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INTRODUCTION

Because of their high centre-of-mass energies, the proton-antiproton colliders at CERN and FNAL offer very large cross-sections for producing pairs of charm and bottom particles. At the CERN $p\bar{p}$ Collider ($\sqrt{s} = 630$ GeV) the predicted cross-sections¹ are $\sigma(c\bar{c}) \approx 100 \mu\text{b}$ and $\sigma(b\bar{b}) \approx 10 \mu\text{b}$. The integrated luminosity delivered to UA1 is $\sim 1 \text{ pb}^{-1}$, so $\sim 10^8$ $c\bar{c}$ and $\sim 10^7$ $b\bar{b}$ pairs must have already been produced. The Antiproton Collector (ACOL) ring at CERN will increase the luminosity of the CERN Collider by about a factor of 20.

Whilst very large numbers of bottom and charm pairs have been produced at CERN in the UA1 detector, it is a difficult task to separate them from the enormous background of light quark and gluon jets, for which the cross-section is ~ 10 mb. The signature of 'prompt', high- p_T muons from semileptonic decays provides the required background rejection power. In UA1, an inclusive muon trigger selects events with candidate prompt muons, with a transverse momentum (measured relative to the direction of the beams) of $p_T^\mu > 3$ GeV/c in the pseudorapidity interval $|\eta| < 1.5$. In order to reduce the background to the muon sample, from decays in flight of pions and kaons, it is necessary to impose a harder cut on the muon transverse momentum, $p_T^\mu > 6$ GeV/c, when analysing single-muon events, although for dimuon events it is possible to work with muon transverse momenta down to 3 GeV/c.

By selecting $c\bar{c}$ and $b\bar{b}$ events containing a muon with $p_T^\mu > 6$ GeV/c, the background from light quark and gluon jets is reduced to an acceptable level. However, only a small fraction of the $c\bar{c}$ and $b\bar{b}$ events which are produced are selected. The heavy quark or antiquark must have a semimuonic decay (branching ratio $\sim 10\%$), and muons with $p_T^\mu > 6$ GeV/c are produced only by c-quarks or b-quarks of rather high p_T . Nevertheless, one is left with a large sample containing several thousand bottom events, the analysis of which is described in the first part of this paper.

There might be the temptation to perform a similar analysis using electrons rather than muons. However, the lepton from the semileptonic heavy-flavour decay is accompanied by hadronic fragmentation and decay products. In UA1 it is only possible to obtain adequate separation between electrons and the background from light quark and gluon jets when the electrons are isolated and at very high p_T : $p_T^e > 12$ GeV/c. It is therefore not possible to use the electron channel for studying charm and bottom production, although it can be used when searching for new, massive flavours of quarks.

The cross-section for producing top (t) at the CERN Collider is substantial, even for t-quark masses as large as $m_t = 50$ GeV/c², for which $\sigma(p\bar{p} \rightarrow W \rightarrow t\bar{b}) + \sigma(p\bar{p} \rightarrow t\bar{t}) \approx 1$ nb is calculated. This corresponds to $\sim 10^3$ events produced, although only a few per cent of these would be detected with semileptonic decays to electrons or muons in the UA1 experiment. Existing limits on the masses of new quarks from measurements at e^+e^- colliders are: $m_t > 26$ GeV/c² (from TRISTAN²) and $m_{b'}/ > 22.7$ GeV/c² (from PETRA³), where b' is a new charge $-\frac{1}{3}$ quark. Recent measurements of $B^0-\bar{B}^0$ mixing^{4,5} have been interpreted⁶ as an indication of a high t-quark mass, $m_t \gtrsim 50$ GeV/c². Measurements of the Standard Model parameters $\sin^2\theta_w$ and q at the CERN

Collider and in deep-inelastic scattering experiments can be interpreted to give an upper limit on the t-quark mass $m_t < 180 \text{ GeV}/c^2$.

The sensitivity of experiments at proton-antiproton colliders to new, massive quarks depends on the production cross-section. If the t-quark mass is below the W mass, $t\bar{t}$ pairs will be produced in decays of W bosons. The cross-section for this process is reliably calculable since it can be normalized to measurements of $p\bar{p} \rightarrow W \rightarrow e\nu$, allowing for colour, phase-space, and radiative corrections. Direct production of $t\bar{t}$ pairs can be calculated using perturbative QCD, but with greater uncertainty than in the case of $W \rightarrow t\bar{t}$. A search for new quarks using events with muons or electrons and jets is described in the second part of this paper. Further details of this work can be found elsewhere.^{7,8}

CHARM AND BOTTOM PRODUCTION

Results from Measurements of Dimuon Production

We have reported⁹ on measurements of dimuon production in proton-antiproton interactions at $\sqrt{s} = 540 \text{ GeV}$ and 630 GeV . Events were selected if both muons were reconstructed with $p_T^\mu > 3 \text{ GeV}/c$ and with a dimuon mass $m_{\mu\mu} > 6 \text{ GeV}/c^2$, and if the muons were accompanied by hadrons. For $b\bar{b}$ pairs with both quarks having $p_T > 5 \text{ GeV}/c$ and $|\eta| < 2.0$, the ISAJET Monte Carlo program¹⁰ and a simulation of the UA1 detector were used to calculate the probability of producing and detecting dimuon events passing the above selection. The main process contributing to this event sample is flavour creation, mainly from gluon fusion. The higher-order processes—gluon splitting and flavour excitation—which are illustrated in Figs. 1b and 1c, are suppressed by the requirements on the dimuon mass and the muon transverse momenta, respectively: in gluon splitting, the b-quark and $\bar{b}$ -quark tend to be collinear and cannot give rise to high-mass muon pairs. In flavour excitation, the ‘spectator’ b-quark normally has low p_T and cannot decay to give a high- p_T muon. The cross-section which is quoted,

$$\sigma(p\bar{p} \rightarrow b\bar{b}; \quad p_T^b > 5 \text{ GeV}/c; \quad |\eta| < 2.0) = 1.1 \pm 0.1 \pm 0.4 \mu\text{b},$$

is for the flavour-creation process only and is in reasonable agreement with the predicted cross-section of $1.7 \mu\text{b}$. The small contributions to the dimuon sample from the flavour-excitation and gluon-splitting processes have been subtracted using the Monte Carlo calculation. Similarly, the small contribution from $c\bar{c}$ production has been subtracted. The large systematic error which is quoted is partly a result of the uncertainty in subtracting these background processes. Other uncertainties which are included are: the parametrization of the b-quark fragmentation function; the average branching ratio for bottom hadrons to muons; the subtraction of background from decays in flight of pions and kaons; and the luminosity measurement.

We have also reported the first evidence of B^0 - $\bar{B}^0$ mixing⁴ from the large fraction of like-sign muon pairs that are observed. We measured $\chi = 0.121 \pm 0.047$, where χ is the fraction of bottom hadrons which decay to ‘wrong-sign’ muons, i.e. $\chi = \text{BR}(b \rightarrow \bar{B}^0 \rightarrow B^0 \rightarrow \mu^+)/\text{BR}(b \rightarrow B \rightarrow \mu^+)$, where the denominator includes all bottom hadrons, including baryons. In the absence of B^0 - $\bar{B}^0$ mixing, $\chi = 0$.

Fig. 1. Illustration of Feynman diagrams: a) gluon fusion, b) gluon splitting, c) flavour excitation.

Fig. 2. Inclusive muon cross-section for $|\eta| < 1.5$ for raw data and background.

Inclusive Muon Data Sample

Events containing $p_T > 6$ GeV/c muon candidates were selected inclusively. This yielded $\sim 20,000$ events, recorded at a centre-of-mass energy of 630 GeV for an integrated luminosity of 556 nb^{-1} . The pseudorapidity acceptance of the first-level muon trigger was limited to about ± 1.5 so as to maintain an acceptable rate. For $|\eta| < 1.5$, the geometrical acceptance times reconstruction efficiency for $p_T^\mu > 6$ GeV/c was about 33%.

Muons were identified in the central detector (CD) by a high- p_T track which, when extrapolated through more than 9 interaction lengths of lead and iron shielding, matched with a track in the muon chambers.

A number of sources of background to prompt muons were considered. Non-interacting hadrons and shower leakage can be neglected because of the very thick shielding between the interaction point and the muon chambers. Leakage through cracks in the shielding was eliminated by fiducial cuts. Cosmic-ray tracks which cross the CD, passing close to an interaction vertex, were identified and removed by software. Misassociation of high- p_T tracks in the CD with tracks in the muon chambers was rendered negligible by tight cuts in the matching, in position and angle, between the extrapolated CD track and the track in the muon chambers.

The only significant background to prompt muons comes from decays in flight of pions and kaons. This background to the inclusive muon sample was calculated using real events recorded with a minimum-bias trigger. Decays in flight of high- p_T particles in the events were simulated, assuming a charged-particle composition of 58% $\pi^\pm$, 23% $K^\pm$, and 19% p and $\bar{p}$, based on measurements from the CERN Collider.¹¹ All the selection criteria, including the trigger algorithm, were applied to the simulated muon events. The events were weighted according to the probability of the high- p_T pion or kaon decaying in flight before interacting in the shielding.

The inclusive muon cross-section is shown in Fig. 2 as a function of p_T^μ , both for the data and for the background. The acceptance was calculated assuming a flat pseudorapidity distribution for $|\eta| < 1.5$. Note that the background fraction falls rapidly with p_T , from over 70% at 6 GeV/c to about 35% for $p_T > 10$ GeV/c. The systematic error on the background calculation is estimated to be $\pm 20\%$, largely due to the uncertainty on the charged-particle fractions.

QCD-Based Monte Carlo Model

The Monte Carlo model¹⁰ used in this analysis was the ISAJET program, version 5.23. This was tuned to e^+e^- data for charm and bottom fragmentation and decays, and to UA1 data for the

Fig. 3. Components of the ISAJET model.

underlying event. Technical modifications were made to improve the efficiency for generating heavy-flavour events with semileptonic decays. The generated Monte Carlo events were passed through a detailed simulation of the UA1 detector, and reconstructed using the same programs as for the real data.

Monte Carlo samples corresponding to an integrated luminosity of 10 pb^{-1} were produced for the following processes:

- i) W and Z production with all decay modes simulated; the cross-sections were normalized to measurements¹² of $W \rightarrow \ell \nu$ and $Z \rightarrow \ell^+ \ell^-$;
- ii) the Drell-Yan mechanism, normalized to the measured cross-section;⁹
- iii) high- p_T T and J/ψ production, normalized to the measured cross-sections;^{9,13}
- iv) QCD production of charm and bottom particles. For this process, the cross-section was predicted by the ISAJET Monte Carlo calculation.

In each of the above cases, the generated events were processed only if they contained high- p_T muons or electrons.

The ISAJET model for charm and bottom production is illustrated in Fig. 3. The momenta of the partons which enter the hard-scattering interaction are determined by the structure functions (EHLQ set 1).¹⁴ The matrix element for the hard scattering is calculated¹ exactly to $O(\alpha_s^2)$, taking $Q^2 = 2 \text{ stu}/(s^2 + t^2 + u^2)$. The QCD radiation is included in the branching approximation.¹⁵ This allows for *gluon splitting* (in the final state) into heavy-quark pairs, and *flavour excitation*, where a gluon splits into a heavy-quark pair in the initial state, as well as the lowest-order *flavour-creation* diagram, as illustrated in Fig. 1. Gluon radiation from the incoming and outgoing partons is also simulated. The outgoing partons are fragmented independently, using the Peterson et al. parametrization¹⁶ with $\epsilon_c = 0.30$ for charm and $\epsilon_b = 0.02$ for bottom. The particles which are produced in the fragmentation are allowed to decay using measured branching ratios where possible; for bottom particles the measured average branching ratio of 12% is used. Semileptonic decays are simulated using V - A matrix elements; other decays are simulated using phase space only.

The underlying event due to the break-up of the spectator systems is simulated using a phenomenological model. It was found necessary to scale down the average charged-particle multiplicity in the spectator system so as to reproduce the level of activity in the data.

Comparison of Predictions and the Data

The predicted inclusive muon cross-section is compared with the data in Fig. 4 as a function of p_T^μ , for $|\eta| < 1.5$. The contribution from $W \rightarrow \mu \nu$ and $Z \rightarrow \mu^+ \mu^-$ decays is shown separately and dominates at large p_T . The large error bars on the data points at low p_T are due to the uncertainty on the background which is subtracted. Good agreement is observed between the prediction and the data over the entire range from 6 GeV/c to 100 GeV/c.

In order to study further the heavy-flavour content of the sample, a selection of events was made with $10 \text{ GeV/c} < p_T^\mu < 15 \text{ GeV/c}$ and $|\eta| < 1.5$. The decays $W \rightarrow \mu \nu$ and $Z \rightarrow \mu^+ \mu^-$

Fig. 4. Inclusive muon cross-section for $|\eta| < 1.5$ after background subtraction.

Fig. 5. Distribution of p_T^{rel} for a subsample of $p_T^{\mu} > 10 \text{ GeV/c}$ muon events.

contribute very little to this sample, and the uncertainty on the background subtraction is not too large. The predicted composition of the data in this sample is 69% bottom decays, 24% charm decays, 5% Drell-Yan mechanism, and $J/\psi \rightarrow \mu^+ \mu^-$ and $\Upsilon \rightarrow \mu^+ \mu^-$ decays, and only 2% $W \rightarrow \mu \nu$ and $Z \rightarrow \mu^+ \mu^-$ decays. The total predicted cross-section is 3.54 nb compared with the measured cross-section of $4.33 \pm 0.20 \pm 0.36 \text{ nb}$. This agreement is surprisingly good considering the large theoretical uncertainties due to the choice of structure functions, to the Q^2 scale, and to unknown terms of higher order in α_s .

The predicted cross-section for producing high- p_T muons from bottom decays exceeds that from charm decays owing to the harder bottom fragmentation function. For muons with p_T^{μ} in excess of 10 GeV/c , only charm and bottom quarks with $p_T^Q \gg m_Q$ contribute, so there is little suppression due to the higher b-quark mass. The relative contribution of bottom and charm decays was measured for the subsample of events with muons of $p_T^{\mu} > 10 \text{ GeV/c}$, containing at least one jet reconstructed in the calorimeters with $E_T > 10 \text{ GeV}$, and with a well-defined charged-particle jet reconstructed near the muon in the CD.

The variable p_T^{rel} is defined as the momentum of the muon perpendicular to the direction of the accompanying charged-particle jet; it is sensitive to the mass of the object which decays to produce the muon and the jet. The distribution of the data in this variable is shown in Fig. 5, together with the predicted distribution for bottom and charm decays and for the background. The solid curve is the result of a fit to the data with a sum of the background (fixed) and the bottom and charm contributions, which were allowed to vary. The result of the fit is $b\bar{b}/(b\bar{b} + c\bar{c}) = 76 \pm 8 \pm 9\%$, compared with the ISAJET prediction of 74% for this sample. Similar good agreement was found using an equivalent method for the dimuon data.⁹

It has been shown that the ISAJET model accounts well for the observed yield of high- p_T muons from bottom and charm decays, and that the relative contribution of bottom and charm is correctly described.

The use of the branching approximation in ISAJET makes possible the simulation of multijet events. A study has been made of how well this model describes the data.

Events were selected requiring a muon with $10 \text{ GeV/c} < p_T^{\mu} < 15 \text{ GeV/c}$ (to reduce the background from pion and kaon decays in flight, and $W \rightarrow \mu \nu$ and $Z \rightarrow \mu^+ \mu^-$ decays), and at least one jet reconstructed in the calorimeters with $E_T > 12 \text{ GeV}$ and separated from the muon by at least one unit in pseudorapidity-azimuth space: $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 1$. The number of jets (N^{jets}) in each event was then counted, including only those jets reconstructed in the calorimetry with

Fig. 6. Comparison of ISAJET predictions and the data for muon-jet events: a) number of jets, b) E_T of highest- E_T jet, c) E_T of second-highest- E_T jet, d) angular distribution of second-highest- E_T jet.

$E_T > 7$ GeV, validated by a charged track reconstructed in the CD with $p_T > 0.5$ GeV/c, and with $\Delta R > 1$ between the jet and the muon. Hadronic energy accompanying the muon, i.e. within the $\Delta R < 1$ cone, is considered separately.

The distribution of N^{jets} in the muon-jet events is shown in Fig. 6a, together with the predictions from the ISAJET model and the background calculation. Excellent agreement is observed. The E_T distributions of the highest- E_T jet (j_1) and of the second-highest- E_T jet (j_2) are plotted in Figs. 6b and 6c. Note that the decay background has E_T distributions softer than those of the data. The angular distribution of the second-highest- E_T jet is shown in Fig. 6d; $\theta_{j_2}^*$ is measured relative to the direction of the $\bar{p}$ beam in the centre of mass of the muon, the two jets, and the neutrino for which only the transverse components were used. The peak towards $|\cos \theta^*| = 1$, associated with initial-state radiation collinear with the beams, is well reproduced by the Monte Carlo.

The distribution of missing transverse energy E_T^ν measured in the muon-jet events is plotted in Fig. 7, together with the predictions from the ISAJET model and the background calculation. The distribution at low E_T^ν is determined mainly by the resolution of the detector, whilst the high- E_T^ν part of the distribution is due to neutrinos from bottom and charm semileptonic decays and from severe momentum mismeasurements caused by kinks in kaon decay tracks. The entire distribution is well reproduced.

Fig. 7. Comparison of ISAJET prediction and the data for missing transverse energy in muon-jet events.

Fig. 8. Comparison of ISAJET prediction and the data for the isolation of the muons in muon-jet events.

The amount of activity near the muons in the muon-jet events can be studied using both the calorimeters and the CD. A combined isolation variable, $I = \sqrt{(\Sigma E_T/3)^2 + (\Sigma p_T/2)^2}$, is chosen because of the complementary geometrical acceptance of the two detectors; ΣE_T and Σp_T are the transverse energy and transverse momentum sums of calorimeter cells and charged tracks in a cone of radius $\Delta R = 0.7$ about the muon direction. The distribution of the data in this variable is shown in Fig. 8 together with predictions from the ISAJET model and the background calculation. The predictions account well for the data; this is also true if ΣE_T and Σp_T are plotted separately.

Conclusions on Charm and Bottom Production

The large rate of high- p_T^μ events in the UA1 experiment at the CERN $p\bar{p}$ Collider is well reproduced by the QCD-based ISAJET model of charm and bottom production with semileptonic decays. This follows earlier UA1 measurements in the dimuon channel.^{4,9} Recent UA1 measurements¹³ of high- p_T J/ψ production through $B \rightarrow J/\psi$ decays are well reproduced by the same Monte Carlo program.

The ISAJET model includes terms of orders higher than α_s^2 using the branching approximation. Predictions for a number of distributions which are sensitive to higher-order processes have been compared with the data and found to fit well.

SEARCH FOR NEW HEAVY QUARKS

Expected Features of Top-Quark Events

Top-quarks may be produced in $W \rightarrow t\bar{b}$ or $Z \rightarrow t\bar{t}$ decays if they are sufficiently light, or in direct QCD $t\bar{t}$ production. In either case, the t-quark is expected to decay semileptonically with a branching ratio of about 1/9 per lepton: $t \rightarrow \ell\nu b$. Owing to the high mass of the t-quark, the decay products will usually have high momenta and be well separated from each other. Because of this, the lepton is expected to be 'isolated', i.e. unaccompanied by hadrons. In the case of $W \rightarrow t\bar{b}(t \rightarrow \ell\nu b)$ decays, two jets are expected, one from the $\bar{b}$ -quark and one from the b-quark. For $t\bar{t}$ production with $t \rightarrow \ell\nu b$, up to four jets are expected since the $\bar{t}$ will mostly decay to three lighter quarks which may be identified as separate jets. Thus a signature for t-quark decays is an isolated lepton with a high- p_T neutrino and at least two jets. The observation of six such events in data from the 1983 CERN Collider run, for which the integrated luminosity was 108 nb^{-1} , led to conjecture that top had been observed.¹⁷ This paper describes a search for new heavy quarks in a larger sample, corresponding to about 700 nb^{-1} .

The ISAJET Monte Carlo program¹⁰ was used to make predictions for top production. For $p\bar{p} \rightarrow W \rightarrow t\bar{b}$ production and decay, the cross-section was normalized to measurements¹² of $p\bar{p} \rightarrow W \rightarrow \ell\nu$. For direct QCD production, $p\bar{p} \rightarrow t\bar{t}$, the cross-section was normalized to a calculation made with the EUROJET Monte Carlo program,¹⁸ which includes terms to $O(\alpha_s^3)$ at the tree level. The structure functions were EHLQ set 1,¹⁴ and $Q^2 = m^2 + p_T^2$ and $\Lambda = 0.2 \text{ GeV}/c^2$ were used. The sensitivity of the calculation of cross-sections to these parameters is described later.

To search for evidence of t -quark decays, events were selected with $p_T^\mu > 10$ GeV/c, at least one jet with $E_T > 12$ GeV, and $\Delta R > 1$, and by requiring the muon-neutrino transverse mass $m_T^{\mu\nu}$ to be less than 40 GeV/c² in order to remove $W \rightarrow \mu\nu$ decays. The distribution of these events in the isolation variable $I = \sqrt{(\Sigma E_T/3)^2 + (\Sigma p_T/2)^2}$ is shown in Fig. 9a. Also shown is the distribution expected from charm and bottom decays and from the other processes discussed earlier, plus the background from decays in flight of pions and kaons. For illustration, the predicted additional contribution from the t -quark is shown (shaded) for $m_t = 30$ GeV/c². The data are consistent with the prediction without top. The effects of additional cuts are shown in Figs. 9b and 9c, where the signal-to-background ratio predicted for $m_t = 30$ GeV/c² improves. In Fig. 9b the muon is required to have $p_T^\mu > 12$ GeV/c (instead of 10 GeV/c) and the jet is required to have $E_T^{j1} > 15$ GeV (instead of 12 GeV). In Fig. 9c, a second jet with $E_T^{j2} > 7$ GeV is required in addition. From the number of events observed with $I < 2$ in Fig. 9c, and taking the EUROJET normalization for the $t\bar{t}$ production cross-section, one obtains a limit on the mass of the t -quark: $m_t > 41$ GeV/c² at 95% CL.

A slightly improved limit can be obtained by performing a likelihood fit to the four event variables I , E_T^ν , E_T^{j1} , and $|\cos\theta_{j2}|$ which are plotted in Fig. 10 for the sample of events with $p_T^\mu > 12$ GeV/c, $m_T^{\mu\nu} < 40$ GeV/c², $I < 10$, $E_T^{j1} > 12$ GeV, and $E_T^{j2} > 7$ GeV; this yields the limits shown in Fig. 11. Systematic errors have been included for the energy scale, the selection efficiency, the integrated luminosity, the cross-section for $p\bar{p} \rightarrow W \rightarrow t\bar{b}$, and the background calculation. From the intersection of the predicted cross-section (EUROJET calculation for $t\bar{t}$ production) and the 95% CL contour, one obtains $m_t > 43$ GeV/c² from the muon channel only.

Fig. 9. Isolation distributions with progressively more restrictive selection criteria.

Fig. 10. Distributions used in the likelihood fit: a) isolation variable, b) missing transverse energy, c) E_T of highest- E_T jet, d) angular distribution of second-highest- E_T jet.

Fig. 11. Cross-section limits for t -quark production from the muon channel.

Search for the Top-Quark in the Electron Channel

The search for the t -quark in the electron channel closely parallels the one in the muon channel. The possibility to study non-isolated and semi-isolated muons was an important aspect of the preceding analysis, which is not possible here. However, semileptonic charm and bottom decays to muons and electrons should be similar, so the results from the muon channel can be taken over to the electron channel.

Electron candidates were selected by requiring a transverse energy cluster in the e.m. calorimeters with $E_T^e > 15$ GeV, matched in position and momentum by a charged track reconstructed in the CD with $p_T^e > 10$ GeV/c. The shower shape in profile and in depth was required to be compatible with an electron. A very strong isolation requirement was made on the electron:

$$\Sigma E_T < 0.1 E_T^e \text{ in } \Delta R < 0.7,$$

$$\Sigma p_T < 0.1 p_T^e \text{ in } \Delta R < 0.7,$$

$$\Sigma E_T < 1 \text{ GeV in } \Delta R < 0.4,$$

$$\Sigma p_T < 1 \text{ GeV/c in } \Delta R < 0.4.$$

This is considerably stronger than the isolation requirement made in the muon channel, and is required in order to control the background from light quark and gluon jets which fluctuate into a single, high- p_T charged particle and a number of π^0 's. Photon conversions in the beam pipe or CD were removed by scanning.

The number of electron candidates selected was 205 for an integrated luminosity of 689 nb^{-1} . Of these, 119 events had $m_T^{e\gamma} > 45 \text{ GeV}/c^2$ and were removed as probable $W \rightarrow e\nu$ events, and a further 26 had a second candidate electron with $E_T^e > 6 \text{ GeV}$ and were removed as probable Drell-Yan or $\Upsilon \rightarrow e^+e^-$ decay events. Of the remaining 60 events, only 26 had a jet with $E_T^e > 12 \text{ GeV}$ outside a cone radius of $\Delta R = 1$ about the electron.

The background to the electron-jet sample from overlapping $\pi^\pm$ and π^0 's was estimated to be $6.3 \pm 0.5 \pm 1.1$ events.¹⁹ The background due to Dalitz pairs and to unrecognized converted photons, mainly from $\pi^0 \rightarrow \gamma\gamma$ decays, was estimated to be 1.8 ± 0.7 events.¹⁹ The estimated contribution to the sample of events with an electron and at least one jet due to charm and bottom semileptonic decays and to the other processes discussed earlier, is 15.3 events.

Combining these sources of electron-jet events, the total number expected is $23.6 \pm 0.9 \pm 2.7$ compared with 26 observed, leaving little room for a contribution from t -quark decays. This leads

Fig. 12. Distributions used in likelihood fit: a) missing transverse energy, b) number of jets.

Fig. 13. Cross-section limits for t-quark production from the electron channel.

to a limit, based only on the number of events, of $m_t > 36 \text{ GeV}/c^2$ at 95% CL, taking the EUROJET cross-section for $t\bar{t}$ production.

As for the muon channel, a better limit can be obtained using a likelihood fit to event variables. Fitting to the two variables E_T^{miss} and N^{jets} which are plotted in Fig. 12 yields the limits shown in Fig. 13. Systematic errors have been included for the energy scale, the selection efficiency, the integrated luminosity, the cross-section for $p\bar{p} \rightarrow W \rightarrow t\bar{b}$, and the background calculation. From the intersection of the predicted cross-section (EUROJET calculation for $t\bar{t}$ production) and the 95% CL contour, one obtains $m_t > 47 \text{ GeV}/c^2$ at 95% CL from the electron channel only.

Mass Limits Combining Muon and Electron Channels

By combining the likelihood distributions from the muon and electron channels, the limits shown in Fig. 14 are obtained. From the intersection of the predicted cross-section (EUROJET calculation for $t\bar{t}$ production) and the 95% CL contour, one obtains $m_t > 56 \text{ GeV}/c^2$ at 95% CL. Note that it is not yet possible to set a mass limit at 95% CL for $W \rightarrow t\bar{b}$ production only. Therefore the uncertainty in the calculation of the $t\bar{t}$ production cross-section must be estimated before giving final mass limits. The effects of different choices of structure function, of the Q^2 scale, and of including $O(\alpha_s^3)$ terms, are shown in Fig. 15, expressed as a K-factor relative to the $O(\alpha_s^2)$ calculation, with EHLQ set 1 structure functions and $Q^2 = m^2 + p_T^2$. The lowest

Fig. 14. Combined cross-section limits for t-quark production from the muon and electron channels.

Fig. 15. Variation of predicted cross-sections with choice of parameters. The UA1 cross-section limit is indicated.

cross-section which was obtained was with Duke and Owens (DO) set 1 structure functions,²⁰ taking $Q^2 = \hat{s}$, and with $O(\alpha_s^2)$ terms only. This yields a conservative limit of $m_t > 44 \text{ GeV}/c^2$ at 95% CL. Note that the EUROJET calculation to $O(\alpha_s^3)$ which was used as a reference in this paper, and which corresponds to $K \approx 1.5$, is not untypical, and that other choices of structure function give higher cross-sections.

Cross-Section Limits for b' Production

The production, via QCD, of a new, heavy, charged $-\frac{1}{3}$ quark b' is similar to t-quark production. However, it is not expected to be produced in W decays since its partner is presumably very heavy. Limits are therefore presented assuming strong production of $b'\bar{b}'$ pairs only. Taking the $O(\alpha_s^3)$ EUROJET prediction for $b'\bar{b}'$ production, one obtains $m_{b'} > 44 \text{ GeV}/c^2$ at 95% CL. For the $O(\alpha_s^2)$ calculation with the most conservative choice of structure functions and Q^2 scale, $m_{b'} > 32 \text{ GeV}/c^2$ at 95% CL is obtained.

Conclusions on the Search for New Heavy Quarks

No evidence for new, heavy quarks is found in the UA1 muon or electron data. Taking a representative estimate of the production cross-sections, using the EUROJET Monte Carlo program which includes $O(\alpha_s^3)$ tree-level terms and EHLQ set 1 structure functions, and taking $Q^2 = m^2 + p_T^2$, one obtains at 95% CL:

$$\begin{aligned} m_t &> 56 \text{ GeV}/c^2, \\ m_{b'} &> 44 \text{ GeV}/c^2. \end{aligned}$$

Taking the lowest estimated production cross-sections, obtained using $O(\alpha_s^2)$ terms only, DO set 1 structure functions, and $Q^2 = \hat{s}$, one obtains at 95% CL:

$$\begin{aligned} m_t &> 44 \text{ GeV}/c^2, \\ m_{b'} &> 32 \text{ GeV}/c^2. \end{aligned}$$

Future measurements at the CERN and FNAL proton-antiproton colliders should be sensitive to the process $p\bar{p} \rightarrow W \rightarrow t\bar{b}$ only, allowing mass limits to be set with much less theoretical uncertainty. The interesting possibility of a very heavy t-quark decaying into real W's is discussed in the paper presented by Eggert at this Workshop.

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REFERENCES

1. B.L. Combridge, Nucl. Phys. **B151**:429 (1979).
2. H. Aihara (TOPAZ Collab.), 'Search for new heavy quarks and leptons', Univ. Tokyo preprint UT HE 87-10 (1987).
 K. Abe et al. (VENUS Collab.), 'Search for the top quark in e^+e^- annihilation at $\sqrt{s} = 50$ GeV: the first result from the VENUS detector at TRISTAN', KEK preprint P 87-79 (1987).
 H. Yoshida et al. (VENUS Collab.), 'Measurement of R and search for new heavy quarks in e^+e^- annihilation at 50 and 52 GeV centre-of-mass energies', KEK preprint P 87-81 (1987).
 H. Sagawa et al. (AMY Collab.), 'Measurements of R and a search for heavy quark production in e^+e^- annihilation at $\sqrt{s} = 50$ and 52 GeV', KEK preprint P 87-84 (1987).
3. H.J. Behrend et al. (CLEO Collab.), Phys. Lett. **144B**:297 (1984).
4. C. Albajar et al. (UA1 Collab.), Phys. Lett. **186B**:247 (1987).
5. H. Albrecht et al. (ARGUS Collab.), Phys. Lett. **192B**:245 (1987).
6. J. Ellis et al., Phys. Lett. **192B**:201 (1987);
 V. Barger et al., Phys. Lett. **194B**:312 (1987);
 I.I. Bigi and A.I. Sanda, Phys. Lett. **194B**:307 (1987).
7. C. Albajar et al. (UA1 Collab.), 'Study of heavy flavour production in events with a muon accompanied by jets at the CERN Proton-Antiproton Collider', preprint CERN-EP/87-189 (1987), to be published in Z. Phys. C.
8. C. Albajar et al. (UA1 Collab.), 'Search for new heavy quarks at the CERN Proton-Antiproton Collider', preprint CERN-EP/87-190 (1987), to be published in Z. Phys. C.
9. C. Albajar et al. (UA1 Collab.), Phys. Lett. **186B**:237 (1987).
10. F. Paige and S.D. Protopopescu, 'ISAJET Monte Carlo', Brookhaven report BNL 38034 (1986).
11. M. Banner et al. (UA2 Collab.), Phys. Lett. **122B**:322 (1983).
 G.J. Alner et al. (UA5 Collab.), Nucl. Phys. **B258**:505 (1985).
12. G. Arnison et al. (UA1 Collab.), Lett. Nuovo Cimento **44**:1 (1985).
 J.A. Appel et al. (UA2 Collab.), Z. Phys. **C30**:1 (1986).
13. C. Albajar et al. (UA1 Collab.), 'High-transverse-momentum J/ψ production at the CERN Proton-Antiproton Collider', preprint CERN-EP/87-175 (1987), to be published in Phys. Lett. B.
14. E. Eichten et al., Rev. Mod. Phys. **56**:579 (1984) and **58**:1065 (1986).
15. G.C. Fox and S. Wolfram, Nucl. Phys. **B168**:285 (1980).
 T. Sjöstrand, Phys. Lett. **157B**:321 (1985).
16. C. Peterson et al., Phys. Rev. **D27**:105 (1983).
17. G. Arnison et al. (UA1 Collab.), Phys. Lett. **147B**:493 (1984).
18. A. Ali et al., Nucl. Phys. **B292**:1 (1987).
19. UA1 Collaboration, Technical note UA1-TN 87-52 (1987), unpublished.
20. D.W. Duke and J.F. Owens, Phys. Rev. **D30**:49 (1984).