Search for relativistic monopoles with ANTARES

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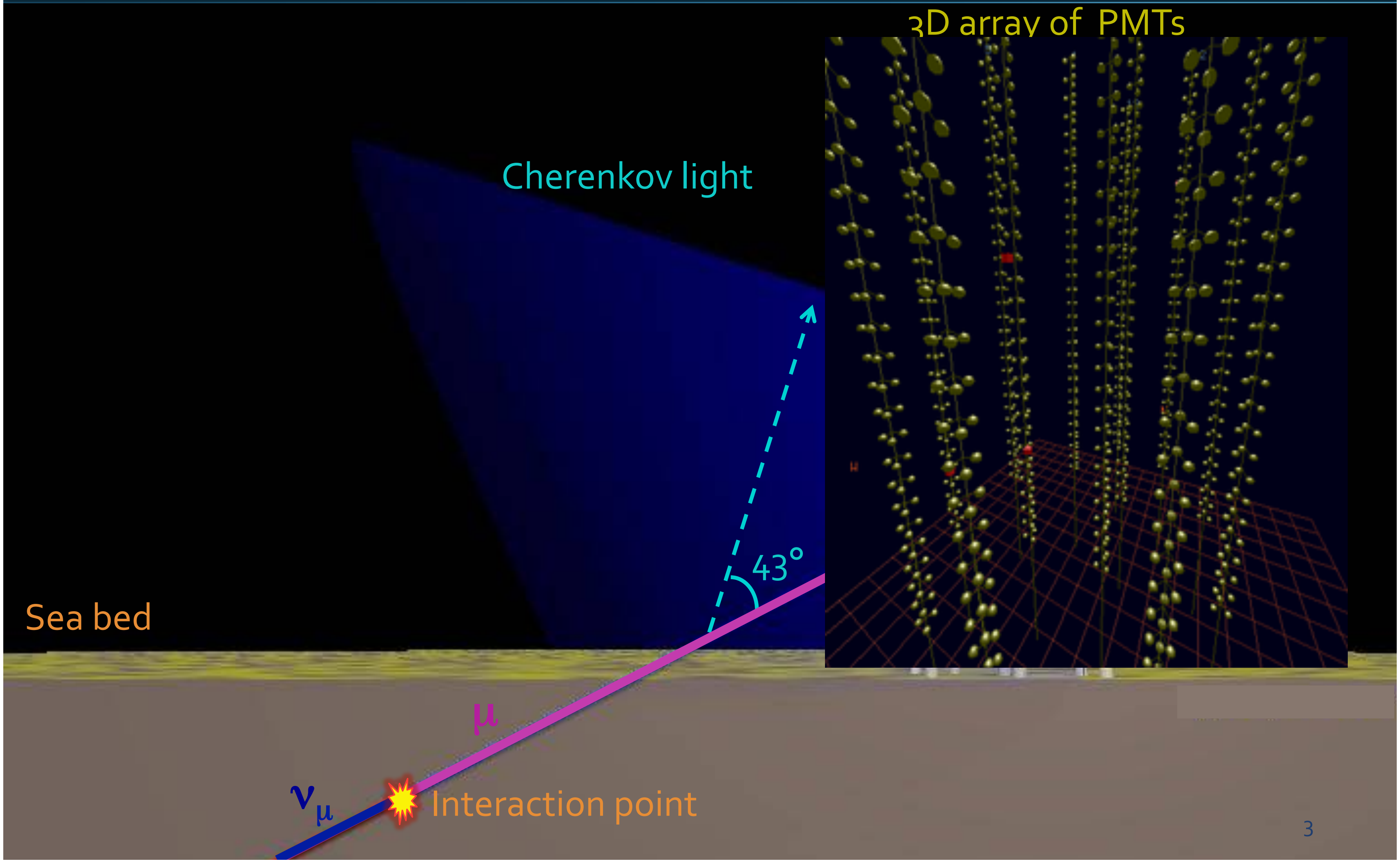
On behalf of the ANTARES Collaboration

Outline

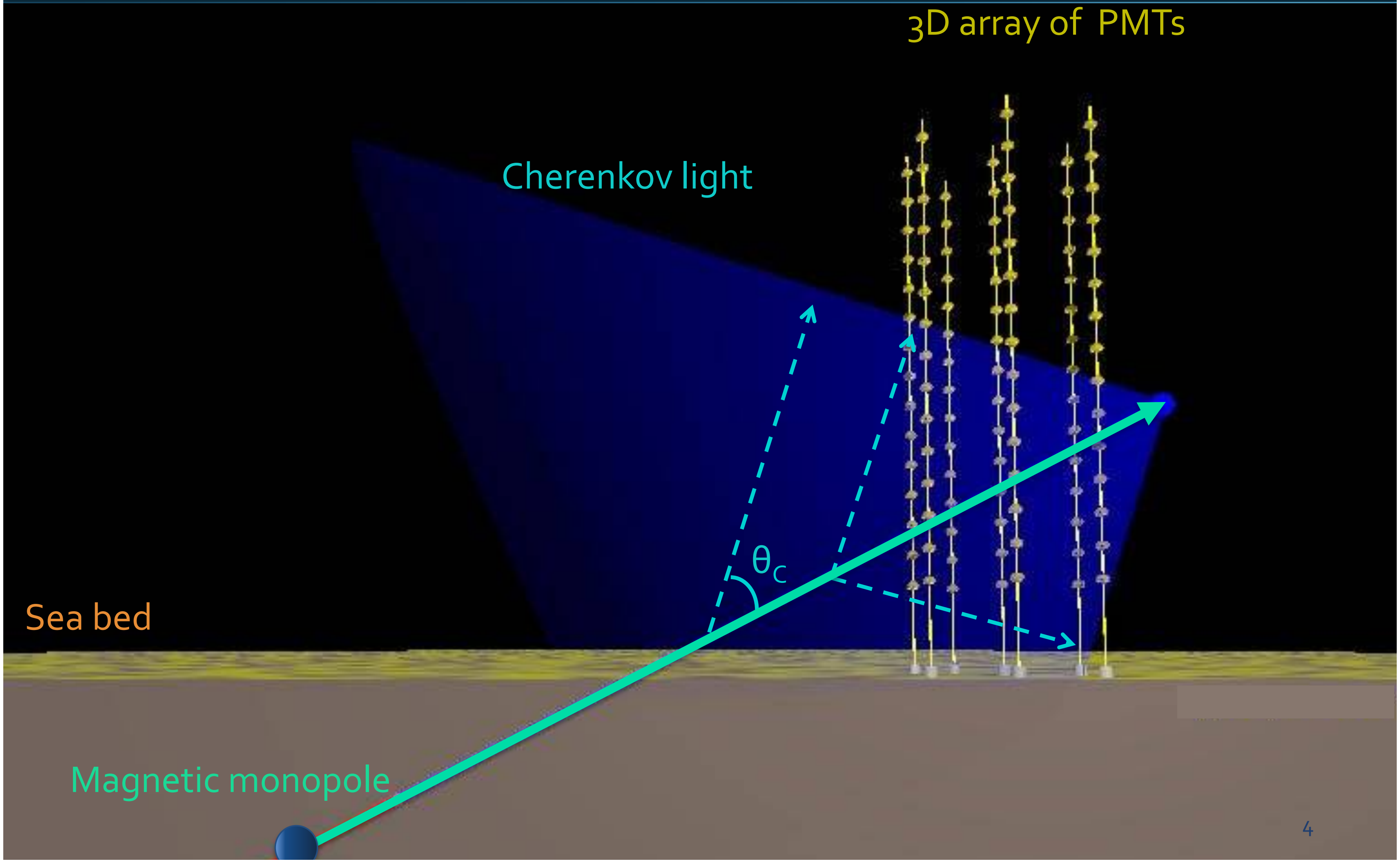
- Monopole detection with a neutrino telescope
- Search strategy applied to ANTARES
    - ✓ Monte Carlo and Data samples
    - ✓ Trigger and event reconstruction
    - ✓ Optimisation of the Model Discovery Factor
- Final upper limit with the ANTARES 2008 data
- Conclusion and perspectives

MONOPOLE DETECTION WITH A NEUTRINO TELESCOPE

The ANTARES detector



The ANTARES detector



Magnetic monopoles signature

Direct Cherenkov radiation if β > 0.74:

Cherenkov angle is $\cos\theta_c = \frac{1}{\beta n}$

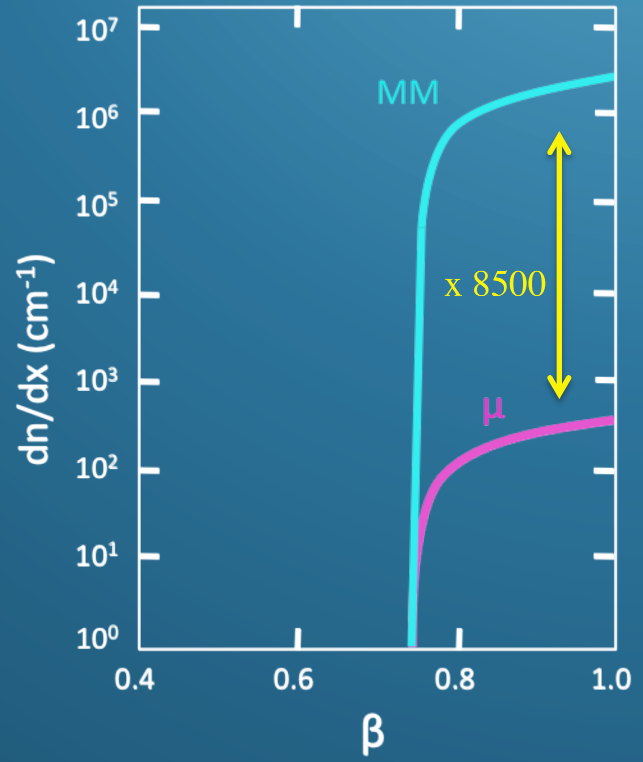
Number of Cherenkov photons is

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

The magnetic charge of a monopole :

$$g_D = e / 2\alpha = 68.5\ e$$

Monopoles with $g = g_D$ are expected to emit about ~8500 times more Cherenkov photons than muons of the same velocity



Magnetic monopoles signature

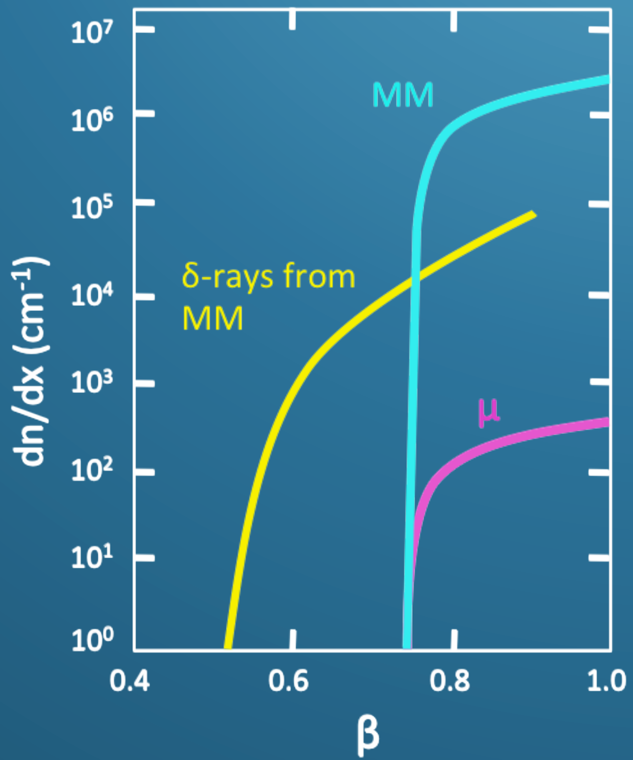
Direct Cherenkov radiation if $\beta > 0.74$:

Monopoles with $g = g_D$ are expected to emit about ~8500 times more Cherenkov photons than muons of the same velocity

Indirect Cherenkov radiation if $\beta > 0.51$:

Energy loss in collisions with the atomic electrons:

➔ these δ-rays emit Cherenkov radiation



Magnetic monopoles can be detected in a neutrino telescope

SEARCH STRATEGY APPLIED TO ANTARES

Method

The search for magnetic monopoles with ANTARES
is based on a "blind" analysis

- Optimization of the S/N ratio using Monte Carlo simulations only

  Here, optimization performed according to
  Model Discovery Factor (MDF)

  G. Punzi, arXiv: 0308063

  MC simulation validated with 15% subsample of data

- Applications of the selection cuts on data in a blinded way

  ➔ Upper limit

  on 85% remaining data

Outline

Search strategy applied to ANTARES

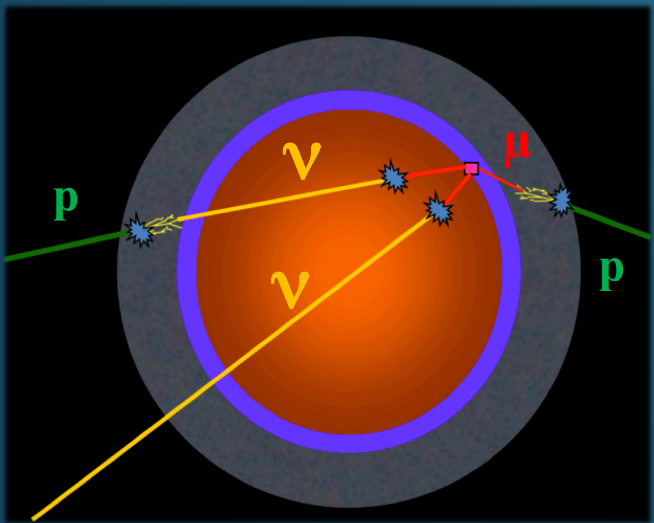
- Monte Carlo and Data samples
- Trigger and event reconstruction
- Optimisation of the Model Discovery Factor

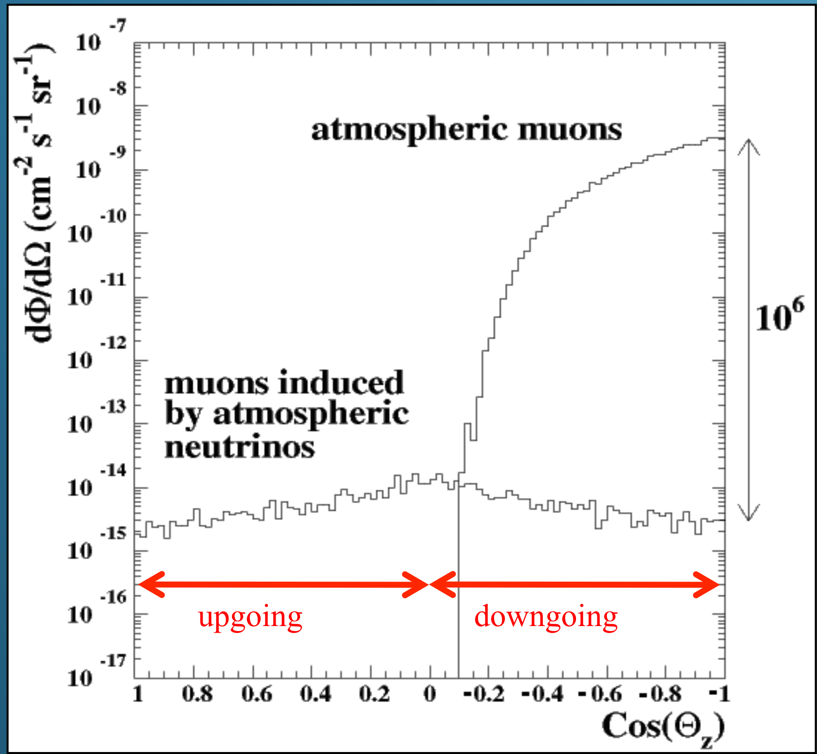
SEARCH STRATEGY APPLIED TO ANTARES

Monte Carlo simulations and data sample

MC simulations

The atmospheric background





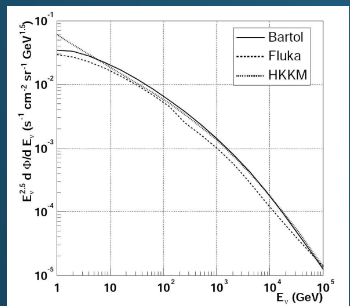
The main source of background events in the search for upgoing MMs due to:

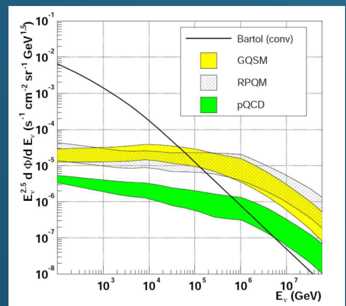
- upgoing muons induced by atmospheric neutrinos
- downgoing atmospheric muons wrongly reconstructed as upgoing

MC simulations

The atmospheric neutrinos sample

- is generated assuming the Bartol atmospheric neutrino flux model (decay of pions and kaons)
- combined with neutrinos coming from the decay of charm mesons as produced by the RQPM model





Choice for the most conservative neutrino flux

The atmospheric muons sample

- Is generated using the CORSIKA air shower program (Hörandel model), in combination with the QGSJET code for the description of hadronic interactions

MC simulations

The magnetic monopoles sample

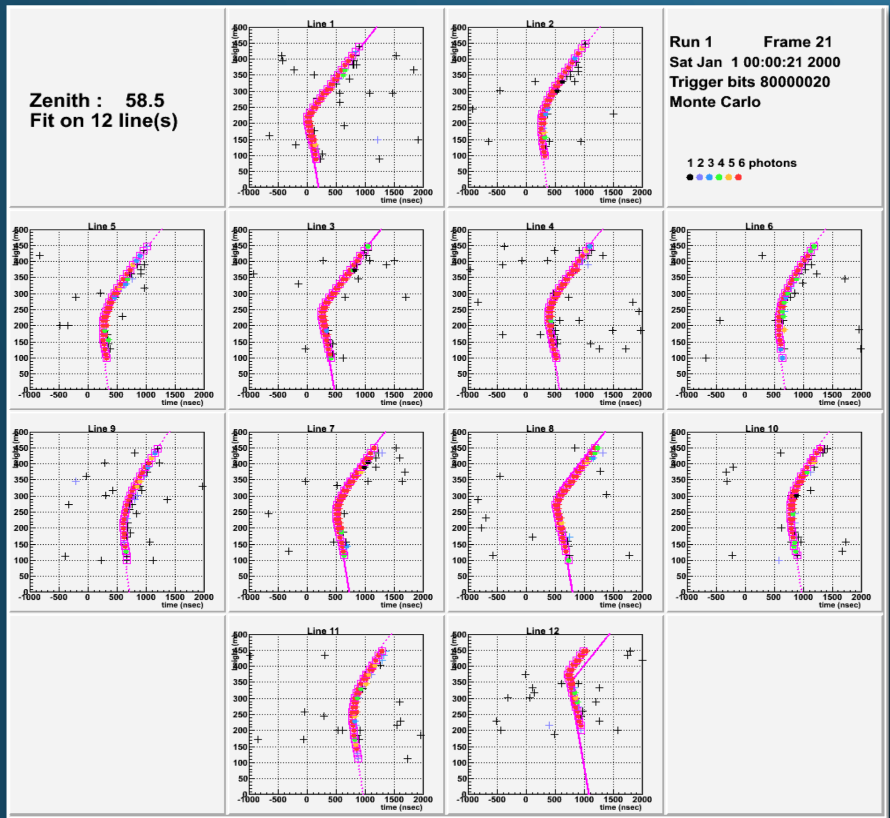
- Monte Carlo simulation based on GEANT3
  Software dev. by Bram van Rens (ANTARES PhD thesis, 2006)
  antares.in2p3.fr/Publications/

Magnetic monopoles with one Dirac charge ($g = g_D$) have been generated:

- As upgoing (isotropic incoming direction over the lower hemisphere)
- For ten ranges of velocities in the region $\beta = [0.550, 0.995]$
- The simulation of emitted photons was processed inside a cylindrical volume with a radius of 480 m (eight times the absorption length), four times larger than that used for the standard ANTARES muon simulation
  ➔ To take into account the large amount of light emitted by a magnetic monopole.

MC simulations

The magnetic monopoles sample : illustration



Neutrino candidate

Monopole candidate with $\beta \sim 0.99$

➔ large amount of light emitted by a magnetic monopole.

The data sample

ANTARES data from December 2007 to December 2008

Quality requirements:
- low levels of bioluminescent activity
- a well calibrated detector

After this selection the data is equivalent to a total of 136.1 days of live time:

Size of the detector	Live time
12 lines	43.6 days
10 lines	45.8 days
9 lines	46.7 days

20 days data used for the 15% subsample
116 days data used for the final limit

SEARCH STRATEGY APPLIED TO ANTARES

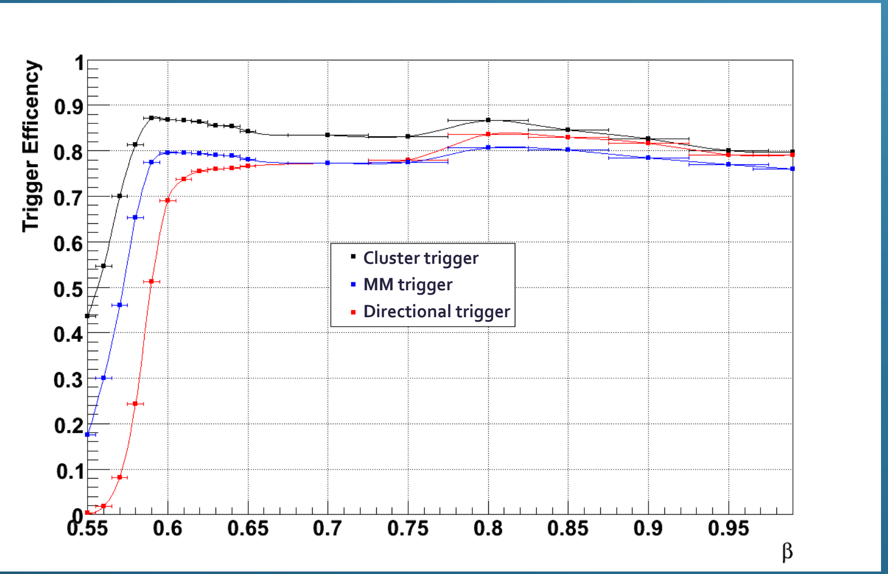
Trigger and event reconstruction

Trigger

Two standard triggers in ANTARES:

- A directional trigger, which requires 5 local coincidences, causally connected, within a time window of 2.2 μs

- A cluster trigger, which requires two T3-clusters, where a T3-cluster is a combination of two local coincidences in adjacent or next-to-adjacent storeys within 100 ns or 200 ns, respectively.



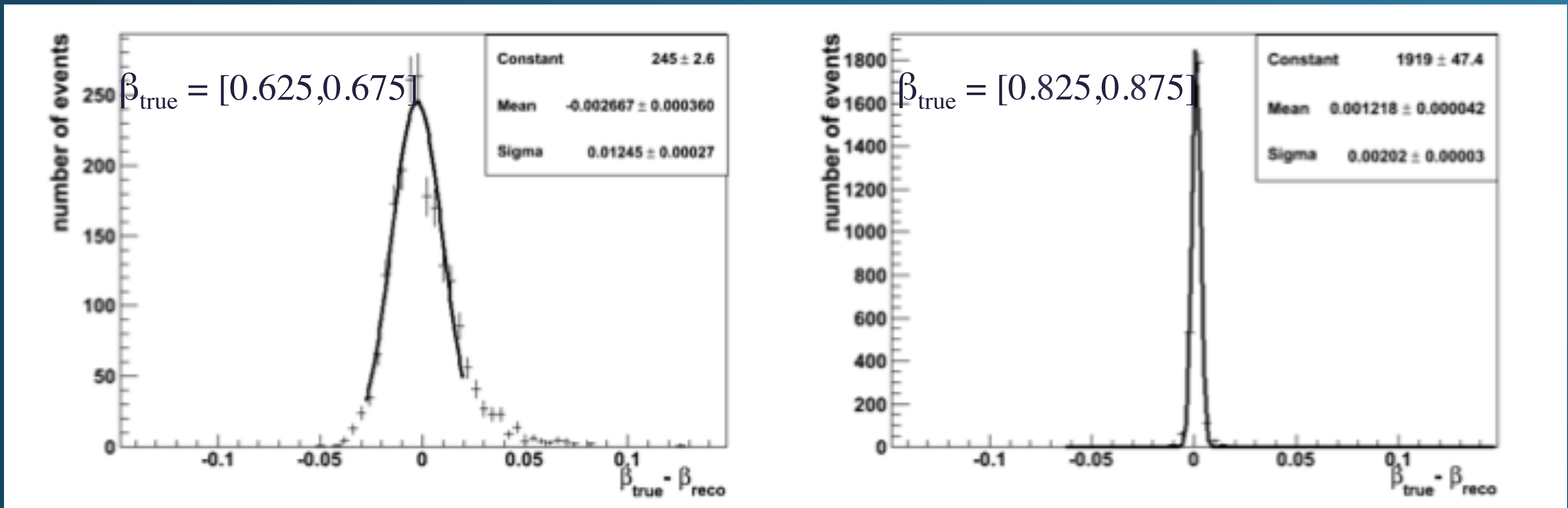
Trigger efficiency for monopoles in respect to their velocity

Event reconstruction

Algorithm BBFit based on the minimization of time residuals using the least square method

Aguilar et al., Astropart. Phys. 34 (2011) 652

Modification of the event reconstruction algorithm, by adding the particle velocity β as a free parameter



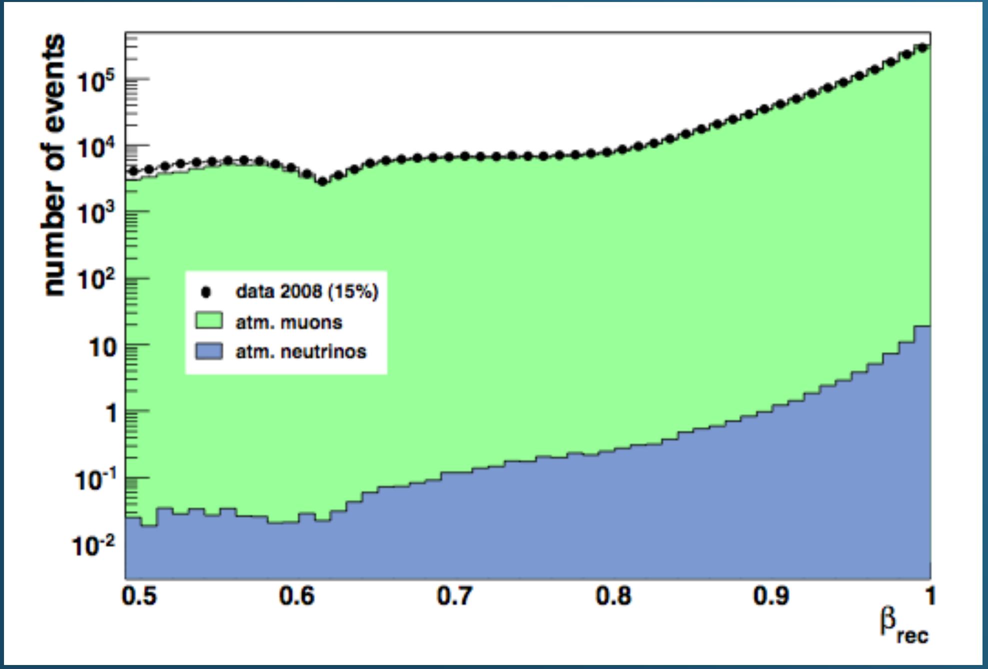
Resolution in the velocity reconstruction

SEARCH STRATEGY APPLIED TO ANTARES

Pre-selection and Optimization of final selection cuts

Pre-selection

Events reconstructed with the modified algorithm



A normalization factor of 1.8 was applied to the atm. muon sample

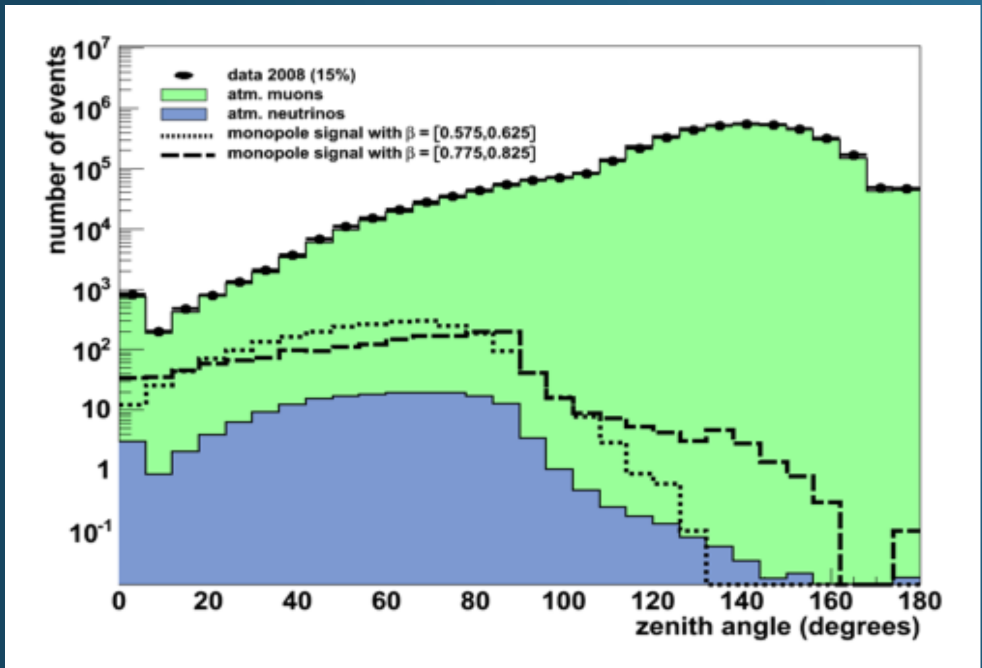
due to the expected uncertainties on:

- the optical module angular acceptance of Cherenkov light from downgoing particles
- parameters of the atmospheric muon flux model.

➔ Excellent agreement between data & MC for $\beta_{rec} > 0.6$

Pre-selection

Events reconstructed with the modified algorithm



First selection level

- Only upgoing events θ< 90°
- Events reconstructed on at least 2 lines

Ready for the optimization of the MDF

Here, only events whose tracks has been reconstructed on at least 2 lines

Model Discovery Factor

Definition of the Model Discovery Factor (MDF):

"Optimization for discovery"

Given the null hypothesis H_0 : background only hypothesis

where observation follows a Poisson distribution with a mean value equal to the expected background μ_B

and the alternative hypothesis H_1 : background + MM signal

The null hypothesis is rejected
if the p-value of observation given H_0 < significance level α

So we are able to define a minimum (critical) number of observed events needed to claim a discovery

$$P(\geq n_{crit} \mid \mu_B) < \alpha$$

Model Discovery Factor

Definition of the Model Discovery Factor (MDF):

In case of signal (H_o rejected), we want that the probability of discovery be $1\text{-}\beta=90\%$

Then the probability to observe a number of events equal to at least n_{crit} is:

$$1-\beta = P(\geq n_{crit} \mid \mu_B + \mu_S)$$

➔ Equality verified for $\mu_S = \mu_{lds}$, where μ_{lds} *is* the *least detectable signal*.

for given values of the threshold level of significance α and the power of the test β.

The MDF is then defined as: $\text{MDF} = \mu_{lds} / \mu_S$

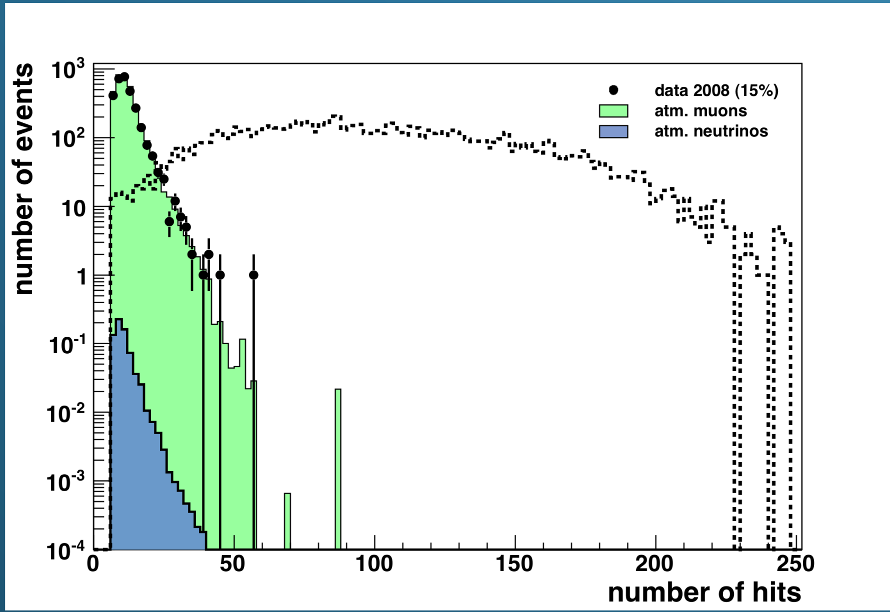
Final selection cuts are optimized to minimize the MDF.

Here, significance level $\alpha = 5\sigma$ at $1\text{-}\beta = 90\%$ probability

Model Discovery Factor

Optimisation of the MDF with respect to:

- An estimator of the quantity of light (number of floors used in the track fit)



Model Discovery Factor

Optimisation of the MDF with respect to:

- An estimator of the quantity of light (number of floors used in the track fit)
- Give advantage to reconstructed tracks with $\beta < 1$ in order to discriminate monopoles from muons

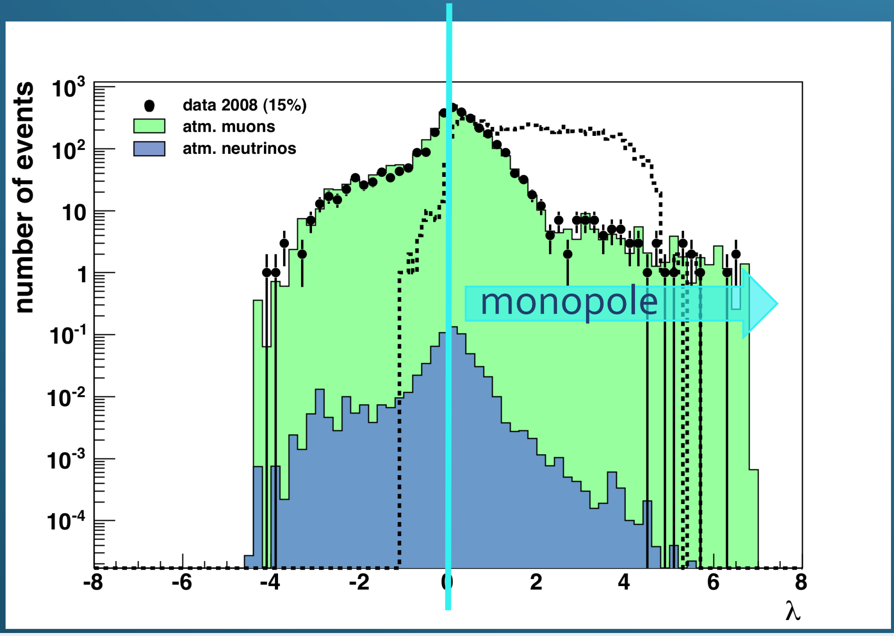
For every triggered events, two reconstruction algorithms are applied:

- the velocity β is set to 1 $X^2_{\beta=1}$

- the velocity β is a free parameter X^2_{β}

Discriminative parameter

$$\lambda = \log(\chi^2_{\beta=1} / \chi^2_{\beta})$$



Model Discovery Factor

Optimisation of the MDF

Velocity β_r	N floors	λ	background		
			μ	ν	Total
0.55	10	45	2.52	$6.8\ 10^{-6}$	2.52
0.60	21	1.1	0.43	$3.5\ 10^{-6}$	0.43
0.65	36	0.7	$<10^{-7}$	$2.2\ 10^{-7}$	$2.2\ 10^{-7}$
0.70	47	0	$3.5\ 10^{-3}$	$2.0\ 10^{-5}$	$3.5\ 10^{-3}$
0.75	53	-2.1	$<10^{-7}$	$2.1\ 10^{-5}$	$2.1\ 10^{-5}$
0.80	81	0.8	$<10^{-7}$	$1.3\ 10^{-8}$	$<10^{-7}$
0.85	93	0.4	$<10^{-7}$	$<10^{-10}$	$<10^{-7}$
0.90	85	0.7	$<10^{-7}$	$<10^{-10}$	$<10^{-7}$
0.95	84	0	$<10^{-7}$	$2.2\ 10^{-5}$	$2.2\ 10^{-5}$
0.99	92	0	$<10^{-7}$	$6.5\ 10^{-3}$	$6.5\ 10^{-3}$

Optimization with the 12-line detector

➔ Optimisation also done with the 9-line and 10-line detectors

Monopole signal efficiencies after all cuts are between 20% and 33%

FINAL UPPER LIMIT

Final upper limit

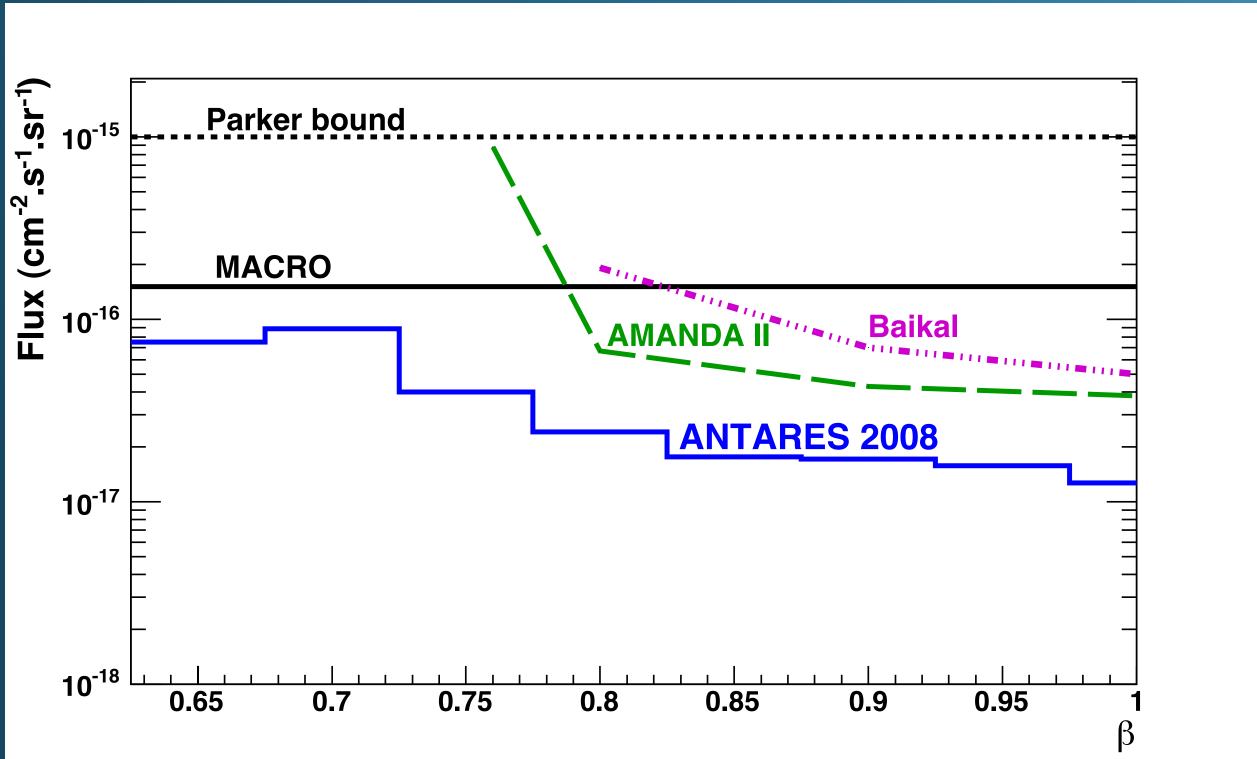
Application on data

Velocity β_r	Expected background	Critical number	Observed events	Upper limit 90% cl ($cm^{-2}\ s^{-1}\ sr^{-1}$)
0.55	6.0	22	12	$4.2\ 10^{-15}$
0.60	0.43	7	3	$5.4\ 10^{-16}$
0.65	$2.2\ 10^{-2}$	2	0	$7.5\ 10^{-17}$
0.70	$1.3\ 10^{-1}$	3	1	$8.9.\ 10^{-17}$
0.75	$4.6\ 10^{-2}$	2	0	$4.0\ 10^{-17}$
0.80	$1.1\ 10^{-6}$	1	0	$2.4\ 10^{-17}$
0.85	$8.2\ 10^{-7}$	1	0	$1.8\ 10^{-17}$
0.90	$6.9\ 10^{-7}$	1	0	$1.7\ 10^{-17}$
0.95	$2.3\ 10^{-5}$	2	0	$1.6\ 10^{-17}$
0.99	$1.3\ 10^{-2}$	3	0	$1.3\ 10^{-17}$

No excess event is observed in respect to expected background, with p-values > α.

➔ So the observation is consistent with the null hypothesis, i.e. the background-only hypothesis

Final upper limit



2008 data
(116 days)

PhD thesis of N. Picot-Clemente, CPPM

Astrop. Phys. 35 (2012) 634.

Conclusion and perspective

Conclusion

New limits with the ANTARES detector for upgoing relativistic magnetic monopoles with $0.65 < \beta < 0.99$ (γ=10)

- Above and below the Cherenkov threshold
- For 2008 data equivalent to 116 days live time
- Monopole masses between 6.10^8 GeV/c^2 (horizontal events) to 10^{14} GeV/c^2

Perspective

This limit could be improved by a factor 10 by using the 2009-2012 data equivalent to ~1000 days of live time.