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Physics Goals of the Next Century @ CERN

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Abstract

After recalling briefly the main physics issues beyond the Standard Model, the main physics objectives of experiments at CERN in the coming decade(s) are reviewed. These include the conclusion of the LEP programme during the year 2000, a limited number of fixed-target experiments during the following years, the CNGS long-baseline neutrino programme and the LHC, both scheduled to start in 2005. Then possible accelerator projects at CERN after the LHC are reviewed, in the expectation that an e^+e^- linear collider in the TeV energy range will be built elsewhere. 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 Beyond the Standard Model

As at other accelerator laboratories, the top priorities at CERN in the 21st century will be experiments probing beyond the Standard Model. Indeed, this is surely the only responsible motivation for major new accelerators.

Problems beyond the Standard Model may conveniently be gathered into three major classes: those of **Mass**, **Unification** and **Flavour**. What is the origin of the particle masses, are they due to a Higgs boson, and if so why are they so small, perhaps because of supersymmetry? Is there a simple group framework containing the strong, weak and electromagnetic gauge interactions, and does it predict new observable phenomena such as proton decay and neutrino masses? Why are there so many types of quarks and leptons, and how can one understand their weak mixing and CP violation, perhaps because they are composite or have extra symmetries?

Beyond these beyonds lurks the **Theory of Everything** that is supposed also to include gravity, reconcile it with quantum mechanics, explain the origin of four-dimensional space-time, etc. The only plausible candidate is what used to be called superstring theory, now M theory. There are ideas how to probe this at accelerators, particularly if there are large extra dimensions, but these will not be featured in the rest of this talk.

2 Setting The Stage

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.

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 have a chance to find the Higgs boson before the LHC in the next run of the FNAL Tevatron collider 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

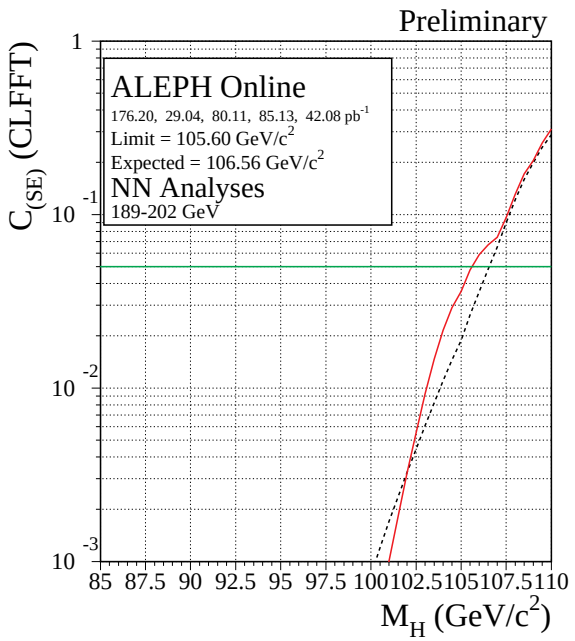

Figure 1: *Preliminary lower limit on the Standard Model Higgs mass obtained by the ALEPH collaboration [4, 6].*

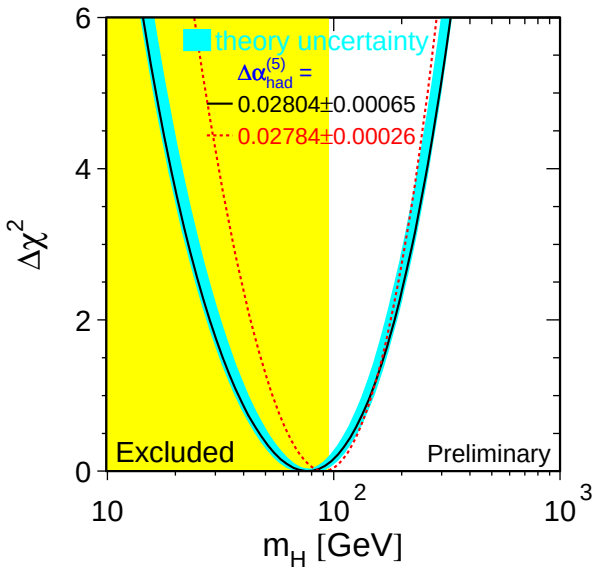

Figure 2: *Estimate of the Higgs boson mass obtained from precision electroweak data [5].*

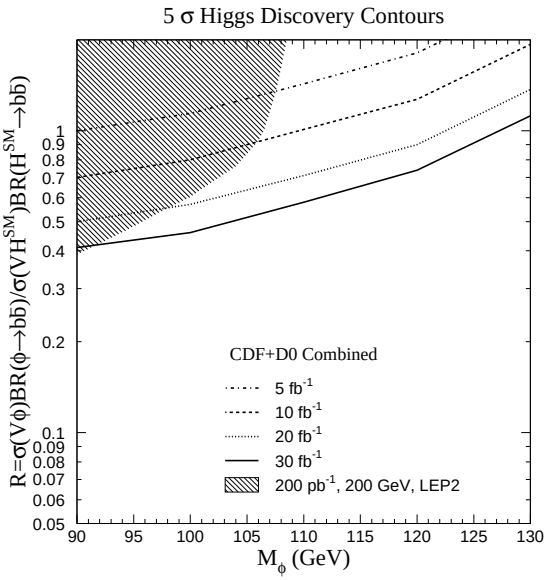

Figure 3: *Comparison of the estimated physics reaches for Higgs searches at LEP 2 and the FNAL Tevatron collider [7], as a function of Higgs mass and collider luminosity.*

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].

The CERN experimental programme in the years leading up to LHC operation has been pared to the bone, because of resource restrictions. The NA48 apparatus will continue to be used to measure ϵ'/ϵ and rare K decays, probably through the year 2003. The COMPASS experiment is starting its programme of gluon polarization and other measurements. The DIRAC experiment has started its programme to measure $\pi - \pi$ scattering lengths via the lifetime of the pionium atom. The antiproton-decelerator (AD) facility is being commissioned for its programme of anti-Hydrogen spectroscopy and CPT tests. The neutron time-of-flight facility and ISOLDE will be in operation for nuclear physics. The SPS heavy-ion programme, which has found evidence for collective effects indicative of a new state of matter that may be associated with the quark-gluon plasma, may acquire a new lease of life from a charm production experiment [9]. The HARP experiment [10] is being proposed to study particle production for ν factory designs and to help reduce uncertainties in the atmospheric ν flux. Finally, a proposal is being prepared to study the seeding of clouds by ionizing particles [11], with the aim of seeing whether fluctuations in the flux of cosmic rays could influence the amount of cloud cover, and hence the climate [12].

3 The CERN-Gran Sasso Long-Baseline ν Project

A promising new area of exploration has been opened by the strong indications for neutrino oscillations found by Super-Kamiokande [13] et al. [14], and several long-baseline neutrino

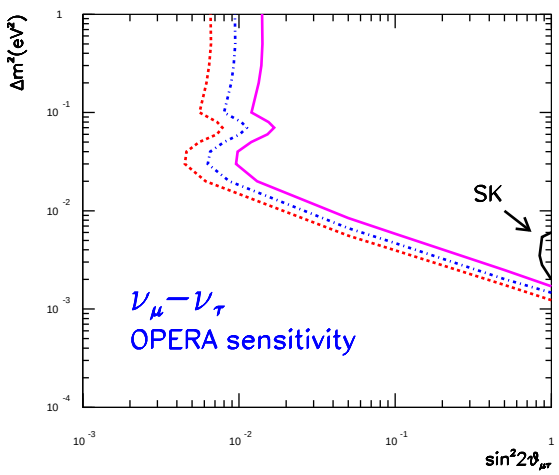

Figure 4: *Estimated sensitivity of the OPERA experiment to τ production by $\nu_\mu \to \nu_\tau$ oscillations [20], after 2,3 and 4 years of operation, compared with the region preferred by Super-Kamiokande [13].*

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 [15]. The data taken in 1999 already find intriguingly few events, compared with no-oscillation expectations. Starting in 2001, KamLAND [16] 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 [17].

We heard at this meeting that CERN-Gran Sasso neutrino beam project (CNGS) [18] has been approved by the CERN Council. The favoured interpretation of the Super-Kamiokande and other data is $\nu_\mu \to \nu_\tau$ oscillations, but the K2K and NuMI/MINOS projects are not designed to look directly for τ appearance: this is the primary objective of the CNGS project. I believe that direct observation of the τ oscillation product is an important scientific objective: "If you have not seen the body, you have not proven the crime", cf. Jimmy Hoffa and the discovery of the gluon in $e^+e^- \to$ three-jet events [19].

The CNGS project makes maximal use of the CERN and Gran Sasso infrastructure, including the SPS-LHC beam transfer line and the preplanned orientation of the Gran Sasso experimental halls. The CNGS beam energy has been optimized for τ production, and there are two major experiments proposed for the CGNS beam: OPERA [20] and ICANOE [21]. These expect to detect the following numbers of τ (background) events if $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2: 18 (<1) for OPERA, 44(6.4) for ICANOE. OPERA will be able to see τ production comfortably over the parameter region favoured by Super-Kamiokande, as seen in Fig. 4, and ICANOE may additionally be able to probe the LMA MSW solution of the solar-neutrino problem, via low-threshold measurements of atmospheric neutrinos, as seen in Fig. 5.

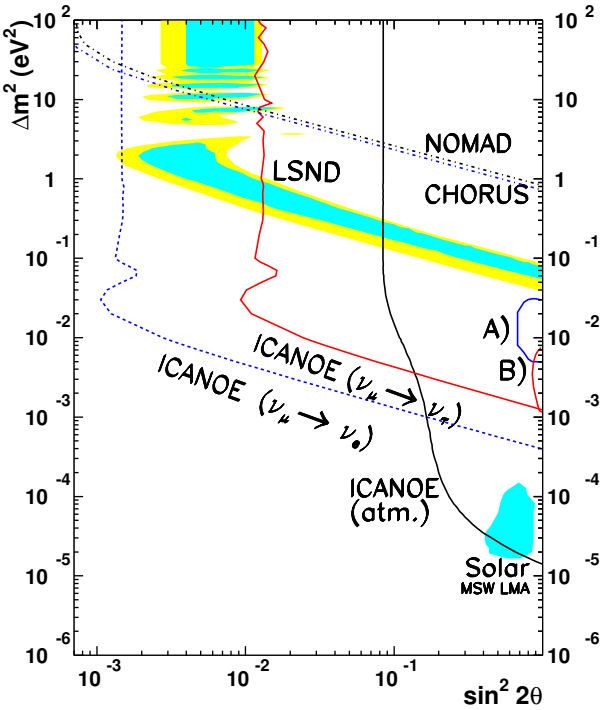

Figure 5: *Estimated sensitivity of the ICANOE experiment to τ production by $\nu_\mu \rightarrow \nu_\tau$ oscillations, and to the LMA MSW solution to the solar neutrino problem [21].*

4 Status of LHC Construction

As far as the LHC machine is concerned, the most critical items are the civil engineering and the overall cost. The surface construction work is currently on schedule. The ATLAS pit has been dug as far as possible down towards the LEP/LHC tunnel. There have been some delays here and for the CMS pit, where there was more difficulty than expected in stopping the underground water flow. There has also been some delay in digging the TI8 (Eastern) SPS-LHC beam-transfer tunnel, but this has no consequence for the overall schedule. The TI2 (Western) SPS-LHC tunnel is on the critical path, and the prospect of a delay there has led to a fall-back plan to install LHC magnets through the L3/ALICE pit.

The second pre-production main-dipole magnet performs nominally, and there is hope of operating the ring at 9 Tesla, which would correspond to $E_{cm} = 15$ TeV. The contracts for the magnet cold masses and other components have been placed, within budget, and the final assembly contracts will be placed in 2001. The various international contributions to the machine, from the U.S., Japan, Russia, Canada and India are proceeding well. For example, several trucks arrive at CERN each month delivering beam-transfer magnets from Novosibirsk.

5 Selected LHC Physics Topics

Although the main lines of the LHC physics programme are well known, there are continual advances. Here I highlight new aspects from the (published) ATLAS physics TDR

and the (forthcoming) CMS physics TDR.

As seen in Fig. 6, the LHC will discover the Standard-Model Higgs boson (if this has not been done already), but this may take some time [8]. However, for any given value of the Higgs mass, the LHC will probably measure only one or two of its decay modes. It will be able to measure their branching ratios with an accuracy of 10 to 20 %, the total width with an error $\lesssim 10$ % for $M_H \gtrsim 300$ GeV, and the mass with an error between 10^{-3} and 10^{-2} for $m_H \lesssim 800$ GeV [22]. The LHC will also be able to discover Higgs bosons in the minimal supersymmetric extension of the Standard Model (MSSM), as seen in Fig. 7, though perhaps not all of them.

Over most of the MSSM Higgs parameter space, it will discover the Higgs in two or more ways. It will also find supersymmetry (if this has not been done already), establish much of the sparticle spectrum, as displayed in Table 1 [23], and measure some distinctive spectral features, as seen in Fig. 8. These will enable the MSSM parameters to be measured with good precision, at least if universal input supergravity parameters are assumed. The cascade decays may also be a rich source of MSSM Higgs bosons, as seen in Fig. 9 [8]. It is also worth noting that the LHC can cover comfortably all the region of MSSM parameter space where the lightest supersymmetric particle could constitute the cold dark matter in the Universe. The LHC can also find supersymmetry in scenarios with R violation [24] or gauge mediation [25].

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 [23]. The spectroscopic measurements will not enable the underlying MSSM parameters to be strongly over-constrained.

Table 1: *The LHC as 'Bevatrino': Sparticles detectable [23] 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	+		+					+	+	+	+	+

6 e^+e^- Linear-Collider Physics

The stage is now set for the entry of the next major actor, the first-generation e^+e^- linear collider which is being proposed by other accelerator laboratories. It will boast a very clean experimental environment and egalitarian production of new weakly-interacting sparticles [26]. 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

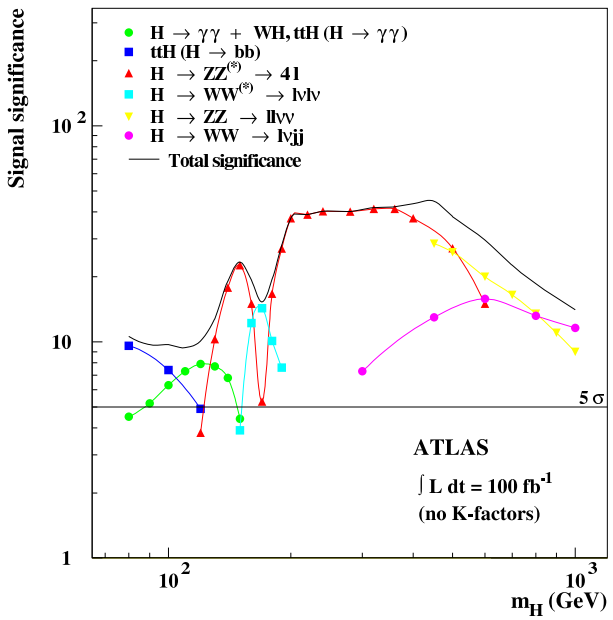

Figure 6: *Estimated significance of the possible Higgs detection at the LHC in various channels, as a function of the assumed value of the Higgs mass [8].*

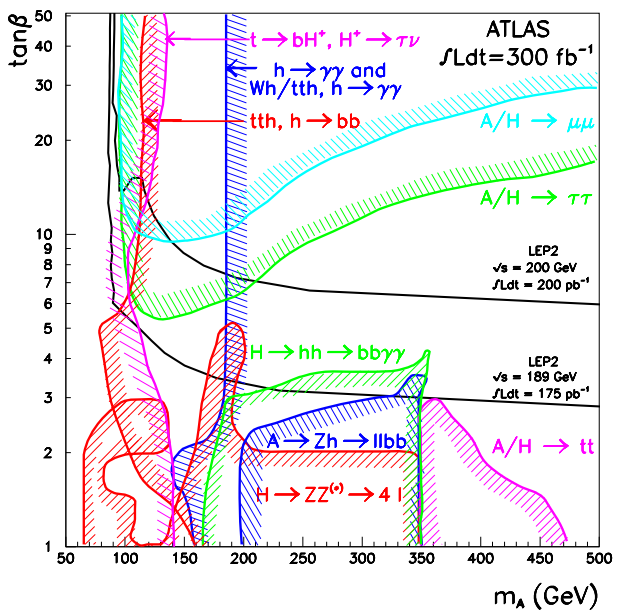

Figure 7: *Detectability of MSSM Higgs bosons at the LHC [8].*

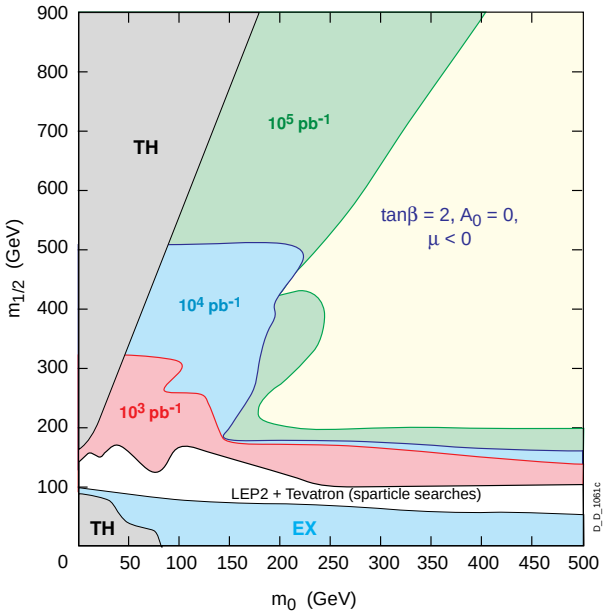

Figure 8: *Region of the MSSM parameter space in which one can detect distinctive 'edge' features in the dilepton spectra due to cascade decays of sparticles, such as* $\tilde{q} \to q + \chi_2, \chi_2 \to \chi_1 + \ell^+\ell^-$ *[8], for the indicated integrated LHC luminosities.*

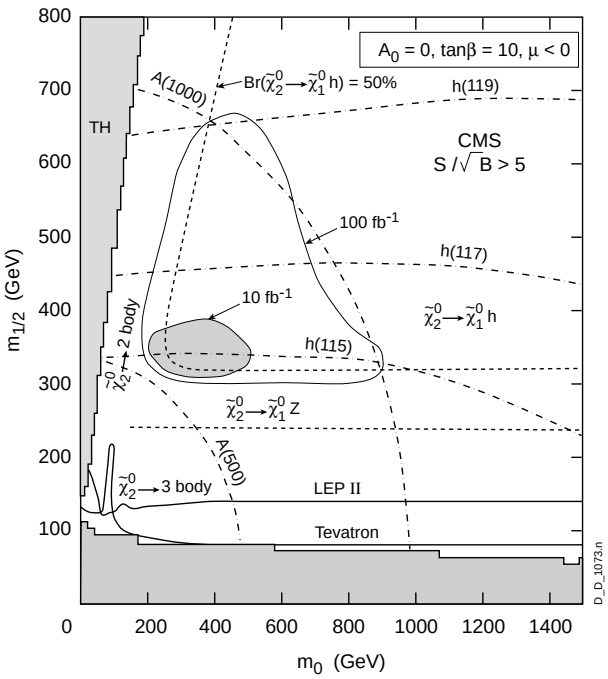

Figure 9: *Region of the MSSM parameter space in which one can detect a Higgs boson in the cascade decays of sparticles [8], assuming universal input supergravity parameters, for the indicated integrated LHC luminosities.*

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 [27]. However, what is the sparticle threshold (assuming there is one), and how/when will be 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 [26]. 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 [28]. 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 [29].

If an e^+e^- linear collider gets above the threshold for producing pairs of supersymmetric particles, it will find a scornucopia of new physics. But how likely is this to happen? The only argument I know that sets a hard upper limit on the sparticle mass scale is that the LSP constitutes the cold dark matter in the Universe [30]. This requirement imposes the upper limit $\Omega_{\rm CDM}h^2 \lesssim 0.3$. However, the supersymmetric relic density Ω_χ rises as m_χ and the input sparticle mass scales m_0, $m_{1/2}$ increase. Therefore, the region of the $(m_0, m_{1/2})$ plane where $\Omega_\chi h^2 \lesssim 0.3$ is bounded, although it has been stretched to larger $m_{1/2}$ by the recent realization [31] that $\chi\tilde{\ell}$ coannihilation processes can be important.

The question then arises, how much of the supersymmetric dark matter region is covered by a linear e^+e^- collider with a given $E_{\rm cm}$? The answer we found [30] was about 60 % if $E_{\rm cm} = 0.5$ TeV, 90 % if $E_{\rm cm} = 1$ TeV, and 100 % if $E_{\rm cm} = 1.25$ TeV, as seen in Fig. 10. The coannihilation processes were costly: without them, $E_{\rm cm} = 0.5$ TeV would have been sufficient to "guarantee" the discovery of supersymmetry, as seen in Fig. 12.

It has long been clear to me that physics needs a 1-TeV linear e^+e^- collider, because of its complementarity to the LHC [32]. 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 somewhere.

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 [33], 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 [34] 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 [35].

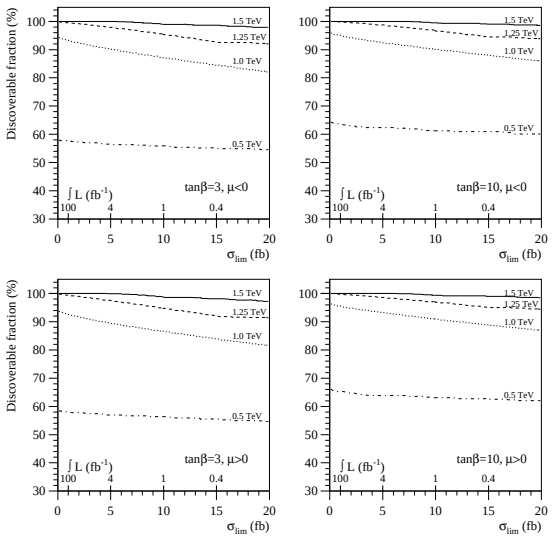

Figure 10: *Percentages of the MSSM parameter space in which the lightest supersymmetric particle could constitute the cold dark matter that could be accessed by a linear collider with the indicated E_{CM} and integrated luminosity [30].*

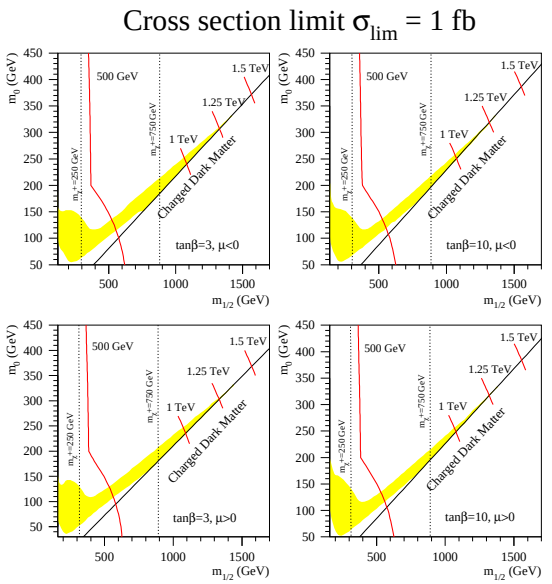

Figure 11: *Illustration of the region of the MSSM parameter space in which the lightest supersymmetric particle could constitute the cold dark matter, compared with the reaches of some channels for e^+e^- annihilation into pairs of sparticles [30].*

7 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} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ would be required to reap full benefit from a FLHC, perhaps even 10^{36} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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.

8 CLIC

The default option for the next major project in CERN's future is probably CLIC, whose physics was first studied in [36], 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 [36]. A study group is now starting to take a further look at the simulation of benchmark process for CLIC [37]. A preliminary list of key physics processes to be studied is given in Table 2.

Table 2: *Examples of Benchmark Physics Processes for CLIC [37].*

[1] We considered an ep collider in the LEP tunnel to be already an established CERN option [38], and in any case not one to be considered a 'flagship' project.

Physics Channel	Main Signature	CLIC Challenges
Heavy Higgs H^0	M_{jj}	L
Strong Symmetry Breaking		$\gamma\gamma$ bkg, Hermeticity
Anomalous W couplings		$\gamma\gamma$ bkg
$e\bar{\nu}W$		$\gamma\gamma$ bkg
Heavy (H^0, A^0, $H^\pm$) Higgses	M_{jj}, b-tag	$\frac{dL}{d\sqrt{s}}$, Pairs, $R_{beam\ pipe}$
SUSY $\tilde{g}$, $\tilde{q}$	E_{miss}, tags	$\gamma\gamma$ bkg, Hermeticity, $R_{beam\ pipe}$
$\tilde{\chi}^+\tilde{\chi}^-$	E_{miss}	$\gamma\gamma$ bkg, Hermeticity
$\tilde{\ell}^+\tilde{\ell}^-$	E_{miss}, ℓ	$\frac{dL}{d\sqrt{s}}$, Hermeticity
Contact interactions		$\sqrt{s}$, L
Z' (M $\simeq$ 3 TeV)	Direct $M_{jj,\ell\ell}$	$\frac{dL}{d\sqrt{s}}$, L
Z' (M $>$ 5 TeV)	A_{FB}, $\sigma_{f\bar{f}}$	Pairs, Mask, $R_{beam\ pipe}$
Extra Dimensions	KK, Indirect	$\gamma\gamma$ bkg, μ bkg

The CLIC two-beam high-energy e^+e^- collider scheme [34], has been used to develop parameter sets for E_{cm} = 3 and 5 TeV. 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 [34]. 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 [34]. 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 $\sim$ 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 [35].

9 Muon Storage Rings

The most speculative option we considered [3] 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 [39], which groups a hundred or more physicists and engineers and has proposed R&D projects, notably on ionization cooling [40]. 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 [41] produced in early 1999 proposed a three-step scenario for physics with muon storage rings at CERN, illustrated in Fig. 12. The first step would be a ν factory [42], 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. One of the most enticing possibilities is the search for CP and/or T violation;

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} , \qquad A_T \equiv \frac{P(\nu_\mu \to \nu_e) - P(\nu_e \to \nu_\mu)}{P(\nu_\mu \to \nu_e) + P(\nu_e \to \nu_\mu)} \tag{1}$$

which becomes feasible if the LMA MSW solution to the solar neutrino deficit, as seen in Fig. 13. This could be followed by a second step (or steps), namely a Higgs factory (or factories) [33], 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, as seen in Fig. 14, 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 [41], 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.

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

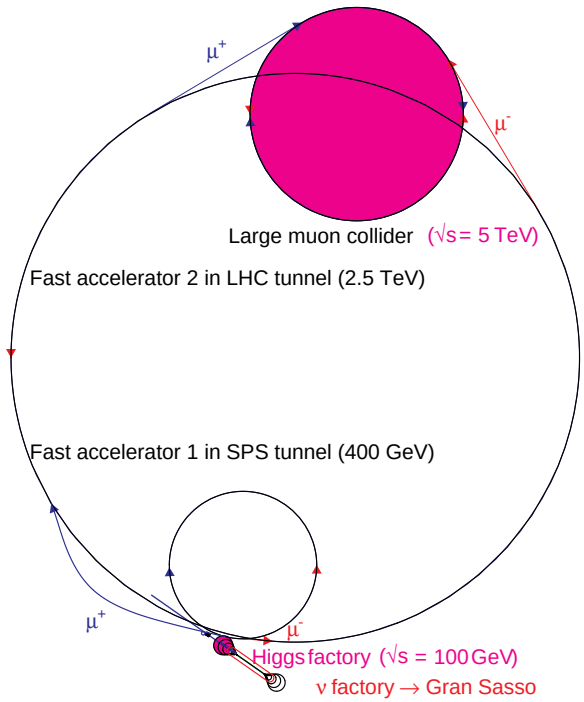

Figure 12: *Schematic layout of a possible three-step neutrino storage ring complex at CERN, including a ν factory, a Higgs factory and a possible high-energy frontier muon collider [41].*

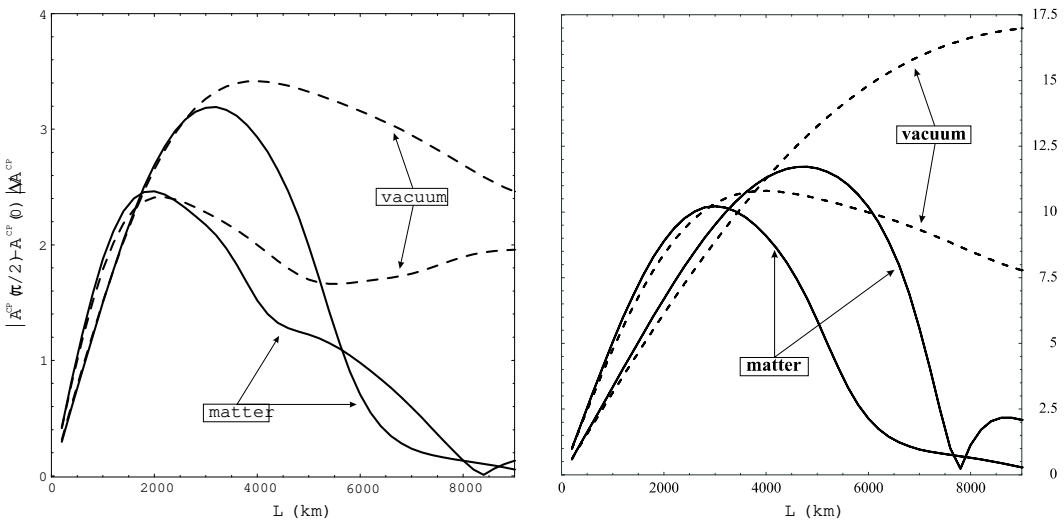

Figure 13: *Significance of the observation of a CP-violating asymmetry A_{CP} with 2×10^{20} (left panel) or 2×10^{21} neutrinos (right panel), including (solid lines) or discarding (dashed lines) matter effects, for the mixing parameters described in [43].*

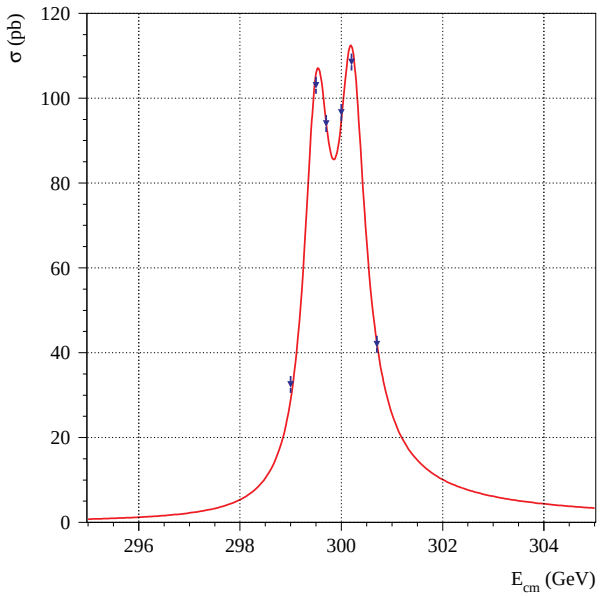

Figure 14: *Simulated measurements of the direct-channel production of the heavier MSSM Higgs bosons* (h, A) *at a Higgs factory, assuming* $m_A = 300$ *GeV,* $tan\beta = 10$*, 25* pb^{-1} *of integrated luminosity per point, and a beam-energy spread of* 3×10^{-5} *[41].*

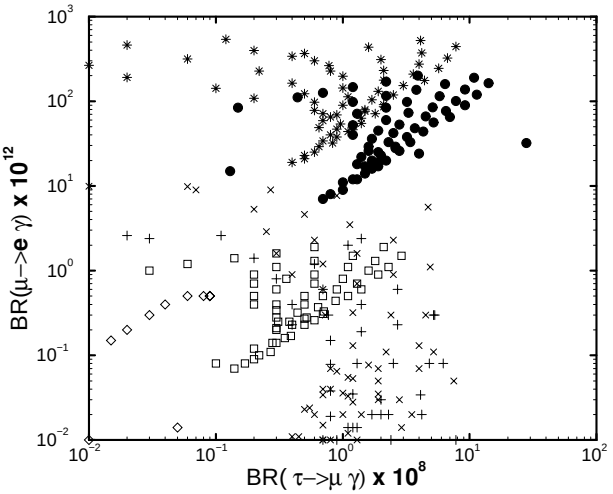

Figure 15: *Rates for* $\mu \to e\gamma$ *and* $\tau \to \mu\gamma$ *decay in some generic supersymmetric GUT models inspired by the Super-Kamiokande data on neutrino oscillations, showing opportunities both for intense* μ *beams and for intense* τ *sources, such as the LHC [45].*

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. 15 [45].

10 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

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

time, and how would high-energy e^+e^- (e.g., CLIC) and $\mu^+\mu^-$ colliders compare'[37]? Their effective mass reaches may be assumed to be similar: E_{cm} for CLIC might be limited for both financial and technical reasons, and E_{cm} for a $\mu^+\mu^-$ collider might be limited by the danger of neutrino radiation [46], 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 [41], 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 [41] was the reaction $\mu^+\mu^- \to \chi^+\chi^-$, where the threshold cross section is much more sensitive to $m_{\chi^\pm}$ than is $e^+e^- \to \chi^+\chi^-$. 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 [41].

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 [37]. Table 3 [41] 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 radia-

tion [46], which may even become a health hazard at $E_{cm} \gtrsim 3$ TeV. Neutrinos will radiate 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.

11 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. It is hoped [34] 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 [47].

As a first step, four specific activities have been proposed [48]:

• an experiment to measure π production [10], which could also constrain calculations of atmospheric neutrino fluxes,

• 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) [49], on $\mu^+\mu^-$ colliders [50], and on other possible physics with stopped muons, ν scattering, etc. [51]. These activities are in parallel to the accelerator and physics working groups at FNAL [52], the Expression of Interest for R&D towards a ν factory submitted to the NSF [53]. The next forum for comparing ideas will be the second international ν factory workshop scheduled for Monterey in May 2000 [54].

12 Prospects

CERN's experimental programme addresses squarely the fundamental problems of physics beyond the Standard Model listed in the Introduction. LEP and the LHC address the problem of **Mass** in their searches for the Higgs boson and supersymmetry. The problem of **Unification** is addressed by the CNGS project and potentially by sparticle mass measurements at the LHC. The problem of **Flavour** is being addressed by the NA48 experiment, to be followed by CNGS and B experiments at the LHC.

As reviewed in this talk, in addition to its ongoing programme at LEP and elsewhere, the CNGS project and its core LHC programme, there are clearly several interesting options for possible accelerators at CERN beyond the LHC, which may pursue these problems further. Some of these future possibilities are being studied quite actively, with CLIC as a default option [34]. The relative priorities of the various options before CERN will depend on project developments elsewhere as well as on physics developments.

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.*

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 [53] for two competing American visions.

To conclude: in addition to preparing the LHC, CERN is preparing actively [34, 37, 47, 48] to play whatever role seems most interesting and appropriate in the generation of accelerators following the LHC.

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G. Rahal (L3):
http://hpl3sn02.cern.ch/analysis/latestresults.html
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