QUARK ASYMMETRIES IN THE PROTON

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We review recent experimental and theoretical developments in the study of the sea quark structure of the proton. In the light quark sector, we analyse the recent pp and pD Drell-Yan data from the E866/NuSea experiment at Fermilab, and their implication on the $\bar{d}/\bar{u}$ asymmetry in the proton. The current status of the strange content of the proton, including the possible difference between strange and antistrange quark distributions and strangeness form factors, is updated. Finally, we point out the implications of the possible non-symmetric charm and anticharm distributions in the nucleon for HERA event rates at large $x$ and $Q^2$.

1 Introduction

The sea of the proton is extremely fertile ground for the study of non-perturbative QCD dynamics and its relation to the substructure of hadrons. In particular, sea quark asymmetries almost universally signal the presence of interesting non-perturbative phenomena, on the background of a perturbative QCD landscape which in comparison is relatively flat and homogeneous.

2 Light Antiquark Asymmetry

The E866/NuSea Collaboration recently measured the spectrum of $\mu^+\mu^-$ Drell-Yan pairs produced in pp and pD collisions at the FNAL Tevatron 1, which has for the first time enabled the shape of the $\bar{d}/\bar{u}$ ratio to be mapped out over a large range of $x$. The relatively large asymmetry found implies the presence of non-trivial dynamics in the $\bar{u}$ and $\bar{d}$ sector of the proton sea which does not have a perturbative QCD origin. The novel and unexpected feature of the E866 data is that the $\bar{d}/\bar{u}$ asymmetry peaks at rather small values of $x$, $x \sim 0.15$, and drops quite rapidly to unity by $x \sim 0.3$.

The simplest and most obvious source of a non-perturbative asymmetry in the light quark sea is the chiral structure of QCD. From numerous studies in low energy physics, including chiral perturbation theory, pions are known to play a crucial role in the structure and dynamics of the nucleon, and there is no reason to believe that the long-range tail of the nucleon should not also play a role at higher energies. As pointed out by Thomas 2, if the proton's wave function contains an explicit $\pi^+n$ Fock state component, a deep-inelastic probe scattering from the virtual $\pi^+$, which contains a valence $\bar{d}$ quark, will automatically lead to a $\bar{d}$ excess in the proton. This is the essential physical
idea behind these expectations, and has been used to address not only the $\bar{d}/\bar{u}$ asymmetry (see Ref. and references therein), but also SU(3) flavour symmetry breaking in the proton sea as well as asymmetries in the strange and heavier flavour sectors, as discussed below.

The essential ingredients of the meson cloud model are the meson–baryon distribution functions, $f_{MB}(y)$, which give the probability to find a meson, $M$, in the nucleon carrying a fraction $y$ of the nucleon’s light-cone momentum. In a hadronic basis the only parameters on which these splitting functions depend are the hadronic vertex functions, or form factors at the nucleon–meson–baryon vertices, which are characterised by an effective momentum scale (cut-off) $\Lambda_{MB}$. From previous studies we know that the dominant contribution comes from the $\pi N$ component of the nucleon, though the $\pi \Delta$ configuration turns out to play a crucial role here also. In Fig.1(a) we show the $\pi N$ and $\pi \Delta$ momentum distributions for (dipole cut-offs) $\Lambda_{\pi N} = 1$ GeV, $\Lambda_{\pi \Delta} = 1.5$ GeV. The relative magnitudes of these are taken from a comparison of the axial form factors for the nucleon and for the $N–\Delta$ transition, which strongly favours an $N–\Delta$ axial form factor that is significantly harder than that of the nucleon. The harder $\pi \Delta$ distribution at large $y$ turns out to be quite important phenomenologically for understanding the E866 data.

The contributions to the antiquark distribution in the proton can be written as convolutions of the meson distribution functions and the antiquark dis-

![Figure 1](image-url)

Figure 1: (a) $\pi N$ and $\pi \Delta$ momentum distribution functions, with dipole form factor cut-offs $\Lambda_{\pi N} = 1$ GeV and $\Lambda_{\pi \Delta} = 1.5$ GeV. (b) Contribution from pion sea to total $\bar{u} + \bar{d}$, with $\Lambda_{\pi N} = \Lambda_{\pi \Delta} = 1$ GeV (largest curve), $\Lambda_{\pi N} = 1$ GeV, $\Lambda_{\pi \Delta} = 1.5$ GeV (middle), and $\Lambda_{\pi N} = \Lambda_{\pi \Delta} = 1.5$ GeV (smallest). The dotted curves are the CTEQ4 and MRS98 global parameterisations.

The contributions to the antiquark distribution in the proton can be written as convolutions of the meson distribution functions and the antiquark dis-
tribution in the (on-mass-shell) pion:

\[
\delta \bar{q}(x) = \sum_{B=N,\Delta} \int_x^1 \frac{dy}{y} f_{\pi B}(y) \bar{q}^B(x/y),
\]

(1)

where the antiquark distribution in the pion is taken from \(\pi N\) Drell-Yan experiments. The contribution to the total \(\bar{u}\) and \(\bar{d}\) distributions from the non-perturbative cloud is shown in Fig.1(b), compared with the CTEQ4\(^7\) and MRS98\(^8\) parameterisations. While at small \(x\) the calculated distributions lie safely below the parameterisation, at large \(x\) the pion cloud already saturates the total sea with cut-offs \(\Lambda_{\pi N} \sim 1\) GeV, \(\Lambda_{\pi \Delta} \sim 1.5\) GeV — although one should add a cautionary note that the antiquark distribution at large \(x\) is not determined very precisely.

Because the meson cloud model is at most a model of part of the non-perturbative sea, it can only be reliably applied to describing the non-singlet \(\bar{d} - \bar{u}\) distribution. To reconstruct the ratio \(\bar{d}/\bar{u}\) from the calculated difference we use, following E866, the total \(\bar{d} + \bar{u}\) from the CTEQ4 parameterization\(^7\) as input. With the above form factor cut-offs, one can get a good fit to the large-\(x\) data\(^9\) stemming from the cancellation of some of the \(\bar{d}\) excess by the \(\pi\Delta\) component. On the other hand, at \(x < 0.2\) the asymmetry is now underestimated somewhat with the hard \(\pi\Delta\) component\(^9\). This suggests that there may be room for other mechanisms which could account for the missing strength.

Going beyond explanations involving meson clouds, one can also investigate the possibility that the bare nucleon itself could be asymmetric with respect to \(\bar{u}\) and \(\bar{d}\). As suggested long ago by Field and Feynman\(^10\), the Pauli exclusion principle can contribute to the asymmetry on the basis of the \(u\) and \(d\) valence quarks being unequally represented in the proton, thereby affecting the likelihood with which \(q\bar{q}\) pairs can be created in different flavour channels.

In a simple model in which the nucleon is considered to be composed of 3 quarks in the ground state, insertion of \(q\bar{q}\) pairs split from the incoming virtual photon leads to a ratio of antiquarks in the proton which must satisfy \(\bar{d} : \bar{u} = 5 : 4\). More quantitative estimates based on the MIT bag model\(^11\) show that the normalisation, \(\Delta_{\text{Pauli}}\), of the \(\bar{d} - \bar{u}\) difference arising from Pauli blocking could be as large as 25\%. Phenomenologically, one can parameterise this contribution as \((\bar{d} - \bar{u})_{\text{Pauli}} = \Delta_{\text{Pauli}}(\alpha + 1)(1 - x)^\alpha\), where \(\alpha\) is some large power. Because the E866 data implies a softer asymmetry than typical global fits of total sea quark distributions would give, empirically the power \(\alpha\) should be > 10 rather than the 5–7 that has been common for the total \(\bar{q}\) fits\(^7\).
The Pauli effect will produce an excess of $\bar{d}$ over $\bar{u}$ over the whole range of $x$, so that it cannot lead to any cancellation of the large-$x$ asymmetry. To be consistent with the trend of the large-$x$ data, especially for the $d/\bar{u}$ ratio, one needs therefore to keep the $\pi NN$ contribution softer than the $\pi N\Delta$. Taking the $\pi N$ and $\pi \Delta$ contributions calculated with $\Lambda_{\pi N} = 1$ GeV and $\Lambda_{\pi \Delta} = 1.5$ GeV as above, we show in Fig. 2 the combined effects of pions and antisymmetrisation. For the latter the exponent $\alpha = 14$, and the normalisation is $\Delta_{\text{Pauli}} \approx 7\%$, which is at the lower end of the expected scale but consistent with the bag model calculations. Together with the integrated asymmetry from pions, $\Delta^\pi \sim 0.05$, the combined value $\Delta = \Delta^\pi + \Delta_{\text{Pauli}} \approx 0.12$ is in quite reasonable agreement with the experimental result, $0.100 \pm 0.018$ from E866 and $0.148 \pm 0.039$ from NMC.

Figure 2: Contributions from pions with $\Lambda_{\pi N} = 1$ GeV and $\Lambda_{\pi \Delta} = 1.5$ GeV (dashed) and from antisymmetrisation (dotted) to the (a) $\bar{d} - \bar{u}$ difference and (b) $\bar{d}/\bar{u}$ ratio, and the combined effect (solid).

3 How Strange is the Nucleon?

There has been a lot of discussion recently about strange matrix elements of the nucleon. Interest in this subject was largely generated by the deep-inelastic scattering experiments with polarised targets at CERN and SLAC, which implied a large polarised strange quark distribution in the proton. At about the same time a measurement of the elastic neutrino–proton scattering cross section at lower values of $Q^2$ had also suggested a non-zero value for the strange axial vector form factor of the proton.
In response to these observations, other processes were sought in which traces of strangeness in the nucleon could be detected, such as parity-violating electron scattering. Some of these have since been performed (at MIT-Bates 13), while others (at Jefferson Lab) will soon provide valuable data on the strangeness radius and magnetic moment of the nucleon.

In the DIS regime, the difference between strange and antistrange quark distributions in the nucleon has recently come to prominence again 14 with the availability of new ν and ¯ν DIS data from the CCFR collaboration, which were analysed for a possible non-zero s–s difference. Perturbative QCD alone would be expected to produce identical s and ¯s distributions, while any asymmetry would have to be non-perturbative in origin. Such an asymmetry arises naturally in a meson cloud picture of the nucleon, where the strangeness of the nucleon is assumed to be carried by the kaon–hyperon components of the physical nucleon. The s and ¯s quarks therefore have quite different origins in this model. Because the s quark originates in the Λ, its distribution is like that of the u quark in the proton, roughly ∼ (1 − x)3 at large x. The ¯s in the kaon, on the other hand, is much harder, ∼ (1 − x). Since the KA distribution function fKA(y) is fairly symmetric around y = 1/2, upon convoluting the momentum distribution with the sΛ and ¯sK distributions, this asymmetry is largely preserved, leading to harder ¯s distributions at large x in the proton.

The asymmetry in the kaon cloud model turns out to be very small, and broadly consistent with the CCFR experiment 14 within the given errors for not too large values of ΛKΛ, Fig. 3(a). To obtain the difference s–s we have used the absolute values of s + ¯s from the parameterisations of Refs. 7, 8. We should point out, however, that there exists some controversy regarding the overall normalisation of the deep-inelastic neutrino data from which the strange quark distribution was extracted, resulting from an apparent inconsistency between the neutrino data and data on inclusive charm production 15, 16. In addition, the CCFR data were collected with Fe nuclei targets, so that one needs to consider possible nuclear EMC corrections in the data analysis 16 before making any definitive conclusions about s and ¯s.

Within the same formalism one can also calculate the strangeness form factors of the nucleon at low Q2. The strangeness (Sachs) radius (defined in terms of the strange electric form factor) is found to be very small and negative, in the vicinity r2 s ≈ −0.004 → −0.008 fm2 for KΛ vertex function cut-offs of ΛKΛ = 0.7–1.3 GeV. The strangeness magnetic form factor, on the other hand, suffers from spurious contributions arising from the breaking of Lorentz covariance due to the use of the impulse approximation on the light-cone (where the calculation is performed 4). Once these are removed, according to the prescription outlined in Ref. 17, the strange magnetic form factor turns
Figure 3: (a) Strange-antistrange quark distribution asymmetry in the nucleon. The solid lines correspond to the asymmetry calculated for $\Lambda_{K\Lambda} = 0.7$ GeV (smallest asymmetry), 1 GeV and 1.3 GeV (largest asymmetry), while the shaded region represents the uncertainty range of the data. (b) Strange magnetic form factor of the proton $G_{SM}(Q^2)$ as a function of $Q^2$. The shaded region is the kaon cloud prediction, for $\Lambda_{K\Lambda} = 1$ (lower curve) and 3 (upper curve) GeV. The data point is from the SAMPLE experiment.

out to be small and positive, as in Fig. 3(b), consistent with the trend of the SAMPLE data, and largely independent of the details of the $K\Lambda$ vertex function.

4 Intrinsic Charm

In 1997 the H1 and ZEUS Collaborations at HERA announced an excess of events at large $x$ and $Q^2$ in $e^+p$ neutral current (NC) and charged current (CC) deep-inelastic scattering, which prompted numerous speculations about whether one has seen evidence for physics beyond the standard model, such as leptoquarks or contact interactions. Since then the apparent signal has decreased, although an excess still persists. More interesting from the point of view of the physics of non-perturbative QCD discussed here, the HERA data opened up an avenue through which to investigate the structure of the heavy quark sea.

It was suggested that a large enhancement of the cross sections could be achieved by slightly increasing some of the quark distributions, such as the $u$ quark, at large $x$. Unfortunately, as pointed out in Ref., the size of the additional $u$ quark contribution necessary to achieve sufficient enhancement would significantly overestimate the SLAC large $x$ data. On the other hand,
the possibility that the charm quark distribution might be enhanced at large $x$, thereby producing a similar effect, has not been ruled out, and indeed, one could more easily imagine that the charm quark distribution could be rather hard, owing to the large $c$ quark mass.

The effect of a non-perturbative, or intrinsic, charm component on the DIS cross sections at HERA kinematics was recently investigated by Gunion and Vogt within a model of the 5-quark component of the nucleon wave function on the light-cone, with normalisation fixed to 1%. After evolving to the HERA kinematics, this intrinsic charm distribution, while considerably harder than that generated through pQCD, was still too soft to account for the excess HERA events. As an alternative to this intrinsic charm model, the charmed sea was taken in Refs. to arise from the quantum fluctuation of the nucleon to a virtual $D^- + \Lambda_c$ configuration, along the lines of the $\pi$ and $K$ cloud models discussed above. A natural prediction of this model is non-symmetric $c$ and $\bar{c}$ distributions.

Because of the large mass of the $c$ quark, one can approximate the $c$ distribution in the $D^-$ meson and the $\bar{c}$ distribution in the $\Lambda_c^+$ by: $c_{D^-}(x) \approx \delta(x - 1)$, $\bar{c}_{\Lambda_c^+}(x) \approx \delta(x - 2/3)$. Quite interestingly, the shape of the resulting $\delta c$ quark distributions is quite similar to that in the intrinsic charm model of Refs. However, although the model of assumes identical shapes for the non-perturbative $c$ and $\bar{c}$ distributions, the meson cloud gives a significantly harder $\bar{c}$ distribution.

Evolving the charm and anticharm distributions to an average value of $Q^2 = 20000$ GeV$^2$, the effects on the CC cross section are seen in Fig.4(a). With a 0.5% (1%) intrinsic charm component the CC cross section increases by a factor $\sim 2$ ($3$) for $200 < M < 250$ GeV, which is similar to the excess observed by H1 in this region.

While the values of $W^2$ corresponding to the $x$ and $Q^2$ values are too low for the SLAC data to be sensitive to the charm component of the nucleon wave function, data are, however, available from the BCDMS Collaboration in the region $x > 0.6$ which are above charm threshold and can be used to provide limits on the size of the intrinsic charm. The effect of adding the intrinsic $c$ distribution to the data on the deuteron structure function is illustrated in Fig.4(b). With the addition of the 0.5% contribution there does not seem to be any inconsistency with the data and, indeed, the agreement is slightly improved at $x = 0.75$. On the other hand, the 1% case may be a little too high for comfort.

Another possibility which could lead to additional enhancement of the cross sections at large $x$ would be a larger $d$ quark distribution. The recent reanalysis, for example, of the SLAC deuteron data in Ref. suggested that
Figure 4: (a) Ratio of modified to standard DIS model CC cross sections at $Q^2 = 20000 \text{ GeV}^2$, with the modifications arising from 0.5% and 1% additional $\delta c$ distributions, as well as a modified $d$ quark distribution at large $x$. (b) Structure function of the deuteron, $F_{2D}$, with 0.5% (solid) and 1% (dashed) additions of non-perturbative charm to the global fit (dotted) from NMC.

the valence $d/u$ ratio does not tend to zero as $x \to 1$, as assumed in global fits to data, but rather is consistent with the expectation of perturbative QCD, namely $d/u \to 1/5$. The effect of the modified $d$ quark distribution is comparable to that of the 0.5% anticharm scenario, as seen in Fig.4(a). The fact that all standard sets of parton distributions assume that $d/u \to 0$ as $x \to 1$ means that there is a possible source of systematic error in the modeling of “background” events which should be accounted for.

5 Conclusion

The high precision deep-inelastic, Drell-Yan and other experiments in the last few years have only begun to unravel the rich substructure of the proton sea.

We have, for the first time, at our disposal important new data from the E866 Collaboration which map out the $x$-dependence of the $\bar{d}/\bar{u}$ asymmetry in the proton. Most importantly, the E866 results confirm the recent observations that the $\bar{d}$ and $\bar{u}$ content of the proton is not symmetric, while an interesting new feature of the data is the relatively fast downturn in the $\bar{d}/\bar{u}$ ratio beyond $x \sim 0.15$, which drops rapidly back to unity by $x \sim 0.3$. The current evidence from large $x$ clearly indicates the necessity of a $\pi \Delta$ component in the nucleon wave function, one which is harder in momentum space than the $\pi N$ component. Consistency with data for the sum of $\bar{d}$ and $\bar{u}$ at $x > 0.2$ requires that
both the $\pi NN$ and $\pi N\Delta$ form factors be relatively soft, making it difficult to avoid underestimating the E866 asymmetry at intermediate $x$, and leaving room for other effects, such as the Pauli exclusion principle, to make up the difference. Along the lines of previous estimates of the Pauli effect, we find the contribution to the $\bar{d} - \bar{u}$ difference from antisymmetrisation to be significant in magnitude, and particularly important small at $x$. Our results suggest that the best description of the E866 data is that in which chiral symmetry and antisymmetrisation play roughly equal roles — consistent with the findings of the earlier analysis of the NMC data for $F^p_2 - F^n_2$. We note, however, that it would be helpful to have more data at large $x$, where the error bars are largest, to verify the downward trend of $\bar{d} - \bar{u}$, and to further explore the possible discrepancy between the Drell-Yan and NMC data.

Using the same meson cloud framework, one can estimate the asymmetry between the $s$ and $\bar{s}$ quark distributions in the nucleon, which has been studied by the CCFR Collaboration in $\nu$ charm production. The magnitude of the $s-\bar{s}$ difference turns out to be very small, consistent with current experimental errors, with the $\bar{s}$ distribution slightly harder than the $s$. More definitive conclusions will be reached with more statistics on the charm production data, and the apparent discrepancy between the inclusive deep-inelastic muon and neutrino data and those on $c\bar{c}$ production resolved.

Finally, the task of identifying a possible intrinsic charm component of the nucleon can be advanced by tagging charm final states in $J/\psi$ production at HERA to measure the charm structure function, or through a thorough comparison of NC and CC cross sections, for both $e^+p$ and $e^-p$ collisions, to enable one to determine whether the large-$x$ enhancement of the cross sections is due to charm or other flavours. Needless to say, we eagerly await further results from the H1 and ZEUS Collaborations. Any experimental evidence supporting the suggestion that the intrinsic charm could have a strong asymmetry would mean a revision of current wisdom, and would undoubtedly lead us to a deeper understanding of the structure of hadronic systems.

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