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Precision physics at a neutrino factory

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Abstract. Neutrino beams of unprecedented flux could be produced in a Neutrino Factory from muon decays. In the vicinity of the storage ring, short baseline experiments would perform a new class of precise tests of the theory and original deep-inelastic-scattering (DIS) studies. Thanks to the availability of high energy ν_e and $\bar{\nu}_e$, the long baseline experiments will be capable of very precise measurements of neutrino oscillations, including ability to solve parameter ambiguities and study of leptonic CP violation, for any value of the mixing angle θ_{13} above a fraction of a degree. Finally, the Neutrino Factory is the first step towards muon colliders.

PACS. 1 3.88.+e Polarization in interactions and scattering – 1 2.15.Ff Quark and lepton masses and mixing – 1 4.60.Pq Neutrino mass and mixing – 2 9.25.-t Particle sources and targets – 2 9.27.-a Beams in particle accelerators – 2 9.20.-c Cyclic accelerators and storage rings

1 Introduction

Neutrinos have historically played an essential role in particle physics, with the discovery of Neutral Currents (NC), the first observations of open charm, precautious scaling and its violations and the early description of the structure of the nucleon. More recently LEP established that there are three species of light neutrinos, thus probably only three families of fermions. Finally, neutrinos have recently be in the limelight with the final demonstration that neutrinos have mass and mix. One of the main goals of the upcoming years will be the observation of leptonic CP violation, which is one of the leading explanations for the matter-antimatter asymmetry of the Universe. The importance of this search will justify substantial investments for the future. One of the leading ideas is that of a neutrino factory, in which neutrinos are produced in a controlled way by means of a stored muon beam.

This presentation and article summarize the work of several hundred of members of the CERN and ECFA studies of a Neutrino Factory Complex, which is contained in the very complete [1]. The Neutrino Factory has been proposed in 1998 [2] and studied extensively thanks in particular to the pioneering work of the Neutrino Factory and Muon Collider collaboration [3].

As we will see in the following sections, such a machine is very polyvalent, and offers opportunities in short baseline physics, neutrino oscillations and is also the first step towards muon colliders.

2 The neutrino factory

The basic layout of a Neutrino Factory is shown in Fig. 1. The principle [4] is to produce the largest possible intensity of low energy muons, accelerate them to an energy of 20 to 50 GeV and store them in a decay ring. A short (1-3 ns) high power (several MW) proton beam of energy in excess of a few GeV hits a renewable target (liquid mercury is the baseline design). The secondary pions are captured by a magnetic device (tapered solenoid or magnetic horn) and fed into a solenoidal magnetic channel where they decay into muons. The muons are then subject to phase rotation and ionization cooling after which the energy spread and transverse emittance are considerably reduced. The beam is by then small enough to be accelerated by means of recirculating linac or FFAG's, and stored in a decay ring equipped with long straight sections. Typically 10^{14} muons are injected per second, producing at the end of the straight sections a very intense, bunched, beam of neutrinos from the decay of muons, $\mu^+ \rightarrow e^+ \nu_e \, \bar{\nu}_\mu$ or $\mu^- \rightarrow e^- \bar{\nu}_e \, \nu_\mu$, the sign being determined by the polarity of a few magnetic elements in the system or by timing.

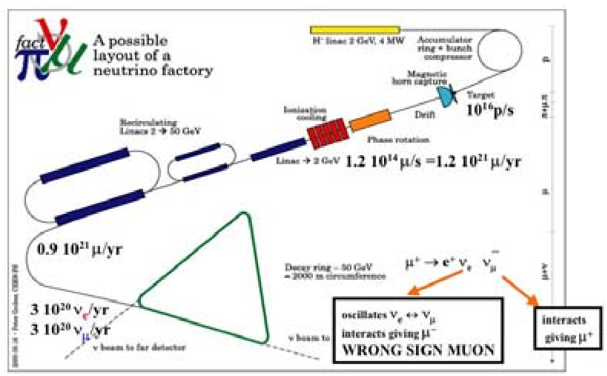

Fig. 1. Possible layout of a neutrino factory

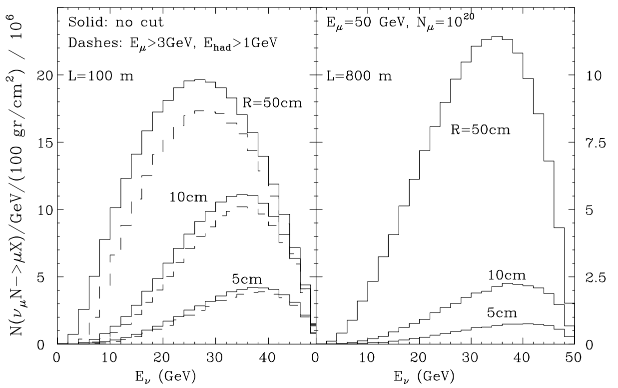

Fig. 2. Event rates at the near detector station of a neutrino factory. Note the vertical scale

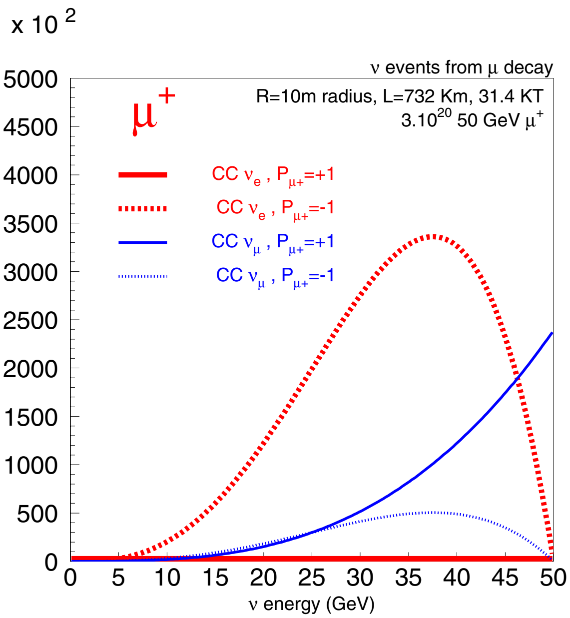

Fig. 3. Event rate at a far detector station of a neutrino factory for positive muon decay. The effect of muon beam polarization is shown. In the race-track or triangle geometry for the storage ring, the polarization can be preserved but averages out for each muon fill

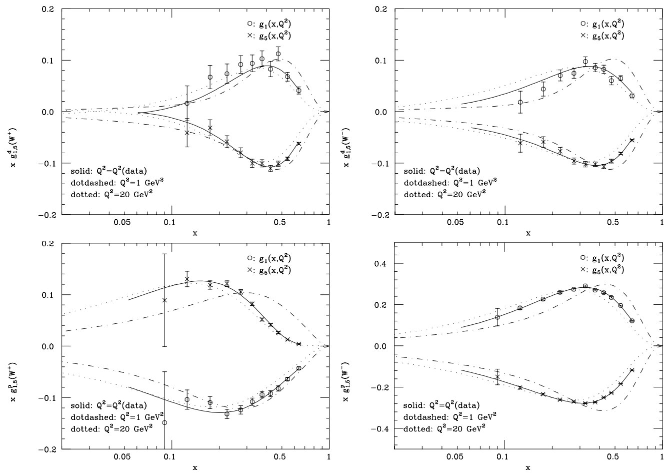

Fig. 4. Expected achievable precision on polarized structure functions g_1 and g_5 on proton (*lower part*) and deuteron (*upper part*) and for neutrino beam (*left part*) and anti-neutrino beam (*right part*) at the near detector of a neutrino factory

The resulting event rates are shown in Fig. 2 for the near detector station and in Fig. 3 for the far detectors. Originating from a stored and monitored beam, the flux of neutrinos should be known to a fraction of a percent [5].

3 Short baseline physics

In the near detector station, a kilogram of material placed on the beam axis would see typically 100 millions of interactions per year, more than in the old 1200 ton CDHS detector, but still only one event every few accelerator pulses. This, being obtained with a well defined flux of neutrinos (which are polarized by nature), opens a new realm of experimentation since the target material can be varied *ad infinitum* and the final state products can bemeasured in detail. The physics potential of high intensity short baseline physics has been discussed quantitatively in [6], although no experimental set up has been simulated so far.

The range of physics accessible to the near detector station is quite large. First, definitive measurements of unpolarized structure functions measurements and their flavour composition, in particular the strange sea, will be possible for the whole accessible kinematic range. This is, in particular, thanks to the assumed capability of the detectors to tag charm production. These ingredients should lead to an improved determination of the strong coupling constant from either global structure function fits or from the GLS sum rule.

Then, the use of small targets being possible, using polarized hydrogen or deuterium targets should allow a detailed decomposition of the spin structure functions, as shown in Fig. 4. Again, the use of charm tag should be determinant in the study of the polarized structure function of the strange quarks.

Maybe one of the most interesting topics shold be the possibility to use a variety of nuclear targets and map systematically the nuclear effects in structure functions.

The study of final states in neutrino scattering offers new possibilities. For instance the study of final state Λ and Λ_c polarization both in charged current and neutral current processes has been given as an example, allowing extraction of the newly introduced polarized fragmentation functions.

The high statistics available should allow precision measurements of standard model processes on electrons. This has a two-fold interest. First, the charged current inverse muon decay process, $\nu_\mu e^- \to \mu^- \nu_e$, although unfortunately applicable only to the muon neutrino component of the beam from μ^+ decay, should allow a very precise flux normalization (provided an adequate target and detector can be built), in a way similar to that provided by Bhabha scattering in e^+e^-experiments. Secondly, the electron final state, which is very rich due to the presence

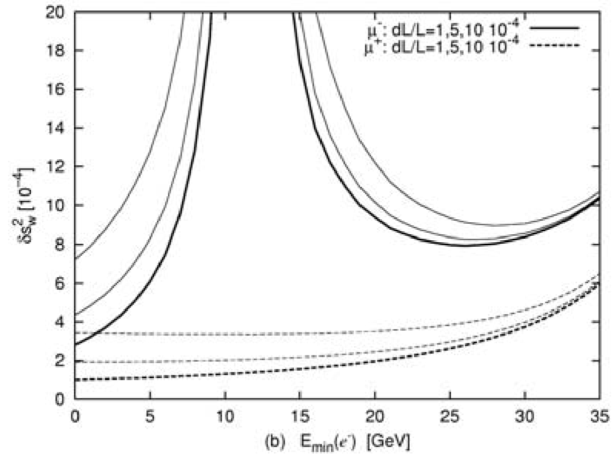

Fig. 5. Expected achievable precision on the weak mixing angle $\sin^2\theta_{\mathrm{w}}^{\mathrm{eff}}$ at small Q^2 from neutrino scattering off electrons. The precision is shown as a function of the cut on the final state electron energy. It is clear that the μ^+ exposure is more interesting for the mixing angle measurement, on the other hand the μ^- exposure is more sensitive to the interference between the NC and CC processes

of the electron neutrino component in the beam, is sensitive to $\sin^2\theta_{\mathrm{w}}^{\mathrm{eff}}$ at small Q^2 with a precision of the order of 2×10^{-4}, similar to that available at the Z pole, as shown in Fig. 5.

Finally, the high statistics allied with the improved knowledge of charm production should allow a complete revision of the measurement of the hadronic neutral current processes (NC/CC ratio) which have recently [7] exhibited a discrepancy with model expectations at the level of three standard deviations.

4 Neutrino oscillations

A large part of the present excitement for Neutrino Factories is, understandably, the long baseline oscillation physics. This has been extensively reviewed in the litterature [5],[8] and only the main results are summarized here.

Neutrino oscillations are now well established and demonstrate that neutrinos have mass. The most striking result of recent measurements are contained in our knowledge of the neutrino mixing matrix. For three flavours of neutrinos there are, naturally, three mixing angles, θ_{12}, θ_{13}, θ_{23}, and two mass differences Δm^2_{12}, Δm^2_{23}, that play a role in the oscillation process. The typical oscillation length is 500 km/GeV for the 'atmospheric oscillation' driven by Δm^2_{23}, and 18000 km/GeV for the 'solar oscillation' driven by Δm^2_{12}. In addition one expects the presence of a phase, yielding perhaps observable leptonic CP violation. The most interesting channel (so-called 'golden channel') to be studied is the $\nu_e \to \nu_\mu$ (and $\bar{\nu}_e \to \bar{\nu}_\mu$) oscillation which is suppressed at 'atmospheric' distances by the small value of the so far unknown θ_{13}. This suppression makes this channel particularly interesting since it makes it possibly sensitive to the interference between the solar and atmospheric oscillations, and thereby to the resulting CP violation, which would manifest itself by an asymmetry between the neutrino and anti-neutrino oscillations. In addition this channel involving electron neutrinos is sensitive to matter effects and should allow a determination of the sign of the mass difference Δm^2_{23}, which is presently unknown.

Table 1. Event rates in a 50 kton magnetized iron detector for one year running at a neutrino factory

Baseline	CC $\bar{\nu}_\mu$	CC ν_e	CC ν_μ Golden signal $\sin^2\theta_{13} = 0.01$
730 km	3.5 10^7	5.9 10^7	1.1 10^5
3500 km	1.2 10^6	2.4 10^6	1.0 10^5

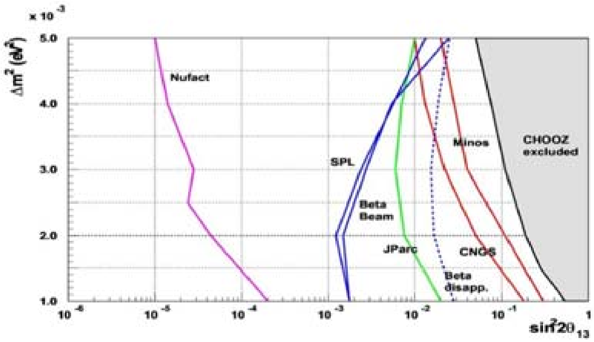

Fig. 6. Comparative sensitivity of various future measurements of θ_{13}

The simulataneous presence of ν_e and $\bar{\nu}_\mu$ in the beam has for consequence that the detector has to be magnetic to separate the CC neutrino interactions generated by the $\bar{\nu}_\mu$ contained in the beam from those generated by ν_μ originating from $\nu_e \to \nu_\mu$ oscillations. A large 50 kton magnetic detector has been suggested, in extrapolation from the well known CDHS or MINOS experiments. The rates are astounding, as shown in Table 1, many times higher than in the case of more conventional neutrino beams. For this process the backgrounds are very small.

The other very strong point of the Neutrino Factory is the capability to study the $\nu_e \to \nu_\tau$ oscillation. This channel is particularly valuable since it allows to lift the unavoidable parameter ambiguities. The sensitivity or precision of the Neutrino Factory to the angle θ_{13} and to the CP violating phase δ are shown in Figs. 6 and 7, and are clearly superior to any other device imagined so far.

5 Muon collider

Finally, it is worth keeping in mind that the Neutrino Factory is the first step towards muon colliders. As shown in [9], the relevant characteristics of muons are that, compared to electrons, i) they have a much better defined energy, since they hardly undergo synchrotron radiation or beamstrahlung, ii) their coupling to the Higgs bosons is multiplied by the ratio $(m_\mu/me)^2$, thus allowing s-channel

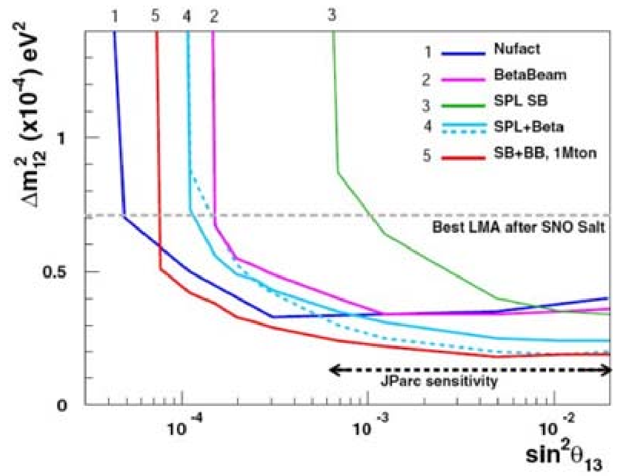

Fig. 7. Sensitivity of various future neutrino options to the CP-violating phase δ

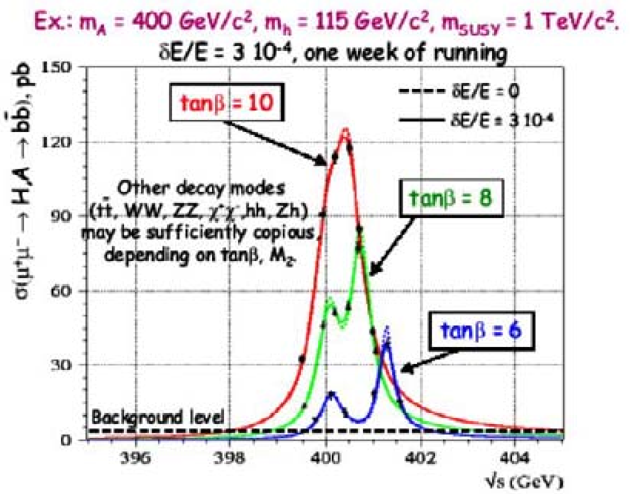

Fig. 8. Study of the supersymmetric H,A system at a muon collider

production with a useful rate. These remarkable properties make muon colliders superb tools for the study of Higgs resonances, especially if, as predicted in supersymmetry, there exist a pair H, A of opposite CP quantum numbers which are nearly degenerate in mass, as evidenced in Fig. 8. The study of this system is extremely difficult with any other machine and a unique investigation of the possible CP violation in the Higgs system would become possible.

6 Conclusions

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