A NEUTRINO FACTORY MANIFESTO

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ABSTRACT

A neutrino factory is capable of answering basic questions in the physics of neutrino oscillations, which address fundamental issues in Grand Unified Theories and flavour physics. In addition, the front end of a neutrino factory offers exciting prospects using slow and stopped muons, such as the search for $\mu \to e$ transitions and the muon electric dipole moment. There are also opportunities to study muonic atoms and in other areas of science. One should also keep in mind the long-term objective of building a muon collider, either for Higgs physics or at the high-energy frontier.

1. Neutrino Masses and Oscillations

Neutrino masses and oscillations offer unique perspectives on physics beyond the Standard Model. There was never any good reason why neutrino masses should vanish, there being no exact gauge symmetry to prevent them from acquiring masses. In the cases of the photon and gluons, the exact $U(1)$ and $SU(3)$ gauge symmetries of the Standard Model safeguard their masslessness. There is no corresponding massless gauge boson coupling to lepton number, so theorists have long being expecting non-zero neutrino masses [1].

There are many models of neutrino masses based on GUTs [2], theories of flavour with additional $U(1)$ generation symmetries [3], and recently models with extra dimensions [4]. In general, one may say that neutrino masses open a window directly on physics at a high mass scale, possibly beyond the reach of collider experiments, providing us with a look at GUTs, flavour physics, and perhaps even quantum gravity [5].

The simplest form of neutrino mass term is the Majorana type $m_\nu \nu\nu$, which could even be generated within the Standard Model, via non-renormalizable interaction of the form [6]

$$\frac{1}{M}\nu H \cdot \nu H \to m_\nu = \frac{\langle 0|H|0\rangle^2}{M} \tag{1}$$

where M is some heavy mass scale $\gg m_W$, and H denotes the Standard Model Higgs field. This mechanism naturally gives $m_\nu \ll m_{q,\ell}$, as is suggested by experiment, but begs the questions where M originates.

The favoured origin of M is in some Grand Unified Theory (GUT) see-saw model [2], which looks like

$$(\nu_L, \nu_s) \left(\begin{array}{cc} 0 & m_0 \\ m_0^T & M_M \end{array} \right) \left(\begin{array}{c} \nu_L \\ \nu_s \end{array} \right) \qquad (2)$$

in its simplest form, where one postulates a singlet neutrino ν_s with a large Majorana mass M_M, and the Dirac mass $m_D = \mathcal{O}(m_{q,\ell})$. After diagonalization, the matrix (2) yields a light mass eigenvalue:

$$m_\nu = m_D \frac{1}{M_M} m_D^T. \qquad (3)$$

Both the equations (3) and (2) should actually be regarded as matrices in flavour space. After their diagonalization, and that of the charged-lepton mass matrix, there will in general be a mismatch in flavour space, that is interpreted as the neutrino mixing matrix:

$$V_{MNS} \equiv V_\ell V_\nu^\dagger \qquad (4)$$

In view of the very different origin (3) from that of quark masses, involving the heavy Majorana mass matrix M_M as well as the Dirac matrix m_D, it should not be surprising if neutrino mixing is very different from that of quarks: $V_{CKM} = V_d V_u^\dagger$.

The see-saw framework (2) may well be a gross simplification of the new physics of neutrino masses. For example, in some models with extra dimensions [4], there are an infinite sequence of excited Kaluza-Klein states coupled to the familiar ν_L. In consequence, there may be observable deviations from naive sinusoidal oscillation patterns *in vacuo* [7], and there may be multiple MSW effects in matter [8]. Intermediate between these Kaluza-Klein models and the minimal see-saw (2) are some string-inspired (or derived) models in which there are a large but finite number of massive states mixing with the ν_L. More exotic possibilities suggested by some quantum theories of gravity include violations of the equivalence principle [9] or Lorentz invariance [10], and quantum decoherence [5].

2. The Emerging Default Option

As discussed by many speakers at this meeting, there is much confirmed evidence for both atmospheric neutrino oscillations, with [11]

$$10^{-2} \text{ eV}^2 \gtrsim \Delta m^2_{Atmo} \gtrsim 10^{-3} \text{ eV}^2, \qquad (5)$$

and solar neutrino oscillations with [12]

$$10^{-4} \text{ eV}^2 \gtrsim \Delta m^2_{Solar} \gtrsim 10^{-11} \text{ eV}^2, \qquad (6)$$

There is also evidence from the LSND experiment for oscillations with a larger value of Δm^2 [13], that cannot be accommodated within any simple three-generation scenario, but could be explained with an additional light sterile neutrino ν_s. If the LSND result were to be confirmed [14], neutrino oscillation physics would be even more interesting. However, in the rest of this review, *we shall stick our heads in the sand and be very conservative, restricting ourselves to the seesaw model (2) and just three light neutrino species*, with Δm^2 in the ranges (5, 6). The geometry of three-flavour mixing may be described by $(\nu_e, \nu_\mu, \nu_\tau)^T = U \cdot (\nu_1, \nu_2, \nu_3)^T$, where

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{7}$$

with three (Euler) mixing angles $\theta_{23,13,12}$ and one CP-violating phase δ.

There are upper limits on neutrino masses from astrophysics and cosmology, which suggest that all three light neutrino flavours weigh less than about 2 eV [15], and Tritium β decay [16], which suggests independently that the state which is predominantly ν_e weighs less than about 2 eV. Hence, we have

$$m_\nu \lesssim 2 \text{ eV} \gg \sqrt{\Delta m^2_{Atmo}} \gg \sqrt{\Delta m^2_{Solar}}. \tag{8}$$

One may ask whether all three neutrino species might have (almost) degenerate masses close to the upper limit $\sim$ 2 eV. If so, there must be strong cancellations to ensure that $\langle m_{\nu_e} \rangle \lesssim 0.2$ eV, as required by neutrinoless double-β decay [17]. This requires almost bimaximal mixing, which is possible if solar neutrino data are described by vacuum oscillations (VO), but not if the small-mixing-angle (SMA) solution is correct, and perhaps not even in the large-mixing-angle (LMA) case, since this is valid only if $\sin^2 2\theta_{12}$ is bounded away from unity. However, in the surviving VO case, one would require $m_\nu \simeq 10^{10} \times \sqrt{\Delta m^2_{Solar}}$, which would be quite impressive, and totally unexpected within a conventional see-saw model. Moreover, such degeneracy and bimaximal mixing are difficult to reconcile with the inevitable renormalization of neutrino masses at sub-GUT scales [18]. *Therefore, we disfavour degenerate neutrino scenarios in the following.*

As is well known, the most likely scenario for interpreting the atmospheric neutrino data is that $\nu_\mu \to \nu_e$ oscillations are not dominant, because of upper limits from the Super-Kamiokande [11] and Chooz experiments [19]. Nor can $\nu_\mu \to \nu_s$ oscillations be dominant, because of the azimuthal-angle distributions observed by Super-Kamiokande [11]. Thus, near-maximal $\nu_\mu \to \nu_\tau$ oscillations are favoured. Moreover, Super-Kamiokande has recently reported [20] the possible detection of τ production at the 2-σ level, close to the expected rate. There are more prospects for confirmation of $\nu_\mu \to \nu_\tau$ oscillations by MINOS [21], and final proof is likely to come from OPERA [22]. *We assume as a default that θ_{23} is large, whilst θ_{13} is small.*

In the case of solar neutrinos, the rates alone do not distinguish between the LMA, SMA, VO and low-mass (LOW) solutions. However, the day-night energy spectra favour LMA [12], though not yet conculsively. Since the physics case for the neutrino factory is strongest in the LMA case, we should avoid jumping to favourable conclusions! Definitive answers may soon be provided by the SNO [23] and KamLAND [24] experiments, and by Borexino [25]. However, for the time being, *we assume the LMA solution, with θ_{12} large and $\Delta m^2_{12} \sim$ few $\times\, 10^{-5}$ eV^2 to 10^{-4} eV^2*, even though this seems almost too good to be true!

Thus, the emerging default option for neutrinos comprises three light neutrinos with hierarchical masses and (almost) bimaximal mixing:

$$V_\nu \simeq \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{9}$$

Their masses are thought to be effectively mainly of Majorana nature, they are expected to have small dipole moments, and their lifetimes are expected to be much greater than the age of the Universe.

This brief summary begs many big issues. Can we exclude the existence of one or more light sterile neutrinos ν_s? Can we exclude (almost) degenerate neutrino masses or an inverse mass hierarchy? If mixing is indeed (nearly) bimaximal (7), how can we discriminate between the LMA and LOW solutions, and how big is θ_{13}? Are we really so lucky that CP violation is observable in neutrino oscillations? If the neutrino masses really are Majorana, can we fix them by neutrinoless double-β decay experiments? If the anomalies in the solar and atmospheric data are indeed due to oscillations, rather than decays, can we see the oscillation pattern?

3. Programme of Work for a ν Factory

There is a very full programme of work for a neutrino factory, with its centrepiece being neutrino oscillation studies [26]. Among the experimental objectives are determining the magnitude of θ_{13}, observing MSW matter effects under controlled conditions [27] and determining the sign of Δm^2_{23}, and measuring the CP violation phase δ. Theoretical details of this programme are discussed here by Pilar Hernandez [26], so here I just note a few points.

The optimal single distance for CP-violation studies is about 3000 to 4000 km [28]. However, the precision may be improved by combining experiments at different baselines [29], as seen in Fig. 1. For this reason, CERN and other laboratories have been looking for sites suitable for experiments at distance around 3000 km. There are not so many suitable places in Europe that are so distant from CERN, but they do include the Santa Cruz de Tenerife in the Canary Islands - where there are many tunnels in the volcanic rock - Lonyearbyen in Spitzbergen - where there are coal mines - and Pyhäsalmi in Finland - where there is a mine for zinc and copper, as seen in Fig. 2 [30].

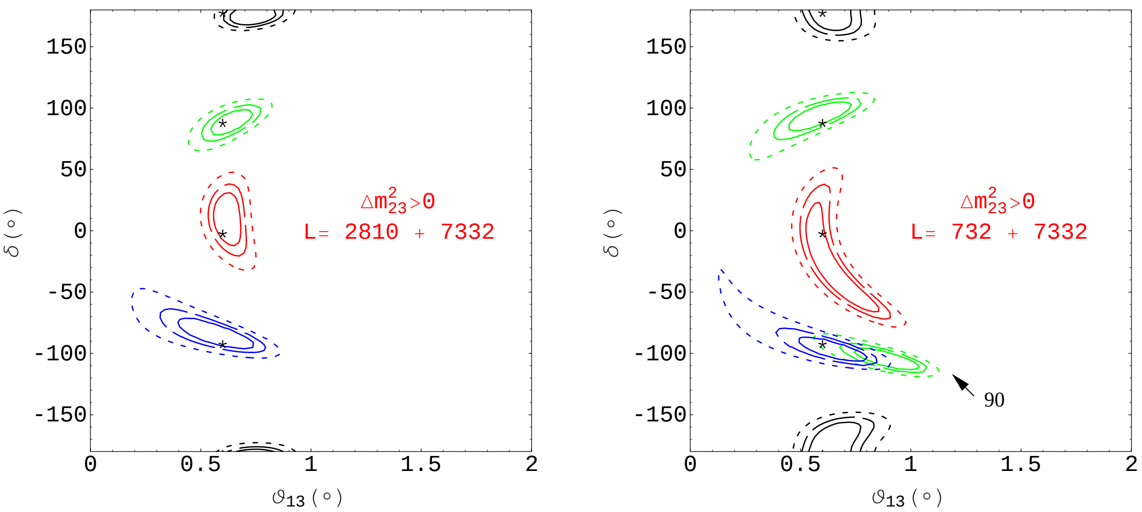

Figure 1: *Estimates of the precisions possible in measurements of θ_{13} and the CP-violating phase δ at a ν factory* [29]*, combining data from two different long baselines.*

In designing a neutrino factory, other physics opportunities should be kept in mind. These include an intense low-energy ν 'superbeam' [31], physics with slow (or stopped) muons [32] - such as flavour-violating processes including $\mu \to e\gamma$ decay and $\mu \to e$ conversion on a heavy nucleus, a new measurement of $(g_\mu - 2)$, deep-inelastic ν (or μ?) scattering [33], neutron physics, physics with radioactive beams, kaon physics, etc. Some of these are described in more detail later, but first let us acquaint ourselves better with the conceptual design of a ν factory.

4. Concept for a ν Factory

A conceptual layout of a ν factory at CERN is shown in Fig. 3. The first requirement is an intense proton source. At CERN, the favoured option is a superconducting linac (SPL) [34], but higher-energy designs based on rapid-cycling synchrotrons are being considered elsewhere [35,36]. The SPL would accelerate H^- ions to 2.2 GeV at a repetition rate of 75 Hz, producing 1.1×10^{16} particles per second, corresponding to 4 MW mean beam power. Much of the acceleration in the SPL would be provided by reusing LEP RF cavities, providing a considerable saving in development effort and cost. The SPL could be used in a shallow tunnel just outside the present CERN boundary fence, with easy connections to the existing CERN accelerator complex [34]. The target system would be non-trivial, in view of the intense beam power. Ideas for an external target include a Mercury jet or a hot, rapidly-rotating, magnetically-levitating metal band.

Figure 2: *Possible locations of long-baseline neutrino detectors that could make measurements using beams from a ν factory at CERN* [30].

The SPL would provide better beams for the CERN PS accelerator, could increase the current to the present isotope facility ISOLDE by a factor 5, and perhaps feed a new radioactive beam facility. Under study are the possibilities of improved PS and SPS beams, e.g., for the CNGS ν beam, and better beams (or at least a shorter filling time) for the LHC. Another option could be a low-energy ν 'superbeam' directed towards a laboratory about 100 km away, e.g., near Modane at the location of the Fréjus tunnel [37].

For a ν factory, the next step would be an accumulator/compressor ring for manipulating the time structure of the SPL beam, which could be housed in the old ISR tunnel. One would also need a horn system for focusing the pions produced in the target and capturing the muons emanating from their decays. Next would be a complex system for muon cooling and phase notation, designed to 'tame' the muon beams. This would be followed by a set of recirculating linacs to accelerate the muons to the preferred storage energy, between 20 and 50 GeV. They would then be transferred to a tilted storage ring, with a triangular or bowtie shape, where they would be allowed to decay, mainly in straight sections sending beams to detectors at various baseline distances.

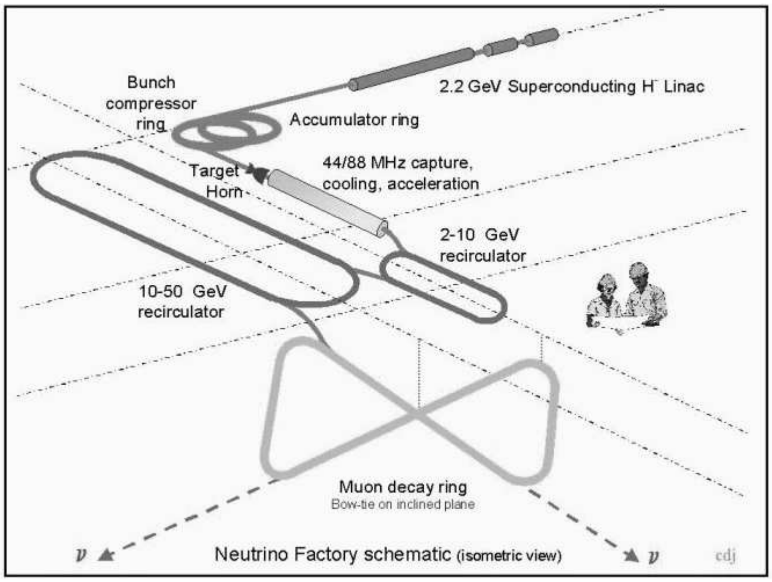

Figure 3: *Conceptual layout of a ν factory at CERN, based on the SPL* [34].

Much more muon cooling would be needed for a muon collider, e.g., one suitable as a factory to produce Higgs bosons (perhaps in the hopes of studying CP violation in their decays), or a high-energy frontier $\mu^+\mu^-$ collider [38]. We should not lose sight of the muon collider as the prospective 'faint blue dot' for the long-term development of a muon storage ring complex.

Other speakers at this meeting discuss in more detail the neutrino oscillation physics opportunities opened up by a neutrino factory [26,39]. In the following sections, I discuss in more detail some of the other physics opportunities offered by such a muon complex.

5. Charged-Lepton-Flavour Violation and Muon Physics

Even before accelerating the muons produced at the front end of a ν factory, there are many physics opportunities using slow and stopped muons, one of the most interesting being the search for $\mu \to e$ transitions.

If neutrino experiments are observing ν oscillations, should one also expect observable transitions violating charged-lepton number, such as $\mu \to e$, $\tau \to \mu$ or $\tau \to e$ transformations? If the only modification to the Standard Model is to add heavy singlet (right-handed) neutrinos in some seesaw model (2), any such transitions would be unobservably rare, since they would be suppressed by inverse powers of the heavy Majorana mass M_M. However, they could be observable in a *supersymmetric* GUT model. Between the GUT scale and the heavy neutrino mass scale M_M, the neutrino

Yukawa couplings λ_D, which in general are off-diagonal, renormalize the slepton and sneutrino mass matrices:

$$\delta m^2_{\tau,\tilde{\nu}} \simeq \frac{1}{8\pi^2}\left(3m_0^2 + A_0^2\right)\ \ell n\left(\frac{m_{GUT}}{M_m}\right)\ \lambda_D^{+}\lambda_D, \tag{10}$$

where m_0 is the soft supersymmetry-breaking scalar mass [a] and A_0 is the trilinear soft supersymmetry-breaking parameter. Once off-diagonal entries in m^2_τ and/or $m^2_{\tilde{\nu}}$ are induced, diagrams similar to those responsible for $(g_\mu - 2)$ induce $\mu \to e$, $\tau \to \mu$ and $\tau \to e$ transitions, suppressed only by powers of $m^2_{\tau,\tilde{\nu}} \lesssim 1$ TeV^2.

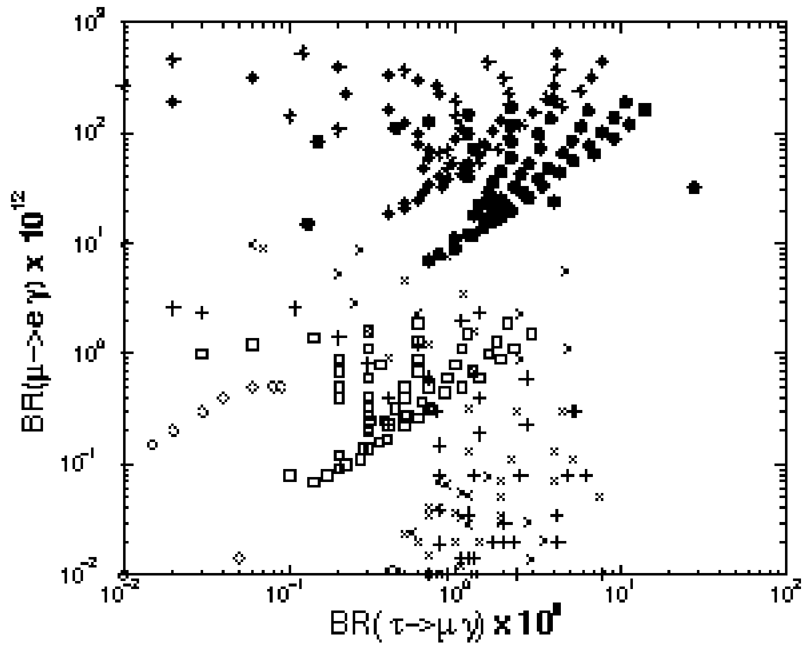

Figure 4: *Scatter plot of predictions for $\mu \to e\gamma$ and $\tau \to \mu\gamma$ in a sampling of supersymmetric GUT models with neutrino flavour textures motivated by the data on neutrino oscillations* [40)].

Fig. 4 shows rates for $\mu \to e\gamma$ and $\tau \to \mu\gamma$ in representative models of fermion mass textures motivated by the neutrino oscillation data [40)]. We see that there may be $\mu \to e$ decays at a rate within two orders of magnitude of the present limit $B(\mu \to e\gamma) < 1.2 \times 10^{-11}$, and it is also possible that $\tau \to \mu\gamma$ might appear within two orders of magnitude of the present limit $B(\tau \to \mu\gamma) < 1.1 \times 10^{-6}$.

Related to $\mu \to e\gamma$ are the processes $\mu \to 3e$, which are expected to proceed mainly via γ exchange with a rate

$$\frac{B(\mu \to 3e)}{b(\mu \to e\gamma)} \simeq \frac{\alpha}{3\pi}\ \left[\ell n(m_\mu^2/m_e^2) - \frac{11}{4}\right] \simeq 6 \times 10^{-3} \tag{11}$$

[a]We assume this to be universal for the different lepton generations: if not, the rates for charged-lepton-flavour violation would be further enhanced.

and $\mu \to e$ conversion on a heavy nucleus such as Titanium. The rate for this process is typically suppressed relative to $\mu \to e\gamma$ by a factor similar to (11), but other diagrams may contribute and this ratio is not universal. The SINDRUM II project at PSI hopes to reach a sensitivity $B(\mu Ti \to eTi) \sim 5 \times 10^{-13}$ [41], the MECO project at BNL aims at $B(\mu Ti \to eTi) \sim 5 \times 10^{-17}$ [42], and an experimentt at the JHF might be able to reach 10^{-18} [43]. These experiments may well be sensitive to the estimated rate of $\mu \to e$ conversion in a supersymmetric GUT.

Table 1: *Experiments which could benefit from the intense stopped muon sources at a ν factory* [32].

Type of Experiment	Physics Issues	Possible Experiments	previously established accuracy	present activities (proposed accuracy)	projected for NUFACT @ CERN
"Classical" Rare & Forbidden Decays	Lepton Number Violation; Searches for New Physics: SUSY, L-R Symmetry, R-parity violation,.....	$\mu^- N \to e^- N$ $\mu \to e\gamma$ $\mu \to eee$ $\mu^+ e^- \to \mu^- e^+$	6.1×10^{-13} 1.2×10^{-11} 1.0×10^{-12} 8.1×10^{-11}	PSI, proposed BNL (5×10^{-17}) proposed PSI (2×10^{-14}) completed 1985 PSI completed 1999 PSI	$< 10^{-18}$ $< 10^{-15}$ $< 10^{-16}$ $< 10^{-13}$
Muon Decays	G_F; Searches for New Physics; Michel Parameters	τ_μ $transv.Polariz.$	18×10^{-6} 2×10^{-2}	PSI (2x), RAL (1×10^{-6}) PSI, TRIUMF (5×10^{-3})	$< 10^{-7}$ $< 10^{-3}$
Muon Moments	Standard Model Tests; New Physics; CPT Tests T- resp. CP-Violation in 2nd lepton generation	$g_\mu - 2$ edm_μ	1.3×10^{-6} $3.4 \times 10^{-19} e\,cm$	BNL (3.5×10^{-7}) proposed BNL ($10^{-24} e\,cm$)	$< 10^{-7}$ $< 5 \times 10^{-26} e\,cm$
Muonium Spectroscopy	Fundamental Constants, μ_μ,m_μ,α; Weak Interactions; Muon Charge	M_{HFS} M_{1s2s}	12×10^{-9} 1×10^{-9}	completed 1999 LAMPF completed 2000 RAL	5×10^{-9} $< 10^{-11}$
Muonic Atoms	Nuclear Charge Radii; Weak Interactions	μ^- *atoms*	*depends*	PSI, possible CERN ($< r_p >$to 10^{-3})	new nuclear structure
Condensed Matter	surfaces, catalysis bio sciences ...	surface μSR	n/a	PSI, RAL (n/a)	high rate

Encouragement to search for $\mu \to e$ transitions has been provided by the recent report of a possible experimental discrepancy with the Standard Model prediction for the muon anomalous magnetic moment, $g_\mu - 2$ [44]. Taken at face value, this suggests a non-trivial flavour-diagonal $\mu^+\mu^-\gamma$ vertex with an internal scale $\lesssim 1$ TeV, corresponding to the appearance of new physics at this scale. Neutrino oscillations suggest that the flavour-diagonal $\mu^+\mu^-\gamma$ vertex should be accompanied by the corresponding flavour-off-diagonal $\mu^\pm e^\pm \gamma$ vertex. A concrete example of this expectation is provided by supersymmetry, as discussed above [45]. Ideally, one uses $(g_\mu - 2)$ to predict the sparticle mass scale and ν oscillation data to quantify the flavour mixing [45]. In practice, there are ambiguities in both these steps. However, as seen in Fig. 5, there is reason to think that $\mu \to e$ transitions might appear within two (or three) orders of magnitude of the present limits if the $(g_\mu - 2)$ discrepancy eventually stabilizes within the present one- (two-) σ range.

There are many other physics opportunities with an intense low-energy muon source [32], notably including a follow-up experiment on $(g_\mu - 2)$ itself! Another interesting search could be that for a muon electric dipole moment d^e_μ, as a probe of CP violation. In many models, this is expected to be enhanced relative to that of the electron by a factor $m_\mu / m_e \sim 200$, so a sensitivity better than 10^{-25} e.cm would have greater physics reach than the present limit on the electric dipole moment of the electron. Muonium-antimuonium conversion is also a possibility, and refined experiments measuring the muon lifetime and Michel decay parameters would be interesting. Looking beyond experiments of interest to particle physicists, one should also mention

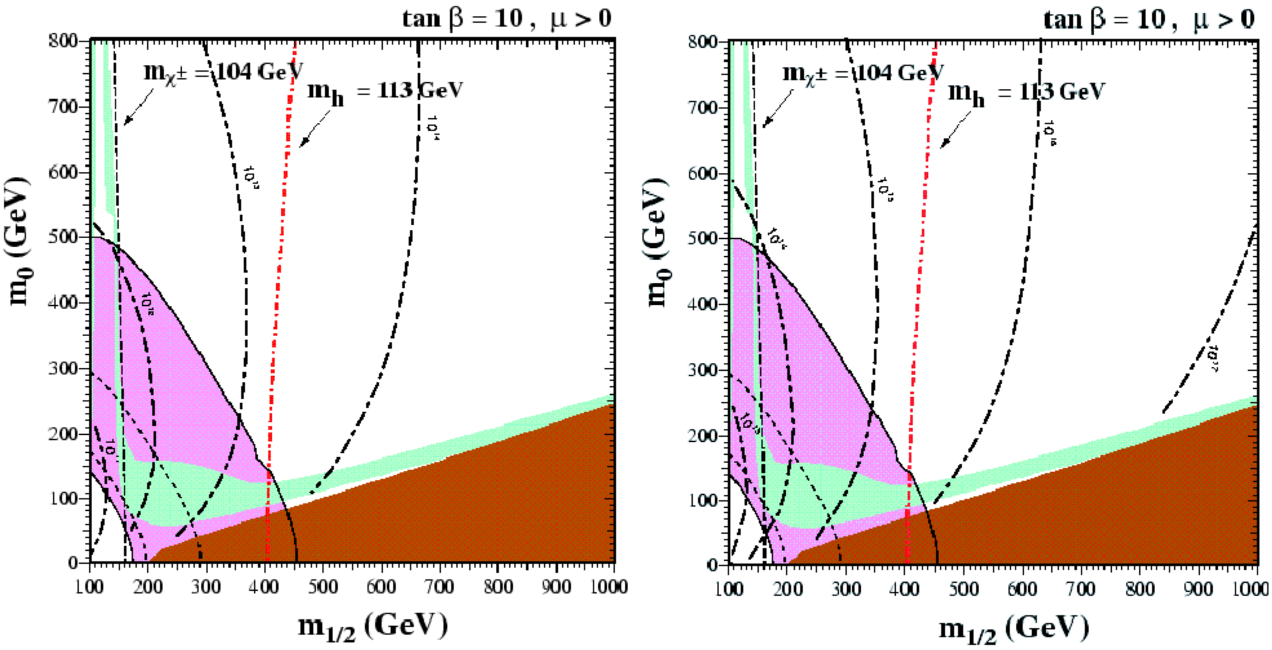

Figure 5: *Examples of the rates for (a) $\mu \to e\gamma$ and (b) $\mu Ti \to eTi$ in a supersymmetric GUT model with $\tan\beta = 10$, $\mu > 0$ and one particular choice of flavour texture for the neutrino mass matrices. The light (turquoise) shaded areas are the cosmologically preferred regions, and in the dark (brick red) shaded regions the LSP is the charged $\tilde{\tau}_1$, which is excluded. The (pink) shaded regions are favoured by the measurement of $g_\mu - 2$ at the 2- (1-)σ level (solid and dotted lines)* [45].

experiments on muonic atoms, and the use of muons as probes in condensed-matter physics and the biological sciences.

6. Deep-Inelastic Scattering

Further new particle physics opportunities arise once muons are accelerated and stored in a 'ring'. Many of the neutrinos produced in the decays of stored muons may be directed towards a short-baseline target and used in conventional deep-inelastic scattering experiments [33]. Experiments with over 10^8 events in the (x, y) plane are feasible, as seen in Fig. 6, enabling 'difficult' combinations of parton distribution functions, such as $s(x) - \bar{s}(x)$, to be measured directly for the first time. The beams are so thin and intense that relatively small detectors will have large rates, opening options such as a polarized target or a silicon vertex detector. There are five measurable structure functions in polarized νp scattering, and $g_1^{W^+ + W^-}$ measures directly the singlet combination $\Delta n + \Delta d + \Delta s (+\Delta c)$, whilst $(g_5)_{p+n}^{\nu - \bar{\nu}} = \Delta s(-\Delta c)$. Using a silicon vertex detector, one will have a much better handle on heavy quark production, enabling measurements of the CKM matrix elements V_{cs} and V_{cd} to be improved. The high statistics will also reduce greatly the statistical errors in the determination of $\alpha_s(m_Z)$, to ± 0.0003, and in $\sin^2 \theta_W$, to ± 0.0002 [33].

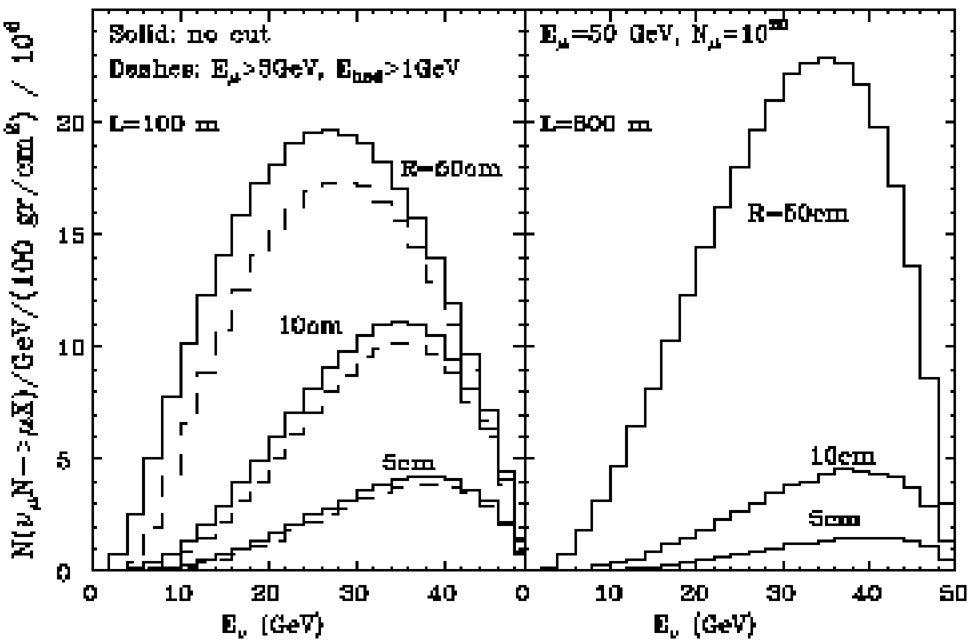

Figure 6: *Examples of the ν deep-inelastic sacttering rates possible in short-baseline experiments at a ν factory* [33].

Another possibility that should be investigated is deep-inelastic μN scattering using an internal target in the muon storage ring. The kinematic range would be similar to that of the proposed ELFE accelerator [46)]. Are there interesting aspects of ELFE physics that could be attacked using muons?

7. High-Intensity Kaon Physics

Large numbers of kaons could be produced with a high-energy ($E \gtrsim 15$ GeV) proton driver for a neutrino factory [b], or by constructing a post-accelerator for some fraction of the protons from an intense low-energy driver. Several interesting physics opportunities would be presented by intense kaon beams [47)].

$K^0_L \to \pi^0 \bar{\nu}\nu$ [47)]: This decay measures the CP-violating combination $ImV^0_{ts}V_{td}$ of CKM matrix elements, and complements the measurements of $\sin 2\beta$ at B factories. In the Standard Model, one expects $B(K^0_L \to \pi^0 \bar{\nu}\nu) = (2.8 \pm 1.1) \times 10^{-11}$, and one could hope for a 10% measurement using a K factory option for a neutrino factory.

$K^+ \to \pi^+ \bar{\nu}\nu$ [48)]: This decay measures $|V_{td}|$, and in combination with the neutral mode would determine $\sin 2\beta$ with an error of ± 0.07 in the Standard Model. This would therefore be the sensitivity to extensions of the Standard Model.

$K^0_L \to \pi^0 e^+ e^-$ [49)]: This interesting decay has contributions from direct CP violation $\propto ImV^*_{ts}V_{td}$ (which may be measurable at the 10% level), indirect CP violation related to $K_s \to \pi^0 e^+ e^-$, and the CP-conserving mechansim $K_L \to \pi^0 \gamma^* \gamma^* \to \pi^0 e^+ e^-$.

$\underline{K^0_L \to \mu^\pm e^\mp}$ [50)]: This process violates both lepton and quark flavour, and may arise from box diagrams in the presence of slepton and/or sneutrino mixing, which is expected in supersymmetric GUT models of neutrino masses. It is possible that $B(K^0_L \to \mu^\pm e^\mp) \sim 10^{-18}$, but this would not be an easy mode to observe at this level.

8. Concluding Remarks

Long-baseline neutrino oscillation experiments are the 'core business' of a neutrino factory. They bear directly upon the fundamental issues of flavour and unification, and offer many fascinating possibilities for interesting experiments.

In addition, neutrino factories open the way to many other exciting projects, such as muon colliders used either as Higgs factories or at the high-energy frontier.

Moreover, there are many interesting physics opportunities which could be exploited earlier, for example in low-energy muon physics using the front end of a neutrino factory: $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion on nuclei, $g_\mu - 2$, d^e_μ, and many more. Once the produced muons are accelerated, new opportunities such as deep-

[b]Such a higher-energy driver has been favoured in some studies [35,36)].

inelastic νN and μN scattering are made available. Intense higher-energy proton beams would also offer interesting possibilities in kaon physics.

A neutrino factory will be a complex and expensive project. Whilst neutrino oscillation physics is its primary motivation, neutrino physicists should recognize that they are a minority of the particle-physics community. We are likely to need the support and active involvement of other communities if a neutrino factory project is to be realized. For this reason, we must work together with these other communities of physicists for the successful realization of a neutrino factory.

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