Asymmetry of antimatter in the proton†

Y. Goto,*1 S. Miyasaka,*2 K. Nagai,*2 F. Sanftl,*2 Y. Kudo,*3 Y. Miyachi,*3 K. Nakano,*1,*2 S. Nara,*3 S. Sawada,*4 and T. -A. Shibata*1,*2 for the SeaQuest Collaboration

The structure of the proton is a prototypical example of a strongly coupled and correlated system with quarks and gluons interacting according to quantum chromodynamics (QCD). An essential feature of QCD is its ability to create matter-antimatter quark pairs inside the proton that exist only for a very short time. Their fleeting existence makes the antimatter quarks within protons difficult to study, but their existence is discernible in reactions in which a matter-antimatter quark pair annihilates. In this picture of quark-antiquark creation by the strong force, the probability distributions as a function of momentum for the presence of up and down antimatter quarks should be nearly identical, given that their masses are very similar and small compared to the mass of the proton.[1)] Here, we provide evidence from muon-pair production measurements that these distributions are considerably different, with down antimatter quarks more abundant than up antimatter quarks over a wide range of momenta.

In the Drell-Yan process in hadron-hadron collisions, a quark and an antiquark annihilate into a virtual photon, which decays into a lepton-antilepton pair.[2)] The ratio of the Drell-Yan cross-section on a deuterium target to that on a hydrogen target has a direct sensitivity to $\bar{d}(x)/\bar{u}(x)$, where $\bar{u}(x)$ and $\bar{d}(x)$ are the distributions of up and down antiquarks in the proton, respectively, as a function of the fractional momentum (x) of the proton. The ratio $\bar{d}/\bar{u}$ from the Drell-Yan process was first reported by NA51 at CERN.[3)] This result is consistent with the down antiquark dominance reported in deep inelastic scattering by NMC at CERN.[4)] The Fermilab NuSea experiment[5)] was able to measure the x dependence of the down antiquark dominance with an 800-GeV proton beam in the kinematic range of $0.015 < x < 0.35$.

The Fermilab SeaQuest experiment was designed to investigate the flavour asymmetry at higher x values than NuSea with the newly constructed experimental apparatus. With a proton beam at an energy of 120 GeV, liquid hydrogen and deuterium targets, and a focusing magnet of 10 Tm after the target region, the experiment was optimized for the study of target antiquarks in the intermediate region, with x around 0.3, by detecting muon ($\mu^+\mu^-$) pairs from decays of the virtual photons produced in the Drell-Yan process.

Figure 1 shows the ratios $\bar{d}(x)/\bar{u}(x)$ in the proton (red filled circles) with their statistical (vertical bars) and systematic (yellow boxes) uncertainties extracted from the present data based on next-to-leading-order calculations of the Drell-Yan cross-sections. Also shown are the results obtained by the NuSea experiment (open black squares) with statistical and systematic uncertainties added in quadrature. The trends between the two experiments at higher x are quite different. No explanation has been found yet for these differences. The horizontal bars on the data points indicate the width of the bins.

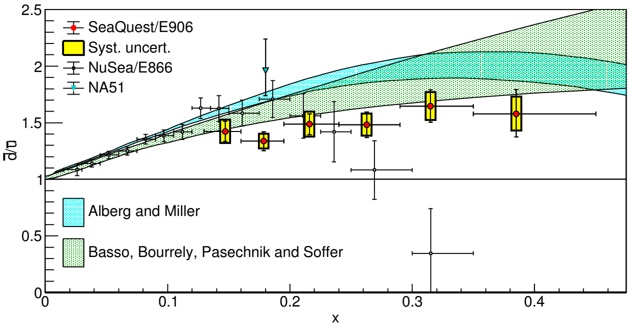

Fig. 1. Ratios $\bar{d}(x)/\bar{u}(x)$.

The present data are reasonably described by the predictions of the statistical parton distributions of Basso *et al.*[6)] (green band) and by the chiral effective perturbation theory of Alberg & Miller[7)] (cyan band), which are also shown in Fig. 1. These two calculations emphasize rather different non-perturbative mechanisms that lead to the differences in $\bar{d}(x)$ and $\bar{u}(x)$. The present data show that $\bar{d}$ is greater than $\bar{u}$ for the entire x range measured in this experiment. This provides important support for these and other non-perturbative mechanisms of the QCD structure of the proton that were disfavoured by the NuSea results.

References

1) D. A. Ross, C. T. Sachrajda, Nucl. Phys. B **149**, 497 (1979).
2) S. D. Drell, T. M. Yan, Phys. Rev. Lett. **25**, 316 (1970); erratum **25**, 902 (1970).
3) A. Baldit *et al.*, Phys. Lett. B **332**, 244 (1994).
4) P. Amaudruz *et al.*, Phys. Rev. Lett. **66**, 2712 (1991); M. Arneodo *et al.*, Phys. Rev. D **50**, R1 (1994).
5) R. S. Towell *et al.*, Phys. Rev. D **64**, 052002 (2001).
6) E. Basso *et al.*, Nucl. Phys. A **948**, 63 (2016).
7) M. Alberg, G. A. Miller, Phys. Rev. C **100**, 035205 (2019).

† Condensed from the article in Nature **590**, 561 (2021)

*1 RIKEN Nishina Center
*2 Department of Physics, Tokyo Institute of Technology
*3 Department of Physics, Yamagata University
*4 Institute of Particle and Nuclear Studies, KEK