Longitudinal Z-boson polarization and the Higgs boson production cross-section

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Abstract

We present a study of the LHC (and HL-LHC) potential towards a precise determination of the gluon parton distribution function of the proton at intermediate Bjorken-x from measurements of Drell-Yan production. To this extent, we exploit a clean and theoretically well predicted observable: the Drell-Yan lepton angular coefficient A_0, associated with the longitudinal polarization of the Z boson. Through a detailed numerical analysis using the open-source xFitter platform, we illustrate how this observable can provide significant sensitivity over current determinations of the gluon PDF, and a reduction in the PDF uncertainty on the Higgs boson production cross-section by a factor of over 50%.

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1 Introduction

The characterisation of the Higgs sector and the investigation of the electroweak symmetry breaking mechanism are among the main physics goals of the LHC and future High Luminosity (HL) LHC. The uncertainties from the knowledge of the parton distribution functions of the proton constitute one of the main limitations to fully exploit its physics potential [1]. In particular, the Higgs cross-section in its dominant gluon-gluon fusion production channel is extremely sensitive to the gluon PDF at intermediate Bjorken-x ranges. Currently, the gluon PDF is determined indirectly from scaling violations in deep-inelastic scattering data, with additional sensitivity coming from LHC measurements such as jet and top quark production. These latter two processes are however challenging to measure, and suffer from theoretical ambiguities making them difficult to predict to high accuracy [2, 3]. In this work [4], we propose a novel determination of the gluon PDF at intermediate Bjorken-x values using neutral current Drell-Yan data and an experimentally clean and easy to measure observable, which can be predicted theoretically to very high accuracy and exhibits a good perturbative stability.

The analysis has been performed using `xFitter` [5,6], an open-source package allowing to extract PDFs and other QCD parameters. It implements a large number of different datasets, and has been used in a variety of QCD studies; most recently an extraction of the pion PDF [7] and a study of the impact of forward-backward asymmetries in Drell-Yan on PDFs [8].

2 The A_0 angular coefficient

We consider Drell-Yan production [9] via Z/γ^* boson exchange at the LHC. The cross section summed over the electroweak boson polarizations has the angular distribution $1+\cos^2\theta$ and is sensitive to the gluon PDF for finite p_T. However, in the small-p_T region where the cross-section is the largest it is sensitive to large logarithmic corrections, while at high-p_T the missing higher order uncertainties become large. In this study we focus on the leptonic angular distributions through the angular coefficient A_0, the ratio of the longitudinal electroweak boson cross section to the unpolarized cross section:

$$A_0(s,M,Y,p_T) = \frac{2d\sigma^{(L)}/dMdYdp_T}{d\sigma/dMdYdp_T}. \tag{1}$$

It associated with the $(3\cos^2\theta-1)/2$ angular dependence of the cross-section on the polar angle θ^* [10], with θ^* measured in the Collins-Soper frame [11]. The longitudinally polarized coefficient A_0 in Eq. (1) vanishes in the parton model and receives leading-order (LO) perturbative QCD contributions at $\mathcal{O}(\alpha_s)$. It has been computed up to $\mathcal{O}(\alpha_S^3)$ [12], showing a very good pertubative stability. The A_0 coefficient is parity-conserving and sensitive to flavor singlet PDFs. The main sensitivity to the gluon distribution arises from the region where the change of A_0 with p_T is largest, i.e., around the turn-over point $\partial^2 A_0/\partial p_T^2 = 0$. For dilepton masses near the Z-boson peak the turn-over occurs for boson p_T of the order of several ten to 100 GeVs.

The angular coefficients in Drell-Yan, and A_0, have been measured by many fixed-target and collider experiments. We consider the A_0 distribution from the ATLAS measurement of the angular coefficients in Z boson production at $\sqrt{s}=8$ TeV [13]. The measurement is performed in 23 p_T bins (we remove the first bins where our fixed-order predictions would not be adequate), going from 11.4 GeV to 600 GeV, and in three different rapidity bins: $0<|Y|<1$, $1<|Y|<2$, and $2<|Y|<3.5$. Predictions at NLO in QCD for finite boson p_T (at order $\mathcal{O}(\alpha^2)$) have been produced with mg5_aMC@NLO and aMCfast [14]. A χ^2 is constructed, incorporating all experimental uncertainties and their correlations, as well as PDF uncertainties. The impact of the A_0 data on PDFs is then evaluated through an Hessian profiling technique [15,16]. We find a good description of the data, with χ^2/ndf of order one, for all modern PDFs: CT18NNLO [17], NNPDF3.1nnlo [18], ABMP16nnlo [19], and MSHT20nnlo [20]. The reduction in the PDF uncertainties after the inclusion of the A_0 data is however found to be negligible.

3 PDF constraints and the Higgs cross-section

3.1 Sensitivity to the gluon PDF

We then generate pseudodata for the A_0 distribution at $\sqrt{s}=13$ TeV for two projected luminosity scenarios of 300 fb^{-1} (the expected integrated luminosity at the end of the LHC Run III) and 3 ab^{-1} (the design integrated luminosity of the HL-LHC stage). To do this we extrapolate the statistical uncertainties, and add a conservative estimate of 0.1% for the dominant

experimental systematic on the lepton momentum scale. We perform a PDF profiling exercise using the CT18NNLO PDF set, first reduced to 68% CL coverage, and find that the increased statistics allows for a significant reduction in the PDF uncertainties. This reduction is particularly large for the gluon density and for the u and d sea-quark densities coupled to gluons through QCD evolution, as shown in Fig. 1. The largest sensitivity is found to come from transverse momenta in the range $p_T \sim 50$ GeV, dying out for $p_T > 100$ GeV. The gain from a 300 fb^{-1} measurement is found to dominate over the 3 ab^{-1} gain, although an improvement is nonetheless present.

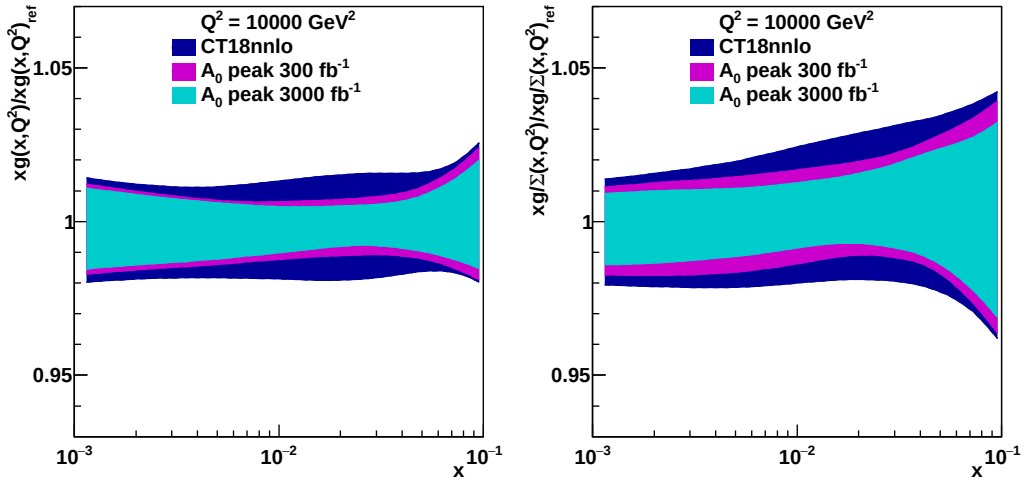

Figure 1: The gluon (xg) and gluon/Sea (xg/Σ) PDFs in the original CT18NNLO analysis (blue) and profiled using A_0 pseudodata corresponding to integrated luminosities of 300 fb^{-1} (magenta) and 3 ab^{-1} (cyan) in the region 80 GeV $< M <$ 100 GeV and $|Y| < 3.5$.

3.2 Impact on Higgs phenomenology

The effect of the longitudinally polarized coefficient on the $Q^2 = 10^4$ GeV^2 gluon PDF near $x \sim 10^{-2}$ will influence the Higgs boson cross section. In Fig. 2 we show the gluon-gluon luminosity for the CT18NNLO PDF, before and after the profiling using A_0 pseudodata. Most of the reduction in the uncertainties is found in the Higgs mass range. In the right plot we show the N^{3}LO gluon-fusion Higgs total cross section and its uncertainty obtained with `ggHiggs` [21, 22]. for the CT18NNLO, NNPDF3.1nnlo and MSHT20nnlo global PDF sets. Notwithstanding the numerical differences, a similar reduction in the PDF uncertainties is seen for the different sets. We also show The PDF4LHC15scen1 and 2 projected sets, which include pseudodata based on complete LHC data sample [23], which show a smaller, but not negligible, reduction in uncertainties.

4 Conclusion

We have studied the impact of precise measurements of the A_0 angular coefficient in neutral current Drell-Yan on the uncertainties of the gluon PDF and on the Higgs boson production cross-section in gluon-gluon fusion. We found that future measurements of A_0 have the possibility to reduce by about a factor of two the uncertainty of the gluon PDFs at intermediate Bjorken-x values. This translates in a large reduction in the PDF uncertainty on the

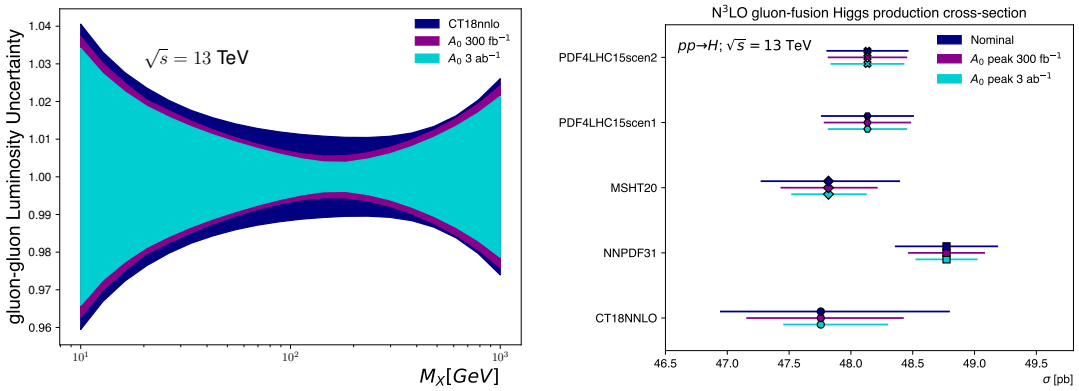

Figure 2: [Left] Ratio of PDF uncertainties for the gluon-gluon luminosity evaluated at $\sqrt{s}$ =13 TeV. The blue band shows the uncertainties of the CT18NNLO PDF set [17], reduced to 68% CL coverage. The magenta and cyan bands show the impact of including constraints from the A_0 measurement and assuming 300 fb^{-1} and 3 ab^{-1}, respectively. [Right] PDF uncertainties on the N3LO gluon-gluon fusion Higgs boson cross-section, shown for different PDF sets before and after the inclusion of the A_0 measurement constraints.

gluon-fusion Higgs production cross-section. Our results open a new area of phenomenological studies on connections between the gauge and Higgs sectors of the SM. Further aspects may be investigated by extending the analysis to the full structure of lepton angular distributions, including polarization interferences, and to mass regions far away from the Z-boson peak.

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