Absolute Drell-Yan Dimuon Cross Sections in 800 GeV/c pp and pd Collisions

J.C. Webb,[7,*] T.C. Awes,[8] M.L. Brooks,[6] C.N. Brown,[3] J.D. Bush,[1] T.A. Carey,[6] T.H. Chang,[7,†] W.E. Cooper,[3] C.A. Gagliardi,[9] G.T. Garvey,[6] D.F. Geesaman,[2] E.A. Hawker,[9,6,‡] X.C. He,[4] L.D. Isenhower,[1] D.M. Kaplan,[5] S.B. Kaufman,[2] D.D. Koetke,[10] D.M. Lee,[6] W.M. Lee,[4,§] M.J. Leitch,[6] N. Makins,[2,†] P.L. McGaughey,[6] J.M. Moss,[6] B.A. Mueller,[2] P.M. Nord,[10] V. Papavassiliou,[7] B.K. Park,[6] J.C. Peng,[6,†] G. Petitt,[4] P.E. Reimer,[6,2] M.E. Sadler,[1] W.E. Sondheim,[6] P.W. Stankus,[8] T.N. Thompson,[6] R.S. Towell,[1,6] R.E. Tribble,[9] M.A. Vasiliev,[9,¶] J.L. Willis,[1] D.K. Wise,[1] and G.R. Young[8]

(FNAL E866/NuSea Collaboration)

[1] *Abilene Christian University, Abilene, TX 79699*
[2] *Argonne National Laboratory, Argonne, IL 60439*
[3] *Fermi National Accelerator Laboratory, Batavia, IL 60510*
[4] *Georgia State University, Atlanta, GA 30303*
[5] *Illinois Institute of Technology, Chicago, IL 60616*
[6] *Los Alamos National Laboratory, Los Alamos, NM 87545*
[7] *New Mexico State University, Las Cruces, NM 88003*
[8] *Oak Ridge National Laboratory, Oak Ridge, TN 37831*
[9] *Texas A&M University, College Station, TX 77843*
[10] *Valparaiso University, Valparaiso, IN 46383*

(Dated: May 11, 2004)

The Fermilab E866/NuSea Collaboration has measured the Drell-Yan dimuon cross sections in 800 GeV/c pp and pd collisions. This represents the first measurement of the Drell-Yan cross section in pp collisions over a broad kinematic region and the most extensive study to date of the Drell-Yan cross section in pd collisions. The results indicate that recent global parton distribution fits provide a good description of the light antiquark sea in the nucleon over the Bjorken-x range $0.03 \lesssim x < 0.15$, but overestimate the valence quark distributions as $x \to 1$.

PACS numbers: 13.85.Qk, 14.20.Dh, 12.38.Qk, 24.85.+p

Drell-Yan dimuon production provides valuable information about the partonic structure of hadrons that is complementary to deep-inelastic scattering (DIS) studies because it distinguishes between quarks and antiquarks. The Drell-Yan cross section for $pA \to \mu^+\mu^- X$ may be written in terms of the parton distribution functions (PDFs) of the colliding hadrons as

$$M^3 \frac{d^2\sigma}{dM\,dx_F} = \frac{8\pi\alpha^2}{9} \frac{x_1 x_2}{x_1 + x_2} \times \sum_q e_q^2 \left[q_1(x_1)\bar{q}_2(x_2) + \bar{q}_1(x_1) q_2(x_2) \right] \quad (1)$$

where the subscript 1 (2) denotes the beam (target) hadron. Measurement of the invariant mass, $M^2 = x_1 x_2 s$, and Feynman-x, $x_F = 2p_L/\sqrt{s} = x_1 - x_2$, of the muon pair (where p_L is the longitudinal momentum of the muon pair, and $\sqrt{s}$ the center-of-mass energy of the hadrons) determines the momentum fraction $x_{1(2)}$ of the beam (target) parton. Equation 1 is exact to leading order, but its general features are also preserved by next-to-leading-order (NLO) calculations.

The Fermilab E866/NuSea Collaboration has measured the Drell-Yan cross sections in 800 GeV/c pp and pd collisions. This represents the first study of the Drell-Yan cross section in pp collisions over a broad kinematic range and the most comprehensive measurement in pd collisions. Previous publications [1, 2] have described the E866 measurement of the $\bar{d}/\bar{u}$ ratio in the proton as a function of x, based on the x_2 dependence of the Drell-Yan cross section ratio $\sigma^{pd}/2\sigma^{pp}$, and those results have been included in recent global PDF fits [3–7].

We present measurements of the pp and pd Drell-Yan dimuon cross sections for pair mass in the ranges $4.2 < M < 8.7$ GeV or $10.85 < M < 16.85$ GeV and $-0.05 < x_F < 0.8$. At the large values of x_F appropriate for much of the E866 data, the first term in the sum in Eq. 1 dominates and the cross sections are primarily sensitive to the valence distributions in the proton beam and the antiquarks at small x in the proton and deuteron targets. Thus, these measurements probe the partonic structure of the nucleon in two important kinematic regions. Recent global PDF fits use the precise HERA DIS cross sections to fix the magnitude of the light quark sea at small x and the E605 pCu cross sections [8] to fix the antiquark distributions for $0.14 \lesssim x \lesssim 0.3$. In contrast, Ref. 9 noted that the magnitude of the antiquark distributions near $x \approx 0.04$ is relatively unconstrained by current data, and this limits the precision of calculations of the W production cross section at the Tevatron. There has also been considerable recent interest in understanding the valence quark distributions in the nucleon as $x \to 1$, which play a key role in searches for physics beyond the Standard Model, e.g., production of additional vector bosons as predicted by left-right symmetric

models. To date, this region is constrained only by DIS cross sections, some of which suffer from limited statistics, while many others involve substantial ambiguities associated with corrections for the nuclear targets used [10, 11]. (See Ref. 12 for a recent review.) The present results provide new constraints on the magnitudes of the antiquark sea for $0.03 \lesssim x < 0.15$ and of the valence quarks for $x \to 1$.

E866 used a 3-dipole magnetic spectrometer employed previously in E605 [8], E772 and E789, modified by the addition of new detectors at the first tracking station. An 800 GeV/c proton beam bombarded identical target flasks containing liquid hydrogen, liquid deuterium and vacuum that were alternated every few minutes. After passing through the target, the beam was intercepted by a copper beam dump that was followed by a thick hadron absorber, ensuring that only muons traversed the spectrometer's detectors. Drell-Yan events were recorded using three different spectrometer magnet settings, chosen to focus low-, intermediate- and high-mass muon pairs and provide acceptance from below the J/ψ to above 15 GeV. A detailed description may be found in Ref. 2.

The present analysis used 55,000 pp and 121,000 pd Drell-Yan events, approximately half the statistics of the E866 $\bar{d}/\bar{u}$ study [2]. The $\bar{d}/\bar{u}$ analysis was optimized to achieve minimum relative uncertainties in $\sigma^{pd}/2\sigma^{pp}$, whereas the present analysis was optimized for absolute measurements of the cross sections. Therefore, more stringent fiducial cuts were adopted in the present analysis, eliminating events for which the absolute acceptance of the spectrometer could not be reliably determined. This minimized systematic uncertainties at the cost of statistical precision, especially for $x_2 \gtrsim 0.15$. In contrast, 7% of the events accepted in this analysis came from data sets that were excluded previously [2, 13]. Several improvements were made to the event reconstruction, notably involving the treatments of energy loss and multiple scattering in the absorber, that led to a more precise reconstruction of the dimuon kinematics and a better match between the real and simulated events.

The spectrometer acceptance was calculated separately for each data set as a function of mass, x_F, and transverse momentum (p_T) using a detailed Monte Carlo simulation of the spectrometer. The virtual photon azimuthal production and decay angles were assumed to be distributed isotropically, and the polar decay angles were assumed to be distributed according to $1+\cos^2\theta_d$, consistent with theoretical expectations and previous Drell-Yan angular distribution studies [14–16]. Drell-Yan Monte Carlo events were thrown with realistic kinematic distributions in mass, x_F, and p_T, then reweighted to provide a precise match to the observed experimental distributions. Triply-differential cross sections, $d^3\sigma/dMdx_Fdp_T$, were calculated for each kinematic bin, then integrated over p_T to obtain the invariant cross sections, $M^3d^2\sigma/dMdx_F$. The transverse momentum acceptance of the spectrometer extended to $p_T \approx 5-7$ GeV/c, but it was nonetheless necessary to extrapolate the integration to large p_T where the Monte Carlo showed zero acceptance. The extrapolation contributed well under 1% in most cases, and was never more than 5%.

A detailed study was performed of the point-to-point systematic uncertainties in the measured cross sections. The two dominant contributions were the statistical uncertainty in the Monte Carlo event samples that were used for the acceptance calculations and the absolute field strength of the spectrometer magnets. Smaller contributions came from the uncertainties in the hodoscope, drift chamber, and trigger efficiencies, the composition and density of the targets, and the extrapolations to large p_T. Finally, some large-x_F events contained a muon that passed very close to the edge of the beam dump, increasing the uncertainty in the energy loss and multiple scattering corrections. An additional $\pm 5\%$ systematic uncertainty was added to the final results for the affected kinematic bins. The total point-to-point systematic uncertainties within any (M,x_F) bin were strongly correlated between the pp and pd cross sections. In addition to the point-to-point systematic uncertainties, there was a $\pm 6.5\%$ overall normalization uncertainty, associated with the calibration of the beam intensity. See Ref. 13 for additional details.

Figure 1 shows the Drell-Yan pp and pd invariant cross sections per nucleon for selected x_F bins. The results agree with previous 800 GeV/c Drell-Yan cross section measurements in pCu collisions by E605 [8]. They also agree with previous measurements in pd collisions by E772 [17] for $x_F < 0.3$. At larger x_F and small M, the E772 cross sections are systematically larger than the present results. E772 quoted a larger point-to-point systematic uncertainty in this kinematic region, but the results of the two experiments differ by more than the combined systematic uncertainties would predict. The largest differences are in the region $0.4 < x_F < 0.6$ and $4.2 < M < 7$ GeV, where inconsistencies between the E772 results and expectations from global PDF fits were noted previously [5]. This region was studied during E866 with very different acceptances by the low- and high-mass spectrometer settings, and the results are consistent.

Figure 1 also shows the results of next-to-leading-order calculations of the Drell-Yan cross sections based on the CTEQ6 [4] and MRST2001 [6] global PDF fits. The agreement with the global fits is very good over the entire kinematic region. This agreement may be quantified by computing a K'-factor, which we define to be the ratio of the experimental cross section to a NLO prediction. Table I shows K'-factors for several recent global PDF fits. With the exception of GRV98, all of the recent PDF fits predict the absolute magnitude of the Drell-Yan cross sections to within the $\pm 6.5\%$ normalization uncertainty.

While the overall normalization is well reproduced, there are systematic deviations between the measure-

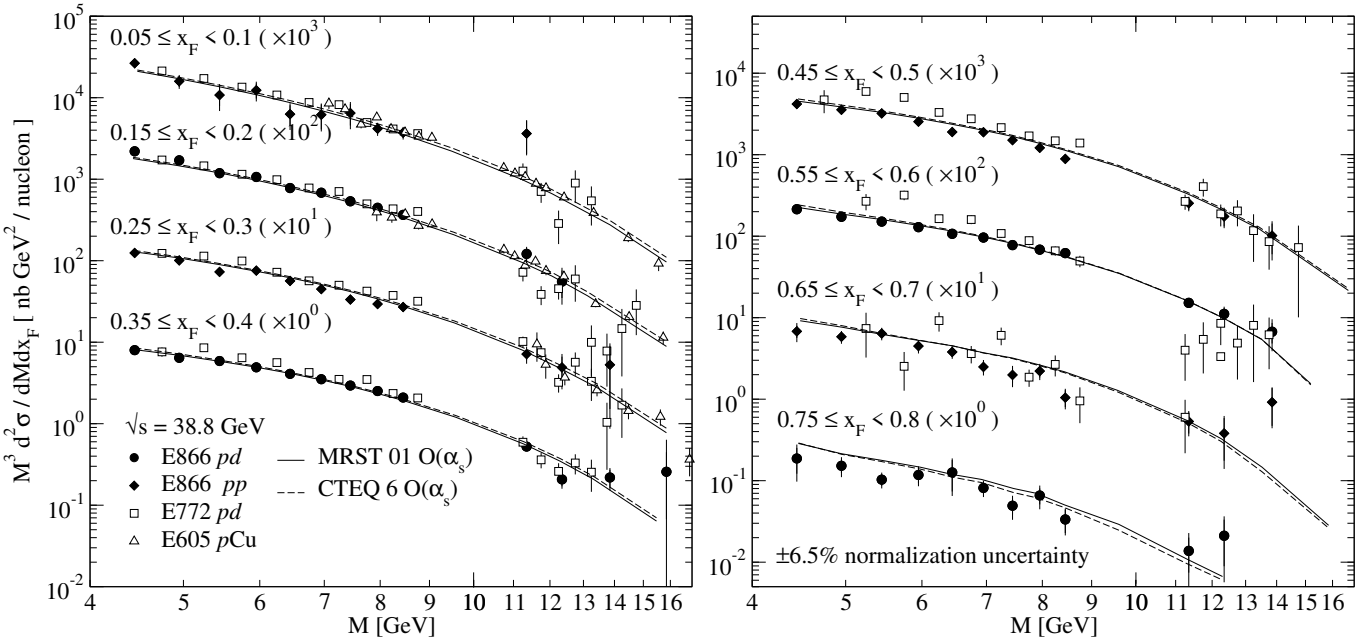

FIG. 1: FNAL E866 Drell-Yan cross sections per nucleon for selected x_F bins. The E866 pd (solid circles) and pp (solid diamonds) cross sections are shown in alternate decades, compared with previous pCu results from E605 [8] (open triangles) and pd results from E772 [17] (open squares). NLO cross section calculations based on the CTEQ6 [4] (dashed curves) and MRST2001 [6] (solid curves) PDF fits are also shown. The error bars on the E605 and E772 data points are statistical only. Those on the E866 data points are the sum in quadrature of the statistical and point-to-point systematic uncertainties. An additional $\pm 6.5\%$ normalization uncertainty is common to all E866 data points.

TABLE I: K'-factors obtained with various PDFs, where $K' = \sigma^{\rm exp}/\sigma^{\rm NLO}$. The χ^2 values include the statistical and point-to-point systematic uncertainties in the experimental cross sections, but not the $\pm 6.5\%$ global normalization uncertainty. The K' fits have 183 and 190 degrees of freedom (dof) for the pp and pd reactions, respectively.

PDF	K'_{pp}	χ^2/dof	K'_{pd}	χ^2/dof
CTEQ5 [3]	0.976	1.42	0.963	2.51
CTEQ6 [4]	1.016	1.39	1.001	2.56
MRST98 [5]	0.973	1.38	0.960	2.37
MRST2001 [6]	0.980	1.45	0.966	2.44
GRV98 [7]	0.811	2.04	0.808	4.15

ments and the predictions that are reflected in the large χ^2 values. To elucidate these deviations, it is useful to examine the experimental cross sections separately as functions of x_1 and x_2. Most of the events have $x_1 \gg x_2$, which implies that the x_1 dependence is primarily sensitive to the valence quarks in the proton beam and the x_2 dependence to the antiquarks in the target. Figure 2 shows the ratios of the experimental cross sections to NLO calculations using the MRST2001 global PDF fit, separately as a function of x_2 and x_1, averaged over the other momentum fraction. The uncertainties in the NLO calculations from the PDF fit are also shown. After accounting for the normalization uncertainty, the MRST2001 partons provide a very good description of the x_2 dependence of the pp cross sections over the full range, and a good description of the pd cross sections for $x_2 < 0.15$. The CTEQ6 fits describe the x_2 dependence equally well. This indicates that the current PDFs interpolate the $\bar{u}$ and $\bar{d}$ distributions successfully between the HERA measurements at small x and the E605 measurements for $x > 0.14$, but these new results provide tighter constraints on the magnitude of the antiquark distributions for $0.03 \lesssim x < 0.15$ than have existed to date [9].

Figure 2b shows the ratios of the cross sections to NLO calculations using the MRST2001 PDF fits as a function of x_1. The qualitative behavior of the CTEQ6 distributions is quite similar: both PDF fits overestimate the valence quarks by $\approx$15–20% at large x_1, and the discrepancy between the data and current PDFs appears to be larger for the pd cross sections than for the pp cross sections. The acceptance of these data includes an anti-correlation between x_1 and x_2 [2], so most of the events at large x_1 also have $x_2 < 0.1$. The NLO calculations describe the average x_2 dependence of the cross sections quite well for $x_2 < 0.1$, so the discrepancy in Fig. 2b is isolated to the subset of the low-x_2 events that also have large x_1. Further comparisons between the measured cross sections and the NLO calculations, in which the x_1 and x_2 dependences are examined for limited ranges of the other variable [13], reinforce this

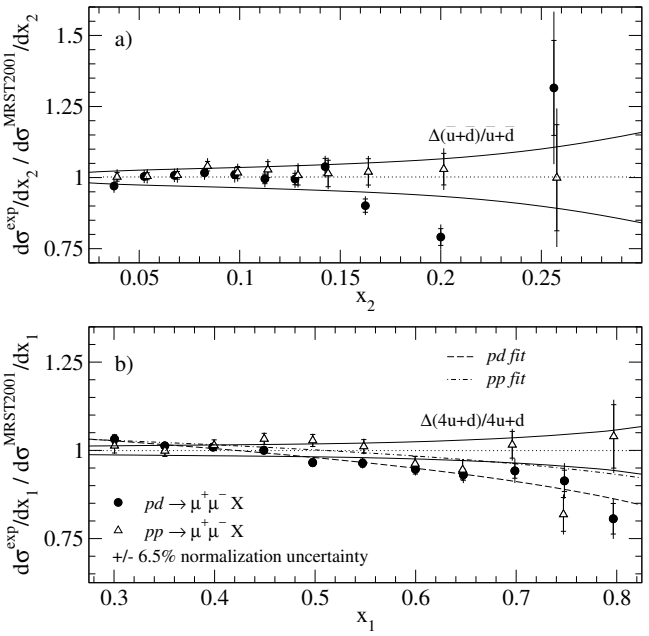

FIG. 2: Ratios of the measured Drell-Yan pp (open triangles) and pd (solid circles) cross sections to NLO calculations based on the MRST2001 [6] PDF fit plotted *vs.* a) x_2 and b) x_1, averaged over the other variable. The inner error bars represent the statistical uncertainty in the ratio, the outer error bar the sum in quadrature of the statistical and point-to-point systematic uncertainties. Solid lines represent the experimental uncertainty ranges [9] on a) $\bar{u}+\bar{d}$ and b) $4u+d$ in the MRST2001 PDF fit. Dashed and dot-dashed lines are the pd and pp fits described in the text.

TABLE II: Fits of data/theory to the phenomenological form $K'(x_1) = \alpha\,(1-x_1)^{\beta}$. Uncertainties on the fits include only the statistical uncertainties in the data.

	MRST2001		CTEQ6	
	pp	pd	pp	pd
α	1.057 ± 0.019	1.080 ± 0.026	1.080 ± 0.020	1.126 ± 0.013
β	0.079 ± 0.026	0.140 ± 0.016	0.122 ± 0.026	0.209 ± 0.016

conclusion. Table II shows the results of fits to the x_1 dependence of the K'-factors with a phenomenological form, $K'(x_1) = \alpha\,(1-x_1)^{\beta}$, for both PDF sets.

Unlike large-x DIS off deuterium targets, these data are in a kinematic region where nuclear-dependence corrections are known to be small [18]. The pp and pd cross sections at large x_1 constrain slightly different linear combinations of $u(x)$ and $d(x)$, with greater sensitivity to u quarks. The results imply that the u quark distributions in CTEQ6 and MRST2001 are overestimated as $x \to 1$. Recent fits to H1 charged- and neutral-current data have also indicated that the global PDF fits appear to overestimate the u quark distribution near $x \approx 0.65$, albeit with limited statistics [12]. The Drell-Yan cross sections may also point to problems with the d/u ratio as $x \to 1$ [10, 11]. However, determination of the d/u ratio at large x from the present data will require a fit to the full two-dimensional invariant cross sections together with the rest of the current world data.

Figure 2 shows that the present results fall well outside the experimental uncertainty [9] for the valence quarks in the MRST2001 PDF fit. A similar comparison shows that the present results track the lower limit on the experimental uncertainty [4] in the CTEQ6 PDF fit. These discrepancies reflect additional uncertainties in the PDF fits [4, 9], and they imply that future PDF fits will see a substantial correction to the u and d quark distributions at large x. The reduced valence quark distributions at large x implied by these results will also lead to predictions of smaller cross sections for some signatures for new physics that are being sought at the Tevatron.

We thank the Fermilab Particle Physics, Beams, and Computing Divisions for their assistance in performing this experiment. We also thank W.K. Tung of the CTEQ Collaboration for providing the code to calculate the next-to-leading-order Drell-Yan cross sections. This work was supported in part by the U.S. Department of Energy.

* Present address: Indiana University, Bloomington, IN 47405
† Present address: University of Illinois, Urbana, IL 61801
‡ Present address: University of Cincinnati, Cincinnati, OH 45221
§ Present address: Florida State University, Tallahassee, FL 32306
¶ On leave from Kurchatov Institute, Moscow, Russia

[1] E.A. Hawker *et al.* (FNAL E866/NuSea Collaboration), Phys. Rev. Lett. **80**, 3715 (1998).
[2] R.S. Towell *et al.* (FNAL E866/NuSea Collaboration), Phys. Rev. D **64**, 052002 (2001).
[3] H.L. Lai *et al.*, Eur. Phys. J. C **12**, 375 (2000).
[4] J. Pumplin *et al.*, JHEP **0207**, 012 (2002).
[5] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. C **4**, 463 (1998).
[6] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. C **23**, 73 (2002).
[7] M. Gluck, E. Reya, and A. Vogt, Eur. Phys. J. C **5**, 461 (1998).
[8] G. Moreno *et al.*, Phys. Rev. D **43**, 2815 (1991).
[9] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, hep-ph/0211080.
[10] U.K. Yang and A. Bodek, Phys. Rev. Lett. **82**, 2467 (1999).
[11] S. Kuhlmann *et al.*, Phys. Lett. **B476**, 291 (2000).
[12] Z. Zhang (H1 and ZEUS Collaborations), J. Phys. G **28**, 767 (2002).
[13] J.C. Webb, Ph.D. thesis, New Mexico State University (2002); hep-ex/0301031.
[14] P.L. McGaughey, J.M. Moss, and J.C. Peng, Ann. Rev. Nucl. Part. Sci. **49**, 217 (1999).
[15] T.H. Chang, Ph.D. thesis, New Mexico State University (1999); hep-ex/0012034.

[16] C.N. Brown *et al.* (FNAL E866/NuSea Collaboration), Phys. Rev. Lett. **86**, 2529 (2001).
[17] P.L. McGaughey *et al.*, Phys. Rev. D **50**, 3038 (1994); **60**, 119903 (1999).
[18] D.M. Alde *et al.*, Phys. Rev. Lett. **64**, 2479 (1990).