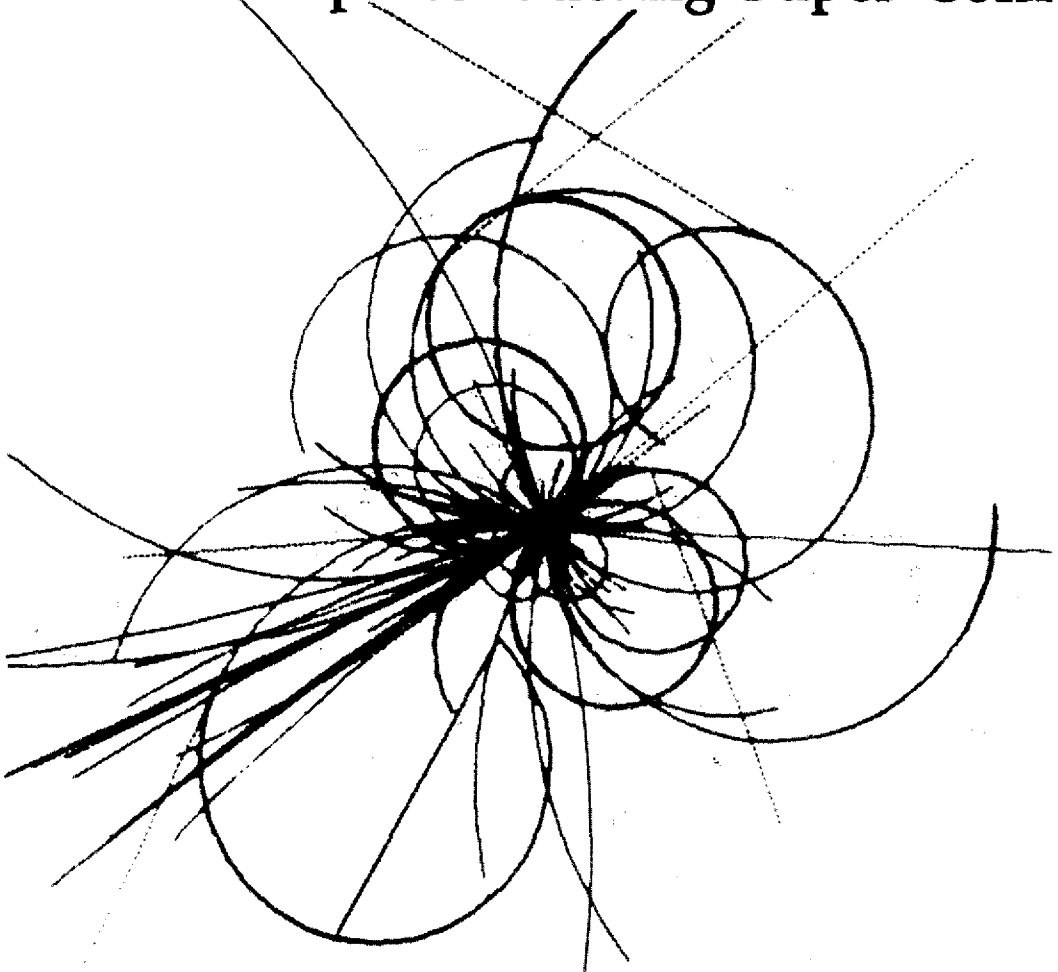
SSC-221

The Superconducting Super Collider



Uses of Particle Identification for Supercollider Physics

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SSC Central Design Group

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USES OF PARTICLE IDENTIFICATION FOR SUPERCOLLIDER PHYSICS*

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Abstract

I summarize the basic characteristics of the Superconducting Super Collider and describe the experimental environment of its high-luminosity interaction regions. I then review some of the discovery possibilities opened by the SSC, with special attention to the advantages conferred by particle identification.

1. The Importance of Particle Identification

In this talk, I will try to remind you of the benefits that experimentation with the SSC can derive from efficient identification of particle species and of the battle conditions under which particle identification will have to be carried out. My presentation will be schematic, in that I will not show simulations of events or comment in detail on event topologies and the complexity of events.[1] Nor will I comment on practical experimental techniques for identifying particles; I shall leave practical matters to the professionals and concentrate on potential benefits. In view of the generality of my remarks, it may be helpful to begin with a statement of my conclusions:

(i) A use will be found for anything you can do: identification of light and heavy quarks, gauge bosons, and leptons will all aid the search for new phenomena and the detailed measurement of familiar processes.

(ii) The requirements for particle identification, measured by the desires of those who conceive experiments, will always exceed what is practical. If one isolated particle can be identified efficiently, we will next want to identify several particles, including those in jets of light hadrons.

(iii) Ideally, we will want to measure the momenta of short-lived particles, not simply to tag them. Generally speaking, the requirements for momentum measurement will be set by the need to identify narrow states that decay into heavy flavors of quarks and leptons.

Although such statements will not come as a surprise to aficionados of particle identification, I will attempt to show you some of the reasons for their correctness—and importance—in the SSC setting.

The parameters of the SSC have been set by considering the demands of hard-scattering processes and by our conviction that it is essential for the next machine to make possible a thorough exploration of the 1-TeV scale. This has been a sensible way to proceed, because the scientific goals are of high importance and because these are the reactions that make the most severe demands on energy and luminosity (both instantaneous and average), the parameters that drive accelerator design. However, the experimental program of the SSC will be broader than the set of experiments we have used to define the capabilities of the machine. It is very important that our vision of experiments or of detector components not be narrowed by what QCD predicts or by what theorists find most interesting today. Similarly, we must not assume that every experiment for the SSC will take the form of a 4π, general-purpose device.

In most of my remarks, I will ignore the virtues of identifying the light quarks and hadrons composed of them. However, it is hard to imagine an initial program of exploration with the SSC that does not include measurements expected to be prosaic, but with the capacity to surprise, such as particle surveys of the kind carried out in the past with highly instrumented single-arm spectrometers. Though the SSC does not seem to be the most favorable environment for producing a quark-gluon plasma, it would be a mistake to deny ourselves the opportunity to look for signs of changes of phase: copious production of strange particles, or of photons, as well as changes in the kinematical characteristics of events. Similar remarks apply to every kind of "zoo" event hinted in cosmic-ray experiments. For many of these studies, which in any case will help give us a general awareness of the characteristics of a typical event, particle identification is an important—perhaps decisive—element.

2. Main Parameters of the SSC

The chief attributes of the SSC's superconducting collider rings and of the cascade of accelerators providing intense proton beams to them are set forth in the 1986 Conceptual Design Report.[2] The SSC is planned as a proton-proton collider with 20 TeV per beam and a peak luminosity of $\mathcal{L} = 10^{33}$ cm^{-2}sec^{-1}. To achieve this luminosity while keeping the number of inelastic events per beam crossing within reason, the Conceptual Design calls for 1.3×10^{14} protons per ring, divided among 1.7×10^4 bunches, each containing about 7×10^9 protons. The bunch length will be about 6 cm; bunches will be spaced by 4.8 m or, in terms more meaningful for the

design of experiments, about 15 ns. The counter-rotating proton beams will be confined by two separate rings of 6.6-T dipoles, one atop the other, with the beam centers separated by about 70 cm. The dipoles will be 17 m long; about 3840 will be needed for each ring.

The collider rings will be fed by a cascade of accelerators. The Conceptual Design Report calls for a 600-MeV linac followed by two rapid-cycling synchrotrons built of conventional (nonsuperconducting) magnets. These will boost the proton momentum to 8 and then to 100 GeV/c. A superconducting High-Energy Booster synchrotron will take the particles up to 1 TeV/c and inject them into the collider rings. The acceleration cycle will take about 1000 sec, and colliding beams will be stored for about a day at a time.

A possible layout[3] of the Supercollider is shown in Figure 1. Four long straight sections are clustered on the two gently curved sides of the collider ring. In this schematic diagram, the near cluster incorporates the injector complex, the radio-frequency accelerating system, beam absorbers, and two of the six interaction halls. The far cluster adds four more interaction halls, two of which will be reserved for development after research begins, according to the Conceptual Design Report. The space between interaction points is gently curved, so muons produced in beam-beam collisions at one interaction region are offset by 94 meters from the next collision point. Current concepts for the interaction regions will leave ±20 m of free space for detectors in the high-luminosity ($\mathcal{L} = 0.06$–10^{33} cm^{-2}sec^{-1}) areas and ±120 m of free space in the intermediate-luminosity ($\mathcal{L} = 0.8$–5.0×10^{31} cm^{-2}sec^{-1}) areas. This work provides a firm foundation for the creation of a site-specific conceptual design; the configuration of the experimental areas will be determined by the scientific program the SSC Laboratory develops in consultation with the user community.

3. Experimental Environment of the SSC

Signals and backgrounds for specific phenomena at the SSC have been studied extensively over the past four years.[4–10] To design experiments, it is also important to be aware of the general environment in which SSC detectors must function and events must be selected and recorded. At the design luminosity of 10^{33} cm^{-2}sec^{-1}, we expect about 10^8 inelastic collisions per second and an average of 1.7 events per crossing. A general-purpose detector will have about 10^6 electronic channels.

A good way to gain respect for the conditions that will prevail at the SSC is to examine the trigger rate for events with transverse energy E_T greater than some threshold E_T^{min}. This is shown in Figure 2 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 to efficiently select interesting events.

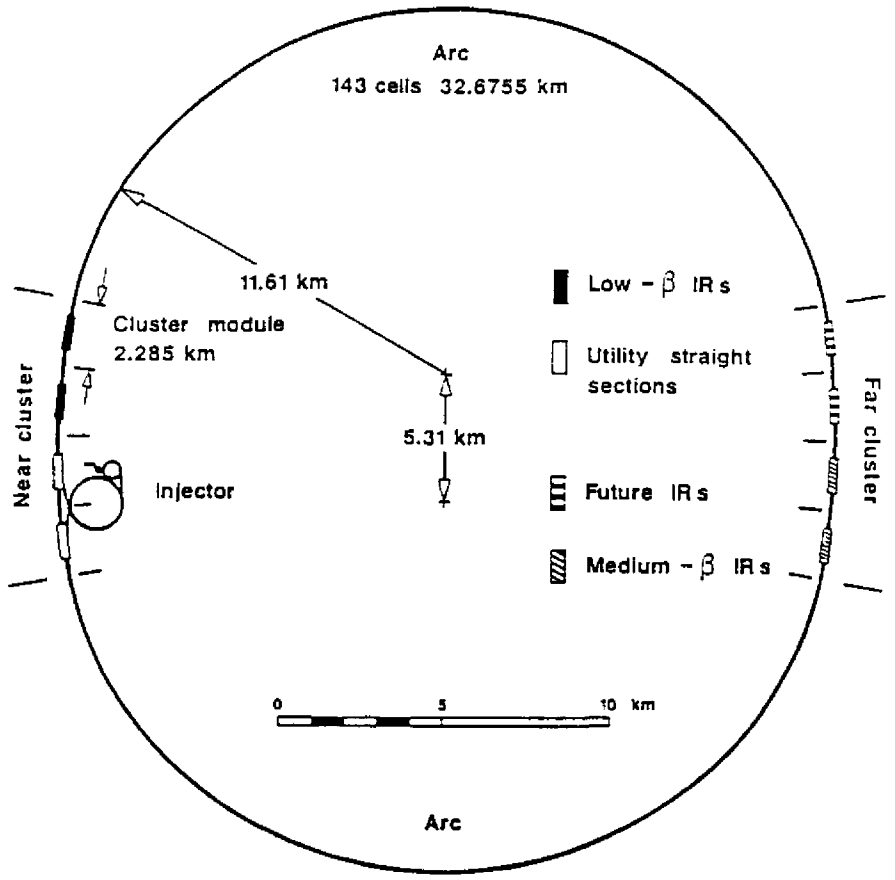

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Figure 1: Collider ring layout envisaged in the 90° (September 1987) Lattice of the SSC [from Ref. 3].

The SSC experimental environment is complex and presents a challenge to technology for many aspects of detector components. This does not mean that we do not know how to build experiments for the SSC, but simply that we can profit from improvements in many areas of detector technology. There is time to carry out detector R&D that can yield rich rewards before designs of first-round experiments must be frozen.[13]

I have listed in Table 1 particles that we wish to identify. I shall have nothing further to say about the first group of light particles. For the examples I will discuss, they play no role except as possible impediments to electron identification. However, it is easy to find processes that make identification of these particles interesting in its own right. The study of prompt photon production and signatures for quark-gluon plasma come immediately to mind. Particles in the second group—the leptons and the quarks with picosecond lifetimes—are those that we should insist on identifying well in SSC experiments. Efficient identification of particles in the final group would make our experimental life much richer and would greatly enhance our ability to explore the new terrain opened up by the SSC.

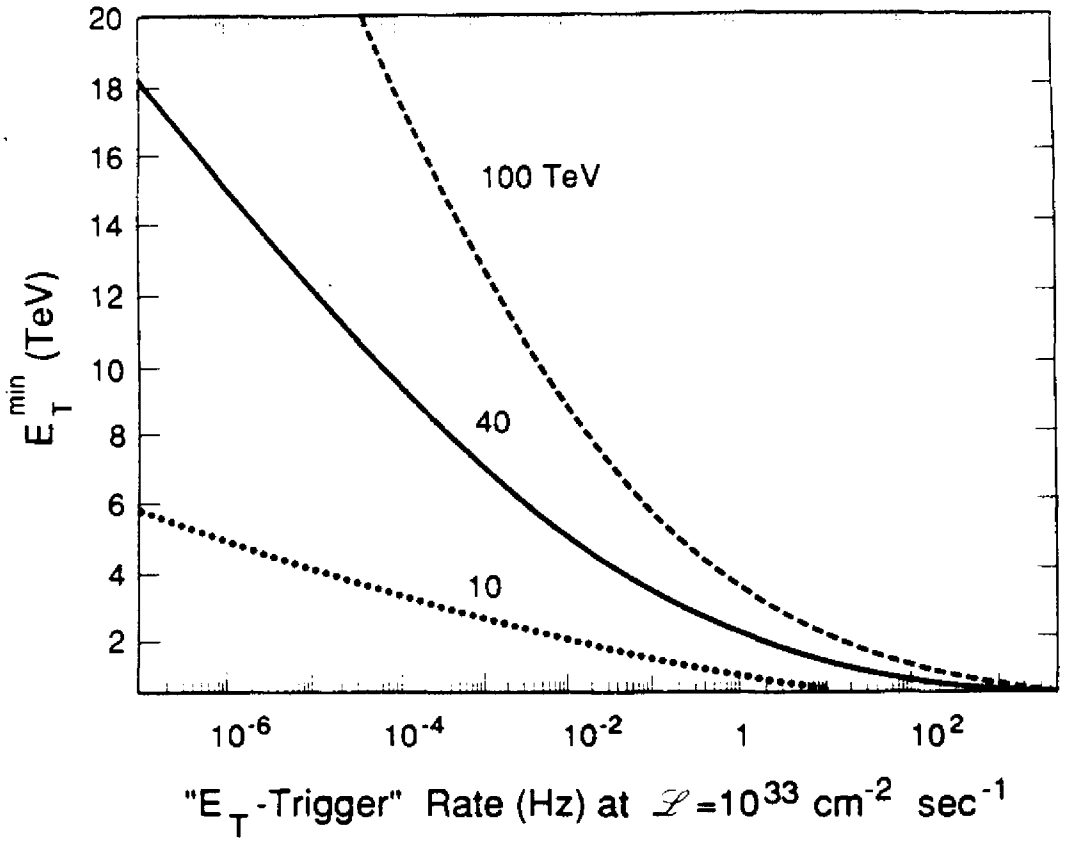

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Figure 2: Counting rate for an E_T-trigger in pp collisions at an instantaneous luminosity of $\mathcal{L} = 10^{33}\text{cm}^{-2}\text{sec}^{-1}$. The threshold is defined for transverse energy deposited in the central region of rapidity, defined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

Table 1. Candidates for Particle Identification

$\pi^{\pm}, K^{\pm}, K^0, p^{\pm}, n, \ldots$
γ, π^0
c, b
e
μ
τ
$W^{\pm}$
Z^0
t
g

Before turning to experimental targets for the SSC, I would like to indicate how the inability to identify particles efficiently may close our eyes to new phenomena at the energies now available. The top quark—which we know must exist—has so far eluded detection.[11,12] The statements of nondiscovery from CDF and UA2 are not yet highly quantitative, but let us take them seriously and ask for possible physics reasons behind the nonobservation. The most conventional possibility is that the top quark is so heavy that it lies outside the explored range. More amusing is the possibility that the expected signal in the weak semileptonic decay

$$t \to b\, \ell^+ \nu \quad , \tag{3.1}$$

which occurs in order G_F^2, might be swamped by the semiweak decay involving a charged technipion or Higgs boson,

$$t \to P^+ + (b \text{ or } s \text{ or } d) \quad , \tag{3.2}$$

which occurs in order G_F. The technipion decay mode would dramatically shorten the t-quark lifetime and thereby reduce the semileptonic branching ratio. Perhaps the nonobservation of the top quark signals the discovery of technicolor!

To check this possibility, we must look—either in this setting or elsewhere—for the light technipions. This can be done in experiments at SLC or LEP, once the study of rare decays of the Z^0 becomes possible. The branching ratio expected for the decay $Z^0 \to P^+ P^-$ exceeds 10^{-3} for technipion masses up to about 40 GeV/c^2. The technipion pairs are to be reconstructed in final states such as $(c\,\bar{b})(\bar{c}\,b)$, etc., for which efficient particle identification is indispensable.

4. Some Hadron Collider Discovery Possibilities

The standard model hints that the frontier of our ignorance lies at about 1 TeV for collisions among the fundamental constituents. This conclusion is specific to electroweak symmetry breaking, but that is not the only interesting issue we face. More generally, the success of our theoretical framework suggests that a significant step is needed to see breakdowns of the standard model. Hadron colliders opening unexplored territory offer a broad range of discovery possibilities. Let us consider a few examples.

4.1 New Gauge Bosons

There are many reasons to be open to the possibility of new gauge bosons. These include the idea of high-energy parity restoration in an electroweak gauge theory based on the symmetry group $SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$ and the occurrence of extra $U(1)$ gauge symmetries in unification groups larger than $SU(5)$, such as the low-energy gauge groups emerging from superstring models.

In a specific theory, the calculation of $W^{\pm}$ and Z^0 production rates is easily modified to yield an estimate of the cross section for the production of new gauge bosons. I show in Figure 3 the cross section for the production of a new W-boson with standard gauge couplings to the light quarks. The discovery signal is an isolated electron or muon—which must be identified—plus missing energy, which is to say an identified neutrino. For the 40-TeV energy projected for the SSC, we may anticipate sensitive searches out to a mass of about 6 TeV/c^2. Once we get over the excitement attending the discovery of a new force, we should also ask about the decay products of the new gauge boson, for they may contain new species of fermions. In an $SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$ electroweak theory, the right-handed W may decay into a neutral heavy lepton

$$W^+ \rightarrow e^+ N_e \quad \hookrightarrow e^+\mu^- \nu_\mu \text{ or } e^-\mu^+ \bar{\nu}_\mu \tag{4.1}$$

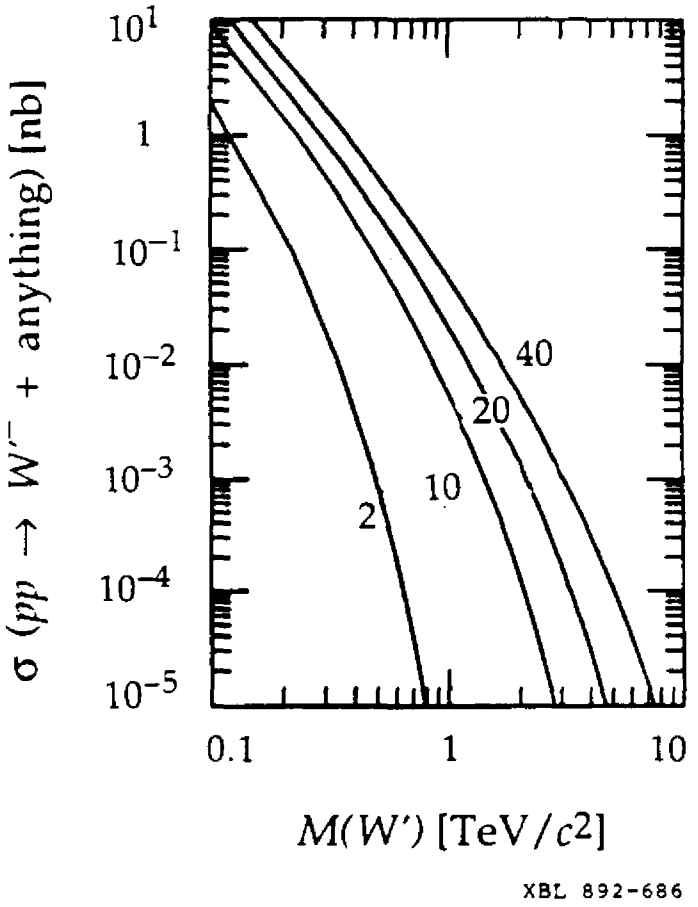

Figure 3: Cross section for the production of a heavy W-boson with rapidity $|y| < 1.5$ in pp collisions at 2, 10, 20, and 40 TeV (after EHLQ).

(In some models, this may be the signature for discovery of the new gauge bosons.) The ability to detect both electrons and muons increases the number of decay channels useful for identifying a heavy W-boson and is essential for examining the decay products of the new W.

The exceptional group E_6 has a long history as a candidate group for the unification of the strong, weak, and electromagnetic interactions. Historically, the motivation for considering E_6 derived mainly from the observation that E_6 is the group beyond $SO(10)$, which is in turn the group beyond $SU(5)$:

$$E_6 \supset SO(10) \supset SU(5)\,. \tag{4.2}$$

The current revival is owed to the possibility that E_6 may be the surviving symmetry of the $E_8 \otimes E_8'$ internal symmetry group of the heterotic string.[14] Like all applications of superstring ideas to phenomenology, the "derivation" of E_6 is very vague and tentative. Nevertheless, it provides us with a reason to look again at some possible consequences of an E_6 gauge symmetry.

The spectrum of quarks and leptons can be read off from the fundamental **27** representation of the group:

$$\begin{array}{llllllllll}
E_6: & \mathbf{27} & = & & \mathbf{16} & & \oplus & & \mathbf{10} & \oplus & \mathbf{1} & : SO(10) \\
 & SU(5): & \mathbf{10} & \oplus & \mathbf{5^*} & \oplus & \mathbf{1} & & \mathbf{5} & \oplus & \mathbf{5^*} & \mathbf{1} \\
 & & u & & d^c & & N_e^c & & h & & h^c & n \\
 & & d & & e & & & & E^+ & & E^- & \\
 & & u^c & & \nu_e & & & & N_E^c & & \nu_E & \\
 & & e^c & & & & & & & & &
\end{array} \tag{4.3}$$

The $\mathbf{10} \oplus \mathbf{5^*}$ of $SU(5)$ constitute the standard generation. The remaining member of the $SO(10)$ **16** is a right-handed neutrino. Among the novel particles characteristic of E_6, the new charge $-\frac{1}{3}$ weak isoscalar quark is of especial interest.

To determine the interactions,[15] we must spontaneously break E_6 down to the low-energy symmetry $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. This leads naturally to one or more extra $U(1)$ factors at low energies, which in turn implies an extra gauge boson, Z'. The Z' is somewhat harder to produce in $p^{\pm}p$ collisions than a standard Z^0 of the same mass, because the couplings to light quarks are inhibited. The branching ratio for the decay into charged leptons, for example, is

$$\Gamma(Z' \to e^+ e^-) \approx 3\%/n_g\,, \tag{4.4}$$

where n_g is the number of generations, which is somewhat smaller (by about $1/n_g$) than that of the conventional Z^0. The production cross sections for the new Z' are shown in Figure 4. We expect to be sensitive to this new object in the e^+e^- or $\mu^+\mu^-$ channel for masses as large as about 3–4 TeV/c^2 at the SSC.

Discovery of the Z' would open the prospect of finding the new fermions that inhabit the fundamental representation of E_6. Table 2 shows that the branching ratio is especially favorable for the charge $-\frac{1}{3}$ quark h. It cannot be absolutely stable, for we have no evidence of it in relics from the big bang. We expect it to decay by mixing with the weak-isodoublet charge $-\frac{1}{3}$ quarks,

$$h \leftrightarrow \left\{ \begin{array}{c} d \\ s \\ b \end{array} \right\} \leftrightarrow \left(\begin{array}{c} u \\ c \end{array} \right) \ell \nu \ , \tag{4.5}$$

or through flavor-changing neutral-current interactions into dilepton channels. Direct detection is hopeless without effective particle identification.

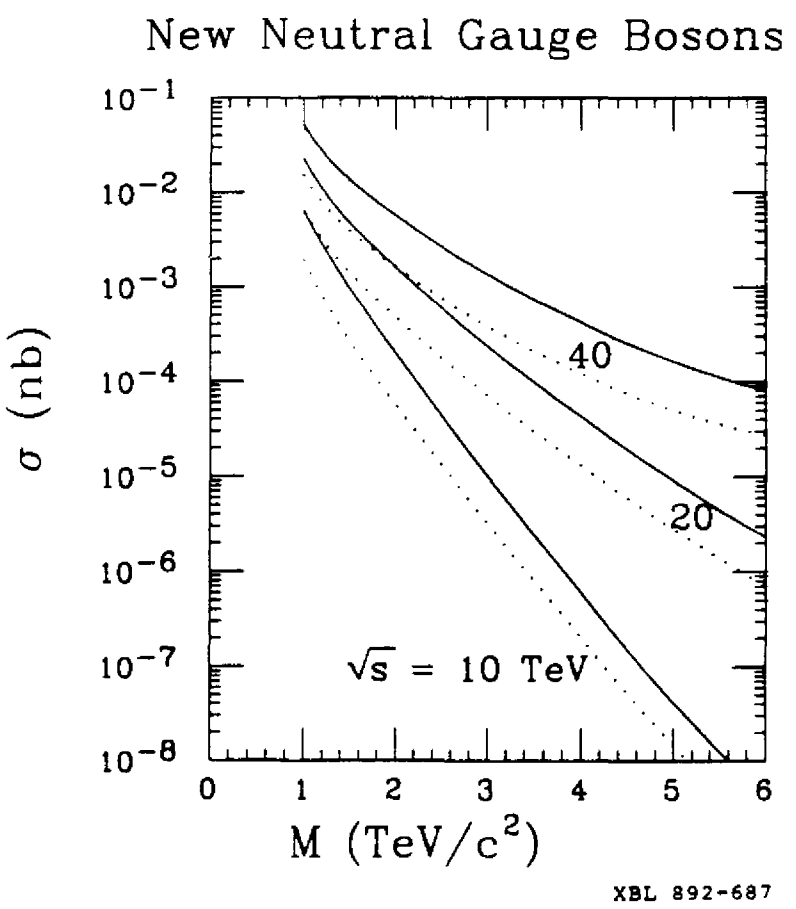

Figure 4: Cross section for the production of a heavy $Z^{0'}$-boson with rapidity $|y| < 1.5$ in pp collisions at 10, 20, and 40 TeV. Solid lines: Weinberg-Salam couplings; dotted lines: E_6 couplings.

Table 2. $Z^{0'}$ Branching Fractions per Generation

$u\bar{u}$	24/180
$d\bar{d}$	15/180
e^+e^-	5/180
$h\bar{h}$	51/180
E^+E^-	17/180
$\nu_e\bar{\nu}_e$	1/180
$\nu_E\bar{\nu}_E$	1/180
$N_e\overline{N_e}$	25/180
$N_E\overline{N_E}$	16/180
$n\bar{n}$	25/180

4.2 Heavy Quarks

The cross sections for the strong-interaction production of heavy quarks are readily calculated in QCD perturbation theory. I show in Figure 5 the yield of heavy quarks from the lowest-order processes $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$ at the SSC. We expect an event rate sufficient for the discovery of heavy quarks with masses up to about 2 TeV/c^2. An evaluation of the requirements for detection depends upon the decay chain. If the dominant decay of the heavy quark is

$$Q \to t + W^- \ , \tag{4.6}$$

as it is likely to be, the ultimate decay products will be different if the top-quark mass is greater or less than the mass of the intermediate boson. Here we see just how useful t-quark and W-boson detectors could be!

4.3 Two-Jet Events

I show in Figure 6 the differential cross section $d\sigma/dp_\perp dy|_{y=0}$ for the reaction

$$p\,p \to \text{jet} + \text{anything} \tag{4.7}$$

at 40 TeV, for elementary quarks ($\Lambda^* = \infty$) and for quarks composite on scales of 10, 15, and 20 TeV. Jets will be produced in numbers sufficient for detailed study out to $p_\perp$ = 6–7 TeV/c. In addition to checking the expectations of QCD for the differential cross section, we should plan to confront the predictions of QCD for the evolution of gluon jets into heavy flavors. To do so requires identifying gluon jets and the heavy quarks.

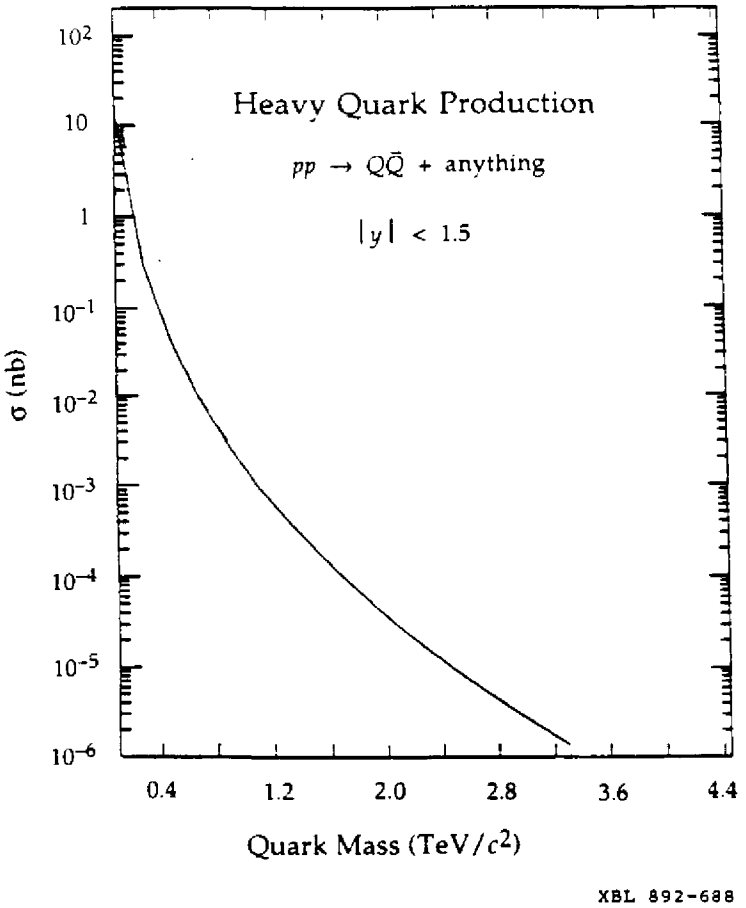

Figure 5: Integrated cross section for pair production of heavy quarks satisfying $|y_Q|$, $|y_{\bar{Q}}| < 1.5$ in pp collisions at 40 TeV.

4.4 Pairs of Gauge Bosons

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 that 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 they 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.

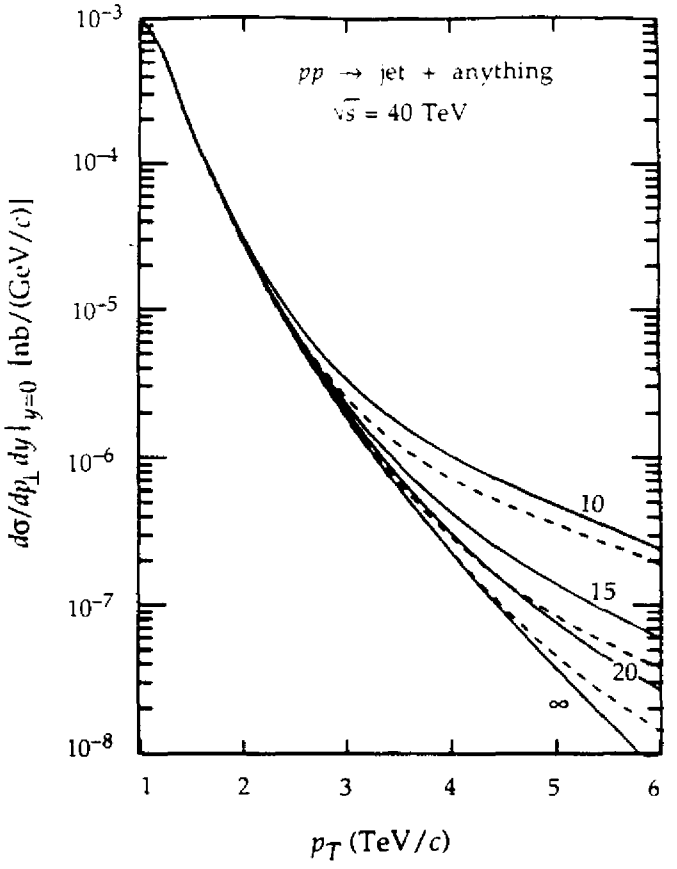

Figure 6: Differential cross section $d\sigma/dp_\perp dy|_{y=0}$ for the reaction $pp \to$ jet + anything at 40 TeV. The curves are labeled by the compositeness scale Λ^* (in TeV). Solid (dashed) lines indicate constructive (destructive) interference between the QCD amplitude for (anti)quark-(anti)quark scattering and the contact term.

The mass spectrum of W^+W^- pairs is of interest both for the verification of gauge cancellations and for the assessment of backgrounds to heavy Higgs boson decays. The calculated spectrum is shown for intermediate bosons satisfying $|y| < 2.5$ in Figure 7. At an energy of 40 TeV and integrated luminosity of 10^{40} cm^{-2} = 10^4 pb^{-1}, we can look forward to 2×10^6 W^+W^- pairs per year. This seems adequate for a test of the gauge cancellations, provided that the intermediate bosons can be detected with high efficiency.

4.5 The Higgs Boson

A heavy Higgs boson (by which we mean one with $M_H > 2M_Z$) will have the characteristic signature of decay into a pair of gauge bosons, with branching fraction roughly 2/3 into the W^+W^- channel and 1/3 into the Z^0Z^0 channel. Event rate permitting, the simplest mode in which to detect a heavy Higgs boson is the four-charged-lepton final state arising from the decay chain

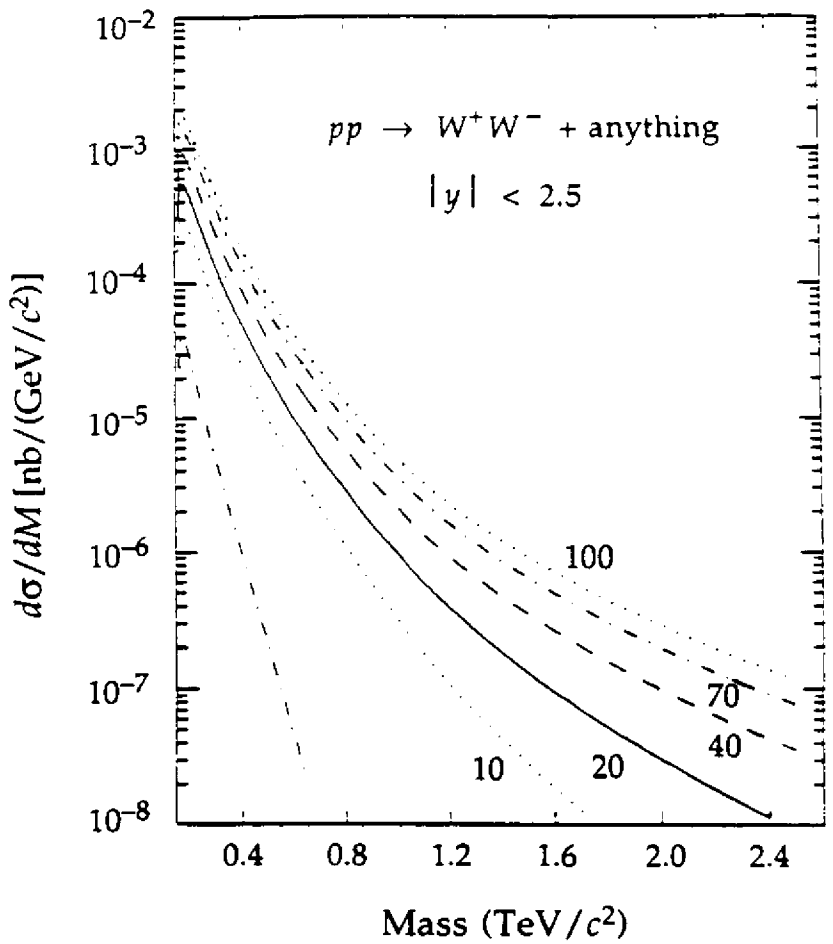

Figure 7: Mass spectrum of W^+W^- pairs produced in pp collisions at 40 TeV, according to the standard model and Set 2 of the EHLQ parton distributions. Both the W^+ and the W^- must satisfy $|y| < 2.5$.

$$H^0 \rightarrow Z^0 \quad Z^0 \qquad (4.8)$$
$$\hookrightarrow \ell^+\ell^- \quad \hookrightarrow \ell^+\ell^-$$

The most promising mechanisms for Higgs-boson production are the gluon fusion process and the intermediate-boson fusion process. The rate for gluon fusion is sensitive to the masses of the quarks circulating in the loop, particularly to the top-quark mass. I show in Figure 8 for various Higgs-boson masses the yield of Z^0Z^0 events detected through the cascade (4.8) in the reaction $pp \rightarrow H^0$ + anything. The signal becomes less distinct at high masses, both because the number of events decreases and because the Higgs-boson width is proportional to $G_F M_H^3$. The SSC should nevertheless allow us to carry out a thorough search for a heavy Higgs boson for masses up to 1 TeV/c^2, if both electrons and muons can be identified efficiently and measured with good precision.

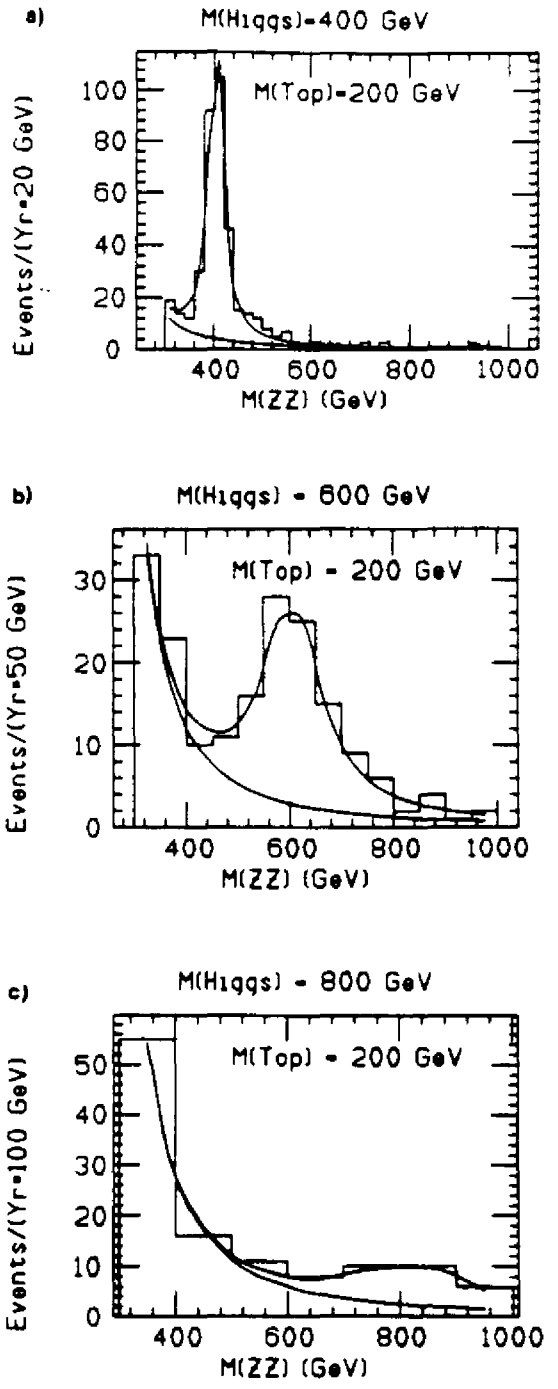

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Figure 8: The ZZ invariant mass distribution arising from the production and decay of a Higgs boson in the reaction $pp \rightarrow H$ + anything, and from the background process $q\bar{q} \rightarrow ZZ$ at $\sqrt{s} = 40$ TeV with an integrated luminosity of 10^{40} cm^{-2}. Both gauge bosons must satisfy the cut $|y_i| < 1.5$. The top-quark mass is taken to be 200 GeV$/c^2$, and perfect resolution and detection efficiency is assumed for both electrons and muons (from Ref. 16).

5. Concluding Remarks

The initial goals of experimentation at the SSC help define detector issues that we should address vigorously. In the realm of particle identification, more is better. The examples we have considered highlight areas of special interest beyond the standard goals of identifying light hadrons, photons, and leptons. High-efficiency W and Z detectors will have great utility. The discovery physics we have considered in assessing the 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. Examples from technicolor and the Higgs sector of the standard model indicate that good-efficiency τ, b, ... 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.

Acknowledgments

It is a pleasure to thank Jorge Morfín and his colleagues for their efficient organization of this Symposium. I am grateful to Kate Metropolis for helpful comments on the manuscript.

Footnotes and References

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