Ref.TH.3682-CERN

HEAVY QUARK JETS AND THEIR SEMI-LEPTONIC FRAGMENTATION

R. Horgan
DAMTP, Cambridge, England

and

M. Jacob
CERN -- Geneva

ABSTRACT

The production of heavy quark jets at collider energy is discussed from the points of view of rates, signature through prompt leptons at large transverse momentum and search for the top quark in the 20 to 50 GeV mass range.

Ref.TH.3682-CERN
August 1983

1. - INTRODUCTION

In a previous paper ¹⁾, we calculated the jet yields expected to occur at collider energy ²⁾. The calculation was developed in the framework of perturbative quantum chromodynamics used in its leading log approximation ³⁾. The approximations involved in these calculations are such that one could not expect to get better than the correct order of magnitude for the jet yields. Nevertheless, since the predicted values were above anything so far measured by many orders of magnitude, the results obtained were of interest. Jet yields have since been measured at collider energy by two experimental collaborations ⁴⁾. The transverse momentum dependence agrees very well with expectations while the actual values of the cross-sections can be considered to be in very reasonable agreement with the predicted ones in view of the necessary approximations made. At present one may conclude that (at $p_T > 20$ GeV/c, say) perturbative QCD is quite suited to production cross-section calculations ^{1),5)}. Of particular importance is that the jet yield measurements made at the ISR ⁶⁾ can now be compared at the same p_T with the much larger jet yields measured at the collider and that the large ratios agree with the predicted ones ¹⁾.

With strengthened confidence in the perturbative QCD approach one may now study in more detail the problem of heavy quark jet production. With the heavy quark jets originating mainly from gluon-gluon and quark-antiquark interactions, the expected yield is typically two orders of magnitude below the full jet yield ¹⁾. Because of the large background their presence must be most likely detected by searching for the prompt leptons at large p_T originating from heavy quark decay. Taking into account the semileptonic branching ratio (set typically at 0.1) and the effect of the fragmentation function we expect a loss in rate of at least two orders of magnitude. This puts lepton yields at large p_T ($p_T > 20$ GeV/c, say) at a level which is barely accessible for study with the present luminosity ⁷⁾. It is important to remark that at such p_T values the lepton over π ratios should be much larger (typically a factor 0.01 to 0.1) than the values familiar at Fermilab-SPS-ISR energies where (at lower p_T where it is measurable) it is of the order 10^{-4} to 10^{-3} .

When considering the $20 < p_T < 40$ GeV/c range, where data can be expected in the not too distant future, one should recognize the fact that the largest prompt lepton source is W, Z formation with subsequent leptonic decay ^{8),9)}. Another contribution to the lepton yield is due to the heavy quark decays of the W and the Z.

While it is certainly interesting to check further the predictions for jet and weak-boson production, one of the most interesting prospects at present is to collect evidence for the existence of the t quark by looking at prompt lepton yields¹⁰⁾.

An important part of this paper is indeed to discuss the search for t quarks and to consider yields and possible related signals using the same approach which has been successful in estimating jet yields¹⁾. This subject has been much discussed already and in particular recently¹⁰⁾⁻¹⁶⁾. However, we account here more particularly for helicity effects and present the relevant fragmentation functions for heavy-quark decay in a way which is convenient for the calculation of the most important experimentally observable effects and yet which are used in the same way as standard fragmentation functions. Some of the available rate estimates^{11),16)} assume that the heavy-quark fragmentation occurs after the initial production of a scalar meson which then decays in an analogous manner to $K \rightarrow \pi \nu$. The distinction between top- and bottom-like quarks is then lost. Some of our results overlap with those of Sehgal et al.¹³⁾ and Rein et al.¹⁴⁾ but are presented in a different manner. Our emphasis is on the estimation of signal over background ratios. Moreover some new results on jet yields complement those of Ref. 1) while being of topical experimental interest.

Considering top quark searches, we consider more particularly two possible approaches. One is to trigger on a large p_T lepton which, for reasons discussed later, is likely to originate from b fragmentation, and look for the recoiling jet on the away side. If the b originates from QCD $b\bar{b}$ production (the background), the recoiling jet is merely a rather straight jet. If on the other hand the b originates from W formation and decay (the signal), the recoiling jet is a t jet with an a priori peculiar fan-like structure associated with the large Q value released in its fragmentation and in any case an invariant mass slightly in excess of the Q value (top quark mass). The question is then what the magnitude of the $b\bar{t}(t\bar{b})$ signal is compared with the $b\bar{b}$ (mainly) background. We find that (for a t quark in the 30 GeV range) it reaches a reasonably high value over a particular p_T range around $p_T \approx 25$ GeV/c. The background is then less than a factor 10 above the expected signal. Figure 5 gives the calculated background and signal at two different angles 90° and 60° .

The second way which we explicitly consider here is to trigger on a large p_T lepton, which would sometimes originate from the fragmentation of the t quark. In such a case one expects an accompanying jet resulting from the b quark in the $t \rightarrow e^+ \nu b$ decay, which would often be at a sizeable angle with respect to the direction of the lepton because of the large Q value released in the decay. Here

the key questions are that of yield, presented in Fig. 6, and that of the p_T and angular distribution of the b jet expected to accompany the lepton which is presented in Figs. 8, 9 and 10. This is discussed in Section 3.

In doing such calculations, we have systematically assumed that the heavy quark fragmentation (b or t) can be considered in an inclusive way, the quark fragmenting in the helicity state in which it appeared from the hard or weak process, irrespective of the global jet fragmentation. This may of course correspond to too strong an hypothesis. Nevertheless we choose to follow it here in order to stress the differences between lepton yields which then arise from b quarks on the one hand and c and t quarks on the other. The reader may easily average away all polarization effects if so wished.

Prior to discussing heavy quark decays in Section 3 we give in Section 2 a few jet production results which merely extend those of Ref. 1) to cases which will soon be relevant.

Several years ago it was already felt bold to consider jets of p_T in excess of 80 GeV. At present, jets of almost twice as high a p_T value have been seen ⁴⁾. We thus extend our jet yield curves to $p_T = 150$ GeV, giving the relative amount of gluon, u quark, b quark and t quark jets expected, assuming a top quark mass of 30 GeV. This is a simple extension of the results of Ref. 1) at $\sqrt{s} = 540$ GeV. Since the CERN $p\bar{p}$ collider may soon operate at 620 GeV, we also give the corresponding curves for that energy (Fig. 1a for $\sqrt{s} = 540$ GeV and Fig. 1b for $\sqrt{s} = 620$ GeV).

The clarity of the jet events, with two jets dwarfing anything else on angular distributions of the transverse energy ⁴⁾, goes beyond any cautious expectation. This makes it possible to reconstruct easily the CM motion of the two-jet system and, while a few years ago distributions in terms of p_T and y or $\cos\theta$ appeared as the most useful ones, one should now consider angular distributions in the parton-parton rest frame, for specific values of p_T . The different jet species give different angular distributions. Yet these differences are rather small for the dominant processes and the most important result so far obtained is the observation ¹⁷⁾ of the forward-backward peaking expected from the basic QCD processes ¹⁸⁾. With increased statistics one may, however, go further and we therefore give the angular distributions expected for gluon and u quark jets for different values of p_T and practical experimental cuts. This is shown in Fig. 2.

2. - JET YIELDS

In Figs. 1a and 1b we show the predictions for jet yields at $\sqrt{s} = 540$ GeV and $\sqrt{s} = 620$ GeV extended to $p_T = 150$ GeV/c. The differential cross-section $d\sigma/dp_T d\cos\theta$ is plotted for $\theta = 90^\circ$ and exactly the same parametrization was used as in our previous paper ¹⁾. The total quark-jet yield ($u+\bar{u}+d+\bar{d}+\dots$) and the gluon-jet yield are equal at $p_T \sim 55$ GeV/c for both $\sqrt{s} = 540$ GeV and $\sqrt{s} = 620$ GeV. However, it should be noted that the absolute cross-section at this point for $\sqrt{s} = 540$ GeV is $d\sigma = 10^{-33.4} \text{ cm}^2/\text{GeV}$ which is smaller than the corresponding cross-section for $\sqrt{s} = 620$ GeV, $d\sigma = 10^{-33.15} \text{ cm}^2/\text{GeV}$, by nearly a factor of two. The ratio of the yield at $\sqrt{s} = 620$ GeV to that at $\sqrt{s} = 540$ GeV for fixed p_T increases with p_T and is over two above $p_T = 100$ GeV/c. If the cross-section is parametrized by

$$\frac{d\sigma}{dp_T^2} = \frac{f(x_T)}{p_T^N}, \quad x_T = \frac{2p_T}{\sqrt{s}}$$

the value of N predicted may be read off these curves. We find $N = 4$. It may seem surprising that scaling violations have not increased N from its scaling value. However, the effect of scaling violations on N is small unless x_T becomes sizeable (≥ 0.5), and there are no fragmentation functions involved. In contrast, for single particle inclusive cross-sections the trigger-bias effect means that the relevant values of z ($\equiv p_{T \text{ hadron}}/p_{T \text{ jet}}$) are near 1 (≥ 0.75) and hence that the cross-section is sensitive to the power law fall off of the fragmentation function near $z = 1$ which is controlled by scaling violations ^{1),3)}. Also the value of x_T for the fragmenting jet is larger.

Also included in Fig. 1 are the inclusive t quark and b quark jet yields. The t quark mass is taken throughout this paper to be $30 \text{ GeV}/c^2$. All mass effects are included in the kinematics and the expressions for the central cross-sections from Ref. 19) include all mass terms. It is also assumed that there is no intrinsic component of t or b in the proton. If this is not correct then these curves are a lower bound on the predicted yields. Even so the t or b jet yield is well over two orders of magnitude below the total yield. However, for t jets with transverse momentum in the range $35 \text{ GeV}/c \leq p_T \leq 45 \text{ GeV}/c$ we find an integrated cross-section of about 100 pb corresponding to about $10\text{-}20$ events in this range at the present integrated luminosity of $\sim 150 \text{ nb}^{-1}$. These events should be recognizable by the two back-to-back wide jets each with an invariant mass of M_t . Although neutrinos may carry away some energy undetected, the characteristic fan-like nature (large invariant mass) of these jets is a likely signal for

t quarks. The background to such events could, however, be troublesome unless some further correlated trigger is asked for. Four jet events which are not fully resolved may simulate two wide jets as may gluon bremsstrahlung from narrower jets. Because the t quark mass is not known and because energetic neutrinos prevent an accurate measurement of the jet mass it is difficult to see how jet mass cuts on candidate two-jet events can enhance the signal over background ratio. Pakvasa et al.¹¹⁾ discuss a number of triggers for detection of t jets, the most likely hadronic signal being a cascade decay containing charmed and strange particles, e.g.,

The background to such events is difficult to assess but it must be severe. In the next section we discuss the possibility of using a high p_T lepton trigger to improve the signal/background ratio for detecting t quarks.

Before ending this section we present in Fig. 2 the differential cross-sections for single jet inclusive production at fixed p_T as a function of the production angle, θ^* , in the parton-parton centre-of-mass frame. $d\sigma/d p_T d \cos\theta^*$ is plotted for various gluon and u quark jets for $p_T = 20, 50, 80$ GeV/c and with a cut on the $p\bar{p}$ centre-of-mass production angle of $45^\circ \leq \theta_{p\bar{p}} \leq 135^\circ$. For $\bar{u}$ quark jets one merely replaces θ^* by $-\theta^*$. The forward peaking evident in all curves is typically a factor of 2-3 as $\cos\theta^* \rightarrow \pm 1$. The energy is $\sqrt{s} = 540$ GeV.

With improved statistics¹⁷⁾ one could look for the expected trend as quark jets eventually dominate over gluon jets with increasing p_T . While the characteristic forward peaking typical of Bhabha scattering presently observed is already interesting¹⁷⁾, getting evidence for a mixture of jet species would add valuable information.

3. - LEPTON TRIGGERS FOR HEAVY QUARKS

To discuss the fragmentation of an unstable particle into its decay products we use a representation of the momenta involved in terms of light-cone or infinite momentum frame variables. Although the following discussion is completely general we will concentrate on the decay $Q \rightarrow Q' \ell \nu$ where Q and Q' are quarks (generally t , b or c) and (ℓ, ν) is a lepton-neutrino pair.

The lepton, ℓ , will be used as the primary trigger from the decay of the high p_T quark, Q . The trigger may be treated as inclusive, in which case the variables of the (Q', ν) system will be integrated over, or the Q' jet will be detected as a secondary trigger. Both possibilities are discussed below. The momentum representation is

$$P_\ell = (P, \vec{0}, P)$$

$$P_Q = \left(xP + \frac{k_T^2 + \mu^2}{4xP}, \vec{k}_T, xP - \frac{k_T^2 + \mu^2}{4xP} \right) \quad (1)$$

where x is a light-cone momentum fraction ($x > 1$). We also use in formulae $z \equiv 1/x$. k_T is the transverse momentum in the jet fragmentation and μ is the mass of the quark, Q . The mass μ is taken fully into account since it may be large. If a $Q\bar{Q}$ pair is produced with invariant mass M then the maximum lepton momentum we may expect is given from (1) with $x = 1$, $\vec{k}_T = 0$.

$$|P_L| \equiv P \quad \text{given by } P - \frac{\mu^2}{4P} = \frac{M}{2}$$

$$\text{or } P = \frac{M + \sqrt{M^2 - 4\mu^2}}{4}$$

Similarly a $Q\bar{Q}'$ pair with mass M and negligible Q' mass gives $|P_L|_{\max} = M/2$. Hence, even though the finite value of μ means that the decay has a finite "Q" value, there is no corresponding enhancement of the lepton yield since the central cross-section depends on M only.

The calculation of the inclusive fragmentation function $G(z, \vec{k}_T)$ for $Q \rightarrow \ell + X$ may be calculated in any frame since it has the invariant definition

$$\frac{2}{3} G(z, k_T) = E_L \frac{d^3 B(Q \rightarrow Q' \ell \nu)}{d^3 p_L} \quad B = \frac{\Gamma(Q \rightarrow Q' \ell \nu)}{\Gamma_{\text{tot}}} \quad (2)$$

where Γ_{tot} is the total Q width and $\Gamma(Q \rightarrow Q' \ell \nu)$ is the partial width into the relevant channel. $B(Q \rightarrow Q' \ell \nu)$ is the branching ratio into this channel for which we take (for lack of precise information) the value 0.1. We are assuming here that Q decays directly into $Q' \ell \nu$. In practice Q forms a meson with light sea quark and then decays into another meson containing Q . However, since Q is very massive it loses no momentum in this preliminary fragmentation

$$\text{i.e., } G(z) \simeq \delta(1-z) \quad \text{for} \quad Q \rightarrow (Q\bar{q}) + X \quad (3)$$

Such an approximation may be deemed too drastic. Nevertheless, there is no compelling reason to go beyond it at present. Insofar as we attempt an estimate at the order of magnitude level it should be sufficient. At a later stage one could include information from heavy quark decay obtained from e^+e^- annihilation²⁰⁾. It seems that an actually slightly higher branching ratio for b leptonic decay than the one assumed and a slightly softer z distribution than the one assumed have in fact compensating effects in the calculation of the inclusive leptonic yield. We thus proceed with the approximation spelled out.

The effect of the helicity of Q is retained with all possible mesons $(Q\bar{q})$ and $(Q'\bar{q})$ summed over thus allowing all intermediate spin and angular momentum states to contribute. This summation together with (3) is taken to correspond to direct decay of the naked quark, Q , the light companion being merely a spectator. This approach differs from that of Pakvasa et al.¹¹⁾ who use (3) but only consider pseudoscalar meson states for $(Q\bar{q})$ and $(Q'\bar{q})$. Consequently the effect of helicity is suppressed and the result is that t and b quarks are not distinguished. We shall comment on the effect of helicity below.

The variables used in the Q rest frame are shown in Fig. 3a). In Fig. 3b we show the corresponding variables in the laboratory frame. The Q quark may be considered in a state of definite helicity. In Fig. 3a the $\hat{k}$ axis is in the direction of the Q quark laboratory momentum and the Q spin may be either parallel (positive helicity) or antiparallel (negative helicity) to this direction.

In the Q rest frame all momenta are denoted with q and we define

$$k = \frac{|\vec{q}_L|}{\mu} \quad k_{Q'} = \frac{|\vec{q}_{Q'}|}{\mu} \quad (4)$$

In this frame the invariant inclusive branching ratio may be expressed in the form

$$E_L \frac{d^3 B(Q, \lambda)}{d^3 p_L} = f_{Q, \lambda}(k, \cos \theta) \quad (5)$$

where λ is the helicity of the Q quark. Note that $d^3p_L/E_L = 2\pi K dK d\cos\theta$.
From Eq. (1)

$$K = \frac{\vec{P}_L \cdot \vec{P}_Q}{\mu^2} = \frac{3}{2} \frac{k_T^2}{\mu^2} \quad (6a)$$

with $\mu_T^2 = k_T^2 + \mu^2$. Also

$$\sin\theta = \frac{|\vec{P}_L| k_T}{|\vec{P}_Q| K \mu} \quad P \equiv |\vec{P}_L| \quad (6b)$$

If the lepton is at angle ψ to the beam direction in the lab., then $|\vec{p}_L| = |p_{TL}|/\sin\psi$. From (6) $\cos\theta$ may be expressed in terms of z , K and P and from (2), (5) and (6) k_T may be integrated, giving

$$G_{Q,\lambda}(z) = \int_{\frac{1}{2}(1-z)}^{\frac{1}{2}} dK f_{Q,\lambda}(K, \cos\theta) \quad (7)$$

replacing $\cos\theta$ by its value in terms of z , K and P . In the collinear limit, $\mu/p \rightarrow 0$, we find $\cos\theta = (z-K)/K$ and helicity dependent fragmentation functions are easily derived.

We also define

$$G_Q(z, \vec{k}_T) = \sum_{\lambda=\pm 1} G_{Q,\lambda}(z, \vec{k}_T)$$

Calculation of t and b decay using the standard V-A theory thus gives

$$\begin{aligned} G_b(z, \frac{k_T^2}{\mu^2}) &= \frac{2}{5} z K (3-4K) \\ G_t(z, \frac{k_T^2}{\mu^2}) &= \frac{12}{5} z K (1-2K) \end{aligned} \quad (8a)$$

with K given by (6a)

$$\begin{aligned} G_{b\pm}(z, \frac{k_T^2}{\mu^2}) &= G_b(z, \frac{k_T^2}{\mu^2}) \left(1 \mp \frac{4K-1}{3-4K} \cos\theta\right) \\ G_{t\pm}(z, \frac{k_T^2}{\mu^2}) &= G_t(z, \frac{k_T^2}{\mu^2}) (1 \pm \cos\theta) \end{aligned} \quad (8b)$$

In the collinear approximation we thus have

$$G_{\ell^-}(\xi) = \frac{2}{15} (1-\xi)(1+\xi+\xi^2) \quad (9a)$$

$$G_{\ell^+}(\xi) = \frac{1}{5} (1-\xi)^2(1+2\xi) \quad (9b)$$

$$G_{t^+}(\xi) = \frac{6}{5} \xi (1-\xi)^2 \quad (9c)$$

$$G_{t^-}(\xi) = \frac{2}{5} (1-\xi)^3 \quad (9d)$$

It can be seen most clearly from (9) that b decay is harder than t decay by a factor of $(1-z)$ and that $\lambda = +1$ decay is harder than $\lambda = -1$ decay by the same factor. The collinear approximation is not valid in practice for t decay since μ/p is expected to be of the order 1. All calculations reported here use full kinematics except that the b quark mass is neglected. The reason for the hierarchy of suppression shown in (9) may be explained in a way relevant to t quark decay at finite P . In the rest frame of Q the differential decay rate contains a factor $(1-\hat{q}_Q \cdot \hat{q})$ where $\hat{q} = \hat{q}_V(\hat{q}_L)$ for $t(b)$ decay. Thus for $t(b)$ decay it is impossible for $Q'v$ ($Q'\ell$) to recoil as a low-mass system against the $\ell(v)$ which is therefore unable to achieve the maximum kinematically allowed energy of $\mu/2$. Lack of phase space as $z \rightarrow 1$ is responsible for one factor of $(1-z)$ [see (7)] but this mechanism introduces another power of $(1-z)$ for fragmentation of $t(b)$ into $\ell(v)$ as $z \rightarrow 1$. Decay of the wrong helicity states provides another $(1-z)$ factor. The allowed fragmentations [i.e., those behaving like $(1-z)$] are ℓ^-/b and v/t .

The rôle of helicity can be elucidated more by considering the actual dispositions of the particle momenta as $z \rightarrow 1$. The decay through the charged weak current involves only negative-chirality particles and positive-chirality antiparticles. For particles with $E \gg m$ chirality is the same as helicity [the chiral projection-operators are $\frac{1}{2}(1 \pm \gamma_5)$ which can only be identified with the helicity projection-operators in the limit $m/E \rightarrow 0$]. In Fig. 4 we show the momenta and helicities as $z \rightarrow 1$ for ℓ^+/t and ℓ^-/b . As $z \rightarrow 1$ all momenta are collinear along the z axis (say) and from Fig. 4a it is clear that the total spin component on the z axis is not conserved between the initial and final for ℓ^+/t and so the configuration is forbidden. In contrast from Fig. 4b the total spin component is conserved and the configuration for ℓ^-/b is dynamically allowed. Note : for wrong helicity t and b spin component is not conserved in either case, the violation being by two units of σ_z for the t quark leading to an even stronger suppression [see (9d)].

Such an inclusive quark fragmentation approach may keep too much spin information when part of it could disappear in the fragmentation of the jet into mesons. Nevertheless it is deemed appropriate to keep it at this stage to stress the possible importance of spin effects in heavy quark search, in particular when their source is both parity conserving (gluon-gluon interactions) and parity violating (W and Z production and decay).

In order to calculate semi-inclusive cross-sections for which the Q' quark jet is also detected after a primary lepton trigger we need the extended fragmentation functions :

$$\begin{aligned}
 G'_{\ell\pm}(\xi, \frac{h_T^2}{\mu^2}, k_c, \delta) &= \\
 \frac{128}{5\pi} (k + k_c - \frac{1}{2})(1 - k - k_c) (1 \mp R(k, k_c) \cos \theta) \\
 R(k, k_c) &= \frac{k_c \cos \varrho + k}{k_c + k} \\
 \cos \varrho &= - \frac{k_c + k \cos \theta_c}{1 - k - k_c} \\
 \cos \theta_c &= \frac{1 - 2k - 2k_c + 2kk_c}{2k_c} \quad (10a)
 \end{aligned}$$

$$G'_{\ell\pm}(\xi, \frac{h_T^2}{\mu^2}, k_c, \delta) = \frac{1}{2\pi k} G_{\ell\pm}(\xi, \frac{h_T^2}{\mu^2}) \quad (10b)$$

The measure of integration introduced is $dK_b d\delta$.

All variables in the lab. frame may be related to the Q rest frame variables by simple geometry and Lorentz transforms (see Fig. 3).

All calculations were done using VEGAS²⁰⁾ an adaptive Monte Carlo integration routine and all differential cross-sections required were calculated by accumulating the computer generated integrand values in appropriately defined bins.

The inclusive results are presented in Figs. 5 and 6. We consider two kinds of trigger.

- (i) The production of a top quark from $W^\pm$ as a member of a $t\bar{b}$ or $\bar{t}b$ pair.

In this case the signal over background ratio is enhanced by detecting the lepton from the b quark decay and looking for a characteristic (high mass) t jet on the away side. The detection of the lepton from the t decay instead is

about a factor three lower in rate than detecting the lepton from b decay in the region of interest (Fig. 6). The background is the production of leptons from b and c decay produced in the usual QCD processes. The background is always larger than the signal but the shapes of the lepton spectra for the signal and background are completely different. The two spectra are shown in Fig. 5 plotted as $d\sigma^2/dp_T d\cos\theta$ for $\theta = 60^\circ$ and 90° . As can be seen, a "bottleneck" occurs in the region $20 < p_T < 30$ GeV/c where signal/background is maximized and has a value of about 0.1. Assuming a 5 GeV p_T bin a significant signal should emerge in this region for integrated luminosities of order 10^3 nb $^{-1}$. In Fig. 6 we show similar curves for the lepton from t decay produced via $W^\pm$ or by QCD sub-processes. [see also Ref. 16].

The correct heavy-quark mass terms were included in all cases. It is also pertinent to comment on the rôle of helicity in the relevant production mechanisms. From QCD an average over helicity states is of course taken. On the other hand, in $W^\pm$ decay the final state quarks are produced predominantly in helicity state $\lambda = -1$ (or $\lambda = +1$ for antiquarks). From (9) we see that this leads to more energetic leptons from $W \rightarrow b \rightarrow \ell^-$ but to less energetic leptons from $W \rightarrow t \rightarrow \ell^+$. In fact because the t is massive the helicity states produced are weighted by probabilities

$$\omega(\lambda = \pm 1) = \frac{(\sqrt{E+\mu} \mp \sqrt{E-\mu})^2}{2(E+\mu)} \quad (11)$$

These factors were included. It could be surmised that some of the polarization is dissipated by gluon-radiation and hadronization. However, collinear gluon bremsstrahlung does not flip helicity and we might expect that a sum over the undetected hadrons preserves a memory of the incident helicity. Other authors¹⁵⁾ have discussed the detection of t quarks produced from the W but they discuss the leptonic decay of the t quark with recoiling b jet and not vice-versa. They and a number of other authors^{11),16)} assume that only a few mesons are dominant in the hadronization and hence that polarization effects are suppressed which will lead to over a factor of two enhancements in their rates for $W \rightarrow t \rightarrow \ell^+$.

Figure 7 shows the distribution for $(1-z)/z$ for a lepton trigger from b quark decay. The distribution is seen to be more or less independent of p_T , the lepton transverse momentum. The b quark is assumed to come from the standard QCD subprocesses and so is unpolarized. The transverse momentum of the accompanying (cv) system is $(1-z)/z p_T$ which, from Fig. 7, is mainly distributed in the region (0.1 to 0.5) $p_T \approx 2-13$ GeV for $p_T = 20-25$ GeV. Since these events form

the background to the signal of $W \rightarrow t(b+cv)$ this range of transverse momentum for the background (cv) system should be compared with $p_T = 15-20$ GeV for the (cv) system accompanying the signal. We thus expect the hadrons accompanying the lepton in the signal events to be substantially more energetic than those in the background events. This probably by a factor two or more although the c quark distribution is not completely determined.

(ii) The characteristics of a t jet containing a lepton from the decay $t \rightarrow b\bar{\nu}$. As is well known¹¹⁾⁻¹⁶⁾ the lepton from t decay will not generally be collinear with the b jet produced as a fragment of the same decay. A good signature for a t quark is to trigger on a single lepton and to search for a b jet nearby and to see a wide (large mass) t jet on the awayside (Fig. 6). With this in mind, we have used the formulae derived earlier in this section to plot the b jet distribution for events with a lepton trigger at 90° and fixed p_T . The t quark is produced from the QCD subprocesses $gg \rightarrow t\bar{t}$, $q\bar{q} \rightarrow t\bar{t}$ including the heavy-quark mass corrections¹⁹⁾. In Fig. 8a and Fig. 8b, we show the cross-section $d\sigma/dp_T dp_b d\cos\theta d\omega$ versus ω for $\theta = 90^\circ$, $p_{T_\mu} = 30$ and 20 GeV, respectively, and p_b in the ranges $10-15$, $15-20$, $20-25$ GeV. Here ω is the angle between the lepton and the b quark jet. In Figs. 9a and 9b we show $d\sigma/dp_T d\cos\theta d\omega$ versus ω for $p_T = 30$ GeV and 20 GeV, respectively for $\theta = 90^\circ$ and for the cuts $p_b > 10$ GeV, >20 GeV, >30 GeV, >40 GeV. In Figs. 10a and 10b, we show $d\sigma/dp_b dp_T d\cos\theta$ versus p_b for $p_{T_\mu} = 30$ and 20 GeV, respectively with $\theta = 90^\circ$. Roy¹⁶⁾ has plotted $d\sigma/d\omega$. This cross-section, however, integrates over p_T and p_b and so far a given lepton trigger does not give a measure of the b jet distribution to be expected.

We now turn to two distributions for the parent t quark. While this illustrates the situation with the kinematics it cannot be directly used since the neutrino carries away momentum.

In Fig. 11a we plot $d\sigma/dp_{T_\mu} d\cos\theta d\phi$ versus ϕ for $\theta = 90^\circ$ and $p_{T_\mu} = 20$ GeV. ϕ is the angle between the trigger lepton and the decaying t quark. In Fig. 11b we show the t quark transverse momentum distribution for the same trigger, plotting $d\sigma/dp_{T_\mu} dp_{T_t} d\cos\theta$ versus p_{T_t} .

4. - CONCLUDING REMARKS

The introduction was written in order to act also as a summary, directing the reader to the main results presented in this paper. Using perturbative QCD in its leading log approximation cannot be considered as providing much more than order of magnitude estimates ^{1),5)}. Nevertheless, one may hope that this information about heavy quark jets can also be of some use for predicting yields, as previous calculations were for global jet production ¹⁾. In view of the approximations involved, we did not consider explicitly the Z source, keeping only the dominant W one. We also did not consider explicitly variations associated with different t quark masses, taking 30 GeV as a typical value ; Figs. 1, 5, 6 and 8 give the general trends, which is the maximum one can give at this stage.

Insofar as we are dealing with ratios of several orders of magnitude, the predicted yields, though approximate, should be of interest. At present three such large factors have been verified experimentally ⁷⁾, namely, jet yield at the collider versus jet yield at the ISR ; jet yield over inclusive pion yield and γ/π ratio at large p_T . The next step is to check for the relatively important prompt lepton yield associated with heavy quark jets and, as one presently hopes, use such leptons for obtaining evidence for the top quark. Its mass, which is larger than 20 GeV ²⁰⁾, could be less than 50 GeV. There is then hope that rates could be large enough for detection at the $p\bar{p}$ collider. The key point is to find proper triggers, since the brilliant jet signal of today ⁴⁾ already appears as an impressive background for the particle search of tomorrow..

REFERENCES

- 1) R. Horgan and M. Jacob - Nuclear Phys. B179 (1981) 441.
For a more complete discussion of physics at collider energy, see :
R. Horgan and M. Jacob, CERN 81-04 (1981), Proceedings of the CERN School of Physics, Malente 1980.
- 2) We refer to the $p\bar{p}$ collisions currently studied at the CERN SPS used in its collider mode. See :
The Staff of the CERN $p\bar{p}$ Project - Phys.Letters 107B (1981) 231.
A reference to a key trigger to the project is also appropriate :
C. Rubbia et al, - Proceedings of the International Neutrino Conference, Aachen (1976), Braunschweig (1977).
- 3) For a general and thorough discussion of perturbative quantum chromodynamics one may consult :
"Perturbative Quantum Chromodynamics", Physics Reports reprint, Vol. 5, North Holland (1982), M. Jacob ed., and "Quantum Chromodynamics", Proceedings of the 1978 La Jolla Institute, AIP Conference Proceedings 55 (1979), W. Frazer and F. Henyey, eds. This includes the important results of Feynman, Field and Fox.
- 4) M. Banner et al. - Phys.Letters 118B (1982) 203 ;
G. Arnison et al. - Phys.Letters 123B (1983) 115 ;
J. Saas - Contribution to the Third Topical Workshop on $p\bar{p}$ Collider Physics, Rome (1983), CERN 83-04 (1983), C. Bacci and G. Salvini eds., p. 393 ;
P. Darriulat - Ibid., p. 190.
- 5) W. Furmanski and H. Kowalski - CERN-EP/83-21 (1983) ;
Z. Kunszt and E. Pietarinen - CERN Preprint TH. 3583 (1983) ;
G. Altarelli - 1983 Rome Workshop, Op.Cit., p. 372.
- 6) T. Akesson et al. - Phys.Letters 118B (1982) 185 and 193.
- 7) M. Jacob - 1983 Rome Workshop, Op.Cit., p. 538.
- 8) G. Arnison et al. - Phys.Letters 122B (1983) 103 ;
G. Arnison et al. - Phys.Letters 126B (1983) 398.
- 9) G. Banner et al. - Phys.Letters 122B (1983) 476 ;
P. Bagnaia et al. - to be published.
- 10) D.M. Scott - "Getting to the top", Proceedings of the Conference on $p\bar{p}$ Collider Physics, Madison (1981).
A discussion with D. Denegri about the present aspect of t quark search is also gratefully acknowledged.
- 11) S. Pakvasa et al. - Phys.Rev. D20 (1979) 2862 ;
V. Barger et al. - RAL Preprints 83-015 and 83-025 (1983) ;
F. Halzen and D.M. Scott - University of Helsinki Preprint HU-TFT-83-26 (1983).
- 12) R. Horgan and M. Jacob - Lecture Notes, Kupari Summer School (1981).
- 13) L.M. Seghal and P.M. Zerwas - Phys.Rev. D16 (1977) 2379 ; Phys.Rev.Letters 36 (1976) 399 ; Nuclear Phys. B108 (1976) 483 ;
L.M. Seghal and P.M. Zerwas - Aachen Preprint P/THA83/10 (1983).
- 14) D. Rein et al. - Nuclear Phys. B138 (1978) 85.
- 15) V. Barger et al. - DPT 83/6 (1983) and MAD/PH/99
A. Martin - Contribution to the 1983 Moriond Meeting.

- 16) D.P. Roy - TIFR/TH/83-15 (1983).;
J. Lindfors and D.P. Roy - UCR-TH-83-5 (1983).
- 17) P. Bagnaia et al. - CERN-EP/83-94 (1983) ;
A. Honma - "Results on the High Energy Jets in the UA1 Experiments", Contribution to the SLAC Topical Conference (1983).
- 18) B.L. Combridge et al. - Phys.Letters 70B (1977) 234.
- 19) B.L. Combridge - Nuclear Phys. B151 (1979) 429.
- 20) E. Lohrmann - "Review of e^+e^- Physics with Petra", Contribution to the SLAC Topical Conference (1983).
- 21) G.P. Lepage - J.Comp.Phys. 27 (1978) 92.

FIGURE CAPTIONS

- Fig. 1 : Inclusive jet yields, at large transverse momentum, at 90° . Global yields and differential yields for g , u , b and t ($m_t = 30$ GeV) jets are shown.
a) $\sqrt{s} = 540$ GeV $p\bar{p}$ collisions, with also s jets.
b) $\sqrt{s} = 620$ GeV $p\bar{p}$ collisions.
- Fig. 2 : Angular distribution for single jet (g and u quark) in the parton-parton centre of mass frame, where $\cos\theta^*$ is the scattering angle. The reconstructed angular distributions correspond to an angular cut $45^\circ \leq \theta \leq 135^\circ$ performed in the $p\bar{p}$ centre of mass frame. They have been calculated for different jet momenta.
- Fig. 3 : The angular variables used to describe heavy quark semi-leptonic decay, where Q' is the daughter jet.
a) Parent quark centre of mass.
b) $p\bar{p}$ centre of mass.
- Fig. 4 : The momentum and spin configuration which are imposed by V-A coupling in the collinear configuration.
a) $t(c)$ decay - forbidden.
b) b decay - allowed.
- Fig. 5 : Prompt lepton yields ($e^\pm$ or $\mu^\pm$) at large p_T . The signal [originating from $W \rightarrow t\bar{b}(\rightarrow e)$], lower curve, and the background [originating from $c\bar{c} b\bar{b}(\rightarrow e)$, as expected in QCD hard processes] are both presented at two different lepton production angles (90° and 60°). The bottleneck shows where to look most efficiently for a peculiar (t quark) recoiling jet.
- Fig. 6 : Prompt lepton yields ($e^\pm$ or $\mu^\pm$) at large p_T expected from t quark decay whether produced through QCD hard processes (upper curve) or originating from W decay (lower curve).
- Fig. 7 : Fraction of the transverse momentum of the trigger lepton expected for the remainder in $b \rightarrow lX$ fragmentation. The distribution in $z' = (1-z)/z$ is an average over quark jet momenta for fixed values of the transverse momentum of the trigger lepton (20-25 GeV upper curve; 25-30 GeV, middle curve and 30-35 GeV, lower curve).

Fig. 8 : Angular distribution of the associated b -jet with respect to the direction (here 90°) of the prompt lepton at large p_T used as a trigger for $t \rightarrow \ell(\nu)b$ decay for different ranges of b quark momentum (10-15 GeV, upper curve; 15-20 GeV, middle curve and 20-25 GeV, lower curve)

- a) transverse lepton momentum of 30 GeV/c
- b) transverse lepton momentum of 20 GeV/c.

Fig. 9 : Angular distribution as in Fig. 8 but now integrated over the measured momentum of the b quark with four different lower limits (10 GeV, upper curve; 20 GeV, upper middle curve; 30 GeV middle curve and 40 GeV, lower curve).

- a) transverse lepton momentum of 30 GeV/c
- b) transverse lepton momentum of 20 GeV/c.

Fig. 10 : The momentum distribution of the associated b jet, as expected from t fragmentation triggered through the observation of a prompt lepton at 90°

- a) transverse lepton momentum of 30 GeV/c
- b) transverse lepton momentum of 20 GeV/c.

Fig. 11 : a) Angular distribution of the parent t quark direction with respect to the prompt lepton momentum taken at 90° used as a trigger. The lepton transverse momentum is taken to be 20 GeV/c.

- b) Transverse momentum distribution of the parent t quark when the daughter lepton is the same as that chosen previously.

Fig. 1

Fig. 2

(a)

(b)

Fig. 3

(a)

(b)

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11