F. Bird
C. Blocker
T. Fukui
P. McBride
F. Paige
T. Pal
M. Takashima
M. Turcotte
J. Siegrist

High p_t Physics Processes

Superconducting Super Collider
Laboratory

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F. Bird, C. Blocker, T. Fukui, P. McBride, F. Paige,
T. Pal, M. Takashima, M. Turcotte, and J. Siegrist

Superconducting Super Collider Laboratory[†]
2550 Beckleymeade Ave.
Dallas, TX 75237

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Introduction

In order to estimate the “physics reach” of various pp or $\bar{p}p$ colliders, several physics processes of interest have been studied. For each process, the number of produced events required to carry out meaningful physics studies or detect statistically significant signals has been estimated. These estimates are largely based on detailed studies for the SDC and GEM design reports. Extrapolation to other energies takes into account calculated cross sections and crude background estimates. To convert the required number of events into an *average* luminosity to be delivered by the machine, a “running year” of 10^7 seconds is used. This time is consistent with SSC design plans, which call for an 80% detector up time and enough stable beam time to result in 10^7 “live” seconds per operating year. Note that when making comparisons with existing facilities, any deviation from these assumptions should be taken into account. The conclusions of this study are generally similar to those reached by Eichten, et al.¹ in 1984 and by the Drell Panel² in 1990.

1 Electroweak Symmetry Breaking

Present indications are that experiments at LEP-II will most likely be capable of discovering the standard-model Higgs boson up to a mass region of roughly 80 GeV³. Experiments at hadron colliders must therefore be prepared to extend the search for the Higgs boson from 80 GeV on upwards. The theoretical upper limit is about 650 GeV but might be stretched to 800 GeV. While the production cross sections are large, 1-100 pb, it is necessary to rely on rare decay modes to overcome backgrounds. The most favorable modes are $H \rightarrow \gamma\gamma$ for $80 < M_H < 130$ GeV, $H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$ for $130 \text{ GeV} < M_H < 2M_Z$, and $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ for $M_H > 2M_Z$.

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Fig. 1a. The instantaneous luminosity required to directly produce Higgs boson events in pp (solid curves) and $\bar{p}p$ interactions (dotted curves) such that the significance (signal / $\sqrt{\text{background}}$) = 5. The Higgs boson events are required to decay via the mode $H^0 \rightarrow \gamma\gamma$. Any increase in the QCD background at higher luminosity is not included.

1.1 Intermediate Mass $H \rightarrow \gamma\gamma$

Strategies to discover the Higgs boson in the mass range $80 \text{ GeV} < M_H < 130 \text{ GeV}$ have been discussed in cases where the Higgs boson is directly produced (predominantly by gluon-gluon fusion) and also when it is produced in association with a W boson or $t\bar{t}$ pair. In both cases, studies have focused on the decay $H^0 \rightarrow \gamma\gamma$. Despite the relatively small branching ratio for this process ($\sim 10^{-3}$), this mode is thought to be the most promising because it does not suffer from large QCD backgrounds for the dominant mode, $H \rightarrow b\bar{b}$.

In the case of direct production, large residual backgrounds from $q\bar{q} \rightarrow \gamma\gamma$, $gg \rightarrow \gamma\gamma$, and $\pi^0 \rightarrow \gamma\gamma$ from QCD two jet events still exist and will impose stringent requirements on the photon detection and π/γ rejection capabilities of the detector. Extremely fine mass resolution will indeed be required to isolate a Higgs mass peak over this large continuum background. The results for direct production are based on a study presented in the GEM Technical Design Report⁴. The curves in Fig. 1a reflect the instantaneous luminosity required for a given $\sqrt{s}$ such that the significance is

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Fig. 1b. The instantaneous luminosity versus $\sqrt{s}$ for the associated production of Higgs boson in the modes WH^0 and $t\bar{t}H^0$. The curves reflect the luminosity required to produce sufficient numbers of Higgs bosons such that the significance ($\text{signal} / \sqrt{\text{background}} = 5$). The Higgs bosons are required to decay via $H^0 \rightarrow \gamma\gamma$ in both cases. The W boson decays leptonically into $e\nu$ or $\mu\nu$. In $t\bar{t}H^0$ events one top quark decays semi-leptonically to produce an electron or muon and the other decays to jets.

$$S = \text{signal} / \sqrt{\text{background}} = 5. \quad (1)$$

It should be mentioned that the background was calculated only for $\sqrt{s} = 40$ TeV. Since the predominant background is $q\bar{q} \rightarrow \gamma\gamma$, the ratio of signal to background will worsen as the center of mass energy is lowered. Therefore, the curves in Fig. 1a are overly optimistic at smaller $\sqrt{s}$.

The associated Higgs production mode cross sections for the processes WH^0 and $t\bar{t}H^0$ suffer by a reduction in nearly an order of magnitude relative to direct production. However, the requirement of a final state $l^\pm + \gamma\gamma + X$ significantly reduces backgrounds compared to only searching for di-photons. This final state therefore requires less photon mass resolution and γ/jet discrimination⁵. The major backgrounds to this processes are $W + \gamma\gamma$ and $Q\bar{Q} + \gamma + \text{jet}$ and $Q\bar{Q} + 2 \text{ jets}$. The results for the associated production modes are based on a study presented in the SDC Technical Design Report⁶. The curves in Fig. 1b reflects the instantaneous luminosity required for a given $\sqrt{s}$ such that the significance $S = 5$. This calculation of the significance was performed using Gaussian statistics, which is marginally correct when considering the numbers of events used (for example in the 80 GeV Higgs case, there are 11 signal and an estimated 16 background events detected) but does overestimated the significance

somewhat. In addition, a similar study presented in the GEM TDR^{4,7} shows a much lower efficiency for detecting signal events when using a more "realistic" detector simulation. However, it is felt the GEM study over-estimates the amount of background, since a significant part of the background comes from $Z\gamma$ events, and it should be possible to veto many of these.

1.2 Intermediate Mass $H \rightarrow ZZ^*$

The decay mode for the Higgs boson: $H^0 \rightarrow ZZ^* \rightarrow (ee)(\mu\mu)$ is the favored mode to search in the mass range $130 \text{ GeV} < M_H < 180 \text{ GeV}$, where the " Z^* " stands for a virtual Z . In this mass range, the Higgs boson width remains quite narrow. A study of the production cross section times the branching ratio has been performed using the PYTHIA⁸ generator with the gg and WW/ZZ fusion processes for the Higgs production. The allowed phase space correctly takes into account the ZZ^* process.

The cross sections are calculated for both pp and $\bar{p}p$ as a function of the center-of-mass energy, and the corresponding luminosity to produce 40 events per SSC year for these cross sections are shown in Fig. 2. A top quark mass of m_t of 150 GeV has been used. Systematic errors on the values of the cross section are mainly due to the structure functions ($\sim 30\%$) and the top quark mass ($\sim 15\%$). Close to the SSC in energy and luminosity are required to observe this mode for low masses or for $M \sim 170 \text{ GeV}$.

Fig. 2. The curves indicate the luminosity needed to produce 40 events/year in the mode $H \rightarrow ZZ^* \rightarrow 4l$ (e or μ) in pp collisions for Higgs masses of 120, 150, and 180 GeV.

1.3 Heavy-mass Higgs

Figure 3 shows the luminosity needed to produce 20 events/year in the mode $H \rightarrow ZZ \rightarrow 4l$ (e or μ only) in pp collisions for Higgs masses of 200, 400 and 800 GeV. The 20 event limit provides a reasonable estimate of the reach for this mode, based on SDC studies⁶ at 40 TeV and $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ luminosity. The curves for $\bar{p}p$ collisions are similar to these.

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Fig. 3. The curves indicate the luminosity needed to produce 20 events/year in the mode $H \rightarrow ZZ \rightarrow 4l$ (e or μ) in pp collisions for Higgs masses of 200, 600, and 800 GeV. Curves for $\bar{p}p$ collisions (not shown) are similar.

This plot provides a conservative estimate of the reach attainable for the heavy Higgs. Note that use of the τ decay modes for one of the two Z 's can increase the event sample by up to a factor of two. Also, for the highest masses decays of one of the two Z 's into neutrinos can be used, as was shown in the SDC and GEM detector Technical Design Reports^{4,6}.

2 Physics of the top quark

The top quark is one of the two particles in the standard model that have not been observed (the other being the Higgs boson). It is presently thought that the top mass lies between 100 and 200 GeV, assuming that there is no new physics affecting higher order corrections to precision electroweak measurements. If the top mass is in this range, it will most likely be discovered at the FNAL Tevatron collider in the next few years. If it is not discovered there, it would almost certainly be discovered at any collider with reasonable luminosity and energy several times the Tevatron due to the rapid rise in the top cross section with center-of-mass energy (Fig. 4).

Even if the top is discovered at the Tevatron, the rapid rise in the cross section indicates that many more top events would be produced in a higher energy machine, enabling better study of the properties of top. It is important to ask what properties of top are important to measure and how well can they be measured as a function of the machine energy and luminosity. The following properties were considered: (1) total cross section, (2) top mass, (3) observation of $t \rightarrow H^+ b$ (where H^+ is a charged Higgs), (4) branching ratios in the decay of the W from the top, (5) flavor changing neutral current decays (such as $t \rightarrow Z + c$), (6) angular distribution in $t \rightarrow W + b$, (7) polarization of the W from top decay, and (8) rate of $t + \bar{t} + X$ as background to Higgs physics signatures at the SSC. Most of these (1, 4, 6 and 7) are probably well predicted by the standard model and unlikely to yield new physics or improved understanding of the standard model. Flavor changing neutral currents at a measurable level also seem unlikely and are probably ruled out by present limits. The decay $t \rightarrow W + s$ is very interesting but is probably impossibly difficult at the expected very small branching ratio and will not be considered further.

A precise measurement of the top mass is interesting because it is coupled with precise measurements of the masses of the W and Z and of other electroweak parameters through higher-order electroweak corrections. This gives a test of the consistency of the standard model and a deviation from expectation could indicate new physics. These higher-order corrections also depend logarithmically on the Higgs mass, so that a precise measurement of the top mass would give an indication of the Higgs mass. To predict the Higgs mass within a factor of two would require an error on the top mass of roughly 3 GeV. The SDC Technical Design Report⁶ considers three methods of determining the top mass: lepton spectra in $e - \mu$ events, lepton spectra in sequential semileptonic decays ($t \rightarrow W + b \rightarrow l + \nu + c + l + \nu$) and invariant mass plots in three jet decays of top. The conclusion is that to achieve a statistical error on the top mass of 3 GeV requires roughly 20000 top events when account is taken of branching ratios, acceptances, and efficiencies. Note that the SDC TDR estimates the systematic error to

Fig. 4. Top cross section as a function of center-of-mass energy for $m_t = 150$ GeV as calculated by PYTHIA using HMRSB structure functions.

be 3 GeV. Figure 5a shows the luminosity required to produce this number of top events as a function of the center-of-mass energy. A pp machine with a center-of-mass energy of 4 TeV would need a luminosity of $2 \times 10^{31} \text{ cm}^{-2}\text{sec}^{-1}$. Any higher energy machine would do this easily. Also note that it is also likely that this precision will be obtained at the Tevatron ($E_{\text{cm}} = 2$ TeV) after the FNAL Main Injector upgrade (luminosity = $10^{32} \text{ cm}^{-2}\text{sec}^{-1}$). The exact reach does depend on the actual top mass.

If a charged Higgs exists with mass less than the top mass, it would be an extremely interesting signature to look for. This, however, is a difficult signature to uncover and is complicated by the fact that the $t \rightarrow H^+ b$ branching ratio and the branching ratios of the various decay modes of the charged Higgs are model dependent. This signature was studied in the SDC TDR⁶. From the work there, it is

estimated that 30 million top events are required to obtain at least a five standard deviation effect for $(m_t - m_{H^+}) \geq 25$ GeV and most choices of the other parameters. Figure 5b shows the luminosity required to produce this number of top events as a function of the center-of-mass energy. As can be seen, this physics requires a machine with approximately the reach of the SSC, as is typical of most Higgs signatures. It should be noted that for parts of the multiple Higgs doublet parameter space the luminosity required to observe the $t \rightarrow H^+ b$ decay is significantly less.

Fig. 5a. Instantaneous luminosity needed to produce 20000 $t\bar{t}$ events as a function of $\sqrt{s}$. This would allow a measurement of the top mass to about 3 GeV.

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Fig. 5b. Instantaneous luminosity needed to produce 3×10^7 $t\bar{t}$ events as a function of $\sqrt{s}$. This would allow discovery of $t \rightarrow H^+ b$ for $m_t - m_{H^+} \geq 25$ GeV.

3 SUSY searches in Gluino pairs

ISASUSY⁹ (ISAJET Version 7.0) was used to compute the required luminosity to produce 10000 gluino pairs in 10^7 seconds in pp and $p\bar{p}$ collisions. The center-of-mass energy was varied between 2 TeV and 80 TeV. The mass of the gluino was set to 300 GeV, 1000 GeV and 3000 GeV. The minimal supersymmetric extension to the standard model was assumed. The mass of the squark, stops, sleptons and sneutrinos was set to twice the gluino mass, and $\tan(\beta) = 5$ and $\mu = -300$ GeV were assumed. The mass of the supersymmetric Higgs was set to 500 GeV and the top quark mass was fixed to 150 GeV. Cross sections were integrated between jet p_T of 10 GeV and 1 TeV for the light and intermediate mass gluinos and 10 GeV and 10 TeV for the heavy gluinos.

From Fig. 6 we conclude that the SSC (40 TeV center-of-mass energy and nominal luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$), 300 GeV or 1 TeV gluinos are within easy reach, while 3 TeV gluinos would be much harder. However, such heavy gluinos would not solve the fine tuning problem which is one of the main motivations for SUSY. The upper limit of about 2 TeV covers the expected range of SUSY masses related to electroweak symmetry breaking comfortably.

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Fig. 6a. Instantaneous luminosity needed to produce 10000 gluino pairs vs. $\sqrt{s}$ for $M_{\tilde{g}} = 300 \text{ GeV}$ and 1000 GeV . This is approximately the number needed for discovery.

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Fig. 6b. Instantaneous luminosity needed to produce 10000 gluino pairs vs. $\sqrt{s}$ for $M_{\tilde{g}} = 1000$ GeV and 3000 GeV. This is approximately the discovery limit.

4 Heavy Gauge Vector Boson searches

The cross section for the production of additional Z' vector bosons has been investigated using the PYTHIA⁸ generator. Only the Z' contribution to the propagator has been used. The width of the Z'

is assumed to increase linearly with the mass, corresponding to the same couplings to quarks and leptons as in the standard model Z^0 . Figure 7 shows the luminosity required to produce 100 events per SSC year for different masses of the Z' as a function of the center-of-mass energy for the pp and $p\bar{p}$ case. The systematic errors ($\sim 40\%$) on the cross section values are mainly due to the structure functions.

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Fig. 7. The curves indicate the luminosity needed to produce 100 Z' events/year in pp (solid) $p\bar{p}$ (dotted) interactions. No branching ratios are included.

The difference between the pp and $p\bar{p}$ initiated cross sections can be explained in terms of the valence quark contributions for the $\bar{p}$'s. The difference is about a factor of 5 for the heaviest observable Z' .

5 Excited Quark searches

The discovery limits have been studied for excited quark decays into $Z^0 + \text{jets}$ using the model of Baur and Zerwas¹⁰ in the PYTHIA 5.6 generator⁸. In this study we assume the following parameters: $f_s = f = f' = 1$, $m_{u^*} = m_{d^*} = \Lambda_c$. The limit was determined for 10^7 seconds running and

$$\frac{N_{\text{signal}}}{\sqrt{N_{\text{background}}}} \geq 5.0.$$

$Z^0 + \text{quark (or gluon)}$ events were generated as the background. The event selection required at least two muons in the range $70 \text{ GeV} \leq M_{\mu\mu} \leq 100 \text{ GeV}$, with $p_{t\mu 1} \geq 50 \text{ GeV}/c$ and $p_{t\mu 2} \geq 20 \text{ GeV}/c$, in addition to one jet ($E_t \geq 100 \text{ GeV}$; with $R = 0.8$) in the opposite hemisphere of the muons. The signal was determined in a window representing four times the decay width, about the central value. Figure 8 shows the luminosity required for the different masses.

We note, however, that searches involving the contribution from the contact interactions¹ are more sensitive than the direct searches. If excited quarks exist, there would also be new interactions between quarks with a scale $\Lambda \sim M$. At $\sqrt{s} = 40 \text{ TeV}$ and $L = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, one is sensitive^{4,6} to $\Lambda \geq 25 \text{ TeV}$.

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Fig. 8. Luminosity required to observe a 5σ effect from $q^* \rightarrow Z + q$ in the model of ref. 6. See Section 5 for discussion.

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