

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

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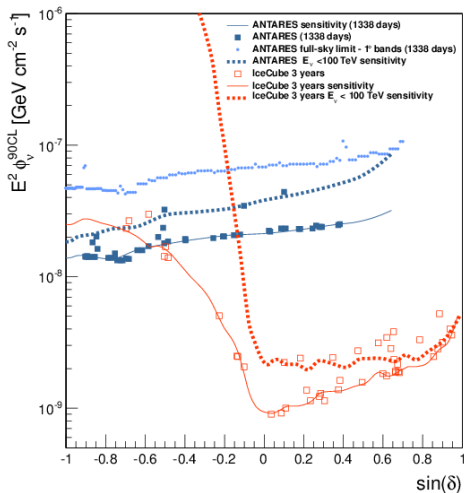
on behalf of the ANTARES collaboration

34th International Cosmic Ray Conference
den Haag, The Netherlands
2015-08-03



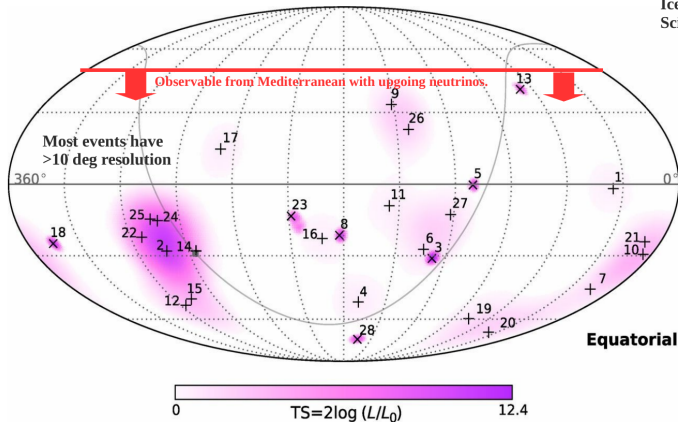
Status Quo:

- even though much smaller than IceCube, ANTARES provides best sensitivities for lower declinations
- ANTARES dominates southern hemisphere below 100 TeV (where most galactic signal is expected)
- best sensitivities so far:
 $E^2 \Phi_\nu \approx 1.4 \text{ GeV cm}^{-2} \text{ s}^{-1}$
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 is large and extends to PeV energies
- possible point source around Galactic Centre has been largely constrained
 \rightarrow Poster by Javier B. Martí (636)

- up to now, muon candidates backbone of most ANTARES analyses
- clean signature and very well reconstructible (median resolution $\approx 0.4^\circ$)
- limits us to $\nu_\mu \rightarrow \mu$ (and $\nu_\tau \rightarrow \tau \rightarrow \mu$) interactions
- shower events open window to
$$\begin{aligned}\nu_e &\rightarrow e \\ \nu_x &\rightarrow \text{hadr.} \\ \nu_\tau &\rightarrow \tau \rightarrow e/\text{hadr.}\end{aligned}$$
- have lower angular resolution but still valuable because of much lower background
- developed a cascade reconstruction algorithm with focus on pointing accuracy

Muons:

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

Showers:

- 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”

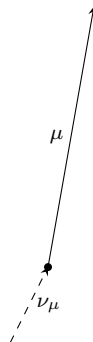


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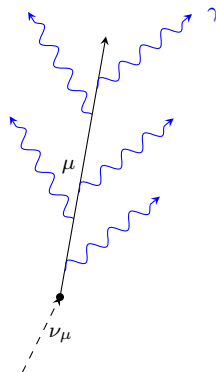


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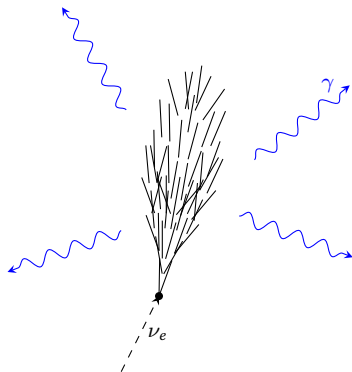


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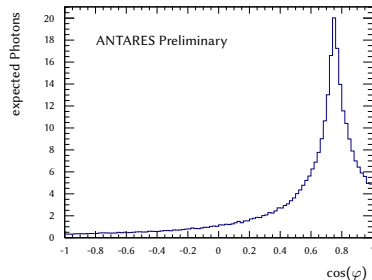


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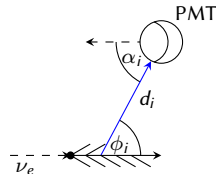


expected number of Photons from a 1 TeV shower on a PMT
100 m from the shower

Reconstruction – Likelihood Function

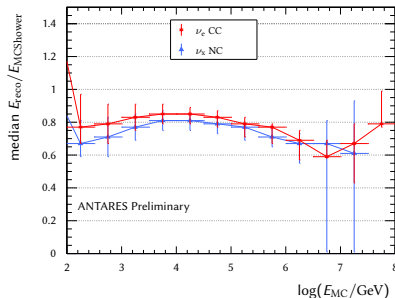
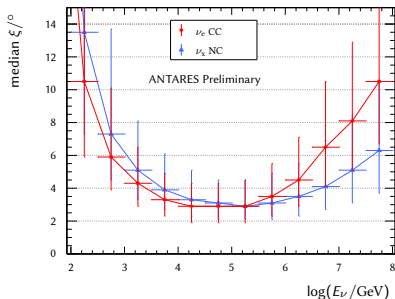
- Likelihood depends on neutrino energy, direction, distance to OM, incident angle
- expected charge q on a PMT described by tabulated PDF
- unhit PMTs and Background rate taken into account

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



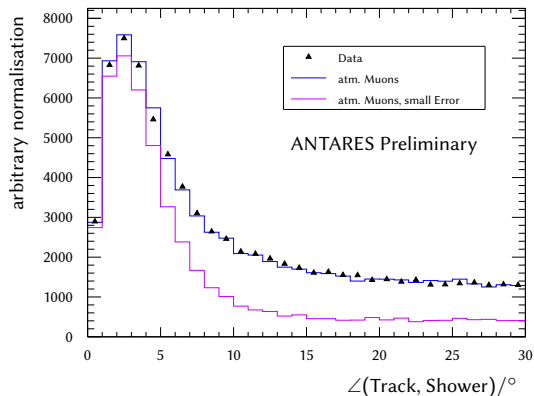
Reconstruction – Performance: Direction & Energy

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





- 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 $2 - 3^\circ$ as found in MC



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Showers:

lots of cuts to suppress atm. muons – i.a.:

- containment $\rho < 300$ m
- angular error estimate $< 10^\circ$
- up-going: $\cos(\vartheta) > -0.1$
- ratio between charge of early and on-time hits

Muons:

same cuts as in last analysis

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

- 1622 days from 2007 to the end of 2013 (185 days of 5-line data not included in shower channel)
- contains 6261 muon track candidates and 156 cascade events (90 % purity)
- $\nu_\tau \rightarrow \tau \rightarrow \mu/e/hadr.$ are taken into account by scaling up $\nu_\mu \rightarrow \mu$ and $\nu_e \rightarrow e$ with respective τ branching ratios
- for E^{-2} flux with 1:1:1 flavour composition, shower channel increases signal event rate by 30 %

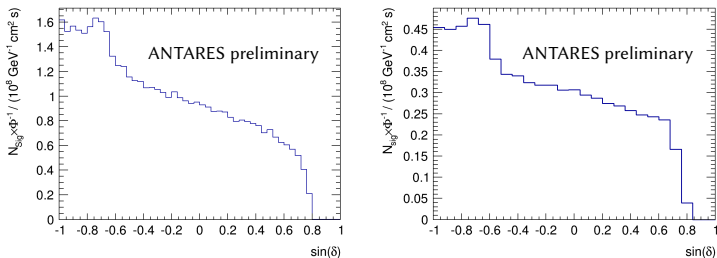


Figure : signal acceptance for **Left:** the track channel and **Right:** the shower channel

- 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
- sum over tracks and showers in reasonably large area around hypothesized source

$$\log \mathcal{L}_{s+b} = \sum_i \log [\mu_{\text{sig}} \times \mathcal{F}(\gamma_i) \times \mathcal{N}_{\text{sig}}(N_i^{\text{Hits}}) + \mathcal{B}(\delta_i) \times \mathcal{N}_{\text{backg}}(N_i^{\text{Hits}})] - \mu_{\text{sig}}$$

$$Q = \log \mathcal{L}_{s+b} - \log \mathcal{L}_b$$

\mathcal{F} : Point-Spread-Function

γ : angle between event and source

\mathcal{B} : background rate

δ : declination

\mathcal{N} : Number of Hits distribution for Signal / Background

Q : Test Statistics to differentiate between Signal and Background

Ingredients

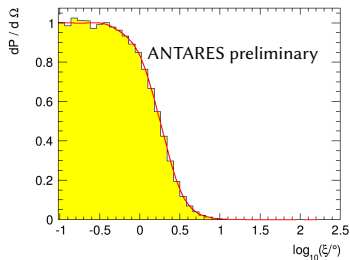
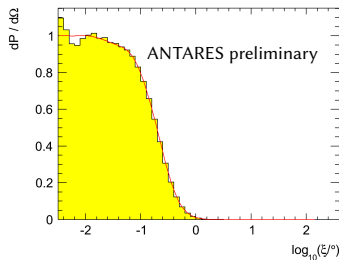
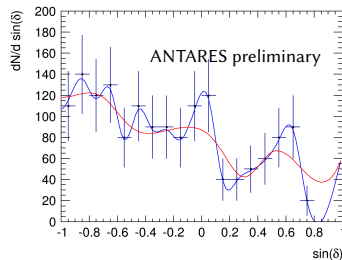
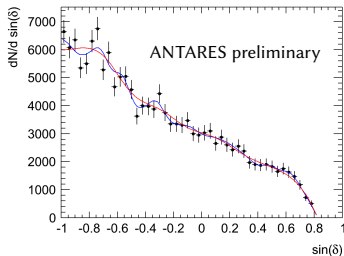


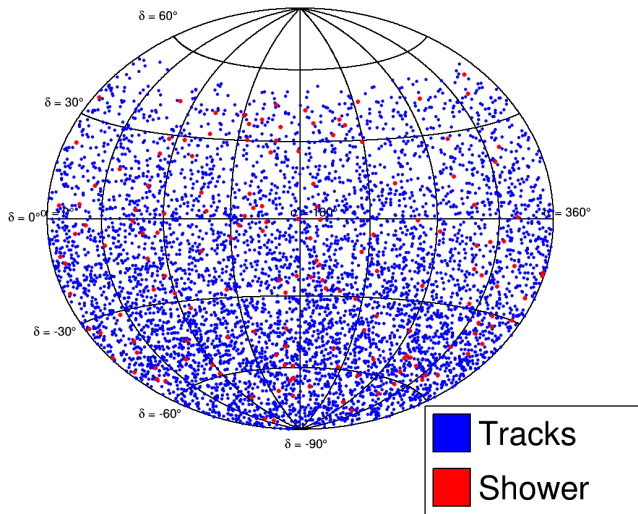
Figure : Top: \mathcal{F} – Bottom: \mathcal{B} – Left: muons – Right: showers



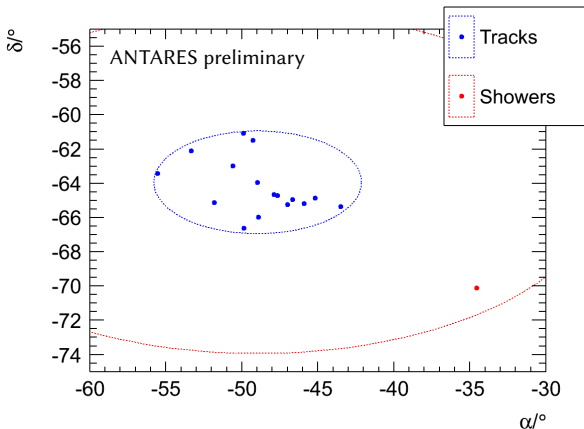
- sensitivities determined with Pseudo Experiments
- background rate (\mathcal{B}) from data
- PSF (\mathcal{F}) from Monte Carlo Simulation

Three different searches presented here:

- Full Sky search: fitting μ_{sig} , α_{sig} and δ_{sig}
- Fixed Point search: α and δ given by candidate list, fitting only μ_{sig}
- IceCube HESE candidates: using direction from 8 IceCube tracks and trying to fit a cluster within 2° cone



most significant cluster in full sky search

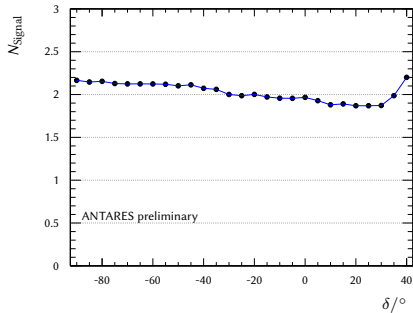
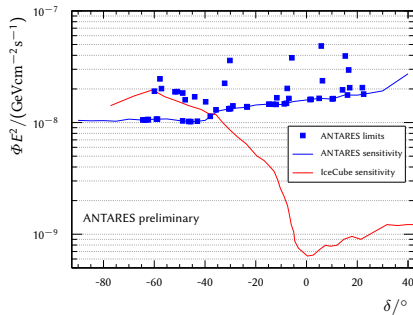


- most significant cluster at similar position as in last analysis:
 $\alpha = -48.3^\circ, \delta = -64.6^\circ$
old analysis (tracks only):
 $\alpha = -46^\circ, \delta = -65^\circ$
- 16 tracks within 3° ,
1 shower within 10°
- $N_{\text{Sig}} = 5.5 \pm 0.8$
(Tracks + Showers)
- significance: 1.33σ , p-value: 0.185
- old analysis (tracks only):
15 tracks within 3°
 $N_{\text{Sig}} = 6.7$
 2.17σ , p-value: 0.029

Point Source Candidate List

Name	$\alpha / ^\circ$	$\delta / ^\circ$	σ	Φ limit	$N_{\text{Hits}}^{\text{limit}}$	Name	$\alpha / ^\circ$	$\delta / ^\circ$	σ	Φ limit	$N_{\text{Hits}}^{\text{limit}}$
HESSJ0632+057	98.24	5.81	0.75	5.0e-08	5.9	HESSJ1837-069	-80.59	-6.95	0.0	1.7e-08	2.1
HESSJ1741-302	-94.75	-30.2	0.75	3.7e-08	5.6	HESSJ1503-582	-133.54	-58.74	0.0	1.1e-08	1.0
HESSJ1023-575	155.83	-57.76	0.49	2.5e-08	5.0	MSH15-52	-131.47	-59.16	0.0	1.1e-08	0.9
3C279	-165.95	-5.79	0.21	3.9e-08	5	HESSJ1837-069	-80.59	-6.95	0.0	1.7e-08	2.1
CirX-1	-129.83	-57.17	0.05	2.1e-08	4.1	HESSJ1503-582	-133.54	-58.74	0.0	1.1e-08	1.0
HESSJ1616-508	-116.03	-50.97	0.03	1.9e-08	3.9	MSH15-52	-131.47	-59.16	0.0	1.1e-08	0.9
HESSJ1614-518	-116.42	-51.82	0.03	1.9e-08	3.9	PKS2155-304	-30.28	-30.22	0.0	1.3e-08	1.6
ESO139-G12	-95.59	-59.94	0.02	2e-08	3.9	HESSJ1303-631	-164.23	-63.2	0.0	1.1e-08	0.7
GX339-4	-104.3	-48.79	0.02	1.9e-08	3.8	RGBJ0152+017	28.17	1.79	0.0	1.6e-08	1.9
VERJ0648+152	102.2	15.27	0.02	4.0e-08	4.3	W28	-89.57	-23.34	0.0	1.4e-08	1.4
PKS0537-441	84.71	-44.08	0.01	1.7e-08	3.6	Geminga	98.31	17.01	0.0	2.1e-08	2.2
HESSJ1632-478	-111.96	-47.81	0.00	1.6e-08	3.3	H2356-309	-0.22	-30.63	0.0	1.3e-08	1.2
PKS0548-322	87.67	-32.27	0.00	2.3e-08	3.5	Crab	83.63	22.01	0.0	2.1e-08	2.2
RXJ1713.7-3946	-101.75	-39.75	0.00	1.6e-08	3.1	QSO1730-130	-96.7	-13.1	0.0	1.5e-08	1.4
KS0235+164	39.66	16.61	0.0	3.0e-08	3.2	HESSJ1507-622	-133.28	-62.34	0.0	1.1e-08	0.0
QSO2022-077	-53.6	-7.6	0.0	2.1e-08	2.8	RCW86	-139.32	-62.48	0.0	1.1e-08	0.0
MGROJ1908+06	-73.01	6.27	0.0	2.4e-08	2.8	W51C	-69.25	14.19	0.0	2.0e-08	2.1
HESSJ1356-645	-151.0	-64.5	0.0	1.1e-08	2.1	1ES1101-232	165.91	-23.49	0.0	1.4e-08	0.8
PKS1454-354	-135.64	-35.67	0.0	1.3e-08	2.2	CentaurusA	-158.64	-43.02	0.0	1.0e-08	0.0
Galactic Centre	-93.58	-29.01	0.0	1.4e-08	2.2	SS433	-72.04	4.98	0.0	1.6e-08	1.2
PKS2005-489	-57.63	-48.82	0.0	1.0e-08	1.6	PKS1406-076	-147.8	-7.9	0.0	1.5e-08	0.3
PSRB1259-63	-164.3	-63.83	0.0	1.1e-08	1.5	HESSJ1834-087	-81.31	-8.76	0.0	1.5e-08	0.3
PKS0727-11	112.58	-11.7	0.0	1.7e-08	2.3	HESSJ1912+101	-71.79	10.15	0.0	1.6e-08	1.1
RXJ0852.0-4622	133.0	-46.37	0.0	1.0e-08	1.5	PKS0426-380	67.17	-37.93	0.0	1.1e-08	0.0
PKS1622-297	-113.5	-29.9	0.0	1.3e-08	2	1ES0347-121	57.35	-11.99	0.0	1.5e-08	0.0
VelaX	128.75	-45.6	0.0	1.0e-08	1.4	PKS1502+106	-133.9	10.52	0.0	1.6e-08	0.4
PKS0454-234	74.27	-23.43	0.0	1.4e-08	2	LS5039	-83.44	-14.83	0.0	1.5e-08	0.0

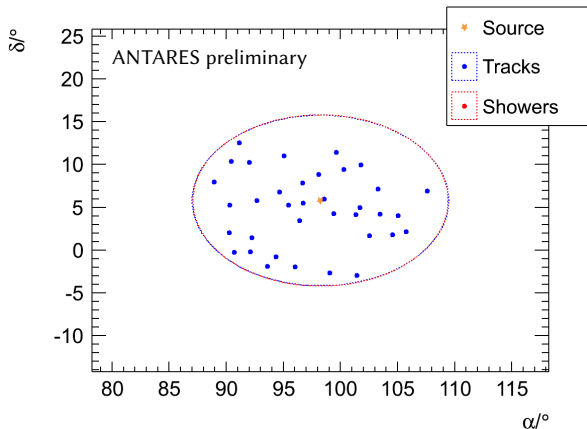
Sensitivity and Candidate Limits



sensitivity down to $1.0 \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1}$ and flat over broad declination range
showers improve sensitivities by about 30 %
world-best limits for many (galactic) candidate objects

most significant source in fixed point search

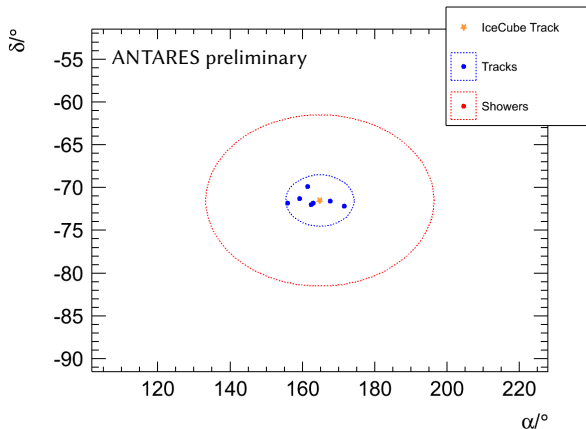
- same source as in last analysis:
HESSJ0632+057
 $\alpha_s = 98.24^\circ$, $\delta_s = 5.81^\circ$
- 36 tracks + 0 showers
within 10°
- $N_{\text{Sig}}: 1.2 \pm 0.2$
(Tracks + Showers)
- significance: 0.75σ , p-value: 0.456
- old analysis (tracks only):
 $N_{\text{Sig}} = 1.51$
 1.64σ



IceCube ID	$\alpha_{\text{fit}}/^\circ$	$\delta_{\text{fit}}/^\circ$	$\beta_{\text{IC}}/^\circ$	N_{Events}	σ	$N_{\text{Signal}} (\text{Tr.+Sh.})$
28	164.8	-71.5	1.3	7	0.0	0.0 + 0.0
3	127.9	-31.2	1.4	11	0.0	0.0 + 0.0
8	-177.6	-21.2	1.3	9	0.0	0.0 + 0.0
5	110.6	-0.4	1.2	5	0.0	0.0 + 0.0
18	-14.4	24.8	1.3	5	0.0	0.0 + 0.0
23	-151.3	-13.2	1.9	6	0.0	0.0 + 0.0
37	167.3	20.7	1.2	1	0.0	0.0 + 0.0
13	67.9	40.3	1.2	1	0.0	0.0 + 0.0

most significant cluster in IceCube candidate search

- IceCube Id: 28
- $\alpha_{\text{IC}} = 164.8^\circ, \delta_{\text{IC}} = -71.5^\circ, \beta_{\text{IC}} = 1.3^\circ$
- 7 tracks within 3° ,
0 showers within 10°
- $N_{\text{Sig}}: 0.0 \pm 0.0$
(Tracks + Showers)
- significance: 0σ



- shower reconstruction algorithm for ANTARES has been developed
- achieves direction resolution of 3° and energy resolution of 5 %
- → water allows pointing with showers
- applied to new point source search, combining tracks and showers
- included data from 2013 in new analysis
- performed three different search methods: full sky, fixed source candidate list, IceCube HESE candidate list
- no significant clusters have been found
- same most significant cluster in full sky search but with reduced significance: $p = 18.5 \%$
- same most significant source (HESSJ0632+057) also with reduced significance: $p = 45.6 \%$
- search for point sources near IC tracks shows no excess
- ANTARES provides world's best limits for several galactic sources

- extended sources
 - different spectral indices
 - write paper, write thesis
-
- shower reconstruction ready to be applied to any other analyses

Backup

longitudinal Emission Spectrum of em-Showers

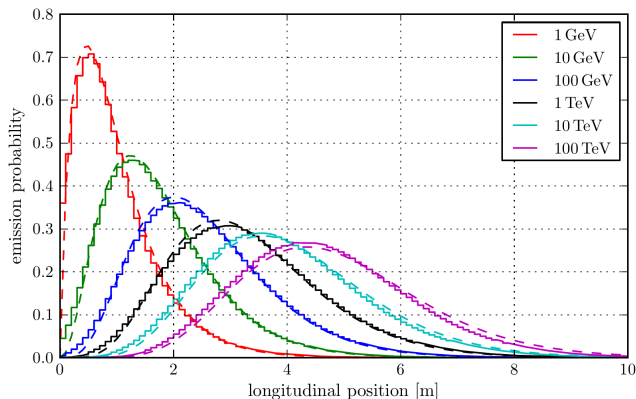


Figure : longitudinal Profile of electromagnetic shower in water

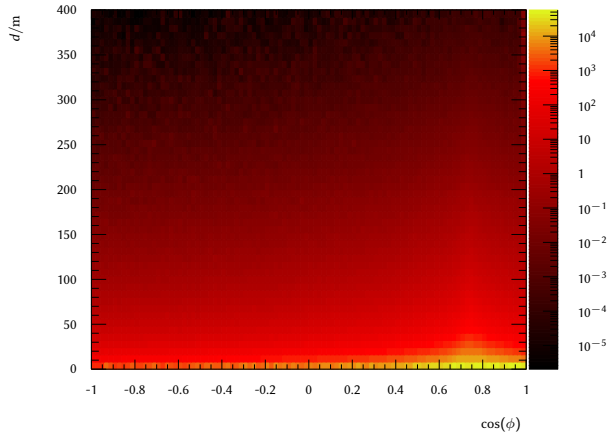


Figure : Expected number of photons for a 1 TeV neutrino (ν_e , charged current interaction) with dependence on the emission angle ϕ from the neutrino direction and the distance d from the shower's position of mean intensity.

Reconstruction – Performance: Position

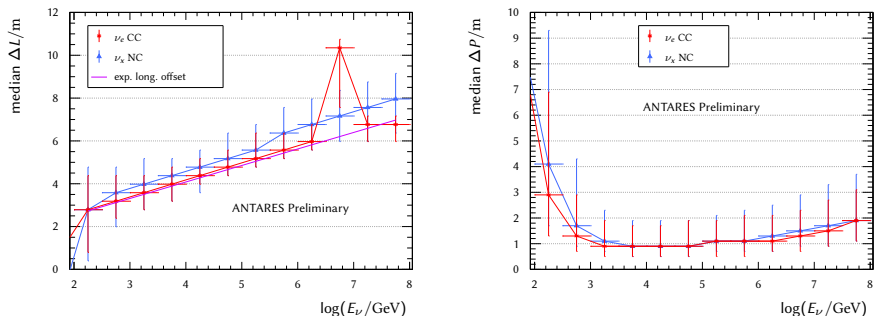


Figure : Performance of the shower position reconstruction, red for electromagnetic showers, blue for hadronic showers, the purple line is the mean of the light emission spectrum for em-showers – **Left:** The distance between the position of the neutrino interaction vertex and the reconstructed shower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

Reconstruction – Performance: Direction & Energy

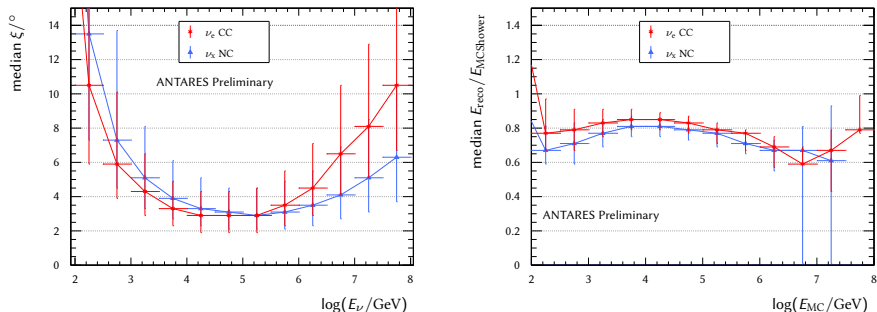


Figure : Performance of the shower energy-direction reconstruction, red for electromagnetic showers, blue for hadronic showers – **Left:** The angle between the directions of the reconstructed shower and the Monte Carlo neutrino. **Right:** The ratio between the reconstructed energy and the Monte Carlo shower energy.

- injected signal can be reasonably well fitted
- the source position can be safely found when 4 or more events are injected

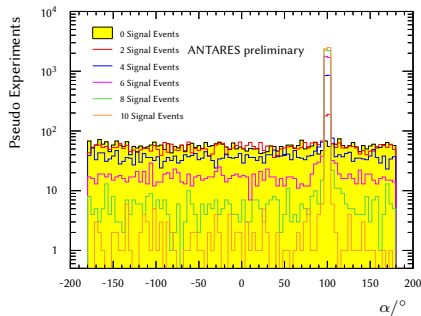
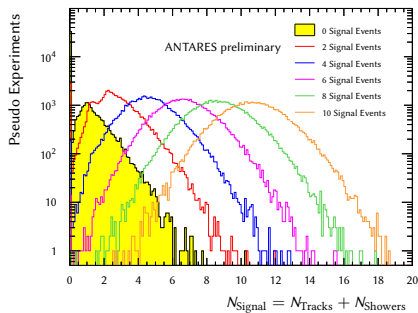


Figure : Pseudo experiments with various numbers of injected signal events **Left:** Fitted number of signal events in fixed point search – **Right:** Fitted right ascension in full sky search.

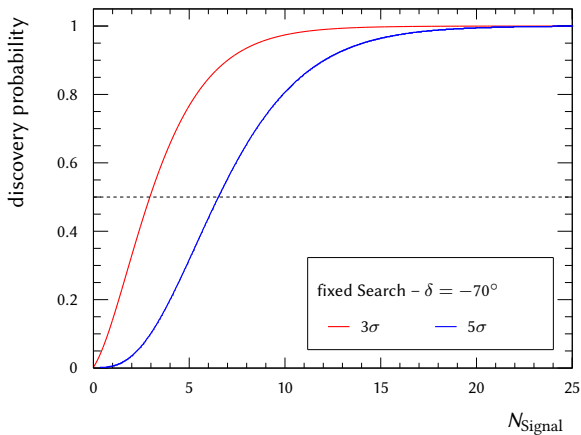


Figure : probability to find a source with 3 / 5 σ depending on the number of signal events with the fixed point search.

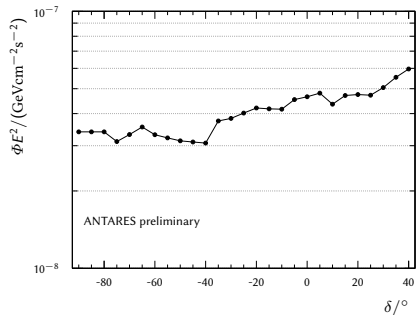
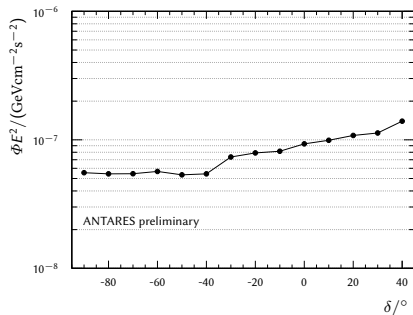


Figure : The flux necessary for a 50 % probability for a 5σ discovery in the **Left**: full sky and **Right**: fixed point search.