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AN APPRAISAL OF LEPTON SIGNATURES FOR THE TOP QUARK
IN COLLIDER EVENTS WITH CONSIDERATION OF GLUON RADIATION EFFECTS

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ABSTRACT

Lepton signatures for top particles in $\bar{p}p$ events at the CERN collider are discussed in detail. QCD radiation effects are duly included. It is shown that because of the QCD effects, the contaminating background is considerably more difficult to handle, especially in view of the present statistical limitations.

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After the recent discoveries of intermediate $W^\pm$ and Z^0 bosons at the CERN $\bar{p}p$ collider^{1),2)}, one naturally expects the observation of top particles as the next step. Decays into top particles should represent a substantial fraction of $W^\pm$ and Z^0 decays (25% for $W^+ \rightarrow t\bar{b}$ and $W^- \rightarrow \bar{t}b$, and 10.5% for $Z^0 \rightarrow \bar{t}t$, neglecting phase space suppressions for massive t quarks). Top particles should also be produced hadronically, by the well-known mechanisms of gluon and quark fusion, ($g+g \rightarrow \bar{t}+t$, $\bar{q}+q \rightarrow \bar{t}+t$), and flavour excitation ($g+t \rightarrow g+t$, $q+t \rightarrow q+t$). Because of the sizeable semileptonic branching ratio expected for top quarks (~ 10 -15%), one is naturally led to look for leptonic signatures, which should reflect the high value of the top quark mass. A number of phenomenological investigations on this subject have already appeared³⁾⁻⁵⁾. In particular, use of the missing p_T , supposedly related to the p_T of the neutrino accompanying the lepton, has been proposed³⁾⁻⁵⁾. But, as we have shown in Ref. 6), the combined effects of (i) experimental errors on the missing p_T , (ii) secondary neutrinos (whose rate increases enormously as one slightly moves above the conventionally assumed value $B_\ell = 0.1$ for the semileptonic branching ratio) and (iii) gluon radiation, make the missing p_T signatures hardly selective with respect to the bottom particle background.

QCD radiation is often neglected when discussing top particle signatures. It may not be easy to calculate, but it is certainly relevant. Besides modifying lepton spectra (typically softening them), it also makes charm and bottom jets fatter (thus kicking leptons and neutrinos out of the main jet-jet axis), and converts apparently innocuous events, like $\bar{p}p \rightarrow W^\pm(+e^\pm \nu)X$, into dangerous background because of the extra jets produced. Concerning the last item, we have recently shown⁷⁾, that the QCD expectation for substantial jet activity accompanying the $\bar{p}p$ production of $W^\pm$ is borne out by the preliminary CERN collider data.

The purpose of this note is to present the results of a study concerned with the feasibility of exploiting lepton signatures for top particles, also taking into due account background channels from which one may expect leakage because of gluon radiation. QCD radiation off both final and initial partons, as well as off the quarks in $W^\pm$ and Z^0 non-leptonic decays, is included in our calculations. Its effects in the decay of top and bottom particles are neglected, however. For top decay, it will certainly be relevant when trying to extract the mass of the top quark from lepton spectra, but not in this type of study, where we have to make hypotheses, moving the top quark mass up and down by factors. For bottom decay, gluon radiation effects⁸⁾ are obliterated by the finite mass effects associated with the charm recoil (which have been routinely neglected in much of the literature, though; see below). In order to calculate QCD radiation, we have employed

a Monte Carlo technique^{9),10)} which has already been discussed at length in its application to hard hadronic collisions¹¹⁾ and hadronic production of Drell-Yan pairs¹²⁾, and $W^\pm$ and Z^0 intermediate bosons⁷⁾ [see also Ref. 13)].

For the hadronic production of heavy flavours, we consider only the contribution from gluon and quark fusion, not because flavour excitation is unimportant^{14)-16),5)}, but because of lack of the necessary experimental information to make its calculation for top and bottom stable. In the case of charm, one is able to get stable results for it by making use of the charm structure function data to fix the low Q^2 cut-off in the evolution, and of data for the charm transverse momentum distribution to regulate the low $\hat{t}$ divergence¹⁶⁾. Such data are, of course, missing in the case of bottom and top. One should be aware of the fact that also fusion, of course, develops a divergence at small $\hat{t}$ at very high energy, when $\hat{t}$ minimum effects associated with the heavy masses of the final quarks eventually disappear. Once this occurs, a regulating procedure similar to that employed for flavour excitation has to be adopted.

For the quark densities we use the parametrization determined from the NA3 experiment on Drell-Yan production¹⁷⁾. For the gluon distribution, a form $xG(x) \propto (1-x)^5$ is assumed. The evolution of the parton densities is, of course, automatically taken care of in the calculation, as part of the process responsible for the emission of quanta. We have taken $\Lambda = 0.100$ GeV. The primordial transverse momentum of partons inside the colliding hadrons has been given a Gaussian distribution with $\langle K_T^2 \rangle = 0.4$ (GeV/c)², as determined from fits to Drell-Yan pair production data done by using the same Monte Carlo procedure¹²⁾. For the total $\bar{p}p \rightarrow W^\pm X$ and $\bar{p}p \rightarrow Z^0 X$ cross-sections, we obtain the values $\sigma_{TOT}(\bar{p}p \rightarrow W^\pm X) = 3.2$ nb and $\sigma_{TOT}(\bar{p}p \rightarrow Z^0 X) = 0.88$ nb, before any corrective K factor is applied.

The calculation includes a full hadronization of the QCD quanta, according to the Field and Feynman model^{18),19)}. As "z" distribution for heavy hadrons from heavy quarks of the same flavour, we adopt the fragmentation function of Ref. 20), although its experimental support is far from established, and a flat fragmentation function for charm is not yet ruled out²¹⁾. In charm background estimates, though, the form of Ref. 20) is certainly more conservative. For the decay of heavy flavour particles, we adopt the model of Ref. 22), as FORTRAN coded in Ref. 19). The calculation also includes the hadrons coming from the beam jets, for which a longitudinal phase space model is adopted, constrained to reproduce the existing UA1 and UA5 small p_T data¹¹⁾.

A review of the results is given in the Table. After the cut on the electron transverse momentum at $p_T^e > 15 \text{ GeV}/c$, experimentally required to avoid hadron contamination, the corresponding (electron inclusive) channel cross-sections times the semileptonic branching ratio B_ℓ ($\equiv 0.1$) are listed in column 1. In column 2, they are converted into event yields for an integrated luminosity $\int L dt = 1000 \text{ nb}^{-1}$. As background channels, we also include $W \rightarrow e\nu$, $\tau\nu$ and $Z \rightarrow e^+e^-$, $\tau^+\tau^-$, the latter limited to events in which the second electron has $p_T^e < 15 \text{ GeV}/c$, and therefore escapes observation. Such events, indeed, quite often contain jets⁷⁾, and can thus mimic topologies of events with top particles.

The electron p_T^e spectra for some of the important channels are plotted in Fig. 1a. A comment on the hadronic $\bar{b}b$ and $\bar{c}c$ contributions is in order. Quite often the semileptonic decays of b and c quarks are treated by assuming a vanishing mass for the recoil quark [see, e.g., Ref. 3)]. This leads to analytically simple, but quantitatively false, electron distributions. The case for b decay is illustrated in Fig. 1b. A numerical, exact calculation with a mass of $m_c = 1.87 \text{ GeV}$ for the charm recoil gives a p_T^e spectrum lower by about an order of magnitude at large p_T^e . The same figure shows that gluon radiation, in the production process, leads to a further softening of the spectrum. Neglecting the finite mass of the recoil, therefore, leads to a considerable overestimate of the background. Figure 1c gives the rapidity distribution for the electrons (counted with opposite rapidity if negative) for some of the main channels. The distributions in Fig. 1c are normalized to the content of column 5 in the Table, after various cuts have been made, as discussed below.

From column 2 of the Table, it is clear that the most serious sources of background are represented by $W \rightarrow e\nu$ and the hadronic $\bar{b}b$ and $\bar{c}c$ continua. A very large fraction, but not all, of the $W \rightarrow e\nu$, $\tau\nu$ events is removed by imposing a cut on the missing transverse momentum $p_T^{\text{miss}} < 0.7 p_T^e$, which does not penalize the signal (column 3) much. Luckily, the residual $W \rightarrow e\nu$ background is represented mostly by events with large p_T^e , the unbalance between p_T^e and p_T^ν being usually due to a relatively hard jet aligned (in the $\vec{p}_T$ plane) with the neutrino, and thus helping in pushing the electron at large p_T . A cut $p_T^e < 25 \text{ GeV}/c$ reduces this background by another factor of 1/4, and affects the signal very little. Still, this type of background remains respectable, and trying more clever cuts to handle it will also substantially reduce the signal. As for the $\bar{c}c$ and $\bar{b}b$ background, one cannot get rid of it by working on the recoil jet if one wants to keep $W \rightarrow tb$ events. Independently of that, anyway, cuts on the total transverse energy of the recoil jet are of no help in discriminating between c , b and t recoils, if the top quark mass is $\sim 25 \text{ GeV}$, as is shown

in Fig. 2b. Looking at the mean distribution of hadronic transverse energy in azimuth, with respect to the electron direction (Fig. 2c), reveals, however, that in events with top the electron is accompanied in its motion by relatively little hadronic E_T , contrary to what happens when the electron comes from b and c decays. One should not be deceived, however, by the remarkable difference in structure at small angles exhibited by Fig. 2c, since it only represents a distribution averaged over many events. On an event per event basis, there are fluctuations, in part contributed also by gluon bremsstrahlung. Let us consider, for this sake, the hadronic transverse energy, E_T^{FW} , deposited within an azimuthal sector of $\pm 30^\circ$ with respect to the electron direction. In E_T^{FW} we also add the missing p_T if it lies within the same azimuthal sector. Such an inclusion of the missing p_T increases E_T^{FW} more frequently for b and c decays than for t decays. Figure 1a gives the distribution in E_T^{FW} , and it is clear from it that a substantial and convenient reduction of the $\bar{c}c$ and $\bar{b}b$ background can be obtained by cutting at low E_T^{FW} . Column 5 in the Table gives the result after the cut $E_T^{FW} < 10$ GeV. The $\bar{c}c + \bar{b}b$ background which survives is still non-negligible. Cutting more in E_T^{FW} , however, would bring down the signal by a substantial factor.

The statistics for the top signal with which one is left after all such cuts is certainly not high, and is comparable to the residual background. The absolute yields in the Table correspond to a semileptonic branching ratio $B_\ell = 0.1$. The actual B_ℓ for bottom and top may turn out to be somewhat higher [≈ 0.125 , as measured at CESR for bottom decays²³⁾]. On the other hand, the top yields from $W^\pm$ and Z^0 decays indicated in the Table should be reduced by phase space factors taking into account the finite mass of the top quark. These uncertainties may quantitatively modify the expected yield, but certainly cannot change the situation qualitatively.

A clear signature for top from W decays is, in principle, provided by the η distribution of electrons. The latter is expected to exhibit a forward-backward asymmetry opposite in sign to that of $W \rightarrow e\nu$, $\tau\nu$ and $Z \rightarrow e^+e^-$, $\tau^+\tau^-$. Since the $\bar{t}t$ continuum gives no asymmetry, its contribution should be removed. This can be achieved in an effective way by considering the angular size and internal correlations of the recoil jet. For this sake, the techniques of Ref. 24) can be employed, which exploit the covariance matrix for a set of jet (shape) variables. Interesting results, however, can also be obtained in a more simple way. Figure 3a shows the distributions for top and bottom jets in the jet invariant mass, defined within a cone of 45° of semiaperture and centred around the jet axis. Gluon radiation effects are included. They essentially produce tails at large values of the invariant mass. A cut $M_{jet} < 10$ GeV removes many of the events with top recoil. One can improve

on that by considering correlations between the jet radius and the charged multiplicity, N_{ch} . Defining the r.m.s radius as $R = (\sum_i (\Delta\alpha_i)^2 E_T^i / \sum_i E_T^i)^{1/2}$, where E_T^i are the transverse energies and $\Delta\alpha_i$ the angular distances from the jet axis of the hadrons (or of the calorimetric cells), the scatter plot of Fig. 3c shows that for the same value of the radius, top jets have lower N_{ch} on average. That is due to the fact that in order to achieve a larger radius, a bottom jet essentially has to develop more gluon radiation, which in turn gives a higher multiplicity. For top jets, instead, gluon radiation is negligible and the number of decay steps is fixed ($t \rightarrow b \rightarrow c \rightarrow s$), which makes the multiplicity practically independent of the radius. One can exploit such characteristic differences in the $R - N_{ch}$ correlations by introducing a variable, which in the scatter plot corresponds to an axis orthogonal to the straight line approximately dividing the two clusters of bottom and top jets. The variable is given in our case by $D^* \approx R(\text{degrees}) - 1.3 N_{ch} - 8.6$, where the finite term is introduced for convenience [it approximately corresponds to the Fisher variable which would be obtained in a covariance matrix treatment²⁴⁾]. Distributions in this variable are given in Fig. 3b. By imposing a cut $D^* \lesssim 0$, one can bring down the contamination from top recoils by a finite factor ($\sim 3-4$) with limited loss of the events of interest. The effects of these cuts on events with a lighter jet as recoil are practically identical to those for bottom jets, since at the scale at which we are working, jet characteristics for flavours lighter than top are almost entirely determined by gluon radiation and are not sensitive to quark masses²⁴⁾.

The above cuts on the recoil jet lead to the event yields of column 6 in the Table. The contamination from the $\bar{b}b$ continuum and the leptonic decays of W and Z are left, of course, essentially unaffected by these cuts. Figure 1c gives the rapidity distribution for the electron expected from the various channels after the cuts. It is clear from the Figure that unless one introduces more stringent cuts, thus further restricting the background, there is no effect left to see. On the other hand, introducing other cuts does not appear sensible with the meager statistics foreseeable at present.

Instead of removing events with a top jet recoiling, one can remove, by the same techniques outlined above, events having a recoiling light jet. In this way, one picks up hadronic $\bar{t}t$ events, as well as $Z \rightarrow \bar{t}t$ events and $W \rightarrow tb$ events where the electron is generated by the b decay. Since the $\bar{b}b$ background is now effectively reduced, the signal stands out much more clearly. However, one can no longer exploit as a signature a clear parity violating effect, as in the case of top from W decays. To be convinced that one is actually left with top events, besides the absolute event yield observed after the cuts, one must exploit

other possible correlations expected within top jets, which might be revealed by a detailed simulation study. It seems apparent, though, that there will be no easy and clear-cut answer to be found in this way.

In conclusion, the exploitation of lepton signatures to establish a top signal appears hindered by the limited statistics available in the near future at the CERN $\bar{p}p$ collider. This is considerably, although not exclusively, due to the effects of gluon radiation, which increases the risks of contamination from other channels. It is possible that the situation may be slightly improved by a more clever choice of background-removing cuts. We find it hard to believe, however, that in doing so one can avoid reducing the signal by a factor $\sim 2-3$, as concluded in this study. The fact that lepton signatures do not appear viable with present statistics does not mean, of course, that the hunt for top should be called off with the present luminosity at the CERN collider. There are also the top non-leptonic decay modes to exploit, which should yield a signal about an order of magnitude stronger, although certainly more subtle to disentangle.

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	σ (nb) B_1 $p_T^e > 15$ GeV/c	$N(\text{events})$ $\int L dt = 1000 \text{ nb}^{-1}$	$p_T^{\text{miss}} < 0.7 p_T^e$	$p_T^e < 25$ GeV/c	$E_T^{\text{FW}} < 10$ GeV	Recoil jet	Recoil jet shape	
	(1)	(2)	(3)	(4)	(5)		Veto top	Veto bottom
$M_{\text{TOP}} = 40$ GeV								
$W \rightarrow t(\rightarrow e)b$ (*)	0.019	19	15	13	9	b	6	1
$W \rightarrow tb(\rightarrow e)$ (*)	0.005	5	4	3	2	t	0	1
$Z \rightarrow \bar{t}t$ (*)	0.003	3	2	2	1	t	0	1
$gg, \bar{q}q \rightarrow \bar{t}t$	0.020	20	15	11	7	t	0	5
$M_{\text{TOP}} = 25$ GeV								
$W \rightarrow t(\rightarrow e)b$ (*)	0.012	12	10	10	5	b	4	0
$W \rightarrow tb(\rightarrow e)$ (*)	0.004	4	3	3	1	t	0	1
$Z \rightarrow \bar{t}t$ (*)	0.003	3	2	2	1	t	0	1
$gg, \bar{q}q \rightarrow \bar{t}t$	0.049	49	42	42	24	t	1	17
$W \rightarrow e\nu$	0.240	240	21	5	3	q,g	2	0
$W \rightarrow \tau\nu$	0.013	13	2	2	2	q,g	1	0
$W \rightarrow cs$	<0.001	0	0	0	0	q,g	0	0
$Z \rightarrow e^+e^-$ (**)	0.004	4	4	3	1	q,g	1	0
$Z \rightarrow \tau^+\tau^-$ (**)	0.003	3	2	1	1	q,g	1	0
$Z \rightarrow \bar{b}b$	0.002	2	2	2	0	b	0	0
$Z \rightarrow \bar{c}c$	<0.001	0	0	0	0	c	0	0
$gg, \bar{q}q \rightarrow \bar{b}b$	0.056	56	52	52	11	b	8	1
$gg, \bar{q}q \rightarrow \bar{c}c$	0.017	17	17	17	2	c	1	0
(*) Without phase space suppression for massive t quarks.								
(**) With the second electron having $p_T^e < 15$ GeV/c.								

Table - Inclusive electron cross-sections times the semileptonic branching ratio ($B_\ell = 0.1$) and event yields for a variety of cuts. Cuts are meant to be applied successively from left to right, except for those in the last two columns, which are independently applied to the contents of column 5.

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FIGURE CAPTIONS

Fig. 1 : Electron distributions.

- a) p_T^e distributions for some of the important channels (top quark masses of 25 and 40 GeV).
- b) p_T^e distribution in hadronic $\bar{b}b$ events calculated (i) neglecting the charm recoil mass and gluon radiation; (ii) with a mass $m_c = 1.87$ GeV for the charm recoil and neglecting gluon radiation; (iii) with a recoil mass $m_c = 1.87$ GeV and including gluon radiation in the production process.
- c) Pseudorapidity distributions of electrons (negative electron counted with opposite rapidity) after various cuts discussed in the paper, and normalized to the contents of column 6 of the Table.

Fig. 2 : Transverse energy distributions.

- a) Distributions in E_T^{FW} (hadronic transverse energy deposited within an azimuthal sector of $\pm 30^\circ$ with respect to the electron momentum, plus the missing p_T if it lies in the sector).
- b) Distributions in E_T^{BW} (hadronic transverse energy deposited within an azimuthal sector of $\pm 30^\circ$ centred around the direction opposite to that of the electron).
- c) Mean azimuthal distributions of hadronic transverse energy with respect to the electron direction.

Fig. 3 : Study of the recoil jet.

- a) Distributions of recoil bottom and top jets in the invariant mass M_{jet} , defined within a cone of 45° of semiaperture centred around the jet direction.
- b) Distributions of bottom and top jets surviving a cut $M_{jet} < 10$ GeV in a variable representing a suitable linear combination of the r.m.s. radius and its charged multiplicity (see Fig. 3c).
- c) Scatter plot of bottom and top jets (top quark mass of 40 GeV) surviving a cut $M_{jet} < 10$ GeV in the r.m.s. radius and charged multiplicity. The axis shown corresponds to the variable D^* used in Fig. 3b. Projecting the scatter plot entries over it gives the distributions in D^* .

Fig. 1

Fig. 2

Fig. 3