QCD predictions for associated production of jets in $\bar{p}p \rightarrow W^{\pm}X$

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The substantial development of hadronic transverse energy experimentally observed in $\bar{p}p \rightarrow W^{\pm}X$ events is discussed. QCD predictions for the jet activity associated with the production of $W^{\pm}$ bosons are reported.

A salient feature of $\bar{p}p \rightarrow W^{\pm}X$ ($W^{\pm} \rightarrow e^{\pm}\nu$) events as observed by the UA1 (Refs. 1 and 2) and UA2 (Ref. 3) experiments is the large value of the total transverse energy of hadrons produced in association with the W boson. This equally applies to the $\bar{p}p \rightarrow Z^0X$ ($Z^0 \rightarrow e^-e^+$) candidates observed by UA1 (Ref. 2). Naively, one might expect that the substantial fraction of energy going into the production of the weak boson should reduce the associated hadronic activity. On the other hand, such a development of transverse energy is naturally expected from QCD. The "hard scale" of the process, set by the intermediate-boson mass, implies the presence of QCD radiation off the annihilating partons, similarly to what occurs in deep-inelastic scattering. This same radiation is (largely) responsible for the transverse momentum with which the weak boson is generated. (If one allows for multiquark interactions, the hadronic E_T is no longer directly related to the transverse momentum of the weak boson. See the discussion by Jacob[4] and Ref. 5.) An appropriate check of the theory can thus take advantage of both pieces of information.

The problem of calculating QCD predictions for the transverse momenta of weak bosons and Drell-Yan pairs, for which similar techniques are to be used, has been tackled in a number of publications.[6,7] Analytic calculations for the gluon transverse energy accompanying Z^0 and Drell-Yan pair production have also been made.[8] If one tries to keep the calculation analytic, substantial simplifications must be made in the correlated treatment of longitudinal and transverse degrees of freedom, and one remains always very far from a full computation of the final state as predicted by perturbative QCD. A numerical, Monte Carlo technique which does just that has been presented in Refs. 9 and 10. It represents a slight modification of a method first proposed for QCD calculations in e^+e^- annihilation,[11,12] and which includes both soft and hard radiation effects. The basic (and only) approximation involved is the leading-pole approximation, which allows the calculation of contributions from dressed tree graphs with an arbitrary number of final quanta (Fig. 1) in terms of the elementary emission probability

$$dP_E = \frac{\alpha_s(K^2)}{2\pi}\frac{dK^2}{K^2}P(z)dz \ ,$$

where $P(z)$ is the splitting probability function appropriate to the vertex ($q \rightarrow qG$, $G \rightarrow GG$, $G \rightarrow \bar{q}q$). The leading-pole approximation adequately covers the important region of phase space. In $e^+e^- \rightarrow q\bar{q}G$, for instance, it just amounts to taking[11]

$$d\sigma/dx_q dx_{\bar{q}} = \tfrac{2}{3}\alpha_s(x_q{}^2 + x_{\bar{q}}{}^2)/(1-x_q)(1-x_{\bar{q}})$$
$$\simeq \tfrac{2}{3}\alpha_s 2/(1-x_q)(1-x_{\bar{q}}) \ .$$

The Monte Carlo technique, among other things, allows us to take easily into account phase-space constraints, both globally and at the local level, and to include non-Abelian contributions, i.e., graphs in which the annihilating parton has a different flavor from that originating the QCD cascade (Fig. 1). With a suitable model for the fragmentation of the quanta into hadrons it allows us to perform a full, exclusive calculation of the final state at the

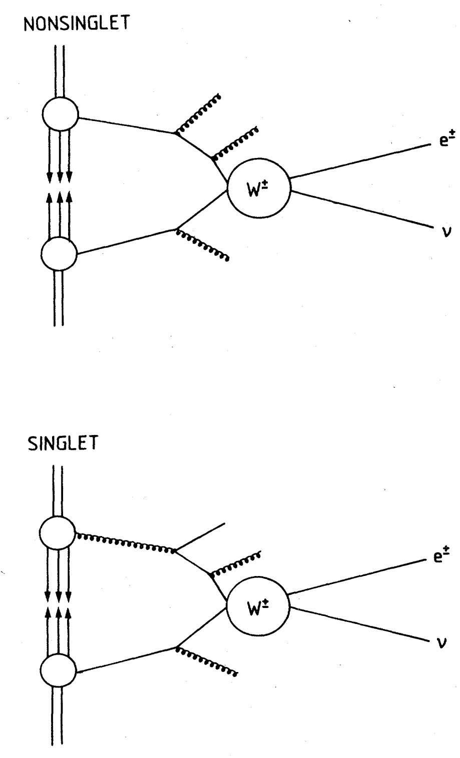

FIG. 1. Examples of nonsinglet and singlet graphs included in the calculation which make use of the leading-pole approximation.

level of hadrons, thus making possible (within the uncertainties of the fragmentation model) a complete comparison of the theory with the experimental data. Extensive calculations of this type have been already presented for e^+e^- annihilation,[11–13] hadron collisions at large p_T,[9,14,15] and Drell-Yan pair production.[9,10]

The calculations reported in this paper have been made in two different ways, in connection with the fixing of the evolution scale and the associated handling of phase-space constraints. As is well known, the evolution scale is uncertain by factors, which can depend on other scaling variables. In deep-inelastic scattering, for instance, instead of the lepton momentum transfer squared Q^2, one can take as evolution scale $\sim Q^2(1-x)/x$ (see, e.g., Ref. 16), a choice of this type actually appearing more appropriate phenomenologically. Basically, the evolution scale should gauge the phase space available for QCD radiation. Also, the enforcement of phase-space constraints meets some ambiguities in a spacelike QCD cascade, due to the lack of strong ordering in the spacelike evolution. In our previous calculation for hadronic collisions at large p_T,[14] we have set the parton transverse momentum $\hat{p}_T$ to fix the evolution scale for the parton cascades and we have imposed phase-space constraints associated, essentially, with the parton transverse momenta generated in the cascade. In the adaptation to the case of weak-boson production we have adopted exactly the same procedure as specified in Ref. 14, replacing $\hat{p}_T$ by the weak-boson mass. In our previous calculation for Drell-Yan pair production,[10] on the other hand, the "length" of the evolution is determined by the subenergy $\hat{s}$ of the initial parton-parton system and by the squared mass of the Drell-Yan pair, M_{DY}^2, the initial cascades being treated as the result of a degradation of the initial $\hat{s}$, whose rate becomes more and more limited as M_{DY} increases. In the adaptation of this calculation to our present problem, we have then simply replaced M_{DY} with the weak-boson mass. We have verified that differences between the results obtained with the two procedures are minor, and can be reabsorbed into moderate changes of the Λ parameter. The results actual-

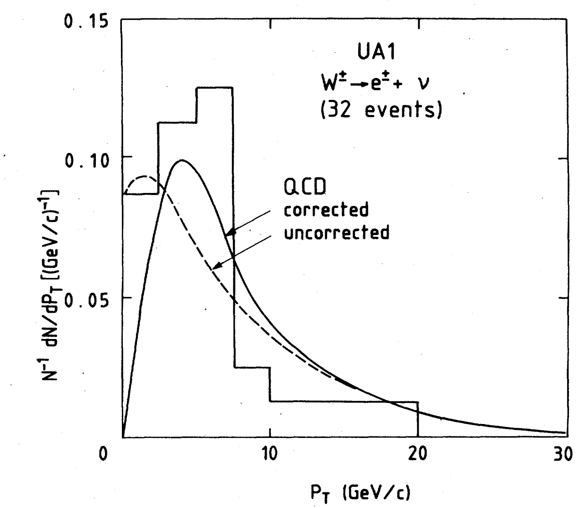

FIG. 2. Comparison with the transverse-momentum distribution of $W^{\pm}$ as measured by UA1 (Ref. 2). Predictions with and without corrections for experimental acceptance and errors are shown.

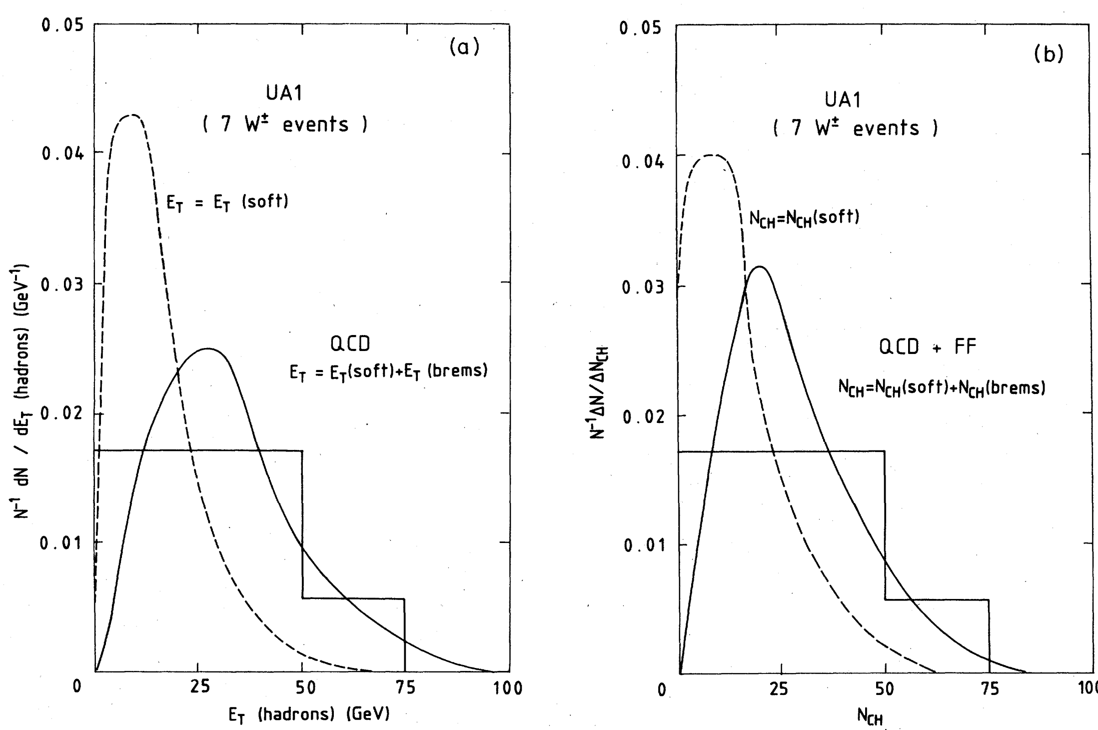

FIG. 3. Comparison with UA1 data (Ref. 1) for the hadrons produced in association with $W^{\pm}$. (a) Distribution in the hadronic transverse energy. (b) Distribution in the charged multiplicity. Dashed curves represent the expectation when neglecting QCD radiation effects.

ly reported in the figures refer to the first procedure, the one we have used in large-p_T collisions.[14]

For the quark densities we use the parametrization determined from the NA3 experiment on Drell-Yan production.[17] 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. The results we show have been obtained with $\Lambda = 0.050$ GeV, to adjust for the observed p_T distribution of the $W^{\pm}$. Moving Λ to moderately higher values does not change them much, though. 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 procedure.[9,10] For the total $\bar{p}p \to W^{\pm}X$ cross section we obtain a value of $\sigma_{\text{tot}}(\bar{p}p \to W^{\pm}X) = 3.4$ nb, before any corrective K factor is applied.

Figure 2 shows the result for the p_T distribution of the $W^{\pm}$ boson. Since the program computes the full final state, we are also able to estimate the corrections for the experimental cuts and uncertainties. The "corrected" curve in the figure includes the effects from (i) a $p_T > 15$ GeV/c cut on the electron, (ii) a $E_T > 15$ GeV cut on the missing transverse energy, (iii) rejection of events with a jet lying at an azimuth with $\Delta\phi > 150°$ with respect to the electron, and (iv) errors on the total-transverse-energy components, described by normal distributions with zero-mean and root-mean-square deviation

$$(\Delta E_T)_{y,z} = 0.4 \left[\sum_i |E_T^i| \right]^{1/2} .$$

Of course, we cannot claim that such corrections allow for a fully quantitative comparison with the data (one should filter the events through the Monte Carlo simulating the apparatus to eventually do that). However, one learns that such corrections can substantially affect the shape of the distribution. In particular, the shift of the distribution peak to a larger p_T is essentially due to the uncertainties in the missing-transverse-momentum determination.

The contribution from the (non-Abelian) singlet graphs, i.e., those in which the annihilating quark has a flavor different from that of the originating parton (Fig. 1), is $\sim 10-15\%$ depending on Λ. This contribution, however, has a $\langle p_T^W \rangle$ about 40–50% higher than the nonsinglet contribution, and becomes comparable in magnitude with the latter for $p_T^W \gtrsim 25-30$ GeV/c. It cannot be neglected, therefore, when discussing the tail of the distribution and the associated event structure, as future higher statistics will hopefully allow us to do.

Figure 3 shows the comparison with existing UA1 data for the distributions in the total transverse energy E_T of the associated hadrons and in their charged multiplicity. The prediction for the E_T distribution is affected very little by the fragmentation model we use, which amounts to an independent fragmentation of the quanta according to the Field and Feynman[18] model (gluons treated as quarks of random, light, flavor), plus the contribution from the

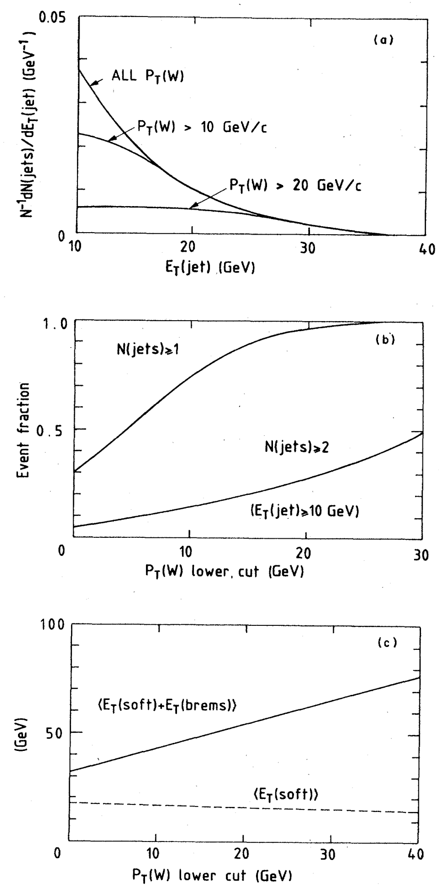

FIG. 4. (a) Inclusive jet cross section for various cuts in the transverse momentum of the $W^{\pm}$ (normalizations are to the total number of events, without cuts). (b) Fractions of events with at least one jet and at least two jets versus a lower cut in the $W^{\pm}$ transverse momentum. (c) $\langle E_T \rangle$ of the hadrons versus a lower cut in the $W^{\pm}$ transverse momentum.

beam jets. The model is exactly the same as that used in Ref. 14 for large-p_T collisions. The beam-jet model has been tuned to the small-p_T data of the UA1 and UA5 experiments. Neglecting the fragmentation of the QCD quanta, the QCD contribution to E_T is reduced by $\sim 15\%$ on average. Because of the QCD radiation, E_T practically doubles on average. The comparison with the UA1 data makes it also clear (pending confirmation from higher statistics) that initial QCD radiation is needed to understand the data. Differently from E_T, the comparison with the multiplicity distribution largely depends on the fragmentation model, and rather than a theoretical test it should be used for support of the fragmentation scheme.

A comparison with the similar UA2 data[3] on the hadronic E_T is harder to do, because of the acceptance conditions under which the existing data have been obtained. Qualitatively, we expect a $\langle E_T \rangle$ lower by more than a factor of 2 with respect to that calculated for UA1, which is not in disagreement with the existing data.

Besides global properties of the W events, we can calculate with the Monte Carlo any other more exclusive feature. In Fig. 4(a) are shown inclusive jet distributions in transverse energy for various cuts in p_T^W. Figure 4(b) gives the fractions of events with at least one jet and at least two jets as a function of p_T^W, where a jet is defined as having a transverse energy of at least 10 GeV. The jet-W correlations are not particularly interesting. As one naturally expects the two are essentially always in a back-to-back configuration ($\langle \Delta\phi \rangle = 166°$ in events with one jet, $\langle \Delta\phi \rangle = 137°$ in events with two jets). In events with two jets we find a mean distance between the jets in azimuth of $\langle \Delta\phi \rangle = 83°$, and in rapidity of $\langle \Delta\eta \rangle = 0.97$. Figure 4(c) shows the behavior of $\langle E_T \rangle$ versus a lower cut in p_T^W.

In conclusion, observed hadron production in $\bar{p}p \rightarrow W^{\pm}X$ events appears to support the presence of QCD radiation in the amount theoretically expected. The hadronic transverse energy is approximately double than that predicted from a model neglecting this extra source of excitation. This makes it clear that QCD radiation off initial partons is an important phenomenon, which should be properly taken into account also in other hard processes. For instance, when studying hadronic collisions at large p_T and their associated jet structure.[19]

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