CERN-EP/88-111

September 1st, 1988

PHYSICS AT THE IMPROVED CERN $\bar{p}p$ COLLIDER

D. Froidevaux
Laboratoire de l'Accélérateur Linéaire,
Orsay, France

P. Jenni
CERN, Geneva, Switzerland

ABSTRACT

The physics prospects expected from the upgraded UA1 and UA2 experiments are discussed for the future data taking periods at the improved CERN $\bar{p}p$ Collider, and compared to the TEVATRON Collider wherever relevant.

1. INTRODUCTION

After five years of very successful operation during 1981 to 1985 the CERN $\bar{p}p$ Collider has been undergoing an important upgrading programme. We recall that the CERN $\bar{p}p$ Collider has been running during the years 1981 to 1983 at $\sqrt{s} = 546$ GeV during which time the UA1 and UA2 experiments collected data for an integrated luminosity $\mathcal{L}$ of about 150 nb^{-1} . The collision energy has been increased to $\sqrt{s} = 630$ GeV for the more recent running periods. The excellent performance of the Collider has allowed the experiments to accumulate $\mathcal{L} \approx 750 \text{ nb}^{-1}$ during the years 1984 and 1985. The CERN $\bar{p}p$ Collider and its experiments have played a very important role in particle physics during these years, in particular with regard to the discovery of the Intermediate Vector Bosons (IVBs) and the study of hard parton scattering in jet phenomena. We will discuss in this article physics motivations and expectations for a second phase of experimentation with upgraded detectors at the improved CERN $\bar{p}p$ Collider (referred to as ACOL in what follows).

The major items of the improvement of the CERN $\bar{p}p$ Collider complex [1] are the addition of a new separate antiproton collector ring (AC) to the existing antiproton accumulator (AA), and the "six-bunch" operation of the SPS in $\bar{p}p$ storage mode. The project has progressed well such that the first Collider run using AC could take place as scheduled in November and December 1987. The peak luminosity is expected to increase by a factor 10, or even more, over the past performance, reaching about $5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$. The experiments expect data samples corresponding to $\mathcal{L} \geq 10 \text{ pb}^{-1}$ to result from the future Collider runs at $\sqrt{s} = 630$ GeV during the next few years. The performance reached during the first run at the end of 1987 (peak luminosity $\sim 3 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ and $\mathcal{L} \sim 50 \text{ nb}^{-1}$ only) was however far below design values due to various technical problems both at the antiproton collector and accumulator complex (AAC) and the SPS itself. It is expected that these problems are overcome for the forthcoming data taking periods as confirmed by very recent successful machine studies.

Section 2 of this article contains a description of the upgraded detectors at the CERN $\bar{p}p$ Collider. The other sections cover the expectations for jet physics and QCD studies (Section 3), for the physics related to the Standard Model of electroweak interactions (Section 4), and for speculative physics beyond the Standard Model (Section 5).

2. UPGRADED DETECTORS

The improved CERN $\bar{p}p$ Collider is being exploited in the near future by four experiments. One of them, UA6 [2], is strictly speaking not a collider experiment as it uses either the circulating proton or antiproton beams with an internal hydrogen gas jet target to study inclusive electromagnetic final states at large transverse momentum and Λ production in pp and $\bar{p}p$ interactions at $\sqrt{s} = 24.3$ GeV. Another experiment, UA8 [3], is studying jet structure in high mass diffractive processes with sets of mini-drift wire chambers installed in so-called Roman-pots on both sides of the interaction region housing UA2. These forward detectors measure the recoil protons (antiprotons) whereas the central energy flow is examined using the information of the UA2 detector.

In the following, we concentrate on the upgrade programmes of the two large-solid-angle general-purpose detectors UA1 and UA2.

2.1 The upgraded UA1 experiment

The main emphasis of the improvement programme for the UA1 experiment [4] is on the replacement of the old central and forward electromagnetic (e.m.) calorimeters (gondolas and bouchons) by a uranium/tetramethyl/pentane (TMP) calorimeter (Fig. 1). The use of uranium allows about 2.6 interaction lengths (λ) to be accommodated in the space occupied by the old e.m. calorimeter alone ($\approx 1\lambda$). The U/TMP calorimeter will therefore not only act as the e.m. calorimeter but, on the average, also absorb a large fraction of the hadronic energy. The calorimeter consists of 4250 cells, each subtending an angle $\Delta\theta \times \Delta\phi = 5^\circ \times 6^\circ$. 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. Ten supergondolas will replace the previous 48 lead/scintillator gondolas (see Fig. 1).

The use of TMP readout - a radiation-hard, room-temperature-liquid ionization-chamber technique - will provide high granularity without dead

Figure 1

- a. The UA1 detector in its original form showing the central and forward (end-cap) e.m. calorimeters (shower counters) that are to be replaced by U/TMP calorimeters.
- b. General layout of the new central (supergondolas) and forward (superbouchons) U/TMP calorimeters.

spaces due to cryogenics. It will potentially allow UA1 to reach accurate, uniform, and stable energy measurements (minimize systematic errors on W and Z mass determinations). Prototype measurements with an e.m. U/TMP calorimeter [5] have shown the expected behaviour in terms of linearity and resolution (Fig. 2). A critical problem is the length and the stability of the electron lifetime, which depend on the purity of the liquid. A value of about 3 μ s has been maintained at the percent level over a three month period [5], which will ensure that most of the charge will be collected (drift time $\approx$ 0.25 μ s).

Figure 2

- a. The response of the calorimeters to electrons of various energies.
- b. The square of the measured energy resolution of the combined calorimeters as a function of electron energy. The solid and dot-dashed lines are for $\Delta E/E = 0.14/\sqrt{E}$ and $0.12/\sqrt{E}$ respectively where E is in GeV. The dashed curve is an estimate of the resolution that would be expected for the combined 2 and 4 mm calorimeters if the intrinsic resolution of a 2 mm calorimeter were $0.12/\sqrt{E}$. (Both from Ref. [5]).

Other components of the UA1 detector will be upgraded as well, in particular :

- a. The muon detection is improved by increasing the hadron absorber thickness both in the central and in the forward regions with additional iron instrumented with planes of limited-streamer tubes and with additional forward drift tubes. Complete muon detection is then provided in the angular range from 15° to 165° with respect to the beam axis.
- b. A new data acquisition system with a multilevel trigger structure using information both from the calorimetry and the muon detection system allows UA1 to cope with the increased collision rate expected for the future runs.

The upgraded UA1 detector is expected to be fully operational in 1989.

2.2 The upgraded UA2 experiment

The upgrading of the UA2 experiment, described in detail elsewhere [6], aimed at mainly two aspects: i) full calorimeter coverage, and ii) better electron identification at low transverse momenta (p_T). Full e.m. and hadron calorimeter coverage is achieved with the addition of new end-cap modules covering the angular regions $6^\circ < \theta < 40^\circ$ with respect to the beam directions. These end-cap calorimeters consist of lead/scintillator samplings for the e.m. part and iron/scintillator samplings for the hadronic part, both read out by the wavelength shifter (WLS) technique. They are assembled in wedge-shaped modules subtending 30° in azimuth (Fig. 3). The construction, performance, and granularity ($\Delta\phi \times \Delta\eta \approx 15^\circ \times 0.2$; $\Delta\eta$ is the pseudorapidity) are chosen to match well the old central calorimeter [7]. This matching is particularly important for the new multilevel triggering scheme, which provides selective triggers for e.m. clusters, hadronic jets, and missing transverse momentum (p_T) over the relevant η range ($-2 < \eta < 2$) and all azimuthal angles ϕ with minimal cracks. In order to use the scintillator/WLS technique, much effort had to be expended on calibrating all the cells in a test beam.

Figure 3

3. General layout of the UA2 calorimeter. The movable support structures which allow to recess the end-caps from the beam pipe are not shown.

This is also valid for the central calorimeter, for which all the scintillator plates in the hadronic compartments were replaced. The UA2 Collaboration is aiming to achieve a systematic energy scale error of $\leq 1\%$ for the e.m. calorimeter and $\leq 2\%$ for the hadronic one.

Electron identification in UA2 is improved by the use of a completely new central detector assembly [6] consisting of the following cylindrical layers around the beryllium vacuum pipe (Fig. 4): the particles are first tracked through a drift chamber vertex detector (jet chamber); a silicon-pad detector then measures the particle dE/dx to reject e^+e^- pairs from photon conversions and Dalitz decays; two layers of transition radiation detectors follow, which provide an independent electron identification in addition to the calorimeter, suppressing backgrounds from accidental overlaps of a γ with a charged pion; finally, a novel

Figure 4

Longitudinal view of the new UA2 central detector.

scintillating-fibre detector gives, in a very limited radial space of 6 cm, a second track segment followed by preshower detection after $1.5 X_0$ of lead absorber. It is planned to install a further layer of silicon-pad detectors [8] just around the beryllium beam pipe during 1988 in order to enhance the tracking capability of the detector in events with multiple interactions, which are expected to occur frequently for the highest Collider luminosity. The track finding and the electron identification are complemented in the forward regions by proportional tube chambers, including a $2 X_0$ lead radiator for preshower detection, mounted on the calorimeter end-caps. All these detector components have given very satisfactory test-beam results. A background rejection of at least a factor of 20 is expected for the inclusive electron measurements as compared with the previous UA2 performance. This will be very important at low p_T (typically 10-15 GeV), where most of the signal electrons from a possible t -quark coming from $W \rightarrow t\bar{b}$ decays are expected (see 4.6).

Finally time-of-flight counter arrays located on both sides of the interaction region provide a fast vertex localization and discriminate against beam-gas backgrounds.

The upgraded UA2 detector has been assembled in time to meet the initial running period of the improved CERN $\bar{p}p$ Collider complex at the end of 1987. All the detector components as well as the new data acquisition and triggering system have been brought into operation successfully, demonstrating the readiness of the experiment for high luminosity running. As already mentioned in the introduction, only a small data sample, corresponding to about 50 nb^{-1} of integrated luminosity, could be accumulated during this period. Figure 5 shows as an example a typical $W \rightarrow e\nu$ candidate event recorded in the upgraded detector from this data sample.

3. JET PHYSICS AND QCD STUDIES

The CERN $\bar{p}p$ Collider has provided a very rich harvest of results on hadronic jet physics confirming that available lowest-order QCD calculations are able to describe the gross features of the strong parton interactions with large momentum transfers [9]. However very detailed quantitative tests of QCD with Collider data suffer from many systematic limitations. From the theoretical side there is a lack in understanding of higher order effects (in the strong coupling constant α_s) and of all "soft" effects due to low momentum transfers which cannot be treated perturbatively. The momentum transfer scale Q^2 is not unambiguously defined, and the fragmentation of scattered partons into hadronic final states is not rigorously described. From the experimental point of view uncertainties arise at some level from the ambiguous assignment of low momentum final state particles to a given jet which may partially overlap with other jets and with spectator hadrons not directly related to the sub-process of interest. Further systematic uncertainties are due to instrumental effects, for example in the detailed knowledge of the calorimeter response to hadronic jets.

The largely increased statistical precision from the jet data samples expected from the improved CERN $\bar{p}p$ Collider will therefore not directly reflect into much higher precision QCD tests in most cases where the systematic uncertainties are already important. Nevertheless significant improvements can be expected over the present data. A few typical jet and

Figure 5

5. Example of a $W \rightarrow e\nu$ candidate event recorded in the upgraded UA2 detector.

- a. transverse energy distribution in the calorimeters
- b. transition radiation signals along the electron track
- c. tracking and preshower signals in the scintillating fibre detector for the electron candidate.

QCD physics topics are considered in the following to illustrate these facts. A different class of QCD tests are possible by the study of IVB production properties as discussed in Section 4.1.

3.1 Inclusive jet cross-section

The inclusive jet cross-sections have been published by UA1 [10] and UA2 [11] already, without including the data from the 1985 running period. The data from both experiments agree with each other, and Fig. 6a shows as an example the data from UA2. The global systematic uncertainties are evaluated to be $\pm 70\%$ and $\pm 45\%$ for UA1 and UA2 respectively. This uncertainty precludes a very quantitative comparison with QCD calculations. It is remarkable though that the shape of the inclusive jet cross-section as a function of the jet transverse momentum p_T is so well described over several orders of magnitudes by lowest-order QCD calculations. For the future runs, UA2 has estimated [12] that with $\mathcal{L} = 10 \text{ pb}^{-1}$ they will extend the p_T range to about 200 GeV/c and that the systematic errors could be reduced to $\pm 35\%$ by an improved control of calibration effects. However much higher p_T 's will be reached by the CDF experiment at the TEVATRON $\bar{p}p$ Collider due to the larger collision energy. This is illustrated in Fig. 6b which compares the calculated [13] inclusive jet cross-sections at $\sqrt{s}$ of 0.63 and 2 TeV.

It is interesting to search for deviations at large jet p_T from the QCD behaviour which could reveal internal structure of the quarks due to a hypothetical super-strong interaction binding preons inside the quarks [14]. A contact interaction could become visible at momentum transfers well below the characteristic energy scale Λ_c describing the strength of this conjectured interaction. Finite values of Λ_c would produce an excess of events compared to ordinary QCD predictions (corresponding to $\Lambda_c = \infty$) at large p_T . From the inclusive jet cross-sections the present 95% CL lower limit is $\Lambda_c > 400 \text{ GeV}$ [10,11]. This limit is expected [12] to improve to about 650 GeV with the future runs at the CERN $\bar{p}p$ Collider, but it cannot compete with the limit $\Lambda_c \geq 1.6 \text{ TeV}$, which can be obtained with even a modest data sample ($\mathcal{L} = 1 \text{ pb}^{-1}$) at $\sqrt{s} = 2 \text{ TeV}$.

Figure 6

6. Inclusive jet cross sections at $\eta = 0$.

a. As an example the UA2 data [11] at $\sqrt{s} = 546$ GeV and 630 GeV.

The effect of a hypothetical new contact interaction is also shown (see text).

b. A comparison of the expected inclusive cross sections at $\sqrt{s} = 630$ GeV and 2 TeV.

3.2 Two-jet cross-section and angular distribution

A study of the two-jet mass and angular distributions allows one to investigate in more detail the parton hard scattering mechanism. Eight basic $2 \rightarrow 2$ processes can contribute in lowest order (α_s^2) to the two-jet cross-section, their respective importance depending on the structure functions describing the initial quark (q) and gluon (g) fluxes [15]. The expected fractions of gg, $q\bar{q}$ and $(qg + \bar{q}g)$ final state two-jet events in the pseudo-rapidity range $-2 < \eta < 2$ are shown in Fig. 7 as a function of the subprocess centre of mass energy $\sqrt{\hat{s}}$ (two-jet invariant mass). Only the future high luminosity running will enable the experiments to accumulate significant data samples with $\sqrt{\hat{s}} \geq 300$ GeV where $q\bar{q}$ states clearly dominate. With such a data sample one could attempt to measure changes in the angular distribution as a function of $\sqrt{\hat{s}}$ due to the changing $q\bar{q}$, gg and $(qg + \bar{q}g)$ fractions.

Figure 7

7. The fractions of $q\bar{q}$, gg and $qg + \bar{q}g$ final state two-jet events in the range $-2 < \eta < 2$ as a function of the subprocess centre of mass energy $\sqrt{\hat{s}}$.

UA1 [16] and UA2 [17] have used their two-jet cross sections and angular distributions to extract an "effective" structure function $F(x)$ for the colliding nucleons, assuming that the contributions from the two nucleons factorize and that the angular distribution is described by a weighted average over all elementary processes [18]. $F(x)$ is a sum of all quark and gluon densities with x being the fraction of the longitudinal momentum carried by the interacting parton. The results, shown in Fig. 8, are in reasonable agreement with measurements from deep inelastic lepton-hadron scattering evolved to the Q^2 of the Collider jets. The low x region ($x \leq 0.2$) is dominated by the gluon distribution. The high x region (≥ 0.5), dominated by the quark distributions, can be probed only with significantly larger data samples as will become available at the improved Collider. However one has to keep in mind that the systematic errors on the data are about $\pm 30\%$, and that the experimental results $\sqrt{K} \cdot F(x)$ depend on the assumptions made for the higher order (α_s^3) corrections (K-factors), Q^2 and Λ_{QCD} .

Figure 8

8. Effective structure function. The data are from UA1 [16] and UA2 [17]. See Ref. [17] for further details.

The two-jet angular distribution is also sensitive to hypothetical contact interactions [14] already mentioned in the previous sub-section, which would cause an enhancement at large scattering angles θ over the pure QCD distribution. Figure 9 shows the UA1 data [19] in the variable $x = (1 + \cos\theta)/(1 - \cos\theta)$ and illustrates the effect of $\Lambda_c = 300$ GeV. Their present 95% CL lower limit on Λ_c from the x distribution is 415 GeV, slightly better than the one from the inclusive jet cross-section alone (see 3.1). Similarly, somewhat improved limits over the ones quoted in the previous section can be expected from the angular distributions from the future large data samples.

Figure 9

The two-jet angular distribution for high mass events from UA1 [19].

3.3 Three-jet events and α_s

The study of three-jet events allows us to extend the QCD tests to order α_s^3 processes, dominated by gluon bremsstrahlung. Various angular and energy distributions of three-jet events have been successfully compared to QCD expectations by UA1 [20] and UA2 [21]. Further detailed studies will be possible with the increased statistics and the larger acceptances of the upgraded detectors (in particular of UA2). As an example it will become possible to pursue a study of the $\cos\xi = (p_2^* - p_3^*) / p_1^*$ distribution [21], which describes the asymmetry of the energies found in the softer two jets (p_1^* , p_2^* , p_3^* are the three jet momenta in their common centre of mass system in decreasing order). The distribution of $\cos\xi$ is characteristic of gluon bremsstrahlung off a $q\bar{q}$ pair in e^+e^- annihilations [22], and provides a test of the spin of the gluon. Though in the $\bar{p}p$ case many different subprocesses contribute to the three-jet production, the $\cos\xi$ distribution remains a sensitive probe of the QCD dynamics.

The most topical interest of the three-jet studies however lies in the possibility to extract α_s . The basic idea follows from the fact that the two - and three-jet cross-sections are approximatively proportional to α_s^2 and α_s^3 respectively, and that therefore the ratio, for which many systematic uncertainties in the cross-section measurements are expected to cancel, should yield a determination of α_s . The calculated cross-section ratio can be adjusted to agree with the experimental value by varying α_s . The calculations are however affected by higher-order α_s corrections (expressed as K_2 - and K_3 - factors for the two - and three-jet cross-sections respectively) implying that the three - to - two jet ratio is proportional to $\alpha_s (K_3/K_2)$. Another theoretical uncertainty arises from the ambiguous choice of the Q^2 scale for the two - and three-jet events. Initial $2 \rightarrow 2$ and $2 \rightarrow 3$ parton scatterings do not contribute alone to the experimentally observed two - and three-jet cross-sections due to incomplete detector acceptance and overlapping jets. This means that further systematic uncertainties in the data analysis arise from model dependent corrections like fragmentation effects, four-(or more) jet contributions, underlying (spectator) event fluctuations, structure functions and so on.

The present results on $\alpha_s(K_3/K_2)$ using the same Q^2 scale for two - and three-jet events are $0.23 \pm 0.02 \pm 0.04$ from UA1 [22] and $0.23 \pm 0.01 \pm 0.04$ from UA2 [21], where the first error is statistical and the second one describes the systematic uncertainties. The Q^2 used is the maximum jet transverse momentum squared, giving average values of 4000 GeV^2 and 1700 GeV^2 for the two experiments respectively. Changing this Q^2 definition for example to the average jet transverse momentum squared, thereby reducing the mean three-jet Q^2 with respect to the mean two-jet Q^2 , would reduce the UA2 result [21] for $\alpha_s(K_3/K_2)$ by 25%.

The value of $\alpha_s(K_3/K_2)$ as a function of $\sqrt{\hat{s}}$ has been studied by UA1 and UA2. As an example Fig. 10 shows the most recent data of UA2 [23]. The expected variation of α_s is shown as well (obtained by computing the variation of α_s as a function of Q^2 at the value of the mean Q^2 for each $\sqrt{\hat{s}}$ bin and assuming that K_3/K_2 remains constant). The present accuracy of the data is obviously not sufficient to demonstrate the "running" of α_s . The expected improvement of the statistical error at high values of $\sqrt{\hat{s}}$ in the future data sample is illustrated for the upgraded UA2 experiment for two 10 GeV wide $\sqrt{\hat{s}}$ bins in Fig. 10. Provided that the data span a sufficiently large $\sqrt{\hat{s}}$ range, the Q^2 dependence should become observable whereas the absolute value will likely remain dominated by the systematic uncertainty. It is interesting to note that these data allow one in turn to extract the ratio K_3/K_2 as a function of $\sqrt{\hat{s}}$, if the QCD scale parameter is known from other measurements.

3.4 Multi-jet production

Four-and more parton final state events are of particular interest because there are many "new physics" processes for which such events are an important background [24]. Multi-jet production occurs not only due to higher order (α_s^4) corrections to the two-jet processes but there is also an interesting new class of interactions, namely the multi-parton scattering, where two pairs of incoming partons from the same nucleons interact [25].

Figure 10

10. The values of $\alpha_s(K_3/K_2)$ as a function of $\sqrt{s}$ from UA2 [23]. The expected improvement on the statistical precision with future runs ($\mathcal{L} = 10 \text{ pb}^{-1}$) is indicated for two $\sqrt{s}$ bins of 10 GeV width.

As an illustrative example the process $\bar{p}p \rightarrow W \rightarrow t\bar{b} \rightarrow 4 \text{ jets}$ is considered at $\sqrt{s} = 630 \text{ GeV}$ with $m_t = 40 \text{ GeV}$. The results of a detailed study by Ref. [24] are shown in Fig. 11. Even after restricting the search to the central region only ($|\eta| < 1$) and requiring that the four-jet invariant mass lies within $\pm 10 \text{ GeV}/c^2$ of the W mass, the QCD $2 \rightarrow 4$ scattering processes dominate the signal by more than two orders of magnitudes, independent of the jet p_T threshold, p_T^{min} . It is worth noting that the flavour combination of the signal differs in general from the one of the QCD background, but there is no way at present to select jets efficiently according to their parton origin. Other examples have been considered in Ref. [24], and there remains the general conclusion that QCD multi-jet events dominate searches for new physics when considering purely hadronic final states.

Figure 11

11. Dependence on the jet transverse momentum threshold $p_T^{\min}$ for the four jet signal (solid curve) and background (dashed curve) for $W \rightarrow t \bar{b}$ production in $\bar{p}p$ collisions at $\sqrt{s} = 630$ GeV, reproduced from Ref. [24].

No multi-parton signal has been observed yet at the CERN $\bar{p}p$ Collider, the present four-jet data [26] is well described by a $2 \rightarrow 4$ scattering QCD model alone. The new multi-level triggering system of the upgraded UA2 experiment aims at reaching lower jet transverse momenta where the multi-parton signal is expected to be enhanced with respect to normal QCD. It is thereby hoped that a signal can be revealed in the future high statistics data sample.

3.5 Direct photon production

The direct photon production $\bar{p}p \rightarrow \gamma + X$ is of particular interest for QCD tests because of two main advantages. First, it is experimentally possible to measure directly the photon transverse momentum in the electromagnetic calorimeters with much better accuracy than for jets, and second fragmentation effects are absent. A complete QCD calculation in next-to-leading order (α_s^2) is available [27]. However the rates expected are about three orders of magnitude smaller than for inclusive jet production. The present data [28,29] on direct photon production are indeed limited by their statistical precision and are confined to transverse momenta well below 100 GeV/c. The systematic uncertainties on the cross-section are about $\pm 20\%$. The data are expected to improve significantly with the increased integrated luminosity in the near future.

4. STANDARD MODEL PHYSICS

In this section, we discuss the physics which can be studied at ACOL, in terms of the Standard Model of electroweak interactions. The extension of the physics results obtained from the study of W, Z decays to the higher luminosities expected at ACOL is discussed in subsections 4.1 to 4.3. Pair production of IVBs is reviewed in 4.4, heavy flavour physics (charm, beauty) in 4.5 and the search for new flavours in 4.6 and 4.7. Finally, for completeness, the search for a neutral Higgs boson is discussed in 4.8. Wherever relevant, the physics potentials of ACOL versus TEVATRON will be compared.

4.1 IVB production properties.

4.1.1 IVB production cross-sections.

The main features of IVB production at hadron colliders are described elsewhere [30] and summarized in Fig. 12. In spite of the clear rise in cross-section for W, Z production (σ_W, σ_Z) when $\sqrt{s}$ increases, we expect that precision measurements in the W, Z sector will become increasingly difficult at higher $\sqrt{s}$. Comparing, for example, the TEVATRON ($\sqrt{s} = 1.8$ TeV) with ACOL ($\sqrt{s} = 630$ GeV), we expect a factor of 3 increase in σ_W and σ_Z , but also a factor of 10 increase in QCD two-jet production, σ_{jet} , with $p_T^{\text{jet}} \approx 40$ GeV/c and $|y_{\text{jet}}| < 2$ (where p_T^{jet} , y_{jet} are the jet transverse momentum and rapidity). This results in a worse signal to background ratio at TEVATRON compared to ACOL, which might affect precision measurements using $W \rightarrow e\nu$ or $W \rightarrow \mu\nu$ decays (the background from fake electrons or muons under the $Z \rightarrow ee$ or $\mu\mu$ peak is negligible). In addition, as shown by Figs. 12b and 12c, the gain in rate at higher $\sqrt{s}$ is ruined by a broader p_T^W distribution and by less central production of the W 's. In particular, the mean p_T^W at TEVATRON is expected to be almost double that at ACOL, thus broadening significantly the Jacobian peak observed in $W \rightarrow e\nu$ decay, and affecting the precision measurements of m_W (see section 4.3).

The accuracy on the measurement of σ_W, σ_Z at ACOL will not improve substantially the present measurements which are already dominated by systematic uncertainties on the luminosity for σ_W . More importantly, the QCD predictions of Ref. 30 are affected by large uncertainties (choice of scale for α_s , structure functions, value of the top quark mass), most of which are not likely to improve in the near future. It will be interesting, however, to compare the measurement of σ_W, σ_Z at TEVATRON with the values obtained at lower $\sqrt{s}$.

4.1.2 Lepton universality.

The measurement of $W \rightarrow e\nu$, $W \rightarrow \mu\nu$ and $W \rightarrow \tau\nu$ decays by UA1 has allowed a quantitative test of lepton universality at large momentum transfer, $Q^2 \approx m_W^2$. In the future, UA1 will probably remain the best equipped experiment to improve the accuracy of this test, without, however, being able to reach the precision of experiments at lower Q^2 (PETRA, PEP ...).

Fig. 12 W production properties as predicted by Ref. [30].
a) Total cross-section for W production (W^+ and W^- , $m_W = 83\text{ GeV}/c^2$) and for hypothetical W's of heavier mass as a function of $\sqrt{s}$.
b) Ratio $R = [d\sigma/dq_T dy]/(d\sigma/dy)$ at $y = 0$ as a function of the W transverse momentum q_T for various $\sqrt{s}$.
c) Normalized rapidity distributions $[(d\sigma/dy)/\sigma]$ for various $\sqrt{s}$ and $m_W = 83\text{ GeV}/c^2$.

4.1.3 Measurement of the W width.

Most of the experimental and theoretical uncertainties discussed in 4.1.1 disappear when measuring cross-section ratios, and it is well known by now that the determination of the σ_Z/σ_W ratio is the best method of extracting the Z width [31] through the relation

$$\Gamma_Z/\Gamma_W = R_{\text{exp}}(\sigma_Z/\sigma_W)[\Gamma(Z \rightarrow ee)/\Gamma(W \rightarrow ev)],$$

where $R_{\text{exp}} = (\sigma_B)_{W \rightarrow ev}/(\sigma_B)_{Z \rightarrow ee}$ is measured experimentally, and the other quantities are predicted from theory. The main uncertainty on the theoretical predictions arises from the uncertainty on the structure function parametrization used to predict σ_Z/σ_W . This uncertainty is not expected to improve in the near future, and we rewrite the above relation as [32] :

$$\Gamma_Z/\Gamma_W = R_{\text{exp}}(0.114 \pm 0.008)$$

or
$$\Gamma_W = \Gamma_Z (8.77 \pm 0.62)/R_{\text{exp}}$$

where the errors take into account the theoretical uncertainty on σ_Z/σ_W . From this we can expect to extract a measurement of Γ_W to better than 10%, once Γ_Z will have been precisely determined at the forthcoming Z factories (SLC and LEP).

4.1.4 IVB production in association with jets.

The prediction of the exact shape of the W transverse-momentum spectrum, p_T^W , is the result of a somewhat unique QCD calculation [30] involving all-order effects from soft gluons for values of p_T^W much smaller than m_W . In principle, this calculation can be compared to the experimentally measured distributions. In the data collected before ACOL, such a comparison was unfortunately impossible because of lack of statistics in the case of $Z \rightarrow ee$ decays, where however p_T^Z is precisely measured from the decay electron and positron, and because of large uncertainties on the measurement of the neutrino transverse momentum, in the case of $W \rightarrow e\nu$ decays.

In practice the comparison should be restricted to values of p_T^W larger than ~ 15 GeV/c, where most of the W transverse momentum is balanced by a hadron jet (or jets) which can be more reliably measured by the calorimetry.

In this subsection, we shall first extrapolate a recent measurement of the strong coupling constant, α_s , using a UA2 sample of 230 $W \rightarrow e\nu$ decays, of which 28 are produced in association with one hard jet ($p_T^{\text{jet}} > 10$ GeV/c) [33]. This measurement uses approximate expressions of the K-factors [34] necessary to extract α_s from the data. We assume for the following that, in the coming years, these approximate expressions will become exact, thus reducing a main source of uncertainty in these measurements.

Table 1 shows the cross-sections for W production in association with 1 or 2 hard jets ($p_T^{\text{jet}} > 15 \text{ GeV/c}$), with subsequent $W \rightarrow e\nu$ decay, at ACOL and TEVATRON, including the relative contributions from the relevant graphs. As expected from Fig. 12b, the fraction of W's produced in association with hard jets is much higher at TEVATRON, and the contribution from gluon graphs has substantially increased.

Table 1

Production of W's in association with hard jets at ACOL and TEVATRON. Electron selection efficiencies and jet reconstruction effects are included.

$p_T^{\text{jet}} > 15 \text{ GeV/c}$	$(W + e\nu) + 1 \text{ jet}$		$(W + e\nu) + 2 \text{ jets}$	
	Cross-section	Contributions	Cross-section	Contributions
ACOL $\sqrt{s} = 630 \text{ GeV}$	12.5 pb (3.3% of all $W + e\nu$)	$q\bar{q} : 79\%$ $qg : 21\%$	1.0 pb (0.3% of all $W + e\nu$)	$q\bar{q} : 76\%$ $qg : 23\%$ $gg : 1\%$
TEVATRON $\sqrt{s} = 1800 \text{ GeV}$	69.0 pb (6.1% of all $W + e\nu$)	$q\bar{q} : 52\%$ $qg : 48\%$	15.0 pb (1.3% of all $W + e\nu$)	$q\bar{q} : 43\%$ $qg : 55\%$ $gg : 2\%$

With an integrated luminosity of 10 pb^{-1} , we can expect 125 reconstructed $W \rightarrow e\nu$ decays with one jet of p_T larger than 15 GeV/c (this number would increase by almost a factor 2 if the threshold were 10 GeV/c). The experimental error on α_s will arise mainly from the effect of the underlying event and the jet energy measurement. One can hope to extract α_s using this method at ACOL, with similar experimental and theoretical (structure functions, higher orders) uncertainties of approximately 10%.

Another approach would be to use the precise measurement of the p_T^Z distribution to extract a measurement of Λ_{QCD} , using the sensitivity of the p_T^Z -spectrum to Λ_{QCD} at low values of p_T^Z , as shown in Fig. 13. Unfortunately, even though the experimental measurement is accurate in the case of $Z \rightarrow ee$ decays, the theoretical uncertainties on the calculation of Ref. 30 remain large for $p_T^Z < 3\text{-}4 \text{ GeV/c}$. They are mainly due to the

definition of Q^2 used for $\alpha_s(Q^2)$, and to the exact value used as a cutoff when Q^2 (or p_T^W) becomes very small. From a simple simulation, we find that we would need about 300 reconstructed $Z \rightarrow ee$ decays to extract Λ_{QCD} to within ± 200 MeV using this method. As we shall see in the next section, such a sample will be available at ACOL or even at TEVATRON in the next few years. Furthermore, as discussed in 4.3, a precise knowledge of the p_T^Z spectrum, extrapolated to the p_T^W spectrum, will greatly reduce systematic errors on the W -mass measurement.

Fig. 13
Sensitivity of the Z transverse-momentum spectrum to Λ_{QCD} .

4.2 IVB decay modes.

4.2.1 Leptonic decay modes.

We first recall that, for approximately 1 pb^{-1} of integrated luminosity at the Sp $\bar{\text{p}}$ S collider, a total of 600 $W \rightarrow (e, \mu, \tau)\nu$ decays and 100 $Z \rightarrow ee$ or $\mu\mu$ decays have been observed in UA1 and UA2 combined. The bulk of the

statistics is dominated by $W \rightarrow e\nu$ and $Z \rightarrow ee$. The $W \rightarrow \mu\nu$, $W \rightarrow \tau\nu$, and $Z \rightarrow \mu\mu$ decay modes have been observed in UA1 with much less statistics, because of smaller acceptance and lower cut efficiencies. This situation is likely to remain in the future, both at ACOL and TEVATRON, because of the difficulty in extracting muon and tau signals from the background. In this subsection, we shall therefore concentrate on the $W \rightarrow e\nu$ and $Z \rightarrow ee$ decay modes, in order to evaluate realistically the expected samples for mass measurements and tests of the standard model (see 4.3).

Table 2 shows the expected W and Z rates in UA2 at ACOL and in CDF at TEVATRON, assuming somewhat optimistically integrated luminosities of 10 pb^{-1} at ACOL and 5 pb^{-1} at TEVATRON by the end of 1989. Taking into account the detector acceptances and electron selection efficiencies (assumed to be 70% for $W \rightarrow e\nu$ decays, and 90% for $Z \rightarrow ee$ decays), we expect a total of 3000 (5000) reconstructed $W \rightarrow e\nu$ decays and 350 (800) reconstructed $Z \rightarrow ee$ decays in UA2 (CDF).

Table 2
W and Z rates at ACOL and the TEVATRON

	UA2 (ACOL)	CDF (Tevatron)	Comments
$\sqrt{s}$ (GeV)	630	1800	
$\int L \, dt$ by end of 1989 (pb^{-1})	10	5	Optimistic estimates
$(\sigma_B)_{W \rightarrow e\nu}(\text{nb})$	0.6	1.8	Rate better at the Tevatron
e/jet ratio at $p_T = 40 \text{ GeV}/c$	10^{-3}	3×10^{-4}	Signal/background better at ACOL
(p_T^W) (GeV/c)	9	14	
No. of reconstructed $W \rightarrow e\nu$	~ 3000	~ 5000	After acceptance and selection
No. of reconstructed $Z \rightarrow ee$	~ 350	~ 800	
No. of $W \rightarrow e\nu$ for mass fit	2000-2500	3500-4000	Depends upon fiducial cuts (calorimeter cracks, etc.)
No. of $Z \rightarrow ee$ for mass fit	150-250	400-600	
Stat. error on m_W (MeV/c^2)	~ 200	~ 200	
Stat. error on m_Z (MeV/c^2)	~ 200	~ 130	

These numbers are substantially reduced if one retains only events within a fiducial volume, which excludes calorimeter cracks, where the uncertainties on the energy measurements are large.

4.2.2 Hadronic decay modes.

The W and Z bosons are expected to decay into $q\bar{q}$ pairs with sizeable rates, and be observed as two-jet final states. Examples of these decays are $W^+ \rightarrow u\bar{d}$ and $c\bar{s}$, and $Z \rightarrow u\bar{u}$, $d\bar{d}$, $c\bar{c}$, $s\bar{s}$, $b\bar{b}$. As noted in Ref. [24], where the specific process $p\bar{p} \rightarrow W \rightarrow u\bar{d}$ is considered, the background from QCD processes, $p\bar{p} \rightarrow u\bar{d}$, is not overwhelming in the two-jet mass range where the W signal is expected. In fact, the two processes have comparable rates at central rapidities, at least at $\sqrt{s} = 630$ GeV. Unfortunately, there is at present no known method for distinguishing jets of a specific flavour on an event-by-event basis. Therefore, the QCD backgrounds to a $W, Z \rightarrow q\bar{q}$ signal are summed over all flavours of quarks, and also over gluons, which are the dominant background process in the W,Z mass range.

As discussed elsewhere, UA2 has observed a signal for the $W, Z \rightarrow q\bar{q}$ decays over the dominant QCD background, but this signal is far from providing overwhelming statistical evidence for this very important IVB decay mode. It turns out that jet-jet spectroscopy is one of the crucial experimental features at future hadron colliders, and the present $p\bar{p}$ colliders are an ideal testing ground for the feasibility of high precision and high granularity calorimeters, within the high luminosity environment of future hadronic machines.

Therefore it will be very interesting to see whether UA1, UA2, CDF and D0, with their different calorimeters, will be able to clearly establish the presence of the $W, Z \rightarrow q\bar{q}$ decays above the QCD background, with the much larger integrated luminosities expected in the near future.

4.3 IVB mass measurements and Standard Model tests.

Future precision mass measurements at hadron colliders will clearly concentrate more and more on m_W , because experiments at the e^+e^- colliders operating at the Z pole (SLC and LEP) will determine m_Z to an accuracy of better than $50 \text{ MeV}/c^2$ [35], which will never be approached by any experiment at ACOL or TEVATRON. This arises from the fact that present mass measurement errors are already dominated by the systematic uncertainties on the energy scale, which are directly linked to the absolute calibration of the electromagnetic calorimeters. The goal of the existing calorimeters (UA2, CDF) and of the forthcoming more ambitious ones (UA1,D0) is to reach the level of an uncertainty of $\pm 1\%$ on the absolute energy scale, which would result in errors of the order of $\pm 1 \text{ GeV}/c^2$ on the W, Z mass measurements. In the following, we shall assume that the Z mass and width will have been precisely measured at SLC and LEP by 1990.

At that time, the experiments at ACOL and TEVATRON will have hopefully accumulated 2000 to 4000 well-measured reconstructed $W \rightarrow e\nu$ decays, as discussed in 4.2.1 and as shown in table 2. Table 2 also shows that the estimated statistical errors on m_W and m_Z are similar, about $200 \text{ MeV}/c^2$, owing to the fact that the W mass cannot be completely reconstructed.

This leads to a discussion of the systematic uncertainties inherent in the method used to extract the W mass. Known theoretical and experimental uncertainties concern the knowledge of the W width (discussed in 4.1.3), of the W transverse momentum p_T^W (discussed in 4.1.4), as well as the measurement of the neutrino transverse momentum. UA2 estimates, after a careful study, that the systematic error on the W mass, due to the method used to extract its value, will not be smaller than $\pm 200 \text{ MeV}/c^2$.

We therefore expect to obtain $\delta m_W = (\pm 0.20 \pm 0.20 \pm 0.80) \text{ GeV}/c^2$ (errors due to statistics, method, and calibration, respectively), assuming an uncertainty of $\pm 1\%$ on the absolute energy scale. This uncertainty cancels in the measurement of $R = m_W/m_Z$, which will be measured with an error of $\delta R = \pm 0.003(\text{stat.}) \pm 0.002(\text{syst.})$. This leads to $\delta m_W \approx \pm 0.35 \text{ GeV}/c^2$, for a known value of m_Z . This accuracy on m_W is unlikely to be improved significantly until LEP operates above the threshold for W pair production.

The direct measurement of the weak mixing angle, $\sin^2\theta_w = 1 - (m_W/m_Z)^2 = 1 - R^2$, will have a statistical error of ± 0.006 and a systematic error of ± 0.004 . The effect of the radiative corrections to the IVB masses will be determined as illustrated in Fig. 14. The improvement with respect to the present situation will be substantial, allowing such a measurement to provide a stringent test of the Standard Model, in particular with respect to the mass of the top quark, if it has not been measured by then.

Fig. 14 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.

4.4 IVB pair production.

The physics potential of studies of electroweak gauge-boson pair production was recognized a long time ago [36]. In the Standard Model, there are important cancellations in the amplitudes for WW and WZ production, which depend upon the gauge structure of the WWZ trilinear

coupling. The rate for $W\gamma$ production is sensitive to the W magnetic moment. Unfortunately, as shown in table 3, the rates for boson pair production, at ACOL and even at the TEVATRON, are too low to allow detailed studies of these potentially very interesting events.

As described in Ref. 24, multijet backgrounds from QCD will swamp any purely hadronic signal for boson pair production. Therefore, in table 3, only events where at least one gauge boson decays into $e\nu$ or ee are considered. Even in this case, it has been pointed out [37] that the background from Standard Model $W,Z + 2$ jets production, where the two-jet invariant mass is required to be within ± 10 GeV/ c^2 of the W,Z mass, will be almost two orders of magnitude above the boson pair signal, both at ACOL and TEVATRON. Since the requirement of a double leptonic decay ($p\bar{p} \rightarrow WW \rightarrow e\nu e\nu$, $p\bar{p} \rightarrow WZ \rightarrow e\nu ee$ or $p\bar{p} \rightarrow ZZ \rightarrow eeee$) will greatly reduce the already small rates shown in table 3, we conclude that the observation of heavy gauge-boson pair production at ACOL or TEVATRON is excluded.

Table 3
Boson pair production rates at ACOL and TEVATRON

At least one boson into $e\nu$ or ee	$W^\pm\gamma$	WW	WZ	ZZ
Events per 10 pb^{-1} at ACOL ($\sqrt{s} = 630 \text{ GeV}$)	11	0.5	0.02	0.03
Events per 5 pb^{-1} at the Tevatron ($\sqrt{s} = 1.6 \text{ TeV}$)	36	2.1	0.1	0.2

These arguments do not apply to $W\gamma$ production, provided one is confident that standard $W + \text{jet}$ production, where the jet fragments into single or multiple π^0 's, can be sufficiently reduced. These events are of particular interest, since they would allow a measurement of the W anomalous magnetic moment κ , which is predicted to be $\kappa = 1 + O(\alpha_{em})$ in the Standard Model. We recall that κ is derived from

$$\mu_W = e(1 + \kappa)/2 m_W,$$

where μ_W is the W magnetic moment.

Fig. 15 shows the expected angular distribution of the photon with respect to the incoming d-quark, in the ($W\gamma$) centre of mass, for events with a transverse mass of the ($e\nu\gamma$) system larger than m_W and with a photon transverse momentum larger than 10 GeV/c.

We first note that, because of the low rate and of the absence of charge measurement in UA2, the measured distributions of this angle, $\cos\theta_{d\gamma}^*$, averaged over W^+ and W^- , will not provide any information on the value of κ . However, as shown by the strong dip expected in the distribution for W^- alone, at $\cos\theta_{d\gamma}^* = 1/3$, perhaps CDF or D0 at the TEVATRON will collect enough data to measure κ to $\pm 50\%$ before LEP II becomes operational.

Figure 15

Measurement of the W anomalous magnetic moment, κ , through the angular distribution of photons produced in association with W bosons.

4.5 Heavy flavour physics.

The UA1 results from the analysis of single and dimuon data [38] have shown that, contrary to electrons, muons are identifiable inside or near to hadron jets, thus opening up an exciting field of heavy-flavour physics, leading in particular to the first measurement of $B_s - \bar{B}_s$ mixing. This field should clearly be pursued, in particular with the upgraded UA1 muon detector, which will be by far the most performant muon detector at $p\bar{p}$ colliders in the future.

4.6 Search for the top quark.

The search for the top quark is one of the highest priorities at ACOL and TEVATRON, especially since the most recent limits on the top quark mass, m_{top} , seem to exclude the possibility of observing $Z \rightarrow t\bar{t}$ decays at SLC or LEP [39]. Fig. 16 shows the cross-sections for top-quark production through $p\bar{p} \rightarrow W + X \rightarrow t\bar{b} + X$ and $p\bar{p} \rightarrow t\bar{t} + X$ as a function of m_{top} , for $\sqrt{s} = 630$ GeV (ACOL) and $\sqrt{s} = 1800$ GeV (TEVATRON). The curves shown are lowest-order cross-sections and we refer the reader to a recent review of higher-order corrections and theoretical uncertainties in heavy flavour production at high-energy hadronic machines [40] for a more detailed discussion of this subject. For the purpose of the present discussion, we just point out that $t\bar{t}$ production through gluon fusion dominates at TEVATRON, independent of m_{top} , whereas, at ACOL, $t\bar{b}$ production through W-decay dominates for $50 \text{ GeV} < m_{\text{top}} < 70 \text{ GeV}$, and $t\bar{t}$ production through quark fusion dominates for $m_{\text{top}} > 70 \text{ GeV}$. The rates at TEVATRON are between one and two orders of magnitude higher than at ACOL, depending upon m_{top} .

From Fig. 16, it is clear that hadronic decays of the top quark would be abundant at ACOL and TEVATRON for the integrated luminosities which are hoped to be achieved by the end of 1989. Unfortunately, as shown in Ref. 24, a possible multijet signal from hadronic top-quark decay ($p\bar{p} \rightarrow W + X \rightarrow t\bar{b} + X \rightarrow 4 \text{ jets} + X$ or $p\bar{p} \rightarrow t\bar{t} + X \rightarrow 6 \text{ jets} + X$) will probably be impossible to extract from the very large QCD background. We therefore restrict ourselves from now on to describing the search for semileptonic decays of the top quark; more specifically, we shall discuss a

quantitative estimate of the signal to background ratios expected in UA2 at ACOL, in a search for $t \rightarrow b \nu$ decays.

Figure 16

Top-quark production cross-section as a function of the top-quark mass. The lowest-order cross-sections for $\bar{p}p \rightarrow W + X \rightarrow t\bar{b} + X$ and $\bar{p}p \rightarrow t\bar{t} + X$ are shown for ACOL ($\sqrt{s} = 630$ GeV) and TEVATRON ($\sqrt{s} = 1800$ TeV).

Fig. 17 shows the expected rates for events with one reconstructed electron ($p_T^e > 12 \text{ GeV/c}$) and at least two reconstructed jets ($p_T^j > 10 \text{ GeV/c}$) in UA2, for an integrated luminosity of 10 pb^{-1} , as a function of m_{top} [41]. Detector acceptance, jet energy measurements, and electron selection efficiency ($\epsilon_e = 23\%$) have been taken into account. In particular, the electron selection efficiency is low, because of the tight cuts required to reduce the background from fake electrons to an acceptable level (about 10 events), as shown in Fig. 17. Also shown are the backgrounds expected from real electron sources, which are dominated by $p\bar{p} \rightarrow W + 2 \text{ jets} + X$, with $W \rightarrow e\nu$ and mainly by $p\bar{p} \rightarrow b\bar{b}g$, with $b \rightarrow c e \nu$. The dominant background from $b\bar{b}$ semileptonic decays has a very steeply falling p_T^e spectrum, but suffers from large systematic uncertainties, since it is greatly reduced by the isolation cuts implicit in any electron selection and the simulation of these cuts requires a detailed knowledge of the fragmentation process and of the calorimeter response to low-energy particles.

Fig. 17 shows that the signal to background is larger than one, for $m_{\text{top}} < 70 \text{ GeV/c}^2$, which is close to the kinematic limit for $W \rightarrow t\bar{b}$ decay. It is hoped that topological cuts and invariant mass reconstruction will allow us to improve this signal-to-background ratio and extract a clean top quark signal for $m_{\text{top}} < 70 \text{ GeV/c}^2$. As already stressed previously, good muon identification, as achieved in UA1, is an important asset in the understanding of heavy flavour production, and, of course, would increase the signal event rate by a factor 2.

We also note that, at TEVATRON, the expected rates are 5 times larger than at ACOL, for $m_{\text{top}} < m_W$, but the backgrounds are even larger and it has yet to be demonstrated that leptons of low p_T are observable above background at these higher energies.

If the top-quark mass becomes close to the W-mass, the electrons from top decay will look more and more like electrons from W decay, and the extra jet (or jets) tend to have smaller and smaller p_T . Therefore it will be difficult to distinguish topologically $W \rightarrow t\bar{b}$, with $t \rightarrow b e \nu$ decays from $W \rightarrow e\nu$ decays, and $t\bar{t}$, with $t \rightarrow b e \nu$ decays from $W \rightarrow e\nu$ decays, associated with jets.

Fig. 17

Expected rates for reconstructed semi-leptonic top decays in UA2 for an integrated luminosity of 10 pb^{-1} as a function of the top-quark mass. Also shown are the expected background levels from fake electrons and from real electron sources (W decay, semi-leptonic b-decay). Acceptances and selection efficiencies are taken into account.

4.7 Search for heavy quarks and leptons.

4.7.1 Search for heavy quarks.

In this subsection, we turn to the search for quarks, with mass, m_Q , above the W mass, whether it be the top quark, which would decay predominantly into a real W boson and a b quark, or a member of a new family, which we assume, in the following, to decay into a real W and a light quark. Such objects will only be observable at ACOL and mainly TEVATRON in the foreseeable future and they can be detected in distinctive final-state topologies, containing one $W \rightarrow e\nu$ decay and four (or more) jets.

Fig. 16 shows that we can only hope to detect such events with observable rates at ACOL, for $m_Q < 100 \text{ GeV}/c^2$, whereas, at TEVATRON, masses of up to $180 \text{ GeV}/c^2$ should be within reach, since the rates are almost two orders of magnitude larger than at ACOL, for such large masses.

The main background to such a signal, $p\bar{p} \rightarrow Q\bar{Q} \rightarrow WWq\bar{q}$, with at least one $W \rightarrow e\nu$ decay, arises from W production in association with jets. Since the signal to background ratio is of order 1 for the range in p_T^e where the signal is expected, it seems reasonable to assume that such heavy quarks could be easily isolated from the background after topological cuts.

4.7.2 Search for heavy leptons.

In this subsection, we consider the case of a fourth-generation charged lepton L , associated with a new massless neutrino ν_L . Production of L^+L^- or $L\nu_L$ through the Drell-Yan mechanism suffers from a very small cross-section [42], so the most promising channel for observing L production, if $m_L < m_W$, is through the decay $W \rightarrow L\nu_L$, followed by $L \rightarrow q\bar{q}\nu_L$ or $L \rightarrow e(\mu)\nu\nu_L$.

The hadronic decay, $L \rightarrow q\bar{q}\nu_L$, leads to final states with one or two jets and missing transverse momentum, where the jets are not compatible with the main physics background from $W \rightarrow \tau\nu_\tau$ decays. As shown by the UA1 analysis [43], the present limit is $m_L > 41 \text{ GeV}/c^2$ at the 90% confidence level. It is straightforward to extrapolate from this to ACOL and TEVATRON

luminosities, where the experiments should reach the kinematic limit of $m_L \sim 70 \text{ GeV}/c^2$, allowed by phase space in W decay.

The leptonic decays, $L \rightarrow e(\mu)\nu\nu_L$, are heavily contaminated by background from the dominant $W \rightarrow ev$ and $W \rightarrow \tau\nu_\tau \rightarrow ev\nu_\tau\bar{\nu}_\tau$ decay modes. The shapes of the electron transverse momentum, p_T^e , and angular distributions can be used to separate the signal from the backgrounds. For 3500 reconstructed $W \rightarrow ev$ decays with $p_T^e > 15 \text{ GeV}/c$, we expect 240 electrons with $p_T^e > 10 \text{ GeV}/c$ from $W \rightarrow \tau \rightarrow e$ decays, 127 from $W \rightarrow L \rightarrow e$ for $m_L = 40 \text{ GeV}/c^2$, and 76 for $m_L = 60 \text{ GeV}/c^2$. These numbers are illustrated in Fig. 18, where it can clearly be seen that the electron signal from $W \rightarrow L \rightarrow e$ will be difficult to separate from the background, especially since uncertainties on the knowledge of Γ_W and p_T^W result in uncertainties on the exact shape of the p_T^e spectrum for the dominant $W \rightarrow ev$ background.

Fig. 18

Electron transverse momentum spectrum from $W \rightarrow Lv_L$, with $L \rightarrow ev\nu_L$ decays, normalized to the $W \rightarrow ev$ spectrum, for different values of m_L .

4.8 Search for the Higgs boson.

The search for the neutral Higgs (H) boson is one of the main topics of physics studies at future accelerators [42]. The various H production mechanisms and experimental signatures are the subject of intensive studies in view of detector design for multi-TeV machines.

At ACOL and TEVATRON, the dominant production mechanism for H production is through gluon-gluon fusion via a heavy quark loop, with subsequent decay of the Higgs boson into the heaviest fermion pair, i.e. into $b\bar{b}$, if the Higgs mass is larger than $10 \text{ GeV}/c^2$. Fig. 19 shows the H production cross-section at ACOL as a function of the Higgs mass. The rates are observable up to Higgs masses of about $50 \text{ GeV}/c^2$. At TEVATRON, the range increases to masses of around $100 \text{ GeV}/c^2$. However, the enormous background from hadron jets (a factor of 10^5 above any possible $H \rightarrow b\bar{b}$ signal) precludes the observation of H production through gluon-gluon fusion, even with an experiment optimized for b-quark tagging.

Figure 19

Higgs production at ACOL as a function of the Higgs mass.

A more promising production process is that in association with a W (or Z) boson, the so-called Higgs bremsstrahlung mechanism [44], which is the dominant source of H production at SLC and LEP. At ACOL and TEVATRON, this process is smaller in cross-section than the gluon-gluon fusion mechanism, as shown in Fig. 19, and yields observable rates only up to Higgs masses of 30 (resp. 50) GeV/c^2 at ACOL (resp. TEVATRON). However, in order to get rid of the background from hadron jets, one would be led to require associated production of a Higgs boson and a real Z, with the latter decaying into a lepton pair, thus reducing the observable rate by an order of magnitude.

Therefore, it seems very unlikely that the Higgs boson could be discovered at existing hadron colliders.

5. PHYSICS BEYOND THE STANDARD MODEL

In this section, we discuss the expected reach of the experiments at ACOL and TEVATRON in terms of searching for hypothetical new particles, which are predicted to be produced with observable rates by many theoretical models. Section 5.1 deals with the search for possible supersymmetric particles [45], denoted in the standard way as $\tilde{e}$, $\tilde{\nu}$, $\tilde{\gamma}$, $\tilde{q}$, $\tilde{g}$... Section 5.2 discusses the search for additional vector bosons, which arise naturally in the framework of many possible extensions of the minimal $SU(2)_L \times U(1)$ Standard Model of electroweak interactions, whether it be through right-handed currents [46], composite models [47], or various models derived from superstring theories [48].

5.1 Search for supersymmetric particles.

5.1.1 Search for $\tilde{q}$ and $\tilde{g}$.

In hadronic machines, the dominant sources of supersymmetric particles are $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$ production [49]. In most models, the photino, $\tilde{\gamma}$, is expected to be the lightest supersymmetric particle, and therefore stable if R-parity conservation is assumed. In the following, we therefore assume

that the $\tilde{g}$ decays into $q\bar{q}\tilde{\chi}$, and the $\tilde{q}$ dominantly into $q\tilde{g}$ (if $m_{\tilde{q}} > m_{\tilde{g}}$), or into $q\tilde{\chi}$ (if $m_{\tilde{q}} < m_{\tilde{g}}$).

The hadronic production of $\tilde{q}$ and $\tilde{g}$ results, in this case, in final states containing two to six jets and missing transverse momentum. The main backgrounds arise from QCD multijet production, where one or more jets are not properly reconstructed in the detector, owing to fragmentation, calorimeter response, or holes in the apparatus, and from W,Z production with jets, where the W,Z decays leptonically and is not seen in the detector ($Z \rightarrow \nu\bar{\nu}$, $W \rightarrow e\nu$ with the electron inside a jet etc...). Whereas the selection cuts in the past analysis had efficiencies of the order of 1% in the relevant $\tilde{q}$ and $\tilde{g}$ mass range, we hope to achieve, with the upgraded detectors, efficiencies of up to 10%, while keeping the backgrounds at a manageable level.

From this we conclude that $\tilde{q}$, $\tilde{g}$ production will be observable with integrated luminosities of 10 pb^{-1} , provided the production cross-section are larger than 10 pb, given the 10% selection efficiency. Fig. 20 shows the summed production cross-section for $\tilde{q}$, $\tilde{g}$ at ACOL and TEVATRON as a function of the $\tilde{q}$ and $\tilde{g}$ masses. The upgraded detectors at ACOL should be sensitive to $\tilde{q}$ and $\tilde{g}$ masses below $120 \text{ GeV}/c^2$, whereas the detectors at TEVATRON should reach $\tilde{q}$ and $\tilde{g}$ masses of about $200 \text{ GeV}/c^2$.

Figure 20

Cross-sections for production of $\tilde{q}$ and $\tilde{g}$ at ACOL ($\sqrt{s} = 630 \text{ GeV}$) and TEVATRON ($\sqrt{s} = 1800 \text{ GeV}$), summed over $q\bar{q}, q\bar{q}\tilde{\chi}$ and $g\tilde{g}$ production, as a function of the $\tilde{q}$ and $\tilde{g}$ masses.

5.1.2 Search for scalar leptons and gauginos.

Scalar leptons ($\tilde{e}, \tilde{\mu}, \tilde{\nu}$) and gauginos ($\tilde{W}$) can be produced with observable rates in W, Z decays. UA1 and UA2 have published limits on $W \rightarrow e\tilde{\nu}$ [50], $Z \rightarrow \tilde{e}\tilde{e}$ and $Z \rightarrow \tilde{W}\tilde{W}$ [51] decays. The final states are characterized by one or two leptons and missing transverse momentum. The background from $W \rightarrow e\nu$, $W \rightarrow \tau \rightarrow e\nu\nu_\tau$ and continuum Drell-Yan production can be overcome with kinematic cuts. Therefore we expect these searches to be pushed to their kinematic limits in the near future. Fig. 21 shows as an example the limits which will be obtained by UA2 at ACOL from the decay $Z \rightarrow \tilde{e}\tilde{e} \rightarrow ee\tilde{\gamma}\tilde{\gamma}$ as a function of the scalar electron and photino masses. Also shown in Fig. 21 are the present existing limits from experiments at PETRA and PEP.

Figure 21

Expected limits on $\tilde{e}$ and $\tilde{\gamma}$ masses at 90% confidence level from a search for $Z \rightarrow \tilde{e}\tilde{e} \rightarrow ee\tilde{\gamma}\tilde{\gamma}$ decays in UA2 at ACOL.

5.2 Search for additional vector bosons.

Fig. 22 shows the production cross-sections for additional charged, W' , or neutral, Z' , vector bosons at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1.8$ TeV, assuming standard couplings to leptons and quarks, and for $W' \rightarrow e\nu$ or $Z' \rightarrow ee$ decays. Fig. 22 shows the obvious benefit of higher $\sqrt{s}$. Whereas the mass limits at ACOL will be $300 \text{ GeV}/c^2$ for a W' and $250 \text{ GeV}/c^2$ for a Z' , they increase to $650 \text{ GeV}/c^2$ for a W' and $550 \text{ GeV}/c^2$ for Z' at TEVATRON. Since there are no known sources of background to the very high transverse momentum electrons and very high mass electron pairs expected from W' and Z' decays, this is clearly a field where high-energy hadron colliders play a unique role, by making a large mass range accessible to experiments.

Figure 22

Production of additional charged (W') and neutral (Z') vector bosons at ACOL and TEVATRON as a function of their mass, assuming standard couplings to leptons and quarks.

6. CONCLUSION

The upgraded experiments at ACOL will eagerly take data in the next few years, in order to test more precisely the prediction of the Standard Model, and hopefully to find its missing elements. The search for the top quark will be the primary goal. But there is also the hope of discovering new physics, which will in most cases also be accessible to TEVATRON, SLC and LEP.

REFERENCES

1. Jones, E., et al., Design study of an antiproton collector (ACOL), ed. E.J.N. Wilson (CERN 83-10, Geneva, 1983);
Jones, E., et al., IEEE Trans. Nucl. Sci. NS-30 (4), 2778 (1983).
2. UA6 Collaboration, "Experiments at CERN in 1987", Geneva, p. 97, (1987).
3. UA8 Collaboration, "Experiments at CERN in 1987", Geneva, p. 101, (1987).
4. UA1 Collaboration, Dowell, J.D., "Proc. 6th Topical Workshop on Proton-Antiproton Collider Physics", Aachen, 1986, eds. K. Eggert et al., (World Scientific, Singapore, 1987), p. 419, and references therein.
5. Albrow, M., et al., Nucl. Instrum. Methods A265, 303 (1988).
6. UA2 Collaboration, Booth, C., same as Ref. [4], p. 381, and references therein.
7. Beer, A., et al., Nucl. Instrum. Methods 224, 360 (1984).
8. UA2 Collaboration, "Proposal for the Installation of a Second Silicon Array in the UA2 Detector", CERN/SPSC 87-14, SPSC/P93 Add. 4 (1987).
9. Bagnaia, P. and Ellis, S.D., "CERN Collider Results and the Standard Model", CERN-EP/88-62, to be published in Ann. Rev. of Nucl. Sci..
10. UA1 Collaboration, Arnison, G., et al., Phys. Lett. 172B, 461 (1986).
11. UA2 Collaboration, Appel, J.A., et al., Phys. Lett. 160B, 349 (1985).
12. Jenni, P., "Proc. Workshop on Physics in the 90's at the SPS Collider, Zinal", 1985, ed. R. Budde (CERN, Geneva, 1985), p. 64.

13. Structure functions from Eichten, E., et al., Rev. Mod. Phys. 56, 579 (1984) have been used.
14. Eichten, E., et al., Phys. Rev. Lett. 50, 811 (1983).
15. Combridge, B.L., Kripfganz, J. and Ranft, J., Phys. Lett. 70B, 234 (1977);
see also : Cutler, R. and Sivers, D., Phys. Rev. D17, 196 (1978).
16. UA1 Collaboration, Arnison, G., et al., Phys. Lett. 136B, 294 (1984).
17. UA2 Collaboration, Bagnaia, P., et al., Phys. Lett. 144B, 283 (1984).
18. Cohen-Tannoudji, G., et al., Phys. Rev. D28, 1628 (1983);
Combridge, B.L. and Maxwell, C.J., RL-83-095 (1983) ;
Halzen, F. and Hoyer, P., Phys. Lett. 130B, 326 (1983).
19. UA1 Collaboration, Arnison, G., et al., Phys. Lett. 177B, 244 (1986).
20. UA1 Collaboration, Arnison, G., et al., Phys. Lett. 158B, 494 (1985).
21. UA2 Collaboration, Appel, J.A., et al., Z. Phys. C30, 341 (1986).
22. UA1 Collaboration, Arnison, G., et al., Phys. Lett. 158B, 494 (1985).
23. UA2 Collaboration, Meier, K., to appear in "Proc. Advanced Research Workshop on QCD Hard Hadron Processes", St. Croix, Virgin Islands, Oct. 8-13, 1987.
24. Kunszt, Z. and Stirling, W.J., "Multijet cross-sections in hadronic collisions", Proc. Workshop on Physics at Future Accelerators, La Thuile 1987, CERN 87-07, Vol. II, p. 548 (1987).
25. Paver, N. and Treleani, D., Nuovo Cimento 70A, 215 (1982);
Humpert, B., Phys. Lett. 131B, 461 (1983).

26. UA2 Collaboration, Einsweiler, K., "Proc. XXI Rencontre de Moriond",
Les Arcs, 16-22 March 1986, Editions Frontières, p. 9 (1986).
27. Aurenche, P., et al., Phys. Lett. 140B, 87 (1984);
Aurenche, P., et al., Nucl. Phys. B297, 661 (1988).
28. UA2 Collaboration, Appel, J.A., et al., Phys. Lett. 176B, 239 (1986).
29. UA1 Collaboration, Albajar, C., et al., CERN-EP/88-45 (1988),
submitted to Phys. Lett. B.
30. Altarelli, G., et al., Nucl. Phys. B246, 12 (1984);
Altarelli, G., et al., Z. Phys. C27, 617 (1985).
31. Cabibbo, N., Proc. Third Topical Workshop on Proton-Antiproton
Collider Physics, Rome, 1983, CERN 83-04, Geneva. p. 567 (1983);
Halzen, F., and Mursula, K., Phys. Rev. Lett. 51, 857 (1983) ;
Hikasa, K., Phys. Rev. D29, 1939 (1984).
32. DiLella, L., Proton-Antiproton Collider Physics : Experimental
Aspects, CERN-EP/88-02.
33. Ruhlmann, V., Thèse de Doctorat, Université de Paris VI (1988);
Jakobs, K., Ph. D. Thesis, University of Heidelberg (1988).
34. Stirling, W.J., and Bawa, A.C., DPT/87/42 (1987).
35. Altarelli, G., et al., in Physics at LEP, eds. J. Ellis and
R. Peccei, CERN 86-02, Geneva, p. 3 (1986).
36. Brown, R.W., and Mikaelian, K.O., Phys. Rev. D19, 922 (1979);
Eichten, E., et al., Rev. Mod. Phys. 56,579 (1984).
37. Stirling, W.J., et al., Phys. Lett. 163B, 261 (1985).
38. UA1 Collaboration, Albajar, C., et al., Phys. Lett. 186B, 237 (1987);
and Phys. Lett. 186B, 247 (1987).

39. UA1 Collaboration, Albajar, C., et al., Z. Phys. C37, 505 (1988);
Ellis, J., et al., Phys. Lett. 192B, 201 (1987).
40. Altarelli, G., et al., CERN preprint, CERN-TH/4978/88.
41. Moniez, M., Thèse d'Etat, LAL preprint, LAL 88-17 (1988).
42. Eichten, E., et al., Rev. Mod. Phys. 56, 579 (1984).
43. UA1 Collaboration, Albajar, C., et al., Phys. Lett. 185B, 241 (1987).
44. Glashow, S.L., et al., Phys. Rev. C18, 1724 (1978).
45. For a review see : Fayet, P. and Ferrara, S., Phys. Rep. 32, 249 (1977).
46. Langacker, P., et al., Phys. Rev. D30, 1470 (1984).
47. Baur, U., et al., preprint MPI-PAE/PTH 29/85 (1985).
48. Cohen, E., et al., Phys. Lett. B165, 419 (1987);
del Aguila, F., et al., Nucl. Phys. B287, 419 (1987) ;
London, D. and Rosner, J., Phys. Rev. D34, 1530 (1986).
49. Dawson, S., et al., Phys. Rev. D31, 1581 (1985).
50. UA1 Collaboration, Arnison, G., et al., Europhys. Lett. 1, 327 (1986).
51. UA2 Collaboration, Ansari, R., et al., Phys. Lett. B195, 613 (1987).