Progress Report of the NuFact Oscillation Working Group

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(Conveners)

CERN, 10 May 2000

~ 40 participants (theorists + experimentalists)

Synergy with HARP experiment

Meeting every ~ 6 weeks

Three areas of work: Physics
Accelerator parameters
Detectors

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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THE NEUTRINO FACTORY: BEAM AND EXPERIMENTS

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Abstract

The discovery of neutrino oscillations marks a major milestone in the history of neutrino physics, and opens a new window to the still mysterious origin of masses and flavour-mixing. Many current and forthcoming experiments will answer open questions; however, a major step forward, up to and possibly including CP violation in the neutrino-mixing matrix, requires the neutrino beams from a neutrino factory. The neutrino factory is a new concept for producing neutrino beams of unprecedented quality in terms of intensity, flavour composition, and precision of the beam parameters. Most importantly, the neutrino factory is the only known way to generate a high-intensity beam of electron neutrinos of high energy. The neutrino beam from a neutrino factory, in particular the electron-neutrino beam, enables the exploration of otherwise inaccessible domains in neutrino oscillation physics by exploiting baselines of planetary dimensions. Suitable detectors pose formidable challenges but seem within reach with only moderate extrapolations from existing technologies. Although the main physics attraction of the neutrino factory is in the area of neutrino oscillations, an interesting spectrum of further opportunities ranging from high-precision, high-rate neutrino scattering to physics with high-intensity stopped muons comes with it.

Physics Landscape - the Conservative View

Within the next decade we expect that the following is established/refined:

- Neutrino oscillations exist
- No sterile neutrino
- Atmospheric neutrinos: $\Delta m^2_{23} \sim 5 \times 10^{-3}$ eV^2, $\theta_{23} \sim 45^\circ$
- Solar neutrinos: $\Delta m^2_{12} \sim 10^{-4}$ eV^2, $\theta_{12} \sim 45^\circ$

The outstanding physics issues will be

- θ_{13}
- matter effects and the sign of Δm^2_{23}
- δ

The neutrino factory is a number of years away.

The European view:

At this early stage of the project, the machine's parameters must be driven primarily by physics considerations, and not by what can be reliably built 'next year'

Neutrino Oscillations

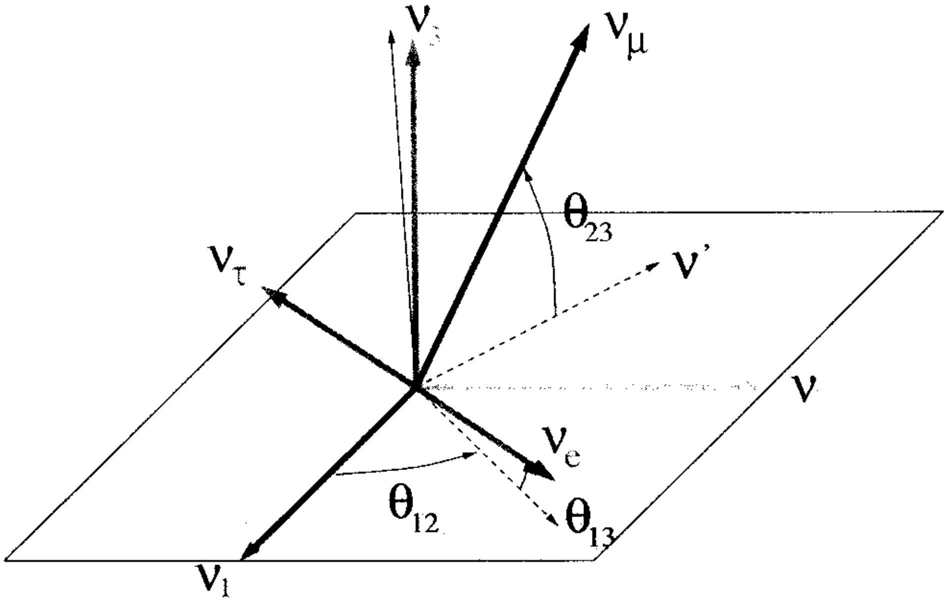

Figure 1: Rotation from mass-eigenstates to flavour-eigenstates.

$$U \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

with $s_{12} \equiv \sin\theta_{12}$ etc.

For $|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$: CP-conserving neutrino oscillations across planetary distances are well described with the three parameters θ_{23}, Δm^2_{23} und θ_{13} as follows:

$$\begin{aligned} P_{\mathrm{CP}}(\nu_e \to \nu_\mu) &= \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}\,L}{4E_\nu}\right) , \\ P_{\mathrm{CP}}(\nu_e \to \nu_\tau) &= \cos^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}\,L}{4E_\nu}\right) , \\ P_{\mathrm{CP}}(\nu_\mu \to \nu_\tau) &= \cos^4\theta_{13}\,\sin^2 2\theta_{23}\,\sin^2\left(\frac{\Delta m^2_{23}\,L}{4E_\nu}\right) . \end{aligned}$$

For the measurement of the CP-violating asymmetry

$$\mathcal{A}^{\mathrm{CP}}_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$$

is the oscillation $\nu_\mathrm{e} \to \nu_\mu$ most promising:

===> 'wrong-sign muon' events.

To first order in Δm^2_{12} one obtains

$$P_{\mathbf{CPviol}} = -8 c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \ \sin\delta \left(\frac{\Delta m^2_{12} L}{4E_\nu}\right) \sin^2\left(\frac{\Delta m^2_{23} L}{4E_\nu}\right)$$

Cervera et al. hep-ph/0002108
Dick et al. /9903308
Freund et al. /9912457

The mixing-angle θ_{13} with simultaneous CP violation

Consider the LMA-MSW parameter range:

$$\Delta m_{12}^2 \sim 10^{-4}\,\mathrm{eV}^2$$

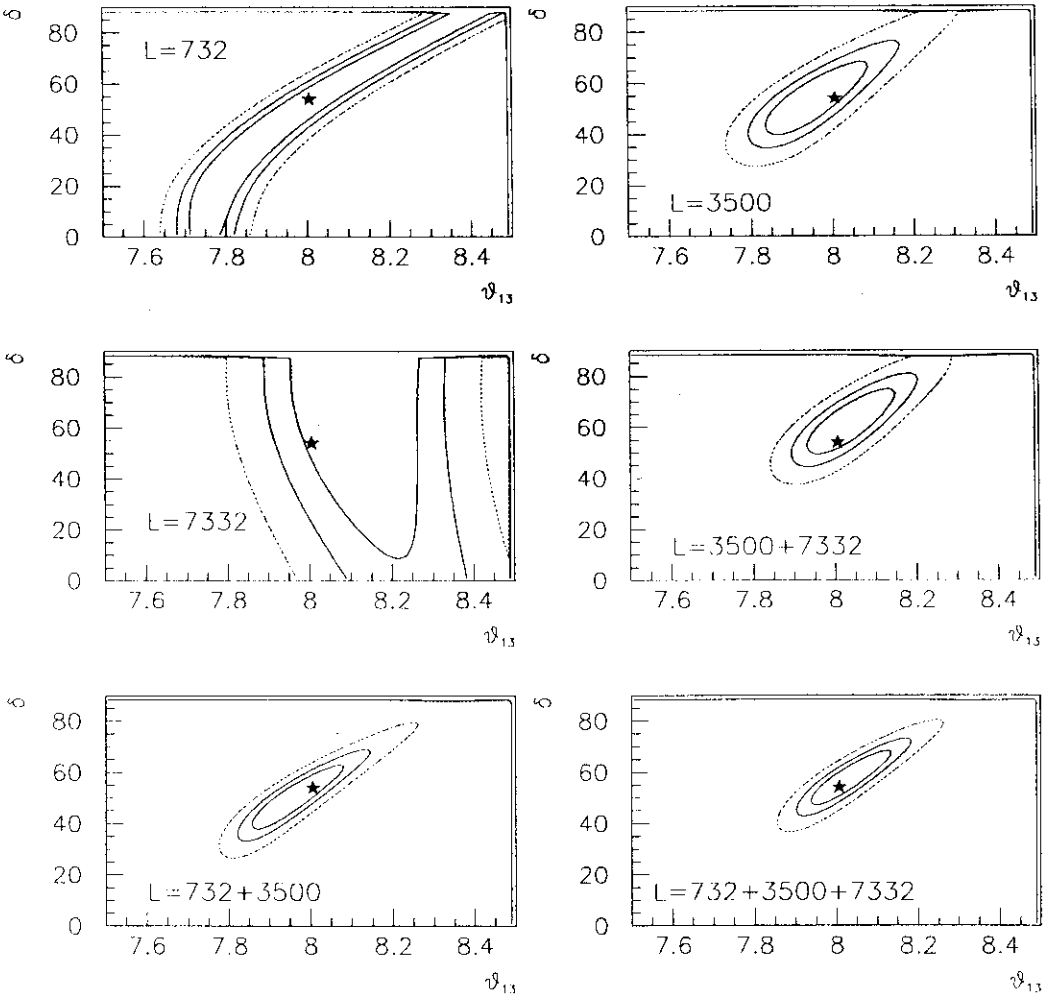

Figure 2: Simultaneous fit of θ_{13} and δ.

Machine parameters: the (European) experimentalist's desiderata

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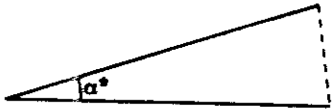
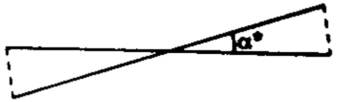
- *Energy of circulating muons*
  The higher the better; default: 50 GeV/c.
- *Charge sign of circulating muons*
  Both signs needed; as far as possible the same intensity; no concurrence of both signs.
- *Injected muons per year*
  Baseline 10^{21}; upgradable to 10^{22} or more.
- *Fraction of 'useful' decays*
  25% or larger.
- *Beam divergence in long straight sections*
  Less than $0.1/(\beta\gamma) = $ 0.2 mrad at 50 GeV/c, known to better than 10%.
- *Geometric configuration of the storage ring*
  'Triangle' or 'bow-tie'.

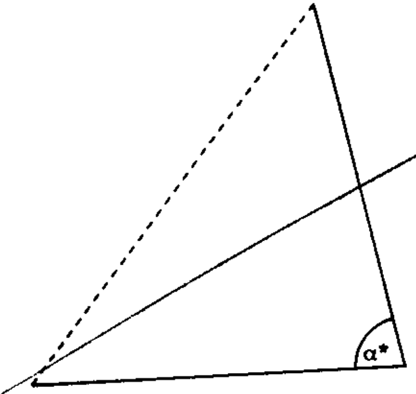
Good and **bad** situations



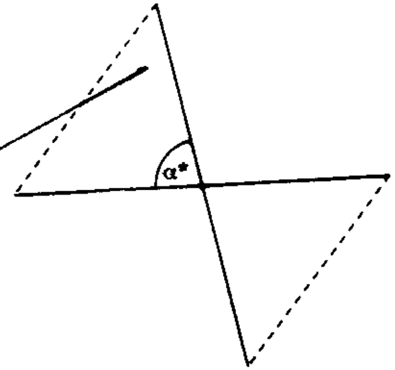
good triangle



good bow-tie



bad triangle



bad bow-tie

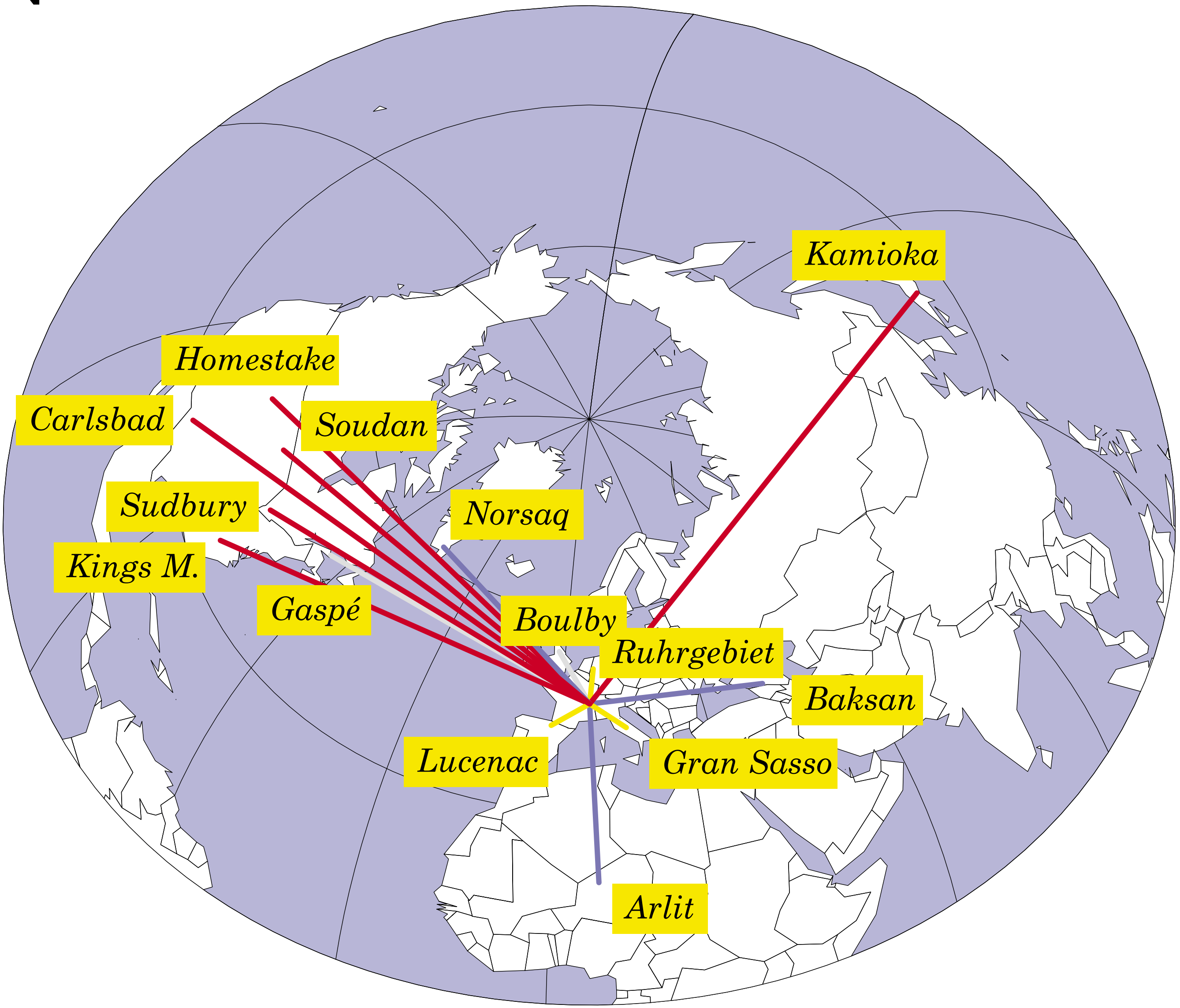
Efficiency: $\eta = \dfrac{\text{length of both straight sections}}{\text{circumference}}$

No bending arcs assymptotic efficiency: $$\eta_{\mathrm{as}} = \frac{2}{2 + \sqrt{2(1-\cos\alpha^*)}}$$

$0.5 < \eta_{as} < 1$ for both detectors

CERN

🟦 Arlit:	2968.5
🟦 Baskan:	2891.7
🟪 Boulby:	1002.2
🟥 Carlsbad:	7925.8
🟨 Essen:	582.4
🟪 Gaspe:	4962.7
🟥 GranSasso:	725.3
🟥 Homestake:	7328.1
🟥 Kamioka:	8760.1
🟥 KingsMountain:	6714.7
🟨 Lucenac:	731.8
🟦 Norsaq:	3570.3
🟥 Soudan:	6616.9
🟥 Sudbury:	6222.6



Comparison long BL

Long baseline							
Cornell	Arlit	Carlsbad	132.3	71.2%	180.0	7547	2488
BNL	Arlit	Carlsbad	131.8	71.0%	179.6	7328	2768
Cornell	Carlsbad	GranSasso	130.9	70.7%	173.7	2488	6637
BNL	Carlsbad	GranSasso	127.4	69.3%	170.7	2768	6506
BNL	Arlit	Homestake	126.2	68.9%	172.9	7328	2538
CERN	Baskan	Kings Mt	125.8	68.7%	170.9	2892	6715
RAL	Baskan	Soudan	124.9	68.4%	168.1	3366	5925
CERN	Baskan	Sudbury	123.4	67.8%	165.9	2892	6223
RAL	Arlit	Homestake	120.6	66.9%	168.7	3636	6655
RAL	Arlit	Soudan	120.4	66.8%	164.8	3636	5925
RAL	Baskan	Carlsbad	120.3	66.8%	170.6	3366	7293
Cornell	GranSasso	Homestake	117.5	65.9%	159.0	6637	2198
CERN	Arlit	Homestake	116.8	65.6%	165.5	2969	7328

Muon polarization

Table 1: Beam composition for different muon polarizations.

	$\mathcal{P} = +1$	$\mathcal{P} = -1$
μ^+	only $\overline{\nu}_\mu$	$\nu_e + \overline{\nu}_\mu$
μ^-	$\overline{\nu}_e + \nu_\mu$	only ν_μ

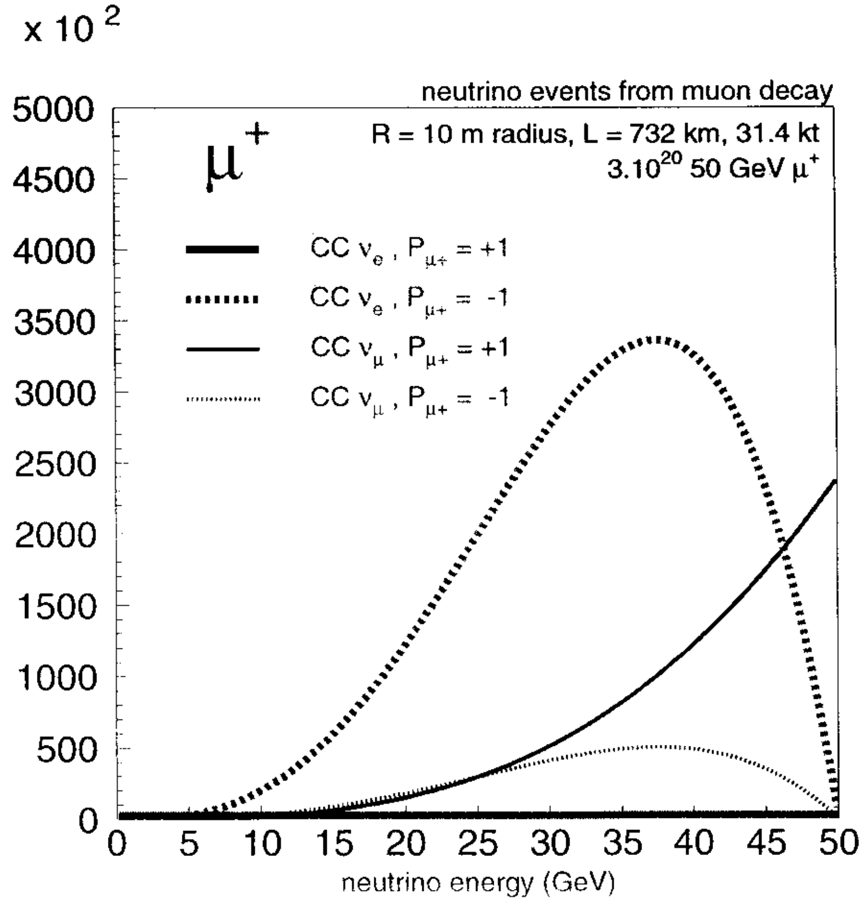


Figure 3: Energy distribution of events in a detector at 732 km distance, for 50 GeV/c $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$ decays and different muon polarizations.

Potential goodies from muon polarization are:

- Increase of number of events
- Variation of signal to background
- surrogate for lack of electron charge measurement

Some numbers

Surprise: there is a big δ–effect in electron event numbers

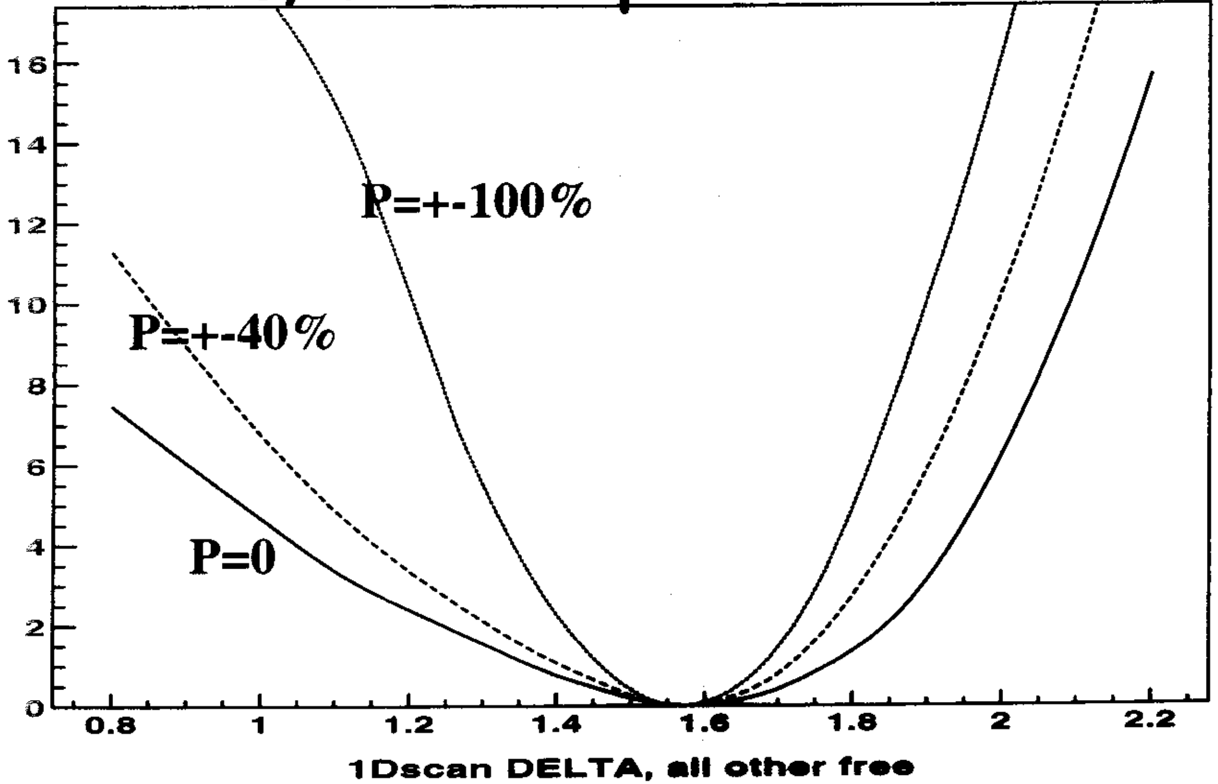
$\mu^-(\to\bar{\nu}_e\ \nu_\mu)$

ELECTRON CLASS:

		δ=π/2		δ=0
	P=0	**59550**	**(-510)**	**60060**
Kills anti-ν_e ⟶	**P=-1**	**6003**	**(-604)**	**6607**
	P=+1	**113100**	**(-400)**	**113500**

δ=π/2 decreases the $\nu_\mu\to\nu_e$ oscillation.

Fit to δ, all other parameters free



P = 0 : $\delta = 1.57 \pm 0.20$

P= ±40% $\delta = 1.57 \pm 0.15$

P= ±100% $\delta = 1.57 \pm 0.10$

±40 % polarisation is equivalent, for this example, to increasing the muon flux by 1.77

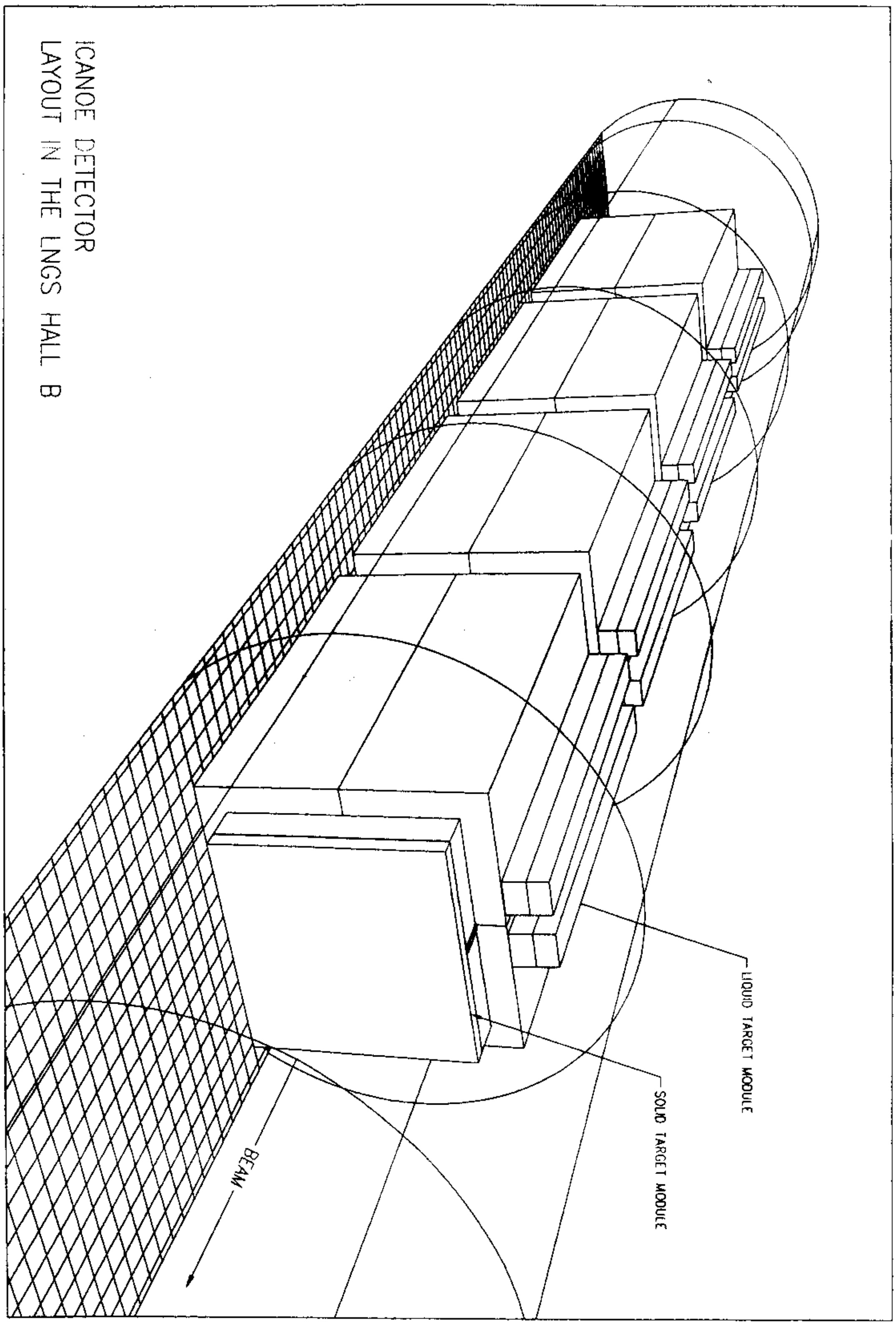
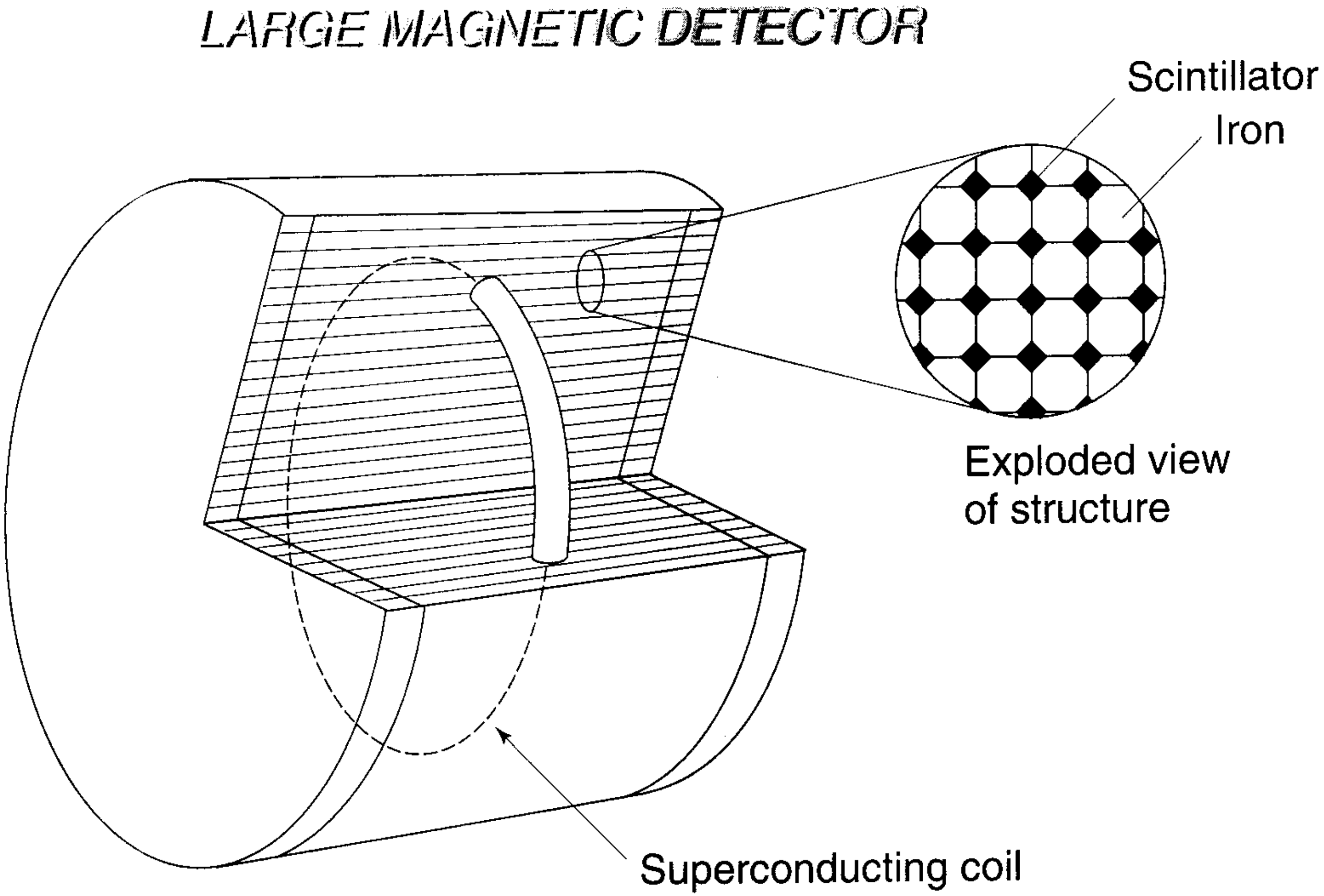


Figure 1.1: Perspective view of the *ICANOE* detector with 4 supermodules inside the Hall B.



Dimension: radius 10 m, length 20 m
Mass: 40 kt iron, 500 t scintillator

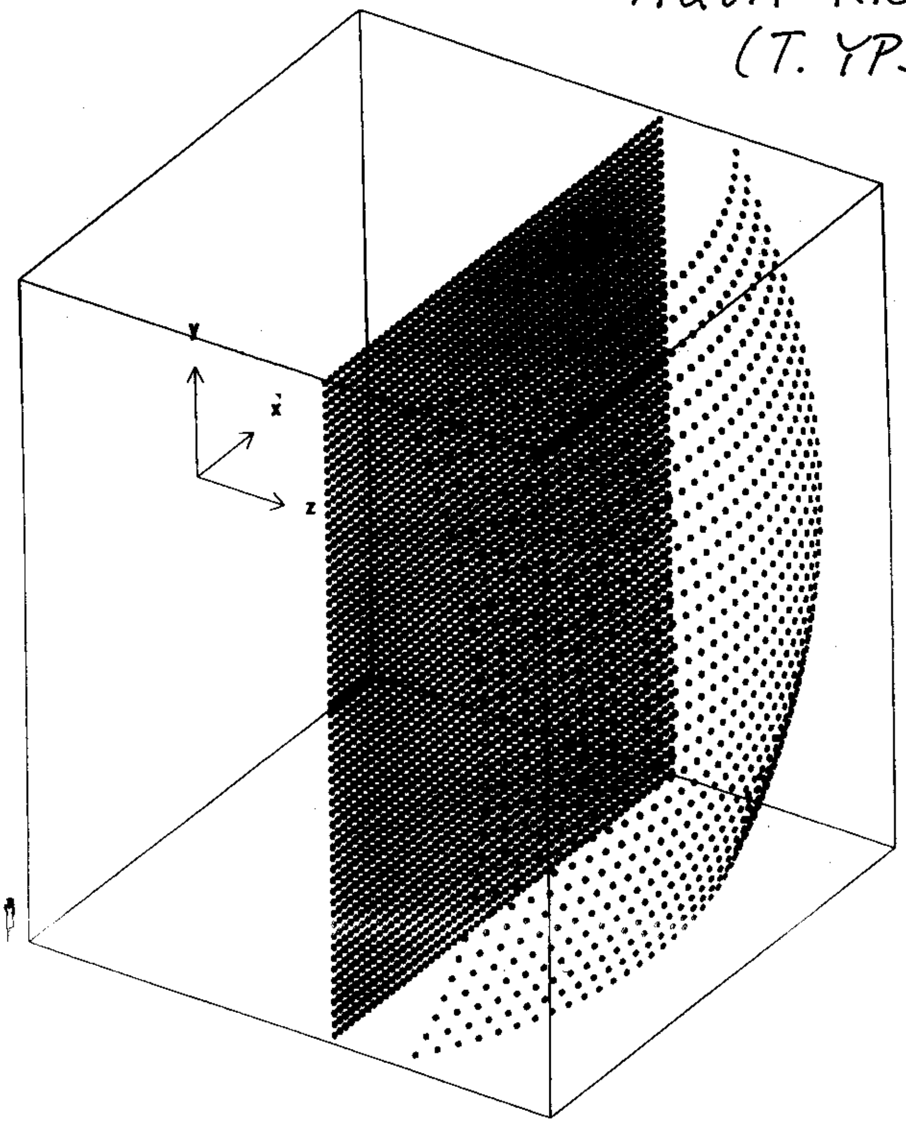
Figure 4:

Megaton Water Cherenkov Detector: HyperKamiokande?

100 m × 100 m × 100 m

In Carlsbad (New Mexico)?

AQUA-RICH
(T. YPSILANTIS et al.)



Underground detector location

Consider the Large Magnetic Detector

at 2500 km: 9×10^{-2} events/s

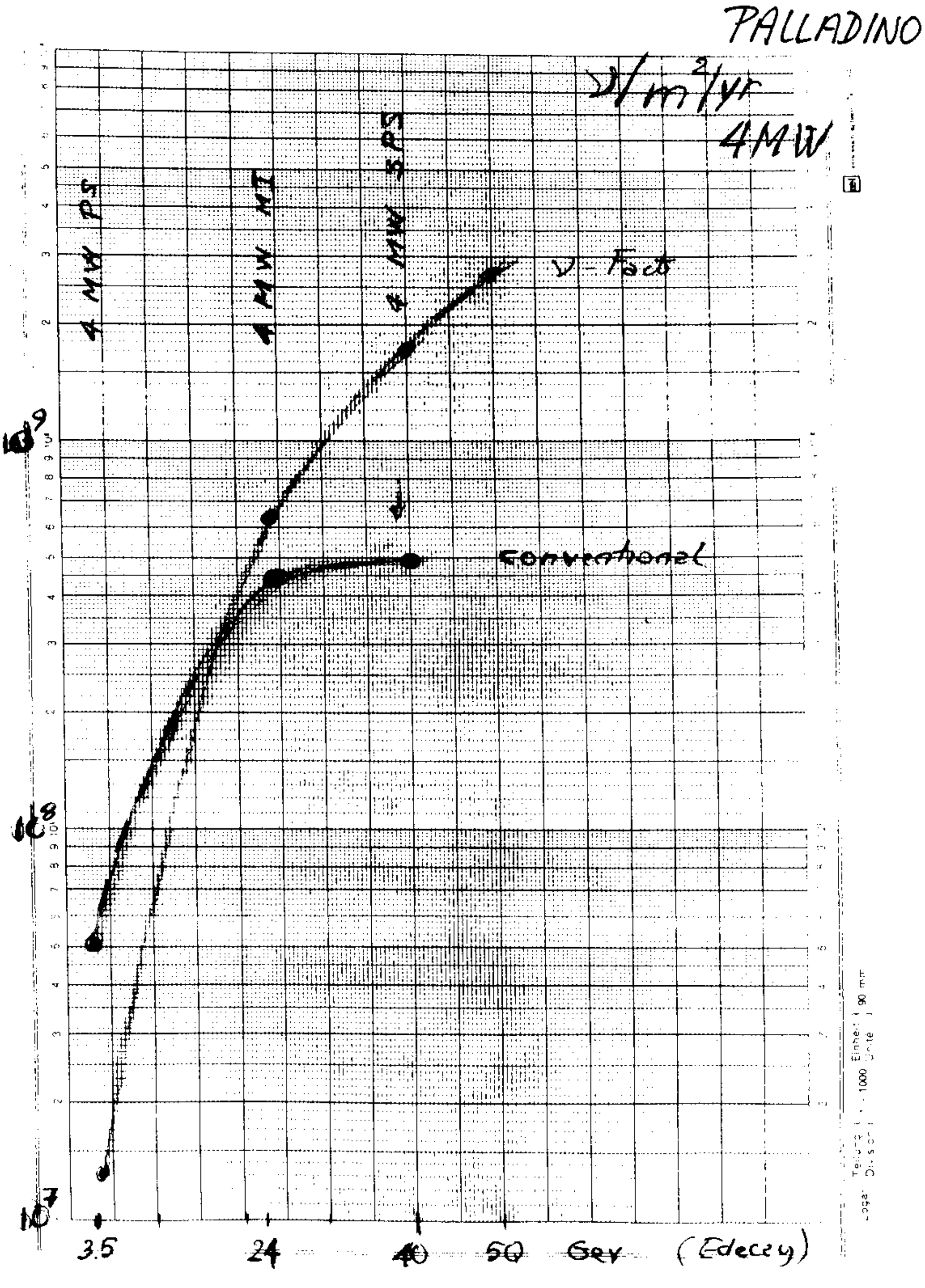
atmospheric neutrinos: 9×10^{-5} events/s

cosmic muons: 7×10^{4} muons/s

Need a factor $\sim 10^{4}$ from absorption in ≤ 2 km water equivalent overburden.

Conventional Beam vs Neutrino Factory

Three arguments:
Electron-neutrino beam
Accelerator costs
Running costs



Programme of further Work...

Beam parameters

- Assessment of 'triangle' versus 'bow-tie': efficiency, polarization
- Beam parameters at 50 GeV/$c$muon momentum: momentum spread, pointing precision, divergence, polarization, interference polarization and divergence: influence on absolute flux uncertainty.
- Measurement of the number of circulating muons.
- Appreciation of the importance of polarization.
- Is timing of individual bunches an important? If so, how?

'Near' detector: neutrino oscillation physics requirements

- Neutrino-antineutrino cross-section ratio: what precision needed, what precision achievable?
- Absolute neutrino cross-section: what precision needed, what precision achievable?
- Transverse size of the 'near' detector.
- Muon background in the near detector.
- What is a realistic beam divergence and its uncertainty? Effects on the radial flux spectrum in the 'near' detector?

‘Far’ detectors

- Development of the ‘large magnetic detector’ concept.
- Investigation of the capabilities of a very large water Cherenkov detector.
- Practical locations of ‘far’ detectors and of an associated neutrino factory.

Background, neutrino radiation

- Radiation issues at the neutrino factory.
- Background in long-baseline detectors from decays at the wrong place.

Conventional high-flux beam vs neutrino factory