CONTEMPORARY PROBLEMS OF PARTICLE PHYSICS

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1 Introduction

The accelerator community has for several decades made impressive progress in providing accelerators at ever-higher centre-of-mass energies, as shown in Fig. 1. The primary purpose of this meeting is to discuss ways in which this progress may be continued, by new projects under construction and being proposed, and by more futuristic schemes still in the research and development stages. My task is to review the physics motivations for this drive to higher energies. I start by reviewing the bedrock upon which all our projects are based, namely the continuing success of the Standard Model. Then I discuss possible indications of physics beyond the Standard Model, and finally I address the issues to be addressed by future accelerators, with particular emphasis on the LHC, a linear e^+e^- collider (LC) in the 1 and/or multi-TeV energy range (CLIC), $\mu^+ \mu^-$ colliders (MC), neutrino factories and a possible future larger hadron collider (FLHC).

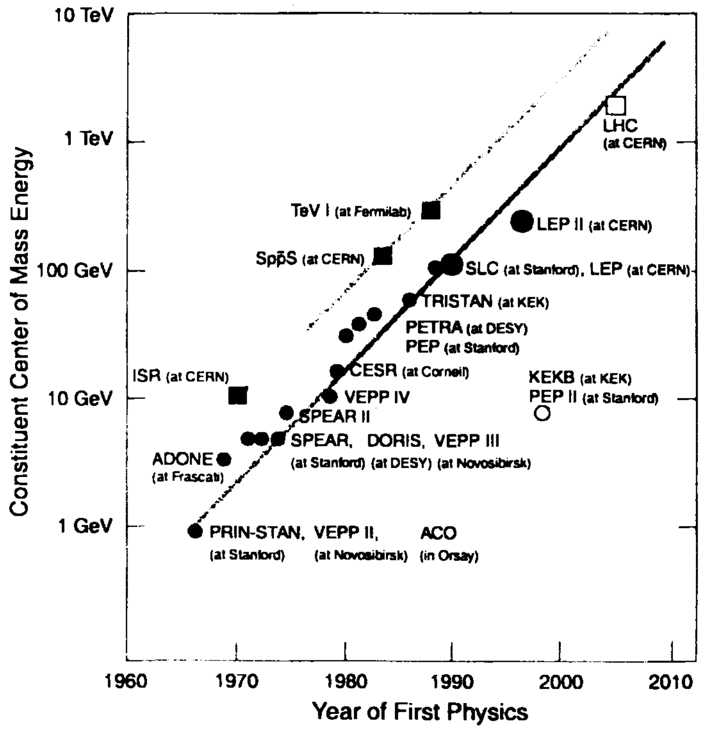
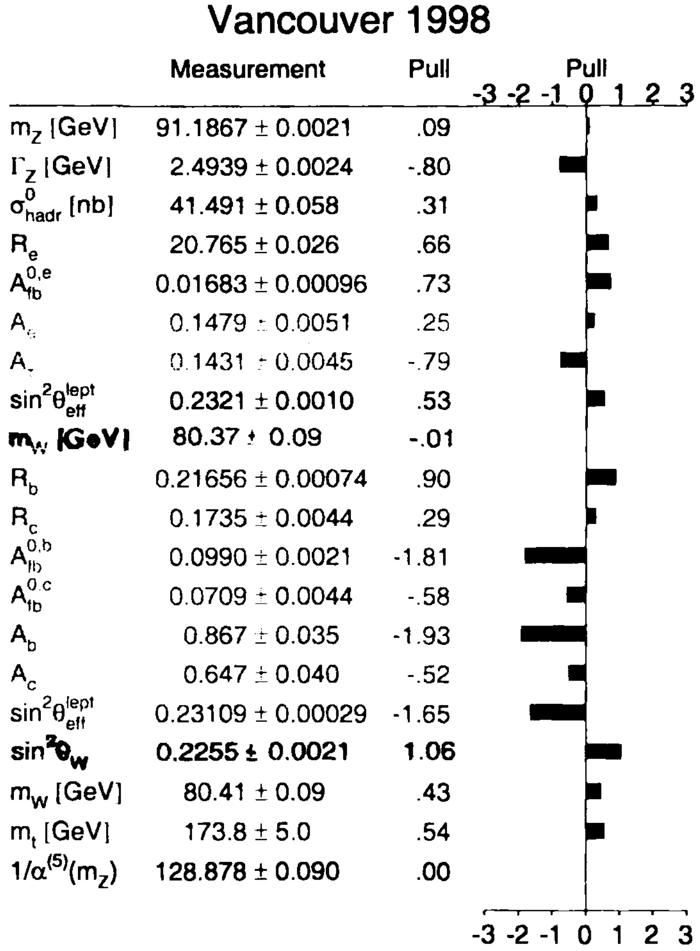


Figure 1: Progress in accelerator centre-of-mass energies.

2 The Standard Model Still Works

As you see in Fig. 2, the latest set of precision electroweak data from the Vancouver conference still agree with the Standard Model [1]. Certain recent anomalies such as the $Z \to b\bar{b}$ branching ratio at LEP and the left-right polarization asymmetry at the SLC have largely evaporated. No observable now differs significantly from the Standard Model, and the overall χ^2 of a global fit is good. Figure 3 compares different measurements of $\sin^2\theta_W^{\rm lept}$, which are decently consistent ($\chi^2/\text{d.o.f} = 8.1/6$), correspond to a value 0.23155 ± 0.00019 which favours supersymmetric Grand Unified Theories (GUTs) as discussed later, and also a light Higgs mass m_H= 0(100) GeV. The LEP data also exclude some possible extensions of the Standard Model. For example, the number of equivalent light neutrino species is measured to be N_ν= 2.994 ± 0.011. There is no room for another light neutrino, and hence no corresponding charged lepton and presumably (in order to cancel triangle anomalies) no more conventional quarks.

The missing link in the Standard Model is of course the Higgs boson. In order to give a mass to a massless gauge boson, its two polarization states must be supplemented by a third one that is provided by a supplementary spin-0 field. In order to obtain $m_{W^\pm,Z^0} \neq 0$, this field must have non-zero electroweak isospin, and the simplest possibility is a single complex isospin doublet. This has four degrees of freedom, three of which are eaten by the $W^\pm$ and Z^0, leaving one physical Higgs boson to be discovered. Its mass is not predicted within the Standard Model, but its couplings are, making its production and decay predictable. The search for the Higgs via the process $e^+e^- \to Z^0 + H$ is one of the hot topics at LEP 2: there has been no luck so far, individual experiments impose $m_H \geq 90$ GeV and a joint analysis implies $m_H \geq 94$ GeV [2]. Future runs at energies $E_{cm} \leq 200$ GeV should enable the Higgs boson to be discovered if $m_H \leq 100$ GeV and excluded up to ~106 GeV.



Vancouver 1998

	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0021	.09
Γ_Z [GeV]	2.4939 ± 0.0024	-.80
σ^0_{hadr} [nb]	41.491 ± 0.058	.31
R_e	20.765 ± 0.026	.66
$A^{0,e}_{fb}$	0.01683 ± 0.00096	.73
A_e	0.1479 ± 0.0051	.25
A_τ	0.1431 ± 0.0045	-.79
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.53
m_W [GeV]	80.37 ± 0.09	-.01
R_b	0.21656 ± 0.00074	.90
R_c	0.1735 ± 0.0044	.29
$A^{0,b}_{fb}$	0.0990 ± 0.0021	-1.81
$A^{0,c}_{fb}$	0.0709 ± 0.0044	-.58
A_b	0.867 ± 0.035	-1.93
A_c	0.647 ± 0.040	-.52
$\sin^2\theta^{lept}_{eff}$	0.23109 ± 0.00029	-1.65
$\sin^2\theta_W$	**0.2255 ± 0.0021**	**1.06**
m_W [GeV]	80.41 ± 0.09	.43
m_t [GeV]	173.8 ± 5.0	.54
$1/\alpha^{(5)}(m_Z)$	128.878 ± 0.090	.00

Figure 2: Electroweak precision measurements compared with a Standard Model fit.

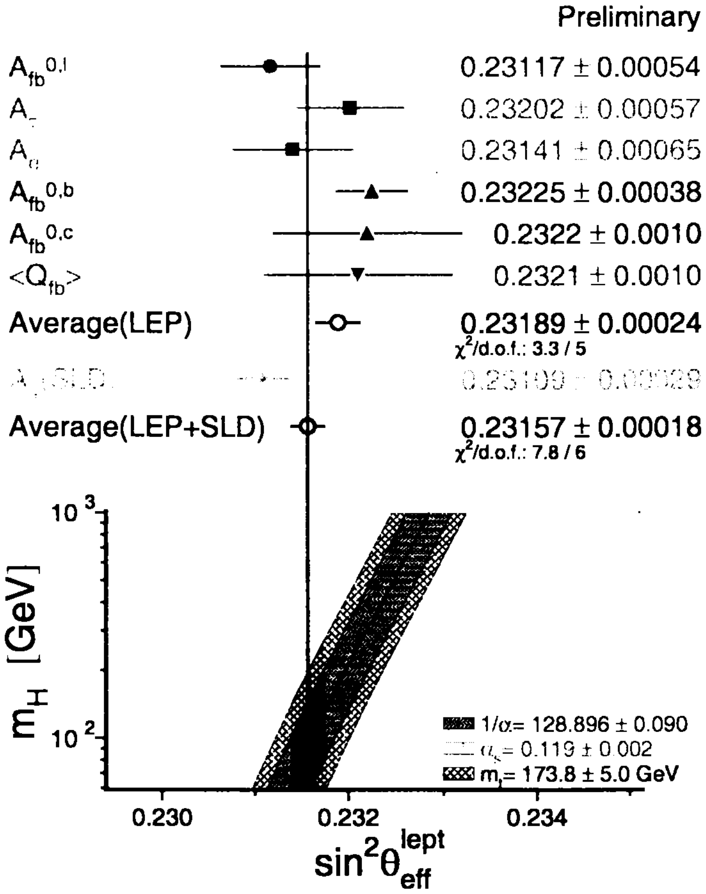


Figure 3: Measurements of the neutral electroweak mixing angle.

One of the other hot topics at LEP 2 is the study of $e^+e^- \to W^+W^-$ and the measurements of m_W, whose current status is shown in Fig. 4. This is now approaching the

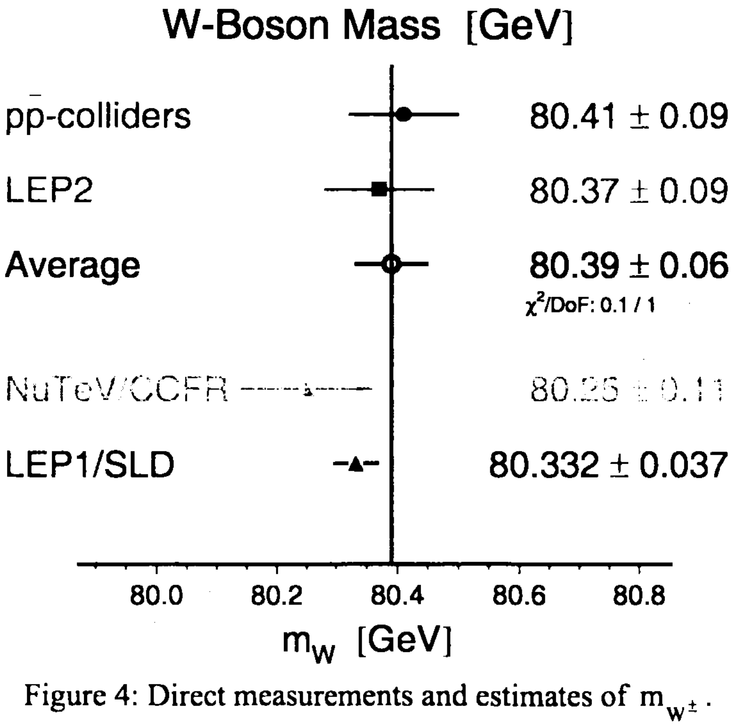


Figure 4: Direct measurements and estimates of $m_{W^\pm}$.

accuracy with which m_W is predicted within the Standard Model on the basis of LEP 1 and SLC data, and helps constrain m_H and possible extension of the Standard Model. The present indirect estimate of the Higgs mass via its quantum contributions to the precision electroweak data is [1]

$$m_H = 90^{+100}_{-60}\ \mathrm{GeV} \tag{1}$$

Even if the minimal Standard Model is not the whole story, this estimate tells us that new physics in the Higgs sector must be nearby!

3 Possible Directions Beyond the Standard Model

Theoretically, the Standard Model is far from satisfactory, and its outstanding problems can be listed in three classes [3].

The *Problem of Mass*: is there a Higgs boson, and why are particle masses so small: $m_W << m_P$? The *Problem of Unification*: are all the gauge interactions combined in a simple group structure, that might predict new interactions leading to proton decay and neutrino masses? The *Problem of Flavour*: why are there just six quarks and six leptons, and what explains their pattern of charged weak-current mixing and CP violation? All these problems should eventually be resolved in a *Theory of Everything* that also resolves all the problems of quantum gravity, for which our only candidate is string theory.

The hierarchy $m_W << m_P$ is equivalent to $G_F = g^2/8m_W^2 >> G_N \equiv 1/m_P^2$, or the observation that the Coulomb potential in an atom is much greater than the Newton potential, since $e^2 = 0(1) >> G_N m_P m_e \approx m_p m_e / m_P^2$. If one tries to set the hierarchy by hand, it is upset by quantum corrections that are quadratically divergent:

$$\delta m_W^2 = 0\left(\frac{\alpha}{\pi}\right)\Lambda^2 \tag{2}$$

where Λ is a cutoff scale at which new physics appears. The prime candidate for this is supersymmetry, which cancels out the quadratic divergences (2), leaving

$$\delta m_W^2 = 0\left(\frac{\alpha}{\pi}\right)\left(m_B^2 - m_F^2\right) \tag{3}$$

where the subscripts B and F denote bosons and fermions that are supersymmetric partners. The residual quantum correction (3) is comparable with the physical value of m_W if

$$\left|m_B^2 - m_F^2\right| \leq 1\ \mathrm{TeV}^2 \tag{4}$$

which motivates the appearance of supersymmetry at accessible energies. Unfortunately, none of the observed fermions can be the supersymmetric partner of any known boson, because their internal quantum numbers (Q_{em}, colour, B, L) do not match. For this reason, one is forced to introduce new "sparticles" as partners: squarks $\tilde{q}$, sleptons $\tilde{l}$, gauginos $\tilde{V}$ and Higgsinos $\tilde{H}$, which are the targets of searches at present and future accelerators. There has been no luck so far: we know from the Fermilab Tevatron collider that $m_{\tilde{q},\tilde{g}} \geq 200$ GeV, and from LEP 2 that $m_{\tilde{l},\tilde{W}^{\pm}} \geq 90$ GeV. However, one piece of indirect evidence for supersymmetry is provided by the estimate (1) of m_H, which agrees perfectly with the prediction of the minimal supersymmetric extension of the Standard Model (MSSM) [4]. Another piece of indirect evidence comes in conjunction with GUTs. These enable $\sin^2\theta_W$ to be predicted as a function of the spectrum of light particles: the measurement in Fig. 2 *disagrees* with non-supersymmetric models, but *agrees* with the MSSM if sparticles weigh ≤ 1 TeV [5].

Recently, more direct evidence for GUTs has come from neutrino studies. First solar neutrinos and now atmospheric neutrinos indicate that different neutrino flavours mix, which is observable only if their masses are unequal. Figure 5 shows the preferred range of $\nu_\mu - \nu_\tau$ mixing parameters favoured by the Kamiokande and super-Kamiokande experiments [6], which are supported by Soudan 2 and MACRO.

To conclude this section, here is a partial list of the *Big Issues* to be addressed by future accelerators. Is there a Higgs boson? What are its properties? Do supersymmetric particles exist? How do quarks and neutrino mix? Is there CP violation outside the neutral K system? Are there neutrino masses?

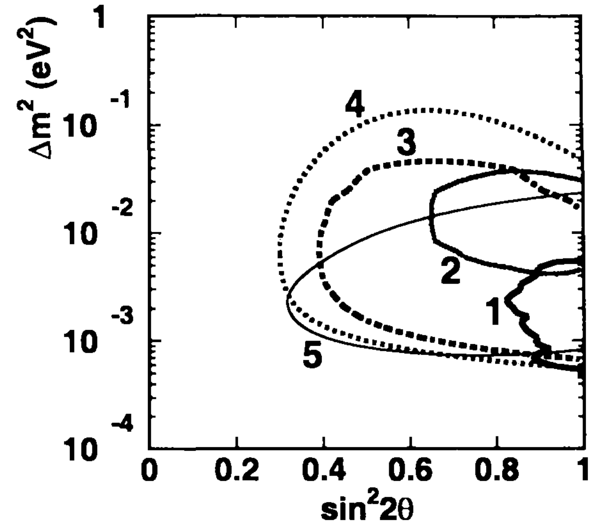


Figure 5: Constraints on $\nu_\mu - \nu_\tau$ mixing from (1,2) contained events in Super-Kamiokande and Kamiokande, (3, 4) upward-going muons in Super-Kamiokande and Kamiokande, and (5) stop/through upward muons in Super-Kamiokande [6].

4 Physics with Future Accelerators

B factories The couplings of the $W^\pm$ mix different quark flavours, and most of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix elements are now known, at least qualitatively. The CP violation discovered in $K_L^0 \to 2\pi$ is explicable if the CKM matrix V has complex entries, but there is no experimental proof of this. The primary experimental goal of the SLAC and KEK B factories is to check the unitarity triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \qquad (5)$$

in B decays via measurements of CP violation in $B \to K_S\, J/\psi$ and $\pi^+\pi^-$ decays. Other runners in this race are HERA-B at DESY and CDF at Fermilab. The ultimate precision in these and other B measurements will be provided at the LHC by the ATLAS, CMS and particularly LHCb experiments. Their goal should be to overconstrain the unitarity triangle (5) and look for possible new flavour physics beyond the Standard Model.

TeV 2000 This tag includes the Run II that is now planned to start in the year 2000 and accumulate $\sim 4\,\text{fb}^{-1}$ of data, and the possible Run III that might aim at $\sim 20\,\text{fb}^{-1}$. Top of the physics agenda are the top quark, whose mass may be measured with a precision $\leq 1\%$, and the $W^\pm$, whose mass may be measured with an error comparable to the Standard Model prediction in Fig. 3. The Tevatron collider may also become a player in the search for the Higgs boson. Run II might be able to discover it if $m_H \leq 100$ GeV, and the hope for Run III would be to reach $m_H \sim 125$ GeV. In parallel, the current searches for squarks and gluinos could be extended up to about 400 GeV.

Long-Baseline ν Beams In my view, the particle physics community will only be convinced by the evidence for neutrino oscillations shown in Fig.5 if they are verified by experiments using a controlled beam with known intensity, energy spectrum and flavour composition, as produced by an accelerator. Two such projects have been approved: K2K over 250 km in Japan at an energy too low to produce directly the τ lepton, and NUMI over 730 km in the USA. A third project sending a beam from the SPS-LHC transfer tunnel at CERN over 730 km to the Gran Sasso Laboratory is under active discussion [7]. These projects cover most, but not all of the preferred $\nu_\mu - \nu_\tau$ parameter space in Fig. 5. However, if they confirm the super-Kamiokande results, there will be scope for further experiments to probe $\nu_e - \nu_\tau$ and $\nu_\mu - \nu_e$ oscillations, as well as CP violation.

LHC The primary purpose of the project is to make the first experimental exploration of the TeV energy range, with the ancillary aims of studying the quark-gluon parameter and B physics. Exploration is the primary objective of the ATLAS and CMS experiments, the quark-gluon plasma that of ALICE, and B physics that of LHCb, though ATLAS and CMS may also contribute to these latter goals.

Top of the LHC search list is the Higgs boson, with the estimate (1) putting a premium on searches for $m_H \leq 300$ GeV. ATLAS and CMS plan to look for $H \to \gamma\gamma$ and possibly $\bar{b}b$ in the range 100 GeV $\leq m_H \leq$ 140 GeV, $H \to 4\, l^\pm$ in the range 130 GeV $\leq m_H \leq$ 700 GeV and $H \to W^+W^-, Z^0Z^0 \to l^+l^-\bar{\nu}\nu$, $l\nu$ jet jet, l^+l^- jet jet in the range 500 GeV $\leq m_H \leq$ 1 TeV, covering all the possible range of m_H. The range around $m_H \sim 170$ GeV is particularly delicate, because difficult-to-see $H \to W^+W^-$ decay dominates over the cleaner $H \to \gamma\gamma$, $4\, l^\pm$ modes. Recent studies [8] suggest that a Higgs-like excess in the W^+W^- channel can be isolated, as seen in Fig. 6, though this would not enable m_H to be reconstructed very accurately. The LHC is able to discover the Higgs boson, whatever its mass, but only in one or perhaps two decay modes for any specific mass value. There will be a great need for subsequent accelerators to explore the Higgs boson in more detail and determine its properties.

The LHC has impressive capabilities to explore and measure the properties of sparticles. There is a large cross section for the production of the strongly-interacting $\tilde{q}$ and $\tilde{g}$, and these have copious cascade decays into lighter sparticles e.g., $\tilde{g} \to \tilde{b}\bar{b}$, $\tilde{b} \to \chi_2 b$, $\chi_2 \to \chi_1\, l^+l^-$, where the χ_i are $\tilde{\gamma} / \tilde{Z}^0 / \tilde{H}^0$ mixtures. Generic signatures are missing transverse enrergy, leptons and jets, whether or not the stability of the lightest sparticle is guaranteed by R parity. As seen in Fig. 7, sparticle searches at the LHC should be able to reach $m_{\tilde{q},\tilde{g}} \sim 2$ or 2.5 TeV, covering several times over the region favoured if the lightest sparticle is the cold dark matter in the Universe. Moreover, there will be many opportunities to reconstruct cascade decays of the $\tilde{q}$ and $\tilde{g}$, measuring with high accuracy the masses and other properties of other sparticles. The Table compiles the abilities of the LHC to reconstruct the sparticle spectrum for five sample choices of MSSM parameters [9].

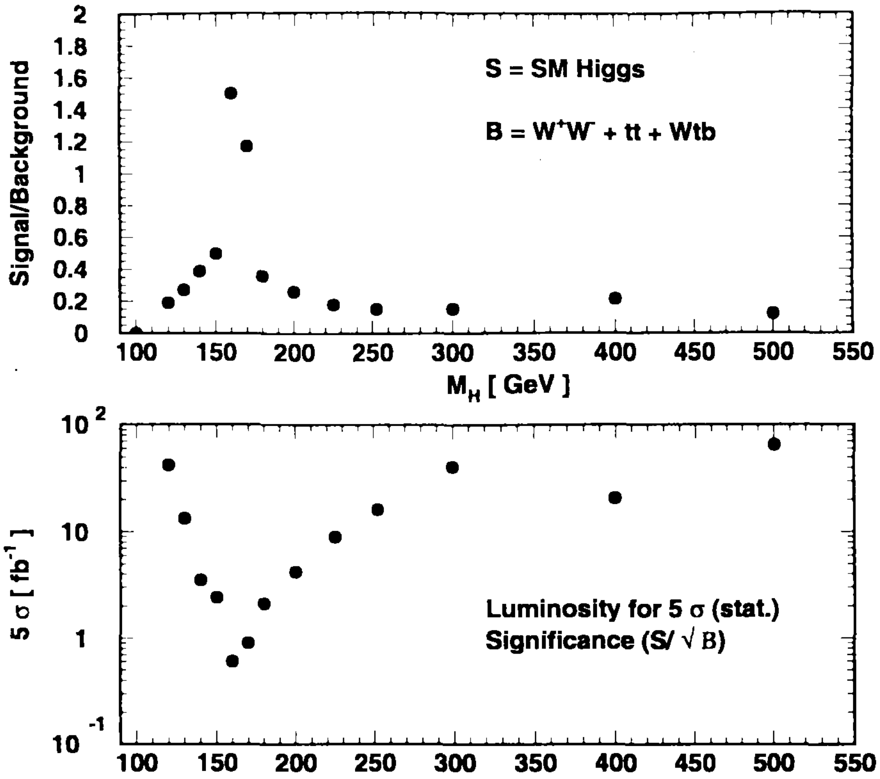


Figure 6: Prospects for the search for $H \longrightarrow W^+W$ at the LHC.

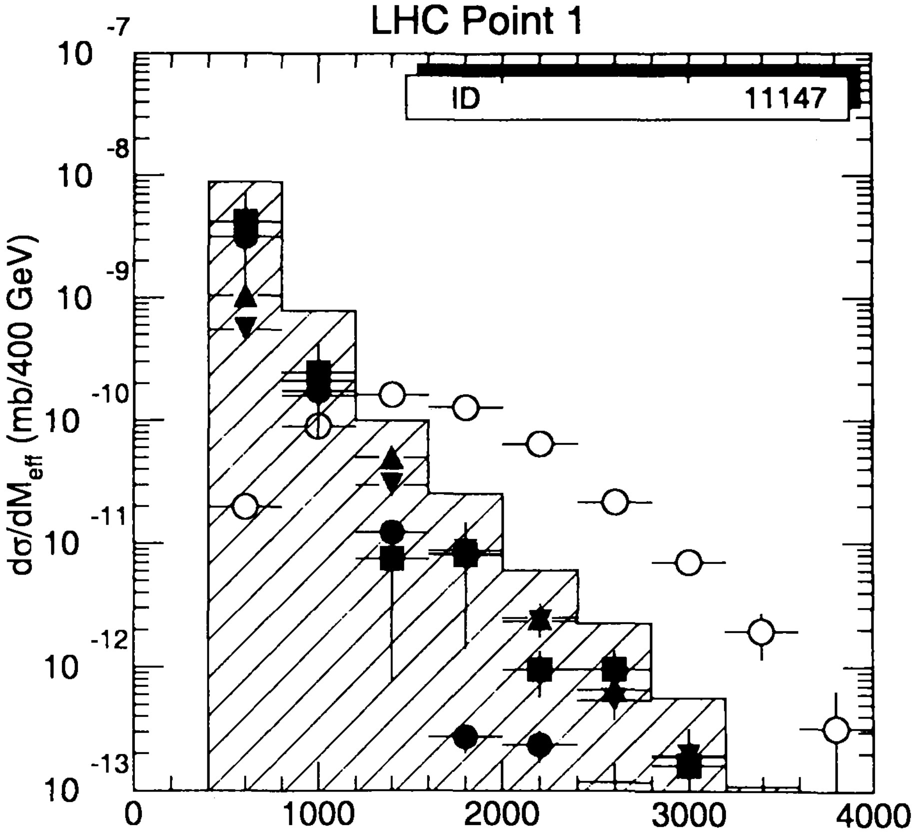


Figure 7: Missing-energy signature for sparticle searches at the LHC.

Table: The LHC as 'Bevatrino': Sparticles detectable at 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	+		+					+	+	+	+	+

Thus we arrive at the following scenario for physics after the LHC. The Higgs will have been discovered, one or two decays observed and its mass measured with a precision $\Delta m_H / m_H \sim 10^{-2}$ or 10^{-3}. Several sparticles will have been discovered and some precision measurements made, but heavier weakly-interacting sparticles such as heavier Higgs bosons and charginos may well still be missing.

TeV Linear e^+e^- Collider This offers a very clean experimental environment, the egalitarian production of new weakly-interacting particles, polarization which is a valuable analysis tool, and the possibility of $e\gamma$, $\gamma\gamma$ and e^-e^- collisions. Thus such a linear collider (LC) is complementary to the LHC [10]. The problem is to identify the most appropriate choice of E_{cm}, which is linked to the appearance of thresholds for new physics. One is established, that for $e^+e^- \to \bar{t}t$ at $E_{cm} = 350$ GeV, and another is strongly suggested in Fig. 4: $e^+e^- \to Z^0 + H$ at E_{cm}, ≤ 400 GeV. However, the threshold for sparticle-pair production is currently open, and flexibility in the accessible range of energies should be incorporated in any LC project.

Copious and clean $e^+e^- \to \bar{t}t$ production will enable m_t to be measured at the 0.1% level, and details of its decay properties and couplings determined. Detailed studies of Higgs couplings will also be possible using $e^+e^- \to Z^0 + H$ and $e^+e^- \to H\bar{\nu}\nu$ production. As seen in Fig. 8, several Higgs decay modes can be measured quite accurately, but not the total Higgs decay width unless Higgs production is measured in the $\gamma\gamma$ collider mode. The lightest MSSM Higgs can certainly be studied in detail, and the heavier MSSM Higgs bosons H, A, $H^\pm$ can be discovered if E_{cm} is large enough.

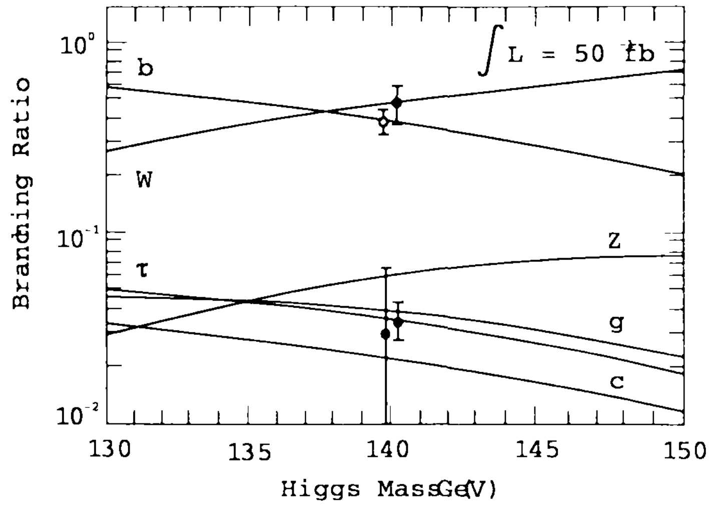


Figure 8: Possible measurements of Higgs branching ratios with a LC.

Sparticle pairs can also be produced cleanly and measured accurately, such as $e^+e^- \to \tilde{l}^+\tilde{l}^-, \tilde{\bar{\nu}}\nu, \tilde{W}^+\tilde{W}^-$ and $\chi_1\chi_2$. These will enable precise measurements of the sparticle masses to be made:

$$\begin{aligned} \delta m_{\tilde{\mu}} &\simeq 1.8\ \mathrm{GeV}, \delta m_{\tilde{\nu}} \simeq 5\ \mathrm{GeV}, \delta m_{\tilde{W}^\pm} \simeq 0.1\ \mathrm{GeV} \\ \delta m_{\tilde{W}^\pm} &\simeq 0.6\ \mathrm{GeV}, \delta m_{\tilde{t}} \simeq 4\ \mathrm{GeV} \end{aligned} \qquad (6)$$

(see, for example, Fig. 9) permitting precision tests of supersymmetric GUT models and over- constraining their parameters. Moreover, many sparticle couplings and spin-parities can be measured *if* one is above threshold. A 1 TeV LC could fill in many of the gaps in sparticle spectroscopy left open by the LHC.

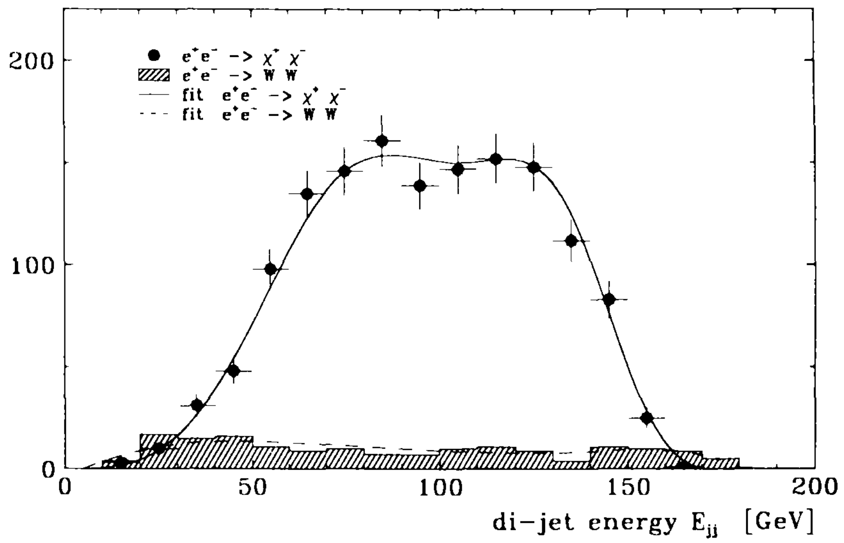


Figure 9: Example of possible sparticle measurement with a LC.

My view is that we shall certainly need a LC in the TeV energy range, to complement the LHC in exploration and precision measurements. One should aim at the widest possible energy range, in view of our ignorance of the thresholds for producing new particles. I wish the world accelerator community could converge on a single project, as I doubt very much that two could be funded. For the rest of this talk, I assume that a LC in the TeV E_{cm} range will be constructed. It will add significantly to our knowledge of the Higgs boson, but some properties such as its decay width may remain unknown. It will add significantly to our sparticle studies, but will not complete our understanding of sparticle spectroscopy unless it goes to $E_{cm} \geq 2$ TeV. For these reasons, we must consider our options for future accelerators in such a post-LC scenario [11].

Multi-TeV Linear e^+e^- Collider With $E_{cm} \geq 2$ TeV, one can complete the supersymmetric spectroscopy. Such a machine should have a very high luminosity: $L \geq 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, in order to ensure an adequate event rate for the interesting cross sections that are $\alpha\ 1/E_{cm}^2$. Getting to several TeV in E_{cm} will require a high accelerating gradient, suggesting a preference for a high-frequency acceleration structure. The most promising approach to this may be CLIC [12], which uses an intense low-energy beam to generate RF power that accelerates the drive beam. Engineering the drive beam is challenging, and a recent suggestion is to split it into several parts that accelerate the main beam sequentially ("double-CLIC").

$\mu^+\mu^-$ Colliders These may eventually provide an alternative route to multi-TeV lepton collisions. Compared to e^+e^- colliders, m^+m^- colliders have essentially no synchrotron radiation or beamstrahlung, and reduced initial-state radiation in collisions. Thus they provide a smaller spread in E_{cm}, and this can be measured very accurately using the decays of polarized muons. Moreover, the flavour dependence of the Standard Model Higgs couplings offers a m^+m^- H coupling larger than the e^+e^- H coupling, and hence the prospect of direct-channel resonant Higgs production. However, muon decay provides a formidable background, and essentially all the technical steps in a m^+m^- collider complex are non-existent, speculative or wild extrapolations of current knowledge [13].

The reduced energy spread could be a boom for studies of the $\mu^+\mu^- \to \bar{t}t$ threshold, or for studies of other thresholds, e.g., for sparticle production. It could also be useful for studying narrow direct-channel resonances. This feature is particularly powerful in combination with the (relatively) large $\mu^+\mu^-$ coupling that makes a Higgs factory possible. Neglecting the beam-energy spread, the Higgs line shape would be

$$\sigma_H^x(s) = \frac{4\pi\,\Gamma(H \to \mu^+\mu^-)\,\Gamma(H \to X)}{(s - m_H^2)^2 + m_H^2\Gamma_H^2} \tag{7}$$

For m_H = 100 GeV and a plausible (possible) energy spread of 0.06(0.01)%, ΔE_{cm} is comparable to the natural width of the Standard Model Higgs. One would be able to measure Γ_H and many Higgs decay branching ratios, make a clear distinction between the Standard Model Higgs and the lightest Higgs in the MSSM as seen in Fig. 10, and separate the heavier MSSM Higgses H and A.

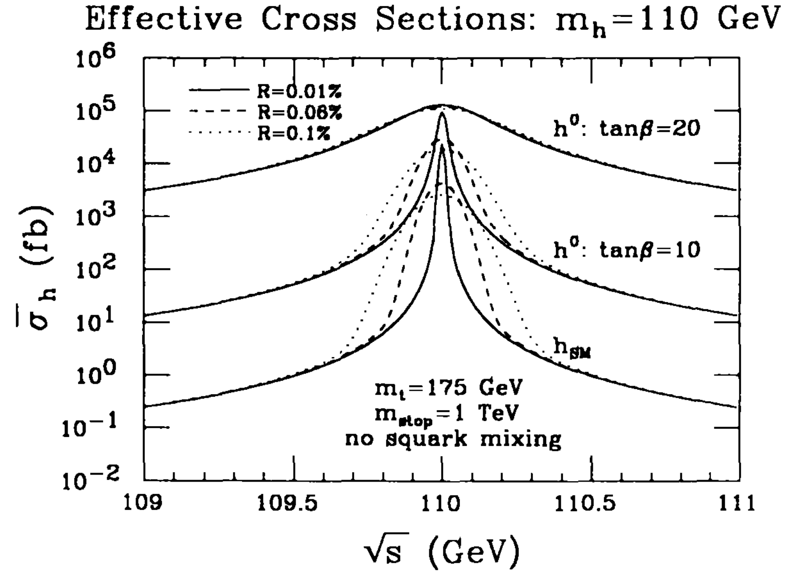


Figure 10: The Higgs line shape at a MC.

The front end of a $\mu^+\mu^-$ collider may also be useful for stopped muon physics ($\mu \to e\gamma$, $\mu N \to eN$, etc.), and a high-energy μp collider could also be interesting. However, more concern and interest attaches to the beams produced by a $\mu^+\mu^-$ collider.

A $\mu^+\mu^-$ collider produces a disc of ν radiation, which is enhanced in the direction of the straight sections. At energies $E_{cm} \geq 1$ TeV, this becomes a safety hazard. A recent conservative estimate of the radiation dose is

$$\left(\frac{\text{Dose}}{\text{U.S. Limit}}\right) \simeq 0.4 \times \left(\frac{\text{length of straight section}}{\text{collider depth}}\right) \times \left(\frac{I_\mu}{10^{20}\mu/\text{y}}\right) \times \left(\frac{E_{cm}}{1\,\text{TeV}}\right)^3 \tag{8}$$

To combat this limitation, options such as shortening the straight sections, burying the collider deeper, using natural geographic features such as mountains, lakes and oceans, wobbling the beams, and reducing the number of $\mu^\pm$ required for the same luminosity are being pursued actively. However, it seems difficult to envisage centre-of-mass energies above a few TeV.

ν Factory Perhaps the $\mu^\pm \to e^\pm \nu\bar{\nu}$ decays vice may be considered a virtue? They provide intense ν beams with flavour separation and known spectra. These could be used for ν oscillation and other studies. For example, a $\mu^+\mu^-$ collider using 6×10^{20} per year at E_{cm} = 500 GeV with 200 m straight sections could produce $5.3 \times 10^7 \times 1\,(\text{g cm}^{-2})$ events per year in a nearby detector, and $2.7 \times 10^7 \times \text{M(kg)}/(\text{l(km)})^2$ in a far detector. This could be the accelerator of choice for completing our understanding of $\nu_{e,\mu}$ oscillations.

FLHC Finally, we turn to the possibility of a future larger hadron collider with E_{cm} = 50 or 100 TeV. This may be the only available way to produce particles weighing up to 10 TeV, as occur in some gauge-mediated extensions of the MSSM. To exploit fully the capabilities offered by the large E_{cm}, a luminosity correspondingly larger than that of the LHC would be desirable: at least $10^{35}\text{cm}^{-2}\text{s}^{-1}$ and preferably higher, if detectors can be designed to cope and the problems of radiated power, stored energy and debris power can be solved. There is currently much discussion whether a high or low magnetic field is preferable. What is clear is that to build such a machine would need a reduction in unit costs by an order of magnitude compared to the LHC.

5 Conclusions

Experimental data are begining to provide hints of possible physics beyond the Standard Model: Grand Unification, Supersymmetry, neutrino masses... . The new accelerators currently under construction will be able to address many of the Big Issues raised by such attempts to transcend the Standard Model. The LHC will play a pivotal role in clarifying these ideas, but will not complete our quest. A TeV linear e^+e^- collider would be complementary and invaluable. Beyond this, there are several other promising ideas for interesting future accelerators. Accelerator physics has a long and promising future ahead.

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