CERN-EP / 88-154
October 31st, 1988

RECENT RESULTS FROM THE UA1 EXPERIMENT

J. D. Dowell

(UA1 Collaboration)

University of Birmingham, England

ABSTRACT

A number of results, obtained in the UA1 experiment before the upgrade of the proton-antiproton collider at CERN, are discussed. In most cases they are the final statements that can be made from the data, based on integrated luminosities of $\sim 130 \text{ nb}^{-1}$ at $\sqrt{s} = 546 \text{ GeV}$ recorded in 1983 and $\sim 570 \text{ nb}^{-1}$ at $\sqrt{s} = 630 \text{ GeV}$ in 1984 and 1985. Where appropriate, an indication of the improvement in precision to be expected with ACOL, the new antiproton collector, is given.

Talk given at the XXIV International Conference on
High Energy Physics, Munich, August 4-10, 1988.

Recent Results from the UA1 Experiment

UA1 Collaboration, CERN

Aachen–Amsterdam (NIKHEF)–Annecy (LAPP)–Birmingham–CERN–Harvard–Helsinki–
Kiel–Imperial College, London–Queen Mary College, London–Madrid (CIEMAT)–MIT–
Padua–Paris (Collège de France)–Riverside–Rome–Rutherford Appleton Lab.–
Saclay (CEN)–Victoria–Vienna–Wisconsin Collaboration

J. D. Dowell

Birmingham University, England

1. Introduction

A number of results, obtained in the UA1 experiment before the upgrade of the proton-antiproton collider at CERN, are discussed. In most cases they are the final statements that can be made from the data, based on integrated luminosities of $\sim 130 \text{ nb}^{-1}$ at $\sqrt{s} = 546 \text{ GeV}$ recorded in 1983 and $\sim 570 \text{ nb}^{-1}$ at $\sqrt{s} = 630 \text{ GeV}$ in 1984 and 1985. Where appropriate, an indication of the improvement in precision to be expected with ACOL, the new antiproton collector, is given.

2. Final W and Z results

UA1 has now obtained final results on W and Z properties from the data taken in 1982–5 [1]. These are based on approximately 400 Ws and 50 Zs decaying into electron, muon or tau. Selected features of the results are summarised.

2.1 Leptonic couplings

The UA1 data allow the first experimental verification of the universality of weak charged and neutral current couplings at $Q^2 = m_W^2(m_Z^2)$. Defining g_ℓ as the electroweak coupling the lepton ℓ , we can express the measured ratio of the decay rates R_ℓ in terms of the coupling constants g_ℓ .

$$R_\ell = \Gamma(W \rightarrow \ell \nu) / \Gamma(W \rightarrow e \nu) = g_\ell^2 / g_e^2$$

From the ratios, which are not affected by the uncertainty on the luminosity, we find:

for charged currents $g_\mu / g_e = 1.00 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (syst)}$

$$g_\tau / g_e = 1.01 \pm 0.10 \text{ (stat)} \pm 0.06 \text{ (syst)}$$

and for neutral currents $g_\mu / g_e = 1.02 \pm 0.15 \text{ (stat)} \pm 0.04 \text{ (syst)}$

2.2 Masses and widths

The W and Z masses have been determined for the electron and muon channels and the W mass also for the τ channel. The results are summarised in Table 1 together with the limits on the directly measured widths from the electron channel. The systematic errors come from the absolute energy or momentum scale uncertainties.

Table 1

Masses and Widths of the W and Z	
	UA1
Electron Decay Channels	
m_W	$82.7 \pm 1.0 \text{ (stat.)} \pm 2.7 \text{ (syst.) GeV/c}^2$
$\Gamma_W \text{ (90\% C.L.)}$	$< 5.4 \text{ GeV/c}^2$
m_Z	$93.1 \pm 1.0 \text{ (stat.)} \pm 3.1 \text{ (syst.) GeV/c}^2$
$\Gamma_Z \text{ (90\% C.L.)}$	$< 5.2 \text{ GeV/c}^2$
Muon Decay Channels	
m_W	$81.8^{+6.0}_{-5.3} \text{ (stat.)} \pm 2.6 \text{ (syst.) GeV/c}^2$
m_Z	$90.7^{+5.2}_{-4.8} \text{ (stat.)} \pm 3.2 \text{ (syst.) GeV/c}^2$
Tau Decay Channel	
m_W	$89 \pm 3 \text{ (stat.)} \pm \text{ (syst.) GeV/c}^2$

	UA1	
	Electron Channel	Muon Channel
$m_Z - m_W \text{ (GeV/c)}^2$	$10.4 \pm 1.4 \text{ (stat.)} \pm 0.8 \text{ (syst.)}$	$8.9^{+7.4}_{-7.7} \text{ (stat.)} \pm 1.9 \text{ (syst.)}$

2.3 Radiative corrections

One of the most important tests of the electroweak model is the need for, and magnitude of, radiative corrections. Using the definition that $\sin^2 \theta_W = 1 - (m_W/m_Z)^2$ [2] one may write

$$m_W^2 = A^2 / (1 - \Delta r) \sin^2 \theta_W$$

where

$$A = (\pi \alpha / \sqrt{2} G_F)^{\frac{1}{2}}$$

$$= 37.2810 \pm 0.0003 \text{ GeV}$$

and Δr is the radiative correction to the Born approximation for m_W .

There are two ways of obtaining Δr experimentally,

- from collider data alone, using m_W and m_Z to calculate $\sin^2 \theta_W$,
- using $\sin^2 \theta_W$ from neutrino experiments, radiatively corrected to the W mass, together with m_W .

Using method i) together with the combined electron and muon data and comparing also to the UA2 results [3] one finds

$$\begin{aligned}\Delta r &= 0.036 \pm 0.100 \pm 0.067 \text{ (UA1)} \\ &0.068 \pm 0.087 \pm 0.030 \text{ (UA2)}\end{aligned}$$

from which one sees that the mass determinations, in particular m_W/m_Z which is largely unaffected by systematic errors, are not yet sufficiently accurate to provide a significant measurement of Δr .

On the other hand, method ii), using $\sin^2 \theta_W = 0.233 \pm 0.003 \pm 0.005$ from a world average of neutral current neutrino experiments [4], gives

$$\begin{aligned}\Delta r &= 0.127 \pm 0.012 \pm 0.060 \text{ (UA1)} \\ &0.068 \pm 0.022 \pm 0.032 \text{ (UA2)}\end{aligned}$$

which is significant at the 2-3 standard deviation level. The one-loop calculation [5] which is sensitive to the top quark and Higgs masses is, for $m_t = 45 \text{ GeV}/c^2$ and $m_H = 100 \text{ GeV}/c^2$,

$$\Delta r = 0.0713 \pm 0.0013$$

The value of Δr decreases with increasing m_t , going through zero for m_t around $220 \text{ GeV}/c^2$. Several authors [6] have used the results of method ii) to place an upper limit on m_t in the region of $180 \text{ GeV}/c^2$.

With the new antiproton collector, ACOL, for an integrated luminosity of 20 pb^{-1} which should be obtained by the end of 1991, combining UA1 and UA2 should give an error on m_W/m_Z in the region of 0.002. Together with a measurement of m_Z from LEP or SLC to $\sim 50 \text{ MeV}/c^2$ it will then be possible to measure Δr from collider data alone to a precision of about 0.02.

2.4 Average p_T of W and Z

The transverse momentum distribution of the W and Z provides a good test of QCD because their leptonic decays produce a final state that is free from QCD effects, leaving initial state gluon bremsstrahlung as the most important mechanism for generating p_T .

In the medium p_T region, less than $25 \text{ GeV}/c$, gluon emission of the incoming quarks has been calculated using the soft gluon resummation technique [7]. The transverse momentum of the W is given by the measurement of the recoil hadrons with a typical error of $4 \text{ GeV}/c$ at low p_T .

Fig. 1 Mean transverse momentum of lepton pairs versus centre of mass energy. The curves are from ref. 8 and the low energy data from ref. 9.

The average p_T can be compared with a QCD expectation of the mean transverse momentum of Drell-Yan produced lepton pairs in pp collisions [8]:

$$\langle p_T \rangle \approx \alpha_s \sqrt{s} f(\alpha_s, \tau)$$

where α_s is the strong coupling constant and $\tau = m_{DY}^2/s$. For fixed τ the average p_T increases linearly with $\sqrt{s}$, as illustrated in fig. 1. The W and Z mean transverse momenta ($\sqrt{\tau} = 0.13 - 0.17$) are in good agreement with the QCD prediction.

2.5 Comparison of invariant cross sections for electroweak boson production

The transverse momentum distribution [10] of the Ws decaying into electrons, corrected for acceptance and detector resolution so that it can be compared directly with theoretical predictions, is shown in Fig. 2. Above 25 GeV/c, no full QCD calculation is currently available. The curve between 25 and 60 GeV/c results from a perturbative calculation to order α_s , normalized to the lowest order W cross section [7] and has been extrapolated using the ISAJET QCD Monte Carlo [11]. The agreement with the data over five orders of magnitude is very good, except possibly at the very highest values of p_T . The characteristics of the individual events in this region have been discussed elsewhere [10].

Isolated direct photon production has been measured in the UA1 experiment by selecting neutral isolated electromagnetic clusters of large transverse energy [12]. Discrimination against π^0 s is achieved by the isolation of the cluster in a cone of the size of a jet, as π^0 s originate from jet fluctuations, and by the longitudinal energy deposition of the shower. After subtracting background, correcting for acceptance and selection efficiencies and unsmearing the energy resolution we obtain the transverse momentum distribution of direct isolated photons with $p_T > 20$ GeV/c, shown in fig.2. The agreement between our data and the QCD predictions of Aurenche et al. [13] is excellent.

Fig. 2 The invariant cross section for W and direct photon production as a function of transverse momentum. The theoretical curves are from Altarelli et al. [7] and Aurenche et al. [13].

To extrapolate the cross-section to lower p_T values (6 - 20 GeV/c) we have used low mass, large p_T Drell-Yan pairs ($m^2 \ll p_T^2$) which are related to direct photon production via the electromagnetic coupling α multiplied by a factor, which is essentially a measure of the virtuality of the intermediate photon. The factor C between Drell-Yan and direct photon production can be calculated under the assumption $m^2 \ll p_T^2$:

$$C = (\alpha/3\pi) \ln m_{\max}^2 / m_{\min}^2 = \alpha/1.91 \text{ for } m_{\min} = 2\mu \text{ and } m_{\max} = 2.5 \text{ GeV}/c^2$$

With this factor, the p_T distribution of our low mass, isolated unlike-sign muon pairs continue the direct photon spectrum smoothly towards lower p_T values [14].

The large transverse momentum production of the electroweak gauge bosons offers a powerful test of QCD theory. The production occurs by quark-antiquark annihilation and the gluon Compton process. More than 70% of W production is due to the annihilation process, whereas the Compton process is responsible for most of the photon production. However, at transverse momenta comparable with the W mass, the annihilation process also takes over in the photon case. Hence, the photon and W cross section exhibit the same behaviour at large transverse momenta ($p_T > 40 \text{ GeV}/c$) and are about the same, demonstrating the similar strengths of the electromagnetic and weak couplings. The data are in good agreement with the theoretical calculations, but in both cases they exceed the theoretical curves in the large p_T tail.

2.6 Number of Light Neutrino Species

The ratio R of the cross sections times branching ratios for leptonic decays of the W and Z is sensitive to the number of light neutrinos, since the total Z width increases by 170 MeV per additional $Z^0 \rightarrow \nu\bar{\nu}$ decay.

$$R = (\sigma_B)_W / (\sigma_B)_Z = (\sigma_W / \sigma_Z) (\Gamma_{\text{tot}}^Z / \Gamma_{\text{tot}}^W) (\Gamma^{W \rightarrow l\nu} / \Gamma^{Z \rightarrow ll})$$

The theoretical prediction for R depends on the predicted production cross-section ratio, the partial leptonic widths, which are well known in the standard model, and the total widths of W and Z . Γ_{tot}^W depends on the top quark mass and Γ_{tot}^Z also on the unknown number of light neutrinos. Fig. 3 shows the total decay width of the W and Z as a function of the top mass in the case of three generations.

Recent calculations of the ratio of the production cross-sections (σ_W / σ_Z) give values between 3.0 and 3.4 with a typical error of 0.15. The different theoretical results come from the different analyses of the nucleon structure functions. Details are given in Ref. 15.

The systematic measurement errors largely cancel in the ratio R and hence the precision is currently limited by the available Z statistics. To obtain the most precise value for R it is necessary to combine the four measurements (electron and muon at two energies) in one fit, assuming lepton universality. The final result is:

$$R = 9.1^{+1.7}_{-1.2}$$

where the errors reflect the limited Z statistics (52 events) and the uncertainties in the experimental efficiencies and background. The UA1 measurement [15] is consistent with the equivalent UA2 result [16]. Combining the UA1 and UA2 likelihood curves, the overall collider result is:

$$R = 8.4^{+1.2}_{-0.9}$$

This value of R gives $N_\nu = 1.8^{+2.0}_{-1.5}$ neutrino types for a light top quark. The associated

The combined (UA1 and UA2) limit on N_ν as a function of the top mass is shown in fig.4. The vertical line indicates our top mass limit. The final result yields less than 6 neutrinos with a mass below half of the Z mass. If a new heavy charged lepton exists with a mass corresponding to the UA1 lower limit of 41 GeV/c², our limits become less restrictive by one neutrino type. The data are presently not sufficiently accurate to allow a statement about an upper limit on the top quark mass. However, in the case of four generations with a heavy lepton heavier than the W, the top quark has to be lighter than 80 GeV/c².

Fig. 3 Dependence of the total decay width of the W and Z on the top quark mass; assuming three generations.

Fig. 4 The total number of light neutrino species deduced from the combined UA1 and UA2 data.

3. Measurement of b-quark production cross section at $\sqrt{s} = 630$ GeV

At the CERN collider ($\sqrt{s} = 630$ GeV), the predicted cross sections for charm and bottom quark pair production are respectively $\sim 100 \mu\text{b}$ and $\sim 10 \mu\text{b}$. The results reported here [17] are discussed in more detail by Kenyon at this conference [18]. Bottom quarks are not directly reconstructed in the UA1 detector, but they can be tagged by the presence of one or more muons which are mostly embedded in hadronic jets. Muons offer the experimental advantage that they can be identified at low transverse momenta ($p_T > 3$ GeV/c) and in the presence of hadronic activity. It is found that the dominant source of muons with large p_T inside jets is $b\bar{b}$ production rather than $c\bar{c}$. At transverse momenta larger than the quark masses involved, b and c quarks are produced with similar p_T spectra. The harder fragmentation of the bottom quark compared to charm gives, on average, a larger fraction of the original quark momentum to the B-hadron. Hence, the harder p_T spectrum of muons from bottom quarks compared with charm quarks favours $b\bar{b}$ over $c\bar{c}$, once a p_T cut is applied to the muons. By using the transverse momentum distribution of the muons with respect to the jet axis, the bottom fraction in heavy flavour events can be fitted, giving for single muon events:

$$\text{bottom}/(\text{bottom} + \text{charm}) = 76 \pm 12\%$$

The background to the muon sample has been studied extensively and is discussed in detail elsewhere [19]. It arises principally from pion and kaon decays. In the data samples discussed here, backgrounds range from about 20% to 40% and have been corrected for.

Four sets of data have been used to evaluate cross sections for various regions of the p_T of the b -quark.

J/ψ events;	$p_T(J/\psi) > 5 \text{ GeV}/c$
Low mass dimuons;	$m_{\mu\mu} < 6 \text{ GeV}/c^2$; $p_T^\mu > 3 \text{ GeV}/c$
High mass dimuons;	$m_{\mu\mu} > 6 \text{ GeV}/c^2$; $p_T^\mu > 3 \text{ GeV}/c$
Single muons;	$p_T^\mu > 10 \text{ GeV}/c$

The measurements at the muon level are related to the cross sections for producing b -quarks using the Monte Carlo program ISAJET [11]. Starting from a (leading order) QCD prediction for b -quark production, one obtains the bottom hadron distribution by convolution with the fragmentation function measured in e^+e^- collider experiments at PEP and PETRA. The muon distribution is then obtained using the semileptonic branching ratio measured at CESR and DORIS and from decay kinematics assuming a V-A form for the matrix element. We then quote the b -quark cross sections for $p_T^b > p_T^{\min}$ where $p_T^{\min}$ is defined such that 90% of the muon events have $p_T^b > p_T^{\min}$.

About one quarter of the J/ψ come from b -decays [20], the remainder coming from χ -decay, and are selected by the presence of hadronic activity around the J/ψ . The single muon events have been divided into three p_T ranges (10 - 15, 15 - 20 and 20 - 25 GeV/c) yielding three determinations of the cross section.

Fig. 5 shows the resulting inclusive b -quark cross sections for six values of $p_T^{\min}$ with $(y^b) < 1.5$. The solid curve is the next to leading order calculation of Nason et al. [21] for $p_T^{\min}$ up to 15 GeV/c . Shown also is the calculation to leading order only, which is poorer agreement with the data. The full ISAJET calculation also describes the data satisfactorily.

Fig. 5 The inclusive bottom cross section for $p\bar{p}$ collisions at $\sqrt{s} = 630 \text{ GeV}$.

Integrating down to $p_T = 0$ and fitting the normalization of the $O(\alpha_s^3)$ spectrum up to 15 GeV/c we obtain the inclusive beauty cross-section:

$$\sigma(p\bar{p} \rightarrow b \text{ or } \bar{b}) = 14.7 \pm 4.7 \mu\text{b}; |y(b)| < 1.5$$

An extrapolation over the total rapidity range yields for the total $b\bar{b}$ pair production:

$$\sigma(p\bar{p} \rightarrow b\bar{b}) = 10.2 \pm 3.3 \mu\text{b}$$

This can be compared with a recent theoretical calculation [22] which gives

$$\sigma(p\bar{p} \rightarrow b\bar{b}) = 12^{+7}_{-4} \mu\text{b} \text{ for } m_b = 5 \text{ GeV}/c^2$$

and

$$\sigma(p\bar{p} \rightarrow b\bar{b}) = 19^{+10}_{-8} \mu\text{b} \text{ for } m_b = 4.5 \text{ GeV}/c^2$$

The quoted errors are due to uncertainties in the choice of structure functions, choice of scale (μ) and choice of Λ . Within the large experimental and theoretical errors, there is good agreement between QCD and the data.

4. Limits on New Quarks (t and b')

UA1 has published lower limits on the masses of the top and b' (fourth generation) quarks of 44 GeV/c² and 32 GeV/c² respectively at the 95% confidence level [23]. These depend on an $O(\alpha_s^2)$ QCD prediction for the cross section for producing heavy quark pairs, added to the $W \rightarrow t\bar{b}$ cross section which is known reliably from experiment. Using the $O(\alpha_s^3)$ calculation of Nason et al. [21] and the DFLM structure functions [24], Altarelli et al. [22] have revised these limits to give

$$m_t > 41 \text{ GeV}/c^2 \text{ (95\% c.l.)}$$

$$m_{b'} > 34 \text{ GeV}/c^2 \text{ (95\% c.l.)}$$

The future prospects with 20 pb⁻¹ using ACOL should allow top masses up to 75 GeV/c² to be explored. In 1988/9, with an expectation of 4 pb⁻¹, both UA1 and UA2 should be sensitive to masses up to 60 GeV/c². In this period, UA1 will be running without the new electromagnetic calorimeter using muons to tag top candidates while UA2 relies on electrons.

5. B⁰- $\bar{B}^0$ oscillations

Evidence for B⁰- $\bar{B}^0$ oscillations has been reported by UA1 from the observation of like sign muon pairs [25]. The ARGUS collaboration has also observed oscillations, specifically in the B⁰_d- $\bar{B}^0$ _d system [26] whereas the UA1 result could be either B⁰_d or $\bar{B}^0$ _s. Below we discuss the consequence of combining the two results and incorporating a constraint from the Kobayashi-Maskawa matrix.

The rate of oscillations compared to the decay rate is determined by $\Delta m/\Gamma$ where Δm is the mass difference between the two mass eigenstates and Γ the decay width. Experimentally, one integrates over the decay time and the probability of observing a wrong sign muon is given by

$$\chi = P(B^0 \rightarrow \bar{B}^0 \rightarrow \mu^-) / P(B^0 \rightarrow \mu^+) = (1/2) (\Delta m/\Gamma)^2 / [1 + (\Delta m/\Gamma)^2]$$

For maximal mixing, which occurs if $\Delta m/\Gamma \gg 1$, χ approaches 0.5. $\Delta m/\Gamma$ can be estimated using box diagrams which are dominated by t-quark exchange and depend on the Kobayashi-Maskawa matrix elements. Approximately, one may write

$$\Delta m/\Gamma(B^0_d) \propto (V_{tb}^* V_{td})^2$$

$$\Delta m/\Gamma(B_s^0) \propto (V_{tb}^* V_{ts})^2$$

as other factors are expected to be similar in the two cases. Hence the main difference between χ_s and χ_d is determined by V_{td} and V_{ts} . In the standard model with three quark families these matrix elements are already constrained by the unitarity of the K-M matrix.

$$0.002 < |V_{td}| < 0.017 \quad ; \quad 0.037 < |V_{ts}| < 0.048$$

This can be used to give an upper limit on χ_d as a function of χ_s

$$\chi_d < 0.21^2 \chi_s / [1 - 2\chi_s(1 - 0.21^2)]$$

with certain assumptions [27]. The result of combining the UA1 and ARGUS results is shown as in Fig. 6 together with this constraint. The most probable value of χ_s is 0.5 (maximal mixing for $B_s^0 - \bar{B}_s^0$) and the shaded region shows the 90% confidence level limit. However, the KM constraint leaves only a small allowed region in the $\chi_s - \chi_d$ plane giving a lower limit $\chi_s > 0.4$ (90% C.L.). Full details may be found in reference 27. In the future, UA1 with ACOL, combined with ARGUS, CLEO [28] and the four LEP experiments, should allow the errors on χ_s and χ_d to be reduced by a factor 4 - 5.

Fig. 6 Combined 90% confidence level limits on χ_s and χ_d from UA1 and ARGUS. The line is the constraint from the Kobayashi-Maskawa matrix.

6. Other new particle limits

Table 2 summarises new particle limits obtained by UA1 and the prospects with 10 pb^{-1} at ACOL including results already discussed. A more detailed account can be found in reference 29.

Table 2

Object	Present UA1 Limit	Confidence level %	Sensitivity at ACOL
<i>New quarks and leptons</i>			
Top quark [23]	$m_t > 44 \text{ GeV}/c^2$	95	$70 \text{ GeV}/c^2$
b' quark [23]	$m_{b'} > 32 \text{ GeV}/c^2$	95	$70 \text{ GeV}/c^2$
Heavy charged leptons [30]	$m_L > 41 \text{ GeV}/c^2$	90	$70 \text{ GeV}/c^2$
Neutrinos [15]	$N_\nu \leq 6 \text{ (UA1 + UA2)}$	90	± 0.7
<i>Compositeness</i>			
Preons [31]	$\Lambda_c \geq 415 \text{ GeV}$	95	650 GeV
Leptoquark [29]	$m > 33 \text{ GeV}/c^2$	90	$70 \text{ GeV}/c^2$
<i>Heavy bosons</i>			
Heavy W [1]	$m_{W'} > 232 \text{ GeV}/c^2$	90	$350 \text{ GeV}/c^2$
Heavy Z [1]	$m_{Z'} > 188 \text{ GeV}/c^2$	90	$300 \text{ GeV}/c^2$
<i>Supersymmetry</i>			
Selectron and sneutrino [1]	$m_{\tilde{e}, \tilde{\nu}} > 30 \text{ GeV}/c^2$	90	$40 \text{ GeV}/c^2$
Gluino [32]	$m_{\tilde{g}} > 53 \text{ GeV}/c^2$	90	$100\text{--}130 \text{ GeV}/c^2$
Squark [32]	$m_{\tilde{q}} > 45 \text{ GeV}/c^2$	90	$100\text{--}130 \text{ GeV}/c^2$
Axigluon [33] $\Gamma_A \leq 0.4 m_A$	$m_A < 150 \text{ GeV}/c^2$ or $m_A > 310 \text{ GeV}/c^2$	95	

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