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**PRODUCTION PROPERTIES OF
THE INTERMEDIATE VECTOR BOSONS W AND Z
AT THE CERN $p\bar{p}$ COLLIDER**

Thomas Müller

CERN, Geneva, Switzerland
(UA1 Collaboration at CERN)

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1. INTRODUCTION

With the commissioning of the CERN $p\bar{p}$ Collider in 1981 [1], a new energy regime was opened up in the field of elementary particle physics, thus allowing the study of hadron-hadron interactions at 546 GeV centre-of-mass energies—an order of magnitude higher than had been achieved until then. Only about one and a half years later, the two large underground-area experiments at the Collider, UA1 and UA2, reported the discovery of the charged intermediate vector bosons (IVBs) W^+ and W^- [2], and less than a year afterwards, in 1983, of the neutral IVB, the Z^0 [3]. The discovery of these massive mediators of weak interactions provided a confirmation of the Glashow-Salam-Weinberg (GSW) theory of the unified electromagnetic and weak interactions [4, 5]. Together with the theory of quantum chromodynamics (QCD), which describes strong interactions, the GSW theory forms our present ‘standard’ picture of the fundamental forces and constituents of matter (only leaving out gravity) the so-called Standard Model. The main advocates of the Collider program—C. Rubbia, who initiated it in 1976 [6], and S. van der Meer [7]—were awarded the Nobel Prize for physics in 1984 [8].

Since 1983, both experiments increased their data samples by an order of magnitude during several Collider runs, before the long shutdown period of the Collider in 1986/87. The analysis of these data has almost come to an end, and it turned out that the study of proton-antiproton collisions at these energies covers a wide range of physics topics: for instance, the phenomena of soft $p\bar{p}$ interactions, deep-inelastic $p\bar{p}$ collisions, heavy-flavour production, $B^0 - \bar{B}^0$ mixing, and physics with W and Z bosons [9]. In all these studies the basic issue is whether the now established theories describing electroweak and strong interactions are verified by the data, or whether, in the realm of the new centre-of-mass energies reached by the Collider, deviations are found, which would hint at new physics.

This report will focus on the physics with W and Z bosons; in particular, it will concentrate on the following questions:

- What is the production mechanism of IVBs in $p\bar{p}$ collisions?
- How sensitive are the data when probing the structure of the proton (or antiproton) using W and Z bosons?
- Are IVBs an appropriate tool for testing QCD? And, more importantly, can we find indications of new phenomena beyond the Standard Model?

The structure of this report is as follows. After a short theoretical review of the standard electroweak theory and of our present understanding of the IVB production mechanism, the basic detector elements of the UA1 and UA2 experiments, which are relevant to the discussion of this topic, are described. In the following section the identification of W and Z bosons with the two detectors is outlined, and in order to get a complete picture, all possible decay modes of the IVBs are then discussed. We compare the basic properties of the boson candidates with expectations from the GSW theory. Having established the genuineness of the collected W and Z candidates, their production properties will be investigated, with emphasis on the above questions. The last section will provide an outlook on possible activities in this field in the next few years, both here at CERN and at FNAL in the United States.

2. THEORETICAL ASPECTS

2.1 The way to a unified description of weak and electromagnetic interactions

Historically, the first weak interaction to be observed was the nuclear β -decay which involved the emission of electrons or positrons from heavy nuclei. The observation that the energy spectrum of the β -rays was continuous led Wolfgang Pauli, in 1930, to postulate the emission of a neutral, spin- $1/2$ particle—the neutrino—in association with the β particle.

Following up this idea, in 1934 Enrico Fermi developed a phenomenology of weak interactions [10], interpreting nuclear β -decay as the radiation of an electron (or positron)-neutrino pair from the nucleon in a way similar to that of photon emission from an excited atom. The principal process would be a point-like interaction of four fermions with a coupling strength G_F , as illustrated in Fig. 1 for the process

$$n \rightarrow p + e^- + \bar{\nu}_e. \quad (2.1)$$

In analogy to the formalism of quantum electrodynamics (QED) developed several years earlier [11], the Lagrangian of process (2.1) appears in the form

$$\mathcal{L} = -(G_F/\sqrt{2})(\bar{\psi}_p O \psi_n)(\bar{\psi}_e O \psi_{\bar{\nu}_e}), \quad (2.2)$$

interpreted as the coupling of a hadronic current J_μ^h with a leptonic current J_μ^ℓ . The operator O characterizes the coupling, which was found experimentally to be of both the vector (V) and the axial-vector (A) type in weak interactions. The observation of parity violation in weak interactions is represented in the (V–A)-structure of the coupling, which implies that only left-handed fermions and right-handed antifermions are involved. An attempt was made to overcome the fundamental difficulty of the hypothesis of the four-fermion interaction—the theory is not renormalizable and violates unitarity at high centre-of-mass energies—by introducing [12] a massive charged spin-1 boson, W^+ or W^- (in short: W), which acts as an exchange particle between the interacting currents in analogy to Yukawa’s theory of meson exchange between nucleons [13].

In this scenario the Fermi coupling constant G_F is replaced by a propagator term of the form $g_W^2/(q^2 + m_W^2)$, where g_W is the coupling strength of the boson to the lepton or hadron current, m_W is the mass of the W boson, and q^2 is the square of the four-momentum transfer in the interaction. Process (2.1), as described by W exchange, is illustrated in Fig. 2. For $q^2 \rightarrow 0$ we derive

$$G_F/\sqrt{2} = g_W^2/m_W^2, \quad (2.3)$$

and assuming that the strength of the weak coupling g_W is similar to that of the electromagnetic (e.m.) coupling e , the boson mass is predicted to be of the order of $100 \text{ GeV}/c^2$.

The large mass of the W boson explains the small cross-section of weak interactions at low q^2 . However, this model still has divergent terms, as for instance in the process of W pair-production. With the introduction of a neutral massive vector boson, the Z^0 (in short: Z), which has characteristics similar to those of the W [4, 14], additional terms occur which cancel these divergences. The weak neutral interaction mediated by the Z , together with the e.m. interaction (mediated by the photon), form the neutral-current part in an overall Lagrangian of e.m. and weak interactions; the weak neutral coupling strength g is adjusted to the strength of the e.m. coupling, so that divergences cancel through interference:

$$g = e/\sin \theta_w \quad (2.4)$$

where θ_w is the electroweak mixing angle. Equation (2.4) implies that the coupling constants of e.m. and weak interactions are connected and of a similar size, which is the direct manifestation of the unified electroweak (e.w.) interaction.

A simple model for a gauge theory of the e.w. interaction was originally written down in 1961 by Glashow [4], and in its final version, the so-called Standard Model, by Salam and Weinberg in 1967 [5]. This model is based on an SU(2) group of ‘weak’ isospin I and a U(1) group of ‘weak hypercharge’ $Y = Q - I_3$, combining to make SU(2) $\times$ U(1). The interaction takes place between fundamental fermions, which are grouped in left-handed isospin doublets and right-handed singlets,

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad (I = 1/2, Y = 1/2),$$

and, in the case of the leptons, (2.5)

$$e_R, \mu_R, \tau_R \quad (I = 0, Y = 1).$$

The quarks—charged constituents of hadrons [15]—are organized in the same way in three ‘generations’,

$$\begin{pmatrix} u \\ d_c \end{pmatrix}_L, \begin{pmatrix} c \\ s_c \end{pmatrix}_L, \begin{pmatrix} t \\ b_c \end{pmatrix}_L \quad (I = 1/2, Y = 1/6),$$

(2.6)

and

$$u_R, d_{cR}, c_R, s_{cR}, t_R, b_{cR} \quad (I = 0, Y = Q).$$

The index c of the ‘down-like’ quarks indicates the fact that they mix; the individual weight factors of their mixing are the components of the Cabibbo–Kobayashi–Maskawa matrix [16]. In a two-generation world, these components are represented by one parameter, the Cabibbo angle θ_C [17].

The fermions couple gauge-invariantly to the isovector field $\vec{W}_\mu$ and the hypercharge field B_μ , as indicated by the Lagrangian

$$\mathcal{L}_{ew} = g \vec{J}_\mu \vec{W}_\mu + g' J_\mu^{(Y)} B_\mu, \quad (2.7)$$

where the coupling strengths are related by

$$\tan \theta_w = g/g'. \quad (2.8)$$

The fields $\vec{W}_\mu$ and B_μ form the physical bosons in the relationships

$$\begin{aligned} W_\mu^\pm &= [W_\mu^{(1)} \pm iW_\mu^{(2)}]/\sqrt{2} \\ Z_\mu^0 &= [gW_\mu^{(3)} + g'B_\mu]/(g^2 + g'^2)^{1/2} \\ A_\mu &= [-g'W_\mu^{(3)} + gB_\mu]/(g^2 + g'^2)^{1/2}. \end{aligned} \quad (2.9)$$

With Eqs. (2.9) the Lagrangian of the e.w. interaction reads as follows:

$$\mathcal{L} = \underbrace{\frac{g}{\sqrt{2}}(J_\mu^- W_\mu^+ + J_\mu^+ W_\mu^-)}_{\text{weak CC}} + \underbrace{\frac{g}{\cos \theta_w}[J_\mu^{(3)} - \sin^2 \theta_w J_\mu^{\text{em}}]}_{\text{weak NC}} Z_\mu + \underbrace{g \sin \theta_w J_\mu^{\text{em}} A_\mu}_{\text{e.m. NC}}. \quad (2.10)$$

It is subdivided into a weak charged-current (CC) part as given in process (2.1), an electromagnetic term, and a weak neutral-current (NC) part. The phenomenon of weak NCs was not observed at the time when the Standard Model was postulated; it was discovered a few years later with the Gargamelle bubble chamber at CERN [18], in the reaction

$$\bar{\nu}_\mu + e^- \rightarrow e^- + \bar{\nu}_\mu. \quad (2.11)$$

The weak IVBs and the fermions acquire mass as a result of their coupling to a scalar field, the Higgs field [19]. In this way the GSW theory remained renormalizable, as was demonstrated by 't Hooft [20]. For details about the GSW model, the reader should consult the existing literature [21].

Even though the Standard Electroweak Theory gives a unified description of e.m. and weak interactions between quarks or leptons with very precise predictions, as will be shown in the next section, many parameters had to be put in 'by hand', i.e. they had to be determined experimentally:

- the e.w. coupling constants e and g and their mixing angle;
- the number of generations, here assumed to be three;
- the masses of quarks and leptons (where neutrinos are assumed to be massless);
- the mixing parameters of down-like quarks;
- the mass of the Higgs boson (or the masses, if there is more than one).

Taking, in addition to the large number of free parameters listed above, the QCD scale parameter Λ_{QCD} , it appears plausible that the Standard Model is probably not the most fundamental description of particles and their interactions. This is why the aim of the experiments described in this report is to find indications for physics phenomena beyond the Standard Model which would manifest themselves either in deviations from the values of predicted Standard Model parameters (see below) or in the occurrence of particles not predicted by this Model.

2.2 General properties of W and Z bosons in the framework of the Standard Model

2.2.1 Properties of the W^+ and W^-

The mass of the charged IVBs can be obtained from the comparison of the weak coupling strength with the experimentally determined Fermi coupling constant:

$$g^2/8m_W^2 = G_F/\sqrt{2}, \quad (2.12)$$

where $G_F = 1.16632 \times 10^{-5} \text{ GeV}^{-2}$ [22].

Replacing g^2 by $e^2/\sin^2 \theta_w = 4\pi\alpha/\sin^2 \theta_w$ and using an average value of $\sin^2 \theta_w = 0.232$ as was determined in (lepton–nucleon) scattering experiments [23], the prediction for the W mass is

$$m_W = 76 \text{ GeV}/c^2. \quad (2.13)$$

By taking into account first-order radiative corrections [24] the mass is expected to amount to

$$m_W = \frac{38.65}{\sin^2 \theta_w} = 80.1 \pm 1.1 \text{ GeV}/c^2. \quad (2.14)$$

The natural width of the W is determined by the sum of all partial widths from the individual decay modes, which in principle are not all known (see the discussion in Section 4). The partial width of the leptonic decay mode $W^- \rightarrow \ell^- \bar{\nu}_\ell$ or $W^+ \rightarrow \ell^+ \nu_\ell$ (in short: $W \rightarrow \ell \nu$) is given by

$$\Gamma(W \rightarrow \ell \bar{\nu}) = G_F m_W^3 / 6\pi\sqrt{2} = 0.22 \text{ GeV}/c^2, \quad (2.15)$$

which, in the W decay, is equal for all lepton pairs as long as their mass can be neglected (the hypothesis of universality). This is the case for the known leptons e, μ , and τ , and for their corresponding neutrinos. The formula for defining the partial width of W decays into quark-antiquark pairs is similar to Eq. (2.15), except that here the Cabibbo mixing of down-like quarks and the colour charge factor of the quarks have to be taken into account; in particular,

$$\begin{aligned} \Gamma(W \rightarrow \bar{u}d) &= N_c \cos^2 \theta_C \Gamma(W \rightarrow \ell \nu), \\ \Gamma(W \rightarrow \bar{u}s) &= N_c \sin^2 \theta_C \Gamma(W \rightarrow \ell \nu), \end{aligned} \quad (2.16)$$

where $N_c = 3$ (colour degree of freedom).

For heavy quarks the width is reduced by a mass-dependent phase-space factor. Finally, QCD radiative corrections give a small additional contribution to Γ [25].

Assuming that the W decays into only leptons and quarks of the three known generations, the total width can be reliably calculated, except for the uncertainty of the contribution from the decay mode $W \rightarrow t\bar{b}$, since the t-quark has not yet been discovered. If we assume that the mass of the t-quark is equal to the conservative lower limit of $44 \text{ GeV}/c^2$, as was recently quoted by UA1 [26], the predicted width amounts to

$$\Gamma_W = 2.55 \text{ GeV}/c^2, \quad (2.17)$$

whereas in the case of a very massive t-quark ($m_t > m_W - m_b$)

$$\Gamma_W = 2.09 \text{ GeV}/c^2. \quad (2.18)$$

This is illustrated in Fig. 3, where the predicted decay widths of W and Z bosons are plotted versus m_t . In this figure the world average of $\sin^2 \theta_w = 0.230$ [23] is used, including also the results of UA1 [27, 28] and UA2 [29], which will be given in more detail in Section 4. In the case where $m_t = 44 \text{ GeV}/c^2$, the branching fraction of the decay into an electron and a neutrino is

$$\text{BR}(W \rightarrow e\nu) = \Gamma(W \rightarrow e\nu)/\Gamma_W = 0.088. \quad (2.19)$$

The occurrence of any decay channel beyond the Standard Model prediction will manifest itself in an increase of the total decay width of the W (and similarly of the Z). A precise measurement of the decay width will therefore allow a conclusion to be reached, in an indirect way, regarding the presence (or absence) of ‘new’ physics in the mass range of the IVBs, given that the mass of the t-quark is known.

2.2.2 Properties of the Z

In the minimal version of the Standard Model with a Higgs doublet, which implies the existence of only one massive Higgs particle, the Z mass is related to the W mass by the expression

$$m_Z^2 = m_W^2 / \cos^2 \theta_w \quad (2.20)$$

which, including radiative corrections, predicts

$$m_Z = 91.6 \pm 0.9 \text{ GeV}/c^2. \quad (2.21)$$

The partial decay widths of the Z are functions of its different axial-vector and vector coupling constants A and V. Neglecting phase-space effects, we find

$$\Gamma(Z \rightarrow \ell^+ \ell^-) = (G_F m_Z^3 / 24\pi) \sqrt{2} \cdot (V_\ell^2 + A_\ell^2), \quad (2.22)$$

and for decays into quark–antiquark pairs,

$$\Gamma(Z \rightarrow q\bar{q}) = (G_F m_Z^3 / 24\pi) \sqrt{2} \cdot 3(V_q^2 + A_q^2). \quad (2.23)$$

Equation (2.22) results in

$$\Gamma(Z \rightarrow e^+ e^-) = 0.08 \text{ GeV}/c^2 \quad (2.24)$$

and

$$\Gamma(Z \rightarrow \nu\bar{\nu}) = 0.17 \text{ GeV}/c^2. \quad (2.25)$$

Quark–antiquark pairs are expected to belong to the same generation because flavour changes are suppressed in weak NC interactions [30]. Assuming that $m_t \gtrsim m_Z/2$, we derive from Eqs. (2.22) and (2.23) a total decay width of

$$\Gamma_Z = 2.52 \text{ GeV}/c^2. \quad (2.26)$$

The branching fraction of the electron decay channel is expected to be

$$\text{BR}(Z \rightarrow e^+ e^-) = 0.033. \quad (2.27)$$

The measurement of Γ_Z can be considered as a method of estimating the total number of neutrino species with $m_\nu < m_Z/2$, since each family of neutrinos adds $170 \text{ MeV}/c^2$ to the total width. Before the discovery of the IVBs, the upper limit on the number of light neutrinos from particle physics experiments was $N_\nu < 1400$, a result obtained from the failure to detect the decay $K \rightarrow \pi \nu \bar{\nu}$ [31]. As will be shown in Section 4, this limit has since been dramatically reduced.

2.3 The production mechanism of W and Z in $p\bar{p}$ collisions

Massive particles such as the weak IVBs can be produced directly in electron–positron, lepton–hadron, or hadron–hadron collisions provided the available energy in the collision is sufficiently high. It is expected that in hadron–hadron interactions—and this includes the case of $p\bar{p}$ collisions which we are discussing here—W or Z bosons are dominantly produced by the annihilation of a quark with an antiquark, in close analogy to the process described by Drell and Yan [32]. This Drell–Yan picture was originally used to describe lepton pair-production in hadron–hadron collisions in the framework of the quark–parton model [33]: a quark of one hadron annihilates with a quark of the other hadron into a virtual photon, which forms an electron–positron pair or a muon pair (see Fig. 4). The invariant mass of this lepton pair is equivalent to the c.m. energy of the subsystem,

which is determined by the fractional momenta of the two annihilating quarks. The distributions of the fractional momenta of quarks in hadrons are described by structure functions, which were obtained in lepton–nucleon scattering experiments [34]. It was found that the three valence quarks of the proton (antiproton) carry, on the average, about half the proton momentum, the other half being transported by the cloud of virtual quark–antiquark pairs (sea quarks) and of gluons which bind the valence quarks. Consequently, in $p\bar{p}$ collisions at the CERN Collider with a c.m. energy of $\sqrt{s} = 630$ GeV, valence quarks annihilate with a typical c.m. energy of $\sqrt{\hat{s}} = \sqrt{x_1 \cdot x_2 \cdot s} \approx 100$ GeV, where x_1 and x_2 are the momentum fractions of the quark and antiquark, respectively. This is sufficient to produce an object of corresponding mass, such as the W or Z.

2.3.1 Production cross-sections

The basic subprocesses for forming a W or Z in $p\bar{p}$ collisions (see Fig. 5), predicted by the Standard Model [35], are

$$\left. \begin{aligned} u + \bar{d} &\rightarrow W^+ & \text{or} & & u + \bar{s} &\rightarrow W^+ , \\ d + \bar{u} &\rightarrow W^- & \text{or} & & s + \bar{u} &\rightarrow W^- , \\ u + \bar{u} &\rightarrow Z , \\ d + \bar{d} &\rightarrow Z , \\ s + \bar{s} &\rightarrow Z ; \end{aligned} \right\} \quad (2.28)$$

Note that s-quarks are sea quarks only. The contributions to subprocesses (2.28) from the heavier sea quarks c, b, and t are believed to be negligible. The production cross-sections depend on three factors:

- the probability that a quark and antiquark have matching fractional momenta so as to obtain a c.m. energy corresponding to m_W or m_Z ;
- the probability that a quark and antiquark form a colour-neutral system (since the weak IVBs are colour singlets);
- the e.w. coupling strength.

The cross-section for W^+ and W^- formation is given by

$$\hat{\sigma}(q_1 + \bar{q}_2 \rightarrow W) = \sqrt{2} \pi G_F m_W \delta(x_1 \cdot x_2 \cdot s - m_W^2) , \quad (2.29)$$

where the function δ constrains the c.m. energy of the subsystem to the W mass, ignoring here the natural width of the IVBs. The inclusive cross-section is obtained by summing over all quark–antiquark combinations and fractional momenta:

$$\begin{aligned} \sigma(p\bar{p} \rightarrow W + X) &= \int_0^1 dx_1 \int_0^1 dx_2 \sigma(x_1, x_2) W(x_1, x_2) \\ &= \sqrt{2} \pi G_F \tau \int_{\tau}^1 (dx/x) W(x, \tau/x) , \end{aligned} \quad (2.30)$$

where

$$\tau = x_1 \cdot x_2 = m_W^2/s ,$$

and

$$W(x, \tau/x) = (1/N_c) [U(x) D(\tau/x) + D(x) U(\tau/x)] \cos^2 \theta_c \\ + (1/N_c) [U(x) S(\tau/x) + S(x) U(\tau/x)] \sin^2 \theta_c ; \quad (2.31)$$

U , D , and S are the probabilities of finding u , d , or s in the proton (antiproton) with a momentum fraction x ; $N_c = 3$ accounts for the colour degree of freedom.

Likewise, the cross-section for inclusive Z production is given by

$$\sigma(p\bar{p} \rightarrow Z + X) = 2\sqrt{2} \pi G_F \tau \int_{\tau}^1 (dx/x) Z(x, \tau/x) , \quad (2.32)$$

where

$$\tau = m_Z^2/s ,$$

and

$$Z(x, \tau/x) = (2/N_c) [U(x) U(\tau/x) (1/4 - 2/3 \sin^2 \theta_w + 8/9 \sin^4 \theta_w)] \\ + (2/N_c) [D(x) D(\tau/x) + S(x) S(\tau/x)] \\ \times (1/4 - 1/3 \sin^2 \theta_w + 2/9 \sin^4 \theta_w) . \quad (2.33)$$

On the basis of Eqs. (2.30) to (2.33) (the so-called naïve Drell–Yan model), in the case of Z the resulting inclusive cross-sections at the CERN $p\bar{p}$ Collider are predicted to be around 1 nb, and for W^+ or W^- about 2 nb each. It is worth mentioning here that in proton–proton collisions of similar c.m. energies the cross-sections are roughly a factor of 5 smaller [36], since in this case antiquarks are only from the sea, and sea quarks carry, on the average, a considerably smaller average fractional momentum.

2.3.2 Polarization of IVBs

Because of the $(V - A)$ coupling of the weak interaction, the W bosons produced at the Collider are predicted to be almost fully polarized along the antiproton direction. Again, owing to the $(V - A)$ coupling of the W to its decay products, this results in a strong asymmetry of the emitted particles with respect to the beam direction: in the case of W decaying to lepton pairs, the positively charged leptons are expected to fly predominantly in the direction of the incoming antiproton; likewise, the negative leptons are emitted in the proton direction. This is illustrated in Fig. 6. The observation of a decay asymmetry of charged leptons is thus an important test of the $V - A$ coupling of the W ; even the spin of the W boson can be inferred from it [37], as will be described in Section 5. Similarly, an asymmetry is also expected in Z decays — but weaker here, since the dominant coupling is of the axial type only.

2.3.3 The QCD-improved Drell–Yan picture

One of the basic elements of QCD, i.e. the colour charge degree of freedom, has already been taken into account in the cross-section formulas for W and Z production, Eqs. (2.31) and (2.33). In addition, QCD predicts the coupling of quarks and gluons with the coupling constant

$$\alpha_s(q^2) = \frac{12\pi}{(33 - 2n_f) \cdot \ln(q^2/\Lambda_{\text{QCD}}^2)} \quad (2.34)$$

where q^2 = square of the four-momentum transfer,

Λ_{QCD} = QCD scale parameter,
 n_f = number of quark flavours.

This coupling influences the cross-section values and also the kinematics of the produced IVBs in the following way:

- i) The structure functions and, hence, the quark momentum distributions, have a small dependence on q^2 , as was observed in deep-inelastic lepton–nucleon scattering experiments [38]. In the range of $x \approx 0.14$ at which quarks most frequently form an IVB (at Collider energies), this q^2 dependence is fortunately quite small, so that an extrapolation from measured results at low q^2 to $q^2 \approx m_{\text{IVB}}^2$ has small uncertainties.
- ii) In addition to the ‘standard’ Drell–Yan-type formation of IVBs through quark–antiquark annihilation, higher-order QCD processes occur which involve the emission or absorption of gluons. In first-order QCD, one of the quarks radiates a gluon in the form of bremsstrahlung (Fig. 7a), or in a Compton-type process a quark is scattered from a gluon followed by radiation of an IVB (Fig. 7b). At the Collider, gluon radiation dominates the Compton term simply because the quark–gluon system has to provide the energy necessary for IVB formation, which is kinematically suppressed owing to the very soft structure function of gluons in the proton. These higher-order QCD processes add to the Drell–Yan annihilation term, thus increasing the total IVB production cross-section by a factor k , which at $\sqrt{s} = 630$ GeV amounts to about 1.3 [39]. Taking this value into account, the inclusive IVB cross-sections are predicted to be

$$\begin{aligned} \sigma(p\bar{p} \rightarrow Z + X) &= 1.6^{+0.5}_{-0.3} \text{ nb} , \\ \sigma(p\bar{p} \rightarrow W + X) &= 5.3^{+1.5}_{-0.9} \text{ nb} . \end{aligned} \quad (2.35)$$

The errors are dominated by the choice of the structure function and the scale of q^2 in the QCD coupling constant α_s .

The radiation processes mentioned above are expected to give rise to a long tail in the transverse momentum spectrum of the weak bosons, and, from a certain $p_{\text{T}}^{\text{IVB}}$ onwards, the recoiling quark or gluon will form an energetic particle jet. In the region of sufficiently large transverse momenta in which QCD perturbation theory is applicable, the shape of the $p_{\text{T}}^{\text{IVB}}$ distribution and the rate of occurrence of associated hadronic jets provide us with a quantitative test of QCD.

Because of this tail in the transverse momentum spectrum, the average $p_{\text{T}}^{\text{IVB}}$ is expected to lie between 5 GeV/c and 10 GeV/c, considerably higher than in the naïve Drell–Yan scenario where only the motion of the quarks inside the proton (antiproton) gives rise to a small transverse momentum of the produced IVB ($p_{\text{T}}^{\text{IVB}} < 1$ GeV/c).

2.4 The structure of events with a W or Z boson

From the above discussion, and especially from Eqs. (2.35), it follows that the production cross-sections of W and Z at the Collider are seven orders of magnitude smaller than the total inelastic cross-section of about 50 mb [40]. The events which constitute the bulk of this cross-section are called ‘minimum-bias’ events, simply because they are collected in an experiment where no selection bias was applied.

Most of these events are produced in strong-interaction processes with low momentum transfer. As a result of the softness of the interaction, perturbative QCD is no longer applicable in these events, which is why only phenomenological descriptions of the particle production mechanism exist so far [41]. Without going into detail, we may assume, in a naïve approach, that after such a soft collision the remaining parts of the proton and antiproton are no longer colour-neutral, and that in the formation of a colour field between these separating fragments, quark–antiquark pairs are produced which further fragment into hadrons. On the average, about 45 charged and neutral hadrons, usually with low transverse momentum ($\langle p_T \rangle \approx 0.4 \text{ GeV}/c$), are emitted in these events [40, 42].

Also in events where a W or Z boson was formed, the remains of the proton and antiproton (both having ‘lost’ a quark) are not colour-neutral. We therefore expect that besides the highly energetic decay products from the IVBs (and eventually a particle jet due to higher-order QCD processes in the IVB production), soft particles are produced, constituting the ‘underlying event’ with a structure similar to that of a minimum-bias event. A discussion of this topic may be found in Ref. [43].

It is plausible that any detector designed for a study of W or Z production not only has to identify the boson by the reconstruction of its decay products but also must be able to pick out the events in which IVBs were produced.

3. THE UA1 AND UA2 EXPERIMENTS AT CERN

3.1 The $p\bar{p}$ Collider

In 1976, C. Rubbia put forward a suggestion to transform the Super Proton Synchrotron (SPS) at CERN into a storage ring with counter-rotating proton and antiproton beams [6]. At that time there was no accelerator available, or under construction, which would generate centre-of-mass (c.m.) energies high enough to produce W's and Z's. For example, the CERN Intersecting Storage Rings (ISR) provided proton-proton collisions at maximum $\sqrt{s} \approx 63$ GeV; the fixed-target proton accelerator at FNAL and the one at CERN (the SPS) achieved typically 25 GeV; and the e^+e^- colliders at SLAC (PEP) and at DESY (PETRA) were designed for ~ 40 GeV c.m. energies.

With a maximum beam energy of 450 GeV, the SPS, as a collider, can generate 900 GeV in the c.m. system. This was achieved during a specially scheduled running period in 1985, when the beam energies were varying between 115 GeV and 450 GeV with a period of 21.6 s [44]. However, to achieve the highest possible collision rates, the beams had to coast at a fixed energy. Because of the limited cooling capacity of the bending magnets, this energy was lower than 450 GeV: in the 1981–1983 Collider runs it was 273 GeV, and in 1984 and 1985, 315 GeV, yielding $\sqrt{s} = 546$ and 630 GeV, respectively.

In these years of Collider operation, the luminosity (which determines the rate at which an interaction with the cross-section σ takes place),

$$dN/dt = L\sigma, \quad (3.1)$$

was increased by a factor of almost 10^5 , from $6 \times 10^{24} \text{ cm}^{-2} \text{ s}^{-1}$ in the very first Collider run in 1981, to the maximum of $4 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ in 1985. From Eq. (3.1) it is clear that because of the very small production cross-section of IVBs at the Collider (see Sections 2 and 5), only long runs at the highest luminosities would yield sufficient data to allow a detailed study of their properties.

In terms of accelerator-related parameters, the luminosity is given by the simplified expression

$$L = \frac{N_p \cdot N_{\bar{p}}}{A} f, \quad (3.2)$$

where

$N_{p(\bar{p})}$ is the number of protons (antiprotons) per bunch,

f is the rate of bunch crossings in the detector (1.3×10^5 Hz at the Collider),

A is the effective cross-sectional area of the two beams in the interaction region.

High luminosities were achieved by reducing the beam size, using focusing magnets near the interaction region, and by circulating the maximum number of protons and antiprotons. Typical values are shown in Table 1. Whilst protons were available from ionizing hydrogen in any required quantity, antiprotons had to be produced in high-energy interactions, collected up to a sufficiently large number, and compressed into bunches ('cooled') which were to circle in the Collider. The technique of stochastic cooling was invented by S. van der Meer in 1972 [45] and further developed in the subsequent years [46, 47]. A detailed description of the production, storage, and acceleration of protons and antiprotons and of the commissioning of the CERN Collider is given in the reports listed in Refs. [48] and [49].

The layout of the CERN accelerators is shown in Fig. 8 [ignoring the Large Electron-Positron Collider (LEP), which is at present under construction]. So far, eight experiments, UA1 to UA8 (UA = underground area), have been accepted for data-taking at the $p\bar{p}$ Collider [50–52], and installed at or close to the two interaction areas LSS4 and LSS5. Only UA1 and UA2, however, are designed to detect the IVBs.

3.2 Status of the experiments UA1 and UA2 up to 1986

3.2.1 The UA1 detector

UA1 was conceived as a general-purpose detector to be used for exploring all physics phenomena occurring in the new energy range at the Collider. The detector was therefore designed to allow full reconstruction of a $p\bar{p}$ event by energy or momentum measurement of possibly all secondary particles produced in the collision, and to identify electrons and muons produced, for instance, in IVBs or heavy-quark decays. The layout shown schematically in Fig. 9 is that of a large tracking chamber around the interaction region, immersed in a magnetic field, and with hermetic e.m. and hadronic calorimeters covering all polar angles of more than 0.2° from the beam direction. This set-up is surrounded by iron absorbers and chambers for muon detection; for a detailed description, the reader is referred to Refs. [50], [53], and [54]. In the following, the basic detector elements are briefly reviewed. A few technical parameters are shown in Table 2.

3.2.1.1 The Central Detector and the magnet. The central piece in the experiment, the Central Detector (CD), consists of a set of six drift chambers arranged cylindrically around the vacuum beam pipe. In its sensitive volume of 5.8 m length and 2.3 m diameter, the CD records charged-particle trajectories covering polar angles from 5° to 175° with respect to the beam axis ($-4 \leq \eta \leq 4$)*). The orientation of the wire planes is such that there would be an approximately constant density of points along the tracks (an average of ~ 110 per track) over all the detector volume, taking into consideration the event topology in $p\bar{p}$ interactions. The three coordinates of any track point are given by i) the location of the corresponding sense wire, ii) the position along the wire obtained by charge division, and iii) the time taken by the electrons to drift towards the sense wire. Whereas the wire position is well known, the charge-division method is precise to typically 1.7% of the wire length, i.e. to a few centimetres. The accuracy of the drift-time coordinate is limited by diffusion of the drifting electrons in the chamber gas, and amounts, on the average, to $290 \mu\text{m}$.

The sign of the charge and the momentum of the particle are determined by the curvature of the track in the horizontal, 0.7 T, magnetic dipole field; the precision of the momentum measurement is limited by the accuracy of the track reconstruction, and is given by

$$\sigma(p) = 0.005p^2 \text{ (p in GeV/c)} . \quad (3.3)$$

This results in a typical relative accuracy of $\pm 20\%$ for a 1 m long track with $p = 40 \text{ GeV/c}$ (as expected from W or Z decay) in the plane normal to the magnetic field. There is, of course, no momentum measurement for particles emitted horizontally in the plane parallel to the magnetic field.

The energy loss (dE/dx) of particles in the chamber gas is derived from the total charge of the pulse from the sense wire, and is determined with a precision of $\sim 6\%$. This allows $p/K/\pi$ separation for low-momentum tracks, as well as the tagging of two overlapping tracks.

Two tracks can be reconstructed separately if their projection in the plane normal to the magnetic field is more than 5 mm apart.

3.2.1.2 The electromagnetic calorimeter. The CD is tightly enclosed within two sets of e.m. calorimeters: the ‘gondolas’, covering the side of the CD and thus an angular range of $25^\circ < \theta < 155^\circ$; and the ‘bouchons’ at both ends, with an angular range of 5° to 25° and 155° to 175° , respectively.

*) The pseudorapidity $\eta = -\ln \tan \theta/2$.

The gondolas are each composed of a set of 24 independent half-rings located on either side of the beam, each half-ring (cell) being 22.5 cm wide and covering almost 180° in azimuth. A cell consists of alternating layers of lead and scintillator plates, adding up to a thickness of 26.6 radiation lengths (X_0) at normal incidence, subdivided in depth into four independent segments with 3.3, 6.6, 10.1, and 6.6 X_0 .

The scintillation light from each of the four segments is collected by wavelength-shifting plates on each side of the cell and guided to photomultipliers (PMs). Each segment is read out by four PMs, two at each end. Light division between the four PMs is used to locate the position of the shower with a precision of $\sigma(\phi) \approx 0.3/\sqrt{E}$ rad in azimuth and $\sigma(x) \approx 6.3/\sqrt{E}$ cm in the beam direction, E being the energy of an e.m. shower in GeV. The total light collected from an e.m. shower, which in most cases is completely contained within the 26.6 X_0 of the gondola, is directly proportional to the energy of the incident electron (positron) or photon, which is determined with a precision of

$$\sigma(E) \approx 0.15 \sqrt{E} . \quad (3.4)$$

A comparison of Eq. (3.4) with Eq. (3.3) shows that energy measurement done with calorimetry is usually superior, at high particle momenta, to momentum measurement from curvature in a magnetic field. However, this does not hold for muons which are normally not absorbed in the calorimeter.

From the layout of the gondolas it follows that two e.m. showers hitting one cell simultaneously will be misreconstructed as one shower, with false energy assignment, located between the two points of impact. This effect results in an important source of background for events with missing transverse energy E_T , which, however, can be overcome by a set of topological cuts (see Section 4).

The bouchons are each divided into 32 azimuthal sectors located 3 m from the interaction point. Each sector consists of a 26.7 X_0 thick lead/scintillator sandwich, segmented four times in depth (3.6, 7.2, 8.7, 7.2 X_0), each segment being read out from behind by one PM. A position detector made of proportional tubes is situated at a depth of 11 X_0 to measure the position of e.m. showers with a precision of ~ 2 mm. The precision of the e.m. energy measurement in the bouchon is

$$\sigma(E) \approx 0.16 \sqrt{E} . \quad (3.5)$$

The absolute energy scale of the bouchons and gondolas is obtained by illuminating the e.m. calorimeter cells with a 5 Ci ^{60}Co source at the beginning and end of each data-taking period. A small number of e.m. cells have been calibrated directly with electron beams of known energy from the CERN SPS; the other e.m. cells are then adjusted so that their response to the ^{60}Co source is the same as that of the calibrated cells.

Since the $p\bar{p}$ Collider came into operation it has been found that the photon yield of the scintillation material has diminished owing to radiation damage. This time-dependent response introduced uncertainties in the calibration and a reduction in resolution to about $0.21 \sqrt{E}$, an effect which makes it imperative to use different, more resistant readout material for experiments in higher-luminosity hadron colliders (see also Section 8).

3.2.1.3 The hadron calorimeter. The yoke of the magnet, which completely surrounds the e.m. calorimeter and coil, is composed of alternating iron and scintillator plates, 5 cm and 1 cm thick respectively. This yoke constitutes the hadron calorimeter. The scintillators, which are read out via wavelength shifters (WLSs) and PMs outside the yoke, are grouped in depth into cells with two segments, each segment being 2.5λ thick in the central region and 3.5λ thick in the forward regions (λ

$\equiv$ interaction length). The hadron calorimeter has 450 cells, each cell having a typical opening angle of $15^\circ \times 18^\circ$ in the central region and $5^\circ \times 10^\circ$ in the forward regions. The energy resolution of the hadron calorimeter is

$$\sigma(E_{\text{had}}) = 0.8 \sqrt{E_{\text{had}}} . \quad (3.6)$$

A better resolution is achieved by including the information from the e.m. calorimeters (1.1 λ) at lower hadron energies.

There is, in addition, forward and very forward e.m. and hadronic calorimetry, extending to ± 6.3 units in pseudorapidity. In Fig. 10, the total absorption length is plotted versus the polar angle θ and the pseudorapidity η , illustrating the hermeticity of the UA1 detector. There are, however, small cracks in the azimuthal acceptance where the detector opens up. This deficiency is overcome by making acceptance cuts (see Section 4).

This hermetic coverage allows us to infer from the apparent lack of momentum conservation in the two components transverse to the beam direction, i.e. missing E_T ($\cancel{E}_T$), that a neutrino (or other weakly interacting particle) was emitted in the event. The $\cancel{E}_T$ is simply defined as the vector sum of the transverse energies of all the individual calorimeter cells. Since a sizeable fraction of the total energy in the interaction is carried by particles that do not leave the vacuum pipe inside the detector, the longitudinal motion of the ‘neutrino’ cannot be determined. The accuracy of $\cancel{E}_T$ is $0.7 \sqrt{E_T}$, where E_T is the scalar sum of the transverse energies deposited in all the calorimeter cells.

3.2.1.4 Muon chambers. The e.m. and hadron calorimeters together with the magnet coil act as a particle filter. In addition, the magnet is surrounded by partially magnetized iron absorbers, 40 cm to 120 cm thick. Only muons with a momentum greater than 3 GeV/c, and weakly interacting particles such as neutrinos, can pass, the former leaving a track in one of the 34 muon chambers [55]. With the exception of the modules on the bottom, each unit is about 4 m $\times$ 6 m in size and consists of two chambers. Each chamber has four layers of drift tubes which define two orthogonal coordinates, these being determined with a resolution of 300–700 μm . The two chambers in a module are 60 cm apart, giving a good lever arm for extrapolating a muon track back to the interaction vertex. The muon detection system covers the polar angle interval $5^\circ < \theta < 175^\circ$ and $\sim 75\%$ of the azimuth. After 1983, layers of proportional tubes [56] were inserted between the muon chambers and the hadron calorimeter, thus providing additional reconstructed points on the trajectory of a muon.

3.2.2 The UA2 detector

UA2 was designed as a compact detector capable of finding the IVBs through their decay mode into electrons [51]. Furthermore, the detector had to be sufficiently versatile to allow the study of high- p_T jets, of heavy quark production, and possibly of exotic phenomena. The layout (shown in Fig. 11) comprises: highly segmented, precise e.m. and hadronic calorimetry in a limited polar acceptance range; two toroidal magnets in the forward direction to measure, for instance, the charge asymmetry in the $W \rightarrow e\nu$ decay; and a small vertex chamber in the centre. For a detailed description, see Refs. [57] and [58].

3.2.2.1 The vertex chamber. This central detector element is a system of cylindrical proportional and drift chambers surrounding the $p\bar{p}$ interaction point. Charged-particle trajectories are measured in a polar acceptance range of about 20° to 160° . The coordinates in the beam direction are determined by charge division to a precision of 1% of the wire lengths, and in the azimuth by drift-time measurement to a precision of $\sim 300 \mu\text{m}$. The interaction point is reconstructed to within 1 mm uncertainty.

The drift chambers are surrounded by a $1.5X_0$ thick tungsten converter followed by a proportional chamber. This preshower detector provides the necessary spatial resolution to separate charged tracks and photons that hit one calorimeter cell simultaneously and thus fake an electron.

3.2.2.2 Calorimetry. The UA2 calorimeter is divided into two regions. In the central region ($40^\circ < \theta < 140^\circ$), each of the 240 e.m. and hadronic calorimeter cells subtends 10° in θ and 15° in ϕ , the front face being located 60 cm away from the centre of the interaction region. Each cell has the shape of a truncated pyramid with the imaginary peak located at its centre, thus minimizing the energy-sharing between adjacent cells. It is segmented in depth into one e.m. compartment made out of lead/scintillator sandwich ($17.5X_0$), and two hadronic compartments of iron/scintillator sandwich ($\sim 4\lambda$), the whole being ~ 4.5 absorption lengths deep. As in the UA1 experiment, the scintillators are read out via WLS bars, the PMs being fixed behind the corresponding cell.

Each forward calorimeter (20° to 37.5° and 142.5° to 160°) consists of 120 independent e.m. calorimeter cells of lead/scintillator sandwich, each cell being segmented into two parts in depth, $24X_0$ and $6X_0$ thick.

Each calorimeter cell was initially calibrated in a 10 GeV/c electron beam, and the energy resolution for isolated electrons was measured to be, on the average,

$$\sigma(E) \approx 0.14 \sqrt{E} . \quad (3.7)$$

After an operating period of more than five years, the uncertainty on the absolute scale of the e.m. energy measurement was found to be $\pm 1.5\%$, with an additional cell-to-cell calibration uncertainty of 2.5% [59]. The corresponding numbers for hadronic energy measurement are 3% and 8%.

3.2.2.3 Forward detectors. The two forward regions (see Fig. 11) are each equipped with 12 toroidal magnet segments having a mean field integral of 0.38 T·m. Three drift chambers are installed behind each segment, thus allowing reconstruction of charged-particle tracks with $200 \mu\text{m}$ resolution per point. In association with the vertex chamber, a momentum measurement with a resolution

$$\sigma(p) \leq 0.02p^2 \quad (3.8)$$

is possible. The chambers are followed by preshower chambers which allow e.m. showers to be localized with a precision of $\lesssim 8$ mm. The forward e.m. calorimeter is installed behind the chambers.

The UA2 detector has no coverage in the forward direction, i.e. at polar angles of less than 20° or more than 160° , so particles emitted in this region can fake the presence of $\cancel{E}_T$. As expected from the kinematics, the probability that a particle gets lost decreases as its p_T increases, which implies that the background to genuine neutrinos reduces with increasing $\cancel{E}_T$.

3.3 Trigger and data-taking

At a luminosity of $4 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$, the $p\bar{p}$ interaction rate is about 25 kHz [60]. In comparison, the event rate that UA1 and UA2 can record on tape is typically 3–5 Hz, so it is necessary to have a fast selection of the events that are of interest. In fact, since already in the subsequent bunch crossing (after $7.6 \mu\text{s}$) an interesting event may occur, the trigger decision has to be made beforehand.

Both experiments use a set of scintillation hodoscopes grouped in the forward directions to select inelastic $p\bar{p}$ collisions and to reject events faked by beam-gas or beam-halo interactions in the

vacuum chamber. This pretrigger accepts typically about 95% of all inelastic $p\bar{p}$ events and is therefore called the ‘minimum-bias trigger’. Data were taken with just this trigger requirement at lower luminosities in order to study soft $p\bar{p}$ interactions, and also to search for exotic phenomena such as ‘Centauro’ events found in cosmic-ray experiments [40].

In coincidence with a pretrigger, further selections were made by applying the following requirements:

UA1 triggers [61]:

- Single electron: the presence of two adjacent e.m. calorimeter cells (‘clusters’) with a total E_T greater than a threshold value (typically 10 GeV).
- Dielectron: two clusters with $E_T > 6$ GeV in adjacent e.m. cells.
- Jet: $E_T > 25$ GeV in four adjacent e.m. cells or four hadronic cells.
- High scalar E_T : total E_T in the central calorimeters > 80 GeV.
- Missing transverse energy: left-right E_T imbalance > 17 GeV in association with a jet of $E_T > 15$ GeV.
- Muon trigger: the presence of a track, in the outer muon chambers, which points back to the interaction vertex within a cone of 150 mrad aperture.

The individual contribution of these triggers to the data-taking is shown in Table 3 [62].

UA2 triggers [63]:

- $W \rightarrow e\nu$ trigger: the presence of $E_T > 10$ GeV in any 2×2 cell matrix in the e.m. calorimeter.
- $Z \rightarrow e^+e^-$ trigger: the presence of two deposits of e.m. E_T , each deposit exceeding 5 GeV, in 2×2 cell matrices separated in azimuth by at least 60° .
- Jet trigger: at least 25 GeV (later 35 GeV) of E_T in the e.m. and hadronic calorimeters.

During a typical three-month running period, the experiments recorded and analysed several million events. The values of integrated luminosities accumulated in each Collider run are listed in Table 4, which indicates how the performance of the Collider increased from year to year. In total, UA1 collected data corresponding to 732 nb^{-1} and UA2 recorded 910 nb^{-1} .

4. DETECTION OF W AND Z BOSONS

The W and Z bosons are identified by the kinematic reconstruction of their decay products. The decay modes and corresponding branching ratios are predicted by the Standard Model (see Section 2) under the assumption that only three quark and lepton generations are involved in the process and, furthermore, that a certain mass is assigned to the top quark. With the assumption that $m_t = 44 \text{ GeV}/c^2$ we estimate that, in total, about 4900 W's and 1500 Z's were produced during the data-taking in UA1 and 6300 W's and 1900 Z's in UA2 (UA2 has accumulated more data than UA1, see Table 4). Even though less than a fourth of the IVBs decay into lepton pairs (owing to the colour degree of freedom of the quarks), the identification of these decay modes is most straightforward since the electron (positron), muon, and even the tau in association with a neutrino have very distinct signatures in the detectors and can be well separated from all known sources of background. The quarks and antiquarks from the hadronic IVB decay, however, each fragment into a particle jet, and therefore the topology of the event is very similar to that of a two-jet event from hard parton-parton scattering, which has a two-orders-of-magnitude higher cross-section in the corresponding p_T range [9]. Only UA2 found a resonance-like structure in the two-jet mass spectrum around the mass of the IVBs (see below).

Both experiments searched for IVB decay modes not predicted by the Standard Model, as will be outlined in the last two parts of this section.

4.1 IVB decays into leptons of the three known generations

The general topology of an event with a leptonic W or Z decay is the presence of a pair of high- p_T leptons standing out from a distribution of particles with generally low p_T , the latter forming the 'underlying event'.

Both UA1 and UA2 have detection capabilities for electrons and, in an indirect way, for neutrinos, as described in Section 3. In addition, UA1 has muon identification and is capable of selecting taus through their hadronic decay modes, although with significantly smaller efficiency than in the electron selection. (UA2 has too poor an E_T resolution to select $W \rightarrow \tau\nu$.)

The samples of, in total, about 660 W and 90 Z candidates with their corresponding efficiencies, background contributions, and integrated luminosities are summarized in Tables 5 and 6 [28, 29]. The way in which the individual W and Z samples were obtained through a process of successive selection steps, each step suppressing a different background topology, is described in detail in Refs. [64] and [29], and is summarized in Ref. [65]. The final samples were always validated using a graphics device [66].

4.1.1 Identification of events satisfying the $W \rightarrow e\nu$ or $Z \rightarrow e^+e^-$ hypothesis

Both detectors use somewhat similar electron identification criteria to exclude the dominant background arising mainly from two-jet events. In UA1 the electrons are identified by their characteristic shower profile in the four depth segments of the e.m. calorimeter. Any leakage into the hadron calorimeter, which is behind the e.m. one, was required not to exceed 600 MeV in the central region and 1.5 GeV in the forward regions. This cut suppresses background from high- p_T hadrons and, in most cases, also from photons (π^0 's) overlapping charged hadrons. In addition, there is the requirement of an associated track in the CD, pointing to the cluster. In the case of W and Z selection, the track and the associated e.m. cluster have to satisfy appropriate isolation requirements to ensure that the electron candidate does not come from a semileptonic heavy-quark decay. The p_T of the track has to exceed 7 GeV/c, and the E_T of the cluster must be more than 15 GeV.

The requirements for W selection are: i) a transverse energy imbalance of $E_T > 15 \text{ GeV}$ (signalling the presence of a neutrino); and ii) the momentum vector of the missing energy not

pointing to within $\pm 15^\circ$ of the vertical axis or in the direction of jet activity. The latter cut helps to avoid fake energy imbalance caused by cracks in the detector acceptance.

Figure 12a shows an event with a candidate decay $W^- \rightarrow e^- \bar{\nu}$ found by UA1. An energetic electron is seen recoiling against a neutrino (only the transverse component of its momentum is known). The lepton pair is clearly visible in the background of low-momentum particles which are—in the case of charged particles—recognized by their large curvature in the magnetic field.

For Z selection the presence of a second electron candidate is required, with slightly relaxed selection criteria to enhance the statistics, and the invariant mass of the resulting e^+e^- system has to exceed $70 \text{ GeV}/c^2$ [64]. An event with a candidate $Z^0 \rightarrow e^+e^-$ is shown in Fig. 12b.

In UA2 the emission of an electron is signalled, as in UA1, by an e.m. calorimeter cluster, having small lateral dimension and energy leakage in the hadronic compartment, and with a charged track pointing towards the cluster [29]. In the forward direction the reconstructed track momentum must be consistent with the energy of the cluster. In addition, a hit must be recorded in the preshower counters. It has to be aligned with the reconstructed track and have a pulse height characteristic of an electron shower.

Because of the poorer $\cancel{E}_T$ resolution, the selection criteria for the final W sample are slightly more strict than those in UA1, setting a transverse energy threshold for electrons, $E_T > 20 \text{ GeV}$, and a transverse mass threshold of the $(e\nu)$ system, $m_{T}^{e\nu} > 50 \text{ GeV}/c^2$, where

$$m_{T}^{e\nu} = \sqrt{2E_T^e \cdot \cancel{E}_T (1 - \cos \Delta\phi)}, \quad (4.1)$$

with $\Delta\phi$ the angle between the electron and the neutrino in the transverse plane.

The case of Z selection requires the presence of a second electron candidate, with selection criteria that are less strict than those for the first one, and with $m_{e^+e^-} > 76 \text{ GeV}/c^2$.

Figure 13 shows an event with a candidate $Z \rightarrow e^+e^-$ found by UA2. Here also, the underlying event has little activity. However, it should be noted that in a sizeable fraction of events the IVB recoils against an energetic jet (see Section 6), in which case the underlying event is quite active.

Taking into account the different detector acceptances and the amounts of data collected, it turns out that the overall background reduction factor resulting from the W and Z selection cuts is about 40,000 [67]. The background remaining in the W sample of UA1 derives mainly from $W \rightarrow \tau\nu$, with $\tau \rightarrow e\nu\bar{\nu}$, and with a small contribution from misidentified jet events or from heavy-flavour production. In UA2 the main contribution is from two-jet events or semileptonic heavy-flavour decays, or even from Z decays with one jet or electron satisfying the electron selection criteria, the other one being emitted in the direction where UA2 has no coverage.

The Z samples have negligible background, and this is mainly from misidentified jet events.

The W samples are plotted in the form of transverse mass distributions of the $(e\nu)$ system (Fig. 14 for UA1 and Fig. 15 for UA2), with the background being indicated separately. In Figs. 16 and 17 the electron-pair mass distributions of Z candidates found by UA1 and UA2 are displayed. In both cases the Z resonance is clearly seen at $\sim 90 \text{ GeV}/c^2$, well separated from the background from jet events and Drell-Yan pairs produced at lower masses. (Figures are taken from Refs. [28, 29, and 68].) The curves in Figs. 14 and 15 represent Monte Carlo simulations of $W \rightarrow e\nu$ including the background processes mentioned, normalized to the number of events measured.

4.1.2 The muon channel

The signature for a muon in the UA1 detector is the existence of a charged track in the CD matched with a track reconstructed in the muon chambers [54, 69].

The momentum of the muon is determined from the curvature of the trajectory in the dipole field of the UA1 magnet, from the deflection in the hadron calorimeter (which has a magnetic field since it forms the flux return yoke of the dipole), and in the magnetized iron absorbers (if they are traversed). The $W \rightarrow \mu\nu$ events are selected by demanding a muon with $p_T > 15$ GeV/c in association with $E_T > 15$ GeV, whilst for $Z \rightarrow \mu^+\mu^-$ a second muon candidate with $p_T > 15$ GeV/c is required. To suppress background from heavy-flavour decays or jets, the muon has to be isolated, in both the CD and the calorimeter. It has to be well separated in space from any significant jet activity. Another important source of background comes from the decays of charged pions or kaons in flight. This source is removed by some technical cuts on the track quality, or is identified, during a visual inspection of the event, by the characteristic ‘kink’ at the decay vertex. Almost all cosmic-ray muons, which make up part of the background to $Z \rightarrow \mu^+\mu^-$, are rejected either because they did not go through the reconstructed collision vertex or because they crossed the detector at a slightly different time than the beam-crossing time t_0 . In the latter case, the track segments in the individual CD segments, being reconstructed under the hypothesis that the muon tracks were formed at t_0 , do not line up.

All events with $W \rightarrow \mu\nu$ candidates produced at $\sqrt{s} = 630$ GeV are plotted in the transverse mass distribution shown in Fig. 18. The dominant contribution to the background (hatched area) is again from $W \rightarrow \tau\nu$ events, where $\tau \rightarrow \mu\nu\bar{\nu}$. The long tail in the distribution towards large m_T is due to the momentum measurement error; this increases as p_T increases and as the direction of the emitted particle approaches that of the magnetic field lines.

The $Z \rightarrow \mu^+\mu^-$ sample is displayed in Fig. 19, which also includes J/ψ and Υ candidates at lower dimuon mass values. Again, as in the case of the $Z \rightarrow e^+e^-$ sample, the muonic Z decays can be well separated from background, which includes a small contribution from Drell–Yan muon pairs.

4.1.3 The tau channel

Topologically, $W \rightarrow \tau\nu$ events are characterized by a single jet emitted approximately back-to-back with significant missing energy. The jet from the τ decay has in most cases a low charged-particle multiplicity and a sizeable hadronic and e.m. energy component, since the dominant decay modes are

$$\begin{aligned}\tau^\pm &\rightarrow \bar{\nu}_\tau + \pi^\pm + n \cdot \pi^0 && \text{(one prong) ,} \\ \tau^\pm &\rightarrow \bar{\nu}_\tau + \pi^+\pi^- + \pi^\pm + n \cdot \pi^0 && \text{(three prongs) .}\end{aligned}\tag{4.2}$$

Because of the low τ mass, the jet is collimated in a narrow cone.

The $W \rightarrow \tau\nu$ sample is extracted [70] from recorded events which satisfied one or more of the following hardware triggers (see also subsection 3.3):

- an electron trigger (same as for the IVB electron channel);
- a jet trigger, requiring a calorimeter jet with $E_T > 25$ GeV in $|\eta| < 2.5$;
- a E_T trigger, requiring a jet with $E_T > 15$ GeV together with a E_T imbalance of 17 GeV.

In a further selection to obtain a clean sample of events with jet-like activity and E_T , all events have to satisfy $E_T > 15$ GeV and $N_\sigma > 4$, where N_σ is the significance of the missing-energy measurement, defined as the ratio of E_T and of the overall E_T resolution,

$$N_\sigma = E_T / 0.7 \sqrt{\Sigma E_T},\tag{4.3}$$

ΣE_T being the scalar sum of the transverse energy observed in all calorimeter cells. As in the $W \rightarrow e\nu$ or $W \rightarrow \mu\nu$ selection, E_T is required to be isolated and must not point towards the vertical crack in the detector; furthermore, events with coplanar jet activity are ignored.

To remove contributions from $W \rightarrow e\nu, \mu\nu$, or heavy-flavour semileptonic decays, events with an electron or muon candidate are vetoed. Finally, additional technical cuts are applied to remove background events such as cosmic rays, beam halo, and double interactions [70].

The $W \rightarrow \tau\nu$ decays are then extracted from the resulting sample of 56 events by requiring the jet to be pencil-like, with low charged multiplicity, and to satisfy good spatial matching between the calorimeter and the CD jet. These three properties are described by three variables that are particularly suitable for separating high- p_T τ jets from ordinary QCD jets; they form a combined function which defines the likelihood L_τ that an observed jet has the same topology as a τ decay. In Fig. 20 the total sample satisfying $N_\sigma \geq 4$ is shown as a scatter-plot of L_τ versus the jet E_T . From the projection for L_τ it can be seen that above $L_\tau = 0$ the number of τ candidates is significantly higher than the predicted background (hatched area); all 32 events with $L_\tau > 0$ are chosen to form the final τ -sample.

The background contribution as well as the selection efficiency are estimated, as in the case of the electron and muon channels, from extensive Monte Carlo calculations simulating full $p\bar{p}$ collisions and the response of the detector [71]. The dominant sources of background are found to come from

- QCD jet fluctuations;
- $W \rightarrow e\nu, W \rightarrow \mu\nu$, or $W \rightarrow \tau\nu \rightarrow$ leptons, where the electron or the muon is not identified and a large- p_T jet is produced; the lepton may be below threshold, or outside the acceptance, or, in the case of the electron and the τ , buried within a jet;
- $W \rightarrow \bar{s}c$, where one or both of the quarks decay semileptonically;
- $Z \rightarrow \tau^+\tau^-$; $Z \rightarrow c\bar{c}$ or $b\bar{b}$, where one or both of the quarks decay semileptonically;
- direct production of $c\bar{c}$ or $b\bar{b}$, where one or both of the quarks decay semileptonically;
- $Z \rightarrow \nu\bar{\nu}$, where the Z is produced at high p_T and is balanced by one or more gluon jets.

This adds up to 2.7 ± 0.6 background events in the region $L_\tau > 0$, and leaves a signal of 29.3 ± 5.7 events, which is compatible with the Monte Carlo prediction of 28.7 ± 1.5 $W \rightarrow \tau\nu$ events.

A nice event with a $W^- \rightarrow \tau^- \bar{\nu}$ decay candidate is shown in Fig. 21. The three high- p_T charged tracks form a system with an invariant mass of $0.99 \text{ GeV}/c^2$; they point towards an e.m. and hadronic energy deposition in the calorimeter (not shown in the figure). Note that all the other charged tracks in the event have low p_T .

A technique similar to that described above could be applied in order to search for $Z \rightarrow \tau^+\tau^-$. These decays would be characterized by a pair of jets with an invariant mass of $\leq m_Z$ and each jet satisfying $L_\tau > 0$, or by one jet ($L_\tau > 0$) and an isolated electron or muon, or by a pair of isolated electrons or muons, in all cases in association with missing energy from the τ -decay neutrino. There exist events in the UA1 data sample which are compatible with $Z \rightarrow \tau^+\tau^-$ decays, but which suffer from low statistics because of the strict selection criteria applied, and also from the high background from dijet or heavy-flavour production.

4.2 Decays into quark-antiquark pairs of the three known generations

The observation of leptonic IVB decays in $p\bar{p}$ collisions at predicted rates verifies the Standard Model coupling of W/Z to light quarks. It is nevertheless of interest to observe the decay of IVBs into quark-antiquark pairs in order to achieve, if possible, a more precise determination of weak coupling to quarks at high momentum transfers ($q^2 \approx m_{IVB}^2$). In its two-jet data taken at $\sqrt{s} = 630 \text{ GeV}$, UA2 observed an enhancement (Fig. 22) in the invariant mass distribution in the region $65 \text{ GeV}/c^2$ to $105 \text{ GeV}/c^2$, after having applied a few acceptance cuts and jet selection criteria [72]. The mass resolution of 10% is not sufficient to separate the W and Z signals (since their mass difference is too small compared with this resolution), but nevertheless makes it possible to extract a signal with a significance of 3σ above a large QCD background. Note, however, that an upward

statistical fluctuation of the signal, counting 632 ± 190 events compared with the expectation of 340 ± 80 events, increased the significance by 1.4σ . In UA1 the high trigger threshold on jet energies did not allow the study of jet-jet masses below $\sim 70 \text{ GeV}/c^2$, thus leaving too short a lever arm below m_W to find a resonance-like structure on top of the large QCD background.

UA1 has tried to extract a W or Z signal from the semileptonic decay into muons of heavy flavours deriving from $W \rightarrow c\bar{s}$, $Z \rightarrow b\bar{b}$, $c\bar{c}$ [73]. It turns out that the expected signal, after all cuts on background, is too small to be significant.

The above results indicate that multijet spectroscopy, which it is anticipated will be an important tool at future colliders and for which W and Z jet decays could provide a mass calibration, is within the scope of UA1 and UA2 and could be performed with the higher-resolution upgraded detectors (see Section 8). Efficient flavour-tagging with little background will, however, require more sophisticated detector technology than is at present available.

Finally, the question arises whether the t-quark has a sufficiently low mass for it to appear in the decays

$$W^+ \rightarrow t\bar{b}, \quad W^- \rightarrow \bar{t}b, \quad \text{and} \quad Z \rightarrow t\bar{t}. \quad (4.4)$$

Whereas, given the lower mass limit quoted by UA1, it seems unlikely that the Z will decay into top, the corresponding W decay modes cannot be ruled out. The uncertainty on the top mass has implications for the cross-section determination of IVBs, as will be discussed in the following subsections.

4.3 Search for IVB decays into leptons and quarks of higher generations

Intermediate vector bosons, once they are produced in a collision, open up a previously unexplored mass range in which to search for massive particles not predicted by the Standard Model.

4.3.1 Fourth-generation quarks and leptons

Direct searches in e^+e^- collisions at PETRA for fourth-generation quarks and charged leptons have placed a limit of m_L and $m_Q > 22.7 \text{ GeV}/c^2$ (90% CL) [74].

i) At the CERN $p\bar{p}$ Collider, fourth-generation quarks may be produced either via strong interaction

$$p\bar{p} \rightarrow Q\bar{Q} + X, \quad (4.5)$$

or in the decay of an IVB. (It is assumed that they have the same strong, e.m., or weak coupling as have the known quarks.) From an unsuccessful search for b' (charge $1/3$ fourth-generation quark) via its semileptonic decay mode, UA1 has deduced a lower mass limit [26],

$$m_{b'} > 32 \text{ GeV}/c^2 \quad (90\% \text{ CL}). \quad (4.6)$$

Assuming that the weak isospin partner of b' , the t' , is much more massive, the mode $W^+ \rightarrow t'\bar{b}'$ (or charge conjugate), seems unlikely. On the other hand, the decay mode $Z \rightarrow b'\bar{b}'$ cannot be ruled out, since the lower mass limit is smaller than $m_Z/2$. Taking into account the phase-space limitations in this decay, we expect a branching fraction for $Z \rightarrow b'\bar{b}'$ of less than $\sim 6\%$.

ii) A fourth-generation charged lepton will be best identified in the process

$$p\bar{p} \rightarrow W^- + X \\ \quad \hookrightarrow L^- \bar{\nu}_L,$$

followed by

$$L^- \rightarrow \bar{c}s\nu_L \quad \text{or} \quad L^- \rightarrow \bar{u}d\nu_L \quad (4.7)$$

(and charge conjugate) since it has a clear signature: the presence of one or two energetic jets in association with significant E_T . The jet is expected to be less narrow and to contain, on the average, more charged particles than in the case of a τ decay, since it is supposed to come from the decay of a system with a mass greater than $22.7 \text{ GeV}/c^2$. Since the heavy lepton derives from the two-body decay of the W , its transverse momentum, and, hence, the transverse energy of the jet(s), will in general be smaller than $1/2 m_W c^2$ (neglecting the transverse motion of the W). In their sample of jet + E_T events, UA1 found 17 events [75] where $L_\tau < 0$ and $E_T^j < 40 \text{ GeV}$ (see Fig. 20). To illustrate the topology of such events in the UA1 detector, a ‘monojet’ candidate with $E_T^j = 43 \text{ GeV}$ is shown in Fig. 23. This number of events and their jet- E_T distribution is fully reproduced by Monte Carlo simulations of background processes of conventional origin, deriving mainly from $W \rightarrow \tau\nu$ or $Z \rightarrow \nu\bar{\nu}$, where the Z recoils against a radiated gluon, or from jet fluctuation.

This leaves no place for a significant lepton signal, as illustrated in Fig. 24 where the jet- E_T for background-subtracted data satisfying $L_\tau < 0$ is plotted. The distribution from a heavy lepton with $m_L = 35 \text{ GeV}/c^2$, as indicated in this figure, would clearly stand out from the background, whereas a lepton with $55 \text{ GeV}/c^2$ mass cannot be ruled out. UA1 finds a limit of $m_L > 41 \text{ GeV}/c^2$ at 90% CL, virtually excluding the decay $Z \rightarrow L^+L^-$, whereas a maximum of 5–6% of all W decays can still go into $L^\pm\bar{\nu}$, assuming that the fourth-generation neutrino is massless.

4.3.2 Number of light neutrino species

Higher-generation neutrinos will occur in the decay $Z \rightarrow \nu_L\bar{\nu}_L$, as long as $m_{\nu_L} < m_Z/2$. Since part of the IVBs are emitted in association with a jet, the observed number of events with jets and E_T is proportional to the abundance of $Z \rightarrow \nu\bar{\nu}$ events, and hence to the number of neutrino species into which the Z can decay. Using the selection criteria $L_\tau < 0$ and $E_T^j < 40 \text{ GeV}$, we expect 1.8 events from $Z \rightarrow \nu\bar{\nu}$ for each neutrino species. Comparing the number of observed events with the number predicted for the standard processes, a limit on the number of *extra* neutrino species $n \leq 7$ (90% CL) is derived.

A similar physical process has been used at e^+e^- colliders to determine the total number of light neutrino species N_ν : events where a single photon with no other activity was recorded, were interpreted as deriving from

$$\begin{aligned} e^+e^- &\rightarrow Z^* + \gamma \\ &\quad \downarrow \\ &\quad \nu\bar{\nu}, \end{aligned} \quad (4.8)$$

where the photon was radiated off the incident electron or positron. Combining the results from the experiments ASP and MAC at PEP (SLAC), and CELLO at PETRA (DESY), an upper limit of $N_\nu < 5$ was derived [76], which is consistent with the value 3 ± 1 deduced from the helium abundance in the Universe [77].

A more direct way to obtain N_ν through Z production is given via the measurement of the width of the Z . As will be mentioned in Section 5, the combined result from UA1 and UA2 yields

$$N_\nu < 6 \text{ (90\% CL)}. \quad (4.9)$$

Note that this value is more valid for higher neutrino masses than the results mentioned above; masses for which formula (4.9) holds must none the less be considerably smaller than $m_Z/2$, otherwise phase-space suppression would allow more decays of $Z \rightarrow \nu\bar{\nu}$ to occur within the limits on the Z -decay width.

4.4 Search for IVB decays into supersymmetric particles

Both UA1 and UA2 have searched for supersymmetric particles in their data samples [78, 79].

i) In most models the squarks and gluinos should be strongly produced in $p\bar{p}$ collisions through the process $p\bar{p} \rightarrow \bar{q}\bar{q}, \bar{q}\bar{g}, \bar{g}\bar{g} + X$, with cross-sections which are calculable within perturbative QCD and which range (for $\sqrt{s} = 630$ GeV) from 0.1 to 100 nb for masses between 70 and 20 GeV/c² [80].

The squarks and gluinos then decay into final states containing quarks or gluons and the lightest supersymmetric particle (LSP), which was taken to be the photino. The photino is assumed to have a small interaction cross-section and will therefore escape detection. Thus the signature for squarks or gluinos produced in $p\bar{p}$ collisions would be jet activity and significant E_T .

No evidence for squark or gluino production was found, and lower mass limits of

$$m_{\bar{q}} > 45 \text{ GeV}/c^2 \quad \text{and} \quad m_{\bar{g}} > 53 \text{ GeV}/c^2 \quad (90\% \text{ CL}) \quad (4.10)$$

are quoted. These limits rule out the possibility that IVBs decay into squarks.

ii) Assuming that the photino is the LSP and that it is stable, the decay of a W into a scalar electron and scalar neutrino,

$$\begin{aligned} W &\rightarrow \tilde{e}\tilde{\nu} \\ &\hookrightarrow e\tilde{\gamma}, \end{aligned} \quad (4.11)$$

will result in an event with an isolated electron and E_T , since the photino and sneutrino are expected not to interact in the detector. Because of the subsequent decay of the selectron into e and $\tilde{\gamma}$, the electron energy, and consequently E_T , will be softer than for conventional two-body $W \rightarrow e\nu$ decays, and the electron angular distribution will be different from the well-established and calculable (V – A) distribution (see Section 5).

The absence of a significant ($\tilde{e}\tilde{\nu}$) signal in the UA1 $W \rightarrow e\nu$ sample means that a region of the selectron versus sneutrino domain is excluded [81], assuming that the photino is massless. In the case where the selectron and sneutrino masses are equal, we have

$$m_{\tilde{e}} = m_{\tilde{\nu}} > 32 \text{ GeV}/c^2 \quad (90\% \text{ CL}) . \quad (4.12)$$

UA2 has searched for $\tilde{e}$ and $\tilde{W}$ candidates in Z decays [79]:

$$Z \rightarrow \tilde{e}^+ \tilde{e}^- \rightarrow e^+ e^- \tilde{\gamma} \tilde{\gamma}, \quad (4.13)$$

and

$$Z \rightarrow \tilde{W}^+ \tilde{W}^- \rightarrow e^+ \tilde{e}^- \tilde{\nu}. \quad (4.14)$$

The signature for such events should be the presence of an electron pair with an invariant mass that is less than in the case of a $Z \rightarrow e^+ e^-$ decay, being emitted—in most cases—with large transverse momenta since the electron and positron recoil against neutrinos. The absence of a significant number of candidates has led UA2 to conclude that for

$$m_{\tilde{\gamma}} < 12 \text{ GeV}/c^2: \quad m_{\tilde{e}} > 30 \text{ GeV}/c^2, \quad (4.15)$$

and for

$$m_{\tilde{\nu}} < 30 \text{ GeV}/c^2: \quad m_{\tilde{W}} > 45 \text{ GeV}/c^2, \quad (4.16)$$

both at 90% CL. Taking into account the more stringent lower limits on the mass of $\tilde{e}$ quoted by e^+e^- experiments [82], the decay of W or Z into sleptons and squarks can be excluded in most (known) supersymmetric scenarios. Only the cases of the Z decaying into light $\tilde{\nu}$ cannot be ruled out.

Since the coupling of Z to $\tilde{\nu}$ is expected to be half as strong as the coupling of Z to ν [83], from (4.9) we can derive an upper limit for the total sum of generations of light neutrinos and light sneutrinos,

$$N_\nu + 1/2 N_{\tilde{\nu}} < 6 \quad (90\% \text{ CL}) , \quad (4.17)$$

which, since three neutrino species are known, yields

$$N_{\tilde{\nu}} < 6 \quad (90\% \text{ CL}) \quad (4.18)$$

for $m_{\tilde{\nu}} \ll m_Z/2$.

Summarizing the results given in Section 4, no evidence was found for W and Z decays into any particle beyond the quarks and leptons of the known three generations. On the other hand, there is room for a limited number of decay modes beyond Standard Model predictions, which have to be allowed for in the calculation of the total production cross-section of W and Z.

5. PROPERTIES OF THE WEAK BOSONS

In the previous section it was shown that both experiments, UA1 and UA2, have identified IVB candidates in various decay modes, all of which the Standard Model predicts.

A precise determination of the IVB masses and of their production and decay properties will enable more direct tests of the $SU(2) \times U(1)$ electroweak theory to be carried out. Furthermore, the decay widths of W and Z contain indirect information about possible decays not predicted by the Standard Model.

5.1 Masses and decay widths

5.1.1 Mass and width of the W

The longitudinal momentum of the neutrino cannot be measured in either of the two experiments. In order to evaluate the W mass, the measured transverse mass distributions (see definition in subsection 4.1) are compared with sets of Monte Carlo simulated distributions, where the assumed W mass is varied. The simulations take into account the (*a priori* unknown) longitudinal and transverse motion of the produced W, its decay width Γ_W (assumed to be $3 \text{ GeV}/c^2$), the acceptance and resolution of the detectors, and the kinematical cuts on the decay products, chosen by the two groups.

For the electronic decay channel, in the UA1 W sample a subsample of 149 $e\nu$ events satisfying $E_T > 30 \text{ GeV}$ and $E_T^e > 30 \text{ GeV}$ was selected in order to eliminate background contributions which are concentrated at low E_T and E_T^e , respectively. The best fit to the data shown in Fig. 25a yields [28]

$$m_W = 82.7 \pm 1.0 \pm 2.7 \text{ GeV}/c^2, \quad (5.1)$$

where the first error is statistical and the second represents the systematic uncertainty in the absolute energy scale. This value agrees within errors with the value predicted by the Standard Model (see subsection 2.2), and with the result from UA2 [29] which was obtained by a fit to the $e\nu$ event sample satisfying $E_T^e > 20 \text{ GeV}$ and $m_T > 50 \text{ GeV}/c^2$ (see Fig. 15):

$$m_W = 80.2 \pm 0.6 \pm 0.5 \pm 1.3 \text{ GeV}/c^2. \quad (5.2)$$

The differences between the UA1 and UA2 results reflect the systematic uncertainties in the mass determination, which are mainly due to the uncertainty in the global energy scale of the e.m. calorimeters [3% in the UA1 experiment, 1.5% in UA2^{*)}]. Further contributions to the systematic errors are the uncertainty on the time dependence of the calorimeter response, and the unknown systematic biases in the determination of E_T .

For the W-mass determination from the muonic decay candidates, events which showed indications of having incorrectly measured muon momenta, or of a kink in the muon track, are removed, leaving 46 $W \rightarrow \mu\nu$ candidates. The mass is derived from fitting the inverse m_T distribution of the $(\mu\nu)$ system (see Fig. 25b). In this case, it is more reliable to make a fit to this distribution than to use the m_T distribution, because the latter has a long tail towards large m_T caused by the measurement error of the muon momentum. The error handling is simplified, since $1/m_T$ corresponds to $1/p_T^\mu$, which is proportional to the curvature of the track and is measured with Gaussian errors [55]. The result is consistent with the measurements from the electron channel; the statistical errors are, however, considerably larger.

For the decay widths of the W, both UA1 and UA2 quote an upper limit which, in the case of UA1, is

^{*)} It should be noted that, unlike in UA1, every segment of the e.m. calorimeters of UA2 was calibrated in a test beam.

$$\Gamma_W < 5.4 \text{ GeV}/c^2 \quad (90\% \text{ CL}) ,$$

more stringent than the UA2 value (this is basically due to the better $\bar{E}_T$ resolution of UA1).

This limit is about $1.9 \text{ GeV}/c^2$ larger than the theoretically expected decay width of the W (see subsection 2.2) and therefore it still leaves room for W decays into $t\bar{b}$ or $L\nu$. With the upgraded detectors, a very precise measurement of Γ_W is anticipated, allowing the exclusion of—or a hint at—possible decay modes beyond the Standard Model predictions, independent of the direct searches foreseen.

Finally, the mass value derived from the tau sample (Fig. 25c) agrees with the above results. All results are summarized in Table 7.

5.1.2 Mass and width of the Z

The Z mass is evaluated from a fit to the dilepton mass distribution, using a relativistic Breit-Wigner shape smeared by the experimental resolution. The result from UA1, derived from the electron channel (Fig. 26),

$$m_Z = 93.1 \pm 1.0 \pm 3.1 \text{ GeV}/c^2 , \quad (5.3)$$

is consistent with the UA2 value

$$m_Z = 91.4 \pm 1.2 \pm 1.7 \text{ GeV}/c^2 . \quad (5.4)$$

Again, as in the case of the W mass, the UA1 value tends to be slightly larger than the one in the UA2 case owing to the same dominant systematic uncertainty, i.e. unknown energy calibration in the e.m. calorimeter. This problem indicates that in order to obtain more precise results from higher statistics, as envisaged with the forthcoming high-luminosity runs at the Collider, both detectors will have to be improved in the areas where they are weakest in this respect: UA2 in missing-energy measurement and UA1 in calorimetry. This will be mentioned again in Section 8.

The result from the mass fit to 19 selected $Z \rightarrow \mu^+\mu^-$ candidates is, as in the case of the W-mass determination, consistent with the predicted value and the result obtained in the electron channel, but again it suffers from a lack of statistics [28, 84].

The values of the widths of the Z-mass distributions in the electron channel are, for

$$\text{UA1:} \quad \Gamma_Z = 2.7^{+1.2}_{-1.0} \pm 1.3 \text{ GeV}/c^2 , \quad (5.5)$$

and for

$$\text{UA2:} \quad \Gamma_Z = 2.7 \pm 2.0 \pm 1.0 \text{ GeV}/c^2 , \quad (5.6)$$

both in good agreement with the Standard Model prediction of $\Gamma_Z = 2.5 \text{ GeV}/c^2$, assuming that there are three generations of quarks and leptons and that $m_t = 44 \text{ GeV}/c^2$. Clearly, the large statistical and systematic errors cannot rule out Z decays into light neutral particle species. In fact, from the upper limits of Γ_Z quoted in Table 7, it is possible to obtain only a rather generous upper limit of $N_\nu \leq 15$ (90% CL). In an indirect way, though, a more precise determination of Γ_Z is possible. This method [85] evaluates the ratio R of the measured cross-section times branching ratios $\sigma_W \cdot \text{BR}(W \rightarrow \ell\nu)$ and $\sigma_Z \cdot \text{BR}(Z \rightarrow \ell^+\ell^-)$ (see Section 6), and compares them with theoretically calculated cross-section ratios:

$$\begin{aligned}
\frac{N(W \rightarrow \ell \nu)}{N(Z \rightarrow \ell^+ \ell^-)} &= \frac{\sigma_W \cdot \text{BR}(W \rightarrow \ell \nu)}{\sigma_Z \cdot \text{BR}(Z \rightarrow \ell^+ \ell^-)}, \\
&= \frac{\sigma_W}{\sigma_Z} \frac{\Gamma(W \rightarrow \ell \nu)}{\Gamma_W} \bigg/ \frac{\Gamma(Z \rightarrow \ell^+ \ell^-)}{\Gamma_Z},
\end{aligned} \tag{5.7}$$

where only Γ_Z is unknown (Γ_W is a function of the unknown t -quark mass). With this method the systematic uncertainties partially cancel; the measurement error is essentially determined by the statistical error in the number of observed Z . Combining the data of UA1 and UA2, we obtain

$$\begin{aligned}
\Gamma_Z &= 2.5^{+0.4}_{-0.3} \text{ GeV}/c^2, \\
&< 3.1 \text{ GeV}/c^2 \quad (90\% \text{ CL}),
\end{aligned} \tag{5.8}$$

from which the upper limit $N_\nu < 6$, as mentioned in the previous section, is derived.

Note that $m_t = 44 \text{ GeV}/c^2$ is used in these calculations. For higher masses of the t -quark the upper limit becomes smaller; in the case where $m_t \geq m_W$, we have $N_\nu < 5$.

The overall agreement of the mass measurements in the different lepton channels and in two different experiments, with each channel having different systematics, proves that the resonances found are genuine and identical. The agreement between data and theoretical prediction within the systematic uncertainties supports the minimal version of the Standard Model. Nevertheless, two important properties predicted for W and Z bosons have still to be demonstrated: the $V-A$ coupling of W and Z to fermions, and the universality of the coupling to members of different generations.

5.2 Charge asymmetry in IVB decays, and the spin of the W

Because of the $V-A$ coupling of the W to fermions, we expect to observe a strong charge asymmetry of the decay products with respect to the beam direction. In the $\ell \nu$ channel, the positively charged leptons are predominantly emitted in the antiproton direction, the negatively charged leptons in the proton direction; they are distributed as

$$dN/d \cos \theta^* = (1 - \frac{q}{|q|} \cos \theta^*)^2, \tag{5.9}$$

where q is the charge of the lepton, and θ^* is its emission angle with respect to the proton direction in the W rest frame. A small fraction of W 's are produced by sea quarks only, which will result in a small deformation of the angular distribution (5.9) because of an additional term $\epsilon(1 + q \cos \theta^*)^2$ (see Fig. 27a). This is simply due to the fact that in 50% of W production through sea-sea annihilation, an antiquark in the proton annihilates with a quark in the antiproton, forming a W whose polarization is opposite to that of the W formed when a quark in the proton annihilates with an antiquark in the antiproton. With higher-energy $p\bar{p}$ collisions the sea-quark annihilation will play an increasing role in IVB formation (because of the soft momentum distribution of sea-quarks), therefore, the decay asymmetry will be less significant. In addition, there are other distorting effects which have to be taken into account:

- i) The transverse motion of the W deflects the polarization vector away from the beam direction and causes a smearing of the $\cos \theta^*$ distribution. To reduce this effect, UA1 has selected only W 's with $p_T < 15 \text{ GeV}/c$.
- ii) The other effect derives from the ambiguity in determining the longitudinal momentum of the W and, as a consequence, $\cos \theta^*$, because of the unknown longitudinal momentum of the neutrino. Imposing $m_{e\nu} = m_W$, the longitudinal momentum of the neutrino p_L^ν can be computed from the

measured p_L^e , p_T^e , and E_T , but this always results in two solutions. Usually, one solution can be excluded because it yields unphysically large values for p_L^W ; otherwise, the solution with the smallest $|p_L^W|$ is chosen, taking into account the rapid fall of the quark structure functions with increasing fractional momentum x_q .

The acceptance- and background-corrected $\cos \theta^*$ distribution for $W \rightarrow (e\nu)$ candidates measured by UA1 is shown in Fig. 27a. There is good agreement with the Standard Model $V - A$ prediction, which is superimposed on the data points; this is also demonstrated by UA2 (Fig. 27b), where the forward spectrometers are used for charge determination [29].

The charge asymmetry can be related to the spin J of the W via the expression [37]

$$\langle \cos \theta^* \rangle = \frac{\langle \lambda \rangle \langle \mu \rangle}{J(J+1)}, \quad (5.10)$$

where $\langle \mu \rangle$ and $\langle \lambda \rangle$ are the global helicities of the production system ($q\bar{q}'$) and the decay system ($e\nu$), respectively, which are both -1 in $V - A$ coupling.

For a spin-1 W , $\langle \cos \theta^* \rangle = 0.5$ is expected. However, taking into account the small effect of depolarization of the W due to sea-sea annihilation, $\langle \cos \theta^* \rangle = 0.46 \pm 0.02$, which is well consistent with the experimental value of

$$\langle \cos \theta^* \rangle = 0.42^{+0.05}_{-0.06} \quad (5.11)$$

found by UA1. A spin-0 W ($\langle \cos \theta^* \rangle = 0$) is clearly ruled out.

It should be noted that since two weak-interaction vertices are involved in $W^\pm$ production and decay, it is not possible to distinguish $V - A$ and $V + A$ coupling, as follows directly from Eq. (5.10): negative and positive helicities in the production and decay lead to the same result for $\langle \cos \theta^* \rangle$. Only polarized beams or the presence of a third weak-interaction vertex (as, for example, in the τ decay in a $W \rightarrow \tau\nu$ event) would allow these couplings to be distinguished.

In contrast to the W case, only a small asymmetry (see Fig. 28) is expected for the angular distribution of Z decay leptons, since the parity-violating term is proportional to $(1 - 4 \sin^2 \theta_w)$, which is small, with $\sin^2 \theta_w$ being close to 0.25. However, the measurement of the decay asymmetry provides an independent measurement of $\sin^2 \theta_w$. From the $\cos \theta^*$ distribution in 33 selected $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ decay candidates (Fig. 28), UA1 derives the value

$$\sin^2 \theta_w = 0.24^{+0.05}_{-0.04}, \quad (5.12)$$

which is consistent with the more precise results obtained from the mass values [28, 29] and with low-energy data. With higher statistics, better decay asymmetry measurements should be possible. The same method of determining $\sin^2 \theta_w$ has been used in e^+e^- collisions at PETRA and PEP [23] and is expected to yield a very accurate value at LEP or the SLC.

6. PRODUCTION PROPERTIES OF W AND Z

Having established the genuineness and cleanliness of the W and Z signals, and the general consistency of the observed IVB properties with predictions of the $SU(2) \times U(1)$ Standard Model, we can now analyse the corresponding events in order to study the way in which the IVBs are produced.

6.1 Production cross-sections and the test of universality

in weak couplings to leptons

The cross-section times branching ratio $\sigma \cdot BR(W \rightarrow \ell \nu)$ for the inclusive process $p\bar{p} \rightarrow W + X$, followed by the decay of the W into a lepton pair, is obtained from the relation

$$N_{W \rightarrow \ell \nu} = L \cdot \sigma_W \cdot BR(W \rightarrow \ell \nu) \cdot \epsilon_W \cdot \eta_W, \quad (6.1)$$

where

$N_{W \rightarrow \ell \nu}$ is the observed number of $W \rightarrow \ell \nu$ decays (background subtracted);

L is the total integrated luminosity;

ϵ_W is the detector acceptance (trigger efficiency included);

η_W is the selection efficiency for this decay mode.

The values of $\sigma \cdot BR(Z \rightarrow \ell^+ \ell^-)$ are derived in a similar way. The results obtained from the W and Z samples listed in Tables 5 (UA1 data) and 6 (UA2 data) are summarized in Table 8 for the decay channel and for the centre-of-mass energy at which the IVBs were produced.

The first errors quoted for the cross-section values are statistical; the second errors reflect a systematic uncertainty of the measurement dominated by the uncertainty on the integrated luminosity of the experiments. UA1 estimates a 15% measurement error on the luminosity, whereas UA2, profiting from a symbiosis with UA4, quotes 8% [86]. All cross-section determinations in one experiment are afflicted by this uncertainty in the same way, but independently in UA1 and UA2.

The good agreement of the cross-section values of the individual W decay channels at a given c.m. energy, which is also visualized in Fig. 29, indicates that W's couple with similar strength to electrons, muons, and taus. Since $\sigma \cdot BR$ is proportional to the square of the weak charged-coupling constant to leptons, g , we obtain a quantitative comparison of the coupling strength to leptons of different generations via

$$(g_1/g_2)^2 = \Gamma(W \rightarrow \ell_1 \nu)/\Gamma(W \rightarrow \ell_2 \nu) = \sigma \cdot BR(W \rightarrow \ell_1 \nu)/\sigma \cdot BR(W \rightarrow \ell_2 \nu). \quad (6.2)$$

Combining UA1 data samples from $\sqrt{s} = 546$ and 630 GeV, it follows that

$$g_\mu/g_e = 1.00 \pm 0.07 \pm 0.04$$

and

$$g_\tau/g_e = 1.01 \pm 0.07 \pm 0.06.$$

(6.3)

Note that in these ratios the systematic uncertainties from luminosity measurements cancel.

These results provide a direct experimental verification of $e-\mu-\tau$ universality of the weak charged coupling at $Q^2 = m_W^2$, which so far has been shown (more precisely) at much lower momentum transfers only [87–89].

In a similar way, the measured cross-sections for $Z \rightarrow \mu^+ \mu^-$ and $Z \rightarrow e^+ e^-$ allow a test of $e-\mu$ universality for the weak neutral couplings at $Q^2 = m_Z^2$. With

$$(k_\mu/k_e)^2 = \Gamma(Z \rightarrow \mu^+ \mu^-)/\Gamma(Z \rightarrow e^+ e^-) = \sigma \cdot BR(Z \rightarrow \mu^+ \mu^-)/\sigma \cdot BR(Z \rightarrow e^+ e^-) \quad (6.4)$$

we obtain from the data in Tables 8 and 9,

$$k_\mu/k_e = 1.02 \pm 0.15 \pm 0.04, \quad (6.5)$$

again in good agreement with unity.

With the (justified) assumption of the $e\text{--}\mu\text{--}\tau$ universality of weak charged and neutral couplings, we may average the individual values of $\sigma \cdot \text{BR}$ measured by UA1 and UA2 in order to compare them with theoretical predictions.

At $\sqrt{s} = 546$ GeV this gives

$$\langle \sigma \cdot \text{BR}(W \rightarrow \ell \nu) \rangle = 0.56 \pm 0.08 \text{ nb}, \quad (6.6)$$

which has to be compared with the theoretical estimate of [39]: $0.38 \pm_{-0.05}^{+0.12}$ nb; and at $\sqrt{s} = 630$ GeV we obtain

$$\langle \sigma \cdot \text{BR}(W \rightarrow \ell \nu) \rangle = 0.60 \pm 0.05 \text{ nb}, \quad (6.7)$$

compared with $0.48 \pm_{-0.07}^{+0.13}$ nb. Likewise, for Z production at 546 GeV we derive

$$\langle \sigma \cdot \text{BR}(Z \rightarrow \ell^+ \ell^-) \rangle = 91 \pm 25 \text{ pb},$$

compared with the theoretical value of $43 \pm_{-7}^{+13}$ pb, and at $\sqrt{s} = 630$ GeV we obtain

$$\langle \sigma \cdot \text{BR}(Z \rightarrow \ell^+ \ell^-) \rangle = 72 \pm 10 \text{ pb}, \quad (6.8)$$

The statistical and systematic errors of the experimental values are added in quadrature. The quoted theoretical uncertainty is due to different choices of structure functions and of Λ_{QCD} . Furthermore, the uncertainty in the QCD momentum scale used in α_s —and, resulting from this, in the contribution of higher-order terms—leads to an asymmetric error in the cross-section.

As follows from Eqs. (6.6) to (6.8), and is also visible in Figs. 29a and 29b, there is an overall agreement between the data and the theory. But the experimental cross-sections seem none the less to be always higher by about 25%. Two possible reasons could explain an underestimate of the theoretical prediction (as outlined in Ref. [62]):

- i) The branching ratios $\text{BR}(W \rightarrow \ell \nu)$ and $\text{BR}(Z \rightarrow \ell^+ \ell^-)$ are *a priori* not precisely known because of the unknown t-quark mass. In the theoretical estimate, $m_t = 44 \text{ GeV}/c^2$ is assumed, in agreement with the lower mass limit given by UA1. In the case where the t-quarks were very massive, $\text{BR}(W \rightarrow \ell \nu)$ would shift from 8.8% to 10.8% and hence augment the predicted theoretical cross-section by 22%. The branching ratio for $Z \rightarrow \ell^+ \ell^-$, however, would in this case increase by only 1%.
- ii) New precise measurements of deep-inelastic μ -nucleon scattering by the BCDMS Collaboration at CERN [90] indicate that in the region of $x_q \approx 0.1\text{--}0.2$, which is the main production region for IVBs at the CERN $p\bar{p}$ Collider, the structure functions used in Ref. [39] underestimate the experimental distribution by about 10%. If this holds true, the predicted cross-sections will be larger by about 20%.

At this stage, the experimental uncertainties are certainly large enough to leave room for either possibility, or even for both; therefore a conclusion regarding the t-quark mass cannot be derived from these cross-section measurements.

Note that there is a third type of uncertainty attached to the theoretical estimates, which arises from the possibility of W and Z decays into higher-generation quarks and leptons or into sneutrinos, and which has not been taken into account so far. If all processes described in Section 4 occur within the quoted 90% CL limits, the branching ratios for the leptonic decay modes, and hence the predicted cross-sections, would be *reduced* by 5% in the case of W production and by 20% in the case of Z production, so the discrepancy with the observed values would be even more pronounced.

Even though all the experimental values are systematically higher than the theoretical cross-section estimates, they are consistent with the predicted increase of σ_Z and σ_W with $\sqrt{s}$, as indicated in Fig. 29. Given the size of these experimental errors, the lever arm between 546 and 630 GeV is too short to allow a test of the theory. A measurement at $\sqrt{s} = 1.8$ TeV, at which the p $\bar{p}$ Collider at Fermilab operates, will provide us with a more significant test.

In spite of the present uncertainties, the agreement between data and theory confirms the colour degree of freedom of quarks. Without colour, the expected $W \rightarrow \ell\nu$ and $Z \rightarrow \ell^+\ell^-$ cross-section would be larger by a factor of about 6, in total disagreement with data [91]. Colour is responsible for a suppression factor of 3 in the production cross-section [see Eq. (2.30)] and a further suppression factor of ~ 2 in the branching ratio

$$\text{BR}(W \rightarrow \ell\nu) = \frac{\Gamma(W \rightarrow \ell\nu)}{\Gamma_W^{\text{tot}}} \approx \frac{1}{N_\ell + N_c \cdot N_q}, \quad (6.9)$$

where

$N_\ell = 3$ is the number of lepton doublets,

$N_q = 2$ or 3 is the number of quark doublets kinematically allowed in W decay, and

N_c is the number of colours, three in QCD.

It follows from the data that

$$2 < N_c < 4 \quad (90\% \text{ CL}). \quad (6.10)$$

6.2 Longitudinal motion of IVBs

The longitudinal motion of the W and Z reflects the difference in the fractional momenta x_q and $x_{\bar{q}}$ of the annihilating quarks. At Collider energies we expect that it is predominantly the u and d valence-quarks that are involved in the production of IVBs, since the fractional momentum of sea-quarks is in general too small; only 4–8% of W/Z derive from sea-quark fusion.

The Feynman-x of the IVB is obtained from the longitudinal momenta of the decay products, in this case ($e\nu$) pairs in the W sample and (e^+e^-) pairs in the Z sample. In the W sample,

$$|x_W| = |x_q - x_{\bar{q}}| = \frac{|p_L^e + p_L^\nu|}{\sqrt{s}/2}, \quad (6.11)$$

and analogously for the (e^+e^-) pairs in the Z sample where the longitudinal momenta of the electron and positron are summed. In the W case the longitudinal momentum of the neutrino is derived, as described in subsection 5.2, by imposing the W mass on the electron-neutrino system.

The two solutions for p_L^ν —one corresponding to the neutrino being emitted forwards in the W rest frame and the other backwards—lead to a twofold ambiguity for x_W . If one of the results is unphysical, i.e. $|x_W| > 1$, it can easily be ruled out; otherwise the smaller value of $|x_W|$ is chosen. In the case of x_Z there is no such kinematical ambiguity. The Feynman-x distributions of W's are drawn separately in Fig. 30 for the two energies, 546 and 630 GeV. There is some indication of the kinematically expected softening of the distributions with increasing $\sqrt{s}$, in agreement with the predictions which use the structure functions of Eichten et al. [92] with $\Lambda_{\text{QCD}} = 0.2$ GeV.

The Feynman- x distribution of Z 's is shown in Fig. 31. Within errors there is again agreement between data and theory.

Using the relation (6.11) and

$$x_q \cdot x_{\bar{q}} = m_W^2/s, \quad (6.12)$$

the distributions of partons involved in W production are obtained (see Fig. 32). We extract the longitudinal momenta of $u/\bar{u}$ and $d/\bar{d}$ quarks by selecting only $W \rightarrow e\nu$ candidates with a well-measured sign of charge. The average momentum fraction of these quarks lies in the expected range: $\langle x_u \rangle = 0.17 \pm 0.01$ and $\langle x_d \rangle = 0.13 \pm 0.01$. Notice that the x_u and x_d distributions of Fig. 32 do not directly represent the structure function of u/d quarks in the proton since they belong to a subsample satisfying Eq. (6.12). A significant distinction between different structure functions using these results is not possible owing to the limited amount of data, but the good overall agreement with theoretical expectations supports the assumption that $q\bar{q}$ annihilation is indeed the dominant process in weak IVB production at the CERN $p\bar{p}$ Collider.

6.3 Transverse emission of W and Z

Both UA1 and UA2 measure the Z transverse momentum p_T^Z by adding the electron and positron transverse momenta. In the case of the W , they add the transverse momentum vectors of the electron (or muon) and of $\vec{E}_T$. UA2, suffering from the lack of coverage in the forward direction, has non-Gaussian errors in the determination of $\vec{E}_T$ —and, hence, in p_T^W —which are expected to dominate at very low values of p_T^W .

6.3.1 Transverse momentum distributions of IVBs

The transverse momenta of 583 W candidates with leptonic decay found by UA1 [28] and UA2 [29] are summed in Fig. 33 (taken from Ref. [67]). The p_T^W distribution peaks at a value of about 4 GeV/c, which primarily reflects the experimental resolution of the measurement of $\vec{E}_T$ in the W event. It is well described by the QCD calculations of Altarelli et al. [39], which use the structure functions of Duke and Owens (DO) [93] and take into account experimental acceptance and resolution effects (Fig. 34). Note that in a simple Drell-Yan parton model this distribution would be much narrower and more concentrated near zero, the p_T^W (or p_T^Z) being determined by only the intrinsic transverse momenta of the quarks. The introduction of gluon radiation from the incoming quarks, as predicted by QCD, is the most plausible explanation of the long p_T^W tail.

Adopting this explanation, we can try to obtain information from the shape of the IVB p_T distribution about the structure function of quarks in the proton (antiproton) and about the QCD scale parameter Λ_{QCD} . In a comparison of the p_T^W distribution measured by UA1 in the range $p_T^W \leq 26$ GeV/c, with theoretical calculations using DO structure functions, the prediction with $\Lambda_{QCD} = 0.2$ GeV fits the data better than with $\Lambda_{QCD} = 0.4$ GeV (see Fig. 34).

This result is to be compared with the experimental distribution of the Z transverse momentum component p_T^Z from UA2 [29] and with theoretical calculations [39], as shown in Fig. 35. Even though the theoretical curve using the structure function of Glück et al. [94] with $\Lambda = 0.4$ GeV seems to fit the data better than the curve using DO structure functions and $\Lambda = 0.2$ GeV, a quantitative distinction on the basis of the low statistics of this data sample is not possible.

It should be emphasized, however, that in spite of the present uncertainty regarding the right choice of structure function and Λ_{QCD} , the agreement between the experimental and theoretical p_T^W distribution is quite impressive, because at low p_T^W , i.e. low Q^2 , the theoretical calculations have to take into account processes of all orders of α_s . This is achieved using the technique of soft-gluon resummation described in Ref. [39], and in references quoted therein.

The high- p_T tails of the W samples of UA1 [95] and UA2 [96], corrected for acceptance losses, background effects, and experimental distortions, are displayed in Fig. 36. The data are in agreement with curves from a recent theoretical calculation including terms of order α_s^2 , from Bawa and Stirling [97], which uses a structure function from Martin et al. [98]. The uncertainties of the experimental results are still too large to allow discrimination between the two theoretical curves based on $\Lambda_{\text{QCD}} = 0.107 \text{ GeV}$ and $\Lambda_{\text{QCD}} = 0.250 \text{ GeV}$. Even though the UA1 data lie systematically above the UA2 distribution, they agree within errors. Only the highest p_T^W bin of UA1 seems to stand out from the overall distribution: it contains two events with p_T^W substantially larger than the rest of the sample, $82 \pm 12 \text{ GeV/c}$ and $105 \pm 14 \text{ GeV/c}$ [95]. The predicted rate at these p_T^W values is roughly one order of magnitude smaller, and according to the authors of Ref. [97] it is not possible to adjust QCD parameters in such a way as to force the theoretical curve in Fig. 36 to be much harder in the tail. Taking into account experimental uncertainties in the determination of p_T^W , these two events are still statistically compatible with the QCD prediction (the predicted number of events is ~ 1 for $p_T^W > 60 \text{ GeV/c}$ and ~ 0.2 for $p_T^W > 80 \text{ GeV/c}$). However, their topology is not compatible with them being from $W + \text{gluon radiation}$. Alternative interpretations will be given in the last two subsections. A significant excess of events with large p_T^W or p_T^Z , compared with theoretical expectation, would signal new physics beyond the Standard Model, but any conclusions seem to be premature at this stage. Clearly, with higher statistics and improved detectors this observed excess will be either verified or rejected.

6.3.2 Jets in IVB events

The QCD-improved Drell-Yan picture predicts that IVBs produced at high p_T recoil against one or more gluons radiated off the incoming annihilating quarks. If these gluons are sufficiently energetic and are emitted at sufficiently large angle to the beam direction, they will be observed as hadron jets balancing the transverse momentum of the IVB. In practice, in about 35% of the observed W's and Z's, one or more hadronic jets with $p_T^j > 5 \text{ GeV/c}$ are found by the individual jet algorithms of UA1 [99] and UA2 [29]. As expected, the fraction of events with IVBs in association with jets rises with increasing p_T^W , and from about 16 GeV/c onwards essentially all events contain at least one jet. Since these jets are supposed to be derived mainly from initial-state gluon bremsstrahlung, their angular distribution is expected to be strongly peaked in the direction of the incoming partons, which is naturally approximately the direction of the beam. This can be seen in Fig. 37, where the distribution of $\cos \theta^*$, measured by UA1, is shown; θ^* is the polar angle between the jet axis and the beam direction in the W-jet rest frame. (Note that we cannot tell whether the gluon was radiated off an incoming quark or antiquark. Therefore, only $|\cos \theta^*|$ is determined.) The data are well reproduced by the theoretical distribution for bremsstrahlung [100], which is basically described by

$$\frac{d\sigma}{d|\cos \theta^*|} \propto (1 - |\cos \theta^*|)^{-1}. \quad (6.13)$$

Another confirmation of the QCD interpretation of $Z + \text{jet}$ or $W + \text{jet}$ events is given by the measured multiplicity distribution of jets in such events, as depicted in Fig. 38. Naïvely one would expect that the cross-section of an IVB event with n jets is proportional to the n^{th} power of α_s . Such an exponential decrease of the cross-section with growing jet multiplicity can be observed in Fig. 38. The data are well reproduced by a QCD calculation of Ellis et al. [100], where experimental cuts such as jet energy threshold are taken into account.

6.3.3 Average IVB transverse momenta as a function of $\sqrt{s}$

After correcting for acceptance effects, the mean transverse momentum of W 's averaged over the results from UA1 and UA2 at $\sqrt{s} = 630$ GeV amounts to

$$\langle p_T^W \rangle = 10.1 \pm 1.2 \text{ GeV}/c, \quad (6.14)$$

where the error is dominated by systematic uncertainties in the measurement of p_T^W and in the absolute energy scale for electrons. The average value for Z yields

$$\langle p_T^Z \rangle = 9.2 \pm 1.2 \text{ GeV}/c, \quad (6.15)$$

where the statistical error of the relatively small Z sample dominates.

As can be seen in Fig. 39, the error bars on the individual $\langle p_T^W \rangle$ and $\langle p_T^Z \rangle$ values are too large to derive a functional dependence on the c.m. energy in the range $\sqrt{s} = 546$ GeV to 630 GeV. But in comparison with the average p_T of lepton pairs measured at lower energies (also shown in this figure), a significant increase is noticeable.

This increase is well reproduced by the theoretical curves in the diagram, which describe the energy dependence of $\langle p_T \rangle$ of Drell-Yan-produced lepton pairs in $p\bar{p}$ collisions via the relation [101]

$$\langle p_T^2 \rangle \propto \alpha_s \cdot s \cdot f(\tau, \alpha_s). \quad (6.16)$$

At fixed values of τ , one expects asymptotically a linear relation between $\langle p_T \rangle$ and $\sqrt{s}$, as demonstrated in Fig. 39. The agreement between the data and the theoretical approach is an indirect confirmation that the production mechanisms of Drell-Yan pairs and weak IVBs are closely related. The data from the CERN $p\bar{p}$ Collider are, however, not accurate enough to allow a choice between the different values of Λ_{QCD} as represented by the two curves in the diagram. Notice that without QCD, $\langle p_T \rangle$ would stay constant at $\lesssim 1 \text{ GeV}/c^2$, independent of $\sqrt{s}$.

6.4 Pair production of weak bosons

The production of two IVBs in one $p\bar{p}$ collision is well predictable within the framework of the Standard Model and the Drell-Yan process. We consider the processes

$$\begin{aligned} p\bar{p} &\rightarrow W^+ + W^- + X, \\ p\bar{p} &\rightarrow W + Z + X, \\ p\bar{p} &\rightarrow Z + Z + X, \\ p\bar{p} &\rightarrow W + \gamma + X, \end{aligned} \quad (6.17)$$

which may be identified in our data samples by a leptonic decay mode of one of the IVBs and two jets from the other boson decay, except for the fourth process where the photon would be identified as an isolated electromagnetic energy deposition in the calorimeters.

It turns out that the two events with the highest p_T^W , mentioned in subsection 6.3, have the topology of a W with a leptonic decay mode recoiling against an energetic dijet system. In both cases the jet-jet invariant mass is about m_W or m_Z . The W -dijet system has a total invariant mass of $\sim 300 \text{ GeV}/c^2$. Even though it is tempting to interpret these events as evidence of boson pair-production, the predicted cross-section of such a process, $\sigma_{WW} \cdot \text{BR} = 0.02 \text{ pb}$ [92, 100], is two orders of magnitude smaller than the cross-section to which the observed event rates correspond, and

therefore this hypothesis is ruled out. The cross-section of $W + Z$ production is almost another order of magnitude smaller.

Even at ten times higher luminosities, as foreseen for future CERN $p\bar{p}$ Collider runs, or at the FNAL Tevatron Collider, the study of weak boson pair-production will be precluded. Also, $W\gamma$ production will be difficult to observe—even though its cross-section is larger—since the background from $W + \text{jet}$ events (where the jet fragments into an energetic π^0) will dominate the signal.

Finally, we consider the production of Higgs bosons (H) at the Collider. The production mechanism which seems most promising for an identification of H is through Higgs radiation off a W or Z. In the search for this process the IVBs would be tagged by their leptonic decay modes [102], and the Higgs, decaying into the heaviest possible quark-antiquark pair, would form one jet or a dijet system. Whereas there is no evidence of $W + H$ production in the present data (we expect 1–2 events of this type if $m_H = 10\text{--}20 \text{ GeV}/c^2$), much higher statistics and the possibility of heavy-flavour tagging (i.e. through the identification of secondary decay vertices) should enable the signal of a light Higgs boson to be separated from the IVB + jet background.

Clearly, this aspect of the Standard Model will be the domain of the next-generation e^+e^- colliders, the SLC and LEP, especially the second stage of LEP where electron-positron annihilations at $\sqrt{s} = 200 \text{ GeV}$ are foreseen.

6.5 Is there a massive object decaying into IVBs?

In the previous subsections it has been shown that the basic production mechanism of weak IVBs in $p\bar{p}$ collisions is understood in terms of Drell-Yan processes and QCD; in fact, data and theory are consistent with each other down to a level of $\sim 10^{-9}$ of the total $p\bar{p}$ cross-section. This does not exclude there being room in the data for a different mechanism for the generation of W's or Z's; take, for example, the decay of a massive quark, where $m_q > m_W$ [103]:

$$\begin{aligned} p\bar{p} &\rightarrow q\bar{q} + X, \\ q &\rightarrow W + q', \\ W &\rightarrow \ell\nu. \end{aligned} \tag{6.18}$$

One could speculate that the two high- p_T^W events mentioned before are due to process (6.18), where the heavy quark (either the t-quark or a new-generation quark) has a mass of about $90 \text{ GeV}/c^2$. In this case the expected number of events with similar kinematics is about 0.02 [95], again failing to give a plausible interpretation of the observed high- p_T^W events.

Without kinematical or experimental restrictions, the number of events producing a heavy quark with $m_q \sim 90 \text{ GeV}/c^2$ is estimated to be about 0.5 with present statistics [26], so it seems possible that with a tenfold increase in statistics, a quark of this mass will be detected at the $p\bar{p}$ Collider.

More generally, one may consider the production of a massive state M which subsequently decays into a W plus one jet, as suggested, for instance, in some composite models [104]. For this study UA1 has selected a subsample of 81 $W + \text{jet}$ events where the W's decay into an electron + neutrino. The invariant mass of the $W + \text{jet}$ system is displayed in Fig. 40a, and compared with a QCD simulation using the Monte Carlo program ISAJET. There is good agreement between the measured spectrum and the prediction, except for an enhancement of events with $M(W + \text{jet})$ near $200 \text{ GeV}/c^2$ which, at this stage, is not significant. This agreement between data and QCD calculation is also demonstrated by UA2 results [29] in Fig. 40b, showing that there is no evidence for an additional production mechanism. It follows that the total production cross-section for a massive state M is typically smaller than 40 pb for masses up to $220 \text{ GeV}/c^2$, and for larger masses it is smaller than 13 pb at 90% CL.

7. SEARCH FOR ADDITIONAL MASSIVE VECTOR BOSONS, W' AND Z'

Additional massive vector bosons are predicted in various extended versions of the minimal $SU(2) \times U(1)$ Standard Model—as, for example, in models which include right-handed weak currents—or in the framework of compositeness or superstring theories [105].

The signature of a Z' or W' in the UA1 or UA2 data is expected to be a resonance-like structure in the lepton-pair spectrum with an invariant mass that is different from m_Z or m_W . Because of the poor momentum resolution for high- p_T muons, UA1 and UA2 investigate the electron decay channel only, with the result that no $W' \rightarrow e\nu$ or $Z' \rightarrow e^+e^-$ candidates have been observed with invariant masses in excess of the IVB masses^{*)}. From this observation UA1 places an upper limit on the production cross-section times branching ratio for $\sqrt{s} = 630$ GeV [28]:

$$\left. \begin{aligned} \sigma_{W'} \cdot \text{BR}(W' \rightarrow e\nu) &< 4.6 \text{ pb} \\ \sigma_{Z'} \cdot \text{BR}(Z' \rightarrow e^+e^-) &< 4.7 \text{ pb} \end{aligned} \right\} \text{ at 90\% CL ,} \quad (7.1)$$

where $m_{Z'} > m_Z$ and $m_{W'} > m_W$.

As shown in Fig. 41, these limits, calculated using the structure functions of Diemoz et al. [106], are equivalent to a lower limit on the masses if standard couplings to quarks and leptons are assumed:

$$\left. \begin{aligned} m_{W'} &> 220 \text{ GeV}/c^2 \\ m_{Z'} &> 173 \text{ GeV}/c^2 \end{aligned} \right\} \text{ at 90\% CL ,} \quad (7.2)$$

well in agreement with the results of UA2 [79].

Most models derived from superstring theories predict at least one extra Z' boson, where the coupling to fermions is expected to be weaker than in the case of the ordinary Z . In this case the expected production cross-section times branching ratio ($\sigma \cdot \text{BR}$) is smaller than for standard coupling $(\sigma \cdot \text{BR})_{\text{st}}$. Consequently, the mass limit becomes less stringent. This is demonstrated in Fig. 42, where lower mass limits for W' and Z' are plotted versus the ratio $(\sigma \cdot \text{BR})/(\sigma \cdot \text{BR})_{\text{st}}$. A similar graph is presented by UA2 in Fig. 43, where certain regions in the plane $m_{W'}$ or $m_{Z'}$ versus $\lambda q^2 \cdot B_e$ (coupling strength times branching ratio) are excluded by 90% CL contours. Figure 43 shows that W' or Z' with masses below $70 \text{ GeV}/c^2$ are essentially ruled out by the data; at higher mass values the lower limits depend entirely on the coupling strength of these bosons to fermions.

In a recent calculation [107], taking the least favourable scenario of superstring-inspired models, a combined analysis of UA1, UA2, and lower-energy neutral-current data yields a mass limit of

$$m_{Z'} > 156 \text{ GeV}/c^2 \quad (90\% \text{ CL}) . \quad (7.3)$$

This limit would correspond to an upper limit of $\sigma \cdot \text{BR} \approx 0.4 \text{ pb}$ at the CERN $p\bar{p}$ Collider, which means that in this pessimistic scenario the superstring Z' would probably remain out of reach for the Collider, even with ten times better statistics.

^{*)} UA2 reports the observation of a W-like artefact with $m_{e\nu} \approx 160 \text{ GeV}/c^2$ [79], which is attributed to the decay of a virtual W. For a W' with decay kinematics similar to those, as observed in this event, 15 events are expected in the case of standard coupling.

8. CONCLUSIONS AND OUTLOOK

In this report it has been shown that the study of events in $p\bar{p}$ collisions, where a weak intermediate vector boson was identified, provides valuable information about the structure of the proton and of the electroweak and strong interactions. Let us summarize our present knowledge of these subjects:

i) Nearly all the leptonic decay modes of IVBs into the three known generations have been observed; this has enabled us to demonstrate the universality of weak charged coupling to e, μ, τ , as well as of weak neutral coupling to e and μ at $q^2 \approx (m_{\text{IVB}})^2$, unprecedented at this large momentum transfer. Also, a glimpse of hadronic IVB decays was caught by UA2 in the attempt to use the technique of jet spectroscopy to search for massive objects. The number of light neutrino generations was constrained to ≤ 5 . Only the presence of the t -quark in UA1 and UA2 data remains an open question; even though the present lower mass limit probably excludes the appearance of the t -quark in Z decays, there is still room for the decay mode $W \rightarrow t\bar{b}$.

The same holds true for the existence of a fourth-generation heavy lepton with a lower mass limit of $41 \text{ GeV}/c^2$. On the other hand, the limit for a fourth-generation down-like quark is still low enough for it to appear in Z decays. No evidence of supersymmetric particles has been found in our data, and (except for sneutrinos) the quoted lower mass limits of such particles make their appearance in W or Z decays very unlikely.

ii) The masses of the IVBs are in agreement with the Standard Model predictions to a precision of a few per cent. They support, within experimental errors, the estimated radiative corrections. The angular distributions of IVB decay leptons display the $(V \pm A)$ -type coupling, and the spin of the W was determined to be 1, as expected.

iii) The longitudinal motion of W 's and Z 's is consistent with the idea of IVB production through quark-antiquark annihilation; the longitudinal-momentum distributions are in very good agreement with parametrizations on the basis of the Drell-Yan model. A choice between the various existing structure functions is, however, not possible, given the present statistics.

The transverse motion of the IVBs clearly deviates from the expectation of the naïve Drell-Yan model, exhibiting a long tail in the transverse-momentum distribution. The p_T dependence of the W production rates is well reproduced by a QCD calculation, including higher-order terms up to $p_T^W \approx 120 \text{ GeV}/c$; the comparison between experiment and theory seems to favour a QCD scale-parameter $\Lambda_{\text{QCD}} \approx 200 \text{ MeV}$. Furthermore, the appearance of high- p_T jets in association with high- p_T IVBs, and their multiplicity distributions, both conform with QCD predictions; the predominant gluon bremsstrahlung nature of these jets was established.

The measured inclusive production cross-sections of W 's and Z 's decaying into lepton pairs are found systematically above the calculated values. This may be due at present to the uncertainties in the choice of structure functions and/or to the branching ratio of $W \rightarrow \ell\nu$ related to m_ℓ . In spite of these uncertainties, the cross-section measurements of W and Z provide us with an unambiguous determination of the colour charge factor of 3.

iv) There is no indication of a massive state decaying into $W + \text{jet}$, nor could additional massive IVBs be detected. Only the two $W + \text{dijet}$ events with an invariant mass of the order of $290 \text{ GeV}/c^2$ stand out from the general distribution.

To summarize these four points, there is good agreement between all measurements involving the observation of an IVB and what is expected in the framework of the standard electroweak theory and of QCD. However, in many cases the experimental uncertainties are too large to allow for significant tests of the theory, thus necessitating further studies with higher statistics and improved detectors. What are the perspectives regarding this in the next few years?

At CERN, the $p\bar{p}$ Collider complex has been undergoing an important upgrading program, the main objective being to augment the luminosity by about an order of magnitude [108], reaching $\sim 5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. This program included the introduction of a six-bunch operating mode and the addition of a separate Antiproton Collector Ring (ACOL) to the existing Antiproton Accumulator (AA) in order to increase the production rate and storage rate of antiprotons. In the forthcoming runs in 1988 and 1989, the experimentalists of UA1 and UA2 can therefore expect a tenfold increase over their present statistics, corresponding to an integrated luminosity of $\sim 10 \text{ pb}^{-1}$ in each experiment.

In order to cope with the higher event rates and to be able to fully exploit the new realm of physics, both experiments have been (or are being) upgraded [109, 110]. The main emphasis of the upgrading program for the UA1 experiment is on the improvement of the calorimetry. The existing electromagnetic calorimeters in the central and forward regions will be replaced by a combined electromagnetic and hadronic uranium calorimeter filled with liquid tetramethyl pentane (TMP) at room temperature as a detecting medium [111]. The deficiencies of the old calorimeter will be made up in the new one, as this will have a considerably higher granularity ($\Delta\theta \times \Delta\phi \approx 5^\circ \times 6^\circ$ per cell), increased hermeticity in the vertical direction, and better resolution and linearity in jet energy measurement. Other components of the UA1 detector will be upgraded as well, in particular the muon detection system in the forward directions, which will receive additional shielding, and the data-acquisition system with a new multilevel trigger structure. At a later stage, a silicon-strip vertex detector may be introduced between the vacuum chamber and the Central Detector.

One of the main improvements to the UA2 detector [112] has been the complete calorimetric coverage of the forward directions down to polar angles of 6° , by adding e.m. lead/scintillator and hadronic iron/scintillator calorimeters. Furthermore, the electron identification in UA2 has been upgraded by the use of a new central detector assembly which will include a silicon-pad detector, a transition radiation detector, and a scintillating-fibre preshower detector.

In competition with the experimental program at the CERN Collider, there is the program at the FNAL Tevatron, providing $p\bar{p}$ collisions up to $\sqrt{s} = 2 \text{ TeV}$. The CDF experiment took its first data in 1987, and found clear evidence for IVBs through leptonic decays [113]. In their forthcoming collider runs, the CDF Group anticipates data samples representing 5 pb^{-1} .

Taking into account the approximately four times higher cross-sections of W and Z at $\sqrt{s} = 2 \text{ TeV}$, the CDF Group may collect about as many IVBs as the UA1 and the UA2 put together. Whilst the statistical errors on measurements of IVB properties—and, hence, Standard Model parameters—should be similar, the upgraded CERN experiments will probably be superior in systematic precision [97]. The sensitivity for finding a heavy fourth-generation lepton will be about the same in all three experiments, since probably the only way to observe it will be through the decay $W \rightarrow L\bar{\nu}$; leptons up to a mass of $\sim 70 \text{ GeV}/c^2$ should be found. If the mass of the t-quark is beyond $\sim 100 \text{ GeV}/c^2$ it could be found only at FNAL, provided its mass is below $\sim 180 \text{ GeV}/c^2$, as deduced from a combined fit of radiative correction measurements in lepton-nucleon scattering experiments and at the $p\bar{p}$ Collider [114]. In their search for W' and Z' (assuming standard couplings), the UA experiments will be sensitive to masses of $\sim 350 \text{ GeV}/c^2$ and $300 \text{ GeV}/c^2$; at FNAL these limits can be pushed to ~ 650 and $550 \text{ GeV}/c^2$ [115].

We have seen that W and Z production is a very good testing ground for QCD. The forthcoming $p\bar{p}$ Collider runs will provide more precise information about the IVB momentum distributions, thus allowing a stricter comparison of data with structure functions, and a more precise determination of Λ_{QCD} . More exciting is the search for massive objects decaying into weak bosons and jets. A powerful implement for carrying out this search is the tagging of the leptonic W or Z decay in those events, as was demonstrated by UA1 and UA2. Clearly, this technique is also applicable in colliders with much larger centre-of-mass energies.

Finally, whilst the present mass limits of the t-quark and of exotic particles seem to preclude their discovery at the two upcoming e^+e^- Colliders, the SLC and LEP I, a precision measurement of the Z mass and decay width and the search for Higgs bosons will be the domain of these machines. At this time the fundamental question about the number of light neutrino species will be answered.

The combined results on W and Z properties obtained at the $p\bar{p}$ and e^+e^- Colliders during the next few years will lead, in an indirect way, to information about electroweak and strong interactions at energy scales reachable only by accelerators foreseen for the long-term future.

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Table 1

Approximate values for the performance
of the SPS Collider in 1985

AA stacking rate	$7 \times 10^9 \bar{p}$ per hour
Transfer efficiency	75%
No. of protons	2×10^{11}
No. of antiprotons	2×10^{10}
Max. initial luminosity	$4 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$
Antiproton beam lifetime	24 h

Table 2

Main parameters of the UA1 detector

<p>1) Magnetic field/track measuring:</p> <p>Type of magnet</p> <p>Track-measuring method</p> <p>Mean number of points per track</p> <p>Precision of point-position measurement</p> <p>$\sigma(p)/p$</p>	<p>Dipole, 0.7 T</p> <p>Drift chamber, charge-division method</p> <p>110</p> <p>$280 \mu\text{m}$</p> <p>0.005p</p>	
<p>2) Electromagnetic calorimetry:</p> <p>Type</p> <p>$\sigma(E)/E$ (initially)</p> <p>Calibration systematics</p> <p>Total depth (normal incidence)</p> <p>No. of channels</p> <p>Segmentation in depth</p> <p>e/π response ratio</p>	<p>Central region</p> <p>Lead/scint. sandwich</p> <p>$0.15/\sqrt{E}$</p> <p>3%</p> <p>$\sim 27X_0$ and 1.1λ</p> <p>768</p> <p>$(3.3/6.6/9.9/6.6)X_0$</p>	<p>Forward region</p> <p>$0.16/\sqrt{E}$</p> <p>256</p> <p>$(3.6/7.2/8.7/7.2)X_0$</p> <p>1.3</p>
<p>3) Hadronic calorimetry:</p> <p>Type</p> <p>$\sigma(E)/E$</p> <p>E_T Resolution</p> <p>Total depth (normal incidence)</p> <p>No. of channels</p>	<p>Iron/scint. sandwich</p> <p>$0.8/\sqrt{E}$</p> <p>$0.7 \sqrt{\sigma_0 E_T }$</p> <p>5λ</p> <p>768</p>	<p>7λ</p>
<p>4) Muon identification:</p> <p>Absorber thickness in front of muon chambers</p> <p>Track measurement</p> <p>σ_{xy}</p> <p>Additional track information</p> <p>σ_{xy}</p>	<p>8.3λ</p> <p>drift tubes; 2×4 readout planes</p> <p>$300 \mu\text{m}$</p> <p>streamer tubes; 2 or 3 readout planes</p> <p>$500 \mu\text{m}$</p>	<p>10.5λ</p>

Table 3

Typical contributions from the different main triggers [62] in UA1

Trigger	Contribution (%)
1 muon	~ 45
1 electron	~ 15
1 jet	~ 15-20
E_T (1985)	~ 10-15
ΣE_T	~ 5-7
2 muons	~ 1

Table 4

Integrated luminosity recorded at UA1 and UA2

Period	$\sqrt{s}$ (GeV)	$\int L dt$ (nb ⁻¹)	
		UA1	UA2
1981 Dec.	546	0.023	0.079
1982 Oct./Dec.	546	28	15
1983 Apr./July	546	136	127
1984 Sept./Dec.	630	263	310
1985 Sept./Dec.	630	305	458

Table 5

Efficiencies, backgrounds, and integrated luminosities, for the various UA1 W and Z event samples

$\sqrt{s}$ (GeV)	Channel	Events	Background ^{a)} events	Efficiency	Luminosity (nb ⁻¹)
546	$W \rightarrow e\nu$	59	6.8 ± 2.0	0.69 ± 0.03	136 ± 20
	$W \rightarrow \mu\nu$	10	0.70 ± 0.10	0.16 ± 0.02	108 ± 16
	$Z \rightarrow e^+e^-$	4	< 0.1	0.69 ± 0.03	136 ± 20
	$Z \rightarrow \mu^+\mu^-$	4	0.07 ± 0.03	0.37 ± 0.05	108 ± 16
630	$W \rightarrow e\nu$	240	19.3 ± 1.7	0.61 ± 0.02	568 ± 85
	$W \rightarrow \mu\nu$	57	3.3 ± 0.5	0.15 ± 0.01	551 ± 83
	$Z \rightarrow e^+e^-$	29	0.20 ± 0.02	0.69 ± 0.02	568 ± 85
	$Z \rightarrow \mu^+\mu^-$	15	0.35 ± 0.16	0.40 ± 0.02	555 ± 83
546 + 630	$W \rightarrow \tau\nu$	32	2.7 ± 0.6	0.068 ± 0.004 $\pm 0.007^b)$	686 ± 103

a) Note: no contributions from top-quark production and semileptonic decay have been included in these background estimates.

b) This additional systematic error is due to the uncertainty on energy scale and τ selection.

Table 6aThe $W \rightarrow e\nu$ event sample of UA2 [29]

$\sqrt{s}$ (GeV)	546	630
Integrated luminosity (nb^{-1})	142	738
Acceptance ϵ_W	0.61 ± 0.02	
Detection efficiency η_W	0.72 ± 0.06	
Number of $W \rightarrow e\nu$ candidates	42	206
Backgrounds:		
Hadronic	1.8 ± 0.3	9.4 ± 1.7
$W \rightarrow \tau\nu, \tau \rightarrow e\nu\bar{\nu}$	0.8 ± 0.1	4.2 ± 0.4
$Z \rightarrow e$ (detected) and e (undetected)	1.5 ± 0.2	7.8 ± 1.3
$W \rightarrow e\nu$ signal	37.9 ± 6.5	184.6 ± 14.5

Table 6bThe $Z \rightarrow e^+e^-$ event sample of UA2

$\sqrt{s}$ (GeV)	546	630
Integrated luminosity (nb^{-1})	142	768
Acceptance ϵ_Z	0.57 ± 0.02	0.55 ± 0.02
Detection efficiency η_Z	0.94 ± 0.03	
Number of $Z \rightarrow e^+e^-$ candidates	9	30
Hadronic background	0.2	1.1
$Z \rightarrow e^+e^-$ signal	8.8 ± 3.0	28.9 ± 5.5

Table 7Masses and widths of the IVBs (in GeV/c^2)

	UA1
Electron decay channels:	
m_W	$82.7 \pm 1.0 \text{ (stat.)} \pm 2.7 \text{ (syst.)}$
$\Gamma_W \text{ (90\% CL)}$	< 5.4
m_Z	$93.1 \pm 1.0 \text{ (stat.)} \pm 3.1 \text{ (syst.)}$
$\Gamma_Z \text{ (90\% CL)}$	< 5.2
Muon decay channels:	
m_W	$81.8^{+6.0}_{-5.3} \text{ (stat.)} \pm 2.6 \text{ (syst.)}$
m_Z	$90.7^{+5.2}_{-4.8} \text{ (stat.)} \pm 3.2 \text{ (syst.)}$
Tau decay channel:	
m_W	$89 \pm 3 \text{ (stat.)} \pm 6 \text{ (syst.)}$
	UA2
Electron decay channels:	
m_W	$80.2 \pm 0.6 \text{ (stat.)} \pm 0.5 \text{ (syst._1)} \pm 1.3 \text{ (syst._2)}$
$\Gamma_W \text{ (90\% CL)}$	< 7
m_Z	$91.5 \pm 1.2 \text{ (stat.)} \pm 1.2 \text{ (syst._1)} \pm 1.7 \text{ (syst._2)}$
$\Gamma_Z \text{ (90\% CL)}$	< 5.6

Table 8

Cross-section times branching ratios for IVBs produced at the Collider

 $p\bar{p} \rightarrow W^\pm + X$ ($\sigma \cdot \text{BR}$ in nb)

$\sqrt{s}$ (GeV)	546	630	630/546	Refs.
$W \rightarrow e\nu$	$0.53 \pm 0.08 \pm 0.09$	$0.61 \pm 0.04 \pm 0.09$	$1.15 \pm 0.18 \pm 0.06$	UA1 [86]
$W \rightarrow \mu\nu$	$0.54 \pm 0.17 \pm 0.12$	$0.61 \pm 0.08 \pm 0.11$	$1.14 \pm 0.40 \pm 0.18$	
$W \rightarrow \tau\nu$	$0.63 \pm 0.13 \pm 0.12$			
$W \rightarrow e\nu$	$0.61 \pm 0.10 \pm 0.07$	$0.57 \pm 0.04 \pm 0.07$	0.93 ± 0.17	UA2 [29]
$W \rightarrow \ell\nu^{*)}$	$0.38^{+0.12}_{-0.05}$	$0.48^{+0.13}_{-0.07}$	1.26 ± 0.02	Theory [39]

*) For $m_t = 44 \text{ GeV}/c^2$, $m_W = 83 \text{ GeV}/c^2$ $p\bar{p} \rightarrow Z + X$ ($\sigma \cdot \text{BR}$ in pb)

$\sqrt{s}$ (GeV)	546	630	Refs.
$Z \rightarrow e^+e^-$	$42^{+33}_{-20} \pm 6$	$74 \pm 14 \pm 11$	UA1 [86]
$Z \rightarrow \mu^+\mu^-$	$98^{+78}_{-46} \pm 20$	$66 \pm 17 \pm 11$	
$Z \rightarrow e^+e^-$	$116 \pm 35 \pm 10$	$73 \pm 14 \pm 7$	UA2 [29]
$Z \rightarrow \ell^+\ell^-^{*)}$	43^{+13}_{-7}	53^{+16}_{-10}	Theory [39]

*) For $m_t = 44 \text{ GeV}/c^2$, $m_Z = 94 \text{ GeV}/c^2$

Table 9

Test of lepton universality of weak charged and neutral currents

Cross-section ratios	$\sqrt{s}$ (GeV)	546	630
Charged currents:			
$\sigma \cdot \text{BR}(W \rightarrow \mu \nu) / \sigma \cdot \text{BR}(W \rightarrow e \nu)$		$1.02 \pm 0.36 \text{ (stat.)} \pm 0.15 \text{ (syst.)}$	$1.00 \pm 0.15 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$
$\sigma \cdot \text{BR}(W \rightarrow \tau \nu) / \sigma \cdot \text{BR}(W \rightarrow e \nu)$		$1.03 \pm 0.20 \text{ (stat.)} \pm 0.10 \text{ (syst.)}$	
Neutral currents:			
$\sigma \cdot \text{BR}(Z \rightarrow \mu^+ \mu^-) / \sigma \cdot \text{BR}(Z \rightarrow e^+ e^-)$		$2.33^{+1.85}_{-1.57} \text{ (stat.)} \pm 0.15 \text{ (syst.)}$	$0.89 \pm 0.29 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$

Ratios of coupling constants		546 GeV/630 GeV
Charged	g_μ / g_e	$1.00 \pm 0.07 \text{ (stat.)} \pm 0.04 \text{ (syst.)}$
	g_τ / g_e	$1.01 \pm 0.11 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$
Neutral	g_μ / g_e	$1.02 \pm 0.15 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$

Figure captions

- Fig. 1 Four-fermion interaction diagram for neutron β -decay
- Fig. 2 Diagram for neutron β -decay by W-exchange
- Fig. 3 Decay width of W and Z as a function of the t-quark mass [27]
- Fig. 4 The Drell-Yan mechanism
- Fig. 5 Diagram for W or Z production in hadron-hadron collisions via the Drell-Yan process
- Fig. 6 Illustration of the angular asymmetry of muons in the decay of W bosons
- Fig. 7 Feynman diagrams for the hadronic production of weak bosons including first-order QCD:
a) gluon bremsstrahlung, b) QCD Compton scattering.
- Fig. 8 The CERN accelerator complex.
- Fig. 9 The UA1 detector: schematic cross-section in the vertical plane along the beam direction
- Fig. 10 Hermeticity of the UA1 detector
- Fig. 11 The UA2 detector: schematic cross-section in the vertical plane along the beam direction.
- Fig. 12 Graphical displays of a) an event with a $W^- \rightarrow e^- \bar{\nu}$ candidate; b) an event with a $Z \rightarrow e^+ e^-$ candidate found by UA1
- Fig. 13 Calorimeter response to a $Z \rightarrow e^+ e^-$ candidate observed by UA2
- Fig. 14 The transverse-mass (m_T) distribution of the UA1 W candidates in the electron channel. Background contributions from jet (QCD) fluctuations and $W \rightarrow \tau \nu$ decays are superimposed on the data points together with the simulation of $W \rightarrow e \nu$ decays assuming $m_W = 83.5 \text{ GeV}/c^2$ (solid curve). The simulation is normalized to the number of observed events.
- Fig. 15 The m_T distribution of the UA2 W-sample of 752 events with $p_T^e > 20 \text{ GeV}/c$. The solid line corresponds to a simulation of all contributing processes; the dashed line represents simulated W decays, where $m_W = 80.2 \text{ GeV}/c^2$.
- Fig. 16 Invariant-mass distribution of two electromagnetic clusters of $E_T > 15 \text{ GeV}$ found in UA1. The shaded region corresponds to the $Z \rightarrow e^+ e^-$ sample.
- Fig. 17 Electron-pair mass distribution found by UA2.
- Fig. 18 Transverse-mass distribution of events in the $W \rightarrow \mu \nu$ sample. The shaded area corresponds to the dominant background from $W \rightarrow \tau \nu$ events.
- Fig. 19 Invariant-mass distribution of two isolated muons found by UA1
- Fig. 20 Scatter plot of τ log-likelihood L_τ versus the transverse energy of the highest- E_T jet. The projections for L_τ and E_T^j are plotted for the data (histogram), all predicted contributions (solid line), and background (shaded area). The different symbols indicate the charged-particle multiplicity n of the highest- E_T jet.
- Fig. 21 Graphics display of all raw digitizations recorded by the UA1 Central Detector for a $W^- \rightarrow \tau^- \bar{\nu}$ event candidate.
- Fig. 22 The UA2 jet-pair mass distribution of events passing the selection criteria as described in Ref. [72]. The smooth curves are the results of the best fit to the strong interaction background alone (curve a) or including two Gaussians describing W and Z decays (curve b).
- Fig. 23 Graphics display of an event with an energetic jet and missing E_T . Only tracks with $p_T > 1 \text{ GeV}/c$ and calorimeter cells with $E_T > 1 \text{ GeV}$ are shown.
- Fig. 24 Jet transverse-energy distribution for background-subtracted data passing the cut $L_\tau < 0$ (points with error bars). Also shown are the predicted distributions from a heavy lepton of mass $m_L = 35 \text{ GeV}/c^2$ (solid line) and $m_L = 55 \text{ GeV}/c^2$ (dashed line).
- Fig. 25 Transverse-mass distributions for W candidates decaying into a) electrons and b) taus.
c) Inverse transverse-mass distribution for W candidates decaying into muons.

- Fig. 26 Invariant-mass distributions of well-measured Z candidates decaying a) into e^+e^- pairs, b) into $\mu^+\mu^-$ pairs. The solid curves represent the results from the mass fit.
- Fig. 27 The distributions of the cosine of the electron (positron) emission angle θ^* with respect to the proton (antiproton) direction in the W rest frame. The dashed band in (a) (UA1 measurement) indicates the estimated contribution from sea-quark annihilation. The UA2 measurement is shown in (b).
- Fig. 28 Distribution of the cosine of the emission angle θ^* of charged leptons in Z decays (for positively charged leptons in the proton direction, for negatively charged leptons in the antiproton direction).
- Fig. 29 a) W and Z production cross-sections times branching ratios measured at $\sqrt{s} = 546$ and 630 GeV. b) Average IVB production cross-sections times branching ratios versus $\sqrt{s}$. The shaded bands in (a) and (b) indicate the range of theoretical predictions, which all assume $m_t = 44 \text{ GeV}/c^2$ [39].
- Fig. 30 Feynman-x distributions of W's, acceptance-corrected. The curves are predictions using the structure functions of Eichten et al. [92].
- Fig. 31 Feynman-x distribution of Z's, acceptance-corrected (background subtracted).
- Fig. 32 Feynman-x distributions of u (or $\bar{u}$) quarks and of d (or $\bar{d}$) quarks sampled in W production. The curves are obtained from an ISAJET simulation using the structure functions of Eichten et al.
- Fig. 33 Transverse-momentum distribution of W's observed by UA1 and UA2. The histogram is taken from Ref. [67]. The curve is based on a prediction from Altarelli et al. [39].
- Fig. 34 Transverse-momentum distribution of W's measured by UA1 compared with theoretical curves from Ref. [39].
- Fig. 35 Distribution of the transverse-momentum component p_T^Z measured by UA1 compared with theoretical curves based on the structure functions from Duke and Owens [93] and Glück et al. [94].
- Fig. 36 Tail of the transverse-momentum distribution of W bosons measured by UA1 [95] and UA2 [96] compared with theoretical predictions from Bawa et al. [97]. The two curves of the theoretical calculations represent the choice of different values of Λ_{QCD} (see text).
- Fig. 37 Angular distributions of the highest- E_T jets in W-jet events found by UA1. The theoretical curve parametrizes the distribution of gluon bremsstrahlung [100].
- Fig. 38 Multiplicity distribution of hadronic jets produced in association with W's and Z's measured by UA1. The solid lines correspond to a QCD calculation of S.D. Ellis et al. [100] which uses 6 GeV as the jet- E_T threshold. The integral of data and theoretical curves is normalized to 1.
- Fig. 39 Average transverse-momentum spectrum of lepton pairs or of IVBs. The curves are a theoretical calculation from Ref. [39].
- Fig. 40 Invariant mass of the W-jet system measured a) in UA1 and b) in UA2. The event point at $m_{(W + \text{jets})} \approx 150 \text{ GeV}/c^2$ in diagram (b) corresponds to the only event where two jets were reconstructed. The curves in both diagrams correspond to theoretical calculations either from a) ISAJET or from b) Ref. [100].
- Fig. 41 Production cross-sections times branching ratio for additional vector bosons W' and Z' as a function of their mass. The upper cross-section limits indicated as horizontal lines are found by UA1. Standard couplings of W' and Z' to fermions are assumed. The curves are normalized to the cross-section values for W and Z found by UA1. Two sets of structure functions are used: Diemoz et al. [106] (continuous line using $\Lambda_{\text{QCD}} = 0.3 \text{ GeV}$, DO1 (dashed line) using $\Lambda_{\text{QCD}} = 0.2 \text{ GeV}$.

- Fig. 42 Lower mass limits at 90% CL for W' and Z' shown as a function of the coupling strength compared with standard coupling, measured by UA1
- Fig. 43 Limits on additional vector bosons W' and Z' shown as 90% CL contours in $m_{W'}$ (or $m_{Z'}$) versus $\lambda q^2 \cdot \text{Br}$, where λq , the coupling to quarks, and Br , the branching ratio for decays into the electron channel, are normalized to the Standard Model values (UA2 measurement).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

a) $W^\pm$ production

b) $W^\pm$ leptonic decay:

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

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Fig. 15

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Fig. 23

Fig. 24

a) Inverse Transverse Mass Distribution

b)

c)

Fig. 25

Fig. 26

Fig. 27

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Fig. 43