Search for magnetic monopoles and nuclearites with the ANTARES detector

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Frame of the analyses

ANTARES data

- Magnetic monopoles: 2008 data (9, 10, 12 line configurations)
- Nuclearites: 2007 & 2008 data (5, 9, 10, 12 line configurations)

Data processing

- L0 hit - basic information of a signal detected by a PMT, above a pre-defined threshold (typically 0.3 pe)
- L1 hit - local coincidence - two L0 hits within 20 ns in the same storey, or a single hit with a large amplitude (high threshold = 3 or 10 pe)
- directional trigger (DT) - 5 L1 hits correlated in space and time (2007 & 2008 data)
- cluster trigger (CT) - two clusters of two L1 hits in adjacent and next-to-adjacent storeys, within 2.2 μs window (2008 data)

Blinding strategy

- search strategy established on MC simulations
- validate the simulation on a fraction (15%) of the available data

Magnetic monopoles

- MM predicted by Dirac in 1931, in order to explain the quantization of electric charge: $eg = n\hbar c/2 = ng_D$
  - for n=1, $g = g_D = 68.5e$, Dirac (elementary magnetic) charge
- MM predicted by 't Hoot and Polyakov in 1974
  - monopole solutions appear in unified gauge theories, as a result of the spontaneous breaking of a semi-simple gauge group that contains $U(1)_{E.M.}$ subgroup
  - the predicted MM masses vary from 10^4 to 10^{20} GeV, depending on the unified gauge group
  - MM with mass below $\sim 10^{14}$ GeV can be accelerated to relativistic velocities in cosmic magnetic fields

Magnetic monopole signal in water

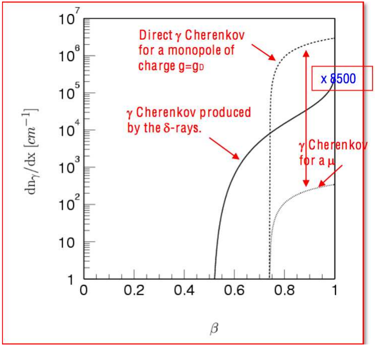
Direct Cherenkov emission $\beta > 0.74$

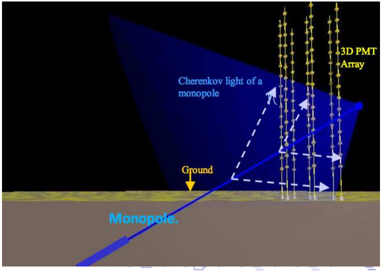
$$\frac{d^2N_\gamma}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(\frac{gn}{e}\right)^2\left(1 - \frac{1}{\beta^2 n^2}\right)$$

- a monopole with Dirac charge emits 8500 more photons than a muon with the same velocity

Indirect Cherenkov emission $\beta > 0.51$

- produced by electrons (δ-rays) pulled out from the atoms ionized by a passing magnetic monopole





Data, simulations and reconstruction

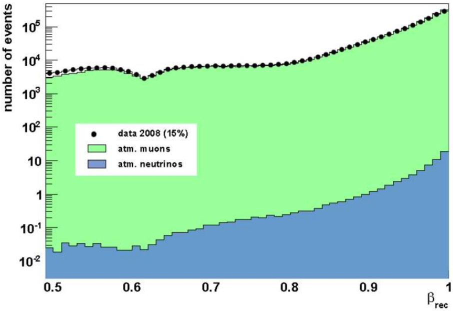
Data & MC simulations

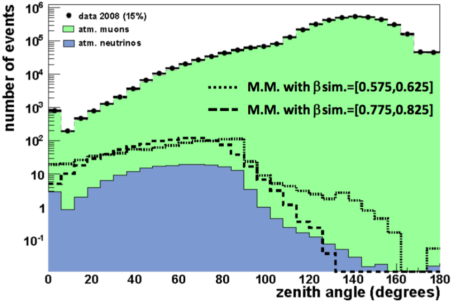
- Data taken in 2008 with 9, 10 and 12 lines, 136 days of live time
- MM simulated for 10 velocity ranges within β=[0.550,0.995]
- MC upgoing atmospheric neutrinos and downgoing atmospheric muons

Modification of the track reconstruction algorithm

- Original algorithm based on the minimisation of time residuals using the chi- square method for the crossing of muons with $\beta = 1$
- Implementation of the velocity as a free parameter in the algorithm, and optimisation for the crossing of magnetic monopoles
- Resolution on the reconstructed monopole velocity:
  $\beta < 0.8$: $\sigma_\beta \sim 0.03$ $\beta > 0.8$: $\sigma_\beta \sim 0.003$

Preliminary cuts



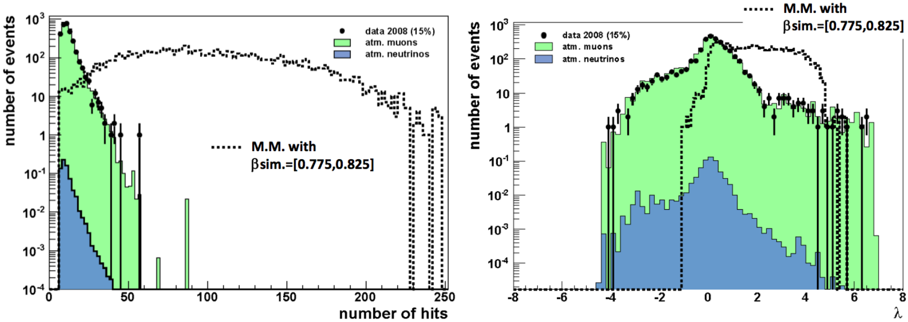


- very good agreement between data and MC, except for region below $\beta_{rec} \sim 0.60$
- events with $\beta_{rec} \leq 0.60$ discarded

- events with zenith angle < 90 degrees selected

Discriminative variables and optimisation method

1. Number of hits used in the reconstruction, nhit
2. parameter $\lambda = log(\frac{Q_t(\beta_{rec}=1)}{Q_t(\beta_{rec}=free)})$
   - $Q_t(\beta_{rec} = 1)$ - standard muon reconstruction
   - $Q_t(\beta_{rec} = free)$ - modified reconstruction



Very good discrimination of monopoles from background with nhit and λ.
Very good agreement between data and MC.

- Optimisation of the Model Discovery Potential in the cut parameter space(nhit, λ) for every region of reconstructed velocities.

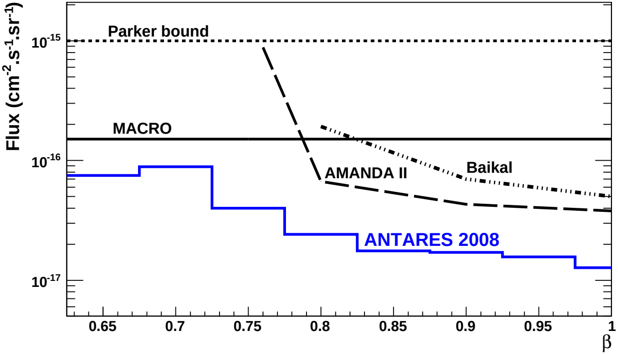
Results after unblinding

- Very good agreement between the 85% of data and the MC

β_{rec} range	# of expected background events	# of observed events	90% C.L. flux u. l. (cm^{-2} s^{-1} sr^{-1})
$[0.625, 0.675]$	2.2×10^{-2}	0	7.5×10^{-17}
$[0.675, 0.725]$	1.3×10^{-1}	1	8.9×10^{-17}
$[0.725, 0.775]$	4.6×10^{-2}	0	4.0×10^{-17}
$[0.775, 0.825]$	1.1×10^{-6}	0	2.4×10^{-17}
$[0.825, 0.875]$	8.2×10^{-7}	0	1.8×10^{-17}
$[0.875, 0.925]$	6.9×10^{-7}	0	1.7×10^{-17}
$[0.925, 0.975]$	2.3×10^{-5}	0	1.6×10^{-17}
$[0.975, 1.025]$	1.3×10^{-2}	0	1.3×10^{-17}

- one event survived selection cuts after unblinding in β_{rec}=[0.675,0.725]
- identified as a downgoing muon reconstructed as upgoing, due to random hits

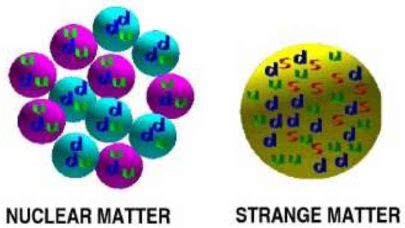
ANTARES 90% C.L. upper limit for upgoing magnetic monopoles for 116 days in 2008



Most stringent upper limit for upgoing magnetic monopoles in the velocity range $0.625 < \beta < 0.995$ (γ=10)

Nuclearites

- lumps of up, down and strange quarks in approximately equal proportion proposed by Witten, in 1984



- stable, essentially neutral (most or all electrons inside the quark core)
- slow massive particles, $\beta \sim 10^{-3}$
- interact mainly through elastic and quasi-elastic collisions
- for $3 \times 10^{13} - 10^{22}$ GeV, they could reach the Antares depth from above

Nuclearite signal in water

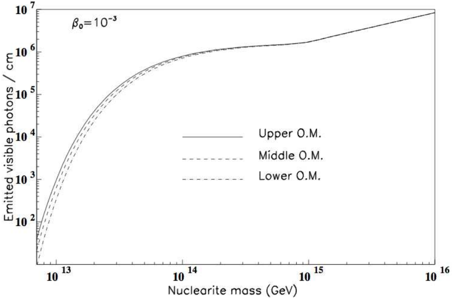
- energy loss:

$$\frac{dE}{dx} = -\sigma \rho v^2$$

- number of visible photons per unit path length:

$$\frac{dN_\gamma}{dx} = \eta \frac{dE/dx}{\pi(eV)}$$

- luminous efficiency (Rujula & Glashow,1984): $\eta \simeq 3 \times 10^{-5}$



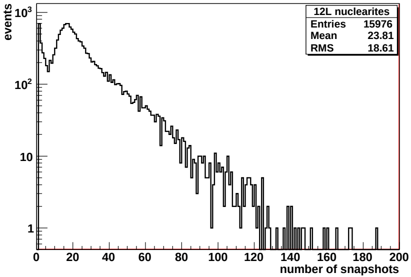
- a nuclearite of 10^{15} GeV mass would emit isotropically about 10^6 visible photons/cm, while muons with $\beta \sim 1$ emit about 4×10^2 Cherenkov photons/cm

Analysis input

Data and MC

- data from 2007 and 2008 taken with various detector configurations (5, 9, 10, 12 lines), $\sim$ 310 active days
- MC down going nuclearites for the mass range 3×10^{13} - 10^{17} GeV
- MC down going atmospheric muons

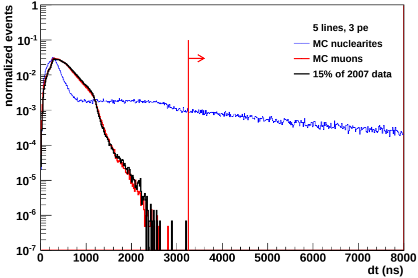
Nuclearite signal inside the ANTARES detector



- the duration of a nuclearite event should be much longer (about 1 ms) than the typical muon crossing time (2.2 μs)
- the isotropic light emitted along the heated path would induce a succession of fake muon signals

Selection cuts

- discriminative variable: snapshot duration, defined as the time difference between the last and the first L1 hits that produce a trigger
- removes the main background due to atmospheric muons

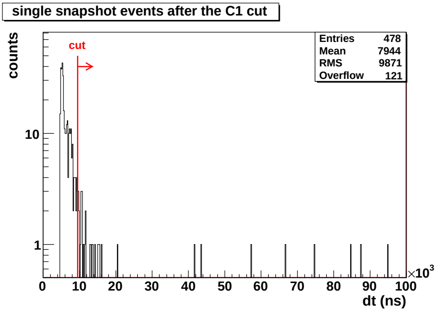


Detector	C1 cut (ns)
5L, DT,10 pe	2500
5L, DT, 3 pe	3250
10L, DT, 10 pe	3200
10L, DT, 3 pe	3500
10L, DT, CT, 3 pe	4200
9L, DT, CT, 3 pe	4250
9L, DT, CT, 10 pe	3350
s 12L, DT, CT, 10 pe	4000
12L, DT, CT, 3 pe	4750

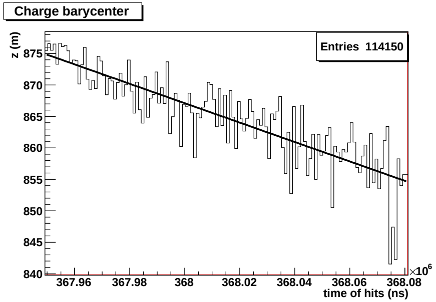
- optimized C1 cuts

Selection cuts

- 11 events found in 15% data sample after the first cut, all consistent with bioluminescent activity
- new cut C2: duration larger than 2×C1 for single snapshot events
- reconstruction procedure proposed
  - fast reconstruction method, based on the charge barycenter vs time distribution
  - MC simulation for events with characteristic topology of nuclearites: down going track and velocity around 10^{-3} c



- 12 line single snapshot nuclearites C2 cut at 9500 ns



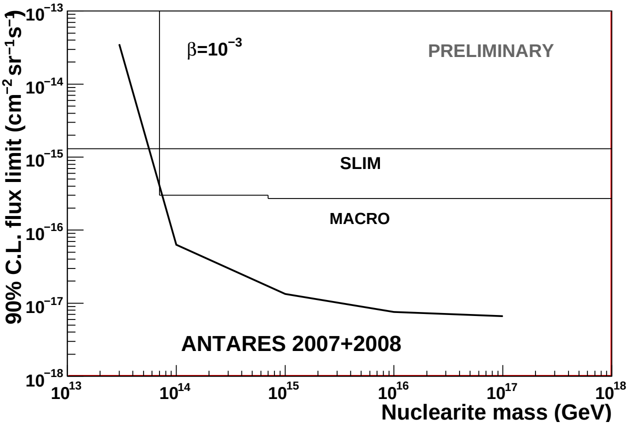
- 10^{15} GeV nuclearite event

Unblinding results

Detector configuration	# of expected background events	# of observed events
5L, DT,10 pe	2.4×10^{-8}	0
5L, DT, 3 pe	1.2×10^{-9}	0
10L, DT, 10 pe	3.5×10^{-10}	0
10L, DT, 3 pe	6.9×10^{-11}	0
10L, DT, CT, 3 pe	5.2×10^{-11}	0
9L, DT, CT, 3 pe	2.3×10^{-10}	3
9L, DT, CT, 10 pe	9.6×10^{-10}	4
12L, DT, CT, 10 pe	7.8×10^{-10}	0
12L, DT, CT, 10 pe	2.5×10^{-11}	0

- 7 events survived the selection cuts after unblinding, however their charge barycenter distributions don't reproduce a downgoing track
- 3 events were identified as a fixed light source (due to a sparking OM)
- 4 events were due to bioluminescence bursts

ANTARES flux upper limit to downgoing nuclearites, 310 active days from 2007 and 2008



Conclusions

Magnetic monopoles

- For the first time a neutrino telescope is sensitive to magnetic monopoles below the Cherenkov threshold
- Most stringent upper limit in the monopole velocity range 0.625 < β< 0.995 (γ=10)

Nuclearites

- ANTARES detector is sensitive to downgoing nuclearites, even when using triggers designed for relativistic particles
- ANTARES improves the MACRO upper limit by more than one order of magnitude for nuclearite masses greater than 10^{15} GeV