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Forward-Backward Drell-Yan Asymmetry and PDF Determination [a]

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We investigate the impact of high-statistics Drell-Yan (DY) measurements at the LHC on the study of non-perturbative QCD effects from parton distribution functions (PDF). We present the results of a PDF profiling analysis based on the neutral-current DY forward-backward asymmetry, using the open source fit platform `xFitter`.

The high statistics at the Large Hadron Collider (LHC) Run II and the forthcoming Run III and high-luminosity HL-LHC open the way to precision measurements at the TeV scale, which will be used both for studies of the Standard Model (SM) and for searches for beyond-Standard-Model (BSM) physics. In order to keep up with the increasing statistical precision of experimental measurements, an impressive effort is being made on the theoretical side to provide higher-order perturbative QCD calculations — see e.g. [1]. With improving perturbative accuracy, nonperturbative QCD contributions such as parton distribution functions (PDF) more and more become a crucial limiting factor in the theoretical systematics affecting both precision SM studies and BSM searches. An important part of the physics program to be carried out with current and upcoming collider data is thus to identify which measurements can be most helpful in placing constraints on the nonperturbative PDF and their uncertainties.

In the Drell-Yan (DY) production channel, measurements of differential distributions in mass and rapidity and of the charged-current (CC) asymmetry have long been used to constrain PDFs (see e.g. [2,3,4,5,6,7] for recent results), while measurements of the neutral current (NC) forward-backward asymmetry (henceforth denoted as A_{FB}) have traditionally been used for determinations of the weak mixing angle θ_W (see e.g. [8,9,10,11,12,13]). In [14,15] it was observed that A_{FB} measurements in NC processes at the LHC can usefully be employed for PDF determinations. Ref. [16] investigates the impact of A_{FB} data on PDF extractions by using the open source fit platform `xFitter` [17], considering different scenarios for luminosities (from Runs II, III to the HL-LHC stage [18]) and performing PDF profiling to analyze quantitatively the effect of A_{FB} on PDF uncertainties. In this article we report on this study.

The five-fold differential DY cross section in the vector boson mass, rapidity, transverse momentum and lepton decay angles may be written in terms of angular coefficients A_k as

$$\frac{d\sigma}{dM_{\ell\ell}dY_{\ell\ell}dP_{\ell\ell}^{\perp}d\cos\theta d\phi} = \frac{d\sigma^{(\mathrm{U})}}{dM_{\ell\ell}dY_{\ell\ell}dP_{\ell\ell}^{\perp}}\frac{3}{16\pi}\Big[1+\cos^2\theta+\frac{1}{2}A_0(1-3\cos^2\theta) \tag{1}$$
$$+ A_1\sin 2\theta\cos\phi+\frac{1}{2}A_2\sin^2\theta\cos 2\phi+A_3\sin\theta\cos\phi$$

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$$+ \quad A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \Big] \ .$$

The azimuthally integrated cross section is given by

$$\frac{d\sigma}{dM_{\ell\ell} dY_{\ell\ell} dP_{\ell\ell}^{\perp} d\cos\theta} = \frac{d\sigma^{(\mathrm{U})}}{dM_{\ell\ell} dY_{\ell\ell} dP_{\ell\ell}^{\perp}} \frac{3}{8} \left[1 + \cos^2\theta + \frac{1}{2} A_0 (1 - 3\cos^2\theta) + A_4 \cos\theta \right] \ , \qquad (2)$$

where the A_4 term is responsible for the forward-backward asymmetry. This may be defined as

$$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \qquad \text{where} \quad \sigma_F = \int_0^1 \frac{d\sigma}{d\cos\theta} \, d\cos\theta \ , \quad \sigma_B = \int_{-1}^0 \frac{d\sigma}{d\cos\theta} \, d\cos\theta \ . \qquad (3)$$

At leading order (LO) in α_s, $A_0 = 0$, $A_4 \neq 0$. The LO triple differential cross section may be written as

$$\frac{d\sigma}{dM_{\ell\ell} dY_{\ell\ell} d\cos\theta} = \frac{\pi\alpha^2}{3M_{\ell\ell} s} \sum_q H_q \left[f_q f_{\bar{q}} + \{ q \leftrightarrow \bar{q} \} \right] \ , \qquad (4)$$

where f is the PDF and H_q is given in terms of the vector and axial couplings v and a and electric charges e by

$$\begin{aligned} H_q \ &= \ e_\ell^2 e_q^2 (1 + \cos^2\theta) \qquad (5) \\ &+ \ e_\ell e_q \frac{2M_{\ell\ell}^2 (M_{\ell\ell}^2 - M_Z^2)}{\sin^2\theta_W \cos^2\theta_W \left[(M_{\ell\ell}^2 - M_Z^2)^2 + \Gamma_Z^2 M_Z^2 \right]} \left[v_\ell v_q (1 + \cos^2\theta) + 2 a_\ell a_q \cos\theta \right] \\ &+ \ \frac{M_{\ell\ell}^4}{\sin^4\theta_W \cos^4\theta_W \left[(M_{\ell\ell}^2 - M_Z^2)^2 + \Gamma_Z^2 M_Z^2 \right]} \\ &\times \ \left[(a_\ell^2 + v_\ell^2)(a_q^2 + v_q^2)(1 + \cos^2\theta) + 8 a_\ell v_\ell a_q v_q \cos\theta \right] . \end{aligned}$$

The A_{FB} is dominated by the Z/γ interference $\cos\theta$ term in the second line of Eq. (5), proportional to $e_\ell e_q a_\ell a_q$, with $a_q = T_q^3/2$, where T_q^3 is the third component of weak isospin. It is thus primarily sensitive to the charge-weighted PDF linear combination $(2/3)u + (1/3)d$.

To carry out the PDF profiling analysis, the A_{FB} is implemented in `xFitter`, and NLO QCD corrections to DY are included via NLO grids obtained with `MadGraph5_aMC@NLO` [19], interfaced to `APPLgrid` [20] through `aMCfast` [21]. At LO the angle θ may be reconstructed using the direction of the boost of the di-lepton system [22,23,24,25,26], while in general we use the definition of angle θ in the CS frame [27]. The cross sections are computed in the detector fiducial region using the acceptance cuts of [28]. Suitable datafiles with pseudodata are generated for the profiling analysis as described in [16].

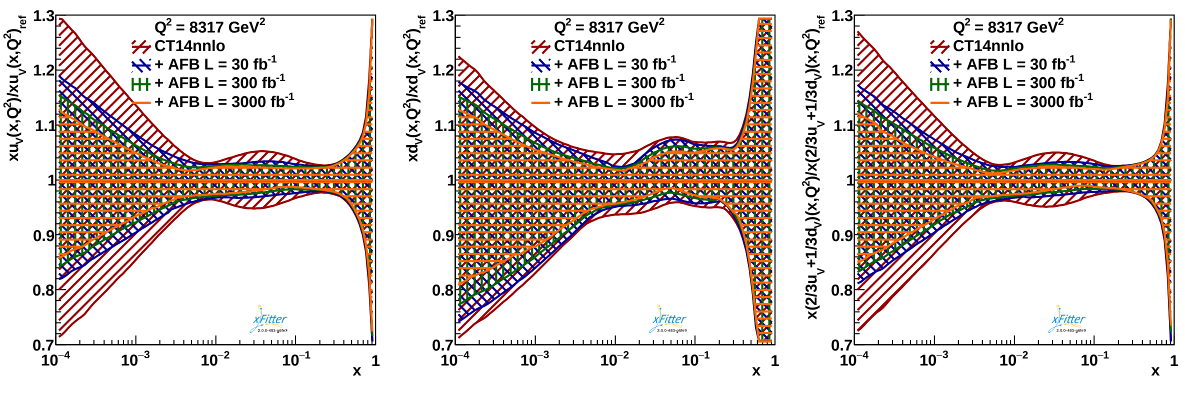

Figure 1 – Original (red) and profiled curves distributions for the normalised distribution of the ratios of (left to right) u-valence, d-valence and $((2/3)u + (1/3)d)$-valence of the CT14nnlo PDF set, using A_{FB} pseudodata corresponding to integrated luminosities of 30 fb^{-1} (blue), 300 fb^{-1} (green) and 3000 fb^{-1} (orange).

Figs. 1 and 2 show results from the profiling analysis [16], illustrating the reduction of PDF uncertainties for various scenarios of A_{FB} pseudodata and various PDF sets. In Fig. 1 the role of different integrated luminosities is illustrated for the case of valence quark distributions in the CT15nnlo set [3]. In Fig. 2 the cases of valence and sea quark distributions are illustrated for NNPDF3.1nnlo [4], MMHT2014nnlo [6], ABMP16nnlo [5] and HERAPDF2.0nnlo [7], using A_{FB} pseudodata corresponding to integrated luminosity of 300 fb^{-1}. The largest effects are observed for u-valence and d-valence distributions in the region of intermediate and low momentum fraction x, and for ABMP16nnlo and HERAPDF2.0nnlo sets. Sea quark determinations show a moderate improvement [16], progressively increasing with the integrated luminosity. For PDF sets with Hessian eigenvectors, it is shown explicitly in [16] by eigenvector reparameterization that u-valence and d-valence eigenvectors are highly correlated and A_{FB} data constrain their charge-weighted sum $(2/3)u_V + (1/3)d_V$.

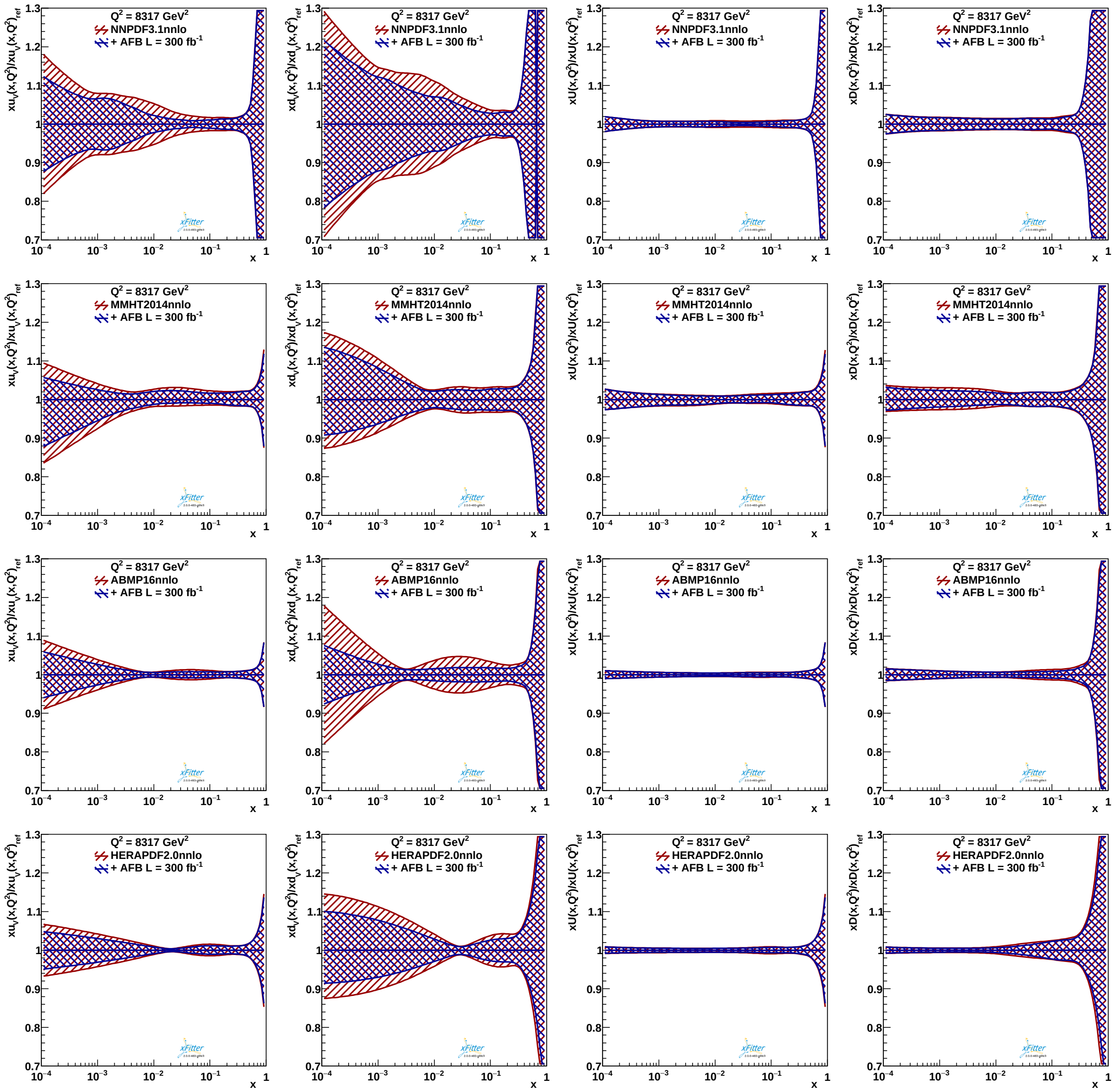

Figure 2 – Original (red) and profiled (blue) distributions for the normalised distribution of the ratios of (left to right) u-valence, d-valence, u-sea and d-sea quarks. The profiled curves are obtained using A_{FB} pseudodata corresponding to an integrated luminosity of 300 fb^{-1}. Distributions are shown for the PDF sets (rows top to bottom) NNPDF3.1nnlo, MMHT2014nnlo, ABMP16nnlo and HERAPDF2.0nnlo.

Ref. [16] also studies different scenarios corresponding to different selection cuts on the di-lepton rapidity. By increasing the rapidity cut, enhanced sensitivity is obtained to quark distributions in the high x region. In this case the high statistics of the HL-LHC is crucial to achieve sufficient precision in the measurement of the $A_{\rm FB}$.

In summary, the study reported in this article shows that neutral-current DY data from Run II, III and HL-LHC can be exploited to constrain nonperturbative QCD effects from PDFs, and thus to reduce the theoretical systematics affecting both precision SM studies and BSM searches. The $A_{\rm FB}$, in particular, plays a complementary role to the lepton charge asymmetry of the DY charged-current channel, which has long been used in PDF global fits. Traditionally the $A_{\rm FB}$ has been used for determinations of the weak mixing angle θ_W. We have found that new PDF sensitivity arises from the di-lepton mass and rapidity spectra of the $A_{\rm FB}$, which encodes information on the lepton polar angle, or pseudorapidity. We have presented quantitative results on PDF uncertainties based on PDF profiling calculations in `xFitter`. The results strongly support using DY data for combined determinations of θ_W and PDFs.

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