HIGH LUMINOSITY $\bar{P}P$ MACHINES: THE PHYSICS GOALS

David B. Cline
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
and
University of Wisconsin, Madison, Wisconsin 53706

Abstract

High energy $\bar{p}p$ collisions will provide a laboratory to observe the interactions of point-like constituents. With machines of luminosity $> 10^{31}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ the production rate of the intermediate vector bosons and possibly of Higgs bosons will be adequate. The production of massive vector particles that decay electromagnetically as well as the direct production of dileptons will extend knowledge of the electromagnetic interactions. Several schemes to increase the luminosity of $\bar{p}p$ storage rings are discussed.

I. Introduction

The scheme for adding an antiproton source to the Fermilab machines which uses the Booster to decelerate the $\bar{p}$'s and a new electron cooling ring to damp the three dimensional $\bar{p}$ phase space has been described by Cline, McIntyre, Mills, and Rubbia previously.[1] This scheme should provide a luminosity of $\sim 10^{30}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ in the energy doubler (Tevatron) ring. At this luminosity many exciting experiments can be carried out including the search for the intermediate vector boson. A lower luminosity is expected in the Main Ring at Fermilab.[1]

Future applications of colliding $\bar{p}p$ machines at Fermilab should likely concentrate on the use of the doubler because:

1. The regular 400-GeV machine program can continue unabated to the experimental areas.
2. Antiproton production can continue simultaneously, thus allowing for a constant luminosity operation.
3. The vacuum in the doubler is expected to give lifetimes in excess of 24 hours.

However, an increased luminosity by a factor of 10-100 would be of extreme interest in order to study exotic weak and strong-interaction processes. As a comparison we may cite e^+e^- machines; very roughly a 2-TeV $\bar{p}p$ machine with a luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ would be equivalent in some sense to an e^+e^- machine (quark-antiquark machine) with a center-of-mass energy of ~ 200 GeV. Thus for purely weak and electromagnetic interactions a high luminosity $\bar{p}p$ machine is in many ways comparable to an e^+e^- machine. However, for strong interactions, especially vector gluon exchange, there is no corresponding e^+e^- process and the $\bar{p}p$ machine has a unique physics capability.

Since this is a workshop, I'd like to discuss two subjects: one is the subject of the Workshop "Can we design high luminosity $\bar{p}p$ machines?" Of course, there is always the question "Should we design high luminosity $\bar{p}p$ machines?" It's a little harder to justify perhaps. For the second part of my talk I will discuss a few points where high luminosity $\bar{p}p$ interactions may give physics an interesting reaction that might be hard to get otherwise.

Let me first start out by reviewing what was said previously. The two machines that are being designed at this moment and are in some stage of being constructed are the $\bar{p}p$ machines at Fermilab which ultimately will have 2 TeV in the center of mass and a luminosity of about $10^{30}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ and the machine at CERN using the SPS will have an energy of 0.54 TeV and again a luminosity of $10^{30}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.[4] The most important question is "Can one achieve a higher luminosity in these machines?" Some of us have gone through the small exercise to start off the Workshop of discussing how you go about making a higher luminosity machine, let's say at Fermilab.[3] Let me first review the existing scheme which will be discussed in more detail this afternoon.

Figure 1 shows the schematics of the machine at Fermilab. Antiprotons are made by extracting the proton beam at 80 GeV/c and the antiprotons will travel cross country through a FODO channel into the Booster, will then be decelerated to 200 MeV (644 MeV/c) and then transferred to a small cooling ring. Electron cooling will be used to collapse the phase space. This will be done repetitively for a large number of cycles until approximately 5×10^{11} antiprotons are collected in a day. So we start on the assumption that there will be an electron cooling device which is already under construction at Fermilab and that 5×10^{11} antiprotons per day will give a luminosity of $10^{30}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

Now the question is "What is a mechanism whereby the number of antiprotons can be increased by at least a factor of 10?" At the Workshop we will have to discuss this extensively. The existing techniques using electron cooling seem to be limited to a few $\times 10^{11}$ antiprotons per day, and in order to collect larger number of antiprotons, it will probably be necessary to build a new large-aperture device to collect a larger phase space of antiprotons. One possible scheme would be to add a precooler as shown in Fig. 1. The Booster in principle could be accepting antiprotons back into the cooling ring during its idle time, so if a new ring were added, let's say a precooling ring with a very large acceptance, it would be available for cooling the phase space of that beam in approximately 2 to 3 seconds. So, for example, if betatron stochastic cooling is used in this ring, there there would be 2 to 3 seconds to do stochastic cooling, so that the antiprotons from that ring could be put through the Booster, transferred to the electron cooling ring, and then phase space completely collapsed. The scheme is outlined in Fig. 2. The precooler would be collecting antiprotons and the electron cooler would be the storage device for keeping antiprotons cool for a very long period of time. Using this technique, provided all the problems can be solved, collecting large phase space antiprotons, target heating, and a large list of these which we'll go into in the Workshop, then it seems possible to get 3 × 10^{12} antiprotons. This scheme depends critically on fast betatron stochastic cooling.

The second scheme is to add a new supercooler ring which would be an enlarged version of the AA ring being constructed at CERN. In this case all the cooling would be done in this ring and the cycling time of the Booster would not set the cooling time required as in the case of the precooler. This scheme has very serious problems because the very large circumference of the Main Ring is not ideally matched to a supercooler. Furthermore, there will be serious target heating problems and finally the large acceptance - large circumference super cooler ring is likely to be extremely expensive if we scale from the expected cost of the CERN AA ring.[2]

II. Increasing the Luminosity of $\bar{p}p$ Machines

In order to improve the luminosity above $10^{30}\text{cm}^{-2}\text{sec}^{-1}$, there are four possibilities: Increase the number of protons or antiprotons; decrease the beta function at the collision point; decrease the number of bunches; or cool the high-energy beams to decrease the size to the point where the beam-beam tune limits the luminosity.

Let us take a specific example. In order to obtain a $\bar{p}p$ luminosity in excess of $10^{31}\text{cm}^{-2}\text{sec}^{-1}$ in the energy doubler it will be necessary to collect more then 10^{12} $\bar{p}$ per machine filling cycle. Depending on the actual gas pressure in the doubler and the other sources of beam blowup the filling time may be as short as every 5 hours. This will set as a goal the collection of 10^{12} $\bar{p}$'s in five hours for the design of the large acceptance ring. As discussed before there are several schemes to improve the $\bar{p}$ collection:

1. Construction of a large aperture "super cooler" ring.

2. Addition of a large aperture pre-cooling storage ring.

In the first case a dc ring is constructed with a large enough aperture to allow space for collection and accumulation of intense $\bar{p}$ beams. In the second case the ring is used primarily for collection and the accumulation is carried out on the electron cooling ring.

Let us first review in detail the steps in obtaining the expected yield of $\bar{p}$'s in the present scheme. Secondary particles at ~ 6.5 GeV/c are produced by 80 GeV/c protons from the Main Ring impinging on a small tungsten target. Particles are injected into the Booster ring and decelerated to 200 MeV. Only $\bar{p}$'s survive at the end of the process. The beam is transferred to the storage ring where it is cooled and added to the stack of previous accumulations. One expects to accumulate 4 × 10^7 $\bar{p}$/pulse leading to ~ 10^{11} particles in 2 × 10^3 pulses (3 hours).

The collected ratio of antiprotons of momentum $P_{\bar{p}}$ to protons on target is given by

$$\frac{N\bar{p}}{N} = \frac{1}{\sigma_a}\left(E\frac{d^3\sigma}{dp^3}\right)(\delta p_\perp{}^2)\left(\frac{dp_\parallel}{E}\right)\epsilon_T ,$$

where σ_a is the absorption cross section, ϵ_T the target efficiency and

$$\frac{dp_\parallel}{E} = \delta P_{\bar{p}}/P_{\bar{p}}$$

$$dp_\perp{}^2 = \frac{4p_{\bar{p}}^2\sqrt{\bar{\epsilon}_x\bar{\epsilon}_y}}{\pi\,\bar{\eta}\,\beta^*},$$

where $\bar{\epsilon}_x$, $\bar{\epsilon}_y$ are the Booster x, y acceptance for 644 MeV/c antiprotons, $\bar{\eta}$ and β^* have the normal meaning for a synchrotron machine. The invariant production cross section $Ed^3\sigma/dp^3$ is not yet well measured to better than a factor of two at 6.5 GeV/c. Figures 3 and 4 show the available data on $\bar{p}$ production in the relevant proton energy range as a function of production angle.

Figure 5 shows the cross section of 6 GeV/c $\bar{p}$ production in the forward direction as a function of incident proton energy. There is apparently little gain in increasing the incident proton energy. The present extraction scheme is limited to about 100 GeV/c protons. The best present estimate for the invariant cross section is ~ 1 mb/GeV/c^2. The measured acceptance of the Booster is

$$\bar{\epsilon}_x = 2.6\pi\text{mm mrad}$$

$$\bar{\epsilon}_y = 1.3\pi\text{mm mrad}$$

$$\delta P/p = \pm\ 0.15\%$$

and the estimated target efficiency ϵ_T is 0.15.

Using these values we obtain

$$N\bar{p}/Np = 2 \times 10^{-7}.$$

For 5 × 10^{13} protons on target (the machine intensity expected in 1979-1980) the yield of $\bar{p}$ for every ·3 sec cycle of the Main Ring is $10^7\bar{p}$/mrad pulse giving ~ 10^{10} $\bar{p}$/hour. Collecting $\bar{p}$ for 10-20 hours gives ~ 10^{11} $\bar{p}$. There are other possible improvements that might increase the yield by a factor of about 5. Clearly in order to further improve the yield the acceptance of the $\bar{p}$ collection ring must be increased.

Let us first turn to the target and collection system requirements. Antiproton emittance matched to the Booster acceptance is given by

$$\bar{\epsilon}_x = \pi\,\theta_x a_x$$

$$\bar{\epsilon}_y = \pi\,\theta_y a_y\ ,$$

where θ_x, θ_y are the maximum production angles accepted and a_x, a_y the spot size of the protons on the target. For the case of a_x = 0.2 mm = a_y and realistic Booster acceptance we obtain

$$\theta_x^{\max} = 13 \text{ mrad}$$

$$\theta_y^{\max} \simeq 6 \text{ mrad.}$$

On the other hand, there are various schemes for increasing the Booster acceptance for the special case of deceleration of $\bar{p}$'s (where space charge effects are probably not too important) and the angular acceptance of the present scheme could well extend to 15-20 mrad. Note that the production angular distribution is relatively flat over a much broader angular range (Fig. 4). Thus we conclude that a sizable gain in antiproduction yield can be obtained by accepting a larger transverse phase space. In the longitudinal phase space the yield is directly proportional to the $dp_{\parallel}/E \sim \delta P_{\bar{p}}/P_{\bar{p}}$. Thus increasing $\delta P/P$ will increase the $\bar{p}$ yield.

In order to increase the yield by at least a factor of 10 consider a collection ring with the following properties

$$\epsilon_x = 20\pi \text{ mm mrad}$$

$$\epsilon_y = 20\pi \text{ mm mrad}$$

$$\delta P_{\bar{p}}/P_{\bar{p}} = \pm 1\%.$$

If a collection system could be constructed to collect a full 20 from the target θ_x, θ_y would increase to

$$\theta_x^{\max} = 100 \text{ mrad}$$

$$\theta_y^{\max} = 100 \text{ mrad}$$

and give an increase of about a factor of 5 and 7 each plane yielding a factor of 35. It is very unlikely that an adequate collection system could be constructed to realize the full yield. However, a factor of 3 × 4 = 12 may be realized (i.e., $\theta_x^{\max} \sim 50 \text{ mrad} \sim \theta_y$).

In the longitudinal direction the gain will be a factor

$$[\delta P_{\bar{p}}/P_{\bar{p}}]\text{new} \;/\; [\delta P_{\bar{p}}/P_{\bar{p}}] \text{ old} = \frac{2.0\%}{0.15\%} = 7$$

for each Booster batch. However, it is necessary to collect all 13 Booster batches every Main-Ring cycle (~ 3 sec). In order to accomplish this it will be necessary to work near transition and to rotate the bunches in phase space. It should then be possible to stack all 13 batches with a total $\delta p/p$ in the ring of ± 1%.

A realistic gain of 7 × 12 in $\bar{p}$ yield can be anticipated giving

$$N_{\bar{p}}/N_p = 1.7 \times 10^{-5}$$

and 10^{12} $\bar{p}$ per hour. Improved target efficiency could give a factor or two larger yields.

One scheme for using a precooler is as follows: Antiprotons are injected into the precooler ring and the longitudinal and transverse phase space is damped down by stochastic cooling to the values of the acceptance of the Booster, namely $\delta P_{\bar{p}}/P_{\bar{p}} = \pm 0.15\%$; $\bar{\epsilon}_{\bar{x}} = 2.6\pi$mm mrad/Booster batch; $\bar{\epsilon}_{\bar{y}} = 1.6\pi$mm mrad/Booster batch. A cooling time of 2-3 sec is available for this phase-space damping. Assuming an effective phase space of $\bar{\epsilon}_{\bar{x}} = 8\pi$mm mrad and $\bar{\epsilon}_{\bar{y}} = 5\pi$mm mrad for the 13 Booster batches the transverse beam damping required is about a factor of 3 in each dimension. The longitudinal phase space must be cooled by a factor of 7 in 2-3 sec. These values of the stochastic cooling time are not out of bounds with the present state of the art in stochastic cooling.

After the beam is stochastically cooled it is injected into the Booster, decelerated and transferred to the electron cooling ring for final cooling.

We have obtained a rough estimate of the parameters of the precooler ring from the above requirements.[3] The machine should be strong focussing with $\gamma_t \sim 9$, $\beta \sim 8$M and $\langle X_p \rangle = 1$M. The transverse space occupied by the beam is

$$\delta P/P_p \, \langle X_p \rangle = 2 \times 10^{-2} \times 1 = 2 \text{ cm.}$$

At the injection point $\langle X_p \rangle \sim 3\text{-}5$ and a free aperture of 10-20 cm is required in the machine, for injection and stacking.

The parameters of a supercooler could be scaled from the design of a similar ring at CERN.[2] Although the $\bar{p}$ momentum is 3.5 GeV/c in the CERN design it would likely be better to collect at 6.5 GeV/c at Fermilab because of the need to transfer the beam back into the Booster and electron cooling ring.

The luminosity for a head-on collection of N_B bunches is given by

$$\mathcal{L} = \frac{3 N_p N_{\bar{p}} f}{\sqrt{\beta_x^* \, \beta_y^*} \; \sqrt{\epsilon_{x_1}^o + \epsilon_{x_2}^o} \; \sqrt{\epsilon_{y_1}^o + \epsilon_{y_2}^o}} \, \frac{1}{N_B} \left(\frac{P_f}{P_i} \right),$$

where P_f is the final $\bar{p}$, p momentum, P_i is the momentum in the cooling ring, f is the revolution frequency, N_p, $N_{\bar{p}}$, are the total number of protons and antiprotons, respectively. β_x^*, β_y^* are the beta function values at the collision point and ϵ_x^o, ϵ_y^o are the emittance of the Booster for p and $\bar{p}$.

In order to increase the luminosity there are several possibilities:

1. Increase N_p, $N_{\bar{p}}$
2. Decrease β_x^o, β_y^*
3. Decrease N_B
4. Increase P_f

For the scheme advocated here $N_{\bar{p}}$ is approximately 6×10^{12}. Clearly β_x^*, β_y^* should be made as small as possible, consistent with the available space in the collision straight section. A further increase in luminosity occurs if N_B, the number of bunches is decreased. Thus it is necessary to increase N_p/N_B. This possibility will be discussed in the next section. In order to obtain a luminosity of $10^{31}\text{cm}^{-2}\text{sec}^{-1}$ with $N_{\bar{p}} = 6 \times 10^{12}$ we take the following parameters

$(p_f = 1\ \mathrm{TeV/c})$

$N_{\bar{p}} = 6 \times 10^{12}$

$N_p = 6 \times 10^{12}$

$\beta^*_x,\ \beta^*_y = 1.5\ \mathrm{M}$

$N_B = 6.$

These parameters require stacking in the doubler and superconducting quadrupoles for the low-β section. For these parameters we find 10^{12} protons per bunch and 10^{12} antiprotons per bunch. The luminosity and vertical tune shift are closely related. We use a simple calculation for the SPS but including the factor of P_f/P_i increase for the L TeV/c proton and antiprotons in the Tevatron. For 10^{12} $p/\bar{p}$ in each bunch the expected luminosity is $8 \times 10^{31} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$. However, the tune shift is 3×10^{-2} which may be too large. Thus it will be necessary to separate the $p/\bar{p}$ at every point except the low β region. Again the large tune shift indicates a limitation of the practical luminosity for $\bar{p}p$ machines of ~ 10^{31}-$10^{32} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

III. Physics Goals of High Luminosity Machines

(i) Point Like Collisions in Hadron-Hadron Interactions. A very large body of evidence now exists in support of the hypothesis that hadrons contain point-like constituents -- so much so that these concepts will play an important role in the future development of particle accelerators. At the same time there is a strong theoretical belief that a field theory of these constitutents is within our grasp (i. e., the QCD theory). This evidence largely comes from the scattering of leptons on hadrons or from e^+e^- scattering with the production of hadrons or from the production of lepton pairs in hadron-hadron collisions. Recently the evidence for point-like constitutents in hadron-hadron collisions has sharpened. Unfortunately, the present generation of machines are at too low an energy to allow completely convincing tests of these concepts for hadron-hadron collisions.

There are five fundamental types of reactions that have been studied:

$$\nu_\mu + \text{hadron} \rightarrow \left[\begin{smallmatrix}\nu & \text{charged}\\ & \text{lepton}\end{smallmatrix}\right] + (\text{hadrons}) \tag{1}$$

$$\text{charged lepton} + \text{hadrons} \rightarrow \begin{matrix}\text{charged lepton} +\\ (\text{hadrons})\end{matrix} \tag{2}$$

$$\text{hadron} + \text{hadron} \rightarrow \begin{matrix}\text{charged}\\ \text{lepton pair}\end{matrix} + (\text{hadrons}) \tag{3}$$

$$\text{electron} + \text{positron} \rightarrow (\text{hadrons}) \tag{4}$$

$$\text{hadron} + \text{hadron} \rightarrow \left(\begin{matrix}\text{large p}\\ \text{hadrons}\end{matrix}\right) + \text{hadrons} \tag{5}$$

The symbol (hadrons) denotes the inclusive production of many hadron states; in the quark model they are thought to be the "spectators" in the hard collision in each case considered.

It is interesting to ask what limits on the "size" of the fundamental constituents come from. The measurement of the limit of the size of the constituents comes from the study of the momentum-transfer distribution in the collisions, much the same as Rutherford measured the "size" of the inside of the atom 60 years ago. Figure 1 shows a typical momentum transfer distribution for high-energy neutrino collisions. Recently there has been some evidence that the constituents carry a "fermi" momentum inside the proton of ~ 800 MeV/c. This possibily has to do with the fact that the constituents are confined (i. e., no free quarks have been seen).

In order to study weak and electromagnetic interactions it seems necessary that an annihilation process occur. For example, the weak neutral vector boson occurs as an annihilation process for

$$e^+e^- \rightarrow Z^o \rightarrow \mu^+ + \mu^-.$$

Other attempts to observe weak processes, say in the scattering of e^+e^- by the exchange of weak boson appear to be hopelessly swamped by the background from ordinary processes (i. e., the exchange of photons). Similarly the detection of weak or electromagnetic processes in hadron + hadron collisions requires the observation of quark-antiquark annihilation, i. e.,

$$q + \bar{q} \rightarrow Z^o \rightarrow \mu^+ + \mu^-.$$

At this point a considerable difference between proton-proton and proton-antiproton collisions becomes apparent -- antiprotons are filled with antiquarks but protons have only a small amount of antiquarks. The evidence for a small component of antiquarks in the proton comes from two sources:

1. Comparison of neutrino and antineutrino collisions with hadrons.

2. The overall rate for the production of lepton pairs by hadron collisions.

Both experiments give information about the momentum spectrum of the antiquarks in the proton as well. Figure 2 illustrates the level and momentum spectrum of the antiquarks as obtained from detailed analyses of neutrino-antineutrino interactions.

For the purpose of the calculations and comparisons in this report we assume that the constituents are truly point like - just like electrons and that the antiquark distribution in the nucleus follows the results of neutrino experiments. Of course the antiproton is considered to be filled mostly with antiquarks and the proton with quarks. The "momentum" spectrum of the quarks (antiquarks) are taken from neutrino experiments. Once these assumptions are made, the resulting calculations are trivial and follow directly from similar calculations for e^+e^- interactions.

(ii) Production of Intermediate Bosons. I will try to go through some graphs to show you what the effect of the different parton-antiparton distribution is on pp or $p\bar{p}$ production cross sections. It's true now, in contrast to a few years ago, the q and $\bar{q}$ distributions have been uniquely extracted from the data so that reliable predictions can be made. The direct evidence for the $\bar{q}q$ interaction now exists, and I believe this gives confidence in the use of $\bar{p}p$ machines. It's almost model-independent. I think the calculations for pp machines are still somewhat model-dependent.

So let me start out first by just showing (this is from the calculation of Quigg) the relative cross sections (Figs 6 and 7). Now what I am going to discuss is the event rates and cross sections for a machine with the luminosity of 10^{31} giving integrated luminosities of 10^{36} or 10^{37}. That's the kind of experiments I would hope to do in these machines in five years or so. So, we show a comparison of $\bar{p}p$ and pp, that shows what high luminosity buys. In other words, the $\bar{p}p$ machine gives much higher efficiency at the high energy, high mass particles.

Now what about backgrounds? For example, I've shown the Z^0 sitting on top of the background in Fig. 8. Even in the most pessimistic analysis, as far as I can tell, the Z^0 should still stand well above background, provided the Z^0 has an appreciable decay rate into charged lepton pairs. However, it's also, I think, interesting that in a high-luminosity machine one can explore lepton-antilepton production, e^+e^-, e^+e^-, out to about 50 to 100 GeV, which is not so far from the energies that people talk about. Perhaps if the luminosity can be improved, then one can go a little bit higher. So this already indicates that a high luminosity $\bar{p}p$ machine can explore very high mass lepton-antilepton production.

Let me briefly discuss charged W production. There are really two ways of estimating the W cross section. One is to use the Drell-Yan calculation. There it seems that you know that only antipartons can be made. Neutrino experiments give you the contribution. However, using dilepton data and CVC and neglecting the isoscalar component, a lower bound on the W cross section can be obtained. Of course, this is equally true for pp or $\bar{p}p$. I was surprised that using the most recent data, as reviewed by Cronin, this cross section is actually greater than $2 \times 10^{-32}\text{cm}^{-2}$, whereas, the straight-forward Drell-Yan cross section gives 6×10^{-33}, so this indicates the cross section for W production could be larger than we think and this is very interesting, especially for high-luminosity machines. In this case you would get 1/5 of an event per second with a luminosity of 10^{31} or 10^{32} would give you between 0.2 and 0.06 W's per second. <u>This would be a W factory</u>.

One of the strongest items for a $\bar{p}p$ machine, I think, in contrast to a pp machine is shown in Figs. 6 and 7. If you imagine that Nature holds some very high-mass W's as well as some very low-mass W's, then in $\bar{p}p$ one can go to a very high mass. For example, using the integrated luminosity discussed before, a very high mass W can be observed. There's one extremely interesting thing about the W of such high mass, it will decay into two jets of 300 GeV each. I doubt even in Feynman's model if there would be a large background at this $p_\perp$. In other words, the W's out in this region may have much less background than we have discussed before. Anyway, one point is that the W can be searched for up to a mass of about 1.2 TeV with a high-luminosity machine of about 2 TeV center-of mass-energy. The cross section for W or $\ell\bar{\ell}$ grows like τ^{-1} to some power so it goes like s^α where α varies from 10 to 0 depending on the machine and so forth. It's clear that the most important parameter is energy in these machines. The second important thing is luminosity in order to get the counting rate and probably the third important thing is $\bar{p}p$ vs. pp to machines. So the ideal machine, I believe would be given by this: 2-10 TeV, luminosity of 10^{31} to 10^{32} and $\bar{p}p$ versus pp. Now, there are one or two more interesting aspects of W production which I'd like to discuss which are a little different than what Feynman mentioned.[4] In the first place, in $\bar{p}p$ collisions the W's are strongly polarized, strongly aligned. This already gives an effect, which has been mentioned by many authors, that when the W decays, it tends to make $\bar{\mu}$'s go the direction of the incident proton rather than the direction of incident antiprotons (Fig. 9). It gives an asymmetry in the wrong direction. Most background effects will not give an effect in $\bar{p}p$ collisions. This has not been looked at in detail, but I think it should be. If, when the W decays into its various hadronic decay modes, for example, I am assuming that there is a hypothetical new quark called a t quark, which may exist, then again similar kinds of effects exist; there will be a polarization. For example, when the W decays into $\bar{c}s$ then the $\bar{c}$ will want to go along the direction of the proton, and also in the case of the $\bar{t}b$, probably. Now I don't know how to calculate the mass effects in here so it has to be carried out in the future. There may be a signature for the W production mainly coming from its alignment and the flavor cascade effectively goes into multi-flavored final states. One aspect of the asymmetry, which we like to call charge conjugation violation because if we were dealing with simply a proton we wouldn't see this, is shown from a graph in proposal P92 at CERN showing the production of ℓ^-'s, in this case versus ℓ^+'s, the angular distribution (Fig. 10). It is shown that by just sitting at one angle, a lot more e^-'s than e^+'s are produced and that would already, I think, be extremely difficult to explain by any conventional background. That could be another argument in favor of the $\bar{p}p$.

Finally let me list the decay modes of the W. In each case in order to design a detector to see these individual modes one has yet to find the unique characteristics. Probably for the leptonic decays it will be necessary to see missing neutrinos, although on the other hand, there's a large asymmetry which may help. For the hadron decays, there will be effects having to do with a net flavor in the final state in the flavor cascade. For the Z^0's it is much more problematic because we don't know the number of neutrinos in nature. If the number of neutrinos happens to be extremely large, then the leptonic channels will go way down. There will always be a lot of hadronic channels, but the hadronic channels don't have net flavor because of the flavor conservation of the weak neutral current.

(iii) Search for the Higgs Boson. Another process which looks extremely interesting for high-luminosity $\bar{p}p$ machines is the search for the Higgs boson. This is a mythical, hypothetical best and the mass is not predicted nor is the best experimental signature known. In fact, the signature for the object depends critically on its mass. $\bar{p}p$ or pp production could give a signature for the Higgs boson (Fig. 11). Let us consider $\bar{p}p$. In $\bar{p}p$ the fundamental process would be $\bar{q}q$ goes to the W pole which then radiates a Higgs meson. This has been calculated in proposal 92 at CERN (Fig. 12). (The fundamental cross section was calculated by Gaillard and Ellis.) Another process, which has recently been suggested by Glashow and Nanopoulas, uses two gluons making a Higgs meson (Fig. 13). As an estimate to detect 10-100 events with a high luminosity $\bar{p}p$ machine, you would be sensitive to Higgs boson mass of about 50 GeV. The signature for looking for the Higgs boson would have to be observation of the W, followed by some aspect of the Higgs decay. For example, if it became the two b quarks that became the two heavy leptons, **there** would be a W plus additional leptons in the final state, which would give a clue that something other than just W production is going on. Clearly the search for Higgs bosons would benefit from a high luminosity $\bar{p}p$ machine.

(iv) Production of New Hadronic Flavors. Finally, let us end up with some speculations on the cross section for producing very high mass new flavors. So far, there is no reliable evidence yet for charm production in pp or $\bar{p}p$ collisions although there are lots of hints, which I'll come to in a moment. Nevertheless one can imagine new flavors, like charm, what have you, could be produced in pp or $\bar{p}p$ collisions and other sorts of things like if color were to become unconfined at extremely high energy could also be produced. We should keep our eye open for that sort of thing. What I've done is to simply illustrate a point. I've taken the best guesses for the cross section for charm production. I've taken the scaling prediction of Halzen and Gaiser to show what the cross section for charm production could look like as a function of energy (Fig. 14). However, there is evidence now from CERN for prompt neutrino production which suggests that the cross section for charm is much higher. So maybe this is even too pessimistic. I've tried to scale for other kinds of objects like b quarks and t quarks. These cross sections are always larger than the W cross section (probably) which means additional backgrounds which we haven't started to think about yet for W search in pp, or $\bar{p}p$ collisions.

IV. Conclusion

In summary, $\bar{p}p$ interactions will provide strong weak and electromagnetic $\bar{p}p$ interactions. That seems to be well established from existing data. $\bar{p}p$ machines that have been designed to achieve a luminosity of $10^{30}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ are in progress. The question is, "Is there a good reason to go to higher luminosity?" My conclusion is that there will be very interesting things to do at higher luminosity. In the first place, there will be large rates for very massive W's if W's exist at much higher masses than the Weinberg-Salam model predicts. On the other hand, the Weinberg-Salam particles seem to exist in relatively low mass regions so they have very large backgrounds. We may have some problems to pull these events out of the background whether we have pp or $\bar{p}p$ collisions. It appears because of the behavior of the lepton pair production at low τ that these machines can reach lepton-antilepton invariant masses up to about 0.05 of the center-of-mass energy. There is a strong argument I believe for the production of exotic states like the Higgs boson where undoubtedly c. m. energy and luminosity will be important. Here is an example in which increased luminosity is extremely important. There probably will be exotic $\bar{p}p$ interactions giving new quark flavors or new massive vector mesons where again high luminosity will be crucial. In comparison to e^+e^- machines, the rates are very favorable, but the backgrounds are very unfavorable (Fig. 15). In pp the backgrounds are 10^7 or 10^8 of the signal whereas in e^+e^- machines in some cases the signal-to-noise is extremely large. I think that on the basis of backgrounds e^+e^- machines look very good; on the basis of rates the $\bar{p}p$ machines certainly can hold their own.

It appears that there are very strong reasons to design high luminosity $\bar{p}p$ machines and I hope this workshop will be the first step in that design study.

References

[1] D. Cline, P. McIntyre, F. Mills, and C. Rubbia, Collecting Antiprotons in the Fermilab Booster and Very High Energy $\bar{p}p$ Collisions, Fermi National Accelerator Laboratory Internal Report TM-689, 1976; D. Cline, Possibility for Antiproton-Proton Colliding Beams at Fermilab, CERN $\bar{p}p$ Note 08, May, 1977. E. Gray et al., IEEE Trans. Nucl. Sci. NS-24, 1954(1977).

[2] CERN $\bar{p}p$ Machine Design Report.

[3] F. Mills, P. McIntyre, C. Rubbia, and D. Cline have had several discussions on the subject at different times.

[4] See Feynman's talk at this Workshop.

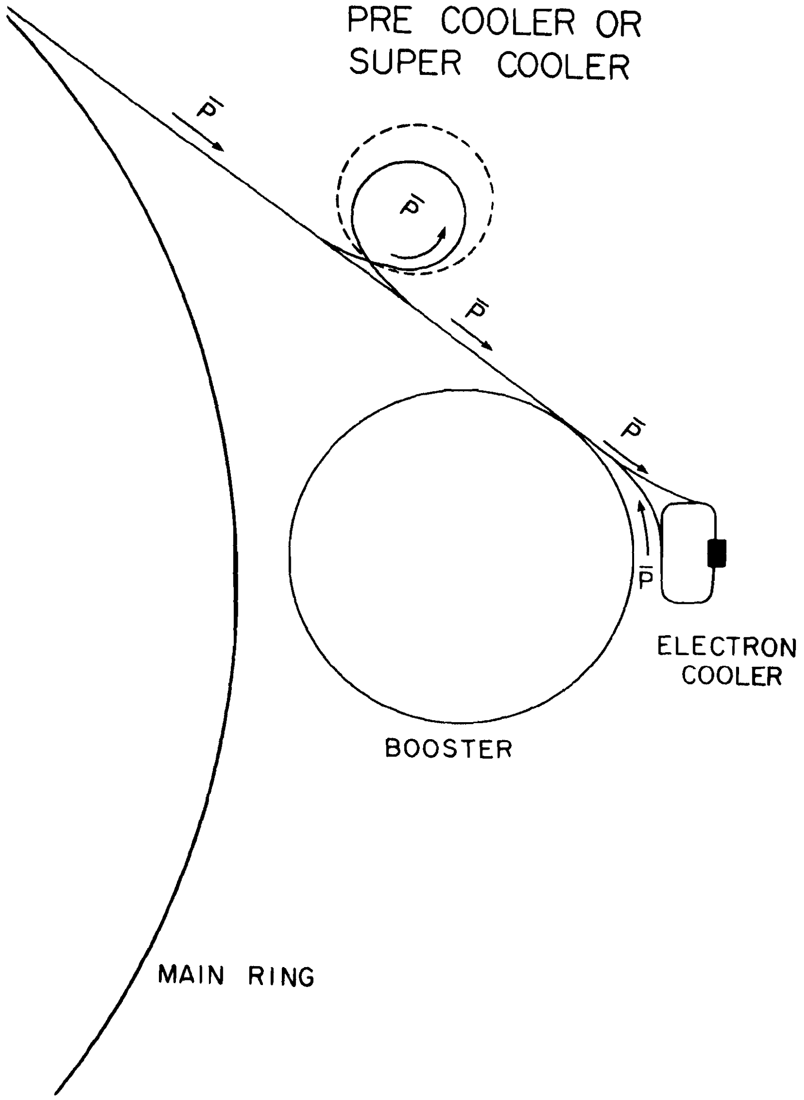

Fig. 1. Fermilab cooling schematic

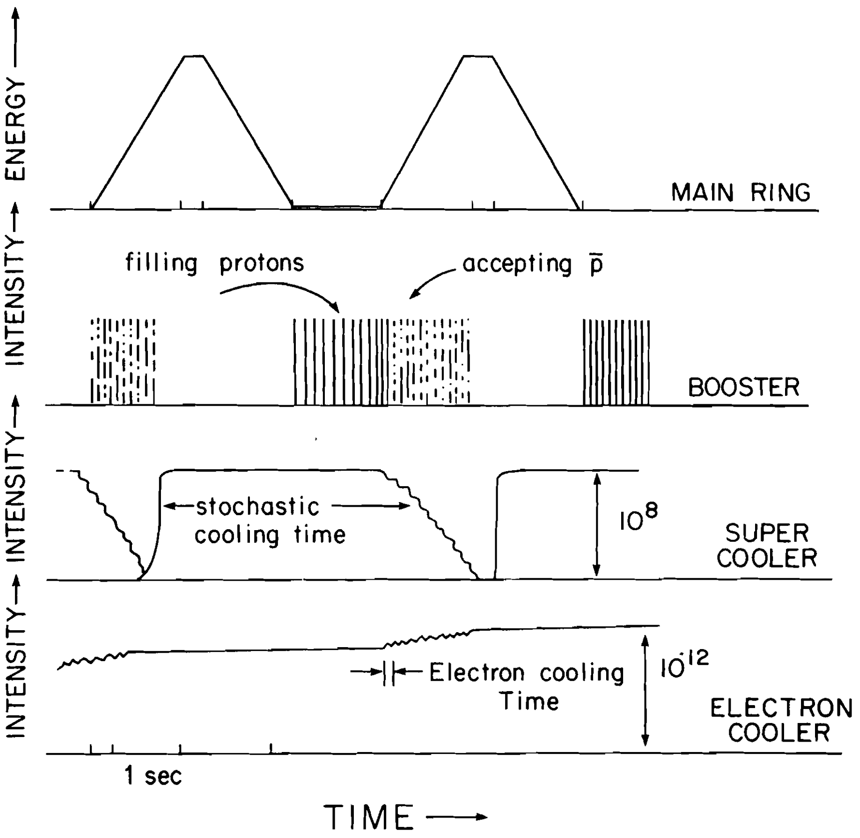

Fig. 2. Basic cooling cycles.

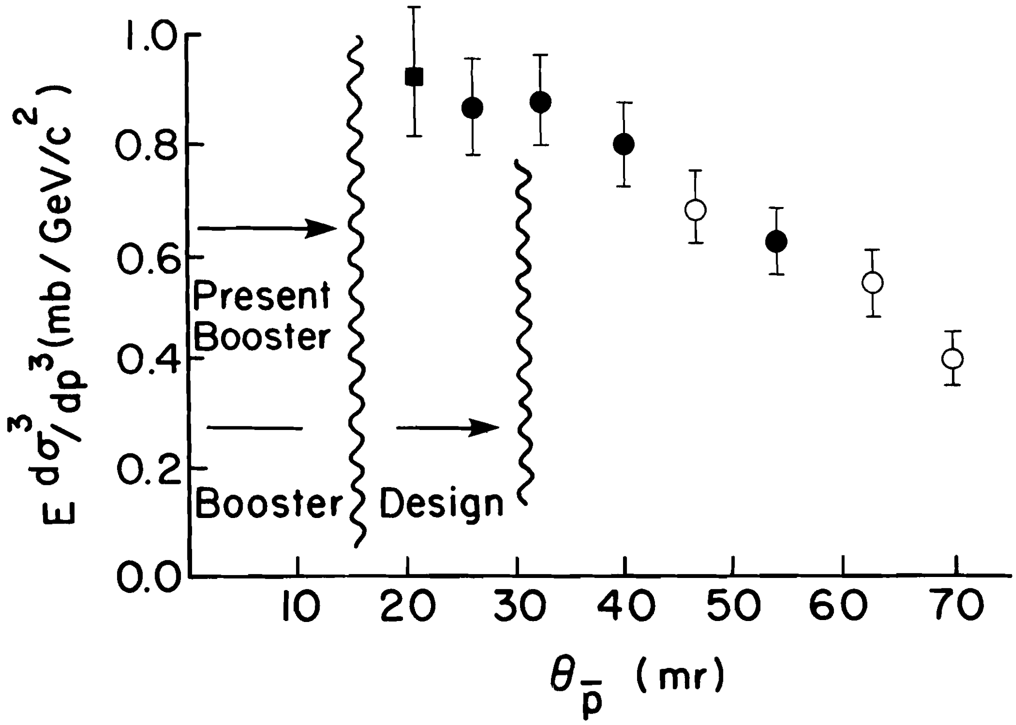

Fig. 3. Production of 6 GeV/c antiprotons.

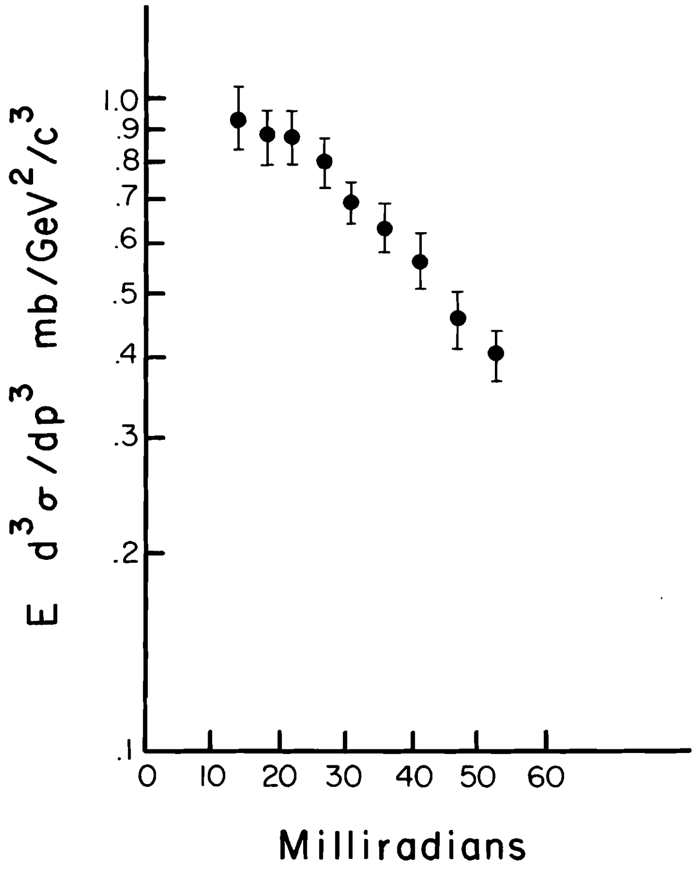

Fig. 4. Production of 9 GeV/c antiprotons from protons on protons at 200 GeV.

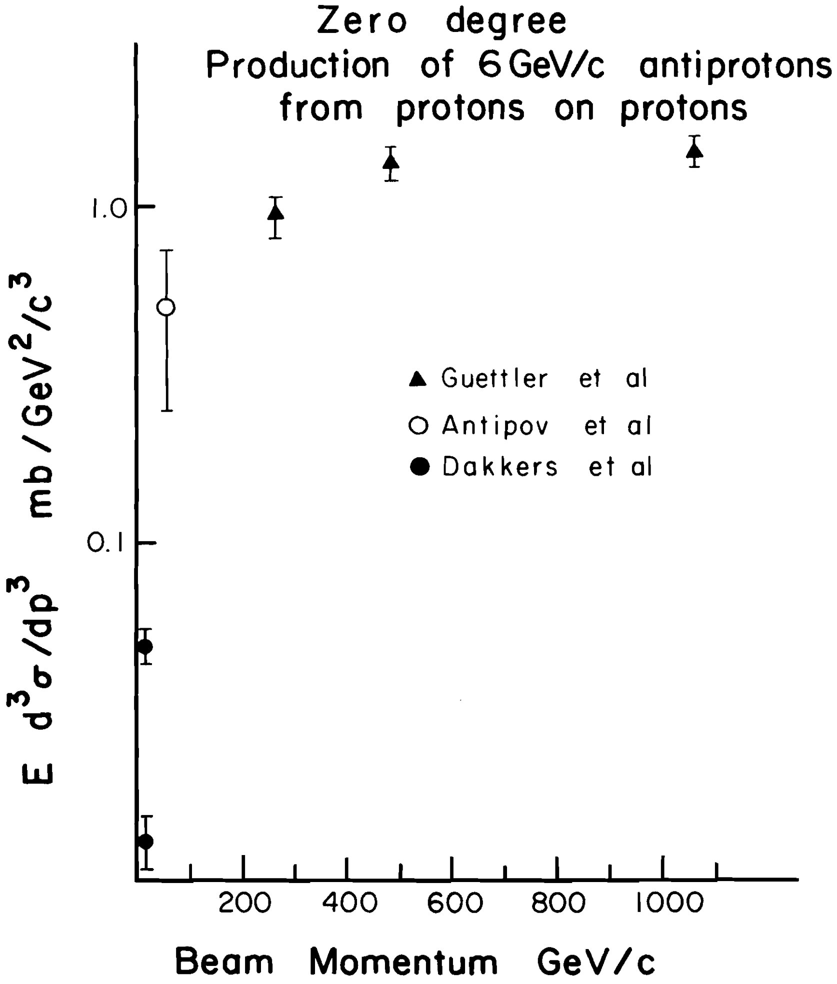

Fig. 5. The production of antiprotons.

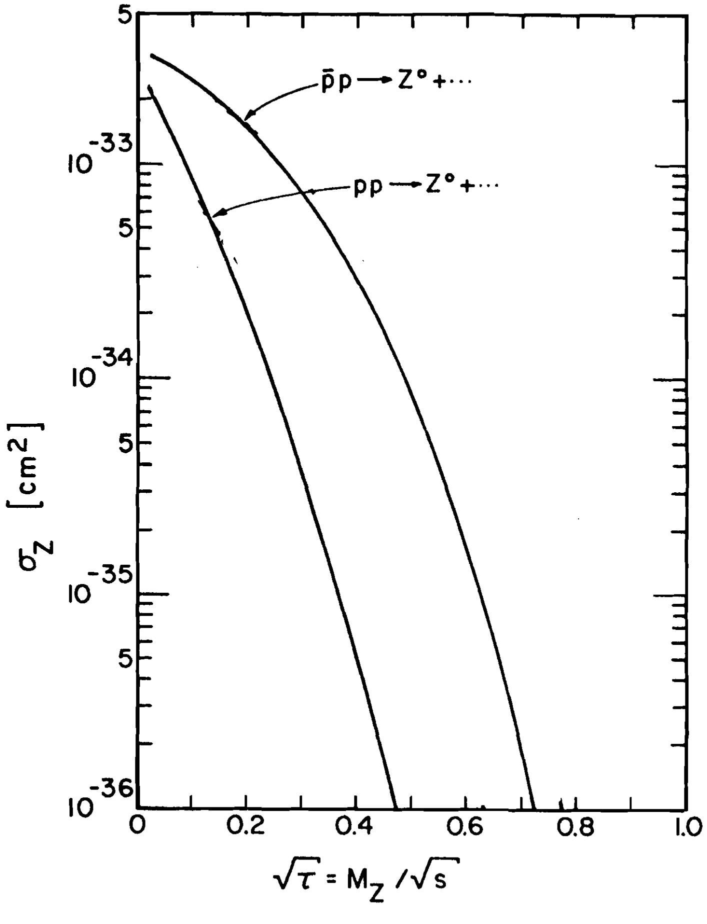

Fig. 6. Z^0 production cross sections.

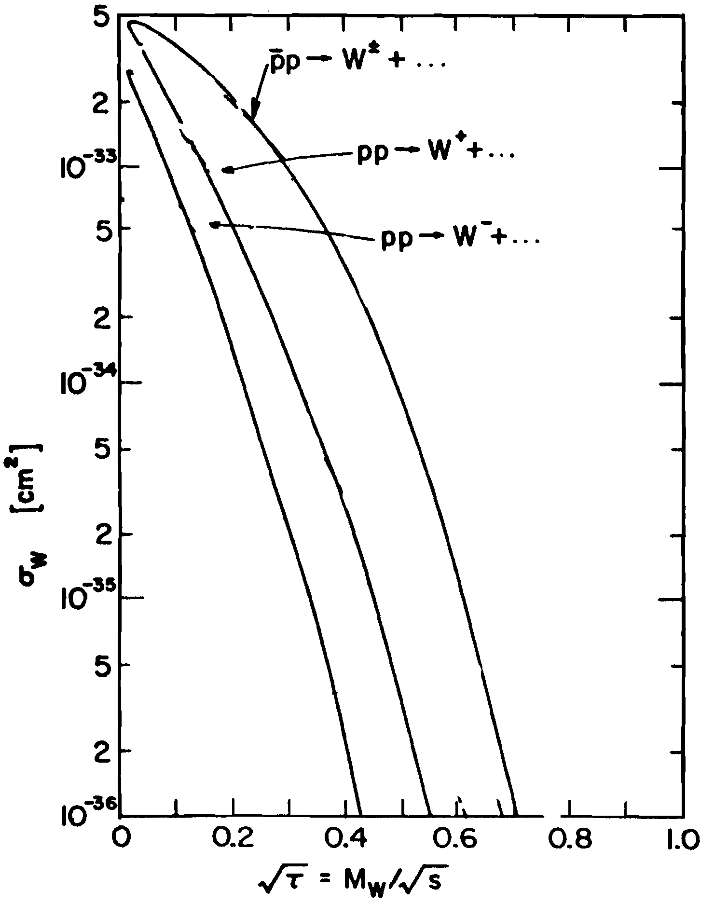

Fig. 7. W± production cross section.

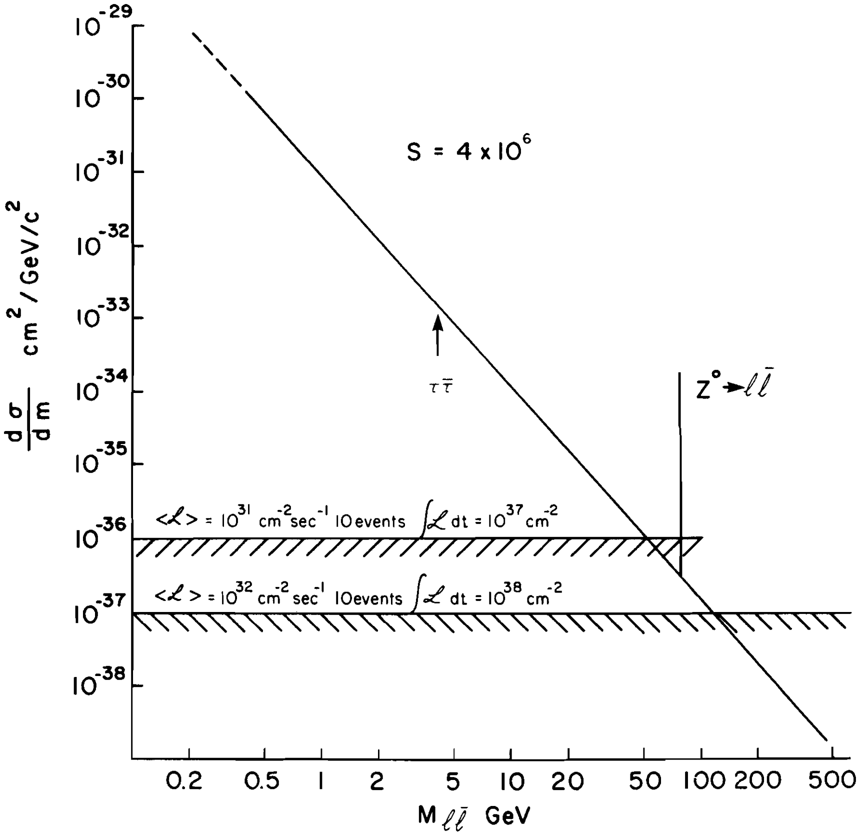

Fig. 8. Lepton pair production cross section.

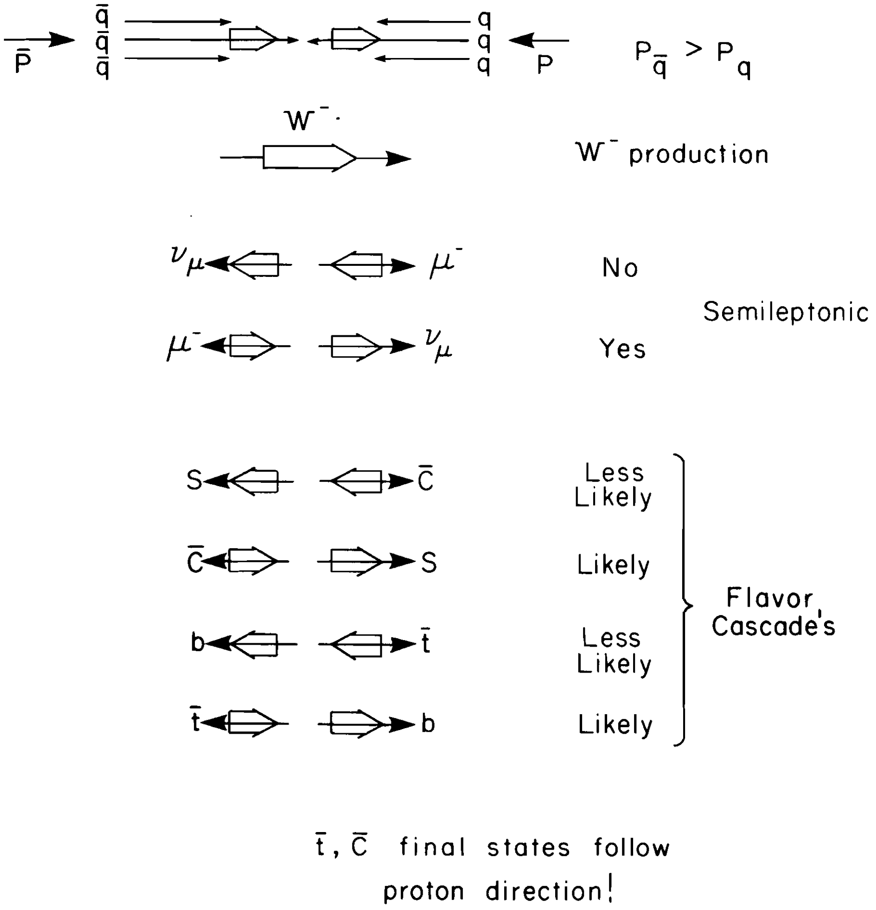

Fig. 9. W± polarization effects in $\bar{p}p$ collisions.

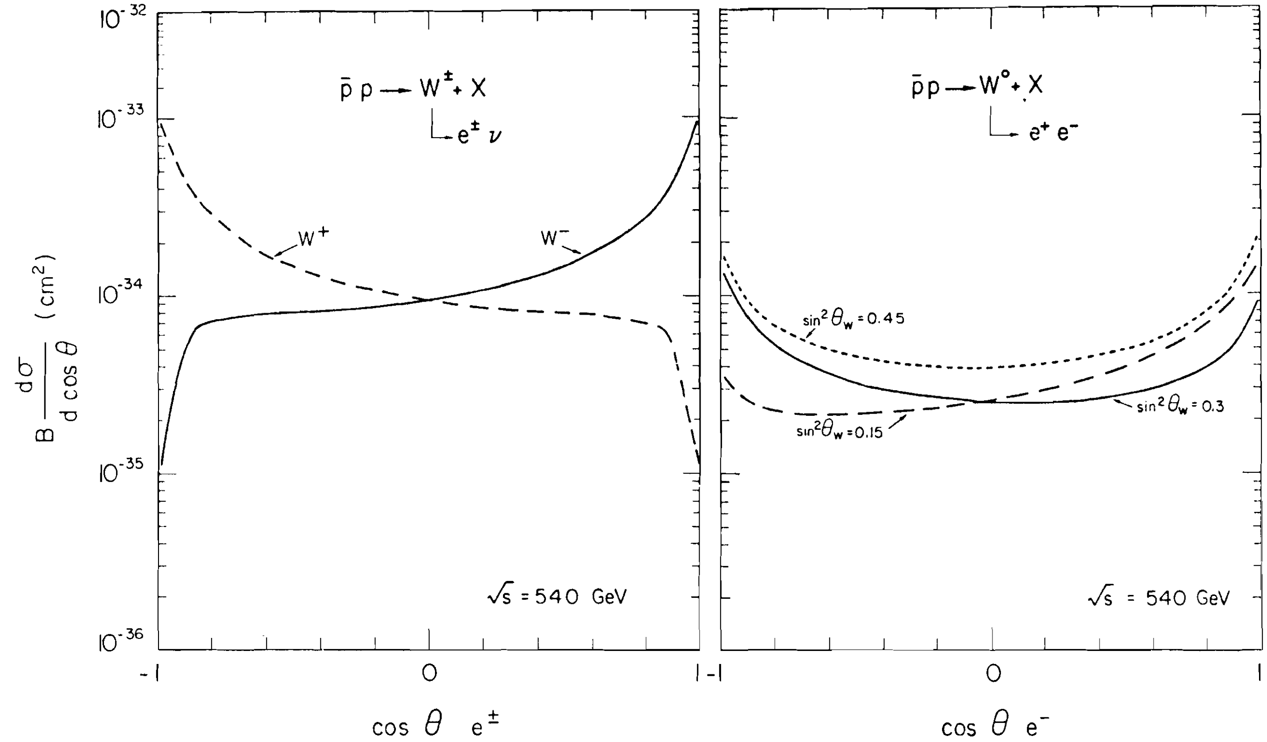

Fig. 10. Charge asymmetries in leptonic decay of intermediate bosons.

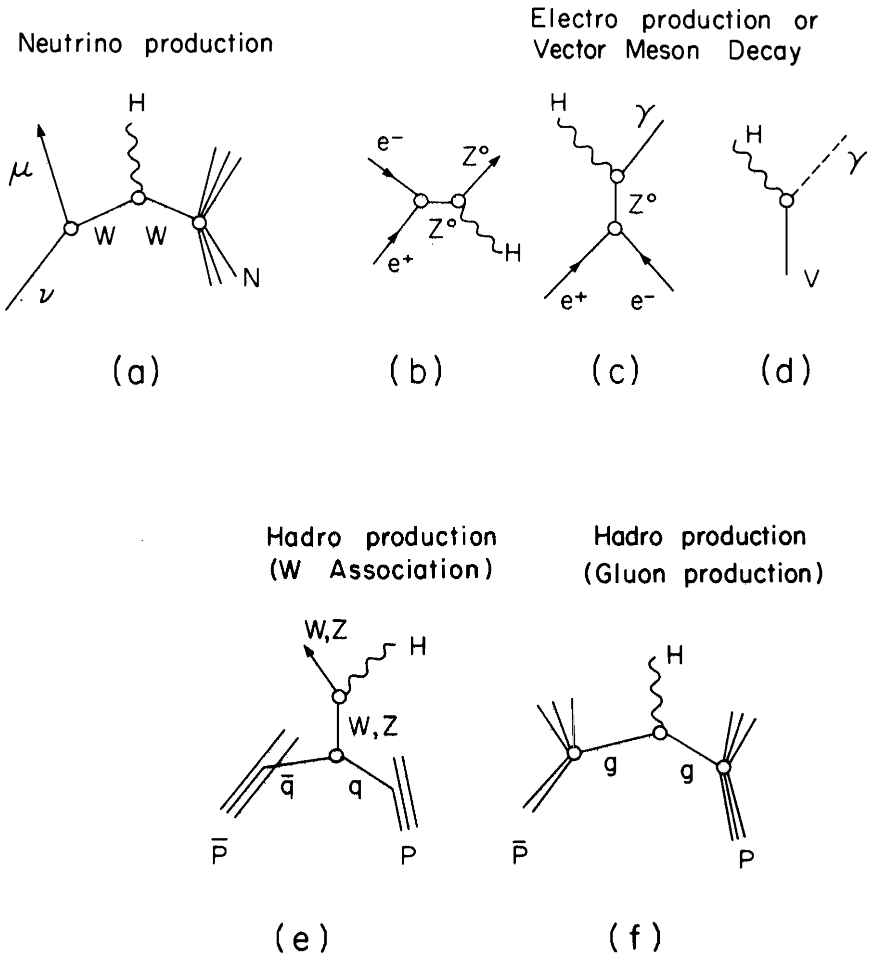

Fig. 11. Mechanisms for Higgs boson production

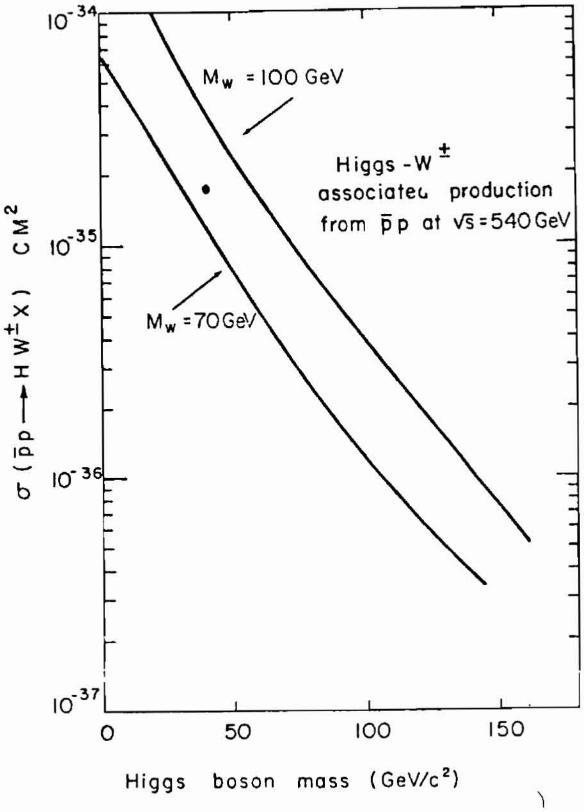

Fig. 12. Associated Higgs-W production according to the quark-parton model and Weinberg Salam couplings

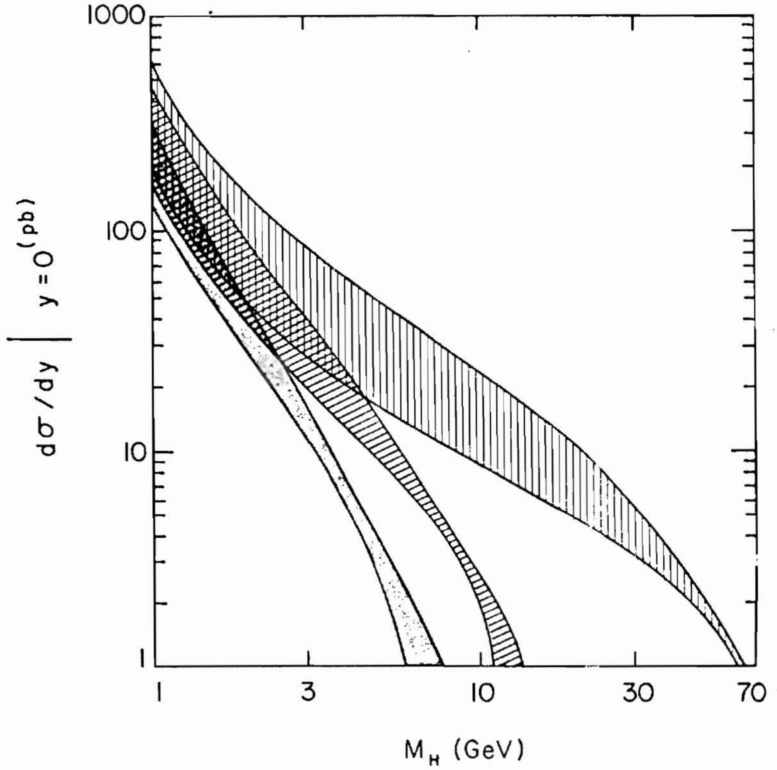

Fig. 13. $d\sigma_H/dy\,|_{y=0}$ as a function of H mass Each shaded band represents a different center-of-mass energy ($\sqrt{s}$ = 27.4, 60, 400 GeV).

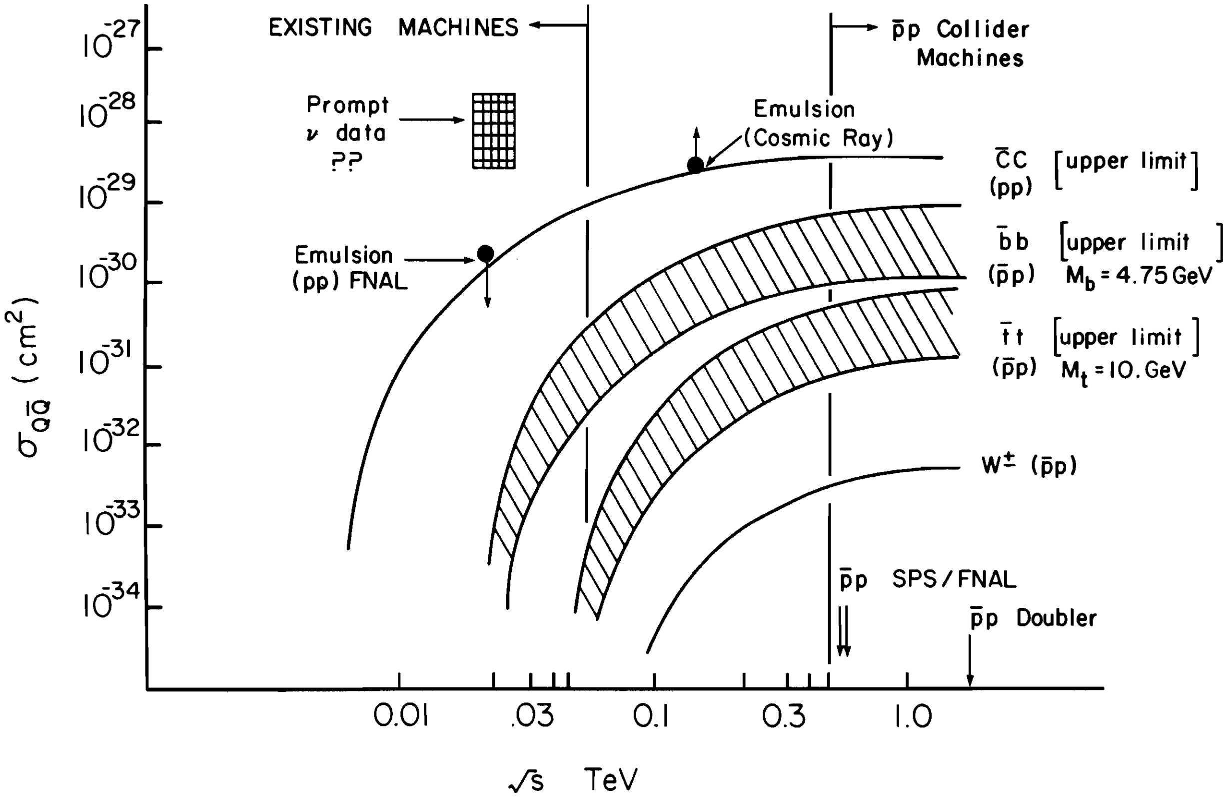

Fig. 14. Production of heavy quarks by $\bar{p}p$ interactions.

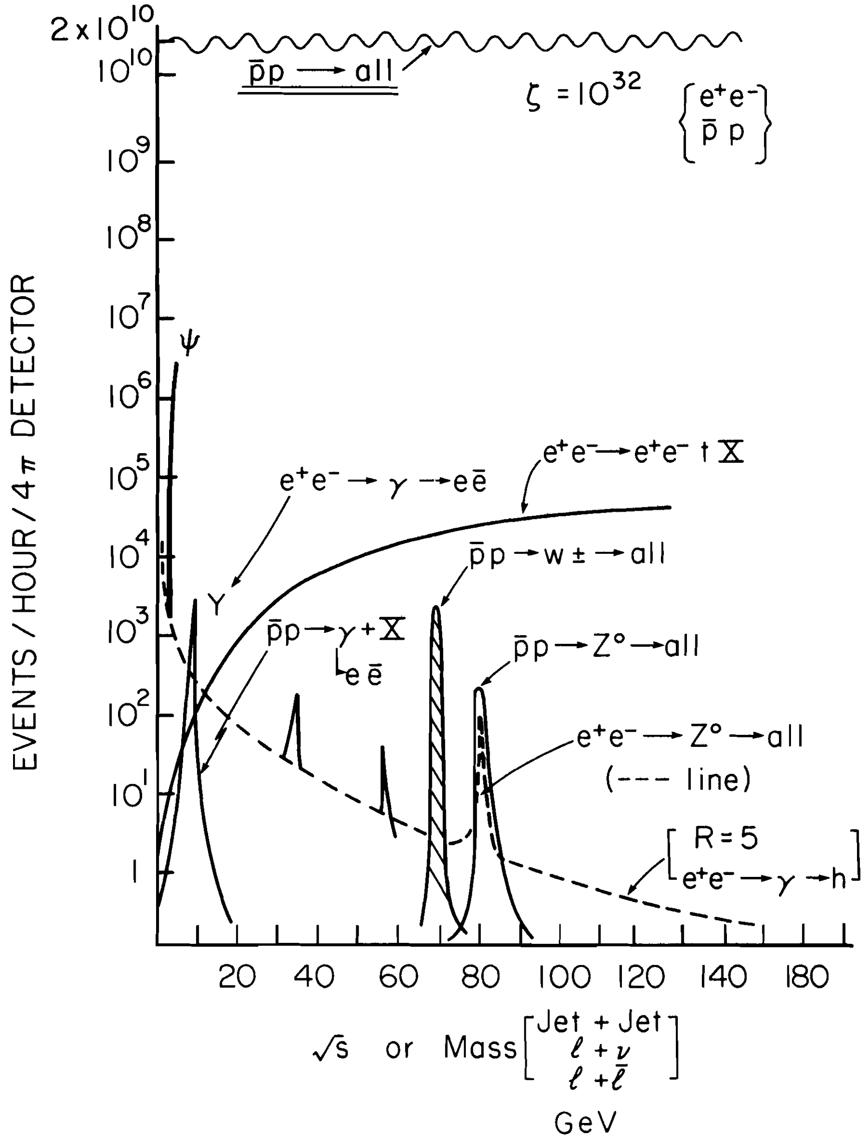

Fig. 15. Comparison of $\bar{p}p/e^+e^-$ rates.

BEAM COOLING TECHNIQUES