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INDIRECT SEARCHES FOR VERY HEAVY QUARKS*

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ABSTRACT

Detailed studies of weak decays can reveal the presence of very massive quanta like heavy top quarks or fourth family quarks. The decay $K^+ \to \pi^+ \nu \bar{\nu}$ and $B_d - \bar{B}_d$ mixing are particularly promising fields for such searches. We infer a rather conservative lower limit of 70 GeV on the top mass from recent ARGUS data on $B_d - \bar{B}_d$ mixing; near-maximal $B_s - \bar{B}_s$ mixing is another consequence. If on the other hand top were detected in Z^0 decays, then the presence of New Physics would be established in B^0 decays. The ratio between $\tau(B^0)$ and $\tau(B^{\pm})$ is of considerable phenomenological relevance here.

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1. Introduction

The existence of charm quarks was inferred from rare K^0 decays;[1] CP violation in K_L decays was invoked as evidence for the third family of quarks consisting of bottom and top quarks.[2] One should note that the mass of charm, bottom and top quarks is much larger than the K mass. History might repeat itself and allow the discovery of yet another family of quarks (or other heavy quanta) in such an indirect way; or at least the scale of the top mass might be obtained this way.

There is hardly a doubt left that top indeed exists in nature: the cleanest, tough still indirect evidence for it comes so far from the observed forward-backward asymmetry of bottom jets produced in e^+e^- annihilation. For the data[3] support the expected assignment of b quarks into an isodoublet; hence there is an isopartner – the top.

This argument does however not give any clue as to the value of the top mass. PETRA data yield a lower limit of 22 GeV whereas a comprehensive analysis of isospin breaking in deep-inelastic lepton nucleon scattering suggests[4] an upper limit:

$$22 \text{ GeV} \leq m_t \lesssim 130 \text{ GeV} \tag{1}$$

A useful nomenclature is provided by the following distinction:

(i) a "light" top allows $W \to t\bar{b}$ to proceed, *i.e.*, $m_t \lesssim 70$ GeV;

(ii) for a "heavy" top $t \to Wb$ occurs instead, *i.e.*, $m_t > 90$ GeV.

Finding a heavy top hadron as a real on-shell state poses a formidable challenge even for TEVATRON experiments. It is my judgment that in the near future there are (at least) two processes that have a very good chance to reveal indirectly the existence of heavy top or even heavier states like quarks from a fourth family:

(A) $K^+ \to \pi^+ \nu\bar{\nu}$;

(B) $B^0 - \bar{B}^0$ mixing.

These, in particular the second one, will be discussed in some detail. There are other reactions like $B \to K^{(*)}\gamma$, $K^{(*)}\ell^+\ell^-$ with a similar potential;[5] they will be treated by other speakers.[6]

Searching for $Z^0 \to b\bar{s} + s\bar{b}$ on the other hand appears to represent a hopeless task since it is hard to see how $BR(Z^0 \to b\bar{s} + s\bar{b})$ could exceed 10^{-7}.

In the end I will make a few short comments on CP violation in B^0 decays.

2. $K^+ \to \pi^+ \nu\bar{\nu}$

Relating $K^+ \to \pi^+ \nu\bar{\nu}$ to $K \to \pi\ell\nu$ one can make very reliable predictions for $BR(K^+ \to \pi^+ \nu\bar{\nu})$ in terms of m_t and the KM parameter $V^*(ts)V(td)$. One finds[7,8]

$$[3.2,\ 3.7,\ 4.2] \times 10^{-11} \lesssim BR(K^+ \to \pi^+ \nu\bar{\nu}) \lesssim [1.0,\ 3.4,\ 7.4] \times 10^{-10} \qquad (2)$$

for

$$m_t = [40,\ 100,\ 160]\ \text{GeV}$$

10^{-10} thus provides an important bench mark: if the measured branching ratio significantly exceeds 10^{-10} then – in the nomenclature introduced above – top has to be "heavy" or/and a fourth family has to exist. In the latter case even a branching ratio of $\mathcal{O}(10^{-9})$ could be generated.[8]

In passing it should be noted that the ARGUS findings on $B_d - \bar{B}_d$ mixing that will be discussed in the next chapter strongly suggest that this branching ratio exceeds 2×10^{-10}.

3. $B^0 - \bar{B}^0$ Mixing

The ARGUS collaboration has presented highly intriguing preliminary findings on $B_d - \bar{B}_d$ mixing as obtained on the $\Upsilon(4s)$ resonance[9]

$$y_p = \frac{N(\ell^\pm \ell^\pm)}{N(\ell^+ \ell^-)} = \begin{cases} (23.4 \pm 6.7 \pm 3.1)\% & \text{inclusive } \ell\ell \\ (19 \pm 10)\% & \text{tagged events} \end{cases} \tag{3}$$

These numbers are rather surprising because of the previous upper bound from CLEO – $y_p \leq 24\%$ (90% C.L.) – and previous theoretical expectations which will be given later.

First we want to address some immediate phenomenological issues:

3.1 $B_d - \bar{B}_d$ versus $B_s - \bar{B}_s$ Mixing

In the Standard Model with three families one obtains in a straightforward manner

$$\frac{\Delta m(B_s)}{\Delta m(B_d)} = \frac{\mathrm{Re}(V(ts))^2}{\mathrm{Re}(V(td))^2} \, \frac{Bf_B^2(B_s)}{Bf_B^2(B_d)} \tag{4}$$

where Bf_B^2 is a measure of the size of the relevant hadronic matrix element. Different theoretical calculations all agree on[10]

$$Bf_B^2(B_s) \;\geq\; Bf_B^2(B_d) \tag{5}$$

The main uncertainty enters via the KM parameters which yield (in the Wolfenstein representation)

$$\frac{\Delta m(B_s)}{\Delta m(B_d)} \geq \frac{\mathrm{Re}(V(ts))^2}{\mathrm{Re}(V(td))^2} = \frac{1}{\lambda^2}\,\frac{1}{(1-\rho)^2-\eta^2} \gtrsim 6.5 \tag{6}$$

and therefore

$$r_s = \frac{\Gamma(B_s \to \ell^+ X)}{\Gamma(B_s \to \ell^- X)} \;\geq\; 0.80 \tag{7}$$

for $r_d \geq 0.09$.

This point is very important for our later discussion: as long as one limits oneself to the Standard Model with three families, then a 10% (or more) B_d mixing leads quite conservatively to near-maximal B_s mixing.

A scenario with $r_d \geq 0.09$ and $r_s \geq 0.80$ by itself is not inconsistent with other data on $B^0 - \bar{B}^0$ mixing as obtained by UA1, Mark II and JADE.[11] This statement rests largely on the fact that the relative abundance of B_s is not known independently and a priori could be as small as 14%.

3.2 $\tau(B^{\pm})$ VERSUS $\tau(B^0)$

While most authors expect the lifetimes and correspondingly also the semileptonic branching ratios of bottom hadrons to agree with each other to within, say, 20%, its should be kept in mind that experimentally a much larger variation is still allowed by CLEO data:

$$\frac{1}{2} \;\lesssim\; \frac{b_{SL}(B^{\pm})}{b_{SL}(B^0)} \;\lesssim\; 2 \tag{8}$$

Theoretically it is very hard to see how this ratio could be smaller than one; thus we restrict our analysis to

$$1 \leq R \equiv \frac{b_{SL}(B^{\pm})}{b_{SL}(B^0)} \leq 2 \tag{9}$$

One finds for y_p, the ratio of like-sign to opposite-sign dileptons on the $\Upsilon(4s)$:

$$y_p = \frac{\chi_d}{\frac{1-f_0}{f_0} R^2 + (1-\chi_d)} \tag{10}$$

where $\chi = r/(1+r)$ and f_0 denotes the fraction of $B^0\bar{B}^0$ pairs. Therefore

$$\chi_d = \frac{y_p}{1+y_p} \cdot \left(\frac{1-f_0}{f_0} R^2 + 1\right) \tag{11}$$

One reads off from (11) that for a given y_p the mixing strength χ_d depends strongly on R. For example if $y_p \simeq 0.04$ one finds

$$\chi_d \simeq [0.09,\ 0.15,\ 0.24] \quad \text{for} \quad R = [1,\ 1.5,\ 2] \tag{12}$$

On the other hand $y_p \simeq 0.09$ leads to

$$\chi_d \simeq [0.19,\ 0.32,\ 0.50] \tag{13}$$

In that case $R \leq 2$ for certain since $\chi \leq 0.5$ must trivially hold.

We will discuss later that if $R \geq 1.5$ indeed holds, then the case for New Physics is significantly strengthened. First we address a more phenomenological issue: when R exceeds unity, one has to increase χ_d correspondingly to reproduce a given ratio of like-sign to opposite-sign dileptons in $\Upsilon(4s) \to B\bar{B}$. The ratio of like-sign to opposite-sign dileptons in bottom production *well above threshold* receives a relatively small enhancement of roughly 10-20% when R goes from one to two and $y_p \simeq$ 0.04-0.09.

Such a change in R has a considerably larger impact on the forward-backward asymmetry of bottom jets in e^+e^- annihilation where one finds[12]

$$A_{FB}(\text{bottom jets}) = \frac{1}{1+\bar{r}}\, A_{FB}(b\bar{b}) \tag{14}$$

with

$$\bar{r} = \frac{2}{R}\, \frac{\chi_d + f_s\, \chi_s}{1 + \frac{1}{R}\left(f_\Lambda + 1 - 2\chi_d + f_s(1-2\chi_s)\right)} \tag{15}$$

where $f_s[f_\Lambda]$ denotes the abundance of $B_s[\Lambda_b]$ states relative to that of B^-. Using $f_s = 1/3$, $f_\Lambda = 0.1$ and $\chi_d = 0.09$ [0.19] one obtains for $R = 1$

$$\bar{r} \simeq 0.24\ [0.40] \tag{16}$$

If instead $R = 2$ were to hold one gets

$$\bar{r} \simeq 0.30\ [0.64] \tag{17}$$

Experimentally a 90% C.L. upper bound has been found[12]

$$\bar{r}_{\text{exp}} \leq 0.35 \tag{18}$$

Thus a moderate increase in experimental sensitivity should reveal a nonvanishing $\bar{r}$, in particular if $R \geq 1.5$ – unless of course there exists New Physics that contributes *destructively* to $B_s - \bar{B}_s$ mixing.

4. Theoretical Estimates on $B_d - \bar{B}_d$ Mixing

The ratio $x = \Delta m/\Gamma$, which is the driving force behind $B^0 - \bar{B}^0$ mixing can be calculated in terms of three main parameters:

— m_t

— the KM parameters $V^*(tb)V(td)$

— the hadronic matrix element $\langle B^0 | J \cdot J | \bar{B}^0 \rangle$ which is conventionally expressed in terms of $B \cdot f_B^2$, $B = 1$ corresponding to "vacuum saturation."

$$\Delta m(B_d) = f(m_t)\,\mathrm{Re}\,(V(td))^2\; Bf_B^2(B_d) \tag{19}$$

$f(m_t)$ is a known function of m_t.[13] Theoretical estimates on B range between 0.5 and 1 and on f_B between 70 and 190 MeV.[10] The different theoretical calculations thus exhibit a much stronger trend to agree than it was the case a few years ago – yet even so one has to reckon with uncertainties of a factor of two to three. A reasonable calibration for theoretical expectations is provided by expressing them in terms of a factor

$$F = \frac{\mathrm{Re}\,(V(td))^2}{(0.01)^2}\;\frac{Bf_B^2}{(100\ \mathrm{MeV})^2} \tag{20}$$

An estimate of r_d with the rather conservative range $F =$ 1-8 is given in Fig. 1; from it we conclude that if $r_d \geq 0.10$ then

$$m_t \;\geq\; 70\ \mathrm{GeV} \tag{21}$$

It is intriguing to note again the upper bound on m_t, $m_t \lesssim 130$ GeV.[4]

Therefore the Standard Model with 3 families does not allow $Z^0 \to t\bar{t}$ to proceed if indeed $r_d \geq 0.10$. Observing $Z^0 \to t\bar{t}$ on the other hand establishes the presence of New Physics in $B_d - \bar{B}_d$ mixing. One – but by no means the only – example is given by an ansatz with four families[8] as shown in Fig. 2.

5. CP Violation in B^0 Decays

A priori a CP asymmetry could show up in *semileptonic* B^0 decays:

$$a_{SL} = \frac{\sigma\left(B^0\bar{B}^0 \to \ell^+\ell^+ + X\right) - \sigma\left(B^0\bar{B}^0 \to \ell^-\ell^- + X\right)}{\sigma\left(B^0\bar{B}^0 \to \ell^+\ell^+ + X\right) + \sigma\left(B^0\bar{B}^0 \to \ell^-\ell^- + X\right)} = \frac{\mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}}}{1 + \frac{1}{4}\left|\frac{\Gamma_{12}}{M_{12}}\right|^2} \tag{22}$$

In the Standard Model with 3 families such asymmetries remain unobservably small; adding New Physics like a fourth family could produce an a_{SL} on the percent level. However if at the same time $r_d \geq 0.10$ has to be reproduced it is an almost inescapable conclusion that $a_{SL} \lesssim 10^{-3}$.

On the other hand the prospects for observing CP asymmetries in *nonleptonic* B_d decays are greatly enhanced. As explained elsewhere in more detailed,[14] the mixing strength optimal for observing a difference between $\Gamma(B^0(t) \to f)$ and $\Gamma(\bar{B}^0 \to \bar{f})$ – f being a common decay mode of B^0 and $\bar{B}^0$ – is $r = 33\%$. Yet also $r_d \geq 10\%$ presents an excellent scenario where CP asymmetries of up to 50% can be realized.

6. Conclusions

The history of K decay studies shows that New Physics – like parity and CP violation and charm – can be found in an indirect way. There is every reason to believe that detailed studies of weak decays will score more such successes in the future; searches for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $B_d - \bar{B}_d$ mixing are just two – though highly promising – examples. In these processes one has sensitivity for mass scales that are beyond the reach of even the TEVATRON as far as direct production is concerned.

The recent ARGUS findings – if they stand the test of further scrutiny – are an eminently intriguing step in such a direction: if $Z^0 \rightarrow t\bar{t}$ is observed or $B_s - \bar{B}_s$ mixing restricted to be less than near-maximal, then one has established the presence of New Physics in B^0 decays. The presumed size of the effect – $r_d \geq 0.10$ – already "smells" of New Physics – yet at the moment we cannot claim for sure that this "new smell" establishes a "new flavor". The discussion given above shows – and $B_d - \bar{B}_d$ mixing thus provides a typical case study for the paradigm of indirect searches – that no gain can be achieved without its proper prize: at each step the reliability of the theoretical reasoning has to be gauged in a careful manner. Here it is our understanding of the B meson wave function that has to be cross-examined. This requires more work, both of a theoretical and an experimental nature.

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Figure Captions

Fig. 1. r_d as a function of m_t in the Standard Model with three families; the theoretical uncertainties are expressed in terms of a factor

$$F = \frac{\mathrm{Re}\,(V(td))^2}{(0.01)^2} \frac{Bf_B^2}{(100\ \mathrm{MeV})^2} \quad .$$

The upper bound on m_t shown here is from ref.4.

Fig. 2. r_d as a function of $m_{t'}$, the mass of a fourth family quark, with $m_t = 40$ GeV kept fixed.

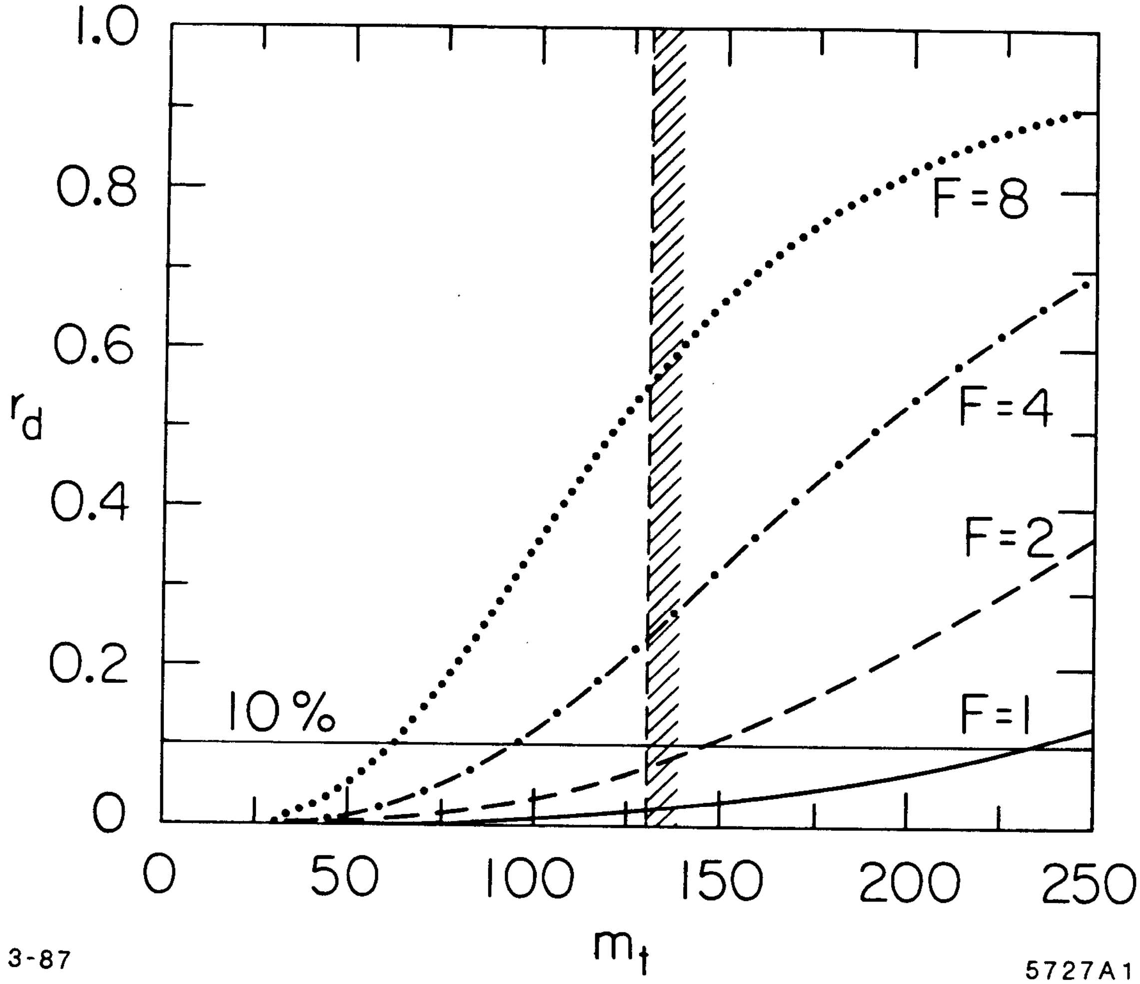

Fig. 1

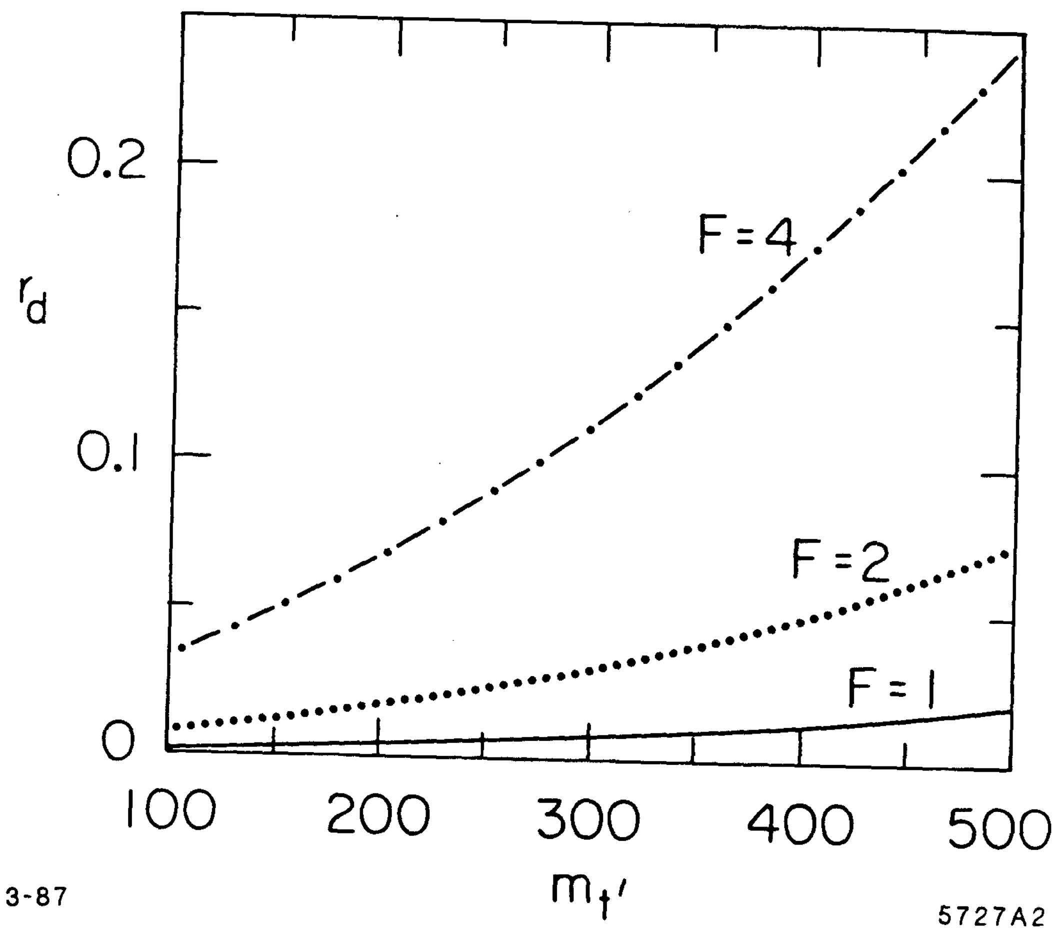

Fig. 2