SCALING VIOLATIONS AND WEAK BOSON PRODUCTION

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Using the most recent parametrizations of distribution functions, we make a quantitative analysis of scaling violations in intermediate vector boson production by proton-(anti) proton collisions. We also include next to leading corrections. It is shown that the various parametrizations predict rather consistently the change in the total cross-sections, from the energy of the CERN $p\bar{p}$ collider to that of the Fermilab project, which appears to be well suited for studying QCD deviations.

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The CERN $p\bar{p}$ collider experiments have recently shown evidence [1] for the existence of the intermediate vector bosons $W^\pm$ and Z^0 which was predicted by the minimal $SU(2) \times U(1)$ version [2] of weak and electromagnetic unification. It is well known that transverse momentum distributions of weak bosons [3] and front-back leptonic asymmetries [4] are of crucial importance to constrain the physical weak parameters. Nevertheless the total cross sections for the leptonic decay modes $p\bar{p} \rightarrow Z^0(\rightarrow \ell^+\ell^-) + X$, $p\bar{p} \rightarrow W^\pm(\rightarrow \ell^\pm \nu_\ell) + X$ and the longitudinal cross sections $d\sigma/dX_F$ of lepton pairs produced through the Z^0 are also quantities of experimental access. They are interesting for QCD because they allow to study deviations from the naïve quark parton model predictions [5]. These deviations can be analyzed in three different ways: i) leading, ii) next to leading, iii) gluon exponentiation schemes.

Scaling violations in heavy boson production have already been computed [6]. The parametrization of structure functions used in these analysis has been improved by both the determination of scale invariant distribution functions resulting from experimental data and the development of more accurate techniques in the computation of scaling violations which take into account the new Λ QCD parameter value. Our purpose in this letter is to use these new techniques and our better understanding of Drell-Yan processes to make a quantitative analysis of scaling violations in intermediate vector boson production and to check the consistency of the various techniques. This study will be done within a domain of center of mass energy $\sqrt{s}$ ranging from 400 GeV to 2000 GeV for proton-antiproton collisions in order to cover the CERN collider and the Fermilab project. We will also consider proton-proton collisions to include the CBA project at $\sqrt{s} = 800$ GeV.

First of all, we will consider the leptonic total cross sections. Within the quark-parton model framework, the cross section for Z^0 production is given by

$$\sigma_{Z^0}^{\text{QPM}} = \frac{8\pi}{3} \frac{G_F^2}{V_Z^2} \sum_q R_q^2 \int \frac{dx}{x} \sum_q R_q^2 \left[q^{H_1}(x) \bar{q}^{H_2}\left(\frac{x}{x}\right) + (q \leftrightarrow \bar{q}) \right] \times B(Z^0 \rightarrow \ell^+\ell^-) \quad (1)$$

where G_F is the Fermi coupling constant, $\tau_{Z^0} = M_{Z^0}^2/s$ and $q(x)$ is the scale invariant distribution function of the q type quark in hadron H . The Z^0 mass, M_{Z^0} , is related to the weak mixing angle θ_W by the following relation, which includes radiative corrections [7]

$$M_{Z^0}^2 = \frac{38.8}{\sin^2 \theta_W \cos \theta_W} [GeV/c^2] \quad (2)$$

Finally $B(Z^0 \rightarrow \ell^+\ell^-)$ is the leptonic branching ratio, with

$$\Gamma(Z^0 \rightarrow \ell^+\ell^-) = \frac{G_F^2}{V_Z^2} \frac{2}{3\pi} M_{Z^0}^2 (V_\ell^2 + A_\ell^2) \quad (3)$$

and

$$\Gamma(Z^0 \rightarrow A\mu) = \frac{G_F^2}{V_Z^2} \frac{2}{3\pi} M_{Z^0}^2 \left\{ \sum_i (V_i^2 + A_i^2) + 3 \sum_q (V_q^2 + A_q^2) \right\}, \quad (4)$$

$$\ell = \nu_\ell, e, \mu, \tau, \dots; \quad q = u, d, c, s, \dots$$

The vector and axial vector coupling constants are given in terms of θ_W , the charge Q and the third component of weak isospin T_3 of fermions by

$$V = -\frac{1}{2} T_3 + Q X_W, \quad X_W = \sin^2 \theta_W = .23 \quad (*)$$

$$A = -\frac{1}{2} T_3 \quad (5)$$

In Eq.(1), R_q^2 depends on the quark coupling constants by

$$R_q^2 = V_q^2 + A_q^2 \quad (6)$$

(*) We checked that all our results are very slightly modified when the value $X_W = .215$ is taken.

Similarly, the cross section for charged vector boson production is

$$\sigma_W^{QPM} = \frac{2\pi}{3} \frac{G_F}{V_Z} \sum_q \int \frac{dx}{x} V_{qq'}^2 \left[q^H(x) \bar{q}^H \left(\frac{\tau_W}{x} \right) + (q \leftrightarrow \bar{q}) \right] \tau_W \quad B(W \rightarrow \ell \nu_\ell) \quad (7)$$

where $V_{qq'}$ is the qq' element of the Kobayashi-Maskawa matrix, $\tau_W = M_W^2/s$, and the W -mass is

$$M_W = M_{Z'} \cos \theta_W \quad (8)$$

$B(W \rightarrow \ell \nu_\ell)$ is the leptonic branching ratio, with

$$\Gamma(W \rightarrow \ell \nu_\ell) = \frac{G_F}{V_Z} \frac{M_W^3}{6\pi} \quad (9)$$

and

$$\Gamma(W \rightarrow A\mu) = \frac{G_F}{V_Z} \frac{M_W^3}{6\pi} (N_\ell + 3N_\tau) \quad (10)$$

where $N_\ell(N_\tau)$ is the number of lepton (quark) doublets. Let us remark that we have included $\mathcal{O}(\alpha_s)$ corrections to weak boson hadronic widths in our actual calculations.

The leading order modifies the quark parton model predictions by including scale violating structure functions in Eq. (1) and (7), the evolution scale being the heavy boson mass. In what follows, we shall compare these two predictions by using three sets of structure functions. The first one is the scale violating parametrization of Baier, Engels and Petersson [8] based on moment formalism. The second one is the Glück, Hoffmann and Reya's [9] using for quarks the Owens and Reya [10] method and for gluons an improved Baulieu and Kounnas [11] formalism, including charm threshold effects at small x . The third set is the scale invariant CHS [12] parametrization evolved according to the Gabellini et al. [13] method consisting of a direct resolution of Altarelli-Parisi [14] equations. The results shown in Figs. 1 and 2 allow to make interesting comparisons, depending on $\sqrt{s}$.

We first remark that the differences between scale invariant and scale breaking structure functions are noticeable whatever the set used. Moreover there is a satisfactory consistency between the leading order predictions. For the CERN $p\bar{p}$ collider energy, the leading order effect is to lower the Born prediction by roughly 40%. For $\sqrt{s} = 2000$ GeV, the leading order cross section is above the parton model prediction by roughly 60%. We must keep in mind that these two energies probe different parts of the structure functions: low $\sqrt{s}$ region is dominated by the valence part, whereas the high $\sqrt{s}$ region is sensitive to the sea and glue contributions. We get similar effects for proton-proton collisions. However for the energy of the CBA project, there is very little difference between Born and leading order predictions.

The study of Drell-Yan processes involving a photon of mass Q has shown that first order next to leading corrections are very important [15] because they increase the leading order result by roughly 70%. The dominant terms are: i) the $\frac{\alpha_s(Q^2) C_F}{2\pi} \pi^2$ term which comes from the analytical continuation of the Dirac form factor from space like to time like Q^2 , ii) an infrared singular term which is important in the region where $\tau = Q^2/s \rightarrow 1$. In the case of weak boson production, τ is small and the full first order correction is well approximated by

$$\sigma_Q^{NLT} = \left(1 + \frac{\alpha_s(Q^2) C_F}{2\pi} \pi^2 \right) \sigma_Q^L \quad (11)$$

where Q is the boson mass, $C_F = \frac{4}{3}$, $\alpha_s(Q^2)$ is the QCD running coupling constant given by

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_f) \ln Q^2/\Lambda^2} \quad (12)$$

and σ_Q^L the leading order cross section. For $N_f = 6$ and $\Lambda = 400$ MeV, the correction to the leading order cross section due to Eq.(11) is

roughly 35%. With the by now more popular value $\Lambda = 200$ MeV [16], the corresponding correction is about 30%, but the leading order result can be modified by 10% (see Figs. 1 and 2). Therefore next to leading corrections cannot be neglected in intermediate vector boson production.

We shall now take advantage of the exponentiation of soft gluon effects in lepton pair production for quark-antiquark annihilation subprocesses [17] in order to study its implications on Z^0 and W production. In this kinematical small τ domain we just have to replace the π^2 term of Eq.(11) by its exponential form, i.e.

$$\sigma_Q^{see} = \exp\left(\frac{\alpha_s(Q^2) C_F \pi^2}{2\pi}\right) \sigma_Q^L \quad (13)$$

Formula (13) increases the full first order result σ_Q^{NTL} by roughly 5%. At the energies we consider, the Compton diagrams give a small contribution and therefore do not affect the previous prediction.

We shall now make predictions for the differential cross section $d\sigma/dx_F$ (x_F being the Feynman variable of the lepton pair) in Z^0 production. The Born cross section reads

$$\frac{d\sigma}{dx_F} = \frac{6\pi}{3} \frac{G_F}{V} \frac{\tau_Z}{\sqrt{x_F^2 + 4\tau_Z^2}} \sum_q R_q^2 \left[q^H(x_1) \bar{q}^H(x_2) + (q \leftrightarrow \bar{q}) \right] \times \mathcal{B}(Z^0 \rightarrow \ell^+ \ell^-) \quad (14)$$

where the fractional momenta are

$$x_{1,2} = \frac{1}{2} \left(\pm x_F + \sqrt{x_F^2 + 4\tau_Z^2} \right) \quad (15)$$

At leading order the structure functions in Eq.(14) become evolved. When next to leading terms are included, the differential cross section is given by

$$\begin{aligned} \frac{d\sigma}{dx_F} = & \frac{6\pi}{3} \frac{G_F}{V} \frac{\tau_Z}{\sqrt{x_F^2 + 4\tau_Z^2}} \int_{x_1}^1 \frac{dt_1}{t_1} \int_{x_2}^1 \frac{dt_2}{t_2} \sum_q R_q^2 \left[q^H(t_1, M_Z^2) \bar{q}^H(t_2, M_Z^2) \right. \\ & + (q \leftrightarrow \bar{q}) \left. \right] \left\{ \delta(1-z_1) \delta(1-z_2) \left[1 + \frac{\alpha_s(M_Z^2)}{2\pi} C_F \left(\pi^2 + \frac{2\pi^2}{3} + 1 \right) \right] \right. \\ & + \delta(1-z_1) \frac{\alpha_s(M_Z^2)}{2\pi} C_F \left(\frac{1+z_1^2}{1-z_1} \ln \frac{2z_2}{1+z_1} + \frac{3}{2(1-z_1)} - 2 - 3z_2 \right) \\ & + (1 \leftrightarrow 2) + \frac{\alpha_s(M_Z^2)}{2\pi} C_F \left. \left(\frac{1+z_2^2}{1+z_1 z_2} \right) \left(\frac{1+z_1^2 z_2^2}{(1+z_1)(1+z_2)} - \frac{2z_1 z_2}{(z_1+z_2)^2} \right) \right\} \end{aligned} \quad (16)$$

where $z_1 = x_1/\tau_1$ and $(1-z)_+$ means the principal value distribution. Fig. 3 points out the X_F distributions for the CERN $p\bar{p}$ collider with $\Lambda = 200$ MeV. Within the X_F domain as shown in the figure, there are no spectacular differences in the fall-off of the distributions between Born, leading and next to leading contributions. We should however mention that important differences appear in the large x_F domain which unfortunately seems out of present experimental access. As shown on Fig. 4 similar conclusions can be drawn at $\sqrt{s} = 2000$ GeV. The decrease of non singlet Brell-Yar cross sections with the rapidity of the lepton pair [18] has exhibited a much pronounced fall-off when soft gluon resummation is taken into account. However the application of soft gluon exponentiation to weak boson production is more difficult to perform because valence terms merely contribute to 75% of the cross section at $\sqrt{s} = 540$ GeV.

In conclusion, we have shown that the total cross sections for weak boson production are sensitive to the scale breaking of structure functions. Next to leading corrections, the main part of which has been exponentiated, increase the leading correction by roughly 35%.

Concerning the $p\bar{p}$ reaction, the enhancement due to non leading terms makes the cross section comparable with the Born expectation at $\sqrt{s} = 540$ GeV whereas at $\sqrt{s} = 2000$ GeV QCD effects increase the Born prediction by roughly a factor of two. Therefore this energy domain is well suited to point out QCD deviations. On the other hand, the CBA

kinematical region provides a good tool to study next to leading corrections.

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FIGURE CAPTIONS

Fig. 1 Z^0 and W total cross sections as a function of $\sqrt{s}$ for the reactions $p\bar{p} \rightarrow Z^0(\rightarrow \ell^+\ell^-) + X$ and $p\bar{p} \rightarrow W(\rightarrow \ell^+\nu_\ell) + X$. Dashed lines correspond to Born contributions and solid lines to leading order. 1 : Maier et al. parametrization; 2 : Gluck et al.; 3 : Gabellini et al. with $\Lambda = 200$ MeV; 4 : same as 3 with $\Lambda = 400$ MeV.

Fig. 2 The same as Fig. 1 for pp reactions. a) : $pp \rightarrow W^+(\rightarrow \ell^+\nu_\ell) + X$ and $pp \rightarrow Z^0(\rightarrow \ell^+\ell^-) + X$; b) : $pp \rightarrow W^-(\rightarrow \ell^-\bar{\nu}_\ell) + X$.

Fig. 3 The differential cross section $d\sigma/dx_f$ for $p\bar{p}$ collisions. The dotted-dashed line corresponds to the next to leading correction. a) : $\sqrt{s} = 540$ GeV; b) : $\sqrt{s} = 2000$ GeV.

- REFERENCES -

- [1] UA1 Collaboration : G. ARNISON et al., Phys. Lett. 122B (1983) 103 ; Phys. Lett. 126B (1983) 398.
 UA2 Collaboration : G. BANNER et al., Phys. Lett. 122B (1983) 476.
- [2] S. WEINBERG, Phys. Rev. Lett. 19 (1967) 1264 ;
 A. SALAM, Proceedings 8th Nobel Symposium, 1968 (Almqvist and Wiksell, Stockholm, 1968), p. 367 ;
 S.L. GLASHOW, Nucl. Phys. 22 (1961) 579.
- [3] F. HALZEN, A.D. MARTIN and D.M. SCOTT, Phys. Rev. D18 (1978) 72, Phys. Rev. D25 (1982) 754 and Phys. Lett. 112B (1982) 160 ;
 M. CHAICHIAN, O. DUMBRAJS and M. HAYASHI, Phys. Rev. D20 (1979) 2873.
 M. CHAICHIAN, M. HAYASHI and K. YAMAGISHI, Phys. Rev. D26 (1982) 3078.
 P. AURENCHIE and J. LINDFORS, Nucl. Phys. B185 (1981) 274, 301.
 P. AURENCHIE and J. KINNUNEN, Preprint LAPP-TH-78, June 21 (1983).
 P. CHIAPPETTA and M. GRECO, Preprint LNF 83/44, June 1983.
- [4] M. PERROTTET, Ann. of Phys. 115 (1978) 107.
 J. FINJORD, G. GIRARDI, M. PERROTTET and P. SORBA, Nucl. Phys. B182 (1981) 427.
- [5] C. QUIGG, Rev. Mod. Phys. 49 (1977) 297.
 R.F. PIERLS, T.-L. TRUEMAN and L.-L. WANG, Phys. Rev. D16 (1977) 1397.
- [6] I. HINCHLIFFE and C.H. LLEWELLYN-SMITH, Phys. Lett. 66B (1977) 281.
 J. KOGUT and J. SHIGEMITSU, Nucl. Phys. B129 (1977) 461.
 M. CHAICHIAN, M. HAYASHI and M. ROOS, Phys. Rev. D26 (1982) 1076.
- [7] W.J. MARCIANO, Phys. Rev. D20 (1979) 274 ;
 M. VELTMAN, Phys. Lett. 91B (1980) 95.
- [8] R. BAIER, J. ENGELS and B. PETERSSON, Z. Physik C2 (1979) 265.
- [9] M. GLUCK, E. HOFFMANN and E. REYA, Z. Physik C13 (1982) 119.
- [10] J.F. OWENS and E. REYA, Phys. Rev. D17 (1978) 3003.
- [11] L. BAULIEU and C. KOUNNAS, Nucl. Phys. B155 (1979) 429.
- [12] J.H. de GROOT et al. Phys. Lett. 82B (1979) 456.
- [13] Y. GABELLINI and J.-L. MEUNIER, Phys. Lett. 113B (1982) 320.
 Y. GABELLINI et al., Nucl. Phys. B211 (1983) 509.
- [14] G. ALTARELLI and G. PARISI, Nucl. Phys. B126 (1977) 298
- [15] For a review, see the Moriond Workshop on Lepton Pair Production, Les Arcs, 1981, ed. J. Tran Thanh Van.
- [16] J.-J. AUBERT et al., Phys. Lett. 114B (1982) 291.
 H. ABRAMOWICZ et al., Z. Physik C17 (1983) 283.
- [17] G. PARISI, Phys. Lett. 90B (1980) 295.
 C. CURCI and M. GRECO, Phys. Lett. 92B (1980) 175.
- [18] P. CHIAPPETTA et al., Nucl. Phys. B207 (1982) 251 ; Nucl. Phys. B219 (1983) 12.

Fig. 1

Fig. 2 a

Fig. 2 b

Fig. 3a

Fig. 3 b