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PROBING NEW PHYSICS IN RARE CHARM PROCESSES * †

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ABSTRACT

The possibility of using the charm system to search for new physics is addressed. Phenomena such as $D^0 - \bar{D}^0$ mixing and rare decays of charmed mesons are first examined in the Standard Model to test our present understanding and to serve as benchmarks for signals from new sources. The effects of new physics from various classes of non-standard dynamical models on $D^0 - \bar{D}^0$ mixing are investigated.

We examine the prospect of using one-loop processes in the charm sector as a laboratory for probing new physics. Similar processes in the K system have played a strong and historical role[1] in constraining new physics, while corresponding investigations have just begun[2] in the b-quark sector. In contrast, charm has played a lesser role in the search for new physics. Due to the effectiveness of the GIM mechanism, short distance Standard Model (SM) contributions to rare charm processes are very small. Most reactions are thus dominated by long distance effects which are difficult to reliably calculate. However, a recent estimation[3] of such effects indicates that there is a window for the clean observation of new physics in some interactions. In fact, it is precisely because the SM flavor changing neutral current (FCNC) rates are so small, that charm provides an important opportunity to discover new effects, and offers a detailed test of the SM in the up-quark sector. Due to space-time limitations,[3] this talk will concentrate on $D^0 - \bar{D}^0$ mixing. First, the SM predictions are reviewed, and then the expectations in various extensions of the SM are discussed. We conclude with a brief summary of SM rates for rare D meson decays.

Currently, the best limits[4] on $D^0 - \bar{D}^0$ mixing are from fixed target experiments, with $x_D \equiv \Delta m_D/\Gamma < 0.083$ (where $\Delta m_D = m_2 - m_1$ is the mass difference), yielding $\Delta m_D < 1.3\times10^{-13}$ GeV. The bound on the ratio of wrong-sign to right-sign final states is $r_D \equiv \Gamma(D^0 \to \ell^- X)/\Gamma(D^0 \to \ell^+ X) < 3.7 \times 10^{-3}$, where

$$r_D \approx \frac{1}{2}\left[\left(\frac{\Delta m_D}{\Gamma}\right)^2 + \left(\frac{\Delta\Gamma}{2\Gamma}\right)^2\right] , \tag{1}$$

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in the limit $\Delta m_D/\Gamma, \Delta\Gamma/\Gamma \ll 1$. Several high volume charm experiments are planned for the future, with 10^8 charm mesons expected to be reconstructed. Several rare processes, including $D^0 - \bar{D}^0$ mixing, can then be probed another $1-2$ orders of magnitude below present sensitivities.

The short distance SM contributions to Δm_D proceed through a W box diagram with internal d, s, b-quarks. In this case the external momentum, which is of order m_c, is communicated to the light quarks in the loop and can not be neglected. The effective Hamiltonian is

$$\mathcal{H}_{eff}^{\Delta c=2} = \frac{G_F \alpha}{8\sqrt{2}\pi x_w}\left[|V_{cs}V_{us}^*|^2\left(I_1^s\mathcal{O} - m_c^2 I_2^s \mathcal{O}'\right) + |V_{cb}V_{ub}^*|^2\left(I_3^b\mathcal{O} - m_c^2 I_4^b\mathcal{O}'\right)\right], \qquad (2)$$

where the I_j^q represent integrals[5] that are functions of m_q^2/M_W^2 and m_q^2/m_c^2, and $\mathcal{O} = [\bar{u}\gamma_\mu(1-\gamma_5)c]^2$ is the usual mixing operator while $\mathcal{O}' = [\bar{u}(1+\gamma_5)c]^2$ arises in the case of non-vanishing external momentum. The numerical value of the short distance contribution is $\Delta m_D \sim 5 \times 10^{-18}$ GeV (taking $f_D = 200\,\mathrm{MeV}$). The long distance contributions have been computed via two different techniques: (i) the intermediate particle dispersive approach yields[3,6] $\Delta m_D \sim 10^{-4}\Gamma \simeq 10^{-16}\,\mathrm{GeV}$, and (ii) heavy quark effective theory which results[7] in $\Delta m_D \sim (1-2)\times 10^{-5}\Gamma \simeq 10^{-17}\,\mathrm{GeV}$. Clearly, the SM predictions lie far below the present experimental sensitivity!

One reason the SM expectations for $D^0 - \bar{D}^0$ mixing are so small is that there are no heavy particles participating in the box diagram to enhance the rate. Hence the first extension to the SM that we consider is the addition[8] of a heavy $Q = -1/3$ quark which may be present, *e.g.*, as an iso-doublet fourth generation b'-quark, or as a singlet quark in E_6 grand unified theories. The current bound[4] on the mass of such an object is $m_{b'} > 85\,\mathrm{GeV}$, assuming that it decays via charged current interactions. We can now neglect the external momentum and Δm_D is given by the usual expression,[9]

$$\Delta m_D = \frac{G_F^2 M_W^2 m_D}{6\pi^2} f_D^2 B_D |V_{cb'}V_{ub'}^*|^2 F(m_{b'}^2/M_W^2)\,. \qquad (3)$$

The value of Δm_D is displayed in this model in Fig. 1a as a function of the overall CKM mixing factor for various values of the heavy quark mass. We see that Δm_D approaches the experimental bound for large values of the mixing factor. A naive estimate in the four generation SM yields[4] the restrictions $|V_{cb'}| < 0.571$ and $|V_{ub'}| < 0.078$.

Another simple extension of the SM is to enlarge the Higgs sector by an additional doublet. First, we examine two-Higgs-doublet models which avoid tree-level FCNC by introducing a global symmetry. Two such models are Model I, where one doublet (ϕ_2) generates masses for all fermions and the second (ϕ_1) decouples from the fermion sector, and Model II, where ϕ_2 gives mass to the up-type quarks, while the down-type quarks and charged leptons receive their mass from ϕ_1. Each doublet receives a vacuum expectation value v_i, subject to the constraint that $v_1^2 + v_2^2 = v_{\mathrm{SM}}^2$. The charged Higgs boson present in these models will participate in the box diagram for Δm_D. The $H^\pm$ interactions with the quark sector are governed by the Lagrangian

$$\mathcal{L} = \frac{g}{2\sqrt{2}M_W} H^\pm[V_{ij}m_{u_i}A_u\bar{u}_i(1-\gamma_5)d_j + V_{ij}m_{d_j}A_d\bar{u}_i(1+\gamma_5)d_j] + h.c.\,, \qquad (4)$$

with $A_u = \cot\beta$ in both models and $A_d = -\cot\beta(\tan\beta)$ in Model I(II), where $\tan\beta \equiv v_2/v_1$. The expression for Δm_D in these models can be found in Ref. (9). ¿From the Lagrangian it is clear that Model I will only modify the SM result for Δm_D for very small values of $\tan\beta$, and this region is already excluded[2,10] from $b \to s\gamma$ and $B_d^0 - \overline{B}_d^0$ mixing. However, enhancements can occur in Model II for large values of $\tan\beta$, as demonstrated in Fig. 1b.

Next we consider the case of extended Higgs sectors without natural flavor conservation. In these models the above requirement of a global symmetry which restricts each fermion type to receive mass from only one doublet is replaced[11] by approximate flavor symmetries which act on the fermion sector. The Yukawa couplings can then possess a structure which reflects the observed fermion mass and mixing hierarchy. This allows the low-energy FCNC limits to be evaded as the flavor changing couplings to the light fermions are small. We employ the Cheng-Sher ansatz,[11] where the flavor changing couplings of the neutral Higgs are $\lambda_{h^0 f_i f_j} \approx (\sqrt{2}G_F)^{1/2}\sqrt{m_i m_j}\Delta_{ij}$, with the $m_{i(j)}$ being the relevant fermion masses and Δ_{ij} representing a combination of mixing angles. h^0 can now contribute to Δm_D through tree-level exchange and the result is displayed in Fig. 2a as a function of the mixing factor. $D^0 - \bar{D}^0$ mixing can also be mediated by h^0 and t-quark virtual exchange in a box diagram, however these contributions only compete with those from the tree-level process for large values of Δ_{ij}. In Fig. 2b we show the constraints placed on the parameters of this model from the present experimental bound on Δm_D for both the tree-level and box diagram contributions.

The last contribution to $D^0 - \bar{D}^0$ mixing that we will discuss here is that of scalar leptoquark bosons. Leptoquarks are color triplet particles which couple to a lepton-quark pair and are naturally present in many theories beyond the SM which relate leptons and quarks at a more fundamental level. We parameterize their *a priori* unknown couplings as $\lambda^2_{\ell q}/4\pi = F_{\ell q}\alpha$. They participate in Δm_D via virtual exchange inside a box diagram,[12] together with a charged lepton or neutrino. Assuming that there is no leptoquark-GIM mechanism, and taking both exchanged leptons to be the same type, we obtain the restriction

$$\frac{F_{\ell c}F_{\ell u}}{m^2_{LQ}} < \frac{196\pi^2\Delta m_D}{(4\pi\alpha f_D)^2 m_D}\,. \tag{5}$$

The resulting bounds in the leptoquark coupling-mass plane are presented in Fig. 3.

We close our discussion by displaying the expected branching fractions for various rare charm decay modes in the SM in Table 1. We present both the short distance predictions (neglecting QCD corrections, which may be important in some decay modes), an upper bound on the long distance estimates, as well as the current experimental limits.[4,13] For more details we refer the reader to Ref. (3). We urge our experimental colleagues to continue the search for rare charm processes!

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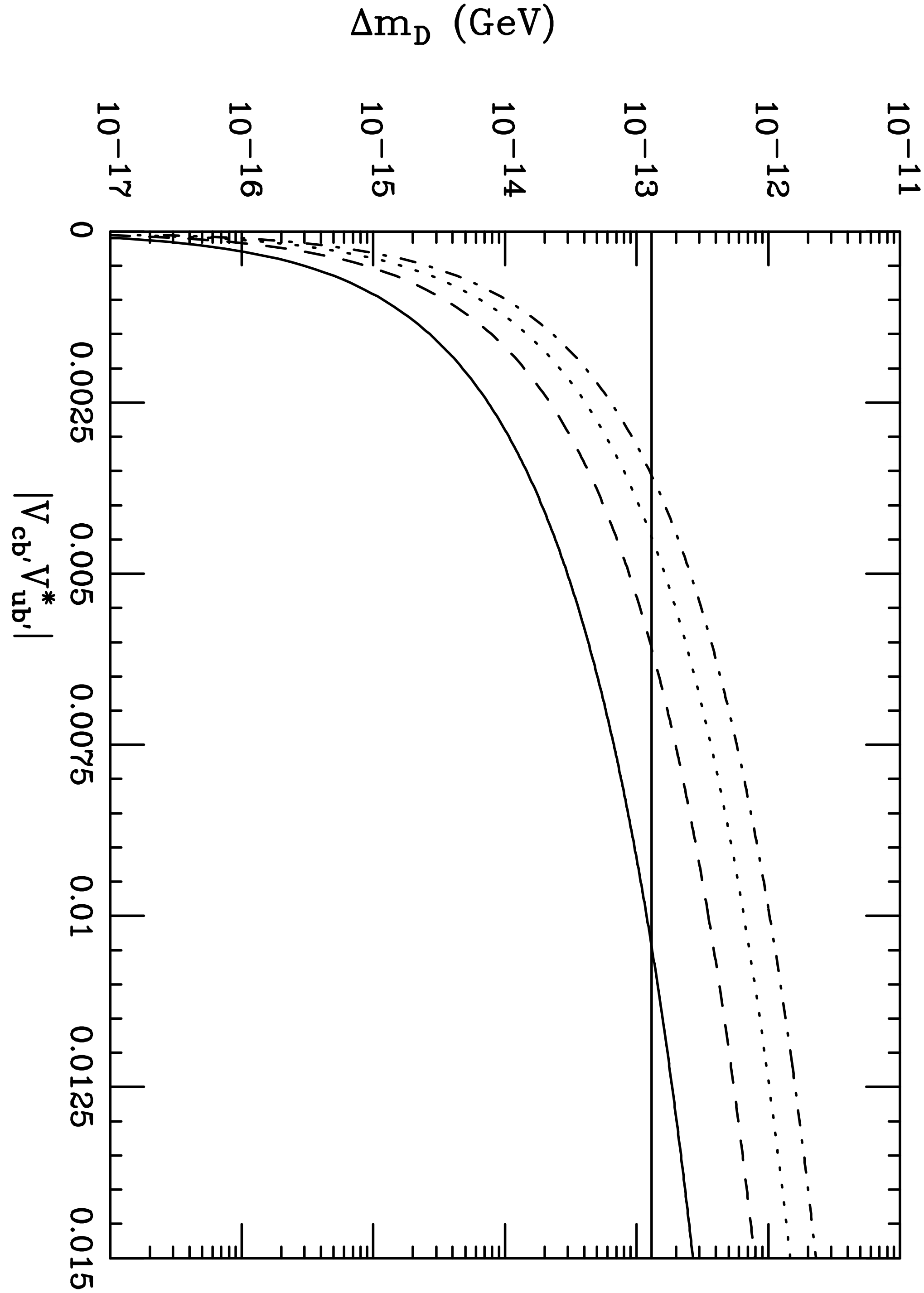
Decay Mode	Experimental Limit	$B_{S.D.}$	$B_{L.D.}$
$D^0 \to \mu^+\mu^-$	$< 1.1 \times 10^{-5}$	$(1-20) \times 10^{-19}$	$< 3 \times 10^{-15}$
$D^0 \to \mu^\pm e^\mp$	$< 1.0 \times 10^{-4}$	0	0
$D^0 \to \gamma\gamma$	—	10^{-16}	$< 3 \times 10^{-9}$
$D \to X_u + \gamma$		1.4×10^{-17}	
$D^0 \to \rho^0\gamma$	$< 1.4 \times 10^{-4}$		$< 2 \times 10^{-5}$
$D^0 \to \phi^0\gamma$	$< 2.0 \times 10^{-4}$		$< 10^{-4}$
$D^+ \to \rho^+\gamma$	—		$< 2 \times 10^{-4}$
$D \to X_u + \ell^+\ell^-$		4×10^{-9}	
$D^0 \to \pi^0\mu\mu$	$< 1.7 \times 10^{-4}$		
$D^0 \to \bar{K}^0 ee/\mu\mu$	$< 17.0/2.5 \times 10^{-4}$		$< 2 \times 10^{-15}$
$D^+ \to \pi^+ ee/\mu\mu$	$< 250/4.6 \times 10^{-5}$	few$\times 10^{-10}$	$< 10^{-8}$
$D^+ \to K^+ ee/\mu\mu$	$< 480/8.5 \times 10^{-5}$		$< 10^{-15}$
$D^0 \to X_u + \nu\bar{\nu}$		2.0×10^{-15}	
$D^0 \to \pi^0\nu\bar{\nu}$	—	4.9×10^{-16}	$< 6 \times 10^{-16}$
$D^0 \to \bar{K}^0\nu\bar{\nu}$	—		$< 10^{-12}$
$D^+ \to X_u + \nu\bar{\nu}$	—	4.5×10^{-15}	
$D^+ \to \pi^+\nu\bar{\nu}$	—	3.9×10^{-16}	$< 8 \times 10^{-16}$
$D^+ \to K^+\nu\bar{\nu}$	—		$< 10^{-14}$

Table 1. Standard Model predictions for the branching fractions due to short and long distance contributions for various rare D meson decays. Also shown are the current experimental limits.

Fig. 1: Δm_D in (a) the four generation SM as a function of the CKM mixing factor with the solid, dashed, dotted, dash-dotted curve corresponding to $m_{b'} = 100, 200, 300, 400$ GeV, respectively. (b) in two-Higgs-doublet model II as a function of $\tan\beta$ with, from top to bottom, the solid, dashed, dotted, dash-dotted, solid curve representing $m_{H^\pm} = 50, 100, 250, 500, 1000\,\mathrm{GeV}$. The solid horizontal line corresponds to the present experimental limit.

Fig. 2: (a) Δm_D in the flavor changing Higgs model described in the text as a function of the mixing factor with $m_{h^0} = 50, 100, 250, 500, 1000\,\mathrm{GeV}$ corresponding to the solid, dashed, dotted, dash-dotted, solid curve from top to bottom. (b) Constraints in the mass-mixing factor plane from Δm_D from the tree-level process (solid curve) and the box diagram (dashed).

Fig. 3: Constraints in the leptoquark coupling-mass plane from Δm_D.



Δm_D (GeV)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
0
0.0025
0.005
0.0075
0.01
0.0125
0.015
$|V_{cb'}V^*_{ub'}|$

Fig. 1a

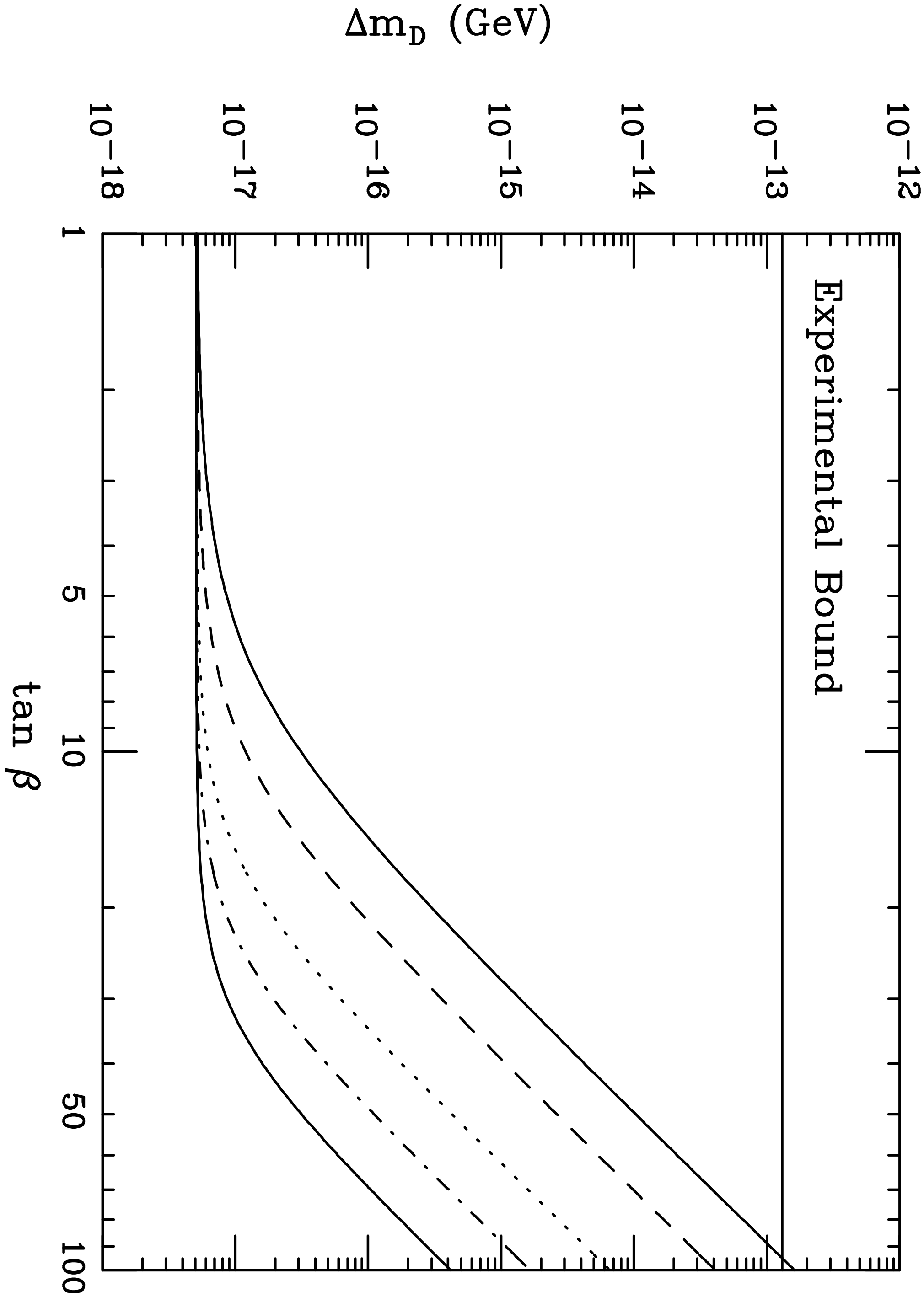

Experimental Bound
Δm_D (GeV)
tan β
10^{-18}
10^{-17}
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
1
5
10
50
100

Fig. 1b

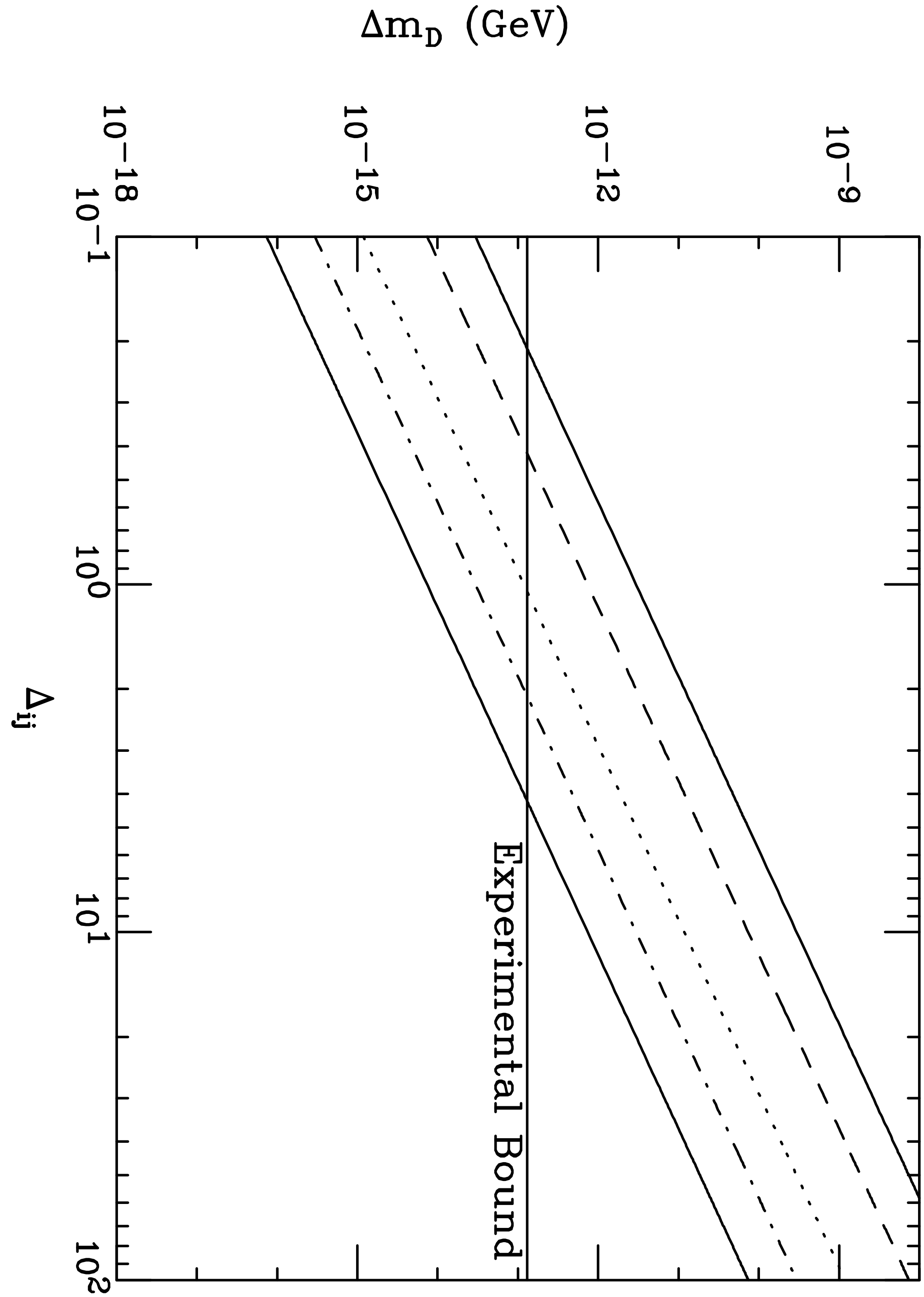
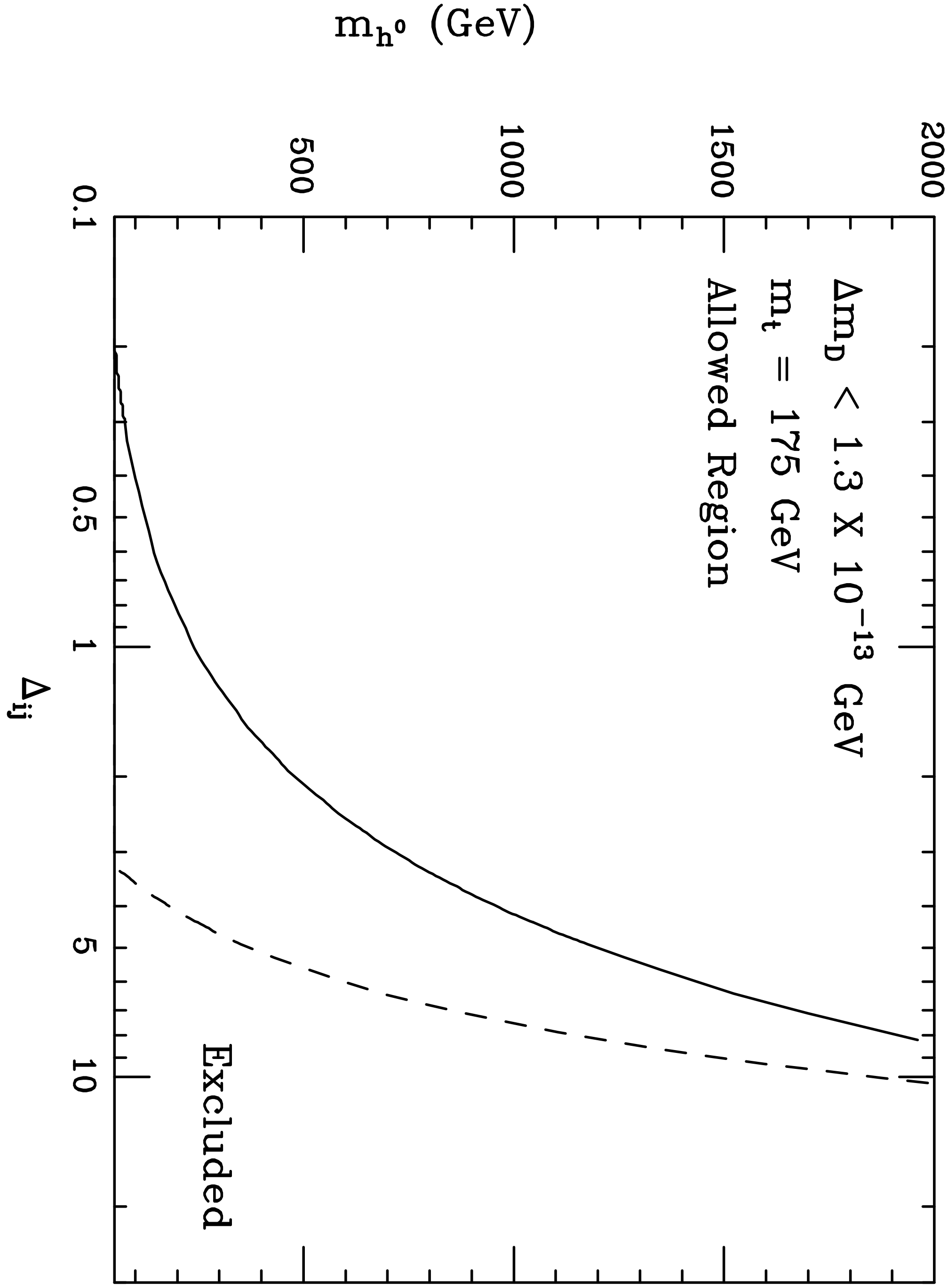
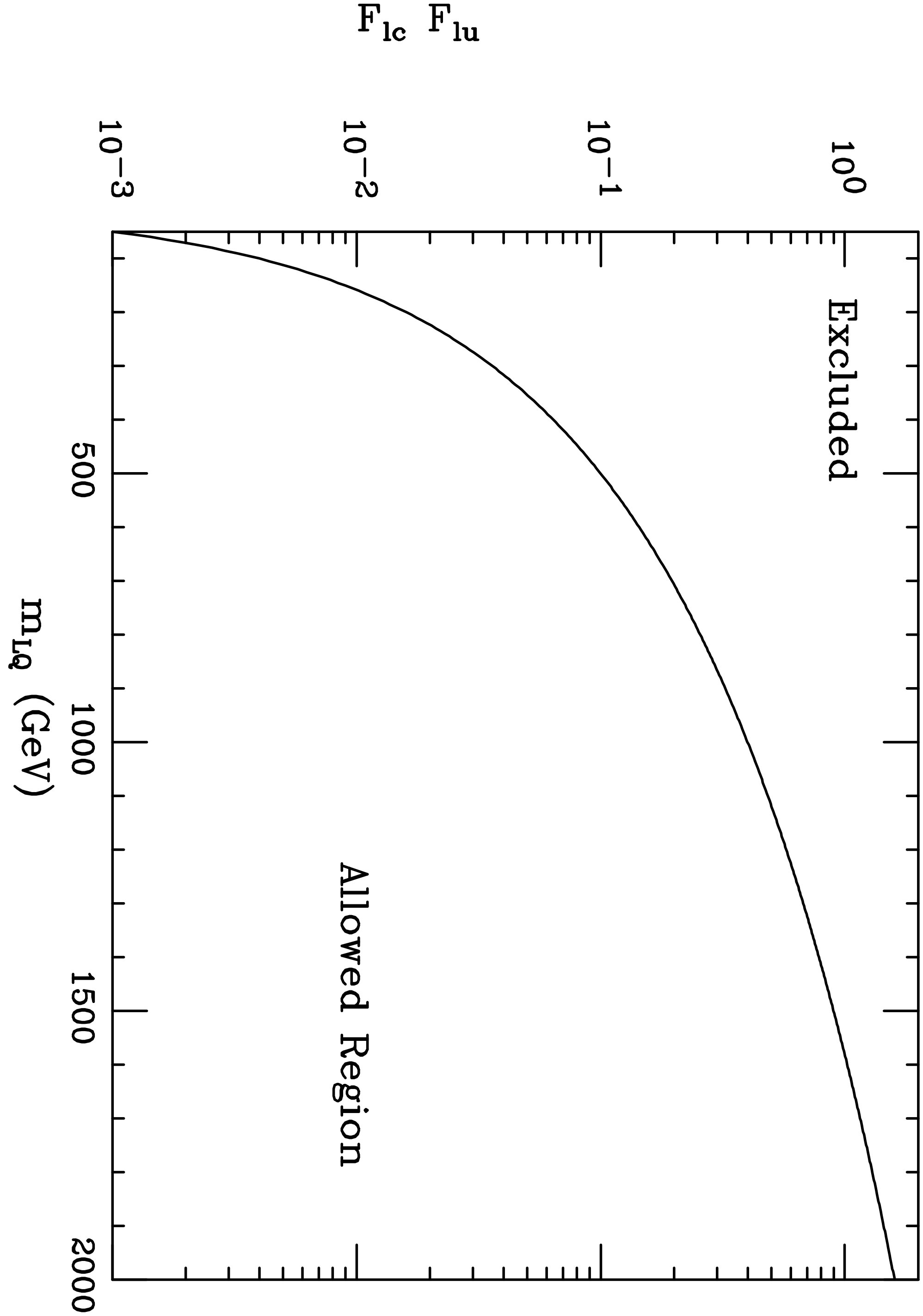

Δm_D (GeV)
10^−9
10^−12
10^−15
10^−18
10^−1
10^0
10^1
10^2
Δ_ij
Experimental Bound

Fig. 2a



m_{h^0} (GeV)
2000
1500
1000
500
0.1
0.5
1
5
10
Δ_{ij}
$\Delta m_D < 1.3 \times 10^{-13}$ GeV
m_t = 175 GeV
Allowed Region
Excluded

Fig. 2b



F lc F lu
10−3
10−2
10−1
100
500
1000
1500
2000
m LQ (GeV)
Excluded
Allowed Region

Fig. 3