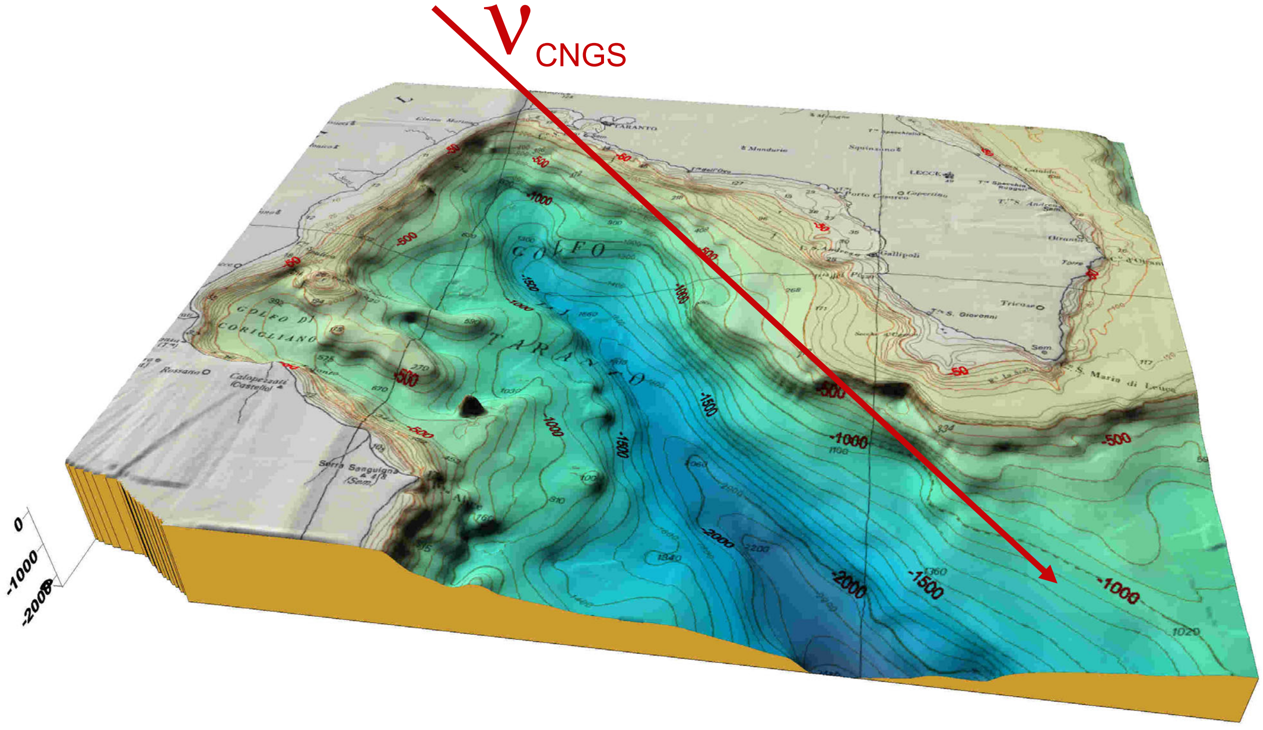
C2GT

CERN Neutrinos to the Gulf of Taranto

An experiment to measure θ_{13} with the CNGS beam off axis and a deep underwater Cherenkov detector in the Gulf of Taranto



Overview

- Exploit alignment of prolonged CNGS beam with deep sea trench in Gulf of Taranto
- Direct search for ν_μ–ν_e oscillations from ν_e appearance in off-axis ‘narrow-band’ beam of 0.8 GeV
- Simple underwater Cherenkov detector
- Moveable experiment allows
  - direct demonstration of oscillation pattern and flavour transition
  - precise measurements of $\sin^2\theta_{23}$, $\Delta m_{23}{}^2$ and search for non-zero $\sin^2\theta_{13}$

The off-axis beam concept

- At ‘magic angle’ $1/\gamma_\pi$, neutrino energy is independent of parent pion energy
- Wide range of pion momenta generates high-intensity ‘narrow band’ component
  - Essential to discriminate CC ν_e events against abundant NC background
- Neutrinos from Kaon decays diluted over large phase space

Off-axis beam kinematics:

Longitudinal and transverse momentum of ν_μ in lab system, from parent pion with γ, β:

$$p_L = \gamma\left(p^* \cos\Theta^* + \beta p^*\right)$$

$$p_T = p^* \sin\Theta^*$$

where $p^* = 0.03$ GeV is ν momentum and and Θ^* is polar angle in pion rest frame, w.r.t. pion direction.

Neutrino emission polar angle in lab frame:

$$\Theta = \frac{R}{L} = \frac{1}{\gamma}\frac{\sin\Theta^*}{1+\cos\Theta^*}, \quad \text{i.e.} \quad \Theta = \frac{1}{\gamma} \text{ at } \Theta^* = 90°$$

(L: distance from target, R: distance from beam center)

Neutrino energy versus R:

$$E_\nu(R) = \frac{2\gamma p^*}{1+(\gamma\frac{R}{L})^2}, \quad \text{i.e. at } \Theta = \frac{1}{\gamma}, \quad E_\nu = \tfrac{1}{2}E_\nu^{\max}$$

At $\Theta = 1/\gamma$, the neutrino energy is independent of parent pion energy to first order ("magic angle"):

$$\frac{\partial E_\nu}{\partial \gamma} = 0$$

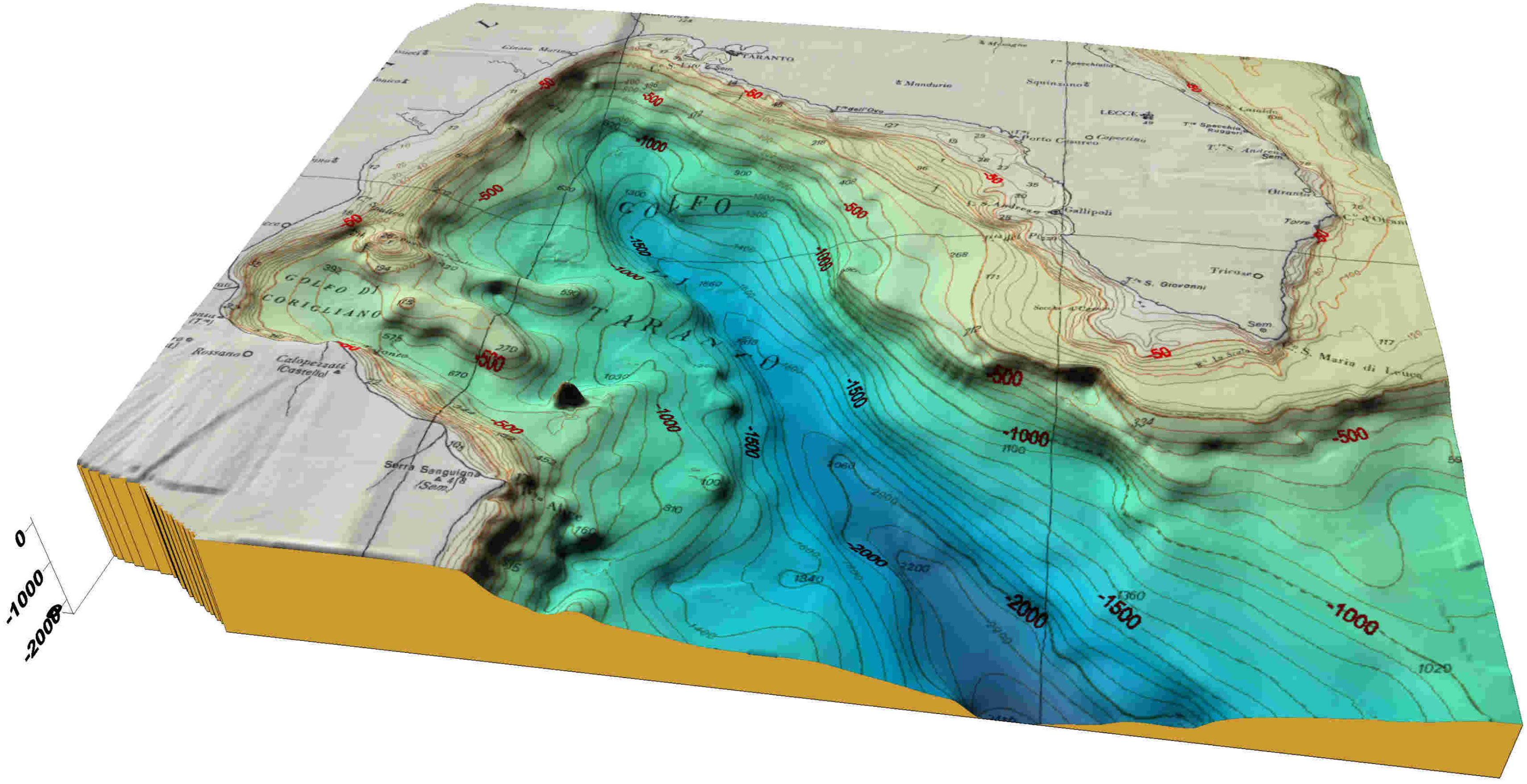
Neutrino flux per pion decay and per unit area:

$$\Phi_\nu(R) = \frac{\gamma^2}{\pi L^2[1+(\gamma\frac{R}{L})^2]^2}, \quad \text{i.e. at } \Theta = \frac{1}{\gamma}, \quad \Phi_\nu = \tfrac{1}{4}\Phi_\nu^{\max}$$

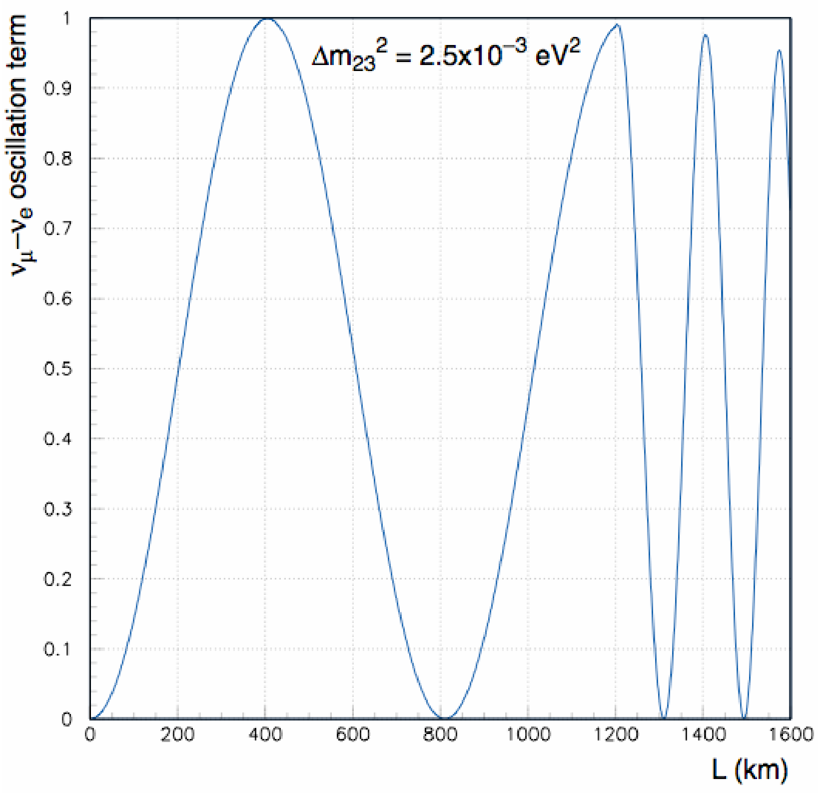
CNGS beam to Gulf of Taranto

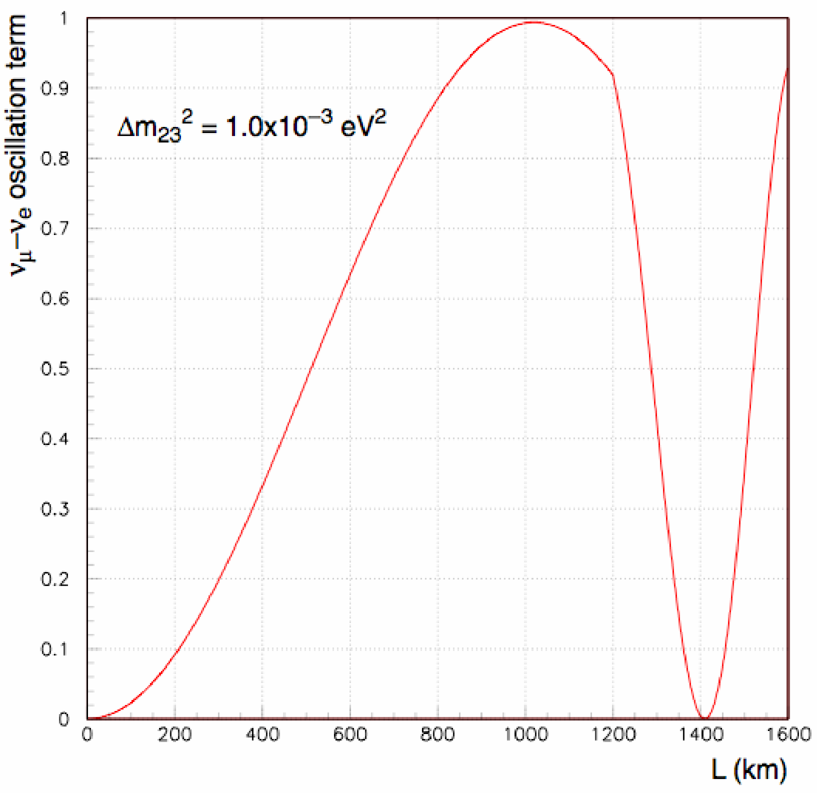
- At $L = 1200$ km, beam axis is 45 km above sea level:
- $\gamma = 27.1$
- $E_\nu = 0.81$ GeV
- Requires pion energies centered at $E_\pi = 3.8$ GeV
- Underwater trench allows for moveable detector at different baselines ($L > 1100$) km and sufficient depth (> 1000 m)

The GoT underwater trench



Oscillation patterns

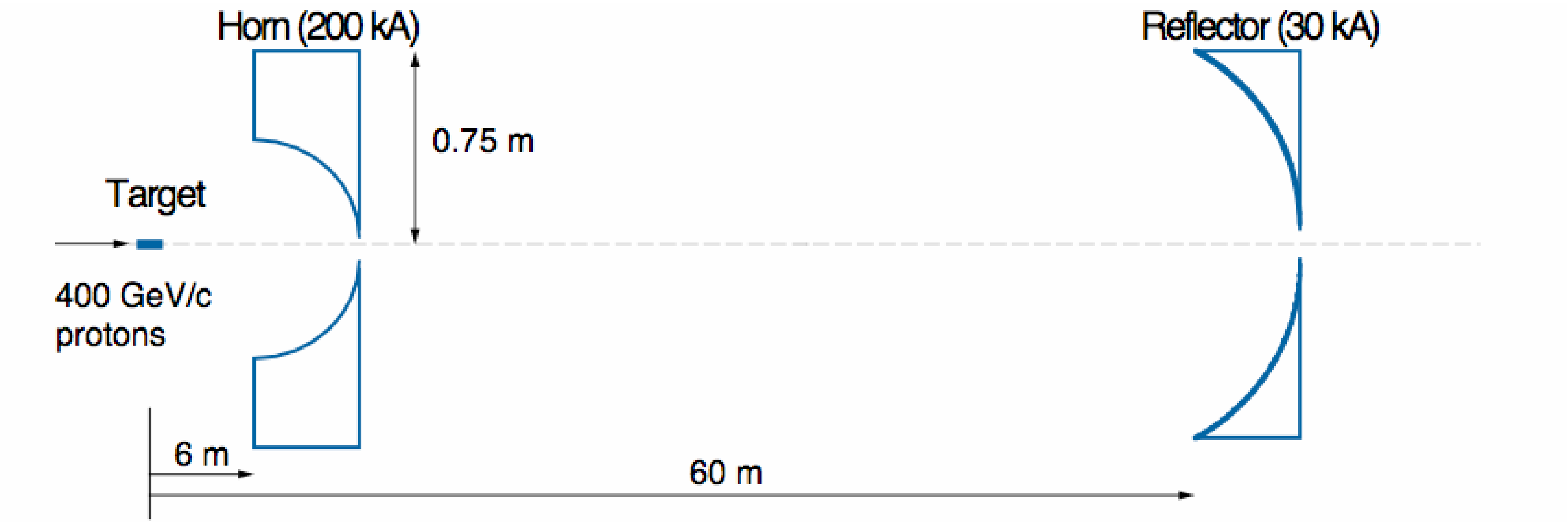




Moving the detector over a range of 200-500 km allows for a detailed measurement of the oscillation pattern for a wide range of Δm_{23}^2

Redesign target & horn area

- Optimise for $E_\pi = 3.8$ GeV
- 3λ graphite target
- Fits into CNGS decay tunnel
  - but: tunnel too long…
- No modifications to primary beam

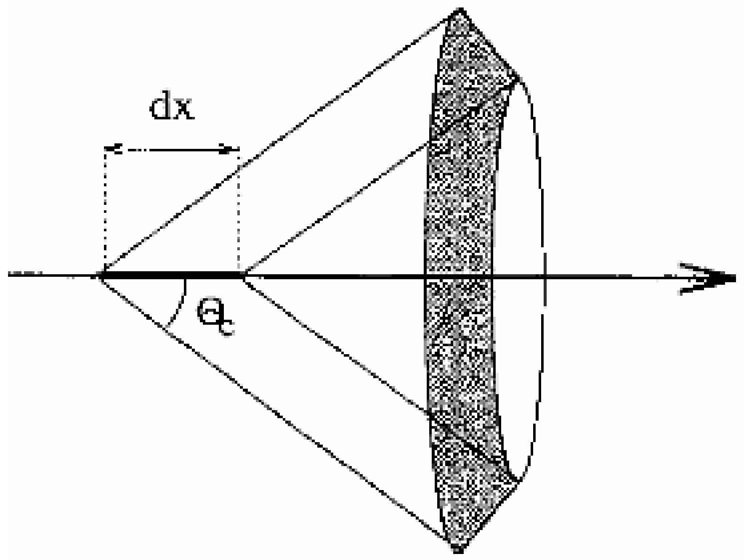


Beam parameters (1000 m below sea level)

Baseline (km) (Distance from CERN)	1200	1400	1600
Radial distance from CNGS axis (km)	45	75	110
γ of parent pion	27.1	19.0	14.6
Neutrino energy from pion decay (GeV)	0.81	0.57	0.44
Neutrino flux per decay pion ($10^{-15}cm^{-2}$)	4.1	1.5	0.7
Parent pion momentum (GeV)	3.8	2.7	2.0
Neutrino energy from Kaon decay	3.4	2.4	1.8

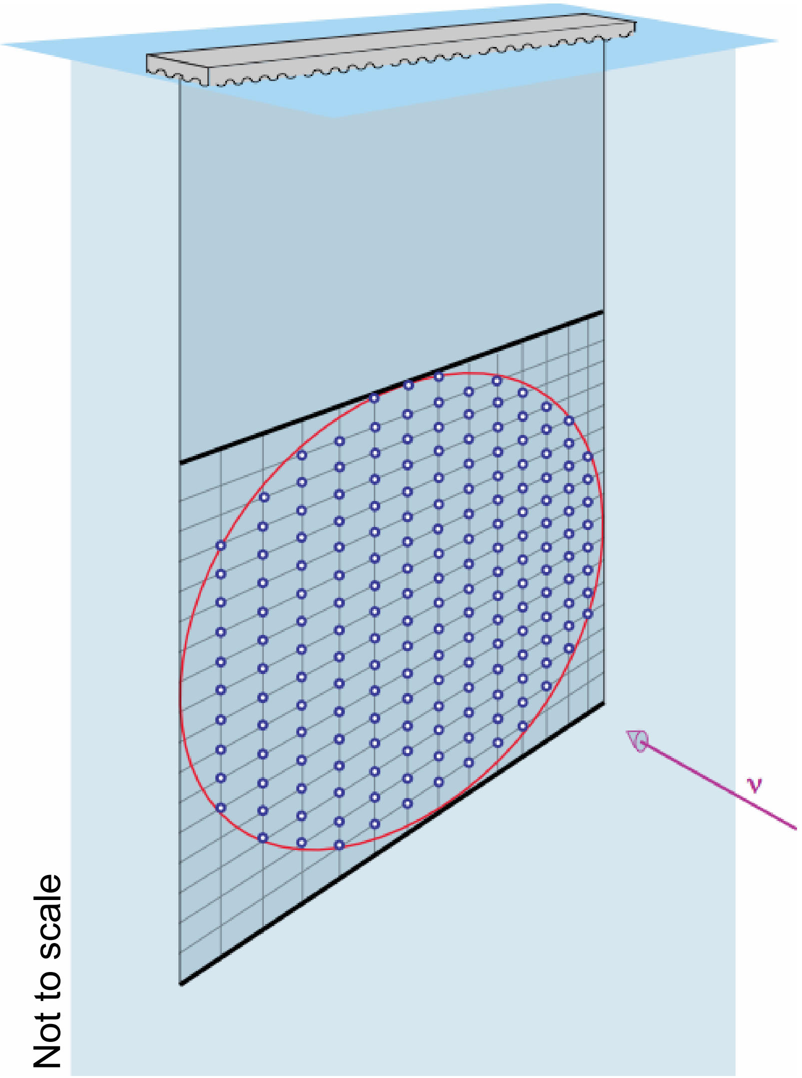
Detection principle

- Muon and electron neutrinos are detected through quasielastic CC reactions in sea water
- Muons and electrons radiate Cherenkov light over a distance dx < 3.5 m
- Electron tracks more 'fuzzy' than muons – translates into more fuzzy ring pattern in detector

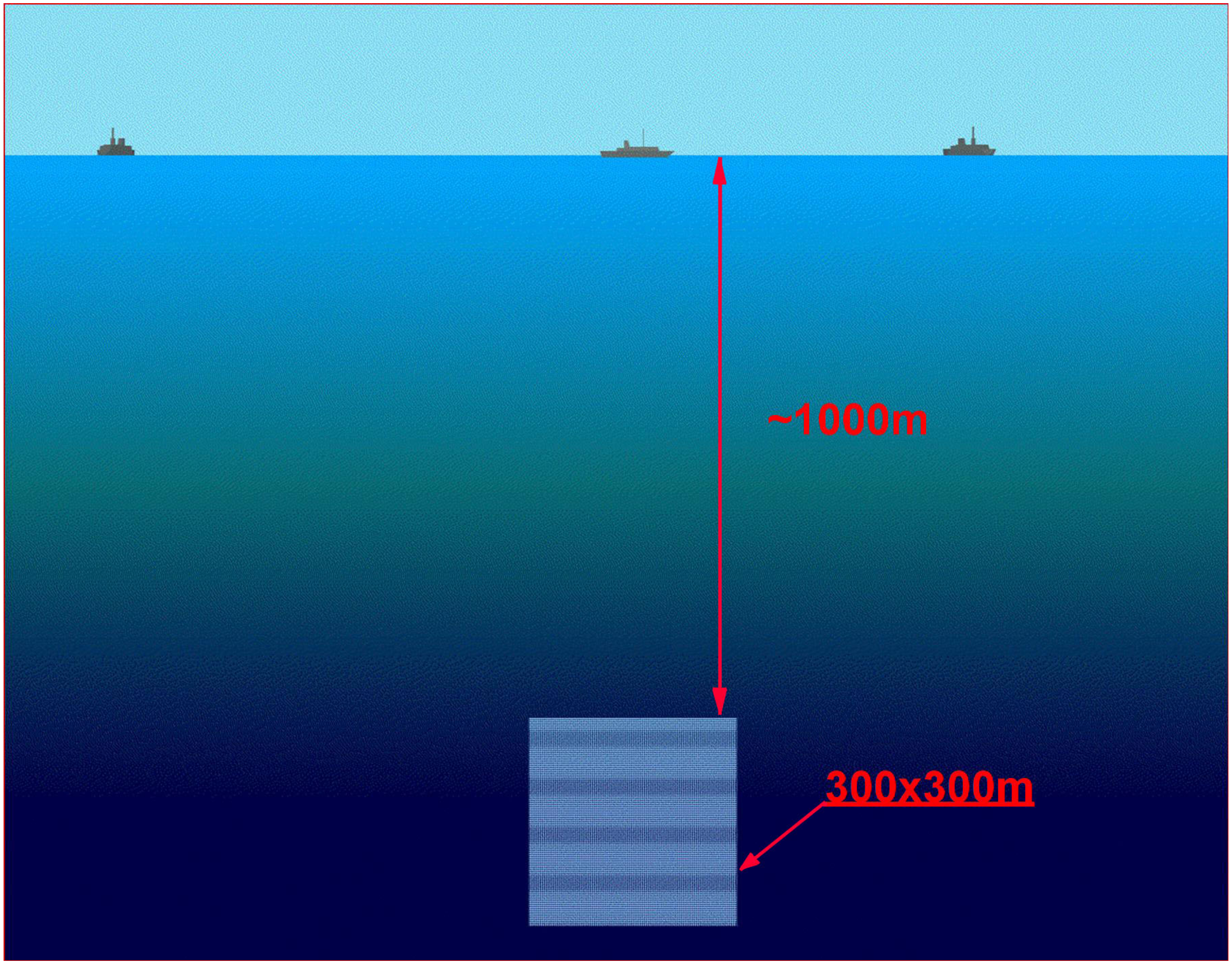


Conceptual detector

- Disc of r ≈ 150 m perpendicular to neutrino beam
- Suspended 1000 m below sea level
  - shield daylight
  - good transparency
- 3x3 m^2 cell size
- 8000 light detection elements
- 2 Mt fiducial mass for λ_{abs} = 50 m – to be verified

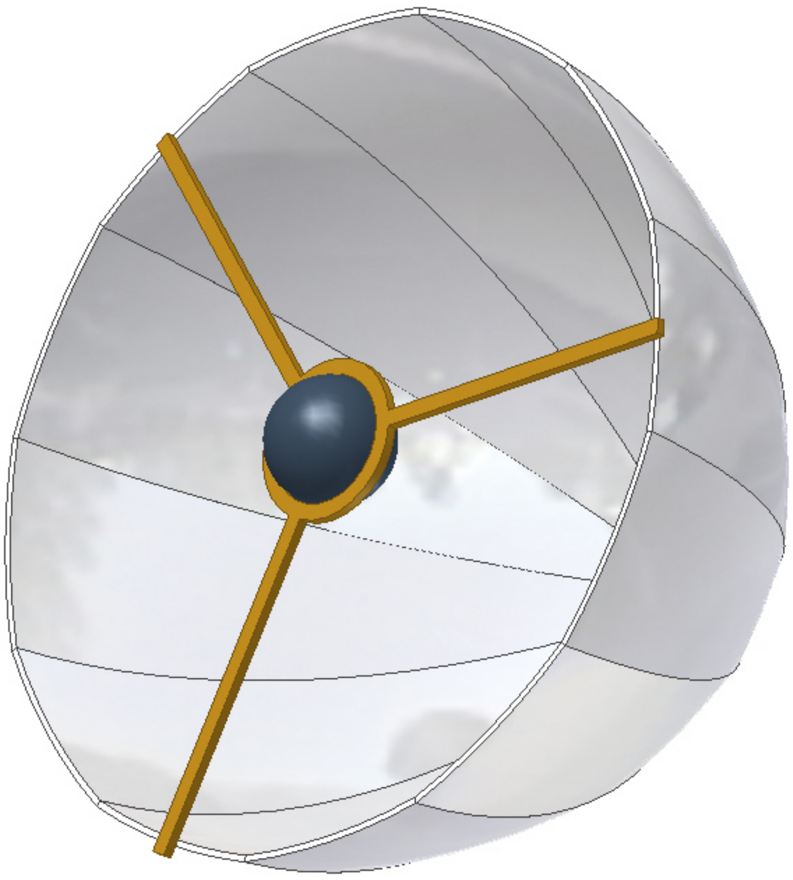


C2GT at operating depth



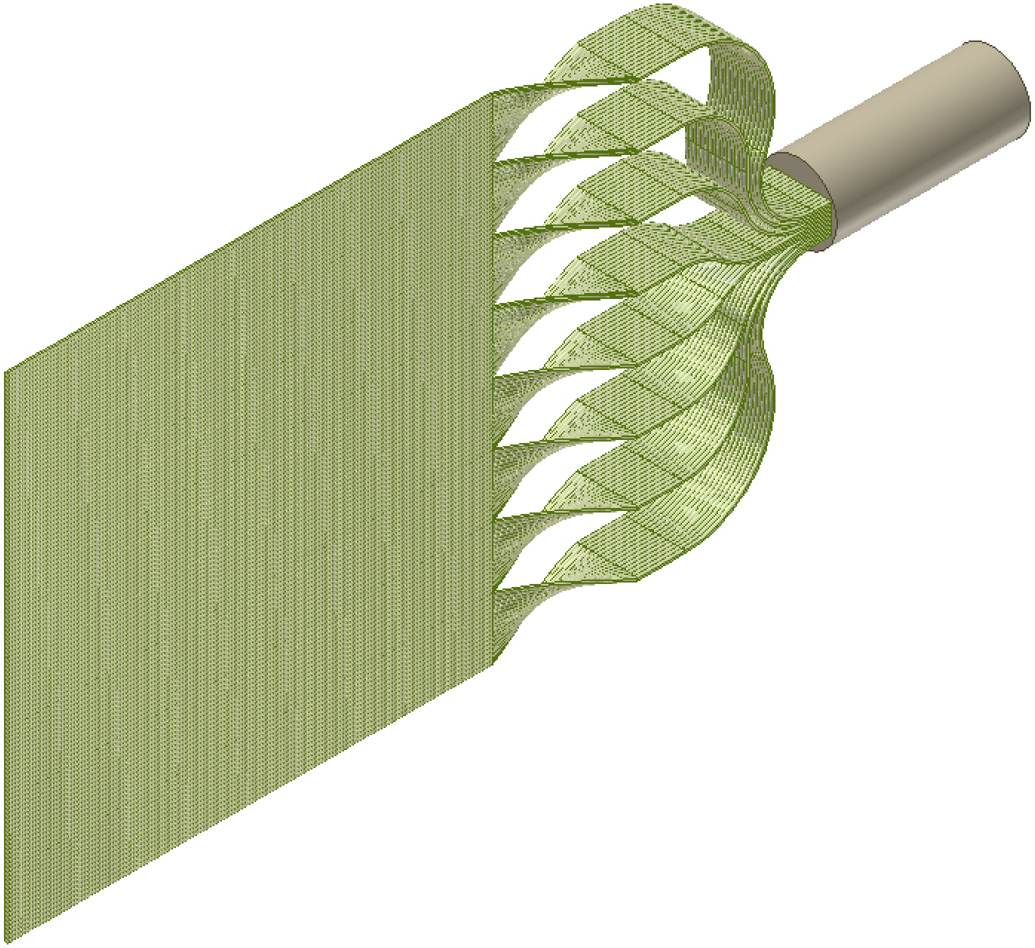
Detector optics

- Present design study concentrates on conventional phototubes with discrete mirror system
- PM diameter vs. mirror shape and number of segments requires careful optimisation
- Perfectly axisymmetric mirror?



Detector optics

Alternative: Wavelength-shifting fibres

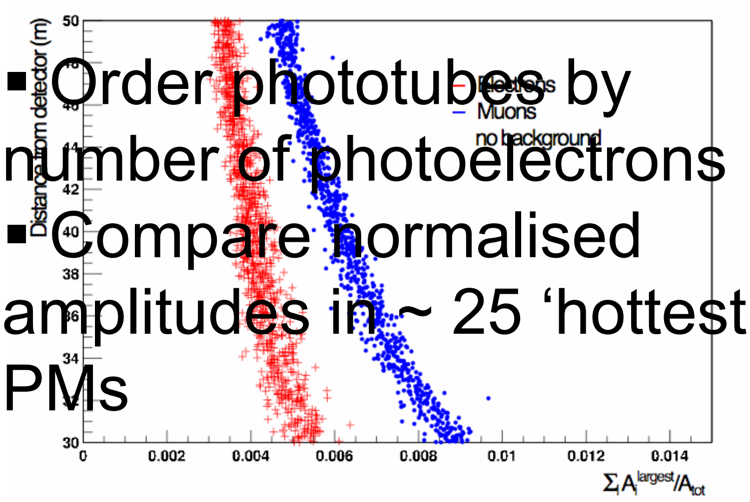


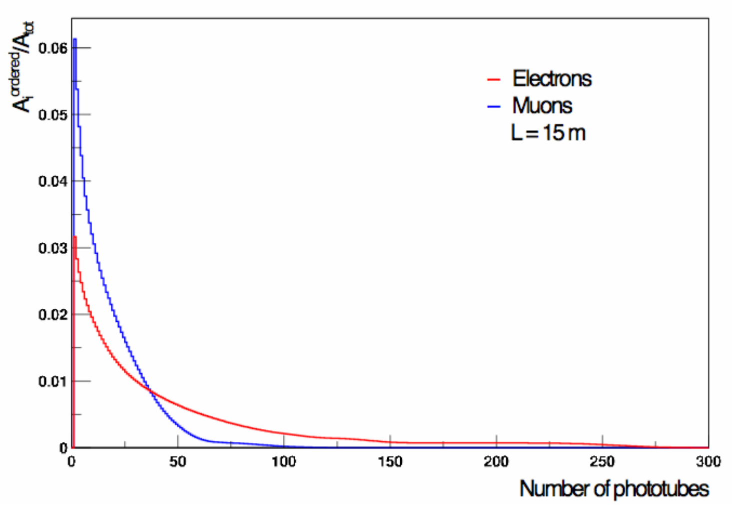
Detector response simulation

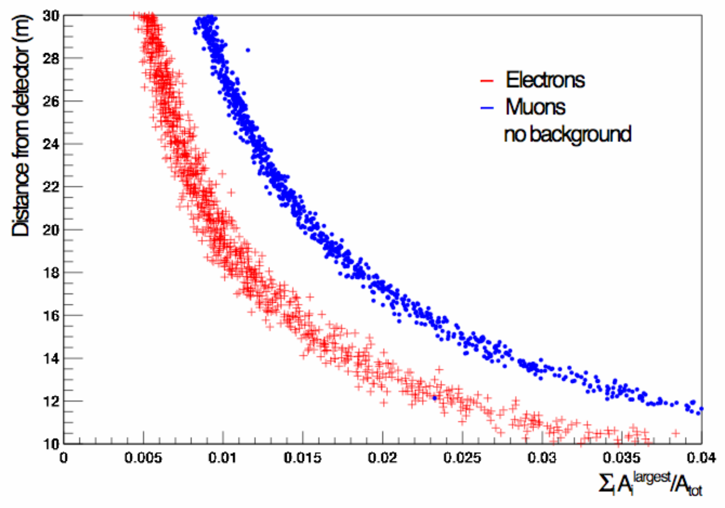
- GEANT4 based
- Assumptions:
  - Vertex distance from detector 10-50 m
  - Water absorption length 50 m
  - Cherenkov light range 300–600 nm
  - Quantum efficiency: 20%
- Primary photons in this spectral range:
  - e: ~ 140’000
  - μ: ~ 120’000
- Expect 2000-3000 photoelectrons/event without absorption in water

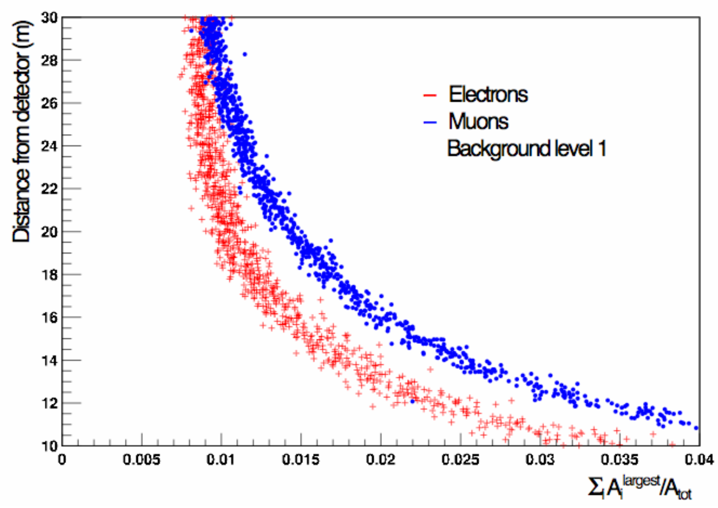
Light distribution

- Order phototubes by number of photoelectrons
- Compare normalised amplitudes in ~ 25 ‘hottest’ PMs

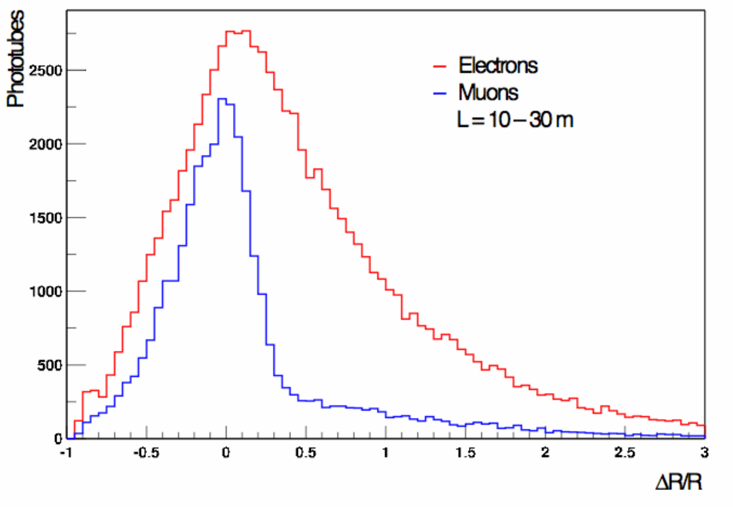






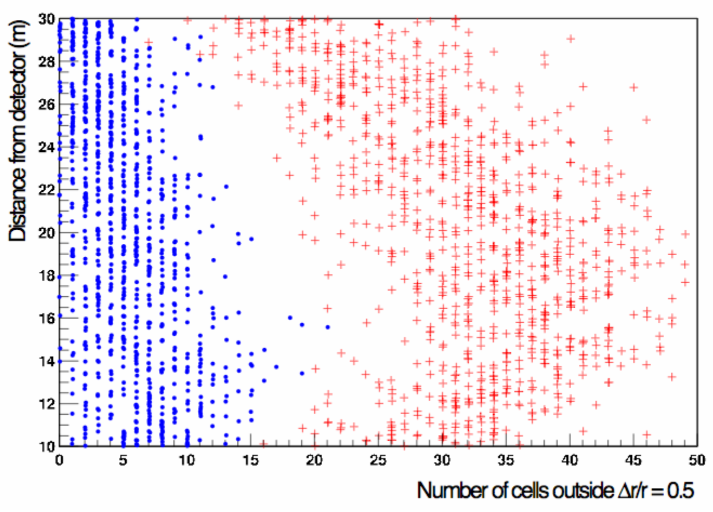


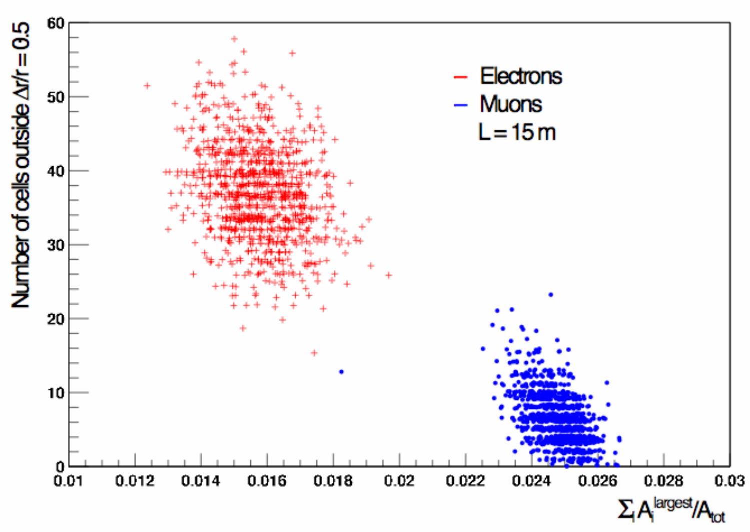
Geometrical distribution



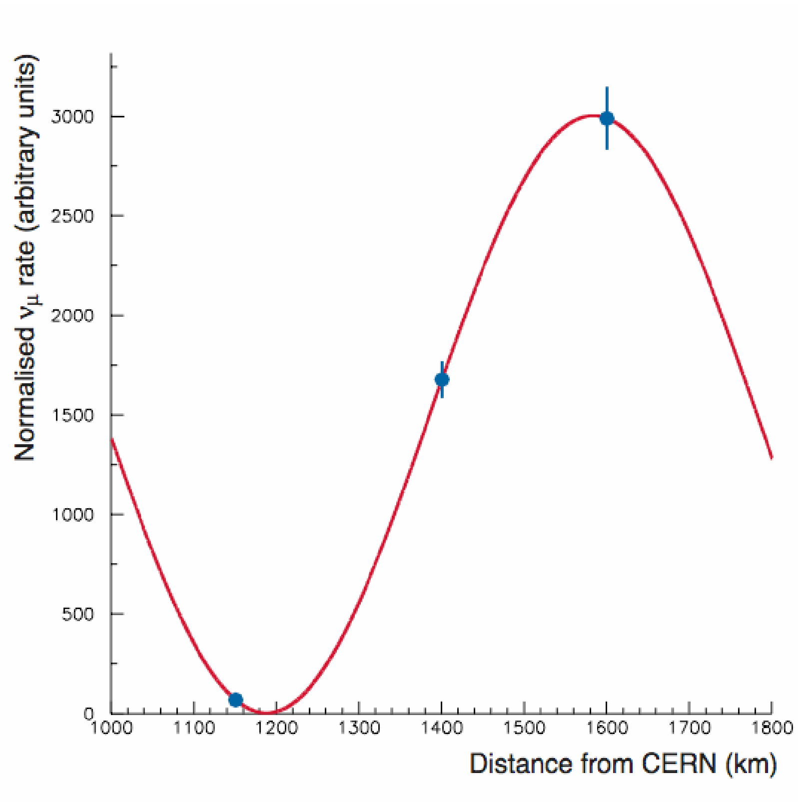
- Based on (normalised) radial distribution of active phototubes
- Compare number of PMs with ΔR/R > 0.5

Combine both methods:





Measurement strategy



- Mesure ν_μ rate at 3 distances from CERN (1 year each)
- Relative normalisation from NC background (dominates errors!)
- No absolute normalisation required
- Measurement of
  - Δm_{23}^2 to < 1% (stat)
  - $\sin^2\theta_{23}$ to ~ 3% (stat)
- Determines optimum location for $\sin^2\theta_{13}$ search

$\sin^2\theta_{13}$ sensitivity

- Assume:
  - 2 years data-taking
  - 5×10^{19} pot/year @ 400 GeV
  - Two ‘forward’ pions per proton on target
- ν–N cross sections poorly known!

	Events
CC $\nu_\mu(\pi)$ events w/o oscillation	14’700
NC background (1 π^0) from $\nu_\mu(\pi)$	50
NC background (1 π^0) from $\nu_\mu(K)$	30
Intrinsic ν_e	20
All backgrounds	100
Error on background (stat + syst)	15
90% CL error on $\sin^2\theta_{13}$	~ 0.002

Summary

1. Direct measurement of oscillation pattern without need for absolute flux normalisation
2. Direct demonstration of neutrino flavour transitions
3. Precise measurement of θ_{23} and Δm_{23}^2
4. Measurement of $\sin^2\theta_{13}$ with ~ 0.002 sensitivity
5. Conceptually simple detector, largely based on R&D and designs of earlier underwater experiments

Acknowledgements

- Special thanks to
  - Georgij Chelkov
  - Friedrich Dydak
  - Alan Grant
  - Alexej Guskov
  - Mike Price
  - Dieter Schinzel
  - Jörg Wotschack
- … and to the organizers of NO-VE 2003!