

## Drell-Yan Process and the Sea Quark Distributions

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The parton substructures in the nucleons and nuclei were first discovered in electron Deep Inelastic Scattering (DIS) experiments at SLAC. Despite much theoretical and experimental efforts, our current knowledge on parton distributions in the nucleons is still far from complete. This situation is well reflected by the many ‘surprises’ discovered in the last 15 years in DIS experiments. The first surprise came from the EMC collaboration when the structure function of a nucleon in a heavy nucleus (iron) was found to be significantly different from that in deuterium [1]. This famous ‘EMC’ effect provided the first unambiguous evidence that nucleon parton distributions are modified in the nuclear environment. The second surprise is the so-called ‘spin crisis’ deduced from polarized DIS experiments which suggested that only a small fraction of the proton spin is carried by the quarks and anti-quarks [2]. The third surprise was the NMC collaboration’s measurement of the ‘Gottfried Sum’ [3]. The NMC experiment [4] showed that the Gottfried Sum deviated significantly from the expected value suggesting that the  $u$  and  $d$  sea-quark distributions in the nucleon are different. These DIS results prompted a series of recent Fermilab experiments which used high-mass dimuon production as another means to probe the parton distributions. In this note, the highlights of the Fermilab experiments and prospects for future experiments will be presented.

The observation of oppositely charged di-lepton pairs with masses greater than 2.5 GeV emerging from the collisions of energetic hadrons was initially surprising but was soon explained by two related electromagnetic (EM) processes operative at the quark level of hadronic composition. The first process, giving rise to narrow peaks at definite mass is the EM annihilation of massive  $q\bar{q}$  vector mesons produced by strong interactions. The second process: which produces a continuous mass distribution, is also the EM annihilation of a  $q\bar{q}$  pair, but in this instance the  $q$  and  $\bar{q}$  come from separate hadrons with the energy being provided by their relative kinetic energy. This so-called Drell-Yan process is named after the theorists who initially identified the  $q\bar{q}$  process that created it [5].

As a tool to study parton distributions, the Drell-Yan process offers several distinct advantages. First, the parton distributions in unstable mesons could only be deduced from Drell-Yan experiments using meson beams. Such information could not be obtained in

DIS experiments. Indeed, the current knowledge on pion and kaon structure functions are entirely due to the Drell-Yan process. Second, the flexibility in the choice of the beam type and the kinematical regions allows one to single out a specific component in the parton distributions for studies. For instance, an antiproton beam could be used to probe the valence quark contents of the target nucleons, while a proton beam can be used to study the antiquark distributions in the target nucleons. Third, polarized Drell-Yan experiments could probe both the sea-quark helicity distributions and the chiral-odd quark structure functions, which can not be obtained in the polarized DIS experiments.

Following the discovery of the EMC effect, which is a systematic dependence on  $A$  ( $A=N+Z$ ), of the structure function per nucleon in nuclei relative to that measured in deuterium, it was believed for a period that the nontrivial EMC effects (effects not to do with simple Fermi motion) might be ascribable to the pion density in a nucleus, which was believed to increase as  $A$  increases. The increase of pions occurs in models of nuclear matter that ascribe the nucleon-nucleon interaction to meson exchange, in which the pion plays a dominant role. Using the fact that the pion carries a readily detectable antiquark, the Drell-Yan reaction was employed in Fermilab experiment E772 to measure the relative antiquark content of nuclei [6]. The relative number of antiquarks were observed to be proportional to  $A$  to within 1.5%, well below the increase expected in sophisticated models of the nucleon-nucleon interaction. The discussion of the observed disagreement of the conventional theory of nuclear matter and the Drell-Yan measurements of the nuclear dependence of relative sea quark density have continued without a clear resolution at this time.

The flavor dependence of the sea quarks provides an important clue for the origin of antiquarks in the hadrons. The conventional wisdom was to assume that the light  $\bar{u}$  and  $\bar{d}$  sea quark distributions are identical in the proton. Since the proton isospin is non-zero, isospin symmetry does not require  $\bar{u}$  be equal to  $\bar{d}$ . However, the  $\bar{u} = \bar{d}$  assumption is a plausible one considering that the only mechanism for generating sea quarks in perturbative QCD is  $g \rightarrow q\bar{q}$ , and the  $g \rightarrow u\bar{u}$  process would have similar probability as the  $g \rightarrow d\bar{d}$  process.

It came as a surprise when the New Muon Collaboration (NMC) reported [4] the observation of a large violation of the Gottfried Sum Rule (GSR). This result strongly suggested that the assumption of  $\bar{u} = \bar{d}$ , which was needed in the derivation of the GSR, is not correct. An independent and more direct method to determine the ratio of  $\bar{u}/\bar{d}$  is to measure proton-induced Drell-Yan yields on hydrogen and deuterium targets [7,8]. To a very good approximation, the Drell-Yan cross section ratio at positive  $x_F$  is given as  $\sigma_{DY}(p+p)/\sigma_{DY}(p+d) \simeq (\bar{u}_p(x_2)/\bar{d}_p(x_2))/(1 + \bar{u}_p(x_2)/\bar{d}_p(x_2))$ , where  $x_2$  is the Bjorken- $x$  of the parton in the target nucleon. The NA51 at CERN carried out such an experiment using a 450 GeV proton beam [9]. They obtained a very interesting result that  $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$  at  $\langle x \rangle = 0.18$ , a surprisingly large difference between the  $\bar{u}$  and  $\bar{d}$ .

At Fermilab, a similar Drell-Yan experiment (E866) aimed at a much higher statistics and much wider kinematic coverage than the NA51 experiment was recently completed. Using a 800 GeV proton beam and a closed-aperture spectrometer capable of handling a high interaction rate, E866 has collected over 330,000 Drell-Yan events for the kinematic regime  $0.020 < x < 0.345$ . The first results [10] from E866 clearly demonstrate the excess of  $\bar{d}$  quarks over the  $\bar{u}$  quarks in the entire range of  $x$  covered by E866. These results show that the violation of the GSR observed by the NMC is indeed caused by the difference in

the  $\bar{u}$  and  $\bar{d}$  distributions. The dependence of the  $\bar{d}/\bar{u}$  ratios on  $x$  is determined for the first time in E866. The  $\bar{d}/\bar{u}$  ratios increase from  $\sim 1.05$  at  $x = 0.04$  to a maximal value of  $\sim 1.7$  at  $x = 0.17$  and then fall back towards unity as  $x$  approaches 0.3. The  $\bar{d}/\bar{u}$  ratios from the most recent parton distribution functions (CTEQ4M [11] and MRS [12]) are in reasonable agreement with the E866 data in the regime  $0.02 < x < 0.2$ , but they disagree with the data at  $x > 0.2$ .

The pronounced asymmetry observed for the  $\bar{u}$  and  $\bar{d}$  sea quark distributions can be understood if the meson degree of freedom is explicitly taken into account in the description of nucleon structure. In the Chiral Quark Model [13,14], the relevant degrees of freedom in the effective Lagrangian are the constituent quarks, gluons, and the Goldstone bosons. In this model, the sea quarks come from the Goldstone bosons which are coupled to the constituent quarks. For instance, the  $\bar{d}$  quarks can come from the  $\pi^+$  boson as a result of the  $u \rightarrow d + \pi^+$  coupling. Similarly, the  $\bar{u}$  quarks are from the  $d$  to  $u + \pi^-$  coupling. The excess of  $\bar{d}$  over  $\bar{u}$  is simply due to the greater number of up valence quarks in the proton. Another approach similar to the Chiral Quark Model in spirit but different in details is the meson-cloud model [15,16]. In this model, the nucleon can be considered as a combination of 'bare' nucleon state plus a number of meson-baryon states. For example, the proton can couple to the  $\pi^+n, \pi^0p, K^+\Lambda$ , and other meson-baryon states. The excess of the  $\bar{d}$  over  $\bar{u}$  is naturally attributed to the greater probability for proton to couple to the  $\pi^+$  meson than the  $\pi^-$  meson. Sullivan [17] has shown that the meson-cloud will contribute to the nucleon structure functions probed at all  $Q^2$ 's. The observation of the large asymmetry between the  $\bar{u}$  and  $\bar{d}$  sea quark distributions provides a crucial support for the validity of the meson-cloud and the Chiral Quark model. These models indeed provide theoretical frameworks for calculating the non-perturbative sea-quark contents in the nucleon. This is quite remarkable considering that the alternative approach using lattice QCD is not yet fruitful.

The interplay between the perturbative and non-perturbative components of the nucleon sea remains to be better determined. Since the perturbative process gives a symmetric  $\bar{d}/\bar{u}$  while the nonperturbative process is needed to generate an asymmetric  $\bar{d}/\bar{u}$  sea, the relative importance of these two components can be reflected in the  $\bar{d}/\bar{u}$  ratios. To this end, it would be very important to extend the Drell-Yan measurements to kinematic regimes beyond the current limits. The future 120 GeV proton beam at the Fermilab Main-Injector will be most suitable for mapping out the  $\bar{d}/\bar{u}$  at  $x > 0.3$ , while RHIC offers the opportunity to extend the data to small  $x$  and large  $Q^2$ . Polarized Drell-Yan measurements at RHIC would also allow a determination of the helicity structure of the nucleon sea. The Chiral and the meson-cloud models both predict that the  $\bar{u}$  and  $\bar{d}$  quarks will carry negligible amount of the proton's spin [18], and such prediction remains to be tested.

Compared to the up and down sea-quarks, the strange quark content in the proton is very poorly known. Neutrino-induced charm production experiments showed that the strange quark content is roughly 40 percent of the lighter up or down sea-quarks. A very interesting consequence of the meson-cloud model is that the  $s$  and  $\bar{s}$  distributions in the proton could have very different shapes, even though the net amount of strangeness in the proton vanishes. By comparing the  $\nu$  and  $\bar{\nu}$  induced charm production, the CCFR collaboration [19] reported that the  $s$  and  $\bar{s}$  distributions are very similar. However, the reliability of extracting the strange quark distributions in the analysis is still being disputed.

Drell-Yan experiments using  $K^\pm$  beams might provide an independent determination of the  $s/\bar{s}$  ratios in the proton. A possible method is simply to measure the  $(K^+ + p)/(K^- + p)$  Drell-Yan cross section ratios, a difficult but feasible experiment for the future.

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