Shower Reconstruction for the ANTARES Neutrino Telescope

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

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

Fluxes of Cosmic Rays

<table>
<thead>
<tr>
<th>Energy [eV]</th>
<th>Flux $[m^2 sr s GeV^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^9$</td>
<td>$10^{-24}$</td>
</tr>
<tr>
<td>$10^{12}$</td>
<td>$10^{-18}$</td>
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<tr>
<td>$10^{15}$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$10^{21}$</td>
<td>$10^{-2}$</td>
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</table>

LHC beam energy, \(\sim E^{-3.0}\), Ankle \(1\) particle per \(km^2\) and year\)

Knee \(1\) particle per \(m^2\) and year\)

\(\sim E^{-2.7}\)
Cosmic Radiation II

Search for sources of high energy cosmic radiation “messengers particles”:

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

**protons** $E < 10^{19}$ eV

**protons** $E > 10^{19}$ eV

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

**neutrinos**
**Cosmic High Energy Neutrinos**

**Production:**
accelerated protons interact with interstellar matter, CMB or synchrotron radiation

\[ p + p/\gamma \rightarrow \pi^{\pm} + X \]
\[ \leftrightarrow \mu + \nu_\mu \]
\[ \leftrightarrow e + \nu_e + \nu_\mu \]

\[ \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0; \text{ neutrino oscillations } \sim \nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1 \]

- + not deflected in magnetic fields ⇒ identification of source
- + proof for hadron acceleration
- hardly interacts with matter
  - + large range
  - - hard to detect ⇒ 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
\[ \Theta_C = \arccos\left(\frac{1}{\beta n}\right) \]

In seawater:
\[ \Theta_C \approx 42^\circ \]
Neutrino Telescopes world wide
ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch

- 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

ANTARES layout as seen from above
**The ANTARES Optical Modules**

- **Glass spheres**: 43 cm in diameter, pressure resistant up to 600 bar.
- **Hamamatsu photo multipliers**: Quantum efficiency > 20% (360 < λ < 460 nm)
- **Geomagnetic field shielded by μ-metal cage**
- 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 ⇒ 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 $^{40}\text{K}$ decays and bacteria bioluminescence
   - mainly single photons
   - rate $\sim 60 \text{ kHz to } \approx 200 \text{ kHz}$ 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

Photons produce signal in photo multipliers. The signal is transmitted to the shore station. Within a time window, the signal in several OM (Optical Modules) must be large enough to generate an event. The event contains hit information such as the position of the OM, hit time, and hit amplitude.
Event Types in ANTARES

\[ \nu_{\mu} \text{ Charged Current reaction} \]

signature: long muon track and hadronic shower

\[ \nu_e \text{ Charged Current reaction} \]

signature: electromagnetic and hadronic shower

Neutral Current reaction

signature: hadronic shower

Other possible event types:

- \( \nu_{\tau} + N \rightarrow \tau + \text{shower} \rightarrow \nu_{\tau} + \text{shower} \Rightarrow \text{“Double Bang”} \)
  efficiency small for this event type
- Glashow resonance: \( \bar{\nu}_e + e^- \rightarrow l + \nu_l \) at \( \bar{\nu}_e \approx 6 \text{ PeV} \)
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 $\approx 10$ m
  $\Rightarrow$ “point-like” events in the detector

**Benefits:**
- Detection of NC processes only possible with shower reconstruction
- additional event class! $\Rightarrow$ enhanced sensitivity of detector
- chance to look upwards
- improvement of reconstruction of contained CC $\nu_\mu$ 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** $\rightarrow$ 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<sub>i</sub>:
  \[
  d_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = \frac{c^2}{n^2} (t - t_i)^2
  \]

- 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 $\Rightarrow$ size of shower sufficient for use in energy, direction reconstruction events at detector edge sometimes not reconstructed well

![Histogram 1](image1)

- Entries: 3284
- Mean: 18.48 ns
- RMS: 9.06 ns

![Histogram 2](image2)

- Entries: 3284
- Mean: 6.337 m
- RMS: 6.009 m
Prefit of Direction and Energy

**Direction:**
- muons: \( \theta_C = \arccos(1/n) \approx 42^\circ \)
- showers: transverse momenta of secondaries \( \Rightarrow \text{broad distribution} \)
- assume \( 42^\circ \) 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

\( \Rightarrow \text{start fit!} \)
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 \(N, \theta, \phi\)
**Results for Direction**

Total angular error $\alpha$:

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

- median $15.2^\circ$
- sigma $4.33^\circ$

Preliminary results show a narrow peak of well-reconstructed events, but also some misreconstructed events. Identify and discard these events with cuts or improve minimisation.
Results for Energy

- 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

\[ \log_{10}(E_{\text{shower}}) \]

\[ \log_{10}(\text{photon number}) \]

\[
\begin{align*}
\text{Entries} & \quad 3284 \\
\text{Mean} & \quad -0.2151 \\
\text{Constant} & \quad 358.9 \\
\text{Mean} & \quad 0.03611 \\
\text{Sigma} & \quad 0.1174
\end{align*}
\]
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

![Graph showing likelihood vs. energy](image-url)

- Preliminary results

- Angular error:
  - $< 10^\circ$
  - $< 30^\circ$
  - $> 30^\circ$
Results after the Cuts

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

Cuts:
- \(| \log_{10}(E_t / E_p) | < 0.5\)
- cuts on likelihood
- instrumented volume

Efficiency of different cuts

**median 4.7°**
**sigma 2.61°**

Preliminary

Resolution: factor 1.27
Likelihood Distribution: Remaining Problems

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

shower energy = 25483 GeV

MC values for position

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

values from position pre-fit
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 $4.7^\circ$, 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

- **$\mu$** (muon)
- **$\tau$** (tau)
- **em.** (electromagnetic)
- **had.** (hadronic)

Graph showing the range of showers and particles as a function of energy (E) in GeV.

- **Shower / particle range (m)**
- **E (GeV)**

The graph plots the range of showers and particles for different energies, with labels for muons, taus, electromagnetic, and hadronic processes.
Correlation Energy - Angular Error

\[ \log_{10} \left( \frac{E_{\text{reco}}}{E_{\text{shower}}} \right) \]

Entries  3284

total angular error [°]