**Search for New Heavy Quarks in Proton-antiproton
Collisions at $\sqrt{s} = 0.63$ TeV**

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ABSTRACT

We report on a search for new heavy quarks decaying semileptonically into muons, using 4.7 pb^{-1} of data taken during the CERN $p\bar{p}$ Collider runs in 1988 and 1989. The properties of isolated muons accompanied by jets are consistent with the predictions from the Standard Model but do not show a signal for a new heavy quark. Combining all the UA1 data (5.4 pb^{-1}), lower mass limits are obtained at $60 \text{ GeV}/c^2$ (95% CL) for the t-quark and $43 \text{ GeV}/c^2$ (95% CL) for a fourth-generation charge $-1/3$ quark (b' -quark).

(This paper is dedicated to the memory of Bruno Gonzalez who participated in collecting the data analysed here but who died in an accident on his way to a data-taking shift.)

1. INTRODUCTION

Among the fundamental fermions of the standard model the top quark (t-quark) and the τ -neutrino have not yet been directly observed. It is possible that more than three families of quarks and leptons exist, but recent measurements [1] of the width of the Z exclude additional light neutrinos. The masses of leptons and quarks are not predicted in the Standard Model. However, within the minimal Standard Model, the t-quark mass is constrained by a variety of precision measurements to be approximately in the range 100–250 GeV/c² [2].

The UA1 collaboration has made a systematic study of heavy-flavour (b-quark and c-quark) production in proton-antiproton collisions at $\sqrt{s} = 630$ GeV using muons from semileptonic decays to tag heavy-flavour jets. The topology of the muon-jet events has been studied in detail and is in good agreement with QCD-based predictions for heavy-flavour production [3, 4]. These heavy-flavour events were used to get a measurement of the b-quark production cross-section [5]; they also led to the first observation of $B^0 - \bar{B}^0$ mixing [6].

Our understanding of the properties of heavy-flavour events allows us to predict their contribution to the background for a new heavy-quark signal. Using data collected up to 1985 in both the muon and the electron channels, for various event topologies that are characteristic of the semileptonic decays of new heavy quarks, an upper limit for the t-quark production cross-section was obtained as a function of the t-quark mass, m_t [7]. Taking into account the contribution from the channel $W \rightarrow t\bar{b}$, and using the QCD calculation [8] of the $t\bar{t}$ production cross-section to order α_s^3 , a lower limit of $m_t = 41$ GeV/c² (95% CL) was obtained by combining a phenomenological analysis [9] with the UA1 cross-section limit [7]. Using a similar method, a lower mass limit of 34 GeV/c² (95% CL) was obtained for a fourth-generation charge-1/3 quark (b'). We assumed standard heavy-quark semileptonic decays with branching ratios of 1/9 for both $t \rightarrow b/\nu$ and $b' \rightarrow c/\nu$.

We present here the results of our search for new heavy quarks using a sample which includes new data recorded in 1988 and 1989. The additional data increase the integrated luminosity in the muon channel by a factor of seven compared to our previous analysis.

2. THE 1988 AND 1989 CERN $p\bar{p}$ COLLIDER RUNS

The commissioning of the Antiproton Collector (ACOL) brought about an order-of-magnitude increase in the luminosity of the CERN $p\bar{p}$ Collider. The peak luminosity exceeded 2×10^{30} cm⁻²s⁻¹, and UA1 collected 4.7 pb⁻¹ of data at $\sqrt{s} = 630$ GeV in the 1988 and 1989 Collider runs.

The central electromagnetic calorimeters (Gondolas and Bouchons) and the forward calorimeters were removed in preparation for the installation of a new Uranium-TMP (tetramethylpentane) calorimeter [10]. The muon detection system was improved prior to the 1988 run by the addition of 820 tonnes of iron shielding in the forward region. The external muon chambers allow the detection of muons in a pseudorapidity range $|\eta| < 2.3$. Muon trigger processors require tracks in the muon chambers which point back to the interaction region. These allow triggering with $|\eta| < 1.5$ for single muons, and with almost the full pseudorapidity acceptance for muon pairs. For $m_t > 40 \text{ GeV}/c^2$, 80% of all muons from simulated t -quark semileptonic decays have pseudorapidity $|\eta| < 1.5$, so the UA1 muon trigger acceptance is well matched to the detection of muons from very heavy quarks.

A new first-level calorimeter trigger processor [11] designed for the upgraded calorimeter was installed and used with the existing iron-scintillator calorimeters. At high luminosity, the muon trigger rate in the forward region ($1.5 > |\eta| > 1.0$) was reduced by requiring a jet of transverse energy (E_T) greater than 10 GeV in coincidence with the muon trigger. In addition, the trigger processor was used to collect an inclusive sample of jet data ($E_T > 10 \text{ GeV}$), which was used to calculate the background to muon-jet events from decays of pions and kaons in flight.

The Central Detector (CD) was operated in a new mode in order to cope with the higher currents induced by the increased Collider luminosity. The wire gain was lowered by a factor of four, which was partially compensated by a factor of three increase in the electronic gain. This resulted in a degradation of the charge-division resolution by about 50% (position along the wires). However averaging over the whole CD volume, the resolution in the drift-time measurement is nearly unchanged at $\approx 300 \mu\text{m}$.

The calorimetric measurements now rely on the iron-scintillator calorimeters alone. A large amount of effort was invested in calibrating these calorimeters using cosmic muons, ^{106}Ru source measurements, minimum bias and laser calibration data, and by studying a complete calorimeter module in test beams. We conclude that the resolution in missing transverse energy, E_T^{miss} , is $\sigma(E_T^{\text{miss}}) = 0.8 \times \sqrt{\Sigma E_T}$ where E_T is in GeV, which is 15% worse than with the previous UA1 calorimeter configuration, and that the systematic error on the jet energy scale is now 12% compared to 8% previously; the hadronic energy resolution is unchanged at $\Delta E/E \approx 0.8/\sqrt{E}$.

3. SEARCH FOR THE t -QUARK

In this paper we explore a t -quark mass range above $40 \text{ GeV}/c^2$, where $p\bar{p} \rightarrow W \rightarrow t\bar{b}$ is more important than the strong production channel at $\sqrt{s} = 630 \text{ GeV}$. We are therefore not very sensitive to uncertainties in the theoretical prediction of the $t\bar{t}$ strong production cross-section.

Since the electromagnetic calorimeters were removed for the 1988 and 1989 data-taking runs, the top search is now restricted to the muon decay channel. The main change in the muon identification capability compared to the previous detector configuration is that the background is higher because of the longer path for decays of pions and kaons in flight between the interaction region and the calorimeters. The degraded resolution of the CD also affects our ability to reject background through tight cuts on the matching between the extrapolated CD track and the track in the muon chambers. A calculation, using the techniques described previously [3], shows that for inclusive muons with transverse momentum, $p_T^\mu > 15$ GeV/c the decay background contribution increases from 20% in the old data to 31% in the new data.

3.1 Study of b-quark and c-quark production

The first step in our search for new heavy quarks is the study of c-quark and b-quark production which constitutes the biggest background.

As in our previous analysis, we used the ISAJET Monte Carlo program [12] to simulate Standard Model processes: $b\bar{b}$ and $c\bar{c}$ production with semileptonic decays to muons, W and Z production with all decay channels simulated, Drell-Yan, Upsilon and J/ψ production with decays to muon pairs. In each case we generated an equivalent integrated luminosity of at least 50 pb^{-1} . The Monte Carlo events were passed through a detailed simulation of the detector and then through our standard reconstruction program. As in our previous analysis [3], it was found necessary to modify the charged-to-neutral particle ratio in ISAJET for particles not associated with the heavy-quark decay in order to reproduce distributions of the charged multiplicity and transverse momentum flow around the muons and jets; the fraction of charged particles was reduced by 30%.

The decay-in-flight background was calculated using the techniques described previously [3]. Briefly, jet data were used to calculate the background by estimating the probability for hadrons in the jet events to decay in flight and be mis-reconstructed as prompt muons. Such events can fake the muon-plus-jet signature used in this analysis.

In Fig. 1, we show the measured muon p_T distribution above 10 GeV/c, compared to the sum of the standard processes listed above, for events containing at least one jet with $E_T > 12$ GeV in the pseudorapidity range $|\eta| < 1.5$ and separated from the muon by $\Delta R > 1.0$ as described below. Note that $\Delta R \equiv (\Delta\phi^2 + \Delta\eta^2)^{1/2}$, where ϕ is the azimuthal angle around the beam direction and η is the pseudorapidity. Throughout the analysis, we use an absolute prediction for the number of events from decays of pions and kaons in flight. The production cross-sections for W, Z, Upsilon and J/ψ are normalized to measurements [13, 4]. The $b\bar{b}$ and $c\bar{c}$ absolute prediction from ISAJET is scaled to normalize the total contribution from standard processes to the observed number of events. The normalization factors applied vary between 1.1 and 1.3

depending on the jet cuts used. This variation is within the systematic errors associated with the jet energy scale uncertainty.

To test the model of standard processes in more detail, we select a sample which is dominated by b-quark and c-quark production with the following cuts:

- One muon with $10 \text{ GeV}/c < p_T < 15 \text{ GeV}/c$ and $|\eta| < 1.5$. For muons with $p_T < 10 \text{ GeV}/c$ there is a high background from decays in flight, and above $15 \text{ GeV}/c$ there is a large contribution from $W \rightarrow \mu\nu$ decays.
- At least one jet with $E_T > 12 \text{ GeV}$ and $|\eta| < 1.5$, and with the jet axis outside a cone $\Delta R = 1$ around the muon direction. The jet transverse energies are measured as in Ref. [3], and the jets must be validated by at least one charged track with $p_T > 0.5 \text{ GeV}/c$ lying within a cone of $\Delta R = 0.4$ about the jet axis.

We compare the data to the sum of the decay background and the simulated processes for a variety of variables which are relevant to the search for new heavy quarks. We only consider additional jets with $E_T > 7 \text{ GeV}$, $|\eta| < 2.0$, and with the jet axis outside a cone of $\Delta R = 1$ around the muon direction. The following distributions are shown in Figs. 2 – 8:

- Jet multiplicity, N_{jets} ;
- Transverse energy of jet₁, the highest transverse energy jet in $|\eta| < 1.5$;
- Transverse energy of jet₂, the highest transverse energy jet in $|\eta| < 2.0$, excluding jet₁;
- Missing transverse energy, E_T^{miss} ;
- Azimuthal angle difference between the muon and jet₁, $\Delta\phi(\mu\text{-jet}_1)$;
- Angular distribution of jet₂ in the centre-of-mass system of $\mu\text{-jet}_1\text{-jet}_2\text{-}E_T^{\text{miss}}$;
- Isolation, $I \equiv [(\Sigma E_T/3)^2 + (\Sigma p_T/2)^2]^{1/2}$. [The sums include calorimeter cells (ΣE_T) and CD tracks (Σp_T) in a cone of $\Delta R = 0.7$ around the muon direction.]

For all the distributions, there is reasonable agreement between the prediction for the sum of standard processes and the data.

The isolation of muons (i.e. the transverse energy flow around the muon as expressed by the variable I defined above) is a crucial variable in the search for new heavy quarks. For $b\bar{b}$ and $c\bar{c}$ production, most of the muons are produced inside jets and are therefore not isolated, as observed in Fig. 8. In contrast, the muons produced when very heavy quarks decay are usually well separated from the jets and are therefore isolated.

3.2 Search for the t-quark in events with a single muon plus jets

We select events which contain an isolated high- p_T muon accompanied by at least two jets as in our previous work [7]. Our analysis suggests that for the present detector configuration the best sensitivity to a possible t-quark signal is obtained by making the following cuts:

- $p_T^\mu > 12 \text{ GeV}/c$;
- $E_T(\text{jet}_1) > 13 \text{ GeV}$;
- $E_T(\text{jet}_2) > 7 \text{ GeV}$;
- muon- E_T^{miss} transverse mass, $m_T < 60 \text{ GeV}/c^2$.

The cut on $m_T \equiv [2 \times p_T^\mu \times E_T^{\text{miss}} \times (1 - \cos \Delta\phi)]^{1/2}$ is imposed to reduce the contribution from $W \rightarrow \mu\nu$ decays.

In Fig. 9 we show the resulting isolation distribution compared to the sum of standard processes. In this plot, the contribution from $b\bar{b}$ and $c\bar{c}$ was normalized to the observed number of events with $I > 2$ where the contribution from top is very small. There are 51 events in the data with $I < 2$, compared to an expected contribution from standard processes of 53 ± 9 events. As shown in Table 1, the main sources of background to the top search are $b\bar{b}$ and $c\bar{c}$ events and decays of pions and kaons in flight; the systematic errors on the background estimate are discussed in Section 4. In Table 2 we give the expected numbers of top events satisfying our cuts for several t-quark masses.

Improved sensitivity to top can be obtained by combining several event variables that differentiate between top events and the background (mainly from $b\bar{b}$ and $c\bar{c}$ events). We define a variable $\mathfrak{I}_1$ as follows:

$$\mathfrak{I}_1 \equiv \Pi \frac{P_{t;i}(X_i)}{P_{b;i}(X_i)},$$

where $P_{t;i}$ is the probability density function of the variable X_i for t-quark events and $P_{b;i}$ is the corresponding function for $b\bar{b}$ and $c\bar{c}$ events; Π indicates a product for all values of the index i . The variables which we use are the isolation (I), the muon transverse momentum (p_T^μ), the missing transverse energy (E_T^{miss}), and the azimuthal angle difference between the muon and the highest E_T jet ($\Delta\phi(\mu\text{-jet}_1)$); events are included only for $I < 6$. The distributions in these four variables are plotted in Figs. 9 – 12 for the data compared to the sum of standard processes, and for top events with $m_t = 50 \text{ GeV}/c^2$. In each case, the data are reasonably well reproduced by the sum of standard processes without a contribution from top decays.

The distribution in $\ln(\mathfrak{I}_1)$ is plotted in Fig. 13 for the data, for the sum of standard processes and for top events with $m_t = 50 \text{ GeV}/c^2$. The contribution from $b\bar{b}$ and $c\bar{c}$ events is normalized to the data in the control region defined as $\ln(\mathfrak{I}_1) < 1$. Taking $\ln(\mathfrak{I}_1) > 4$ as our search region, we observe 2 events consistent with the 2.8 ± 0.8 events expected from standard processes (Table 1). In Table 2 we give the expected numbers of top events satisfying our cuts for several t-quark masses.

We calculate the upper limit on the t-quark production cross-section that is consistent with the number of events observed in the search region. We then derive a

limit on the t -quark mass by using calculations of the cross-sections for the strong production of $t\bar{t}$ pairs [8, 9], and for t -quark production via $W \rightarrow t\bar{b}$ normalized to the measured cross-section for $p\bar{p} \rightarrow W \rightarrow l\nu$ [13]; we use $\sigma(p\bar{p} \rightarrow W \rightarrow l\nu) = 0.63 \pm 0.03$ nb, which is obtained by combining the UA1 and UA2 measurements adding statistical and systematic errors quadratically. The branching ratio for $W \rightarrow t\bar{b}$ is calculated [14] including radiative corrections of order α_s ; the resulting branching ratio is higher than the lowest order one by a factor of 1.13 at $m_t = 40$ GeV/c² and by a factor of 1.25 at $m_t = 60$ GeV/c². We take $m_W = 80$ GeV/c² [15] for the calculation of phase space and radiative correction factors. The systematic errors which are included in the calculation of the mass limits are discussed in Section 4. From the new single-muon-plus-jet data alone we obtain: $m_t > 52$ GeV/c² (95% CL) and $m_t > 56$ GeV/c² (90% CL).

3.3 Search for the t -quark in dimuon events

Since $W \rightarrow t\bar{b}$ is the most important top production process at the CERN collider for m_t between 40 GeV/c² and 75 GeV/c², we search for events where the produced t -quark and b -quark both decay semileptonically into a muon. The muon coming from the t -quark decay usually has the larger transverse momentum and is isolated, whilst the muon from the b -quark decay is normally not isolated. In this analysis we combine all the data collected by UA1 between 1983 and 1989 to search for muon pairs arising from t -quark production; the total integrated luminosity is 5.4 pb⁻¹.

We made the following selection where we include muon pairs with both opposite and equal charges:

- at least one muon with: $p_T > 8$ GeV/c, $|\eta| < 1.6$;
- a second muon with: $p_T > 3$ GeV/c;
- dimuon mass $6 \text{ GeV/c}^2 < m(\mu_1, \mu_2) < 50 \text{ GeV/c}^2$;
- loose isolation requirement for the higher p_T muon: $I(\mu_1) < 6$;
- non-isolation requirement for the lower p_T muon: $I(\mu_2) > 2$;
- at least one jet with $E_T > 10$ GeV, $|\eta| < 1.5$.

The lower dimuon mass cut is needed to remove muon pairs coming from $J/\psi \rightarrow \mu^+\mu^-$ and from b -quark cascade decays ($b \rightarrow c\mu\nu$; $c \rightarrow s\mu\nu$). The upper dimuon mass cut rejects $Z \rightarrow \mu^+\mu^-$ decays. The isolation requirement on the first muon suppresses high- p_T $b\bar{b}$ production where both the b and the $\bar{b}$ decay semileptonically to muons, whereas the non-isolation requirement on the second muon removes muons from Upsilon decays and the Drell-Yan mechanism.

We select 94 events whilst we predict 84 events from standard processes as shown in Table 3 – here the quoted contribution from $b\bar{b}$ and $c\bar{c}$ production is the absolute prediction from the Monte Carlo. In Table 4, we give the expected numbers of top events for several t -quark masses. The predicted physics contributions were

calculated using the Monte Carlo simulation described in Section 3.1. The decay-in-flight background was estimated using a sample of single muon events by considering the probability for hadrons in the events to decay in flight and be mis-reconstructed as additional prompt muons.

These cuts provide insufficient sensitivity to t-quark production. However, as in the single muon analysis, increased sensitivity can be obtained by combining several event properties that differentiate between top events and the dominant background of $b\bar{b}$ and $c\bar{c}$ events. As in the single-muon analysis, we define a variable $\mathfrak{Z}_2$ as follows:

$$\mathfrak{Z}_2 \equiv \Pi \frac{P_{t;i}(X_i)}{P_{b;i}(X_i)},$$

where Π , P and X have the same meaning as in Section 3.2. The variables, X_i , which we use in the dimuon analysis are the transverse momentum of μ_1 , the isolation of μ_1 in a cone of $\Delta R = 0.4$ and the difference in azimuthal angle between the two muons, $\Delta\phi(\mu_1, \mu_2)$. The smaller cone size used here for the isolation variable was chosen to optimize the sensitivity to top decays. We show in Figs. 14 – 16 the distributions in these variables for the data compared to the sum of standard processes, and for t-quark events with $m_t = 50 \text{ GeV}/c^2$. In these plots the $b\bar{b}$ and $c\bar{c}$ contributions are scaled up by a factor of 1.15 as described below. Good agreement is observed in all the distributions between the data and the prediction without a top quark contribution.

In Fig. 17 we compare the distribution of $\ln(\mathfrak{Z}_2)$ for the dimuon data with the prediction without a contribution from the top quark. The $b\bar{b}$ and $c\bar{c}$ contributions are scaled by a factor of 1.15 to normalize to the number of events with $\ln(\mathfrak{Z}_2) < 0$; also shown is the additional contribution expected for a t-quark of $m_t = 50 \text{ GeV}/c^2$. The data do not show a signal for t-quark production. We define a search region with $\ln(\mathfrak{Z}_2) > 2$ in which we find 2 events in the data, whilst we expect a total of 4.5 ± 1.0 events from standard processes (Table 3); the systematic errors on the background estimate are discussed in Section 4. The predicted numbers of top events with $\ln(\mathfrak{Z}_2) > 2$ are given in Table 4 for several t-quark masses.

Using the same technique as for the single muon analysis described in Section 3.2, we obtain limits on the t-quark mass based on the dimuon data alone: $m_t > 46 \text{ GeV}/c^2$ (95% CL) and $m_t > 51 \text{ GeV}/c^2$ (90% CL).

4. t-QUARK MASS LIMIT

Table 5 summarizes the results of the t-quark search in the four different channels. The backgrounds quoted are normalized to the data in the control region and then extrapolated to the search region. The limits based on the electron-jet and muon-jet data from the 1983–1985 period have been re-evaluated using the predicted $t\bar{t}$

production cross-sections of Refs. [8] and [9], and by combining the statistical and systematic errors in quadrature as for the new data.

All of the channels, which have no events in common, are combined to obtain an overall mass limit for the t-quark. Most of the systematic errors are correlated between channels: for instance, the error on the theoretical t-quark production cross-section is common to all the data samples. We take the most unfavourable case where we assume that all the errors are correlated to obtain a conservative limit on m_t . For each channel listed in Table 5 we define a likelihood function which takes into account the statistics in the top search region and in the control region used to normalize background, and two types of systematic errors: those affecting the signal and those affecting the background. The limit quoted below is obtained by combining the likelihood distributions from the different channels [16].

The systematic errors affecting the background estimate for the single-muon and dimuon channels are listed in Table 6. The 12% uncertainty on the jet energy scale has relatively little effect because we have normalized the background to the data in the low $\ln(\mathcal{L})$ region. Similarly, the 20% uncertainty on the normalization of the decay-in-flight background estimate (mainly due to our lack of knowledge of the fractions of charged particles which are kaons and pions) affects the background estimate in the search region only insofar as the shape of the $\ln(\mathcal{L})$ distribution differs between the decay-in-flight background, and $b\bar{b}$ and $c\bar{c}$ processes. The cross-sections for W, Z, Drell-Yan, J/ψ and Υ events containing several high- E_T jets have not been accurately measured. We ascribe a 50% error to the cross-section for $W(Z) + \text{jets}$ and, independently, a 50% error to the contribution from the Drell-Yan mechanism, J/ψ and Υ decays. Since these processes contribute only a small fraction of the background in the search region, the overall error from these sources is not large. We also include an error to account for the background model dependence. This includes uncertainties associated with the isolation definition used, the validation of jets and the b-quark fragmentation function. The statistical errors are given separately for the Monte Carlo and decay-in-flight background estimate, and for the number of events in the low $\ln(\mathcal{L}) < 1$ region where the background is normalized.

The systematic errors affecting the predicted numbers of top events are given in Table 7. The uncertainty in the cross-section for strong production of $t\bar{t}$ pairs (30%) is taken from Ref. [9]; it includes the estimated errors on the structure functions, the scale used for the QCD calculation, and on the strong coupling constant, α_s . The cross-section for weak production via $W \rightarrow t\bar{b}$, is normalized to measurements of $p\bar{p} \rightarrow W \rightarrow l\nu$, as described in Section 3.2. The largest source of uncertainty to this cross-section comes from the calculation of radiative corrections to the $W \rightarrow t\bar{b}$ partial decay width [14]. We add a 10% error on this cross-section, which includes the uncertainty on the

parameters m_W , m_b and α_s entering into the calculation of the phase space and radiative correction factors. The error from Monte Carlo model dependence includes uncertainties associated with the isolation definition used, the validation of jets and, for the dimuon analysis, the b-quark fragmentation function. The 12% uncertainty on the jet energy scale is propagated to evaluate the error on the expected number of top events in the search region.

The 90% and 95% CL limits on the t-quark production cross-section are shown in Fig. 18 as functions of m_t . Also shown is the central value of the total predicted cross-section for t-quark production and the corresponding curve for $W \rightarrow t\bar{b}$ alone. The mass limits are:

$$m_t > 60 \text{ GeV}/c^2 \text{ (95\% CL),}$$

$$m_t > 63 \text{ GeV}/c^2 \text{ (90\% CL).}$$

If we assume production via $p\bar{p} \rightarrow W \rightarrow t\bar{b}$ only, the limits are $m_t > 54 \text{ GeV}/c^2$ (95% CL) and $m_t > 58 \text{ GeV}/c^2$ (90% CL). The above 95% CL limit of $m_t > 60 \text{ GeV}/c^2$ is not very sensitive to where one cuts on $\ln(\mathfrak{F}_1)$ and $\ln(\mathfrak{F}_2)$. If the cut on $\ln(\mathfrak{F}_1)$ which defines the search region is varied in the range 1 – 4, or if the cut on $\ln(\mathfrak{F}_2)$ is made at 1 instead of 2, the limit does not fall below $57 \text{ GeV}/c^2$.

Searches for new heavy quarks in $p\bar{p}$ [17] and e^+e^- [18] interactions have recently been reported. Results from the CDF experiment exclude the t-quark mass range $28 \text{ GeV}/c^2 < m_t < 77 \text{ GeV}/c^2$ (95% CL) with the hypothesis of a 1/9 semileptonic branching ratio for the top-quark, whilst lower masses are excluded by e^+e^- experiments.

5. b'-QUARK MASS LIMIT

The search for the b'-quark (fourth-generation charge-1/3 quark) is similar to the search for the t-quark in the single-muon channel. We assume that the b'-quark is not produced in decays of W bosons, and that the b'-quark decays only through standard charged currents: $b' \rightarrow cW^*$. For the same quark mass, the production cross-sections for $b'\bar{b}'$ and $t\bar{t}$ are the same, but the muon spectrum from b' decays is harder than the one for t-quark decays because of the properties of the V-A decay amplitude. Using the same single-muon-plus-jets sample as for the t-quark search, we obtain lower limits on $m_{b'}$ of $43 \text{ GeV}/c^2$ (95% CL) and $45 \text{ GeV}/c^2$ (90% CL).

These limits are weakened if the b' also decays through second-order weak processes: $b' \rightarrow b g$ or $b' \rightarrow b \gamma$ [19]. In Fig. 19 we show excluded regions in the plane $m_{b'}$ versus the branching fraction for $b' \rightarrow cW^*$ for two cases: (i) assuming that

we are sensitive only to events in which the b' and $\bar{b}'$ both decay through $b' \rightarrow cW^*$ (lower curve); (ii) assuming that the loss of sensitivity comes only from the reduction in the semileptonic branching ratio (upper curve). Limits have also been derived for b' decays in several other experiments [17, 18].

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Figures

- Fig. 1 Muon transverse momentum distribution, p_T^μ .
- Fig. 2 Jet multiplicity, N_{jets} .
- Fig. 3 Highest jet transverse energy, $E_T(\text{jet}_1)$.
- Fig. 4 Second highest jet transverse energy, $E_T(\text{jet}_2)$.
- Fig. 5 Missing transverse energy, E_T^{miss} .
- Fig. 6 Azimuthal angle difference between the muon and the highest- E_T jet, $\Delta\Phi(\mu\text{-jet}_1)$.
- Fig. 7 Angular distribution of the second highest E_T jet, $\cos\theta^*(\text{jet}_2)$.
- Fig. 8 Isolation, $I \equiv [(\sum E_T/3)^2 + (\sum p_T/2)^2]^{1/2}$ (see text).
- Fig. 9 Isolation, $I \equiv [(\sum E_T/3)^2 + (\sum p_T/2)^2]^{1/2}$ (see text) for events with $p_T^\mu > 12$ GeV/c, $E_T(\text{jet}_1) > 13$ GeV, $E_T(\text{jet}_2) > 7$ GeV and $m_T < 60$ GeV/c².
- Fig. 10 Muon transverse momentum: (a) the data compared to the sum of standard processes, (b) the additional contribution from t-quark decays for $m_t = 50$ GeV/c².
- Fig. 11 Missing transverse energy: (a) the data compared to the sum of standard processes, (b) the additional contribution from t-quark decays for $m_t = 50$ GeV/c².
- Fig. 12 Azimuthal angle difference between the muon and the highest E_T jet: (a) The data compared to the sum of standard processes, (b) the additional contribution from t-quark decays for $m_t = 50$ GeV/c².
- Fig. 13 Distribution in $\ln(\mathfrak{Z}_1)$ for single muon events. The data are compared with a simulation of standard processes and with the prediction for t-quark decays, with $m_t = 50$ GeV/c².
- Fig. 14 Transverse momentum of highest p_T muon: (a) comparison of the data with a simulation of standard processes, (b) expected distribution from t-quark decays, with $m_t = 50$ GeV/c².
- Fig. 15 Isolation of highest p_T muon in a cone of $\Delta R = 0.4$: (a) comparison of the data with a simulation of standard processes, (b) expected distribution from t-quark decays, with $m_t = 50$ GeV/c².
- Fig. 16 Azimuthal angle difference between the two muons: (a) comparison of the data with a simulation of standard processes, (b) expected distribution from t-quark decays, with $m_t = 50$ GeV/c².
- Fig. 17 Distribution in $\ln(\mathfrak{Z}_2)$ for muon pairs. The data are compared with a simulation of standard processes and with the prediction for t-quark decays, with $m_t = 50$ GeV/c².
- Fig. 18 Limits on the t-quark production cross-section $[\sigma(t) + \sigma(\bar{t})]$ as a function of the t-quark mass. Also shown are the predicted cross-sections (see text).

Fig. 19 Lower limits on $m_{b'}$ (95% CL) as a function of the branching fraction for $b' \rightarrow bW^*$. The curves labelled (i) and (ii) refer to the two assumptions discussed in the text.

	$I < 2$	$\ln(\mathcal{L}_1) > 4$
K and π decays in flight	21.6	1.6
W and Z decays	2.3	0.4
Drell-Yan, J/ψ and Upsilon	2.5	0.0
b-quark and c-quark decays	26.9	0.8
Total from standard processes	53.3	2.8
Data	51	2

Table 1: Backgrounds to the t-quark search in the single-muon-plus-jets channel. Sources of uncertainties in the background estimate are discussed in Section 4 and summarized in Table 6.

		t-quark mass [GeV/c ²]			
		40	50	60	70
$I < 2$	Weak production	15.8	16.1	7.7	1.7
	Strong production	16.5	8.5	3.4	1.5
	Total	32.3	24.6	11.1	3.2
$\ln(\mathcal{L}_1) > 4$	Weak production	2.9	4.1	2.3	0.4
	Strong production	3.8	2.1	1.0	0.5
	Total	6.7	6.2	3.3	0.9

Table 2: Predicted numbers of top events for the single-muon-plus-jet channel. Sources of uncertainties on these predictions are discussed in Section 4 and summarized in Table 7.

	Selection	$\ln(\mathfrak{L}_2) > 2$
K and π decays in flight	14.5	0.6
W, Z, Drell-Yan, J/ψ and Upsilon	2.2	0.3
b-quark and c-quark decays	66.9	3.5
Total from standard processes	83.6	4.5
Data	94	2

Table 3: Backgrounds to the t-quark search in the dimuon channel. Sources of uncertainties in the background estimate are discussed in Section 4 and summarized in Table 6.

		t-quark mass [GeV/c ²]			
		40	50	60	70
Selection	Weak production	8.6	5.7	2.6	0.6
	Strong production	5.2	2.1	1.0	0.5
	Total	13.8	7.8	3.5	1.1
$\ln(\mathfrak{L}_2) > 2$	Weak production	3.8	2.8	1.3	0.4
	Strong production	2.4	1.1	0.6	0.3
	Total	6.2	3.9	1.9	0.7

Table 4: Predicted numbers of top events in the dimuon channel after applying the selection criteria described in Section 3.3 and with the additional cut of $\ln(\mathfrak{L}_2) > 2$. Sources of uncertainties on these predictions are discussed in Section 4 and summarized in Table 7.

	Data	Background	Expected number of top events				95% CL limit on m_t [GeV/c ²]
			$m_t = 40$ [GeV/c ²]	$m_t = 50$ [GeV/c ²]	$m_t = 60$ [GeV/c ²]	$m_t = 70$ [GeV/c ²]	
Electrons plus jets (1983 – 1985)	26	26.0	11.7	8.5	4.1	1.5	41
Muons plus jets (1983 – 1985)	10	11.4	7.9	4.7	2.3	0.8	40
Muons plus jets (1988 – 1989)	2	2.8	6.7	6.2	3.3	0.9	52
Dimuon (1983 – 1989)	2	4.5	6.2	3.9	1.9	0.7	46

Table 5: Summary of t-quark searches in different data samples. Sources of uncertainties are discussed in Section 4 and summarized in Tables 6 and 7 for the background estimate and top expectations respectively.

	Error on single- muon background estimate [%]	Error on dimuon background estimate [%]
Jet energy scale (12% energy scale uncertainty)	8	10
Normalization of decay-in-flight background	11	0
Normalization of W, Z, D-Y, J/ ψ , Upsilon	7	3
Background model uncertainty	15	7
Statistical error on Monte Carlo	15	15
Statistical error on number of events in normalization region	7	11
Total error on background estimate in search region	27	20

Table 6: Errors affecting the background estimates after cuts on $\ln(\mathfrak{L})$. Note that the numbers given refer to the 1988/1989 detector configuration.

	Error on total prediction for top production (single muons) [%]	Error on total prediction for top production (dimuons) [%]
Integrated luminosity and cross-sections	12	12
Monte Carlo model uncertainty	6	5
Jet energy scale	17	7
Selection efficiency	8	8
Monte Carlo statistical error	7	9
Total error	24	19

Table 7: Errors affecting the prediction for the number of top events in the single-muon and dimuon channels after cuts on $\ln(\mathfrak{L})$.

FIG. 1

FIG. 2

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FIG. 4

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