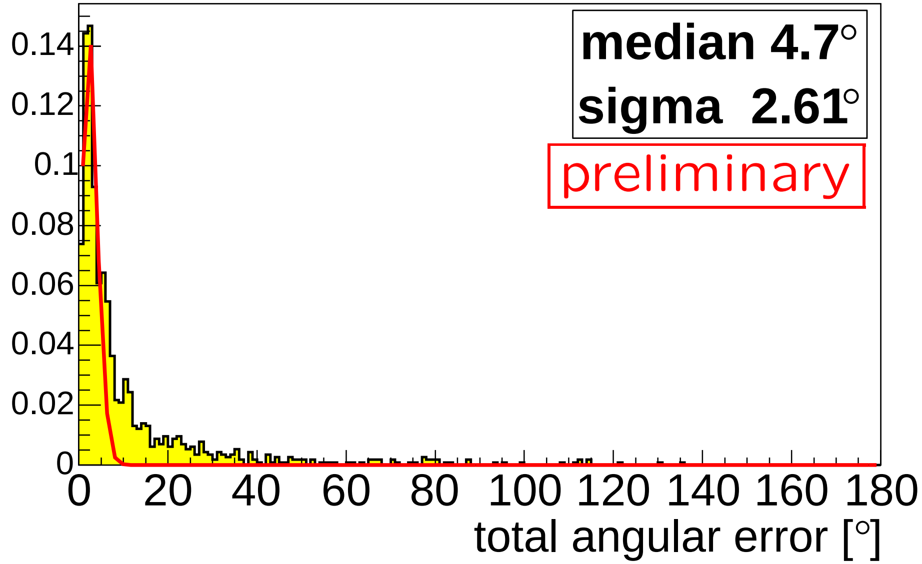
- prefit energy vs. fit energy:
  cut on $|\log(E_{\text{Prefit}}) - \log(E_{\text{Fit}})| < 0.5$ (0.5 = resolution of prefit)
- cut on likelihood value (see figure)
- select events reconstructed inside instrumented volume

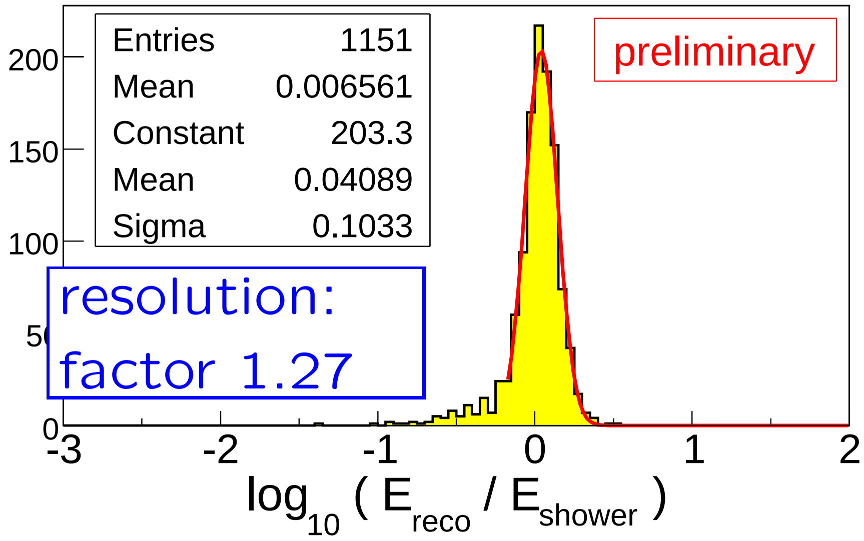


Results after the Cuts

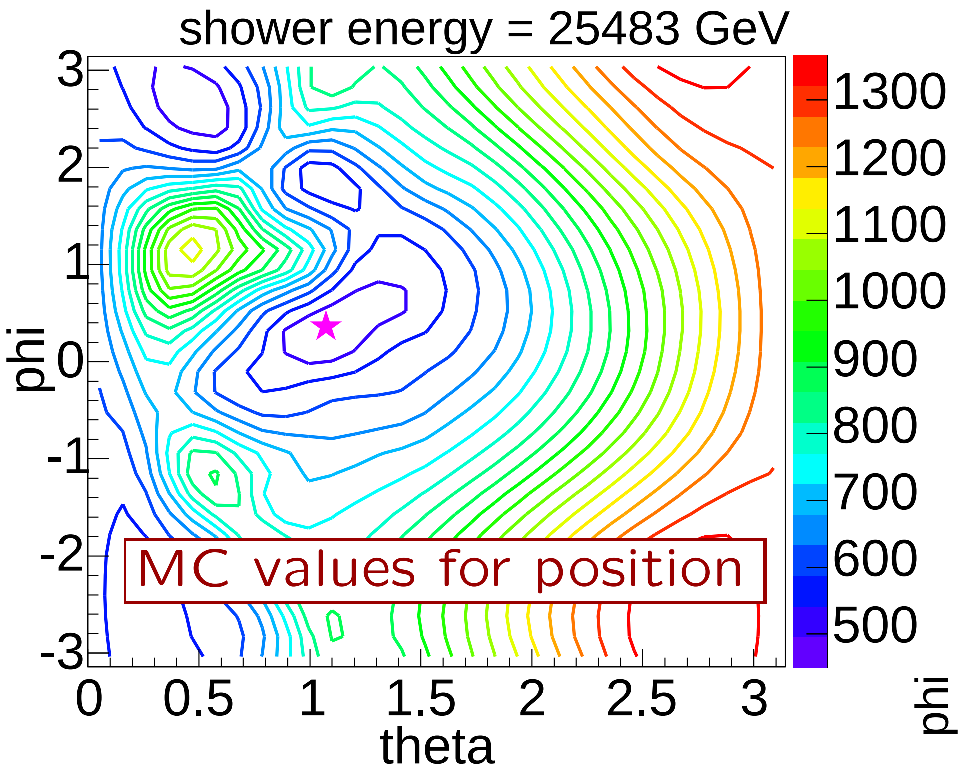
- cuts work well!
- bad events almost all cut off!
- efficiency good!



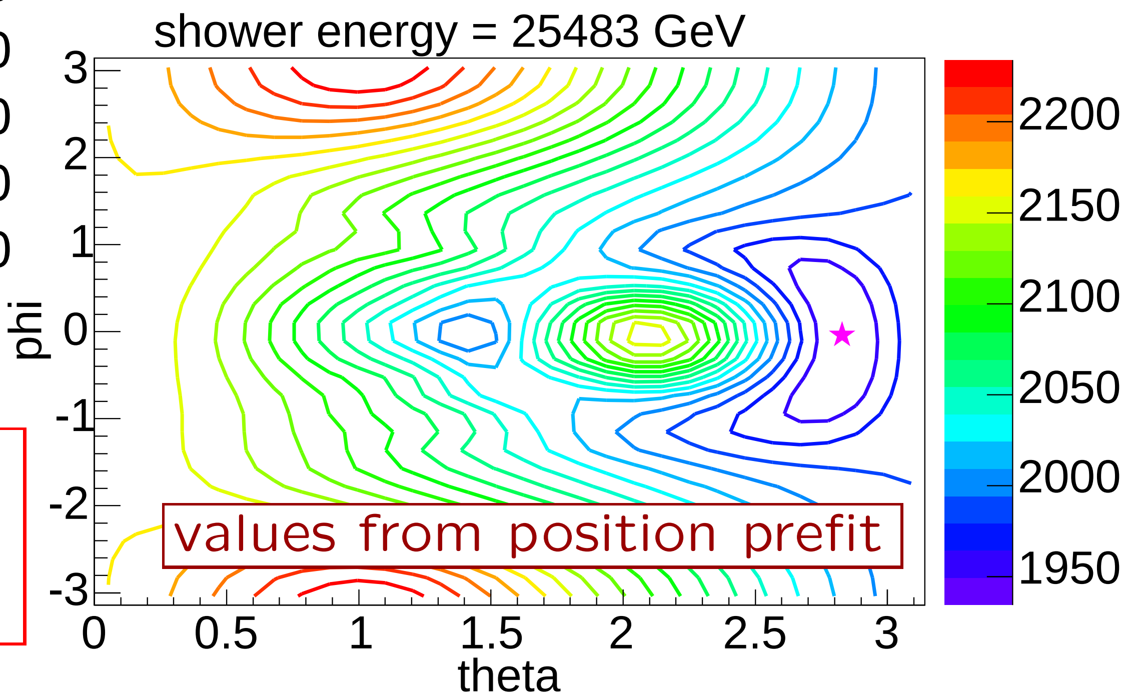




Likelihood Distribution: Remaining Problems



example for failure of fit:
wrong reconstruction of position
⇒ no minimum in likelihood at
true direction, energy value



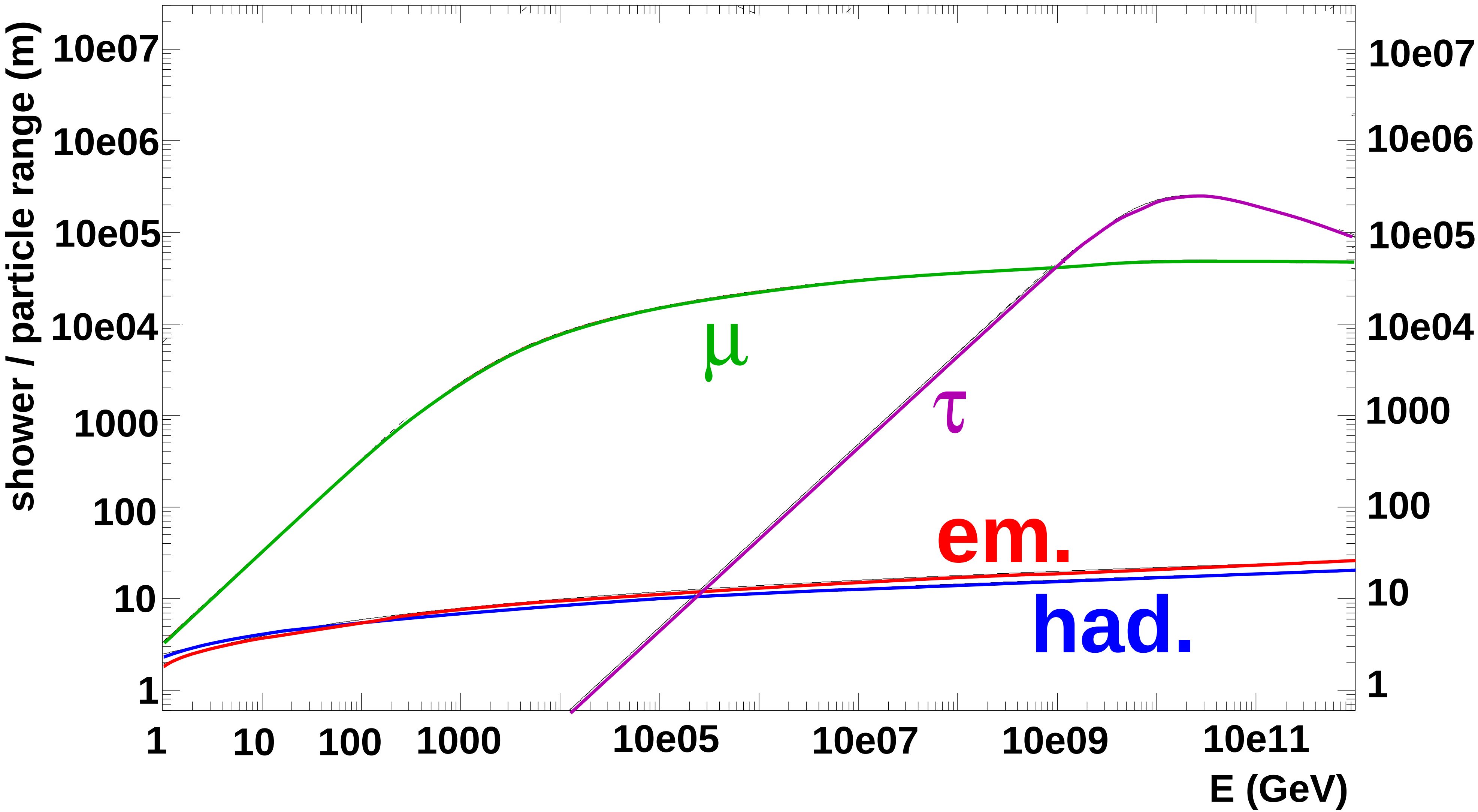
R. Auer (Erlangen):
development of improved
minimisation algorithm

Summary and Outlook

- Neutrino astronomy important for astrophysics
- ANTARES experiment under construction, to be completed 2007
- reconstruction of showers:
  - first algorithm for ANTARES shower events
  - enhances ANTARES' sensitivity for cosmic neutrinos
  - algorithm for combined reconstruction of shower direction and energy developed
  - results after cuts: angular resolution 4.7°, factor 1.27 in energy

- problems of fit to be solved
- repeat reconstruction with more statistics (mass production)
- include effect of bursts
- investigate effect of atmospheric muon background

Shower / Muon Range



Correlation Energy - Angular Error