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THE SUPERCONDUCTING SUPER COLLIDER: SCIENTIFIC MOTIVATION AND TECHNICAL PROGRESS

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ABSTRACT

I summarize the case for new physics at the TeV scale, and review speculations about new phenomena which may occur there. I then discuss in brief the physics prospects of a multi-TeV hadron collider, and mention some of the processes which may be studied in detail with such an instrument. Finally, I report progress toward the design and construction of the SSC.

1 WHERE WE STAND

The picture[1] of the fundamental constituents of matter and the interactions among them that has emerged in recent years is one of great beauty and simplicity. All matter appears to be composed of *quarks* and *leptons*, which are pointlike, structureless, spin-$\frac{1}{2}$ particles. If we leave aside gravitation, which is a negligible perturbation at the energy scales usually considered, the interactions among these particles are of three types: weak, electromagnetic, and strong. All three of these interactions are described by gauge theories, and are mediated by spin-1 gauge bosons. The quarks experience all three interactions; the leptons participate only in the weak and electromagnetic interactions. The Standard Model, represented in Fig. 1, has an appealing simplicity and an impressive generality. The picture has a pleasing degree of coherence, and holds the promise of deeper understanding – in the form of a further unification of the interactions – still to come.

This is an accomplishment worthy of the pleasure we take in it, but if we have come impressively far in the past two decades, we still have quite far to go. The very success of the standard $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ model prompts new questions: Why does it work? Can it be complete? Where will it fail? The standard model itself hints that the frontier of our ignorance lies at ~ 1 TeV for collisions among the fundamental constituents. In more general terms, the success of our theoretical framework suggests that a significant step beyond present-day energies is needed, to see breakdowns of the theory. The SSC is conceived to take such a step, and to make possible a thorough exploration of the 1 TeV scale.

In addition to these generalities, there are many specific issues to be faced. There is, for example, our incomplete understanding of electroweak symmetry

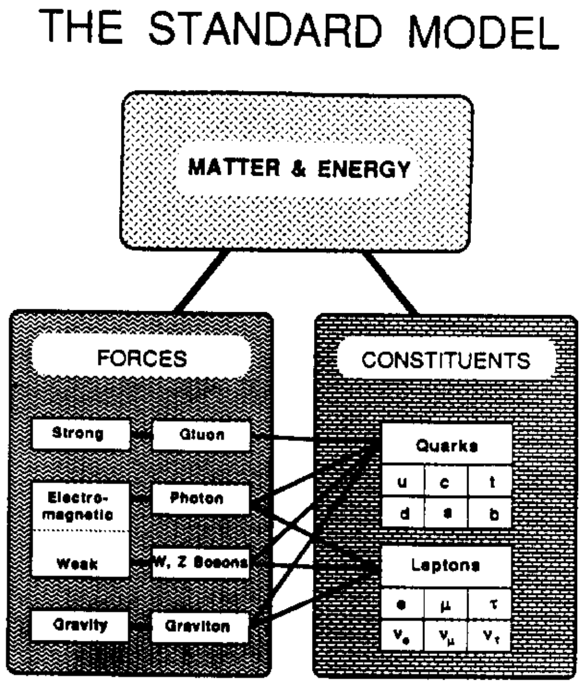


Figure 1: The Standard Model of Particle Physics.

breaking and the suggestion (from the "bound" $M_{\text{Higgs}} < 1$ TeV/c^2, for example) that the 1 TeV scale will be crucial to a resolution of this problem. The Higgs mechanism provides a means for generating quark and lepton masses and mixing angles, but leaves the values as free parameters. We do not understand what CP-violation means. The idea of quark-lepton generations is suggested by the necessity for anomaly cancellation in the electroweak theory, but the *meaning* of generations is unclear. We may even dare to ask what is the origin of the gauge symmetries themselves. Such questions – and this is but a partial list – are stimulated by the standard model itself, and by our desire to find ever simpler descriptions of Nature, of ever more general applicability.

Beyond our search for more complete understanding, there are many reasons to be dissatisfied with the standard model. A powerful aesthetic objection is raised by the arbitrariness of the theory, which requires us to specify a multitude of apparently free parameters:

- 3 coupling parameters α_s, α_{EM}, and $\sin^2\theta_W$,
- 6 quark masses,
- 3 generalized Cabibbo angles,
- 1 CP-violating phase,

- 2 parameters of the Higgs potential,
- 3 charged lepton masses,
- 1 vacuum phase angle,

for a total of 19 arbitrary parameters. The situation is not improved by the unification of the strong, weak, and electromagnetic interactions.

Three of the problems that draw our attention are indicated in Fig. 2, together with theoretical inventions that respond to one or more of them. The three issues are the generation question, the idea of unification and the origin of gauge symmetries, and the hierarchy problem. We have already mentioned the first and second of these. A brief reminder of the hierarchy problem will be given in Section 4. Because of the pressure of time, and the fact that other talks at this meeting have dealt with the proposed strategies and the experimental signatures they lead us to expect, I shall give only a very few short examples.

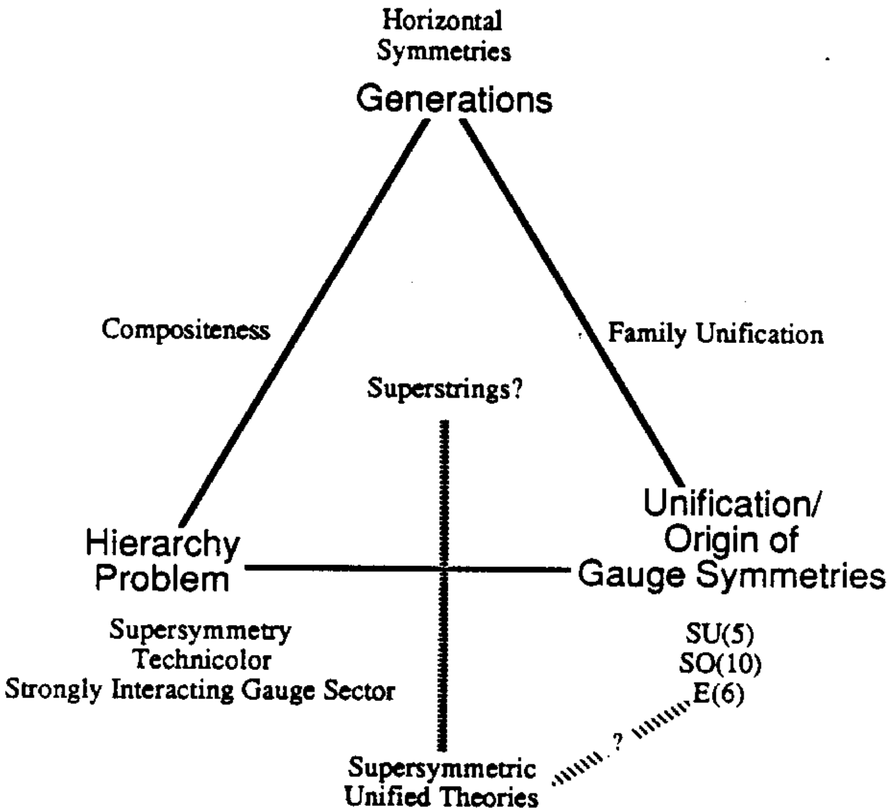


Figure 2: Three problems and some responses to them.

2 Cosmology and the SSC

Over the past few years, cosmology and particle physics have become increasingly interwoven. To understand what took place in the high-temperature, high-density early universe, one is forced to look at the physics of elementary particles. Similarly, the unified theories of elementary particle physics have striking consequences at extremely high temperatures and energies. The only "laboratory" available to check these extrapolations of unified theories is the first instants after the Big Bang, when extraordinarily high temperatures and densities were reached. The SSC will be operating at energies far beyond those previously achievable in a laboratory and will simulate the conditions that prevailed about 10^{-15} second after the primordial explosion when the temperature of the universe was about 10^{17} K.

Direct observations by optical telescopes are limited to events that occurred some 300,000 years after the Big Bang because the universe was opaque to photons at earlier times. To reconstruct what happened in the early universe, we must know the nature of basic interactions at high energies and the complete spectrum of elementary particles. In particular, the relics left over from those early times are of basic importance to cosmology. Any long-lived particle produced in the primordial explosion would survive and be an ingredient in the present-day universe.

One of the major issues in cosmology is to find the "dark matter" of the universe.[2] Studies of the motion of stars within galaxies and of galaxies within clusters have established that these systems must contain a great deal of matter in addition to what is visible in the stars. This nonluminous matter may in fact account for the bulk of the mass in the universe. The properties that we impute to the dark matter depend on the character of the small density fluctuations in the early universe that grew into the galaxies and clusters observed today. According to current ideas about galaxy formation, the dark matter may be quite different from the ordinary matter of which we are made. Particle physics yields a mechanism for generating the primordial density fluctuations and provides candidates for the dark matter as well. Experimentation at the SSC will allow broad searches for new particles that may play the role of the dark matter.

In addition to the possibility of resolving the question of dark matter of the universe, the SSC will clarify the structure and symmetry of the fundamental interactions and allow us to extrapolate with greater confidence back to early times. One of the most interesting recent developments in cosmology has been the suggestion that the large-scale homogeneity and isotropy of the universe[3] were established during an early symmetry-breaking phase transition,[4] during which the vacuum energy of the universe was large enough to cause the universe to expand exponentially. This exponential expansion, or inflation, is capable of explaining in a natural way a great deal about the present structure of the universe: homogeneity and isotropy in the large-scale distribution of galaxies, the great age of the universe, its spatial flatness, its large entropy, and possibly the existence of small primordial perturbations in the distribution of matter that eventually grew to become galaxies, stars, planets, and people.

We know that the exponential phase did not occur in the electroweak symmetry breaking transition. However, if nature is more symmetric at high energies than at low energies, the electroweak transition is but the last in a series of similar transitions. Detailed exploration of the electroweak (1 TeV) scale at the SSC will give us a clearer picture of how the electroweak symmetry is hidden, and point the way to an understanding of the Higgs system of inflation.

3 HIGGS BOSONS

Before saying a few words about extensions to the standard model, it will be useful to recall why a Higgs boson, or its *Doppelgänger*, must exist. One path to the (theoretical!) discovery of the Higgs boson involves the role of the Higgs boson in the cancellation of high-energy divergences. An illuminating example is provided by the reaction

$$e^+e^- \to W^+W^-, \tag{3.1}$$

which is described in lowest order in the Weinberg-Salam theory by the four Feynman graphs in Fig. 3. The leading divergence in the $J = 1$ amplitude of the neutrino-exchange diagram in Fig. 3(a) is cancelled by the contributions of the direct-channel γ- and Z^0-exchange diagrams of Figs. 3(b) and (c). However, the $J = 0$ scattering amplitude, which exists in this case because the electrons are massive and may therefore be found in the "wrong" helicity state, grows as $s^{1/2}$ for the production of longitudinally polarized gauge bosons. The resulting divergence is precisely cancelled by the Higgs boson graph of Fig. 3(d). If the Higgs boson did not exist, we should have to invent something very much like it. From the point of view of S-matrix theory, the Higgs-electron-electron coupling must be proportional to the electron mass, because "wrong helicity" amplitudes are always proportional to the fermion mass.

Let us summarize: Without spontaneous symmetry breaking in the standard model, there would be no Higgs boson, no longitudinal gauge bosons, and no extreme divergence difficulties. (Nor would there be a viable low-energy phenomenology of the weak interactions.) The most severe divergences are eliminated by the gauge structure of the couplings among gauge bosons and leptons. A lesser, but still potentially fatal, divergence arises because the electron has acquired mass – because of the Higgs mechanism. Spontaneous symmetry breaking provides its

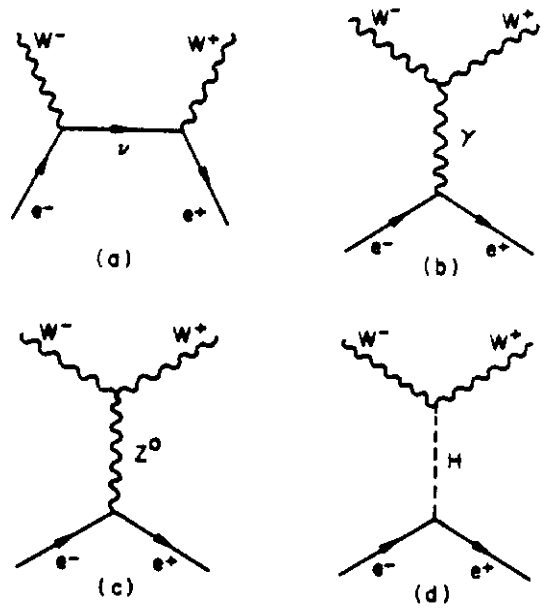


Figure 3: Lowest-order contributions to the reaction $e^+e^- \to W^+W^-$ in the standard model.

own cure by supplying a Higgs boson to remove the last divergence. A similar interplay and compensation must exist in any satisfactory theory.

It is well known that the standard model does not give a precise prediction for the mass of the Higgs boson. We can, however, use arguments of self-consistency to place plausible lower and upper bounds on the mass of the Higgs particle in the minimal model. A lower bound is obtained by computing[5] the first quantum corrections to the classical potential

$$V(\phi^\dagger\phi) = \mu_0^2\phi^\dagger\phi + |\lambda|\,(\phi^\dagger\phi)^2 \, . \tag{3.2}$$

Requiring that $\langle\phi\rangle \neq 0$ be an absolute minimum of the one-loop potential yields the condition

$$\begin{aligned} M_H^2 &> 3G_F\sqrt{2}(2M_W^4 + M_Z^4)/16\pi^2 \\ &\gtrsim 7 \text{ GeV}/c^2 \, . \end{aligned} \tag{3.3}$$

Unitarity arguments[6] lead to a conditional upper bound on the Higgs boson mass. It is straightforward to compute the s-wave partial-wave amplitudes for gauge boson scattering at high energies in the

$$W^+W^- \quad Z^0Z^0 \quad HH \quad HZ^0 \tag{3.4}$$

channels. These are all asymptotically constant (*i.e.*, well-behaved), and proportional to $G_F M_H^2$. Requiring that the Born diagrams respect the partial-wave unitarity condition $|a_0| \leq 1$ yields

$$M_H < \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} = 1\ \text{TeV}/c^2 \tag{3.5}$$

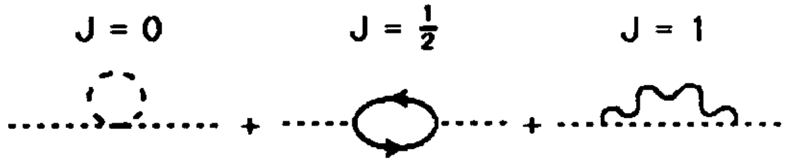
as a condition for perturbative unitarity.

4 WHY THERE MUST BE NEW PHYSICS ON THE 1 TEV SCALE

The standard model is incomplete[7]; it does not explain how the scale of electroweak symmetry breaking is maintained in the presence of quantum corrections. The problem of the scalar sector can be summarized neatly as follows.[8] The Higgs potential of the $SU(2)_L \otimes U(1)_Y$ electroweak theory is given by (3.2) above. With μ_0^2 chosen less than zero, the electroweak symmetry is spontaneously broken down to the $U(1)$ of electromagnetism, as the scalar field acquires a vacuum expectation value fixed by the low energy phenomenology,

$$< \phi >= \sqrt{-\mu_0^2/2|\lambda|} \equiv (G_F\sqrt{8})^{-1/2} \approx 175\ \text{GeV}\ . \tag{4.1}$$

Beyond the classical approximation, scalar mass parameters receive quantum corrections involving loops containing particles of spins $J = 1, 1/2$, and 0:

$\mu^2(p^2) = \mu_0^2 +$ 

(4.2)

The loop integrals are potentially divergent. Symbolically, we may summarize the content of Eq. (4.2) as

$$\mu^2(p^2) = \mu^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots\ , \tag{4.3}$$

where Λ defines a reference scale at which the value of μ^2 is known, g is the coupling constant of the theory, and C is a constant of proportionality, calculable in any particular theory. Instead of dealing with the relationship between observables and parameters of the Lagrangian, we choose to describe the variation of an observable with the momentum scale. In order for the mass shifts induced by radiative corrections to remain under control (*i.e.*, not to greatly exceed the value measured on the laboratory scale), either

- Λ must be small, so the range of integration is not enormous; or
- new physics must intervene to control the integral.

In the standard $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ model, the natural reference scale is the Planck mass,

$$\Lambda \sim M_{Planck} \approx 10^{19} \text{ GeV} . \tag{4.4}$$

In a unified theory of the strong, weak, and electromagnetic interactions, the natural scale is the unification scale

$$\Lambda \sim M_U \approx 10^{15} \text{ GeV} . \tag{4.5}$$

Both estimates are very large compared to the scale of electroweak symmetry breaking (4.1). We are therefore assured that new physics must intervene at an energy of approximately 1 TeV, in order that the shifts in μ^2 not be much larger than (4.1).

Only a few distinct classes of scenarios for controlling the contribution of the integral in (4.3) can be envisaged. One solution to the challenge of the enormous range of integration in (4.3) is offered by theories of dynamical symmetry breaking such as Technicolor.[9] In the technicolor scenario, the Higgs boson is composite, and new physics arises on the scale of its binding, $\Lambda_{TC} \approx 1$ TeV. Thus the effective range of integration is cut off, and mass shifts are under control.

The supersymmetric solution is especially elegant.[10] Exploiting the fact that fermion loops contribute with an overall minus sign (because of Fermi statistics), supersymmetry balances the contributions of fermion and boson loops. In the limit of unbroken supersymmetry, in which the masses of bosons are degenerate with those of their fermion counterparts, the cancellation is exact:

$$\sum_{i=\substack{\text{fermions}\\ +\text{bosons}}} C_i \int dk^2 = 0 . \tag{4.6}$$

If the supersymmetry is broken (as it must be in our world), the contribution of the integrals may still be acceptably small if the fermion-boson mass splittings ΔM are not too large. The condition that $g^2 \Delta M^2$ be "small enough" leads to the requirement that superpartner masses be less than about 1 TeV$/c^2$.

There is, of course, no guarantee that the mass of the Higgs boson will remain small, or that perturbation theory will always be trustworthy. If not, we can look forward to the emergence of strong interactions among the electroweak gauge bosons on the 1 TeV scale, and to the phenomena that strong interactions traditionally imply: the formation of WW bound states or resonances, and multiple production of electroweak gauge bosons. W-boson interactions on the TeV scale could then closely resemble the interactions of pions on the GeV scale.

On a logarithmic scale, 1 TeV lies midway between common experience (at around 1 eV) and the Planck mass. It is a compelling goal as we look toward the twenty-first century.

5 SSC PHYSICS: A FIRST LOOK

5.1 PRELIMINARIES

The discovery reach of a hadron supercollider is determined by hard scattering processes in which the constituents interact at high energies. Cross sections may be calculated in the renormalization group improved parton model, provided we know the behavior of the quark and gluon distributions within the proton as functions of x and Q^2. Structure functions suitable for the extrapolation to supercollider energies are available,[11] and the parton-level cross sections are known for a great many reactions of potential interest.

One indication that the parton-model procedure is sound, and that knowledge of the structure functions derived from experiments on deeply inelastic lepton scattering is adequate, is provided by $S\bar{p}pS$ data on hadron jets. Figure 4 shows representative data from the UA-1 Collaboration[12] on the inclusive jet cross section $d\sigma/dp_{\perp}dy\,|_{y=0}$, compared with the predictions of the QCD Born term. The agreement is quite satisfactory.[13]

Thus satisfied with the reasonableness of our procedure, we may make the extrapolation to supercollider energies. A useful way to display the results is to examine the trigger rate for events with transverse energy E_T greater than some threshold E_T^{min}. This is shown in Fig. 5 for the nominal operating conditions of the SSC: $\sqrt{s} = 40$ TeV and $\mathcal{L} = 10^{33}$ cm^{-2}sec^{-1}, as well as at 10 and 100 TeV. At 40 TeV, a "high-E_T" trigger with threshold set at 2 TeV will count at 1 Hz from two-jet QCD events. This is of interest in planning triggers which will efficiently select "interesting" events from the $2 \cdot 10^8$ interactions which will take place each second in an SSC interaction region.

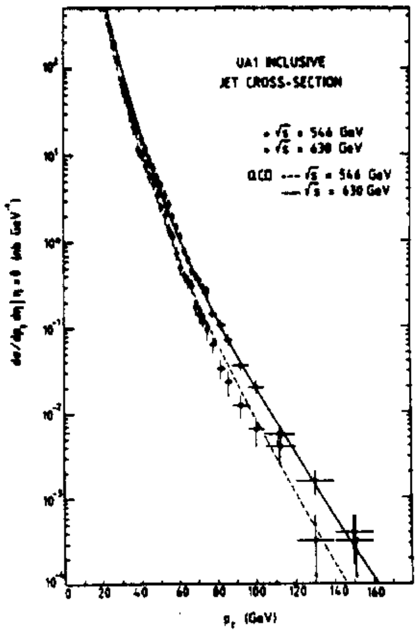


Figure 4: The inclusive jet cross section for the pseudorapidity interval $|\eta| < 0.7$, as a function of the jet transverse momentum, as measured by the UA-1 Collaboration. The open dots correspond to the data at $\sqrt{s} = 546$ GeV and the solid dots to those at $\sqrt{s} = 630$ GeV.

5.2 Electroweak physics

The principal standard model issues to be addressed with a multi-TeV hadron collider are these:

- The rate of $W^{\pm}$ and Z^0 production. This is chiefly of interest for investigations of the production mechanism itself and for the study of rare decays of the intermediate bosons. We expect that by the time a supercollider comes into operation the more basic measurements such as precise determinations of the masses and widths of the intermediate bosons will have been accomplished.

- The cross section for pair production of gauge bosons. These are sensitive to the structure of the trilinear couplings among gauge bosons, and must be understood as potential backgrounds to the observation of heavy Higgs bosons, composite scalars, and other novel phenomena.

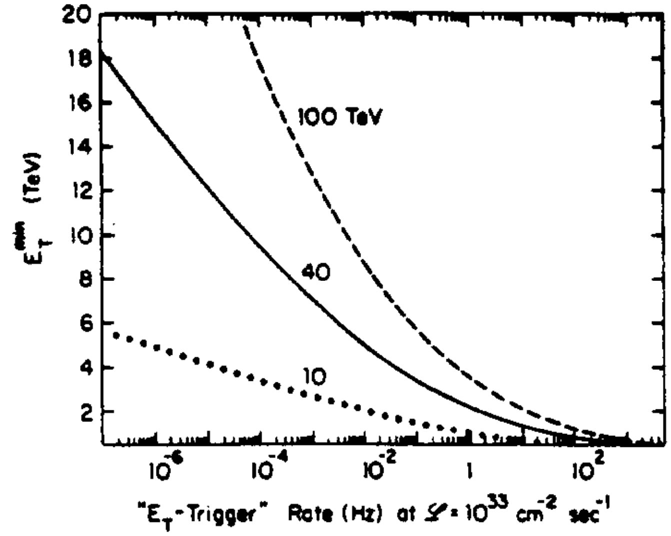


Figure 5: Counting rate for an E_T-trigger in pp collisions at an instantaneous luminosity of $\mathcal{L} = 10^{33}$ cm^{-2}sec^{-1} (after *EHLQ*). The threshold is defined for transverse energy deposited in the central region of rapidity, defined by $|y_i| < 2.5$ for jets 1 and 2.

- The Higgs boson itself. In the minimal electroweak model, this is the lone boson remaining to be found. Elucidating the structure of the Higgs sector (and mot merely finding a single Higgs scalar) is one of the primary goals of experimentation in the TeV regime.

Let us take a moment to look briefly at each of these points.

The integrated cross sections for W^+ and W^- production in pp collisions are shown in Fig. 6 as functions of the c.m. energy $\sqrt{s}$. Also shown are the cross sections for production of $W^\pm$ in the rapidity interval $-1.5 < y < 1.5$. The number of intermediate bosons produced at a high-luminosity supercollider is impressively large. At 40 TeV, for example, a run with an integrated luminosity of 10^{40} cm^{-2} would yield approximately $6 \cdot 10^8$ Z^0s and $2 \cdot 10^9$ $W^\pm$s. For comparison, at a high-luminosity Z^0 factory such as LEP ($\mathcal{L} \simeq 2 \cdot 10^{31}$ cm^{-2}sec^{-1}) the number of Z^0s expected in a year of running is approximately 10^7. There is no competitive source of *charged* intermediate bosons.

The angular distribution of the produced intermediate bosons is of great importance for the design of experiments. At supercollider energies, many intermediate bosons will be produced within a narrow cone about the beam direction. In a 40 TeV machine with an average luminosity of 10^{33}, there will be a flux of about 10 W^+/second emitted within 2° of the beam direction, in each hemisphere. Special purpose detectors deployed near the forward direction may thus have significant

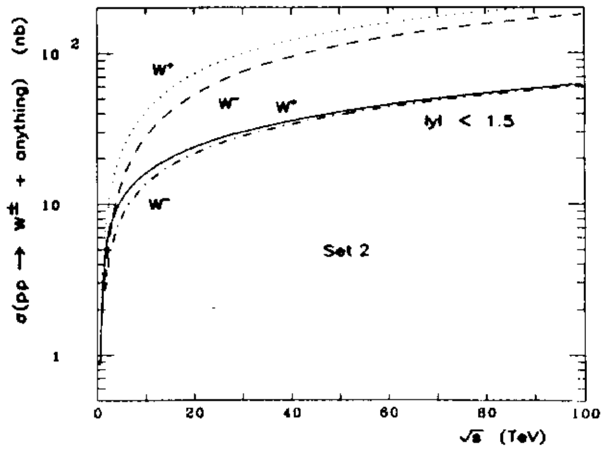


Figure 6: Cross sections for $W^{\pm}$ production in pp collisions in the Drell-Yan picture, integrated over all rapidities, and restricted to the interval $|y| < 1.5$ (after *EHLQ*).

advantages for the study of rare decays.

There are many reasons to be open to the possibility of new gauge bosons:

- High energy parity restoration in an $SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$ electroweak gauge theory;
- The occurrence of extra $U(1)$ gauge symmetries, implying additional Z^0s, for example in unification groups larger than $SU(5)$, as suggested in superstring models.[14]

In a specific theory, the style of calculation just described leads to an estimate of the cross section for the production of new gauge bosons. As an example, I show in Fig. 7 the cross section for production of a new W-boson with standard gauge couplings to the light quarks. For the 40 TeV energy projected for the SSC, we may anticipate sensitive searches out to a mass of about 6 TeV/c^2.

Incisive tests of the structure of the electroweak interactions may be achieved in detailed measurements of the cross sections for the production of W^+W^-, $W^{\pm}Z^0$, Z^0Z^0, $W^{\pm}\gamma$, and $Z^0\gamma$ pairs. The rate for $W^{\pm}\gamma$ production is sensitive to the magnetic moment of the intermediate boson. In the standard model there are important cancellations in the amplitudes for W^+W^- and $W^{\pm}Z^0$ production which rely on the gauge structure of the WWZ trilinear coupling. The Z^0Z^0 and $Z^0\gamma$ reactions do not probe trilinear gauge couplings in the standard model, but are sensitive to nonstandard interactions such as might arise if the gauge bosons were composite. In addition, the W^+W^- and Z^0Z^0 final states may be significant backgrounds to the detection of heavy Higgs bosons and possible new degrees of freedom.

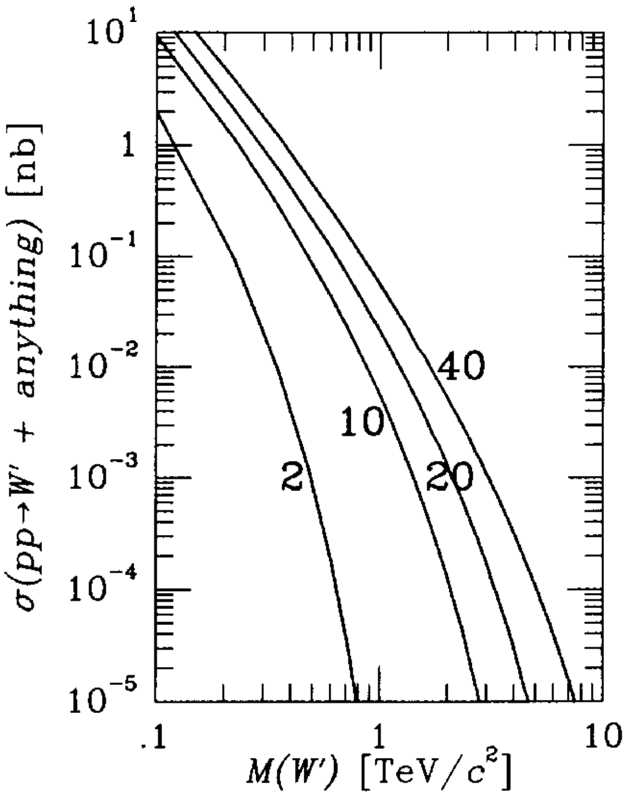


Figure 7: Cross section for the production of a heavy W-boson with rapidity $|y| < 1.5$ in pp collisions at 2, 10, 20, and 40 TeV (after *EHLQ*).

5.3 Supersymmetry at the SSC

As an illustration of the capability of the SSC to search for phenomena beyond the standard model, let us consider one example from supersymmetry. In a supersymmetric theory, particles fall into multiplets which are representations of the supersymmetry algebra. Superpartners share all quantum numbers except spin; if the supersymmetry is unbroken, they are degenerate in mass. The number of fermion states (counted as degrees of freedom) is identical with the number of boson states. By examining the quantum numbers of the known particles, we readily see that there are no candidates for supersymmetric pairs among them. Supersymmetry therefore means doubling the particle spectrum, compared with the standard model. In fact, we must expand the spectrum slightly further, because the minimal supersymmetric extension of the standard model requires at least two doublets of Higgs bosons. The interactions among old and new particles are prescribed by the supersymmetric extension of the usual interaction Lagrangian, which we shall take to be the $SU(3)_{color} \otimes SU(2)_L \otimes U(1)_Y$ theory. If supersymmetry is an invariance of the Lagrangian, it is evidently a broken symmetry, because observationally boson masses are not equal to the masses of their fermion counterparts. For supersymmetry to resolve the hierarchy problem, we have seen in §2 that it must be effectively unbroken above the electroweak scale of $O(1\text{ TeV})$. This suggests that the superpartner masses will themselves be $\lesssim 1\text{ TeV}/c^2$.

The outlines of the search for supersymmetry at the SSC are given in *EHLQ*.[1] Progress since Snowmass '84 was summarized recently at the Oregon workshop by Dawson.[15] Cross sections for the production of superpartners will be quite ample for a luminosity of $10^{32}\text{ cm}^{-2}\text{sec}^{-1}$ or more, and a c.m. energy of 40 TeV. As an example, I show in Fig. 8 the integrated cross section for the production of gluinos with rapidities $|y_i| < 1.5$, in the reaction

$$pp \to \tilde{g}\tilde{g} + \text{anything}. \tag{5.1}$$

On the basis of these and other cross sections and a rudimentary assessment of the requirements for detection, we have estimated the discovery limits for various energies and luminosities. The estimates for gluinos are shown in Fig. 9. Consideration of similar curves for the whole range of conjectured superpartners leads to the judgment that a supercollider like the SSC will be adequate to establish the presence or absence of the superpartners predicted by models of low-energy supersymmetry.

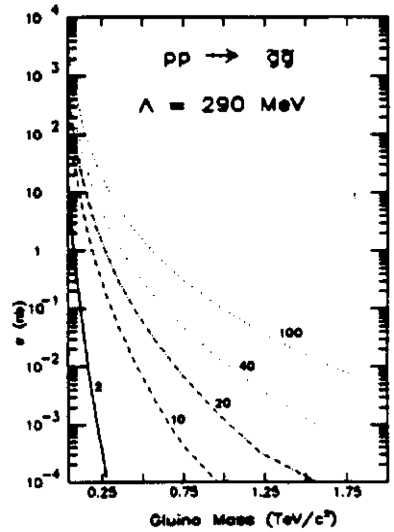


Figure 8: Cross sections for the reaction $pp \to \tilde{g}\tilde{g}$ + anything as a function of gluino mass, for collider energies $\sqrt{s} = 2, 10, 20, 40,$ and 100 TeV. Both gluinos are restricted to the interval $|y_i| < 1.5$. For this illustration, the squark mass is set equal to the gluino mass. [From *EHLQ*, Ref. 1.]

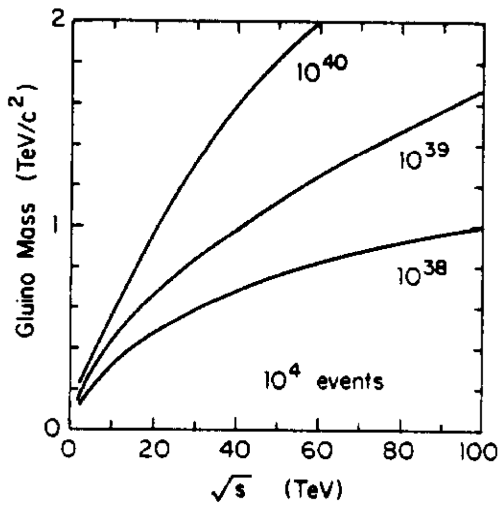


Figure 9: "Discovery limits" for gluinos in pp and $\bar{p}p$ collisions. Contours show the largest mass for which 10^4 gluino pairs are produced with $|y_i| < 1.5$, for specified energy and luminosity.

5.4 CONCLUDING REMARKS

In this brief survey, it has been possible only to scratch the surface of the physics opportunities presented by a high-energy, high-luminosity hadron collider. The examples we have considered here do begin to indicate the scope of physics issues to be addressed, ranging from detailed study of known particles, such as the intermediate bosons, to the search for high-mass exotica. The comprehensive studies of physics possibilities carried out over the past three years have shown convincingly that

> A 40 TeV collider which permits experimentation at integrated luminosities of at least 10^{39} cm^{-2} will make possible detailed exploration of the 1 TeV scale.

This conclusion is based on detailed consideration of the canonical inventions intended to improve the standard model, technicolor and supersymmetry, and of the standard model itself. In addition, there are many opportunities for exploring constituent interactions at subenergies up to about 10 TeV in the study of jets, the search for additional gauge bosons, *etc.* "Fixed-target style" colliding beams experiments may be well suited to address rare W decays and heavy flavor physics, for example. The SSC is not by any means a one-issue facility, and it is important that we mount a diversity of experimental initiatives, to realize its full scientific potential.

With respect to experimentation at the SSC, there are a few detector issues which I like to raise at every opportunity.

- The utility of high-efficiency W and Z detectors. The discovery physics we have considered in assessing the physics prospects of the SSC can all be done by relying upon the leptonic decays of the gauge bosons, but we can move to a deeper level of experimentation by learning to use the nonleptonic decays as well.
- The UA-1 experiment has already indicated the value of "hermetic" detectors, which can capture and measure all the visible energy emitted in the central region. For a general-purpose SSC detector, it is of interest to require hermeticity for rapidities $|y| < 3$.
- Examples from technicolor and the Higgs sector of the standard model indicate that good-efficiency $\tau, b, \ldots$ tags will be of considerable value in enhancing signals over background. Full utilization of the heavy flavor tag requires measuring the four-momenta of the short-lived particles as well.
- How to reduce the interaction rate of $\sim 10^8$ Hz to the $O(1 \text{ Hz})$ rate at which complex events can be written on storage media (magnetic tapes, optical discs)? There are many opportunities for creativity here!
- Bringing remote local intelligence into the detector components themselves requires the implementation of radiation-hardened electronics, especially near the beam directions.

We are faced with great opportunities!

6 AN UNOFFICIAL HISTORY OF THE SSC

The concept of a multi-TeV accelerator was first discussed more than a decade ago, in part in the context of a "Very Big Accelerator" as a World Machine. Workshops sponsored by the International Committee on Future Accelerators at Fermilab in 1978 and at CERN in 1979 examined various possibilities for very-high-energy accelerators, including pp colliders at tens of TeV per beam. The idea of the SSC itself began to take shape at the 1982 Summer Study on Elementary Particle Physics and Future Facilities organized in Snowmass, Colorado, by the Division of Particles and Fields of the American Physical Society. The SSC initiative was followed up with workshops on accelerator and detector issues held during 1983 at Cornell University and the Lawrence Berkeley Laboratory.

It was in this setting, and encouraged by the dramatic physics results from the $S\bar{p}pS$ and by the successful first operation of the Tevatron, that a High Energy

Physics Advisory Panel Subpanel on Future Facilities formulated its recommendation for "the immediate initiation of a multi-TeV high-luminosity proton-proton collider project with the goal of physics experiments at this facility at the earliest possible date." This recommendation was transmitted to the U. S. Department of Energy with the unanimous endorsement of HEPAP in July of 1983. The DOE responded by initiating preliminary R&D for the SSC in the fall of 1983.

In December, 1983, the DOE and the Directors of the U. S. High Energy Laboratories chartered a Reference Designs Study to produce example designs of a *pp* collider with energy of 20 TeV/beam and luminosity of 10^{33} $cm^{-2}sec^{-1}$. Three different approaches were investigated, and it was found that any of them could form the basis of a technically feasible SSC, at a cost of approximately $\$3 \cdot 10^9$ 1984 dollars.

Early in 1984, the DOE assigned responsibility for the preconstruction research and development to Universities Research Association (URA), and an SSC Board of Overseers was created to take on this task. By July of 1984, URA had formed the SSC Central Design Group to direct and coordinate the national R&D effort. The CDG was established at the Lawrence Berkeley Laboratory, with Maury Tigner of Cornell University as its Director.

Meanwhile, a series of physics workshops had been organized to help detail the experimental goals and machine requirements for the SSC. The Physics at the SSC Discussion Group (PSSC) met at regular intervals around the country, and produced a summary report[16] on its activities. A week-long workshop on the antiproton option was held at the University of Chicago,[17] and a weekend workshop at the Texas Accelerator Center explored the fixed-target option.[18] Similar workshops were held in Europe in the context of Large Hadron Collider (LHC) studies.[19] In the same period, Estia Eichten, Ian Hinchliffe, Ken Lane, and I produced *EHLQ*.[1] All of this led up to a Summer Study on the Design and Utilization of the SSC,[20] again held in Snowmass, which examined the Reference Designs and reaffirmed the primary design parameters as well suited to the experimental goals and to thinkable experimental techniques. Physics studies have continued in workshops at Oregon[21], UCLA,[22] and Madison, in addition to many individual contributions.

The CDG has accomplished a great deal in its two years of operation. It has prepared a Site Criteria Document[23] to guide the preparation of site proposals, coordinated very productive work on superconducting materials, selected a magnet style, and produced an extraordinarily thorough Conceptual Design Report.[24] As we meet, yet another Summer Study on the Physics of the SSC is in progress at Snowmass.

The dipole magnets chosen for the conceptual design are superconducting (fields determined by conductor placement) "$\cos\theta$" two-layer collared coils surrounded by cold iron. Each magnet is sealed in an individual cryostat, the so-called "one-in-one" option. The peak operating field is 6.6 T at a current of 6504 A. The magnetic length of each dipole is 16.54 m, and the vacuum chamber has an inside diameter of 3.226 cm. The two independent rings for the two proton beams will sit one atop the other, at a separation of 0.7 m. The conceptual design calls for $2 \times 3840 = 7680$ dipoles. A cutaway drawing of the SSC dipole magnet is shown in Fig. 10.

Research on the quality and manufacturing technology of superconducting wire for the cable of the SSC magnet coils has produced a significant improvement in the current-carrying capacity of the wire. The ability to produce superconductor in finer filaments of more uniform cross section than before, together with the development of manufacturing techniques that eliminate the formation of CuTi nodules, have led to an increase by a factor of 1.5 in current-carrying capacity. The cooperative work in the National Laboratories, in Universities, and in Industry to develop superconductor for the SSC has resulted in an increase in current densities from the 1800 A/mm^2 characteristic of Tevatron wire to at least 2600 A/mm^2, with further increases of about 10% foreseen when large-scale mass production is begun.[25] The improvement in superconducting wire translates into a reduced

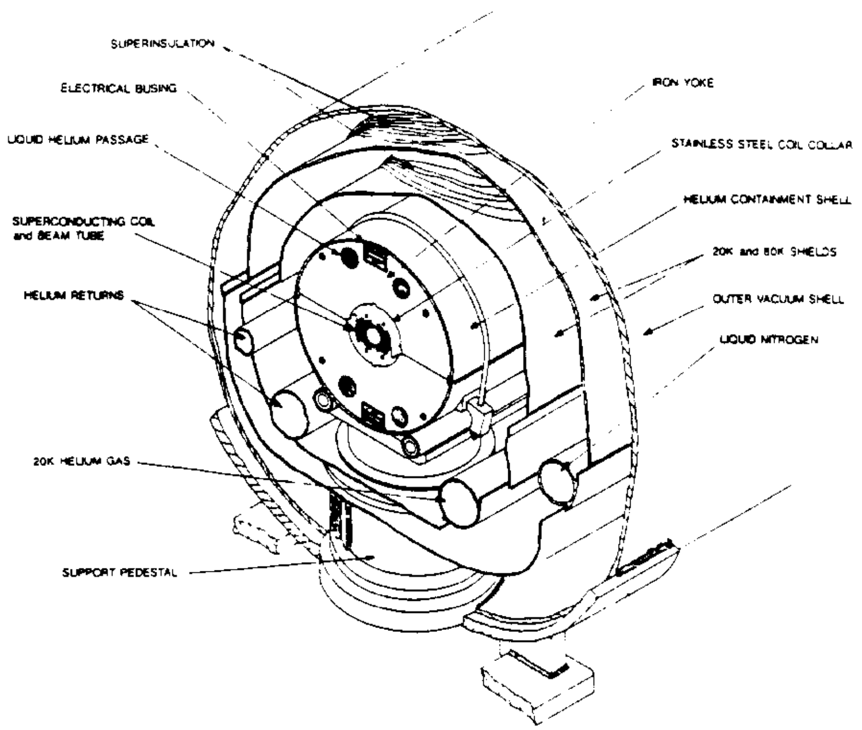


Figure 10: Isometric perspective drawing of a cutaway of the 6.6 T dipole magnet for the SSC.

requirement for costly superconducting materials for a given field, or a higher field for a given amount of superconductor.

7 THE CONCEPTUAL DESIGN REPORT

The Conceptual Design prepared by the Central Design Group is a non-site-specific conception of a $20\otimes 20$ TeV proton-proton collider 83 km in circumference. The design calls for two clusters of interaction regions incorporating both physics experimental areas and major supporting equipment, a configuration which seems advantageous from the point of view of operating efficiency, economics, sociology, and accelerator physics. At the design luminosity of 10^{33} cm^{-2}sec^{-1}, interactions will occur at the rate of

$$0.016 \cdot (\sigma/1 \text{ mb}) \text{ interactions/crossing;} \tag{7.1}$$

adjacent bunches are separated by 4.8 m. The complete parameter list in the Conceptual Design Report comes to 36 pages. An abbreviated list is given in Table 1. A sketch of the layout proposed for the SSC is shown in Fig. 11.

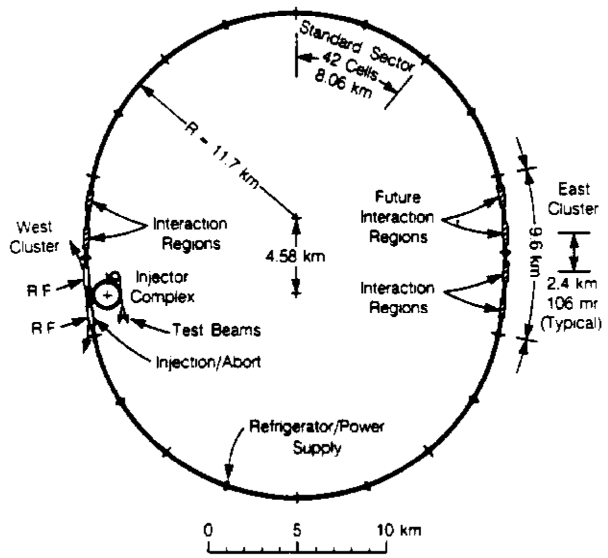


Figure 11: SSC collider ring layout. East and west clusters are joined by arcs of 11.7 km radius. The east cluster consists of four interaction regions separated by 2.4 km. The west cluster has two interaction regions and two utility straight sections (open rectangles) for injection and abort and for acceleration (rf). The cascade of synchrotrons that form the injector is inside the main ring at the utility straight sections. There are 10 refrigeration and power units around the ring (black diamonds).

Table 1: SSC Parameter Summary

type of machine	proton-proton collider
beam energy, max	20 TeV
circumference (revolution frequency)	82.944 km (f_0 = 3614 Hz)
straight-section configuration, initial	West cluster: 2U + 2XL (β^* = 0.5 m) East cluster: 2U + 2XM (β^* = 10 m)
luminosity at β^* = 0.5 m/10 m	$10^{33}/cm^2s/5.6 \times 10^{31}/cm^2s$
bunch separation, no. bunches per ring	4.8 m (min), 1.71×10^4 (max)
avg. no. reactions/bunch crossing at $10^{33}/cm^2s$	1.4 (90 mb cross section)
no. protons	7.3×10^9 per bunch, 1.27×10^{14} per ring
beam current	2.0 A (pk), 73 mA (avg)
beam energy per ring	405 MJ
normalized transverse emittance	1.0×10^{-6} rad-m
luminosity lifetime	~1 day
synch. rad. power	9.1 kW per ring
synch. rad. energy damping time	12.5 h
beam-beam tune shift, linear/long-range, XL	0.84×10^{-3}max/2.1×10^{-3} per IR
rms energy spread, inj/20 TeV	$1.75/0.5\times10^{-4}$
long emittance, inj/20 TeV (rms area/π)	0.035/0.233 eV-s
arc lattice/total no. long-arc cells	FODO, 60°, 192-m cells/332
betatron tune, x,y	78.27, 78.28
momentum compaction factor	0.000223
natural chromaticity	−204
nominal IP space betw. magn. quad ends	±20 m (± 101 m)
beta max, min in arc	332, 111 m
horiz dispersion, max, min in arc	3.92, 2.36 m
crossing angle	75 μrad (typ),150 μrad (max)
distance between adjacent IPs	2.40 km
angle between adjacent IPs	106 mrad
superconducting magnet type	collared, cold iron, 1-in-1
magnet configuration	over/under, 0.7 m separation
magnetic field, dipole	6.6 T (max)
magnetic radius of curvature	10.1 km
magnetic gradient, arc quad	212 T/m
dipole length (magnetic/slot)	16.54/17.34 m
arc quad length (magnetic/slot)	3.32/4.32 m
no. regular SC dipoles/quads (both rings)	7680 horiz. dipoles/1776 quads
excitation current (dipole and cell quad)	6504 A (nominal)
vacuum chamber ID, normal	3.226 cm
rf: frequency/wavelength/harmonic	374.74 MHz/0.80 m/103,680
acceleration period	1000 s
energy gain per turn per proton	5.26 MeV
peak rf voltage/total rf power per ring	20 MV, 2 MW
rf system slot length (per ring)	25 m
rms bunch length	6.0–7.3 cm
synchrotron tune (inj/20 TeV)	$8.2/1.9\times10^{-3}$
Injector system	0.6 GeV linac, 8 GeV/c LEB, 100 GeV MEB, 1 TeV HEB

For cost estimating purposes in the initial conceptual design, two high and two intermediate luminosity collision regions were designed. The essential point is that the ring optics have been structured in such a way that a wide variety of crossing zones can be accommodated. This flexibility will permit modification of the crossing zones to optimize experimental usage over the life of the facility. Bending is included in the spaces between interaction regions to prevent particles produced in one region from interfering with the study of collisions in another.

The tunnel configuration envisaged for the SSC is shown in Fig. 12. There we see the two rings of magnets, one above the other, each in a plane. The water, cryogen, electrical, and controls system mains are also indicated in the figure.

Since the conceptual design is not site-specific, a detailed model for a realistic cost estimate was based on three different "sites."

A: A soft ground tunnel, characterized by a gently rolling topography with various soft soils and sedimentary rocks, and a water table crossing the tunnel elevation. The tunnel is located at a depth of about 15 m below the surface, and a tunnel-boring machine with tooth cutters is the appropriate method of construction.

B: A hard rock tunnel, characterized by a rolling topography primarily of hard crystalline rock and a water table above the tunnel. The tunnel lies about 50 m below the ground surface and is driven by a tunnel-boring machine with disc cutters.

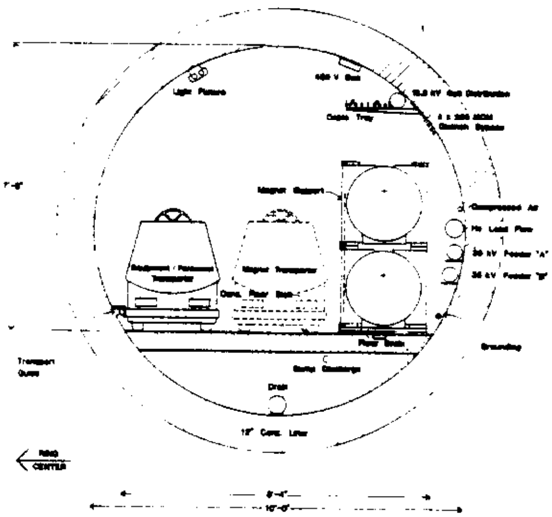


Figure 12: Collider Ring Tunnel profile showing the position of the two collider rings, the tunnel service vehicle, and routing of tunnel utilities service mains.

C: A cut-and-cover tunnel, characterized by a flat topography, with primarily soft soils and a water table well below the tunnel elevation. The tunnel is constructed near the surface using primarily surface construction excavation techniques

The resulting cost estimate is summarized in Table 2. Taking the Fermilab experience as a precedent, we assume that the cost of site acquisition will be borne by State which is the successful bidder for the SSC Laboratory.

Table 2: Cost Summary

		FY 86 K$
Superconducting Super Collider		3,010,318
Technical components		1,424,161
Injector systems	189,252	
Collider ring systems	1,234,909	
Conventional facilities		576,265
Site and infrastructure	85,433	
Campus area	42,860	
Injector facilities	39,758	
Collider facilities	346,803	
Experimental facilities	61,412	
Systems engineering and design		287,607
EDI	195,404	
AE/CM services	92,203	
Management and support		192,334
Project management	114,749	
Support equipment	52,635	
Support facilities	24,950	
Contingency		529,951

The bottom line is a price of $\$3.010 \cdot 10^9$ 1986 dollars for the laboratory, accelerator, and experimental facilities. This includes a contingency of about 20%, but does not include detectors and computer facilities, which are traditionally separated from construction costs in DOE accounting. The Conceptual Design itself and the cost analysis are being subjected to a thorough review by the Department of Energy, and we are hopeful that a recommendation to proceed with the project will be the end result of the review process. We believe that the SSC can foster a new level of international cooperation in particle physics. As a front-line research facility, it will certainly attract to its experimental program many of the best particle physicists from around the world. This of course is traditional in our field, but we may hope for more: active international collaborations established early enough to allow significant foreign participation in the design and construction of the SSC and its detectors, and not just in their utilization.

We are quite confident that the SSC can be built to the desired specifications at the advertised price. Standard methods of accelerator design have been found applicable to the SSC. All the design parameters resulting from the accelerator physics studies are within current practice or straightforward extensions to it. The engineering realization of the required systems and components can be based firmly on experience. The generic magnet design is founded on the existing Tevatron Collider at Fermilab, and detailed magnet modeling is well along.

Thanks to two years of intensive effort at the CDG, the National Laboratories, and the Universities, the SSC is well defined. A detailed cost estimate with a prudent contingency leads to a pricetag of three billion FY 1986 dollars. A construction schedule of six and one-half years from the notice to proceed, set out in the Conceptual Design Report, is ambitious but possible. The key critical path item is the selection of a site for the Supercollider Laboratory.

With the support of our government, hard work, and a little bit of luck, we may have, by 1995, a new instrument to explore the 1 TeV scale, and to bring us closer to the dream of an enduring understanding of all natural phenomena.

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