Z^0 and test of sea-quark polarization

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(Received 17 January 1986)

The spin-spin asymmetry in the Drell-Yan process with polarized protons in both the beam and target is discussed including Z^0 effects. The role which this quantity could play to test sea-quark polarization is considered above the Z^0 peak. Numerical calculations are made for models with a polarized and an unpolarized sea.

I. INTRODUCTION

In my previous paper[1] I discussed the spin-spin asymmetry in the Drell-Yan process for pp collisions, limiting the consideration to a region of energy such that only the photon could play a role as an intermediate particle. This asymmetry was found to be a very sensitive probe of the sea-quark polarization.

The spin-spin asymmetry is defined as

$$A=\frac{d\sigma_{\uparrow\uparrow}/dQ^2-d\sigma_{\uparrow\downarrow}dQ^2}{d\sigma_{\uparrow\uparrow}/dQ^2+d\sigma_{\uparrow\downarrow}/dQ^2}\ , \tag{1}$$

where the parallel arrows mean that chiralities of the colliding protons are equal and the antiparallel ones mean that chiralities are opposite; $(Q^2)^{1/2}$ is the mass of the lepton pair.

If the sea is unpolarized, asymmetry A is exactly equal to zero in the leading order and less than 2–3% in the next-to-leading order. So any experimental result which shows a larger asymmetry would signal a sea polarization. For the models with a polarized sea, asymmetry reaches the value -20% for $(Q^2/s)^{1/2}=0.7$. A great advantage of using the spin-spin asymmetry is that this quantity is not sensitive to large QCD corrections.[1]

This paper concentrates on a region of energy such that the Z^0 must be included in the description of the Drell-Yan process. Under such circumstances spin-spin asymmetry depends explicitly on the chirality configuration of the colliding protons (and we will define later A^L and A^R). We found that the values of both A^L and A^R can be affected by the sea polarization for all values of the energy, except in the immediate vicinity of the Z^0 peak, where Z^0 dominates any other effects. The great advantage of using spin-spin asymmetries, i.e., the cancellation of the large next-to-leading logarithmic corrections, is still valid.

In Sec. II the Drell-Yan process is described, including Z^0 effects and the definition of spin-spin asymmetries in this case. Numerical results and conclusions close the paper.

II. THE PROCESS $p_\uparrow p_{\uparrow\downarrow}\rightarrow(\gamma,Z^0)\rightarrow\mu^+\mu^-x$

As is well known, the Drell-Yan cross section factorizes to all orders in perturbation theory into the convolution of a constituent cross section with structure functions that give the probabilities for finding the colliding constituents in the incoming hadrons.[2] Diagrams for the annihilation of a quark and an antiquark into leptons through an intermediate Z^0 or photon are described, e.g., in Ref. 3. Taking these diagrams into account, one finds that, to leading order in the strong coupling constant, the Drell-Yan cross section is given by

$$\frac{d\hat{\sigma}_f^{h_q,h_{\bar q}}}{dQ^2}=\frac{4\pi\alpha^2}{gQ^2}\delta(\hat{s}-Q^2)\mathcal{N}_f^{h_q,h_{\bar q}}(\hat{s})\ , \tag{2}$$

where h_q and $h_{\bar q}$ $(h_q,h_{\bar q}=L,R)$ denote the chiralities of the quark and antiquark, respectively, and $(Q^2)^{1/2}$ is the mass of the lepton pair. We define

$$\mathcal{N}_f^{L,R}(\hat{s})=e_f^2e_\mu^2+(g_v^f+g_a^f)^2(g_v^{\mu 2}+g_a^{\mu 2})x^4GG^*+2x^2e_fe_\mu(g_v^f+g_a^f)g_v^\mu\,\mathrm{Re}G\ , \tag{3a}$$

$$\mathcal{N}_f^{R,L}(\hat{s})=e_f^2e_\mu^2+(g_v^f-g_a^f)^2(g_v^{\mu 2}+g_a^{\mu 2})x^4GG^*+2x^2e_fe_\mu(g_v^f-g_a^f)g_v^\mu\,\mathrm{Re}G\ , \tag{3b}$$

where $G=1/(\hat{s}-M_{Z^0}{}^2+i\Gamma M_{Z^0})$ and $x=1/2\cos\theta_W\sin\theta_W$. e_f, g_a^f, and g_v^f denote the electric charge, axial-vector, and vector coupling of the fermion f to Z^0 ($f=\mu$ denotes muon), M_{Z^0} and Γ denote Z^0 mass and width. Values of e_f, g_a, g_v, M_{Z^0}, $\sin\theta_W$, Γ are collected in Table I.

Because of the parity-violating nature of the Z^0 coupling one can define longitudinal asymmetry A in two chirality configurations. For the configuration (proton right, proton right) and (proton right, proton left) we obtain the following spin-spin asymmetry:

$$A^R=\frac{(\bar{q}_+\Delta q\otimes d\hat{\sigma}^{R,L}/dQ^2-\bar{q}_-\Delta q\otimes d\hat{\sigma}^{L,R}/dQ^2)+(q\leftrightarrow\bar{q})}{(\bar{q}_+q\otimes d\hat{\sigma}^{R,L}/dQ^2+\bar{q}_-q\otimes d\sigma^{L,R}/dQ^2)+(q\leftrightarrow\bar{q})}\ , \tag{4a}$$

where $q_{+(-)}$ denote densities of quarks polarized parallel

TABLE I. Values of the coupling constants to γ and Z^0 for different flavors.

Fermion	e_f	g_a^f	g_v^f
e,μ,t	-1	$-\frac{1}{2}$	$-\frac{1}{2}+2\sin^2\theta_W$
u,c,t	$+\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2}-\frac{4}{3}\sin^2\theta_W$
d,s,b	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$
$\sin^2\theta_W=0.23$, $M_{Z^0}=88.7$ GeV, $\Gamma=2.5$ GeV			

TABLE II. The quark and gluon densities at $(Q_0{}^2)^{1/2}=8$ GeV (from Ref. 5).

$xu_v(x)=0.77x^{0.3}(1-x)^3(1+4x)$
$xd_v(x)=1.25x^{0.5}(1-x)^4$
$xs(x)=0.029(1-x)^8[1+(1-x)^2]/1$ flavor
$xG(x)=2.05(1-x)^6[1+(1-x)^2]$
$x\,\Delta u_v(x)=[xu_v(x)-\frac{2}{3}xd_v(x)]\cos 2\theta$
$x\,\Delta d_v(x)=-\frac{1}{3}xd_v(x)\cos 2\theta$
$x\,\Delta s(x)\equiv 0$ for unpolarized sea
$x\,\Delta s(x)=0.014(1-x)^8[1-(1-x)^2]/1$ flavor
$x\,\Delta G(x)=0.57(1-x)^6[1-(1-x)^2]$
$\cos 2\theta=1/[1+0.03(1-x)^2/\sqrt{x}\,]$

or antiparallel to the parent proton, q is the quark density, and $\Delta q=q_+-q_-$ is the helicity density. The symbol $\otimes$ stands for appropriate convolution;[1] a sum over quark flavor is implied. For the configuration (proton left, proton left) and (proton left, proton right) we have

$$A^L=\frac{(\bar q_+\Delta q\otimes d\hat\sigma^{L,R}/dQ^2-\bar q_-\Delta q\otimes d\hat\sigma^{R,L}/dQ^2)+(q\leftrightarrow\bar q)}{(\bar q_+ q\otimes d\hat\sigma^{L,R}/dQ^2+\bar q_- q\otimes d\hat\sigma^{R,L}/dQ^2)+(q\leftrightarrow\bar q)}\,. \tag{4b}$$

Because the most important part of the QCD correction is proportional to the lowest-order cross section [Eq. (2)] with a constant of proportionality that is independent of chirality, the QCD corrections largely cancel in the spin-spin asymmetry. (This phenomenon is discussed for the case of Drell-Yan annihilation into a photon in Ref. 1.)

III. NUMERICAL RESULTS AND CONCLUSIONS

The parton densities were defined at $(Q_0{}^2)^{1/2}=8$ GeV (see Table II) and subsequently evolved to the appropriate energy by the use of method presented in Ref. 4 with $\Lambda_{QCD}=0.5$ GeV. The results for $\sqrt{s}=27$ GeV (from Ref. 1) are reproduced in Fig. 1.

The next two figures present the results of numerical calculations for $\sqrt{s}=210$ and 540 GeV. One can easily see a large difference between A^L and A^R. In contrast with the case where only the photon-exchange contribution to muon pair production was taken, both asymmetries A^L and A^R are nonzero if sea quarks are unpolarized (see Fig. 2). Moreover, in the region of the Z^0 peak, asymmetries for polarized and unpolarized sea reach nearly the same value. So the region $70<\sqrt{Q^2}<110$ GeV is not useful to test the sea polarization. If we go with $(Q^2)^{1/2}$ much above the Z^0 peak (see Fig. 3) the values of the asymmetries can again be a signal for sea polarization. In this region, having both the Z^0 and the photon as intermediate particles enhances to an even larger degree the contribution of sea polarization to spin-spin asymmetries [up to

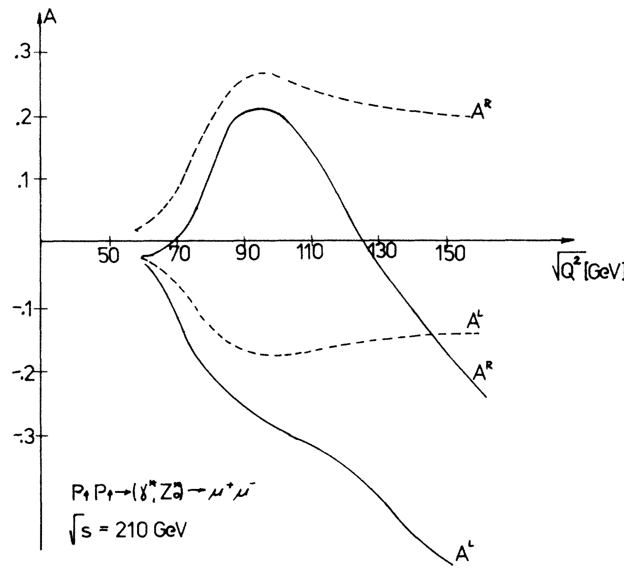

FIG. 2. The spin-spin asymmetries with photon and Z^0 as intermediate particles for $\sqrt{s}=210$ GeV (to leading-logarithmic order). The solid lines are for the model with polarized sea, dashed curves for the model with unpolarized sea. The quark and gluon distribution are given in Table II.

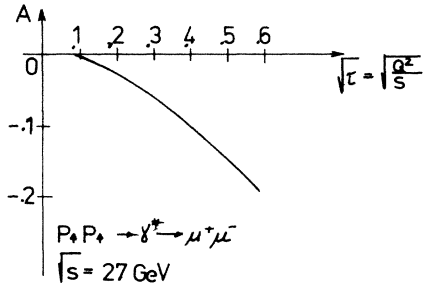

FIG. 1. The spin-spin asymmetry below the Z^0 region (figure taken from Ref. 1). The solid curve is for the model with polarized sea.

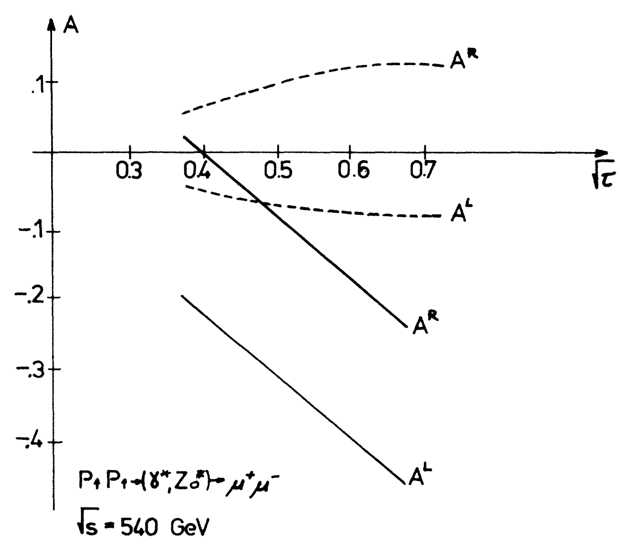

FIG. 3. Same as in Fig. 2 for $\sqrt{s}=540$ GeV.

-40% for $(Q^2/s)^{1/2}=0.5]$, as compared to the pure electromagnetic case. In the case of the unpolarized sea, asymmetries are no longer equal to zero (they reach values of 10% for A^R and -10% for A^L).

The conclusion is that the previously proposed method[1] for testing the problem of sea polarization is still valid after including Z^0, except in the immediate vicinity of the Z^0 peak.

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