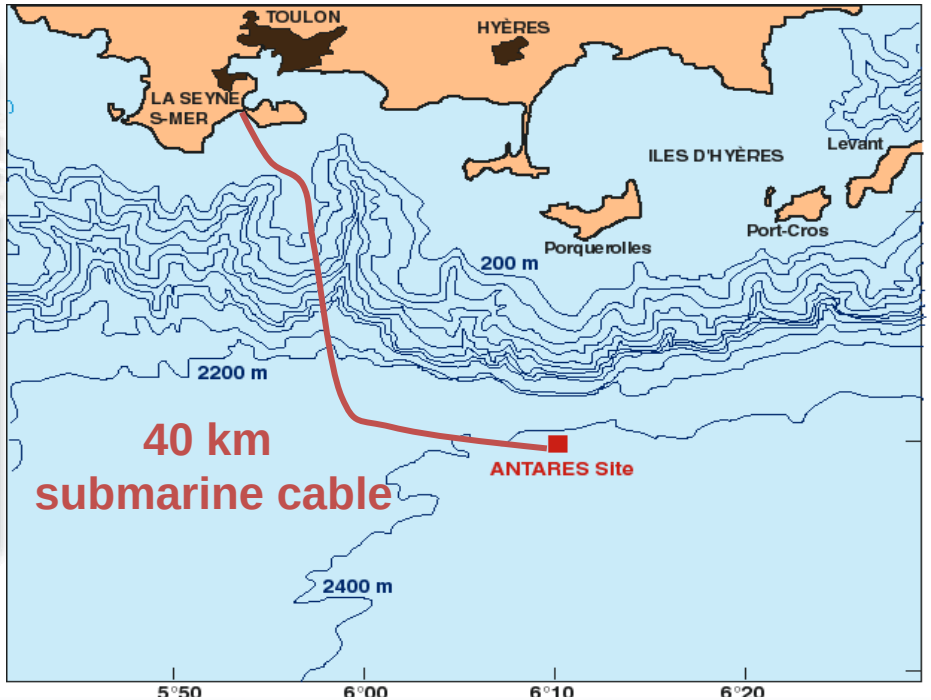
Measurement of Neutrino Oscillations with ANTARES

J. Brunner

14/09/2012

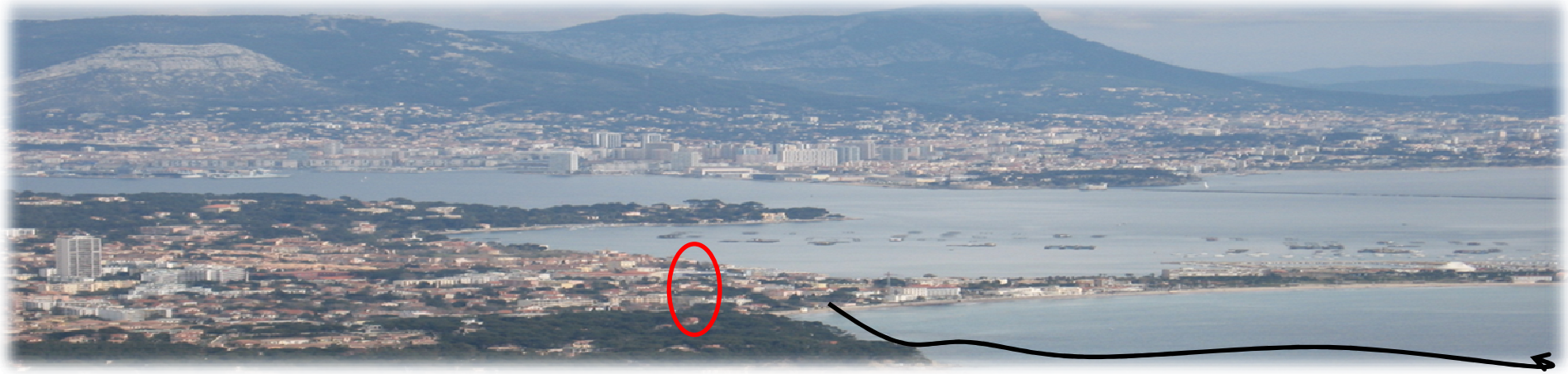
The ANTARES Site & Infrastructure


IFREMER Toulon Centre

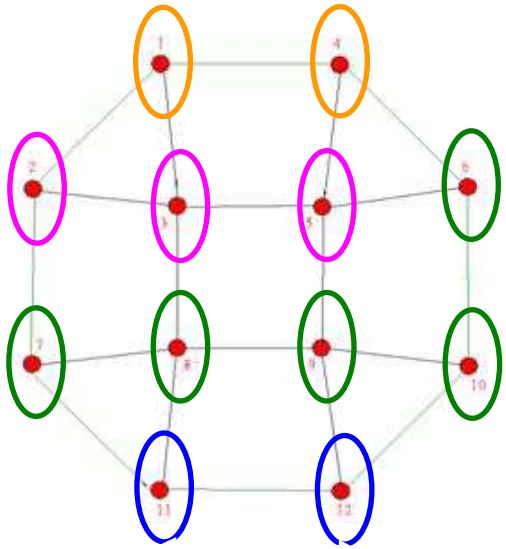


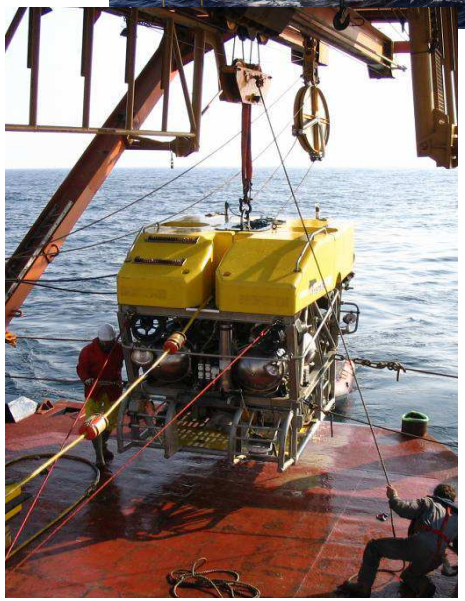

Shore Station

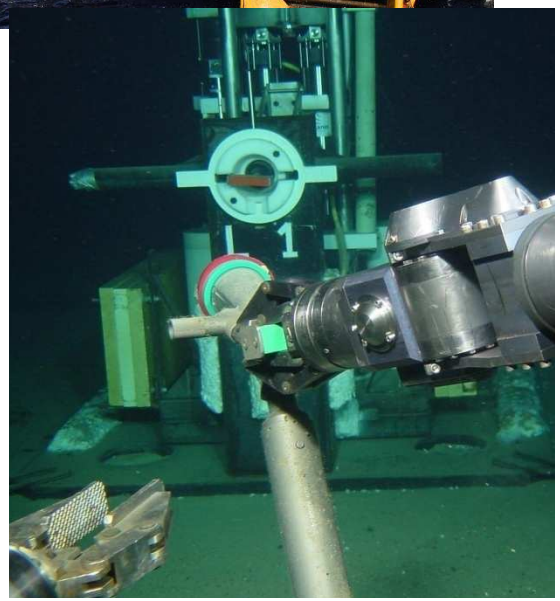

FOSELEV Marine



2006 – 2008: Construction of the Detector

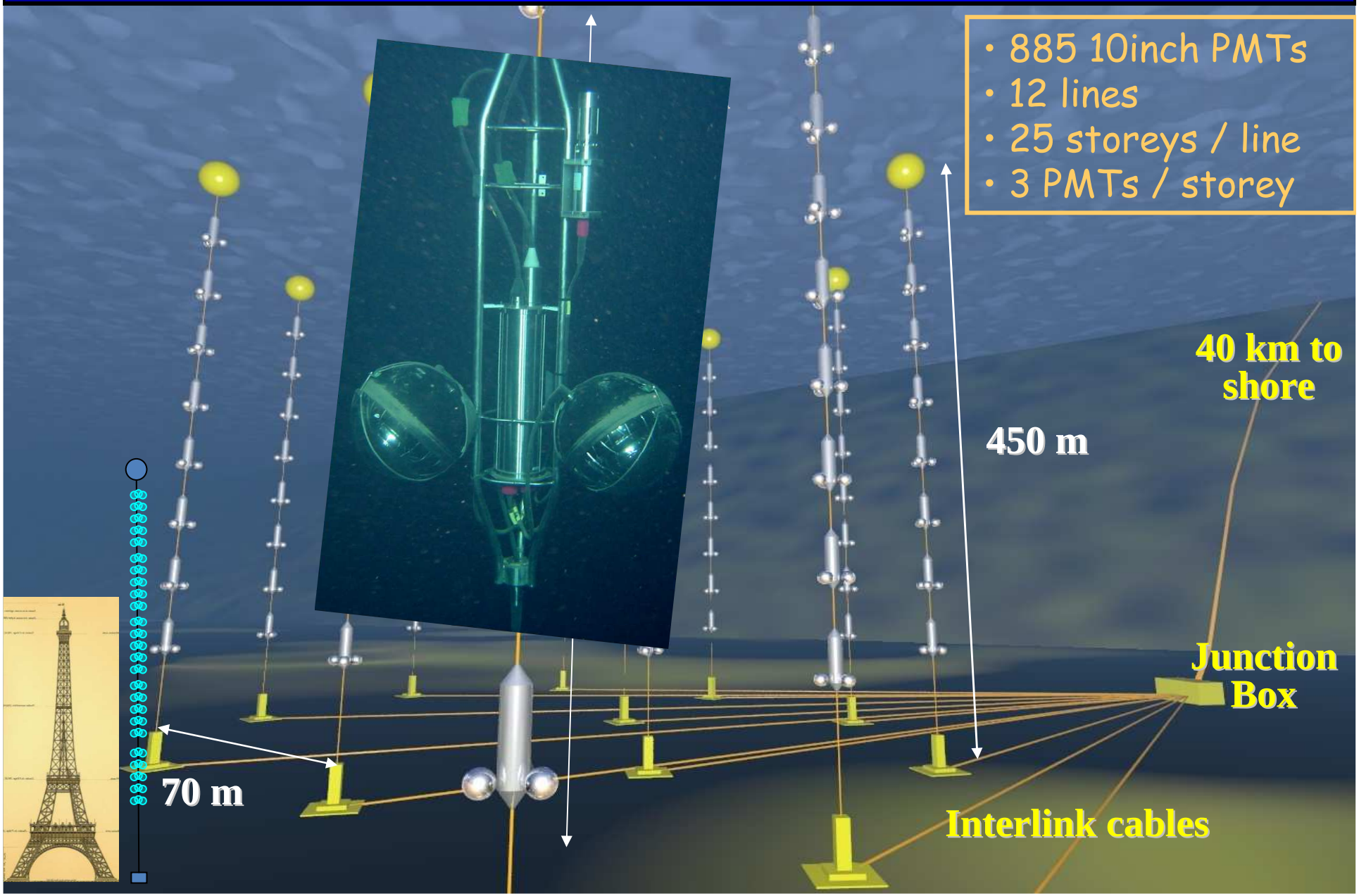






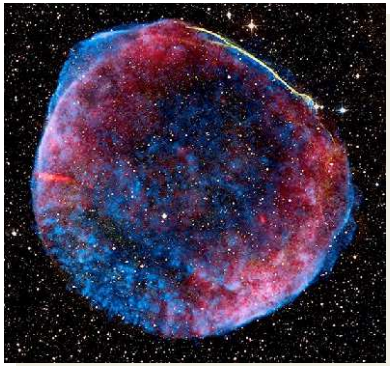
- **Junction box** **2001**
- **Main cable** **2002**
- **Line 1, 2** 2006
- **Line 3, 4, 5** 01 / 2007
- **Line 6, 7, 8, 9, 10** 12 / 2007
- **Line 11, 12** 05 / 2008

The ANTARES Detector

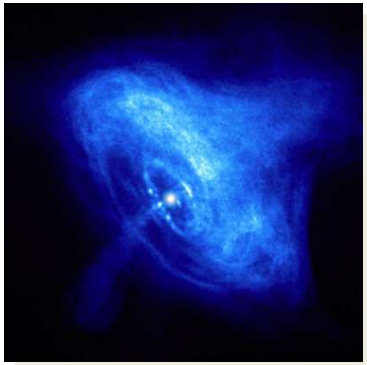


The high-energy universe

supernova remnants
(SN1006, optical, radio, X-ray)

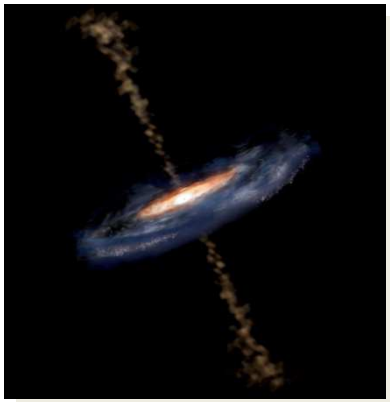


pulsars
(Crab, X-ray, Chandra)

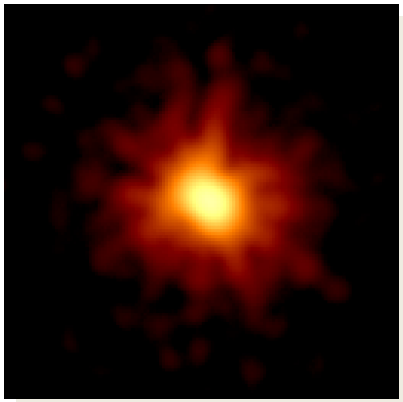


Galactic

active galactic nuclei
(artist's view)

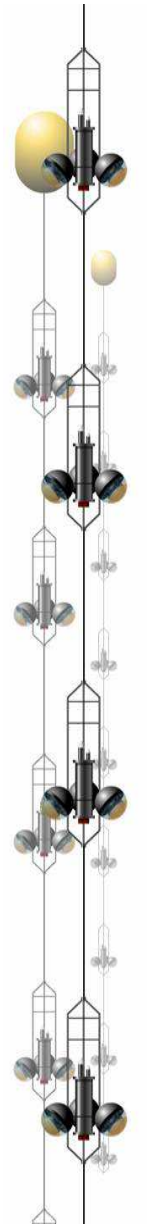


gamma-ray bursts
(GRB 080319B, X-ray, SWIFT)



Extra-Galactic

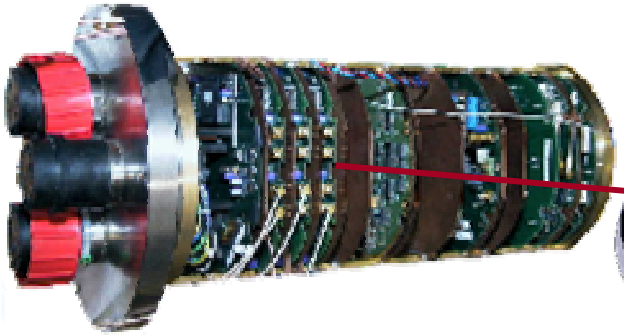
Basic element: The Storey



Titanium frame: *support structure*

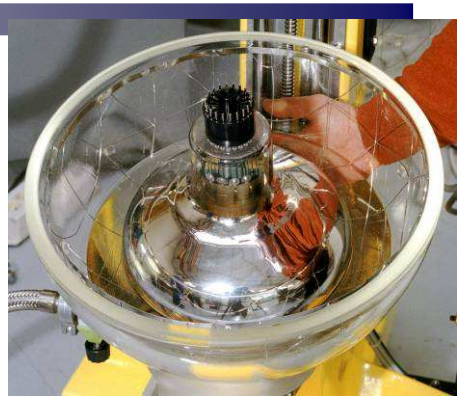
Optical Beacon
with blue LEDs:
timing calibration

NIM **A578** (2007) 498
Astrop. Phys **34** (2011) 539



Local Control Module (Ti):
Front-end ASIC, DAQ/SC, DWDM,
Clock, tilt/compass, power distribution…

NIM **A570** (2007) 107
NIM **A622** (2010) 59



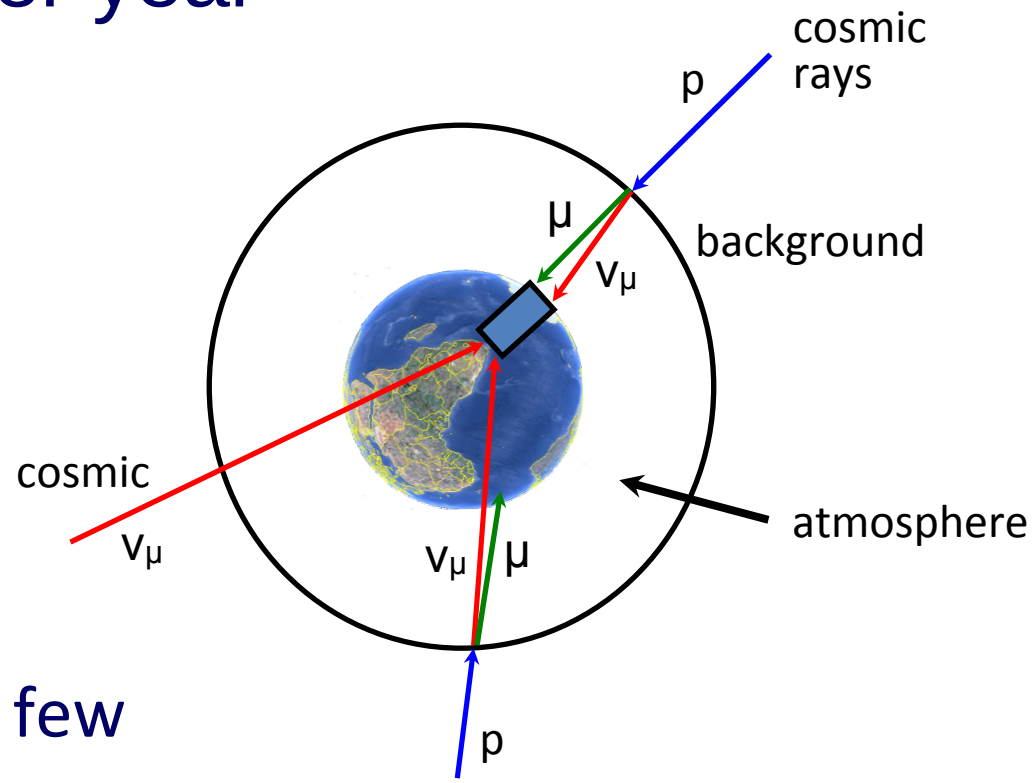
Optical Module:
10” Hamamatsu PMT in 17” glass sphere
photon detection

NIM **A484** (2002) 369
NIM **A555** (2005) 132

Hydrophone:
acoustic positioning

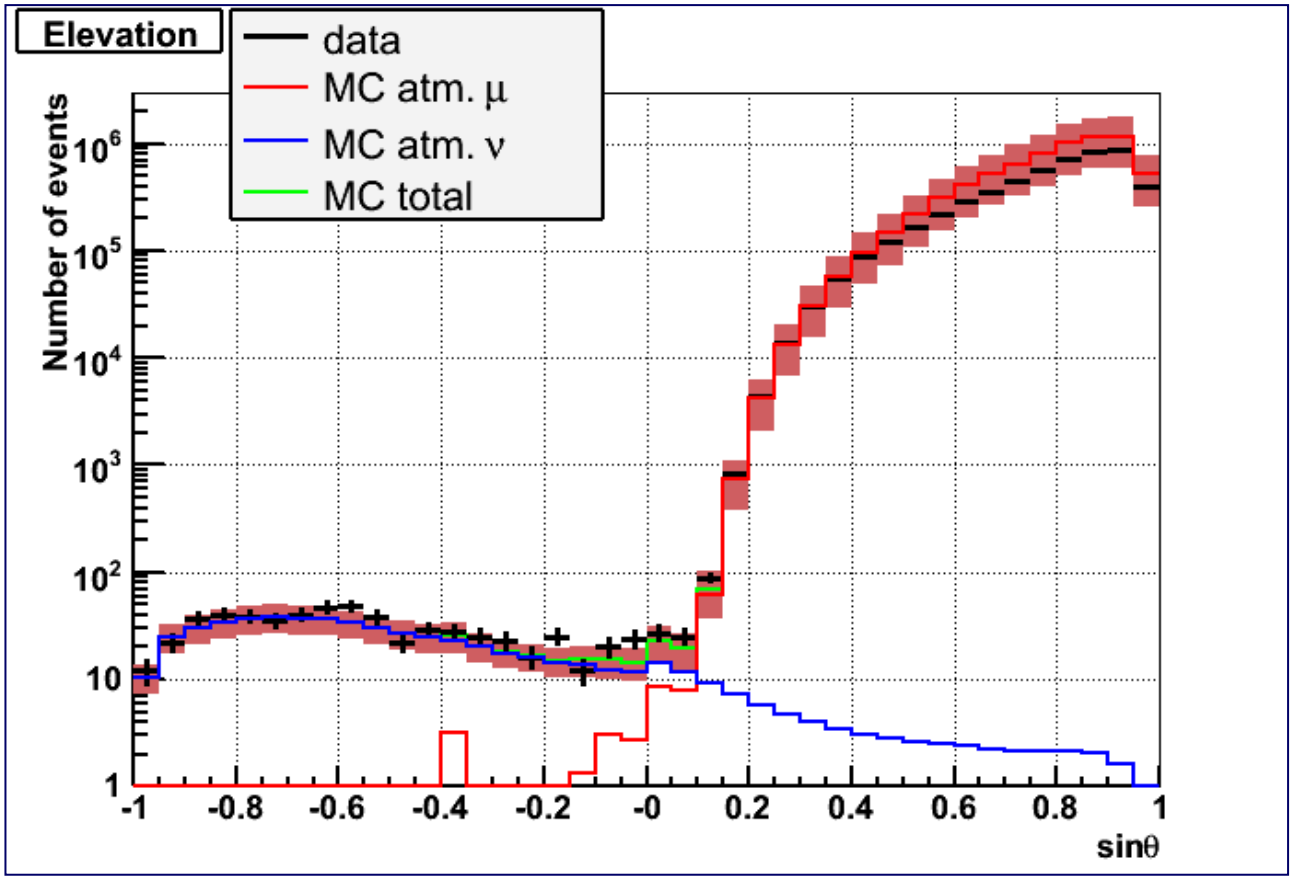
Muon tracks in the detector

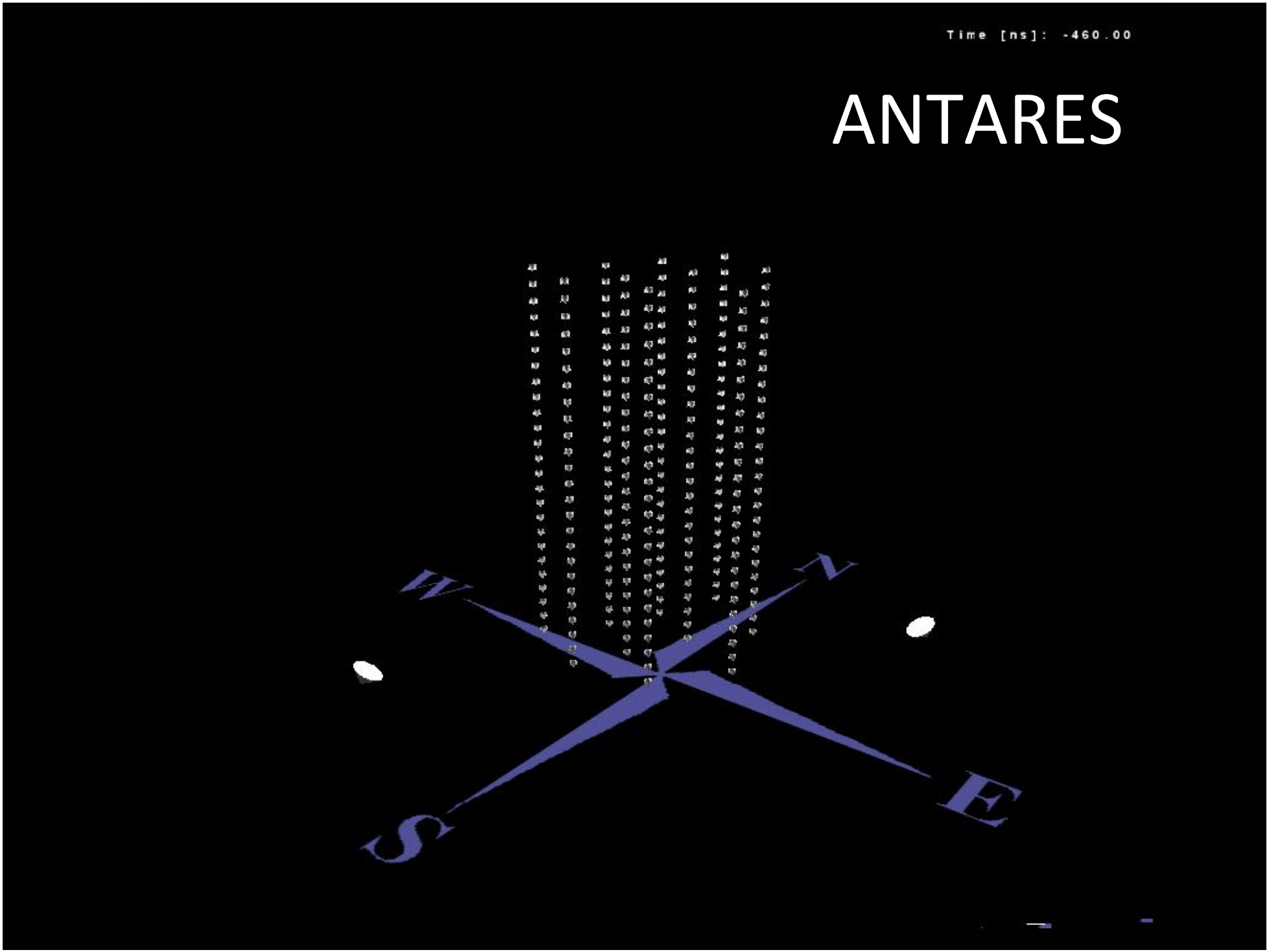
- Muons detected per year (Antares)
  - Atmospheric μ
    7×10^{8} = 20 Hz
  - Atmospheric ν→μ
    2×10^{3} = 5 per day
  - cosmic ν→μ few



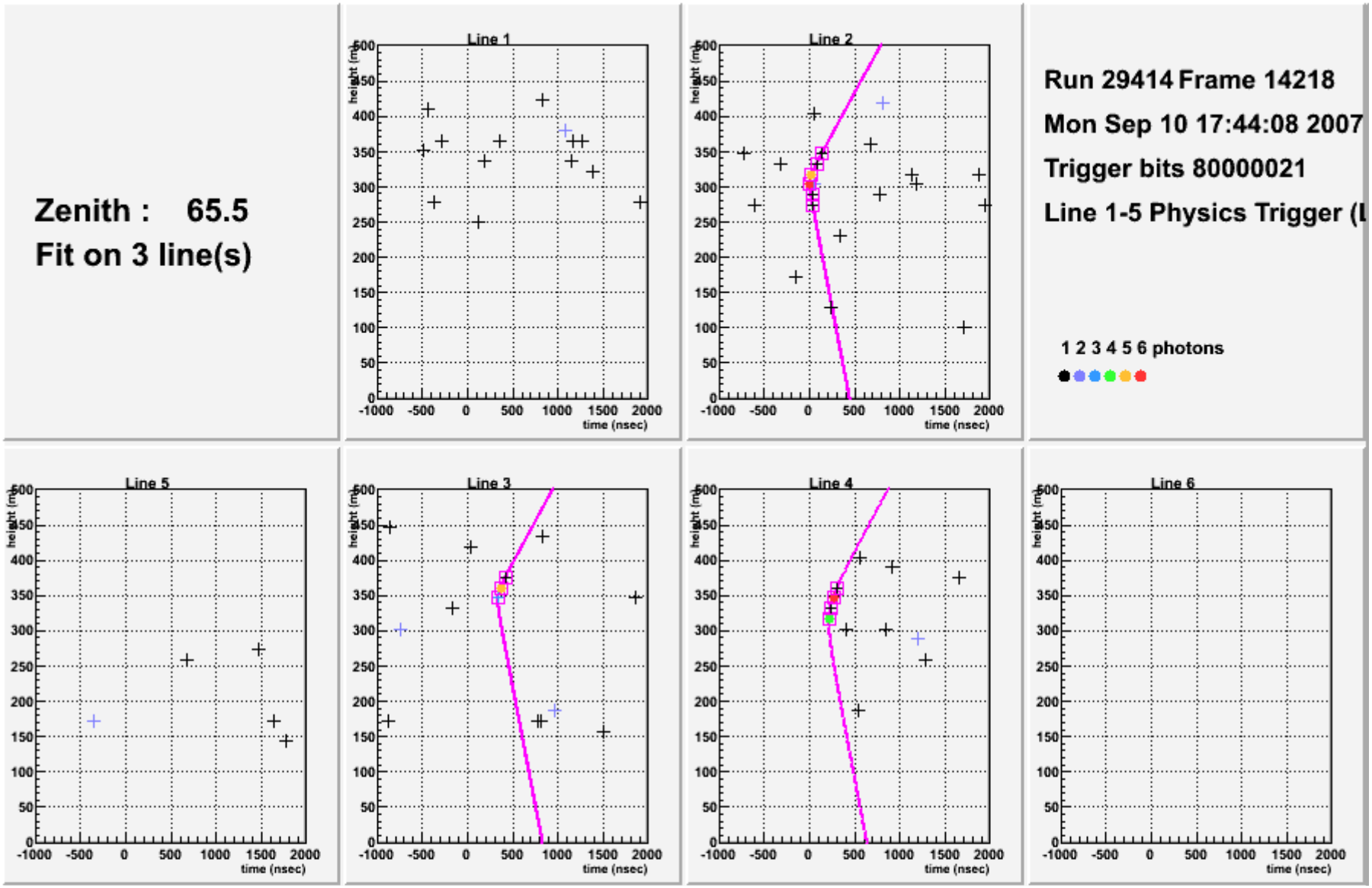
upward μ from CC ν_μ interactions

ANTARES, clean sample of ν_μ isolated (2008)



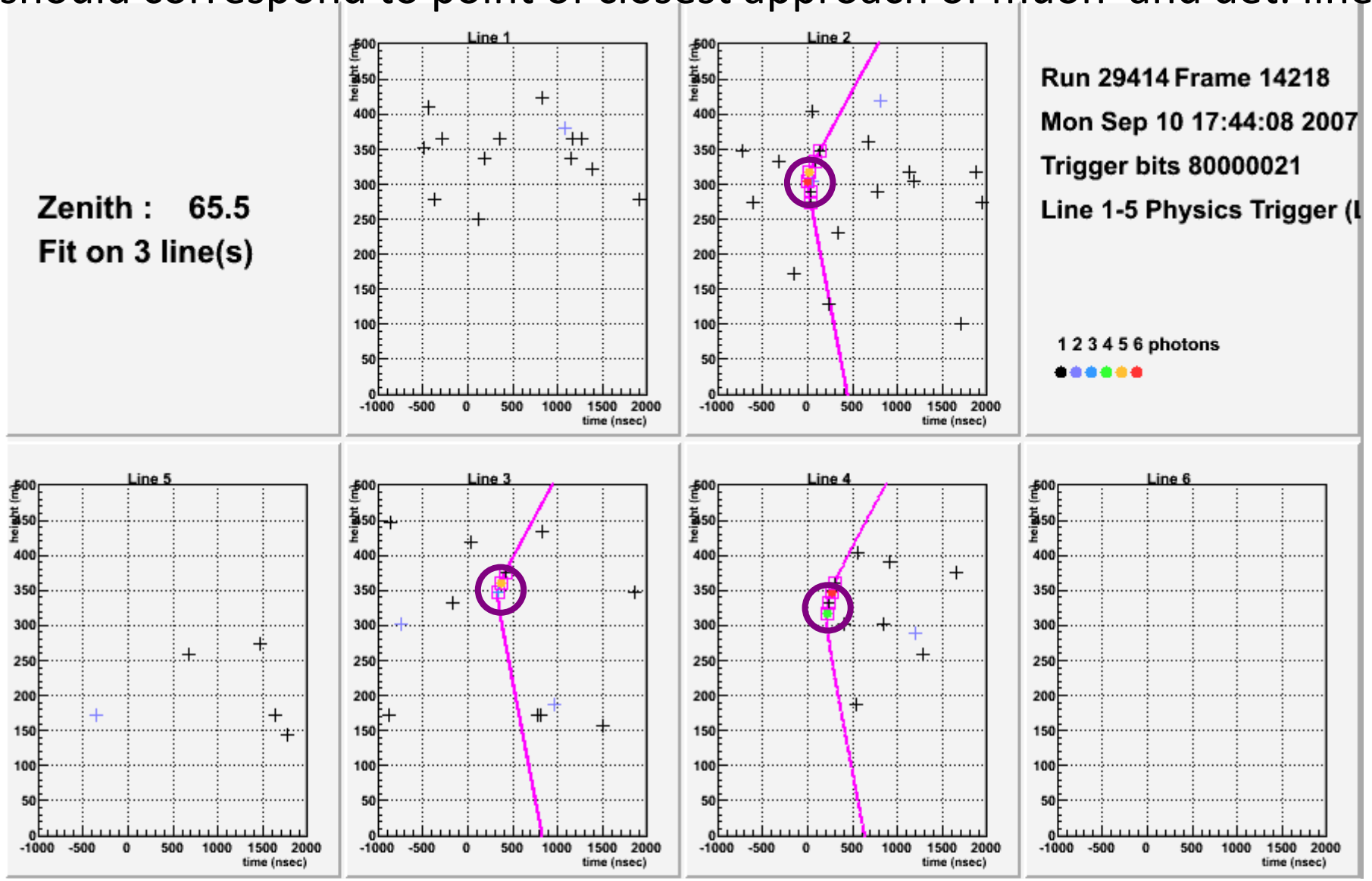

Time [ns]: -460.00
ANTARES
W
N
S
E

Reconstruction Concept



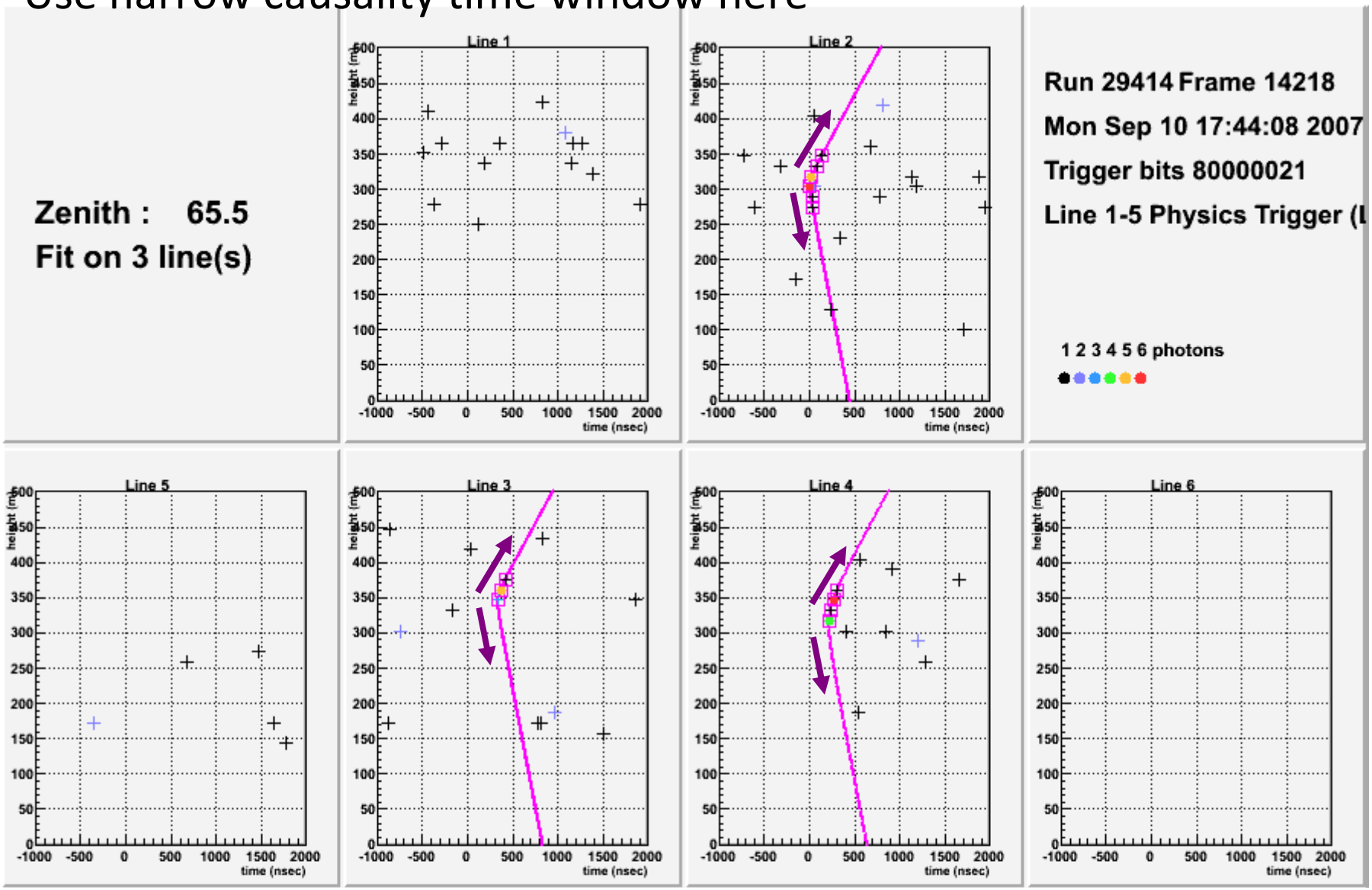
1. Select “hot spots” at each detector string

should correspond to point of closest approach of muon and det. line



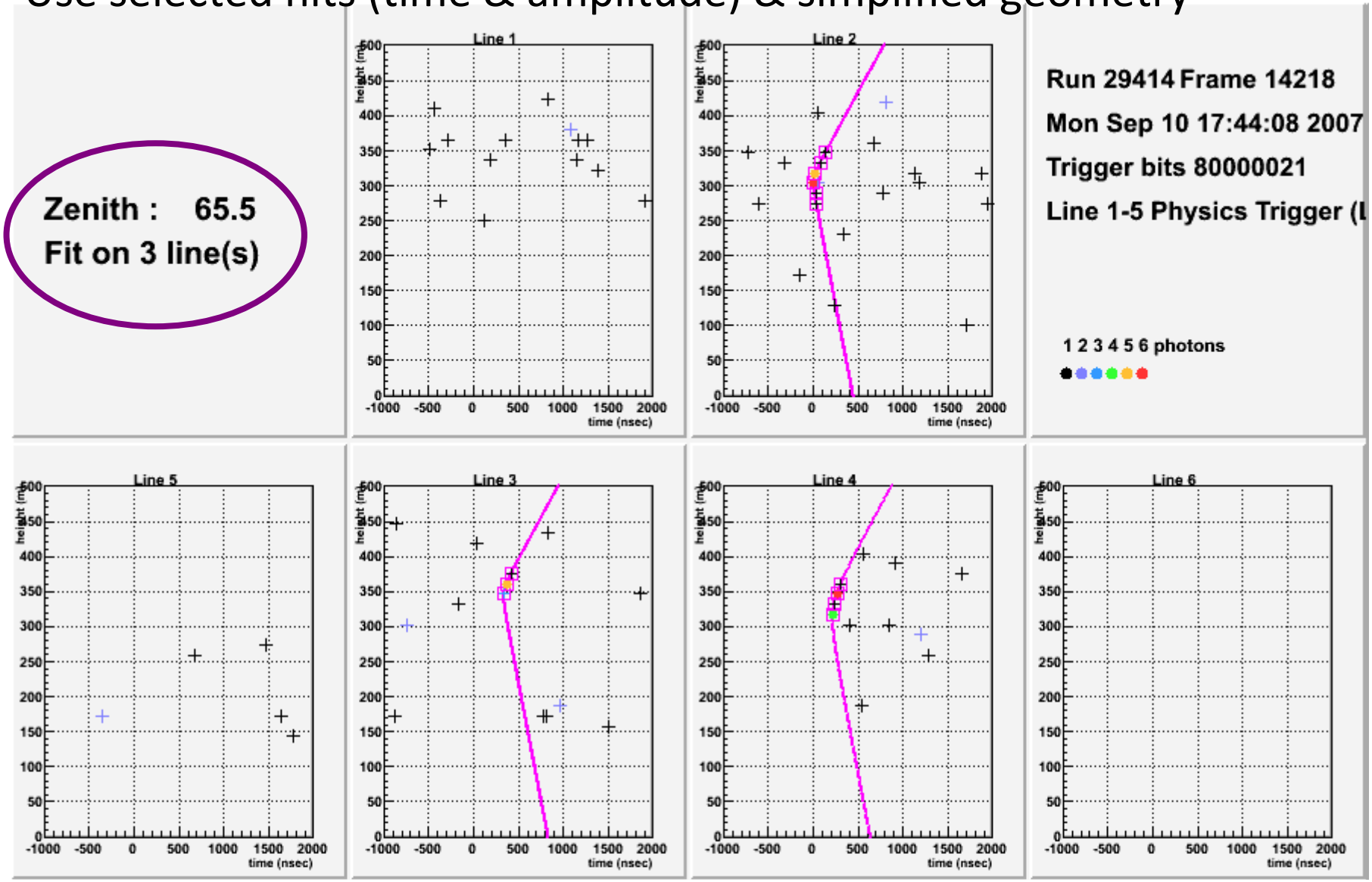
2. Add hits from adjacent storeys

Use narrow causality time window here



3. Perform track fit

Use selected hits (time & amplitude) & simplified geometry

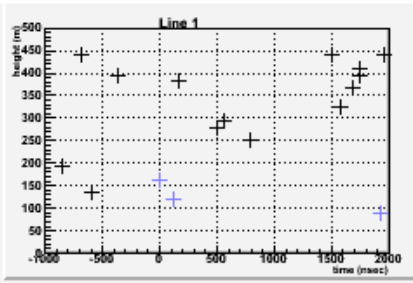


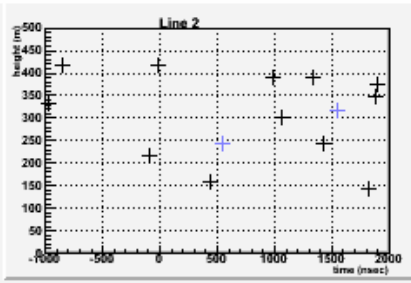
Clean low energy single-line event

Close to vertical

Zenith : 9.8
Fit on 1 line

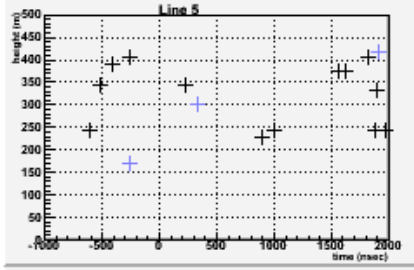
Good fit

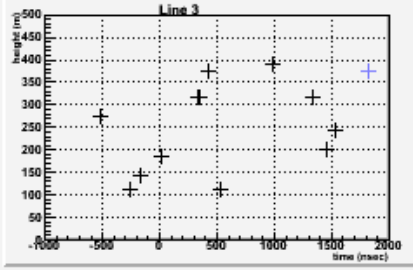


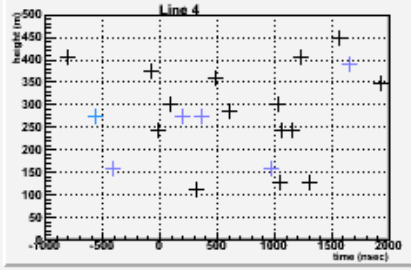


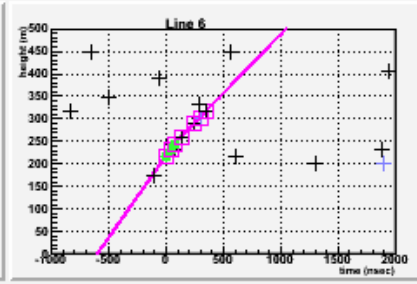
Run 59570 Frame 77125
Thu Sep 8 18:56:39 2011 UTC
Trigger bits 2000
Line 1-12 Physics Trigger
3N+2T3+K40+TS0 June2011

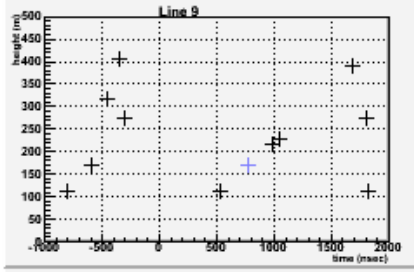
1 2 3 4 5 6 photons

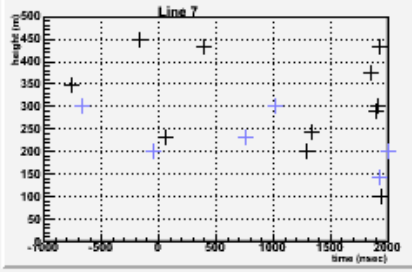


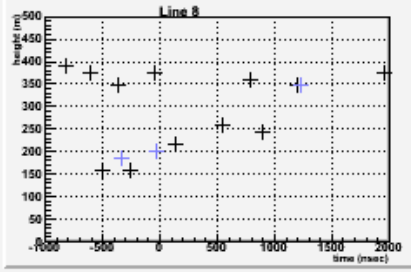


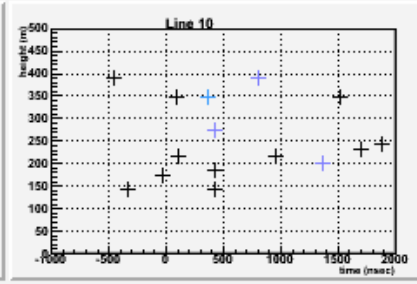


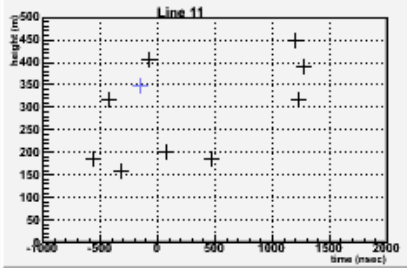


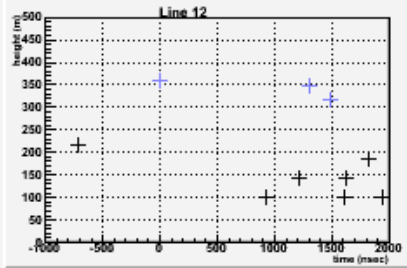






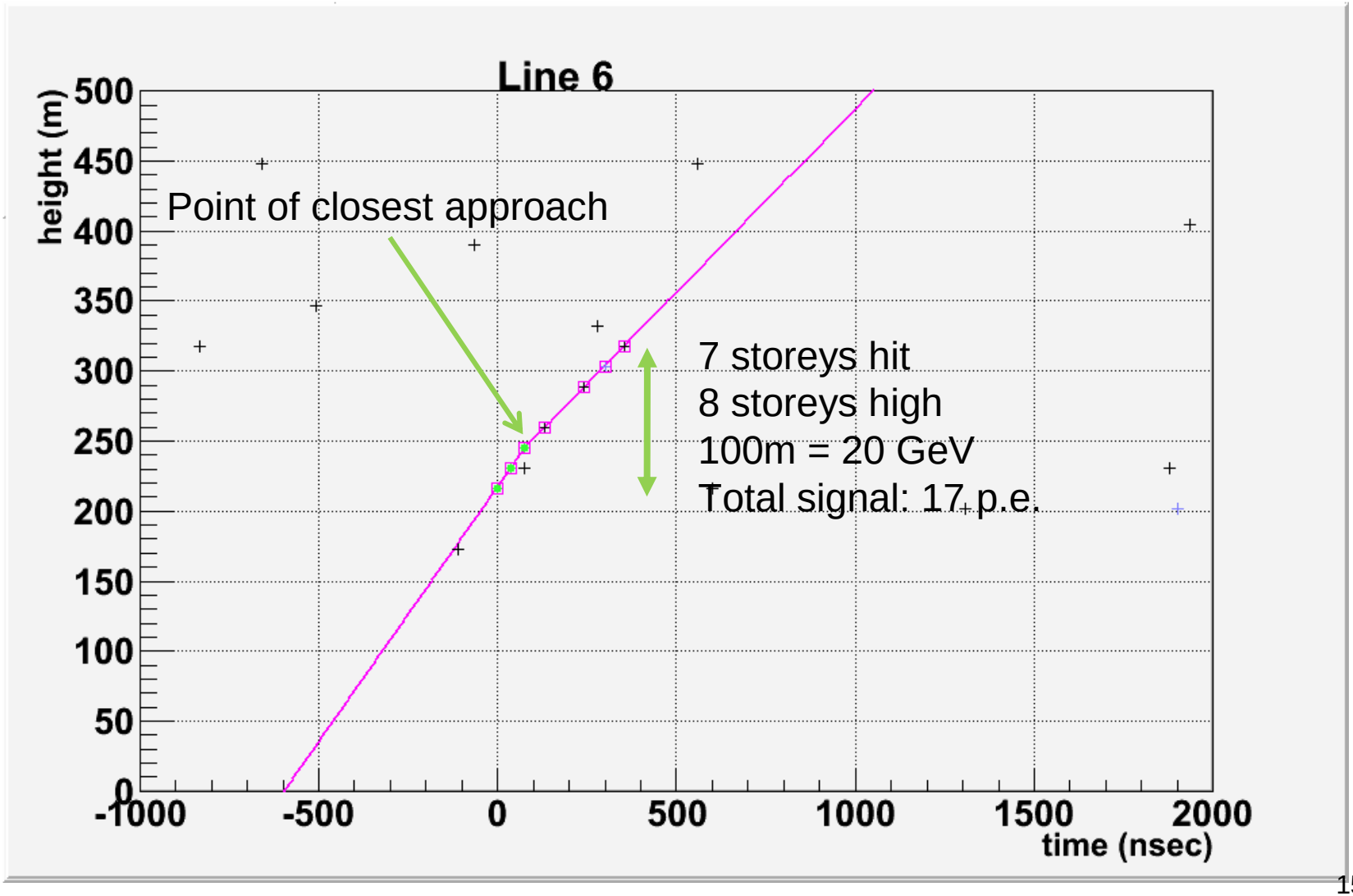






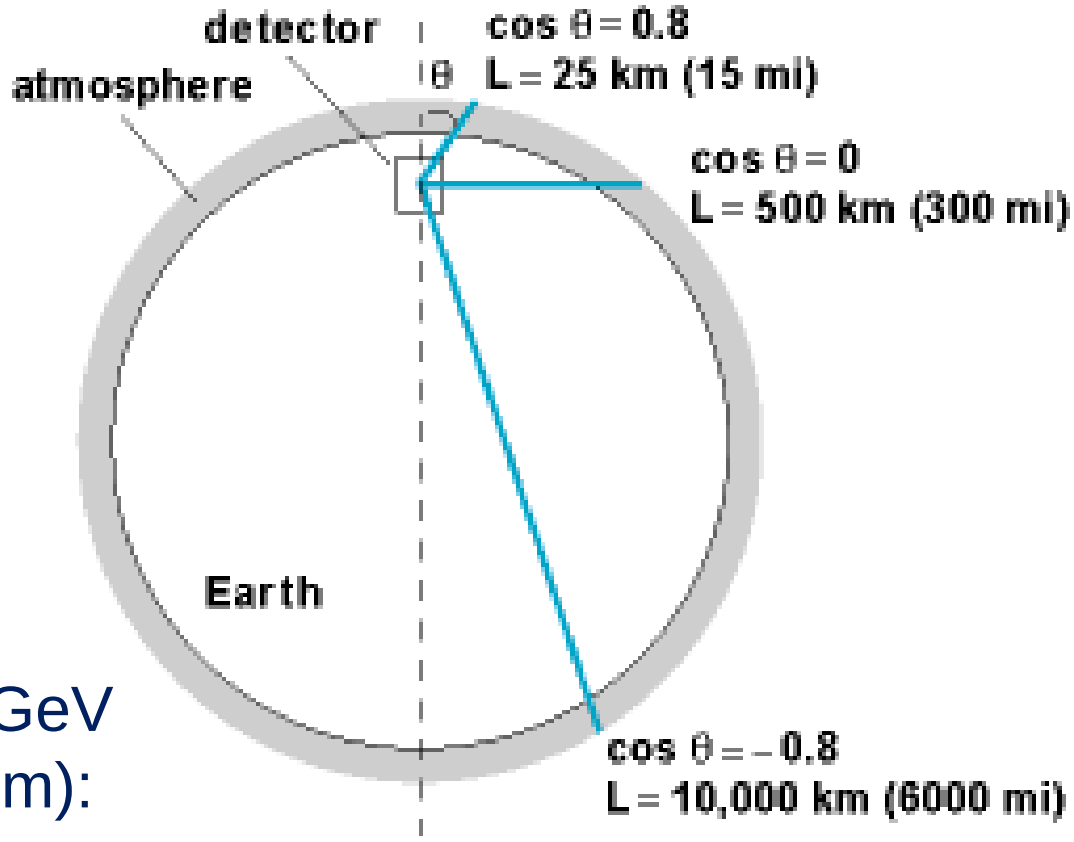
No correlated activity in any other line

Clean low energy single-line event



Oscillations with Atmospheric Neutrinos

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{16200\ \Delta m^2_{32} \cos\Theta}{E_\nu}\right)$$



For upgoing tracks

$L=2\ R_{Earth}\ \cos\Theta$

Oscillations maximal at 24 GeV for vertical neutrinos (~120m):

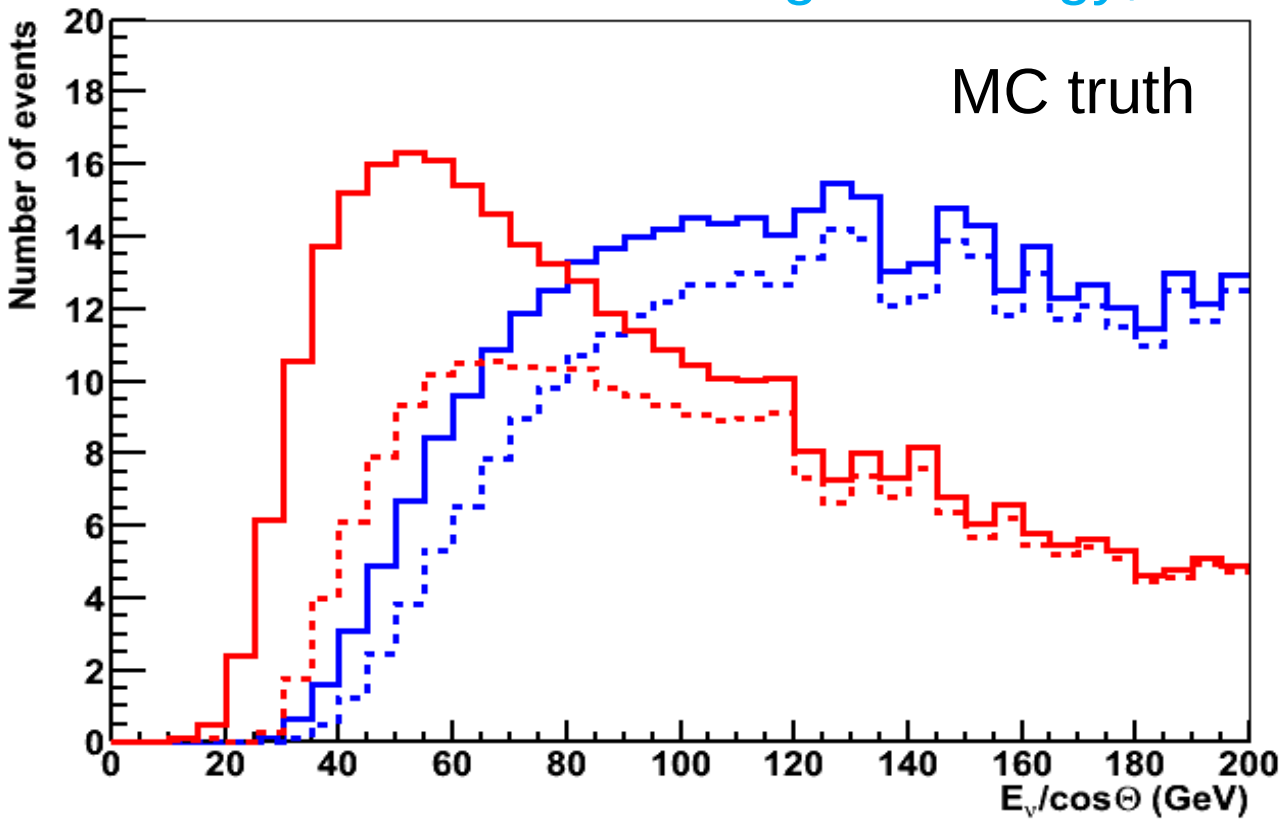
Oscillations with Atmospheric Neutrinos

Large effect

single-line events : low energy, vertical

Small effect

multi-line events : higher energy, isotropic



Solid

No oscillations

Dashed

Oscillations PDG

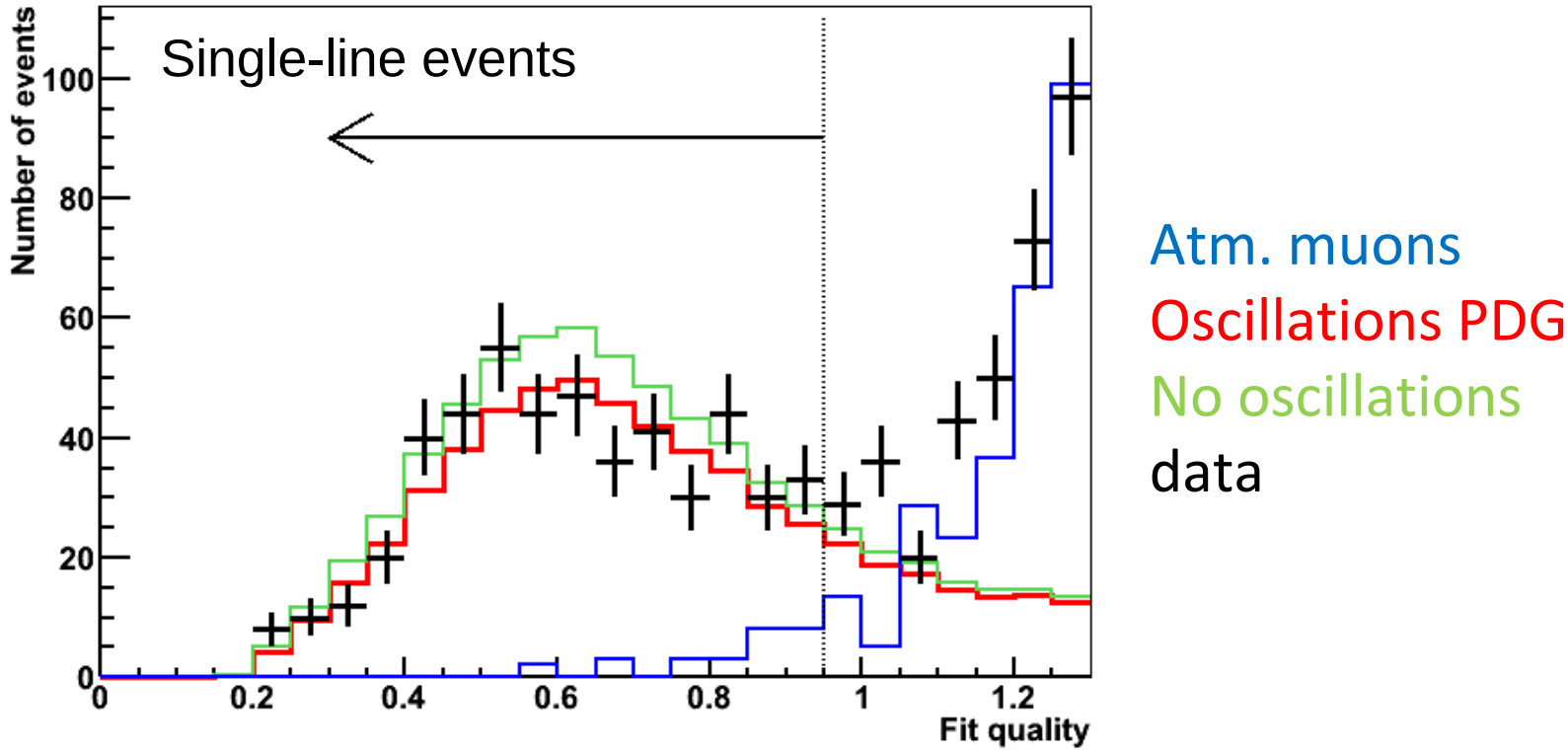
Neutrino Oscillations: Track Selection

Select pure sample of atmospheric neutrinos (<5% muon contamination)

Require upgoing tracks with more than 7 storeys hit

Special low energy fit– do not fit azimuth

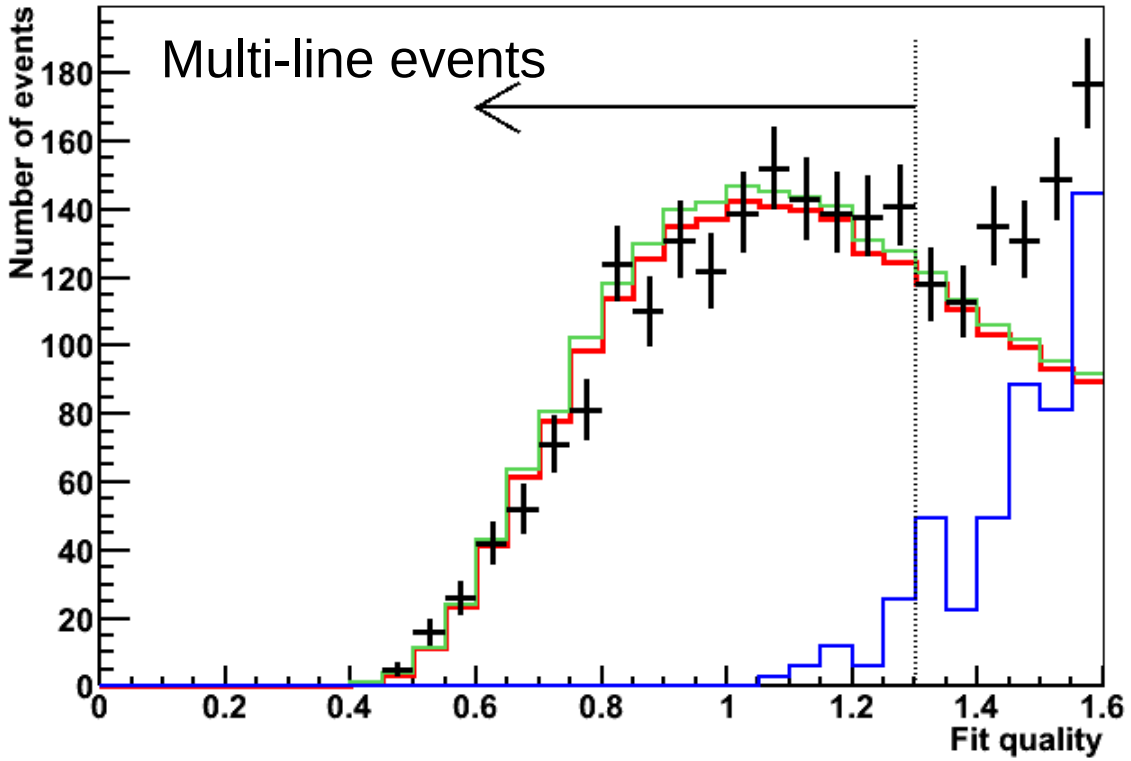
zenith angle resolution : 3 degrees



Neutrino Oscillations: Track Selection

Select pure sample of atmospheric neutrinos (<5% muon contamination)

- Require upgoing tracks with more than 5 storeys hit
- More than 9 degrees from horizon
- zenith resolution 0.8 degrees



Atm. muons

Oscillations PDG

No oscillations

data

Event Reduction

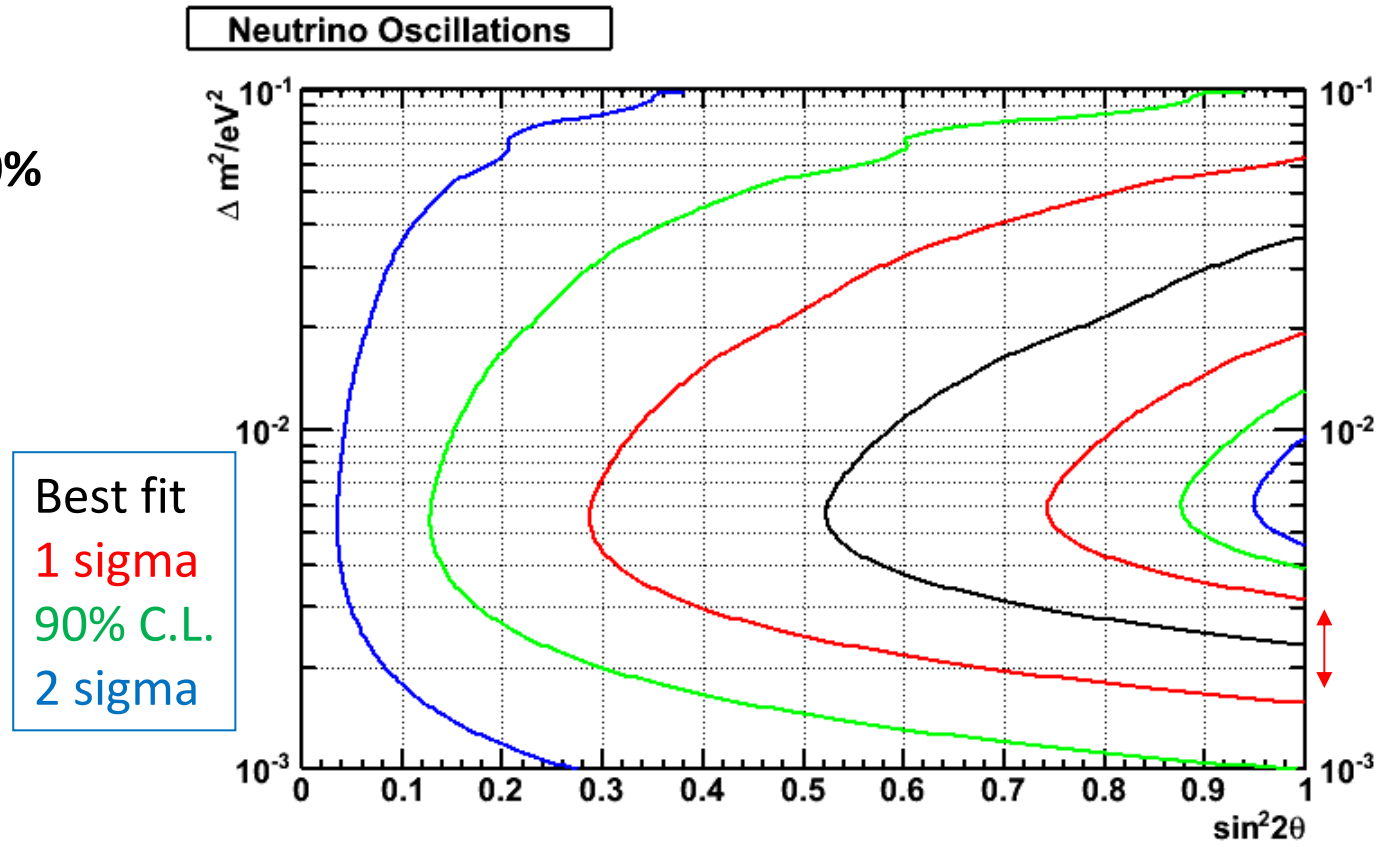
- 2007 to 2010 ; 863 days of active time
- Good agreement data/MC on all cut levels
- Efficiency w.r.t. trigger 23% (ML) and 7% (1L)
- Small but measurable reduction due to oscillations
- Effect more pronounced for single-line sample

	Multi-line			Single-line		
	data	ν MC	μ MC	data	ν MC	μ MC
Triggered	$1.42\ 10^8$	8755	$1.23\ 10^8$	$1.51\ 10^8$	8242	$1.51\ 10^8$
Nstorey cut	$1.33\ 10^8$	8248	$1.18\ 10^8$	$4.44\ 10^7$	1260	$3.03\ 10^7$
Upward	$2.74\ 10^6$	5512	$1.84\ 10^6$	$7.97\ 10^5$	1242	$2.93\ 10^7$
Fit quality	1632±40	1971±6 1910±6	52±12	494±22	651±3 557±3	28±9

Preliminary contour from event ratio

Data R = 494/1632 = 0.303+/-0.015
MC Non-Osc: R = 651/1971 = 0.330
Non-oscillation hypothesis at 2.1 sigma from measured ratio

δ N1/N2 : 5.0%
δ Δm² : 37%

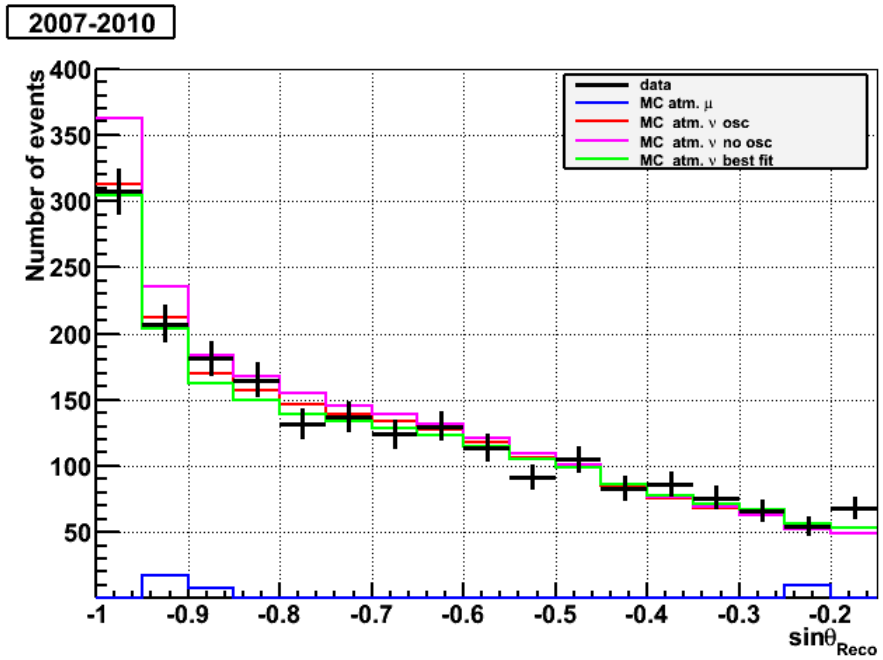


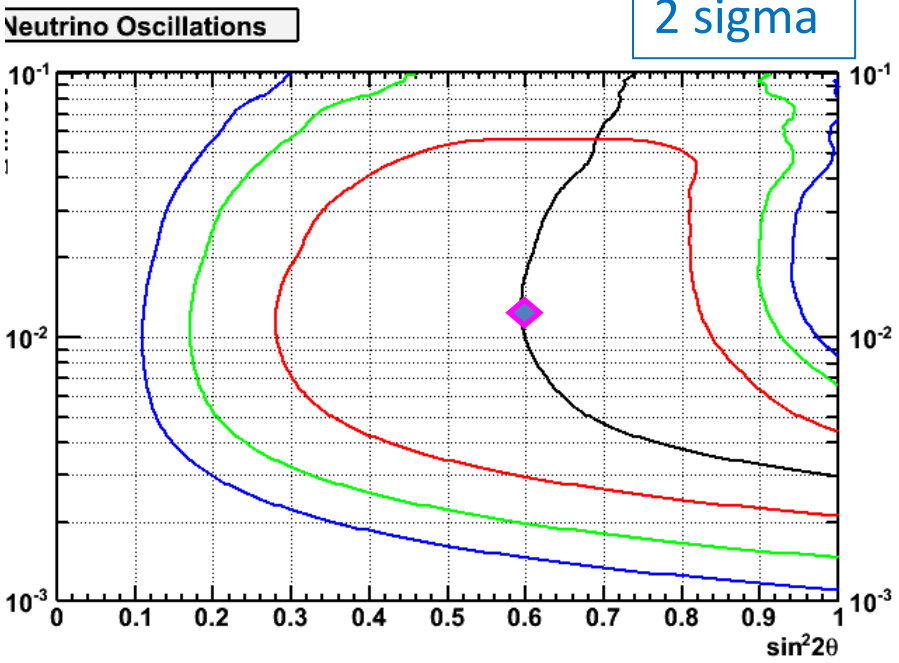
Zenith angle only

- Effect of oscillation in first two bins
- close to vertical

- $\Delta m^2=(3.0\text{-}0.9\text{+}1.4)\ 10^{-3}\ eV^2$

Best fit
1 sigma
90% C.L.
2 sigma



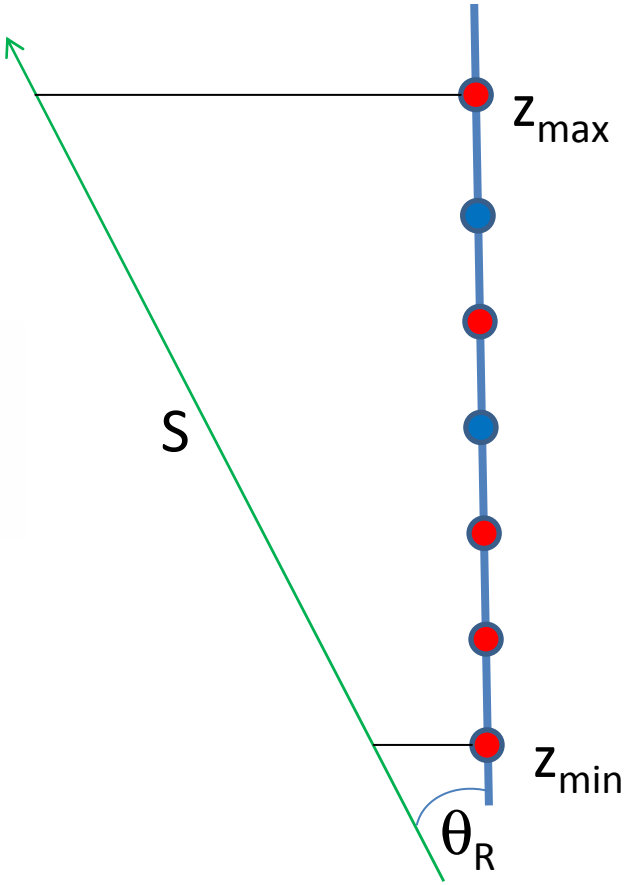


Energy reconstruction

- Derived from approximative muon range

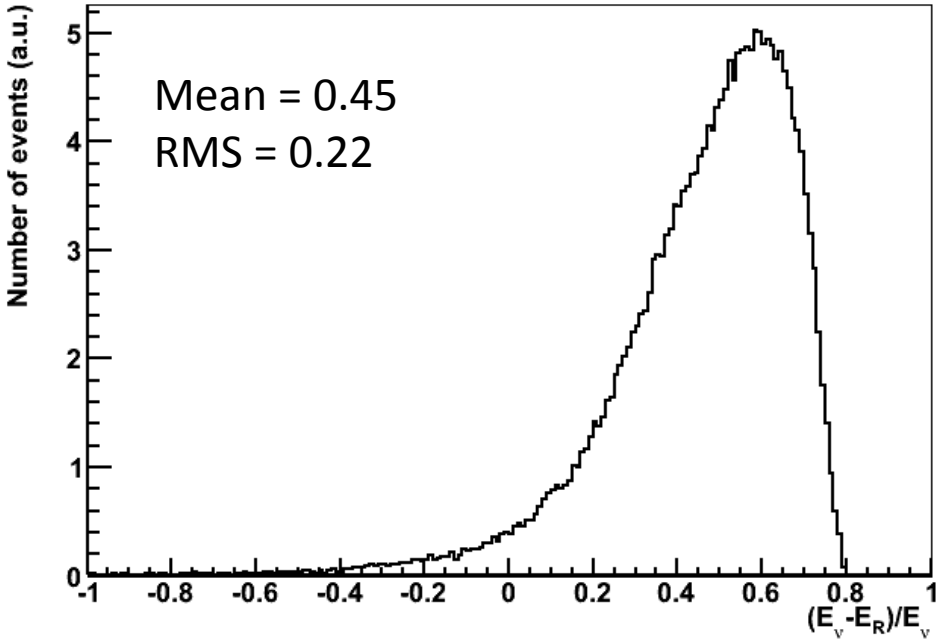
$$S = (z_{max} - z_{min}) / \cos \Theta_R .$$

$$E_R = S \cdot 0.2\ \mathrm{GeV/m}.$$



Energy Resolution

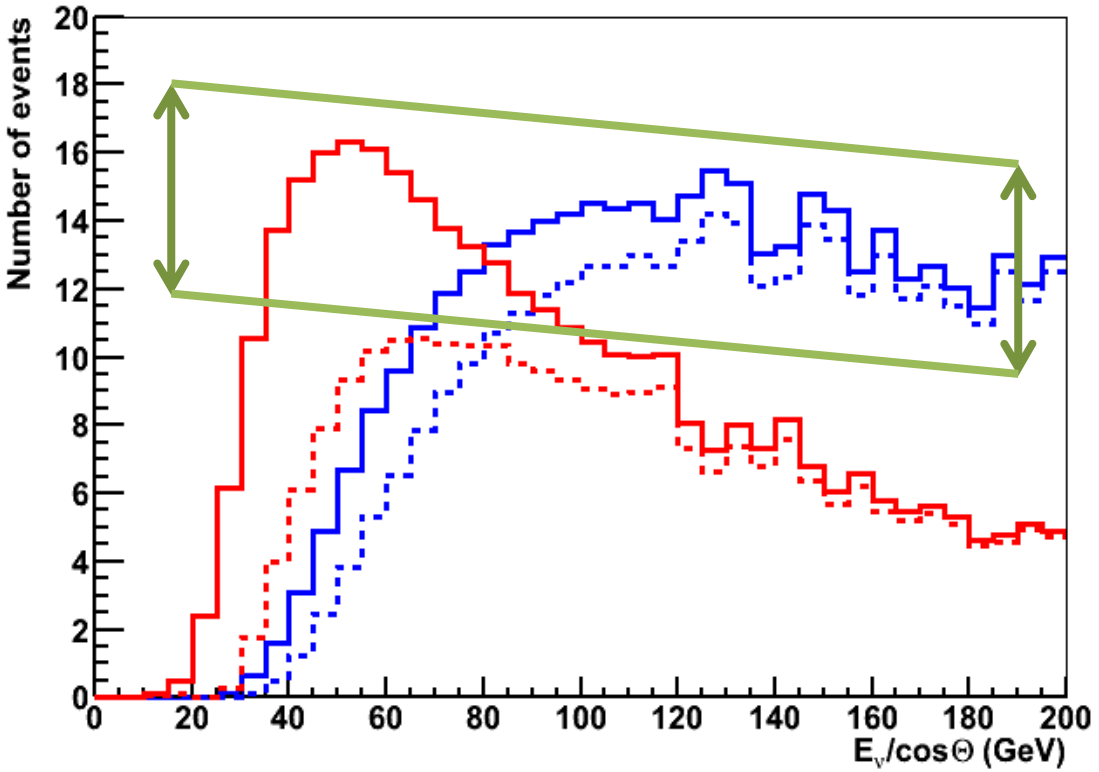
- Zenith angle resolution (median, neutrino)
  - Multiline events : 0.8˚
  - Single line events : 3.0˚
- Energy resolution for E < 100 GeV :



Systematics

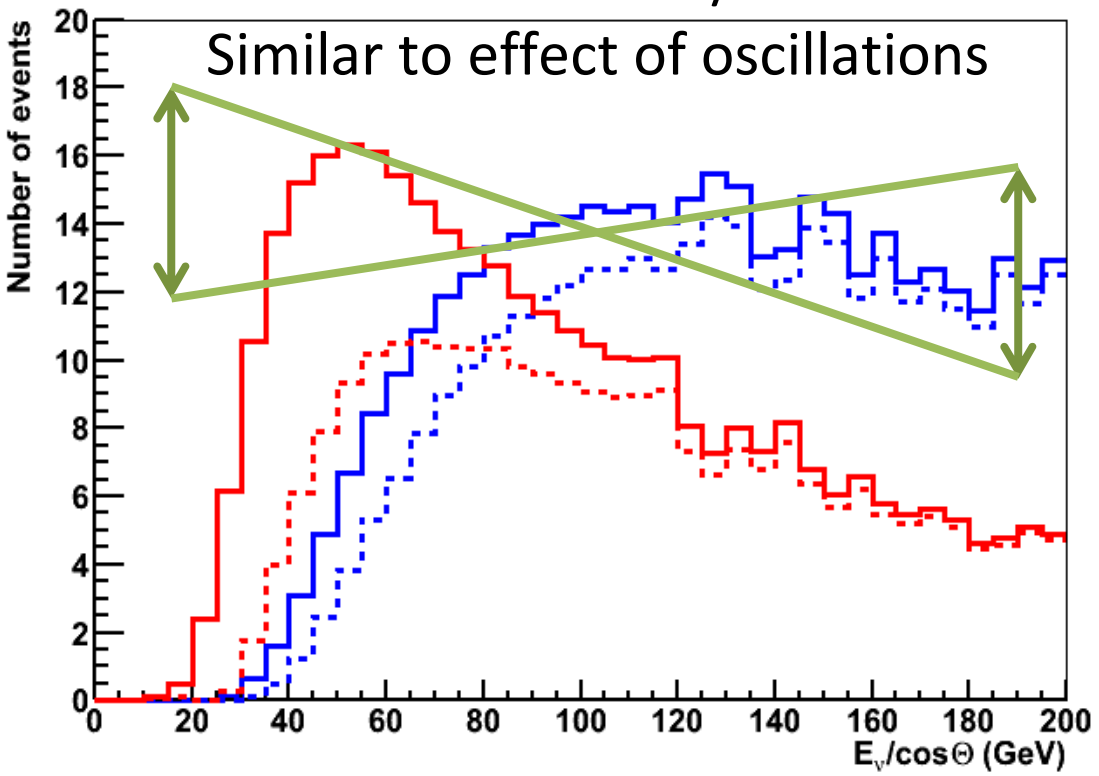
Total Normalisation

Affects 1L and ML in the same way



Systematics

Changes of histogram shape
Affects 1L and ML differently
Modifies ratio R=1L/ML
Similar to effect of oscillations



Systematics

$$\chi^2 = \sum_i \left[N_i - (1+\epsilon) MC_i^{1L} - (1+\eta) MC_i^{ML} \right]^2 / \sigma_i^2 + (\epsilon - \eta)^2 / \sigma_R^2 .$$

Absolute normalisation not constrained

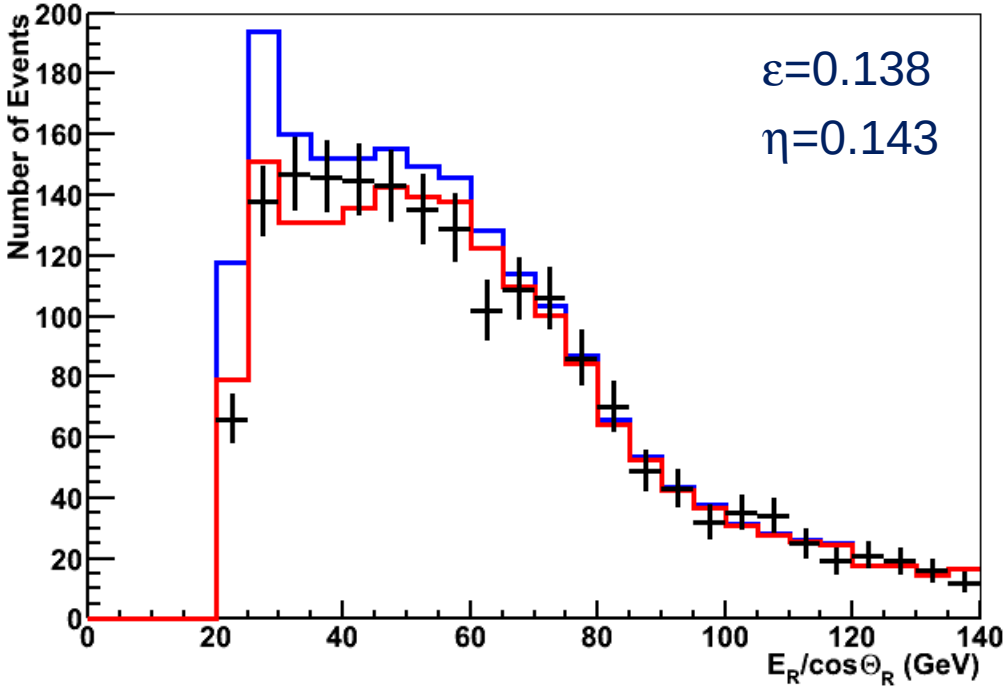
Individual pull factor for both event samples

- Absorption length: ±10%
- Detector efficiency: ±10%
- Spectral index of ν flux: ±0.03
- OM angular acceptance
- Cut values varied → analysis stability

Results in σ_R=5% - relative pull between samples

Final distribution - E/cosθ

- Cutoff at 20 GeV
- E_ν > 20 GeV corresponds to 8 storey
- Effect of oscillations in 7-8 leftmost bins



No oscillations

Best fit

data

Result

No oscillation

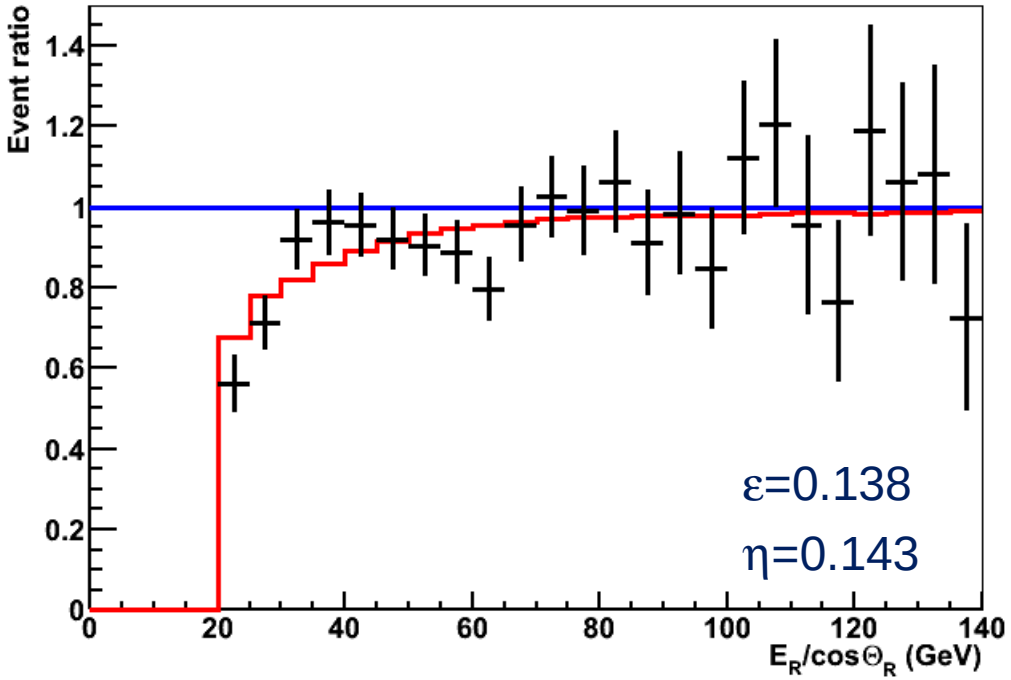
χ^2/NDF = 40/24 (2.1%)

Best fit

χ^2/NDF = 17.1/21

$\Delta m^2 = 3.1\ 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.00$



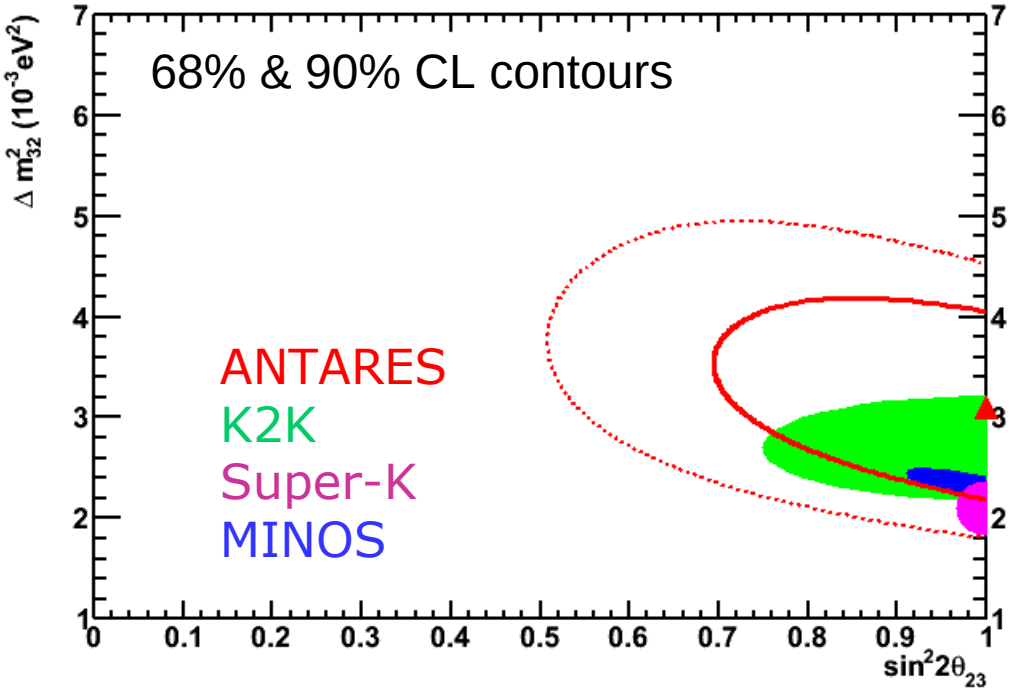
No oscillations

Best fit

data

Result

First measurement of oscillation parameters with high energy neutrino telescope



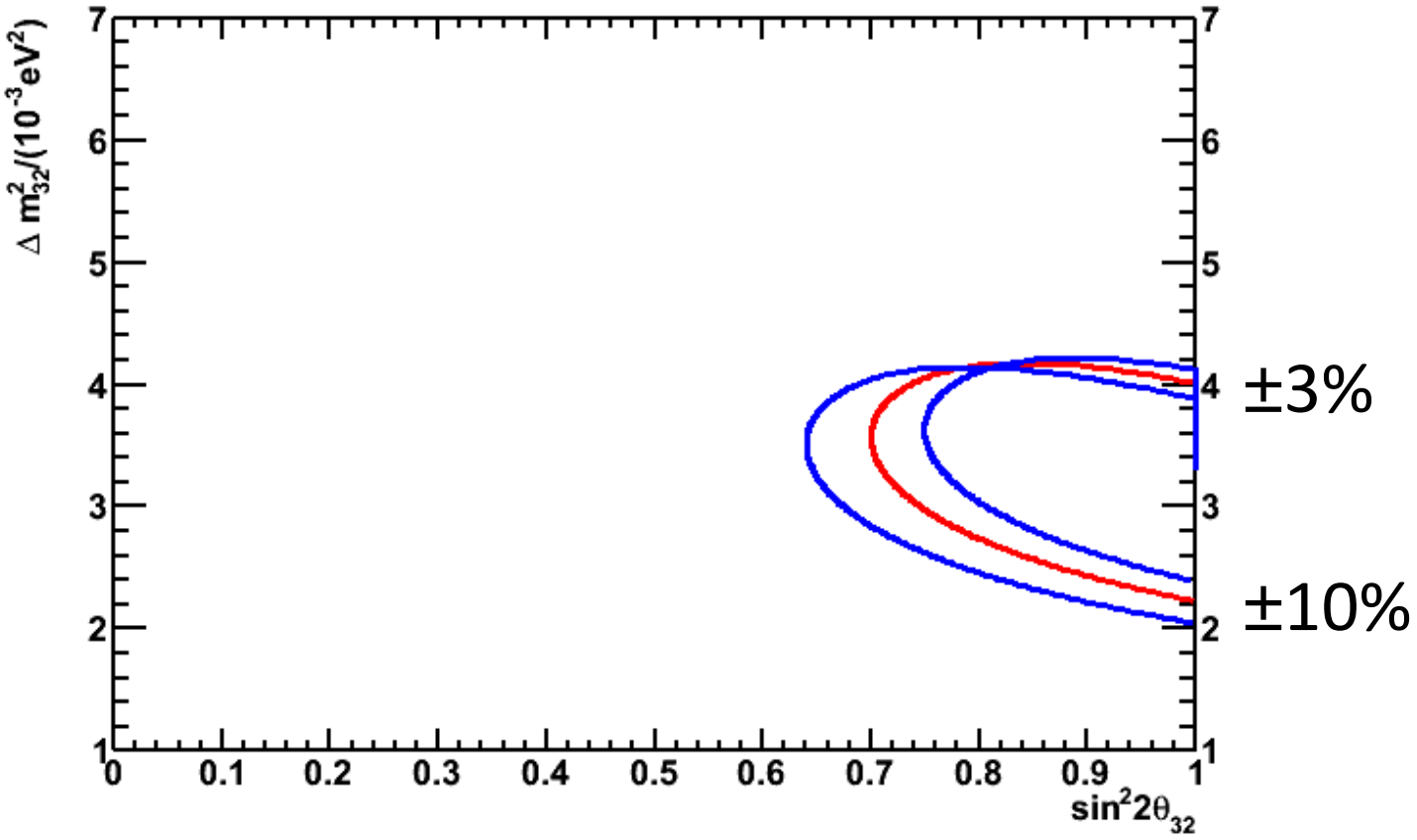
Assuming maximal mixing: $\Delta m^2 = (3.1 \pm 0.9)\ 10^{-3}$ eV^2

Published in PLB 714 (2012) 224

Backup

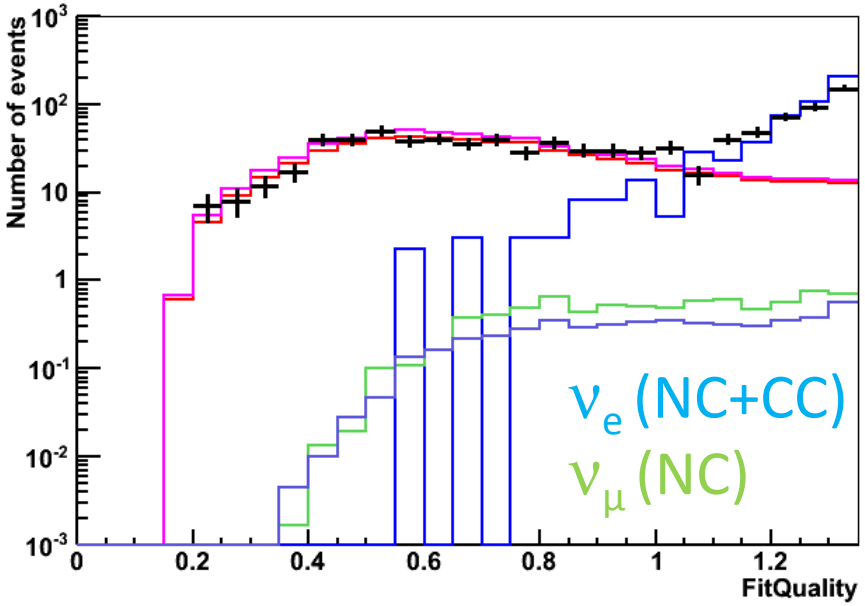
Sanity check – Contour Stability

- Change of spectral index of 0.03



Contribution from cascades

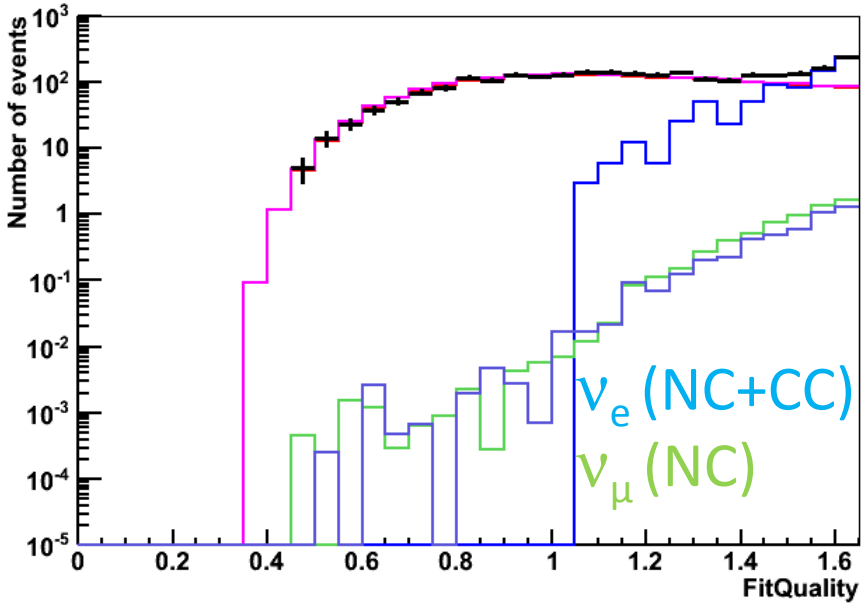
Single line sample



Contribution : 6 events

Reminder Atm muons : 28

Multi line sample



Contribution : 1 events

Reminder Atm muons : 52

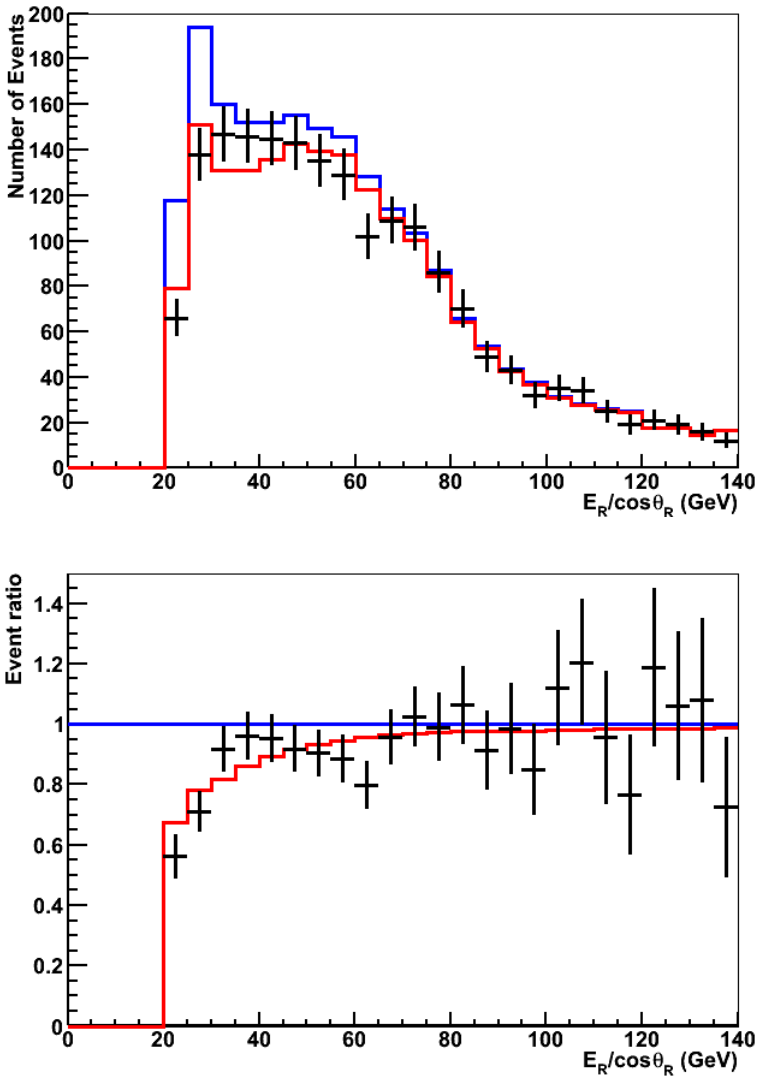
Results

Shown in plot:

Best Fit

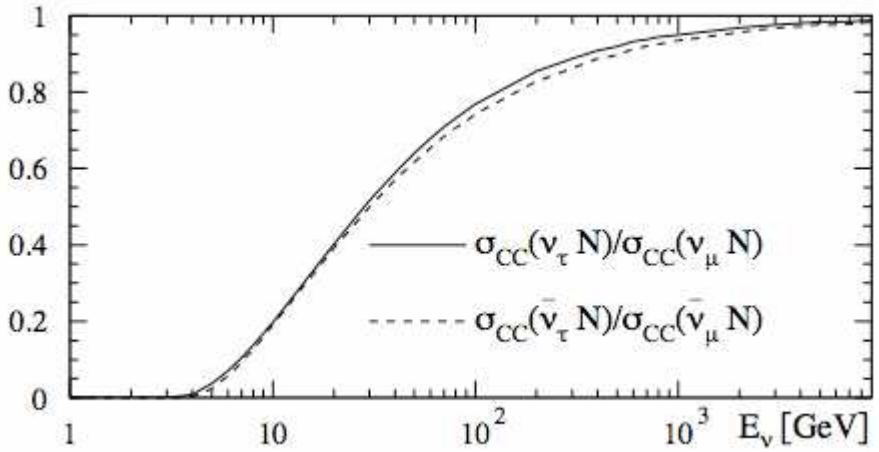
No oscillations

	Best Fit	PDG	No osc.	No osc.
χ^2	17.1/21	18.4/21	31.1/23	40.0/24
Δm^2	3.06	2.43	---	---
$\sin^2 2\theta$	1.00	1.00	0.00	0.00
ε	-0.138	-0.180	-0.302	-0.225
η	-0.142	-0.162	-0.196	-0.225
ΔR	0.4%	2.2%	11.5%	0.0



Tau Neutrino appearance ?

- Oscillations reduce data sample by 155 events (1L : 94 ; ML : 61)
- ν_τ CC cross section lower (threshold)
- 83% cascade like events
  - Cascade-like events effectively suppressed (<1 event remaining)
- 17% branching ratio into muons
  - Muon energy lower compared to ν_μ
  - <5 events (3%)



Lowering energy threshold ?

- Nstorey>7 : hard cut to suppress muons
- tchi2<0.95
- Nstorey == 7 might be usable in future analyses