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Lepton pair production from polarized hadrons: Parity violation and vector mesons

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The theoretical framework previously used to calculate parity-violating asymmetries in lepton pair production in the continuum is extended to include the effects of a vector meson resonance [such as the Υ (9.46 GeV)]. It is shown how the measurement of these asymmetries in hadron–polarized-hadron collisions can provide a new test of models of vector-meson production. Parity and charge-symmetry violations arising from unpolarized-hadron–hadron collisions are also mentioned.

Parity-violating asymmetries have been predicted to occur in lepton pair production from hadron–polarized-hadron collisions.[1-4] The calculations are based on the Drell-Yan[5] mechanism, including an interference between electromagnetic and weak neutral currents. If the weak interactions and parton model[6] are given as input, then measurement of these asymmetries in pion–polarized-proton collisions can be used to help determine the polarization structure of the proton. In particular, given the u and d quark-parton distributions in the proton, the measurement of the asymmetries determines the corresponding distributions for polarized u and d quarks *separately*.[1,2]

If the invariant mass of the lepton pair is at or near a vector meson resonance [such as the Υ (9.46 GeV)] the pair production mechanism is dominated by the effects of the resonance, which were omitted in the previous work. The corresponding weak asymmetries at a resonance are sensitive to the method of transfer of polarization to the vector meson from the polarized hadron; thus they can be used to analyze the production mechanism of the vector meson.

Hadronic vector-meson production mechanisms usually discussed fall into three general classes, which are illustrated in Fig. 1. The first[7-9] mechanism occurs by the fusion of light- (u,d,s) quark–antiquark pairs [Fig. 1(a)], which then couple to the vector meson via an intermediate photon, Z^0, or multiple gluons. This latter coupling violates the Okubo-Zweig-Iizuka (OZI) rule[10] and thus[9] is expected to be of the order $g_{q\bar{q}V}{}^2/4\pi \sim 10^{-5}$, roughly of the same order as the one-photon process. Another variation[7-9,11] on the quark-fusion theme involves the fusion of heavy sea quarks [Fig. 1(b)]. The rate for this process is suppressed because of the very small number of heavy quarks in the hadron sea, and thus is expected[9] to be of the same order as the rate for light-quark–antiquark fusion. The third class [Fig. 1(c)] is that of gluon-fusion mechanisms.[8,12,13] These require initial gluons, and thus should be less important than valence-quark processes in the threshold region, where partons with large momentum fractions are required.

The parity-violating contributions to the resonance cross section from hadron–polarized-hadron collisions are of two varieties, both of which are proportional to (and antisymmetric in)

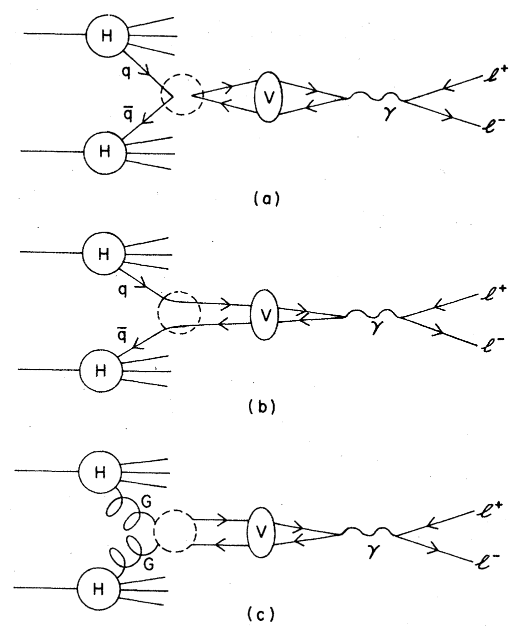

FIG. 1. The three candidate mechanisms for vector-meson production. (a) depicts light-quark (u, d, s) annihilation to produce a heavy-quark–antiquark pair, which forms a vector resonance and then decays to lepton pairs. (b) depicts heavy (sea) quark fusion to form the vector meson, while (c) is the gluon-fusion process, where the radiation of soft gluons or photons to produce a charge-conjugation-minus color-singlet state is understood. In each case, the dotted circles indicate unspecified processes, several of which are mentioned in the text.

the helicity of the polarized hadron. The first variety is symmetric under the interchange of the final-lepton-pair momenta, and is produced by such mechanisms as the interference of the electromagnetic [Fig. 2(a)] and weak [Fig. 2(b)] vector-meson production processes. The ratio of this parity-violating piece of the differential cross section to that part of the cross section which is independent of (and thus symmetric in) the helicity of the polarized hadron is called[1,2] the "helicity asymmetry." The second parity-violating contribution to the cross section is *antisymmetric* under the exchange of the final-lepton-pair momenta, and arises from the interference of the electromagnetic [Fig. 3(a)] and weak [Fig. 3(b)] decay amplitudes. This latter contribution occurs regardless of the method of vector-meson production, provided that information on the polarization state of the initial polarized hadron is transmitted to the produced resonance. The ratio of the differential cross section for this parity-violating asymmetry to the total (helicity-independent) decay rate to lepton pairs is called[1,2] the "charge-helicity asymmetry." Explicit definitions and calculations of these asymmetries are presented later.

Both of these asymmetries are quotients of a parity-violating cross section (or "numerator") and a parity-conserving cross section (or "denominator"), which can vary independently in principle. The denominator is made up of contributions from the production mechanisms such as the ones in Fig. 1, which require valence

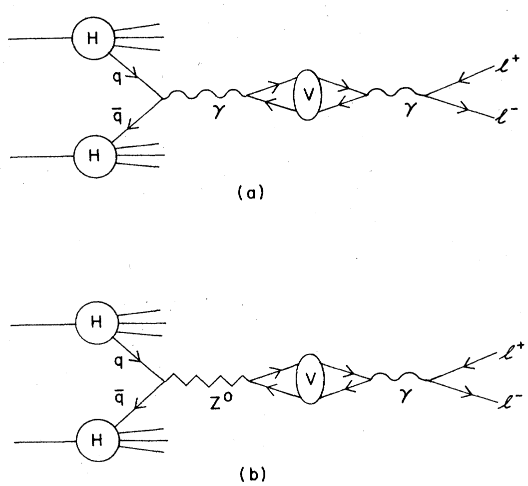

FIG. 2. (a) Electromagnetic production mechanism for the vector meson. Light quarks (u, d, s) from the initial hadron annihilate to form a photon, which then produces a heavy-quark–antiquark pair. These form a vector resonance and then decay to lepton pairs via a photon. (b) is the same as (a), except that the vector meson is produced via a Z^0 instead of a photon.

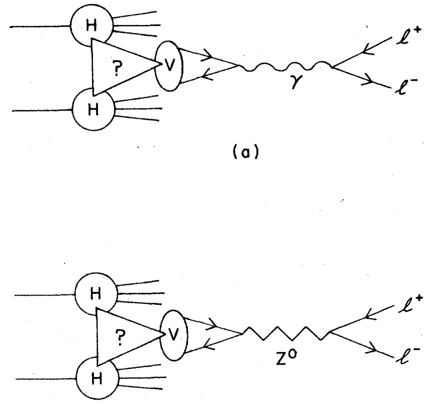

FIG. 3. (a) Vector-meson production via an unspecified mechanism with subsequent electromagnetic decay. (b) Same as (a), except that the decay of the vector meson is via a Z^0.

quarks, sea quarks, or gluons from the original hadron. In order for any of these production mechanisms to make a contribution to the numerator, however, at least one of the initial partons involved in the particular mechanism which produced the resonance must carry information on the polarization state of the initial polarized parent hadron. In addition, for the charge-helicity asymmetry, this information must be transmitted through the resonance. Traditionally, the spin of the proton is assumed to be carried by the valence quarks, although an SU(3) sum rule[14] suggests that approximately 40% of the proton spin (on the average) could be carried by other constituents. In the limit where the valence quarks carry all the proton spin, the production mechanisms which do not arise from a valence quark (such as gluon fusion) can only contribute to the denominator, and thus reduce both asymmetries from the value calculated for entirely valence-quark processes. Alternatively, in the limit where gluons carry a sizable fraction of the proton spin and gluon fusion is the dominant mode of production, the charge-helicity asymmetry should be of the same order as in the limit of the purely valence process. The helicity asymmetry on the other hand is much smaller, since there is no corresponding weak production process initiated by gluon fusion. These arguments show that the measurement of the two asymmetries can help determine the mechanics of vector-meson production, and also shed light on the pathway by which polarization is transferred from the initial polarized hadron to the resonance.

Calculations presented here are for the limit of entirely electromagnetic and weak production. For these calculations to be relevant, the process and the kinematic region measured must be chosen to maximize the importance of the quark-antiquark annihilation process, and thus electroweak production. Data taken near threshold[15] (at a beam energy of 39.5 GeV/c) indicate that the rate of J/ψ production from antiproton-nucleon collisions is roughly 5 times that arising from proton-nucleon collisions. This is to be contrasted with data taken at higher beam energies [200 GeV/c (Ref. 16) and 225 GeV/c (Ref. 17)], which give antiproton to proton production ratios near unity. Thus, (valence) quark-antiquark mechanisms apparently dominate in resonance production from antiproton-nucleon collisions at lower energies. The importance of electromagnetic vector-meson production relative to production via a direct hadronic coupling to the annihilating quark-antiquark pair can be studied using an upper bound[12] on the total coupling between the vector meson and light quarks. This bound is obtained from the total hadronic decay width of the vector meson, which is greater than the decay width to single quark-antiquark pairs and thus gives an upper bound on the coupling of the resonance to $q\bar{q}$ pairs. If the total coupling between the vector meson and the annihilating quark-antiquark pair in the production process is parametrized by replacing the fine-structure constant α in the one-photon-exchange production cross section by an effective coupling α_{eff}, the bound is

$$\frac{\alpha^2}{\alpha_{eff}{}^2} \geqslant \frac{\Gamma(V \to \text{“}\gamma\text{”} \to \text{hadrons})}{\Gamma(V \to \text{hadrons})_{\text{total}}} \approx 20\% \quad \text{for the } J/\psi \tag{1a}$$

$$\approx 10\% \quad \text{for the } \Upsilon\,, \tag{1b}$$

where V is the appropriate vector meson. The value for the J/ψ follows[12] from combining the observations[18] that the ratio for $(J/\psi \to \mu^-\mu^+)/(J/\psi \to \text{hadrons})$ is approximately 8% and the value of $R = (\text{“}\gamma\text{”} \to \text{hadrons})/(\text{“}\gamma\text{”} \to \mu^-\mu^+)$ is between 2.5 and 3.0 *off* resonance. The result for the Υ follows from similar observations,[19] which give approximately 2.5% for the ratio $(\Upsilon \to \mu^-\mu^+)/(\Upsilon \to \text{hadrons})$, and a value of approximately 4 for R off resonance.

With the Weinberg-Salam model,[20] augmented by the Glashow-Iliopoulos-Maiani (GIM) mechanism,[21] it is possible to estimate the helicity and charge-helicity asymmetries arising via a vector meson composed of a quark-antiquark pair. For simplicity, these asymmetries are calculated for a single antiquark–polarized-quark annihilation, and evaluated to lowest order in the weak interaction. The initial (light) quarks are assumed to be massless and on their mass shell, while the final lepton mass is included to account for heavy lepton production. The Drell-Yan[5] and parton[6] models are used, and the vector meson is assumed to be produced entirely via the electromagnetic and weak interactions.

The generic forms of the electromagnetic and weak neutral currents are (e is the charge of the electron, $e^2 \equiv 4\pi\alpha$)

$$J^{\mu}_{f,\text{em}} = |e| Q_f \bar{f}\gamma^{\mu} f\,, \tag{2a}$$

$$J^{\mu}_{f,\text{weak}} = \bar{f}\,(V_f + A_f\gamma_5)\gamma^{\mu} f\,, \tag{2b}$$

where f is replaced by l for lepton, q for initial quark, and V for the constituent quarks of the vector meson (for example, $Q_e = -1$, $Q_u = +\frac{2}{3}$, $Q_\psi = +\frac{2}{3}$). The vector meson is assumed to be a quark-antiquark system, whose coupling is

$$\langle 0 | \bar{V}\gamma^{\mu} V | V, \lambda\rangle = F_V \epsilon^{\mu}(\lambda)\,, \tag{3}$$

where $\epsilon^{\mu}(\lambda)$ is the polarization vector of the meson.

The helicity asymmetry $\mathcal{A}_h$ for a hadronic collision is defined[1,2] by

$$\mathcal{A}_h \equiv \frac{\left[\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-}\right]_{h=+1} - \left[\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-}\right]_{h=-1} + (l^+ \leftrightarrow l^-)}{\left[\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-}\right]_{h=+1} + \left[\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-}\right]_{h=-1}}\,, \tag{4a}$$

where l^+ and l^- are the final-lepton pair momenta, and h is the helicity of the polarized hadron. If purely electroweak production of the resonance is assumed, $\mathcal{A}_h$ is equal to the lepton charge-symmetric part of the ratio of the electroweak interference [Figs. 2(a) and 2(b)] to the electromagnetic [Fig. 2(a)] production cross section. The four-momentum of the virtual photon is $Q \equiv l^+ + l^-$; by assumption, the mass of the virtual photon is much less than the mass of the Z^0, i.e., $Q^2 \ll M_Z{}^2$. Neglecting the nonresonance background and evaluating $\mathcal{A}_h$ for a single antiquark–(perfectly) polarized-quark annihilation gives

$$\mathcal{A}_h\Big|_{q\bar{q}} = \frac{+2}{4\pi\alpha}\,\frac{Q^2}{M_Z{}^2}\left(\frac{V_V}{Q_V}\right)\left(\frac{A_q}{Q_q}\right)\,, \tag{4b}$$

where the mass of the virtual photon is approximately equal to the mass of the vector meson, $Q^2 \approx M_V{}^2$. Note that this asymmetry is isotropic, and is proportional to Q^2 (for $Q^2 \ll M_Z{}^2$).

The charge-helicity asymmetry $\mathcal{A}_{ch}$ for a hadronic collision is likewise[1,2] defined to be

$$\mathcal{A}_{ch} \equiv \frac{\left[\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-}\right]_{h=+1} - \left[\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-}\right]_{h=-1} - (l^+ \leftrightarrow l^-)}{\left[\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-}\right]_{h=+1} + \left[\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-}\right]_{h=-1}}\,. \tag{5a}$$

This is evaluated in the hadron center-of-mass frame with the incoming quarks collinear along the $\hat{z}$ direction (the antiquark is in the $+\hat{z}$ direction). Then, the result for a single antiquark–(perfectly) polarized-quark annihilation gives

$$\mathcal{A}_{ch}\Big|_{q\bar{q}} = \frac{+2}{4\pi\alpha}\,\frac{Q^2}{M_Z^{\,2}}\left(\frac{V_V}{Q_V}\right)\left(\frac{A_l}{Q_l}\right)F(\beta,\theta_l,\mu)\,, \tag{5b}$$

where the function $F(\beta,\theta_l,\mu)$ is the analog of the corresponding function $F(\beta,\theta_l)$ defined in Refs. 1 and 2, generalized to include lepton-mass effects. Explicitly,

$$F(\beta,\theta_l,\mu) \equiv \frac{2(1-\beta^2)^{1/2}(1-\beta^2\cos^2\theta_l)^{1/2}(1-\mu^2)^{1/2}}{1+\mu^2+(1-\mu^2-2\beta^2)\cos^2\theta_l}\cos\theta_l\,, \tag{6}$$

where $\beta \equiv Q_z/Q_0$ is the "velocity" of the virtual photon; $\mu^2 \equiv 4m_l^{\,2}/Q^2$, with m_l the lepton mass, and

$$\cos\theta_l \equiv \frac{(\vec{l}^{\,+}-\vec{l}^{\,-})\cdot\hat{z}}{|\vec{l}^{\,+}-\vec{l}^{\,-}|}. \tag{7}$$

Note that $F(\beta,\theta_l,\mu)$ is odd in $\cos\theta_l$ (it is "charge asymmetric" by construction) and is largest in magnitude when $\theta_l = 0$ or π. It takes the values $\pm(1-\mu^2)^{1/2}$ when $\cos\theta_l = \pm 1$ for any $\beta^2 < 1$, $\mu^2 < 1$; and varies monotonically between the two limits, being generally of order unity.

Thus there are two different asymmetries, distinguishable by angular distribution, arising from the interference of weak and electromagnetic interactions. Note that, as in the analogous process in e^+e^- annihilation,[22] both asymmetries are independent of F_V, the coupling of the meson to the vacuum, and of the vector-meson propagator. This simplification occurs because the nonresonance background is neglected.

In the Weinberg-Salam (Ref. 20)–GIM (Ref. 21) model,

$$\frac{Q^2}{M_Z^{\,2}}\,\frac{V_V}{Q_V}\,\frac{A_q}{Q_q} = \frac{+G_F Q^2}{2\sqrt{2}}\;\frac{(2T_{3,V}-4Q_V\sin^2\theta_W)2T_{3,q}}{Q_V Q_q}\,, \tag{8a}$$

$$\frac{Q^2}{M_Z^{\,2}}\,\frac{V_V}{Q_V}\,\frac{A_l}{Q_l} = \frac{+G_F Q^2}{2\sqrt{2}}\;\frac{(2T_{3,V}-4Q_V\sin^2\theta_W)}{Q_V} \tag{8b}$$

with $T_{3,q}$ and $T_{3,V}$ the weak isospin of the annihilating initial quarks and constituent quarks of the vector meson. The weak Fermi coupling is taken to be $G_F \simeq 1.17\times10^{-5}\ \mathrm{GeV}^{-2}$ and $\sin^2\theta_W = 0.225$ is the Weinberg angle. The above equations give, for $\bar{u}$-polarized-u (e.g., $\bar{\pi}p$ or $\bar{p}p$) annihilation to a $b\bar{b}$ vector meson [like the Υ(9.46 GeV)], with $Q^2 = (9.46\ \mathrm{GeV})^2$:

$$\mathcal{A}_h\Big|_{q\bar{q}} \cong +2.5\times10^{-2}\,, \tag{9a}$$

$$\mathcal{A}_{ch}\Big|_{q\bar{q}} \cong +1.7\times10^{-2}F(\beta,\theta_l,\mu)\,. \tag{9b}$$

The helicity asymmetry for antiquark–polarized-quark annihilation is approximately an order of magnitude greater than the corresponding value away from the resonance[1-4] because the latter is proportional to the leptonic weak vector coupling, which vanishes at $\sin^2\theta_W = \frac{1}{4}$. The order of magnitude of the asymmetries in Eq. (8) is determined by the ratio of the weak to the electromagnetic interaction at the resonance,

$$\mathcal{A}\Big|_{q\bar{q}} \sim \frac{G_F M_V^{\,2}}{4\pi\alpha}\,, \tag{10a}$$

which is of order 1% for the Υ(9.46 GeV) resonance.

The contributions of production processes other than electroweak $q\bar{q}$ annihilation and the incomplete polarization of the quark will lead to measured asymmetries smaller than those given by Eqs. (9). The latter effect (discussed at length in Refs. 1 and 2 and references contained therein) is not expected to be important at threshold, but the former effect can reduce the measured asymmetry by an order of magnitude. If, as suggested by Eq. (1), electromagnetic production accounts for 10–20% of the resonance production near threshold where $q\bar{q}$ annihilation is dominant, then the experimental asymmetries are a factor of $\frac{1}{10}$ to $\frac{1}{5}$ smaller than Eq. (9), i.e.,

$$\mathcal{A} \sim \tfrac{1}{10}\,\mathcal{A}\Big|_{q\bar{q}}\,, \tag{10b}$$

which might still be measurable.

If the invariant mass of the lepton pair is not precisely at the resonance value, the contributions from nonresonance diagrams cannot be neglected. The nonresonance electromagnetic and weak diagrams are shown in Figs. 4(a) and 4(b). The inclusion of these diagrams modifies the results for the asymmetries given in Eqs. (4) and (5). For example, the numerator of the helicity asymmetry receives contributions from the interference of the resonance diagram Fig. 2(a) and the nonresonance diagram Fig. 4(b), as well as from the interference of those in Figs. 2(b) and 4(a). There are also contributions from the interference of the (nonresonance) diagrams Figs. 4(a) and 4(b). When all of these (and the corresponding contributions to the denominator of the asymmetry) are included along with the resonance diagrams the asymmetries become

$$\mathcal{A}_h\Big|_{q\bar{q}} = \frac{+2}{4\pi\alpha}\left(\frac{Q^2}{M_Z^2}\right)\left(\frac{A_q}{Q_q}\right)\frac{\dfrac{V_l}{Q_l} + \dfrac{w}{Q^2D}\left[\left(\dfrac{V_l}{Q_l} + \dfrac{V_V}{Q_V}\right)(Q^2 - M_V^2) + \dfrac{V_V}{Q_V}\dfrac{w}{Q^2}\right]}{1 + \dfrac{w}{Q^2D}\left[2(Q^2 - M_V^2) + \dfrac{w}{Q^2}\right]} \tag{11a}$$

$$\to \frac{+2}{4\pi\alpha}\left(\frac{Q^2}{M_Z^2}\right)\frac{A_q}{Q_q}\begin{cases}\dfrac{V_l}{Q_l} & \text{away from resonance,}\\[2ex] \dfrac{V_V}{Q_V} & \text{at resonance}\end{cases} \tag{11b}$$

and

$$\mathcal{A}_{ch}\Big|_{q\bar{q}} = \frac{+2}{4\pi\alpha}\left(\frac{Q^2}{M_Z^2}\right)F(\beta,\theta_l,\mu)\left(\frac{A_l}{Q_l}\right)\frac{\dfrac{V_q}{Q_q} + \dfrac{w}{Q^2D}\left[\left(\dfrac{V_q}{Q_q} + \dfrac{V_V}{Q_V}\right)(Q^2 - M_V^2) + \dfrac{V_V}{Q_V}\dfrac{w}{Q^2}\right]}{1 + \dfrac{w}{Q^2D}\left[2(Q^2 - M_V^2) + \dfrac{w}{Q^2}\right]} \tag{11c}$$

$$\to \frac{+2}{4\pi\alpha}\left(\frac{Q^2}{M_Z^2}\right)F(\beta,\theta_l,\mu)\frac{A_l}{Q_l}\begin{cases}\dfrac{V_q}{Q_q} & \text{away from resonance,}\\[2ex] \dfrac{V_V}{Q_V} & \text{at resonance,}\end{cases} \tag{11d}$$

where $D \equiv (Q^2 - M_V^2)^2 + M_V^2\Gamma^2$ is the absolute square of the inverse propagator of the vector meson and Γ is its total decay width, while $w \equiv e^2 Q_V^2 |F_V|^2 = 3\Gamma_{ee} M_V^3/\alpha$ and Γ_{ee} is the electronic width of the resonance.

These asymmetries are maximized at a value of Q^2 slightly less than the resonance value, as shown schematically in Fig. 5. At the maximum of Eqs. (11) the difference $(M_V^2 - Q^2)/M_V^2$ is of order of $w/M_V^4 \sim 10^{-4}$ for the Υ. The asymmetries $\mathcal{A}\,|_{q\bar{q}}$ can be an order of magnitude larger than the resonance value at this value of Q^2. However, in practice this effect is likely to be washed out by other resonance contributions to the denominator of the asymmetry, as well as by the experimental resolution in energy.

The effect of this finite energy resolution is understood simply by averaging separately the parity-conserving and parity-violating cross sections for each asymmetry over N total widths, i.e., over a symmetric range $M_V^2 - \frac{1}{2}NM_V\Gamma \le Q^2 \le M_V^2 + \frac{1}{2}NM_V\Gamma$. The quotient of these two Q^2-

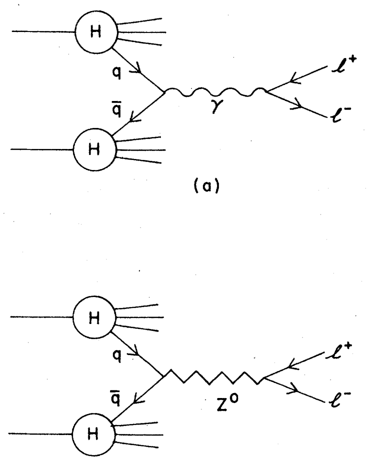

FIG. 4. (a) The "Drell-Yan" process. A quark and an antiquark from two hadrons annihilate to produce a highly virtual photon, which then decays to a lepton pair. (b) The same process, but with a Z^0 exchanged instead of a photon.

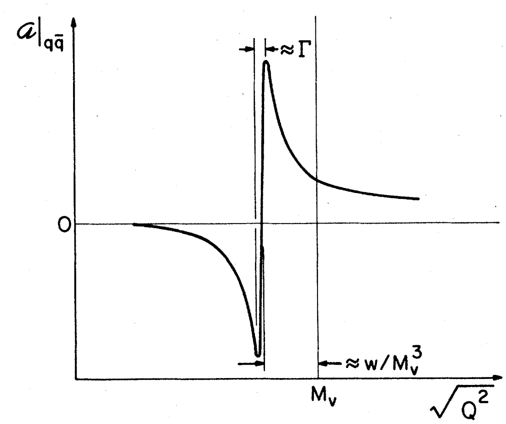

FIG. 5. Structure of the asymmetries Eqs. (11), which include the effects of both resonance and background contributions to the cross section. The asymmetries exhibit a minimum, a sign change, and a maximum at values of $(Q^2)^{1/2}$ less than M_V.

averaged cross sections is then referred to as the averaged asymmetry. In the limit $N\Gamma/M_V \ll 1$, the averaged helicity asymmetry is

$$(\mathcal{A}_h|_{q\bar{q}})_{\mathrm{avg}} \cong \frac{2}{4\pi\alpha}\frac{M_V^2}{M_Z^2}\frac{A_q}{V_q}\frac{(V_l/Q_l)\Delta + V_V/Q_V}{\Delta+1}, \tag{12a}$$

where $\Delta \equiv N\Gamma^2 M_V^6/(w^2\pi) = N\alpha^2\Gamma^2/9\pi\Gamma_{ee}^2$ is explicitly independent of M_V. Similarly, the averaged charge-helicity asymmetry is approximately given by

$$(\mathcal{A}_{ch}|_{q\bar{q}})_{\mathrm{avg}} \cong \frac{2}{4\pi\alpha}\frac{M_V^2}{M_Z^2}F(\beta,\theta_l,\mu)\frac{A_l}{Q_l}\frac{(V_q/Q_q)\Delta + V_V/Q_V}{\Delta+1}. \tag{12b}$$

Note that each asymmetry reduces to the value calculated from resonance diagrams only in the limit $\Delta \to 0$, corresponding to perfect resolution. In the limit $\Delta \to \infty$, which is the limit of extremely poor resolution, the asymmetries approach the nonresonance value calculated in Refs. 1–4. The turning point is $\Delta \sim 1$, corresponding to $N \sim 100$ for the $\Upsilon(9.46\ \mathrm{GeV})$. This means that the resolution must be of the order of $100\Gamma \sim 10$ MeV for the Υ in order for the resonance to have an effect on the experimentally perceived asymmetry.

There is also a charge asymmetry $\mathcal{A}_c$, which is independent of the helicity of the initial quark and so conserves parity:

$$\mathcal{A}_c \equiv \frac{\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-} - (l^+ \leftrightarrow l^-)}{\dfrac{d^6\sigma(l^+,l^-)}{d^3l^+d^3l^-} + (l^+ \leftrightarrow l^-)}, \tag{13a}$$

$$\mathcal{A}_c|_{q\bar{q}} = \frac{-2}{4\pi\alpha}\left(\frac{Q^2}{M_Z^2}\right)F(\beta,\theta_l,\mu)\left(\frac{A_l}{Q_l}\right)\left(\frac{A_q}{Q_q}\right)\frac{1+\dfrac{w}{Q^2D}(Q^2-M_V^2)}{1+\dfrac{w}{Q^2D}\left[2(Q^2-M_V^2)+\dfrac{w}{Q^2}\right]} \tag{13b}$$

$$\to \left(\frac{Q^2}{M_Z^2}\right)F(\beta,\theta_l,\mu)\frac{A_l}{Q_l}\frac{A_q}{Q_q}\times\begin{cases}\dfrac{1}{1+\dfrac{w^2}{M_V^6\Gamma^2}} \approx \dfrac{\Gamma^2 M_V^6}{(e^2Q_V^2|F_V|^2)^2} = \frac{1}{9}\alpha^2\dfrac{\Gamma^2}{\Gamma_{ee}^2} & \text{at resonance},\\ 1 & \text{away from resonance.}\end{cases} \tag{13c}$$

This charge asymmetry has been discussed previously[1,2,23] for the nonresonance case. It arises from the product of the quark and lepton axial-vector currents. Resonance diagrams contain only products of vector and axial-vector currents to lowest order in the weak interaction since the vector meson only couples to vector currents. Thus, the charge asymmetry is reduced at a vector-meson resonance and is zero in the limit $\Gamma \to 0$. Since the charge asymmetry in Eqs. (13) is independent of the helicity of the initial hadron it can also occur in unpolarized-hadron–hadron collisions.

As with the helicity and charge-helicity asymmetries, the experimentally perceived charge asymmetry is altered from the value given in Eq. (13b). Averaging over Q^2 as in Eq. (12) gives

$$(\mathcal{A}_c|_{q\bar{q}})_{\mathrm{avg}} \cong \frac{-2}{4\pi\alpha}\frac{M_V^2}{M_Z^2}F(\beta,\theta_l,\mu)\frac{A_l}{Q_l}\frac{A_q}{Q_q}\frac{\Delta}{\Delta+1} \tag{14}$$

in the limit $N\Gamma/M_V \ll 1$. This shows that the experimentally perceived charge asymmetry is reduced in the region of a vector meson resonance if the energy resolution is sharp enough (i.e., if Δ is small).

In the above calculation the corrections due to perturbative quantum chromodynamics (such as displayed in Fig. 6) have been neglected, even though large corrections to the parton-model result occur in similar processes.[24] Indeed, such effects may give rise[25] to a new parity-violating asymmetry proportional to the pseudoscalar triple product of the beam direction and the lepton-pair momenta in *unpolarized*-hadron–hadron collisions. A similar effect would seem to occur here due to the interference of such diagrams as Figs. 6(a) and 6(d), as well as from the interference of the diagrams in Figs. 6(b) and 6(c). The reason is that there is a phase introduced from the vector-meson propagator, as well as one from the weak interaction. Therefore, one might expect a phase difference and hence an asymmetry from an electromagnetic-weak interference term. However, the parity-violating effect from the interference of diagrams Figs. 6(a) and 6(d) is of equal magnitude but opposite sign from the effect arising from the interference of diagrams Figs. 6(b) and

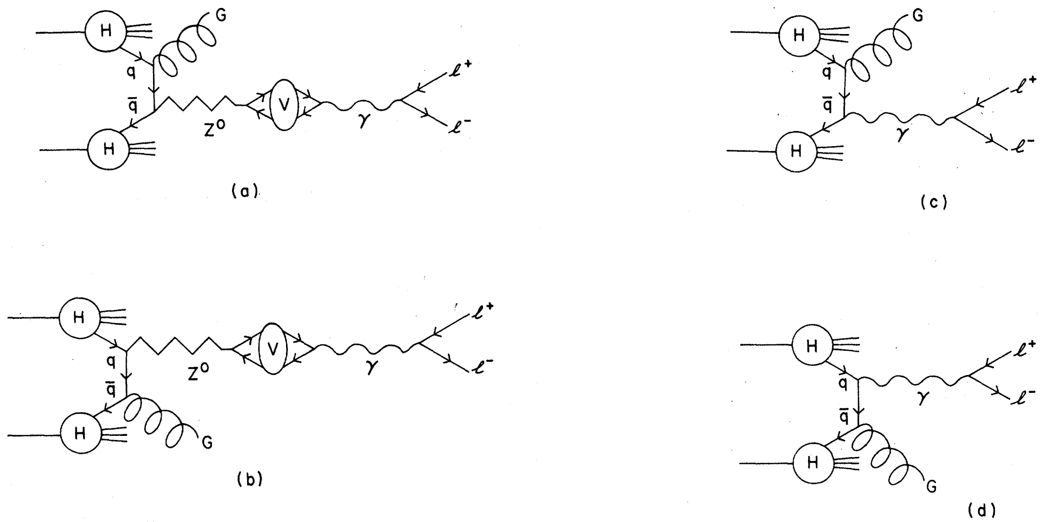

FIG. 6. (a) Light-quark–antiquark pair radiate a single gluon and annihilate to form a Z^0, which then couples to a vector meson. The vector meson then decays electromagnetically to a lepton pair. (b) The crossed diagram to (a), required by gauge invariance. (c) Light-quark–antiquark pair radiate a gluon and annihilate to produce a virtual photon, which then decays to a lepton pair. (d) The crossed diagram to (c).

6(c). Thus the diagrams cancel pairwise, as do all such parity-violating effects to first order in perturbative QCD in the absence of polarization or off-shell initial quarks.[25]

In summary, previous work[1-4] has been extended to include the effects of a vector meson resonance on parity-violating asymmetries in lepton pair production from hadron–polarized-hadron collisions. Two different types of asymmetry, distinguishable by angular distribution, have been predicted to occur. Explicit calculations of these asymmetries were presented for the case of electroweak production from a single antiquark–polarized-quark pair. The significance of this calculation was discussed in light of the possibility of a large fraction of the spin of the incident polarized hadron being carried by gluons or by sea quarks.[26] Thus, measurement of these weak asymmetries at a vector meson resonance can give a fresh look at the polarization structure of the initial polarized hadron, as well as the method of transfer of polarization from the hadron to the vector meson.

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