Measurement of the proton structure parameters in the forward-backward charge asymmetry

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The forward-backward asymmetry (A_{FB}) in the Drell-Yan process $pp/p\bar{p} \to Z\gamma^* \to \ell^+\ell^-$ is sensitive to the proton structure information. Such information has been factorized into well-defined proton structure parameters which can be regarded as experimental observables. In this paper, we extract the structure parameters from the A_{FB} distributions reported by the CMS Collaboration in pp collisions at $\sqrt{s} = 8$ TeV, and by the D0 Collaboration in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. It is the first time that the unique parton information in the A_{FB} spectrum can be decoupled from the electroweak calculation and measured as standalone observables, which can be used as new data constraints in the global quantum chromodynamics analysis of the parton distribution functions. Although the parton information in the pp and $p\bar{p}$ collisions are different, and the precisions are statistically limited, the results from both the hadron colliders indicate that the down quark contribution might be higher in the data than their theoretical predictions.

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I. INTRODUCTION

The forward-backward asymmetry (A_{FB}) of the Drell-Yan process $pp/p\bar{p} \to Z/\gamma^* \to \ell^+\ell^-$ is proved to be sensitive to the proton structure information, and could have important impact on the global quantum chromodynamics (QCD) analysis of the parton distribution functions (PDFs) [1–4]. Although A_{FB} has been measured with quite a good precision at both the Tevatron and the Large Hadron Collider (LHC), the results are not yet included in the global analysis of PDFs. The difficulty is the correlation between the proton structure information and the electroweak (EW) contribution in the A_{FB} measurement, which causes large uncertainties extrapolating from one to the other [4]. In the global analysis of NNPDF4.0 [5], it is clearly stated that the A_{FB} spectrum observed at the LHC has to be removed from the dataset due to the difficulties in handling the correlation.

In a recent study [6], the proton structure information in the A_{FB} spectrum has been factorized into well-defined structure parameters, which can be used as new experimental observables and determined together with the effective weak mixing angle ($\sin^2\theta^{\ell}_{\rm eff}$), so that the correlation with the EW can be automatically taken into account.

In this paper, we extract the structure parameters from the A_{FB} distributions measured by the CMS Collaboration using the pp collision data at $\sqrt{s} = 8$ TeV [7], and by the D0 Collaboration using the $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV [8]. This work, the details of which will be discussed in the following sections, provides unique constraints on the proton structure information. Specifically, the structure parameters from the A_{FB} separately reflect the contributions from u and d type quarks, which are always mixed and undistinguishable in the total cross section measurements of the Drell-Yan production. As pointed out in Ref. [6] and Ref. [9], these structure parameters can also constrain the dilution effect, which represents the contribution of a sea quark having higher energy than a valence quark in the initial state of the vector boson productions in pp collisions.

Although a complete global analysis of PDFs is needed to finally confirm the impact of the extracted structure parameters in this work, the direct comparison between the measured values and their theoretical predictions already indicates that the down type quark contribution might be higher than the expectation at the relevant momentum fraction range, represented by the Bjorken variable x. Such

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indication is consistent with the conclusion from the recent PDF global analysis that when the LHC data (other than A_{FB}) is included in the global fitting, the d valence quark PDF becomes larger at x around 0.1. [5,10,11]. Nevertheless, the extracted structure parameters in this work can be introduced into the global analysis of the PDFs, providing unique constraints on the corresponding proton structure information.

II. STRUCTURE PARAMETERS OBERSVED FROM THE LHC DATA

In this section, we discuss the extraction of the structure parameters using the A_{FB} spectrum in $pp \to Z/\gamma^* \to \ell^+\ell^-$, $(\ell = e,\ \mu)$ events measured by the CMS Collaboration using the 8 TeV pp collision data [7]. The A_{FB} distributions are measured as a function of the dilepton mass (M) in a range of [40, 2000] GeV, and separately in five Z boson rapidity bins (Y) of [0, 1], [1, 1.25], [1.25, 1.5], [1.5, 2.4], and [2.4, 5]. The central values and uncertainties of the observed asymmetry are provided, and the detailed numbers of the bin-by-bin correlations of systematics are given elsewhere [12]. The combined A_{FB} of e^+e^- and $\mu^+\mu^-$ events, and the corresponding uncertainties are replotted in Fig. 1, together with the theoretical predictions in the rapidity bin $|Y|$ of [1.5, 2.4] as an example. The theoretical predictions are computed using the CT18 NNLO PDF [10], and the RESBOS [13] package in which the QCD interaction is calculated at approximate next-to-next-to-leading order (NNLO) plus next-to-next-to-leading logarithm (NNLL), and the EW interaction is calculated based on the effective born approximation [14], which gives precise predictions on the relationship between A_{FB} and $\sin^2\theta^\ell_{\rm eff}$ around the Z pole. The reported A_{FB} distributions are unfolded to a phase space with no lepton acceptance cuts, thus the extracted structure parameters correspond to the same phase space in terms of M and Y.

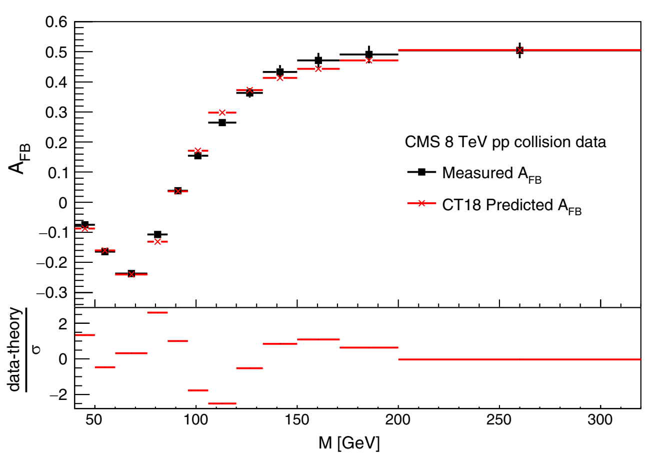

FIG. 1. The CMS 8 TeV $A_{FB}(M)$ measurement from the combined e^+e^- and $\mu^+\mu^-$ events with $M = [40, 320]$ GeV and $1.5 < |Y| < 2.4$, compared to the RESBOS prediction with CT18NNLO PDFs. The bottom panel is the difference between the CMS measured A_{FB} and the RESBOS+CT18 prediction, expressed in the unit of the total uncertainties σ, including the experimental uncertainty and the PDF uncertainty. The uncertainties on the theoretical predictions correspond to the 68% C.L. PDF uncertainties.

At the LHC, A_{FB} is measured in the Collins-Soper frame [15] with its z axis defined according to the direction of the momentum of the dilepton system. According to Ref. [6], the observed A_{FB} in a specific dilepton rapidity and mass configuration can be factorized as

$$\begin{aligned} A_{FB}(M) &= \frac{\sum_{q=u,c}[1-2D_q(M)]\alpha_q(M)}{\alpha_{\rm total}(M)}\cdot A^u_{FB}(M;\sin^2\theta^\ell_{\rm eff}) \\ &\quad+\frac{\sum_{q=d,s,b}[1-2D_q(M)]\alpha_q(M)}{\alpha_{\rm total}(M)}\cdot A^d_{FB}(M;\sin^2\theta^\ell_{\rm eff}) \\ &\equiv [\Delta_u(M)+P^u_0]\cdot A^u_{FB}(M;\sin^2\theta^\ell_{\rm eff}) \\ &\quad+[\Delta_d(M)+P^d_0]\cdot A^d_{FB}(M;\sin^2\theta^\ell_{\rm eff}), \end{aligned} \tag{1}$$

where α_q is the cross section of a specific subprocess with virtual photon and Z boson coupled to $q\bar{q}$ ($q = u, d, s, c, b$) in the initial state; while $\alpha_{\rm total}$ is the total cross section. $A^u_{FB}(M;\sin^2\theta^\ell_{\rm eff})$ and $A^d_{FB}(M;\sin^2\theta^\ell_{\rm eff})$ represent the original hard process asymmetries in the up-type and down-type subprocesses, respectively. Their calculations correspond to a special Collins-Soper frame, in which the directions of quark and antiquark are assumed to be known [6]. The values of A^u_{FB} and A^d_{FB} are solely determined by the single EW parameter of the effective weak mixing angle $\sin^2\theta^\ell_{\rm eff}$, which are independent of PDF. The dilution factors D_q in the first equality of Eq. (1), is defined as the probability of having the antiquark energy higher than the quark energy, and can be modeled and predicted by the PDFs as

$$D_q(x_L, x_S) = \frac{q(x_S)\bar{q}(x_L)}{q(x_S)\bar{q}(x_L) + q(x_L)\bar{q}(x_S)}, \tag{2}$$

where x_S and x_L are the Bjorken variables, respectively, for the small and large values in a $q\bar{q}$ pair. They are related to the boson kinematics as $x_{L,S} = \sqrt{M^2+Q_T^2}/\sqrt{s}\times e^{\pm Y}$, where Q_T is the transverse momentum of the dilepton system. In Drell-Yan productions at the LHC, the larger fraction x_L varies from $\mathcal{O}(10^{-2})$ to $\mathcal{O}(10^{-1})$, while the smaller one x_S is at an order of $\mathcal{O}(10^{-4})$ to $\mathcal{O}(10^{-3})$.

Based on the factorization formalism, the proton structure information, which is presented by the cross sections α_q and dilution factors D_q, is thereafter decoupled from the EW calculations, as the coefficients in front of the A^u_{FB} and A^d_{FB} terms. It can be further factorized as the structure parameters of P^u_0, P^d_0, $\Delta_u(M)$, and $\Delta_d(M)$. P^u_0 and P^d_0 represent the magnitude of the up-type and down-type coefficients averaged over the mass range of the A_{FB} spectrum; $\Delta_u(M)$ and $\Delta_d(M)$ correspond to the mass dependence of the coefficients, as shown in the second equality of Eq. (1). The detailed discussions can be found in Ref. [6]. Since the dilution factors of the s, c, and b quarks are close to 0.5, P_0^u, and P_0^d are dominated by the u and d (anti)quark contributions.

A simultaneous fit can then be performed to determine the values of the structure parameters and $\sin^2\theta_{\text{eff}}^{\ell}$, by searching for the best agreement between the measured $A_{FB}(M)$ spectrum and the corresponding calculations of Eq. (1). Specifically, P_0^u, P_0^d, and $\sin^2\theta_{\text{eff}}^{\ell}$ are treated as free parameters, so that the correlations between each one of them can be properly considered. As discussed in Ref. [6], when used as the sole data input in the fit, the $A_{FB}(M)$ spectrum is not sufficient enough to constrain all those parameters. Therefore, the $\Delta(M)$ parameters have to be fixed to PDF predictions. The PDF choice on the $\Delta(M)$ predictions would introduce additional theoretical uncertainties to the measurement of P_0^u, P_0^d, and $\sin^2\theta_{\text{eff}}^{\ell}$. However, when A_{FB} is measured in a narrow mass window around the Z pole, $\Delta(M)$ corresponds to the variation of the parton densities in a small range of x. Consequently, we will see the Δ-induced uncertainty much smaller than the experimental extrapolated uncertainties in this work.

Following the above strategy, the proton structure and EW parameters are then extracted from the CMS A_{FB} with four $|Y|$ bins up to 2.4, while the bin of $|Y| > 2.4$ is not used in this work due to its low statistic. The A_{FB} results with $M > 320$ GeV are also excluded, due to their low sensitivity and large uncertainties from $\Delta(M)$. The fitted $\sin^2\theta_{\text{eff}}^{\ell}$ values, as given in Table I, are statistically consistent with the value of 0.23101 ± 0.00053 measured by the CMS Collaboration using the same data [16]. The correlations between the extracted $\sin^2\theta_{\text{eff}}^{\ell}$ and P_0 parameters are also provided. The correlation is positive to P_0^u and negative to P_0^d, with similar size. It is fully understandable, as later we will see the fitted P_0^u and P_0^d parameters have a large negative correlation between each other. The sizable correlation between $\sin^2\theta_{\text{eff}}^{\ell}$ and the P_0 parameters reflects the fact that A_{FB} at hadron colliders is governed by both the EW physics and the proton structure information. Nevertheless, we focus on the P_0 parameters in this work. $\sin^2\theta_{\text{eff}}^{\ell}$ is fitted more on the purpose of dealing with the correlations.

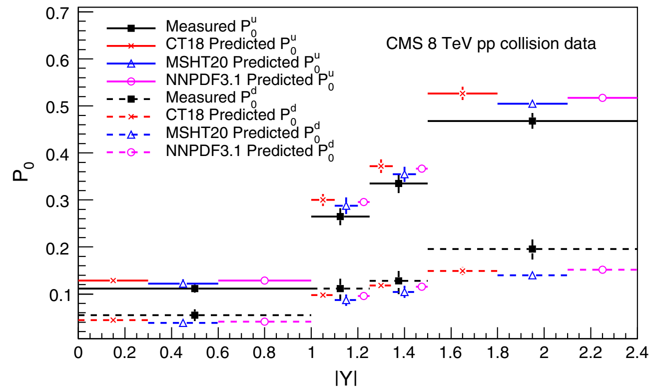

FIG. 2. The P_0^u and P_0^d parameters extracted from the $A_{FB}(M)$ spectrum in $|Y|$ bins of [0, 1.0], [1.0, 1.25], [1.25, 1.5], and [1.5, 2.4], and the corresponding RESBOS predictions from CT18, MSHT20, and NNPDF3.1. The error bars of the extracted P_0^u and P_0^d correspond to the total uncertainty including the experimental part and the $\Delta(M)$ induced part. The error bars of the predicted P_0^u and P_0^d correspond to the 68% C.L. PDF uncertainties.

The observed structure parameters P_0^u and P_0^d, as a function of $|Y|$, are shown in Fig. 2, compared to the RESBOS predictions with CT18, MSHT20 and NNPDF3.1 [10,11,17] PDFs. In all $|Y|$ bins, the observed P_0^u values are smaller than the theory predictions, while the P_0^d values are larger than the expectations. The deviation implies that there might be more significant contribution from the down-type quark subprocesses with respect to the theory prediction of current PDF sets. Such results reflect the behavior of the $A_{FB}(M)$ distributions reported by CMS. Due to the difference between the Z boson couplings to the down-type and up-type quarks, the magnitude of A_{FB}^d around the Z pole is smaller than that of A_{FB}^u. Consequently, if the measured A_{FB} values around M_Z are closer to zero than expectation, it could naturally imply a higher weight of A_{FB}^d in the data. This feature can be clearly seen through the CMS reported A_{FB} around the Z pole, as depicted in Fig. 1.

In principle, as shown in Eq. (1), P_0^u and P_0^d contain various information. Their values are governed by the light quark (u and d) PDFs at both x_L and x_S regions; The s, c, and b quark contributions, which appear in the denominators in Eq. (1), can also change the observed P_0 values; it might even be complicated by taking the difference between q and $\bar{q}$ densities for s, c, and b quarks into account.

TABLE I. Fitted values and uncertainties of $\sin^2\theta_{\text{eff}}^{\ell}$ from the CMS 8 TeV $A_{FB}(M)$ measurements. The uncertainty includes the fitting error derived from experimental uncertainty, and the theoretical error arising from $\Delta(M)$ estimated by using CT18 error sets.

$\lvert Y\rvert$ bins	Measured $\sin^2\theta_{\text{eff}}^{\ell}$ and uncertainties	Correlation with P_0^u	Correlation with P_0^d
[0, 1.0]	$0.2336 \pm 0.0017\,(\text{exp}) \pm 0.0006(\Delta)$	−0.64	0.78
[1.0, 1.25]	$0.2323 \pm 0.0016\,(\text{exp}) \pm 0.0006(\Delta)$	−0.63	0.76
[1.25, 1.5]	$0.2300 \pm 0.0016\,(\text{exp}) \pm 0.0006(\Delta)$	−0.67	0.80
[1.5, 2.4]	$0.2313 \pm 0.0006\,(\text{exp}) \pm 0.0004(\Delta)$	−0.69	0.78

TABLE II. Fitted values and uncertainties of P_0^u and P_0^d from the CMS $A_{FB}(M)$ measurement. The first uncertainties in the breakdown are extrapolated from the experimental uncertainties on the $A_{FB}(M)$, with the bin-by-bin correlation on systematics taken into account. The second uncertainties in the breakdown correspond to the theoretical errors arising from $\Delta(M)$ estimated by using the CT18 error sets.

$\lvert Y\rvert$ bins	$P_0^u \pm (\mathrm{exp}) \pm (\Delta)$	$P_0^d \pm (\mathrm{exp}) \pm (\Delta)$	Correlation
[0, 1.0]	$0.1118 \pm 0.0081 \pm 0.0030$	$0.0551 \pm 0.0118 \pm 0.0039$	−0.92
[1.0, 1.25]	$0.2644 \pm 0.0176 \pm 0.0048$	$0.1116 \pm 0.0247 \pm 0.0073$	−0.93
[1.25, 1.5]	$0.3350 \pm 0.0193 \pm 0.0053$	$0.1282 \pm 0.0273 \pm 0.0083$	−0.93
[1.25, 1.5]	$0.4681 \pm 0.0155 \pm 0.0069$	$0.1955 \pm 0.0193 \pm 0.0105$	−0.92

However, α_s, α_c, and α_b are not as large as α_u and α_d, thus not dominating the Z boson production. Contribution from the difference between q and $\bar{q}$ densities, for c and b at NNLO, is expected to be negligible; For the s quark, $s(x) \neq \bar{s}(x)$ is already allowed at the leading order (LO) in the global analysis of both MSHT20 and NNPDF4.0, but the difference between $s(x)$ and $\bar{s}(x)$ in the relevant x region of this work does not induce noticeable contribution to P_0. Therefore, the leading sensitivity of P_0^u and P_0^d as experimental observables is on the u and d quark distributions. As discussed in the introduction, recent global analyses yield a stronger d quark contribution after including the measurements of the single inclusive W and Z boson productions (without A_{FB}) at the LHC. Based on the above discussions, the results from the CMS A_{FB} measurement, to a certain degree, support the conclusion from the recent global analysis, which is one possible explanation on the deviation between the measured P_0 values and the theory predictions.

The measured structure parameters can now be used as standalone data constraints in the PDF global analysis. In Table II, we list the P_0^u and P_0^d values extracted from the CMS 8 TeV $A_{FB}(M)$ data. The total uncertainties are dominated by the experimental extrapolated uncertainties (including systematics and statistical ones). In most cases, the Δ-induced uncertainty increases the total uncertainty by only a few percent.

In principle, there should be additional uncertainties in predicting the relationship between $\sin^2\theta_{\mathrm{eff}}^{\ell}$ and $A_{FB}^{u,d}$, mainly from the calculation on the soft gluon radiations which generates Q_T of the dilepton system. At hadron colliders with nonzero Q_T, $A_{FB}^{u,d}$ can be smeared from its original EW symmetry breaking [15]. For a given Q_T, the smear effect can be precisely calculated. But for a sizable range of Q_T, an uncertainty can rise from the shape of the Q_T spectrum. Fortunately, such uncertainty is very small, because most of the Drell-Yan events gather within a small Q_T region lower than 20 GeV. In this work, we change the shape of the Q_T spectrum from the RESBOS predictions (NNLO + NNLL) to PYTHIA [18] predictions, and repeat the simultaneous fit. The difference between the RESBOS-based measurements and the PYTHIA-based measurements, if quoted as additional uncertainty, causes negligible increase on the total uncertainties of the P_0 parameters.

III. STRUCTURE PARAMETERS FROM THE TEVATRON DATA

In this section, we extract the structure parameters from the $A_{FB}(M)$ spectrum measured in $p\bar{p} \to Z/\gamma^* \to e^+e^-$ events at $\sqrt{s} = 1.96$ TeV by the D0 Collaboration [8]. Unlike the LHC, the hard processes in Tevatron $p\bar{p}$ collision are dominated by the valence u and d quarks. Besides, due to a relatively low beam energy, even the smaller momentum fraction x_S at the Tevatron is around 10^{-2}. As a result, the Tevatron data could provide a direct constraint especially in the x region above 0.01, on the valence u and d quark PDFs.

At the Tevatron, A_{FB} can be measured in the Collins-Soper frame, of which the z axis is defined according to the directions of the proton and antiproton beams. The factorization of the $A_{FB}(M)$ in $p\bar{p} \to Z/\gamma^* \to \ell^+\ell^-$ events shares exactly the same form in Eq. (1), while the dilution factor is differently defined as the probability of having a quark from the antiproton beam and an antiquark from the proton beam; namely, both partons are governed by the parton distributions of antiquarks in proton:

$$D_q(x_1, x_2) = \frac{\bar{q}(x_1)\bar{q}(x_2)}{q(x_1)q(x_2) + \bar{q}(x_1)\bar{q}(x_2)}, \tag{3}$$

where no requirement of $x_1 > x_2$ or $x_1 < x_2$ is needed. Nonetheless, the dilution factors at the Tevatron are small anyway. They are in general lower than 10%, while at the LHC they can be as large as 40% in the low rapidity region.

The D0 Collaboration provided their $A_{FB}(M)$ results in a Y-integrated phase space, in a mass range up to 1 TeV. In this paper, we use the data in the mass window of [50, 250] GeV to extract the structure parameters. Higher mass region is excluded due to their low statistic and large uncertainty from $\Delta(M)$. In Fig. 3, we compare the D0 $A_{FB}(M)$ data and the RESBOS prediction with CT18NNLO, as a function of M.

The comparison shows the same tendency as the CMS data, that the observed asymmetry A_{FB} at the Tevatron has smaller absolute values around Z pole than predictions. The extracted values of the P_0^u and P_0^d, together with their

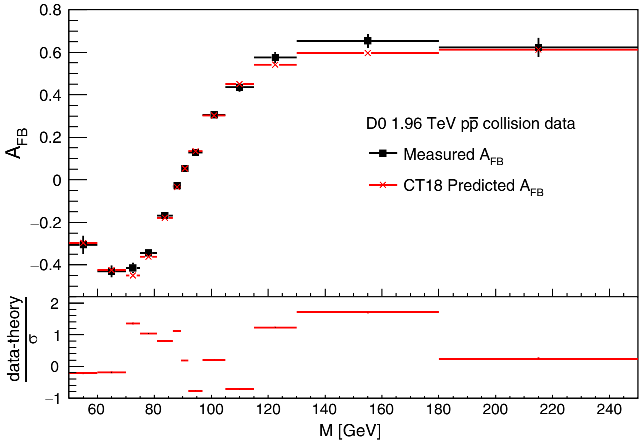

FIG. 3. The spectrum of $A_{FB}(M)$ measured using the Tevatron data, and the corresponding uncertainties. The bottom panel is the difference between the D0 measured A_{FB} and the RESBOS+CT18 predicted ones. The uncertainties on the theoretical predictions correspond to the 68% C.L. PDF uncertainties.

uncertainties, are compared to the RESBOS predictions using various PDFs in Table III. The correlation between the uncertainties of the extracted P_0^u and P_0^d is −0.95. As expected, the observed structure parameters indicate more significant contribution from the d quarks. In fact, P_0^u and P_0^d reflect the relative strength of the $u\bar{u}$ and $d\bar{d}$ subprocesses in Drell-Yan productions, rather than their absolute contributions. Accordingly, when the observed d quark contributions are enhanced, the u quark ones are expected to be suppressed. These negative correlations have been demonstrated in both the observations of P_0^u and P_0^d form the CMS and D0 data.

On the other hand, the fitted $\sin^2\theta_{\rm eff}^{\ell}$ gives 0.2318 ± 0.0014, which is consistent with the value of 0.2309 ± 0.0010 extracted by the D0 Collaboration [8], using the same data with conventional method. The correlation between the fitted $\sin^2\theta_{\rm eff}^{\ell}$ and P_0^u is −0.69, while it is 0.78 between $\sin^2\theta_{\rm eff}^{\ell}$ and P_0^d. As concluded in Ref. [19], the PDFs change the $A_{FB}(M)$ distribution on its shape as a rotation around the Z pole, while $\sin^2\theta_{\rm eff}^{\ell}$ governs $A_{FB}(M)$ more on its average value. Therefore, both the results of the Figs. 1 and 3 call for a change in their corresponding P_0^u and P_0^d values, rather than the $\sin^2\theta_{\rm eff}^{\ell}$ value.

IV. CONCLUSION

In this paper, we present the first application of the factorization formalism of A_{FB} at hadron colliders, and determine the structure parameters P_0^u and P_0^d by fitting to the CMS and D0 data. The measured P_0^u and P_0^d can be used as experimental inputs in the PDF global analysis. Though the observed structure parameters are still statistically limited, the CMS and D0 data coincidently hint at an indication that the down-type quark contribution might be higher than the predictions of current PDFs.

We would like to point out that (i) The indication by now simply comes from the direct comparison between the extracted values of P_0^u and P_0^d and their theoretical predictions based on the factorization formalism presented in Ref. [6]. To understand the impact of the structure parameter measurements, the numerical results of this work should be introduced into a complete PDF global analysis; (ii) to confirm the deviation of observed P_0^u and P_0^d, a larger data sample should be used at both hadron colliders. For the LHC, the 130 fb^{-1} data at 13 TeV has already been collected during its run 2 period, and more data will be collected in the future. For the Tevatron, the $A_{FB}(M)$ distribution used in this work corresponds to only half of the D0 data with one single channel of the dielectron final state. It could be several times more events if the full dataset collected by both the D0 and CDF detector can be used, with both dielectron and dimuon final states included.

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TABLE III. Predictions on P_0^u and P_0^d in $p\bar{p}$ collisions from CT18, MSHT20, and NNPDF3.1, compared to the extracted values from the D0 $A_{FB}(M)$. The first uncertainty labeled with Expt. on the extracted P_0^u and P_0^d corresponds to the experimental uncertainty, while the second on labeled with Δ comes from the theoretical error of $\Delta(M)$ estimated by using the CT18 error sets. Uncertainties on the predictions correspond to the 68% C.L. PDF uncertainties.

	P_0^u	P_0^d
D0 data	0.6395 ± 0.0356 (Expt) $\pm 0.0059(\Delta)$	0.2706 ± 0.0662 (Expt) $\pm 0.0061(\Delta)$
CT18	0.6994 ± 0.0089	0.1733 ± 0.0062
MSHT20	0.6887 ± 0.0066	0.1658 ± 0.0075
NNPDF3.1	0.6919 ± 0.0054	0.1703 ± 0.0055

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