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Exotic quark production at DESY HERA energies

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In this paper we present a study of the production and decay of exotic heavy quarks in the fermion–mirror-fermion, vector singlet, and vector doublet models. A Monte Carlo final-state reconstruction of events is given for kinematical distributions. At energies reached at DESY HERA we show that exotic quarks in the mass range 100–150 GeV, and with mixing angles of the order of $\sin^2\theta = 0.05$, can be clearly dominant over the standard "top" quark production. We discuss experimental cuts that can eliminate the "bottom" background. We compare the theoretical predictions of the three models above in order to indicate a way to establish the origin of a possible experimental signal of an exotic quark. Even if no such signal is found, HERA can still improve the experimental bounds on exotic objects, although there is some model dependence on the estimates of total cross sections.

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I. INTRODUCTION

The DESY *ep* collider HERA can explore both the standard model and some of its extensions. The H1 and ZEUS Collaborations have already published results that cover kinematical regions which were inaccessible in the recent past. It is expected that with increasing luminosity more data will improve these results.

Despite the fact that the standard model is in remarkable agreement with experimental data, there is a general belief that it is not the ultimate theory. Many models have been proposed as generalizations, and it will be a major task of experimental physics to decide which of them, if any, is a more complete description of nature.

In this paper we turn our attention to the possibility of detecting some new experimental signal beyond the standard model at the HERA accelerator. If such a signal is found, then the main question will be to establish its origin on theoretical grounds. To this end, it is important to have a reconstruction of the detected final-state particles in the framework of nonstandard models. This was recently done [1] for the leptonic sector. Here we concentrate on the prospects for detection of an exotic quark at HERA energies, and show how to achieve a clear separation between standard and exotic signals.

This paper is organized as follows: In Sec. II we present the models that we have taken into account, their general properties, and some useful bounds; in Sec. III we discuss our results for the production and decay of an exotic heavy quark, as well as the standard heavy-quark contributions; in Sec. IV we present the main kinematical distributions obtained from a Monte Carlo reconstruction of the final-state particles; in Sec. V we briefly discuss the conclusions that can be drawn from our study.

II. THE MODELS FOR EXOTIC QUARKS

All models that generalize the standard model allow for the existence of new particles. To the new fermionic degrees of freedom corresponds, in principle, a large number of unknown mixing angles and fermionic masses. An extensive comparison between low energy data and exotic quark models was made in Ref. [2]. Experimental searches for these particles were also carried out by many groups [3]. In all searches a lower bound on the exotic quark mass around 90 GeV was found. Mixing angles are expected to be small, but for masses higher than 90 GeV the experimental limit is very weak.

We have considered the following models for exotic heavy quarks.

(a) The fermion–mirror-fermion (FMF) model.

The main point of this model is to restore the right-left symmetry in the fermionic sector. New fermions are postulated, similar to the standard-model assignment, but with opposite L and R attributes. For the first family we have

$$\begin{pmatrix} U \\ D \end{pmatrix}_R, \quad (U)_L, \quad (D)_L.$$

(b) Vector singlet model (VSM).

A possible explanation for the smallness of the mass of some of the known fermions, in particular the neutrino mass, is the seesaw mechanism. This mechanism demands the existence of new heavy singlet fermions of the type

$$(U)_L, \quad (U)_R, \quad (D)_L, \quad (D)_R.$$

(c) Vector doublet model (VDM).

TABLE I. Coupling constants for light-to-heavy-quark transitions in the framework of vector singlet (VSM), vector doublet (VDM), and fermion–mirror-fermion (FMF) models.

Parameters	VDM	FMF	VSM
$c_V^{(u,D)}$	$\cos\theta_L^u \sin\theta_L^d$	$\sin(\theta_L^d - \theta_L^u) - \cos\theta_R^d \sin\theta_R^u$	$\cos\theta_L^u \sin_L^d - \cos\theta_R^d \sin\theta_R^u$
$c_A^{(u,D)}$	$\cos\theta_L^u \sin\theta_L^d$	$\sin(\theta_L^d - \theta_L^u) + \cos\theta_R^d \sin\theta_R^u$	$\cos\theta_L^u \sin_L^d + \cos\theta_R^d \sin\theta_R^u$
$g_V^{(d,D)}$	$\cos\theta_L^d \sin\theta_L^d$	$\cos\theta_R^d \sin\theta_R^d$	$\cos\theta_R^d \sin\theta_R^d - \cos\theta_L^d \sin\theta_L^d$
$g_A^{(d,D)}$	$\cos\theta_L^d \sin\theta_L^d$	$-\cos\theta_R^d \sin\theta_R^d$	$-\cos\theta_R^d \sin\theta_R^d - \cos\theta_L^d \sin\theta_L^d$

The possibility of grand unification with the E_8 group implies large basic representations with the inclusion of new fermions of the type

$$\begin{pmatrix} U \\ D \end{pmatrix}_L , \begin{pmatrix} U \\ D \end{pmatrix}_R .$$

Exotic quarks (U D) and standard quarks $\begin{pmatrix} u \\ d \end{pmatrix}$ can mix and interact with the weak vector bosons W^+, W^-, and Z^0 according to the Lagrangians

$$\mathcal{L}_{\rm CC} = \frac{g}{2\sqrt{2}} \{ \bar{Q}_i \gamma^\mu (c_V^{ij} - c_A^{ij} \gamma^5) q_j \} W_\mu ,$$

$$\mathcal{L}_{\rm NC} = \frac{g}{4\cos\theta_W} \{ \bar{Q}_i \gamma^\mu (g_V^{ij} - g_A^{ij} \gamma^5) q_j \} Z_\mu .$$

In Table I we give coupling constants for light-to-heavy-quark transitions, in terms of the mixing angles, for the three models. As there is a large number of possibilities for the mixing angles, we have considered only three extreme cases: $V + A$, $V - A$, and V or A couplings. These cases are realized by considering all mixing angles to be equal. Since we are interested in estimating upper bounds for exotic-quark production, we take for the mixing angle the maximum value $\sin^2\theta = 0.05$. With the energy and luminosity accessible at HERA, the exotic-energy mass upper limit will be around 150 GeV.

III. PRODUCTION AND DECAY

The production of heavy quarks takes place through two mechanisms: a partonlike deep inelastic scattering and a vector-boson–gluon fusion process. Since the corresponding formulas for the production cross sections and kinematical relations are rather lengthy and well documented in the literature, we do not reproduce them here. Deep inelastic scattering (DIS) and kinematical cuts for heavy-quark production can be found in Cashmore *et al.* [4]. The vector-boson–gluon fusion (BGF) process is discussed by Schuler [5]. In the light-to-heavy-quark transition we employed the slow-rescaling variable $x' = x + M^2/2m\nu$ [6]. For the quark and gluon distribution functions we used the set 1 of Ref. [7]. Other updated parametrizations [8] did not lead to any substantial differences in the production rates. In order to make the cross section estimates more realistic, angular cuts $\theta_i > 0.1$ rad were applied to the angles θ_i of the charged final-state particles with respect to both the backward and forward directions. This angular range is consistent with the polar angle coverages of HERA detectors. To ensure that all events fall in the deep inelastic region, further cuts were imposed on the momentum transfer squared and on the square of the invariant mass of the final hadronic system, namely, $Q_2 > 4$ GeV^2 and $W^2 > 5$ GeV^2. Moreover, the Bjorken scaling variable was constrained to lie within the range $x > 10^{-3}$.

The total cross sections (DIS) for the three models are shown in Figs. 1 and 2. The curves show no model dependence. For neutral-current interactions the curves have the same shape, although in this case no distinction between the vector singlet and vector doublet models is seen. However, the basic mechanism for heavy quark production is model dependent. Even at the parton level we see from Fig. 3 that the rescaling variable reduces the total cross section by one order of magnitude. The BGF calculation for the standard top-bottom production is also shown, and is considerably smaller than the exotic contribution. The DIS contribution for top production is suppressed by the Kobayashi-Maskawa mixing. The BGF contribution for exotic quark production is similar to the top-bottom cross section, but suppressed by the mixing factor 0.05. The continuous curve is to be considered

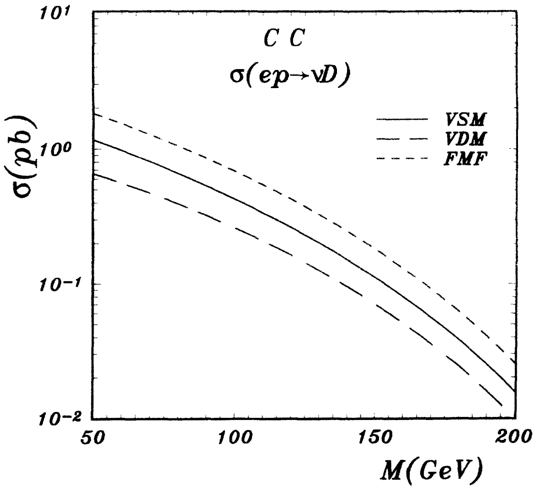

FIG. 1. Total cross section for the electroproduction of a D quark in a charged current process versus the exotic quark mass, according to the vector-singlet (VSM), vector-doublet (VDM), and fermion–mirror-fermion (FMF) models.

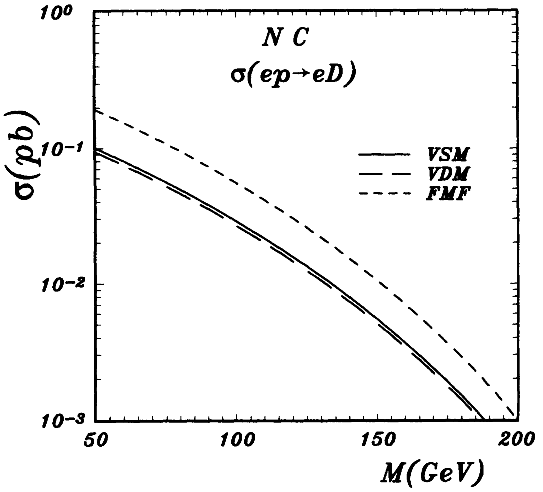

FIG. 2. Same as Fig. 1, but for a neutral current exchange.

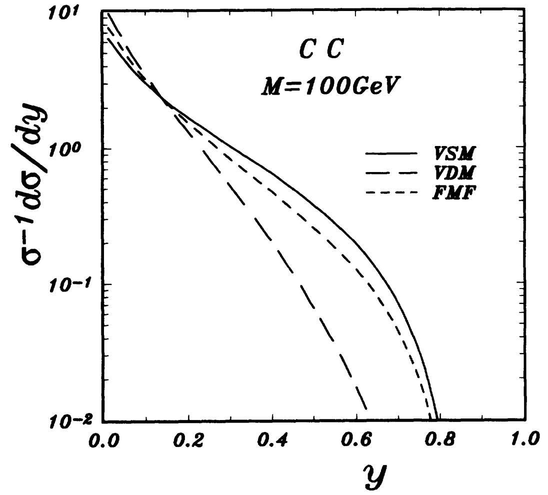

FIG. 4. Distributions in the kinematical variable y for each of the three models, taking $M = 100$ GeV.

the theoretical prediction for the upper bound for exotic quark production. In Fig. 4 we show the normalized y distributions corresponding to each model for a 100 GeV exotic quark. At the current HERA energies these distributions become essentially model independent once one goes to very high exotic-quark masses.

For the decay of a heavy exotic quark we have studied two models. The first one is the tree-level decay $Q \to q + (W, Z) \to q + \bar{f}_i + f_j$. The second one is the fragmentation of the heavy quark into a heavy meson. For this case we considered that the exotic heavy process is similar to the standard top fragmentation and decay. At HERA energies both models for a heavy-quark decay give the same results. This is illustrated in Fig. 5, where we show the angular distribution (relative to the electron beam) of the most energetic secondary charged lepton. The fragmentation calculation was done using JETSET [9]. There is no significant difference among the models. For all the other distributions we have employed the tree-level decay.

IV. KINEMATICAL DISTRIBUTIONS

In this section we present the main results of an extensive Monte Carlo calculation of kinematical distributions. The motivation for this calculation was twofold: to separate a possible exotic-quark signal from the standard heavy-quark background, and identify its theoretical origin. We concentrated our attention on the semileptonic decays $D \to u + W \to u + l + \bar{\nu}_l$, where l stands for any standard lepton, and imposed the same set of cuts discussed in Sec. III. We did not attempt to include detector

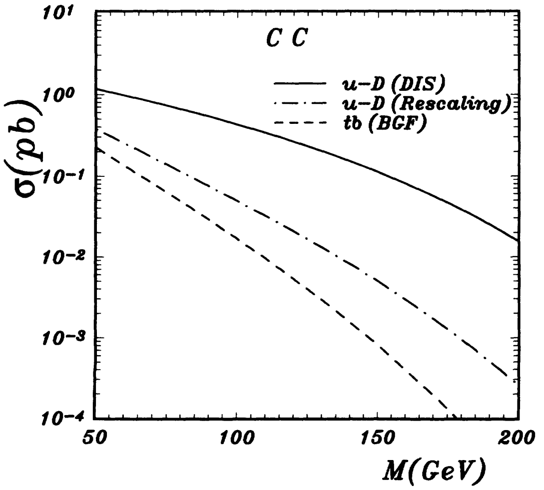

FIG. 3. Integrated cross section for the production of a heavy quark as a function of the mass, according to three different production mechanisms.

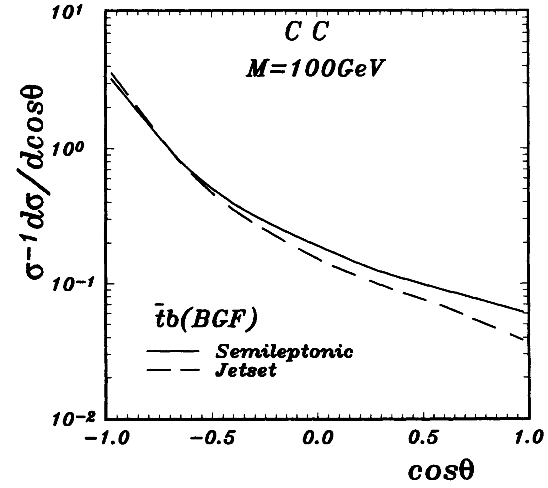

FIG. 5. Normalized angular distribution of the most energetic secondary charged lepton, according to two different decay mechanisms.

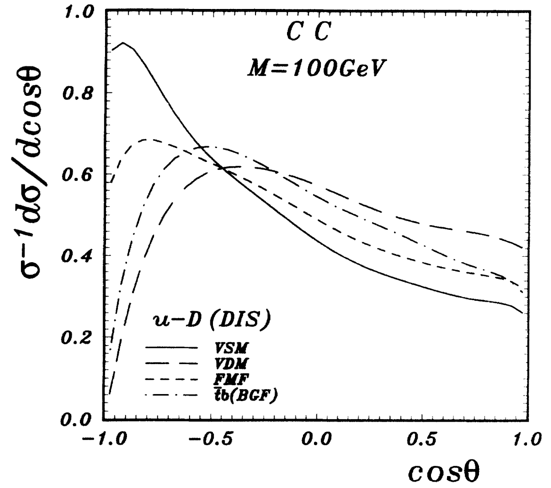

FIG. 6. Normalized angular distribution of the primary lepton in charged current processes for each nonstandard model. Top quark production via boson-gluon fusion is also shown for comparison.

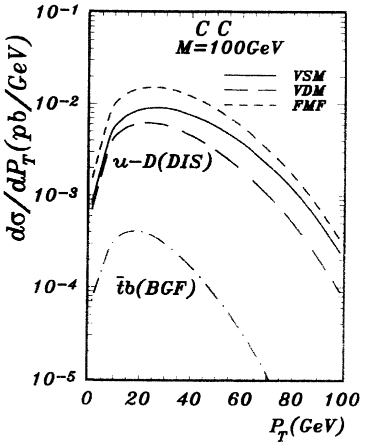

FIG. 8. Transverse momentum distribution of the primary lepton for a 100 GeV heavy quark, according to each of the three nonstandard models. Top production via boson-gluon fusion is also shown.

resolutions and geometrical acceptances in the simulation.

The most useful observable to distinguish the model under study was found to be the angular distribution of the primary lepton in the charge-current exchange. This is shown in Fig. 6 for a 100 GeV heavy quark. The VDM and FMF curves show broad peaks in the interval $\theta \sim 100^\circ$–120°, whereas the VSM event rate clearly dominates in the backward region. The distribution in the case of top-quark production via boson-gluon fusion is also shown for comparison. As illustrated in Fig. 7, in the neutral current case the angular distribution of the primary lepton is not as effective to distinguish the three models. We checked that the overall behavior of the primary lepton angular distribution does not change substantially for heavy-quark masses greater than 100 GeV.

We next consider the transverse momentum spectra of the primary and secondary leptons, plotted in Figs. 8 and 9. In both graphs the shapes of the curves are very similar, with peaks around p_T =20–30 GeV, although the secondary lepton distributions are roughly an order of magnitude smaller than the corresponding distributions for the primary electrons. No significant differences were found in the neutral current case. While these transverse momentum distributions of final-state charged leptons could hardly be used to settle the question as to which of the three models is best suited to explain any eventual nonstandard physics, they nevertheless suggest that an adequate p_T cut might be efficient to suppress the standard heavy-quark background. Indeed, a transverse momentum cut $p_T > 30$ GeV imposed on the lepton produced at the hadronic vertex leads to a considerable reduction of the standard bottom and top contributions, as shown in Fig. 10.

An interesting distribution which can be used to de-

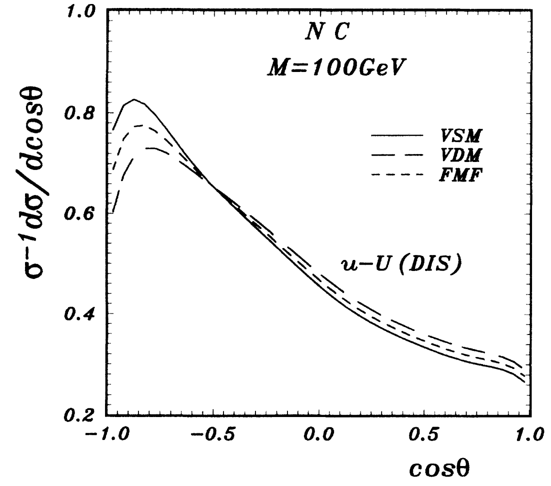

FIG. 7. Same as Fig. 6, but for a neutral current exchange.

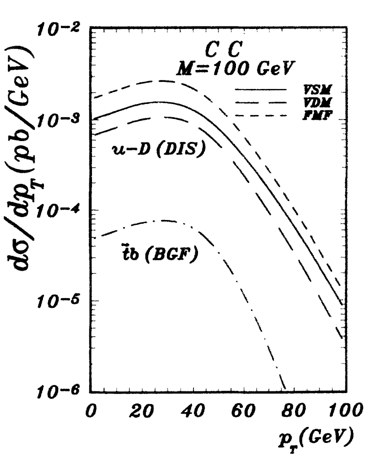

FIG. 9. Same as Fig. 8, but for the secondary lepton.

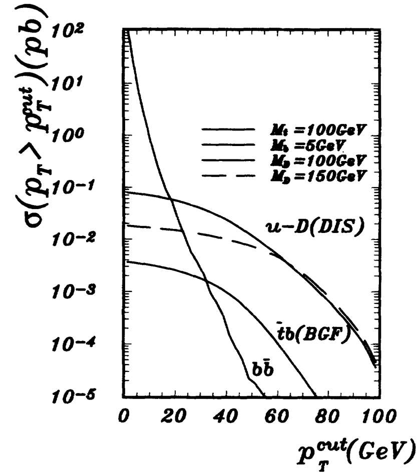

FIG. 10. Dependence of the integrated cross section of the p_T cut imposed on the secondary lepton.

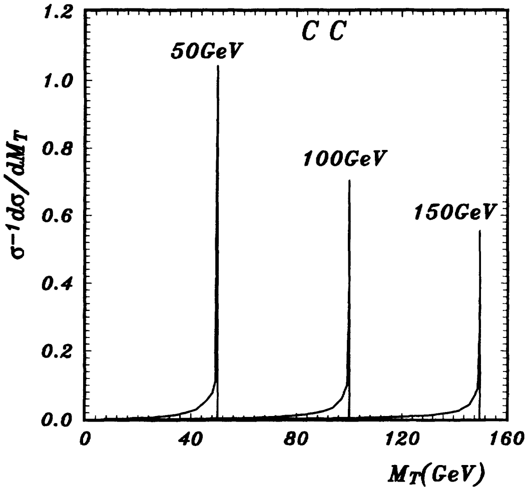

FIG. 11. Normalized cluster transverse mass spectrum.

termine the exotic quark mass is the cluster transverse mass [10] spectrum. For the semileptonic decays of a D quark considered in this paper, the cluster transverse mass gives information about the recoiling u-quark jet and has a sharp peak at the exotic quark mass, as displayed in Fig. 11. The dependence of the cluster transverse mass distribution on the three models with which we are concerned is negligible.

V. CONCLUSIONS

We have investigated the production and decay of an exotic heavy quark into light fermions at HERA energies. By a Monte Carlo simulation, and working in the context of the vector singlet, vector doublet, and fermion–mirror-fermion models, we have analyzed several kinematical distributions of the final-state particles, and searched for observables that could distinguish one nonstandard model from another. The angular distribution of the primary lepton was found to be the most sensitive quantity.

There remains a theoretical uncertainty about the basic mechanism for the production cross section. For the decay mechanism we found no difference between a tree-level decay and a more detailed fragmentation process. The theoretical origin of a possible exotic heavy quark depends on the undetected final-state neutrino of a charged current exchange, as shown in Fig. 6. The standard-model background can be eliminated by an appropriate p_T cut on semileptonic channels.

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