ON THE FEASIBILITY OF MEASURING QUARK MIXING ANGLES AT THE TEVATRON

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In the six-quark version of the standard $SU(2)_L \times U(1)$ electroweak theory[1] the mixing of quark mass eigenstates to form gauge group eigenstates is determined by the matrix V

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \tag{1}$$

The charged current is then

$$J_\mu = (\bar{u}, \bar{c}, \bar{t})_L \, \gamma_\mu V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \tag{2}$$

In the convenient Kobayashi-Maskawa parametrization[2]

$$V = \begin{pmatrix} c_1 & s_1c_3 & s_1s_3 \\ -s_1c_2 & c_1c_2c_3 - s_2s_3c^{i\delta} & c_1c_2s_3 + s_2c_3e^{i\delta} \\ -s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\delta} & c_2s_2s_3 - c_2c_3e^{i\delta} \end{pmatrix}, \tag{3}$$

where $c_1 = \cos\theta_1$, $s_1 = \sin\theta_1$, etc.

From a precise comparison of super allowed nuclear β decay with μ decay and a Cabibbo fit to strange hyperon semileptonic decays the matrix elements (i.e., coupling coefficients) $|V_{ud}|$ and $|V_{us}|$ have been reasonably well determined to be[2]

$$|V_{ud}| = |c_1| = 0.9737 \pm 0.0025 \tag{4}$$

$$|V_{us}| = 0.219 \pm 0.011$$

This yields (modulo unphysical quadrant ambiguities)

$$|s_3| = 0.28 \,{}^{+0.21}_{-0.28}.$$

More indirectly, from an analysis of the K^0-$\bar{K}^0$ transition amplitude[3] and $K_L \to \mu^+\mu^-$ decay[4] one can derive a set of correlated constraints on quark mixing angles.

A very important contribution by the Tevatron would be direct experimental measurement of the heavy quark coupling coefficients or mixing angles, analogous to the measurements of the d → u coupling via nuclear β decay and the s → u coupling via hyperon decays. As will be seen, however, this would be very difficult.

In order to measure these angles one uses semi-leptonic charged current weak processes, in particular, (anti) neutrino reactions and semi-leptonic decays of heavy hadrons. We shall concentrate on the first of these and comment later on the second. First, in passing, we note that a crude determination of $|V_{cd}|$ and $|V_{cs}|$ could in principle be obtained from ν_μ and $\bar{\nu}_\mu$ induced charm production, assuming that an absolute rate is measured and that the d and s parton distributions are sufficiently well known. The usual signature is opposite-signed dimuon production. Conventionally, these couplings were **assumed** to be $\sin\theta_c$ and $\cos\theta_c$, and the dimuon data were used to extract the s and $\bar{s}$ sea content. To proceed in the opposite direction, i.e., assume the s-quark parton distribution as given and infer $|V_{cs}|$ could only yield a crude value since the only prior source of information on this distribution is from electroproduction data, which do not determine it very well.

A further question concerns the measurement of $|V_{ub}|$ and $|V_{cb}|$. The $(\bar{b})$ can be produced through the reactions.

$$\bar{\nu}_\mu(u,c,t) \to \mu^+ b$$

and (5)

$$\nu_\mu(\bar{u},\bar{c},\bar{t}) \to \mu^- \bar{b}.$$

The method again would be to detect the semi-leptonic signal from the $(\bar{b})$, determine the rate, and, knowing the initial parton distribution, extract the respective coupling coefficient. Clearly, only the reaction $\bar{\nu}_\mu u \to \mu^+ b$ could be used with much reliability because only the u-quark parton distribution is measured. One could, of course, try to calculate the c and with more uncertainty, the t-quark distributions, as predicted by various theoretical models, but they have not been measured, so this is heavily dependent on these models. Accordingly, we shall concentrate on the reaction $\bar{\nu}_\mu u \to \mu^+ b$. The production and detection of $(\bar{b})$ quarks have been studied theoretically[5,6,7] by several groups with basically similar conclusions. For maximal mixing, i.e., $|s_3| = 0.5$ (with $|s_1|$ known to be ~ 0.23) $|V_{us}|^2 = 0.013$; assuming this case, it was found that for E between $\sim 10^2$ and

~ 10^3 GeV the rate for b production by $\bar{\nu}_\mu$ relative to the total $\bar{\nu}_\mu$ cross section was less than ~ 0.3%. Indeed, given the assumption that $|V_{cb}| = |V_{cb}|_{max}$ and a reasonable model for the c-quark parton distribution, it was found that for E $\gtrsim$ 600 GeV the $\bar{\nu}_\mu c \to \mu^+ b$ transition would dominate slightly over the $\bar{\nu}_\mu u \to \mu^+ b$ one. Although this may be regarded as fortunate for the question of total b production, it is not for the task of measuring $|V_{ub}|$ itself. Moreover, even if the $\bar{\nu}_\mu c \to \mu^+ b$ reaction dominates, one cannot obtain a very reliable determination of $|V_{cb}|$ because of the uncertainty in the c-quark distribution mentioned before.

Furthermore, in order to measure a rate one must be able to identify unambiguously the b quark signal. Again, all studies are in basic agreement: it is very difficult. One would look for a $\mu^-\mu^+$ signal from

$$\begin{aligned} &\bar{\nu}_\mu u \to \mu^+ b \\ &\qquad\qquad\quad \hookrightarrow \mu^- + c + \ldots \end{aligned}$$

In particular, one could test the energy asymmetry of the $\mu^+\mu^-$ and the transverse momentum distribution of the μ^- relative either to the "current" direction q or to the beam direction. The results require further assumptions concerning the p_t dependence in B hadron production, B fragmentation and, for background comparisons, similar quantities for charmed hadrons. By cutting at $p_\perp > 2.5$ GeV one could perhaps isolate a B semileptonic decay signal but by doing so one would be left with only about 1% of the initial b's, according to Phillips' calculations.[7] Searching for the $\mu^+\mu^+$ signal from $b \to c$ + hadrons; $c \to \mu^+\nu_\mu$+ hadrons gives similar conclusions regarding the detectability of a b signal as does the multi-leptonic signal from $b \to c+\mu^-+\ldots$; $c \to \mu^++\ldots$ Using the primary $p_\perp$ distribution as the signal, if one requires 100 $\mu^+\mu^-$ dimuons with $p_\perp > 2.5$ GeV to establish a b signal, this necessitates ~ 10^6 $\bar{\nu}_\mu N$ events at high energies of several hundred GeV. Moreover, it must be emphasized that the task of accurately measuring $|V_{ub}|$ (or $|V_{cb}|$) is substantially more difficult than the task of just isolating a b-quark signal. This is especially true if there are several quark transitions contributing with comparable strengths to b production since then one has not only the job of determining the relevant initial parton distribution but also the task of somehow (perhaps by x_{vis} and/or y_{vis} distributions) determining how many of the b's come from each of the different quark transitions. Thus the determination of the b-quark mixing angles at the Tevatron appears, on the basis of several existing studies, to be extremely difficult. However, further studies would be worthwhile.

Another topic concerns the production of the assumed t quark and the measurement of its coupling coefficients. In the standard model the reactions which yield ($\bar{t}$) are

$$\nu_{\mu}(d,s,b) \rightarrow \mu^{-}t$$

and

$$\bar{\nu}_{\mu}\ (\bar{d},\bar{s},\bar{b}) \rightarrow \mu^{+}\ \bar{t}\ .$$

Here the $\nu_{\mu}d \rightarrow \mu^{-}t$ reactions occur off a well-measured valence quark distribution. The $\nu_{\mu}s \rightarrow \mu^{-}t$ process uses a sea-quark distribution which is not as reliably measured and which is more subject to uncertainty from the models used to estimate its evolution in Q^2. A helpful specific analysis of t production and detection has been performed by Phillips.[8] The present lower bound on m_t from PETRA is ~ 18 GeV. If one assumes that $m_t = 20$ GeV and scales up the Fermilab or CERN ν spectra to one appropriate for the Tevatron then one finds the relative rate $N(\nu_{\mu}N \rightarrow \mu^{-}t)\ /\ N(\nu_{\mu}N \rightarrow \mu^{-}x) \approx 2 \times 10^{-5}$ ($E > 200$ GeV). For $m_t = 20$ GeV, at a typical energy $E = 500$ GeV, assuming maximal mixing, the $\nu_{\mu}d \rightarrow \mu^{-}t$ reaction is expected to dominate over the $\nu_{\mu}s \rightarrow \mu^{-}t$ process by a factor of about 10, with the $\nu_{\mu}b \rightarrow \mu^{-}t$ substantially smaller. This difference decreases for higher energies. The smaller production rate of t relative to b is to some extent compensated by the larger $p_{\perp}$ of the μ^{+} from t decay. The obvious signature is the $\mu^{-}\mu^{+}$ from $\nu_{\mu}N \rightarrow \mu^{-}t+\ldots$; $t \rightarrow \mu^{+}+\ldots$; with the μ^{+} distinguished by its large $p_{\perp}$ of the μ^{+} from t decay. The obvious signature is the $\mu^{-}\mu^{+}$ from $\nu_{\mu}N \rightarrow \mu^{-}t+..$; $t \rightarrow \mu^{+}+\ldots$, with the μ^{+} distinguished by its large $p_{\perp}$ tail of dimuons from charm, a serious background problem is that due to $\bar{\nu}_{\mu}$ events of the type $\bar{\nu}_{\mu}N \rightarrow \mu^{+}\bar{c}$; $\bar{c} \rightarrow \mu^{-}\ldots$, which are misidentified as ν_{μ} events. Because of this misidentification the μ^{+} will appear to have larger $p_{\perp}$ relative to the (apparent) production plane. Hence it again looks very difficult to extract t-quark coupling coefficients from neutrino reactions at the Tevatron. However with sufficiently high $\overset{(-)}{\nu}_{\mu}$ energies of order 1000 GeV and sufficient statistics perhaps one will be able to make some progress toward this goal.

Further possibilities for studying heavy quark mixing angles include ep collisions, via the specific reactions $e^{-}\ (u,c,t) \rightarrow \nu_{e}b$, $e^{+}(\bar{u},\bar{c},\bar{t}) \rightarrow \bar{\nu}_{e}\bar{b}$, $e^{-}(\bar{d},\bar{s},\bar{b}) \rightarrow \nu_{e}t$, and $e^{+}(d,s,b) \rightarrow \bar{\nu}_{e}t$. Preliminary studies indicate that one might achieve production rates for b and t of order 10^{-2} of the corresponding total weak e^{-} or e^{+} rates.[9,10] Finally, some information on the ratio $|V_{ub}|/|V_{cb}|$ could be obtained from studies of the strange particle final state content of b decay, **if** one could reliably isolate the b-hadron signal.

With the large number of b-quarks expected at the Tevatron it may be possible to perform all the relevant measurements for the b, or at least get very useful limits.

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