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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 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ 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:

$$22\ \text{GeV} \le m_t \lesssim 130\ \text{GeV} \qquad (1)$$

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 $O(10^{-9})$ 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

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

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

$$B f_B^2(B_s) \geq B f_B^2(B_d) \tag{5}$$

The main uncertainty enters via the KM parameters which yield (in the Wolfen-

stein 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

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

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 $R \le 2$ for certain since $\chi \le 0.5$ must trivially hold.

We will discuss later that if $R \ge 1.5$ 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]

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

with

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

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 $R = 1$

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

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

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

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

$$r_{exp} \leq 0.35 \tag{18}$$

Thus a moderate increase in experimental sensitivity should reveal a nonvanishing 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."

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

$f(m_t)$ 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

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

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

$$m_t > 70\ \mathrm{GeV} \tag{21}$$

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:

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

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 $\Gamma(\bar{B}^0 \to f)$ – 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 $K^+ \to \pi^+ \nu\bar{\nu}$ 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 $Z^0 \to t\bar{t}$ 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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References

1. S. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D2 (1970) 1285.
2. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49 (1973) 652.
3. D. H. Saxon, Rutherford preprint RAL-84-094 (1984).
4. W. Marciano, these Proceedings.
5. G. Hou, talk given at the APS Meeting, Salt Lake City, 1987, with references to earlier work.
6. A. Soni, these Proceedings.
7. F. Gilman and J. Hagelin, Phys. Lett. **133B** (1983) 443; U. Türke, Phys. Lett. **168B** (1986) 296.
8. I. I. Bigi and S. Wakaizumi, SLAC-PUB-4180, to appear in Phys. Lett.
9. H. Albrecht, these Proceedings.
10. I. I. Bigi and A. I. Sanda, Nucl. Phys. **281** (1987) 41, with references to earlier work.
11. See for example: A. Ali, these Proceedings; E. A. Paschos, *ibidem*.
12. W. Bartel *et al.*, Phys. Lett. **146B** (1984) 437. I. I. Bigi, Phys. Lett. **155B** (1985) 125;
13. T. Inami and C. S. Lim, Prog. theor. Phys. **65** (1981) 297.
14. I. I. Bigi, invited talk given at the UCLA Workshop on $B\bar{B}$ Factories, January 1987, to appear in the Proceedings.

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

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

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.

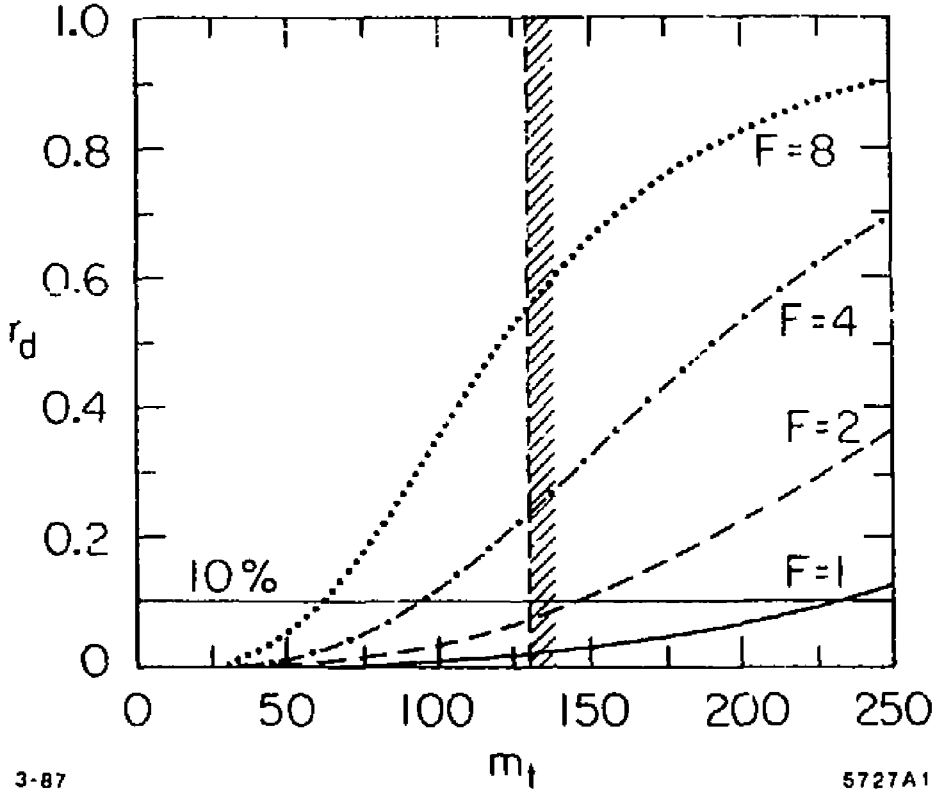

Fig. 1

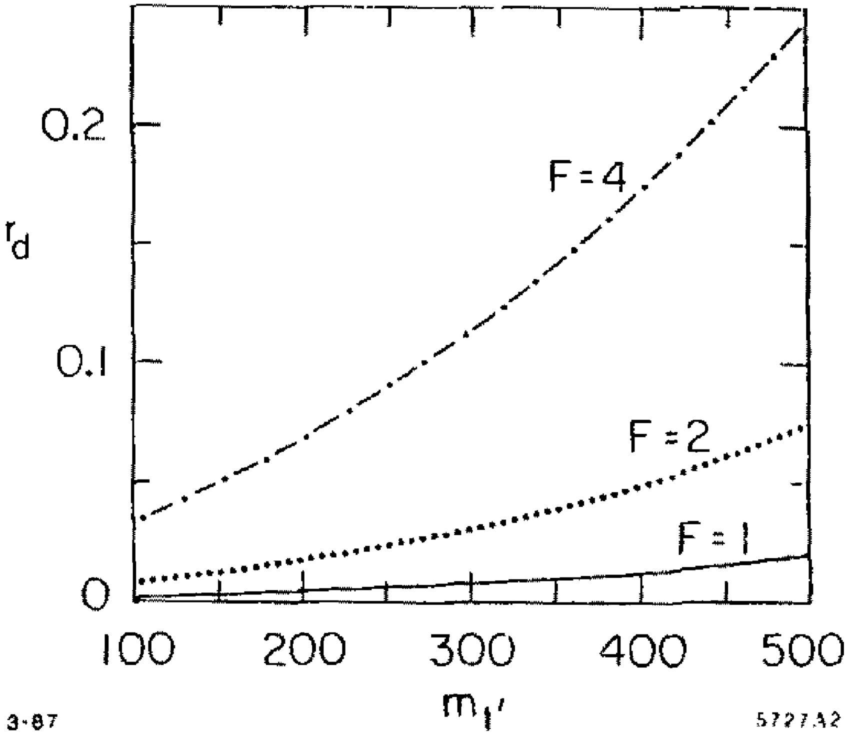

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Fig. 2