Drell-Yan Processes as a Probe of Charge Symmetry Violation in the Pion and the Nucleon

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Abstract

We extend earlier investigations of charge symmetry violation in the valence quark distributions of the nucleon, and make similar estimates for the pion. The sensitivity of pion-induced Drell-Yan measurements to such effects is then examined. It is shown that combinations of $\pi^+$ and $\pi^-$ data on deuterium and hydrogen are sensitive to these violations, and that the pion and nucleon charge symmetry violating terms separate as a function of $x_\pi$ and $x_N$ respectively. We estimate the background terms which must be evaluated to extract charge symmetry violation.

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At the present time the flavor structure of the nucleon is a topic of intense interest [1-8]. This is largely a consequence of unexpected experimental results, such as the discovery by the New Muon Collaboration (NMC) of a violation of the Gottfried sum-rule [9] and the so-called “proton spin crisis” [10, 11, 12] of EMC. There have also been recent theoretical calculations of the violation of charge symmetry in the valence quark distributions of the nucleon [13, 14].

In most nuclear systems, charge symmetry is obeyed to within about one percent [15], so one would expect small charge symmetry violation [CSV] in parton distributions. The theoretical calculations suggest that there is a CSV part of the “minority” valence quark distributions ($d_p$ or $u_n$), with a slightly smaller violation in the “majority” valence distributions ($u_p$ or $d_n$). Although both CSV contributions are rather small in absolute magnitude, the fractional charge symmetry violation in the minority valence quark distributions $r_{\text{min}}(x) \equiv 2(d_p(x) - u_n(x))/(d_p(x) + u_n(x))$ can be large, because at large momentum fraction $x$, $d_p(x)/u_p(x) << 1$. Rodionov et al. [14] predicted charge symmetry violation as large as $5 - 10\%$ for the ratio $r_{\text{min}}(x)$, in the region $x > 0.5$. The relative size of these CSV effects might require a change in the standard notation for parton distributions [16] in this region; in addition, Sather [13] showed that CSV effects of this magnitude could significantly alter the value of the Weinberg angle extracted from neutral and charged current neutrino interactions.

Since (in this particular region of Bjorken $x$) we predict fractional CSV violations as large as $5 - 10\%$, it is important to explore experiments which would be sensitive to the relative minority quark distributions in the neutron and proton. Observation of a CSV effect at this level would reinforce confidence in our ability to relate quark models to measured quark-parton distributions – and hence to use deep inelastic scattering as a real probe of the non-perturbative aspects of hadron structure [17]. Drell-Yan processes have proven to be a particularly useful source of information on the anti-quark distributions in nuclei [18]. If one uses beams of pions, and concentrates on the region where Bjorken $x$ of the target quarks is reasonably large, then the annihilating quarks will predominantly come from the nucleon and the antiquarks from the pion. Furthermore, for $x \geq 0.4$ to good approximation the nucleon consists of three valence quarks, and the pion is a quark-antiquark valence pair – in particular, $\pi^+$ contains a valence $\bar{d}$ and $\pi^-$ a valence $\bar{u}$. Comparison of Drell-Yan processes induced by $\pi^+$ and $\pi^-$ in this kinematic region will provide a good method of separately measuring $d$ and $u$ quark distributions in the nucleon.

Consider the Drell-Yan process in which a quark with momentum fraction $x_1$ in a deuteron annihilates with an anti-quark of momentum fraction $x_2$ in a $\pi^+$. Provided that $x_1, x_2 \geq 0.4$, to minimize the contribution from sea quarks, this will be the dominant process. Neglecting sea quark effects, the Drell-Yan cross section will be proportional to:

$$\sigma_{\pi^+D}^{\text{DY}} \sim \frac{1}{9} (d_p(x_1) + d_n(x_1)) \bar{d}^{\pi^+}(x_2).$$

The corresponding cross section for $\pi^-D$ is:

$$\sigma_{\pi^-D}^{\text{DY}} \sim \frac{4}{9} (u_p(x_1) + u_n(x_1)) \bar{u}^{\pi^-}(x_2),$$

so that if we construct the ratio, $R_{\pi D}^{\text{DY}}$:

$$R_{\pi D}^{\text{DY}}(x_1, x_2) = \frac{4\sigma_{\pi^+D}^{\text{DY}} - \sigma_{\pi^-D}^{\text{DY}}}{(4\sigma_{\pi^+D}^{\text{DY}} + \sigma_{\pi^-D}^{\text{DY}})/2},$$

(3)
only charge symmetry violating (CSV) terms contribute. In fact, defining

\[ \delta d = d^p - u^n, \quad \delta u = u^p - d^n, \quad \delta \bar{d} = \bar{d}^p - \bar{u}^n, \]

(and recalling that charge conjugation implies \( \bar{d}^+ = d^− \) etc.) we find that, to first order in the small CSV terms, the Drell-Yan ratio becomes:

\[ R_{\pi D}^{DY}(x_1, x_2) = \left( \frac{\delta d - \delta u}{u^p + d^p} \right)(x_1) + \left( \frac{\delta \bar{d}}{d^p} \right)(x_2), \]

\[ = R_N^{\pi D}(x_1) + R^\pi(x_2), \]

Equation (5) is quite remarkable in that only CSV quantities enter, and there is a separation of the effects associated with the nucleon and the pion. Because \( R_{\pi D}^{DY} \) is a ratio of cross sections one expects a number of systematic errors to disappear – although the fact that different beams (\( \pi^+ \) and \( \pi^- \)) are involved means that not all such errors will cancel. This certainly needs further investigation, since \( R^{DY} \) is obtained by almost complete cancellation between terms in the numerator. The largest “background” term, contributions from nucleon or pion sea, will be estimated later in this letter. However we note that Equ. (5) is not sensitive to differences between the parton distributions in the free nucleon and those in the deuteron [19, 20, 21, 22]. For example, if the parton distributions in the deuteron are related to those in the neutron and proton by

\[ q^D_i(x) = (1 + \epsilon(x)) (q^p_i(x) + q^n_i(x)), \]

then by inspection equ. (6) will be unchanged. Any correction to the deuteron structure functions which affects the proton and neutron terms identically will cancel in \( R^{DY} \).

It should not be necessary to know absolute fluxes of charged pions to obtain an accurate value for \( R^{DY} \). The yield of \( J/\psi \)'s from \( \pi^+ - D \) and \( \pi^- - D \) can be used to normalize the relative fluxes, since the \( J/\psi \)'s are predominantly produced via gluon fusion processes. The gluon structure functions of the \( \pi^+ \) and \( \pi^- \) are identical, so the relative yield should be unity to within 1%.

Next we turn to the predictions for the charge symmetry violating terms, \( \delta d, \delta u \) and \( \delta \bar{d} \) which appear in equ.(5). For the former two there has been an extensive discussion by Sather [13] and Rodionov et al.[14] from which there is at least a theoretical consensus that the magnitude of \( \delta d \) is somewhat larger than \( \delta u \). This is easy to understand because the dominant source of CSV is the mass difference of the residual di-quark pair when one quark is hit in the deep-inelastic process. For the minority quark distribution the residual di-quark is \( uu \) in the proton, and \( dd \) in the neutron. Thus, in the difference, \( d^p - u^n \), the up-down mass difference enters twice. Conversely, for the majority quark distributions the residual di-quark is a \( ud \)-pair in both proton and neutron, so there is no contribution to CSV.

In Fig. 1(a) we show the predicted CSV terms for the majority and minority quark distributions in the nucleon, as a function of \( x \), calculated for the simple MIT bag model [14, 23, 24]. There are, of course, more sophisticated quark models available but the similarity of the results obtained by Naar and Birse [25] using the color dielectric model suggests that similar results would be obtained in any relativistic model based on confined current quarks. The bag model parameters are listed in this Figure. The mean di-quark masses are chosen as 600 MeV for the \( S = 0 \) case, and 800 MeV for the \( S = 1 \) case.
(note that for the minority quark distributions the di-quark is always in an $S = 1$ state). The di-quark mass difference, $m_{dd} - m_{uu}$, is taken to be 4 MeV, a rather well determined difference in the bag model. We note that $\delta u$ is opposite in sign to $\delta d$ and, therefore, these two terms add constructively in the Drell-Yan ratio $R^{DY}$ of equ. (3).

Fig. 1.
(a) Predicted charge symmetry violation (CSV), calculated using the MIT bag model. Dashed curve: “minority” quark CSV term, $x\delta d(x) = x (d^{p}(x) - u^{n}(x))$; solid curve: “majority” quark CSV term, $x\delta u(x) = x (u^{p}(x) - d^{n}(x))$. (b) Fractional minority quark CSV term, $\delta d(x)/d^{p}(x)$, vs. $x$, as a function of the average di-quark mass $\overline{m}_{d} = (m_{uu} + m_{dd})/2$. The di-quark mass difference is fixed at $\delta m_{d} = m_{dd} - m_{uu} = 4$ MeV. From top to bottom, the curves correspond to average di-quark mass $\overline{m}_{d} = 850, 830, 810, 790, 770$, and $750$ MeV. The curves have been evolved to $Q^{2} = 10$ GeV$^{2}$. This quantity is the nucleonic CSV term for the Drell-Yan ratio $R^{DY}_{\pi N}$ of Equ. (11).
In Fig. 1(b) we show the fractional change in the minority quark CSV term, \(2(d^p - u^n)/(d^p + u^n)\) vs. \(x\) for several values of the intermediate mean di-quark mass. Although the precise value of the minority quark CSV changes with mean di-quark mass, the size is always roughly the same and the sign is unchanged. This shows that “smearing” the mean di-quark mass will not dramatically diminish the magnitude of the minority quark CSV term (the mean di-quark mass must be roughly 800 MeV in the \(S = 1\) state to give the correct \(N - \Delta\) mass splitting).

In Fig. 2 we show the nucleon CSV contribution, \(R^N_{x_D}(x_1)\), calculated using the same bag model. As is customary in these bag model calculations, this term is calculated at the bag model scale (0.5 GeV for \(R = 0.8\) fm) and then evolved to higher \(Q^2\) using the QCD evolution equations [26]. As the main uncertainty in our calculation is the mean di-quark mass (the splitting between \(S = 0\) and \(S = 1\) is kept at 200 MeV [27]), the results are shown for several values of this parameter. In the region \(0.4 \leq x \leq 0.7\), we predict \(R^N\) will be always positive, with a maximum value of about 0.015. For \(x > 0.7\) the struck quark has a momentum greater than 1 GeV which is very unlikely in a mean-field model like the bag. As a consequence the calculated valence distributions for the bag model tends to be significantly smaller than the measured distributions in this region. In these circumstances one cannot regard the large, relative charge symmetry violation found in this region as being reliable and we prefer not to show it. It would be of particular interest to add \(q - q\) correlations which are known to play an important role as \(x \to 1\) [28].

For the pion, calculations based on the MIT bag model are really not appropriate. In particular, the light pion mass means that center of mass corrections are very large, and of course bag model calculations do not recognize the pion’s Goldstone nature. On the other hand the model of Nambu and Jona-Lasinio (NJL) [29] is ideally suited to treating the
structure of the pion, and there has been recent work, notably by Toki and collaborators, in calculating the structure function of the pion (and other mesons) in this model \[30, 31\]. The essential element of their calculation was the evaluation of the so-called handbag diagram for which the forward Compton amplitude is:

\[
T_{\mu\nu} = i \int \frac{d^4k}{(2\pi)^4} \text{Tr}[\gamma_\mu Q \frac{1}{k} \gamma_\nu Q T_-] + (T_+ \text{term}),
\]

where

\[
T_- = S_F(k - q, M_1)g_{\pi qq}\tau_+ i\gamma_5 S_F(k - p - q, M_2)g_{\pi qq}\tau_- i\gamma_5 S_F(k - q, M_1),
\]

represents the contribution with an anti-quark of mass \(M_2\) as spectator to the absorption of the photon (of momentum \(q\)) by a quark. In equ.(8) \(g_{\pi qq}\) is the pion-quark coupling constant, \(Q\) the charge of the struck quark, \(p\) the momentum of the target meson, and \(S_F\) the quark propagator. \(T_+\) is the corresponding term where the quark is a spectator and the anti-quark undergoes a hard collision. As in our bag model studies this model was used to determine the leading twist structure function at some low scale (0.25 GeV in this case), and then evolved to high-\(Q^2\) using the Altarelli-Parisi equations [26]. The agreement between the existing data and the calculations for the pion and kaon obtained in ref.(30) was quite impressive.

\[
\begin{align*}
\text{--- 250MeV} & \\
\text{--- 10 GeV} & \\
\end{align*}
\]

In the light of the successful application of the NJL model to the structure functions of the pion and the kaon, where the dominant parameter is the mass difference between the constituent strange and non-strange quarks (assumed to be about 180 MeV), it seems natural to use the same model to describe the small difference \(\delta \bar{d}\pi\) (c.f. equ.(4)) arising from the 3 MeV constituent mass difference of the u and d[15]. We have carried out such
a calculation. Figure 3 shows the pionic contribution to the CSV Drell-Yan ratio, $R^{\pi}(x_2)$, corresponding to this mass difference and an average non-strange quark mass of 350 MeV – as used in ref.\([30, 31]\). The dashed curve is the result at the bag scale, and the solid curve shows the result evolved to $Q^2 = 10 \text{ GeV}^2$. For $x_2 \geq 0.3$, we predict that $R^{\pi}$ will be positive and increase monotonically, reaching a value of about 0.01 at $x_2 = 0.8$ and increasing to about 0.02 as $x_2 \to 1$. (We note that there is some ambiguity in translating the usual Euclidean cut-off in the NJL model into the cutoff needed for deep inelastic scattering. In order to study charge symmetry violation we are particularly concerned to start with a model that gives a good description of the normal pion structure function. For this reason we have chosen to follow the method used in ref.\([30]\) rather than ref.\([31]\).)

Up to this point we have neglected the nucleon and pion sea quark contributions. Since the Drell-Yan ratios arising from CSV are very small (viz. Figures 2 and 3), even small contributions from sea quarks could make a substantial effect. The dominant contribution will arise from interference between one sea quark and one valence quark. Assuming charge symmetry for the quark distributions, and using the same form for the quark and antiquark distributions in the pion, the sea-valence contribution to the Drell-Yan ratio of Eq. (5) has the form

$$
R_{\pi D}^{SV}(x_1, x_2) = \frac{3\sigma_{\pi D}^{SV}(x_1, x_2)}{\left(\frac{2d^p_\pi(x_2)}{5d^p_\pi(x_2)} + \frac{2d^p_\pi(x_1)}{5d^p_\pi(x_1)}\right)};
$$

$$
\sigma_{\pi D}^{SV}(x_1, x_2) = \frac{5}{9} \left[2\pi_s(x_2)u_p^p(x_1) + \pi_s(x_2)u_p^p(x_1) + d_p^p(x_1)\right].
$$

Unlike the CSV contributions of Eq. (5), the sea-valence term does not separate. In Figure 4 we show the sea-valence term as a function of $x_1$ and $x_2$ using recent phenomenological nucleon and pion parton distributions \([32]\). The sea-valence contribution, although extremely large at small $x$, decreases rapidly as $x$ increases. For $x \geq 0.5$, the sea-valence term is no larger than the CSV “signal”. With accurate phenomenological nucleon and pion quark distributions, it should be possible to calculate this contribution reasonably accurately (the main uncertainty is the magnitude of the pion sea). For smaller values ($x_1 \approx x_2 \approx 0.4$, where the background dominates, we could use the data to normalize the pion sea contribution; we should then be able to predict the sea-valence term rather accurately for larger $x$ values, where the CSV contributions become progressively more important. We could also exploit the very different dependence on $x_1$ and $x_2$ of the background and CSV terms. We conclude that the CSV terms could be extracted even in the presence of a sea-valence “background”. We emphasize that our proposed Drell-Yan measurement would constitute the first direct observation of charge symmetry violation for these quark distributions.

The Drell-Yan CSV ratio $R_{\pi D}^{DY}$ of Eq. (6) is the sum of the nucleon CSV term of Fig. 2 and the pion term of Fig. 3, at the respective values of Bjorken $x$. Since both quantities are positive, they will add to give the experimental ratio. Despite the fact that the fractional minority quark CSV term is as large as 10% (c.f. Fig. 1(b)), the nucleonic CSV ratio $R_{\pi D}^{N}$ is more like 1-2%. This is because $\delta d$ in equ. (6) is divided by $u^p + d^p$ and since $d^p(x) << u^p(x)$ at large $x$ the nucleon CSV term is significantly diminished. A much larger ratio could be obtained by comparing the $\pi^+ - p$ and “$\pi^- - n$” Drell-Yan
processes through the ratio:

\[ R_{\pi N}^{DY}(x_1, x_2) = \frac{4\sigma_{\pi^+ p}^{DY} + \sigma_{\pi^- p}^{DY} - \sigma_{\pi^- D}^{DY}}{4\sigma_{\pi^+ p}^{DY} - \sigma_{\pi^- p}^{DY} + \sigma_{\pi^- D}^{DY}} / 2. \]  \hfill (10)

To first order in the small CSV quantities, this ratio can be written:

\[ R_{\pi N}^{DY}(x_1, x_2) = \frac{\delta d}{dp}(x_1) + \left( \frac{\delta d}{dp}(x_2) \right), \]

\[ = R^N_{\pi N}(x_1) + R^x(x_2). \]  \hfill (11)

Once again, the ratio separates completely in \( x_1 \) and \( x_2 \), and the pion CSV term is identical with equ. (5). However, the nucleon CSV term is much larger – in fact, it is precisely the ratio given in Fig. 1(b), so we expect CSV effects at the 5-10% level for this quantity.

Fig. 4. The sea-valence contribution \( R_{SV}^{\pi D} \) to pion-induced Drell-Yan ratios on deuterons, as a function of nucleon \( x_1 \). Solid curve: pion \( x_2 = 0.4 \); dashed curve: \( x_2 = 0.6 \); long-dashed curve: \( x_2 = 0.8 \). This quantity was calculated using nucleon and pion parton distributions of Ref. [32].

Some care will need to be taken to normalize cross sections since one is comparing Drell-Yan processes on protons and deuterons. This should be feasible by bombarding both hydrogen and deuterium targets simultaneously with charged pion beams. Eq. (11) assumes that deuteron structure functions are just the sum of the free nucleon terms; if we include corrections in the form of Eq. (6), we obtain an additional first-order correction

\[ \delta R_{\pi N}^{DY}(x_1) = -\epsilon(x_1) \left( \frac{u^p + d^p}{d^p} \right)(x_1) \]  \hfill (12)

This preserves the separation into nucleonic and pionic CSV terms, but depends on ‘EMC’ changes in the deuteron structure functions relative to free proton and neutron distributions, and on the \( u/d \) ratio of proton distributions. For large \( x, u(x)/d(x) \gg 1 \), so the
EMC term could be significant even for small values of $\epsilon(x)$. For $x \sim 0.5$, where $w_p/d_p \approx 4$, if $\epsilon(x)$ is as large as -0.02 then $\delta R_{\pi N}^{DY}(x = 0.5) \approx 0.10$. At larger $x$ the EMC contribution could be even bigger, and might conceivably dominate the CSV terms. Since all terms (pion and nucleon CSV, and EMC) are predicted to have the same sign in the region $0.3 < x < 0.8$ (we expect $\epsilon(x) < 0$ in this region), the ratio $R_{\pi N}^{DY}$ could be as large as 0.3. In view of this sensitivity to the EMC term, it is important that accurate calculations be carried out of Fermi motion and binding corrections for the deuteron, including possible flavor dependence of such corrections. Melnitchouk, Schreiber and Thomas $^{[22, 33]}$ have recently studied the contributions to $\epsilon(x)$ in the deuteron.

We have also calculated the sea-valence contribution to the Drell-Yan ratio $R_{\pi N}^{DY}$. Relative to the deuteron measurement, we predict a CSV contribution which increases by about a factor 5. The sea-valence background also increases by about the same factor. So our remarks about the sea-valence background and the CSV “signal” are equally valid for these Drell-Yan processes.

In conclusion, we have shown that by comparing the Drell-Yan yield for $\pi^+$ and $\pi^-$ on nucleons or deuterons, one might be able to extract the charge symmetry violating [CSV] parts of both pion and nucleon. We discussed two different linear combinations of $\pi^+$ and $\pi^-$ induced Drell-Yan cross sections, which produce a result directly proportional to the CSV terms. Furthermore, we found that the ratio of Drell-Yan cross sections separates completely into two terms, one of which $(R_N^{N}(x_N))$ depends only on the nucleon CSV, and the other $(R_{\pi}^{\pi}(x_{\pi}))$ depends on the pion CSV contribution. Thus if this ratio can be accurately measured as a function of $x_N$ and $x_{\pi}$, both the nucleon and pion CSV terms might be extracted. The largest background should arise from terms involving one sea quark and one valence quark. Such contributions, although relatively large, should be predicted quite accurately, and may be subtracted off through their very different behavior as a function of nucleon and pion $x$. As the $x_1$ and $x_2$ values of interest for the proposed measurements are large $(x > 0.5)$, a beam of 40-50 GeV pions will produce sufficiently massive dilepton pairs that the Drell-Yan mechanism is applicable. A flux of more than $10^9$ pions/sec. is desirable, which may mean that the experiment is not feasible until the new FNAL Main Ring Injector becomes operable.

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References

[1] A.D.Martin, W.J.Stirling and R.G.Roberts, Phys. Lett. B252 (1990) 653; S.D.Ellis and W.J.Stirling, Phys. Lett. B256 (1991) 258.

[2] A.Signal, A.W.Schreiber and A.W.Thomas, Mod. Phys. Lett. A6 (1991) 271.

[3] E.M.Henley and G.A.Miller, Phys. Lett. B251 (1990) 453.

[4] G.Preparata, P.G.Ratcliffe and J.Soffer, Phys. Rev. Lett. 66 (1991) 687.

[5] S.Kumano, Phys. Rev. D43 (1991) 59; S.Kumano and J.T.Londergan, Phys. Rev. D44 (1991) 717.
[6] W. Melnitchouk and A. W. Thomas, Phys. Rev. D47 (1993) 3783; V.R. Zoller, Phys. Lett. B279 (1992) 145; B. Badelek and J. Kwiecinski, Nucl. Phys. B370 (1991) 278.

[7] W. Melnitchouk, A. W. Thomas and A. I. Signal, Zeit. Phys. 340 (1991) 85.

[8] M. Sawicki and J. P. Vary, Phys. Rev. Lett. 71 (1993) 1320.

[9] P. Amaudruz et al. (NMC Collaboration), Phys. Rev. Lett. 66 (1991) 560.

[10] J. Ashman et al. (EMC Collaboration), Phys. Lett. B206 (1988) 364; Nucl. Phys. B328 (1990) 1.

[11] B. Adeva et al. (SMC Collaboration), Phys. Lett. B302 (1993) 533; P. L. Anthony et al., Phys. Rev. Lett. 71 (1993) 959.

[12] R. Windmolders, Int. J. Mod. Phys. A7 (1992) 639; S. D. Bass and A. W. Thomas, J. Phys. G19 (1993) 925.

[13] E. Sather, Phys. Lett. B274 (1992) 433.

[14] E. Rodionov, A. W. Thomas and J. T. Londergan, Mod. Phys. Lett. A9, 19 (1994) 1799.

[15] G. A. Miller, B. M. K. Nefkens and I. Šlaus, Phys. Rep. 194 (1990) 1.

[16] F. E. Close, "An Introduction to Quarks and Partons" (Academic, London, 1979); E. Leader and E. Predazzi, "Gauge theories and the New Physics" (Cambridge University Press, Cambridge, 1982).

[17] A. W. Thomas and W. Melnitchouk, University of Adelaide preprint: ADP-93-217/T135, to appear in Proc. JSPS-INS Spring School, World Scientific (1994).

[18] D. M. Alde et al., Phys. Rev. Lett. 64 (1990) 2479.

[19] A. Bodek and J. L. Ritchie, Phys. Rev. D23 (1981) 1070.

[20] L. L. Frankfurt and M. I. Strikman, Phys. Rep. 160 (1988) 235.

[21] R. P. Bickerstaff and A. W. Thomas, J. Phys. G15 (1989) 1523.

[22] W. Melnitchouk, A. W. Schreiber and A. W. Thomas, Phys. Rev. D49 (1994) 1183.

[23] A. Chodos et al. Phys. Rev. D10 (1974) 2599.

[24] A. I. Signal and A. W. Thomas, Phys. Rev. D40 (1989) 2832; A. W. Schreiber, A. W. Thomas and J. T. Londergan, Phys. Rev. D42 (1990) 2226.

[25] E. Naar and C. Birse, Phys. Lett. B305 (1993) 190.

[26] G. Altarelli and G. Parisi, Nucl. Phys. B126 (1977) 298.

[27] F. E. Close and A. W. Thomas, Phys. Lett. B212 (1988) 227.
[28] G. Farrar and D. Jackson, *Phys. Rev. Lett.* **35** (1975) 1416.

[29] Y. Nambu and G. Jona-Lasinio, *Phys. Rev.* **122** (1961) 345; *ibid.* **124** (1961) 246.

[30] T. Shigetani, K. Suzuki and H. Toki, *Phys. Lett.* **B308** (1993) 383.

[31] T. Shigetani, K. Suzuki and H. Toki, Tokyo Metropolitan University preprint: TMU-NT940101 (1994).

[32] P.N. Harriman, A.D. Martin, W.J. Stirling and R.G. Roberts, *Phys. Rev.* **D42** (1990) 798; P.J. Sutton, R.G. Roberts, A.D. Martin and W.J. Stirling, *Phys. Rev.* **D45** (1992) 2349. We used the nucleon parton distribution HMRS(B), and pion fit 3, for which the pion sea carries 10% of the pion’s momentum at $Q^2 = 4 \text{ GeV}^2$.

[33] W. Melnitchouk, A. W. Schreiber and A. W. Thomas, *Phys. Lett.* **B 335** (1994) 11.