Future Prospects for Finding Weak Bosons

J. D. Dowell

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Future prospects for finding weak bosons

By J. D. Dowell
Department of Physics, The University of Birmingham,
P.O. Box 363, Birmingham B15 2TT, U.K.

The Cern proton–antiproton collider is due to come into operation in the second half of 1981. This will provide a total centre of mass energy of 540 GeV with a design luminosity of 10^{30} cm^{-2} s^{-1}, sufficient to produce easily detectable rates of charged and neutral weak intermediate bosons, $W^{\pm}$ and Z^0. The bosons are produced in the elementary collisions of quarks with antiquarks for which a well understood theoretical description exists. Two experiments are being prepared that are optimized towards the detection of these particles through their decay modes $Z^0 \rightarrow e^+e^-$ or $\mu^+\mu^-$, $W^{\pm} \rightarrow e\nu$ or $\mu\nu$. Both detectors incorporate electron and hadron calorimeters that are used to trigger the central track detectors on event candidates having high 'transverse energy' deposition as well as to measure the electron energies precisely. One of the experiments has comprehensive muon detection and measurement. Prospects for studying the bosons at other proposed accelerators are mentioned.

1. Introduction

The proton–antiproton collider at the Cern SPS will begin operation during the second half of 1981, providing for the first time at an accelerator sufficient centre of mass energy, $\sqrt{s} = 540$ GeV, to produce the W and Z weak bosons. Two experiments are being prepared having the capability of detecting the bosons. The Cern project is several years ahead of other accelerators offering the prospect of such high energies. Consequently this paper will describe the situation for the Cern experiments. Some comparative figures will, however, be given for the other machines.

The decays of W and Z into leptons give rise to high-p_T electrons or muons and these provide the characteristic signatures for their detection. For W-decays a Jacobian peak in the charged lepton p_T-distribution is expected at $p_T = \frac{1}{2}m_W$ while the Z is characterized by a peak in the effective mass plot of the decay lepton pair. These features dictate the requirements of a suitable detector which should have large angular acceptance, good discrimination between hadrons and leptons, and good mass resolution for the Z. The latter requirement is most easily achieved by the use of electron calorimeters whose relative energy resolution improves with increasing energy.

2. The Cern proton–antiproton collider

After the success of the initial cooling experiment (Carron *et al.* 1978) which demonstrated the feasibility of the stochastic cooling technique, Cern decided to proceed with plans to use the SPS as a proton–antiproton collider with fixed-field operation at 270 GeV, an idea suggested by C. Rubbia. A full account of the machine aspects is given in a design study report (Autin *et al.* 1978). Antiprotons produced by the PS at 3.5 GeV are accumulated and cooled in an accumulator ring and subsequently injected into the SPS by using the PS. The design figure of 6×10^{11} $\bar{p}$ per day has not yet been reached but one a factor of ten lower has been achieved regularly, and one a factor of five lower occasionally. On the basis of this and studies made of the properties of stored proton beams (lifetime, size etc.) in the SPS, it is anticipated that a luminosity of 10^{29} cm^{-2} s^{-1} will be achieved during the first year of operation, to be compared with the design luminosity of 10^{30} cm^{-2} s^{-1}. The first SPS run with a stored $\bar{p}$ beam is planned for August 1981.

3. The experiments UA1 and UA2

The code names UA1 and UA2 refer to the two experiments located in underground areas excavated around the SPS tunnel. UA1 (Astbury *et al.* 1978) is a global apparatus having a uniform 0.7 T dipole field covering the volume of the central track detector which consists of a system of drift chambers giving a three-dimensional coordinate read-out with a precision in the sagitta direction of 0.25 mm. The corresponding momentum accuracy is expected to be typically a small percentage for a momentum of 50 GeV/c. The return yoke of the magnet acts as a hadron calorimeter while the electromagnetic calorimeters are placed inside the aluminium coil. The main part of the detector (barrel and end caps) covers the angular range from 5° to 175°. Additional forward detectors cover the region from 5° down to 3 mrad. The electromagnetic calorimeters are of the lead-scintillator sandwich type, and both these and the hadron calorimeters make use of the BBQ wavelength shifting technique (Attwood *et al.* 1976) to carry the scintillation light to the photomultipliers. Two layers of muon drift chambers surround the magnet including the space below it. The acceptance in pseudo-rapidity of the detector is ± 4.5 units.

UA2 (Banner *et al.* 1978) is more specifically designed for W and Z detection. A toroidal magnetic field is provided in the 20°–40° and 140°–160° polar angle regions to determine the signs of particles where the asymmetry in W decay is large (see §5). Electromagnetic calorimeters cover these angular regions. The portion between 40° and 140° is without magnetic field and has both hadron and electromagnetic calorimeters directed towards the event origin, which is surrounded by multiwire proportional chambers and drift chambers. Again the BBQ technique is used for light collection. The rapidity coverage is ± 2 units and no muon detection is provided.

The energy resolution of the electromagnetic calorimeters in both experiments is $\Delta E/E = 0.14/\surd E$. For the hadron calorimeters UA1 has energy resolution $0.8/\surd E$ and UA2 $0.6/\surd E$.

A highly selective trigger will be necessary to reduce the 6000 events per second at a luminosity of 10^{29} cm^{-2} s^{-1} to about ten per second, a number that can be recorded. High transverse energy deposition in the calorimeters provides the basis of the trigger ($E_T = \sum E_i \sin \theta i$). For single electrons a cut at 10 GeV should be sufficient, although for hadrons a higher threshold will be necessary. For muons, requiring the tracks to point to the vertex imposes an effective p_T cut provided they are produced above some angle to the beam direction. Microprocessors working on the drift times are used in this case.

4. Mass, width and branching ratios of W and Z

The mass, width and branching ratios of the W and Z have been discussed for example by Paige (1979). The masses are given by the following expressions

$$m_W = \left(\frac{\pi\alpha}{\sqrt{2G_F}}\right)^{\frac{1}{2}} \frac{1}{\sin\theta_W}, \quad m_Z = \frac{m_W}{\cos\theta_W}$$

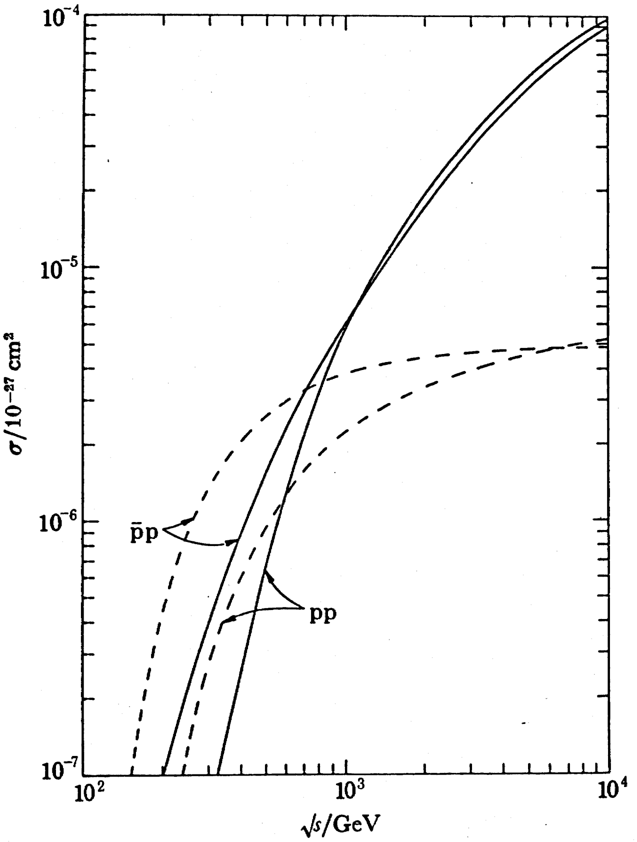

Figure 1. Total cross section for W^+ against energy (Paige 1979). Solid curves, non-scaling distributions; dashed curves, scaling distributions.

where α is the fine structure constant, G_F the Fermi coupling constant and θ_W the weak mixing angle. Putting $\sin^2\theta_W = 0.23$ yields masses of 77.8 GeV/c^2 and 88.6 GeV/c^2 for the W and Z respectively.

The widths of the W and Z are given by

$$\Gamma_W = (Gm_W^3/12\pi\surd 2)\,(3n_q+n_l),$$
$$\Gamma_Z = (Gm_Z^3/12\pi\surd 2)\,[3\sum_q (a_q^2+b_q^2)+\sum_l (a_l^2+b_l^2)],$$

where n_q and n_l are the numbers of quark and lepton flavours, a_i and b_i are the vector and axial vector couplings of the Z to fermions, and the factor 3 accounts for the quark colours. Taking six quarks and six leptons, and $mt \ll \frac{1}{2}m_Z$, one obtains

$$\Gamma_W = 2.47\ \text{GeV}; \quad \Gamma_Z = 2.49\ \text{GeV}.$$

The experimental resolution for the Z will be about ± 1.3 GeV for the e^+e^- mode and 5–10 GeV for the $\mu^+\mu^-$ mode, depending on the angle of decay. First-order QCD corrections (Rizzo 1980) multiply the widths by a factor $1+\alpha_s(m^2)/\pi$, an increase of about 10%. A heavier t-quark reduces them.

The branching ratios are $B(W^+ \rightarrow e^+\nu) = \frac{1}{12}$ and $B(Z^\circ \rightarrow e^+e^-) = 3.08\,\%$ (Paige 1979).

5. Cross sections and event rates

The Drell–Yan process in which a quark from one of the colliding particles annihilates with an antiquark from the other accounts for the production of both W and Z. The W^+ is produced dominantly by $u\bar{d}$ annihilation since $u\bar{s}$ production is Cabibbo suppressed. The Z, like the virtual photon, is produced from $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ annihilations. The leading-order QCD calculation is identical to the simple Drell–Yan formula (Paige 1979) provided scale-violating structure functions $q(x, m^2)$, $\bar{q}(x', m^2)$ are used for the quarks and antiquarks. The cross section is proportional to the overlap of the structure functions with $xx' = m^2/s$. At $\sqrt{s} = 540$ GeV the effect of scaling-violation is small (less than 1.5) because of the value of xx'. The leading-order calculation is shown in figure 1 (Paige 1979) for $p\bar{p}$ and pp producing W^+, as a function of $\sqrt{s}$.

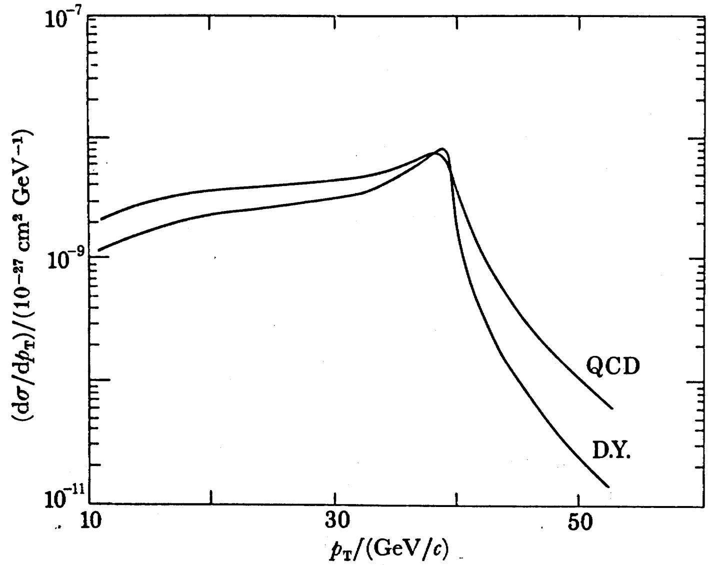

Figure 2. The cross section $d\sigma/dp_T(p\bar{p} \rightarrow W^+ \rightarrow l^+x)$ at $\sqrt{s} = 540$ GeV integrated over W rapidity and decay angle. The leading order (Drell–Yan, D.Y.) and first-order (QCD) calculations are shown (Aurenche & Lindfors 1981; Aurenche *et al.* 1981 *a*, *b*).

Higher-order processes involving gluons in the initial or final state increase the cross sections and produce finite p_T-values for the bosons, balanced by recoiling quark or gluon jets. Aurenche and Lindfors (Aurenche & Lindfors 1981; Aurenche *et al.* 1981 *a*, *b*) have made a first-order calculation which is expected to double the cross section and produce $\langle p_T^2 \rangle$ of the order of 100 $(GeV/c)^2$, which smears out the Jacobian peak for the W (figure 2). The increase in the cross section corresponds to the so called *K*-factor observed experimentally in Drell–Yan continuum production (Badier *et al.* 1979; Barate *et al.* 1979; Corden *et al.* 1980).

Event rates, based on the leading-order calculation for W-production have been estimated

(Kinnunen *et al.* 1981) for the UA1 experiment. Taking a luminosity of 10^{29} cm^{-2} s^{-1} and a p_T-cut on the charged lepton of greater than 10 GeV/c, and allowing for the geometrical acceptance, essentially 100% for electrons and 80% for muons ($25° < \theta < 155°$), one finds the following combined rates:

$$W^{\pm} \rightarrow e \text{ or } \mu, \qquad 5 \text{ day}^{-1},$$

$$Z \rightarrow e^{+}e^{-} \text{ or } \mu^{+}\mu^{-}, \qquad 0.5 \text{ day}^{-1}.$$

The acceptances for UA2 are 75% for the W and 63% for the Z giving rates of 2 day^{-1} and 0.17 day^{-1} respectively.

Detection efficiency (*ca.* 80%) and overall running efficiency will reduce these figures but will be offset by the K-factor, not taken into account in the above calculation. A ten-day run for UA1 could therefore yield about 50 detected W decays into leptons.

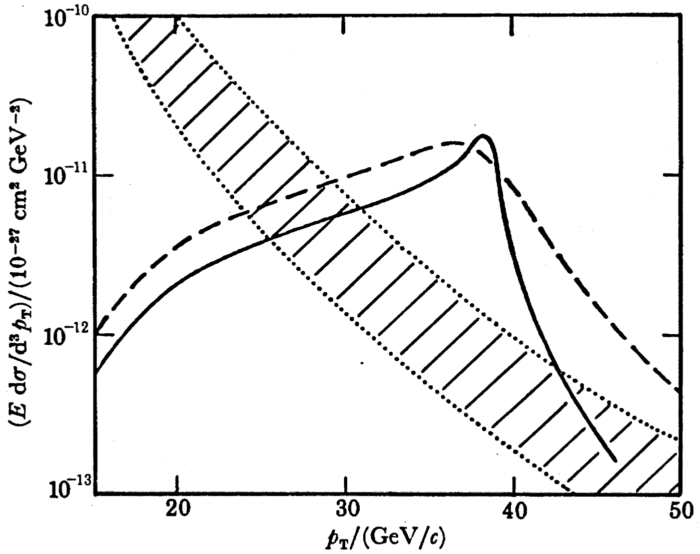

FIGURE 3. Lepton spectrum at 90°. The solid (dashed) line is the leading- (first-) order QCD calculation (Aurenche & Lindfors 1981; Aurenche *et al.* 1981 *a*, *b*). The hatched band shows the estimated background from c and b quark semileptonic decays (Halzen & Scott 1980).

6. W → eν, μν: SIGNATURE, BACKGROUND AND ANGULAR DISTRIBUTIONS

The characteristic peak in the lepton p_T for decays near 90° to the beam in the W rest frame is not seriously degraded by the smearing effect caused by the expected $\langle p_T^2 \rangle$ of the W (figure 2) and should still give an adequate signature provided the backgrounds are not too high. The major expected source of background is from heavy quark (c, b, t) semileptonic decays, especially from the b quark if one assumes a 10% branching ratio (for example for $b \rightarrow cl\bar{\nu}$) (Halzen & Scott 1980; Pakvasa *et al.* 1979). For p_T large compared with the quark masses, the probability of producing heavy quarks by processes involving initial-state or intermediate gluons is the same as that of producing light quarks.

Figure 3 shows the estimated background, the range of values corresponding to different choices for the gluon structure function. Unlike the W decay leptons the background leptons will be inside jets from the decay quark fragmentation. The other sources of muon background are from $\pi \rightarrow \mu$; $K \rightarrow \mu$ decays, and hadron punch-through, and amount to about 3×10^{-3} of the single charged π rate at the large p_T-values relevant to W decay. For electrons, asymmetric Dalitz pairs and γ conversions in the accelerator vacuum pipe amount to the order of 10^{-4} of the single π^0 rate at a given p_T, being considerably suppressed by the 'daughter' effect in the decay and conversion process. Hadron misidentification in the electron calorimeters brings the total background to about 10^{-3} of the single π rate. However, according to the QCD calculations of Horgan and Jacob (Horgan & Jacob 1980), who take into account scaling violations in both the structure functions and fragmentation functions in calculating the single-particle yields from quark jets, both the μ and e backgrounds from these sources should be lower than those from the heavy quark decays. Therefore the background should be acceptable even without making use of the p_T imbalance in the apparatus arising from the undetected neutrino. The inclusion of this criterion should make W detection perfectly clean provided the $\langle p_T \rangle$ of the W itself is not grossly underestimated by the first-order QCD calculations.

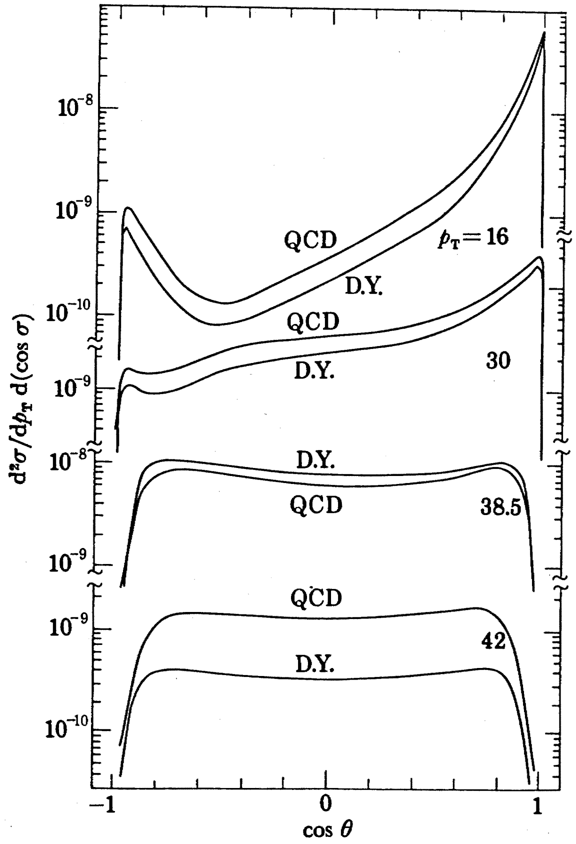

FIGURE 4. The forward-background asymmetry for the decay of W^+ produced in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV as a function of the transverse momentum of the lepton (Aurenche & Lindfors 1981; Aurenche *et al.* 1981 *a*, *b*). (D.Y., Drell–Yan.)

A further characteristic feature of W decay is the asymmetry of the decay lepton with respect to the incoming $\bar{p}$ direction. This arises from the V – A nature of the reaction. Helicity conservation causes the lepton (e^- or μ^-) to tend to move in the direction of the incoming antiquark which comes mainly from the $\bar{p}$. However, if the W decays at right angles to the beam direction in its own rest frame, there is no asymmetry; the angular spread in this case comes from the longitudinal motion of the W. Consequently the asymmetry is larger for smaller p_T-values of the lepton (figure 4).

7. Z → e$^+$e$^-$, μ$^+$μ$^-$: Signature, background and angular distribution

The detection of the Z is more straightforward as it is signalled by a peak in the effective mass plot of e$^+$e$^-$ or μ$^+$μ$^-$. For e$^+$e$^-$ the calorimeter signals provide a clean trigger. Backgrounds from conventional sources should be negligible while heavy quark decays are expected to provide a significant but acceptable background as shown in figure 5 (Halzen & Scott 1980).

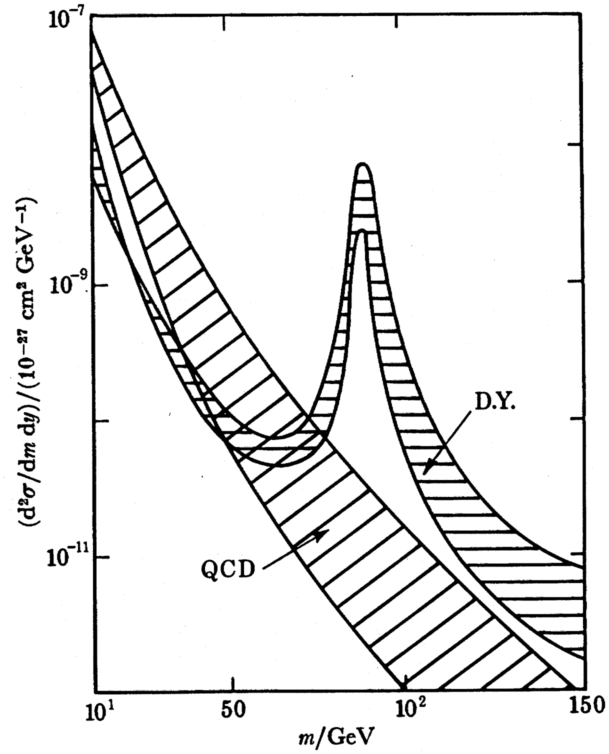

Figure 5. Dilepton spectrum at 90° from c$\bar{c}$ and b$\bar{b}$ production, and semileptonic decay (QCD), and from the Drell–Yan (D.Y.) process (γ + Z) (Halzen & Scott 1980). The bands indicate variations from different choices of parton densities.

The asymmetry in the angular distribution is small (*ca.* 20%) in this case because of the smallness of the vector coupling of the Z to leptons, and will not provide an effective signature with the anticipated statistics. The shape is approximately $1+\cos^2\theta$.

8. W and Z → jet + jet

Decays into pairs of quark jets account for 75% of W decays and 94% of Z decays. Furthermore they permit a measurement of the W mass with a resolution of ± 5–7 GeV/c^2. However, the backgrounds due to pairs of high-p_T hadronic jets from parton scattering appear to be larger than the signals (Horgan & Jacob 1980).

Figure 6 illustrates decays of W$^+$ → u$\bar{d}$ and Z → u$\bar{u}$ compared with the corresponding hadronic jet pairs. In this figure jet–jet masses within the experimental resolution of the W and Z masses have been taken. The background from gluon jets is even higher, which makes the prospect of studying the jet decays of the bosons discouraging.

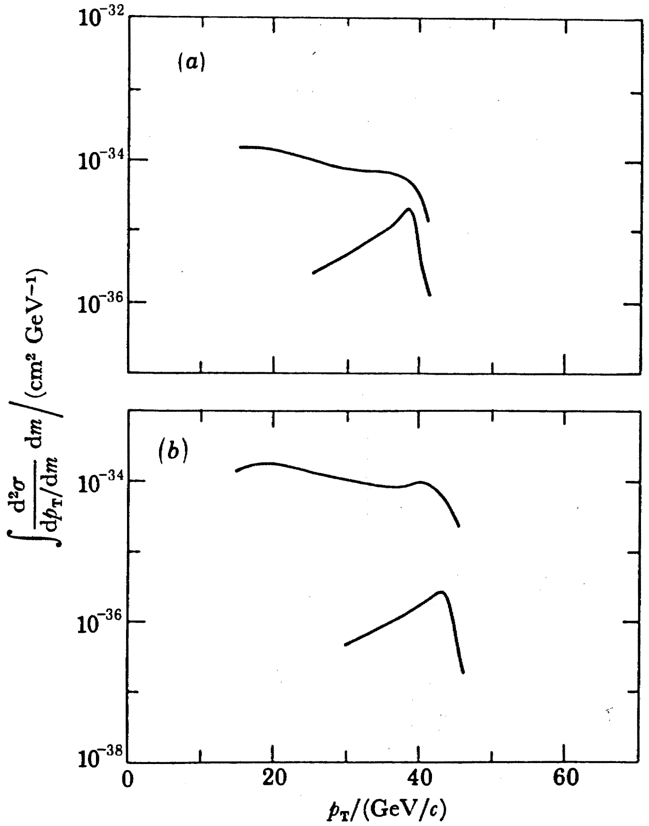

Figure 6. Differential cross sections for fixed jet–jet invariant mass. (Production of (*a*) u$\bar{d}$ from hadronic interactions (upper curve) and W^+ formation (lower curve) with masses in the range 72–84 GeV. (*b*) Production of u$\bar{u}$ from hadronic interactions (upper curve) and Z formation (lower curve) with masses in the range 82–94 GeV. (Horgan & Jacob 1980.)

9. Other planned accelerator developments

The proton–proton colliding beam machine Isabelle at Brookhaven will have a centre of mass energy of 800 GeV, giving a similar cross section for W production to the Cern collider but with a design luminosity of 10^{32} cm^{-2} s^{-1}. Because of the identical nature of incoming particles there are no decay asymmetries. Problems with perfecting the superconducting magnets will delay this project beyond 1985.

The Fermilab collider using the Tevatron at $\sqrt{s}$ = 2000 GeV will give a W cross section twice as large as at 540 GeV. With the present progress the collider could come into operation in 1984/1985. The expected luminosity is 2×10^{29} cm^{-2} s^{-1}.

The electron–positron machine LEP proposed for Cern is planned for completion in 1987 and would produce 10–100 $Z \rightarrow \mu\mu$ decays per hour depending on the luminosity obtained, allowing much more refined studies than could ever be achieved at the proton accelerators.

10. CONCLUSIONS

In summary, the p$\bar{\text{p}}$ collider is expected to come into operation during 1981 with $\sqrt{s}$ = 540 GeV and a luminosity of 10^{29} cm^{-2} s^{-1}. Estimated rates for detected W decays into leptons are in the region of five per day for the UA1 experiment and two per day for UA2 while Z yields are an order of magnitude lower. The Z mass resolution is ± 1.3 GeV, comparable with the natural width of 2.49 GeV. Higher-order QCD processes, while increasing the cross sections by a factor of two, produce large p_T-values for the bosons (*ca.* 10 GeV/c) which smear the peak in the W decay p_T-distribution, but not to a serious extent. Leptonic backgrounds appear to be dominated by the semileptonic decays of heavy quarks but should be at an acceptable level. However, the predominant decays of W and Z into pairs of quark jets are likely to be obscured by high-p_T jets from hard scattering processes. Other accelerators capable of producing the bosons are not likely to be available for several years.

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REFERENCES (Dowell)

Astbury, A. *et al.* 1978 CERN SPSC/P92.
Attwood, W. B. *et al.* 1976 SLAC preprint TN-76-7.
Aurenche, P. & Lindfors, J. 1981 CERN TH.3016.
Aurenche, P. *et al.* 1981 *a* CERN TH.2992.
Aurenche, P. *et al.* 1981 *b* *Physics Lett.* B 96, 171.
Autin, B. *et al.* 1978 CERN/PS/AA 78-3.
Badier, J. *et al.* 1979 *Physics Lett.* B 89, 145.
Banner, M. *et al.* 1978 CERN/SPSC/P93.
Barate, R. *et al.* 1979 *Phys. Rev. Lett.* 43, 1541.
Carron, G. *et al.* 1978 *Physics Lett.* B 77, 353.
Corden, M. J. *et al.* 1980 *Physics Lett.* B 96, 417.
Halzen, F. & Scott, D. M. 1980 University of Wisconsin preprint, DOE-ER/00881-161.
Horgan, R. & Jacob, M. 1980 CERN TH.2824.
Kinnunen, R. & Rubbia, C. 1981 CERN p$\bar{\text{p}}$ note 67.
Paige, F. E. 1979 BNL-27066.
Pakvasa, S. *et al.* 1979 *Phys. Rev.* D 20, 2862.
Rizzo, T. G. 1980 BNL-27441.