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OBSERVATION OF $W^{\pm}$ AND Z^0 THROUGH THEIR
LEPTONIC DECAY MODES IN $\bar{p}p$ AND pp COLLISIONS

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ABSTRACT

We exploit the results of a recent calculation of first order QCD corrections to direct lepton production. As a signature of $W^{\pm}$ production in $\bar{p}p$ scattering we present various aspects of the single lepton inclusive cross-section including the forward-backward asymmetry. Predictions for polarized proton beams are also made. For Z^0 a better signal is obtained when both leptons are detected. We discuss QCD corrections as well as polarization effects for this channel also. The weak boson production in pp collisions is discussed in the Appendix.

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1. INTRODUCTION

One of the main motivations for the very high energy pp and $\bar{p}p$ colliders now under construction is to find the vector bosons $W^\pm$ and Z^0 of the standard $SU(2) \times U(1)$ model for electroweak interactions. The weak bosons are expected to be seen most readily through their leptonic decay modes, $W^\pm$ in the single lepton spectrum and Z^0 in the lepton pair mass distribution. As the estimated production rates for the weak bosons are very small, especially in the $\bar{p}p$ colliders, it is important to find out the circumstances (kinematical regions, effects of beam polarization, etc.) where the signals for $W^\pm$ and Z^0 are the strongest. Most estimates on weak boson production^{1),2)} are based on the Drell-Yan model, but the higher order QCD corrections could considerably change the leading logarithmic Drell-Yan prediction. Firstly, this is because of previous experience from other processes, especially lepton pair production where the cross-section is more than twice as large as the Drell-Yan expectation³⁾. This is also in qualitative agreement with theoretical calculations⁴⁾. Secondly, the Drell-Yan process has a limited phase space because of the $2 \rightarrow 2$ kinematics at the parton level. In the single lepton spectrum this results in an effective cut-off for the lepton transverse momentum at $k_{1T} = M_W/2$.

The first order QCD corrections arise from the diagrams of Figs. 1b -d, which differ from the basic contribution of Fig. 1a by the emission or absorption of a gluon. Several approaches have been considered in the literature to regularize the divergences appearing in the evaluation of the above diagrams^{5),6)}. We follow here the method of Ref. 6), which is based on the factorization theorem⁷⁾. The divergences are absorbed into the initial quark and antiquark distributions and give rise to scaling violations. For a given choice of the large mass scale setting the strength of the scaling violations, one can write the first order QCD corrections unambiguously when using this method.

In the following, we shall rely on our previous calculation⁶⁾ of these diagrams and study various aspects of the single lepton spectrum for $W^\pm$ production at the CERN $\bar{p}p$ collider. In Section 3 we consider briefly beam polarization effects for $W^\pm$. In Section 4 we discuss the lepton pair mass spectrum near the Z^0 mass, and again effects of beam polarization are also considered. Finally, in the Appendix we study the weak boson production in pp collisions at ISABELLE energies.

2. THE SINGLE LEPTON SPECTRUM

The diagrams contributing to direct lepton production to first order in QCD are shown in Fig. 1. We use the results of Ref. 6) and write the single lepton inclusive cross-section for the collision of two partons (j and k) as

$$k_{10} \frac{d\sigma}{d^3k_1}^{jk} = A_q A_\ell \cdot V^{jk}(x_1, x_2) + B_q B_\ell \cdot A^{jk}(x_1, x_2) \quad (1)$$

where the scaling variables x_i ($i = 1, 2$) are related to the observed lepton momentum k_1 and initial parton momenta p_i by $x_i = k_{1T}^2 / 2p_i \cdot k_1$. A_q and B_q (A_ℓ and B_ℓ) are numbers depending on the vector and axial couplings of the gauge bosons to the quarks (leptons). More precisely, if the gauge boson coupling to fermion f is defined by $a_f + b_f \gamma_5$ one has

$$\begin{aligned} A_f &= a_f^2 + b_f^2 \\ B_f &= 2 a_f b_f \end{aligned} \quad (2)$$

The analytic forms for the functions V^{jk} and A^{jk} are complicated and can be found in Ref. 6) for the cases ($j = \text{quark}, k = \text{antiquark}$) and ($j = \text{quark}, k = \text{gluon}$). If one observes an antilepton instead of a lepton or, if one changes quark to antiquark in the initial state, only the sign of the axial part in Eq. (1) is changed. From Eq. (1) the cross-section at the hadron level is written as

$$k_{10} \frac{d\sigma}{d^3k_1} = \sum_{j,k} \int_{X_1}^{1-X_2} \frac{dx_1}{x_1} \left[\frac{X_1}{x_1} f^j\left(\frac{X_1}{x_1}\right) \right] \int_{X_2}^{1-X_1} \frac{dx_2}{x_2} \left[\frac{X_2}{x_2} f^k\left(\frac{X_2}{x_2}\right) \right] \cdot k_{10} \frac{d\sigma}{d^3k_1}^{jk} \quad (3)$$

where X_i 's are defined using the initial hadron momenta P_1 and P_2 by $X_i = k_{1T}^2 / 2P_i \cdot k_1$ ($i = 1, 2$).

In the following, we shall compare the Drell-Yan prediction (Fig. 1a) with the full first order QCD calculation (Figs. 1a- d). We now concentrate on the μ^+ (or e^+) spectrum from $W^\pm$ production in $\bar{p}p$ collisions at $\sqrt{s} = 540$ GeV. We use the parton distribution of Ref. 8), but we have checked that the results are insensitive to various choices of parametrizations⁶⁾. The single lepton spectrum $k_{10} d\sigma/d^3k_1$ is shown in Fig. 2 at fixed lepton rapidity y as a function of k_{1T} . At $y = 0$ one finds the well-known Jacobian peak at $k_{1T} = M_W/2$. The effect of QCD corrections is to increase the cross-section and also to partly smear the peak and move it to a lower value of k_{1T} . As expected, the QCD corrections are relatively larger above the value $k_{1T} = M_W/2$. The corrections are made up of two parts; the terms coming from the virtual diagrams (Fig. 1b) produce an upward renormalization of the Drell-Yan prediction over the whole transverse momentum range while those originating in the real diagrams (Figs. 1c and 1d) become important

at the Jacobian peak and above^{*)}. At the peak they are negative so that the total corrected curve falls below its Drell-Yan value and above the peak they are positive and dominate over the lowest order prediction. This last fact can be understood as follows. Assuming that the initial partons have no primordial transverse momentum, the maximum k_{1T} allowed in the Drell-Yan process is $k_{1T} = M_W/2$ since the gauge boson is produced with no transverse momentum. In the QCD processes, however, the W boson can recoil against a final state quark or gluon and then communicate some of its transverse momentum to the decay leptons.

The shape of the spectrum changes with y under the combined effects of dynamics and kinematics. As y increases, the low k_{1T} part of the spectrum is enhanced because of the $V - A$ of the W boson coupling. The helicity conservation argument tells that the antilepton (μ^+ or e^+) prefers the direction of the antiquark in the antiproton, i.e., forward direction ($\bar{p}$ is assumed to move in the positive z axis direction). However, when $k_{1T} = M_W/2$ the leptons have only transverse momentum in the W rest frame (for the Drell-Yan process), and the longitudinal motion of the leptons is controlled by that of the weak boson. The y distribution is then flat at $k_{1T} = M_W/2$ because we assume similar x distributions for up and down quarks. Had we chosen the up and down quark distributions so that $\langle x_u \rangle > \langle x_d \rangle$ there would have been even a reversal of the forward-backward asymmetry [Peierls et al., Ref. 1)]. The phase space constraint $k_{1T} \leq \sqrt{s}/(2 \cosh y)$ tends to reduce the high k_{1T} end of the spectrum when $|y|$ becomes large so that for $|y| = 2$ the Jacobian peak at $k_{1T} = M_W/2$ is already lost even for the Drell-Yan result.

The shape of the k_{1T} spectrum is affected considerably by the QCD corrections, whereas the angular distribution is essentially similar for the leading logarithmic Drell-Yan prediction and for the full $O(\alpha_s)$ QCD calculation. This can be seen better from Fig. 3 where we show curves for $d\sigma/dk_{1T}d\cos\theta$ at fixed k_{1T} (θ is the polar angle of the lepton in the over-all centre of mass system). The sharp forward and backward peaks arise from the Jacobian for the change of variables $d\sigma/d\cos\theta = (1/\sin^2\theta)d\sigma/dy$. Also, the backward peak at small k_{1T} values can be associated with sea-sea collisions where an antiquark from the proton annihilates a quark from the antiproton. All these features of the single lepton spectrum are qualitatively summarized in the three dimensional plots of Fig. 4. Since the luminosity of the CERN $\bar{p}p$ collider is low ($L = 10^{30} \text{ cm}^{-2}\text{s}^{-1}$), the previous plots are rather of theoretical interest and it is useful to present more

*) The exact magnitude of the virtual and real contributions depends on the definition of parton distributions beyond leading order. However, the QCD corrected spectrum should not depend on it as it is a physical quantity. [See Ref. 6) for details.]

integrated quantities. In Fig. 5 we show the cross-section $d\sigma/dk_{1T}$ integrated over rapidity and azimuthal angle. The shape of this distribution does not differ much from the k_{1T} spectrum at small y . In particular, the Jacobian peak of the Drell-Yan cross-section is still present. The counting rates for this distribution (7×10^{-3} events/hr/GeV at $k_{1T} = 38$ GeV/c) should be sufficient to study the forward-backward asymmetry defined as

$$A(k_{1T}) = \frac{\int_0^1 d\cos\theta \frac{d\sigma}{d\cos\theta dk_{1T}} - \int_{-1}^0 d\cos\theta \frac{d\sigma}{d\cos\theta dk_{1T}}}{\int_0^1 d\cos\theta \frac{d\sigma}{d\cos\theta dk_{1T}} + \int_{-1}^0 d\cos\theta \frac{d\sigma}{d\cos\theta dk_{1T}}} \quad (4)$$

which is shown in Fig. 6. To double the statistics, one can also include $\mu^-(e^-)$ events in the asymmetry by using the relation $A^{\mu^-}(k_{1T}) = -A^{\mu^+}(k_{1T})$. We have only presented the Drell-Yan prediction, but the QCD corrections do not affect the shape of the curve except for a slight filling of the dip at $k_{1T} = M_W/2$. The above discussion could also be carried out for single leptons from Z^0 decay. At $y = 0$ the k_{1T} dependence is very similar to that of the W channel, but the y dependence is flatter and the forward-backward asymmetry smaller. Indeed, the relevant quantity characterizing angular asymmetries is the ratio $B_q B_\ell / A_q A_\ell$ which is 1 for $W^\pm$ production, but 0.10 for Z^0 production by $(u\bar{u})$ quark pairs and 0.15 for $(d\bar{d})$ quark pairs.

3. POLARIZATION EFFECTS

The possibility of having a polarized proton beam at the $\bar{p}p$ collider allows one to look further into the vector and axial properties of the weak bosons. We shall discuss effects of longitudinal polarization of the proton beam for the Drell-Yan process and then indicate how the results can be generalized to the higher order QCD diagrams.

For W production, the analysis at the parton level is simple. Because of the $V - A$ coupling to quarks and leptons the only non-vanishing amplitude is between left-handed quarks and right-handed antiquarks. Hence, for a quark (momentum p_1 , helicity h_1) scattering off an antiquark (p_2, h_2) the single lepton Drell-Yan cross-section is

$$\begin{aligned} k_{10} \frac{d\hat{\sigma}}{dk_{13}} (h_1 = -1, h_2 = +1) &= c \cdot \hat{t}^2 \\ k_{10} \frac{d\hat{\sigma}}{dk_{13}} (h_1 \neq -1 \text{ or } h_2 \neq +1) &= 0 \end{aligned} \quad (5)$$

with the notation $\hat{u} = -2p_2 \cdot k_1$ ($\hat{t} = -2p_1 \cdot k_1$).

More generally, the parton cross-section for single lepton production by polarized quarks can be written in the form

$$k_{10} \frac{d\sigma^{jk}}{dk_1^3} = (1 - h_1 h_2) (A^q + h_1 B^q) \cdot [A^l V^{jk}(x_1, x_2) + h_1 B^l A^{jk}(x_1, x_2)] \quad (6)$$

where V^{jk} and A^{jk} are the same functions as in Eq. (1). This equation is valid for the Drell-Yan term and also for the $O(\alpha_s)$ QCD annihilation diagram of Fig. 1c. Summing over the initial quark helicities, we retain the unpolarized cross-section of Eq. (1). To obtain predictions at the hadronic level one must rely on models for the distribution of polarized quarks inside the polarized proton. We use the simple model based on SU(6) where⁹⁾

$$\begin{aligned} u_v^+ &= \frac{5}{6} u_v, & u_v^- &= \frac{1}{6} u_v \\ d_v^+ &= \frac{1}{3} d_v, & d_v^- &= \frac{2}{3} d_v \end{aligned} \quad (7)$$

and where the sign + (-) indicates the same (opposite) polarization for the valence quark as for the proton. The sea is assumed to be unpolarized. We present a more detailed analysis only for the Drell-Yan process, for which the polarized cross-sections are given by

$$\begin{aligned} k_{10} \frac{d\sigma}{d^3k_1} (\bar{p}p \rightarrow l^+ X; h_p = -1) &= C \cdot \int [(d_v + s)(\frac{5}{3} u_v + s) \hat{t}^2 + ss \hat{u}^2] \\ k_{10} \frac{d\sigma}{d^3k_1} (\bar{p}p \rightarrow l^+ X; h_p = +1) &= C \cdot \int [(d_v + s)(\frac{1}{3} u_v + s) \hat{t}^2 + ss \hat{u}^2] \end{aligned} \quad (8)$$

We have used a shorthand notation for the integration over the parton distributions [See Eq. (3)].

We see that W^+ is produced about five times more copiously by helicity = -1 protons than by helicity = +1 protons. The polarization asymmetry

$$A_{LL} = \frac{\frac{d\sigma}{d^3k_1}(\bar{p}p; -1) - \frac{d\sigma}{d^3k_1}(\bar{p}p; +1)}{\frac{d\sigma}{d^3k_1}(\bar{p}p; -1) + \frac{d\sigma}{d^3k_1}(\bar{p}p; +1)} \quad (9)$$

can be evaluated using Eq. (8) and neglecting sea contributions its value is

$A_{LL} = 2/3$. When sea effects are taken into account, A_{LL} is a function of k_{1T} and $\cos\theta$. At low k_{1T} values ($k_{1T} < 20$ GeV/c) the sea terms reduce the asymmetry to $A_{LL} \approx 0.30$ in the backward direction ($\cos\theta < -0.8$). However, at $k_{1T} = 35$ GeV/c, $A_{LL} \approx 0.65$ over the whole $\cos\theta$ range. From Eq. (6) it is straightforward to calculate the polarization asymmetry including the QCD annihilation diagrams. These QCD corrections do not essentially change the result $A_{LL} \approx 2/3$ as the dominant $O(\alpha_s)$ terms are common for the vector part $V^{q\bar{q}}$ and for the axial part $A^{q\bar{q}}$ in Eq. (6).

4. LEPTON PAIR MASS DISTRIBUTION

Z^0 is expected to show up as a resonance peak in the invariant mass spectrum of lepton pairs. The Drell-Yan prediction is given at the parton level by

$$\frac{d\hat{\sigma}}{dM^2} = \frac{4\pi\alpha^2}{3M^2} \langle \frac{1}{3} \rangle \delta(\hat{s} - M^2) N_f(M^2) \quad (10)$$

where we have defined

$$N_f(M^2) = Q_f^2 + \frac{A^l A^q}{\sin^4\theta_w \cos^4\theta_w} \frac{M^4}{(M^2 - M_z^2)^2 + (\Gamma_z M_z)^2} - 2 Q_f \frac{a^l a^q}{\sin^2\theta_w \cos^2\theta_w} \frac{M^2(M^2 - M_z^2)}{(M^2 - M_z^2)^2 + (\Gamma_z M_z)^2} \quad (11)$$

This factor $N_f(M^2)$ factorizes to all orders of perturbative QCD and we can use directly the results for $O(\alpha_s)$ QCD corrections to Eq. (10) calculated for the photon case⁴⁾. The result is

$$\frac{d\sigma}{dM^2} = \langle \frac{1}{3} \rangle \frac{4\pi\alpha^2}{3M^4} \sum_f N_f(M^2) \cdot \int_0^1 \frac{d\xi_1}{\xi_1} \int_0^1 \frac{d\xi_2}{\xi_2} \cdot z \left\{ F_f^{q\bar{q}}(\xi_1, \xi_2) \cdot \left[\delta(1-z) + \theta(1-z) \langle \frac{4}{3} \rangle \frac{d_s(M^2)}{2\pi} \cdot f_{q\bar{q}}^{DY}(z) \right] + F_f^{qg}(\xi_1, \xi_2) \cdot \theta(1-z) \cdot \langle \frac{1}{2} \rangle \frac{d_s(M^2)}{2\pi} \cdot f_{qg}^{DY}(z) \right\} \quad (12)$$

where the z variable is given by

$$z = \frac{M^2}{\hat{s}} = \frac{\tau}{\xi_1 \xi_2} \quad \left(\tau = \frac{M^2}{s} \right) \quad (13)$$

The functions $f_{q\bar{q}}^{DY}$ and f_{qg}^{DY} depend on the definition of the parton distributions beyond leading order. Two cases have been considered in the literature. For the definition of Altarelli et al.⁴⁾ (denoted by AEM) one has

$$f_{q\bar{q}}^{DY}(z) = 2(1+z^2) \frac{\ln(1-z)}{1-z} \Big|_+ + \left(\frac{4\pi^2}{3} + 1 \right) \delta(1-z) + \frac{3}{1-z} \Big|_+ - 6 - 4z$$

$$f_{qg}^{DY}(z) = [z^2 + (1-z)^2] \ln(1-z) + \frac{9}{2} z^2 - 5z + \frac{3}{2} \quad (14)$$

and for the definition of Ref. 10) (denoted by BKKU)

$$f_{q\bar{q}}^{DY}(z) = 4(1+z^2) \frac{\ln(1-z)}{1-z} \Big|_+ - 2 \frac{1+z^2}{1-z} \ln z + \left(\frac{2\pi^2}{3} - 8 \right) \delta(1-z)$$

$$f_{qg}^{DY}(z) = [z^2 + (1-z)^2] \ln \frac{(1-z)^2}{z} - \frac{3}{2} z^2 + z + \frac{3}{2} \quad (15)$$

The parton distribution are in the two functions

$$F_f^{q\bar{q}}(\xi_1, \xi_2) = \xi_1 \xi_2 [q_f(\xi_1) \bar{q}_f(\xi_2) + (1 \leftrightarrow 2)]$$

$$F_f^{qg}(\xi_1, \xi_2) = \xi_1 \xi_2 [(q_f(\xi_1) + \bar{q}_f(\xi_1)) \cdot g(\xi_2) + (1 \leftrightarrow 2)] \quad (16)$$

and their scaling violation parameter is $Q^2 = M^2$: $q(\xi) \rightarrow q(\xi, M^2)$. We have presented in Fig. 7 the mass distribution of lepton pairs produced in $\bar{p}p$ collisions at $\sqrt{s} = 540$. The non-leading QCD corrections (here for the BKKU case) are about 35 - 40% of the Drell-Yan result over the whole range $M = 10 - 130$ GeV. In particular, the QCD Compton contribution is negligible for $\bar{p}p$ collisions ($\lesssim 3\%$ of the Drell-Yan term). It should be noted that the Drell-Yan contribution includes leading logarithmic QCD effects in the scaling violations at the quark and anti-quark distributions. These results are in agreement with those of Ref. 11) who considered the AEM prescription. We have further analysed Z^0 production at the Drell-Yan level by looking at the angular distribution of a decay lepton in the rest system of the vector boson. As we will also discuss shortly the effects of longitudinal polarization of the colliding hadrons, we write down the angular distribution for general helicity states at the annihilating quark (helicity h_1) and antiquark (helicity h_2)

$$\frac{16\pi}{3} \cdot \frac{d\hat{\sigma}}{dM^2 d\Omega} = (1 - h_1 h_2) \langle \frac{1}{3} \rangle \frac{4\pi\alpha^2}{3M^2} \delta(s - M^2)$$

$$\left\{ Q_f^2 (1 + \cos^2\theta) + \frac{A_f^{q\bar{q}} + h_1 B_f^{q\bar{q}}}{\sin^4\theta_w \cos^4\theta_w} \cdot \frac{M^4 [A_f^l (1 + \cos^2\theta) + h_1 B_f^l \cos\theta]}{(M^2 - M_z^2)^2 + (\Gamma_z M_z)^2} \right. \quad (17)$$

$$\left. - 2 Q_f \cdot \frac{a_f^{q\bar{q}} + h_1 b_f^{q\bar{q}}}{\sin^2\theta_w \cos^2\theta_w} \cdot \frac{M^2 (M^2 - M_z^2)}{(M^2 - M_z^2)^2 + (\Gamma_z M_z)^2} [a_f^l (1 + \cos^2\theta) + h_1 b_f^l \cos\theta] \right\}$$

The $1 + \cos^2\theta$ terms arise from the vector part of the matrix element and the parity violating $\cos\theta$ terms arise from the axial part. In Fig. 8a we show the angular distribution at $M = M_Z = 88.7$ GeV calculated for unpolarized and for proton longitudinally polarized $\bar{p}p$ collisions. Again we assumed the SU(6) symmetric parton distributions of Eq. (6) for the polarized case. The cross-section for helicity = -1 protons is about 50% larger than for helicity = +1 protons, and we argue that the non-leading QCD corrections do not change this conclusion. As in the single lepton spectrum this is because the most important correction terms are the same for the vector and axial parts. The onset of the polarization asymmetry is illustrated in Fig. 8b where the asymmetry is presented as a function of the lepton pair mass.

5. CONCLUSIONS

We have presented a detailed analysis of the single lepton spectrum for $W^\pm$ decay in $\bar{p}p$ collisions. We have found that the first order QCD correction increases the magnitude of the cross-section, especially at large values of the lepton transverse momentum. The shape of the k_{1T} spectrum, whether at fixed rapidity or integrated over rapidity, is also affected. We stress that the predictions are independent of the parton distribution parametrizations we have tried. The normalized forward backward asymmetry, as well as the polarization asymmetry are calculated in the leading logarithm approximation and they are rather insensitive to the QCD corrections^{*)}. The production of the neutral weak boson was also analysed through its dilepton decay channel. In particular, the lepton angular distribution was calculated at the Z^0 mass for both polarized and unpolarized protons.

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^{*)} Our work is complementary to that of Finjord et al.¹²⁾ who considered the corrections at fixed values of the transverse momentum of the hadronic jet recoiling from the weak boson.

APPENDIX - W^+ PRODUCTION IN pp COLLISIONS

We briefly discuss here the weak boson production in pp collisions at a typical ISABELLE energy $\sqrt{s} = 800$ GeV. As before, we use the parton distribution parametrization of Ref. 8). The transverse momentum distributions of positive leptons at fixed rapidity are shown in Fig. 9. The QCD corrections to the Drell-Yan process are similar to the $\bar{p}p$ case: the Jacobian peak is smeared and the corrections are especially large above $k_{1T} > M_W/2$ where the Compton process now amounts to about half of the total $pp \rightarrow \ell^+ X$ cross-section. The variation of the single lepton cross-section as a function of rapidity is now somewhat different and can be understood again in a qualitative way. A positive muon at large $|y|$ and with $k_{1T} < M_W/2$ can be produced either by a fast valence quark (going in the same direction) and a slow antiquark from sea, or by a fast antiquark and a slow quark (going in the opposite direction). In the first case, the cross-section is suppressed by the $V - A$ structure of the W^+ coupling, and for the latter case the structure functions give a small probability. This results at medium values of k_{1T} (≈ 30 GeV/c) in a decrease of the cross-section with increasing $|y|$. This can be seen well in Fig. 10, where the angular distribution of the lepton is shown for fixed values of k_{1T} . Because of the larger $\sqrt{s}$ value the peaking of the distribution near $|\cos\theta| = 1$ survives for large transverse momentum values ($k_{1T} > 38.5$ GeV/c) which was not the case in $\bar{p}p$ collisions at $\sqrt{s} = 540$.

We have also checked the results by using the Owens-Reya parametrization of parton distributions¹³⁾. The predictions for pp collisions are not so stable as for the $\bar{p}p$ case, and the changes for $k_{1T} < M/2$ resulting from the use of the two different sets of parton distributions are roughly of the same size as the QCD corrections.

In conclusion, we mention that some aspects of W production by polarized beams in pp collisions have been considered in Ref. 2). The QCD corrections will not drastically change their conclusions.

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FIGURE CAPTIONS

- Fig. 1 : The Feynman diagrams for vector boson production ($V = \gamma, Z^0, W^\pm$).
- a) The Drell-Yan process $q\bar{q} \rightarrow \ell\bar{\ell}$
 - b) QCD virtual correction for $q\bar{q} \rightarrow \ell\bar{\ell}$
 - c) The QCD annihilation process $q\bar{q} \rightarrow g + \ell\bar{\ell}$
 - d) The QCD Compton process $qg \rightarrow q + \ell\bar{\ell}$
- Fig. 2 : Single lepton cross-sections for $\bar{p}p \rightarrow W^+ \rightarrow \ell^+ X$ at $\sqrt{s} = 540$ and at rapidity $y = 1, 0, -1$ are shown for the Drell-Yan (DY) and the $O(\alpha_s)$ QCD calculations.
- Fig. 3 : Single lepton angular distributions for $\bar{p}p \rightarrow W^+ \rightarrow \ell^+ X$ at $\sqrt{s} = 540$ are shown for fixed values of $k_{1T} = 16, 30, 38.5$ and 42 GeV/c.
- Fig. 4 : Three dimensional plots of the single lepton spectrum in $\bar{p}p$ collisions at $\sqrt{s} = 540$ GeV.
- a) $k_{10}^{d\sigma/d^3k_1}$ for Drell-Yan process
 - b) $k_{10}^{d\sigma/d^3k_1}$ including QCD corrections
 - c) $d\sigma/dk_{1T}d\cos\theta$ for the Drell-Yan process
 - d) $d\sigma/dk_{1T}d\cos\theta$ including QCD corrections
- Fig. 5 : The cross-section $d\sigma/dk_{1T}$ ($\bar{p}p \rightarrow W^+ \rightarrow \ell^+ X$) at $\sqrt{s} = 540$ is shown for Drell-Yan and QCD calculations.
- Fig. 6 : The forward backward asymmetry at the $\bar{p}p$ collider $\sqrt{s} = 540$ as a function of k_{1T} (transverse momentum of the lepton).
- Fig. 7 : The mass distribution $d\sigma/dM^2$ of lepton pairs produced by γ or Z^0 in $\bar{p}p$ collisions at $\sqrt{s} = 540$. As before, DY and QCD denote the leading approximation Drell-Yan calculation and the full $O(\alpha_s)$ QCD calculation respectively.
- Fig. 8a : The angular distribution of ℓ^+ in the rest system of Z^0 and at $M = M_Z$. Shown are the unpolarized cross-section and the cross-sections for proton beam longitudinally polarized (proton helicity $h_p = +1$ or -1).
- Fig. 8b : The polarization asymmetry $R_{LL} = [\sigma(\bar{p}p_-) - \sigma(\bar{p}p_+)]$ as a function of the dilepton mass.

Fig. 9 : The same as in Fig. 2, but for pp collisions at $\sqrt{s} = 800$.

Fig. 10 : The same as in Fig. 3, but for pp collisions at $\sqrt{s} = 800$.

a)

b)

c)

d)

Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

Fig. 4c

Fig. 4d

Fig. 5

Fig.6

Fig. 7

Fig. 8a

Fig. 8b

Fig. 9

Fig. 10