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PROTON-ANTIPROTON COLLIDER PHYSICS: EXPERIMENTAL ASPECTS

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1. INTRODUCTION

These lectures review recent experimental results of relevance to the Standard Model of the electroweak interaction, which have been obtained at the CERN $p\bar{p}$ Collider in a series of data-taking runs between 1982 and the end of 1985. This review includes the measurement of the W and Z masses, their decay and production properties, and also searches for the top quark and other possible new particles postulated by a variety of theoretical models. The data, which will be discussed in sections 4 to 6, have been collected by the two major experiments, UA1 and UA2, at two values of the total centre-of-mass energy, $\sqrt{s} = 546$ and 630 GeV. The total integrated luminosity, accumulated mostly at $\sqrt{s} = 630$ GeV, is of the order of 0.8 pb^{-1} for each of the two experiments. A substantial increase of the event sample (by a factor of about 10) is expected from a new series of data-taking runs between the end of 1987 and the middle of 1989, as a result of improvements to the $\bar{p}$ source and to the SPS itself. In order to match the increased luminosity, both the UA1 and UA2 experiments have been, or are in the process of being upgraded. In Section 7, the physics expectation from the forthcoming Collider runs will be discussed and compared with the expectations from the $p\bar{p}$ Tevatron collider at Fermilab which has recently started operation at $\sqrt{s} = 1.8 \text{ TeV}$.

Other physics subjects under study at $p\bar{p}$ colliders, such as the production of hadronic jets at high transverse momentum, are covered in the lectures given by M. Jacob at this school¹⁾.

2. THE DETECTORS

A typical experimental apparatus at a hadron or e^+e^- collider consists, in general, of many successive layers of different kinds of detectors.

Moving outwards from the region where the beams collide, one finds first a tracking detector which serves to reconstruct charged-particle tracks. Such a detector

may be located in a magnetic field, which provides a measurement of the charged-particle momenta.

Following the tracking detector, one finds an electromagnetic calorimeter with large angular coverage, which is used to measure the energy of secondary electrons and photons. Such a device contains a high-Z material, and is thick enough to absorb almost completely the electromagnetic showers produced by high-energy electrons or photons.

Just behind the electromagnetic calorimeter, a hadronic calorimeter is installed, in general, to absorb hadronic showers associated with strongly interacting particles, such as π , K, or nucleons, and to measure their energies.

A calorimeter is generally subdivided into many independent cells, in order to cope with the high multiplicity of secondary particles. Such a property is often called *granularity*.

If the calorimeters are thick enough, no known long-lived particles, except for muons and neutrinos, can escape. Muon detectors, consisting in general of large-area tracking chambers, can be used therefore as the outermost shell of the apparatus. To measure muon momenta, a magnetic field is required. Such a field could either be the same field as is used in the central region, or it could be provided by magnetized iron, or both.

The UA1 experiment (Fig. 1) contains all the features described above. It is based on a general-purpose magnetic detector², which was designed to achieve an almost complete solid-angle coverage down to polar angles of 0.2° with respect to the beams, using both track detection and calorimetry. The *magnet* is a dipole which produces a horizontal field of 0.7 T perpendicular to the beam axis over a volume of $7 \times 3.5 \times 3.5 \text{ m}^3$.

The magnet contains the *central track detector*, which is a system of drift chambers filling a cylindrical volume 5.8 m in length and 2.3 m in diameter.

The magnetic field volume contains also the *large-angle electromagnetic (e.m.) calorimeter*, which covers the polar angle interval 25° – 155° and the full azimuth. This calorimeter consists of two half-cylindrical shells on either side of the beam, each made of 24 independent total-absorption counters called ‘gondolas’. A gondola subtends an angular interval $\Delta\theta = 5^\circ$, $\Delta\phi = 180^\circ$. It consists of a multilayer lead/scintillator sandwich with a total thickness equivalent to 26.6 radiation lengths (r.l.) subdivided in depth into four independent segments with thickness 3.3, 6.6, 10.1, and 6.6 r.l., respectively. The azimuthal granularity of this calorimeter is rather poor, because two particles separated by as much as 180° in azimuth may hit the same gondola. In this case, their individual energies cannot be measured in the calorimeter.

The two *end-cap e.m. calorimeters*, also located inside the magnet, cover the polar angle interval 5° – 25° with respect to the beams. Each calorimeter consists of 32 azimuthal sectors of lead/scintillator multilayer sandwich at a distance of 3 m from the centre of the beam crossing. These counters have a total thickness of 27 r.l. and are segmented four times in depth.

Fig. 1 Views of the UA1 detector: a) view with the two magnet halves opened up; b) a cut of the detector normal to the beam axis; c) a cut of the detector by the vertical plane containing the beam axis.

In both the large-angle and end-cap e.m. calorimeters, the energy of an electron is measured with a resolution $\sigma_E/E = 0.15/\sqrt{E}$ (E in GeV). The configuration of both calorimeters can be seen in Figs. 1b and 1c.

The yoke of the magnetic spectrometer is laminated, and scintillator is inserted between the iron plates to form the *central hadronic calorimeter* which surrounds both e.m. calorimeters. The hadronic calorimeter (see Figs. 1a and 1c) consists of 450 independent cells, with typical size $\Delta\theta \times \Delta\phi$ equal to $15^\circ \times 18^\circ$ in the central region and $5^\circ \times 10^\circ$ in both forward regions. Their thickness is ≈ 5 and ≈ 7 absorption lengths, respectively. The energy resolution is typically $\sigma_E/E \approx 0.8/\sqrt{E}$ (E in GeV).

Muon detectors surround the magnet yoke (see Figs. 1a and 1c). They consist of two planes of drift chambers covering the polar angle interval $5^\circ < \theta < 175^\circ$ and the full azimuth, separated by a distance of 60 cm. Each of these planes is made of 50 drift chambers of $\approx 4 \times 6 \text{ m}^2$. Each chamber consists of four layers of drift tubes (maximum drift space 7 cm), which define two orthogonal coordinates. By knowing the position of the interaction vertex and the muon-track parameters in these chambers, it is possible to obtain an independent measurement of the muon momentum with a relative precision of $\approx 20\%$ through the determination of its deflection in the magnet yoke.

In addition to the detectors just described, more calorimeters and track detectors located along the beam pipe on both sides of the spectrometer cover the region of polar angles from 5° down to $\approx 0.2^\circ$ with respect to the beam line (see Fig. 1b).

The UA2 detector (Fig. 2a) consists of three parts³:

- i) The *vertex detector*, which is a system of cylindrical chambers to reconstruct charged-particle tracks in a region without magnetic field. This detector covers the polar angle interval $20^\circ < \theta < 160^\circ$. A ‘preshower’ counter, consisting of a 1.5 r.l. thick tungsten cylinder followed by a multiwire proportional chamber (MWPC) with cathode strip readout and pulse-height measurement on the wires, is located just behind the last chamber, covering the central region $40^\circ < \theta < 140^\circ$. As we shall see later, this device is essential for electron identification.
- ii) The *central calorimeter*, which is a system of 240 independent counters covering the full azimuth (see Fig. 2b) and the polar angle interval $40^\circ < \theta < 140^\circ$. Each counter has an angular acceptance $\Delta\theta \times \Delta\phi = 10^\circ \times 15^\circ$ and consists of a first e.m. section (lead/scintillator) 17 r.l. thick, followed by two independent hadronic sections (iron/scintillator), each 2 absorption lengths thick. The energy resolution is $\sigma_E/E \approx 0.15/\sqrt{E}$ for e.m. showers, and $\approx 0.32E^{-1/4}$ for hadronic showers (E in GeV).
- iii) The two *forward detectors*, covering the polar angle intervals $20^\circ < \theta < 37.5^\circ$ and $142.5^\circ < \theta < 160^\circ$ and the full azimuth. Each detector consists of 12 sectors in which a toroidal magnetic field is generated by 12 coils equally spaced in azimuth (the field integral is $\approx 0.38 \text{ T}\cdot\text{m}$). Following the magnetic field volume, each sector contains nine drift-chamber planes, which are used to measure the charged-particle momenta together with the information from the vertex detector. A preshower counter, consisting of a 1.5 r.l. thick lead/iron plate followed by four layers of proportional tubes, is located after these chambers. Energy measurement, limited to e.m. showers only, is performed with a calorimeter

Fig. 2 Views of the UA2 detector: a) cut by the vertical plane containing the beam axis; b) a cut of the central detector normal to the beam axis; c) exploded view of a sector in one of the forward detectors.

containing ten independent counters per sector ($\Delta\theta \times \Delta\phi = 3.5^\circ \times 15^\circ$ per counter). Each counter is a lead/scintillator multilayer sandwich, subdivided in depth into two independent sections, 24 and 6 r.l. thick. Energy resolution is similar to that of the central calorimeter.

A view of a sector of a forward detector is shown in Fig. 2c.

No muon detector is implemented in the UA2 experiment.

3. MISSING TRANSVERSE MOMENTUM

The presence of one or more non-interacting particles, such as neutrinos, among the outgoing secondaries, can be detected, at least in principle, by measuring the total momentum vector associated with all observed final-state particles. Such a vector should be zero within the measurement errors, if no high-energy particle escapes detection.

In practice, even in the case of a detector with very large angular coverage, the presence of the machine vacuum chamber prevents the observation of particles emitted at angles smaller than $\approx 0.5^\circ$. The total momentum carried by these particles may be large and undergoes important fluctuations from one event to the other, thus making the total longitudinal momentum a useless quantity. Such undetected particles, however, carry a negligibly small transverse momentum; hence a measurement of the total transverse momentum in the event can still be effectively used to detect the presence of invisible high- p_T particles.

The missing transverse momentum vector, $\vec{p}_T^{\text{miss}}$, is defined as

$$\vec{p}_T^{\text{miss}} = -\vec{p}_T^\mu - \sum_i \vec{p}_T^i, \quad (1)$$

where $\vec{p}_T^\mu$ is the total transverse momentum carried by muons (if any), and $\vec{p}_T^i$ is a vector with magnitude given by the energy deposited in the i -th cell of the calorimeter, and directed from the event vertex to the cell centre. In Eq. (1), the sum is extended to all calorimeter cells.

Obviously, the measurement of $\vec{p}_T^{\text{miss}}$ requires as large an angular coverage as possible (this property is often called hermeticity), and this is indeed the case for the UA1 apparatus, with the exception of two holes at central rapidities, having the shape of an azimuthal sector of $\pm 4^\circ$ with respect to the vertical axis, which are needed to let through the signals from the various detectors contained in the magnet. The main consequence of these holes is that, in most cases, if $\vec{p}_T^{\text{miss}}$ makes an angle of less than $\pm 15^\circ$ with the vertical axis, its measurement is not reliable. After excluding such events from a sample of purely hadronic final states, it is found⁴ that each component of $\vec{p}_T^{\text{miss}}$ has a Gaussian distribution centred at zero, with a r.m.s. value $\sigma = 0.5 (\sum_i E_T^i)^{1/2}$, where E_T^i is the transverse energy (in GeV) observed in the i -th calorimeter cell. Hence the distribution of $|\vec{p}_T^{\text{miss}}|^2$ has the form $\exp(-|\vec{p}_T^{\text{miss}}|^2/2\sigma^2)$.

As described in Section 2, the UA2 apparatus does not detect any particles below an angle of 20° to the beams, and measures only partially hadronic jets emitted at polar angles between 20° and 40° . As a consequence, in a certain fraction of events a large value of p_T^{miss} may result from instrumental effects, such as partially contained

or undetected high- p_T jets. In the case of two-jet events, the probability of losing one of the jets is found to decrease from $\approx 10\%$ at $p_T(\text{jet}) = 15 \text{ GeV}$, to $\approx 2\%$ at $p_T(\text{jet}) = 40 \text{ GeV}$. We also recall that there is no muon detector in UA2.

4. PHYSICS OF THE INTERMEDIATE VECTOR BOSONS (IVBs)

4.1 Detection

For both IVBs, $W^\pm$ and Z , a large fraction of the decay modes (about 70%) consists of $q\bar{q}$ pairs which appear as two high- p_T hadronic jets⁵. In searching for such configurations we expect a background from the continuum of high- p_T two-jet events which results from hard-parton scattering. Such a background is approximately two orders of magnitude larger than the IVB signal, and it cannot be easily reduced experimentally because there is no way to distinguish jets from W and Z decay from those which result from hard-parton scattering. A measurement of the two-jet invariant mass with excellent resolution (of the order of the natural width of the IVBs) would certainly help to identify a peak superimposed on the smooth mass distribution of the background. However, in both UA1 and UA2, jet energies are measured using conventional calorimetry, and the resolution so obtained for the two-jet invariant mass in the region of the IVB masses is $\approx 8 \text{ GeV}/c^2$, a value barely adequate for the event sample available at present (see subsection 4.14).

For these reasons, both experiments have chosen to detect the IVBs by identifying their leptonic decays:

$$\left. \begin{array}{l} W^\pm \rightarrow e^\pm \nu_e(\bar{\nu}_e) \\ Z \rightarrow e^+ e^- \end{array} \right\} \text{ in both UA1 and UA2 } ,$$

$$\left. \begin{array}{l} W^\pm \rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu) \\ Z \rightarrow \mu^+ \mu^- \end{array} \right\} \text{ in UA1 only } ,$$

for which the backgrounds are much lower, as we shall see later, in spite of the smaller branching ratios.

The decision to detect electrons instead of muons in the UA2 experiment was based on the possibility of measuring electron energies with good precision using compact e.m. calorimeters (typically only $\approx 25 \text{ cm}$ thick), whereas muon detection implies large magnetic field volumes for momentum measurement and the use of thick iron absorbers.

When searching for the decay $Z \rightarrow e^+ e^-$, or $Z \rightarrow \mu^+ \mu^-$, the Z mass can be directly determined by measuring the energies (or momenta) of the two leptons and the angle α between their directions:

$$m^2 = 4E_1 E_2 \sin^2 \alpha / 2 \quad .$$

The mass resolution σ_m can be estimated from a knowledge of the measuring errors σ_{E1} , σ_{E2} , and σ_α :

$$\sigma_m/m = \frac{1}{2} \sqrt{(\sigma_{E1}/E_1)^2 + (\sigma_{E2}/E_2)^2 + (\sigma_\alpha/\tan \alpha/2)^2} .$$

The opening angle α is measured using tracking devices, and its error $\Delta\alpha$ can easily be made as low as 0.01 rad, or less. Its effect on σ_m/m is then negligible, because at Collider energies α is generally larger than 90° .

Electron energies are measured in calorimeters with a resolution $\sigma_E/E \approx 0.15/\sqrt{E}$ (E in GeV, see Section 2), giving

$$\sigma_m/m \approx 0.15/\sqrt{m} ,$$

where m is in GeV for a symmetric decay configuration. For $m \approx 90$ GeV the mass resolution is $\sigma_m \approx 1.4$ GeV, which is comparable with the expected natural width⁴, $\Gamma_Z \approx 2.5$ GeV.

For the decay $Z \rightarrow \mu^+ \mu^-$, muon momenta p_1 and p_2 replace the electron energies. They are determined by measuring the muon deflection in the magnetic field with a resolution which is typically $\sigma_p/p \approx 0.5\%$ p (p in GeV/c) in the UA1 detector (there is only a 0.6 mm sagitta in a 1 m long track from a 45 GeV/c particle). In this case we obtain

$$\sigma_m/m \approx 1.8 \times 10^{-3} m ,$$

where m is in GeV, which corresponds to a mass resolution $\Delta m \approx 14$ GeV at $m \approx 90$ GeV and is a much worse value than in the e^+e^- case. Furthermore, $\Delta m/m$ increases linearly with m, whereas for e^+e^- pairs it decreases as $m^{-1/2}$, showing the superiority of the e^+e^- channel in searching for possible new particles with masses larger than those of the IVBs.

The detection of the decay mode $W \rightarrow \ell \nu$, where ℓ is either an electron or a muon, is based on a completely different method, because the neutrino cannot be detected. In the W rest frame the lepton energy is just $m_W/2$. If we neglect the W transverse momentum p_T^W , the lepton transverse momentum $p_T = (m_W/2) \sin \theta^*$ (where $\sin \theta^*$ is the decay angle with respect to the beam direction in the W rest frame) is Lorentz invariant, and the p_T spectrum can be obtained from the decay angular distribution $f(\theta^*)$ by a simple change of variables:

$$dn/dp_T \propto [1 - (2 p_T/m_W)^2]^{-1/2} f[\sin^{-1}(2 p_T/m_W)] .$$

The singularity at $p_T = m_W/2$ arises only from the change of variables and is often called the Jacobian peak. The W transverse motion and the W natural width have the effect of smearing this peak. However, if the mean value of p_T^W is much smaller than $m_W/2$, the Jacobian peak is still the most distinctive feature of the charged-lepton p_T distribution in the decay $W \rightarrow \ell \nu$.

In addition to the peculiar shape of the charged-lepton p_T distribution, $W \rightarrow \ell \nu$ decays are characterized by a large missing transverse momentum, which results from the presence of a high- p_T neutrino. Obviously, the p_T^{miss} distribution will also show a Jacobian peak.

4.2 The Decay $W \rightarrow e\nu$

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 π^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.
- 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 3σ). 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 4σ .
- vi) A distinctive feature of the UA2 detector is the presence of a 'preshower' counter (see Section 2) 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 $\approx 40^\circ$ half-angle around the electron track. In UA2 this cone has a half-angle of typically $\approx 15^\circ$.

The combination of all these cuts is estimated to be $\approx 75\%$ efficient for isolated electrons in both experiments.

Figure 3 shows, for UA1⁶ and UA2⁷, examples of distributions of events containing at least one electron candidate in the (p_T^e, p_T^e) plane, where p_T^e is the measured electron transverse momentum, and $p_T^e \equiv p_T^{\text{miss}}$. In the high- p_T^e region

Fig. 3 Examples of distributions of the events containing at least one electron candidate in the p_T^e , p_T^ν plane: a) UA1 data; b) UA2 data.

Fig. 4 Examples of p_T^ν distributions for events containing at least one electron candidate with $p_T^e > 15 \text{ GeV/c}$: a) UA1 data; b) UA2 data.

($p_T^e \geq 25$ GeV/c), the signal from $W \rightarrow e\nu$ ($p_T^e \approx p_T^\nu$) is clearly visible above the background of misidentified hadrons, which is dominant at low p_T^e . The events with high- p_T^e values and small p_T^ν result mostly from $Z \rightarrow e^+e^-$ decays, and will be discussed in subsection 4.10.

Examples of p_T^ν distributions are shown in Fig. 4. They demonstrate clearly that the rejection power against background of a cut on p_T^ν is much larger in UA1 than in UA2. The UA1 data (Fig. 4a) show two well-separated classes of events: those with $p_T^\nu > 15$ GeV/c, which show the characteristic Jacobian structure expected from $W \rightarrow e\nu$ decay; and those with $p_T^\nu < 15$ GeV/c, which are mostly misidentified hadronic final states. In the latter class the non-zero value of p_T^ν is the effect of the p_T^{miss} resolution. The simple requirement $p_T^\nu > 15$ GeV/c is sufficient, therefore, to select an almost pure sample of $W \rightarrow e\nu$ decays. A typical p_T^ν distribution for events satisfying such a requirement is shown in Fig. 5a for a partial event sample, together with the estimated background and signal contributions.

The separation between the two classes of events is much less clear in the UA2 data (Fig. 4b), as a result of the non-Gaussian tails of the p_T^{miss} resolution in the UA2 experiment. In the UA2 data, a cut on p_T^ν is not sufficient to reduce the hadronic background to a tolerable level. For this reason, the W sample is restricted to the events containing an electron candidate of $p_T^e > 20$ GeV/c. For these events, a transverse mass m_T , with the property $m_T \leq m_W$, is evaluated using the formula

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

where $\Delta\phi$ is the azimuthal separation between $\vec{p}_T^e$ and $\vec{p}_T^\nu$. Of all the $W \rightarrow e\nu$ decays for which the electron falls within the acceptance of the UA2 apparatus, 80% are expected to satisfy the requirements $p_T^e > 20$ GeV/c, $m_T > 50$ GeV. These criteria, applied to the total UA2 event sample, select 251 events, whose p_T^ν distribution is shown in Fig. 5b, together with the estimated background and signal contributions.

Background contributions, given as fractions of the total number of events in the sample, are listed in Table 1. We note that the contribution from $W \rightarrow \tau\nu_\tau$, followed by $\tau \rightarrow e\nu_e\nu_\tau$, is larger in UA1 than in UA2, because of the lower p_T^e threshold used to define the final sample. However, the contribution from $Z \rightarrow e^+e^-$ decays with one electron outside the detector acceptance is larger in UA2, because the probability of detecting both electrons is only $\approx 60\%$ in UA2, whilst it is nearly 100% in UA1.

Table 1. Background Contributions to the $W \rightarrow e\nu$ Event Samples
(in percent of the number of events in the sample)

	UA1 (%)	UA2 (%)
Hadronic background	3.1	4.6
$Z \rightarrow e$ (detected) e (undetected)	–	3.8
$W \rightarrow \tau\nu_\tau, \tau \rightarrow e\nu_e\nu_\tau$	5.3	2.1
$W \rightarrow \tau\nu_\tau, \tau \rightarrow \nu_\tau\pi^0 + \text{hadrons}$	1.6	–

Fig. 5 a) Example of a p_T^e distribution for electron candidates in events having $p_T^e > 15$ GeV/c (UA1); b) The p_T^e distribution for $W \rightarrow e\nu$ candidates satisfying the UA2 selection criteria (see text). Broken curve: estimated hadronic background. Full curves: expected distributions for values of m_W as given by Eqs. (3) and (3').

Fig. 6 The ratio $R = [(d\sigma/dp_T^W dy)/(d\sigma/dy)]$ at W rapidity $y = 0$, as given by Altarelli et al.⁸ for four different choices of structure functions and definitions of the Q^2 scale.

4.3 Determination of the W Mass

A value of the W mass, m_W , can be extracted from the $W \rightarrow e\nu$ event samples by a best-fit procedure to either the p_T^e or the m_T distribution, because the Jacobian peak, whose position is related to m_W , is present in both distributions.

In practice, although p_T^e is measured, in general, more precisely than m_T , the p_T^e distribution is sensitive to the W transverse momentum, p_T^W , whose distribution has large theoretical uncertainties⁸ (see Fig. 6), which cannot be reduced using the present experimental data. For this reason, both experiments use the m_T distribution, which is rather insensitive to the W transverse motion.

In the UA1 experiment⁹, a sample of 149 events, for which both p_T^e and p_T^{ν} exceed 30 GeV/c, is selected from the total event sample, which corresponds to a total integrated luminosity of $\mathcal{L} = 706 \text{ nb}^{-1}$. The m_T distribution for this sample, which is background-free, is shown in Fig. 7a.

In UA2, the m_T distribution of the events containing an electron candidate of $p_T^e > 20 \text{ GeV/c}$ is shown in Fig. 7b.

A Monte Carlo simulation is 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. The large backgrounds in the UA2 sample (see Fig. 7b) 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

$$\text{UA1}^9: m_W = 82.7 \pm 1.0 \text{ (stat.)} \pm 2.7 \text{ (syst.) GeV;} \quad (3)$$

$$\text{UA2}^7: m_W = 80.2 \pm 0.8 \text{ (stat.)} \pm 1.3 \text{ (syst.) GeV.} \quad (3')$$

The best-fit curves, which correspond to these values, are superimposed on the experimental m_T distributions in Fig. 7.

In both experiments, the fit is performed using the Standard Model value⁵ for the W width, $\Gamma_W \approx 2.6 \text{ GeV}$. By using Γ_W as a second free parameter, it is possible to obtain an upper limit on Γ_W . The results from the two experiments are $\Gamma_W < 5.4 \text{ GeV}$ [UA1⁹] and $< 7 \text{ GeV}$ [UA2⁷], at the 90% confidence level (CL).

The systematic error in Eqs. (3) and (3') reflects the uncertainty on the absolute energy scale of the calorimeter, and it will be discussed in detail in the next subsection. It is quoted separately because it cancels in the ratio m_W/m_Z .

4.4 Mass Scale Uncertainty

The m_W measurement discussed in the previous subsection and the measurement of the Z mass, m_Z , from the decay $Z \rightarrow e^+e^-$ (see subsection 4.10), involve energy measurements in the calorimeter.

Fig. 7 Electron-neutrino transverse mass distribution for the UA1 (a) and UA2 (b) event samples. The full curves are expectations for values of m_W as given by Eqs. (3) and (3'). The broken curve in Fig. 7b represents the $W \rightarrow e\nu$ contribution to the UA2 event sample.

It is possible, at least in principle, to calculate the energy lost by a particle of a given energy in the calorimeter scintillator. However, what is finally measured in both UA1 and UA2 is the total electric charge collected at the anodes of several photomultipliers (PMs), which results from the conversion of energy loss into scintillation light, followed by photoelectric effect and amplification by secondary emission in the PM. The conversion factors which describe these two steps cannot be predicted, because they depend on the quality of the scintillator and of the optical coupling to the PM, and on the PM quantum efficiency and gain. The only way to know the ratio between the particle energy and the electric charge collected at the PM anode (such a ratio is often called calibration constant), is to measure it for each PM by exposing the calorimeter to test beams of electrons and pions of known energies. These special calibration runs are performed before assembling the detector at the Collider.

An additional complication arises from the fact that the calorimeter properties and PM gains may vary with time (for example, as an effect of natural deterioration of the various materials or because of radiation damage during Collider operation). It is necessary, therefore, to monitor the calibration constant for each PM during the entire duration of the experiment. This is done, in general, by using artificial light flashes and radioactive sources, and also by periodically recalibrating a few calorimeter modules using test beams of known energies.

There are two kinds of calibration uncertainties: a cell-to-cell uncertainty, which results in a deterioration of the energy resolution; and an overall energy scale uncertainty, which corresponds to a systematic error in the unit of energy (this is why such an error cancels in the ratio m_W/m_Z). The latter is estimated to be $\pm 3\%$ in UA1⁶ and $\pm 1.6\%$ in UA2⁷.

The smaller UA2 error results from a better control of the calorimeter calibration, which was performed for all calorimeter cells in 1981, before the start of the experiment. This calibration has then been repeated periodically for a fraction of the calorimeter modules. A recalibration of 39 calorimeter cells performed in July 1986 is consistent with the quoted uncertainty. On the contrary, in the UA1 experiment only a few calorimeter modules were initially calibrated, and no recalibration has been made because the large size of the calorimeter modules makes them cumbersome and practically impossible to transport to a test-beam area.

It should be noted that a contribution of $\approx 0.7\%$ to the quoted UA2 energy scale uncertainty results from the uncertainty on the energy of the test beams used to calibrate the calorimeters.

The calorimeter calibration represents a less severe problem in experiments with e^+e^- machines, where elastic scattering and two-jet production via the reaction $e^+e^- \rightarrow q\bar{q}$ provide calibration standards 'in situ'. No known source of mono-energetic particles or jets, on the contrary, is available at hadron colliders.

4.5 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 (anti-quarks) is -1 ($+1$) and the W is almost fully polarized along the $\bar{p}$ beam. At higher energies (e.g. at the Fermilab Tevatron 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 ν_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 θ^* 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 convention¹⁰ is used to define θ^* .

A further complication arises from the fact that p_L^e is not measured, and the condition that the invariant mass of the $e\nu$ pair be equal to m_W gives two solutions for p_L^e or p_L^W . The UA1 analysis^{6,9} retains only those events for which one solution is unphysical and the charge sign is unambiguously determined (149 events). In UA2⁷, the solution corresponding to the smaller value of $|p_L^W|$ is chosen.

Figure 8a shows the $\cos \theta^*$ distribution from UA1, corrected for the detector acceptance.

In the UA2 experiment⁷, 47 events containing an electron candidate with $p_T^e > 20$ GeV/c and $m_T > 40$ GeV are detected in the forward regions, where the magnetic spectrometers allow a measurement of the electric charge. The background to this sample from misidentified hadrons is estimated to be 4.2 ± 0.3 events. The background-subtracted $\cos \theta^*$ distribution is shown in Fig. 8b, where it is compared with the expected $(1 + \cos \theta^*)^2$ form, distorted by the effect of the detector acceptance.

Both distributions of Fig. 8 agree well with the expected $(1 + \cos \theta^*)^2$ form. It must be noted, however, that this result cannot 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.

A more general discussion of the asymmetry expected in the case of the decay of a W of arbitrary spin, is given by Jacob in his lectures at this School¹. It is shown there that the UA1 result (Fig. 8a) provides the demonstration that the W has spin 1.

Fig. 8 The UA1 and UA2 distributions of the product $q \cos \theta_e^*$ for electrons ($q = -1$) and positrons ($q = +1$) from $W \rightarrow e\nu$ decay. The angle θ_e^* is measured with respect to the incident $\bar{p}$ beam.

Fig. 9 Inverse transverse mass distribution for muon-neutrino pairs in UA1. The variable $1/m_T$ is chosen instead of m_T , because the error resulting from momentum resolution is Gaussian in $1/m_T$ and not in m_T .

4.6 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 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 are used to select $W \rightarrow \mu\nu$ candidates¹¹. The main background in this search arises from medium-energy $K^\pm$ mesons, which decay into $\mu\nu$ at angles such that the decay kink on the track occurs in a direction opposite to the magnetic deflection. In these cases the track curvature appears smaller than it is in reality, thus simulating a high-momentum muon. To reject this background, which is absent in the $W \rightarrow e\nu$ channel, a careful visual inspection of the track is performed in order to identify the $K \rightarrow \mu\nu$ decay kink, using a high-resolution graphics display.

A sample of 57 $W \rightarrow \mu\nu$ events is selected from the full data sample, with negligible background contamination⁹. Since the momentum measurement error is gaussian in $1/p$, and not in p , the distribution of the variable $1/m_T$, rather than m_T , is more convenient to display the Jacobian peak structure expected from $W \rightarrow \mu\nu$ decay (see Fig. 9). We recall that in UA1 the momentum resolution for a 40 GeV/c muon is $\approx \pm 20\%$, whereas it is $\approx \pm 2.5\%$ 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 $\approx 1/3$ 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.

A fit to the distribution of Fig. 9, using the expected shape of the $1/m_T$ distribution, distorted by the effects of momentum resolution, provides an independent determination of m_W . The result is⁹

$$m_W = 81.8^{+6.0}_{-5.3} (\text{stat.}) \pm 2.6 (\text{syst.}) \text{ GeV} ,$$

where the systematic error results from uncertainties in the corrections for track distortions in the central detector. This result agrees with the determination from the $W \rightarrow e\nu$ channel [Eq. (3)], but is affected by a much larger statistical error.

4.7 The Decay $W \rightarrow \tau\nu_\tau$

The decay chain $W \rightarrow \tau\nu_\tau$, $\tau \rightarrow \nu_\tau + \text{hadrons}$ is expected to result in purely hadronic events with large p_T^{miss} . Furthermore, since the τ energy is generally much larger than the τ mass, hadrons from τ decay will appear as a highly collimated jet with low charged-particle multiplicity (we remind the reader¹² that the decay $\tau \rightarrow \nu + \text{hadrons}$ represents $\approx 64\%$ of all τ decays, and of these decays, the fraction with five or more charged particles amounts to less than 1%).

A search for purely hadronic events with large values of p_T^{miss} has been performed in the UA1 experiment¹³ from a data sample corresponding to a total integrated luminosity of 715 nb^{-1} . The main selection criteria are:

- i) $p_T^{\text{miss}} > 15 \text{ GeV}/c$;
- ii) $p_T^{\text{miss}}/0.7 (\sum_i E_{Ti})^{1/2} > 4$ (as discussed in Section 3, this requirement ensures that the large p_T^{miss} value is not an effect of the p_T^{miss} resolution);
- iii) the presence of at least one jet with transverse energy $E_T > 12 \text{ GeV}$;
- iv) absence of muons or electrons in the event.

A total of 57 events satisfy these requirements. In this sample, $W \rightarrow \tau$ events are identified using the following three variables:

- i) the fraction F of the jet energy contained in a cone with half-aperture $R = (\Delta\phi^2 + \Delta\eta^2)^{1/2} = 0.4$, where $\Delta\phi$ ($\Delta\eta$) is the azimuthal (pseudorapidity) separation with respect to the jet axis (in UA1, jets are defined by a cone with $R = 1$ and thus F is a measure of the jet collimation);
- ii) the separation $r = (\Delta\phi^2 + \Delta\eta^2)^{1/2}$ between the charged-particle track with the highest momentum and the jet axis;
- iii) the charged-particle multiplicity, ν_{ch} , in a cone with $R = 0.4$ around the jet axis.

For each event, a τ likelihood, L_τ , is defined as

$$L_\tau = \ln[(dn/dF)(dn/dr)(dn/d\nu_{\text{ch}})] \quad ,$$

where dn/dF , dn/dr , and $dn/d\nu_{\text{ch}}$ are the expected distributions for $W \rightarrow \tau$ decay, as obtained by Monte Carlo simulations, calculated at the measured values of the three variables F , r , and ν_{ch} .

The L_τ distribution for the 56 events is shown in Fig. 10, where it is compared with the expected distribution from $W \rightarrow \tau$ decay (normalized to the expected number of $W \rightarrow \tau$ events), and also with the distribution measured for ordinary jets from a sample of two-jet events. The cut $L_\tau > 0$, which is satisfied by 78% of all hadronic τ decays, and which rejects 89% of the ordinary jets, selects a sample of 32 events. Figure 11 shows the m_T distribution for these events, together with the expected distribution for a W mass of $82.7 \text{ GeV}/c^2$ (in this case m_T is evaluated from Eq. (2) using $\vec{p}_T^{\text{miss}}$ and $\vec{p}_T^{\text{jet}}$ in the place of $\vec{p}_T^{\text{e}}$ and $\vec{p}_T^{\text{e}}$). A fit to this distribution gives $m_W = 89 \pm 3 \text{ (stat.)} \pm 6 \text{ (syst.) GeV}$, in agreement with the measurements from $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decay.

4.8 W Production Cross-Section and $e\text{-}\mu\text{-}\tau$ Universality

The cross-sections for inclusive W production, followed by the decay $W \rightarrow \ell\nu$, σ_W^ℓ (where $\ell \equiv e, \mu$ or τ), are computed in a straightforward way from the number of events in the samples, after subtracting the various background contributions and correcting for the geometrical acceptance of the detector, the efficiency of the selection criteria, and the machine luminosity.

Experimental values of σ_W^ℓ , as measured by UA1⁹ and UA2¹⁴, are listed separately in Table 2 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 UA4¹⁵ in the same interaction].

Fig. 10 Distribution of the τ -likelihood for the UA1 data (56 events, solid histogram). The solid curve is a Monte Carlo expectation for $W \rightarrow \tau \nu \rightarrow \nu \bar{\nu} + \text{hadrons}$, absolutely normalized. The broken curve is the τ -likelihood, as measured for hadronic jets in UA1, normalized to 56 events.

Fig. 11 Transverse mass distribution for events passing the τ selection criteria in UA1 (32 events, solid histogram). The solid curve is a Monte Carlo prediction for $W \rightarrow \tau \nu \rightarrow \nu \bar{\nu} + \text{hadrons}$, normalized to the expected number of 28.7 events. The shaded area represents the expected hadronic background (2.7 events).

Table 2. W Cross-Sections (nb)

		$\sqrt{s} = 546 \text{ GeV}$	$\sqrt{s} = 630 \text{ GeV}$
UA1 ⁹	σ_W^e	$0.55 \pm 0.08 \text{ (stat.)} \pm 0.09 \text{ (syst.)}$	$0.63 \pm 0.04 \text{ (stat.)} \pm 0.10 \text{ (syst.)}$
	σ_W^μ	$0.56 \pm 0.18 \text{ (stat.)} \pm 0.12 \text{ (syst.)}$	$0.63 \pm 0.08 \text{ (stat.)} \pm 0.11 \text{ (syst.)}$
	σ_W^τ	$0.63 \pm 0.12 \text{ (stat.)} \pm 0.11 \text{ (syst.)}$	
UA2 ¹⁴	σ_W^e	$0.61 \pm 0.10 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$	$0.57 \pm 0.04 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$
Theory ⁸	σ_W^t	$0.46^{+0.14}_{-0.07} \pm 0.06$	$0.57^{+0.18}_{-0.10} \pm 0.07$

Theoretical calculations of the inclusive W production cross-sections, σ_W , including next-to-leading order QCD corrections, predict⁸ $\sigma_W = 4.7^{+1.4}_{-0.7} \text{ nb}$ at $\sqrt{s} = 546 \text{ GeV}$, and $\sigma_W = 5.8^{+1.8}_{-1.0} \text{ nb}$ at $\sqrt{s} = 630 \text{ GeV}$. In these predictions, the errors reflect theoretical uncertainties on structure functions and ambiguities in the choice of the Q^2 scale.

To obtain σ_W^f from these values, we need to know the branching ratio for $W \rightarrow \ell\nu$ decay, $B_W(\ell\nu)$. In the framework of the Standard Model with three fermion families, $B_W(\ell\nu)$ falls in the range 0.086–0.11, depending on the mass of the top quark, m_t . In Table 2, we quote the theoretical values of σ_W^f using the central value of $B_W(\ell\nu)$ (which corresponds to $m_t \approx 65 \text{ GeV}$), and we add a second error to take into account its uncertainty. Within the statistical and systematic errors, the UA1 and UA2 results agree with each other, and also with the theoretical predictions.

From the ratios of σ_W^μ/σ_W^e and σ_W^τ/σ_W^e , which are not affected by uncertainties on the machine luminosity, the UA1 Collaboration^{9,13} obtains the following values for the ratios of weak coupling constants:

$$\begin{aligned} g_\mu/g_e &= 1.01 \pm 0.07 \text{ (stat.)} \pm 0.04 \text{ (syst.)} , \\ g_\tau/g_e &= 1.01 \pm 0.11 \text{ (stat.)} \pm 0.06 \text{ (syst.)} , \end{aligned}$$

where the constants g describe the strength of the $(\ell\nu)$ current coupling to the W. These results provide direct evidence for e- μ - τ universality at $Q^2 = m_W^2$.

4.9 Transverse Momentum of the W

The W transverse momentum $\vec{p}_T^W$ is equal and opposite to the total transverse momentum carried by all hadrons produced in association with the W itself. Figure 12 shows the p_T^W distribution, as measured by UA1¹⁶ and UA2¹⁴ for a sample of $W \rightarrow e\nu$ or $W \rightarrow \mu\nu$ events. A QCD prediction⁸, also shown in Fig. 12, agrees with the data over the full p_T^W range. The W bosons produced with high p_T^W are expected to recoil against one or more jets, as a result of higher order QCD effects, and such jets are indeed observed experimentally.

Fig. 12 Distribution of p_T^W for both $W \rightarrow e \nu$ and $W \rightarrow \mu \nu$ events in UA1, and for $W \rightarrow e \nu$ events in UA2. The curve represents a QCD prediction⁸, and the shaded band shows the theoretical uncertainty in the region of high p_T^W .

Table 3. Parameters of UA1 Events A ($W \rightarrow \mu\nu$) and B ($W \rightarrow e\nu$), and of the UA2 Event ($W \rightarrow e\nu$)

		A (UA1)	B (UA1)	UA2
p_T [GeV/c]	Charged lepton	22 ± 3	19 ± 1	35 ± 3
	Neutrino	85 ± 11	99 ± 14	55 ± 6
	Jet 1	72 ± 11	90 ± 13	38 ± 5
	Jet 2	20 ± 4	17 ± 4	24 ± 3
p_T^W [GeV/c]		82 ± 12	105 ± 14	36 ± 5
$M(jj)$ [GeV]		82 ± 10	97 ± 12	54 ± 10
$M(Wjj)$ [GeV]		299 ± 28	279 ± 28	151 ± 16

As shown in Fig. 12, the two UA1 events with the highest p_T values correspond to a rate in reasonable agreement with QCD expectations. However, both events contain a high-mass two-jet system recoiling against the W. Such a configuration is rather unlikely, as illustrated in Fig. 13, where $M(jj)$, the two-jet invariant mass, is plotted against $M(Wjj)$, the invariant mass of the W + two jet system, for all W + two jet events of the UA1 sample (only jets with $E_T > 7$ GeV are considered for this plot). A comparison with a QCD Monte Carlo calculation¹⁷, which includes terms of order α_s^2 , represented by equal-probability contours in Fig. 13, shows that the two events (designated as A and B in Fig. 13) lie in a region where the probability is only a few per cent.

A list of measured parameters for the two events is given in Table 3. Within measurement errors, the $M(jj)$ values for the two events is consistent with either m_W or m_Z , and also $M(Wjj)$ is consistent with a unique value around 290 GeV. It is tempting, therefore, to interpret these events in terms of WW or WZ production. However, the production of pairs of gauge bosons by standard mechanisms is much too low to be observable in the present event sample.

An alternative mechanism, first suggested by Denegri¹⁸, considers QCD production of a heavy quark-antiquark pair $Q\bar{Q}$, with $m_Q > m_W$. In such a case the decay $Q \rightarrow q + W$, where q is a lighter quark, would result in a final state containing two W bosons. However, as recently discussed¹⁹, also in this case the expected event rate is too low to explain the occurrence of two events in the UA1 data sample.

In the UA2 data sample¹⁴, only one event containing a W produced in association with two jets is observed (in this analysis, only jets with $E_T > 10$ GeV are considered). The parameters of this event are also listed in Table 3. The occurrence of such an event in the UA2 data sample agrees with QCD expectations (see Fig. 14).

Clearly, a much larger event sample is needed before claiming evidence for a new mechanism of boson pair production.

Fig. 13 Correlation between the W-jet-jet invariant mass and the two-jet invariant mass for 10 W-jet-jet events in UA1 (3 $W \rightarrow \mu\nu$ and 7 $W \rightarrow e\nu$ decays). Only jets having $E_T > 7$ GeV are considered in this plot. The contours are second-order QCD predictions¹⁷, distorted by the jet energy resolution, containing the event fraction as indicated. Events A and B are emphasized in the plot.

Fig. 14 Invariant mass distribution of the W + jet(s) system, as measured by UA2¹⁴. Only jets having $E_T > 10$ GeV are considered in this plot. The shaded event is the only one with two jets.

4.10 The $Z \rightarrow e^+ e^-$ Event Samples

As observed in subsection 4.2, 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. 15 for UA1, and in Fig. 16 for UA2. Both distributions show a clear peak near $m_{ee} \approx 90$ GeV, which is interpreted as the result of $Z \rightarrow e^+ e^-$ decay. Such a peak is visible in the UA2 sample even using calorimeter information alone (Fig. 16a).

The low-mass continuum in Fig. 16b is mostly due to background from two-jet events. Such a background is negligible under the Z peak, as demonstrated by the fact that very few events are observed between the low-mass continuum and the peak. A background estimate gives 1.3 events under the Z peak for the distribution of Fig. 16b.

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 is⁹

$$m_Z = 93.1 \pm 1.0 \text{ (stat.)} \pm 3.1 \text{ (syst.) GeV}/c^2 \quad . \quad (4)$$

The corresponding UA2 result is⁷

$$m_Z = 91.5 \pm 1.2 \text{ (stat.)} \pm 1.7 \text{ (syst.) GeV}/c^2 \quad . \quad (4')$$

In both cases the systematic error reflects the uncertainty in the absolute calibration of the calorimeter energy scale (see subsection 4.4).

Cross-sections for inclusive Z production followed by the decay $Z \rightarrow e^+ e^-$, σ_Z^e , are listed in Table 4. Within the rather large statistical and systematic errors, the results of the two experiments are consistent with each other and also with the theoretical predictions⁸.

Table 4. $Z \rightarrow e^+ e^-$ Cross-Sections

	σ_Z^e (pb)	
	$\sqrt{s} = 546$ GeV	$\sqrt{s} = 630$ GeV
UA1 ⁹	$42^{+33}_{-20} \pm 6$	$74 \pm 14 \pm 11$
UA2 ¹⁴	$116 \pm 39 \pm 11$	$73 \pm 14 \pm 7$
Theory ⁸	43^{+13}_{-6}	54^{+17}_{-11}

(The second error in the experimental values is the systematic uncertainty)

Fig. 15 Invariant mass distribution for e^+e^- pairs in the UA1 data sample, shown above a mass value of 70 GeV. The curve represents the best fit to the data.

Fig. 16 Invariant mass distribution for e^+e^- pairs in the UA2 data sample: a) only calorimetric selections are applied; b) at least one electron candidate is required to satisfy all electron identification criteria. The broken lines show the estimated hadronic background. The hatched region shows the m_{ee} distribution of the 25 events used in the evaluation of the Z mass [see Eq. (4')].

4.11 The Decay $Z \rightarrow \mu^+ \mu^-$

By requiring the simultaneous presence of two muons, each having $p_T^\mu > 15 \text{ GeV}/c$ and such that their invariant mass $m_{\mu\mu}$ exceeds 40 GeV , a total of 19 events are selected in the UA1 experiment⁹. The $m_{\mu\mu}$ distribution of these events (Fig. 17) clearly shows the peak expected from $Z \rightarrow \mu^+ \mu^-$ decay. Such a peak is much broader than that measured in the $e^+ e^-$ decay channel, because of the poor momentum resolution in UA1 (see subsection 4.1). Since the resolution is Gaussian in $1/p$, and not in p , the measured $m_{\mu\mu}$ distribution from $Z \rightarrow \mu^+ \mu^-$ decay has an asymmetric shape, with a tail extending to large mass values (four of the 19 events are not shown in Fig. 17 because the measured $m_{\mu\mu}$ value exceeds 160 GeV).

A fit to the peak of Fig. 17 gives

$$m_Z = 94.1^{+8.4}_{-6.6} (\text{stat.}) \pm 2.8 (\text{syst.}) \text{ GeV} , \quad (5)$$

where the systematic error reflects uncertainties mostly associated with distortions in the tracking detector.

A more precise result can be obtained by requiring that the dimuon transverse momentum be equal and opposite to the total transverse momentum carried by all other particles in the event (this method assumes that there is no real neutrino or other undetected particle in the event). In this case the fit gives⁹

$$m_Z = 90.7^{+5.2}_{-4.8} (\text{stat.}) \pm 3.2 (\text{syst.}) \text{ GeV} . \quad (5')$$

The cross-section for inclusive Z production, followed by the decay $Z \rightarrow \mu^+ \mu^-$, is measured to be⁹

$$\sigma_Z^\mu = 67 \pm 17 (\text{stat.}) \pm 11 (\text{syst.}) \text{ pb}$$

at $\sqrt{s} = 630 \text{ GeV}$. A comparison of this value with the measured value of σ_Z^e (see Table 4) provides a test of μ - e universality in Z decay:

$$g_\mu/g_e = 1.03 \pm 0.03 (\text{syst.}) ,$$

where $g_\mu(g_e)$ is the Z coupling constant to the muon (electron) weak neutral current.

4.12 The Z Width and the Number of Neutrino Species

Within the context of the Standard Model, the value of the Z width, Γ_Z , is related to the number of fermion doublets for which the decay $Z \rightarrow f\bar{f}$ 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

$$\Gamma_Z = \sum_\ell \Gamma_Z(\ell\bar{\ell}) + \sum_q \Gamma_Z(q\bar{q}) + N_\nu \Gamma_Z(\nu\bar{\nu}) ,$$

where $\ell \equiv e, \mu, \tau$, $q \equiv u, d, c, s, t, b$, and N_ν is the number of neutrino species.

Fig. 17 Invariant mass distribution for $\mu^+\mu^-$ pairs in UA1, before momentum balance. Four events having $m_{\mu\mu} > 160$ GeV are not shown. The curve represents the best fit to the data.

Fig. 18 The value of Γ_Z/Γ_W displayed with both statistical and theoretical uncertainties [see Eq. (10)]. Also shown is the 95% CL upper limit with its theoretical uncertainty [Eq. (10')]. The solid lines are the expected variations of Γ_Z/Γ_W with the top-quark mass, m_t , for 3, 4, and 7 neutrino types. The error bars at the ends of these curves represent the $\sin^2 \theta_W$ uncertainty. The shaded region marks the lower limit on m_t ($m_t > 25$ GeV) as determined by experiments at the e^+e^- machine TRISTAN³⁵.

A value of Γ_Z can be obtained, in principle, by the same maximum-likelihood fit as used to determine m_Z . However, the expected width for three fermion families ($\Gamma_Z \approx 2.5 \text{ GeV}/c^2$) is comparable with the experimental mass resolution achieved in UA1 and UA2. Under these circumstances the determination of Γ_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 provide meaningful results:

$$\begin{aligned} & \Gamma_Z < 5.2 \text{ GeV (90\% CL)} \quad \text{from UA1}^9; \\ \text{and} \\ & \Gamma_Z = 2.7 \pm 2.0 \text{ (stat.)} \pm 1.0 \text{ (syst.) GeV}; \\ & \Gamma_Z < 5.6 \text{ GeV (90\% CL)} \quad \text{from UA2}^7. \end{aligned}$$

A model-dependent method²⁰, which does not depend on the mass resolution, consists in measuring the ratio $R = \sigma_W^{\ell}/\sigma_Z^{\ell}$ ($\ell \equiv e$ or μ), which is related to the ratio of total widths, Γ_Z/Γ_W , by the equation

$$\Gamma_Z/\Gamma_W = R(\sigma_Z/\sigma_W)[\Gamma_Z(\ell\bar{\ell})/\Gamma_W(\ell\nu_{\ell})] \quad , \quad (6)$$

where $\sigma_Z(\sigma_W)$ is the inclusive cross-section for $Z(W)$ production. This equation can be easily derived from the definition of σ_W^{ℓ} and σ_Z^{ℓ} .

The measured values of R are:

$$\begin{aligned} \text{UA1}^{21}: R &= 9.1^{+1.7}_{-1.2} \quad ; \\ R &< 11.5 \text{ (90\% CL)}; \\ R &< 12.2 \text{ (95\% CL)}; \end{aligned} \quad (7)$$

$$\begin{aligned} \text{UA2}^7: R &= 7.2^{+1.7}_{-1.2} \quad ; \\ R &< 9.5 \text{ (90\% CL)}; \\ R &< 10.4 \text{ (95\% CL)}. \end{aligned} \quad (7')$$

In these results, the errors are dominated by statistics, because the value of the integrated luminosity cancels out. The UA1 result is obtained by combining both electron and muon data.

In Eq. (6) both σ_Z/σ_W and the ratio of the leptonic partial widths depend on $\sin^2 \theta_W$, explicitly through the neutral-current couplings and implicitly via the W and Z masses. However, their product is constant to within 1% over the range $\sin^2 \theta_W = 0.229 \pm 0.005$. A further, more serious uncertainty results from the use of different sets of structure functions in the theoretical calculation of σ_Z/σ_W . Calculations based on all published parametrizations give values of σ_Z/σ_W ranging between the two extreme values 0.285 and 0.325. More recent estimates give $\sigma_Z/\sigma_W = 0.308 \pm 0.019^8$; 0.298 ± 0.008^{22} ; 0.293 ± 0.007^{23} , and 0.305 ± 0.014^{24} . Here we choose the value $\sigma_Z/\sigma_W = 0.305 \pm 0.020$ with a rather conservative error, and we rewrite Eq. (6) in the numerical form

$$\Gamma_Z/\Gamma_W = (0.114 \pm 0.008)R \quad , \quad (8)$$

where the error reflects the theoretical uncertainty on σ_Z/σ_W as quoted above. Using R as in Eqs. (7) and (7') we evaluate

$$\text{UA1: } \Gamma_Z/\Gamma_W = 1.04^{+0.19}_{-0.14} (\text{stat.}) \pm 0.07 (\text{theor.}) \quad ; \quad (9)$$

$$\text{UA2: } \Gamma_Z/\Gamma_W = 0.82^{+0.19}_{-0.14} (\text{stat.}) \pm 0.06 (\text{theor.}) \quad . \quad (9')$$

These results can be statistically combined to give

$$\Gamma_Z/\Gamma_W = 0.96^{+0.14}_{-0.10} (\text{stat.}) \pm 0.07 (\text{theor.}) \quad , \quad (10)$$

$$\Gamma_Z/\Gamma_W < 1.20 \pm 0.08 (\text{theor.}) (95\% \text{ CL}) \quad , \quad (10')$$

where the theoretical error reflects the uncertainty on σ_Z/σ_W .

The ratio Γ_Z/Γ_W is sensitive both to the number of neutrino types, N_ν , and to the mass of the top quark, m_t . The results are summarized in Fig. 18, which shows the expected variation of Γ_Z/Γ_W with m_t if the number of light neutrino species is 3, 4, or 7. The error bars at the end of each line show the effect of the uncertainty on $\sin^2 \theta_W$. Also shown in Fig. 18 is the combined result on Γ_Z/Γ_W [Eq. (10)], together with the 95% CL upper limit [Eq. (10')]. The following conclusions can be drawn from Fig. 18:

- i) for $N_\nu = 3$, the data provide no bound for the t-quark mass, m_t ;
- ii) $N_\nu \leq 6$ independent of m_t ;
- iii) if $m_t \geq 75 \text{ GeV}$, $N_\nu \geq 4$ is excluded. Hence it is not possible to have at the same time a heavy t quark and more than three neutrino types.

Finally, we note that the method just discussed will become obsolete as soon as the forthcoming Z factories (SLC, LEP) begin operation, because Γ_Z will be directly measured with a precision of $\pm 30 \text{ MeV}$ at these machines²⁵. At that moment, Eq. (8) will be used to determine Γ_W with a precision far superior to any other possible method.

4.13 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. We shall use the scheme where $\sin^2 \theta_W$ is defined as²⁶

$$\sin^2 \theta_W = 1 - (m_W/m_Z)^2 \quad , \quad (11)$$

which leads to the following predictions for the W and Z masses:

$$m_W^2 = A^2 / [(1 - \Delta r) \sin^2 \theta_W] \quad ; \quad (12)$$

$$m_Z^2 = 4A^2 / [1 - \Delta r) \sin^2 2\theta_W] \quad ; \quad (12')$$

where $A = (\pi\alpha/\sqrt{2} G_F)^{1/2} = (37.2805 \pm 0.0003) \text{ GeV}$, and Δr represents the effect of one-loop radiative corrections^{27,28}. Recent calculations, which assume $m_t = 45 \text{ GeV}$ and a value of 100 GeV for the mass of the Higgs boson, m_H , give²⁹ $\Delta r = 0.071 \pm 0.007$. While the dependence of Δr on m_H is too weak to be measured, the dependence on m_t becomes important if the t quark is heavy: for example, for $m_t \gg 45 \text{ GeV}$, one can write²⁸

$$\Delta r = 0.071 + \delta \quad ,$$

where

$$\delta = - [(3\alpha)/(16\pi)][(\cos^2 \theta_w)/(\sin^4 \theta_w)][(m_t^2)/(m_W^2)] \quad ,$$

with the consequence $\Delta r = 0$ for $m_t \approx 250 \text{ GeV}$. Hence a precise measurement of Δr provides information on the t -quark mass, as well as on the existence of further fermion families with large mass splittings between the two members of the same isodoublet.

However, the present experimental values of m_W and m_Z [see Eqs. (3), (3'), (4), (4')] are not precise enough even to test the presence of the Δr term in Eqs. (12) and (12'). This is shown in Fig. 19, which compares the UA1 and UA2 measurements of m_W and m_Z with the Standard Model expectations for both $\Delta r = 0.07$ and $\Delta r = 0$. A large reduction of both statistical and systematic errors is clearly needed for a precise test of radiative corrections.

From the measured values of m_W and m_Z , a value of $\sin^2 \theta_w$ can be extracted using Eq. (11), with the advantage that the systematic error on the mass scale cancels out. One obtains:

$$\text{UA1}^9: \sin^2 \theta_w = 0.211 \pm 0.025 \quad ;$$

$$\text{UA2}^7: \sin^2 \theta_w = 0.232 \pm 0.027 \quad .$$

The weighted average of these two results is

$$\sin^2 \theta_w = 0.220 \pm 0.018 \quad . \quad (13)$$

A more precise value can be obtained by a simultaneous fit of the measured mass values to the theoretical formulae [Eqs. (12) and (12')]. The results are

$$\text{UA1}^9: \sin^2 \theta_w = 0.218 \pm 0.005 (\text{stat.}) \pm 0.014 (\text{syst.}) \quad , \quad (14)$$

$$\text{UA2}^7: \sin^2 \theta_w = 0.232 \pm 0.003 (\text{stat.}) \pm 0.008 (\text{syst.}) \quad , \quad (14')$$

where the systematic error reflects the uncertainty on the mass scale.

These values can be compared with the value of $\sin^2 \theta_w$, as obtained in low-energy experiments. The most precise values of $\sin^2 \theta_w$ have been obtained in studies of deep-inelastic neutrino-nucleon interactions, by measuring the cross-section ratio between neutral- and charged-current interactions, $R_\nu = \sigma(\nu_\mu N \rightarrow \nu_\mu X)/\sigma(\nu_\mu N \rightarrow \mu^- X)$. The weighted average of the two most precise experiments³⁰ is

Fig. 19 Confidence ellipses (68% level) in the m_W , m_Z plane from the UA1 and UA2 measurements. The error bar applied to the centre of the ellipse represents the systematic uncertainty on the mass scale. The curves represent Standard Model predictions with or without radiative corrections.

Fig. 20 Comparison of the value of $\sin^2 \theta_W$, as determined from ν -N deep-inelastic scattering [see Eq. (15)], with the values obtained from the measurements of the W and Z masses [Eqs. (3), (3'), (4), and (4')]. a) Values obtained from lowest-order formulae; b) values obtained from formulae which include radiative corrections. The broken error bars represent theoretical uncertainties for the ν N point, and the systematic uncertainty in the mass scale for the measurement of m_W and m_Z .

$$\sin^2 \theta_w = 0.231 \pm 0.004 \text{ (stat.)} \pm 0.005 \text{ (theor.)} , \quad (15)$$

where the theoretical error includes the effect of a ± 0.3 GeV uncertainty on the mass of the c quark.

This result is in good agreement with the Collider values only if radiative corrections are taken into account (see Fig. 20). In fact, a recent global fit to all neutral-current data and to the W- and Z-mass values quotes³¹ $\Delta r = 0.077 \pm 0.037$, which would correspond to $m_t < 180$ GeV (90% CL) for $m_H = 100$ GeV and under the assumption that only three fermion families exist.

We finally note that the definition of $\sin^2 \theta_w$ given by Eq. (11) contains the assumption that in the electroweak theory the IVB masses are generated by a weak isospin doublet of complex Higgs fields (this assumption is implicit in the Standard Model). The isospin structure of the Higgs sector is described by the so-called ρ parameter, defined as³²

$$\rho = m_W^2 / (m_Z^2 \cos^2 \theta_w) , \quad (16)$$

which is equal to 1 in the Standard Model.

We can test this assumption by extracting a value of $\sin^2 \theta_w$ from the measurement of m_W alone [Eq. (12)], and replacing it in Eq. (16), together with the measured mass values. The results are

$$\text{UA1}^9: \quad \rho = 1.009 \pm 0.028 \text{ (stat.)} \pm 0.020 \text{ (syst.)} ;$$

$$\text{UA2}^7: \quad \rho = 1.001 \pm 0.028 \text{ (stat.)} \pm 0.006 \text{ (syst.)} ,$$

where the systematic error reflects the uncertainty on the mass scale. Both results are in good agreement with the Standard Model value, $\rho = 1$.

4.14 The Decays $W, Z \rightarrow$ Two Jets

As we have seen in subsection 4.1, the W and Z bosons are expected to decay into $q\bar{q}$ pairs with calculable rates. These decays can be observed, in general, as two-jet final states. Examples of these decays are $W^+ \rightarrow u\bar{d}$ and $c\bar{s}$, and $Z \rightarrow u\bar{u}$, $d\bar{d}$, $c\bar{c}$, $s\bar{s}$, and $b\bar{b}$. Decays involving the t quark, if kinematically allowed, are expected to result in more than two jets because of the heavy t-quark mass.

Under the assumption that the decays which are kinematically allowed involve only the fermions belonging to the three known families, the branching ratios into two jets are expected to be between 55% and 66% for the W, and between 62% and 69% for the Z, depending on the mass of the t quark. However, in spite of such sizeable values, the observation of these decays is made difficult by the QCD background of two-jet final states from hard-parton collisions³³. In the region of the W and Z masses, this background consists mostly of gluon jets. This does not help, however, because at present there is no known method for distinguishing a gluon jet from a quark jet on an event-by-event basis.

Obviously, the signal-to-noise ratio depends on the two-jet mass resolution, because the QCD background has a smooth and rapidly falling distribution, whereas the two-jet invariant mass distribution from the decays of the W and Z is peaked at the mass values of these particles. For a mass resolution $\sigma_M \approx 8 \text{ GeV}/c^2$, which is relevant for the present UA1 and UA2 calorimeters, the signal-to-noise ratio is expected to be of the order of 1/100. In the ideal case of a perfect mass resolution it is dominated by the natural width of the W and Z bosons, and becomes $\approx 1/10$.

The signal-to-noise ratio can be optimized by suitably choosing the rapidity interval over which the two jets are observed, because the angular distribution for W and Z decay into $q\bar{q}$ has the form $1 + \cos^2 \theta^*$, whilst for hard collisions it is strongly peaked at forward angles³³. The signal-to-noise ratios quoted above correspond to the choice $|\eta| < 0.85$, which is well matched to the acceptance of the UA2 central calorimeter and is very close to the optimal value.

We note that the good agreement between the measured and predicted values of the cross-sections for W and Z production in $p\bar{p}$ collisions provides evidence for the validity of the Standard Model couplings of the intermediate bosons to $q\bar{q}$ pairs, which have been used to calculate the branching ratio values quoted above.

Results from a search for the decay of the W and Z particles into two jets have been reported by UA2³⁴. The data were collected at $\sqrt{s} = 630 \text{ GeV}$ and correspond to a total integrated luminosity of 730 nb^{-1} . The trigger for this search requires the presence of two jets at opposite azimuth in the central calorimeter, with a transverse energy threshold for each jet low enough (typically between 12.5 and 20 GeV) to ensure full efficiency in the W and Z mass regions. For lower masses, a measure of the trigger efficiency was obtained by comparing data taken at different thresholds.

The main concern of this search is to ensure that the jet energies are measured as well as possible. A source of measurement errors is the limited acceptance of the calorimeter, which covers the pseudorapidity interval $|\eta| < 1$ over the full azimuth. Jets close to the calorimeter edges, which might have been contained only partially, are rejected by requiring that the jet axis satisfy the condition $|\eta| < 0.85$.

To define the jet energy, a cone is constructed around the jet axis, and the energies deposited in the calorimeter cells within the cone are added together. We note that a large cone aperture ensures full jet containment, but adds to the jet the energies of the spectators which happen to fall within the cone. Hence for large cone apertures we expect, in general, $E(\text{cone}) > E(\text{jet})$. This inequality is particularly dangerous in the presence of a background which decreases rapidly as the energy of the jet increases, because low-energy jets, which are produced with large cross-sections, may be shifted to higher energies and therefore overwhelm the real, high-energy jets which are produced with smaller cross-sections.

For small cone apertures we expect, in general, that the reverse inequality holds: $E(\text{cone}) < E(\text{jet})$. It is possible, therefore, to find a cone aperture which optimizes the jet energy resolution. If ω is the half-aperture of the cone, the best resolution is found over the range $0.2 < \cos \omega < 0.6$, and the value $\cos \omega = 0.6$, which corresponds to the narrowest cone, is used.

Other important criteria for ensuring good mass resolution are the following:

- i) Jets with more than 4 GeV deposited in the region between two cones with $\cos \omega = 0.5$ and $\cos \omega = 0.7$ are rejected. This ensures that the jet is well contained within the cone.
- ii) The hadronic shower associated with each jet must be well contained in depth. In the UA2 central calorimeter, each cell consists of three independent compartments, and a jet is rejected if the energy fraction deposited in the third compartment exceeds a given threshold (typically set at 40%).
- iii) The total transverse momentum of the two-jet system must satisfy the condition $p_T < 24 \text{ GeV}/c$. This condition rejects events with a large p_T imbalance, which might be due to measurement errors.

All these requirements remove 34% of the events from the original sample. A further reduction of approximately 40% is obtained by requiring that the energy of all other particles not contained in the cones does not exceed 10 GeV in the central calorimeter and 6 GeV in the two forward ones. This condition ensures that the energy associated with the spectators is not too large, because it is conceivable that the jet energy measurement is less precise in 'noisy' than in 'quiet' events.

The selection criteria just described are meant to provide optimal energy resolution. However, it is plausible that they have had the effect of enriching the final sample in quark jets, because gluon radiation by gluons is more probable than gluon radiation by quarks, and, as a consequence, gluon jets are likely to be more affected than quark jets by the selection criteria.

The mass resolution for the final sample is estimated to be of the order of $8 \text{ GeV}/c^2$ for two-jet masses of $80 \text{ GeV}/c^2$, and $9 \text{ GeV}/c^2$ for masses of $90 \text{ GeV}/c^2$.

Figure 21 shows the two-jet mass distribution for the final sample. In order to remove most of the QCD fall-off, the data are multiplied by the factor M^5 . An almost constant statistical error is obtained for all data points by increasing the bin size as M increases.

Given the estimated mass resolution quoted above, the W and Z peaks are not resolved. However, a broad bump is visible in the expected region of the spectrum of Fig. 21.

A maximum-likelihood fit to these data is made by using the form

$$d\sigma/dM = A[M^{-\alpha} \exp(-\beta M) + xS(M)] \quad , \quad (17)$$

where the first term in the square brackets is meant to parametrize the QCD background. The second term (the signal) is the sum of two Gaussians and has the form

$$S(M) = \frac{1}{\sqrt{2\pi}} \left\{ \frac{1}{\sigma_W} \exp \left[-\frac{(M-m_W)^2}{\sigma_W^2} \right] + \frac{1}{3\sigma_Z} \exp \left[-\frac{(M-m_Z)^2}{\sigma_Z^2} \right] \right\} \quad ,$$

Fig. 21 Two-jet invariant mass distribution for events passing the UA2 selection criteria (see text). The distribution has been multiplied by the factor $(M/100)^5$ to make it less steep. The curves are results of the best fits to the QCD background alone (curve a), and by adding to it two Gaussians describing W and Z decays (curve b).

where the factor $1/3$ in front of the second Gaussian reflects the ratio of the Z to the W inclusive cross-section, as expected from the Standard Model.

In the fit, the free parameters are α , β , x , and m_W . For the mass resolution, fixed values of $\sigma_W = 8 \text{ GeV}/c^2$ and $\sigma_Z = 9 \text{ GeV}/c^2$ are used, as quoted above. The Z mass is taken to be $m_Z = 1.14 m_W$, in agreement with the mass measurements from the leptonic decay modes. For each set of parameters, the constant A in Eq. (17) is adjusted to provide the appropriate normalization.

The best-fit value of m_W is $82 \pm 3 \text{ GeV}/c^2$, in agreement with the value obtained from the decay $W \rightarrow e\nu$, and the integral of the signal term in Eq. (17) is found to correspond to 632 ± 190 events. This number is consistent with the number of events expected from the Standard Model after correcting for the acceptance and the efficiency of the selection criteria. It has a statistical significance which corresponds to 3.3 standard deviations. The result of the fit is shown as curve (b) in Fig. 21.

If the signal term is suppressed in Eq. (17), one obtains a poor fit to the data ($\chi^2 = 21.1$ for 12 degrees of freedom). If, however, the data points contained in the interval $65 < M < 105 \text{ GeV}/c^2$ are excluded, the fit becomes good ($\chi^2 = 4.7$ for 7 degrees of freedom), as shown by curve (a) in Fig. 21.

Other fits, using either a different parametrization of the QCD background or different data samples obtained by small changes of the selection criteria, always give a non-zero signal with a statistical significance which varies between 2 and 3.5 standard deviations.

This result is encouraging, in the sense that the data suggest the presence of a structure in the two-jet mass distribution, with the properties expected from the decay of the W and Z particles into $q\bar{q}$ pairs. However, the statistical significance of this structure is far from providing overwhelming evidence, and more data are needed to confirm it.

5. SEARCH FOR THE TOP QUARK

In the Standard Model, the top quark represents one of the missing pieces, the other one being the scalar Higgs boson. The first physics run at the e^+e^- machine Tristan³⁵ has set a new lower bound of 25 GeV for the t-quark mass, m_t , superseding the previous limit obtained at PETRA³⁶.

Within the Standard Model, the existence of the t quark prevents the occurrence of flavour-changing neutral-current transitions involving b quarks³⁷, such as the decay $B \rightarrow \mu^+ \mu^- + \text{anything}$. The experimental upper limit for the branching ratio of such a decay mode is³⁸ $\approx 10^{-3}$, implying that the t quark must exist.

At the CERN $\bar{p}p$ Collider, the main sources of t quarks are the decay $W^+ \rightarrow t\bar{b}$ (or $W^- \rightarrow \bar{t}b$), if kinematically allowed, and QCD production of $t\bar{t}$ pairs by gluon-gluon fusion or $q\bar{q}$ annihilation. Once produced, the t quark decays into an intermediate state consisting of a W and a b quark, which results in a final state

containing either three jets or one jet accompanied by a charged lepton (e or μ) and a neutrino. In view of the large background of multi-jet events from QCD processes, the only hope of discovering the t quark is to look for its semi-leptonic decay modes, which are expected to occur with a branching ratio of the order of $\approx 1/9$ for each charged lepton. The interesting final states consist, therefore, of an electron (or muon) and two more jets.

Figure 22 shows the expected number of events as a function of m_t , for a total integrated luminosity of 700 nb^{-1} , before applying any selection criteria (the value of 700 nb^{-1} corresponds roughly to the present UA1 data sample). The contribution from $W \rightarrow t\bar{b}$, which dominates in the m_t range between ≈ 40 and $\approx 80 \text{ GeV}$, can be precisely estimated, as a function of m_t , from the measured value of σ_W^0 (see sub-section 4.8), through the relation

$$\sigma(W \rightarrow t\bar{b}) = 3\sigma_W^0 \Phi(m_t) \quad ,$$

where $\Phi(m_t)$ is a known phase-space suppression factor³⁹, and the factor of 3 reflects the three possible colour states of the t quark.

On the contrary, the estimate of the $t\bar{t}$ contribution from QCD processes is affected by a rather large theoretical uncertainty, which results from uncertainties in the gluon and quark structure functions, as well as from ambiguities in the choice of the Q^2 scale and from the fact that a complete higher-order calculation is still missing. As a result, the $t\bar{t}$ contribution is affected by an uncertainty of roughly $\pm 50\%$. The curve of Fig. 22 has been obtained using the EUROJET program⁴⁰ with a specific choice of structure functions.

The search for the t quark at the CERN Collider has been pioneered by the UA1 Collaboration⁴¹, which has recently reported the result of a negative search in both the electron and the muon channel⁴².

Among the selection criteria used by UA1, a particularly important one is the requirement that the observed lepton be isolated, or, in other words, that there be no other high- p_T particle present within a relatively narrow cone around the lepton direction. This requirement reduces drastically the background from semileptonic decay of high-energy light quarks (b or c), because in this case the charged lepton is emitted at small angles to the other decay products. On the contrary, in the case of a heavy quark the decay products are emitted at large angles from each other because of the large mass value of the parent particle.

In the UA1 analysis, various sets of selection criteria are used, leading to samples of very few t-quark candidates, whose number is always consistent with the expected background. For example, in the muon channel the criteria $p_T^\mu > 12 \text{ GeV}/c$, $E_T(\text{jet } 1) > 15 \text{ GeV}$, $E_T(\text{jet } 2) > 7 \text{ GeV}$, $m_T(e\nu) < 40 \text{ GeV}$, together with the requirement that the muon be isolated, select a sample of only 10 events, with an estimated background of 11.4 ± 0.9 (stat.) ± 1.2 (syst.) events. The dominant contribution to this background comes from $b\bar{b}$ final states (6.6 events), and the rest is due to muons from π or K decay, and also to various sources of lepton pairs (W, Z, J/ψ , Υ , and the Drell-Yan continuum) produced in association with jets. It must be pointed out that

Fig. 22 The expected number of events with one semi-leptonic decay of a top quark ($t \rightarrow b e^+ \nu_e$ or $b \mu^+ \nu_\mu$) for an integrated luminosity equivalent to the total UA1 data sample (700 nb^{-1} , left scale), and for the data sample expected from future physics runs (10 pb^{-1} , right scale). The four main contributions to t production are shown separately as broken lines, and their sum is shown as a full curve. The production of $t\bar{t}$ pairs is calculated using the QCD program EUROJET⁴⁰. No selection criteria are applied to the events.

Fig. 23 a) Confidence level contours for the t -quark production cross-section versus the t -quark mass. The regions above the curves are excluded at 90% CL and 95% CL, respectively. The cross-section for $t\bar{t}$ pair production has been calculated using the QCD program EUROJET⁴⁰.

b) Sensitivity of the mass limit to the ratio $K = [\sigma(t\bar{t}) + \sigma(W \rightarrow t\bar{b})] / [\sigma_0(t\bar{t}) + \sigma(W \rightarrow t\bar{b})]$, where $\sigma_0(t\bar{t})$ is the lowest-order cross-section calculated using the structure functions of Eichten et al.⁴⁴ (set I) and the definition $Q^2 = m_t^2 + p_t^2$. The region above the curve labelled UA1 is excluded at the 95% CL. The choice of structure functions and Q^2 scale giving the lowest prediction is shown as a shaded curve.

the observation of non-isolated muons in the UA1 detector provides a way to measure directly the background from semileptonic decay of light quarks⁴³.

The negative result of the UA1 experiment is expressed as an upper limit for t -quark production as a function of m_t (see Fig. 23a). It appears from this figure that the possibility of discovering the t quark in the present event sample relies entirely on $t\bar{t}$ production, because the experimental upper limit lies above the $W \rightarrow t\bar{b}$ contribution for all values of m_t .

From Fig. 23a, the lower bound $m_t > 56$ GeV (95% CL) can be extracted. Such a bound, however, does not take into account the theoretical uncertainties in the QCD estimate of $t\bar{t}$ production. These uncertainties are illustrated in Fig. 23b, which displays the ratio of various theoretical estimates to the result of a lowest-order calculation which uses the parametrization of Eichten et al.⁴⁴ for the structure functions, with the choice $Q^2 = p_T^2 + m_t^2$ (the cross-section so obtained is called σ_0 in Fig. 23b). Also shown is the UA1 95% CL upper limit, divided by σ_0 . Clearly, depending on the particular theoretical estimate, it is possible to obtain lower bounds for m_t ranging between 44 GeV for the most pessimistic estimate, and 56 GeV for the EUROJET prediction⁴⁰, which, however, is the only one to include the effect of higher-order diagrams.

As a final result, the UA1 Collaboration prefers to quote the most pessimistic lower bound⁴²,

$$m_t > 44 \text{ GeV}.$$

This negative result puts the top quark beyond reach of the forthcoming Z factories, SLC, and LEP I.

6. SEARCHES FOR 'EXOTIC' PROCESSES

6.1 Search for Supersymmetric Particles

There are many theoretical speculations which predict the existence of a totally new class of phenomena beyond those expected within the framework of the Standard Model. Among these theories, great interest has been raised by the idea of supersymmetry⁴⁵ (SUSY), and the CERN $p\bar{p}$ Collider represents an obvious laboratory where a search can be made for the SUSY partners of the existing elementary particles.

In many models, the lightest SUSY particle is the photino, $\tilde{\gamma}$, which in this case is stable and does not interact appreciably with matter. As a consequence, the production of heavy SUSY particles will result, in general, in final states characterized by large values of p_T^{miss} . As discussed in subsection 4.7, a study of hadronic final states with large p_T^{miss} in the UA1 detector has led to the identification of a sample of $W \rightarrow \tau\nu_\tau$ decays, followed by the decay $\tau \rightarrow \nu_\tau + \text{hadrons}$. In the selected sample of

Table 5. Expected Number of Events with Large p_T^{miss} and $L_\tau < 0$ in UA1⁴⁶

Process	Number of events
$W \rightarrow \ell \nu (\ell \equiv e, \mu)$ $W \rightarrow \tau \nu \rightarrow \text{leptons}$ $W \rightarrow \tau \nu \rightarrow \nu \bar{\nu} + \text{hadrons}$	2.0
$Z \rightarrow \tau^+ \tau^-$	0.1
$Z \rightarrow \nu \bar{\nu} (N_\nu = 3)$	7.1
$c\bar{c}, b\bar{b}$ (QCD)	0.2
Jet measurement errors	3.4
Total	$20.8 \pm 5.1 \text{ (stat.)} \pm 1.0 \text{ (syst.)}$

56 events, however, 24 events had $L_\tau < 0$ and could not all be explained, therefore, in terms of $W \rightarrow \tau \nu_\tau$ decay¹³. The p_T^{miss} and jet transverse-energy (E_T^{jet}) distributions for these events are shown in Fig. 24.

There are many standard processes which may give rise to final states containing high- p_T hadronic jets with large values of p_T^{miss} . Such processes include the production of W or Z bosons in association with high- p_T jets, followed by the decay $W \rightarrow \ell \nu_\ell$, with the charged lepton undetected, or $Z \rightarrow \nu \bar{\nu}$. Table 5 shows the results of a Monte Carlo calculation⁴⁶ which takes all known sources into account. The sum of all contributions amounts to $20.8 \pm 5.1 \text{ (stat.)} \pm 1.0 \text{ (syst.)}$ expected events with $L_\tau < 0$, in agreement with the observation of 24 events. The predicted p_T^{miss} and E_T^{jet} distributions are also in agreement with the observed ones (see Fig. 24). Thus there is no need for new processes to explain the UA1 results.

By comparing the 24 events observed with the predicted number, an inclusive limit is derived by UA1⁴⁶ for the total cross-section σ of any new processes producing events with large values of p_T^{miss} and jets having $L_\tau < 0$. Such a limit is

$$\sigma\epsilon < 20 \text{ pb (90\% CL)} \quad , \quad (18)$$

where ϵ is the detection efficiency, which depends, of course, on the particular process being considered.

This limit can be used to obtain lower bounds for the mass values of squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), which can be strongly produced in $p\bar{p}$ collisions through the following processes:

$$p\bar{p} \rightarrow \tilde{g}\tilde{g} + \text{anything} \quad , \quad (19')$$

$$p\bar{p} \rightarrow \tilde{g}\tilde{q} (\tilde{g}\bar{\tilde{q}}) + \text{anything} \quad , \quad (19'')$$

$$p\bar{p} \rightarrow \tilde{q}\bar{\tilde{q}} + \text{anything} \quad , \quad (19''')$$

Fig. 24 Missing transverse energy (a) and jet transverse energy distribution (b) for the 24 UA1 events passing the cut $L_\tau < 0$, compared with the expected distributions (see Table 5).

with calculable cross-sections. In the case where $m(\tilde{q}) > m(\tilde{g})$, the squark decays into $q\tilde{g}$ and the gluino decays into $q\tilde{q}\tilde{\gamma}$; in the case where $m(\tilde{q}) < m(\tilde{g})$, the decay modes are $\tilde{q} \rightarrow q\tilde{\gamma}$ and $\tilde{g} \rightarrow \tilde{q}\bar{q}$ ($q\tilde{q}$). In both cases, the event topology consists of hadronic jets (from the fragmentation of the outgoing q and $\bar{q}$) and missing transverse momentum (from the outgoing $\tilde{\gamma}$'s).

Figure 25 shows the region of the $m(\tilde{q})$ vs. $m(\tilde{g})$ plane excluded by UA1⁴⁷ together with the region already excluded by lower energy experiments⁴⁸. In the case where $m(\tilde{g}) \gg m(\tilde{q})$, the lower bound $m(\tilde{q}) > 45$ GeV is obtained. Similarly, the bound $m(\tilde{g}) > 53$ GeV is obtained if $m(\tilde{q}) \gg m(\tilde{g})$. If, however, $m(\tilde{q})$ and $m(\tilde{g})$ are equal, the more stringent bound $m(\tilde{q}), m(\tilde{g}) > 75$ GeV is obtained, because in this case the expected number of events is increased by the contribution from reaction (19").

Supersymmetric leptons can be searched for among the W and Z decay products. The decay $W \rightarrow \tilde{e}\tilde{\nu}$, followed by $\tilde{e} \rightarrow e\tilde{\gamma}$, if energetically possible, will result in an event with an isolated electron and missing transverse momentum. However, both p_T^{miss} and p_T^e will tend to be softer than for the decay $W \rightarrow e\nu$, and the electron angular distribution will be very different. The p_T^e and angular distribution measured by UA1 (see subsections 4.2 and 4.5) are well described by standard processes only, enabling the exclusion of a region of the $m(\tilde{e}), m(\tilde{\nu})$ plane⁴⁹. Such a region is shown in Fig. 26, under the assumption that $m(\tilde{\gamma}) = 0$.

Another possible channel is the decay chain $Z \rightarrow \tilde{e}\tilde{e} \rightarrow e^+e^- \tilde{\gamma}\tilde{\gamma}$. In this case one would observe electron pairs with a large value of the total transverse momentum, because, for small values of p_T^Z (as is generally the case), the large $\vec{p}_T^{\text{miss}}$ carried by the two $\tilde{\gamma}$'s is approximately balanced by the transverse momentum of the pair. Hence a search for this decay mode can be performed in the UA2 detector, despite the rather poor measurement of $\vec{p}_T^{\text{miss}}$ (see Section 3).

Figure 27 shows the distribution of electron-pair candidates, as measured by UA2⁵⁰, in the M_{ee}, p_T^Z plane, where M_{ee} is the invariant mass and p_T^Z is the orthogonal component of the total transverse momentum of the pair which is measured with the highest accuracy. For $M_{ee} > 10$ GeV, a total of 57 events is observed. The contribution from the conventional decay $Z \rightarrow e^+e^-$ is clearly visible in the high-mass region of this plot (we note, however, that the number of events is lower than that given in Section 4.10, because of the tighter selection criteria used here). Also shown is the region where one expects $\approx 75\%$ of the electron pairs from the decay $Z \rightarrow \tilde{e}\tilde{e}$. Most of the events with $M_{ee} < 70$ GeV have small values of p_T^Z , as expected for pairs from Drell-Yan continuum and hadronic backgrounds. The limit obtained from this plot is shown in Fig. 28a as a 90% CL contour in the $m(\tilde{e}), m(\tilde{\gamma})$ plane, together with the contours of the regions excluded by e^+e^- experiments⁴⁸. It can be clearly seen that, in this case, the UA2 limit does not improve the results already obtained by the e^+e^- machines.

The plot of Fig. 27 can also be used to extract a limit for the mass of the supersymmetric partner of the W boson, $\tilde{W}$, under the assumption that the decay $Z \rightarrow \tilde{W}^+\tilde{W}^-$ is energetically possible⁵⁰. In this case one again expects to observe e^+e^- pairs with large values of the total transverse momentum from the decay $\tilde{W} \rightarrow e\tilde{\nu}$, where the $\tilde{\nu}$ escapes detection (stable $\tilde{\nu}$ or $\tilde{\nu} \rightarrow \nu\tilde{\gamma}$).

Fig. 25 Limits (at 90% CL) on $\tilde{q}$ and $\tilde{g}$ masses from the UA1 experiment⁴⁷. The arrows indicate the asymptotic value of the contour as $m(\tilde{q})$ and $m(\tilde{g})$ become infinitely large.

Fig. 26 Constraints on $\tilde{e}$ and $\tilde{\nu}$ masses from a search for the decay chain $W \rightarrow \tilde{e} \tilde{\nu} \rightarrow e \tilde{\nu} \gamma$ in the UA1 experiment⁴⁹.

Fig. 27 Distribution of electron-pair mass, M_{ee} , versus the best measured component of the total transverse momentum of the pair, p_T^γ , for a sample of 57 events in the UA2 experiment⁵⁰. Also shown (within dashes) is the region where most of the electron pairs from $Z \rightarrow e\bar{e}$ or $Z \rightarrow W^+W^-$ are expected.

Fig. 28 UA2 limits⁵⁰ on $\tilde{e}$ and $\tilde{\tau}$ masses (a), and on $\tilde{W}$ and $\tilde{\nu}$ masses (b), shown as 90% CL contours. The dashed area illustrates the systematic uncertainty. Also shown (broken curves) are the most recent limits from a variety of e^+e^- experiments⁴⁸.

The region of the $m(\tilde{W}), m(\tilde{\nu})$ plane excluded by UA2 is shown in Fig. 28b, together with the results from searches at e^+e^- machines⁴⁸. In this case, the UA2 result improves significantly on the e^+e^- limits.

The more stringent bound obtained on $m(\tilde{W})$, with respect to $m(\tilde{e})$ (see Fig. 28a), is the result of the stronger Z coupling to a $\tilde{W}^+\tilde{W}^-$ pair than to $\tilde{e}^+\tilde{e}^-$. Neglecting phase-space suppression factors, one would expect $\Gamma(Z \rightarrow \tilde{W}\tilde{W})/\Gamma(Z \rightarrow \tilde{e}\tilde{e}) \approx 18.4$, thus explaining the difference between Figs. 28a and 28b. It must also be noted that these two results are obtained under the assumption that the two decay modes $Z \rightarrow \tilde{e}\tilde{e}$ and $Z \rightarrow \tilde{W}\tilde{W}$ are not both energetically possible.

6.2 Search for Excited Electrons

Excited electrons are expected in models in which leptons are composite particles⁵¹. If such states, e^* , do indeed exist, they decay into an electron and a photon, hence a suitable channel to search for these particles at the $p\bar{p}$ Collider is the decay chain $W \rightarrow e^*\nu \rightarrow e\gamma\nu$.

In the UA2 detector, isolated photons are identified by the expected properties of the electromagnetic shower in the calorimeter, the absence of charged-particle tracks pointing to the energy cluster, and the observation of a possible conversion in the preshower counter (see section 2). No event having $p_T^e > 11$ GeV/c, $p_T^\gamma > 10$ GeV/c and $p_T^{\text{miss}} > (m_W - m^*)/4$ is observed⁵⁰ (m^* is the invariant $e\text{--}\gamma$ mass), whereas more than 95% of the events originating from the decay chain $W \rightarrow e^*\nu \rightarrow e\gamma\nu$ are expected to satisfy these requirements for $m^* \geq 20$ GeV.

To interpret this negative result, it is assumed that the W couples to the transition magnetic moment of the $e^*\nu$ current, thus producing an effective gauge-invariant Lagrangian, which has the form

$$\mathcal{L} = (g/\sqrt{2})(\lambda/m^*)W_\alpha e^{*\sigma^{\alpha\beta}}q_\beta\nu_L + \text{h.c.} \quad ,$$

where $g = e/\sin\theta_W$, λ represents the coupling strength, and m^* is the mass of the excited electron. The assumptions made to derive this form have also been used to predict the production of excited electrons at e^+e^- machines⁵².

Figure 29 shows the region of the $\lambda\text{--}m^*$ plane which is excluded at the 95% CL by the absence of observed events, together with the most stringent limits obtained at e^+e^- machines^{48,52}.

6.3 Search for Heavy Leptons

The UA1 limit [Eq. (18)] has been used to provide a lower bound to the mass value, m_L , of a possible sequential charged lepton, L. In the case where $m_L + m(\nu_L) < m_W$, the decay $W \rightarrow L\nu_L$ is energetically possible and occurs at a calculable rate. The heavy lepton then decays into ν_L and a quark-antiquark pair ($u\bar{d}$ or $c\bar{s}$ from L^+ , $\bar{u}d$ or $\bar{c}s$ from L^-), resulting in final states which contain one or two energetic jets in association with large missing transverse momentum.

Fig. 29 UA2 limits on excited electrons⁵⁰, shown as the 95% CL contour in the λ - M^* plane (see text). Also shown is the most recent limit⁵² from $e^+ e^-$ experiments.

As discussed in subsection 6.1, there is no evidence for any unconventional source of such events in the UA1 data, and the statistical upper limit on the number of events expected from an additional lepton family sets the lower bound⁴⁶ $m_L > 41$ GeV at the 90% CL, under the assumption that $m(\nu_L) = 0$.

It must be pointed out that, if additional fermion families exist, the rate of events containing the invisible decay $Z \rightarrow \nu\bar{\nu}$ is larger than the standard value with $N_\nu = 3$. If the Z is produced in association with an energetic hadronic jet, such events are expected to appear as hadronic events with large values of p_T^{miss} . In the region $E_T^{\text{jet}} < 40$ GeV, $L_\tau < 0$ (see subsection 6.1), 1.8 events are expected in the UA1 data sample for each neutrino type⁴⁶, under the assumption that $m(\nu) = 0$, and a comparison with the observed number of events provides the limit $N_\nu \leq 10$ at the 90% CL.

We finally note that, in deriving the lower bound $m_L > 41$ GeV discussed above, the value $N_\nu = 4$ was assumed for consistency.

7. THE FUTURE OF THE CERN $\bar{p}p$ COLLIDER

7.1 Machine Improvements

In October 1983 a design study was prepared proposing an upgrade of the $\bar{p}$ production facility, with the aim of increasing the $\bar{p}$ accumulation rate by a factor of 10. This project, called the Antiproton Collector (ACOL), was approved in January 1984.

The ACOL project consists of three parts⁵³:

- i) A new $\bar{p}$ target area, with a new $\bar{p}$ focusing device based on a lithium lens⁵⁴.
- ii) A new ring (designated as AC in Fig. 30), built around the existing AA. The AC ring accepts 3.5 GeV/c $\bar{p}$'s from the production target, with a momentum spread of $\pm 3\%$ and an angular divergence of 100 mrad. These $\bar{p}$'s ($\approx 10^8$ per pulse, compared with 6×10^6 $\bar{p}$ per pulse injected into the AA during previous operation) are debunched and precooled in the AC ring in about 2 s, then transferred to the AA ring, which will only be used, therefore, as a storage ring where the accumulated $\bar{p}$ stack undergoes continuous cooling.
- iii) A completely new stochastic cooling system in the AA, to accommodate the more than tenfold increase in $\bar{p}$ flux.

Altogether, these improvements are expected to increase the maximum $\bar{p}$ stack from 5×10^{11} $\bar{p}$'s accumulated over ≈ 100 hours, to 10^{12} $\bar{p}$'s accumulated over ≈ 10 hours, with an $\approx 30\%$ higher phase-space density.

An obvious advantage is that, in the case of an accidental beam loss, a new $\bar{p}$ stack can be quickly made available for injection into the SPS.

In order to exploit fully the new $\bar{p}$ source, the following improvements are being implemented in the SPS:

Fig. 30 A view of the upgraded $\bar{p}$ source at CERN, with the new Antiproton Collector (AC) ring surrounding the Antiproton Accumulator (AA).

- i) a new operation mode with six p and six $\bar{p}$ bunches, instead of the three bunches used previously;
- ii) a modification of the RF system, to accept longer, and, therefore, more intense bunches at injection.

Altogether, the improvements to the $\bar{p}$ source and to the SPS will result in a peak luminosity of $\approx 4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, which is a factor of 10 higher than the maximum luminosity achieved so far.

The first Collider run which includes operation of the AC ring has started in November 1987. The main data-taking period is foreseen to take place between September 1988 and July 1989.

7.2 Improvements to the UA1 Detector

The major improvement to the UA1 detector⁵⁵ is the replacement of both large-angle and end-cap electromagnetic calorimeters (see section 2) by a high-granularity ionization calorimeter consisting of uranium plates as the passive material, and tetramethyl-pentane (TMP) as the sensitive medium. This calorimeter consists of 4250 cells, each subtending an angle $\Delta\theta \times \Delta\phi = 5^\circ \times 6^\circ$. The use of uranium allows ≈ 2.6 interaction lengths to be accommodated in the space occupied by the old calorimeter, so that the new calorimeter also has the function of a partial hadronic calorimeter.

Tetramethyl-pentane is a room-temperature liquid which, if pure enough, is characterized by an electron lifetime of several microseconds, so that all electrons from the primary ionization may drift in the liquid and may be collected by appropriate electrodes parallel to the U plates. This technique avoids the need for a detailed calibration of each cell, and ensures uniform response as a function of the impact point. An obvious alternative would have been to use liquid argon; however, this choice was rejected because of the dead spaces imposed by the cryogenics.

The electromagnetic section of this calorimeter consists of 2 mm U plates, and is subdivided longitudinally into four sections of 3, 6, 9, and 6 radiation lengths, whilst the hadronic part has 5 mm thick U plates and two samplings.

A critical question is the stability of the electron lifetime, which is related to the purity of the liquid. A test calorimeter using 4 mm thick U plates has been built and exposed to particle beams over a period of 40 days. Its pulse height has been found to be constant at a percent level over this period. Its linearity has been verified using electron beams of energies between 10 and 70 GeV, and its energy resolution has been found to be $\sigma/E \approx 0.2/\sqrt{E}$ (E in GeV). Later, a second test calorimeter with 2 mm thick U plates has given the expected resolution, $\sigma/E \approx 0.14/\sqrt{E}$ (E in GeV).

Further improvements to the UA1 detector are as follows:

- i) The addition of 60 cm of magnetized iron on the magnet sides, and of 1 m of non-magnetized iron at the front, corresponding to a total of 9 and 14 hadronic interaction lengths, respectively. Planes of limited-streamer tubes (a total of $\approx$

50,000 tubes) and additional forward drift chambers, have already been installed⁵⁶, providing muon detection from 15° to 165° with respect to the beam.

- ii) The construction of a new data-acquisition system to cope with the tenfold increase of the collision rate expected with ACOL. This system allows for sophisticated trigger algorithms, which are needed to reduce the trigger rate while at the same time being fully efficient for the events of interest.
- iii) The installation of a microvertex detector, which is a high-precision tracking device surrounding the vacuum chamber, in order to detect unstable particles (such as b mesons), decaying at distances of the order of a millimetre from the collision point.

7.3 Improvements to the UA2 Detector

A view of the upgraded UA2 detector⁵⁷ is shown in Fig. 31a. The forward magnetic detectors have been replaced by end-cap calorimeters down to an angle of 6° to the beam axis. These calorimeters contain both an electromagnetic (lead/scintillator) and a hadronic (iron/scintillator) compartment, and each cell has a size $\Delta\eta \times \Delta\phi \approx 0.1^\circ \times 15^\circ$, which is similar to that of the central calorimeter.

The main purpose of this modification is to improve the capability of the detector to identify neutrinos and other possible non-interacting particles by measuring the missing transverse energy. In the previous detector configuration, such a measurement was affected by the incomplete coverage below 40° .

Tracking and preshower chambers, consisting of proportional tubes, are installed in front of the end-cap calorimeters.

The cylindrical tracking detector, which fits inside the central calorimeter and covers the polar angle region down to 20° to the beam axis (see Fig. 31b) is totally new and consists of the following items:

- i) A cylindrical drift chamber providing 13 space-points for each charged-particle track.
- ii) A cylinder of 3024 silicon counters, each 40 mm by 8.7 mm. These counters provide a measurement of the energy loss by ionization, with the main purpose of identifying single, high-energy electrons against a background of doubly ionizing, unresolved e^+e^- pairs from photon conversion.
- iii) Two transition radiation detectors (TRDs), each consisting of a radiator and an X-ray detector. Transition radiation is produced when a charged particle passes through a region of rapidly changing refractive index, and the production rate is proportional to the γ -factor of the particle⁵⁸. This form of radiation thus forms the basis of an efficient detection of high-energy electrons. Each radiator consists of ≈ 400 , 20 μm thick, polypropylene foils, 200 μm apart. When an electron passes through the radiator, X-rays are produced with a mean energy of 6 keV, and are detected in a xenon-filled proportional chamber.
- iv) A new type of tracking detector, consisting of 24 cylindrical layers of scintillating optical fibres, arranged in eight triplets. Each triplet has a layer of fibres parallel to the beam axis, and the other two layers at $\pm 15^\circ$ or $\pm 21^\circ$ to it, in order to provide stereo reconstruction. The fibres (a total of $\approx 60,000$) are 2.1 m long and

Fig. 31 a) View of the upgraded UA2 detector along the beam axis; b) Details of the upgraded central detector.

have a diameter of 1 mm (the total length of fibre amounts to ≈ 150 km). Within the angular range covered by the central calorimeter, a lead converter is inserted before the last two triplets, which therefore act as a preshower counter. Fibres are read out at one end by image intensifiers and charge-coupled devices which, by means of suitable electronics, measure the amount of light delivered by each fibre.

- v) As is the case for UA1, UA2 also has a totally new triggering and data-acquisition system to cope with the increased collision rate expected with ACOL.

The upgraded UA2 detector is fully assembled and has taken data during the first ACOL run at the end of 1987.

7.4 Physics Expectations

During the main running period, between September 1988 and July 1989, the two experiments, UA1 and UA2, are expected to collect data samples corresponding to an integrated luminosity of at least 10 pb^{-1} , a more than tenfold increase over the present statistics. It is useful, therefore, to discuss some of the physics subjects that can be studied at the improved Collider, taking into account the upcoming competition with the Tevatron collider at Fermilab, which operates at $\sqrt{s} = 1.8 \text{ TeV}$.

7.4.1. Search for the t Quark

The expected number of events containing at least one semileptonic decay of the t quark is shown in Fig. 21 for a total integrated luminosity of 10 pb^{-1} . A straightforward extrapolation of the present UA1 result⁴² (see Section 5) suggests that the upgraded UA1 detector should be able to detect the t quark up to mass values as large as 75 GeV. A large fraction of these events would result from the decay $W \rightarrow t\bar{b}$ (see Fig. 21), with the advantage that the cross-section for this process is known.

In the upgraded UA2 detector, the rejection against hadrons simulating high- p_T electrons is greatly improved (by at least a factor of 20) with respect to the performance of the previous detector, thus making the search for t quarks possible. For $m_t = 40 \text{ GeV}$, ≈ 70 events containing the decay $t \rightarrow b\ell\nu$ are expected for an integrated luminosity of 10 pb^{-1} , above a background of ≈ 10 events. The corresponding numbers for $m_t = 60 \text{ GeV}$ are ≈ 20 and ≈ 4 events, respectively. For $m_t = 40 \text{ GeV}$, the contributions from $W \rightarrow t\bar{b}$ and $t\bar{t}$ productions are roughly equal, while at $m_t = 60 \text{ GeV}$ $t\bar{t}$ production represents only $\approx 25\%$ of the total event rate.

As m_t approaches m_W , the event rate drops and the distribution of the invariant mass of the $\ell\nu$ pair from $t \rightarrow b\ell\nu$ decay ($\ell \equiv e$ or μ) develops a peak near the upper end of the spectrum as the effect of virtual W exchange between the quark and lepton currents. For the same reason, the energy of the jets associated with the outgoing b and $\bar{b}$ quarks decreases. Thus, as m_t increases, it becomes increasingly difficult to distinguish the $W \rightarrow t\bar{b}$, $t \rightarrow b\ell\nu$ decay chain from W production in association with jet(s), followed by the decay $W \rightarrow \ell\nu$. However, by the same argument the QCD process of $t\bar{t}$ production will result in final states containing an $\ell\nu$ and a two-jet pair with invariant mass values very close to m_W , and actually equal to m_W if $m_t > m_W$.

The expected number of $t\bar{t} \rightarrow WW b\bar{b}$ events, with $WW \rightarrow \ell\nu j_1 j_2$, is shown in Fig. 21 for a total integrated luminosity of 10 pb^{-1} . Such a number is very small, even if both types of charged leptons are detected, as is the case in UA1. A background to these final states is QCD production of a single W in association with two high- p_T jets having $M(j_1 j_2) \approx m_W$ within the measurement errors. Thus the only way to detect $t\bar{t}$ production in the case $m_t \geq m_W$ is to observe an accumulation of $\ell\nu j_1 j_2$ events at $M(j_1 j_2) = m_W$, having at the same time a value of the $\ell\nu$ transverse mass consistent with $W \rightarrow \ell\nu$ decay.

At the Fermilab collider ($\sqrt{s} = 1.8 \text{ TeV}$), the signal-to-noise ratio in the $W \rightarrow t\bar{b}$ channel is less favourable than at $\sqrt{s} = 630 \text{ GeV}$, because the cross-sections of all QCD processes contributing to the background increase with $\sqrt{s}$ more rapidly than does the cross-section for inclusive W production (the latter increases only by a factor of 3 from $\sqrt{s} = 0.63 \text{ TeV}$ to 1.8 TeV). However, by the same argument the cross-section for $t\bar{t}$ production¹⁹ is much larger at $\sqrt{s} = 1.8 \text{ TeV}$ than at 0.63 TeV (see Fig. 32). Thus, if $m_t \geq m_W$, and for a total integrated luminosity of 10 pb^{-1} , experiments at the Fermilab collider should be sensitive to the t quark up to mass values of the order of 180 GeV .

7.4.2. Precision Measurement of the IVB Masses

As discussed in subsection 4.13, a precision measurement of the IVB masses represents an important test of the Standard Model. Such a measurement should be precise enough to be sensitive to the radiative correction parameter Δr [see Eqs. (12) and (12')], whose value depends, in particular, on the mass splitting between fermions belonging to the same isodoublet, and thus on the mass of the t quark. We have also seen that the present measurements cannot even test the presence of Δr , because of the large errors involved (see Fig. 18).

For an integrated luminosity of 10 pb^{-1} , $\approx 3000 W \rightarrow e\nu$ and $\approx 300 Z \rightarrow e^+e^-$ events are expected in each of the two experiments, of which $\approx 80\%$ will be useful to measure m_W and m_Z . A straightforward scaling of the statistical error with the inverse square root of the number of events gives a statistical error of $\pm 0.3 \text{ GeV}$ for m_Z .

To determine m_W from a high-statistics sample of $W \rightarrow e\nu$ decays, the most accurate method is a fit to the electron transverse momentum distribution, dn/dp_T^e , which, contrary to dn/dm_T , is not affected by possible systematic uncertainties in the measurement of p_T^e . The uncertainty on the W transverse momentum, p_T^W , which affects dn/dp_T^e (see subsection 4.3), is greatly reduced by measuring the distribution of p_T^Z accurately from the $Z \rightarrow e^+e^-$ sample, and using this distribution in the place of dn/dp_T^W (QCD calculations⁸ show that the p_T^W and p_T^Z distributions are practically identical).

Other uncertainties are related to the W width, Γ_W , and to the electron energy resolution. The width Γ_W will be determined from the measured ratio Γ_W/Γ_Z [see subsection 4.12, Eq. (8)], using the value of Γ_Z as measured with an error of $\pm 30 \text{ MeV}$ at the forthcoming Z factories²⁵ (SLC, LEP). Finally, the electron energy resolution can be determined from the shape of the Z peak in the e^+e^- invariant mass distribution. From these arguments, it should be possible to measure m_W with a statistical error of $\pm 0.25 \text{ GeV}$.

Fig. 32 Cross-section for inclusive production of a heavy quark-antiquark pair, as predicted¹⁹ by QCD. The arrows show the cross-section for Standard Model production of $W^+ W^-$ pairs from $q\bar{q}$ interactions at the two energies.

Fig. 33 Expected precision in the knowledge of m_W and m_Z after the completion of the next round of Collider experiments with ACOL, and following a precision measurement of m_Z at e^+e^- machines. The horizontal error bar assumes that the UA1 and UA2 results are statistically combined. The exact position of the measured point in the m_W, m_Z plane is arbitrary.

Since it is not possible to reduce the systematic error on the mass values which results from the uncertainty in the calorimeter calibration, much below 1%, the uncertainty on m_W and m_Z will then be dominated by this error, which is still too large to provide any meaningful determination of Δr . However, as discussed in subsections 4.3 and 4.4, such an error cancels in the ratio m_W/m_Z , which will be measured, therefore, with an error of ± 0.004 , thus providing a determination of $\sin^2 \theta_w$ [see Eq. (11)] with an uncertainty of ± 0.007 .

From the measured ratio m_W/m_Z , and using the value of m_Z as measured at e^+e^- machines⁵⁹ with an uncertainty of ± 50 MeV, it is possible to determine m_W with a statistical error of ± 0.4 GeV and no systematic error. A further reduction of this error by $\sqrt{2}$ is achieved by combining statistically the UA1 and UA2 results.

The knowledge of m_W and m_Z which is expected by 1990, following the completion of the collider experiments and after the first physics runs of the e^+e^- machines at the Z pole, is summarized in Fig. 33. The improvement with respect to the present situation (Fig. 18) is dramatic. Such measurements will provide a stringent test of the Standard Model, if the t-quark mass, m_t , is known, or, alternatively, they will tell us where the t quark is, if at that time it has not yet been discovered.

As mentioned earlier, the W and Z production rate at the Fermilab collider is higher than at CERN by a factor of 3. However, while the m_Z measurement benefits directly from this factor, this is not the case for the W, because $\langle p_T^W \rangle$ is expected to be⁸ of the order of 15 GeV at $\sqrt{s} = 1.8$ TeV, twice as much as at $\sqrt{s} = 0.63$ TeV. This has the effect of smearing the Jacobian peak in the p_T^e distribution (see subsection 4.1), thus making the statistical error substantially larger (by about a factor of 2 for the same number of $W \rightarrow e\nu$ events).

7.4.3. Search for Heavy Leptons

A search for a possible sequential lepton belonging to the fourth generation, $L^\pm$, has been described in subsection 6.3. The present UA1 bound⁴⁶, $m_L > 41$ GeV (90% CL) can easily be extrapolated to an integrated luminosity of 10 pb^{-1} . Both UA1 and UA2 should be sensitive to leptons with mass values as high as 70 GeV, very close to the maximum allowed in W decay.

7.4.4. Search for Supersymmetric Particles

As an illustration of the potentiality of the improved $p\bar{p}$ Collider in searching for supersymmetric particles, we consider the case of equal $\tilde{q}$ and $\tilde{g}$ masses. The total cross-section for $\tilde{q}$ or $\tilde{g}$ production, summed over all possible channels⁴⁴, is of the order of 10 pb for $m(\tilde{q}, \tilde{g}) = 100$ GeV. Studies made for the upgraded UA2 detector suggest that this experiment should be sensitive to $\tilde{q}$ and $\tilde{g}$ masses below 120 GeV, whereas the detectors at the Tevatron collider should reach $\tilde{q}$ and $\tilde{g}$ masses of ≈ 200 GeV, showing the advantage of higher $\sqrt{s}$ values in searches for heavy particles.

7.4.5 Higgs Production

There is little hope of discovering the neutral Higgs boson, H, at the present colliders, even in the case of an integrated luminosity as high as 10 pb^{-1} . The

dominant mechanism for H production is gluon-gluon fusion via a heavy-quark loop⁴⁴, from which observable rates are predicted for $m_H \leq 50$ GeV. The H boson decays into a $b\bar{b}$ pair (if $m_H \geq 10$ GeV), resulting in two-jet final states. However, the background from hadronic jets is huge (about five orders of magnitude stronger than the $H \rightarrow b\bar{b}$ signal), thus precluding the observation of a peak in the two-jet invariant mass, even using b-quark tagging techniques based on the identification of the b-decay vertex.

A better signal-to-noise ratio is expected from the so-called bremsstrahlung mechanism⁶⁰, which consists of the associated production of the H boson with either a virtual or a real IVB. For $\sqrt{s} \leq 2$ TeV, this mechanism gives a smaller cross-section than gluon-gluon fusion, predicting observable yields up to $m_H \approx 30$ GeV. However, the background from multi-jet events is again overwhelming, and the only practical way to reduce it to a tolerable level is to require H production in association with a real Z, followed by the decay $Z \rightarrow \ell^+ \ell^-$ ($\ell \equiv e$ or μ). In this case the background is greatly reduced, but so is the event rate (by about an order of magnitude), reducing the highest observable m_H value to slightly above 10 GeV.

As shown elsewhere⁶¹, a Higgs boson with a mass of less than 50 GeV should be easily observable above background at the SLC or LEP.

8. CONCLUSIONS

The event samples collected by the UA1 and UA2 experiments at the CERN $p\bar{p}$ Collider from 1982 to 1985 have produced many important physics results, all in agreement with the Standard Model, and have at the same time imposed constraints on possible theoretical extensions of this model.

Over the next two years, the upgraded experiments will collect data samples corresponding to an integrated luminosity of 10 pb^{-1} , which represents a more than tenfold increase over the present samples. The analysis of these samples will provide more stringent tests of the Standard Model, through a precise measurement of the ratio m_W/m_Z , coupled with the measurement of m_Z at the forthcoming e^+e^- machines. It is also hoped that evidence for the top quark will be found in these data, as well as hints for new phenomena. It should be kept in mind, however, that the larger $\sqrt{s}$ value available at the Tevatron collider represents a great advantage in searches for new states with masses above 100 GeV.

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