PERSPECTIVE OF THE UPGRADED UA2 DETECTOR
AT THE IMPROVED CERN $p\bar{p}$ COLLIDER

L. Mapelli
CERN, Geneva, Switzerland

ABSTRACT

In order to fully exploit the physics potentials of the improved CERN $p\bar{p}$ Collider, the UA2 detector has been substantially upgraded. This paper reviews the motivations and the main aspects of such improvements and the physics that we intend to address with the new detector. Some of the physics perspectives discussed are compared with the results obtained at the CERN $p\bar{p}$ Collider in previous runs and with the expectations from the FNAL $p\bar{p}$ Collider. The first data taken with the new UA2 detector in November–December 1987 are also discussed briefly.

Paper presented at
Les Rencontres de Physique de la Vallée d’Aoste,
La Thuile, 1 March 1988
INTRODUCTION

The success of the $p\bar{p}$ Collider program at CERN [1] in the years 1981–1985 has made a contribution of fundamental importance to the field of particle physics. The discovery of the intermediate vector bosons (IVBs) $W$ and $Z$ [2], carriers of the electroweak force, has given confirmation to the validity of the Standard Model of Glashow, Weinberg, and Salam [3] for the unification of the electromagnetic and weak forces. Furthermore, the observation of hadronic jets [4], produced by the interaction of the proton and antiproton constituents, has opened the way to important studies of hard parton scattering [5].

Encouraged by such achievements and motivated by equally exciting physics topics still unrevealed but possibly within reach (the top-quark and supersymmetry searches are just prominent examples), CERN has undertaken an important upgrading of the $p\bar{p}$ Collider complex [6]. The installation of a new lithium lens [7], the separation of the antiproton collection and accumulation phases in two separate rings (the AC and AA), and the ‘six-bunch’ operation of the $p\bar{p}$ Collider will provide a tenfold increase in the $p\bar{p}$ luminosity, reaching $4 \times 10^{30}$ cm$^{-2}$ s$^{-1}$.

In order to fully exploit the physics potentials of the upgraded Collider, substantial upgrades of both the UA1 and UA2 detectors [8, 9] were approved. This paper will review, in Section 2, the motivations and the main aspects of the upgraded UA2 detector (for convenience, we will refer to it simply as UA2'). Preliminary results on the performance of UA2 during the first run in November–December 1987 are also reported in Section 2. The physics that UA2' intend to address is discussed in: Section 3 (topics related to the Standard Model); Section 4 (minimal extension to the Standard Model); Section 5 (search for Exotics); and Section 6 (QCD measurements). Some of the physics perspectives discussed will also be compared with the results reached so far at the CERN Collider and with the expectations from the $\sqrt{s} = 1.8$ GeV $p\bar{p}$ Collider at FNAL (the Tevatron).

THE UPGRADING OF UA2

The main motivations for the upgrading of the UA2 detector were i) a better electron identification in the central region, and ii) a better ‘neutrino’ identification through an improved missing transverse momentum measurement.

Many of the solutions adopted have been constrained by the tight schedule imposed by the improvement program for the $p\bar{p}$ complex and the need to be ready with the full configuration for the starting of the improved machine. All the detectors of the substantially modified apparatus have been successfully operational through the whole $p\bar{p}$ running period in November and December 1987.

A detailed description of the upgraded UA2 detector can be found elsewhere [10]. Only the general features are outlined here, together with preliminary indications of the performance during the first data-taking period.

2.1 Electron identification

The major difficulty in improving the electron identification in the central region of UA2 was the limited space available, defined by the central calorimeter (CC) edges [9] and almost entirely occupied by multiwire proportional and drift chambers for track-finding and vertex reconstruction.

It was only with the development of a scintillating-fibre detector [11], providing 18 points in three projections in a radial space of less than 4 cm, that enough room could be made for the introduction of transition radiation detectors, which, together with a silicon hodoscope, constitute the ‘atouts’ of the improved electron identification in UA2’. The resulting rejection power against hadrons is expected to increase by a factor of at least 20 with respect to UA2, as measured with electron and pion beams.

Figure 1 outlines the different detector configurations in the central region of UA2 (Fig. 1a) and UA2’ (Fig. 1b). The latter consists of the following units:
- A cylindrical drift chamber of the ‘jet type’ [Jet Vertex Detector (JVD)] to measure tracks close to the vertex. It surrounds a beryllium beam-pipe of 35 mm radius and extends to 135 mm. It consists of 16 azimuthal sectors, each with 13 sense wires parallel to the beam to measure $R \times \phi$ (Fig. 2). The outer cathode is divided into 160 strips perpendicular to the wires and measures the $z$-coordinate of the pulse induced by the outermost sense wires. Both wires and strips are equipped with 100 MHz FADCs [12] to give precise reconstruction of the pulse shape. The wires are read at both ends, thus providing a second $z$ measurement via charge division. From test-beam results the resolution of the JVD is expected to be about 0.15 mm in $R \times \phi$ and 1 cm in $z$ from charge division (the strips give 1 mm on the outer layer); with the present level of calibration, the resolution on Collider data is 0.35 mm and 3 cm, respectively.

- A silicon hodoscope [13] made of 3024 high-resistivity pads, supported by a carbon fibre cylinder of 140 mm radius. The size of each pad is $\Delta \phi \times \Delta z = 15^\circ \times 8.7$ mm; the area of the detector is about 1 m$^2$. The typical pulse height of a minimum-ionizing particle is about 260 ADC counts above the pedestal, whose spread has a sigma of 21 ADC counts. The main functions of the silicon hodoscope are the rejection of gamma-conversion by $dE/dx$ measurement, and the removal of ‘ghost’ tracks. The behaviour of the silicon detector during the 1987 run is shown in Fig. 3, where the pulse-height distribution of pads traversed by reconstructed tracks from a minimum-bias trigger is compared with test-beam data.

- A scintillating-fibre detector (SFD) [11] provides track segments and the start of electromagnetic showers in front of the CC. It consists of about 60,000 polystyrene fibres, 1 mm in diameter, doped with butyl-PBD and POPOP to produce scintillation light. They are arranged in 24 coaxial cylindrical layers forming 8 stereo triplets. The detector has an inner radius of 380 mm and extends close to the CC at a radius of 440 mm. The active length of the detector is 2.1 m along the beam. A lead converter, 1.5 radiation lengths thick, is inserted before the last two stereo triplets, all along the angular range covered by the CC. The stereo angle for the ‘tracking’ triplets is 15.75$^\circ$, whilst for the ‘preshower’ ones it is 21$^\circ$. The 60,000 fibres are read via 32 readout chains, each consisting of three image intensifiers, one CCD, and a FASTBUS digitizer, providing the necessary light amplification and image demagnification, multiplexing, and data compaction. The performance of the SFD during the first Collider run is indicated in Fig. 4.

- A transition radiation detector (TRD) fills the gap between the silicon detector and the SFD. Transition radiation is emitted when a charged particle traverses a medium of rapidly changing refractive index. The rate of X-ray production being proportional to the $\gamma$ of the particle, this detector is very efficient in identifying high-energy electrons. The UA2' TRD consists of two coaxial cylindrical chambers, each made of a stack of polypropylene radiators followed by a xenon chamber (Fig. 5). Each radiator is made of 350 foils, 20 $\mu$m thick and separated by 200 $\mu$m. The chambers have an asymmetric geometry, with a long drift space preceding the amplification region: the X-ray photons produced by electrons in the converter are rapidly absorbed by the xenon in the early part of the chamber, and generate large signals at a late time with respect to the ones produced in the amplification region by any ionizing particle. Signals are digitized by 100 MHz FADCs. The outer cathode of each chamber, made of helical strips, is also connected to 15 MHz FADCs, enabling the charge induced by the sense wire avalanches to be measured.

The different signatures of electrons and other particles in the UA2' central detectors are summarized schematically in Fig. 6.

Tracking and electron identification in the forward regions are provided by a set of proportional tube chambers (ECPT) located in front of the end-cap calorimeters. The ECPT detector is described in Ref. [10], which also gives details of a fast time-of-flight system aimed at measuring the vertex position with good precision.
2.2 ‘Neutrino’ identification

Non-interacting particles—such as neutrinos—among the final-state products can, in principle, be detected by measuring the total-transverse-momentum vector associated with the visible particles. The missing-transverse-momentum vector is defined as

$$\vec{p}_T = - \sum_i \vec{p}^i_T,$$

where $\vec{p}^i_T$ is a vector with magnitude given by the energy of the $i^{\text{th}}$ calorimeter cell and directed from the event vertex to the cell centre. The sum extends to all calorimeter cells.

The quality of the $p_T$ measurement is a function of the angular coverage of the calorimeter. The UA2 apparatus had full calorimetry in the central region ($40^\circ < \theta < 140^\circ$) and only electromagnetic calorimeters between 20° and 40°, whilst there was no detection of particles below 20°. Such an incomplete coverage was detrimental to the calculation of the missing transverse energy; the probability of losing one jet in a two-jet event was $\sim 10\%$ at $p_T^{\text{jet}} = 15 \text{ GeV/c}$, decreasing to $\sim 2\%$ at $p_T^{\text{jet}} = 40 \text{ GeV/c}$, and the overall $p_T$ distribution presented long, non-Gaussian tails.

In UA2 the CC has undergone only minor changes: the scintillators in the hadronic compartment have been replaced and the edge electromagnetic cells have been modified to make more room for the vertex detectors described in the previous subsection. On the contrary, the forward regions have been completed equipped with new End-Cap Calorimeters (EC) extending to $5^\circ$ from the beam axis. As the ECs are of the same kind as the CC, uniform hadronic measurement is guaranteed over $5^\circ < \theta < 175^\circ$ and for the full azimuthal coverage. The different calorimetric coverage of UA2 and UA2' can be seen in Fig. 7. A three-dimensional view of the UA2' calorimeters is shown in Fig. 8, where one can also notice that each 30° module of the ECs is tilted by 50 mrad around its axis perpendicular to the beam line in order to avoid cracks projecting towards the interaction point.

Preliminary results on the quality of the $p_T$ measurement in UA2' during the 1987 run are summarized in Fig. 9. Since the two components of the $p_T$ vector are Gaussian (Fig. 9a) with the same $\sigma = \sigma_T = \sigma_Y$, one can show that $d\Gamma/dp_T^2 \propto \exp[-(p_T/\Delta)^2]$, where $\Delta = \sqrt{2}\sigma$ depends on $\Sigma E_T$. Figure 9b shows the trend of $\Delta$ as a function of $\Sigma E_T$, which can be parametrized by $\Delta = 1.06 \times (\Sigma E_T)^{0.4} \text{ GeV}$ (solid line in Fig. 9b). This result is likely to improve with the final energy calibration.

2.3 Trigger and data acquisition

One major item in the UA2 upgrading is indeed the capability of the experiment to face the expected luminosity of $4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ and the large volume of data generated by the sophisticated UA2' detectors, i.e. the trigger and the data-acquisition (DAQ) systems [14]. Two additional levels of software triggers were added to the hardware trigger of UA2, based on a fast trigger processor (XOP) [15] for the second level and on a general-purpose FASTBUS master using the M68020 microprocessor (ALEPH Event Builder, AEB) [16] for the third level. The DAQ system itself had to be upgraded to provide two stages of event processing and buffering, based on a total of 12 AEBs, closely integrated into the main data-acquisition computer.

During the first data-taking period in 1987, technical problems in both the AA/AC and the SPS resulted in a poor performance of the Collider, with a peak luminosity never exceeding $3 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$, the same as the old machine, and a tiny integrated luminosity of $\sim 50 \text{ nb}^{-1}$, only 5% of the one accumulated so far by UA2. None of the problems is of a fundamental nature and they are expected to be overcome in time for the next running periods, when the design luminosity of $4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ should be reached.

At the design luminosity of the upgraded $p\bar{p}$ Collider the expected rate from the first-level trigger will be of the order of 100 Hz and the amount of data to be collected per event will average
80-100 kbytes. Several special runs were made in order to simulate running conditions at $4 \times 10^{39}$ cm$^{-2}$ s$^{-1}$ and to test the performance of the trigger and DAQ systems. No particular problems were detected, and the system operated at a primary trigger rate of 150 Hz with a live time of about 80%.

3. THE PHYSICS OF UA2' — THE STANDARD MODEL

3.1 W and Z physics

The accurate measurement of the IVB masses ($m_W$, $m_Z$) is of primary importance for testing the Standard Model. While $m_Z$ will be measured very accurately in the near future at the SLAC Linear Collider (SLC) and at LEP [expect $\Delta(m_Z) \sim \pm 50$ MeV/c$^2$], the W sector will remain the domain of $p\bar{p}$ colliders until LEP Phase II.

3.1.1 Measurement of the W and Z masses

The published results of W and Z from UA2 [17] are based on $251 W^+ \rightarrow e^+ \nu$ and $39 Z^0 \rightarrow e^+ e^-$ decays, corresponding to an integrated luminosity of 910 nb$^{-1}$. In total, $\sim 600 W^+ \rightarrow \ell^+ \nu$ ($\ell = e, \mu, \tau$) and $\sim 100 Z^0 \rightarrow \ell^+ \ell^-$ ($\ell = e, \mu$) have been observed in UA1 and UA2 so far [17, 18].

The mass values of W and Z measured by UA2 are

i) $m_W = 80.2 \pm 0.6$ (stat.) $\pm 0.5$ (syst.) $\pm 1.3$ (syst. 2) GeV/c$^2$;

ii) $m_Z = 91.5 \pm 1.2$ (stat.) $\pm 1.7$ (syst. 2) GeV/c$^2$.

as obtained by fitting i) the transverse-mass, $m_T$, distribution of the electron-$p_T$ system in events consistent with the reaction $p\bar{p} \rightarrow W + X \rightarrow e \nu + X$; ii) the mass distribution of the electron-positron system in events consistent with the reaction $p\bar{p} \rightarrow Z^0 + X \rightarrow e^+ e^- + X$. The quoted systematic errors reflect uncertainties from the fit (syst. 1) and from the knowledge of the calorimeter energy scale (syst. 2).

For a total of 10 pb$^{-1}$ of integrated luminosity, $\sim 3000 W^+ \rightarrow e^+ \nu$ and $\sim 350 Z^0 \rightarrow e^+ e^-$ are expected in the upgraded UA2 detector. After applying fiducial cuts to select events with good energy measurement, the previous numbers will reduce to 2000-2500 and 200-250, respectively. The expected improvement in the measurement of $m_W$ and $m_Z$ is based on the following considerations:

- The statistical error scales approximately as $K/\sqrt{n}$, where $K$ is $\sim 10$ GeV for the W and $\sim 3$ GeV for the Z, and n is the total number of electrons in the sample. Therefore, with 10 pb$^{-1}$ the expected statistical error is 220 MeV/c$^2$ for the W and $\sim 300$ MeV/c$^2$ for the Z.

- The systematic error from the fit of the W mass depends on theoretical and experimental uncertainties on the width of the W ($\Gamma_W$), the production transverse momentum of the W ($p_T^W$), and the evaluation of $p_T^W$ through the measurement of $p_T$. The uncertainty on $\Gamma_W$ can be reduced by combining the measurements of the ratio $R_{exp} = \sigma_W / \sigma_Z$ at the CERN $p\bar{p}$ Collider, and of $\Gamma_Z$ at LEP/SLC, where a precision of 30 MeV/c$^2$ is expected. The relation $\Gamma_Z / \Gamma_W = R_{exp} (\sigma_Z / \sigma_W) (\Gamma_Z / \Gamma_W)$ will then give $\Gamma_W$. The error from $p_T^W$ would decrease by using $p_T^Z$ from $Z^0 \rightarrow e^+ e^-$ to scale the theoretical calculation of $p_T^W$ [19]. Finally, the uncertainty on $p_T^W$ can be reduced by extracting $m_Z$ using the same method as for $m_W$. It has been shown [20] that with high statistics the fit to the $p_T^Z$ distribution, sensitive to $p_T^W$ but insensitive to $p_T^Z$, gives a more precise result than the fit to $m_T$, once the recipe just described for extracting $p_T^W$ is followed. In this case, the expected systematic error from the fit of $m_W$ is of the order of 200 MeV/c$^2$.

- The uncertainty on the knowledge of the energy scale (syst. 2) is expected to improve from the 1.6% of UA2 to 1.0%, thanks to complete test-beam calibration of all the calorimeter modules and an improved calibration system.

In conclusion, one expects
\[ \Delta m_W = \pm 0.22 \pm 0.20 \pm 0.80 \text{ GeV/c}^2, \]
\[ \Delta m_Z = \pm 0.30 \pm 0.90 \text{ GeV/c}^2. \]

The error on the energy scale, by far the dominant one, cancels to a large extent in the ratio \( m_W/m_Z \): \[
\Delta (m_W/m_Z) = \pm 0.003 \pm 0.002. \tag{1}
\]

Assuming, then, that \( m_Z \) will be measured with an accuracy of \( \sim \pm 50 \text{ MeV/c}^2 \) at \( e^+e^- \) machines, the combination of \( p\bar{p} \) Collider and LEP/SLC measurements will give \[
\Delta m_W = \pm 350 \text{ MeV/c}^2.
\]

### 3.1.2 Standard Model parameters

The measurements of \( m_W \) and \( m_Z \) allow the predictions of the Standard Model to be checked, once properly renormalized and radiatively corrected quantities are used. In the scheme where \( \sin^2 \theta_w \) is defined [21] as

\[ \sin^2 \theta_w = 1 - (m_W/m_Z)^2, \tag{2} \]

the Standard Model predicts

\[ m_W^2 = A^2/[(1 - \Delta r) \sin^2 \theta_w] \tag{3} \]
\[ m_Z^2 = 4A^2/[(1 - \Delta r) \sin^2 2\theta_w] \tag{3'} \]

where \( A = (\pi \alpha / \sqrt{2} \text{ GeV})^{1/2} = (37.2810 \pm 0.0003) \text{ GeV} \), using the experimental measurements of the Fermi coupling constant \( G_F = (1.16637 \pm 0.00002) \times 10^{-5} \text{ GeV} \), and of the fine structure constant \( \alpha^{-1} = 137.03604 \pm 0.00011 \). The value of \( \Delta r \), which accounts for one-loop radiative corrections at the \( W \) mass [22], is not constrained by experimental data. Recent calculations [23], based on a value for the \( t \)-quark mass of 45 GeV/c\(^2\) and for the Higgs of 100 GeV/c\(^2\), give \( \Delta r = 0.0711 \pm 0.0013 \).

The Standard Model can be tested by extracting i) \( \sin^2 \theta_w \), ii) \( \phi \), or iii) \( \Delta r \), from the measured values of \( m_W \) and \( m_Z \).

i) Equation (2) provides a direct measurement of \( \sin^2 \theta_w \) independent of other experiments and of theoretical uncertainties. UA2 finds

\[ \sin^2 \theta_w = 0.232 \pm 0.025 \text{ (stat.)} \pm 0.010 \text{ (syst.)}, \]

where the systematic error is mostly related to the \( m_W \) fit, the mass scale uncertainty cancelling out in the ratio \( m_W/m_Z \). In UA2', using Eq. (2) and for 10 pb\(^{-1}\), we expect

\[ \Delta (\sin^2 \theta_w) = \pm 0.006 \text{ (stat.)} \pm 0.004 \text{ (syst.)}. \]

A more precise value of the weak mixing angle can be extracted by a simultaneous fit of the measured \( m_W \) and \( m_Z \) to the theoretical equations (3) and (3'). The UA2 result is

\[ \sin^2 \theta_w = 0.232 \pm 0.003 \text{ (stat.)} \pm 0.008 \text{ (syst.)}, \]

where now the systematic error is dominated by the error on the mass scale, and the measurement relies on other experimental results and theoretical calculations [respectively, \( A \) and \( \Delta r \) in Eqs. (3) and (3')]. The expected precision of this measurement in UA2' is
$$\Delta(\sin^2 \theta_w) = \pm 0.001 \text{ (stat.)} \pm 0.005 \text{ (syst.)},$$
to be compared with the foreseen $\pm 0.005$ of CHARM II [24].

ii) Any departure from the Minimal Standard Model would result in modifications to the formalism presented above. For example, values of $\sin^2 \theta_w$ from Eqs. (2) and (3) and from low-energy neutrino experiments would, in general, differ. Although all existing measurements are in agreement with the Standard Model, they can be used to place limits on eventual deviations from the Minimal Standard Model. In particular, the quantity

$$\varrho = \frac{m_\ell^2}{m_\tau^2 \cos^2 \theta_w}$$
is expected to be 1 in the Minimal Standard Model. UA2 measures

$$\varrho = 1.001 \pm 0.028 \text{ (stat.)} \pm 0.006 \text{ (syst.)},$$
whilst the sensitivity of UA2 is expected to be

$$\Delta \varrho = \pm 0.008 \text{ (stat.)} \pm 0.009 \text{ (syst.)}.$$

iii) The radiative correction parameter $\Delta r$ can also be extracted from the measured values of $m_W$ and $m_Z$. Eliminating $\sin^2 \theta_w$ from Eqs. (3) and (3'), the UA2 result is

$$\Delta r = 0.068 \pm 0.087 \text{ (stat.)} \pm 0.030 \text{ (syst.)},$$
whilst using $\sin^2 \theta_w$ from low-energy experiments we get

$$\Delta r = 0.068 \pm 0.022 \text{ (stat.)} \pm 0.032 \text{ (syst.)}.$$

This result can be visualized in the $m_W$-$m_Z$ plane (Fig. 10). The present measurements, although in good agreement with the Standard Model, are not precise enough to test the magnitude of $\Delta r$. The expected sensitivity at the upgraded CERN pp Collider is also summarized in Fig. 10, from which we can conclude that UA2 will test radiative corrections, once a precise measurement of $m_Z$ will be available from the SLC or from LEP. The importance of a precise measurement of $\Delta r$ resides in the fact that $\Delta r$ would deviate from the computed 7% if a new fermion family existed with a large mass splitting, or if there were additional gauge bosons, or again if the t-quark were very heavy. For example, $\Delta r = 0$ if $m_t \sim 240 \text{ GeV}/c^2$.

3.2 Search for the top-quark

The t-quark and the Higgs boson are the two missing pieces of the Standard Model. The most recent mass limit for the t-quark has been set by TRISTAN as a lower bound of 26 GeV/c$^2$ [25].

At pp colliders the main mechanisms of t-quark production are

$$pp \rightarrow W + X \rightarrow t\bar{b},$$

if kinematically allowed, and QCD production...
\[ p\bar{p} \rightarrow t\bar{t} + X \] (5)

via quark-antiquark annihilation or gluon-gluon fusion. At \( \sqrt{s} = 630 \text{ GeV} \), reaction (4) is the dominant one for \( 40 < m_t < 80 \text{ GeV/c}^2 \). The production cross-section can be precisely estimated through the relation

\[ \sigma(W \rightarrow t\bar{t}) = 3\sigma(W \rightarrow e\nu) \phi(m_t), \]

where \( \sigma(W \rightarrow e\nu) \) has been measured at the CERN Collider, \( \phi(m_t) \) is a known phase-space suppression term, and the factor of 3 is for colour. Outside the above mass range, the t production is dominated by direct \( t\bar{t} \) production [reaction (5)]. A recent complete calculation of the next-to-leading order QCD corrections to the total cross-section for heavy-flavour production [26] and a set of proton structure functions including up-to-date experimental results [27] have allowed the authors of Ref. [28] to give reliable predictions for the \( t \) production.

The \( t \) decay proceeds as

\[ t \rightarrow (Wb) \rightarrow 3 \text{jets} \quad \text{or} \quad t \rightarrow (Wb) \rightarrow t\nu + \text{jet}. \]

The final state will therefore consist of \( \geq 4 \) jets or a charged lepton accompanied by two or more jets in events with missing transverse energy. Given the high rate of multijet events from QCD processes, the interesting final state at \( p\bar{p} \) colliders is the one connected with the semileptonic decay modes which, at the price of a branching ratio of \( \sim 1/9 \) for each charged lepton, give a much cleaner signature.

The analysis requires very strict selection criteria to improve the signal-to-background ratio. With the standard UA2 electron cuts [29], about 10 \( t \) events are expected over a background of 300 in the existing UA2 data sample. Strong requirements of electron isolation, both in tracking and preshower detectors and in the calorimeter, are necessary to improve the signal-to-background ratio. In this case, in the 910 nb\(^{-1}\) data sample, for an expectation of 3–4 events UA2 finds 30 candidates, entirely consistent with background in both rate and event topology.

In UA1 as well, the search for the \( t \)-quark is negative, both in the electron and in the muon channels. On the basis of their negative result [30] the UA1 Collaboration puts a lower limit on the \( t \)-quark mass of \( m_t > 44 \text{ GeV/c}^2 \), for a conservative choice of structure functions and \( Q^2 \) scale, or \( m_t > 56 \text{ GeV/c}^2 \) using the EUROJET prediction [31] which takes into account higher-order diagrams. More recently, the limit has been recalculated by the authors of Ref. [28] to be \( m_t > 41 \text{ GeV/c}^2 \).

The greatly improved electron identification power of UA2’ should allow the detection of the \( t \)-quark at the CERN \( p\bar{p} \) Collider if its mass is smaller than the \( W \) mass. For 10 pb\(^{-1}\) we estimate that about 70 events containing a \( t \rightarrow b\nu \) are expected, over a background of about 10 events, if \( m_t = 40 \text{ GeV/c}^2 \), where the contributions from \( W \rightarrow t\bar{b} \) and \( t\bar{t} \) are about equal. For \( m_t = 60 \text{ GeV/c}^2 \) the contribution from \( t\bar{t} \) is about 25% of the total, and the predicted signal and background are 20 and 4 events, respectively. For \( t \)-quark masses approaching \( m_w \), the b jets are softer; therefore, it becomes more and more difficult to distinguish \( W \rightarrow t\bar{b} \) from \( W + \) jets production. On the other hand, for the same kinematical reasons, the \( t\bar{t} \) channel will result in a final state containing a \( t\bar{t} \) and a two-jet pair with invariant masses close to \( m_w \). Finally, for \( m_t > m_w \), the most promising channel is \( t\bar{t} \rightarrow WWb\bar{b} \) followed by a semileptonic decay of one \( W \). For \( m_t = 100 \text{ GeV/c}^2 \), for example, about 10 events are expected before any selection cut which is necessary to reduce the background of \( W + \) two-jet production. We can therefore consider \( m_t = 100 \text{ GeV/c}^2 \) as an (optimistic) upper limit of the sensitivity of the \( t \)-quark search in UA2’.

At the FNAL Tevatron (\( \sqrt{s} = 1.8 \text{ TeV} \)) the cross-section of inclusive \( W \) production increases by a factor of 3 with respect to \( \sqrt{s} = 630 \text{ GeV} \), i.e. much less than the QCD processes which are the
background to $W \rightarrow t\bar{b}$, making the signal-to-noise ratio less favourable than at the CERN Collider. On the contrary, the $t\bar{t}$ production cross-section [32] is much larger at $\sqrt{s} = 1.8$ TeV than at $\sqrt{s} = 630$ GeV (Fig. 11), making the search for the $t$-quark at the Tevatron feasible up to masses of the order of 180 GeV/c$^2$ for an integrated luminosity of 10 pb$^{-1}$.

The conclusion is that in the search for the $t$-quark, UA2' can be considered as the favourite for $m_t < m_W$ and CDF for $m_W < m_t < 180$ GeV/c$^2$.

3.3 Search for Higgs

The main mechanisms for the production of neutral Higgs bosons (H) at $p\bar{p}$ colliders are i) gluon-gluon fusion via a heavy-quark loop [33], and ii) associated production of Higgs with a virtual or real IVB (bremsstrahlung mechanism) [34]. Figure 12 shows the production cross-sections for the two reactions at $\sqrt{s} = 630$ GeV. An integrated luminosity of 10 pb$^{-1}$ would give observable rates for Higgs-mass values up to about $\sim 50$ GeV/c$^2$ and $\sim 30$ GeV/c$^2$ for (i) and (ii), respectively.

The Higgs decays in the heaviest pair of quarks, i.e. $b\bar{b}$ for $m_H \geq 10$ GeV/c$^2$ giving two-jet (i) or four-jet (ii) final states, unfortunately overwhelmed by the huge hadronic jet backgrounds. The two-jet production, for example, is five orders of magnitude bigger than $H \rightarrow b\bar{b}$, thus precluding any possibility of observing a peak in the two-jet mass distribution, even after b-quark tagging.

Despite the lower cross-section, the bremsstrahlung process is more promising, since one can select final states containing a lepton pair coming from the IVB decay. The background is greatly reduced, but so is the signal by one order of magnitude, decreasing the sensitivity to $m_H \leq 10$ GeV/c$^2$.

In conclusion, existing $p\bar{p}$ colliders stand very little chance of discovering the Higgs, the Fermilab Collider being only marginally better than the CERN one. Higgs search therefore remains one of the main subjects of study for future machines [33]. On the other hand, significant signals of Higgs masses up to $\sim 70$ GeV/c$^2$ are expected at LEP II [35].

3.4 Boson pair production

Measurements of production cross-sections of gauge-boson pair production would lead to very important tests of the structure of the electroweak interactions. The $W^+W^-$ and $W^0Z^0$ production amplitudes are subject to important cancellations, a consequence of the gauge structure of the WWZ trilinear coupling. The $Z^0Z^0$ and $Z^0\gamma$ channels do not probe trilinear couplings, but are sensitive to unorthodox interactions such as the ones involving composite gauge bosons, for example. Finally, the rate for the production of $W^+\gamma$ is sensitive to the magnetic moment of the W.

Furthermore, it is important to understand the $W^+W^-$ and $Z^0Z^0$ final states, since they might constitute a significant background to the search for the Higgs.

Unfortunately, rates are too small and background conditions are prohibitive at the CERN $p\bar{p}$ Collider, and even at the Tevatron the possibility to study double-boson production is marginal. For example, at $\sqrt{s} = 2$ TeV, $\sigma(W^+W^-) = 10$ pb, whilst $\sigma(W + \text{two jets}) = 10^5$ pb and $\sigma(\text{four jets}) = 10^7$ pb. Selecting the leptonic decay of one of the bosons, for $p_T > 10$ GeV/c and $|\eta| < 3$, would give 0.5, 0.02, and 0.03 events for $W^+W^-$, $W^0Z^0$, and $Z^0Z^0$ pairs, respectively, in UA2' for $L = 10$ pb$^{-1}$. The corresponding numbers at the Tevatron are 4, 0.2, and 0.4. In addition, the background from $W + \text{two jets}$ [36] still dominates, the signal-to-noise ratio becoming acceptable only in the case of double leptonic decay, as shown in Fig. 13, but the extra tenfold reduction in rate inhibits the search completely.

Boson pair production therefore seems a chapter of physics for LEP II, the LHC and the SSC. More promising, at least at the Tevatron, is the $W^+\gamma$ channel, provided the background of $W + \text{jet}$, with the jet fragmenting into $n^l(s)$, is sufficiently reduced. In fact, 3 events are expected in the lepton channel at the CERN $p\bar{p}$ Collider and 10 events at the FNAL Tevatron for 10 pb$^{-1}$. 

8
4. THE PHYSICS OF UA2’ — MINIMAL EXTENSION OF THE STANDARD MODEL

4.1 New electroweak gauge bosons

Additional vector bosons, $W'$ and $Z'$, arise naturally from any extension of the minimal SU(2)$_L \times U(1)$ group of the Standard Model, such as ‘left-right symmetric models’ based on SU(2)$_L \times SU(2)_R \times U(1)$ [37], composite models [38] or models derived from Superstring theories [39].

At $p\bar{p}$ colliders they would be produced through $q\bar{q}$ annihilation and they would be detected through their leptonic decay, the decay into quarks being dominated by the two-jet background from QCD processes. The sensitivity of experiments is a function of their masses, $m_{W'}$ and $m_{Z'}$, their coupling to quarks, and their branching ratio to leptons.

A search in UA2 [40] excludes, at a 90% confidence level, the existence of a $W'$ of $m_{W'} < 209$ GeV/c$^2$ and a $Z'$ of $m_{Z'} < 180$ GeV/c$^2$, in the mass region above $m_W$ and $m_Z$ and for standard coupling to quarks and electrons. Details of the analysis, and variation of the limits for different couplings and for masses around and below $m_W$ and $m_Z$, can be found in Ref. [40]. A similar analysis by UA1 [41] excludes, at 90% CL, $m_{W'} < 232$ GeV/c$^2$ and $m_{Z'} < 188$ GeV/c$^2$.

The sensitivity of UA2’ will be about 300 GeV/c$^2$ for $m_{W'}$ and 250 GeV/c$^2$ for $m_{Z'}$, for an integrated luminosity of 10 pb$^{-1}$. Experiments at the Tevatron will benefit from the higher $\sqrt{s}$, as can be seen in Fig. 14, and will reach mass values of the order of 650 GeV/c$^2$ for $m_{W'}$ and 500 GeV/c$^2$ for $m_{Z'}$.

4.2 New quarks and leptons

Our present lack of understanding of the pattern of fermion generations and masses imposes that we consider the possible existence of new flavours. In this paragraph the expectations from searches for new quarks and new leptons in UA2’ will be analysed and compared with the ones at the FNAL Tevatron.

4.2.1 Search for heavy quarks

It must be stressed that in the near future the $p\bar{p}$ Colliders at CERN and FNAL will be the only machines to produce heavy quarks at a rate and with topologies that should make them observable. The case of new quarks with mass below $m_W$ can be reduced to the t-quark search discussed in subsection 3.2. For masses larger than the W mass, the search will most likely concentrate on the pair production of heavy quarks and their subsequent decay into a W and a lighter quark:

$$p\bar{p} \rightarrow Q\bar{Q} + X$$

$$\rightarrow Wq$$

with the W's decaying into q\bar{q} or lepton-neutrino pairs. In the case of both W's decaying hadronically, the final state of six jets will be dominated by the heavy background of multijet events from QCD processes. The promising signature is that of one leptonic decay which gives a final state with one high-p$_T$ electron and four jets in events with missing transverse momentum. The sensitivity of UA2’ will be up to $m_Q = 100$ GeV/c$^2$ for $L = 10$ pb$^{-1}$, as can be evaluated on the basis of Fig. 15. At the Tevatron the corresponding number is 180 GeV/c$^2$.

4.2.2 Search for heavy leptons

The search for next-generation leptons, L and associated $\nu_L$, at present hadron colliders is limited to masses smaller than $m_W$. In fact, given the small cross-section of Drell–Yan production of
L^+ L^- and L^\mp L^\pm (even at the SSC the accessible range does not exceed 300 GeV/c^2), the most promising signal comes from the decay

\[ W \rightarrow L_{PL} \]
\[ \rightarrow q\bar{q}_{PL} \]
\[ \rightarrow \ell \bar{\nu}_{PL} \] (6)

(7)

The final state from reaction (6) consists of one or two jets (depending on m_L) and p_T. The main physics background is from W \rightarrow \tau\nu, \tau \rightarrow q\bar{q}_{\nu}, and can be sufficiently reduced by selecting jets not compatible with a \tau decay. The present limit from p\bar{p} Collider data is from UA1 [42]: m_L > 41 GeV/c^2 at 90% CL. The same analysis at the new p\bar{p} colliders would explore the entire phase space available in W decay, i.e. up to m_L = 70 GeV/c^2.

The search for heavy leptons through their leptonic decay (7) is more complicated. In fact, the 80 (130) W \rightarrow L \rightarrow e events expected for m_L = 40 (60) GeV/c^2 would compete with 240 W \rightarrow \tau \rightarrow e and 3500 W \rightarrow \nu e\nu decays. The shape of p_T and cos \theta_\nu distributions would have to be used to separate the signal, as indicated in Fig. 16 for p\bar{p}. Unfortunately, the uncertainty in the knowledge of \Gamma_w and p_T^\nu, leading to uncertainties on the exact shape of the p_T distribution from the dominant W \rightarrow e\nu decay, makes the extraction of an eventual W \rightarrow L \rightarrow e signal very difficult.

5. THE PHYSICS OF UA2' - SEARCH FOR EXOTICS

5.1 Supersymmetric particles

Among the many mechanisms proposed for overcoming the theoretical difficulties associated with the Higgs sector of the standard electroweak theory, supersymmetry (SUSY) seems to be the most far-reaching, since it provides a natural framework for spontaneously broken gauge theories involving elementary scalars.

At p\bar{p} colliders, the highest cross-sections, for any given mass of the supersymmetric particles, would be for the strongly interacting ones, the squark \tilde{q} and the gluino \tilde{g}, the dominant production channels being p\bar{p} \rightarrow \tilde{g}\tilde{g}, p\bar{p} \rightarrow \tilde{q}\tilde{\bar{q}} (\tilde{g}\tilde{g}), p\bar{p} \rightarrow \tilde{q}\tilde{\bar{q}} [43]. The subsequent decay depends on the relative values of the squark mass m_{\tilde{q}} with respect to the gluino mass m_{\tilde{g}}: i) \tilde{q} \rightarrow q\tilde{g}, \tilde{q} \rightarrow q\tilde{\bar{q}} if m_{\tilde{q}} > m_{\tilde{g}}; or ii) \tilde{g} \rightarrow q\bar{q}, q\tilde{g} \rightarrow q\tilde{\bar{q}} if m_{\tilde{g}} < m_{\tilde{q}}. Since in most models the photino \tilde{\gamma} is the lightest, non-interacting SUSY particle, the final states would consist of many (two to six) jets and p_T. At the CERN p\bar{p} Collider, the UA1 detector was better placed than the UA2 detector for the study of such configurations, thanks to its larger \theta-coverge. By selecting events with at least two jets and large p_T, UA1 finds, at 90% CL, m_{\tilde{g}} > 53 GeV/c^2 for m_{\tilde{q}} > m_{\tilde{g}}, or m_{\tilde{q}} > 45 GeV/c^2 for m_{\tilde{g}} > m_{\tilde{q}}. With the assumption that the \tilde{q} and the \tilde{g} have the same mass, the UA1 limit becomes m_{\tilde{\gamma},\tilde{g}} > 75 GeV/c^2 [41].

The better granularity of UA2 made it possible to study the case of an unstable photino which, through the decay \tilde{\gamma} \rightarrow \gamma\tilde{H}, would produce a final state with two photons and jets [40]. From the absence of events with a two-photon pair with invariant mass larger than 10 GeV/c^2 and at least two jets with p_T^{jet} > 10 GeV/c, UA2 excludes gluinos in the mass range 15-50 GeV/c^2 and squarks in 9-46 GeV/c^2.

For SUSY searches, UA2' will take advantage of the improved p_T measurement and of the increased acceptance. Assuming a selection efficiency of 10%, the sensitivity to scalar quarks and gluinos for L = 10 pb\(^{-1}\) should reach mass values of the order of 100 GeV/c^2, as shown in Fig. 17. From the same figure, one can estimate that the limit at the Tevatron would be about 200 GeV/c^2 for equivalent luminosity and efficiency.
5.2 Compositeness

The most striking indications of composite quarks and leptons are for $\sqrt{s} > \Lambda_c$, where $\sqrt{s}$ is the centre-of-mass energy at the constituent level and $\Lambda_c$ the characteristic compositeness scale. Which processes would occur depends on the model, but, in general, multijet and multilepton events, or events containing jets and leptons, would eventually dominate the standard $SU(3)_c \times SU(2)_L \times U(1)$ processes.

For $\sqrt{s} < \Lambda_c$ the departure from the Standard Model is quantitative more than qualitative, and one has to look for hints of departure from the expected point-like behaviour. A typical test is to search for deviations in the QCD jet production cross-section due to effective four-fermion interaction terms, which are proportional to $1/\Lambda_c^2$ [44]. The existing limit from UA2 [45] is $\Lambda_c > 410$ GeV at 95% CL, which reduces to $\Lambda_c > 370$ GeV when all theoretical and experimental uncertainties are taken into account. UA1 finds $\Lambda_c > 415$ GeV [46] at 95% CL., which corresponds to the partons being point-like down to $5 \times 10^{-17}$ cm. Present $e^+e^-$ experiments give lower limits already of the order of a few TeV, but the compositeness scale for leptons is not necessarily the same as that for quarks.

The expected sensitivity of UA2' is about 650 GeV, to be compared with the 2-3 TeV attainable at the Tevatron.

6. THE PHYSICS OF UA2' — QCD MEASUREMENTS

6.1 Multijet studies

The study of final states containing hadron jets of high transverse energy has been one of the main activities of UA1 and UA2 at the CERN $p\bar{p}$ Collider. The properties of the two- and three-jet configurations have been successfully compared with QCD to leading and next-to-leading order in $\alpha_s$ [47, 48]. To higher order in $\alpha_s$, QCD predicts multigluon bremsstrahlung giving rise to final states containing many jets. The study of such configurations would provide additional tests of perturbative QCD. In particular, four-jet events have been the subject of a recent analysis by UA2, which has also compared such configurations with the hypothesis of double-parton interaction. Restricted to the central region, $|\eta| < 1$, and for $p_T^j > 10$ GeV/c, the UA2 four-jet analysis finds no evidence of multiparton scattering [49].

These and more complicated many-jet final states will obviously take advantage of the increased $\theta$-acceptance of UA2', $|\eta| < 3$, from the refined jet triggers, which would allow the $p_T^j$ threshold to be reduced, and from the increased integrated luminosity expected from the upgraded CERN Collider.

6.2 Measurement of $\alpha_s$

As mentioned in the previous subsection, QCD predicts the occurrence of gluon bremsstrahlung as first-order perturbative correction in the strong coupling constant $\alpha_s$ to the parton–parton scattering. Final states containing three jets should be observed at a rate dependent on the value of $\alpha_s$. Therefore, the yield of three-jet relative to two-jet events gives a measure of $\alpha_s$. Unfortunately, the contributions, $k_2$ and $k_3$, from higher-order corrections in $\alpha_s$ to the two- and three-jet cross-sections has not been calculated yet, and the quantity $\alpha_s(k_3/k_2)$ can only be extracted with this method. UA2 finds $\alpha_s(k_3/k_2) = 0.23 \pm 0.01 \pm 0.04$ [50].

A similar approach consists in using the yield R of the W + jet relative to W production. By fitting the prediction of a QCD Monte Carlo by Ellis–Kleiss–Stirling [51] to the measured value of R, one can extract the value $\alpha_s(k_3/k_0)$, where the $k_3$ and $k_0$ factors take into account the corrections of higher-order diagrams to the W + jet and W cross-sections, respectively. The advantage of this method is given by a recent evaluation of $k_0$ and $k_1$ [52], which makes it possible to extract an absolute value for $\alpha_s$. A preliminary analysis on the UA2 data [53] gives
\[ \alpha_s(m_W) = 0.13 \pm 0.03 \text{ (stat.)} \pm 0.03 \text{ (syst. 1)} \pm 0.02 \text{ (syst. 2)}, \]

where syst. 1 is the experimental error and syst. 2 takes into account theoretical uncertainties.

Some uncertainties, such as the one related to the knowledge of the energy scale or to the effect of the underlying event, will improve in UA2'. Taking into account the statistical error corresponding to an integrated luminosity of 10 pb\(^{-1}\), the overall error on the determination of \(\alpha_s\) in UA2' using this method is expected to be of the order of 0.015–0.020.

7. CONCLUSIONS

The upgrading of the UA2 detector has been successfully completed in time for the first run of the improved CERN p\(\bar{p}\) Collider complex in November–December 1987. The data taken, although amounting to a meagre 50 nb\(^{-1}\), have shown that every piece of the new apparatus worked satisfactorily, including the sophisticated trigger and data-acquisition systems.

The increased electron identification power in the central region and the wide angular coverage of the apparatus open up the horizon not only for new exciting physics—primarily, the top and supersymmetric particle searches—but also to important standard measurements, most significant of all being the one of the W mass at a precision which will be the domain of hadron colliders until LEP II.

For these physics goals to be reached, UA2 needs to accumulate of the order of 10 pb\(^{-1}\) of data. In this paper on various physics cases, the comparisons between the UA2 at CERN and the CDF at the Fermilab Tevatron Collider make it clear that for UA2 to remain competitive the bulk of the luminosity has to be delivered in the next 1–2 years, a task that the improved CERN p\(\bar{p}\) Collider should be able to fulfil.
REFERENCES


[8] UA1 Collab., A proposal to upgrade the UA1 detector in order to extend its physics programme, CERN/SPSC 83–48 SPSC/P93 Add. 3 (1983).
J.D. Dowell (UA1 Collab.), same Proceedings as Ref. [6], p. 419.


P. Baehler et al., The XOP trigger processor integrated into the UA2 data-acquisition system, to appear in same Proceedings as Ref. [14].


See references therein for previous UA2 publications.

C. Albajar et al. (UA1 Collab.), Studies of W and Z properties at the CERN Super Proton Synchrotron Collider, in preparation, to be submitted to Z. Phys.
See references therein for previous UA1 publications.


Figure captions

Fig. 1 Longitudinal view of the central detectors of a) UA2 and b) UA2'. Note the smaller beryllium beam pipe and the shortened calorimeter edges of UA2'.

Fig. 2 Cross-section of one of the 16 sectors of the jet vertex detector.

Fig. 3 Pulse-height distribution of the silicon detector signals from test-beam and collider data.

Fig. 4 Distribution of the residuals of the 18 tracking layers of the SFD with respect to the fitted track.

Fig. 5 Radial view of a section of a TRD chamber.

Fig. 6 Principle of electron identification in the UA2' central region.

Fig. 7 Longitudinal view showing the different calorimetry of a) UA2 and b) UA2'.

Fig. 8 Three-dimensional view of the UA2' calorimeters.

Fig. 9 a) One component of the $\vec{p}_T$ vector at a given $\Sigma E_T$. Both $p_x$ and $p_y$ components show Gaussian behaviour for all values of $\Sigma E_T$.

b) Resolution function of the $p_T$ measurement in UA2'.

Fig. 10 a) Present $m_Z$ versus $m_W$ measurements from UA1 and UA2. The ellipses represent the 1σ statistical errors, and the bar centred on the points is the systematic uncertainty on the mass scale.

b) Expected accuracy with 10 pb$^{-1}$ in UA2' and following a precision measurement of $m_Z$ at SLC/LEP. The position of the point in the $m_W$-$m_Z$ plane is arbitrary.

Fig. 11 QCD-predicted [32] cross-section for inclusive production of a heavy quark-antiquark pair.

Fig. 12 Cross-section of the two main mechanisms of Higgs production in pp interactions at $\sqrt{s} = 630$ GeV.

Fig. 13 W + W and W + (two jets) production cross-sections from Ref. [36].

Fig. 14 Production cross-sections of W' and Z', assuming standard coupling to quarks and leptons.

Fig. 15 Cross-sections for the production of a quark pair followed by a fully hadronic or a semileptonic decay.

Fig. 16 Transverse-momentum distribution of electrons coming from different W decay channels.

Fig. 17 Total production cross-sections of squarks and gluinos at $\sqrt{s} = 0.63$ and 1.8 TeV.
Fig. 2

Fig. 3

SILICON PULSE-HEIGHT

- Data from pp collider
- Test beam data
Fig. 4

σ = 0.389 mm

Residual (mm)
Fig. 6
UA2 PRELIMINARY

- $\Sigma E_t = 69.0$
- $\sigma = 3.95 \pm 0.05$

Figure 9

$\Delta = a(\Sigma E_t)^b$
- $a = 1.063 \pm 0.021$
- $b = 0.404 \pm 0.005$
Fig. 11
Higgs production at $\sqrt{s} = 630$ GeV

Gluon-gluon fusion

Higgs bremsstrahlung

Fig. 12
Fig. 13
Fig. 14
$p\bar{p} \rightarrow Q\bar{Q} + X \quad \sqrt{s} = 630 \text{ GeV}$

$Q\bar{Q} \rightarrow W W q\bar{q} \rightarrow 6 \text{ jets}$

$Q\bar{Q} \rightarrow W W q\bar{q} \rightarrow (\text{ev}) + 4 \text{ jets}$

Fig. 15
Fig. 16

- $W \rightarrow e$
- $W \rightarrow L \rightarrow e$ with $m_L = 25 \text{ GeV}/c^2$
- $W \rightarrow L \rightarrow e$ with $m_L = 60 \text{ GeV}/c^2$
- $W \rightarrow \tau \rightarrow e$

Arbitrary units

$p_T^e \text{ (GeV}/c)$

0 20 40 60
Fig. 17