LEPTON PAIR PRODUCTION AT ISR ENERGIES AND QCD

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Abstract

Motivated by some recent results from the ISR we have considered all available data on the production of Drell-Yan pairs by high energy proton beams. We show that the lepton pair cross-sections and q_T distributions are correctly described by QCD using the known distributions of partons in the proton and acceptable values of the QCD scale Λ . No other free parameter is required. Within the accuracy of the data no appreciable intrinsic transverse momentum is needed.

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We have recently made[1] a theoretical re-evaluation of the QCD description of lepton pair production in hadron-hadron collisions. A full treatment of the complete transverse momentum (q_T) dependence was given including the large amount of theoretical information about this process which has been accumulated over the last few years. The resulting q_T and y distribution reproduces the correct perturbative behavior[2] at large q_T and contains the soft gluon exponentiation at leading[3] and next-to-leading[4, 5] double logarithmic accuracy. Upon integration over q_T it reproduces the known perturbative results[6] for the total cross-section and rapidity distribution $d\sigma/dy$ (including the terms of order α_s which give rise to the "K-factor"). The phenomenological implications for W/Z^0 production at the CERN Collider and for the physics of the future Multi-Tev Colliders have been discussed in detail in refs.[1, 7]. On the experimental side, new data from the ISR [8] on Drell-Yan lepton pair production have recently been presented ($\sqrt{S} \simeq 62 \text{ GeV}$). The investigated range of lepton pair mass Q was extended up to $Q \simeq 25 \text{ GeV}$ and the q_T distribution of the pair was measured. This set of data completes a series of excellent experiments on lepton pair production[9, 10, 11] performed over the years at the ISR which is now being dismantled.

In view of this theoretical and experimental progress it appears timely to make a complete analysis of all the available data on (continuum) lepton pair production in both $p-p$ and $p-\bar{p}$ collisions. We shall concentrate our attention on the data set at large values of the pair mass Q , i.e. above the Υ resonances ($Q \geq 11 \text{ GeV}$). These data are most appropriate for a comparison with the asymptotic QCD predictions which are only valid if Q is large enough. For completeness we shall also extrapolate our calculations to values of Q in the range $Q \simeq 5 - 9 \text{ GeV}$ between the J/Ψ and the Υ . The relevant set of data also includes Drell-Yan $p-N$ processes at $\sqrt{S} \simeq 19 - 27 \text{ GeV}$ [12] and $p-p$ processes at ISR with $\sqrt{S} = 44, 62 \text{ GeV}$. If we also include the results from the CERN Collider on W/Z^0 production[13] , which proceeds via the same Drell-Yan mechanism, the explored range of $\sqrt{S}$ and $\tau = Q^2/S$ is given by $\sqrt{S} \simeq 19 - 540 \text{ GeV}$ and $\sqrt{\tau} \simeq 0.1 - 0.4$.

In contrast to the naive parton model, QCD predicts[14] that the q_T distribution becomes harder when $\sqrt{S}$ increases at fixed τ . The shape of the q_T distribution and pattern of variation provide stringent quantitative tests of the detailed QCD dynamics. We shall show in the following that all the quantitative features of the data are neatly reproduced using a value

of Λ entirely consistent with experimental information and reasonable parametrisations of the parton distributions of the proton, suitably evolved according to QCD. No fine tuning or extra hypotheses about the transverse size of the proton are needed. Given the present accuracy of the data and the size of the theoretical errors, there appears no compelling reason to include an appreciable amount of intrinsic transverse momentum.

In proton-proton collisions the Drell-Yan cross-sections are mainly determined by the annihilation of valence and sea quarks. In the interval $\sqrt{\tau} \simeq 0.1 - 0.4$ the results depend on the small tail at relatively large x of the poorly known distributions of sea quarks in the proton. Thus the precision of our predictions for the cross-sections is limited by our ignorance of the sea quark distributions. The ISR data are particularly interesting in this respect because, even for Q above the Υ , $\sqrt{\tau}$ is not too large. In fact our knowledge of the sea distributions is even poorer in the region at large x where they are very small.

In the following we shall use the parameterisation of quark and gluon densities given by Duke and Owens [15]. Of the two sets of distributions given there we adopt the one with $\Lambda = 0.2 \text{ GeV}$ denoted by DO1. This value of Λ is compatible with all the available experimental information on $\Lambda_{\overline{MS}}$. The inclusion of the Kodaira-Trentadue [4] subleading term in the soft gluon exponentiation has been implemented in our formulae using the form which it takes with the $\overline{MS}$ definition of α_s . Although, strictly speaking, the DO1 parameterisation is only guaranteed to work for the quoted value of Λ , some variation in Λ will be allowed in the following in order to estimate the effect of a change in the QCD scale. The advantage of using the distributions of ref.[15] is that the data on $S^3 d\sigma/dQdy$ at $|y| \leq 0.1$ for lepton pair production, obtained at FNAL and at the ISR, were used together with other experimental information in order to constrain the distributions of sea quarks inside the proton. Thus the Q dependence of $d\sigma/dQdy$ at $y = 0$ is directly reproduced (see fig.1) and we can mostly concentrate on the shape of q_T distributions which provide much independent information. The total cross-sections $d\sigma/dQdy$ at $y \simeq 0$ for $\sqrt{S} \simeq 27.4$ and 62 GeV are displayed in fig.1. Also shown are the theoretical curves with $\Lambda = 0.1, 0.2 \text{ GeV}$ and the results for $\alpha_s = 0$ but with $\Lambda = 0.2 \text{ GeV}$ for the distribution functions (i.e. without the "K-factor"). The variation of the results with Λ is very small due to a compensation between the change in the parton distributions and in α_s . The value of the theoretical "K-factor" is $K \simeq 1.55(1.45)$ for $\alpha_s = \alpha_s(Q^2)$ and $\Lambda = 0.2 \text{ GeV}(0.1 \text{ GeV})$.

at $\sqrt{S} \simeq 62 \text{ GeV}$ if Q^2 is chosen as the appropriate scale for the running coupling constant. The uncertainties in the data and in the normalization of the distributions of sea quarks do not at present permit an experimental confirmation of this factor in proton-proton scattering at the ISR.

We now consider the q_T and y distribution, which is given by[1]:

$$\frac{d\sigma}{dQ^2 dq_T^2 dy} = N \left(\int \frac{d^2\vec{b}}{4\pi} e^{-i\vec{q}_T \cdot \vec{b}} R(b^2, Q^2, y) e^{S(b^2, Q^2, y)} + Y(q_T^2, Q^2, y) \right) \quad (1)$$

Where $N = 4\pi\alpha^2/9Q^2S$, the kernel R and the regular term (at $q_T = 0$) Y are given by eq.(57) and (62) of ref.[1], and :

$$S(b^2, Q^2, y) = \int_0^{A_T^2} \frac{dk^2}{k^2} \frac{4\alpha_s(k^2)}{3\pi} (J_0(bk) - 1) \left((1 + D\alpha_s(k^2)) \ln\left(\frac{Q^2}{k^2}\right) - \frac{3}{2} \right) \quad (2)$$

Here A_T is the maximum value of q_T at fixed y :

$$\frac{A_T}{\sqrt{S}} = \left(\frac{(1 + \tau)^2}{4ch^2(y)} - \tau \right)^{\frac{1}{2}} \quad (3)$$

and D is given [4] by:

$$2\pi D = \left(\frac{67}{6} - \frac{\pi^2}{2} - \frac{5n_f}{9} \right) \quad (4)$$

In fig.2 the data at $\sqrt{S} \simeq 62 \text{ GeV}$ for the normalized q_T distribution $d\sigma/dq_T dy$ at $y = 0$ and $Q = 11 - 25 \text{ GeV}$ are compared with the theoretical curves with $\Lambda = 0.1 - 0.2 \text{ GeV}$. The relatively good precision of the data and the accuracy of the theoretical fit can be better appreciated if one notes that fig.2 is a linear plot. $d\sigma/dq_T^2$ is often displayed on a logarithmic scale where only the gross features of the data can be reproduced (see for example fig.3 which refers to the extrapolated predictions at values of Q below the Υ).

In figs4,5 the average transverse momentum $\langle q_T \rangle$ is plotted as a function of $\sqrt{\tau}$ at fixed values of $\sqrt{S}$ ($\sqrt{S} = 27.4, 44, 62 \text{ GeV}$) and as a function of $\sqrt{S}$ at fixed $\sqrt{\tau} \simeq 0.22$. Below ISR energies we see that the effects of scaling violations and of sub-asymptotic contributions from soft gluons significantly distort the linear behaviour of the average value of q_T as a function of $\sqrt{S}$. The extrapolation of the linear slope of $\langle q_T \rangle$ to the Collider energy $\sqrt{S} = 540 \text{ GeV}$ leads to $\langle q_T \rangle \simeq 7 - 8 \text{ GeV}$, in good agreement with the observed value for W/Z^0 production[16] despite the fact that one is comparing $p - p$ with $p - \bar{p}$, different values of $\sqrt{\tau}$ and virtual photons with weak bosons.

In conclusion we see that the important features of the q_T distributions are correctly reproduced without any attempt at optimization. We have taken one recent parameterisation of the parton distributions from the literature and let Λ vary in a relatively narrow interval well within the range allowed by experiment. Note that the dependence on Λ of the q_T distributions is much stronger than for the total cross-sections. Similarly we could easily improve the agreement with the data by making a fine tuning of the normalization and shape of the sea quark distributions. We also should add some amount of intrinsic transverse momentum. It is quite remarkable that within the accuracy of the data and of the remaining theoretical ambiguities there is apparently no need for an intrinsic component of q_T . This also limits the component of transverse momentum from initial state interactions[17] between active and spectator quarks, which although absent in the total cross-section[18] could be present in differential cross-sections. We remind the reader that the amount of intrinsic q_T required to fit the Drell-Yan data has decreased with time as a result of theoretical progress. The main drop of intrinsic q_T was first obtained as a result of the soft gluon resummation. Now we have shown that by implementing the correct interplay between the perturbative and the soft components and by adding the Kodaira-Trentadue sub-leading term (which sizeably contributes to increase the resulting value of $\langle q_T \rangle$) the observed value of the intrinsic q_T is perfectly compatible with the small value of about 300 MeV per quark typically observed in deep inelastic scattering experiments.

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Figure captions

Fig.1: The data on $d\sigma/dQdy$ at $y = 0$ for $\sqrt{S} = 62 \text{ GeV}$ ($\circ$ ref.[8], $\square$ ref.[10]) and $\sqrt{S} = 27.4 \text{ GeV}$ ($\triangle$ ref.[12]), for lepton pair masses above and below the Υ , are compared with the theoretical predictions based on the parton densities of ref.[15]. The two solid curves for each energy refer to $\Lambda = 0.1 - 0.2 \text{ GeV}$. The dashed curve is obtained by omitting the corrective terms of order α_s , i.e. with a unit "K-factor" (although the quark densities are evolved at the scale Q^2 by using $\Lambda = 0.2 \text{ GeV}$).

Fig.2: The data on q_T distributions at $\sqrt{S} = 62 \text{ GeV}$ and large pair mass from ref.[8] ($\circ$) and ref.[11] ($\square$) compared with the theoretical predictions for the parton densities of ref.[15] with $\Lambda = 0.1 - 0.2 \text{ GeV}$. The data on the curves are all normalized to the same area. No intrinsic q_T is included.

Fig.3: Data on the q_T distributions at $\sqrt{S} = 62 \text{ GeV}$ and relatively small values of the pair mass (ref.[11]) compared with the theoretical curves obtained with the parton densities of ref.[15] with $\Lambda = 0.1 - 0.2 \text{ GeV}$. No intrinsic q_T is included.

Fig.4: The average value of q_T , $\langle q_T \rangle$, as a function of $\sqrt{\tau}$ at fixed $\sqrt{S} = 27.4, 44, 62 \text{ GeV}$. The data at $\sqrt{S} = 27.4 \text{ GeV}$ are from ref.[12], at $\sqrt{S} = 44 \text{ GeV}$ from ref.[11], and at $\sqrt{S} = 62 \text{ GeV}$ from refs.[8, 9, 10, 11]. The lower and upper curves given for each value of $\sqrt{S}$ correspond to the parton densities of ref.[15] and $\Lambda = 0.1 - 0.2 \text{ GeV}$ respectively. No intrinsic q_T is included.

Fig.5: $\langle q_T \rangle$ versus $\sqrt{S}$ at fixed $\sqrt{\tau} \simeq 0.22$. The data at $\sqrt{S} = 19, 27.4 \text{ GeV}$ are from ref.[12], at $\sqrt{S} = 44 \text{ GeV}$ from ref.[11] and at $\sqrt{S} = 62 \text{ GeV}$ from refs.[8, 11]. The curves are the theoretical predictions obtained by using the parton densities of ref.[15] and $\Lambda = 0.1 - 0.2 \text{ GeV}$. No intrinsic q_T is included. At large values of $\sqrt{S}$, $\langle q_T \rangle$ increases linearly with $\sqrt{S}$. At smaller values of $\sqrt{S}$ marked deviations from the linear law are visible, which are due to soft gluon and scaling violation pre-asymptotic effects.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5