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QCD p_T EFFECTS IN W-Z AND JET PRODUCTION

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Abstract

Theoretical aspects of transverse momentum distributions in QCD are discussed in connection to weak bosons and dijet production at $Sp\bar{p}S$ collider energies.

The production of W and Z bosons[1)] at the CERN $Sp\bar{p}S$ collider allows a very important test of the Drell-Yan mechanism[2)] in perturbative QCD in a completely new kinematical regime. The $O(\alpha_s)$ corrections to the total production cross section are of reduced size compared to fixed target energies and therefore the absolute production rates can be quite reliably predicted from perturbation theory[3)].

On the other hand the transverse momentum distribution is probed in the soft region of $q_T \ll Q$, which, at lower energies, is not clearly separated from the "intrinsic q_T" ($q_T \sim \Lambda$) and large q_T ($q_T \sim Q$) regions, where non perturbative and $O(\alpha_s)$ effects respectively dominate the spectrum. Therefore one encounters here a unique opportunity to test those theoretical ideas which have been developed to resume to all orders the class of large logarithms of Q^2/q_T^2 arising from the emission of soft quanta. Conversely, a precise evaluation of these QCD effects is quite important for obtaining the accuracy desired to test the electroweak part of these process, referring in particular to the W mass, which is determined from the transverse spectrum of the decay lepton.

Much theoretical work has been recently dedicated to this subject[4)]. In particular a very detailed analysis of the q_T spectrum has been recently performed[5)], which authomatically combines the soft gluon resummation at $q_T \ll \ll Q$ with the $O(\alpha_s)$ perturbative distribution at large q_T, without the ad hoc introduction of matching procedures between hard and soft radiation. The main formulae and the comparison with UA1 and UA2 experimental results have been already discussed by K. Ellis[6)]. In the following I will first compare those results with recent theoretical analyses[7)] of the same problem in order to clarify the different approximations performed and the corresponding limits of validity. Next I will discuss the transverse momentum spectrum of the leptons produced in the decay of the weak bosons, which are closely related to the parent distribution and are of great importance for an accurate determination of the W boson's mass. Finally some transverse momentum effects in the production of dijets will be briefly discussed, showing possible evidence in favor of the three gluon coupling at collider energies.

The expression for the cross section for the production of a W^+ boson reads[5)]

$$\frac{d\sigma}{dq_T^2 dy} = \frac{\pi^2 \alpha}{6S\sin^2\theta_W} \int b\, db\, J_o(b q_T)\, e^{S(b^2,Q^2,A_t^2)} R_q(b^2,Q^2,y) + \\ + Y_q(q_T^2, Q^2, y) + (\text{gluon terms}) \,, \tag{1}$$

where

$$R_q(b^2,Q^2,y) = H(x_1^o, x_2^o, P^2)\left[1 + \frac{\alpha_s C_F}{2\pi}\left(1 + \frac{5}{3}\pi^2 - \ln^2\left(\frac{A_t^2}{Q^2}\right) - \right.\right. \\ \left.\left. - 3\ln\left(\frac{A_t^2}{Q^2}\right)\right] + \frac{\alpha_s C_F}{2\pi}\left[\int_{x_1^o}^1 \frac{dz}{z} f_q(z) H\left(\frac{x_1^o}{z}, x_2^o, P^2\right) + \right. \\ \left. + \int_{x_2^o}^1 \frac{dz}{z} f_q(z) H\left(x_1^o, \frac{x_2^o}{z}, P^2\right)\right] \,, \tag{2}$$

and $\tau = M^2/S$, $x_{1,2}^o = \sqrt{\tau}\exp(\pm y)$, $A_t^2 = \left[(S+Q^2)^2/4S\cosh^2 y - Q^2\right]$ is the kinematical bound of the transverse momentum squared for gluon emission, and $f_q(z) = 3/2(1-z)_+^{-1} - (1+z^2)\left[\ln(1-z)/(1-z)\right]_+ + (1+z^2)\ln z/(1-z) - 2 - 3z$. Furthermore the product of the parton distribution functions is defined

$$H(x_1,x_2,P^2) = \left\{\left[u(x_1,P^2)\bar{d}(x_2,P^2) + c(x_1,P^2)\bar{s}(x_2,P^2)\right]\cos^2\theta_c + \right. \\ \left. + \left[u(x_1,P^2)\bar{s}(x_2,P^2) + c(x_1 P^2)\bar{d}(x_2 P^2)\right]\sin^2\theta_c\right\} + \left\{1 \leftrightarrow 2\right\} \,, \tag{3}$$

where the scale P^2 at which the parton densities are probed is given by $P^2 \sim \sim 4e^{-2\gamma_E}/b^2$ at large b.

The Sudakov form factor $S(b^2, Q^2, A_t^2)$, at the leading double and single logarithmic accuracy, is given by

$$S(b^2, Q^2, q^2_{Tmax}) = \frac{C_F}{\pi} \int_0^{q^2_{Tmax}} \frac{dq^2}{q^2} \, \alpha(q^2) \left[\ln(\frac{Q^2}{q^2}) - \frac{3}{2} \right] \left[J_o(bq) - 1 \right] , \quad (4)$$

with $q^2_{Tmax} = A_t^2$. The residual term Y_q in eq. (1) includes finite terms from annihilation graphs for $q_T \to 0$. Finally the gluon terms refer to the Compton scattering graphs, which give additive contributions to R_q and Y_q.

The bulk of the q_T distribution, where most of the data have been collected, comes from the soft part of eq. (1). Of course the residual finite terms play a major role for large q_T, say $q_T \gtrsim 30$ GeV where eq. (1) tends to the $O(\alpha_s)$ perturbative result. Then, for comparison with previous analyses of the soft contribution, it is useful to discuss some approximate forms of the Sudakov form factor (4).

First, taking $q^2_{Tmax} = Q^2$ as upper limit, the replacement can be made

$$\exp\left[S(b^2, Q^2, A_t^2)\right] \simeq \exp\left[S(b^2, Q^2, Q^2)\right] (1 + \int_{Q^2}^{A_t^2}) , \quad (5)$$

with obvious notations. This is allowed because $\alpha(q^2)$ is small for $Q^2 \leq q^2 \leq \leq A_t^2$. The resulting additional contribution to R cancels in this case the terms $\ln^2(A_t^2/Q^2) - 3\ln(A_t^2/Q^2)$ appearing in eq. (2) in the large b limit. A similar result holds approximately for $q^2_{Tmax} = Q^2/e^3 \sim (Q/4)^2$. Different choices of q_{Tmax}, with no compensating terms, would not agree with the exact result (1). Furthermore the next to leading constant term in integrand of eq. (4) is given by (- 3/2), and its presence is quite relevant for the falloff of the distribution $(d\sigma/dq_T dy)$ after the peak. In fact the so called "leading approximation", where one keeps only the logarithmic term $\ln(Q^2/q^2)$ in eq. (4) gives a very poor description of the weak boson distribution and consequently of the decay lepton spectrum, as discussed later. Finally no double counting between the soft and the hard finite contribution must be present, as in eq. (1).

The above discussion puts some doubts on the accuracy of previous analyses[7] of this problem and indeed only in a few cases[8] the answer is reasonably good up to $q_T \lesssim 20$ GeV, where however the treatment of hard effects is unsatisfactory. In the other hand a detailed knowledge of the full q_T distribution, which is crucial to describe the QCD background for new phenomena at large q_T [9], can only be obtained from ref. 5.

We would like to discuss now the p_T distribution of the decay leptons from W-Z decays, which is relevant for an accurate determination of the charged boson's mass. The starting formula is given by[10]

$$E_p \frac{d\sigma}{d^3p} = \int \frac{d^3k}{E_k} \left(E_k \frac{d\sigma^W}{d^3k}\right) \frac{1}{2\pi} \delta\left(pk - \frac{M_W^2}{2}\right), \tag{6}$$

where $d\sigma^W$ is the invariant cross section for producing a W boson, times its leptonic branching ratio, see eq. (1), and the δ function reflects the two body decay kinematics. The technical details of integrating eq. (6) are given in ref. 11. We will give here only the main results, compared with the leading approximation analyses[10,12]. In Fig. 1 we show[11] the invariant cross section at

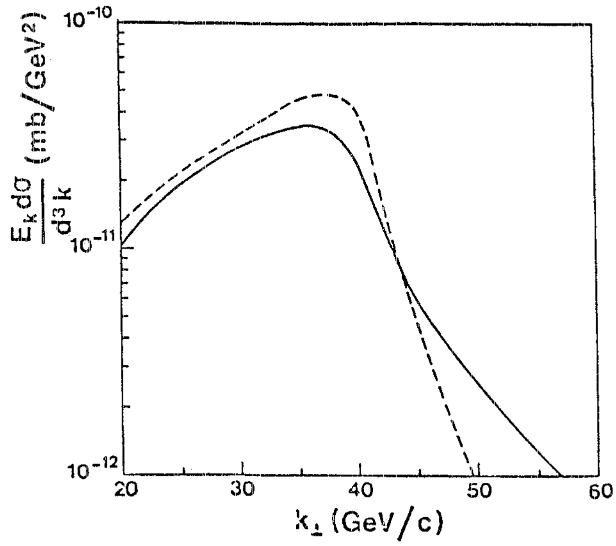

Fig. 1

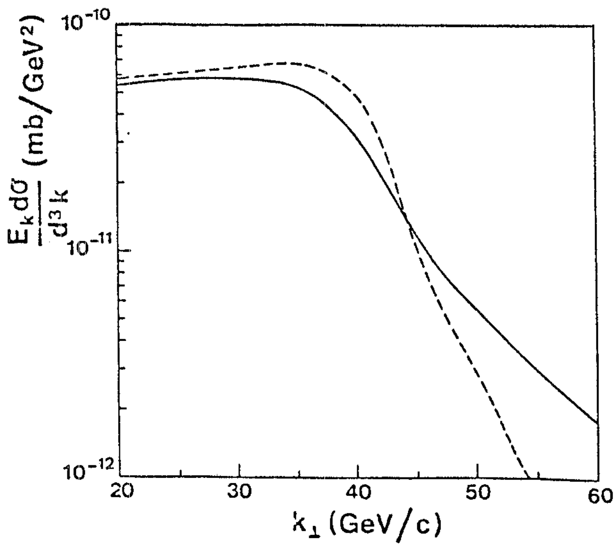

Fig. 2

a lepton angle $\theta = 90^o$, having used the Glück et al.[13] parametrization of the structure functions. A different choice of the parton densities, given for example, by Baier et al.[14], gives similar results. The leading approximation (solid curve), defined above, gives rise to a much broader p_T distribution than the one resulting from the inclusion of subleading terms (dashed curve) corresponding to eq. (1), which is reminescent of what observed for the q_T distribution of the W. Similar results are found[11] at $\sqrt{s} = 2000$ GeV (see Fig. 2), where however one observes an excess of events for small p_T compared to $\sqrt{s}$ = 540 GeV, due to the much more sizeable effect of the sea when the energy increases. The relevant role played by the subleading terms is consistent with the UA1 data[15], which show no events for $p_\perp$ above 50 GeV.

As last topics, I would like to discuss now some transverse momentum effects in dijet production. The basic idea is the following[16,17]. At collider energies the subprocess of gluon-gluon scattering gives the dominant contribution to jet production, in contrast to the case of weak boson production, where only the quarks essentially play a role. The corresponding Sudakov form factors depends upon C_A instead of C_F, leading to a relative k_T dijet distribution which is regulated by the process of bremsstrahlung initiated by gluons instead of quarks. This observation provides a rather clean test of the three gluon coupling which can be easily studied by looking at the relative k_T distribution of two hard back-to-back jets. Then for k_T not very large, say $k_T \leqslant 20$ GeV, the distribution is dominated by soft gluon emission and is much broader than the corresponding quark case. This is shown in Fig. 3[17], where the k_T spectrum obtained by using a Glück at al.[13] parametrization of the gluon density (full line), is compared to the hypothetical case where gluons would radiate like quarks ($C_A = C_F$, dotted line). The theoretical uncertainty related to our poor knowledge of the gluon structure function is represented, in the same figure, by the dashed line which gives the analogous result for the CDHS gluon parametrization[18].

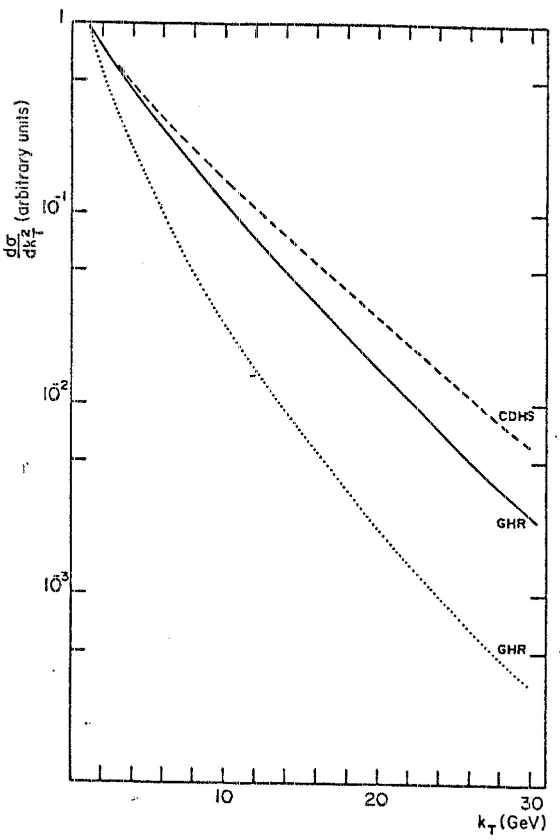

Fig. 3

Experimentally, it is better to define a projected k_T distribution perpendicularly to the trigger jet ($k_{T\perp}$). Then the UA1 preliminary data[19] are shown in Fig. 4 and compared to the theoretical predictions the two sets of gluon densities. An experimental resolution $\sigma = 5$ GeV is also included in the curves. There is a quite good agreement between theory and experiments for $(k_{T\perp}) \leqslant$

$\leqslant$ 20 GeV. At higher transverse momenta the theoretical predictions are not reliable, not including finite terms of order α_s coming from hard gluon bremsstrahlung and virtual one loop corrections, which have not been all computed. Finally, in Fig. 5 the hypothetical case of gluons radiating like quarks is also shown, clearly in a much poorer agreement with data.

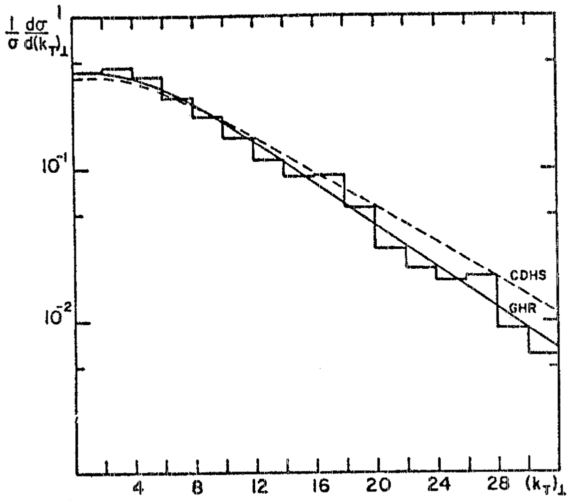

Fig. 4

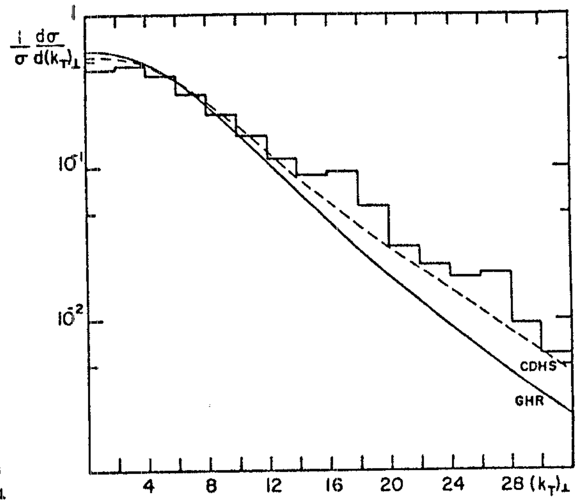

Fig. 5

In conclusion, we have discussed the relevance of detailed studies of p_T effects in W-Z production for precise tests of QCD as well as for the determination of the electroweak parameters. Similar effects observed in the production of back-to-back jets at collider energies are in good agreement with the expectations from the three gluon coupling.

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