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TEVATRON MASS LIMITS FOR HEAVY QUARKS DECAYING VIA FLAVOR CHANGING NEUTRAL CURRENT

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ABSTRACT

The dimuon and dielectron data from the Tevatron $\bar{p}p$ collider are used to probe for heavy quarks, which decay dominantly via flavour changing neutral current. Depending on whether the $FCNC$ decay occurs at the tree or loop level, one gets a lower mass limit of 85 or 75 GeV. The former applies to singlet, vector doublet and mirror type quarks while the latter applies to a lefthanded quark doublet of the fourth generation.

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By far the most extensive search for the top quark has been carried out by the CDF experiment [1] at the Tevatron $\bar{p}p$ collider, leading to a 95% CL mass limit of $m_t > 91$ GeV. The most important channels for this top search program are the isolated large-p_T dilepton channels $e\mu, \mu\mu$ and ee, which account for a mass bound of $m_t > 86$ GeV. The relevant processes for these channels are $t\bar{t}$ pair production by gluon-gluon and quark-antiquark fusion

$$gg(q\bar{q}) \rightarrow t\bar{t} \tag{1}$$

followed by the charged current semileptonic decay of both the top quarks

$$t \rightarrow b\ell^{+}\nu, \quad \bar{t} \rightarrow \bar{b}\ell^{-}\bar{\nu} \tag{2}$$

where $\ell = e, \mu$. With the e and μ decay branching ratios of 10% each one gets an overall branching ratio of 4% for $t\bar{t}$ decay into the above dilepton channels. Together with the dilepton detection efficiency of about 16%, arising from the various cuts, this results in an overall efficiency of $t\bar{t}$ detection in the dilepton channels $\simeq 0.6\%$.

It has been generally recognised that one has the same dilepton branching ratio and a similar detection efficiency for any other heavy quark decaying via charged current interaction [2]. Combined with the QCD prediction of same production cross-section, it implies that the above mentioned mass limit of 86 GeV holds for all such quarks. However, the first set of conditions would not apply to quarks, which decay mainly via flavour changing neutral current. Indeed, there has been no search for such heavy quarks using the Tevatron data so far. The present work is devoted to this excercise. We shall see below that a systematic analysis of the Tevatron $\mu\mu$ and ee data leads to an equally strong mass limit for these quarks as well. More precisely one gets a lower mass limit of 85 or 75 GeV depending on whether the $FCNC$ decay occurs at the tree or the loop level.

Let us first recall the models, where one may expect a heavy quark Q to decay dominantly via $FCNC$. For singlet, vector doublet and mirror type quarks [3] both

$FCNC$ and CC decays occur at the tree level and are generally of comparable magnitude. Now consider a singlet quark of charge $-1/3$, which occurs e.g. in the E_6 grand unified model [4]. If this quark is lighter than the top then only the $FCNC$ decay into the 3rd generation would be kinematically allowed. In this case one expects the $FCNC$ decay to dominate, provided the ratio of the mixing angles are in the range

$$\sin^2\theta_{Qs,Qd}/\sin^2\theta_{Qb} \lesssim 10^{-1}. \tag{3}$$

According to most of the fermion mass matrix models [3]

$$\sin^2\theta_{Qi} \sim (m_i/m_Q)^{1 \text{ to } 2} \tag{4}$$

implying

$$\sin^2\theta_{Qs}/\sin^2\theta_{Qb} \sim (m_s/m_b)^{1 \text{ to } 2} \sim 10^{-1 \text{ to } -2}. \tag{5}$$

The corresponding ratio for d quark is of course much smaller. Thus for the plausible range of the mixing angles one expects dominant $FCNC$ decay. The same holds true for a charge $-1/3$ quark of a vector doublet [5] or a mirror doublet [6], provided it is lighter than its accompanying charge $2/3$ quark as well as the top. The above three models shall be collectively referred to as exotic quark models, since they correspond to non-standard $SU(2)$ representations.

Consider next a charge $-1/3$ quark belonging to 4th generation of the standard $SU(2)$ doublet. In this case the $FCNC$ decay occurs only at the one-loop level due to the GIM cancellation. So $FCNC$ dominance holds only over a limited range of the ratio (3), i.e.

$$\sin^2\theta_{Qs}/\sin^2\theta_{Qb} \lesssim 10^{-4}. \tag{6}$$

This is evidently outside the range (5). On the other hand it may be reasonable in models where one approximates the 4×4 CKM matrix by a block diagonal form containing two 2×2 matrices [7-9]. This corresponds to a scenario where the mixing between the first two generations, as well as that between the last two, are substantial, whereas the two pairs of generations mix rather feebly with each other. In any case the range (6) is a phenomenologically allowed part of the parameter space [3,10]. Hence it is necessary to extend the heavy quark search to the $FCNC$ decay channel in order to close this window.

Thus there is a good chance of dominant $FCNC$ decay for the charge -1/3 quark of the exotic models and (to a lesser extent) for that of the 4th generation. Hence it is important to search for such quarks in the $FCNC$ decay channels. Besides, the search for a possible heavy quark with dominant $FCNC$ decay is important for another reason – i.e. its nuissance value to the Higgs and $SUSY$ search programmes at hadron colliders, as emphasised in refs [8,9]. For, a heavy quark pair decaying via $FCNC$ will be a formidable source of 4 lepton ($ZZ \to \ell^+\ell^-\ell^+\ell^-$) and missing-$p_T$ ($ZZ \to \nu\bar{\nu}\nu\bar{\nu}$) events, which are crucial channels for Higgs and $SUSY$ searches respectively.

We should mention here that the current mass limits for quarks with dominant $FCNC$ decay come from LEP [11], i.e.

$$m_Q > M_Z/2. \tag{7}$$

Therefore we shall restrict our search to above this region.

Our analysis is based on a parton level Monte Carlo calculation. The $Q\bar{Q}$ production process is identical to that of $t\bar{t}$ production, as given by eq. (1). The results presented below have been obtained with the structure functions and the QCD coupling parameter of GHR [12]. The more recent parametrisations give a somewhat smaller cross-section due to a smaller value of the QCD coupling parameter $\wedge$. We have checked this using the parametrisation of $DFLM$ [13], which reduces the size of the cross-section by $\sim 25\%$. On the other hand the higher order QCD effects, not included in this calculation, are expected to enhance the cross-section by $\sim 50\%$ [14]. Thus we expect that the uncertainty in the QCD

parametrisation and the higher order QCD effects can reduce or enhance the size of the cross-section presented below by a factor of 1.5.

For the exotic quarks, we have tree level $FCNC$ decay which is easy to handle. Since the tree level $FCNC$ decay proceeds necessarily via Z, the decay channel of our interest

$$Q(p) \to b(p')\ell^+(p_1)\ell^-(p_2) \tag{8}$$

has a brnaching ratio of 3.3% for each lepton species. For a singlet Q the tree level $FCNC$ arises from the mixing of lefthanded quarks. The resulting matrix element for the above decay is

$$M = \frac{g^2 \sin\theta_{Qb}\cos\theta_{Qb}}{2\cos^2\theta_W} \cdot \frac{\bar{u}_b(p')\gamma_\mu \left[\frac{1-\gamma_5}{2}\right] u_Q(p)\bar{u}_\ell(p_1)\gamma_\mu \left[\alpha\frac{1-\gamma_5}{2} + \beta\frac{1+\gamma_5}{2}\right] v_\ell(p_2)}{(p_1+p_2)^2 - m_Z^2} \tag{9}$$

where

$$\alpha = -1/2 + \sin^2\theta_W, \quad \beta = \sin^2\theta_W \tag{10}$$

The corresponding squared matrix element is

$$|M|^2 = \frac{g^4 \sin^2\theta_{Qb}\cos^2\theta_{Qb}\left[\beta^2(m_Q^2 - s_2)(s_2 - m_b^2) + \alpha^2(m_Q^2 - s_3)(s_3 - m_b^2)\right]}{2\cos^4\theta_W\left[(s_1 - m_Z^2)^2 + m_Z^2\Gamma_Z^2\right]} \tag{11}$$

$$s_1 = (p-p')^2, \quad s_{2,3} = (p-p_{1,2})^2.$$

The quark mixing angle drops out from the resulting distribution function $d\Gamma/\Gamma$, where Γ is the partial decay width for (8). The dilepton differencial cross-section is obtained by convoluting this quantity with the $Q\bar{Q}$ production cross-section together with the above branching ratio. For a vector doublet Q the $FCNC$ arises from the mixing of right landed quarks. The corresponding squared matrix element is obtained from (11) simply by interchanging α^2 and β^2. For a mirror doublet the $FCNC$ arises from the mixing of both lefthanded and righthanded quarks. In this case the quark mixing-angles would not in general drop out of $d\Gamma/\Gamma$. It is well known however that this quantity is insensitive to the squared matrix element and depends mainly on the phase space factor. Thus for simplicity we assume equal mixing angles for the left and right handed quarks. In this case the mixing angle factors out and the squared matrix element corresponds to (11) with α^2 and β^2 each replaced by $(\alpha^2 + \beta^2)$. The resulting dilepton cross-sections are practically identical for the three cases, because (1) the decay distributions are insensitive to the squared matrix element as mentioned above and (2) $\alpha^2 \simeq \beta^2$ for $\sin^2\theta_W \simeq 0.23$. Therefore, they shall be represented below by a common set of curves, obtained with eq. (11).

For the 4th generation quark the one-loop $FCNC$ decay proceeds via Z as well as γ and the gluon. Consequently the branching ratio for the decay (8) is lower in this case. The exact value depends on the masses of t and the corresponding 4th generation quark t', which appear as internal lines in the loop diagrams. We shall conservatively assume this branching ratio to be = 1%, which corresponds to $m_t = 100$ and $m_{t'} = 200$ GeV [8]. As one can see from the last paper of ref [7], this branching ratio increases with increasing m_t or $m_{t'}$ – increasing by a factor of 2 for $m_t \rightarrow 120$ GeV and a factor of 3 for $m_{t'} \rightarrow 300$ GeV. The former would compensate for any decrease coming from $m_{t'}$ being less than 200 GeV. It should be noted here that under our assumption of negligible mixing between the fourth generation and the first two, the mixing between the third and fourth generations can be parametrised by a single angle. It appears as a common factor in all the loop diagrams mentioned above and hence drops out from the branching ratio. For the same reason it also drops out from the distribution function $d\Gamma/\Gamma$ for the decay process (8). To obtain this distribution function one has to compute the contributing one-loop diagrams. In the 't Hooft-Feynman gauge, there are 10 such diagrams; 6 of these entail computation of three-point functions and the remaining 4 of two-point functions. Since there are massive particles in the external legs, we have to make use of the algorithm involving form-factors that are complicated functions of the external and internal masses. Ultimately all these form factors are expressible in terms of Spence functions [15]. The effective QbZ vertex turns out to be of the form

$$\mathcal{L}^{eff}_{QbZ} = \bar{u}_b(p') \left[\rho\gamma_\mu \frac{(1-\gamma_5)}{2} + \lambda p_\mu \frac{(1-\gamma_5)}{2} + \eta p'_\mu \frac{(1+\gamma_5)}{2} \right] u_Q(p) \qquad (12)$$

where ρ, λ and η can be written in terms of the above mentioned form factors. The expressions for these quantities and the resulting squared matrix element are too long to write down here [16]. Some of these quantities may be found in ref. [7]. Although the squared matrix element depends on the masses of t and t', the dependence in rather smooth. Consequently the resulting distribution function $d\Gamma/\Gamma$ is very insensitive to these masses.

Before presenting the results let us summarise the main features of the CDF $\mu\mu$ and ee data [1], which are relevant to our analysis. The data sample corresponds to an integrated luminosity of 4.1 pb^{-1} for electrons and 3.5 pb^{-1} for muons, taken at a CM energy of 1.8 TeV. The relevant cuts and efficiency factors are as follows:

i) Each lepton has a p_T cut of

$$p_T^\ell > 15 \text{ GeV}.$$

ii) Muons are detected by the central muon detector and by minimum ionisation over the rapidity intervals

$$\eta_\mu = 0 - 0.6(CM) \text{ and } 0.6 - 1.2(MI),$$

while the electrons are detected by the central and plug electromagnetic calorimeters over

$$\eta_e = 0 - 1(CE) \text{ and } 1.26 - 2.22(PE)$$

iii) There is an isolation cut on each lepton requiring the accompanying E_T

within a cone of radius $\Delta R = [\Delta\phi^2 + \Delta\eta^2]^{1/2} = 0.4$ to be

$$E_T(\Delta R) < 5 \text{ GeV } (< 0.1 p_T^\ell \text{ for } PE)$$

iv) The coverage in the aximuthal angle ϕ is 84 and 89% for central and plug electrons and 85% for the muons.

v) The identification efficiency in 88% (99%) for the 1st (2nd) central electron and 79% for the plug electron, while it is 98% for each muon.

vi) The triggering efficiency is 98% for CE (91% for CM); which is required to cover at least one of the electrons (muons). The net triggering efficiency for the dilepton events corresponds to

$$f_{tr} = 1 - (1 - f_{tr}^1)(1 - f_{tr}^2). \tag{13}$$

Note that in each of the earlier cases the efficiency factor for the dilepton events corresponds to the product of those for the individual leptons. The cuts (i-iii) are incorporated in the Monte Carlo program; and the resulting cross-section is multiplied by a combined efficiency factor

$$f(CE - CE, CE - PE, CM - CM, CM - MI) = .62, .51, .68, .63 \tag{14}$$

arising from (iv-vi). Finally a dilepton mass cut $M_{\ell\ell} \neq 75$-105 GeV is imposed to suppress the Z decay background.

The resulting $\mu\mu$ and ee cross-sections are shown against the dilepton azimuthal angle in Fig. 1 for the exotic quark case. The corresponding CDF events are also shown for comparison. The CDF events are largely concentrated in the back-to-back direction [17], as expected for the Drell-Yan and the residual Z decay backgrounds. In contrast the predicted cross-section are either isotropic or peaked at smaller azimuthal opening angles depending on the heavy quark mass. The corresponding distributions for the 4th generation quark case are very similar. It is clear from Fig. 1 that an azimuthal cut of $\phi_{\ell\ell} < 120^\circ$ removes all the $\mu\mu$ events and most of the ee events without reducing the signal cross-section seriously. It may be mentioned here that the corresponding azimuthal cut for the $t\bar{t}$ search [1] was at 160° since most of the dilepton events could be eliminated by a missing-p_T cut. Since there is no neutrino and hence no missing-p_T for the $FCNC$ decay, one has to impose a relatively stronger azimuthal cut.

Fig. 2 shows the predicted cross-sections after the $\phi_{\ell\ell} < 120^\circ$ cut, as functions of the heavy quark mass for (a) $\mu\mu$, (b) ee, (c) $\mu\mu + ee$ channels. The predictions of the exotic and the 4th generation quark models are shown by solid and dashed lines respectively. The right hand scale shows the corresponding number of events for a common integrated luminosity of 4.1 pb^{-1}; the $\mu\mu$ cross-section has been accordingly scaled down by a factor of 3.5/4.1. The arrows indicate the 95% CL upper limits of 3 and 9.15 events corresponding respectively to 0 $\mu\mu$ and 4 ee events in the data. Evidentry the strongest mass limits come from the $\mu\mu$ case (Fig. 2a); i.e.

$$m_Q(\text{exotic, 4th gen.}) > 90, 80 \text{ GeV} \tag{15}$$

at the 95% CL. One sees from Fig. 2b that, while the ee cross-section is marginally larger than $\mu\mu$ the experimental limit is thrice as large. Consequently the mass limits drop to 83 and 65 GeV for the two models. For the same reason the combined $\mu\mu$ and ee data, shown in Fig. 2c, gives marginally lower mass limits than the $\mu\mu$ case – i.e. $m_Q = 88$ and 75 GeV for the exotic and 4th generation quarks respectively. It should be noted here that the relative value of the two mass limits essentially reflect the relative size of the branching ratios for the tree and loop level $FCNC$ decay (8), which is 3:1. Indeed, a comparison of the solid and dashed lines of Fig. 2 shows that the relative size of the corresponding cross-sections is paractically identical to this ratio – i.e. the final cross-section is insensitive to the detailed shape of the decay matrix element, as mentioned earlier.

Although our program does not include jet fragmentation and jet energy resolution, the only effect of jets on the dilepton cross-section is through the lepton isolation cut. Since the isolation cut is rather mild for a quark mass of 80-90 GeV (accounting for a loss of only $\sim 30\%$ dilepton events), we do not expect the above effects to influence the dilepton corss-section appreciably. We believe the largest sources of uncertainty are the QCD parametrisation alongwith the higher order QCD correction. As mentioned earlier, they can increase or decrease the cross-section by a factor of 1.5. The resulting uncertainty in the mass limits of eq. (15) is ± 5 GeV. Thus one may take the conservative mass limits for exotic and 4th generation quarks to be $m_Q > 85$ and 75 GeV respectively. Of course there is an additional source of uncertainty in the latter case – i.e. the m_t and $m_{t'}$ dependence of the corresponding branching ratio for the decay process (8). Having chosen a conservative value for this branching ratio, however, we feel the above conservative mass limit should not be affected.

Finally, let us compare our mass limits for quarks decaying via $FCNC$ with that obtained earlier for quarks decaying via CC [1]. For exotic quarks, having tree level $FCNC$ decay, the $\mu\mu$ branching ratio is 3.3%. This means a 6.6% branching ratio for the $Q\bar{Q}$ to decay into the dimuon channel. This is already larger than the 4% branching ratio for $Q\bar{Q}$ to decay into all the dilepton channels in the CC case. While the lepton detection efficiencies for the two cases are similar, the larger branching ratio for the former case is effectively compensated by the stronger $\phi_{\mu\mu}$ cut. Consequently one gets very similar mass limits for the two cases. One can combine the two to obtain a conservative mass limit of 85 GeV for exotic quarks, which is valid for all values of the quark mixing angles. Similarly one can combine the mass limits for CC and loop level $FCNC$ decays to obtain a corresponding mass limit of 75 GeV for the 4th generation quark.

In summary, $FCNC$ decay occurs at tree level for exotic quarks (singlet, vector doublet and mirror doublet) and at one-loop level for quarks of the 4th generation. For some of the heavy quarks, this is expected to dominate over the CC decay over a wide range of quark mixing angles in the first case and a more limited range in the second. The present Tevatron mass limit on heavy quarks would not apply in these cases, since it has been obtained under the assumption of CC decay. However, a systematic analysis of the Tevatron $\mu\mu$ and ee data gives comparable mass limits for heavy quarks decaying via $FCNC$ - i.e. $m_Q > 85$ and 75 GeV for the exotic and the 4th generation cases respectively. Taken together with the earlier limit, it implies that these mass limits for exotic and 4th generation quarks are valid for all values of the quark mixing angles.

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Figure Captions

Fig. 1 The distribution of the (a) $\mu\mu$ and (b) ee cross-section in the azimuthal opening angle of the lepton pair for different values of the heavy quark mass m_Q (in GeV). The right hand scale shows the corresponding number of events per 30° for the integrated luminosity of 3.5 and 4.1 pb^{-1} for the $\mu\mu$ and ee data [1]. The data points are shown by the histograms.

Fig. 2 The dilepton cross-sections after the $\phi_{\ell\ell} < 120°$ cut are shown against the heavy quark mass for tree (solid lines) and loop level (dashed lines) $FCNC$ decay. The right hand scale shows the corresponding number of events for a luminosity of 4.1 pb^{-1}. The arrows indicate the 95% CL upper limits of 3 $\mu\mu$ and 9.15 ee events corresponding to 0 $\mu\mu$ and 4 ee events in the data [1].