

Relative difference between up and down quark structure of the proton

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We present a novel determination of the down-to-up quark composition ratio using the forward-backward asymmetry observed in the proton-proton collisions at the LHC. This method offers unique insights into the flavor-specific difference between down and up quarks, which are difficult to isolate in traditional cross-section measurements due to the inherent mixing of contributions from both flavors. In this study, we systematically measure the down-to-up quark ratio over a broad momentum fraction (x) range of 0.01 to 0.1, utilizing the sensitivity of the forward-backward asymmetry to quark-level couplings. Our findings reveal significant deviations in both the value and x dependence of this ratio compared to predictions from current parton distribution functions. These discrepancies highlight potential limitations in existing parton distribution function parametrization and emphasize the importance of flavor-separated measurements for advancing our understanding of proton structure.

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The relative difference between the up and down quark distributions is of importance in both the proton structure and quantum chromodynamics (QCD) studies. For the “valence” component at large momentum fraction of $x \sim 0.1$, u and d quark densities have significant non-perturbative contributions, of which the ratio is related to the constituent description of the proton. For the “sea” component, the relative difference between $u(\bar{u})$ and $d(\bar{d})$ directly reflects the impact of both the nonperturbative and perturbative (arising from gluon splitting) QCD dynamics. Therefore, the relative difference between $u(\bar{u})$ and $d(\bar{d})$ parton distribution functions (PDFs), as a function of the parton momentum fraction x and the energy scale Q , is essential to the studies of both proton structure and perturbative QCD. Although various measurements have been performed to study the up and down quark distributions in past decades, direct observations of the relative difference in these PDFs are very rare. It is because most physical interactions, from the lepton-nucleon and neutrino-nucleon deep inelastic scattering to the hadron-hadron Drell-Yan process, can happen via both flavors with comparable cross sections and similar final state particles, so that the $u(\bar{u})$ and $d(\bar{d})$ contributions always mix and are

indistinguishable. For example, in the latest global analysis of PDFs [1–3], such a mixture dominates in the measurements of both the Z boson productions [4–10] and the γ^* -exchanged interactions [4,11–16]. Even in the charged-current $W^\pm$ boson productions, the observed cross sections can still be a mixture of u and $\bar{d}$, or d and $\bar{u}$ [17–22].

In this paper, we report a determination of the relative difference between the up and down quark contributions from the forward-backward asymmetry (A_{FB}) of the $pp \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^-$ process. It has been shown in Ref. [23] that the $u(\bar{u})$ and $d(\bar{d})$ quark information in A_{FB} can be separately factorized into new structure parameters, P_u and P_d , without any mixture of the two types. The ratio $R = P_d/P_u$, thus, reflects the unique information of the relative difference between up and down quarks, of which the contributions of s , c , and b quarks nearly perfectly canceled. This is because $q(x, Q) = \bar{q}(x, Q)$, for $q = s$, c , and b , up to the next-to-leading order in QCD interactions, assuming that $q(x, Q_0) = \bar{q}(x, Q_0)$ at the initial scale Q_0 around 1 GeV. This new method has already been applied at both the LHC and Tevatron. In the first application of Ref. [24], P_u and P_d were extracted from the A_{FB} distributions reported by the CMS Collaboration with their 8 TeV data [25], giving a tendency of R to be higher than the current PDF predictions around $x > 0.05$. However, the precision in R was limited because the effective weak mixing angle $\sin^2 \theta_{\text{eff}}^\ell$ was simultaneously fitted as an additional free parameter, which smeared the sensitivity to the parton information. Following that, the D0 Collaboration measured P_u and P_d using the data collected during its run IIb period [26], giving R higher

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than the PDF predictions by more than 3.5 standard deviations at $x \sim 0.1$. In the D0 measurement, $\sin^2 \theta_{\text{eff}}^\ell$ was fixed to its experimentally determined value, and the corresponding uncertainty arising from varying its value to the determination of R is found to be negligible.

In this work, we measure P_u , P_d , and R using the latest A_{FB} measurement reported by the CMS Collaboration with 138 fb^{-1} data at 13 TeV [27,28]. We also remeasure the R parameter using the previous CMS 8 TeV A_{FB} with $\sin^2 \theta_{\text{eff}}^\ell$ value fixed to improve the precision of the measurement. As illustrated later, this new determination gives precise observation in a wide range of x . The R parameter is found to be significantly higher than the current PDF predictions when $x > 0.05$, while at $x \approx 0.01$ it is instead lower than the predictions. The new results not only give large deviation in the down-to-up ratio, but also indicate a different shape in the x dependence. The deviation also reflects the fact that direct constraint on the up-to-down relative difference is very weak in current PDF global analysis. As a new observation with unique information, the findings from this work is expected to have important impact on both the proton structure study and the perturbative QCD predictions.

According to Ref. [23], A_{FB} in the $pp \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^-$ process can be factorized up to all orders as

$$A_{\text{FB}}(Y, M, Q_T) = C_u(Y, M, Q_T) A_{\text{FB}}^u(Y, M, Q_T; \sin^2 \theta_{\text{eff}}^\ell) + C_d(Y, M, Q_T) A_{\text{FB}}^d(Y, M, Q_T; \sin^2 \theta_{\text{eff}}^\ell), \quad (1)$$

where Y , M , and Q_T are the rapidity, invariant mass, and transverse momentum, respectively, of the dilepton system. C_u and C_d are the structure parameters representing the parton information in the initial state. A_{FB}^u and A_{FB}^d are the forward-backward asymmetries corresponding to the $u\bar{u} \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^-$ and $d\bar{d} \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^-$ hard processes, respectively. They are independent of the parton information in the initial state and can be precisely predicted. A_{FB}^u and A_{FB}^d are naturally different, especially as functions of the invariant mass of the lepton pair M around the Z boson mass pole. Therefore, C_u and C_d can be simultaneously determined from the observed A_{FB} distribution.

In each $Y - M - Q_T$ interval, the structure parameters can be written in terms of parton densities as

$$C_u = \frac{[u(x_1)\bar{u}(x_2) - u(x_2)\bar{u}(x_1)]\mathcal{N}_u}{\sum_{q=u,c,d,s,b}[q(x_1)\bar{q}(x_2) + q(x_2)\bar{q}(x_1)]\mathcal{N}_q}, \quad C_d = \frac{[d(x_1)\bar{d}(x_2) - d(x_2)\bar{d}(x_1)]\mathcal{N}_d}{\sum_{q=u,c,d,s,b}[q(x_1)\bar{q}(x_2) + q(x_2)\bar{q}(x_1)]\mathcal{N}_q}, \quad (2)$$

where $\mathcal{N}_q$ are the event rates contributed by the hard scattering processes involving $q - \bar{q} - Z/\gamma^*$ couplings and C_u and C_d contain all higher-order QCD corrections

included in the factorized form of Eq. (1), with the parton momentum fractions x_1 and x_2 defined by

$$x_{1,2} = \frac{\sqrt{M^2 + Q_T^2}}{\sqrt{s}} \times e^{\pm Y}, \quad (3)$$

where $\sqrt{s}$ is the collider energy. Therefore, it is equivalent to have (x_1, x_2) and (Y, M, Q_T) to describe the dependences. C_u and C_d contain only the up and down quark information in their numerators. The denominator is the total cross section of the Drell-Yan process, which cancels in the ratio of $R = C_d/C_u$. Therefore, R is an observable purely related to the relative difference between the $d(\bar{d})$ and $u(\bar{u})$ contributions. In the LHC's high-energy collisions, x_2 is usually at $\mathcal{O}(10^{-3})$, where the perturbative QCD contribution becomes dominant in the light quark densities, resulting in consistent distributions of light quarks within their uncertainties. At $x_1 > 0.01$, however, the nonperturbative contributions still can cause sizable difference between light quarks [1]. Taking the assumption of $u(x_2) \approx \bar{u}(x_2) \approx d(x_2) \approx \bar{d}(x_2)$, we have $R \approx (d(x_1) - \bar{d}(x_1))/(u(x_1) - \bar{u}(x_1)) = d_V(x_1)/u_V(x_1)$, which is an experimental observable nearly perfectly reflecting the valence quark ratio without any mixture of other quark information.

Given the fact that the (Y, M, Q_T) intervals cannot be infinitely small in practice, it is the average structure parameters, P_u and P_d , actually being measured:

$$C_u(Y, M, Q_T) = P_u + \Delta_u(Y, M, Q_T), \quad C_d(Y, M, Q_T) = P_d + \Delta_d(Y, M, Q_T). \quad (4)$$

$\Delta_u(Y, M, Q_T)$ and $\Delta_d(Y, M, Q_T)$, which describe the kinematic dependences in that interval, are usually fixed and defined to yield zero when integrated over Y , M , and Q_T . In principle, fixing Δ_u and Δ_d introduces uncertainties on P_u and P_d . However, as demonstrated in Refs. [23,24,26], such uncertainties can be small with current binning of experimental observations.

In the recent CMS 13 TeV new measurement, the asymmetry of the Drell-Yan events is measured as the effective angular coefficient A_4 , defined in the cross section:

$$\frac{d\sigma}{d \cos \theta dY dM} \propto 1 + \cos \theta^* + A_4(Y, M) \cos \theta^* + \frac{1}{2} A_0(Y, M) (1 - 3 \cos^2 \theta^*) \quad (5)$$

in full phase space. θ^* is the scattering angle of the event defined in the Collins-Soper frame [29]. By this definition, the overall A_4 directly relates to the forward-backward asymmetry as $A_{\text{FB}} = (3/8)A_4$. For simplicity, we do not distinguish A_{FB} and A_4 in the rest of this paper, as they

differ by only a constant factor. A_{FB} is observed in nine intervals of $|Y|$ from 0 to 3.4 and in a mass window not wider than 100 GeV around the Z boson mass pole. Although A_{FB} are observed in different mass bins, P_u and P_d can be measured only in function of $|Y|$ accordingly, because the simultaneous fit on P_u and P_d relies on the information of the difference in the mass dependence between A_{FB}^u and A_{FB}^d [23]. Therefore, in this study, we measure P_u and P_d as averages over the Z boson mass pole in each $|Y|$ interval.

The central values of P_u and P_d in each $|Y|$ interval are determined by requiring the best agreement between the experimentally measured A_{FB} and the predicted A_{FB} in Eqs. (1) and (4) via the minimum χ^2 fit:

$$\chi^2 = \sum_i \frac{(A_{\text{FB}}^{\text{data}}(M_i) - A_{\text{FB}}^{\text{pred}}(M_i))^2}{\sigma^2(M_i)}. \quad (6)$$

According to the CMS report, the bin-by-bin correlations of the total uncertainties $\sigma(M_i)$ are negligible [28]. In the calculations of $A_{\text{FB}}^{\text{pred}}$, the hard-process-level asymmetries A_{FB}^u and A_{FB}^d are computed using the ResBos [30] package in which the QCD interaction is calculated at approximate next-to-next-to-leading order plus next-to-next-to-next-to-leading logarithm, and the electroweak interaction is calculated based on the effective Born approximation [31], which gives precise predictions on the relationship between A_{FB} and $\sin^2 \theta_{\text{eff}}^e$ around the Z pole. $\sin^2 \theta_{\text{eff}}^e$ in the calculation is fixed to the average of the LEP-SLC measurement [32]. Results from the hadron colliders are excluded in order to avoid the influence from the PDFs used in those measurements. It would not have impact anyway, because the hadron collider measurements [33–36] give $\sin^2 \theta_{\text{eff}}^e$ values very close to the LEP-SLC combination. The fixed Δ_u and Δ_d which describe the dependences on Y , M , and Q_T in the intervals corresponding to the CMS measurement are predicted from the CT18 next-to-next-to-leading-order PDF [1]. We apply the same method to the previous CMS 8 TeV A_{FB} observation [25]. However, compared to the previous work in Ref. [24], we have fixed the $\sin^2 \theta_{\text{eff}}^e$ value in this study, as explained earlier. Our analysis confirms that varying the $\sin^2 \theta_{\text{eff}}^e$ value within its current uncertainty does not have noticeable effect on the determination of the proton parameters. By doing so, the uncertainties on the extracted P_u and P_d are reduced by roughly 50%. Because of its lower collision energy, the 8 TeV measurement corresponds to a larger x value compared to the 13 TeV measurement.

The extracted central values of P_u and P_d in each $|Y|$ interval, together with the predictions from various PDFs, are given in Fig. 1 for the 13 TeV measurement and in Fig. 2 for the 8 TeV update, respectively. Numerical results are listed in Tables I and II. The uncertainties on the measured P_u and P_d consist of three parts: (i) extrapolated from the experimental uncertainties on the original measured A_{FB} ,

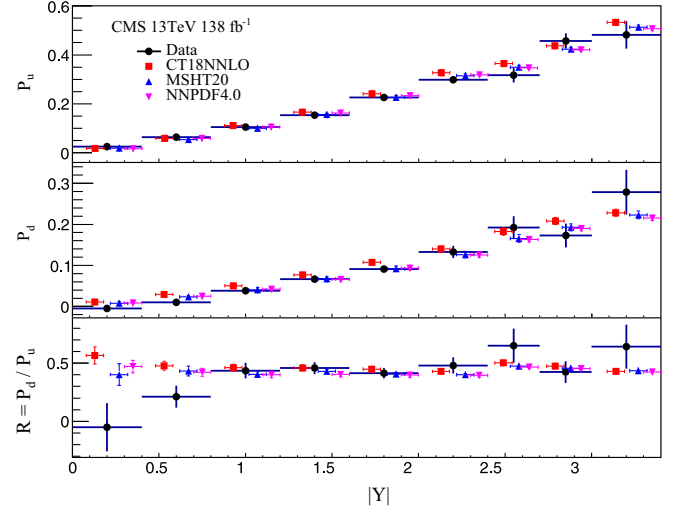


FIG. 1. P_u , P_d , and R measured from the CMS 13 TeV A_{FB} in each $|Y|$ interval, compared to the predictions from CT18, MSHT20, and NNPDF4. Error bars of the measured P_u , P_d , and R parameters correspond to the total uncertainties including those from experimental uncertainty extrapolation and the fixed Δ_u and Δ_d .

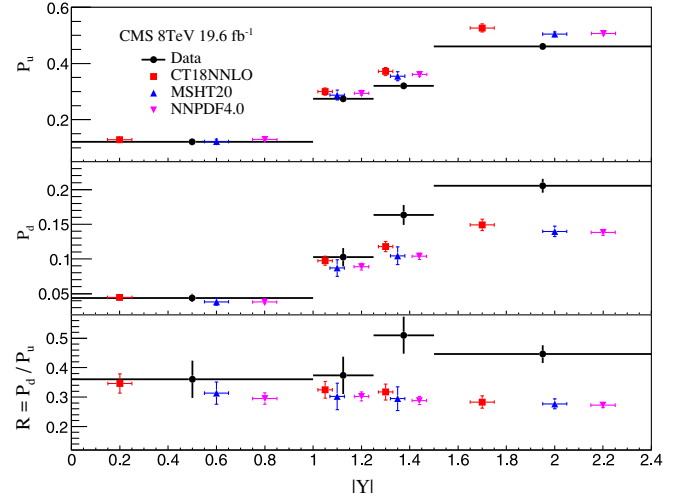


FIG. 2. P_u , P_d , and R measured from the CMS 8 TeV A_{FB} in each $|Y|$ interval, compared to the predictions from CT18, MSHT20, and NNPDF4. Error bars of the measured P_u , P_d , and R parameters correspond to the total uncertainties including those from experimental uncertainty extrapolation and the fixed Δ_u and Δ_d .

which is acquired directly in the minimal χ^2 fitting and dominates the total uncertainty; (ii) due to the fixed $\sin^2 \theta_{\text{eff}}^e$, which is estimated by varying its value according to the experimental uncertainty of the LEP-SLC determination and found to be negligible; (iii) arising from the fixed Δ_u and Δ_d , which can be computed using the PDF error sets provided by CT18. It has been checked that other PDFs, such as the MSHT20 and NNPDF4.0 [2,3], give consistent predictions

TABLE I. Fitted values and uncertainties of P_u and P_d from the CMS 13 TeV A_{FB} measurement. The first uncertainties in the breakdown are extrapolated from the experimental uncertainties. The second uncertainties in the breakdown correspond to the theoretical errors arising from Δ_u and Δ_d estimated by using the CT18 error sets. The last column gives the correlation factor between the P_u and P_d uncertainties.

$ Y $	$P_u \pm (\text{exp}) \pm (\Delta)$	$P_d \pm (\text{exp}) \pm (\Delta)$	ρ
0–0.4	$0.0242 \pm 0.0039 \pm 0.0004$	$-0.0012 \pm 0.0052 \pm 0.0002$	–0.88
0.4–0.8	$0.0651 \pm 0.0041 \pm 0.0005$	$0.0138 \pm 0.0054 \pm 0.0006$	–0.88
0.8–1.2	$0.1054 \pm 0.0041 \pm 0.0004$	$0.0460 \pm 0.0055 \pm 0.0008$	–0.88
1.2–1.6	$0.1574 \pm 0.0049 \pm 0.0006$	$0.0720 \pm 0.0060 \pm 0.0007$	–0.88
1.6–2.0	$0.2307 \pm 0.0066 \pm 0.0010$	$0.0956 \pm 0.0079 \pm 0.0011$	–0.88
2.0–2.4	$0.2966 \pm 0.0130 \pm 0.0012$	$0.1423 \pm 0.0148 \pm 0.0021$	–0.88
2.4–2.7	$0.3159 \pm 0.0297 \pm 0.0018$	$0.2054 \pm 0.0278 \pm 0.0038$	–0.91
2.7–3.0	$0.4503 \pm 0.0315 \pm 0.0026$	$0.1907 \pm 0.0292 \pm 0.0043$	–0.91
3.0–3.4	$0.4656 \pm 0.0557 \pm 0.0022$	$0.2993 \pm 0.0542 \pm 0.0042$	–0.92

TABLE II. Fitted values and uncertainties of P_u and P_d from the CMS 8 TeV A_{FB} measurement. The first uncertainties in the breakdown are extrapolated from the experimental uncertainties. The second uncertainties in the breakdown correspond to the theoretical errors arising from Δ_u and Δ_d estimated by using the CT18 error sets. The last column gives the correlation factor between the P_u and P_d uncertainties.

$ Y $	$P_u \pm (\text{exp}) \pm (\Delta)$	$P_d \pm (\text{exp}) \pm (\Delta)$	ρ
0–1.0	$0.1216 \pm 0.0062 \pm 0.0021$	$0.0439 \pm 0.0071 \pm 0.0013$	–0.88
1.0–1.25	$0.2743 \pm 0.0136 \pm 0.0033$	$0.1025 \pm 0.0157 \pm 0.0025$	–0.88
1.25–1.5	$0.3205 \pm 0.0147 \pm 0.0033$	$0.1636 \pm 0.0174 \pm 0.0027$	–0.88
1.5–2.4	$0.4609 \pm 0.0132 \pm 0.0021$	$0.2056 \pm 0.0144 \pm 0.0030$	–0.88

on Δ_u and Δ_d within the uncertainties [24,26]. According to the CMS report, the experimental uncertainties on the observed A_{FB} are dominated by the statistical fluctuation. The uncertainties in the extracted P_u and P_d are highly correlated, as both parameters are simultaneously fitted from A_{FB} . These correlations should be accounted for when calculating the uncertainty in the R parameter. Ideally, the correlation should reflect only the contributions from experimental uncertainties. However, using it as the total uncertainty correlation has no significant impact, as the Δ -induced uncertainties remain small.

As shown in Fig. 2, the measured R values are significantly larger than current PDF predictions in the two high $|Y|$ intervals in the 8 TeV extraction, while in the two lower $|Y|$ intervals the measured values are consistent with predictions. According to Eq. (3), the two high $|Y|$ intervals correspond to x_1 between 0.05 and 0.1 and x_2 around 0.002. For the two lower $|Y|$ intervals, $x_1 \approx 0.02$ and $x_2 \approx 0.005$. As demonstrated previously, the R parameter is a direct observable on $d_V(x_1)/u_V(x_1)$, which can be sizably biased due to lack of directly experimental observation in current PDF global analysis. The deviation is consistent with the D0 measurement [26], which gives R at $x \sim 0.1$ larger than PDF predictions by 3.5 standard deviations.

The 13 TeV extraction includes both overlapping and extended x_1 regions compared to the 8 TeV LHC and the D0 studies. In the 13 TeV data, the corresponding x_2 is even

smaller, making the light quark distribution more consistent. For the high $|Y|$ intervals which correspond to $x_1 > 0.05$, R is also measured to be, in general, larger than the predictions. However, the statistical fluctuation limits the precision. The most important results of the 13 TeV analysis come from the lower $|Y|$ intervals with high precision. In the $|Y|$ intervals between 1.0 and 2.0, the R parameter is precisely determined to be consistent with the predictions. It corresponds to $0.02 < x < 0.05$, the same region as the 8 TeV extraction, which also yields results consistent with the predictions. The low $|Y|$ bins correspond to $x < 0.02$, which is not covered by the 8 TeV kinematics. Within these intervals, the measured R value is lower than the PDF prediction, reversing the trend described above. Note that the measured P_d value is close to zero in the lowest $|Y|$ bin. According to Eq. (2), it means d and $\bar{d}$ quarks have almost consistent parton densities in the corresponding x region. In another word, the measured structure parameter indicates that the perturbative QCD contribution is more significant with respect to the current PDF predictions.

According to Eq. (2) and the arguments following Eq. (3), the impact of this new determination is clear that R is mainly the ratio between $d_V(x_1)$ and $u_V(x_1)$. Focusing on the region where $x_1 > 0.05$, the data suggest a higher value of the down-to-up valence quark ratio, which can also be explained as either the d/u ratio must increase or the

$\bar{d}/\bar{u}$ SU(2) flavor asymmetry must be significantly suppressed. Similarly, at $x \sim 0.01$, an opposite shift in parton distributions is required to align with the observed data behavior. In other words, we conclude that the forward-backward asymmetries observed at the Tevatron and the LHC indicate a different x dependence of the light-quark PDFs, particularly in the ratios of d/u and $\bar{d}/\bar{u}$. These asymmetries can be sensitively probed only through this class of experimental observables rather than through total cross-section measurements. In future global analyses of PDFs, incorporating the forward-backward asymmetry of Drell-Yan data will be crucial for enhancing our understanding of parton densities inside the proton. This is not only important for investigating light-quark PDFs, but also for heavy-quark PDFs, through the interplay of various QCD sum rules, such as the momentum sum rule.

Finally, we note that all our numerical predictions used in the data comparisons include the full contributions from the

s , c , and b quarks and antiquarks, consistent with the adopted PDF sets, with full kinematic dependence consistently implemented in every component of the ResBos framework. The approximations described above are, therefore, conceptual simplifications made for clarity, not omissions in the actual calculations.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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