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Physical Review D, 2006; 73(7):076004

http://link.aps.org/doi/10.1103/PhysRevD.73.076004

Parton charge symmetry violation: Electromagnetic effects and W production asymmetries

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(Received 23 March 2006; published 18 April 2006)

Recent phenomenological work has examined two different ways of including charge symmetry violation in parton distribution functions. First, a global phenomenological fit to high energy data has included charge symmetry breaking terms, leading to limits on the magnitude of parton charge symmetry breaking. In a second approach, two groups have included the coupling of partons to photons in the QCD evolution equations. One possible experiment that could search for isospin violation in parton distributions is a measurement of the asymmetry in W production at a collider. In this work we include both of the postulated sources of parton charge symmetry violation. We show that, given charge symmetry violation of a magnitude consistent with existing high energy data, the expected W production asymmetries would be quite small, generally less than 1%.

DOI: 10.1103/PhysRevD.73.076004 PACS numbers: 11.30.Hv, 12.15.Mm, 12.38.Qk, 13.15.+g

Charge symmetry represents a specific form of isospin invariance (a rotation of 180° about the "2" axis in isospin space) that is quite well respected at low energies [1,2]. Since there is no direct experimental evidence of charge symmetry violation (CSV) for PDFs [3,4], it was reasonable, at least in the beginning, to assume that it held as well for parton distribution functions (PDFs). However, we know that small violations of charge symmetry do arise from both the mass differences of light current quarks, and from electromagnetic effects. There have been some theoretical estimates of charge symmetry violation in PDFs, and recently charge symmetry violation has been included in phenomenological PDFs. Furthermore, the estimated size of the CSV is such that it can produce important effects in some experiments, for example, in precise tests of physics beyond the Standard Model [5,6].

Global fits of PDFs by Martin, Roberts, Stirling and Thorne (MRST) [7] included the possibility of charge symmetry violating PDFs for valence and sea quarks. By construction, the resulting parton distributions will agree with the array of experimental data used in global fits. The valence quark CSV PDFs were chosen to have the specific form

$$\begin{aligned} \delta u_{\rm v}(x) &= -\delta d_{\rm v}(x) = \kappa(1-x)^4 x^{-0.5}(x - .0909) \\ \delta u_{\rm v}(x) &= u_{\rm v}^p(x) - d_{\rm v}^n(x); \qquad \delta d_{\rm v}(x) = d_{\rm v}^p(x) - u_{\rm v}^n(x) \end{aligned} \tag{1}$$

At both small and large x the valence quark CSV term is qualitatively similar to phenomenological valence quark distributions [8], and the first moment of the valence CSV distribution is zero, a necessary condition to preserve valence quark normalization. The single coefficient κ was varied in the global fit to high energy data. To minimize the resulting computing time, MRST neglected the Q^2 dependence of this CSV effect. The best value they obtained was $\kappa = -0.2$, and the 90% confidence level included the range $-0.8 \leq \kappa \leq +0.65$. It is interesting to note that for the best fit obtained by MRST, the valence quark CSV distributions are in very good agreement both in sign and magnitude with predictions from quark model calculations [9,10]—see also the model independent constraint on the second moment obtained in Refs. [5,11].

In a separate global fit to the same data, MRST included the possibility of sea quark CSV effects. The MRST functional form chosen for sea quark CSV was

$$\bar{u}^n(x) = \bar{d}^p(x)[1+\delta] \qquad \bar{d}^n(x) = \bar{u}^p(x)[1-\delta] \tag{2}$$

This form was chosen to insure that the total momentum carried by antiquarks in the neutron and proton was approximately equal. Once again, they assumed no Q^2 dependence for these CSV distributions. The best fit was obtained for $\delta = 0.08$.

An alternative, phenomenological approach to the problem of charge symmetry violation associated with the electromagnetic interaction has been proposed by both MRST [12] and Glueck, Jimenez-Delgado and Reya [13]. By analogy with the usual QCD evolution involving gluon radiation, these authors suggested that one assume charge symmetry at some initial low-mass scale, and include in the evolution equations the effect of photon radiation. When one includes QED contributions in this way, to

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lowest order in both the strong coupling α_S and the EM coupling α, the so-called DGLAP evolution equations due to Dokshitzer [14], Gribov and Lipatov [15] and Altarelli and Parisi [16] are modified. The MRST group obtains

$$\begin{aligned} \frac{\partial q_i(x,\mu^2)}{\partial \log\mu^2} &= \frac{\alpha_S}{2\pi}[P_{qq}\otimes q_i + P_{qg}\otimes g] \\ &\quad + \frac{\alpha}{2\pi}[\tilde{P}_{qq}\otimes e_i^2 q_i + P_{q\gamma}\otimes e_i^2\gamma], \\ \frac{\partial g(x,\mu^2)}{\partial \log\mu^2} &= \frac{\alpha_S}{2\pi}\Big[P_{gq}\otimes \sum_j q_j + P_{gg}\otimes g\Big], \\ \frac{\partial \gamma(x,\mu^2)}{\partial \log\mu^2} &= \frac{\alpha}{2\pi}\Big[P_{\gamma q}\otimes \sum_j e_j^2 q_j + P_{\gamma\gamma}\otimes \gamma\Big]. \end{aligned} \tag{3}$$

In Eq. (3), the right-hand side of the schematic evolution equations represents a convolution of the splitting functions with the quark and gluon distributions (which have an explicit dependence on the factorization scale parameter μ^2). Inclusion of the electromagnetic contribution to QCD evolution introduces a "photon parton distribution" $\gamma(x,\mu^2)$ which is coupled to the quark and gluon distributions. The new splitting functions that occur in Eq. (3) are related to the standard QCD splitting functions by

$$\begin{aligned} \tilde{P}_{qq} &= P_{qq}/C_F; \qquad P_{\gamma q} = P_{gq}/C_F \\ P_{q\gamma} &= P_{qg}/T_R; \qquad P_{\gamma\gamma} = -\frac{2}{3}\sum_i e_i^2\delta(1-y) \end{aligned} \tag{4}$$

Conservation of momentum is assured by the relation

$$\int_0^1 dx x\Big[\sum_i q_i(x,\mu^2) + g(x,\mu^2) + \gamma(x,\mu^2)\Big] = 1 \tag{5}$$

It is necessary to simplify Eqs. (3). First, since the EM interaction is not asymptotically free, it is not clear how to set the starting values for the various PDFs that are coupled by these QED effects. In particular, it is not clear where the QED effects should be assumed to vanish. Second, inclusion of the QED couplings could in principle more than double the number of parton distribution functions (one must now differentiate between proton and neutron PDFs, in addition to the new photon parton distributions). Two groups have adopted somewhat different strategies, with similar overall results. Glueck *et al.* [13] point out that the photon parton distribution is already of order α, as is clear by inspection of Eq. (3). Consequently to leading order in α they drop terms involving $\gamma(x,\mu^2)$ from the right-hand side of Eq. (3). When they adopt the standard convention for DIS reactions of setting the scale $\mu^2 = Q^2$, Glueck *et al.* then obtain convolution equations for the charge symmetry violating valence quark distributions arising from QED coupling,

$$\begin{aligned} \frac{d}{d\ln Q^2}\delta u_{\rm v}(x,Q^2) &= \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}P\Big(\frac{x}{y}\Big)u_{\rm v}(y,Q^2) \\ \frac{d}{d\ln Q^2}\delta d_{\rm v}(x,Q^2) &= -\frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}P\Big(\frac{x}{y}\Big)d_{\rm v}(y,Q^2) \\ P(z) = (e_u^2 - e_d^2)P_{qq}(z) &= (e_u^2 - e_d^2)\Big(\frac{1+z^2}{1-z}\Big)_+ \end{aligned} \tag{6}$$

Similar relations hold for the antiquark distributions. Glueck *et al.* assume that the average current quark mass $\bar{m}_q$, taken as 10 MeV, is the kinematical lower bound for a photon emitted by a quark. This is analogous to taking the electron mass as the lower limit for radiation of photons in the earliest calculations of the Lamb shift (before the advent of renormalization group arguments) [17]. Equation (6) is then integrated from $\bar{m}_q^2$ to Q^2. The rationale here is to evaluate QED evolution effects while keeping the QCD effects fixed. Thus, the quark distributions appearing on the right-hand side of Eq. (6) are taken from the GRV leading-order parton distributions [18]. In the resulting integrals, in the region $q^2 < \mu_{\rm LO}^2 = 0.26$ GeV^2 corresponding to momentum transfers below the input scale for GRV, the PDFs are "frozen," i.e., in this region they are assumed to be equal to their value at the input scale $\mu_{\rm LO}^2$.

The resulting valence isospin asymmetries $x\delta u_{\rm v}$ and $x\delta d_{\rm v}$ are plotted in Fig. 1 at $Q^2 = 10$ GeV^2. For comparison, they are plotted along with the valence quark isospin asymmetries obtained by Rodionov *et al.* [10,19]. The latter CSV distributions were obtained from bag model calculations, where charge symmetry violation was assumed to arise from mass differences of the residual diquarks $\delta\tilde{m} = m_{dd} - m_{uu}$ and from the target nucleon mass difference $\delta M = M_n - M_p$. The quantity $\delta\tilde{m}$ was taken as 4 MeV [9,10], which includes an estimate of the EM contribution to this mass difference. While the quantity $\delta u_{\rm v}$ is quite similar in both sign and magnitude for both the bag model and the QED calculations, the QED results for $\delta d_{\rm v}$ are roughly half as large as the bag model results. As noted previously, the bag model results for valence quark CSV are extremely close to those obtained by MRST using the phenomenological form of Eq. (1), for the best-fit value $\kappa = -0.2$.

The MRST group [12] solves the evolution equations of Eq. (3) with assumptions about the parton distributions at the starting scale $Q_0^2 = 1$ GeV^2. At the starting scale, the sea quark and gluon distributions are assumed to be isospin symmetric. The starting photon parton distributions are taken as those due to one-photon radiation from valence quarks in leading-logarithm approximation, evolved from current quark masses $m_u = 6$ MeV and $m_d = 10$ MeV to Q_0. This produces different photon PDFs for neutron and proton at the starting scale. Enforcing overall quark momentum conservation from Eq. (5) requires valence quark isospin asymmetry at the starting scale. MRST assume that this takes the form

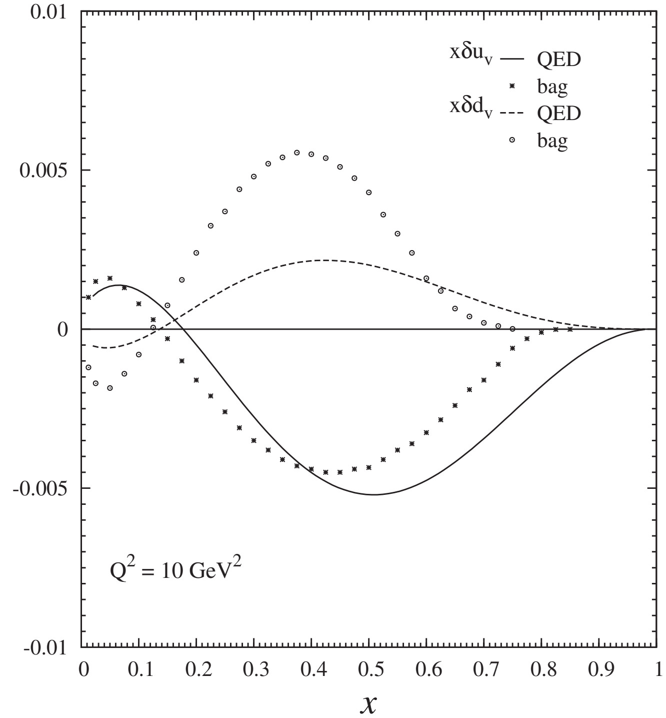

FIG. 1. The isospin-violating majority $x\delta u_v$ (solid curve) and minority $x\delta d_v$ (dashed curve) valence parton distributions obtained by Glueck *et al.* [13] at $Q^2 = 10\ \mathrm{GeV}^2$, assuming QED evolution from a scale set by the current quark mass. These are compared with majority (solid points) and minority (open circles) CSV distributions obtained from theoretical bag model calculations [10].

$$d_v^n - u_v^p = 2(d_v^p - u_v^n) = \epsilon(u_v^p - 2d_v^p). \tag{7}$$

Equation (7) is a simple phenomenological form chosen to obey the valence quark normalization condition, and it produces isospin-violating distributions that resemble the valence PDFs at large and small x. The parameter ϵ is determined from the overall quark momentum conservation condition.

Having determined the starting distributions for the photon parton distribution, and the asymmetry parameter ϵ, the proton's quark and gluon distributions at the starting scale Q_0^2 are determined in the same way as for other MRST global fits. The only change is that separate DGLAP evolution equations are used for partons in the neutron and proton.

If we adopt the MRST functional form for charge symmetry violating PDFs, we can estimate the magnitude of effects one might expect in a dedicated experiment designed to test parton charge symmetry. In a recent paper [20], we estimated the magnitude of effects in two promising experiments. The first was a comparison of Drell-Yan cross sections induced by charged pions on an isoscalar target (e.g., the deuteron). The second experiment involved semi-inclusive deep inelastic scattering involving charged pion production in $e - D$ interactions.

In this report, we consider another possible experimental test of parton charge symmetry. This involves measurements of W production at hadron colliders, specifically W-boson production in high energy $p - D$ collisions. This was initially suggested by Vigdor [21]. Boros *et al.* made estimates of the effects that might be expected at colliders such as RHIC and LHC [22], and concluded that one might expect several percent effects in certain observables. However, these effects occurred because the authors had assumed very large charge symmetry violation in the parton sea. This large sea quark CSV was necessary to account for significant discrepancies between the F_2 structure functions extracted from high energy $\mu - D$ interactions measured by the NMC Collaboration [23,24], and the F_2 from $\nu - Fe$ DIS measured by CCFR [25]. However, these discrepancies disappeared when the neutrino reactions were reanalyzed [26,27].

There were two reasons for significant changes of F_2^ν upon reanalysis. First, experimental neutrino cross-sections measure a combination of F_2 and xF_3. In the initial analysis the quantity xF_3 was calculated from phenomenological PDFs. In the reanalysis, this quantity was extracted from experiment, by using the fact that the two structure functions have different y dependences in the cross sections. The value of xF_3 that was extracted differed considerably from the phenomenological xF_3, and this subsequently changed the value of F_2 that was extracted. The second significant change arose through the use of next-to-leading-order (NLO) equations for charm quark mass effects [27], rather than the "slow rescaling" model [28,29]. Although the MRST analysis found evidence for sea quark CSV [7], it was considerably smaller than that extracted from the original data, including the slow rescaling contribution.

The cross sections for the processes $p + D \to W^+ + X$ and $p + D \to W^- + X$ have the form

$$\begin{aligned}\frac{d\sigma}{dx_F}(pD \to W^+X) &\sim \cos^2\Theta_C[u(x_1)(\bar{u}(x_2) + \bar{d}(x_2) - \delta\bar{u}(x_2)) + \bar{d}(x_1)(u(x_2) + d(x_2) - \delta d(x_2))]\\ &\quad + \sin^2\Theta_C[2u(x_1)s(x_2) + s(x_1)(u(x_2) + d(x_2) - \delta d(x_2))]\\ \frac{d\sigma}{dx_F}(pD \to W^-X) &\sim \cos^2\Theta_C[\bar{u}(x_1)(u(x_2) + d(x_2) - \delta u(x_2)) + d(x_1)(\bar{u}(x_2) + \bar{d}(x_2) - \delta\bar{d}(x_2))]\\ &\quad + \sin^2\Theta_C[2\bar{u}(x_1)s(x_2) + s(x_1)(\bar{u}(x_2) + \bar{d}(x_2) - \delta\bar{d}(x_2))]\end{aligned} \tag{8}$$

In the absence of CSV terms, if we take the sum of the W^+ and W^- cross sections,

$$\sigma_S(x_F) \equiv \left(\frac{d\sigma}{dx_F}\right)^{W^+} + \left(\frac{d\sigma}{dx_F}\right)^{W^-}, \tag{9}$$

then the Cabibbo-favored terms in σ_S are invariant under the exchange $x_1 \leftrightarrow x_2$, or alternatively under the transformation $x_F \longrightarrow -x_F$, where $x_F = x_1 - x_2$. Consequently, we define the forward-backward asymmetry $A(x_F)$ as

$$A(x_F) = \frac{\sigma_S(x_F) - \sigma_S(-x_F)}{\sigma_S(x_F) + \sigma_S(-x_F)} \tag{10}$$

The only terms remaining in the quantity $A(x_F)$ are charge symmetry violating terms, plus terms containing strange quarks in the Cabibbo-unfavored sector.

We have calculated the effects to be expected for the forward-backward asymmetry $A(x_F)$ for W-production at a hadron collider, using the charge symmetry violating PDFs calculated by the MRST group. We have used PDFs corresponding to three different sources of charge symmetry violation. First, we used the valence quark and sea quark CSV PDFs extracted by the MRST group from global fits to high energy data [7]. Then we have added the CSV PDFs calculated by the MRST group by including the "QED" contributions to QCD evolution, with assumptions about the parton distributions at the starting scale $Q_0^2 = 1$ GeV^2 [12,30]. Note that the various CSV PDFs were extracted using different procedures. The valence and sea quark PDFs were calculated in independent global fits to high energy data. In these fits, one assumed a particular functional form for the valence (or sea) quark CSV PDFs, which depended upon an overall variable parameter for the strength. That parameter was determined by minimizing the χ^2 of the global fit. For simplicity MRST neglected the Q^2 dependence of the CSV distributions.

In these various global fits, one obtains different valence parton distributions in the minimization process (the sea quark and gluon distributions were essentially identical to those obtained assuming charge symmetry). So the best-fit valence quark PDFs obtained by MRST when they allowed valence quark CSV differed somewhat from those obtained when they allowed sea quark CSV. In addition, the MRST global fits that allowed parton CSV did not explicitly include the QED contributions to QCD evolution. We explore the various contributions to the W production asymmetry, despite some questions regarding the consistency in the different parton distributions that give rise to CSV effects.

In Fig. 2, we plot the forward-backward asymmetry expected for W production, as defined in Eq. (10). The parton distribution functions are obtained from the MRST analysis that includes the QED contribution to DGLAP evolution; this analysis includes electromagnetic couplings in the evolution equations that give rise to isospin violation [12], as given by Eq. (3). The input data for these global fits was that used in the MRST2004 analysis [31]. The top figure is calculated for $\sqrt{s} = 500$ GeV, and the bottom figure is calculated for $\sqrt{s} = 1000$ GeV. All three curves in Fig. 2 include the sea quark CSV terms from Eq. (2). They differ in the amount of valence quark CSV of the type given by Eq. (1). In each graph, the solid line corresponds to no valence CSV ($\kappa = 0$), while the short-dashed and long-dashed curves are for $\kappa = -0.8$ and $\kappa = +0.65$, the parameters corresponding to the 90% confidence limit obtained in the MRST global fit.

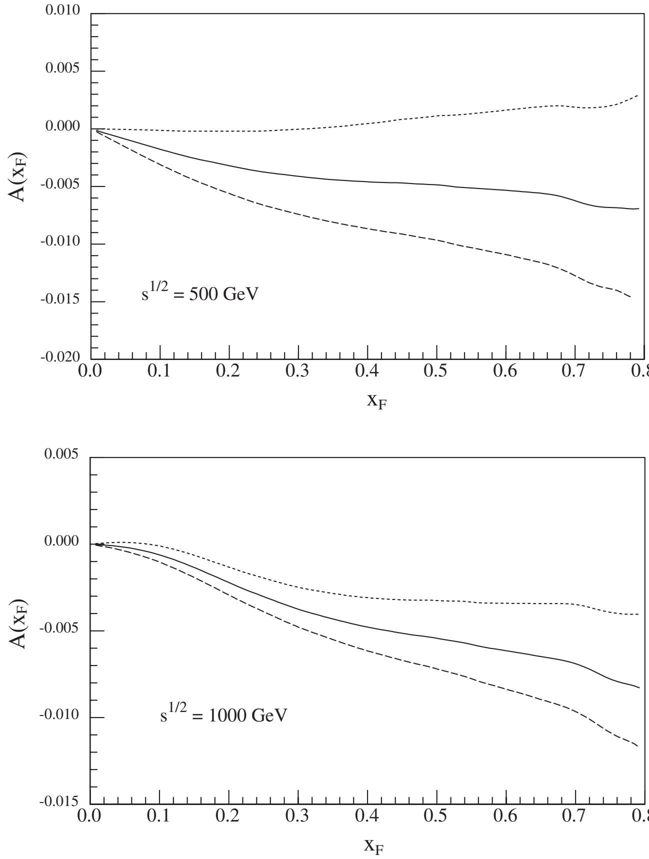

FIG. 2. The forward-backward asymmetry $A(x_F)$ defined in Eq. (10) as a function of x_F. Top graph: $\sqrt{s} = 500$ GeV; bottom graph: $\sqrt{s} = 1000$ GeV. The curves include CSV generated by QED effects, and sea quark CSV described by Eq. (2). They differ in the amount of valence quark CSV defined by Eq. (1). Solid curve: no valence quark CSV, $\kappa = 0$; long-dashed curve: $\kappa = +0.65$; short-dashed curve: $\kappa = -0.8$.

Figure 2 shows that the sea quark CSV and the QED isospin violation tend to produce negative forward-backward W asymmetries. The contributions from valence quark CSV, with magnitudes at the 90% confidence level extracted by MRST, contribute a roughly equal magnitude to the asymmetries produced by the other sources of CSV. For negative values of κ, which agree with theoretical estimates of valence quark CSV [9,10], the valence CSV terms tend to cancel the asymmetry produced by sea quark

CSV; while for positive values of κ the various sources of isospin violation tend to add. Note that the predicted forward-backward asymmetries are quite small. The magnitude is less than 0.01 for almost all values of x_F. These results are considerably smaller than those obtained by Boros *et al.* [22], who predicted rather large positive values for $A(x_F)$, as large as $A(x_F) \sim +0.07$ for $x_F \sim 0.7$. There are two reasons for this difference. First, the sea quark CSV terms are substantially smaller for MRST than those extracted by Boros *et al.*, by a factor of 5 or six; the sea quark CSV terms obtained by MRST and Boros also have opposite signs. Second, with the very large values of sea quark CSV extracted by Boros, the Cabibbo-unfavored terms were negligible. However, with the much smaller sea quark CSV obtained by MRST, the Cabibbo-unfavored terms can no longer be neglected, and they tend to cancel the Cabibbo-favored contribution.

This calculation of the forward-backward asymmetry for W production finds that the expected effects are quite small, generally less than 1% for the range of CSV effects obtained by MRST. With the expected levels of isospin violation in PDFs, it will be necessary to measure these asymmetries to better than 1% if this observable is to provide a test for charge symmetry violation in parton distributions.

This work was supported in part [J. T. L] by National Science Foundation research contract No. PHY0244822 and [A. W. T] by DOE contract No. DE-AC05-84150, under which SURA operates Jefferson Laboratory.

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