Neutrino point source search including cascade events with the ANTARES neutrino telescope

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- Specialisation in nuclear and particle physics
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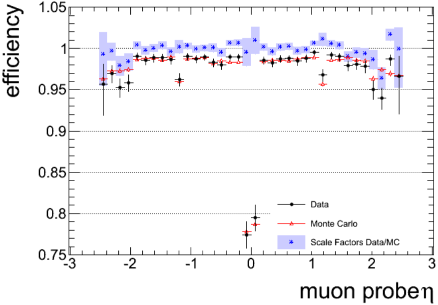

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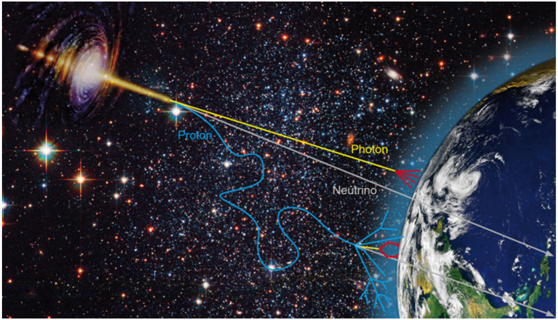
Why Neutrinos?



- photons absorbed by interstellar medium and scatter at CMB with increasing energy
  $\rightarrow$ highest energies not accessible
- cosmic rays deflected by galactic magnetic fields
  $\rightarrow$ hardly point back to their origin

Solution: Neutrinos

- pass unhindered through interstellar medium
- electrically neutral $\rightarrow$ no deflection
- point back right to their source
- open access to highest energies

Detection Principle

- biggest advantage also biggest challenge:
- small interaction cross section

$\rightarrow$ large scale water Cherenkov detector

- neutrino interacts with ambient water nuclei
- creating charged particles in the process
- enough energy to induce Cherenkov radiation
- light gets picked up by 3D array of optical modules with photo multiplier tubes (PMTs)

$\rightarrow$ need a dark, translucent place

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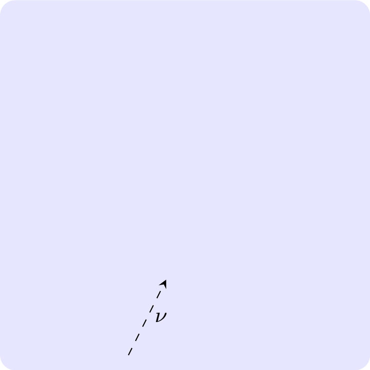

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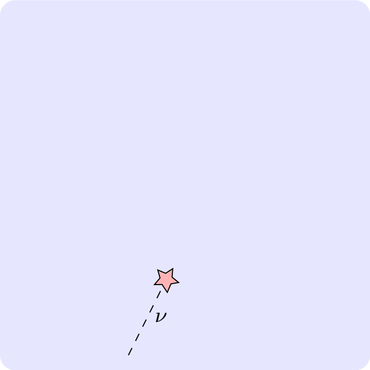

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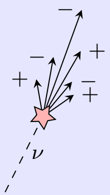

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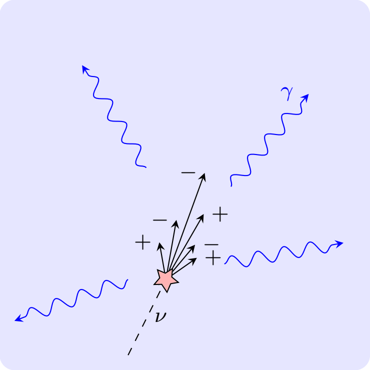

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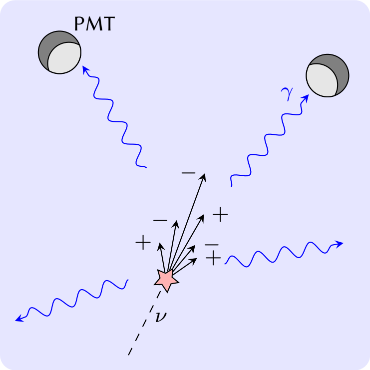
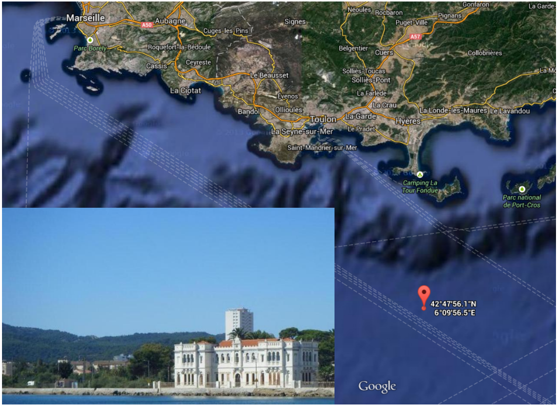
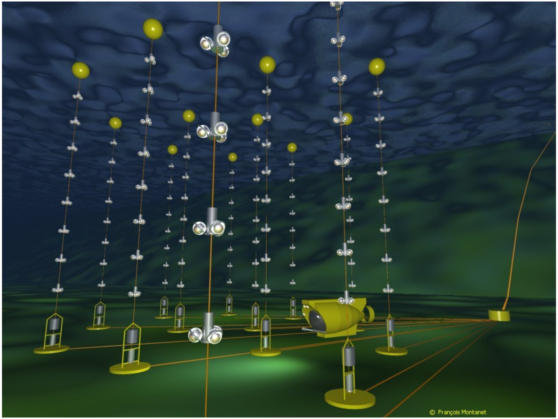


ANTARES – Location



- 2500 m below sea surface
- 40 km off the coast of Toulon, France
- connected via electro-optical cable
- control room right at the shore

ANTARES – The Detector

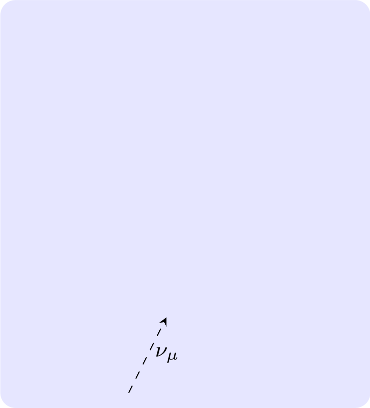


- complete since 2008-05
- 12 Lines, 885 PMTs + IL
- radius: 90 m
  height: 400 m
- 0.5 ns time resolution
- $<$ 10 cm acoustic positioning

Muon Track Reconstruction

- can pass through detector
- Cherenkov radiation along track
- photons emitted at $\varphi_{\mathrm{Ch}} \approx 42^\circ$
- clean signature

- maximum likelihood fit based on hit time residuals
- $\approx 0.4^\circ$ median angular resolution



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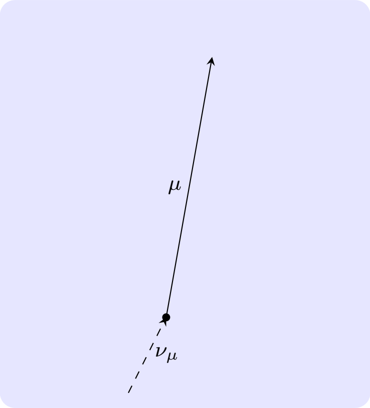

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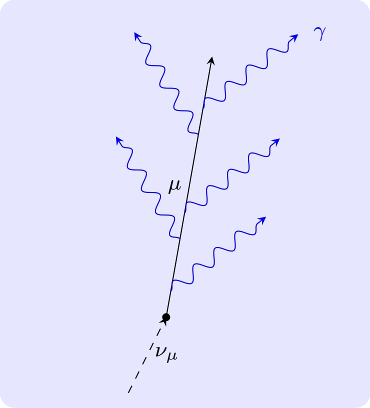

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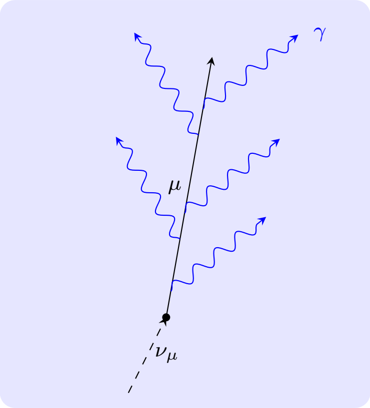
- limit us to $\nu_\mu \to \mu$ (and $\nu_\tau \to \tau \to \mu$) interactions



Shower Reconstruction

- shower events open window to

  $\nu_e \rightarrow e$

  $\nu_x \rightarrow hadr.$

  $\nu_\tau \rightarrow \tau \rightarrow e/hadr.$

- cascade of particles within few metres
- can be approximated as point source
- emits shell of light in all directions
- still, more light emitted under "Cherenkov angle"

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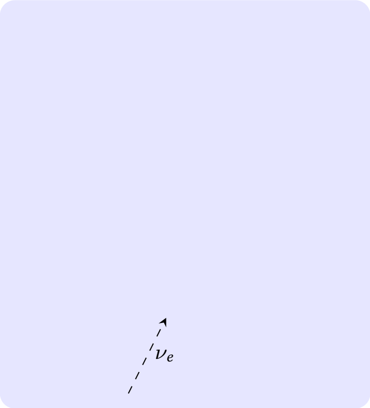

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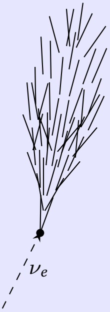

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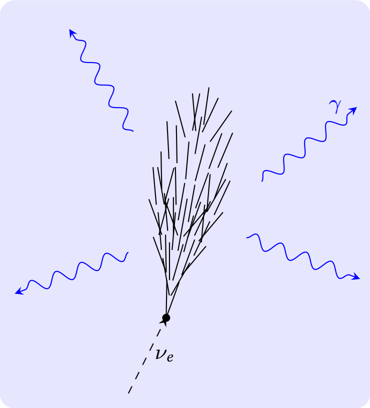

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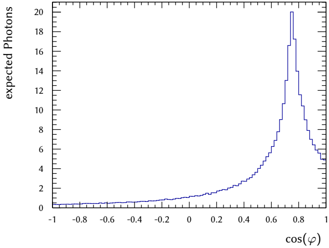
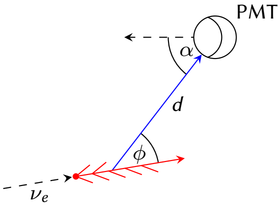


expected number of Photons from a 1 TeV shower on a PMT in 100 m distance

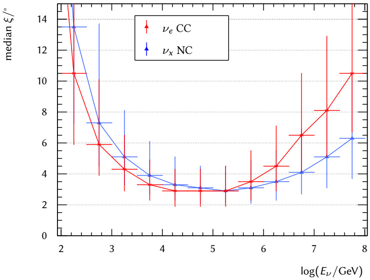
Shower Reconstruction – Likelihood Function

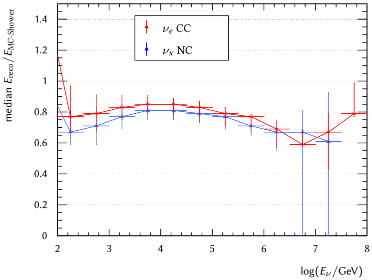
- expected charge q on a PMT described by tabulated PDF
- likelihood depends on neutrino energy, direction, distance to OM, incident angle
- unhit PMTs and Background rate taken into account

$$\mathscr{L} = \sum_{i=1}^{N_{\text{selected Hits}}} \log\left\{P_{q>0}(q_i|E_\nu, d_i, \phi_i, \alpha_i) + P_{\text{bg}}(q_i)\right\} + \sum_{i=1}^{N_{\text{unhit PMTs}}} \log\left\{P_{q=0}(E_\nu, d_i, \phi_i)\right\}$$



Shower Reconstruction – Performance: Direction & Energy





- position of shower mean reconstructed with accuracy of about 1 m
- median angular error $\xi \approx 3°$ in relevant energy range
- systematic offset in energy of 20 % easily corrected
- energy resolution of 5 % – 10 %

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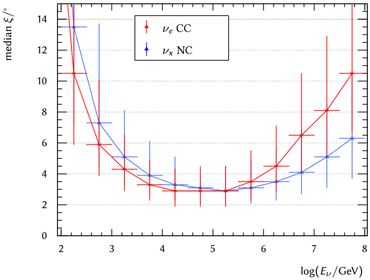

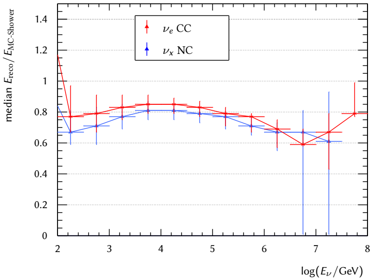

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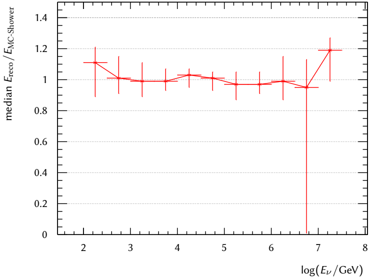
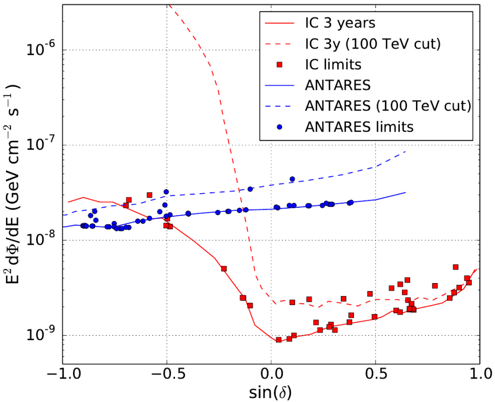


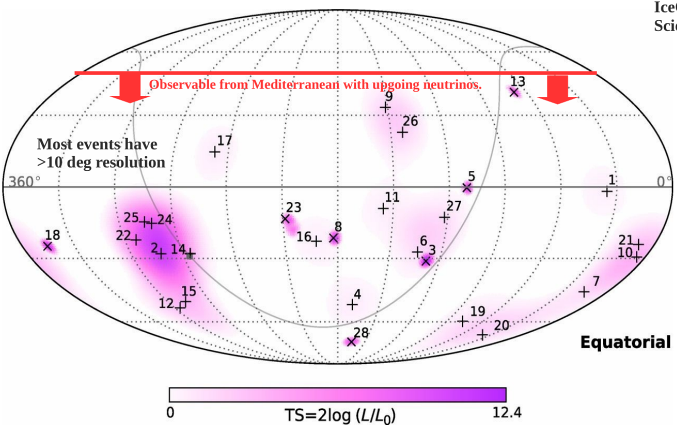
Previous Sensitivities

Status Quo:

- previous point source searches focused mainly on muon tracks
- ANTARES provides best sensitivities for lower declinations; even though much smaller than IceCube at South Pole
- ANTARES dominates southern hemisphere below 100 TeV
- best sensitivities so far: $E^2\Phi \approx 1.4 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ and slowly rising for higher declinations



Cosmic Neutrinos discovered by IceCube

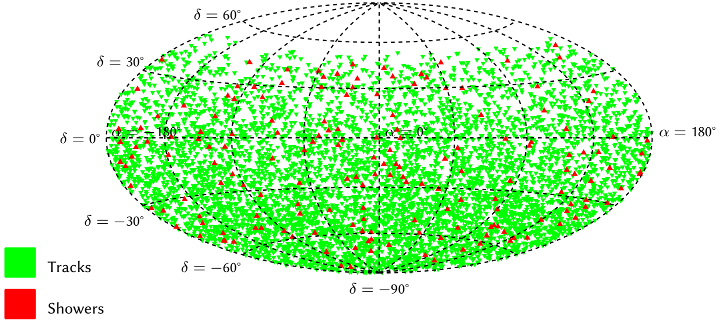


IceCube Collaboration,
Science 342, 1242856 (2013)

- most of the events have resolution $> 10^\circ$ $\rightarrow$ sources unknown!
- flux extends to PeV energies
- possible point source around Galactic Centre has been largely constrained

Data Set

- 1690 days of life time from 2007 to the end of 2013
- contains 6490 muon candidates and 172 cascade events
- for E^{-2} flux with 1:1:1 flavour composition, shower channel increases signal event rate by 30 %



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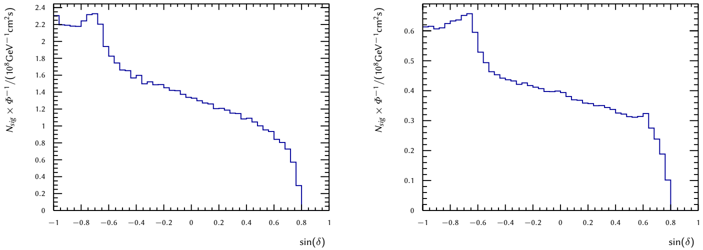

Figure : signal acceptance for **Left:** the track channel and **Right:** the shower channel

Point Source Search

- signature of a point source is cluster of events
- distribution of signal around source described by Point-Spread-Function (PSF)
- background rate considered as function of declination
- number of selected hits to further separate between atmospheric background and cosmic signal

$$\log \mathscr{L}_{\mathrm{s+b}} = \sum_{\mathcal{S}} \sum_{i \in \mathcal{S}} \log \left[\mu^{\mathcal{S}}_{\mathrm{sig}} \cdot \mathscr{F}^{\mathcal{S}}(\eta_i) \cdot \mathscr{N}^{\mathcal{S}}_{\mathrm{sig}}(N_{\mathrm{i}}) + \mathscr{B}^{\mathcal{S}}(\delta_i) \cdot \mathscr{N}^{\mathcal{S}}_{\mathrm{bkg}}(N_{\mathrm{i}}) \right] - \mu^{\mathcal{S}}_{\mathrm{sig}}$$
$$+ \mathscr{P}(\mu^{\mathrm{sh}}_{\mathrm{sig}} | \mu^{\mathrm{tr}}_{\mathrm{sig}} \cdot \mathcal{A}^{\mathrm{sh}}(\delta) / \mathcal{A}^{\mathrm{tr}}(\delta))$$

$\mathscr{F}$: Point-Spread-Function
$\mathscr{B}$: background rate
$\mathscr{P}$: Poisson Function
$\mathscr{N}$: Number of Hits distribution for Signal / Background
$\mathcal{A}$: acceptance for tracks/showers

μ_{sig} : number of signal events
η: angle between event and source
δ: declination

Search Methods

sensitivities determined with Pseudo Experiments:

- generating lots of fake sky maps
- background rate ($\mathscr{B}$) from data
- injecting artificial signal at various points in the sky
- signal distribution around source ($\mathscr{F}$) from Monte Carlo Simulation

Various searches performed:

- Full Sky search: fitting $\mu_{\text{sig}}^{\mathcal{S}}$, α_{sig} and δ_{sig}
- Fixed Point search: α and δ given by candidate list, fitting only $\mu_{\text{sig}}^{\mathcal{S}}$
- IceCube HESE candidates: using direction from 8 IceCube tracks and trying to fit a cluster within 4° cone
- Galactic Region: like full sky but restricted around the Galactic Centre, testing different energy spectra
- Extended Source: Testing if Galactic Centre is an extended source

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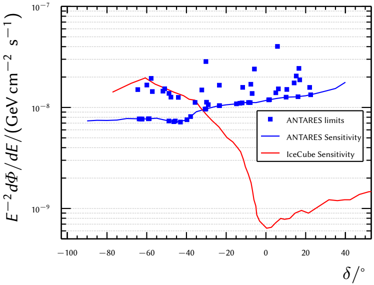
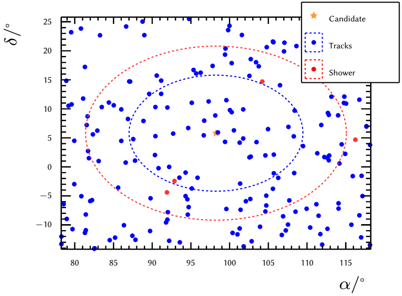
improved Sensitivity and Limits (Candidate List Search)

- Sensitivity improved from
  $1.4 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ to
  $7.2 \times 10^{-9}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$
- best limits for many candidates in galactic region from single experiment
- challenged only by combined ANTARES/IceCube analysis (to be published)



most significant candidate:

- HESSJ0632+057 ($\alpha = 98.24°, \delta = 5.81°$)
- 35 tracks and 3 showers within $10\,°/15\,°$ cones
- 1 track $< 0.3°$
- $E^2\Phi^{90\,\%} = 4.02 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$
- $N_{\mathrm{sig}}^{90\,\%} = 6.6$
- Significance: $32\,\%$ or 1σ



Extended Source at Galactic Centre

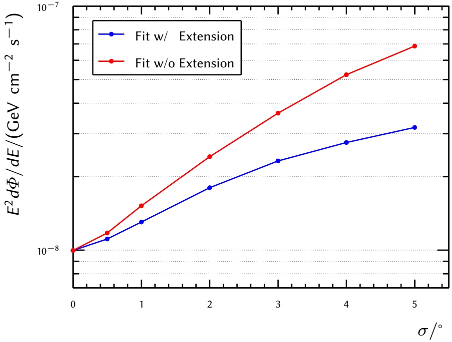
- simulated extended source at the Galactic Centre ($\alpha = -93.58°, \delta = -29.01°$)
- used 2D Gauß function:

$$\mathcal{G} = A \cdot \exp\left\{-\frac{1}{2} \cdot \left(\frac{\alpha - \alpha_s}{\cos(\delta)\sigma_\alpha}\right)^2\right\} \cdot \exp\left\{-\frac{1}{2} \cdot \left(\frac{\delta - \delta_s}{\sigma_\delta}\right)^2\right\}$$

- convoluted with PSF:

$$\mathscr{F}(\eta(\alpha_s, \delta_s)) \rightarrow \iint \mathscr{F}(\eta(\alpha, \delta)) \times \mathcal{G}(\alpha_s, \delta_s, \sigma_\alpha, \sigma_\delta)\, d\alpha d\delta$$

Extended Source at Galactic Centre– Sensitivity



Extension	$E^2\Phi^{90\,\%}$	$N_{sig}^{90\,\%}$
0°	1.19e-8	2.5
0.5°	1.52e-8	3.2
1°	2.43e-8	5.2
2°	2.84e-8	6.0
3°	3.01e-8	6.4
4°	3.67e-8	7.8
5°	4.62e-8	9.8

flux limit in units of GeV $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

- only fit number of signal events (coordinates of GC are known)
- fit with (correct) morphology or assuming point source

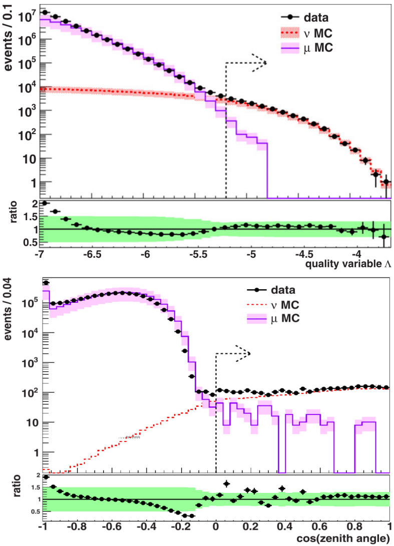
Summary

- developed shower reconstruction algorithm for ANTARES
- achieves direction resolution of 3° and energy resolution of $5\,\% - 10\,\%$
- $\rightarrow$ water allows pointing with showers
- will play even bigger role for KM3NeT

- combined point source search performed on data from 2007 to 2013
- various approaches investigated
- no significant clusters have been found

Backup

- $\approx 3 - 10$ atmospheric muons per second
- cut on direction and fit quality parameter Λ
  $\rightarrow \; \approx 4$ atmospheric muon neutrinos per day
- visibility: $\approx 3/4$ of the sky, most of galactic plane – including galactic centre



longitudinal Emission Spectrum of em-Showers

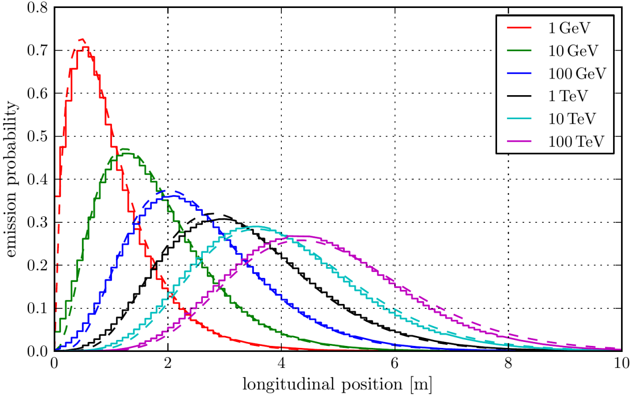


Figure : longitudinal Profile of electromagnetic shower in water

Reconstruction – Performance: Position

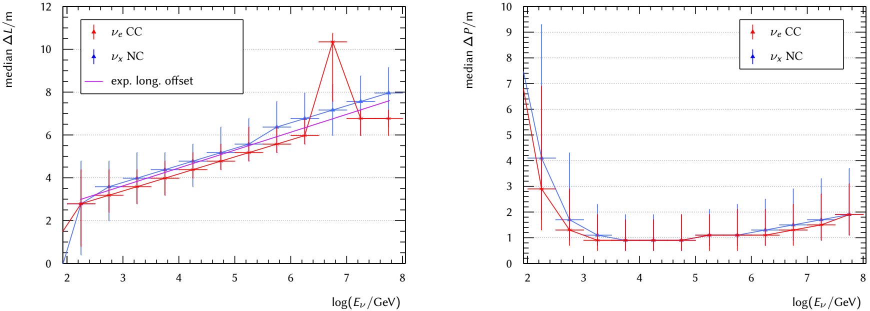
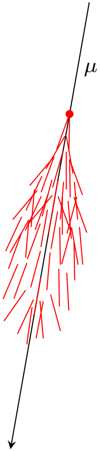


Figure : Performance of the shower position reconstruction, red for electromagnetic showers, blue for hadronic showers, the purple line is the mean of the light emission spectrum for em-showers – **Left:** The distance between the position of the neutrino interaction vertex and the reconstructed shower position along the neutrino axis. **Right:** The distance of the reconstructed shower position perpendicular to the neutrino axis.

Shower Reconstruction – Direction Resolution directly from Data



- resolution can be measured on muon-induced showers
- comparing directions as reconstructed by track and shower algorithm
  (we trust the reconstructed muon direction)
- reconstructed track direction depends only on timing, shower direction only on charge
- shows clear peak at low angles
- confirms angular resolution of 2° to 3° as found in MC

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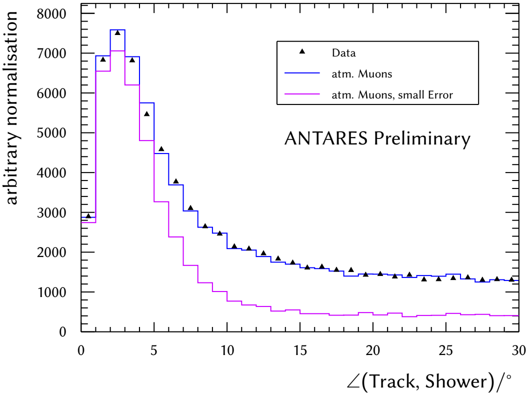

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Event Selection

Muons:

same cuts as in last analysis

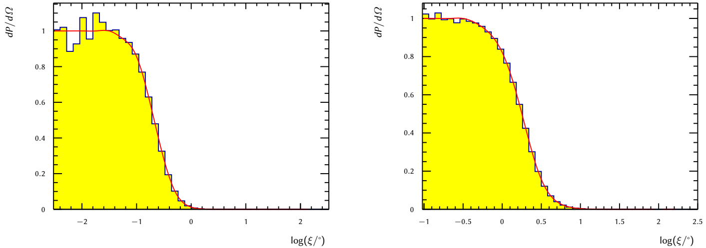
- quality parameter $\Lambda > -5.2$
- angular error estimate $< 1^\circ$
- up-going: $\cos(\vartheta) > -0.1$

Showers:

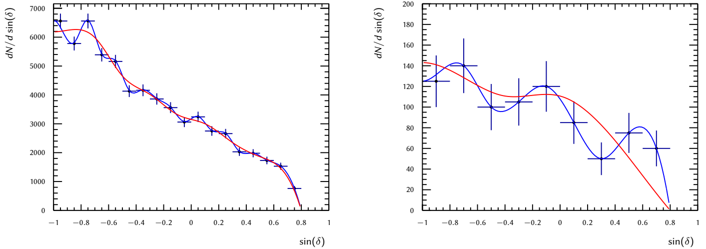
various cuts to suppress atm. muons:

- not selected as muon
- containment $\rho < 300\,\mathrm{m}$, $|z| < 200\,\mathrm{m}$
- angular error estimate $< 10^\circ$
- up-going: $\cos(\vartheta) > -0.1$
- distribution of hits/recorded charge in detector
- $\chi^2_{\mathrm{pos}} < 1000$
- $\left(\frac{R_{\mathrm{GridFit}}}{1.3}\right)^3 + \left(\frac{N_{\mathrm{Hits}}}{150}\right)^3 < 1$
- $R_{\mathrm{ShowerLikelihood}} > 20$
- $R_{\mathrm{Charge}} = Q_{\mathrm{early}}/Q_{\mathrm{on-time}} < 0.05$

Ingredients



Top: $\mathscr{F}$ – **Bottom:** $\mathscr{B}$ – **Left:** muons – **Right:** showers



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