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Possible Accelerators @ CERN Beyond the LHC

John Ellis

Theoretical Physics Division, CERN
CH - 1211 Geneva 23
E-mail: john.ellis@cern.ch

Abstract

The physics and world-wide accelerator context for possible accelerator projects at CERN after the LHC are reviewed, including the expectation that an e^+e^- linear collider in the TeV energy range will be built elsewhere. Emphasis is laid on the Higgs boson, supersymmetry and neutrino oscillations as benchmarks for physics after the LHC. The default option for CERN's next major project may be the CLIC multi-TeV e^+e^- collider project. Also interesting is the option of a three-step scenario for muon storage rings, starting with a neutrino factory, continuing with one or more Higgs factories, and culminating in a $\mu^+\mu^-$ collider at the high-energy frontier.

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1 The Context

By comparison with other high-energy physics laboratories, CERN is fortunate to have an exciting physics programme beyond the year 2005 already approved and under construction, centred on the LHC. However, the time scales for the R&D, approval and construction of major new accelerators are very long: the first LEP physics study started in 1975 [1], 14 years before the first data, and the first LHC physics study was in 1984 [2]. Therefore, it is already time to be thinking what CERN might do for an encore after (say) ten years of physics with the LHC. Although necessary, extrapolation to the likely physics agenda beyond 2015 is foolhardy, since several major accelerators will be providing cutting-edge data during the intervening period, and we do not know what they will find. (Otherwise, it would not be research, would it?) Nevertheless, we should try to set the après-LHC era in context by surveying the ground that these intervening accelerators will cover [3], even if our crystal ball does not reveal what they will find there.

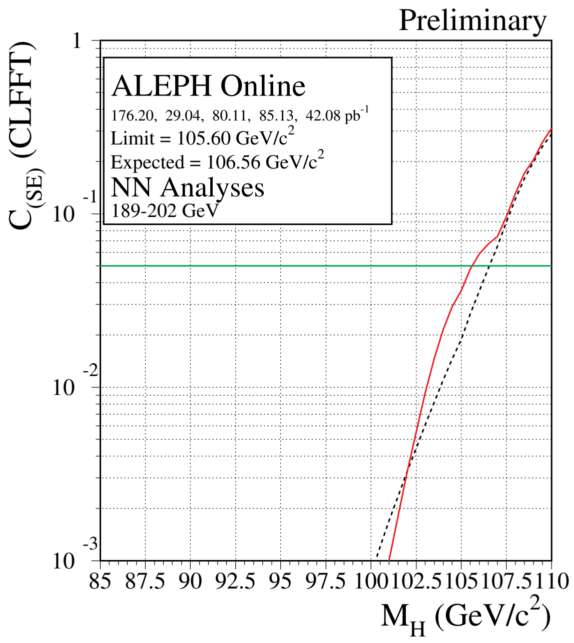

Figure 1: *Preliminary lower limit on the Standard Model Higgs mass obtained by the ALEPH collaboration [4, 6].*

LEP operation will terminate in 2000, after providing sensitivity to Higgs masses below about 110 GeV. The current lower limit from the data of an individual LEP experiment reaches about 106 GeV, as seen in Fig. 1 [4], and a combined analysis of the full 1999 data might increase the sensitivity to about 109 GeV. The most optimistic projection for 2000 that I have seen would extend this to about 113 GeV. Clearly, the overall picture changes if LEP discovers the Higgs boson. However, the precision electroweak data and supersymmetric models independently suggest that $m_H \lesssim 200$ GeV, as seen in Fig. 2 [5], in which case the programme of exploring in detail the properties of the Higgs boson is already well posed, just as the LEP programme was outlined before the discovery of the $W^\pm$ and Z^0.

CDF and Dϕ at the FNAL Tevatron collider have a chance to find the Higgs boson before the LHC in its next run starting in 2001, as seen in Fig. 3 [7]. This figure is based on theoretical assessments of the capabilities of the Tevatron detectors, and the experiments may fare better or worse. However, taken at face value, it seems that the Tevatron detectors would need more than 5 or even 10 pb^{-1} to explore masses beyond LEP's reach. Will these be available for the LHC's scheduled start in 2005? FNAL's window of opportunity will extend somewhat beyond LHC start-up, since ATLAS and CMS will take some time to accumulate the luminosity needed to explore the difficult region $M_H \lesssim 130$ GeV [8].

CDF [9] and the OPAL [10] and ALEPH [6] experiments at LEP together measure $\sin 2\beta = 0.91 \pm 0.35$ in $B \to J/\psi K_s$ decays. The B factories PEP-II (with BaBar) and KEK-B (with Belle) have already started operation, to be followed soon by HERA (with HERA-B) and CESR (with CLEO 3). All being well, the first accurate measurements of CP violation in the B sector should emerge in 2000, and many more will follow. There are also ample B-physics opportunities for CDF and Dϕ, which will be the first to explore CP

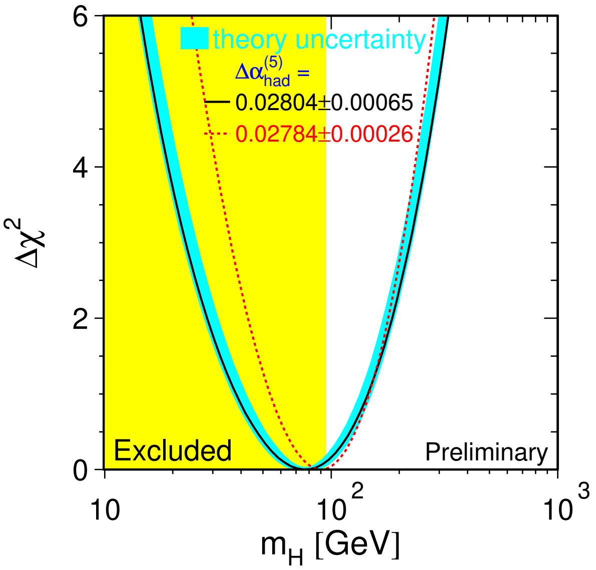

Figure 2: *Estimate of the Higgs boson mass obtained from precision electroweak data [5].*

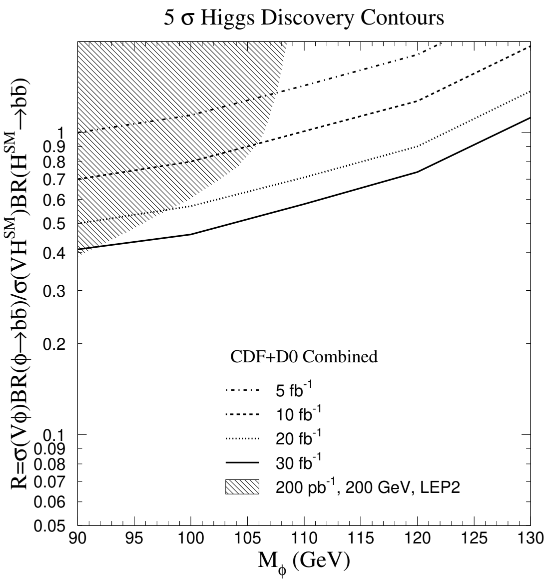

Figure 3: *Comparison of the estimated physics reaches for Higgs searches at LEP 2 and the FNAL Tevatron collider [7], as a function of Higgs mass and collider luminosity.*

violation in the B_s system. These will be followed by the LHC experiments, particularly LHCb, and possibly by BTeV. My crystal ball gets cloudy at this point: will any non-Standard-Model physics reveal itself in B decays? If so, there may be more heavy-flavour physics to pursue [11].

A promising new area of exploration has been opened by the strong indications for neutrino oscillations found by Super-Kamiokande [12] et al. [13], and several long-baseline neutrino projects are underway. K2K has started taking data, and will be able to measure ν_μ disappearance in much of the region of atmospheric-neutrino parameter space favoured by Super-Kamiokande [14]. Starting in 2001, KamLAND [15] will explore the large-mixing-angle (LMA) MSW solution of the solar-neutrino problem. In 2003/2004, MINOS will start exploring ν_μ disappearance, the NC/CC ratio and other oscillation signatures in the FNAL NuMI beam [16]. The CERN-Gran Sasso beam is planned to start providing opportunities in 2005 to look for $\nu_\mu \to \nu_\tau$ oscillations via τ production [17].

What of the LHC? As seen in Fig. 4, it will discover the Standard-Model Higgs boson (if this has not been done already), but this may take some time [8]. It will also be able to discover Higgs bosons in the minimal supersymmetric extension of the Standard Model (MSSM), though perhaps not all of them. It will also find supersymmetry (if this has not been done already), establish much of the sparticle spectrum, as displayed in Table 1 [18], and measure some distinctive spectral features, as seen in Fig. 5. To baseline the subsequent discussion, we surmise that the LHC will not only discover the Higgs boson, but also measure its mass with a precision between 0.1 % and 1 % [8]. However, it will only be able to observe a couple of Higgs decay modes. Within the context of the MSSM, the LHC will have found many sparticles, but perhaps not the heavier Higgs bosons and weakly-interacting sparticles such as sleptons and charginos [18]. The spectroscopic measurements will not enable the underlying MSSM parameters to be strongly over-constrained.

Table 1: *The LHC as 'Bevatrino': Sparticles detectable [18] at five selected points in supersymmetric parameter space are denoted by +*

	h	H/A	χ_2^0	χ_3^0	χ_1^-	$\chi_1^\pm$	$\chi_2^\pm$	$\tilde{q}$	$\tilde{b}$	$\tilde{t}$	$\tilde{g}$	$\tilde{\ell}$
1	+		+					+	+	+	+	
2	+		+					+	+	+	+	
3	+	+	+			+		+	+		+	
4	+		+	+	+	+	+	+			+	
5	+		+					+	+	+	+	+

The stage is now set for the entry of the next major actor, the first-generation e^+e^- linear collider. It will boast a very clean experimental environment and egalitarian production of new weakly-interacting sparticles, as discussed here by Zerwas [19]. Polarization will be a useful analysis tool, and $e\gamma, \gamma\gamma$ and e^-e^- colliders will come 'for free'. In many ways, it will be complementary to the LHC. The trickiest issue may be how to fix its maximum energy scale. The location of the $\bar{t}t$ threshold is known, and the precision electroweak data [5] indicate that the ZH threshold is probably below 300 GeV. This is also expected on the basis of calculations of the lightest Higgs mass in the MSSM [20]. However, what is the sparticle threshold (assuming there is one), and how/when will be

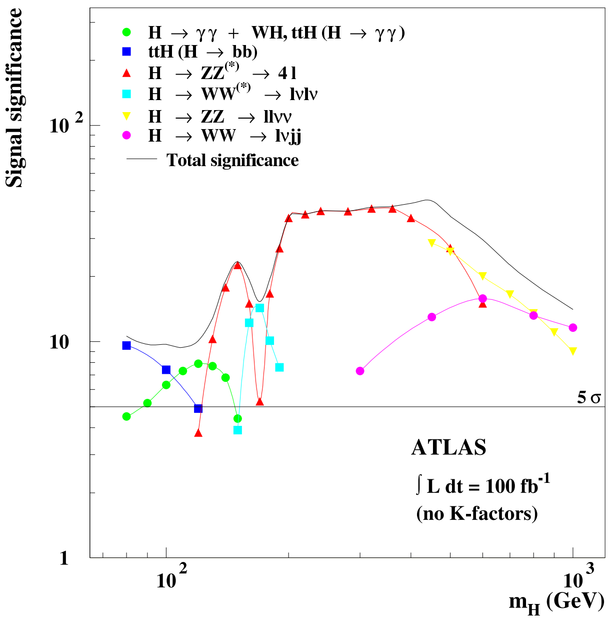

Figure 4: *Estimated significance of the possible Higgs detection at the LHC in various channels, as a function of the assumed value of the Higgs mass [8].*

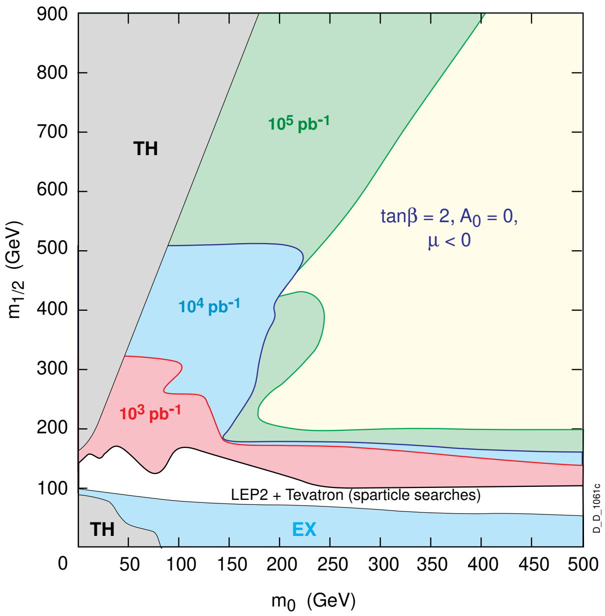

Figure 5: *Region of the MSSM parameter space in which one can detect distinctive 'edge' features in the dilepton spectra due to cascade decays of sparticles, such as* $\tilde{q} \rightarrow q + \chi_2, \chi_2 \rightarrow \chi_1 + \ell^+\ell^-$ *[8], for the indicated integrated LHC luminosities.*

able to fix it? Flexibility in the linear-collider centre-of-mass energy is surely essential. In addition to the $\bar{t}t$ and ZH thresholds, obtaining a sample of 10^9 polarized Z bosons would provide a very precise determination of $\sin^2\theta_W$, and the W mass could be measured very precisely at the W^+W^- threshold [19]. However, a centre-of-mass energy of 2 TeV would be necessary to ensure full complementarity to the LHC enabling, e.g., the sparticle spectrum in Table 1 to be completed.

The first-generation linear collider will enable detailed studies of the Higgs boson (or the lightest Higgs boson in the MSSM) to be made. Its mass will be measured to a few parts in 10^4, and all its major decay modes will be measured quite accurately [21]. This will enable, e.g., a Standard-Model Higgs boson to be distinguished from the lightest MSSM Higgs boson, if the heavier MSSM Higgs bosons weigh less than several hundred GeV. Even if the centre-of-mass energy is restricted to 1 TeV, most of the weakly-interacting sparticles and Higgs bosons will still be observed directly, and the many spectroscopic measurements will permit detailed checks of supersymmetric models [22].

It has long been clear to me that physics needs a 1-TeV linear e^+e^- collider, because of its complementarity to the LHC [23]. It will be able to follow up explorations made with the LHC by making many precision measurements. As already emphasized, the widest possible energy range is desirable. This implies that any initial lower-energy phase should be extensible to at least 1 TeV, and running back in the LEP energy range would also be desirable. For the rest of this talk, I assume that these physics arguments are sufficiently strong that a first-generation 1-TeV linear e^+e^- collider will be built.

Nevertheless, there may still be some items on the theoretical wish-list after the first-generation linear e^+e^- collider. It would be desirable to have an accurate direct measurement of the total Higgs decay width via s-channel production, and its mass could be measured much more precisely with a muon collider [24], as discussed below. Completing the sparticle spectrum may require a centre-of-mass energy of 2 TeV or more, as provided by a second-generation linear e^+e^- collider [25] or a higher-energy muon collider, and the latter could also produce heavier MSSM Higgs bosons in the direct channel. Looking further afield, the first glimpse of the 10 TeV energy range could be provided by a future larger hadron collider with $E_{cm} \gtrsim 100$ TeV [26].

2 Options for Future Colliders @ CERN

In mid-1997, the CERN Director-General at the time, Chris Llewellyn Smith mandated '... a brief written report, ..., on possible future facilities that might be considered at CERN after the LHC'. This should '... not [be] a major assessment of long-term possibilities'. I would phrase it as thinking about thinking (about thinking?). The principal options considered in our report [3] were (i) a next-generation linear e^+e^- collider with $E_{cm} \gtrsim 2$ TeV, based on CLIC technology, (ii) a $\mu^+\mu^-$ collider, ultimately in the multi-TeV E_{cm} range, but perhaps including a 'demonstrator' Higgs factory, and (iii) a future larger hadron collider (FLHC), primarily for pp collisions with $E_{cm} \gtrsim 100$ TeV, but perhaps including options for an e^+e^- top factory and ep collisions in the same (large) tunnel [1].

Starting with the option that we considered least appetizing for CERN, if only from the point of view of geography [3], it seems apparent that a luminosity of at least 10^{35} cm^{-2}s^{-1} would be required to reap full benefit from a FLHC, perhaps even 10^{36} cm^{-2}s^{-1}

[1] We considered an ep collider in the LEP tunnel to be already an estalbished CERN option [29], and in any case not one to be considered a 'flagship' project.

if $E_{cm} \sim 200$ TeV. This would pose very severe radiation problems for the detectors, but such a machine could provide the opportunity to explore the decade of mass between 1 and 10 TeV, which history suggests would be a priority after the LHC.

The default option for the next major project in CERN's future is probably CLIC, whose physics was first studied in [27], where its complementarity to the LHC was stressed. See, in particular, the contributions by Altarelli (p.36), Froidevaux (p.61), Pauss and myself (p.80), and the review by Amaldi (p.323) in [27]. A study group is now starting to take a further look at the simulation of benchmark process for CLIC [28].

The CLIC two-beam high-energy e^+e^- collider scheme was presented here by Delahaye [25], so I do not discuss it in detail. Parameter sets for $E_{cm} = 3$ and 5 TeV have been developed, and the central aim is a cost-effective, affordable strategy for such a higher-energy linear collider, since the key CLIC advantages of a high accelerating gradient and (relatively) simple components are not needed for a first-generation $E_{cm} \lesssim 1$ TeV linear collider. Two CLIC test facilities have already been built and operated successfully, CTF1 and CTF2 [25]. However, the need for at least two more demonstrator projects is foreseen before construction of CLIC itself can be envisaged. These are CTF3 in the years 2000 to 2005, to demonstrate the acceleration potential in a 0.5 GeV machine, and then CLIC1 in the years 2005 to 2009, which should attain 75 GeV [25]. Recall also that no major capital investment money will become available at CERN before 2009, because of the LHC payment schedule. For both the reasons in the two previous sentences, CLIC is necessarily on a longer time scale than that proposed for first-generation linear collider projects such as TESLA, the JLC or the NLC.

A CERN geological study has indicated that the tunnel for a linear collider ~ 30 km long could be excavated parallel to the Jura, entirely in suitable molasse rock: similar conclusions were reached in a study conducted for Swissmetro (the group that proposes to build a high-speed underground railway connecting Geneva and other major Swiss cities) [3]. Also, even a $E_{cm} = 4$ TeV $\mu^+\mu^-$ collider would fit comfortably within the area bounded by the existing SPS and LEP/LHC tunnels. On the other hand, it is difficult to see how even a high-field FLHC with $E_{cm} = 100$ TeV (which would require a tunnel circumference in excess of 100 km) could be accommodated in the neighbourhood of CERN.

As far as technological maturity is concerned, even though several hurdles need to be crossed before the CLIC technology is mature – for example, the beam delivery system has hardly been studied – it may be the closest to mass shell of the next-generation collider concepts. The technology required for a FLHC exists in principle, but the key problem is to reduce the cost per TeV by an order of magnitude compared to the LHC. This will require innovative ideas for tunnelling, as well as magnets and other machine components [26].

The most speculative option we considered was a $\mu^+\mu^-$ collider, many of whose components are at best extrapolations of current technologies, with many others not existing in any form. Considerable R&D is required even to establish the plausibility of the $\mu^+\mu^-$ collider concept. This challenge spurred the formation some years ago in the US of the Muon Collider Collaboration [30], which groups a hundred or more physicists and engineers and has proposed R&D projects, notably on ionization cooling [31]. Until recently, there was little activity in Europe on muon colliders, although some individual CERN staff members worked with the Muon Collider Collaboration. This disparity led RECFA to commission in 1998 a prospective study of $\mu^+\mu^-$ colliders, whose brief was to specify the physics case, to identify areas requiring R&D, and look for potential European resources outside CERN and DESY.

The corresponding report [32] produced in early 1999 proposed a three-step scenario for physics with muon storage rings at CERN, illustrated in Fig. 6. The first step would be a ν factory [33], in which an intense proton source would be used to produce muons, that would be captured and then cooled by a limited factor, before being accelerated and stored in a ring and allowed to decay, without being brought into collision. Such a ν factory had not been considered in [3]: the physics interest in such a machine had been amplified in the mean time, in particular by the emerging evidence for atmospheric neutrino oscillations. The big advantages over a conventional ν beam produced directly by hadronic decays are that the ν beams produced by μ decay would have known fluxes, flavours, charges and energy spectra, and would comprise equal numbers of ν_μ and $\bar{\nu}_e$ (or $\bar{\nu}_\mu$ and ν_e). Such a ν factory would surely be the 'ultimate weapon' for ν oscillation studies. This could be followed by a second step (or steps), namely a Higgs factory (or factories) [24], which could measure accurately the mass, width and other properties of a Standard Model Higgs via its direct s-channel production, and thus distinguish between it and the lightest Higgs in the MSSM, strongly constraining its parameter space in the latter case. A second factory operating on the adjacent peaks of the other neutral H and A Higgs bosons of the MSSM would also be interesting, possibly opening a novel window on CP violation in the Higgs sector. The third step would be a high-energy frontier $\mu^+\mu^-$ collider. Its advantages over an e^+e^- collider would include superior beam-energy resolution and calibration [32], whereas an e^+e^- collider such as CLIC would also offer beam polarization and the possibilities of $e\gamma, e^-e^-$ and $\gamma\gamma$ collisions.

The ν and Higgs factories are discussed in the next two sections of this talk, followed by a comparison of the e^+e^- and $\mu^+\mu^-$ strategies for attaining the high-energy frontier in lepton-lepton collisions.

3 A Neutrino Factory

The basic concept of a ν factory [32] starts with an intense low-energy proton driver providing one to 20 MW (say 4 MW) of beam power, based either on a linac or a rapid-cycling synchrotron. Beam energies between a few and 30 GeV are discussed actively [34], and the 50 GeV JHF project could be an interesting prototype project [35]. A typical source intensity would be $1.5\times10^{15} p/s$ at 16 GeV. This beam is used primarily to produce pions, which are allowed to decay into muons that must be captured, and a typical rate might be 0.2 μ/p. Of these, about a half, namely 0.1 μ/p, would survive being cooled by a factor 10 to 100 in phase space. These would then be accelerated, perhaps by a recirculating linac, to the chosen storage energy, which would probably lie in the range 10 to 50 GeV. As seen in Fig. 7, the storage 'ring' itself could be quite irregular, with two or three straight sections that would each yield $\mathcal{O}(3 \times 10^{20})\bar{\nu}_\mu$ and ν_e per year (or ν_μ and $\bar{\nu}_e$) in any given direction. Two of these directions should be those of large underground detectors located far away, perhaps one at several hundred kilometres and one at several thousand, optimized for oscillation studies. There could be a third detector close to the 'ring', optimized for Standard Model studies with neutrinos [36].

There are many accelerator issues for such a concept [37]. In addition to the choice of a rapid-cycling (how many Hz are possible?) synchrotron or a linac (could it re-use the LEP superconducting RF?), these include: the target – a liquid Mercury jet has been studied, and solid metal wires or strips have been proposed, pion capture – which would require

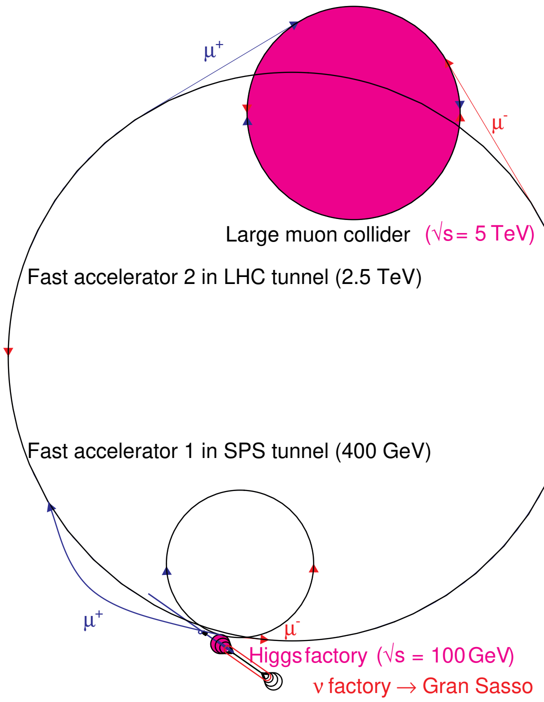

Figure 6: *Schematic layout of a possible three-step neutrino storage ring complex at CERN, including a ν factory, a Higgs factory and a possible high-energy frontier muon collider [32].*

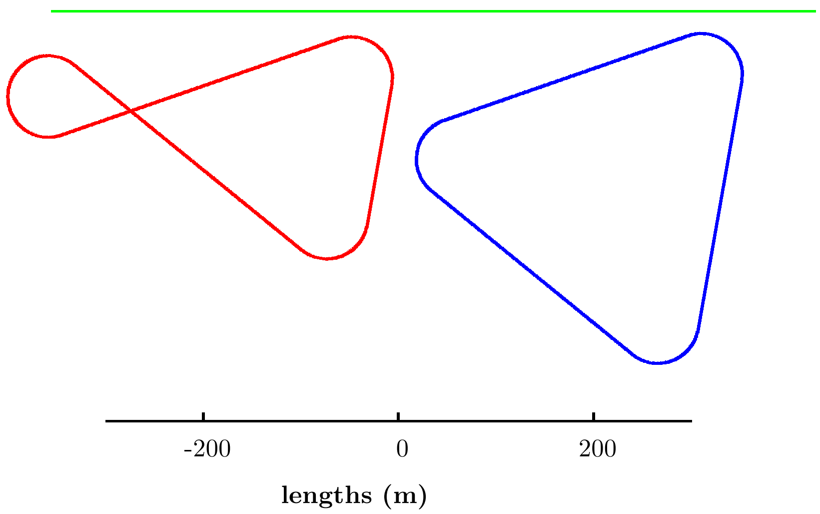

Figure 7: *Schematic geometries of possible muon storage 'rings' for a ν factory [37], with straight sections pointing towards long-, very-long-, and short-baseline experiments. The upper horizontal line is the ground surface.*

a 20 Tesla solenoid, a monochromator – which would require high-field (pulsed?) RF working in a high-radiation environment with a strong magnetic field, a cooling channel – which need only compress the muon phase space by a factor of 10 to 100 rather than the 10^6 needed for a collider, and a recirculating linac to accelerate the muons – which might be another application for the LEP RF.

Before discussing the primary physics objective of neutrino oscillations, we first review basic formulae for neutrino mixing [38]. Analogously to the Cabibbo-Kobayashi-Maskawa mxing of quarks, one has

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12}e^{i\delta} - c_{12}s_{13}s_{23} & c_{12}c_{23}e^{i\delta} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{23}s_{12}e^{i\delta} - c_{12}c_{23}s_{13} & -c_{12}s_{23}e^{i\delta} - c_{23}s_{12}s_{13} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

where the $\nu_i : i = 1, 2, 3$ are mass eigenstates. In addition to the CP-violating phase δ in (1), there are also two CP-violating relative Majorana phases that are unobservable at energies $E \gg m_{\nu_i}$, but need to be taken into account in considering the constraints imposed by double-β decay. In the simplified limit: $\Delta m^2_{12} \ll E/L \sim \Delta m^2_{23}$, one has the following oscillation probabilities [39]:

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23}\sin^2\theta_{13}\sin^2\left(\frac{\Delta m^2_{23}L}{4E}\right) \tag{2a}$$

$$P(\nu_e \to \nu_\tau) = \sin^2\theta_{23}\sin^2\theta_{13}\sin^2\left(\frac{\Delta m^2_{23}L}{4E}\right) \tag{2b}$$

$$P(\nu_\mu \to \nu_\tau) = \sin^4\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{23}L}{4E}\right) \tag{2c}$$

and the same for the time-reversed transitions $P(\nu_\mu \to \nu_e)$, etc., since the CP-violating phase δ is observable only when both Δm^2_{12} and Δm^2_{23} are large.

Figure 8 shows the sensitivity in the $(\sin^2\theta_{23}, \Delta m^2_{23})$ plane of a neutrino factory, for oscillations in the atmospheric range in a 'long'-baseline experiment: $L = 730$ km, in both the ν_μ disappearance and appearance modes for different values of θ_{13} [39]. The updated region allowed by Super-Kamiokande ($\Delta m^2_{23} \gtrsim 2 \times 10^{-3}$ eV^2) is comfortably within reach. Figure 9 shows the sensitivity in the $(\sin^2\theta_{13}, \Delta m^2_{23})$ plane for $\nu_\mu \leftrightarrow \nu_e$ oscillations, again in both appearance and disappearance modes [39]. For the current range of Δm^2_{23}, the appearance mode has access to values of $\sin^2\theta_{13}$ for below the current upper limits imposed by Super-Kamiokande and Chooz, and also far below what can be reached with a conventional hadronic-decay ν_μ beam, which contains ν_e contamination close to the 1 % level.

The fluxes obtained from a ν factory are so intense that experiments over a range of several thousand kilometres become feasible [40], and new domains of oscillation phenomena become accessible, perhaps including the CP- and T-violating asymmetries [41]:

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e)}{P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e)}, \qquad A_T \equiv \frac{P(\nu_\mu \to \nu_e) - P(\nu_e \to \nu_\mu)}{P(\nu_\mu \to \nu_e) + P(\nu_e \to \nu_\mu)} \tag{3}$$

The CP-violating asymmetry may be large if both Δm^2_{12} and θ_{12} are large:

$$A_{CP} \simeq \frac{4\sin\theta_{12}\sin\delta}{\sin\theta_{13}} \quad \sin \quad \left(\frac{\Delta m^2_{12}L}{2E}\right) \tag{4}$$

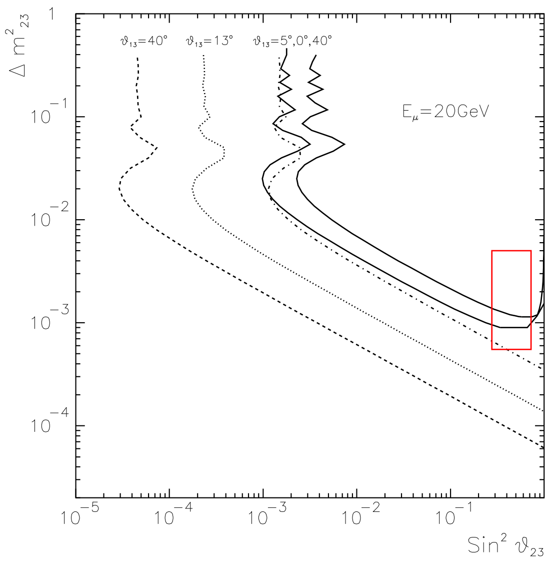

Figure 8: *Sensitivity in the* $(sin^2\theta_{23}, \Delta m^2_{23})$ *plane of a long-baseline* ν *factory detector looking in a* ν_μ *beam for* ν_μ *disappearance (solid line) or* ν_μ *appearance (dashed line) [39], for different values of* θ_{13}*.*

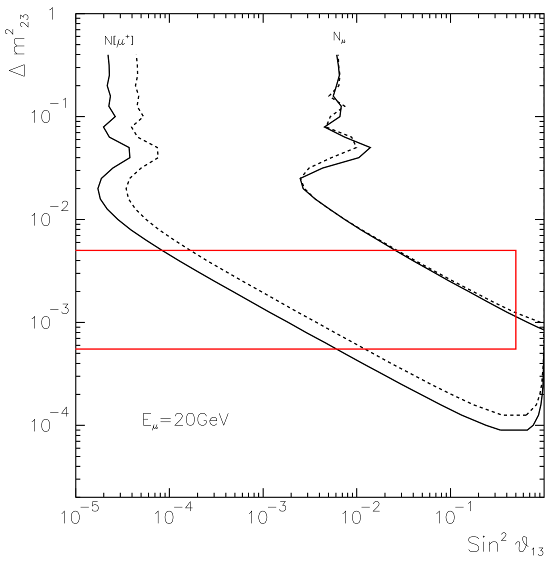

Figure 9: *Sensitivity in the* $(sin^2\theta_{13}, \Delta m^2_{23})$ *plane of a long-baseline* ν *factory detector looking in a* ν_μ *beam for* ν_μ *disappearance and* ν_μ *appearance (more sensitive) for* $\theta_{23} = \pi/4, \pi/6$ *(dashed, solid lines) [39].*

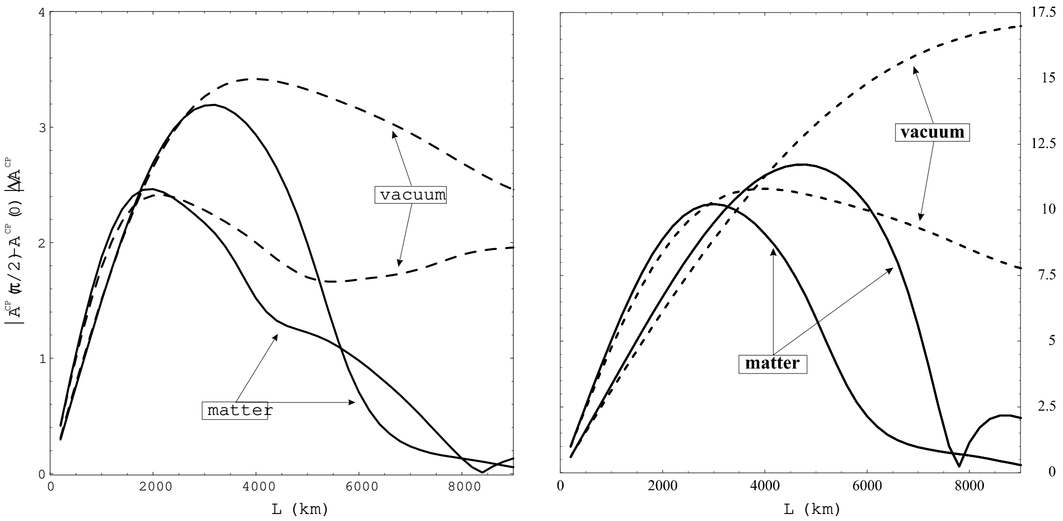

Figure 10: *Significance of the observation of a CP-violating asymmetry A_{CP} with 2×10^{20} (left panel) or 2×10^{21} neutrinos (right panel), including (solid lines) or discarding (dashed lines) matter effects, for the mixing parameters described in [42].*

and may be observable if the solar-neutrino deficit is due to the large-mixing-angle MSW solution. On the other hand, measuring A_T would require $e^{\pm}$ discrimination, which is difficult in a muli-kiloton detector. Measurements of A_{CP} must contend with the fact that the Earth is not CP-invariant, so that matter effects also contribute to A_{CP}, e.g.,

$$A_{CP}^{MSW} \simeq 0.7 \times 10^{-6} \times \frac{L^2(km^2)}{E(\text{GeV})} \tag{5}$$

for $\Delta m^2_{23} = 3 \times 10^{-3}$ eV^2 and $\Delta m^2_{12} = 3 \times 10^{-4}$ eV^2. This means that the matter effect (5) dominates for $L \gtrsim 4000$ km, as seen in Fig. 10 [42].

The preferred baseline for observing the intrinsic A_{CP} (4) seems to be $L \sim 2000$ to 3000 km, and it seems that a $5 - \sigma$ effect could be observed throughout the large-angle MSW region with a 50 kt detector operated for five years in conjunction with a 20 MW source. Further studies will be needed to optimize the choice of L, depending, e.g., on what we learn from future solar-neutrino experiments, KamLAND [15] and possibly atmospheric neutrinos in a low-threshold detector such as ICANOE [43]. It could well be that CP violation is unobservable, e.g., if the deficit is due to either the small-angle MSW solution or vacuum oscillations, or if δ is small. The matter oscillations that dominate at larger L in Fig. 10 might be of supplementary interest, either in their own right, to fix the sign of Δm^2_{23} or even to probe the internal structure of the Earth.

Other interesting particle physics [44] would also be possible with the intense proton driver needed for a ν factory. For example, it might be possible to improve by several orders of magnitude the current upper limits on charged-lepton-flavour violation in the processes $\mu \to e\gamma$, $\mu \to 3e$ and $\mu Z \to eZ$. Such experiments could explore the range of interest to supersymmetric GUT models of ν oscillations, as seen in Fig. 11 [45]. Other quantities of interst for possible physics beyond the Standard Model include the muon's anomalous magnetic moment – can an experiment with better sensitivity than that presently running at BNL be envisaged? and can the uncertainties in the hadronic

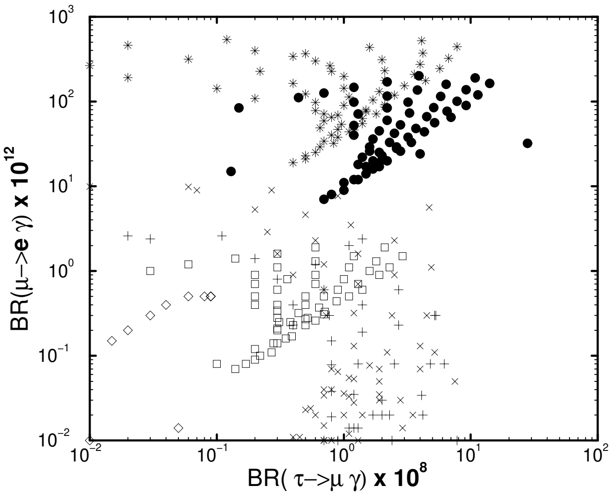

Figure 11: *Rates for $\mu \to e\gamma$ and $\tau \to \mu\gamma$ decay in some generic supersymmetric GUT models inspired by the Super-Kamiokande data on neutrino oscillations, showing opportunities both for intense μ beams and for intense τ sources, such as the LHC [45].*

contributions be controlled sufficiently to look, e.g., for possible supersymmetric contributions? It might also be possible to look for an electric dipole moment – measuring it with a precision $\sim 10^{-24}$ e.cm would have significance comparable to the present limit of 4×10^{-27} e.cm for the electron, since in many models $d_\mu / d_e \simeq m_\mu / m_e \simeq 200$. Other physics opportunities might be offered by rare K decays, such as $K_L^0 \to \pi^0 \bar{\nu}\nu$, $K^+ \to \pi^+ \bar{\nu}\nu$, $K \to \pi \ell^+ \ell^-$, $K \to \mu e$ and $K \to \pi \mu e$, if the beam energy of the proton driver is sufficiently high to produce kaons copiously.

As has already been mentioned, 'traditional' neutrino physics could be pursued using a nearby detector, with very high statistics [36]. This could be of interest for measuring $\sin^2 \theta_W$ and Cabibbo-Kobayashi-Maskawa matrix elements very precisely, and one could perhaps even use a polarized target and probe the nucleon spin in a novel way. One could also perform μ scattering experiments with a target in the μ 'ring' itself. How much of the ELFE physics programme [46] could be addressed by these NULFE and MULFE options?

Beyond particle physics, the proton driver could be used for many other experiments of interest to nuclear physicists, e.g., on muonic atoms, μ capture and radioactive beams [44]. Also the necessary high-intensity proton-beam technology would have much in common with requirements for other classes of applications, e.g., an advanced Spallation Neutron Source, radioactive waste disposal and the concept of an energy amplifier.

Therefore, this first step in the scenario for physics with muon storage rings could be of interest to a broad community.

4 Higgs Factories

The second step – the Higgs factory (or factories) requires much more beam cooling, and relies on the relatively large $\mu^+ \mu^- H$ coupling: $\Gamma(H \to \mu^+ \mu^-) \sim 4 \times 10^4 \Gamma(H \to e^+ e^-)$, and the superior beam-energy calibration and small energy spread to render direct s-channel Higgs production $\mu^+ \mu^- \to H \to X$ measurable. Neglecting beam energy spread, the

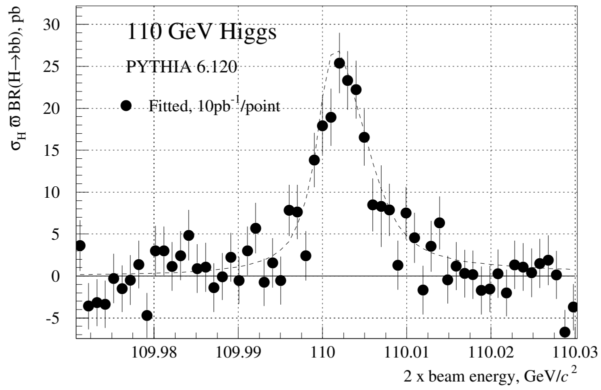

Figure 12: *Simulated measurements of the direct-channel line shape at a Higgs factory, for a Higgs boson with mass 110 GeV, assuming 10 pb^{-1} of integrated luminosity but excluding the possible beam energy spread [32].*

Higgs line shape would be [24, 32]

$$\sigma_H(s) \simeq \frac{4\pi\Gamma(H\to\mu^+\mu^-)\Gamma(H\to X)}{(s-m_H^2)^2+M_H^2\Gamma_H^2} \tag{6}$$

Since the natural width Γ_H of the Higgs is measured in MeV if $m_H \simeq 100$ GeV, a beam-energy spread $\lesssim 10^{-4}$ is desirable. Fig. 12 shows what could be attainable using a Higgs factory for a Standard Model Higgs weighing 110 GeV [32]. Thanks to the natural beam-energy calibration provided by the decay of polarized muons, it will be possible to calibrate the beam energy with a precision of 5 keV each fill [47], enabling m_H to be measured with an error of 0.1 MeV, and Γ_H could be measured with an error of 0.5 MeV by making a three-point scan [32].

This should enable the nature of the Higgs boson to be clarified. For example, the lightest MSSM Higgs boson typically has a much larger width than a Standard Model Higgs boson of the same mass, particularly for small m_A. As seen in Fig. 13, the parameters of the MSSM could be inferred [32] much more precisely from $\mu^+\mu^-$ measurements than with the LHC and/or an e^+e^- linear collider.

A second Higgs factory could then be constructed to explore the twin peaks of the H and A in the MSSM. Fig. 14 shows the result of a case study based on a coarse scan of $\pm$ 60 GeV in a previously-established mass region with $1pb^{-1}$/GeV, followed by a fine scan of six points with 25 pb^{-1}/point [32]. These would be sufficient to establish the peak cross sections with precisions $\Delta\sigma_{peak}^{H,A}/\sigma_{peak}^{H,A} = \pm 1\%$, $\Delta m_{H,A} = \pm$ 10 MeV, $\Delta\Gamma_{H,A} = \pm$ 50 MeV. Many detailed studies of H and A decay modes would be possible, and one of the enticing possibilities would be to look for CP violation in their decays [48].

5 The High-Energy Frontier

A lepton collider with several TeV of centre-of-mass energy would have a physics reach extending beyond the LHC in many respects. What might be interesting physics at that time, and how would high-energy e^+e^- (e.g., CLIC) and $\mu^+\mu^-$ colliders compare? Their effective mass reaches may be assumed to be similar: E_{cm} for CLIC might be limited for

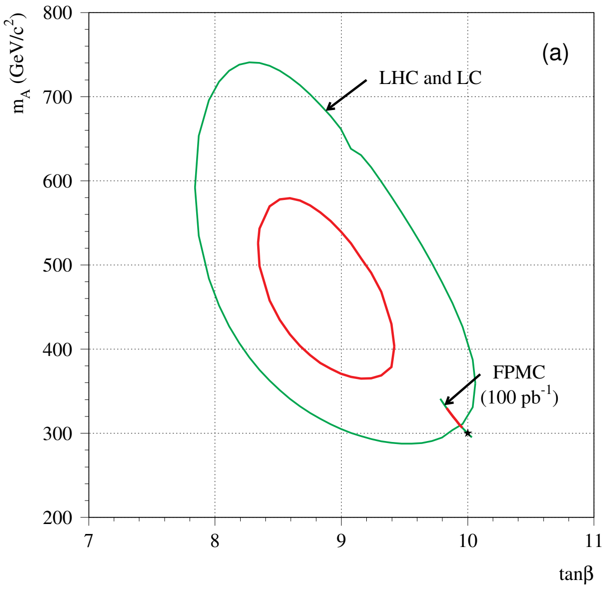

Figure 13: *Estimated precision with which direct-channel measurements of the Higgs line shape at a Higgs factory could be used to constrain MSSM parameters, compared with analogous estimates for the LHC and an e^+e^- linear collider [32].*

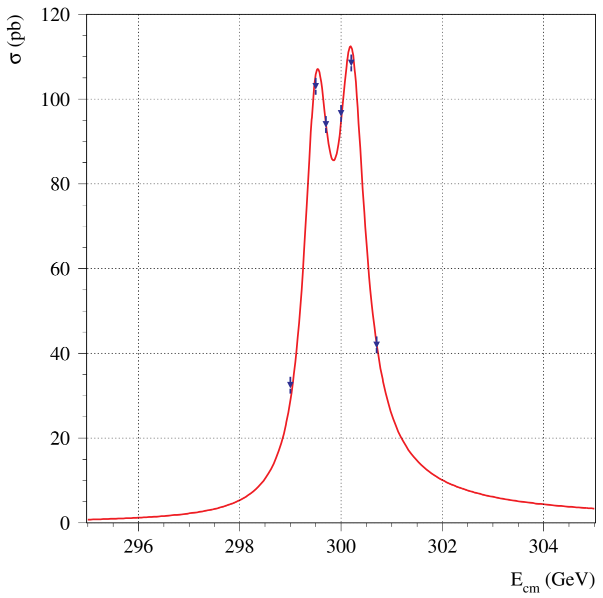

Figure 14: *Simulated measurements of the direct-channel production of the heavier MSSM Higgs bosons (h, A) at a Higgs factory, assuming $m_A = 300\ GeV$, $tan\beta = 10$, $25\ pb^{-1}$ of integrated luminosity per point, and a beam-energy spread of 3×10^{-5} [32].*

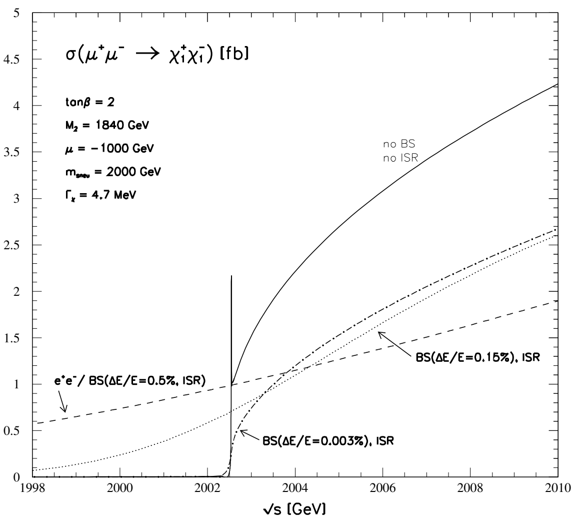

Figure 15: *Calculation of the $\mu^+\mu^- \to \chi^+\chi^-$ chargino-pair threshold, showing the effects of initial-state radiation (ISR) and beamstrahlung (BS) [32].*

both financial and technical reasons, and E_{cm} for a $\mu^+\mu^-$ collider might be limited by the danger of neutrino radiation [49], as discussed later.

The difference between the lepton flavours might play a role in some physics processes, for example in the context of R-violating supersymmetry [32], where e^+e^- and $\mu^+\mu^-$ colliders are sensitive to different couplings. We have already seen how the larger Higgs-$\mu^+\mu^-$ coupling could confer advantages on a lower-energy $\mu^+\mu^-$ collider. The same would be true of a higher-energy $\mu^+\mu^-$ collider if, for example, m_A were very large, i.e., above 2 TeV. The smaller energy spread and better energy calibration of a higher-energy $\mu^+\mu^-$ collider could also be interesting, for example for threshold measurements. One example studied [32] was the reaction $\mu^+\mu^- \to \chi^+\chi^-$, where the threshold cross section is much more sensitive to $m_{\chi^\pm}$ than is $e^+e^- \to \chi^+\chi^-$:

$$\left.\frac{d\sigma}{dm_{\chi^\pm}}\right|_{\mu^+\mu^-} \simeq 24 \times \left.\frac{d\sigma}{dm_{\chi^\pm}}\right|_{e^+e^-} \tag{7}$$

after inclusion of initial-state radiation and beamstrahlung effects, as shown in Fig. 15. There could also be some advantage in the study of narrow resonances, as might occur in some models of strongly-coupled Higgs sectors and/or extra dimensions [32].

On the other hand, there are some instances where the availability of $e\gamma$, $\gamma\gamma$ and e^-e^- collisions with an e^+e^- collider could be advantageous. Table 2 [32] lists some relevant physics topics, summarizes the principal capabilities of high-energy $\mu^+\mu^-$ and e^+e^- colliders and compares them with the LHC. Noted specifically are examples where the energy precision (E) or flavour non-universality (F) would be advantageous for a $\mu^+\mu^-$ collider, and where the availability of $e\gamma$ and/or $\gamma\gamma$ collisions (γ) or beam polarization (P) would favour an e^+e^- collider. It should also be commented that the experimental environment at a high-energy $\mu^+\mu^-$ collider is likely to be far more difficult than a CLIC. There is no way to prevent off-momentum $\mu^\pm$ passing through the detector, though it should be possible to shield out the $e^\pm$ from $\mu^\pm$ decays.

The biggest obstacle to obtaining high energies in $\mu^+\mu^-$ colliders may be ν radiation [49], which may even become a health hazard at $E_{cm} \gtrsim 3$ TeV. Neutrinos will radiate

Table 2: *A comparison of some of the capabilities of high-energy colliders, including the LHC, a second-generation linear e^+e^- collider and a $\mu^+\mu^-$ collider at the high-energy frontier. for the latter two cases, we note instances where photon beams (γ), polarization (P), flavour non-universality (F) and energy calibration and resolution (E) might be advantages.*

Physics topics	LHC	e^+e^-	$\mu^+\mu^-$
Supersymmetry			
Heavy Higgses H, A	X?	?:γ	Y:F,E
Sfermions	$\tilde{q}$	$\tilde{\ell}$	$\tilde{\ell}$: F
Charginos	X?	Y: P	Y: F,E
R Violation	$\tilde{q}$ decays	λ_{1ij}	λ_{2ij}: F,E
SUSY breaking	some	more	detail: F,E
Strong Higgs sector			
Continuum	$\lesssim$ 1.5 TeV	$\lesssim$ 2 TeV	$\lesssim$ 2 TeV
Resonances	scalar, vector	vector, scalar	vector (E), scalar (F)
Extra dimensions			
Missing energy	large E_T	Y	Y : E?
Resonances	q^*, g^*	γ^*, Z^*, e^*	γ^*, Z^*, μ^*: E

in all directions in the plane of the collider ring, with particular concentrations in the directions of any straight sections. In contrast to a ν factory, where these should be as long as possible relative to the arcs, in a high-energy $\mu^+\mu^-$ collider one would like them to be as short as possible. Other strategies for reducing the ν radiation hazard include burying it in a deeper tunnel, learning to be more efficient in using muons to produce collider luminosity, and subtle choices of 'ring' geometry.

6 Present Accelerator R&D Activities at CERN

In its current Medium-Term Plan, the present CERN management has expanded accelerator R&D activities at CERN, including work on both linear colliders and high-intensity proton sources. A larger fraction of the resources available will be directed towards CLIC. As discussed here by Delahaye [25], it is hoped to continue the previous successful studies with two successive stages, CTF3 and CLIC1, before reaching a stage (after 2008) when CLIC could be built. In parallel, a working group has recently been charged to map out a strategy for R&D towards a ν factory, including studies of the proton driver, targetry, π capture, μ cooling and acceleration [50].

As a first step, four specific activities have been proposed [51]:

- an experiment to measure π production,
- tests of RF cavities in a radiation environment with a strong magnetic field,
- measurements of wide-angle muon scattering, with a view to better modelling of cooling channels, and
- target studies.

In parallel to these accelerator R&D activities, there are physics study groups for ν beams and detectors (concentrating on oscillation experiments) [52], on $\mu^+\mu^-$ collid-

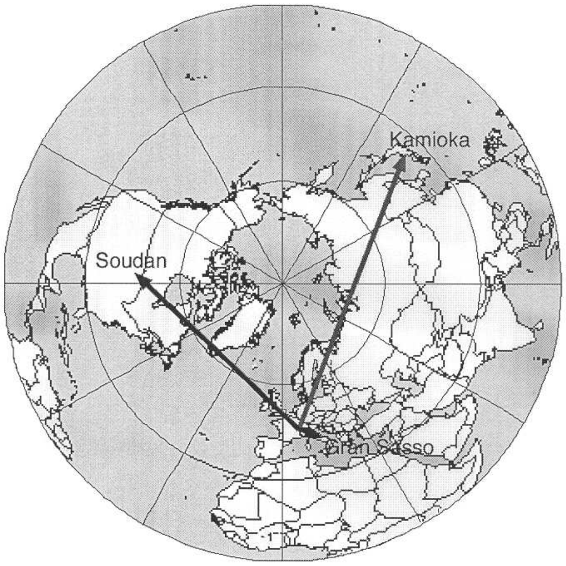

Figure 16: *A Eurocentric view of the possible World-Wide Neutrino Web, showing a source at CERN sending ν beams to the Gran Sasso laboratory, the Soudan mine and Super-Kamiokande.*

ers [53], and on other possible physics with stopped muons, ν scattering, etc. [54]. Simultaneously, there are parallel accelerator and physics working groups at FNAL [55], the NSF has commissioned an Expression of Interest for R&D towards a ν factory [37], and a second international workshop is scheduled for Monterey in May 2000 [56].

7 Prospects

As reviewed in this talk, there are clearly several interesting options for possible accelerators at CERN beyond the LHC, some of which are being studied quite actively, with CLIC as a default option [25]. The relative priorities of the various options before CERN will depend on project developments elsewhere as well as on physics developments. In the coming years, there will clearly need to be mutual understanding and coordination between accelerator laboratories in different regions of the world, so as to arrive at a suitable distribution of projects. There is already worldwide interest in linear e^+e^- colliders, and active discussion of different projects. In a few years' time, a similar stage may be reached for ν factories. Global coordination on R&D is already underway, and a similarly cooperative approach to siting optimization would be desirable. Hopefully, we will eventually see a 'World-Wide Neutrino Web' consisting of an intense proton source in one region feeding neutrino beams to detectors in different regions – a true World Laboratory for ν Physics. A Eurocentric vision of this concept is shown in Fig. 16: see [37] for two competing American visions.

CERN is preparing actively [25, 28, 50, 51] to play whatever role seems most interesting and appropriate in the generation of accelerators following the LHC.

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