PHYSICS FROM THE p\bar{p} COLLIDER

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1. INTRODUCTION

The modification of the CERN Super Proton Synchrotron (SPS) into a $p\bar{p}$ Collider was originally suggested as a quick and relatively inexpensive way of producing and detecting the weak Intermediate Vector Bosons, W and Z [1].

The first $p\bar{p}$ collisions at a total centre-of-mass energy $\sqrt{s} = 546$ GeV were observed in July 1981 [2]. At the end of that year the first physics run took place, providing the first clear evidence of the production of hadronic jets, with high transverse momentum ($p_T$), from hadron-hadron collisions [3, 4].

One year later, a second physics run led to the discovery of the W [5, 6]. Soon afterwards, in spring 1983, the Z was also discovered [7, 8].

In a more recent run during autumn 1984, the collision energy was increased to the value of 630 GeV. By the end of that run, the two major experiments, UA1 and UA2, had accumulated data corresponding to a total integrated luminosity $L = 399$ and $452$ nb$^{-1}$, respectively.

Finally, during the month of March 1985 a new mode of operation was successfully tried during a special physics run, with the collision energy varying between two flat tops at 200 and 900 GeV, with a period of 21.6 seconds.

At present, the physics topics being studied at the Collider cover a domain which extends well beyond the original motivation for this machine, and to deal with them all in a single summary talk is an impossible task for me. For this reason I shall discuss only two subjects: the physics of the W and Z bosons; and recent UA1 results from a study of low-mass muon pairs.

Other topics which are also part of the main streams of research at the Collider — such as the study of high-$p_T$ jets, or the measurement of total cross-sections and particle multiplicities — are covered in other plenary sessions at this Conference [9–12].
2. PHYSICS OF THE INTERMEDIATE VECTOR BOSONS

2.1 Electron identification

In a search for high-\(p_T\) electrons at the Collider, the main background results from hadronic jets consisting of one or more high-\(p_T\) \(\pi^0\)'s and one charged particle, which could be either a charged jet fragment or an electron from photon conversion. Such a configuration is hard to distinguish from a genuine electron in the UA1 and UA2 detectors.

As a consequence, both experiments use somewhat similar electron identification criteria, which aim at a high rejection against jets while maintaining a reasonably high efficiency for electrons. These criteria require the energy deposition in the calorimeter to match that expected from an isolated electron, which implies that a very large fraction of events containing electrons inside or near a jet are rejected. In the following, we describe the main cuts used to select an inclusive electron sample.

i) The transverse energy \(E_T\) associated with the energy cluster in the calorimeter is required to exceed a given threshold. For the data discussed here, this threshold is set at 15 GeV for both experiments.

ii) The shower energy leakage into the hadronic compartment of the calorimeter is required to be small.

iii) In the UA1 experiment the longitudinal development of the electromagnetic shower, which is measured over four samples, is required to be compatible with that expected for an electron. In the UA2 experiment, the lateral shower profile is required to be small, using the small cell size of the calorimeters.

iv) The presence of a charged-particle track pointing to the energy cluster in the calorimeter is required.

v) In the UA1 experiment the momentum measurement is used to ensure that the track transverse momentum is larger than 7 GeV/c (or compatible with 15 GeV/c within 3\(\sigma\)). In UA2, a magnetic field exists only in the two forward regions \(20^\circ < \theta < 37.5^\circ\) with respect to the beams. In these regions the track momentum is required to match the particle energy, as measured in the calorimeter, within 4\(\sigma\).

vi) A distinctive feature of the UA2 detector is the presence of a 'preshower' counter (a 1.5 radiation length thick converter, followed by a proportional chamber) in front of the calorimeters. This counter is used to verify that the electromagnetic shower is initiated in the converter and is also associated with the measured charged-particle track, as expected for electrons. This is done in practice by requiring that the observed signal exceeds a threshold corresponding to several minimum-ionizing particles, and, furthermore, that its position in space matches the track impact point within the space resolution of the counter itself (a few millimetres).

vii) Finally, an explicit isolation criterion is applied. In UA1 this is done by requiring only a limited amount of transverse energy (typically less than 3 GeV) associated with charged particles and calorimeter cells contained in a cone of \(\sim 40^\circ\) half-angle around the electron track. In UA2 this cone has a half-angle of typically \(\sim 15^\circ\).

The combination of all these cuts is estimated to be \(\sim 75\%\) efficient for isolated electrons in both experiments. Figure 1a shows the distribution of the transverse momentum \(p_T\) for the electron candidates in the UA1 experiment [13], selected from the 1984 data sample (\(\sqrt{s} = 630\) GeV, \(L = 263\) nb\(^{-1}\)). The UA2 distribution, corresponding to the full data sample [14], is shown in Fig. 1b.

At this stage of the analysis, most of the electron candidates are misidentified high-\(p_T\) hadrons, as suggested by the rapidly falling \(p_T\) distributions at low values of \(p_T\). However, a shoulder in the region \(p_T \approx 40\) GeV/c is clearly visible in both distributions of Fig. 1. Such a structure is expected from the Jacobian peak which results from the kinematics of \(W \rightarrow e\nu\) decay.
2.2 Neutrino identification

The presence of a non-interacting high-\(p_T\) neutrino in the final state is characteristic of \(W \rightarrow e\nu\) decays. Since a large fraction of the total collision energy is carried by particles at very small angles, which cannot be detected because they remain inside the machine vacuum pipe, only the missing transverse momentum \(p_T^{\text{miss}}\) can be reliably measured. For events containing an electron candidate, \(p_T^{\text{miss}}\) is identified with the neutrino transverse momentum \(\vec{p}_T\).

In the UA1 experiment, for events containing an electron candidate of transverse momentum \(p_T^e\), one defines \(\vec{p}_T^e\) as

\[
\vec{p}_T^e = \vec{p}_T - \sum_i \vec{p}_T^i ,
\]

where \(\vec{p}_T^i\) is a vector with magnitude equal to the energy deposited in the \(i^{\text{th}}\) cell of the calorimeter, and directed from the event vertex to the estimated impact point on the cell. The sum is extended over all calorimeter cells.

However, the central part of the UA1 detector (|\(\eta\)| < 1.5, where \(\eta\) is the pseudorapidity) has imperfect calorimetry in two azimuthal sectors at \(\pm 15^\circ\) to the vertical axis. For this reason, the measurement of \(p_T^e\) is unreliable whenever \(\vec{p}_T^e\) is within these regions. After rejecting such events, the \(\vec{p}_T^e\) resolution becomes almost Gaussian.

In the case of the UA2 detector, there is no particle detection at angles \(\theta < 20^\circ\) to the beams. Furthermore, the two forward regions \((20^\circ < \theta < 40^\circ\) to the beams) provide only partial detection because of incomplete azimuthal coverage (due to 12 toroid coils) and incomplete hadronic calorimetry. This results in non-Gaussian tails in the \(p_T^{\text{miss}}\) resolution. The probability of losing one of the jets in a two-jet event varies between \(\sim 10\%\) at \(p_T = 15\ \text{GeV/c}\) and \(\sim 2\%\) at \(p_T = 40\ \text{GeV/c}\).
For each event containing an electron candidate, the UA2 definition of $\vec{p}_T$ is

$$\vec{p}_T = -\vec{p}_T^e - \sum_j \vec{p}_T^j - \lambda \vec{P},$$

where the sum extends to all reconstructed jets with $p_T^j > 3$ GeV/c, and the vector $\vec{P}$ is the total transverse momentum carried by the system of all other particles not belonging to the jet. The factor $\lambda$, of the order of 1.5, is an empirical correction factor which takes into account the non-linearity of the calorimeter response to low-energy particles. Its value is determined by applying the condition $\langle \vec{p}_T^e \rangle = 0$ to the sample of $Z \rightarrow e^+e^-$ events observed in UA2.

2.3 The final $W \rightarrow e\nu$ event samples

Figure 2 shows, for UA1 and UA2, the distribution of the events containing at least one electron candidate with $p_T^e > 15$ GeV/c in the $(p_T^e, \vec{p}_T)$ plane. In the high-$p_T^e$ region ($p_T^e > 25$ GeV/c), signals from $W \rightarrow e\nu$ ($p_T^e = p_T^f$) and $Z \rightarrow e^+e^-$ ($p_T^f = 0$) are clearly visible above the background of misidentified hadrons, which is dominant at low $p_T^f$. It must be noted that the UA1 sample corresponds to the 1984 data only, while the UA2 distribution represents the full sample.

The projection of the two distributions onto the $p_T^e$ axis (Fig. 3) demonstrates clearly that the rejection power against background of a cut on $p_T^e$ is much larger in UA1 than in UA2. The UA1 data (Fig. 3a) show two well-separated classes of events: those with $p_T^e > 15$ GeV/c, which show the characteristic Jacobian structure expected from $W \rightarrow e\nu$ decay; and those with $p_T^e < 15$ GeV/c, which are mostly misidentified hadronic final states. In the latter class the non-zero value of $p_T^f$ is the effect of the $p_T^f$ resolution. The separation between the two classes of events is much less clear in the UA2 data (Fig. 3b), as a result of the non-Gaussian tails of the $p_T^f$ resolution in the UA2 experiment.

The final UA1 $W \rightarrow e\nu$ sample is defined by requiring $p_T^e > 15$ GeV/c. In the full data sample this condition is satisfied by 172 events. Background contributions to this sample

![Fig. 2. Distribution of the events containing at least one electron candidate in the $p_T^e, \vec{p}_T$ plane: a) UA1, 1984 sample; b) UA2, full sample.](image-url)
Fig. 3 Distribution of $p_T$ for events containing at least one electron candidate with $p_T > 15$ GeV/c: a) UA1, 1984 sample; b) UA2, full sample.

Table I

<table>
<thead>
<tr>
<th></th>
<th>UA1</th>
<th>UA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ threshold (GeV/c)</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Number of events</td>
<td>172</td>
<td>119</td>
</tr>
<tr>
<td>Hadronic background</td>
<td>5.3 ± 1.9</td>
<td>5.6 ± 1.7</td>
</tr>
<tr>
<td>$Z^0 \rightarrow e$ (detected) e (undetected)</td>
<td>-</td>
<td>4.4 ± 0.8</td>
</tr>
<tr>
<td>$W \rightarrow \tau e$ ($\tau \rightarrow e \nu \nu\nu$)</td>
<td>9.1 ± 0.5</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>$W \rightarrow \tau e$ ($\tau \rightarrow \nu \pi^0$ + hadrons)</td>
<td>2.7 ± 0.4</td>
<td>-</td>
</tr>
<tr>
<td>$W \rightarrow e$ signal</td>
<td>155 ± 13</td>
<td>107 ± 11</td>
</tr>
</tbody>
</table>

are listed in Table I. The background from misidentified hadrons is estimated from the shape of the $p_T$ resolution. After rejecting events for which either $p_T^\tau$ or $p_T^e$ points in the direction of the vertical axis within ±15°, 148 events are left. The $p_T$ distribution of these events is shown in Fig. 4a.

The final UA2 $W \rightarrow e$ sample is defined by applying a topological cut which minimizes the background from misidentified hadrons accompanied by a jet at opposite azimuth. As a measure of the fraction of the electron transverse momentum balanced by jets at opposite azimuth, the quantity

$$e_{opp} = -\sum_j p_T^j / |p_T|^2$$

(3)
Fig. 4 a) The $p_T$ distribution for electron candidates in events having $p_T > 15$ GeV/c (UA1); b) the $p_T$ distribution for electron candidates satisfying the requirement $q_{opp} < 0.2$ (UA2). Broken curves: estimated hadronic background. Full curves: expected distributions for values of $m_W$ as given by Eqs. (5) and (5').

is defined, where the sum extends over all reconstructed jets (if any) with $p_T > 3$ GeV/c, separated in azimuth from $p_T$ by at least 120°. Most $W \to e\nu$ decays belong to the category of events with large $p_T$ imbalance ($q_{opp} \approx 0$), whereas for misidentified high-$p_T$ hadrons values of $q_{opp}$ near unity are expected.

Figure 4b shows the $p_T$ distribution of all electron candidates satisfying $q_{opp} < 0.2$. Although the Jacobian peak structure has been strongly enhanced with respect to the inclusive $p_T$ spectrum of Fig. 1b, the hadronic background is still dominant for $p_T < 20$ GeV/c. For this reason the final UA2 $W \to e\nu$ sample consists only of the 119 events having $p_T > 25$ GeV/c. Background contributions to this sample are listed in Table I. The background from misidentified hadrons is estimated from a sample of high-$p_T$ $\pi^0$s which have the opposite jet outside the detector acceptance.

We note (see Table I) that the contribution from $W \to \tau\nu$, followed by $\tau \to e\nu\nu\epsilon$, is larger in UA1 than in UA2 because of the lower $p_T$ threshold used to define the final sample. However, the contribution from $Z \to e^+e^-$ decays with one electron outside the detector acceptance is larger in UA2, because the probability of detecting both electrons is only ~ 60% in UA2, while it is nearly 100% in UA1.

2.4 Cross-sections for inclusive W production

The cross-sections for inclusive $W$ production, followed by the decay $W \to e\nu$, $\sigma_W$, are computed in a straightforward way from the number of events in the samples, after subtracting the various background contributions.

The results obtained by the UA1 and UA2 experiments are listed separately in Table II for $\sqrt{s} = 546$ and 630 GeV. The quoted systematic uncertainties arise mainly from the uncertainties on the total luminosity ($\pm 15\%$ in UA1, and $\pm 8\%$ in UA2 which benefits from the measurement of the total cross-section by UA4 [15] in the same intersection).
Table II

$W \rightarrow e\nu$ cross-sections

<table>
<thead>
<tr>
<th>$\sigma_W$ (nb)</th>
<th>$r = \sigma_W(630\text{ GeV})/\sigma_W(546\text{ GeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 546\text{ GeV}$</td>
<td>$\sqrt{s} = 630\text{ GeV}$</td>
</tr>
<tr>
<td>UA1</td>
<td>$0.55 \pm 0.08 \pm 0.09$</td>
</tr>
<tr>
<td>UA2</td>
<td>$0.50 \pm 0.09 \pm 0.05$</td>
</tr>
<tr>
<td>Theory [16]</td>
<td>$0.36 \pm 0.11$</td>
</tr>
</tbody>
</table>

(The second error is the systematic uncertainty.)

These results are consistent with (but systematically higher than) the corresponding theoretical predictions [16], also given in Table II. These predictions have large uncertainties arising from uncertainties in the structure functions and higher-order QCD corrections.

In contrast, the ratio $r = \sigma_W(630\text{ GeV})/\sigma_W(546\text{ GeV})$ has negligible systematic errors and small theoretical uncertainties. The average of the two measurements, $r = 1.11 \pm 0.15$, agrees with the theoretical prediction [16], $r = 1.26 \pm 0.02$.

2.5 Determination of the W mass

To extract a value of the W mass $m_W$ from the $W \rightarrow e\nu$ event samples, both experiments define for each event a transverse mass $m_T$:

$$m_T^2 = 2p_T^e p_T^\nu (1 - \cos \Delta\phi),$$

with the property that $m_T \leq m_W$, where $\Delta\phi$ is the azimuthal separation between $p_T^e$ and $p_T^\nu$. A Monte Carlo simulation is then used to generate $m_T$ distributions for different values of $m_W$, and the most probable value of $m_W$ is found by a maximum-likelihood fit to the experimental distributions. This technique has the advantage that $m_T$ is rather insensitive to the W transverse motion, contrary to other variables such as $p_T^e$ or $p_T^\nu$.

In the UA1 experiment, a sample of 86 events for which both $p_T^e$ and $p_T^\nu$ exceed 30 GeV/c is selected from the 148 events of Fig. 4a. The $m_T$ distribution for this sample, which is virtually background-free, is shown in Fig. 5a.

In UA2, the $m_T$ distribution of the entire $W \rightarrow e\nu$ sample (119 events) is used (Fig. 5b). The backgrounds discussed in Section 2.3 have a negligible effect on the mass determination, because they are predominantly at small $m_T$, and the best-fit value of $m_W$ depends mainly on the upper edge of the distribution.

The results of the fit are

UA1: $m_W = 83.5^{+1.1}_{-1.0} \text{ (stat.)} \pm 2.8 \text{ (syst.) GeV/c^2}$ ,

UA2: $m_W = 81.2 \pm 1.1 \text{ (stat.)} \pm 1.3 \text{ (syst.) GeV/c^2}$ .

The systematic errors reflect the uncertainty on the absolute energy scale of the calorimeters, which is $\pm 3\%$ in UA1 and $\pm 1.6\%$ in UA2. These errors are quoted separately
because they cancel in the ratio $m_W/m_Z$. An additional systematic error of $\pm 0.5$ GeV/c$^2$ in the UA2 result, mainly due to uncertainties in the measurement of $p_T$, has been added in quadrature to the statistical error.

The smaller systematic uncertainty of the UA2 experiment [see Eqs. (5) and (5')] results from a better control of the calorimeter calibration, which was performed for all calorimeter cells, using beams of known energies, before the start of the experiment. This calibration has then been repeated periodically for a fraction of the calorimeter modules.

The expected $p_T$ and $m_T$ distributions for the $m_W$ values given by Eqs. (5) and (5') are shown in Figs. 4 and 5.

A fit to the $m_T$ distributions, using the $W$ width $\Gamma_W$ as a second free parameter, provides a way to obtain an upper limit on $\Gamma_W$. The results from the two experiments are $\Gamma_W < 6.5$ GeV/c$^2$ (UA1) and $< 7$ GeV/c$^2$ (UA2) at the 90% confidence level.

2.6 Charge asymmetry in the decay $W \rightarrow e\nu$

At the energies of the CERN $p\bar{p}$ Collider, $W$ production is dominated by $q\bar{q}$ annihilation involving at least one valence quark or antiquark. As a consequence of the $V - A$ coupling, the helicity of the quarks (antiquarks) is $-1$ ($+1$) and the $W$ is almost fully polarized along the $\bar{p}$ beam. At higher energies (e.g. at the TEV-I Collider) the contribution from $q\bar{q}$ annihilation with both partons belonging to the sea is important, and the $W$ polarization is greatly reduced.

Similar helicity arguments applied to $W \rightarrow e\nu$ decay predict that the leptons ($e^-$ or $\nu_e$) should be preferentially emitted opposite to the direction of the $W$ polarization, and antileptons ($e^+$ or $\bar{\nu}_e$) along it. More precisely, the angular distribution of the charged lepton in the $W$ rest frame has the form $dn/d\cos \theta' \propto (1 + \cos \theta')^2$, where $\theta'$ is the $e^+$ ($e^-$) angle in the $W$ rest frame, measured with respect to a direction parallel (antiparallel) to the $W$ polarization. This axis coincides with the direction of the incident $\bar{p}$ (p) beam only if the $W$
transverse momentum $p_T^W$ is zero. For $p_T^W \neq 0$ the initial parton directions are not known, and the Collins–Soper convention [17] is used to define $\theta^*$.

A further complication arises from the fact that $p_T^L$ is not measured, and the condition that the invariant mass of the $\ep$ pair be equal to $m_W$ gives two solutions for $p_T^L$ or $p_T^W$. The UA1 analysis [13] retains only those events for which one solution is unphysical and the charge sign is unambiguously determined (75 events). In UA2 [14], the solution corresponding to the smaller value of $|p_T^W|$ is chosen.

Figure 6a shows the $\cos \theta^*$ distribution from UA1, corrected for the detector acceptance. The expected $(1 + \cos^2 \theta^*)$ form agrees well with the data.

In the UA2 experiment only the charge-averaged $\cos \theta^*$ distribution can be measured, because there is no magnetic field over most of the solid angle. The experimental data agree well with the form $1 + \cos^2 \theta^*$ expected in this case (see Fig. 6b).

It has been shown [18] that for a particle of arbitrary spin $J$, one expects

$$\langle \cos \theta^* \rangle = \langle \mu \rangle J / (J + 1),$$

where $\langle \mu \rangle$ is, respectively, the global helicity of the production system (up), and of the decay system ($\ep\nu$). For $V - A$ one has $\langle \mu \rangle = \langle \lambda \rangle = -1$, which, together with the assignment $J = 1$, leads to a maximal value $\langle \cos \theta^* \rangle = 0.5$. The UA1 result [13] is $\langle \cos \theta^* \rangle = 0.43 \pm 0.07$, in agreement with maximal helicity states at production and decay, and with the assignment $J = 1$. For $J = 0$ one obviously expects $\langle \cos \theta^* \rangle = 0$; for any other spin value $J \geq 2$, $|\langle \cos \theta^* \rangle| \leq 1/6$. Hence the UA1 result demonstrates that the $W$ boson has indeed spin 1.
It must be noted that no measurement done so far can distinguish between \( V - A \) and \( V + A \). In the latter case, all helicities change sign and the angular distribution remains the same. In order to separate the two alternatives, a direct measurement of the lepton helicity would be needed.

In the UA2 experiment [14], 28 electrons with \( p_T > 20 \text{ GeV/c} \) and \( q_{\text{opp}} < 0.2 \) are observed in the two forward regions where a magnetic field is present. Of these, 20 are observed in the region favoured by the \( V - A \) coupling and 8 in the opposite region, giving an asymmetry \( A = 0.43 \pm 0.17 \). This value is in good agreement with the result of a Monte Carlo calculation, \( A = 0.53 \pm 0.06 \), which assumes a \( V - A \) decay matrix element.

More generally, if \( x \) is the ratio between the \( A \) and \( V \) couplings, the distribution of the charged lepton with respect to the direction of the proton beam has the form

\[
\frac{dN}{d\cos \theta^*} \propto (1 - q \cos \theta^*)^2 + 2q \alpha \cos \theta^*,
\]

where \( q = -1 \) ( +1) for electrons (positrons), and \( \alpha = [(1 - x^2)/(1 + x^2)]^2 \). The distribution \( \frac{dN}{dp_T^* \, d\theta^*} \) for the 28 \( W \rightarrow e\nu \) events observed in UA2 is consistent with \( \alpha = 0 \), as expected for \( V - A \) coupling. A maximum likelihood fit gives \( \alpha \leq 0.39 \) (68% confidence level), corresponding to \( 0.48 < |x| < 2.1 \). We note that the value of \( \alpha \) does not provide any information about the sign of \( x \), or about the choice of \( x \) or \( 1/x \).

2.7 Longitudinal momentum of the \( W \)

Figure 7 shows the distribution of the fractional beam momentum carried by the \( W \) boson, \( x_w = 2p_T^W/s \), for the total UA1 sample (here the smaller \( |p_T^W| \) value is chosen in events for which both solutions are physical). This distribution, shown separately for \( \sqrt{s} = 546 \) and 630 GeV, is expected to reflect the structure functions of the annihilating partons. From the well-known relations

\[
x_w = p_p - p_\bar{p}
\]

\[
m_w^2/s = x_p \, x_{\bar{p}} \quad \text{(if } p_T^W < m_w) \]

Fig. 7 The UA1 \( x_w \) distribution. The curves are expectations from \( q\bar{q} \) annihilation, using the structure functions of Ref. [19].
one can extract the fractional momentum \( x_q \) of the parton contained in the incident \( p \) or \( \bar{p} \). Using the events with an unambiguous determination of the charge sign (118 events in the UA1 sample), \( x_q \) can be identified with the fractional momentum of a \( u \) (\( \bar{d} \))-quark for a \( W^+ \), and a \( d \) (\( \bar{u} \))-quark for a \( W^- \).

Figures 8a and 8b show the resulting \( u \) and \( d \)-quark \( x \)-distributions, which agree with the expectation from the structure functions (the parametrization of Eichten et al. [19] is used in Fig. 8).

### 2.8 Transverse momentum of the \( W \)

The \( W \) transverse momentum \( p_T^W \) is obtained by adding the measured vectors \( p_T^\bar{p} \) and \( p_T^\bar{p} \). In the case of the UA2 sample, the topological cut discussed in subsection 2.3 may reject high-\( p_T^W \) events if they contain jets emitted opposite to the decay electron in a plane normal to the beams. For this reason the cuts \( p_T^W > 25 \text{ GeV/c} \) and \( \phi_{\text{opp}} < 0.2 \) [see Eq. (3)] used to define the \( W \rightarrow e\nu \) sample are replaced by the cuts \( p_T^W > 15 \text{ GeV/c} \), \( p_T^W > 25 \text{ GeV/c} \), and \( m_T > 20 \text{ GeV/c}^2 \). Figure 9 shows the \( p_T^W \) distributions for UA1 and UA2. The two sets of data agree well with each other and with QCD predictions [16].

The events containing at least one jet with \( E_T > 5 \text{ GeV} \) are shown as dashed areas in Fig. 9. As expected, they correspond to \( W \) bosons produced at high values of \( p_T^W \). The \( E_T \) distributions of these jets are shown in Fig. 10 where they are compared with the results of a QCD calculation to second order in \( \alpha_s \) [20]. In UA2, 28\% of the \( W \)'s are observed in association with at least one jet, whereas this fraction is 38\% in UA1. This difference reflects the larger acceptance of the UA1 detector for jets. As shown in Fig. 11, the jets associated with the UA1 sample are seen to display an angular distribution of the form \( d\bar{n}/d[\cos \theta^*] \propto (1 - |\cos \theta^*|)^{-4} \), where \( \theta^* \) is the angle between the jet and the beam direction in the \( W \)-jet(s) rest frame. Such a form is expected from higher-order QCD diagrams [20].

It must be recalled that the UA2 Collaboration published the observation of three anomalous events from the 1983 data sample [21]. These events could be interpreted as
Fig. 9  The $p_T$ distribution, as measured by UA1 (a) and UA2 (b). The shaded regions represent events which contain at least one jet with $E_T > 5$ GeV/c. The three events shown as dark areas in Fig. 9b are the anomalous UA2 events discussed in Ref. [21]. The curves are QCD predictions from Ref. [16].

Fig. 10  The $E_T$ distribution of jets produced in association with $W \rightarrow e\nu$ events for UA1 (a) and UA2 (b). Only jets with $E_T > 5$ GeV are considered. The curves are QCD predictions from Ref. [20].
Fig. 11 Distribution of $|\cos \theta^*|$ for jets produced in association with $W \rightarrow e \nu$ events. The angle $\theta^*$ is the jet angle in the $W$-jet(s) rest frame with respect to the beam axis. Only jets with $E_T > 5$ GeV are considered. The curve is a QCD prediction [20].

$W \rightarrow e \nu$ decays in association with very hard jets. Two of these events, emphasized in Fig. 9b, could not be easily interpreted as originating from higher-order QCD processes because of the very high values of $p_T^W$ and of the jet transverse energies. No additional event as extreme as these has been observed in the 1984 sample, in spite of a more than threefold increase of the integrated luminosity, thus making the interpretation of these events in terms of higher-order QCD processes much more likely.

The QCD prediction [16] shown in Fig. 9b, normalized to the observed number of events having $p_T^W < 30$ GeV/c, gives 2.7 events for $p_T^W > 30$ GeV/c, to be compared with 6 observed events and an estimated background of 0.7 events. This QCD prediction is affected by an uncertainty of $\pm 50\%$ which results mainly from uncertainties in the structure functions. In the curve of Fig. 9b the structure functions given by Glück et al. [22] are used.

2.9 The $Z \rightarrow e^+ e^-$ event samples

As observed in subsection 2.1, the efficiency of the electron identification criteria is about 75% in both experiments, and their application to both electrons from $Z$ decay would result in the loss of about 50% of the $Z \rightarrow e^+ e^-$ event samples. The selection of electron-pair candidates is therefore performed by using less selective but more efficient criteria which require that both energy clusters be compatible with an electron from calorimeter information alone, and that at least one cluster satisfy the full electron identification criteria. Such a selection leads to samples of electron pair candidates whose invariant mass, $m_{ee}$, has the distributions shown in Fig. 12. Above a threshold of 20 GeV/c$^2$, both distributions show a rapidly falling continuum at mass values of less than 50 GeV/c$^2$, and a well-separated peak near $m_{ee} = 90$ GeV/c$^2$. The events in this peak are interpreted as $Z \rightarrow e^+ e^-$ decays (18 events in UA1, 16 in UA2).

The low-mass continuum is mostly due to background from two-jet events. Such a background is negligible under the $Z$ peak, as demonstrated by the fact that no event is
observed in a wide interval of $m_{ee}$ between the low-mass continuum and the peak. Background estimates give less than 0.3 events under the $Z$ peak for both distributions of Fig. 12.

A value of $m_Z$ can be obtained from the $m_{ee}$ distributions in the high-mass region by a maximum likelihood fit of a Breit–Wigner shape distorted by the experimental mass resolution. The UA1 result, based on 14 well-measured $e^+e^-$ pairs, is

$$m_Z = 93.0 \pm 1.4 \text{ (stat.)} \pm 3.2 \text{ (syst.) GeV/c}^2.$$  \hfill (9)

The corresponding UA2 result, based on 13 well-measured $e^+e^-$ pairs, is

$$m_Z = 92.5 \pm 1.3 \text{ (stat.)} \pm 1.5 \text{ (syst.) GeV/c}^2.$$  \hfill (9')

In both cases the systematic error reflects the uncertainty in the absolute calibration of the calorimeter energy scale.

Cross-sections for inclusive $Z$ production followed by the decay $Z \to e^+e^-$, $\sigma_Z$, are listed in Table III. Within the rather large statistical and systematic errors, the results of the two experiments are consistent with each other and also with the theoretical predictions [16].

**Table III**

$Z \to e^+e^-$ cross-sections

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{s} = 546$ GeV</th>
<th>$\sqrt{s} = 630$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_Z$ (pb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UA1</td>
<td>$41 \pm 20 \pm 6$</td>
<td>$85 \pm 23 \pm 13$</td>
</tr>
<tr>
<td>UA2</td>
<td>$110 \pm 39 \pm 9$</td>
<td>$52 \pm 19 \pm 4$</td>
</tr>
<tr>
<td>Theory [16]</td>
<td>$42^{+13}_{-6}$</td>
<td>$51^{+16}_{-10}$</td>
</tr>
</tbody>
</table>

(The second error is the systematic uncertainty.)
2.10 The Z width and the number of neutrino species

Within the context of the Standard Model, the value of the Z width \( \Gamma_Z \) is related to the number of fermion doublets for which the decay \( Z \to f\bar{f} \) is kinematically allowed. Under the assumption that for any additional fermion family only the neutrino is significantly less massive than \( m_Z/2 \), we can write

\[
\Gamma_Z = \Gamma_Z (\text{three families}) + 0.18 \Delta N_e, \tag{10}
\]

where \( \Gamma_Z \) is in GeV/c^2, and \( \Delta N_e \) is the number of additional neutrino species.

A value of \( \Gamma_Z \) can be obtained, in principle, by the same maximum likelihood fit used to determine \( m_Z \). However, in the present experiments the expected width for three fermion families (\( \sim 2.8 \text{ GeV/c}^2 \)) is comparable with the experimental mass resolution. As an example, in the UA2 sample the r.m.s. deviation of the 13 mass values from the value of \( m_Z \) given by Eq. (9') is 3.58 GeV/c^2, which is very similar to the average of the measured errors, \( \langle \sigma \rangle = 3.42 \text{ GeV/c}^2 \). Under these circumstances the determination of \( \Gamma_Z \) depends critically on a precise knowledge of both the measurement errors and the shape of the experimental resolution. In the present experiments, given also the small event samples available, this method does not lead to reliable results.

A model-dependent method [23], which does not depend on the mass resolution, consists in measuring the ratio \( R = \sigma_Z/\sigma_W \), which is related to \( \Gamma_W \) and \( \Gamma_Z \) by the equation

\[
R = (\sigma_Z/\sigma_W)(\Gamma_Z/\Gamma_W)(\Gamma_W/\Gamma_Z), \tag{11}
\]

where \( \sigma_Z/\sigma_W \) is the inclusive cross-section for Z (W) production, and \( \Gamma_Z/\Gamma_W \) is the partial width for the decay \( Z \to e^+e^- \) (\( W \to e\bar{\nu} \)). Although \( \Gamma_Z/\Gamma_W \) and \( \Gamma_W/\Gamma_Z \) are given directly by the Standard Model, the ratio \( \sigma_Z/\sigma_W \) can be calculated in the framework of QCD, with the property that most theoretical uncertainties cancel out. A recent estimate [16] gives \( \sigma_Z/\sigma_W = 0.30 \pm 0.02 \).

The measured values of \( R \) are

\[
\text{UA1: } R = 0.108^{+0.025}_{-0.033}, \tag{12}
\]

and

\[
\text{UA2: } R = 0.136^{+0.041}_{-0.033}, \tag{12'}
\]

where in both cases the errors are dominated by statistics because the value of the integrated luminosity cancels out. Both values agree with the expectation [24] \( R = 0.11 \pm 0.01 \), based on three fermion families.

By further assuming that any additional fermion family does not affect \( \Gamma_W \) because the masses of the charged fermions are all heavy, it is possible to determine \( \Gamma_Z \) and \( \Delta N_e \) using Eqs. (11) and (10). In UA1 the lower limit \( R > 0.077 \) (90% confidence) is used to provide the limit \( \Delta N_e < 7 \) for the additional number of neutrino species. In UA2, Eqs. (12') and (11) give the result \( \Gamma_Z = 2.19^{+0.70}_{-0.59} \text{ (stat.)} \pm 0.22 \text{ (syst.) GeV/c}^2 \), where the systematic error represents the uncertainty of the QCD calculation as well as the uncertainties of the values used for the partial widths. The UA2 lower limit \( R > 0.094 \) (90% confidence) corresponds to the limit \( \Gamma_Z < 3.17 \pm 0.31 \text{ GeV/c}^2 \), which gives \( \Delta N_e < 2.6 \pm 1.7 \), where the errors reflect the theoretical uncertainties. We note that such a stringent limit results mainly from the rather large value of \( \sigma_Z^2 \) measured in the UA2 experiment at \( \sqrt{s} = 546 \text{ GeV} \) (see Table III).
2.11 Radiative Z decays

Among the four $Z \rightarrow e^+e^-$ events recorded by UA1 in 1983, one event of the type $Z \rightarrow e^+e^+\gamma$ was observed [25]. The event contained a 39 GeV photon separated in space by $14^\circ \pm 4^\circ$ from an electron of 9 GeV. A similar event, with a 24 GeV photon separated in space by $31^\circ \pm 1^\circ$ from an electron of 11 GeV, was also present among the eight events recorded in 1982–83 by UA2 [8, 26]. The probability of observing these ee\gamma configurations (or less likely ones) as a result of internal bremsstrahlung in a total sample of 12 events was estimated to be $\sim 0.6\%$.

From the analysis of the 1984 data, the total $Z \rightarrow e^+e^-$ (or $e^+e^-\gamma$) sample has increased from 12 to 34 events. However, no new event compatible with $Z \rightarrow e^+e^-\gamma$ decay has been observed. As a consequence, the probability of the internal bremsstrahlung hypothesis has increased from $\sim 0.6\%$ to $\sim 4\%$, and the need for a new mechanism to explain these events is no longer justified.

2.12 The decay $W \rightarrow \mu\nu$

The observation of high-$p_T$ muons is possible only in the UA1 experiment, since there is no muon detector in UA2. The criteria used in UA1 to identify $W \rightarrow \mu\nu$ have already been described [27]. The requirements of an isolated track consistent with a high-$p_T$ muon ($p_T^\mu > 15$ GeV/c) and of a missing transverse momentum in excess of 15 GeV/c select a sample of 47 events [13]. The $p_T^\mu$ distribution of this sample is shown in Fig. 13, where it is compared with the spectrum expected from $W \rightarrow \mu\nu$ decay for $m_W = 83$ GeV/c$^2$. The Jacobian peak structure, clearly observed in the decay $W \rightarrow e\nu$ (see Fig. 4), is not visible in this case because of the distortions due to the poor momentum resolution of the magnetic spectrometer for high-momentum tracks. We recall that in UA1 the momentum resolution for a 40 GeV/c muon is $\sim \pm 20\%$, whereas it is $\sim \pm 2.5\%$ for a 40 GeV/c electron as measured in the calorimeter.

It must also be noted that the number of events in the $W \rightarrow \mu\nu$ sample is $\sim \frac{1}{3}$ of that of the $W \rightarrow e\nu$ sample. This is due to the incomplete angular coverage of the muon trigger, which was not operational over the whole solid angle during data taking.

Whilst the $W \rightarrow \mu\nu$ sample cannot be used to obtain a precise measurement of $m_W$, it provides a measurement of $\sigma_W$, the cross-section for $W$ production followed by the decay $W \rightarrow \mu\nu$. The measured ratio [13] $\sigma_W/\sigma_{e\nu} = 1.07 \pm 0.17$ (stat.) $\pm 0.13$ (syst.) represents a test of $\mu-e$ universality.

![Fig. 13](image.png)

Fig. 13 Transverse momentum spectrum for muons from $W \rightarrow \mu\nu$ decay (UA1). The expectation from $m_W = 83$ GeV/c$^2$ is also shown.
2.13 The decay $Z \rightarrow \mu^+ \mu^-$

By requiring the simultaneous presence of two muons, each having $p_T > 3$ GeV/c and such that their invariant mass $m_{\mu\mu}$ exceeds 6 GeV/c$^2$, a total of 222 events are selected in the UA1 experiment [13]. The $m_{\mu\mu}$ distribution of these events (Fig. 14) shows a rapidly falling continuum at low masses (to be discussed in Section 3), well separated from 10 events which all have $m_{\mu\mu} > 70$ GeV/c$^2$. These high-mass events, which all consist of $\mu^+ \mu^-$ pairs, are identified as $Z^0 \rightarrow \mu^+ \mu^-$ decays. The errors affecting the individual mass values are also shown in Fig. 14. These errors are asymmetric because momentum measurement by magnetic deflection gives errors which are Gaussian in $1/p$ and not in $p$. The event with $m_{\mu\mu} > 140$ GeV/c$^2$ in Fig. 14 is consistent with a $Z \rightarrow \mu^+ \mu^-$ decay within the large measurement error.

A best fit of a Breit-Wigner shape distorted by the mass resolution gives the value [13] $m_Z = 88.8^{+5.5}_{-4.6}$ GeV/c$^2$, in good agreement with the value obtained from the $e^+ e^-$ channel [see Eqs. (9) and (9')]. These events correspond to a measured cross-section $\sigma_Z = 51.4 \pm 17.1$ (stat.) $\pm 8.6$ (syst.) pb, which agrees with the measured $\sigma_Z$ values, and also with theoretical predictions based on $\mu$-e universality (see Table III).

2.14 Comparison with the Standard Model

In order to compare the measurements of $m_W$ and $m_Z$ with the predictions of the Standard Model, we must use suitably renormalized and radiatively corrected quantities [28]. We shall use the scheme where $\sin^2 \theta_w$ is defined as [29]

$$\sin^2 \theta_w = 1 - (m_W/m_Z)^2,$$

which leads to the following predictions:

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

$$m_Z^2 = 4A^2/((1 - \Delta r) \sin^2 2\theta_w).$$
where \( A = (\pi \alpha / \sqrt{2} G_F)^{1/2} = (37.2810 \pm 0.0003) \text{ GeV}/c^2 \) using the measured values of \( \alpha \) and \( G_F \). The quantity \( \Delta r \) reflects the effect of one-loop radiative corrections, and has been computed to be \( 0.0696 \pm 0.020 \) for a mass of the top quark \( m_t = 36 \text{ GeV}/c^2 \) and assuming that the mass of the Higgs boson \( m_H \) is equal to \( m_Z \).

Using Eqs. (14) and (14') we can extract two values of \( \sin^2 \theta_w \) from the values of \( m_W \) and \( m_Z \) measured in each experiment. We then combine them to obtain

\[
\text{UA1: } \sin^2 \theta_w = 0.216 \pm 0.004 \text{ (stat.)} \pm 0.014 \text{ (syst.)},
\]

and

\[
\text{UA2: } \sin^2 \theta_w = 0.226 \pm 0.005 \text{ (stat.)} \pm 0.008 \text{ (syst.)}.
\]  

(15)

(15')

In both cases the systematic error reflects the uncertainty on the mass scale from the uncertainty of the calorimeter calibration.

Because of the systematic errors, a weighted average of the two results is not possible. Within errors, the two values of \( \sin^2 \theta_w \) agree with each other, and also with the value \( \sin^2 \theta_w = 0.220 \pm 0.008 \) obtained from an average of low-energy data [30] after applying radiative corrections. The low-energy data include recent results from the CDHS [31] and CCFR [32] experiments.

By using Eq. (13) it is possible to measure \( \sin^2 \theta_w \) with no systematic error from the mass scale. The results are

\[
\text{UA1: } \sin^2 \theta_w = 0.194 \pm 0.031,
\]

and

\[
\text{UA2: } \sin^2 \theta_w = 0.229 \pm 0.030.
\]  

(16)

(16')

The weighted average of these two results is

\[
\sin^2 \theta_w = 0.212 \pm 0.022,
\]

which represents a less precise measurement than the results given by Eqs. (15) and (15'), in view of the limited event samples available at present.

By using the \( \sin^2 \theta_w \) definition given by Eq. (13) we have implicitly assumed that the \( q \) parameter, defined as [33]

\[
q = m_W^2/(m_Z^2 \cos^2 \theta_w)
\]

(17)

is equal to 1. We can test this assumption by combining Eqs. (14) and (17) to obtain

\[
q = m_W^2/[m_Z^2 (1 - B^2/m_W^2)]
\]

(17')

where \( B^2 = A^2/(1 - \Delta r) \). The UA1 result is

\[
q = 1.028 \pm 0.037 \text{ (stat.)} \pm 0.019 \text{ (syst.)},
\]

(18)

and the corresponding UA2 result is

\[
q = 0.996 \pm 0.033 \text{ (stat.)} \pm 0.009 \text{ (syst.)}.
\]  

(18')
Fig. 15 68% confidence level contours in the plot of $m_Z - m_W$ versus $m_Z$ taking into account the statistical errors only. The error bars applied to the centre of the ellipses represent the translations allowed by the magnitude of the systematic errors. Curve 1 (2) is the prediction of the Standard Model with (without) radiative corrections. The region between the two dashed lines is the region allowed by the low-energy measurement of $\sin^2 \theta_W$; that between curve 1 and the dash-dotted line is allowed by the low-energy measurement of $\phi$.

These two results agree with each other and with the value $\phi = 1.02 \pm 0.02$ (see the compilations [29] and [34]). We recall that the value $\phi = 1$ corresponds to the minimal Standard Model with only one isodoublet of complex Higgs fields.

The sensitivity of the measurements of $m_W$ and $m_Z$ to the radiative corrections is illustrated in Fig. 15, which shows the 68% confidence level contours from the two experiments in the plot of $m_Z - m_W$ versus $m_Z$. Also shown in Fig. 15 is the region allowed by the low-energy measurements of $\sin^2 \theta_W$ and $\phi$. Within the present statistical and systematic errors, the need for radiative corrections in the Standard Model cannot be demonstrated.

2.15 Search for the decay $W \rightarrow \bar{t}b$

No results from the search for $W \rightarrow \bar{t}b$ has been presented at this Conference. However, this subject was one of the highlights at the 1984 Leipzig Conference [35], and the UA1 Collaboration has presented preliminary results from the analysis of the 1984 data at the recent conference on Physics in Collision [36]. It seems appropriate, therefore, to summarize here all the new information available on this subject.

We recall that, from an analysis of the 1982–83 data sample, the UA1 Collaboration published [37] the observation of six events, each consisting of an isolated high-$p_T$ electron (three events) or muon (three events) produced in association with two hard jets. Thresholds in this analysis were set at 15 GeV/c for the electron $p_T$, 12 GeV/c for the muon $p_T$, and 8 and 7 GeV/c for the $p_T$ value of the first and second jet, respectively.

Background from high-$p_T$ hadrons simulating a lepton was estimated to be a fraction of each lepton type. Furthermore, the event configuration was not consistent with that expected from QCD background. In particular, the azimuthal separation between the lepton momentum and the momentum of the jet having the higher $p_T$ (jet 1) was
different from 180°. In addition, the jet having the smaller \( p_T \) (jet 2) was produced rather centrally, suggesting that it was not associated with gluon radiation of initial-state partons.

In all six events a small missing transverse momentum (typically less than 8 GeV/c) was measured and identified with the presence of a neutrino. The invariant mass of the \((E_T p_1 p_2)\) system, \( m_4 \), calculated under the assumption \( p_T = 0 \), was found to be consistent with \( m_W \) for all six events, suggesting a new decay mode of the W boson. To identify the decay, the invariant mass of the \((E_T p_2)\) system, \( m_3 \), was also calculated, and was found to be consistent with a unique value of approximately 40 GeV/c². The six events were then interpreted as being consistent with the decay \( W \to t\bar{b} \), followed by the semileptonic decay \( t \to b\ell\nu_t \), where \( t \) is the top quark with a mass \( m_t \) bounded between 30 and 50 GeV/c².

From the analysis of the data recorded by UA1 in 1984, six new events containing an electron and two jets have been found [36] (the analysis of the muon channel is still in progress). The properties of these events are similar to those of the six events observed in the 1982–83 data. The distribution of the total sample of 12 events (9 with an electron and 3 with a muon) in the \((m_4, m_3)\) plane (see Fig. 16) shows a clear accumulation of events in the region \( m_4 \approx m_W, m_3 \approx 40 \) GeV/c². In Fig. 16 this distribution is compared with that of a much larger sample of background events, in which the lepton is replaced by a neutral hadronic system consistent with a high-\( p_T \) isolated \( \pi^0 \). The probability that the two populations are statistically compatible with a unique distribution is estimated to be \( 8.5 \times 10^{-3} \). At this point, one can safely conclude that the increased statistics have confirmed the earlier observation [37].

![Fig. 16](image_url)

**Fig. 16** Distribution of 12 events containing a lepton and two jets (full circles), and of a sample of \( \pi^0 \)-like particles produced in association with two jets (points) in the \( m_4, m_3 \) plane. Also shown are the projections on the \( m_4 \) and \( m_3 \) axes. The shaded areas in the two projections represent the events with a lepton.
Fig. 17 The $m_4$ distribution of the 12 events containing a lepton and two jets, compared with the expected shapes from $W \rightarrow t \bar{b}$ and $t \bar{t}$ pair production, under the assumption $m_t = 40$ GeV/c$^2$.

However, the number of events expected from the decay $W \rightarrow t \bar{b}$, followed by $t \rightarrow b e \nu_e$, can be reliably predicted from the measured cross-section for $W$ production and the expected branching ratios. Such a calculation gives an expected number of $\sim 1.5$ to $\sim 3$ events (depending on the value of $m_t$), whilst the observed number is 9. This disagreement is resolved by assuming that about $\frac{3}{5}$ of the events result from QCD production of $t \bar{t}$ pairs, followed by the semileptonic decay of the $t$ ($t\bar{t}$)-quark. In this case the accumulation of events at $m_w \approx m_w$ results from the combined effects of $t \bar{t}$ threshold and of the decrease of the $t \bar{t}$ production cross-section with increasing values of the $t \bar{t}$ invariant mass (see Fig. 17).

The contribution from $t \bar{t}$ production is estimated using the QCD-inspired Monte Carlo programs EUROJET [38] and ISAJET [39]. In Table IV, taken from Ref. 36, the observed numbers of events containing an electron produced in association with 1, 2, or 3 jets are compared with expectations from $W \rightarrow t \bar{b}$ and $t \bar{t}$ production, followed by the semileptonic decay of the $t$ ($t\bar{t}$)-quark, for three different $m_t$ values. Also listed in Table IV are the expected contributions from other possible sources not involving $t$-quarks.

It must be stressed that the predictions relative to the $t \bar{t}$ channel rely heavily not only on a correct description of $t \bar{t}$ production but also on a detailed knowledge of $t$-quark fragmentation and decay modes. To the extent that all of these properties are correctly taken into account by the Monte Carlo programmes mentioned above, the observed numbers of events are consistent with the semileptonic decay of a $t$-quark produced both from $W \rightarrow t \bar{b}$ decay and by $t \bar{t}$ pair production.

Whilst a $t$-quark in the mass range between 30 and 50 GeV/c$^2$ represents a possible explanation for the UA1 events, its existence is not established at present. The need for $t \bar{t}$ production, in my opinion, weakens the previous evidence [37] because it adds a contribution from events of complicated topologies which involve multi-jet final states. A full understanding of such events requires QCD-inspired Monte Carlo programs whose reliability in describing a $t \bar{t}$ final state remains to be proved.

More data are needed in order to reach a firm conclusion about the existence of the top quark. The analysis of the events containing a high-$p_T$ muon produced in association with jets is of particular importance, because hadronic backgrounds in the muon and electron channels have different sources, and consistency of the two results would represent an independent proof that the leptons are indeed real.

Further progress is expected from the addition of a 'microvertex' detector to the UA1 apparatus. This is a high-precision drift chamber surrounding the machine vacuum pipe for the purpose of observing the decay vertex of the associated $b$-quarks. Such an observation would support the interpretation of the UA1 events in terms of final states containing at least one $t$-quark.
Table IV

Observed and expected numbers of events containing a high-\(p_T\) electron and jets [36]

<table>
<thead>
<tr>
<th>No. of experimental events</th>
<th>One jet</th>
<th>Two jets</th>
<th>Three jets</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD background</td>
<td>2.3 ± 0.5</td>
<td>1.1 ± 0.2</td>
<td>1 ± 0.2</td>
<td>4.4</td>
</tr>
<tr>
<td>(b\bar{b}, c\bar{c})</td>
<td>3.9</td>
<td>1.2</td>
<td>1.2</td>
<td>6.3</td>
</tr>
<tr>
<td>(Z^0 \rightarrow \tau^+\tau^-)</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
</tr>
<tr>
<td>W + jet</td>
<td>1.6</td>
<td>-</td>
<td>-</td>
<td>1.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(m_t) (GeV)</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t\bar{t})</td>
<td>7.4</td>
<td>3.9</td>
<td>1.6</td>
<td>6.6</td>
<td>5.0</td>
<td>2.3</td>
<td>19.2</td>
</tr>
<tr>
<td>(W \rightarrow t\bar{b})</td>
<td>2.0</td>
<td>2.3</td>
<td>2.9</td>
<td>1.4</td>
<td>2.3</td>
<td>2.8</td>
<td>10.3</td>
</tr>
<tr>
<td>Total</td>
<td>10.3</td>
<td>9.6</td>
<td>7.4</td>
<td>19.2</td>
<td>15.0</td>
<td>14.3</td>
<td>40.9</td>
</tr>
</tbody>
</table>

3. LOW-MASS DIMUONS

As already mentioned in subsection 2.13, a search by the UA1 experiment for events containing two muons, each having \(p_T > 3\) GeV/c and such that their invariant mass, \(m_{\mu\mu}\), exceeds 6 GeV/c\(^2\), leads to a sample of 222 events. The 10 events having \(m_{\mu\mu} > 70\) GeV/c\(^2\) (all identified as \(Z \rightarrow \mu^+\mu^-\) decays) have already been discussed in subsection 2.13. Here we discuss the remaining 212 events (150 \(\mu^+\mu^-\) and 62 \(\mu^+\mu^+\) or \(\mu^-\mu^-\) pairs), whose mass distribution is shown in Fig. 14 [40].

Muon pairs of opposite-sign charge are expected from the following sources:

i) the Drell–Yan process \(q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-\), where \(\gamma^*\) is a virtual photon state;

ii) the production of T particles, followed by their decay into a \(\mu^+\mu^-\) pair (the \(J/\psi\) is excluded by the requirement \(m_{\mu\mu} > 6\) GeV/c\(^2\));

iii) QCD production of a pair of heavy quarks (\(c\bar{c}, b\bar{b}\)), followed by semileptonic decay of both quarks.
Sources of same-sign dimuons are also expected. The most common one is represented by $b\bar{b}$ production, where the $\mu^-$ ($\mu^+$) is produced from semileptonic decay of the $b$ ($b$)-quark, and the other $\mu^-$ ($\mu^+$) is produced from semileptonic decay of the $\bar{c}$ ($c$)-quark which results from hadronic decay of the $b$ ($b$)-quark.

Another very interesting source of same-sign dimuons relies on the existence of $B^0-\bar{B}^0$ transitions, where $B^0$ is a neutral meson containing a $b$-quark, in complete analogy with $K^0-\bar{K}^0$ transitions. In this case the $\mu^-$ ($\mu^+$) is again given by semileptonic decay of the $b$ ($b$) quark, whilst the $b$ ($b$) quark first fragment into a $\bar{B}^0(B^0)$ meson which turns into a $B^0(\bar{B}^0)$ state and then decays semileptonically into a $\mu^-$ ($\mu^+$).

Whilst in the case of the Drell–Yan process or $T$ decay both muons are expected to be isolated, all sources of dimuons involving decays of heavy quarks are expected to give rise to muons accompanied by other high-$p_T$ hadrons, which are either jet fragments or decay products. It must be stressed that muons are the only charged leptons that can be identified even when they are embedded in a hadronic jet.

In order to subdivide the dimuon sample into two classes of events, one containing isolated dimuons and the other non-isolated ones, a cone having half-aperture $R = (\Delta \eta^2 + \Delta \phi^2)^{1/2} = 0.7$ is constructed around the momentum vector of each muon (for which $\Delta \eta = \Delta \phi = 0$), and the total transverse energy $\Sigma E_T$ carried by all other particles in the cone is measured. For each dimuon an isolation parameter $S$ is then defined as

$$S = \left[ (\Sigma E_T^{(1)})^2 + (\Sigma E_T^{(2)})^2 \right],$$

(19)

where the two terms of the sum correspond to the two cones.

Most muons from $W \rightarrow \mu \nu$ or $Z \rightarrow \mu^+\mu^-$ decay satisfy the condition $\Sigma E_T < 3$ GeV. For this reason, the condition $S < 9$ GeV$^2$ is used to define the class of isolated dimuons, whilst the condition $S > 9$ GeV$^2$ defines non-isolated ones. The choice of the value $S = 9$ GeV$^2$ to separate the two classes can be further justified by examining the $S$-distribution for $\mu^+\mu^-$ pairs (Fig. 18a): for $S > 9$ GeV$^2$ this distribution is flat within errors, but a clear

![Fig. 18](image)

**Fig. 18** Distribution of the isolation variable $S$ for $\mu^+\mu^-$ pairs (a) and for same-sign pairs (b). The broken lines represent the average numbers of events per bin in the region $S > 9$ GeV$^2$. 

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excess of events is visible for $S < 9 \text{ GeV}^2$, as expected for isolated dimuons from the Drell-Yan process and T decay. No such excess is visible in the S-distribution of same-sign dimuons (Fig. 18b), which is consistent with being constant over the entire range of S.

Figure 19 shows the $m_{\mu\mu}$ distributions for the two dimuon classes, and for opposite- and same-sign pairs separately.

The $m_{\mu\mu}$ distribution of the 44 isolated $\mu^+\mu^-$ pairs is shown again in Fig. 20 with a finer binning. These events are interpreted as the sum of three contributions: the Drell-Yan process ($20.4 \pm 5.2$ events); $\mu^+\mu^-$ decay of T particles ($9.7 \pm 3.3$ events); and $14 \pm 3.7$ events associated with bb production. This last contribution is obtained directly from the S-distribution of Fig. 18a by extrapolating the constant distribution observed for $S > 9 \text{ GeV}^2$ into the region defining isolated pairs ($S < 9 \text{ GeV}^2$).

From the data of Fig. 20 the value of the cross-section for the Drell-Yan process, integrated over the region $m_{\mu\mu} > 11 \text{ GeV/c}^2$, is measured to be $[40] \sigma_{\text{DY}} = 264 \pm 104 \text{ pb}$, in good agreement with a theoretical prediction [41], $\sigma_{\text{DY}} = 290 \text{ pb}$. The value $\sigma(T) = 375 \pm 192 \text{ pb}$ is also obtained for inclusive production of $T$, $T'$, and $T''$ particles, followed by their decay into a $\mu^+\mu^-$ pair [40].

Non-isolated $\mu^+\mu^-$ pairs (a total of 106 events) are interpreted as resulting mostly from bb production, followed by semileptonic decay of both b and $\bar{b}$. Using the EUROJET Monte Carlo programme [38] to estimate the detector acceptance, the UA1 Collaboration obtains the value $[40] \sigma(b\bar{b}) = 1.3 \text{ pb}$ for the cross-section for inclusive production of b$\bar{b}$ pairs, integrated over the region of b and $\bar{b}$ transverse momentum $p_T > 5 \text{ GeV/c}$ and rapidities $|y| < 2$.

The sample of same-sign dimuons consists of 55 non-isolated and 7 isolated pairs. The ratio $R = [N(\mu^+\mu^-) + N(\mu^-\mu^+)]/N(\mu^+\mu^-)$, calculated from the non-isolated events only, is found to be $R = 0.45 \pm 0.10$ (after background subtraction), with a lower limit $R > 0.30$ at the 90% confidence level. By using all events, after subtracting the Drell-Yan and T contributions, the corresponding values are $R = 0.45 \pm 0.11$ and $R > 0.29$.

![Fig. 19 The $m_{\mu\mu}$ distributions for the four classes of dimuons observed in the UA1 experiment.](image-url)
Fig. 20 The $m_{\mu\mu}$ distribution for 44 isolated $\mu^+\mu^-$ pairs. Dashed line: contribution from the Drell–Yan process. Dash-dotted line: the contribution from $b\bar{b}$ production has been added to the previous process. Full line: the contribution from the T family has also been added.

These results can be used to extract information on the $B^0 - \bar{B}^0$ transition rate by comparing them with the results of Monte Carlo programmes in which the $B^0 - \bar{B}^0$ transition rate is one of the input parameters. However, the conclusion depends crucially on the correctness of the Monte Carlo programmes to describe all aspects of heavy-quark production, including fragmentation and decay. Since the reliability of the available programmes has not yet been proved, no conclusion can be reached at present on the need for $B^0 - \bar{B}^0$ transitions to explain the measured value of $R$.

4. CONCLUSIONS

If we try to compare the results from the $p\bar{p}$ Collider presented at this Conference with those available a year ago at the Leipzig Conference, the most obvious difference is the disappearance of most, if not all, unexplained effects which had been observed by the UA1 and UA2 Collaborations in the 1982–83 data. The more than threefold increase of the data samples from the 1984 run has shown that these effects were most likely due to large statistical fluctuations of standard physics.

The main feature of the results discussed in this paper is the remarkable agreement between the $W$ and $Z$ properties, as measured by UA1 and UA2, and the prediction of the Standard SU(3) × SU(2) × U(1) Model. The most impressive results are the precision reached by the Collider experiments in providing an independent measurement of $\sin^2 \theta_W$; and the upper limit obtained on the additional number of light neutrino species, $\Delta N_e < 2.6$ with a theoretical uncertainty of two neutrino species.

In the search for events involving the production of top quarks, much work still remains to be done. Progress in this field is expected in the immediate future from a comparison of the electron and muon results. However, I believe that improvements in the detectors, such as the use of microvertex chambers to identify the decay of b-quarks, is essential for obtaining convincing proof that a top quark with the expected properties has indeed been discovered.

The UA1 experiment has shown that dimuons represent a very useful tool for studying the production of heavy quarks. Same-sign dimuons are of particular interest, because they may provide information on the $B^0 - \bar{B}^0$ transition rate. Here work is needed to ensure
that the QCD-inspired Monte Carlo programmes that are being used to interpret the data, describe correctly the final states resulting from $b\bar{b}$ production. This is an essential step towards arriving at a definitive conclusion on $B^0-B^\bar{0}$ mixing.

In the immediate future (September 1985 – June 1986) the data samples collected by UA1 and UA2 will be increased by a factor of 2 to 3 with respect to the present ones. Then, after a shutdown of a little more than one year, the Collider will resume operation with a tenfold increase of its instantaneous luminosity, thanks to the new Antiproton Collector (ACOL) now under construction. The two major detectors will also be upgraded.

By the end of 1988, the data samples should correspond to an integrated luminosity of about 10 pb$^{-1}$ in each experiment. Of course it cannot be excluded that, in spite of these improvements, no new phenomenon will be discovered because the Collider energy is not high enough. However, even so the experiments will collect $\sim 10^5 W \rightarrow e\nu$ decays and $\sim 10^3 Z \rightarrow e^+e^-$. With the use of good electromagnetic calorimetry, it appears possible from such samples to measure the ratio $m_\omega/m_Z$ with a precision of $\sim 1.5 \times 10^{-3}$. Then, using the value of $m_Z$ measured at SLC and LEP with an absolute precision of $\pm 50$ MeV/c$^2$, one can determine $m_\omega$ with an error of $\pm 150$ MeV/c$^2$. This is a fundamental measurement in electroweak physics, because it can test the radiative corrections to the masses of the intermediate bosons at the one-loop level. Such a precision is similar to that expected from measurements of $W^- W^+$ production in the second phase of the LEP project.

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