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Report from Snowmass 96
New Directions for High Energy Physics

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A workshop, *New Directions for High Energy Physics*, was held June 25 – July 12, 1996, at Snowmass, Colorado, under the joint auspices of the Division of Particles and Fields and the Division of Physics of Beams of the American Physical Society. The workshop was organized to study proposed future facilities for high energy physics in the United States. This report summarizes some of the conclusions describing accelerator and particle physics opportunities in the LHC era.

1 Origin of the Workshop

My path to the Snowmass 96 workshop began with concern for the SSC in the summer of 1993. At that time, the Executive Committee (EC) of the Division of Particles and Fields (DPF) of the American Physical Society started to think about how to develop a future U.S. high energy physics program without the SSC. Only a few months later the worst fears for the SSC were realized with the cancellation of the project. The DPF EC organized the Committee on Long-Term Planning (CLTP) as one of its principal responses to this event.

The CLTP did not try to duplicate or compete with the work of the Drell Subpanel of the Department of Energy's High Energy Physics Advisory Panel that began about the same time. This Subpanel was asked to provide – in a short time and within a fairly narrowly defined charge – a vision of the future of the U.S. high energy physics program without the SSC. Given these restrictions, there was substantial opportunity for the CLTP to go beyond the effort of the Subpanel.

The CLTP consisted of a broad-based nationwide group of particle and accelerator physicists, organized in 11 working groups, each led by several convenors. Each working group made an in-depth study of the accomplishments of its subfields and the opportunities that future facilities could provide. The CLTP report[1] demonstrated that the field of high energy physics was surprisingly robust despite the SSC setback, reaffirmed the intellectual vitality of the U.S. and international HEP programs, and endorsed the conclusions of the Drell Subpanel. However, the CLTP did not attempt to compare capabilities of different facilities proposed for the future. Such comparisons would require even broader participation and more direct interaction among participants than was possible with the CLTP. This sort

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of effort is more appropriate for a Snowmass workshop and the Report proposed such a workshop to promote common understanding and start to build a consensus for the future. Members of the EC of the APS Division of Physics of Beams (DPB) were simultaneously thinking along the same lines, so the two Executive Committees joined forces to organize the workshop. It was clear that the issues for the workshop could have a substantial impact on the futures of both accelerator and high energy physics.

My personal goals in helping to organize this workshop were to provide an opportunity for individuals interested in different future facilities to interact with each other in order to: provide a common understanding of accelerator and particle physics issues, develop a common understanding of possible contributions of proposed facilities to addressing the particle physics issues, and start to build a consensus for the future U.S. program.

Table 1: Benchmark accelerators for particle physics studies.

Machine	Energy [TeV]	Luminosity Goals [cm^{-2} s^{-1}]	[fb^{-1}/yr]
TeV33	2	1×10^{33}	10
LHC	14	10×10^{33}	100
NLC	0.5	5×10^{33}	50
NLC	1.0	20×10^{33}	200
NLC	1.5	20×10^{33}	200
$\mu^+\mu^-$	0.5	0.7×10^{33}	7
$\mu^+\mu^-$	0.5	5×10^{33}	50
$\mu^+\mu^-$	4	100×10^{33}	1,000
pp	60	10×10^{33}	100
e^+e^-	5	100×10^{33}	1,000
ep	1	0.1×10^{33}	1

2 Scientific Organization

The workshop was organized around an accelerator working group and 5 particle physics working groups. The latter groups addressed specific physics topics and examined the possible contributions of several "benchmark accelerators", given in Table 1, to address these issues. These benchmark accelerators were chosen to provide standards, limit options, and avoid confusion among the working groups. An Accelerator Working Group[2] studied a subset of the proposed accelerators. The accelerator group focused on studying feasibilities and technical issues, and identifying fruitful areas for future R&D effort. No attempt was made to evaluate the costs of proposed facilities because cost studies would have required massive additional effort and the proponents of the proposed new facilities were not ready to make responsible cost estimates. Finally, a Detector Coordinating Committee[3] helped to identify a benchmark detector for each accelerator facility and to coordinate changes in these detectors as new physics or accelerator requirements arose. I will not discuss the work of this group in this report.

The five particle physics groups were named: Light Higgs,[4] Supersymmetry[5] (SUSY), Strong Coupling,[6] New Phenomena,[7] and QCD.[8] The first three studied known approaches to understanding electroweak symmetry breaking (EWSB), the source of elementary particle masses. The New Phenomena working group studied the potential of proposed new facilities for discovering a variety of possible new particles and interactions. The QCD group studied the contributions that new facilities could provide for clarifying our understanding of this fundamental theory. No groups were organized to study b and ν flavor physics because the next generation of facilities to address these topics is already underway, but a subgroup of the Strong Coupling Working Group did study top physics. The possible contributions of astrophysics to particle physics had been the subject of Snowmass 94, so additional effort on this subject was not required at this time.

The results of the workshop will be published in a Proceedings which will contain contributions from the speakers at the Opening Plenary session, the Convenors of the Working Groups and Subgroups, and individual participants and *ad hoc* groups of participants. The proceedings will be available[9] as a conventional paperback book, a CD in the Adobe Acrobat PDF format, and on the WWW. The CD will also include several reports[10,11,12,13] on proposed new facilities and their particle physics potentials that were submitted to the Snowmass workshop.

3 Accelerator Working Group

The Accelerator Working Group[2] studied the feasibilities of a subset of the proposed facilities (TeV33, NLC, $\mu^+\mu^-$, RLHC, and Multi-TeV e^+e^-) and identified R&D efforts that would be required for progress in designing these facilities. Much was learned and no show-stoppers were identified. This section is a short summary of some of the proposed facilities and the results of these studies:

3.1 Hadron Colliders

TeV33 is a relatively modest upgrade of the existing Tevatron facility (including the Main Injector now under construction). The Tevatron will define the energy frontier at $\sqrt{s} = 1.8$ TeV until the LHC. The integrated luminosity that each experiment (CDF and DØ) has from the completed Run I is ~ 0.1 fb^{-1}; the corresponding goal for the Main Injector (Run II) is 2 fb^{-1} and the goal for for TeV33 is about 30 fb^{-1}.

The LHC will define the energy frontier at $\sqrt{s} = 14$ TeV for the foreseeable future. The goals for integrated luminosity are 10 fb^{-1}/yr early in the program and 100 fb^{-1}/yr later. The LHC is nearing final approval and we expect that it will be built!

The Really Large Hadron Collider is the working name for a hadron collider with very high energy ($\sqrt{s} > 60$ TeV) and high integrated luminosity (100 fb^{-1}/yr) goals. So far such a device is at the initial conceptual stages. Groups are exploring high-field (> 10 T) and low-field (~ 2 T) options – both require substantial R&D effort to reduce costs to an acceptable level. There have been promising recent developments in high T_C superconductors which may be the key to an RLHC. In addition, new ideas for reducing tunnel and installation costs, such as remotely controlled and guided tunnel boring machines, and robotic installation and maintenance, are being considered.

3.2 Lepton Colliders

Lepton colliders can complement the programs of hadron colliders by providing a number of distinct features that are especially useful for precision studies of new phenomena. The initial state (either one or two photons) is particularly clean and free of the multi-gluon background found at hadron colliders. Tuning the beam energies can often enhance the signal/background ratio. Polarization of one or both of the beams can also enhance the signal/background ratio and can be invaluable in establishing spin-parity quantum numbers. However, energy loss due to synchrotron radiation ($\Delta E_{\rm SR} \propto E^4/R$ per turn) severly limits the energy of practical circular e^+e^- colliders. For example, at LEP2 with a circumference of 26.7 km and $E = 96$ GeV/beam, the energy loss is $\Delta E_{\rm SR} = 2.7$ GeV/turn. Providing this much accelerating voltage per turn is already a major challenge for rf accelerator technology. For a circular e^+e^- collider with $E \sim 250$ GeV/beam and the same circumference, $\Delta E_{\rm SR}$ is about half of the beam energy, so it is difficult to imagine a circular e^+e^- collider with $\sqrt{s} \gtrsim 0.5$ TeV.

The particle physics advantages of e^+e^- colliders can be realized in a linear collider which eliminates the problems with synchrotron radiation, although accelerating the beams to very high energy remains a substantial technical challenge. The SLC is the first e^+e^- collider to exploit this possibility and it provides invaluable experience in the design, construction, and operation of a linear collider. Considerable effort at DESY, KEK, and SLAC has gone into the design of a higher energy linear collider. Such a facility is called the Next Linear Collider (NLC) at SLAC; in this report "NLC" will be used as a generic term for a high energy linear e^+e^- collider. A "Zeroth-Order Design" has been completed and reports[11,12] describing this effort were submitted to the Workshop. The aim is to build a facility (about 30 km long – comparable to the circumference of LEP) that would initially provide $\sqrt{s} = 0.5$ TeV. An upgrade to 1 TeV would be adiabatic, primarily involving replacement of the initial klystrons with higher power devices. An extension to 1.5 TeV would require lengthening the facility. The primary disadvantages of linear colliders are that the energy is limited by existing rf accelerating technology to a fraction of the energy of hadron colliders, the cross section is much lower than at hadron colliders, and the beam energy spread due to beamstrahlung is a significant problem for experiments.

A $\mu^+\mu^-$ collider[13] would overcome some of the disadvantages of a linear e^+e^- collider. A circular accelerator with higher energy is possible because the energy loss due to synchrotron radiation is substantially reduced since $m_\mu \gg m_e$. In fact, a facility in the range of 2 – 4 TeV is being discussed. Furthermore, a $\mu^+\mu^-$ collider would provide the same clean initial single photon state found at an NLC, the CM energy would be better defined due to substantially less beamstrahlung and initial state radiation, and the much larger cross section for s-channel production of Higgs bosons would be a singular advantage in studying the Higgs mechanism of Electroweak Symmetry Breaking ($\sigma \propto m_\ell^2$, where m_ℓ is the mass, m_e or m_μ, of the colliding lepton). However, it would be very difficult to achieve high polarization and high luminosity simultaneously in a $\mu^+\mu^-$ collider and there would be very serious backgrounds in a detector due to μ decay. Finally, a $\mu^+\mu^-$ collider requires a substantial number of untried technologies, particularly in providing the μ beams and cooling them. These must be addressed in a very aggressive theoretical and experimental R&D program in order to decide whether or not a $\mu^+\mu^-$ collider is technically feasible and cost-effective.

A number of possible ideas for a Multi-TeV e^+e^- Collider ($\sqrt{s} > 5$ TeV) were also studied. It is clear that such a facility would require extensive and creative R&D on new accelerating technologies and reconsideration of the conventional wisdom on how to handle beam-beam radiative effects in e^+e^- colliders.

4 Origin of Electroweak Symmetry Breaking

The Standard Model (SM) has been extremely successful in describing experimental results in elementary particle physics. The agreement between the SM and the precision electroweak measurements at LEP and SLC, and the agreement between the top mass derived from LEP measurements and the value measured at the Tevatron collider, are particularly impressive. There are very few hints of new phenomena; indeed, the $R_{b\bar{b}}$ anomaly in earlier LEP measurements that was still drawing attention at Snowmass has largely disappeared since the workshop.[14]

However, the SM has a number of serious limitations, including the fact that theory does not determine important SM parameters: the masses of the leptons, quarks, and gauge bosons; and the coupling constants of the interactions. All in all, there are 18 parameters to explain (or 25 if neutrinos have nonzero mass). The origin of mass is a particular problem for the SM because the SM is based on gauge symmetry which requires zero masses for the gauge bosons.

The SM includes the Higgs mechanism – interaction with a complex doublet of elementary scalar fields – for breaking electroweak symmetry and generating masses for the gauge bosons and the fermions (leptons and quarks). This interaction results in at least one Higgs scalar h^0_{SM} with a mass on the order of the EW scale ($M_W \sim M_Z$). However, this scalar cannot be fundamental; it can only be a low energy approximation because elementary scalar bosons should acquire masses on the order of the Planck scale via radiative corrections. There are three basic pictures of how to avoid these large radiative corrections to scalar masses:

- Fine tune a number of parameters in the theory to cancel corrections. However, this requires incredibly accurate tuning – about 1 part in 10^{16} in mass – a formidable challenge, indeed!
- Supersymmetry, in which a new boson-fermion symmetry is introduced to exactly cancel all large corrections. This results in doubling the mass spectrum of elementary particles. So far, no SUSY partner of the SM particles has been found so this symmetry must also be broken.
- Strongly Coupled EWSB (SC-EWSB) models posit that elementary Higgs scalars do not exist. Instead, EWSB could be due to a new strong interaction whose nature could only be revealed at some higher energy.

Whichever scenario of EWSB is correct, we generally expect some new EWSB physics on the TeV scale, because the vacuum expectation value involved in breaking EW symmetry in the SM Higgs field is $v = 246$ GeV, suggesting that Higgs masses are $\lesssim 1$ TeV.

5 Light Higgs Working Group

Understanding the dynamics of EWSB must be a principal goal of future high energy accelerators. This should start by searching for a SM Higgs scalar h^0_{SM} with an EW scale mass.

However, there is no evidence that there is only one Higgs scalar, so we must be prepared for more general possibilities. A second Higgs doublet is a quite "generic" feature of models for physics beyond the SM. If there are two Higgs doublets, a total of 4 Higgs scalars must be found: h^0 and H^0, two CP even neutral scalars; A^0, a CP odd neutral scalar; and a charged scalar $H^{\pm}$. Hence, we must be prepared to search for multiple Higgs bosons with masses up to at least 1 TeV, unless the Higgs sector is completely revealed at lower masses. The Light Higgs Working Group[4] studied prospects for Higgs searches in this mass range.

The parameter space in which to search for light Higgs particles is quite large. However, the Minimal Supersymmetric Model (MSSM) is generally considered a good place to start. In this model, SUSY constraints determine tree-level Higgs properties in terms of two parameters, generally chosen to be M_A, the mass of the A^0 and $\tan\beta$, a ratio of vacuum expectation values. In this model, $M_{h_{SM}} \lesssim 125$ GeV although it may be larger in non-MSSM models. More generally in the light Higgs or weakly-coupled limit, most models require $h^0 \simeq h^0_{SM}$, $M_{h^0} \sim \mathcal{O}(M_Z)$, and $M_{h^0} < M_{H^0} \sim M_{A^0} \sim M_{H^{\pm}}$.

In order completely understand the Higgs sector, experiments must:

- be capable of finding h^0, H^0, A^0, and $H^{\pm}$, if they exist;
- measure the masses to compare with theoretical mass relationships;
- measure each J^{PC} to verify $J = 0$ and the appropriate CP; and
- measure the decay widths to verify the theoretical couplings.

Table 2: Mass limits for light Higgs searches for several of the benchmark facilities. TeV-MI refers to the 2 fb^{-1} Main Injector run.

Accelerator	M_{h^0}
LEP2	95 GeV
TeV–MI	100 GeV
Tev33	120 GeV
LHC	1 TeV
NLC	$0.7\sqrt{s}$
$\mu^+\mu^-$	$\sqrt{s}$

There are a number of typical Higgs signals that can be used to discover light Higgs and measure these properties; they include: $h^0(H^0)(A^0) \to \gamma\gamma$, $h^0 \to b\bar{b}$, $h^0(H^0) \to ZZ^{(*)} \to 4\ell$, $h^0 \to ZZ(WW)$, $H^0(A^0) \to \tau\bar{\tau}$, $H^0(A^0) \to \mu\bar{\mu}$, and $H^{\pm} \to \tau^{\pm}\nu_{\tau}$. The mass limits for discovery of a light Higgs that can be reached by several of the benchmark facilities are given in Table 2 and illustrated in Figure 1, where the most appropriate decay modes have been used in each region of the M_A and $\tan\beta$ parameter space.

An NLC is a particularly suitable facility for discovering light Higgs bosons because the final states are very clean and do not involve the superfluous jets that will be present in events at hadron colliders. The luminosity required for discovery of a light Higgs at an NLC is illustrated in Figure 2.

The LHC, augmented by LEP2, can discover Higgs bosons in a very large region of the $\tan\beta$ versus M_A plane, as illustrated in Figure 3. On the other hand, if Higgs bosons do not exist in this region of the parameter space, these two facilities would rule out their existence at the 95% Confidence Level.

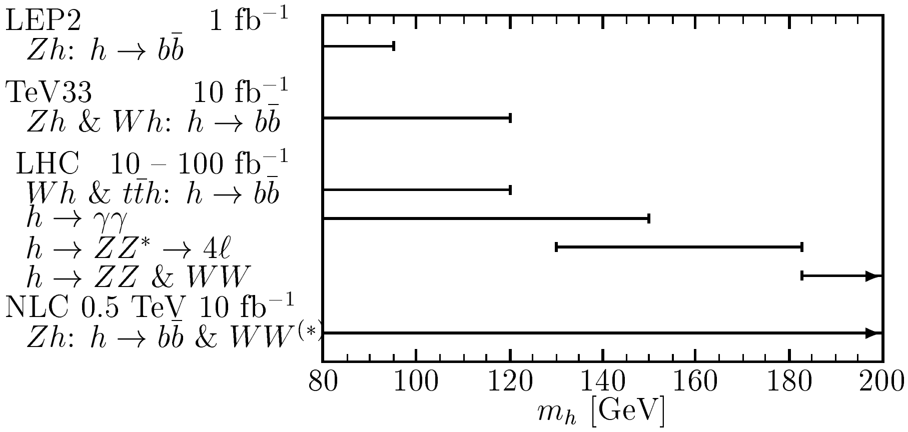

Figure 1: Discovery Ranges for the light Higgs boson h at LEP2, TeV33, LHC, and NLC.

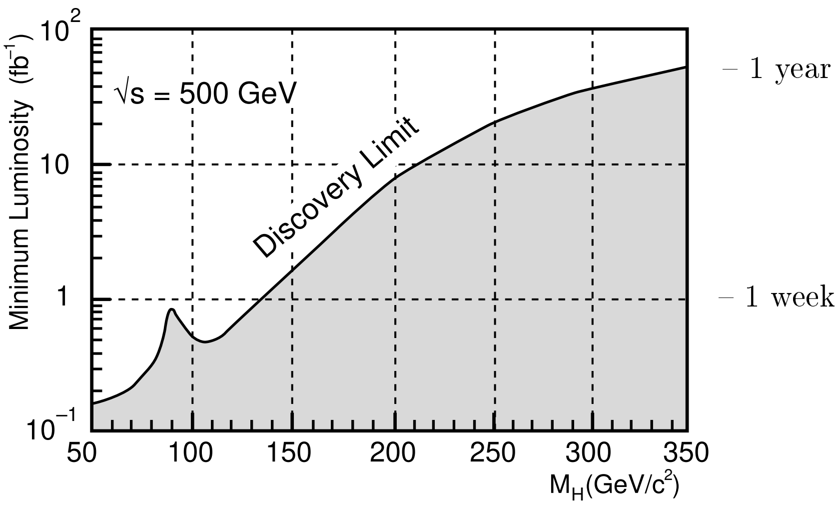

Figure 2: Minimum luminosity needed to discover a SM Higgs at an NLC.[11] Note that a mass limit of about 130 GeV could be reached in 1 week of running at the design luminosity, and 350 GeV could be reached in 1 year.

The contributions of these facilities to understanding the dynamics the Higgs sector can be summarized as follows: LEP2 and TeV33 should find any Higgs scalars with $M \lesssim 0.1$ TeV; the LHC should find those with $M \lesssim 1$ TeV; and and both of these facilities can demonstrate some Higgs behavior and measure couplings to about 20% – 30%. An NLC or $\mu^+\mu^-$ collider may be necessary for more detailed measurements including precision masses, branching fractions, widths, and J^{PC}, because studying these at a lepton collider will be easier with simpler Higgs production events, the response of production cross sections to beam energy, and the use of polarization at an NLC. The s-channel Higgs production in $\mu^+\mu^-$ colliders is a particular advantage for these facilities. However, we should not underestimate the ingenuity of LHC physicists who will very likely have substantial data samples before any data are available at a lepton collider. Early experience with real data may well lead to techniques for discovery and measurements well beyond those envisioned now.

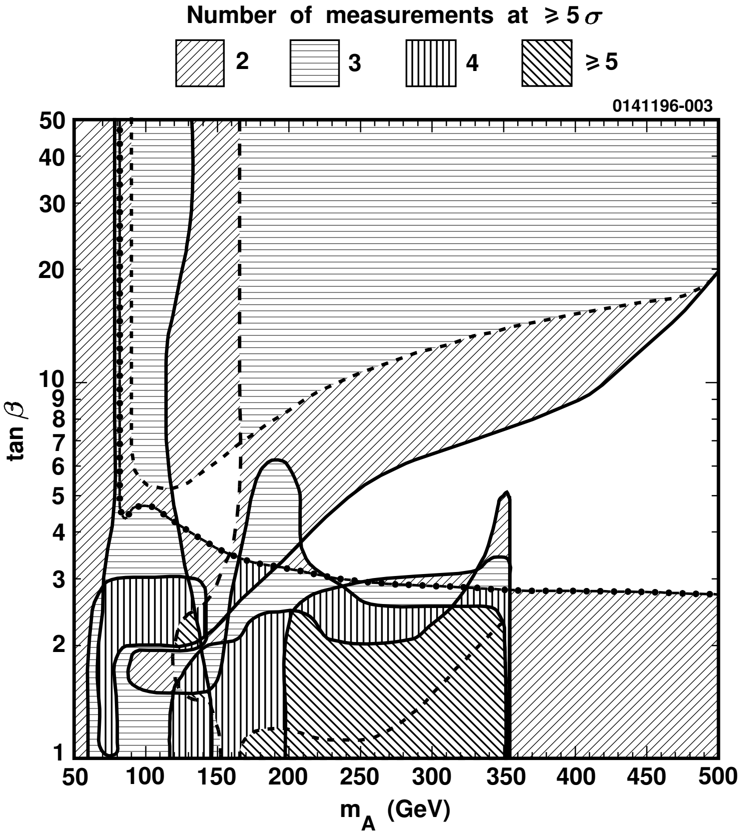

Figure 3: Regions in the M_A–$\tan\beta$ plane that can be covered by various search strategies at LEP2 and LHC.[15] The calculations assume $M_t = 175$ GeV, LEP2 luminosity of 0.15 fb^{-1} and energy $\sqrt{s} = 192$ GeV, and luminosities of 300 fb^{-1} for each of ATLAS and CMS at LHC. Note that more than 2 measurements at 5 standard deviations are possible in most regions of this plane.

6 SUSY Working Group

As mentioned earlier, Supersymmetry introduces a fermion–boson symmetry to stabilize scalar Higgs masses against divergent radiative corrections. This results in a duplication of the spectrum of fundamental particles, a Boson for every Fermion and vice versa (quarks–squarks, leptons–sleptons, gauge-bosons–gauginos, and Higgs-bosons–Higgsinos), the introduction of many new couplings, and the introduction of a new mechanism for breaking Supersymmetry because the Fermion and Boson masses are not equal. More than 100 parameters appear in the theory, so most investigations of experimental capabilities use a very restricted subset of these parameters. The SUSY Working Group[5] utilized the commonly used SUGRA parameters: M_0, a common scalar mass; $M_{\frac{1}{2}}$, a common gaugino mass; A_0, a common trilinear coupling; $\tan\beta$, a ratio of vacuum expectation values; and the sign of a parameter μ. In order for coupling constants to unify by the Plank scale, SUSY particles should appear with masses $M \lesssim 1$ TeV, which sets the scale of masses required for an exhaustive search.

Subgroups studying SUSY at each facilities studied reconstruction and measurements with different sets of SUGRA parameters, but all subgroups used a Common Point that yields low SUSY masses: $M_0 = 200$ GeV, $M_{\frac{1}{2}} = 100$ GeV, $A_0 = 0$, $\tan\beta = 2$, and $\mu < 0$. Table 3 gives the masses of SUSY particles at the Common Point.

Table 3: Masses of SUSY particles at the Common Point.

Name	Mass [GeV]	Name	Mass [GeV]	Name	Mass [GeV]	Name	Mass [GeV]
h^0	68	$\tilde{\chi}_1^0$	45	$\tilde{q}_L$	317	$\tilde{\ell}_L$	216
H^0	379	$\tilde{\chi}_2^0$	97	$\tilde{b}_L$	274	$\tilde{\nu}_L$	207
A^0	371	$\tilde{\chi}_3^0$	257	$\tilde{t}_1$	264	$\tilde{\ell}_R$	207
$H^{\pm}$	379	$\tilde{\chi}_4^0$	274	$\tilde{q}_R$	317	$\tilde{g}$	298
		$\tilde{\chi}_1^{\pm}$	96	$\tilde{b}_R$	313		
		$\tilde{\chi}_2^{\pm}$	257	$\tilde{t}_2$	239		

Table 4: Typical SUSY decay modes and detectable signatures.

Decay Mode	Branching Fraction	Signature
$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0\, \ell^+ \nu_\ell$	22 %	$\ell^+\ \not\!\!E_T$
$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0\, q\bar{q}$	66 %	2 Jets $\not\!\!E_T$
$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\, \ell^+\ell^-$	33 %	$\ell^+\ell^-\ \not\!\!E_T$
$\tilde{g} \to \tilde{\chi}_2^0\, b\bar{b}$ with $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\, \ell^+\ell^-$	76 %	$b\,\bar{b}\,\ell^+\ell^-\ \not\!\!E_T$

The lightest SUSY particle ($\tilde{\chi}_1^0$ in this case) is stable if R parity conservation is assumed (R parity distinguishes between ordinary particles and SUSY particles). Since $\tilde{\chi}_1^0$ is neutral it will not be detected, resulting in missing transverse energy ($\not\!\!E_T$) in a detector. Therefore, typical SUSY signatures, given in Table 4, will include $\not\!\!E_T$. The capabilities of TeV33, LHC, and an NLC for discovery of SUSY particles are illustrated in Figure 4.

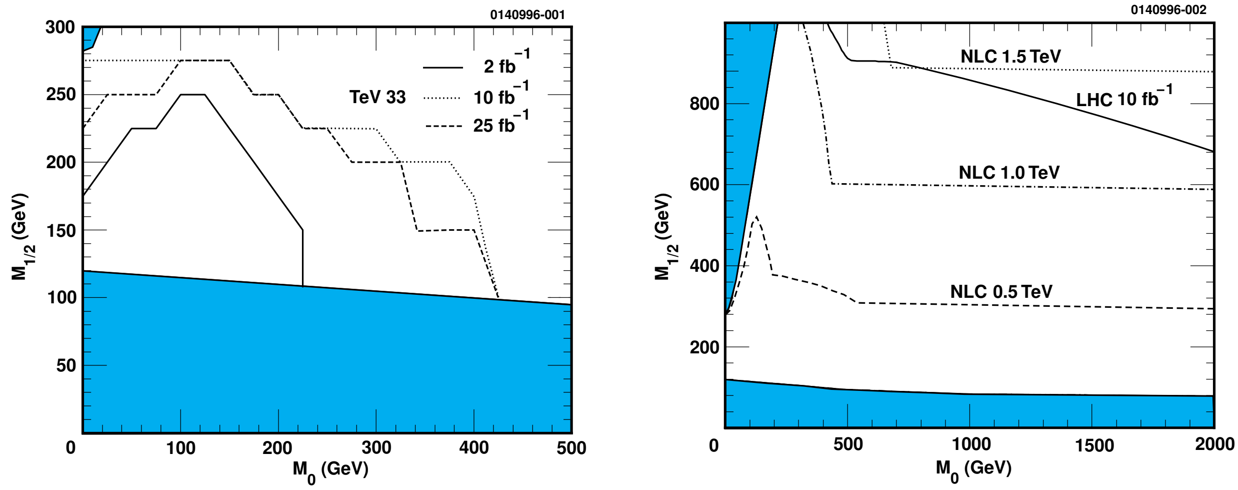

Figure 4: SUSY discovery capabilities[16] of Tev33, the LHC, and NLC's at three different energies. For these figures, $A_0 = 0$, $\tan\beta = 2$ and $\mu < 0$. The lower shaded region is already ruled out by experiments and the upper shaded region is ruled out by theory. Note the substantial difference in scales between the two graphs.

Table 5: Typical capabilities for facilities to measure the masses of SUSY particles.

Facility	$\int \mathcal{L}dt$ fb^{-1}	Mass Measurement	Result [GeV]
TeV33	30	$M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$	52.0 ± 0.3
		$M_{\tilde{g}} - M_{\tilde{b}}$	20 ± 3
		$M_{\tilde{b}} - M_{\tilde{\chi}_2^0}$	182 ± 10
LHC	10	$M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$	52.00 ± 0.05
		$M_{\tilde{g}} - M_{\tilde{b}}$	20 ± 2
		$M_{\tilde{g}} - M_{\tilde{\chi}_2^0}$	182 ± 5
NLC (O.5 TeV)	50	$M_{\tilde{\chi}_2^0}$	95 ± 5
		$M_{\tilde{e}_L}$	218 ± 6
	20	$M_{\tilde{\nu}_e}$	207 ± 4
		$M_{\tilde{\chi}_1^+}$	96 ± 1
		$M_{\tilde{e}_R}$	207 ± 2

In summary, each proposed facility offers unique capabilities and opportunities for studying SUSY particles:

- TeV33 should discover SUSY first if masses are low enough and can explore many channels and measure many parameters.
- The LHC covers the full range of reasonable SUSY parameter space ($M \lesssim 1$ TeV). The event rates are extremely high for low masses and systematic errors are likely to dominate. There are characteristic signals in straight-forward distributions for many SUSY particles and precision measurements of many parameters are possible.
- An NLC would utilize simple production states that yield clear signals and facilitate precision measurements. Polarization can substantially improve signal/background ratios and can aid in precision measurements of SUSY couplings. An NLC should be able to establish the entire SUSY structure if the energy is high enough.
- A $\mu^+\mu^-$ collider could have the clean-signal advantages of an NLC along with higher lepton energy and s-channel Higgs production.

Table 5 illustrates the precision with which TeV33, LHC, and NLC can measure the masses of SUSY particles at the common Point. Note that while TeV33 and LHC can make quite precise measurements of a number of mass differences, an NLC can measure individual masses – often with comparable precision.

7 Strong Coupling Working Group

The Strong Coupling Working Group[6] examined the possibility that elementary Higgs scalars do not exist, and that EWSB could be due to a new strong interaction whose nature would be revealed at some higher energy. There are a variety of possible ways for SC-EWSB to manifest itself, but it must restore unitarity in production and scattering of longitudinal gauge bosons at high energy. In the new strong interaction, the triplet (W_L^+, Z_L, W_L^-) plays the role of the pion triplet in QCD, which suggests searching for resonances in W_LW_L, W_LZ_L, and Z_LZ_L scattering analogous to the resonances in $\pi\pi$ scattering. These resonances could be detected by observing the resonance peaks or the increases in cross sections due to tails of nearby resonances. In the Snowmass study, only gold-plated W and Z decays, $Z \to \ell^+\ell^-$ and $W \to \ell\nu$, were used because high p_T isolated leptons are clean. However, the branching fractions are small, so yields would be low. There are also backgrounds due to scattering of transverse W and Z and nonresonant scattering.

All studies of SC-EWSB indicate that experiments are hard, so they will require maximum energy and luminosity. For that reason, the Working Group concentrated on the discovery reach and sensitivity to resonance mass with a 100 fb^{-1} run at the LHC and the same luminosity at a 1.5 TeV NLC with 80% polarization of the e^- beam. The assumption that resonances are responsible for restoring unitarity to W_LW_L scattering leads to to unitarity limits of $M_0 < 1,800$ GeV and $M_1 < 4,000$ GeV for the masses of $I = 0$ and $I = 1$ resonances. The results for direct searches for strong coupling resonances are given in Table 6. Note that LHC and NLC could find an $I = 0$ resonance up to the unitarity limit and that NLC could also find an $I = 1$ resonance at the unitarity limit.

Table 6: Reaches of the LHC and a 1.5 TeV NLC for discovery of strong coupling resonances and the accuracies with which the masses of the resonances could be measured.

	Channel	I	Reach [GeV]	M_I [GeV]	
LHC	$qq' \to qq'ZZ$	0	1,600	$1,500^{+100}_{-70}$	*
	$q\bar{q} \to WZ$	1	1,500	—	
	$qq' \to qq'W^+W^+$	2	1,950	$2,000^{+250}_{-200}$	
NLC	$e^+e^- \to \nu\nu ZZ$	0	1,800	$1,600^{+180}_{-120}$	*
	$e^+e^- \to \nu\nu t\bar{t}$	0	1,600	$1,500^{+450}_{-160}$	
	$e^+e^- \to W^+W^-$	1	4,000	$3,000^{+180}_{-150}$	

* Results for ZZ modes ($I = 0$) assume no $I = 2$ resonance

A number of indirect searches could also probe SC-EWSB:

- searches for anomalous couplings, *e.g.*, $\Delta\kappa_\gamma$ and λ_γ in the γWW vertex, where SC-EWSB effects expected to be of order $\mathcal{O}(10^{-3})$;
- a 1.5 TeV NLC might just be sensitive enough to detect effects in $d\sigma/d\Omega$ for $e^+e^- \to W^+W^-$ (the LHC is sensitive to effects of $\mathcal{O}(10^{-2})$; and
- searches for certain types of exotica, *e.g.*, neutral technipions at a 1 TeV NLC and searches for topcolor bosons at TeV33.

The working group reported the following conclusions:

- Experiments are hard.
- This subject needs the highest energy (1.5 TeV NLC) and full design luminosity (100 fb^{-1}/yr at LHC & NLC).
- LHC can discover SC-EWSB.
- LHC can probe effects of scalar resonances to ~ 1.6 TeV ($M_0 \lesssim 1.6$ TeV from unitarity) and vector resonances to ~ 1.5 TeV.

- NLC at 1.5 TeV can probe effects of resonances in the $I = 1$ channel to ~ 4 TeV ($M_1 \lesssim 4$ TeV from unitarity) through an accurate measurement of the $I = 1$ phase shift in $e^+e^- \rightarrow W^+W^-$.
- NLC at 1.5 TeV can study the coupling of top to the symmetry breaking sector.
- Many – but not all – models of SC-EWSB predict low energy phenomena in the range 0.2–0.7 TeV that can be searched for at TeV33, LHC, and NLC.
- A detailed understanding of SC-EWSB will probably have to wait for machines with parton energies greater than 5 TeV and luminosities greater than 10^{35} cm^{-2} s^{-1}.

Finding something at a lower energy facility would be sensational. Failure to find anything there would not conclusively rule out SC-EWSB, but would restrict the low energy phenomena of models.

7.1 Top Physics

The Strong Coupling Working Group also studied how different proposed facilities could contribute to a top physics program to complement the discovery and initial mass measurements. A program should include measurements of:

- M_t with high precision because it is a basic EW parameter;
- Γ_t because it is sensitive to new and exotic decays;
- λ_t, the $t\bar{t}H$ coupling, in order to understand the interaction between t quarks and Higgs bosons;
- V_{tb} to test 3 generation unitarity;
- tW, $t\gamma$, and tZ couplings which can be a window on SC-EWSB; and
- rare decays which could be a window on other new physics at high mass.

Table 7: The precisions with which M_t, Γ_t, and V_{tb} can be measured at TeV33, LHC, and a 0.5 TeV NLC.

		TeV33	LHC	NLC
$\sigma(M_t)$	[GeV]	2	2	0.2
$\sigma(\Gamma_t)$	%	~ 8	~ 8	7
$\sigma(V_{tb})$	%	~ 2	~ 2	3.5

Table 7 illustrates the precisions with which M_t, Γ_t, and V_{tb} can be measured at TeV33, LHC, and an NLC. Although the precisions listed for these facilities are comparable, there are substantial differences in their top programs. TeV33 and LHC are likely to be limited by systematic errors, *e.g.*, the statistical error for M_t is about 1 GeV for 10 fb^{-1} at TeV33. At a 0.5 TeV NLC, a $\gtrsim 30$ fb^{-1} scan around the top threshold can simultaneously measure M_t, Γ_t, α_S, and λ_t and NLC systematic errors are entirely different from those at TeV33 or LHC. Furthermore, an NLC offers opportunities for more detailed studies and greater precision, and can uniquely probe neutral current couplings of top quarks. On the other hand, the high event rates at the LHC will provide useful sensitivity for studying rare decays.

8 New Phenomena Working Group

Searching for new phenomena is essential[7] because we need to determine the complete particle spectrum at $\lesssim 1$ TeV in order to extrapolate to the Planck mass scale, we need to understand all the interactions among elementary particles, and we need to expect and prepare for the unexpected – it's the only way we will learn anything really new. Efforts to find new phenomena should include searches for:

- new gauge bosons – Z' and W';
- new particles, including leptoquarks, axigluons, heavy quarks, heavy leptons, diquarks, and dileptons;
- new interactions, including technicolor, topcolor, compositeness, and contact interactions; and
- the truly weird.

Table 8 summarizes the capabilities of some of the proposed facilities for finding new gauge bosons, other new particles, and new couplings.

Table 8: Discovery reaches in TeV for finding new gauge bosons, other new particles, and new couplings at TeV33, LHC, a 1 TeV NLC, a 4 TeV muon collider, and three RLHC's. The units of the mass and coupling constant limits are all TeV.

		TeV33	LHC	NLC	$\mu^+\mu^-$	pp	pp	$\bar{p}p$
Energy	[TeV]	1.8	14	1.0	4	60	200	200
$\int \mathcal{L}dt$	fb^{-1}	10	100	100	1000	100	1000	1000
Z'		0.9	4.1	3.0	10	12	30	56
		1.1	5.2	6.3	21	15	50	75
W'	LRM	0.5	5.1	0.4		16	52	52
		1.2	5.9	0.6		20	65	83
New Particles *		0.3	1.6	0.5				
		1.3	5	6.5				
$\Lambda(\ell\ell \to \ell\ell)$					300			
$\Lambda(qq \to qq)$		2	15				200	
$\Lambda(qq \to \ell\ell)$		18	100		300		1000	

* This includes scalar and vector leptoquarks, axigluons, heavy quarks, heavy leptons, diquarks, and dileptons – each type of particle has different limits within these ranges

Although this is a vast subject that is difficult to encompass in a short and crisp summary, several general observations are useful:

- New physics may reveal itself in many ways so we must look everywhere.
- Energy generally wins over luminosity so upgrade or expansion of an NLC beyond 0.5 TeV would be essential.
- Polarization in lepton colliders is a useful tool.
- Lepton and hadron colliders complement each other in discovery regions and understanding new phenomena.
- The $e\gamma$, $\gamma\gamma$, and e^-e^- options at a linear collider may be useful.

Of course, more study is needed.

9 QCD Working Group

Studying and understanding QCD is essential[8] because: QCD makes important contributions to physics at all energy scales, there is a single coupling constant over a wide range of energies, and QCD is the only relativistic quantum field theory that can be tested beyond the first few orders of perturbation theory. There is a long list of QCD phenomena that require deeper understanding:

- quark confinement, high temperature, and high density phases,
- the relationship between perturbative and non-perturbative QCD,
- how the rapid rise in F_2 saturates at very low x,
- the different contributions to the spins of hadrons,
- rapidity gaps, and
- Pomeron effects.

Finally, QCD has substantial impact on other subjects via jets, parton distribution functions (PDF's), and α_S; so precision measurements of PDF's and α_S are very important.

Requirements for QCD studies generally do not lead to crisp distinctions among accelerator facilities because there are important QCD experiments at essentially all energies and facilities. However, QCD studies do generally prefer higher energies to explore new territory or new or novel facilities and detectors which can provide new kinds of access to known phenomena; examples include:

- polarization at RHIC, HERA, SLAC, and NLC for spin physics,
- ν beams at TeV33, LHC, or $\mu^+\mu^-$ for xF_3,
- LEP colliding with LHC for high Q^2 and low x to understand the saturation of the rapid rise of F_2 at very low x, and
- TeV33, LHC, and RLHC for diffraction and low x.

There is currently no satisfactory understanding of what could saturate the unexpected very rapid rise of F_2 at very low x discovered at HERA – this is one example of a QCD effect that could lead to discovery of new physics.

10 Remarks

I name this section "Remarks", rather than "Conclusions" because we did not try to claim that there was an overall consensus or conclusion reached by the participants in Snowmass 96. Furthermore, developing a consensus on where the field should go is the responsibility of the entire community – not just the DPF EC, not just the DPB EC, and not just those who participated in Snowmass 96. I have tried to give an accurate and fair summary of the principal results and conclusions reported by the individual particle physics working groups in order to indicate where physics opportunities, problems, and topics for further study lie. I hope that this effort can contribute towards reaching a consensus on future facilities.

None of the proposed facilities can be realized without substantial expenditure of money and political will. Therefore, I feel that it is imperative that the DPF & DPB communities develop a consensus on a number of key questions, including the following:

- How compelling is the physics program with the TeV33 luminosity goal?
- How much can the LHC actually accomplish and what essential physics must be done at other facilities?
- How compelling is the case for an NLC in the 0.5 – 1.5 TeV energy range?
- Is a 2 – 4 TeV $\mu^+\mu^-$ collider feasible and does it have a compelling physics program?
- Can and should we find practical new technologies for a hadron collider beyond the LHC?
- Can and should we find practical new technologies for a multi-TeV e^+e^- collider?

If a community consensus crystalizes for any of the options beyond Tev33 and LHC, we still need to find a time scale for the project that is consistent with a responsible amount of R&D, our ability to marshal the financial resources, and the timeliness of the facility in the overall international HEP program.

I feel that it is essential that members of our particle and accelerator physics communities learn, think, discuss these issues, and then *act*; in order to insure a high energy physics program in the US in the LHC era.

Acknowledgments

The material in this report is adapted from the reports presented the plenary sessions at Snowmass 96 or from material submitted to the workshop. However, some results or conclusions given here may differ from the final reports of the working groups, because these contributions were not available at the time this report was written. (Alternatively I may have misinterpreted the sources – I apologize for any errors of this sort that may have occurred.) Since I do not know who actually provided the individual items that I use, I cite the convenors of the working groups as proxies for all those who produced the results presented here. I am delighted to use this forum to thank all participants, organizers, convenors, and speakers for their excellent contributions to the workshop! The Snowmass 96 workshop was made possible by the generous financial support of the U.S. Department of Energy, U.S. National Science Foundation, and the high energy divisions of Argonne National Laboratory, Brookhaven National Laboratory, Cornell University, Fermilab, Lawrence Berkeley Laboratory, and the Stanford Linear Accelerator Center. Cynthia Sazama of Fermilab deserves special thanks for her tireless effort and outstanding performance in organizing and managing the workshop. She was assisted by a very able and efficient secretarial staff from Fermilab, LBNL, and SLAC. All participants appreciated the excellent computing service that was provided by the computing staff of Fermilab. Finally, it was a pleasure to work with Robert Siemann of SLAC, who shared responsibility for organizing the workshop.

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