FERMILAB-PUB-07-434

arXiv:hep-ex/0609005 v1 6 Sep 2006

Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

L.Y. Zhu,[6] J.C. Peng,[6,7] P.E. Reimer,[2,7] T.C. Awes,[10] M.L. Brooks,[7] C.N. Brown,[3] J.D. Bush,[1] T.A. Carey,[7] T.H. Chang,[9] W.E. Cooper,[3] C.A. Gagliardi,[11] G.T. Garvey,[7] D.F. Geesaman,[2] E.A. Hawker,[11] X.C. He,[4] L.D. Isenhower,[1] D.M. Kaplan,[5] S.B. Kaufman,[2] S.A. Klinksiek,[8] D.D. Koetke,[12] D.M. Lee,[7] W.M. Lee,[3,4] M.J. Leitch,[7] N. Makins,[2,6] P.L. McGaughey,[7] J.M. Moss,[7] B.A. Mueller,[2] P.M. Nord,[12] V. Papavassiliou,[9] B.K. Park,[7] G. Petitt,[4] M.E. Sadler,[1] W.E. Sondheim,[7] P.W. Stankus,[10] T.N. Thompson,[7] R.S. Towell,[1] R.E. Tribble,[11] M.A. Vasiliev,[11] J.C. Webb,[9] J.L. Willis,[1] D.K. Wise,[1] and G.R. Young[10]

(FNAL E866/NuSea Collaboration)

[1] *Abilene Christian University, Abilene, TX 79699*
[2] *Physics Division, 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] *University of Illinois at Urbana-Champaign, Urbana, IL 61801*
[7] *Los Alamos National Laboratory, Los Alamos, NM 87545*
[8] *University of New Mexico, Albuquerque, NM 87131*
[9] *New Mexico State University, Las Cruces, NM 88003*
[10] *Oak Ridge National Laboratory, Oak Ridge, TN 37831*
[11] *Texas A&M University, College Station, TX 77843*
[12] *Valparaiso University, Valparaiso, IN 46383*

(Dated: September 6, 2006)

We report a measurement of the angular distributions of Drell-Yan dimuons produced using an 800 GeV/c proton beam on a deuterium target. The muon angular distributions in polar angle θ and azimuthal angle ϕ have been measured over the kinematic range $4.5 < m_{\mu\mu} < 15$ GeV/c^2, $0 < p_T < 4$ GeV/c, and $0 < x_F < 0.8$. No significant cos2ϕ dependence is found in these proton-induced Drell-Yan data, in contrast to the situation for pion-induced Drell-Yan. The data are compared with expectations from models which attribute the cos2ϕ distribution to a QCD vacuum effect or to the presence of the transverse-momentum-dependent Boer-Mulders structure function $h_1^\perp$. Constraints on the magnitude of the sea-quark $h_1^\perp$ structure functions are obtained.

PACS numbers: 13.85.Qk, 14.20.Dh, 24.85.+p, 13.88.+e

The Drell-Yan process [1], in which a charged lepton pair is produced in a high-energy hadron-hadron interaction via the $q\bar{q} \to l^+l^-$ process, has been a testing ground for perturbative QCD and a unique tool for probing parton distributions of hadrons. The Drell-Yan production cross sections can be well described by next-to-leading order QCD calculations [2]. This provides a firm theoretical framework for using the Drell-Yan process to determine the antiquark content of nucleons and nuclei [3], as well as the quark distributions of pions, kaons, and antiprotons [4].

Despite the success of perturbative QCD in describing the Drell-Yan cross sections, it remains a challenge to understand the angular distributions of the Drell-Yan process. Assuming dominance of the single-photon process, a general expression for the Drell-Yan angular distribution is [5]

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi, \quad (1)$$

where θ and ϕ denote the polar and azimuthal angle, respectively, of the l^+ in the dilepton rest frame. In the "naive" Drell-Yan model, where the transverse momentum of the quark is ignored and no gluon emission is considered, $\lambda = 1$ and $\mu = \nu = 0$ are obtained. QCD effects [6] and non-zero intrinsic transverse momentum of the quarks [7] can both lead to $\lambda \neq 1$ and $\mu, \nu \neq 0$. However, λ and ν should still satisfy the relation $1 - \lambda = 2\nu$ [5]. This so-called Lam-Tung relation, obtained as a consequence of the spin-1/2 nature of the quarks, is analogous to the Callan-Gross relation [8] in Deep-Inelastic Scattering. While QCD effects can significantly modify the Callan-Gross relation, the Lam-Tung relation is predicted to be largely unaffected by QCD corrections [9].

The first measurement of the Drell-Yan angular distribution was performed by the NA10 Collaboration for $\pi^- + W$ at 140, 194, and 286 GeV/c, with the highest statistics at 194 GeV/c [10]. The $\cos 2\phi$ angular dependences showed a sizable ν, increasing with dimuon transverse momentum (p_T) and reaching a value of ≈ 0.3 at $p_T = 2.5$ GeV/c (see Fig. 1). The observed behavior of ν could not be described by perturbative QCD calculations which predict much smaller values of ν [6]. The Fermilab E615 Collaboration subsequently performed a measure-

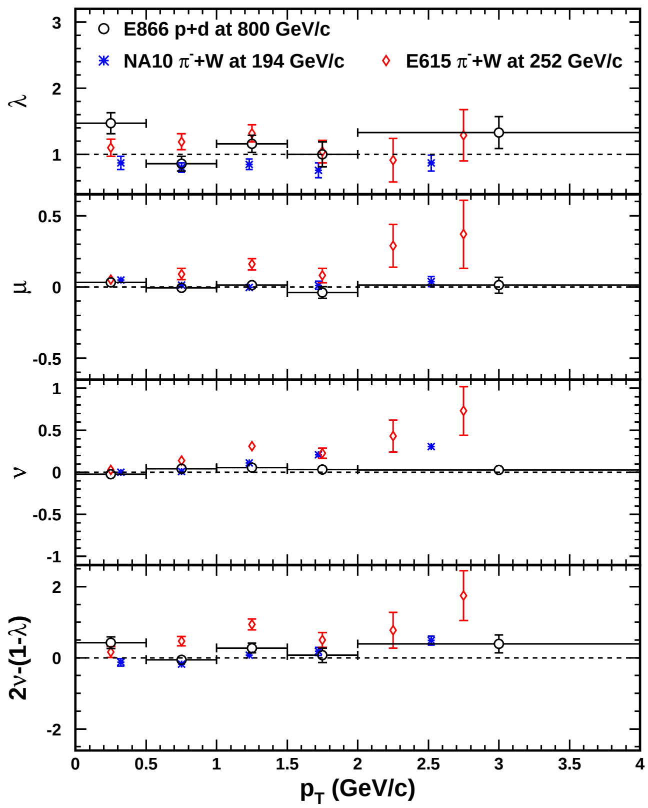

FIG. 1: Parameters λ, μ, ν and $2\nu - (1-\lambda)$ vs. p_T in the Collins-Soper frame. Solid circles are for E866 $p+d$ at 800 GeV/c, crosses are for NA10 $\pi^- + W$ at 194 GeV/c, and diamonds are E615 $\pi^- + W$ at 252 GeV/c. The error bars include the statistical uncertainties only.

ment of $\pi^- + W$ Drell-Yan production at 252 GeV/c with broad coverage in the decay angle θ [11]. The E615 results showed that λ deviates from 1 at large values of x_π (the Bjorken-x of the incident pions), and both μ and ν have large non-zero values. Furthermore, the E615 data showed that the Lam-Tung relation, $2\nu = 1 - \lambda$, is clearly violated. (See Fig. 1.)

The NA10 and E615 results on the Drell-Yan angular distributions strongly suggest that new effects beyond conventional perturbative QCD are present. Several attempts have been made to interprete these data. Brandenburg, Nachtmann and Mirke suggested that a factorization-breaking QCD vacuum may lead to a correlation between the transverse spin of the antiquark in the pion and that of the quark in the nucleon [12]. This would result in a non-zero $\cos 2\phi$ angular dependence consistent with the data. As pointed out by Boer *et al.*, a possible source for a factorization-breaking QCD vacuum is helicity flip in the instanton model [13]. Several authors have also considered higher-twist effects from quark-antiquark binding in pions [14, 15], motivated by earlier work of Berger and Brodsky [16]. This model predicts behavior of μ and ν in qualitative agreement with the data. However, the model is strictly applicable only in the $x_\pi \to 1$ region while the NA10 and E615 data exhibit nonperturbative effects over a much broader kinematic region.

More recently, Boer pointed out [17] that the $\cos 2\phi$ angular dependences observed in NA10 and E615 could be due to the k_T-dependent parton distribution function $h_1^\perp$. This so-called Boer-Mulders function [18] is an example of a novel type of k_T-dependent parton distribution function, and it characterizes the correlation of a quark's transverse spin and its transverse momentum, k_T, in an unpolarized nucleon. It has an interesting property of being a time-reversal odd object and owes its existence to the presence of initial/final state interactions [19]. The Boer-Mulders function is the analog of the Collins fragmentation function [20], which describes the correlation between the transverse spin of a quark and the transverse momentum of the particle into which it hadronizes. Model calculations for the nucleon (pion) Boer-Mulders functions have been carried out [21, 22, 23, 24] in the framework of quark-diquark (quark-spectator-antiquark) model, and can successfully describe the ν behavior observed in NA10 [24].

To shed additional light on the origins of the NA10 and E615 Drell-Yan angular distributions, we have analyzed $p+d$ Drell-Yan angular distribution data at 800 GeV/c from Fermilab E866. There are several physics motivations for this study. First, there has been no report on the azimuthal angular distributions for proton-induced Drell-Yan – all measurements so far have been for polar angular distributions [3, 25]. Second, proton-induced Drell-Yan data provide a stringent test of theoretical models. For example, the $\cos 2\phi$ dependence is expected to be much reduced in proton-induced Drell-Yan if the underlying mechanism involves the Boer-Mulders functions. This is due to the expectation that the Boer-Mulders functions are small for the sea-quarks. However, if the QCD vacuum effect [12] is the origin of the $\cos 2\phi$ angular dependence, then the azimuthal behavior of proton-induced Drell-Yan should be similar to that of pion-induced Drell-Yan. Third, the validity of the Lam-Tung relation has never been tested for proton-induced Drell-Yan, and the present study provides a first test.

The Fermilab E866 experiment was performed using the upgraded Meson-East magnetic pair spectrometer. Details of the experimental setup have been described elsewhere [26]. An 800 GeV/c primary proton beam with up to 2×10^{12} protons per beam spill was incident upon one of three identical 50.8 cm long cylindrical stainless steel target flasks containing either liquid hydrogen, liquid deuterium or vacuum. A copper beam dump located inside the second dipole magnet (SM12) absorbed protons that passed through the target. Downstream of the beam dump was an absorber wall that completely filled the aperture of the magnet. This absorber wall removed hadrons produced in the target and the beam dump.

TABLE I: Mean values of the λ, μ, ν parameters and the quantity $2\nu - (1-\lambda)$ for three Drell-Yan measurements. The p_T dependence of these quantities is shown in Fig. 1.

	$p+d$ 800 GeV/c (E866)	$\pi^- + W$ 194 GeV/c (NA10)	$\pi^- + W$ 252 GeV/c (E615)
$\langle\lambda\rangle$	1.07 ± 0.07	0.83 ± 0.04	1.17 ± 0.06
$\langle\mu\rangle$	0.003 ± 0.013	0.008 ± 0.010	0.09 ± 0.02
$\langle\nu\rangle$	0.027 ± 0.010	0.091 ± 0.009	0.169 ± 0.019
$\langle 2\nu - (1-\lambda)\rangle$	0.12 ± 0.07	0.01 ± 0.04	0.51 ± 0.07

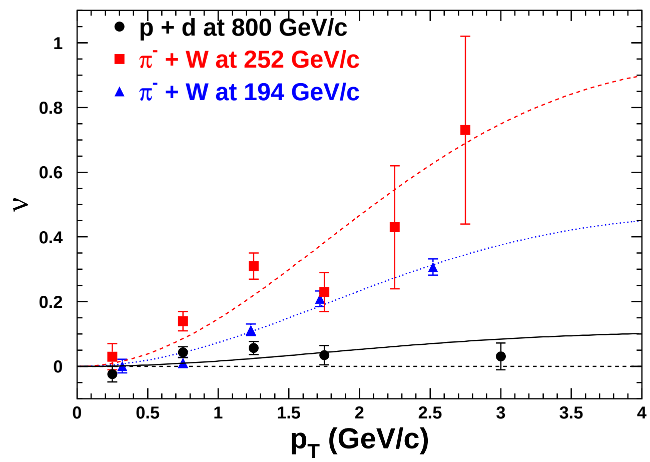

FIG. 2: Parameter ν vs. p_T in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c^2 are also shown.

Several settings of the currents in the three dipole magnets (SM0, SM12, SM3) were used in order to optimize acceptance for different dimuon mass regions. Data collected with the "low mass" and "high mass" settings [26] on liquid deuterium and empty targets were used in this analysis. The detector system consisted of four tracking stations and a momentum analyzing magnet (SM3). Tracks reconstructed by the drift chambers were extrapolated to the target using the momentum determined from the bend angle in SM3. The target position was used to refine the parameters of each muon track.

From the momenta of the μ^+ and μ^-, kinematic variables of the dimuons $(x_F, m_{\mu\mu}, p_T)$ were readily reconstructed. The muon angles θ and ϕ in the Collins-Soper frame [27] were also calculated. To remove the quarkonium background, only events with $4.5 < m_{\mu\mu} < 9$ GeV/c^2 or $m_{\mu\mu} > 10.7$ GeV/c^2 were analyzed. A total of 118,000 $p+d$ Drell-Yan events covering the decay angular range $-0.5 < \cos\theta < 0.5$ and $-\pi < \phi < \pi$ remain. Detailed Monte-Carlo simulations for the experiment using the MRST98 parton distribution functions [28] for NLO Drell-Yan cross sections have shown good agreements with the data for a variety of measured quantities.

Figure 1 shows the angular distribution parameters λ, μ, and ν vs. p_T. To extract these parameters, the Drell-Yan data were grouped into 5 bins in $\cos\theta$ and 8 bins in ϕ for each p_T bin. A least-squares fit to the data using Eq. 1 to describe the angular distribution was performed. Only statistical errors are shown in Fig. 1. The primary contributions to the systematic errors are the uncertainties of the incident beam angles on target. The analysis has been performed allowing the beam angles to vary within their ranges of uncertainty. From this study, we found that the systematic errors are comparable to the statistical errors for each individual p_T bin. However, the p_T averaged values $\langle\lambda\rangle, \langle\mu\rangle$, and $\langle\nu\rangle$, are dominatd by the statistical errors.

For comparison with the $p+d$ Drell-Yan data, the NA10 $\pi^- + W$ data at 194 GeV/c and the E615 $\pi^- + W$ data at 252 GeV/c are also shown in Fig. 1. To test the validity of the Lam-Tung relation, also shown in Fig. 1 is the quantity, $2\nu - (1-\lambda)$, for all three experiments. For $p+d$ at 800 GeV/c, Fig. 1 shows that λ is consistent with 1, in agreement with previous studies [3, 25], while μ and ν deviate only slightly from zero. This is in contrast to the pion-induced Drell-Yan results, in which much larger values of ν are found. Table I lists the mean values of λ, μ, ν and $2\nu - (1-\lambda)$ for these three experiments. Again, the qualitatively different behavior of the azimuthal angular distributions for $p+d$ versus $\pi^- + W$ is evident. It is also interesting to note that while E615 clearly establishes the violation of the Lam-Tung relation, the NA10 and the $p+d$ data are largely consistent with the Lam-Tung relation.

In an attempt to extract information on the magnitude of the $h_1^\perp$ function from the NA10 data, Boer [17] assumed that $h_1^\perp$ is proportional to the spin-averaged parton distribution function f_1:

$$h_1^\perp(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x), \qquad (2)$$

where k_T is the quark transverse momentum, M_H is the mass of the hadron H (pion or nucleon), and M_C and C_H are constant fitting parameters. A Gaussian transverse momentum dependence of $e^{-\alpha_T k_T^2}$ with $\alpha_T = 1$ (GeV/c)$^{-2}$ was assumed. The $\cos 2\phi$ dependence then results from the convolution of the pion $h_1^\perp/f_1$ term with the nucleon $h_1^\perp/f_1$ term, and the parameter ν is given as

$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \qquad (3)$$

where $\kappa_1 = C_{H_1} C_{H_2}/2$, and H_1, H_2 denote the two interacting hadrons. As shown in Fig. 2, a good description of the NA10 data is obtained with $\kappa_1 = 0.47 \pm 0.14$ and $M_C = 2.4 \pm 0.5$ GeV/c^2. A fit to the E615 ν data at 252 GeV/c using $M_C = 2.4$ GeV/c^2, also shown in Fig.

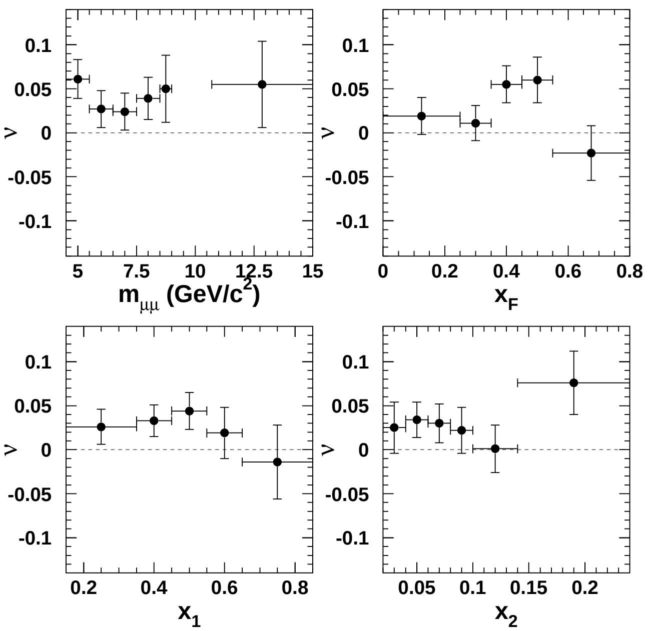

FIG. 3: Parameter ν vs. $m_{\mu\mu}$, x_F, x_1, and x_2 in the Collins-Soper frame for p+d at 800 GeV/c. The error bars correspond to the statistical uncertainties only.

2, gives $\kappa_1 = 0.93 \pm 0.10$. These large values of κ_1 suggest sizable $h_1^\perp$ functions for the valence antiquarks in the pion and for the valence quarks in the nucleon.

A fit to the E866 $p + d$ data using Eq. 3 yields $\kappa_1 = 0.11 \pm 0.04$ for $M_C = 2.4$ GeV/c^2, as shown in Fig. 2. As noted earlier, proton-induced Drell-Yan involves a valence quark annihilating with a sea quark. A comparison of the values of κ_1 from proton-induced Drell-Yan with those from pion-induced Drell-Yan suggests that the ratio $h_1^\perp/f_1$ for the nucleon sea quarks is substantially below that for valence quarks. More specifically, the value of C_H for the sea is approximately a factor 4–8 smaller than that for valence quarks.

The Drell-Yan angular distributions have also been analyzed for other kinematic variables. Figure 3 shows the values of ν for p+d vs. $m_{\mu\mu}, x_F, x_1$, and x_2, where x_1 and x_2 are the Bjorken-x for the beam and target partons, respectively. Again, for each bin the data were divided into 5 bins in $\cos\theta$ and 8 bins in ϕ in order to extract the angular distribution parameters. Figure 3 shows no significant dependence on these kinematic variables.

In summary, we report a measurement of the angular distributions of Drell-Yan dimuons for $p + d$ at 800 GeV/c. The pronounced $\cos 2\phi$ azimuthal angular dependence observed previously in pion-induced Drell-Yan is not observed in the $p + d$ reaction. The Lam-Tung relation, found to be strongly violated in the E615 pion-induced Drell-Yan, remains largely valid for $p + d$ Drell-Yan. These results put constraints on theoretical models that predict large $\cos 2\phi$ dependence originating from QCD vacuum effects. They also suggest that the Boer-Mulders functions $h_1^\perp$ for sea quarks are significantly smaller than those for valence quarks.

This work was supported in part by the U.S. Department of Energy and the National Science Foundation.

[1] S.D. Drell and T.M. Yan, Phys. Rev. Lett. **25**, 316 (1970); Ann. Phys. (NY) **66**, 578 (1971).
[2] W.J. Stirling and M.R. Whalley, J. Phys. **G19**, D1 (1993).
[3] P.L. McGaughey, J.M. Moss, and J.C. Peng, Annu. Rev. Nucl. Part. Sci. **49**, 217 (1999).
[4] I.R. Kenyon, Rep. Prog. Phys. **45**, 1261 (1982); K. Freudenreich, Int. J. Mod. Phys. **A5**, 3643 (1990).
[5] C.S. Lam and W.K. Tung, Phys. Rev. **D18**, 2447 (1978).
[6] P. Chiappetta and M. LeBellac, Z. Phys. **C32**, 521 (1986).
[7] J. Cleymans and M. Kuroda, Phys. Lett. **B105**, 68 (1981).
[8] C.G. Callan and D. J. Gross, Phys. Rev. Lett. **22**, 156 (1969).
[9] C.S. Lam and W.K. Tung, Phys. Rev. **D21**, 2712 (1980).
[10] NA10 Collaboration, S. Falciano *et al.*, Z. Phys. **C31**, 513 (1986); M. Guanziroli *et al.*, Z. Phys. **C37**, 545 (1988).
[11] E615 Collaboration, J.S. Conway *et al.*, Phys. Rev. **D39**, 92 (1989); J.G. Heinrich *et al.*, Phys. Rev. **D44**, 1909 (1991).
[12] A. Brandenburg, O. Nachtmann, and E. Mirkes, Z. Phys. **C60**, 697 (1993).
[13] D. Boer, A. Brandenburg, O. Nachtmann, and A. Utermann, Eur. Phys. J. **C40**, 55 (2005).
[14] A. Brandenburg, S.J. Brodsky, V.V. Khoze, and D. Müller, Phys. Rev. Lett. **73**, 939 (1994).
[15] K.J. Eskola, P. Hoyer, M. Väntinnen, and R. Vogt, Phys. Lett. **B333**, 526 (1994).
[16] E.L. Berger and S.J. Brodsky, Phys. Rev. Lett. **42**, 940 (1979).
[17] D. Boer, Phys. Rev. **D60**, 014012 (1999).
[18] D. Boer and P.J. Mulders, Phys. Rev. **D57**, 5780 (1998).
[19] S.J. Brodsky, D.S. Hwang, and I. Schmidt, Phys. Lett. **B530**, 99 (2002).
[20] J.C. Collins, Nucl. Phys. **B396**, 161 (1993).
[21] L.P. Gamberg, G.R. Goldstein, and K.A. Oganessyan, Phys. Rev. **D67**, 071504(R) (2003).
[22] D. Boer, S.J. Brodsky, and D.S. Hwang, Phys. Rev. **D67**, 054003 (2003).
[23] A. Bacchetta, A. Schäfer, and J.-J. Yang, Phys. Lett. **B578**, 109 (2004).
[24] Z. Lu and B.-Q. Ma, Phys. Lett. **B615**, 200 (2005).
[25] Fermilab E866 Collaboration, C.N. Brown *et al.*, Phys. Rev. Lett. **86**, 2529 (2001); T.H. Chang *et al.*, Phys. Rev. Lett. **91**, 211801 (2003).
[26] Fermilab E866 Collaboration, E.H. Hawker *et al.*, Phys. Rev. Lett. **80**, 3715 (1998); J.C. Peng *et al.*, Phys. Rev. **D58**, 092004 (1998); R.S. Towell *et al.*, Phys. Rev. **D64**, 052002 (2001).
[27] J.C. Collins and D.E. Soper, Phys. Rev. **D16**, 2219 (1977).
[28] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. **C4**, 463 (1998).