

PHYSICS AT FUTURE COLLIDERS**John ELLIS**Theoretical Physics Division, CERN
CH - 1211 Geneva 23**ABSTRACT**

After a brief review of the Big Issues in particle physics, we discuss the contributions to resolving that could be made by various planned and proposed future colliders. These include future runs of LEP and the Fermilab Tevatron collider, B factories, RHIC, the LHC, a linear e^+e^- collider, an $e-p$ collider in the LEP/LHC tunnel, a $\mu^+\mu^-$ collider and a future larger hadron collider (FLHC). The Higgs boson and supersymmetry are used as benchmarks for assessing their capabilities. The LHC has great capacities for precision measurements as well as exploration, but also shortcomings where the complementary strengths of a linear e^+e^- collider would be invaluable. It is not too soon to study seriously possible subsequent colliders.

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1 The Big Issues

The discoveries for which future colliders will probably be remembered are not those which are anticipated. Nevertheless, we cannot avoid comparing their capabilities to address our present prejudices as to what big issues they should resolve. These include, first and foremost, the **Problem of Mass**: is there an elementary Higgs boson, or is it replaced by some composite technicolour scenario, and is any Higgs boson accompanied by a protective bodyguard of supersymmetric particles? As we were reminded at this meeting [1], precision electroweak data persist in preferring a relatively light Higgs boson with mass

$$m_H = 115_{-66}^{+116} \text{ GeV} \quad (1)$$

which is difficult to reconcile with calculable composite scenarios. However, we should be warned that the range (1) is compatible with the validity of the Standard Model all the way to the Planck scale [2], as seen in Fig. 1, with no new physics to stabilize the electroweak coupling or keep the Standard Model couplings finite. Nevertheless, the range (1) is highly consistent [3] with the prediction of the minimal supersymmetric extension of the Standard Model [4], so we use in this talk supersymmetry [5] as one of our benchmarks for future colliders. The **Problem of Flavour** includes the questions why there are just six quarks and six leptons, what is the origin of their mass ratios and the generalized Cabibbo mixing angles, and what is the origin of CP violation? The Standard Model predicts the presence of CP violation, but we do not yet have any quantitative tests of the Kobayashi-Maskawa mechanism [6]: detailed studies may reveal its inadequacy. Finally, the **Problem of Unification** raises the possibility of neutrino masses and proton decay, that are not addressed by colliders. However, GUTs also predict many relations between couplings, such as $\sin^2 \theta_W$ [7], and masses, such as m_b/m_τ [8], that can be tested at colliders, such as detailed predictions for the spectroscopy of sparticles - if there are any!

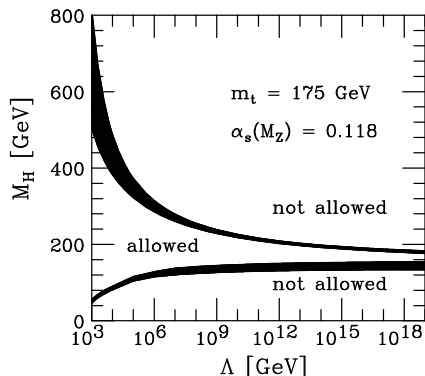


Figure 1: The range of M_H allowed if the Standard Model remains valid, unmodified, up to an energy scale Λ [2].

2 Catalogue of Future Colliders

Table 1 lists future high-energy colliders, both approved and under discussion, together with some of their key parameters and their planned start-up dates [9]. To these should be added LEP 2000, which is the proposal to extend the scheduled running of LEP through the year 2000, for which approval and extra funding is now being sought from the CERN Member States. By using some of the LHC cryogenic facilities, this and the 1999 run of LEP could be at a higher energy, possibly the 200 GeV foreseen in the original LEP design. This would extend the LEP reach for the Standard Model Higgs boson through the LEP/LHC transition region to above 100 GeV. The principal gain for Higgs physics of the extra year's run would be to be sure of overcoming the Z background around 90 GeV. Running LEP at 200 GeV would also extend significantly the LEP coverage of MSSM Higgs

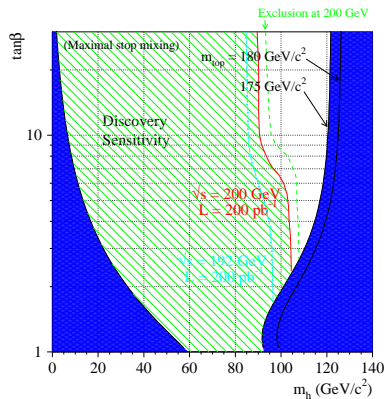


Figure 2: The sensitivity to MSSM Higgs bosons that may be achieved at LEP 2 [10].

bosons [10], passing a definitive verdict on the region $\tan\beta \lesssim 2$ favoured in many theoretical models, as seen in Fig. 2, and would also provide closure on supersymmetric interpretations of the CDF $e^+e^-\gamma\gamma p_T$ event [11].

Table 1: Table of future collider parameters

Collider	Particles	E_{cm} (GeV)	Luminosity($\text{cm}^{-2}\text{s}^{-1}$)	Starting Date
PEP II	e^+e^-	10	3×10^{33}	1999
KEK-B	e^+e^-	10	10^{33}	1999
RHIC	$Au - Au$	200A	2×10^{26}	1999
LHC	pp	14×10^3	10^{34}	2005
LHC	$Pb - Pb$	1.15×10^6	10^{27}	2005
LHC	ep	1300	10^{32}	?
LC	e^+e^-	500/2000	$5 \times 10^{33}/10^{34}$	2008 ?
FMC	$\mu^+\mu^-$	$m_H/4000$	$2 \times 10^{33}/10^{35}$?
FLHC	pp	$1/2 \times 10^5$	10^{34}	?

Also in the category of future runs of present accelerators is the TeV 2000 programme [12]. This actually comprises two runs: Run II, which is approved to run from 1999 to about 2002, and is slated to accumulate $4fb^{-1}$ of data, and Run III, which is proposed to start a couple of years later and continue until the LHC kicks in, gathering about $20fb^{-1}$ of data. Top of the TeV 2000 physics agenda is top physics [12], with such objectives as decreasing the uncertainty in m_t to ~ 2 GeV in Run II and perhaps 1 GeV in Run III, measuring $\sigma_{\bar{t}t}$ with an accuracy of 7(5) % (which would test “topcolour” models), and determining Γ_t to 20(12) %. TeV 2000 also offers new prospects in W physics: $\delta m_W \simeq 40(20)$ MeV, $\delta\Gamma \simeq 15$ MeV and measuring triple-gauge couplings at the 10 % level. The TeV 2000 programme also has a nice chance of finding the Higgs boson of the Standard Model, with a reach extending above 100 GeV in Run II and perhaps to 125 GeV in Run III [12]. Beyond this Standard Model physics, TeV 2000 can search for gluinos up to 400 GeV or so, and charginos up to about 220 GeV, depending on the details of the model [12].

The next new colliders to start taking data will presumably be the B factories at SLAC and KEK, with their experiments BaBar and Belle [13], respectively. Their tasks will be to understand CP violation, possibly within the Standard Model by measuring or overconstraining the unitarity triangle [6]

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (2)$$

or (we can but hope!) finding new physics beyond it, as well as to improve limits on (and measurements of) rare B decays. This will be a crowded field, with HERA-B [14] and the Tevatron Run II starting in 1999, as well as

BaBar and Belle. The field will become even more crowded during the next decade, with BTeV [15] perhaps starting around 2003, as well as CMS [16, 17], ATLAS [18] and LHC-B [19] in 2005. To these should be added CLEO, which will continue to provide useful complementary information on B physics, as well as SLD, which also has a chance to measure the B_s mixing parameter x_s .

Another collider due to start taking data in 1999 is RHIC, which expects to reach nuclear energy densities ~ 6 GeV/fm³. As we heard here from Plasil [20], this will have two large experiments: STAR [21] which will measure general event characteristics and statistical signatures, and PHENIX [22] which will concentrate more on hard probes such as $\ell^+\ell^-$ pairs. RHIC will also have two smaller experiments: PHOBOS [23] and BRAHMS [20]. In the longer run, the LHC also offers relativistic heavy-ion collisions at an nuclear energy density which is model-dependent, but expected to be considerably higher than at RHIC. There will be a dedicated heavy-ion experiment at the LHC, ALICE [24], which aims at both statistical signatures and $\ell^+\ell^-$ pairs. There is also interest in heavy-ion physics from CMS [16, 26], which may be able to observe jet quenching in events with a large- $p_T Z^0$ or γ trigger, and ATLAS would also have interesting capabilities for heavy-ion physics.

3 LHC Physics

The primary task of the LHC, approved in late 1994 and scheduled for first beams in 2005 [25], is to explore the 1 TeV energy range. The two major “discovery” experiments ATLAS [18] and CMS [16] were approved in early 1996, and construction of some of their detectors has begun. ALICE [24] was approved in early 1997, and the dedicated CP-violation experiment LHC-B [19] has passed successfully through the preliminary stages of approval and is expected to receive final approval soon.

Top of the physics agenda for the LHC is the elucidation of the origin of particle masses, i.e., the mechanism of spontaneous electroweak symmetry breakdown. Within the Standard Model, this means looking for the Higgs boson, whose mass is currently estimated in (1). The branching ratios and production cross sections for the Higgs at the LHC are well understood, including first-order QCD corrections, as reviewed here by Spira [27] and shown in Fig. 3.

However, work is still needed on the QCD corrections to some backgrounds, such as $\gamma\gamma$. Favoured search signatures [18, 16] include $H \rightarrow \gamma\gamma$ for $100 \text{ GeV} \lesssim m_H \lesssim 140 \text{ GeV}$, $H \rightarrow 4\ell^\pm$ for $130 \text{ GeV} \lesssim m_H \lesssim 700 \text{ GeV}$ and $H \rightarrow W^+W^-, Z^0Z^0 \rightarrow \ell^+\ell^-jj, \bar{\nu}\nu\ell^+\ell^-, \ell\nu jj$ for $m_H \gtrsim 500 \text{ GeV}$. As seen in Fig. 4, one delicate mass region is $m_H \lesssim 120 \text{ GeV}$, where the requirements on electromagnetic calorimeters are particularly stringent [28]. Recent studies indicate that the channel $W + (H \rightarrow \bar{b}b)$ may play a useful rôle in this mass region [29]. Another delicate mass region is $m_H \sim 170 \text{ GeV}$, where the branching ratio for the preferred $H \rightarrow ZZ^* \rightarrow 4\ell^\pm$ signal is reduced, as seen in Fig. 4, because the $H \rightarrow W^+W^-$ channel opens up. The possibility of isolating the $H \rightarrow W^+W^- \rightarrow (\ell^+\nu)(\ell^-\bar{\nu})$ decay mode in this mass region has recently been re-examined [30, 29]. By making suitable cuts on the charged leptons ($|\eta| < 2.4, p_T > 25 \text{ GeV}, p_{T_2} > 10 \text{ GeV}, m_{\ell^+\ell^-} > 10 \text{ GeV}, |m_{\ell^+\ell^-} - m_Z| > 5 \text{ GeV}$) and vetoing events with jets (no $p_{T_j} > 20 \text{ GeV}$ in $|\eta| < 3$), as well as cuts on the polar and transverse opening angles of the $\ell^+\ell^-$, it was found possible to display an excess above the continuum W^+W^- background, which is clearest when $m_H \sim 170 \text{ GeV}$, as seen in Fig. 5. However, this technique does not produce a well-defined resonance peak.

It is hard to find any theorist who thinks that the single Higgs boson of the Standard Model is the whole of the story, and many would plump for the minimal supersymmetric extension of the Standard Model (MSSM). The mass of the lightest neutral Higgs boson h in the MSSM is restricted to $m_h \lesssim 120 \text{ GeV}$ [4], which is, as already mentioned, quite consistent [3] with the range (1) indicated by precision electroweak measurements [1]. The MSSM Higgs branching ratios and production cross sections at the LHC have also been studied intensively, including leading-order QCD corrections [27]. It has been known for some time that, although there are extensive regions of the MSSM Higgs parameter space where one or more of the MSSM Higgs bosons may be detected [31], there is a region around $m_A \sim 150$ to 200 GeV and $\tan\beta \sim 5$ to 10 which is difficult to cover. As seen in Fig. 6, after several years of running the LHC at the design luminosity, even this region may be covered by combining

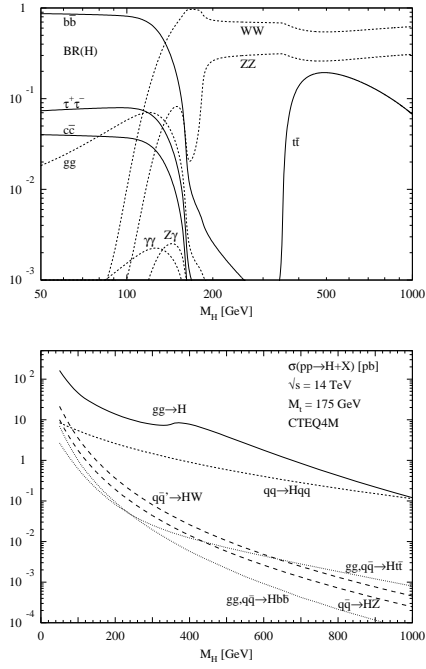


Figure 3: (a) Branching ratios and (b) cross sections for Higgs production at the LHC, including radiative corrections [28].

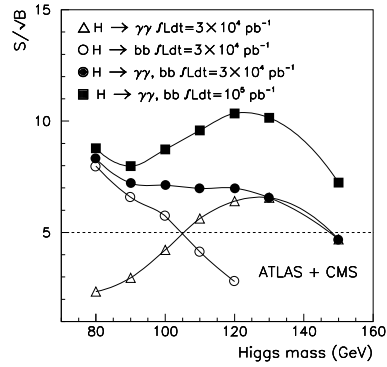


Figure 4: Estimated significance of light-mass Higgs detection at the LHC: note the “delicate” regions $m_H \lesssim 120$ GeV and ~ 170 GeV [30].

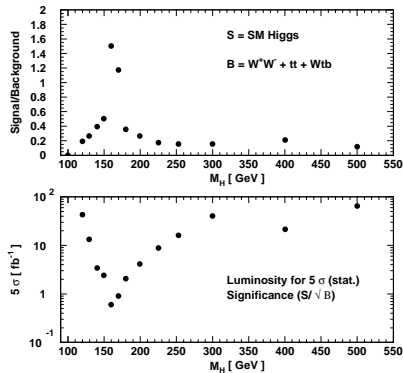


Figure 5: Possible improvement in the sensitivity to $m_H \sim 170$ GeV at the LHC, using cuts optimized for $H \rightarrow W^+W^-$ decay [31].

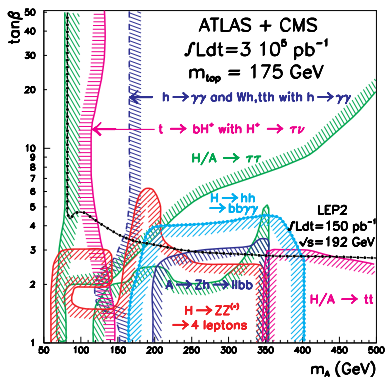


Figure 6: Detectability of MSSM Higgs bosons at the LHC. In most of the plane, more than one experimental signature is visible [32].

data from ATLAS and CMS [31]. However, one would be more comfortable if there were more coverage, and in particular with more help from LEP by covering a larger area of the $(m_A, \tan\beta)$ plane by running at $E_{cm} = 200$ GeV [10].

We can still hope that supersymmetry may be discovered before the start-up of the LHC [32], but the LHC has unprecedented mass reach in the search for supersymmetric particles [33]. Cross sections for producing the strongly-interacting squarks \tilde{q} and gluons \tilde{g} have been calculated including leading-order QCD corrections [34]. Since these are expected to be among the heaviest sparticles, if R parity is conserved one expects their generic decays to involve complicated cascades such as $\tilde{g} \rightarrow \tilde{b}\tilde{b}, \tilde{b} \rightarrow \chi_2 b, \chi_2 \rightarrow \chi_1 \ell^+ \ell^-$ where neutralinos are denoted by χ_i . Therefore generic signatures are missing energy, leptons and hadronic jets (which may include b quarks) [35]. These are also interesting signatures if R parity is violated [36], with the added possibility of reconstructing mass bumps in lepton + jet combinations. As is well known, the R -conserving missing-energy signal would stick out clearly above the Standard Model background, enabling \tilde{q} and \tilde{g} with masses between about 300 GeV and 2 TeV to be discovered, as discussed here by [33].

The main recent novelty has been the realization that the \tilde{q} or \tilde{g} decay cascades may be reconstructed and detailed spectroscopic measurements made [37]. The following is the basic strategy proposed.

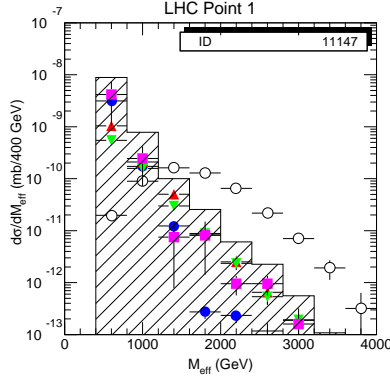


Figure 7: Significance of m_{eff} (3) signal at the LHC, compared to Standard Model backgrounds [38].

1. Identify a general supersymmetric signal, e.g., in four-jet + missing energy events via the global variable

$$m_{eff} = p_{T_{j_1}} + p_{T_{j_2}} + p_{T_{j_3}} + p_{T_{j_4}} + \cancel{p}_t \quad (3)$$

as seen in Fig. 7, whose mean is found from the Monte Carlo studies to be around $2m_{(\tilde{q} \text{ or } \tilde{g})}$.

2. Reconstruct decay chains starting from the end, e.g., in the above case via $\chi_2 \rightarrow \chi_1(\ell^+\ell^-)$ which should exhibit a characteristic edge in the spectrum at $m_{\ell^+\ell^-} = m_{\chi_2} - m_{\chi_1}$, then adding (for example) b and \bar{b} jets to reconstruct $m_{\tilde{b}}$ and $m_{\tilde{g}}$.
3. Finally, make a global fit to MSSM parameters within an assumed standard parametrization such as that suggested by supergravity, namely $m_{1/2}$ (a common gaugino mass), m_0 (a common scalar mass), A (a common trilinear soft supersymmetry-breaking parameter), $\tan\beta$ (the ratio of Higgs vacuum expectation values), and the sign of the Higgs mixing parameter μ [5].

This strategy has been applied within the framework of a study commissioned by the LHC experiments committee of five particular points in this parameter space [38]. The values of representative sparticle masses for these parameter choices are shown in Table 2. A typical $(\ell^+\ell^-)$ spectrum is shown in Fig. 8, where we see a sharp edge that would enable $m_{\chi_2} - m_{\chi_1}$, to be measured with a precision of 100 MeV [33, 37]. Events close to this edge can be used to reconstruct $\tilde{q} \rightarrow q\chi_2$ decays, such as $\tilde{b} \rightarrow b\chi_2$ and $\tilde{g} \rightarrow \tilde{b}\bar{b}$ decays [33, 37], as seen in Fig. 9. For generic other parameter choices, as seen in Fig. 10, one may reconstruct $h \rightarrow \tilde{b}\bar{b}$ decays in the cascade [33, 35]. Another possibility discussed here [33] is that $\chi_2 \rightarrow \chi_1 + (\tau^+\tau^-)$ decays dominate at large $\tan\beta$, in which case one may observe an excess in the $M_{\tau^+\tau^-}$ distribution. Table 3 shows the MSSM particles that may be discovered at each of the five points in parameter space that have been explored in detail [38]. We see that a sizeable fraction of the spectrum may be accessible at the LHC.

Table 2: Test points for supersymmetry studies at the LHC (masses in GeV)

	m_0	$m_{1/2}$	A_0	$\tan\beta$	$m_{\tilde{g}}$	$m_{\tilde{u}_R}$	m_{χ^\pm}	$m_{\tilde{e}_R}$	m_h
1	400	400	0	2	1004	925	325	430	111
2	400	400	0	10	1008	933	321	431	125
3	200	100	0	2	298	313	96	207	68
4	800	200	0	10	582	910	147	805	117
5	100	300	300	2.1	767	664	232	157	104

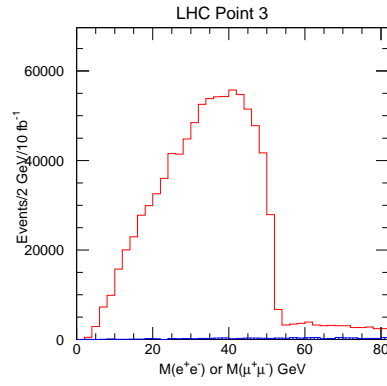


Figure 8: Typical $\ell^+\ell^-$ spectrum from $\chi_2 \rightarrow \chi_1, \ell^+\ell^-$ decay in cascade decays of \tilde{q}/\tilde{g} at the LHC [38].

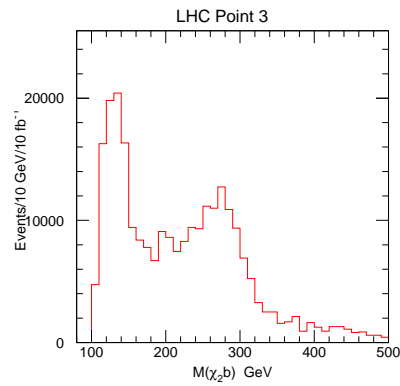


Figure 9: Typical $\tilde{b} \rightarrow \chi_2 b$ decay signature at the LHC [38].

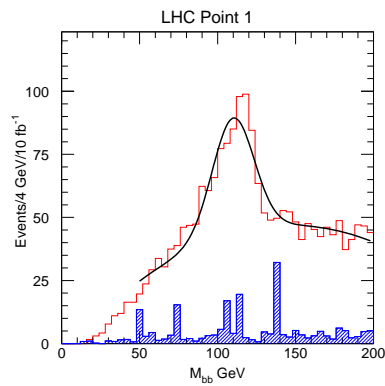


Figure 10: Typical $h \rightarrow \tilde{b}b$ decay signal from cascade \tilde{q}/\tilde{g} decays at the LHC [38].

Table 3: The LHC as “Bevatrino”: Sparticles detectable at selected points in supersymmetric parameter space and denoted by +

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

Moreover, precision determinations of the supergravity model parameters are possible if one combines the different measurements of endpoints, masses, products of cross sections and branching ratios, etc. [33, 37]. For example, it has been estimated that one could attain

$$\Delta(m_{\chi_2} - m_{\chi_1}) = \pm \begin{cases} 50 \text{ MeV} \\ 1 \text{ GeV} \end{cases} @ \text{ point } \begin{cases} 3 \\ 4 \end{cases} \quad (4)$$

$$\left. \begin{aligned} \Delta m_{\tilde{b}_1} &= \pm 1.5 \Delta m_{\chi_1} \pm 3 \text{ GeV} \\ \Delta(m_{\tilde{g}} - m_{\tilde{b}_1}) &= \pm 2 \text{ GeV} \end{aligned} \right\} @ \text{ point } 3 \quad (5)$$

A global fit at point 5 yielded

$$\Delta m_0 = \pm 5(\pm 3) \text{ GeV}, \quad \Delta m_{1/2} = \pm 8(\pm 4) \text{ GeV}, \quad \Delta \tan \beta = \pm 0.11(\pm 0.02) \quad (6)$$

where the different errors refer to different stages in the sophistication of the analysis, and other examples are shown in [33].

These are not the only precision aspects of physics at the LHC. Parton distributions are the limiting uncertainties in present experiments, of the large- E_T jet cross section at FNAL [39] and the large- x data at HERA [40]. Previously, it had been thought difficult to determine the pp collision luminosity with a precision better than 5%. A new approach [41, 42] is to bypass this step, and measure directly the parton-parton luminosity functions via the rapidity distributions of the W^\pm, Z^0 , which could fix the products $q(x_1)\bar{q}(x_2)$ for $10^{-4} \gtrsim x \gtrsim 0.1$ with an accuracy of $\pm 1/2\%$, of the LEP luminosity error of $\pm 1/4\%$ from Bhabha scattering. The problem in exploiting this is primarily theoretical: can one relate the cross section for W^\pm or Z^0 production to other production cross sections, e.g., for W^+W^- pairs or the Higgs, with comparable accuracy? This would require a significant advance in the state of the art of higher-order QCD calculations. So far, one-loop corrections to jet cross sections are known [43], including those due to strongly-interacting sparticle loops [44]. These amount to several percent in some subprocess cross sections, and may have observable structures at to the supersymmetric threshold $M_{jj} = 2m_{\tilde{q}}$ or $m_{\tilde{q}} + m_{\tilde{g}}$ or $2m_{\tilde{g}}$.

Beyond the approved (or almost approved) parts of the LHC programme, there are two further experimental initiatives now circulating. One is for a full-acceptance ($|\eta| < 11$) detector called FELIX [45] to operate at moderate luminosity ($\mathcal{L}_{pp} \gtrsim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$) with a physics agenda centred on QCD. This would include novel hard phenomena, such as small- x physics, had diffraction, rapidity-gap physics, the BFKL pomeron and minijets, as well as soft QCD effects at large impact parameters and in central collisions. The proposed programme also includes hard and soft QCD in pA collisions and $\gamma\gamma$ physics in pp and AA collisions, as well as the search for an astroparticle connection to “anomalies” in cosmic-ray collisions, possibly via disordered chiral condensates. FELIX would require bringing the LHC beams into collision in a new interaction point, and has yet to leap the hurdle of assembling a large involved community of experimentalists.

TOTEM [46] is a modest “classical” proposal to measure the total pp cross section ($\Delta\sigma \sim 1 \text{ mb}$), elastic scattering in the range $5 \times 10^{-4} \text{ GeV}^2 \gtrsim |t| \gtrsim 10 \text{ GeV}^2$ and diffractive production of systems weighing up to 3 TeV. It could very likely be placed at the same interaction point as one of the (almost) approved experiments.

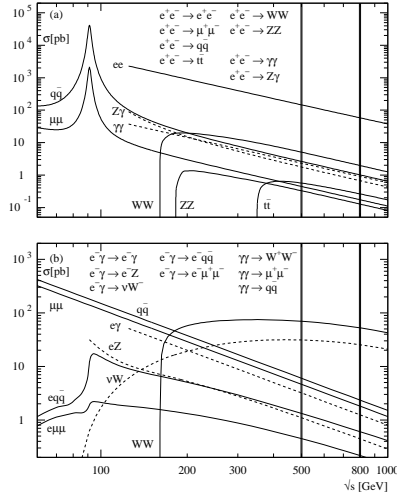


Figure 11: Important cross sections at a linear collider [50].

To conclude this review of the LHC physics programme, and set the stage for proposed subsequent accelerators it is appropriate to conclude this section by reviewing some potential weaknesses of the LHC, as regards probing the MSSM. It is not suitable for producing and studying the heavier charginos $\chi_{2,3}^{\pm}$ and neutralinos $\chi_{3,4,0}$, nor sleptons if they weigh $\gtrsim 400$ GeV. It may have difficulty studying the heavier MSSM Higgs bosons H, A, H^{\pm} , and even the lightest Higgs boson h if it has non-standard decay modes. It is not well suited for measuring squark mass differences, since, e.g., it cannot distinguish \tilde{u}, \tilde{d} and \tilde{s} . Thus it is questionable whether it provides enough cross-checks on the validity of the MSSM and test simplified parametrizations such as those based on supergravity with a universal scalar mass m_0 . There will be plenty of scope for further studies of supersymmetry, even if it discovered earlier at the LHC (or LEP or the FNAL collider).

4 e^+e^- linear collider physics

These machines offer a very clean experimental environment and egalitarian production of new weakly-interacting particles. Moreover, polarizing the beam is easy and can yield interesting physics signatures, and $e\gamma, \gamma\gamma$ and e^+e^- collisions can also be arranged quite easily. Thus linear colliders have many features complementary to those of the LHC [47].

It is likely that the first linear collider would have an initial centre-of-mass energy of a few hundred GeV. Some of the cross sections for important physics processes [48] are shown in Fig. 11 [49]. In the absence (so far) of any clear indication of a threshold in this energy range for new physics, we start by reviewing the bread-and-butter Standard Model physics agenda of such a machine. Pride of place goes to top physics. Detailed measurements of $\sigma_{\bar{t}t}$ and momentum spectra around the threshold at $E_{cm} \sim 350$ GeV, shown in Fig. 12, should enable the error in the top quark mass to be reduced to ~ 120 MeV, and it should be possible to measure Γ_t with an error around 10%. It will also be possible to search very cleanly for non-standard top decays and measure static parameters of the t quark, such as $g_{A,V}^Z, \mu_t$, its Higgs coupling [50] and its electric dipole moment. Turning to W^{\pm} and Z^0 physics, precision on the triple-gauge couplings can be improved over the LHC down to the 10^{-3} level. Moreover, if one is able to run the collider with high luminosity at the Z^0 peak, one can quickly obtain a precise measurement of $\sin^2 \theta_W$ (± 0.0001), and running at the W^+W^- threshold could enable the error on m_W to be reduced to 15 MeV.

The range of Higgs masses preferred (1) by the precision electroweak measurements gives hope that the Higgs boson may lie within the kinematic reach of a first linear collider, via the reactions $e^+e^- \rightarrow Z + H$ and $e^+e^- \rightarrow$

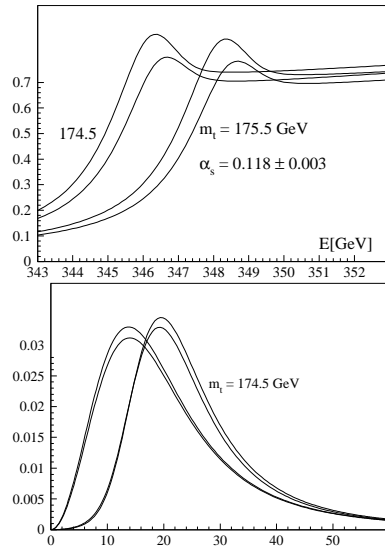


Figure 12: (a) Cross section and (b) kinematic measurements of $e^+e^- \rightarrow \bar{t}t$ at a linear collider [50].

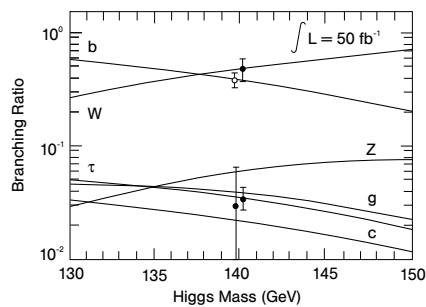


Figure 13: Accuracy with which Higgs decay branching ratios may be measured at a linear collider [50].

$H\bar{\nu}\nu$. Moreover, it is easy to detect a Higgs boson in the mass ranges that are “delicate” at the LHC, namely $m_Z \gtrsim m_H \gtrsim 120$ GeV and $m_H \sim 170$ GeV [49, 51]. Even if the Higgs discovery is made elsewhere, a linear collider could tell us much more about its couplings and branching ratios: g_{ZZH} , $B(\bar{b}b)$, $B(WW^*)$, $B(\tau^+\tau^-)$ and $B(\bar{c}c + gg)$, as seen in Fig. 13, enabling us to verify that it does its job of giving masses to the gauge bosons, quarks and leptons, and giving us a window on possible non-minimal Higgs models. One can also measure $\Gamma(\gamma\gamma)$ using the $\gamma\gamma$ collider modes and the spin-parity of the Higgs can be measured [49]. Turning to the MSSM, production and detection of the lightest MSSM Higgs h is guaranteed, and the heavier Higgs bosons H^\pm, H, A can also be observed if the beam energy is high enough.

As for supersymmetry proper, if its beam energy is above threshold, a linear collider will produce cleanly electroweakly-interacting sparticles such as the $\tilde{\ell}^\pm, \tilde{\nu}, \chi^\pm$ and χ_i that are problematic at the LHC [49, 52], as seen in Fig. 14. Moreover, sparticle masses can be measured accurately:

$$\begin{aligned}
 \delta m_{\tilde{\mu}} &\sim 1.8 \text{ GeV}, \delta m_{\tilde{\nu}} \sim 5 \text{ GeV}, \\
 \delta m_{\chi^\pm} &\sim 0.1 \text{ GeV} \\
 \delta m_{\chi} &\sim 0.6 \text{ GeV}, \delta m_{\tilde{\tau}} \sim 4 \text{ GeV}
 \end{aligned}
 \tag{7}$$

enabling one to test supergravity mass relations, over-constrain model parameters and check universality (is $m_{\tilde{\ell}} = m_{\tilde{\mu}} = m_{\tilde{\tau}}$, for example?). Moreover, the couplings and spin-parities of many sparticles can be measured. Thus a linear collider will certainly be able to add significantly to our knowledge of supersymmetry [49], even if the LHC discovers it first, and despite the large range of measurements possible at the LHC – provided the

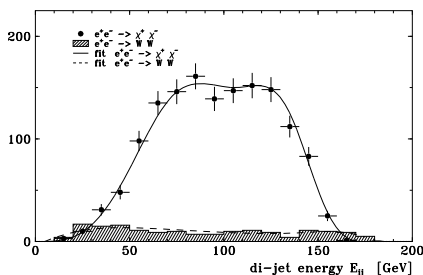


Figure 14: Possible measurement of $e^+e^- \rightarrow \chi^+\chi^-$, $\chi^\pm \rightarrow jj\chi$ at a linear collider [50].

linear collider beam energy is large enough!

In my view, we will need a linear collider to complete our exploration of the TeV energy range, begun by the LHC, to pin down the mechanism of electroweak symmetry breaking, and to complement the LHC programme with more precision measurements. To have physics reach comparable to the LHC, the collider energy should be able to reach $E_{cm} \sim 2$ TeV, and it would be desirable to be able to operate back in the LEP energy range and the Z peak and the W^+W^- threshold. Thus the machine should be flexible, with an initial E_{cm} in the few hundred GeV and the possibility of subsequent upgrades. Unfortunately, we do not yet know exactly where to start, in the absence of clear information on new physics thresholds. A final personal comment is that I hope very much that the linear collider community can converge on a single project. Can the world afford two such colliders? In the recent past, our political masters have decided to support just one hadron collider.

5 Beyond the Standard Colliders

Even though construction of the LHC will not be completed for another 8 years, and no linear collider proposal has even been submitted, it is already time to think what might come next, since we need to maintain a long-term vision of the future of accelerator-based particle physics, and the $R \times D$ lead time for any new accelerator project is necessarily very long.

One possible future option which has been kept in mind since the inception of the LHC project has been an ep collider in the LEP tunnel, using an LHC beam and an e^\pm beam circulating in a rearranged LEP ring [53]. The latest design envisages beam energies of 7 TeV and 67 GeV, yielding collisions at a centre-of-mass energy of 1.37 TeV with a luminosity $\mathcal{L}_{ep} \sim 10^{32} \text{cm}^{-2} \text{s}^{-1}$. The physics interest of this ep option will be easier to judge after the physics potential of the HERA collider (and in particular the interpretation of the current large- Q^2 anomaly [40]) has been further explored: certainly it would be great for producing leptoquarks or R -violating squarks up to masses around 1 TeV.

However, this option is presumably not a complete future for CERN, let alone the world high-energy physics community. More complete possibilities for the future are $\mu^+\mu^-$ colliders [54], which may be the best way to collide leptons at $E_{cm} = 4$ TeV or more, and a possible next-generation pp collider (variously named the Eloisatron, RLHC or VLHC, called here a ‘Future Larger Hadronic Collider’ or FLHC) with $E_{cm} = 100$ to 200 TeV [55]. We now discuss each of these possibilities in turn.

Many technical issues need to be resolved before a multi-TeV $\mu^+\mu^-$ collider can be proposed: the accumulation of the μ^\pm , their cooling, shielding the detectors and the surrounding populace from their decay radiation, etc. These should be addressed by a smaller-scale demonstrator project, much as the SLC demonstrates the linear-collider principle. A very exciting possibility for this demonstrator is a Higgs factory [56], exploiting the non-universality of the HL^+L^- couplings, which implies that $\sigma(\mu^+\mu^- \rightarrow H)/\sigma(e^+e^- \rightarrow H) \sim 40,000$, and

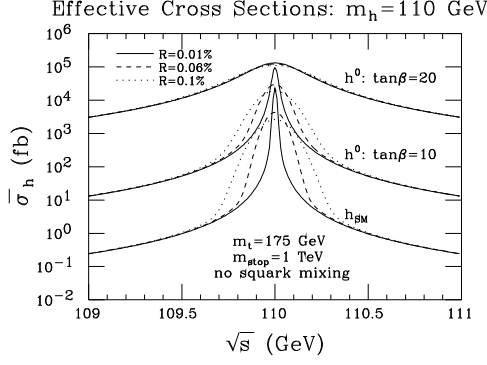


Figure 15: Cross sections for Higgs production at a $\mu^+\mu^-$ collider run as a “Higgs factory” [55,57].

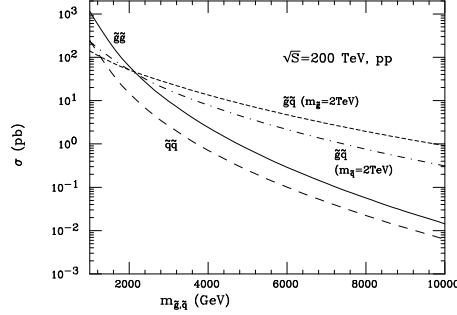


Figure 16: Cross sections for \tilde{q} and \tilde{g} production at a FLHC [58].

the possibly reduced energy spread in $\mu^+\mu^-$ collisions, which may be as small as 0.01%. Neglecting the energy spread, the $\mu^+\mu^-$ cross section in the neighbourhood of the H peak is given by

$$\sigma_H(s) = \frac{4\pi \Gamma(H \rightarrow \mu^+\mu^-) \Gamma(H \rightarrow X)}{(s - m_H^2)^2 + m_H^2 \Gamma_H^2} \quad (8)$$

where the natural width of a 100 GeV Higgs is expected to be about 3 MeV, whereas $\Delta\sqrt{s}$ may be as low as 10 MeV. Typical line shapes for Standard Model and MSSM Higgs bosons in this mass range are shown in Fig. 15. Such a Higgs factory would be able to measure Higgs decay branching ratios into channels such as $b\bar{b}$, $\tau^+\tau^-$, WW^* and ZZ^* . It could also draw a clear distinction between the Standard Model H and the MSSM h , could (at higher energies) separate the H and A of the MSSM, and also make detailed studies of their properties. Other possible applications of the narrow $\mu^+\mu^-$ spread in E_{cm} include the measurement of m_H with a precision ~ 45 MeV, and improved precision in the values of m_t and m_W [54].

As for a possible FLHC, this is clearly the tool of choice for exploring the 10 TeV energy range, as is shown by one example in Fig. 16 [57]. At present, we do not know what physics may lie there – the messenger sector of a gauge-mediated scenario for supersymmetry breaking [5]? a Z' ? a fifth dimension? We will never know unless we go and look.

References

- [1] D.R. Ward, Plenary Talk 15 at this conference, hep-ph/9711515.
- [2] T. Hambye and K. Riesselmann, hep-ph/9708416.
- [3] J. Ellis, G.L. Fogli and E. Lisi, Physics Letters B389 (1996), 321-326, and references therein.
- [4] M. Carena, M. Quiros and C.E.M. Wagner, Nuclear Physics B461 (1996) 407-436; H.E. Haber, R. Hempfling and A.H. Hoang, Zeit. für Physik C75 (1997) 539-554.
- [5] P. Binetruiy, Plenary Talk 9 at this conference.
- [6] C. Jarlskog, Plenary Talk 5 at this conference, M. Feindt, Plenary Talk 7 at this conference.
- [7] H. Georgi, H. Quinn and S. Weinberg, Physical Review Letters 33 (1974), 451-454.
- [8] M.S. Chanowitz, J. Ellis and M.K. Gaillard, Nuclear Physics B128 (1977), 506.
- [9] P. Mättig, Parallel session Talk 1801 at this conference.
- [10] P. Janot, Plenary Talk 17 at this conference.
- [11] S. Park, in *Proceedings of the 10th Topical Workshop on Proton-Antiproton Collider Physics*, Fermilab, 1995, edited by R.Raja and J. Yoh (AIP, New York, 1995), p. 62.
- [12] J.M. Butler, Parallel Session Talk 1802 at this conference; D. Gerdes, Contributed Paper 238.
- [13] K.Schubert, Parallel Session Talk 1819 at this conference; BaBar collaboration, Contributed Paper 005.
- [14] P. Krizan, Parallel Session Talk 1818 at this conference.
- [15] J.N. Butler, Parallel Session Talk 1820 at this conference.
- [16] CMS collaboration, G.L. Bayatian et al., Technical Proposal, CERN/LHCC/94-38, LHCC/P1 (1994).
- [17] CMS collaboration, Contributed Paper 542.
- [18] ATLAS collaboration, W.W. Armstrong et al., Technical Proposal, CERN/LHCC/94-43, LHCC/P2 (1994).
- [19] S. Semenov, Parallel Session Talk 1821 at this conference.
- [20] F. Plasil, Plenary Talk 12 at this conference.
- [21] STAR collaboration, J.W. Harris et al., Nuclear Physics A566 (1994), 277c-286c.
- [22] PHENIX collaboration, J.C. Gregory et al., BNL-PROPOSAL-R2 (1992).
- [23] B. Wosiek, Parallel Session talk 604 at this conference.
- [24] ALICE collaboration, S. Boelè et al., Technical Proposal, CERN/LHCC 95-71, LHCC/P3 (1995) and Addendum CERN/LHCC 96-32 (1996).
- [25] J.-C. Gourber, Plenary Talk 18 at this conference.
- [26] R. Kvatadze, Parallel Session Talk 606 at this conference.
- [27] M. Spira, Parallel Session Talk 1805 at this conference, hep-ph/9711394.
- [28] R.J. Cashmore, Plenary Talk 13 at this conference.

- [29] L. Poggioli, Parallel Session Talk 1806 at this conference.
- [30] M. Dittmar and H. Dreiner, *Physical Review D* 55 (1997), 167-172.
- [31] J. Tuominiemi, Parallel Session Talk 1807 at this conference.
- [32] M. Dittmar, Parallel Session Talk 1812 at this conference.
- [33] F. Paige, Parallel Session Talk 1814 at this conference.
- [34] W. Beenakker, R. Hopker, M. Spira and P. Zerwas, *Nuclear Physics B* 492 (1997), 51-103.
- [35] S. Abdullin, Parallel Session Talk 1813 at this conference;
D. Denegri, A. Kharchilava, W. Majerotto and L. Rurua, Contributed Paper 540;
D. Denegri, W. Majerotto and L. Rurua, hep-ph/9711357.
- [36] H. Baer, C.-H. Chen and X. Tata, *Physical Review D* 55 (1997) 1466-1470.
- [37] I. Hinchliffe, F.E. Paige, M.D. Shapiro, J. Soderqvist and W. Yao, *Physical Review D* 55 (1997), 5520-5540.
- [38] LHCC supersymmetry workshop, <http://www.cern.ch/Committees/LHCC/SUSY96.html>.
- [39] CDF collaboration, F. Abe et al., *Physical Review Letters* 77 (1996) 438-443.
- [40] E. Elsen, Plenary Talk 26 at this conference.
- [41] F. Behner, Parallel Session Talk 1803 at this conference.
- [42] M. Dittmar, F. Pauss and Zürcher, *Physical Review D* 56 (1997), 7284-7290.
- [43] R.K. Ellis and J.C. Sexton, *Nuclear Physics B* 269 (1986), 445.
- [44] J. Ellis and D.A. Ross, hep-ph/9708312.
- [45] FELIX collaboration, E. Lippmaa et al., CERN/LHCC 97-45, LHCC/I10 (1997).
- [46] TOTEM collaboration, W. Kienzle et al., CERN/LHCC 97-49, LHCC/I11 (1997).
- [47] B. Wiik, Plenary Talk 14 at this conference.
- [48] M. Martinez, Parallel Session Talk 1804 at this conference;
E. Boos, Parallel Session Talk 1809 at this conference;
V. Ilyin Parallel session Talk 1811 at this conference.
- [49] ECFA/DESY LC Physics Working Group, E. Accomando et al., DESY-97-100 (1997), Contributed Paper 673;
see also H. Murayama and M.E. Peskin, *Annual Reviews of Nuclear and Particle Science* 46 (1997), 533.
- [50] S. Bar-Shalom, Parallel session Talk 1816 at this conference, hep-ph/9710355.
- [51] H.-J. Schreiber, Parallel Session Talk 1808 at this conference, hep-ph/9711468;
G.-L. Lin, Parallel session Talk 1817 at this conference;
G. Montagna et al. Contributed Paper 281.
- [52] H. Martyn, Parallel Session Talk 1815 at this conference.
- [53] E. Keil, *LHC e-p Option*, LHC Project Report 93 (1997).

- [54] The $\mu^+\mu^-$ Collider collaboration, *Muon Muon Collider: A Feasibility Study*, BNL-52503, FERMILAB-CONF-96/092, LBNL-38946 (1996).
- [55] See, for example, D. Denisov and S. Keller, Summary of the Very Large Hadron Collider Physics and Detector Subgroup, in *Proc. New Directions for High-Energy Physics*, Snowmass 1996, p.277;
G. Anderson et al., Summary of the Very Large Hadron Collider Physics and Detector Workshop, FERMILAB-CONF-97/318-T.
- [56] V. Barger, M. Berger, J. Gunion and T. Han, *Physical Review Letters* 78 (1997), 3991-3994 and *Physical Review D* 56 (1997), 1714-1722.
- [57] M. Mangano, private communication (1997).