VALIDITY OF FLAVOR SYMMETRY AND CHARGE SYMMETRY FOR PARTON DISTRIBUTIONS

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Recent experimental measurements of the Gottfried Sum Rule, and pp and pD Drell-Yan processes, suggest significant violation of flavor symmetry in the proton sea. This interpretation rests on the assumption of parton charge symmetry. Our model calculations suggest charge symmetry violation [CSV] for parton valence distributions of a few percent. Precision measurements of structure functions in muon and neutrino reactions allow us to set rather stringent experimental limits on CSV in certain kinematic regions. In another region, these experiments suggest substantial CSV effects. We suggest experiments which could test parton CSV.

1 Flavor Symmetry in Parton Distributions

The basic features of parton distributions have been well established through measurements of deep inelastic scattering [DIS], Drell-Yan processes and direct photon experiments. Precision tests of approximate symmetries allow us to understand the details of nucleon parton distributions. For example, we know that the strange quark distribution is substantially smaller than the light non-strange sea, due to the relatively large mass of the s quark (this is sometimes termed SU(3) flavor symmetry violation). A new generation of precise high energy experiments allows us to examine finer details of parton distributions. An example of this is the NMC experiment which measured µp and µD DIS, and accurately tested the Gottfried Sum Rule \( S_G \) by comparing \( F_{2\mu p} \) and \( F_{2\mu n} \). Assuming \( d^p(x) = \bar{u}^p(x) \) one predicts \( S_G = 1/3 \). pQCD predicts very small deviations from 1/3. The NMC result \( S_G = 0.235 \pm 0.026 \) was four standard deviations lower than the “naive” prediction, apparently indicating significant flavor symmetry violation [FSV] in the proton sea.

This was followed by a comparison of pp and pD Drell-Yan [DY] processes. For large \( x_F \) the ratio of DY cross sections will be larger than one if \( d^p(x) > \bar{u}^p(x) \), as observed in the E866 experiment (for a detailed discussion see the talk by W. Melnitchouk at this conference). The most promising theoretical model to date is the “meson-cloud” picture. In these models one includes a quark “core” for the nucleon plus a “cloud” of baryon-meson Fock components, and the virtual photon scatters from any of these components. Melnitchouk showed that quantitative agreement with E866 data can be achieved with a model including nucleon, pion and \( \Delta \) components.
Charge Symmetry Violation in Parton Distributions

At first sight, the DY and NMC experiments appear to show a large FSV contribution to the proton sea. However, all these results depend on the assumption of parton charge symmetry. Ma showed that both the DY and NMC experiments could be reproduced, even if flavor symmetry was exact, by assuming a sufficiently large violation of parton charge symmetry. In this talk we examine the following questions: 1) Are there theoretical grounds for expecting parton CSV? 2) What are the present experimental limits on parton charge symmetry? 3) What are the most promising experiments which could improve the current limits on parton CSV?

2.1 A Model for Parton Charge Symmetry Violation

Charge symmetry for parton distributions has been investigated recently by several groups. We review here the work of Benesh and Londergan. This is based on the Adelaide model for evaluating twist-two parton distributions with proper support. It involves evaluating contributions to parton distributions through the relation

\[ q(x, \mu^2) = M \sum_X |\langle X | \psi_+(0) | N \rangle|^2 \delta(M(1-x) - p_X^+) \]  

(1)

In Eq. 1, \( \psi_+ = (1 + \alpha_3)\psi/2 \), and \( X \) represents a complete set of eigenstates of the Hamiltonian \( H \). The parton distribution \( q(x, \mu^2) \) is guaranteed to have proper support, i.e. it vanishes by construction for \( x > 1 \).

For relatively large \( x \) values, the dominant contribution to the valence quark distribution comes from the lowest two-quark spectator state contributing to Eq. 1. In this case, we can derive an analytic form for the change in the quark distribution \( \delta q(x) \) arising from a small change \( \delta m \) in the diquark mass,

\[ \delta q(x) \approx \frac{2m \delta m(1-x)}{M^2(1-x)^2 + m^2} \frac{dq(x)}{dx} \]  

(2)

From this equation, we can estimate the magnitude of charge symmetry violation directly from phenomenological parton distributions without using quark models. The results obtained are in very good agreement with direct quark model calculations of CSV effects through Eq. 1. Alternatively, we can relate CSV effects to spin-flavor effects on parton distributions. In Fig. 1, we show calculations of parton charge symmetry violation in which we include both diquark mass contributions and nucleon mass differences; the quark CSV terms...
Figure 1: CSV valence quark distributions $x\delta u(x)$ (neg) and $x\delta d(x)$ (pos), taken from Ref. 6. CSV terms arise from mass difference in spectator diquark, and from $n-p$ mass difference.

are defined through

\[ \delta d_v(x) = d_v^p(x) - u_v^n(x) \]
\[ \delta u_v(x) = u_v^p(x) - d_v^n(x) \]

(3)

The theoretical parton CSV terms are predicted to be approximately equal and opposite, i.e. $\delta u_v(x) \approx -\delta d_v(x)$. Since at large $x$ we have $d_v(x) \ll u_v(x)$, the fractional CSV term will be much larger for the “minority quark” term $d_v(x)$ than for $u_v(x)$. We predict $\delta d_v(x)/d_v(x)$ to be of order 3-6% at large $x$. The effect shown here is sufficiently large that one could question its reliability. However, it appears to be robust since it is obtained through either simple quark models, or through the analytic result using, e.g., CTEQ parton distribution. It is important that this prediction be verified experimentally. However, it requires experiments which specifically probe the “minority” quark distribution, since this is substantially smaller than the “majority” quark distribution at large $x$.

2.2 Experimental Status of Parton Charge Symmetry

The most sensitive experimental test of parton charge symmetry to date is the “charge ratio”. There is a simple relation between the $F_2$ structure functions for charged lepton DIS and neutrino charged current reactions on an isoscalar
Figure 2: Charge ratio $R_c(x)$ of Eq. 4 obtained using NMC $\mu$-D structure functions and CCFR $\nu$-iron. Solid circles: heavy target shadowing corrections calculated specifically for neutrinos; open circles: $\nu$ heavy target corrections taken from shadowing observed in charged lepton DIS.

The relation $R_c(x) = 1$ should hold for all $x$ and $Q^2$, with no QCD corrections. The only things which break this relation are parton CSV terms, or contributions from $s(x) \neq \bar{s}(x)$.

In Fig. 2 we plot $R_c(x)$, the ratio of NMC $\mu$-D structure functions to CCFR $\nu$-Fe measurements. The solid circles show the ratio $R_c(x)$, when the heavy target corrections are calculated specifically for neutrinos. For intermediate values $x > 0.1$ the agreement between structure functions is very good, and we can set upper limits of a few percent on parton CSV. However, in the region $x < 0.1$, $R_c$ deviates from unity by as much as 10%. This is discussed in the paper by C. Boros at this conference. From Eq. 4 it would appear that the low-$x$ discrepancy could be accommodated by allowing $s(x) \neq \bar{s}(x)$. However,
if one combines NMC and CCFR data with opposite-sign dimuon production data from neutrino reactions (which is used to extract $s(x)$), then one can show that the discrepancy cannot be removed unless one takes $\bar{s}(x) < 0$, which is not physically reasonable. Thus, if the existing data are correct, they are not compatible unless one assumes a very large sea quark CSV effect (roughly 25%) at small $x$.

3 Proposed Experimental Tests of Parton Charge Symmetry

3.1 Test of Weak Current Relation $F_1^{W^+N_0}(x) = F_1^{W^-N_0}(x)$

At sufficiently high energies, the charge-changing structure functions on an isoscalar target are equal except for contributions from valence quark CSV, and possible strange or charmed quark terms, i.e.

$$\frac{2(F_1^{W^+N_0}(x, Q^2) - F_1^{W^-N_0}(x, Q^2))}{F_1^{W^+N_0}(x, Q^2) + F_1^{W^-N_0}(x, Q^2)} \approx \frac{\delta d_v(x) - \delta u_v(x)}{Q(x)}$$

$$+ \frac{2(s(x) - \bar{s}(x))}{Q(x)}$$

$$\equiv R_{CSV}(x) + R_s(x)$$

$$Q(x) = \sum_{j=u,d,s} q_j^2(x) + q_\bar{j}^2(x) \quad \text{(5)}$$

In Eq. 5 we have expanded to lowest order in the small CSV terms. At the enormous values of $Q^2$ that can be probed at HERA, weak interaction processes such as $e^- p \to \nu_e X$ are not impossibly small compared to the electromagnetic process $e^- p \to e^- X$. If deuteron beams were available at HERA, this would provide a very clean test of charge symmetry, and/or the equality of strange/antistrange quark distributions. The $(e^-, \nu_e)$ reaction picks out positively charged partons in the target, while the $(e^+, \bar{\nu}_e)$ reaction measures the negatively charged partons.

The difference between the structure functions $F_1^{W^+D}$ and $F_1^{W^-D}$ has been studied recently. The results are shown in Fig. the $s - \bar{s}$ term was taken from the model of Melnitchouk and Malheiro. For sufficiently large $x$ values predicted results are as large as a few percent. This experiment would provide a strong test of charge symmetry in parton distributions, and would require almost none of the corrections necessary for the “charge ratio” test. Note that at small $x$ this comparison could test whether $\bar{s}(x) = s(x)$, and thus distinguish between the strange/antistrange and CSV contributions to the small-$x$ charge ratio discrepancy.
3.2 Drell-Yan Processes Initiated by Charged Pions on Isoscalar Targets

One way to test parton charge symmetry is to compare DY processes for charged pions on isoscalar targets. This is most evident in the “valence-dominated” region, where both $x_π$ and $x$ are large. In this region,

$$|π^+⟩ \sim u^+ π^+ \bar{d}^+; \quad |π^-⟩ \sim d^+ \bar{u}^+; \quad |p(n)⟩ \sim u_v + d_v.$$  \hspace{1cm} (6)

Thus, in $|π^+⟩$ ($|π^-⟩$) DY, a $\bar{d}$ ($\bar{u}$) in the pion will annihilate a down (up) valence quark in the nucleon. We can test charge symmetry by forming the following ratio for an isoscalar target $N_0$:

$$R^{DY}_{πN_0}(x, x_π) = \frac{4σ^{DY}_{π^+N_0}(x, x_π) - σ^{DY}_{π^-N_0}(x, x_π)}{4σ^{DY}_{π^+N_0}(x, x_π) + σ^{DY}_{π^-N_0}(x, x_π)} \approx \frac{δd(x) - δu(x)}{u_v^p(x) + d_v^p(x)}. \hspace{1cm} (7)$$

This has been investigated by Londergan et al. who conclude that CSV could be tested even in the presence of valence-sea interference terms (not shown in Eq. 7). With sufficiently intense pion beams, these measurements could decrease the current upper limits on quark CSV.
3.3 Charged Pion Leptoproduction from Isoscalar Targets

A process like \( e^- + A \rightarrow \pi^+(-) + X \) could also be a sensitive probe of CSV in nucleon valence distributions. There are “favored” and “unfavored” fragmentation modes; for example, a \( u \) quark is more likely to fragment into a \( \pi^+ \) which contains a \( u \) valence quark. Tests of CSV involves comparison of \( \pi^+ \) and \( \pi^- \) electroproduction from isoscalar targets. Londergan, Pang and Thomas\(^{13}\) concluded that CSV tests would be feasible in this process. This quantity could in principle be obtained at the HERMES experiment at HERA, which is presently measuring pion fragmentation functions for electroproduction on deuterons.

4 Conclusions

Suggestions of large SU(2) FSV, i.e. \( \bar{d}^F(x) > \bar{u}^F(x) \), are confirmed by FNAL experiment E866, which compared \( pp \) and \( pD \) DY processes. pQCD contributions are too small for experiment, but “meson-cloud” models achieve quantitative success. The conclusion that flavor symmetry is broken rests on the implicit assumption of parton charge symmetry. Theoretical calculations suggest valence quark CSV of a few percent. Current experiments set upper limits of a few percent on parton CSV for \( x > 0.1 \), but suggest uncomfortably large CSV effects for \( x < 0.1 \). We suggest three experiments which could accurately test parton CSV. The first compares structure functions measured in weak charge-changing reactions which could be accessed in \( e^- + D \) and \( e^+ + D \) reactions at HERA. The second type of reaction compares DY processes for \( \pi^+ \) and \( \pi^- \) beams on isoscalar targets; this might be done in fixed-targets at FNAL following the Main Injector upgrade. The third reaction compares charged pion leptoproduction from isoscalar targets; this experiment is currently being carried out in the HERMES experiment at HERA.

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