Parton distribution functions and constraints on the intrinsic charm content of the proton using BHPS approach

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In this work, a new set of parton distribution functions taking into account the intrinsic charm (IC) contribution is presented. We focus on the impact of the EMC measurements on the large $x$ charm structure function as the strongest evidence for the intrinsic charm when combined with the HERA, SLAC and BCDMS data. The main goal of this paper is the simultaneous determination of the intrinsic charm probability $P_{c\bar{c}/p}$ and strong coupling $\alpha_s$. This allows us to study the interaction of these two quantities as well as the influence on the PDFs in the presence of IC contributions. By considering $\alpha_s$ which can be fix or free parameter from our QCD analysis, we find that although there is not a significant change in the extracted central value of PDFs and their uncertainties, the obtained value of $P_{c\bar{c}/p}$ change by factor 7.8%. The extracted value of $P_{c\bar{c}/p}$ in the present QCD analysis is consistent with the recent reported upper limit of 1.93%, which is obtained for the first time from LHC measurements. We show the intrinsic charm probability is sensitive to the strong coupling constant and also the charm mass. The extracted value of the strong coupling constant $\alpha_s(M_Z^2) = 0.1191 \pm 0.0008$ at NLO is in good agreement with world average value and available theoretical models.

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1. INTRODUCTION

The distribution of heavy quarks in the proton can provide a comprehensive overview of the nucleon structure, and it is essential for processes in the perturbative QCD (pQCD) calculations at the LHC physics.

According to the Brodsky, Hoyer, Peterson, and Sakai (BHPS) model [1, 2], the charm quark distribution of the nucleon consists of two separate contributions. The first one is generated perturbatively by gluon splitting to $c\bar{c}$ ($g \rightarrow c\bar{c}$) from DGLAP evaluation equations [3], which is generally referred to “extrinsic charm”, see [4–6]. This extrinsic charm distribution depends logarithmically on the charm mass $m_c$ and is most important at low $x$. Next is the “intrinsic charm” (IC) which has a non-perturbative origin, in contrast to extrinsic charm, and is associated with bound state hadron dynamics. This distribution is described by Fock state in the nucleon structure which is dominant at large $x$ arises from multiply connected charm quark pairs by the valence quarks. With same rapidities of the quarks which constituent the nucleons, this contribution is maximal in the minimal off-shellness and depends on the non-perturbative structure of the nucleon. While the intrinsic charm contribution is dominant at high $x$ and depends on $1/m_c^2$, the extrinsic charm distribution is dominant at small $x$ and depends logarithmically on charm mass.

A review of the intrinsic heavy quark content of the nucleon has been reported in Ref. [7]. Several theoretical and phenomenological studies have been performed taking into account the IC component in the proton [8–17]. Also, according to BHPS approach, the intrinsic light-quark sea in the proton are studied in Refs. [18, 19].

Other studies have been performed using the intrinsic quark components to find the effects on charm quark production [20–37]. Recently, QCD analyses of parton distribution functions (PDFs) taking into account IC contribution are reported by NNPDF3IC [38] and CT14 [39] collaborations. Also, there are explanations of how one can probe the intrinsic charm in different ways, i.e., directly [40] and indirectly [41].

The intrinsic charm contribution is important for estimating the flux of high energy neutrino which observed in the IceCube measurement. In Ref. [13], the prompt neutrino spectrum using the intrinsic charm contribution is estimated. It is shown that the prompt atmospheric neutrino flux taking into account the intrinsic charm...
contribution is comparable with the extracted results of QCD calculations without taking to account the intrinsic charm. Undoubtedly, the IceCube measurements will constrain the IC component in the proton. This kind of measurements will also contribute to the main questions in high energy physics phenomenology in the future \[42\].

Not only intrinsic charm quark but also intrinsic strange and bottom quarks are principle property of the wave functions of hadronic bound states. The application of the operator product expansion shows that the probability for the analogous intrinsic bottom contribution from \[|uudbb\rangle\] Fock states is suppressed relative to intrinsic charm by a factor of \(m_u^2/m_b^2\).

There are some processes which are sensitive to the charm quark distribution in the large \(x\) region. For example the European Muon Collaboration (EMC) \[43\] provided the charm structure function data \(F_2^c\) as strong evidence for intrinsic component at large \(x\) \[42\]. The measurement at \(x=0.42\), \(Q^2=75\) GeV\(^2\) is approximately 30 times higher than predicted from gluon splitting. It should be noted that the EMC data is the only DIS evidence for intrinsic charm at high \(x\) and it is worthwhile to include these data in the study of intrinsic charm.

A description of the EMC data with intrinsic charm is presented in Refs. \[48, 49, 50\]. In Ref. \[48\], the NNPDF included the EMC data with using the standard \(W^2 > 12.5\) GeV\(^2\) cut to avoid the presence of dynamical higher twists. Although the EMC data are included without nuclear corrections in NNPDF collaboration \[48\], several fit variants have been performed to assess the impact of nuclear corrections on the EMC data and find a moderate impact.

In Ref. \[44\], Hoffmann and Moore performed the NLO calculation of the BHPS model using EMC data. The first NLO analysis of both extrinsic and intrinsic contributions with EMC data was done by Harris, Smith, and Vogt \[45\].

Since the first experimental evidence of IC originated from the EMC measurement at large \(x\), a variety of charm hadrons measurements are consistent with the existence of IC. In the case of hadron-hadron collisions, the intrinsic charm leads to the production of charm hadrons such as the \(\Lambda_c(cud)\) as observed in ISR experiments \[46\] and more recently by SELEX \[47\] at high \(x_F = x_c + x_u + x_d\) from the coalescence of the charm quark with its coming valence quarks, as well as quarkonium productions at high \(x_F = x_c + x_c\). Double intrinsic charm Fock states such as \([uudccb]\) in the proton lead to the production of double-charm baryons as well as double quarkonia at high \(x_F\), see Ref. \[48\]. Previous fixed target \(J/\psi\) measurements also show signs of significant IC contribution, taking into account the nuclear mass dependence, as measured at CERN and Fermilab, see e.g. \[49, 50\].

On the other hand, the production of the prompt photons at hadron colliders in \(pp(\bar{p}) \rightarrow \gamma + c\)-jet is sensitive to the charm distribution and may provide good evidence for IC at high \(p_T\). In Refs. \[51, 52\] the results of \(c\)-jet production accompanied by vector bosons \(Z, W^\pm\) is studied by using the intrinsic charm quark component. The impact of IC contributions for the prediction of \(\gamma + c\)-jet production in \(pp\) collisions at the LHC is reported in Ref. \[54\], where this impact for large \(p_T\) can be distinguished from the case in which the IC contribution is not considered. Without considering IC contribution, the D0 data for \(\gamma + c\)-jet differential cross section \[55\] can not be described by solely using an extrinsic charm PDF based on the DGLAP evolution equation. In contrast, the D0 data for \(\gamma + b\)-jet differential cross section is explained by the extrinsic standard PDFs. This is consistent with the fact that the ratio of the intrinsic bottom distribution to the intrinsic charm distribution in the proton is suppressed by \(m_b^2/m_c^2\).

In addition to the typical observables for IC, the intrinsic bottom (IB) quarks also contribute to diffractive Higgs production in which the Higgs boson carries a remarkable fraction of the proton momentum. Measuring the high \(x_F\) process \(pp \rightarrow HX\) via intrinsic quarks (IQ) at the LHC would give new constraints on the Higgs couplings to quark pairs, including \(H \rightarrow bb\) \[54\].

Additionally, the new ATLAS measurements at the LHC \[57\] have shown that the production of prompt photons accompanied by a charm-quark jet in \(pp\) collisions are sensitive to the intrinsic charm content of the nucleon. By having these new ATLAS measurements at 8 TeV, the upper limit of the intrinsic charm probability is found to be about \(P_{c^i/p}=1.93\%\) \[58\]. They proposed a method that reduced the uncertainty on the determination of intrinsic charm probability. Undoubtedly, demonstrating the compatibility of the DIS data and the new LHC data for the \(P_{c^i/p}\) extraction \[58\], would be worth. Regarding the importance of intrinsic heavy quarks, now we have sufficient motivation to incorporate the IC contributions in our QCD analysis.

In this paper, we perform our QCD analysis based on the \textsc{xFitter} open source framework \[53, 60\], which was previously known as HERA\textsc{fitter}. Recently, the low \(x\) resummation of QCD analysis is performed by \textsc{xFitter} \[61\], which leads to the better description of the data at low \(x\) and low \(Q^2\). Other QCD analysis based on \textsc{xFitter} framework are performed in Ref. \[62, 63\]. In Refs. \[62, 64\] we extracted the strong coupling constant using HERA I and II combined data and Neutrino-nucleon structure function data using \textsc{xFitter}. More recently, we also determined the strong coupling constant with polarized data \[65\]. Note that one of the main purposes of this paper is to determine \(\alpha_s\) concurrently with the IC probability.

The paper is organized as follows. In the Sec.\[1\] we briefly outline the basic formalism and provide a theoretical overview of the intrinsic heavy quark distributions. In this section, we also introduce the \(Q^2\) evolution of the intrinsic heavy quark distribution functions and the intrinsic heavy quark component of the structure functions. The experimental data which we use in the present analysis is presented in Sec.\[II\]. The PDF parametrizations are discussed in Sec.\[IV\]. In Sec.\[V\] we present the fit results for the PDFs including the intrinsic charm at NLO,
and we make comparisons with other different theoretical analyses from literature. Finally, our discussion and conclusion are given in Sec. VI

II. BHPS MODEL AND EVOLUTION OF INTRINSIC HEAVY QUARK STRUCTURE FUNCTION

According to the light-cone formalism, the proton wave function can be represented as a sum over the complete basis of free quark and gluon states based on a superposition of the proton wave function and a n-particle Fock fluctuation components, $|q_1 q_2 q_3\rangle$, $|q_1 q_2 q_4\rangle$, $|q_1 q_2 q_3 q_5\rangle$, etc. as

$$\left| \Psi_p \right| = \psi_{3q/p}(x_i, \mathbf{k}_{\perp i})|ud\rangle + \psi_{3qg/p}(x_i, \mathbf{k}_{\perp i})|udg\rangle + \ldots ,$$

where the light-front wave functions $\psi_{j/p}(x_i, \mathbf{k}_{\perp i})$ depend on the relative momentum coordinates $k_{\perp i}$ and $x_i = k_{\perp i}^2 / P^+$ in which $k_i$ explains the parton momenta and $P$ denotes the hadron momentum. For a proton with mass of $m_p$, the general form of the Fock wave function is

$$\psi_n/p(x_i, \mathbf{k}_{\perp i}) = \frac{\Gamma(x_i, \mathbf{k}_{\perp i})}{m_p^n - M^2} = \frac{\Gamma(x_i, \mathbf{k}_{\perp i})}{m_p^n - \sum_i m_i^2 / x_i} ,$$

where $\hat{m}_i^2 = m_i^2 + \langle \mathbf{k}_{\perp i}^2 \rangle$ is the square of the average transverse mass of parton $i$. Note that by decreasing $m_p^n - M^2$, the $\Gamma$ as a vertex function, expected to be a slowly varying. This form can be applied to the higher Fock components for an arbitrary number of light and heavy quarks. The momentum conservation for $n$ number of partons in state $|j\rangle$ demands $\sum_i \mathbf{k}_{\perp i} = 0$ and $\sum_i x_i = 1$.

In the BHPS model \cite{1}, the probability distribution in the 5-particle intrinsic Fock state is

$$\frac{dP_{IC}}{dx_1 \cdots dx_5} = N_5 \frac{\delta(1 - \sum_i x_i)}{m_p^5 - \sum_i m_i^2 / x_i} ,$$

where $N_5$ normalizes the 5-particle Fock state probability that is determined by $P_{\bar{c}/p} = \int_0^1 dx_1 \cdots dx_5 \frac{dP_{IC}}{dx_1 \cdots dx_5}$, where $P_{\bar{c}/p}$ is the intrinsic charm probability in the proton. In the heavy quark limit, $m_c, m_{\bar{c}} \gg m_p, m_g$, where the mass of light quark and proton are negligible compared to the heavy quarks mass, the Fock state probability distribution is written as

$$\frac{dP_{IC}}{dx_1 \cdots dx_c dx_{\bar{c}}} = N_5 \delta(1 - \sum_i x_i) \frac{x_c^2 x_{\bar{c}}^2}{(x_c + x_{\bar{c}})^2} ,$$

where $N_5 = N/m_c^4 \bar{c}$ is determined from Eq. \ref{3} by integrating over $dx_1 \cdots dx_{\bar{c}}$, so the intrinsic heavy quark probability distribution is given by

$$c_{int}(x_c) = \int dx_1 \cdots dx_{\bar{c}} \frac{dP_{IC}}{dx_1 \cdots dx_c dx_{\bar{c}}} = P_{\bar{c}/p} 1800 x_c^2 \left[ \frac{1 - x_c}{3} (1 + 10 x_c + x_c^2) + 2 x_c (1 + x_c) \ln(x_c) \right] .$$

We can simplify the above equation by considering $P_{\bar{c}/p} = 1\%$ IC probability. For more details see Refs. \ref{23} \ref{24}.

According to Eq. \ref{3}, as the BHPS model predicts \cite{1}, the existence of the intrinsic bottom (IB) distribution is very similar to the IC, but differs in the normalization factor by a coefficient $m_b^2 / m_c^2$. Therefore, $P_{bb/p} = P_{\bar{c}/p}(m_b^2 / m_c^2) \sim 0.001$ taking into account the 1% IC probability distribution.

As mentioned above, the heavy quark distribution in the standard approach, which is used by almost all global PDFs analyses, is generated by quark-gluon fusion in the DGLAP equations at the starting scale on the order of the heavy quark mass. As the BHPS model predicts, the purely perturbative treatment can not give a good description of the proton structure. Therefore the full charm parton distribution must be expressed by the sum $x_c(x, Q^2) = x_c ext(x, Q^2) + x_c int(x, Q^2)$, where $x_c ext(x, Q^2)$ and $x_c int(x, Q^2)$ indicate the extrinsic charm that is radiatively generate by the DGLAP equation (perturbative) and the intrinsic charm (non-perturbative) at an initial scale $Q_0 \approx m_c$, respectively. This decomposition is a good approximation at any scale since the intrinsic charm is controlled by non-singlet evaluation equations \ref{66}. Therefore the evaluation of heavy quarks must be divided into independent parts, singlet and non-singlet. The compact form of the DGLAP equation used by the standard global analyses, is given by

$$\dot{f}_i = \sum_{j=q,g,Q} P_{ij} \otimes f_j ,$$

where $\dot{f}_i$ denotes the light quarks, heavy quarks and gluon and $P_{ij}$ is the splitting function which is known up to three-loop order in the massless $\overline{MS}$ scheme \ref{67} \ref{68}. By considering the intrinsic heavy quark distribution $Q_{int}$ in the proton, one can find the non-singlet equation as \ref{66}

$$\dot{Q}_{int} = P_{QQ} \otimes Q_{int} .$$

In perturbative QCD, the structure functions can be written as a convolution between the hard scattering coefficient function and parton distribution functions which are parametrised and determined from experimental data.

The deep-inelastic structure functions $F(x, Q^2)$ consists of the heavy and light flavor component

$$F(x, Q^2) = F^h(x, Q^2) + F^l(x, Q^2) ,$$
where $F^h$ is the heavy contribution of DIS structure function, which is valid if only the heavy quark electric charge is non-zero.

As we plan to study the intrinsic charm component of the proton structure function, then we need to add the intrinsic structure function $F_{\text{int}}(x,Q^2)$ to the extrinsic heavy structure function $F_{\text{extr}}^{c\bar{c}/p}(x,Q^2)$ using the Thorne-Roberts (RT) scheme [69] as

$$F^h(x,Q^2) = F_{\text{extr}}^{c\bar{c}/p}(x,Q^2) + F_{\text{int}}^{c\bar{c}/p}(x,Q^2).$$

The definition of the heavy quark probability distribution in Eq. (5), using $F_{\text{extr}}^{c\bar{c}/p}$ is 1%, for the $|uudc\rangle$ Fock state, leads to a simple form for the IC component in the proton structure function, as $F_{\text{int}}^{c\bar{c}/p}(x,Q^2) = \frac{8}{7} \int dx_1 \cdots dx_\ell \frac{dp^\ell}{dx_1 \cdots dx_\ell dx_\ell} = \frac{8}{9} x c_{\text{int}}(x,Q^2)$ with $c_{\text{int}}$ from Eq. (5), when thecharm mass is negligible in the leading order [7]. By considering mass effects, the IC component in the proton structure $F_{\text{int}}^{c\bar{c}/p}(x,Q^2,m_c)$ using the mass variable $\xi = 2ax(1 + (1 + 4m_c^2/Q^2)^{1/2})^{-1}$ where $a = [(1 + 4m_c^2/Q^2)^{1/2} + 1]/2$, is as follows [44]

$$F_{\text{int}}^{c\bar{c}/p}(x,Q^2,m_c) = \frac{8a^2}{9(1 + 4m_c^2/Q^2)^{3/2}} \left[ \frac{1 + 4m_c^2/Q^2}{\xi} c(\xi,\gamma) + 3\hat{g}(\xi,\gamma) \right],$$

with $c(z,\gamma) = c_{\text{int}}(z) - z c_{\text{int}}(\gamma)/\gamma$ for $z \leq \gamma$. Also, $\gamma$ as another mass scaling variable which depends on $Q^2$ and is defined by $\gamma = 2ax(1 + (1 + 4m_c^2/Q^2)^{1/2})^{-1}$, where $\hat{x} = [1 + 4m_c^2/Q^2 - m_c^2/Q^2]^{-1}$. In the above, $\hat{g}(\xi,\gamma)$ is

$$\hat{g}(\xi,\gamma) = \frac{2m_c^2}{(1 + 4m_c^2/Q^2)^{1/2}} \int_\xi^\gamma \frac{dt c(t,\gamma)}{t} \left[ (1 - m_c^2/m_c^2) + 2m_c^2/Q^2 \right] .$$

For more detail see Refs. [44, 70].

III. DATA SETS

For the QCD analysis of PDFs including intrinsic charm, different DIS processes which are generally important in the presence of intrinsic charm are used to determine the unknown parameters in the PDFs parametrization, strong coupling constant $\alpha_s$, and $P_{c\bar{c}/p}$ as the extra fit parameters.

The experiments contributing to this analysis are the combined HERA inclusive proton DIS cross sections [71], fixed target inclusive DIS $F_2^p$ BCDMS [72], DIS $F_2^p$ SLAC [73], H1-ZEUS combined charm cross section [74], and DIS $F_2$ EMC data [33].

The neutral current (NC) and charged current (CC) cross section data at HERA have explored a wide kinematic region of the Bjorken variable $x$ and negative boson transverse momentum squared $Q^2$. In this paper we used the NC and CC inclusive DIS experimental data collected by H1 ans ZEUS [72, 73] from both HERAI and HERAII with the proton beam energy $E_p = 460, 575, 820$ and 920 GeV$^2$ related to center of mass energy $\sqrt{s} = 225, 251, 300$ and 320 GeV, respectively.

High $Q^2$ CC data, together with difference between the NC $e^-p$ and $e^+p$ at high $Q^2$, constrain the u and d-valence PDFs which dominate at large $x$ [71]. The wide kinematic region of the precise NC and CC cross-sections data allow us to extract PDF sets.

We also choose the proton structure function data which are reported by BCDMS [72] in deep-inelastic scattering of muons on the hydrogen target at the beam energy of 100, 120, 200 and 280 GeV.

The SLAC data on ep scattering used in our analysis, as well. It is obvious that our motivation to choose this data set of experimental data is due to the kinematic range of large $x$, where the intrinsic charm is dominant.

Also, the combine charm reduced cross sections, $\sigma_{\text{red}}^{c\bar{c}}$ by H1 and ZEUS are used in the present QCD analysis. The charm quark predominantly produce by boson gluon fusion, $\gamma g \rightarrow c\bar{c}$, which is sensitive to the gluon distribution in the proton [71, 81, 83, 85].

In the HERA kinematic domain, where the virtuality $Q^2$ of the exchanged boson is small, $Q^2 \ll M^2_Z$, charm production is dominated by virtual photon exchange, where the $x F_2^{c\bar{c}}(x,Q^2)$ is negligible. Therefore the neutral current deep-inelastic ep cross section by considering the running electromagnetic coupling, $\alpha(Q^2)$, without QED and electro-weak radiative corrections, may be written in terms of the structure functions $F_2^{c\bar{c}}(x,Q^2)$ and $F_2^L(x,Q^2)$. Since the $F_2^{c\bar{c}}$ contribution is suppressed only at low rapidity $y$ [80] at HERA, it is possible to neglect this contribution. So the important contribution to the reduced charm cross section is the charm structure function, $F_2^{c\bar{c}}$. Therefore additional correction must be done in this contribution in the presence of IC contribution. The importance of this kind of data set is due to the existence of charm PDFs, where the IC contribution can be included.

Since the main goal of this paper is to determine the intrinsic charm probability in the proton, we need to include the charm structure function data in the high $x$ region, where the intrinsic charm is dominant. Therefore, in this analysis, we choose the EMC measurement of the large $x$ charm structure function as a first experimental evidence of IC. These data are produced in inclusive dimuon and triton neutron iron target. Since the EMC $F_2$ data are extracted using the nuclear target, we need to consider the nuclear corrections in the present QCD analysis, as we will explain in the next section.

Although the fixed-target Drell-Yan data [57] are sensitive to the distributions of anti-quark in large $x$ and can be used in the QCD global analysis, we did not find
a significant impact on PDF parametrization by includ-
ing this kind of dataset in the presence of IC contribu-
tion. On the other hand, in our previous analysis [63], we
have also investigated that including the jet and W, Z
boson data at the LHC [69, 81] do not any impacts on
the PDFs in the presence of IC contribution. So we can
exclude these data sets in the present analysis.
In this analysis, we apply the \((W^2 - W_{th}^2)/W^2\) with
\(W_{th}^2 = 16\) on heavy quark structure function to sup-
press charm production near threshold as suggested in
Ref. [92]. Note that, we exclude the data using
assumes that the charm distribution is generated per-
compute the perturbative part of heavy quark contribu-
tions are reduced from 1939 to 1535.

In this article, we perform our QCD analysis using the
xFitter open source framework [62, 64], which previously
was known as HERAfit [63]. Very recent analyses using
xFitter package are reported in Refs. [61, 62].
The numerical solutions of the DGLAP evolution equa-
tions for PDFs in pQCD framework at NLO are imple-
mented in the QCDNUM package in \([94]\). To com-
pute the perturbative part of heavy quark contribu-
tions of the DIS structure-function, we used the
optimal Thorne-Roberts (RT-opt) [60], General-Mass Var-
iable Flavor Number (GM-VFN) scheme. This scheme
assumes that the charm distribution is generated pertur-
bulatively by gluon and light quark splittings, and its
value depends strongly on the charm mass. If the PDFs
are parameterized as a function of \(x\) at initial scale \(Q_0^2\),
the QCD evolution will help us to achieve it at any value
of \(Q^2\). In the present analysis, the initial QCD scale is
chosen to be \(Q_0^2 = 1.9\) GeV\(^2\), which is below the charm
threshold. In this approach, we choose the heavy quark
masses \(m_u = 1.50\) GeV and \(m_c = 4.5\) GeV, and we take
\(\mu_F = \mu_F = Q\) for the QCD re-normalization and fac-
torization scale.
We choose a standard parametrization for the PDFs at
the input scale \(Q_0^2 = 1.9\) GeV\(^2\) [71] to be:
\[
xf_i(x, Q_0^2) = A_i x^{B_i} (1 - x)^{C_i} \left(1 + D_x + Ex^2\right). \quad (12)
\]

The parameterised PDFs are the valence distributions,
\(xu_v, xd_v,\) the u-type and d-type anti-quarks distribu-
tions, \(x\bar{U}, x\bar{D},\) and the gluon distribution, \(xg.\) We
assume the relations \(x\bar{U} = x\bar{u}\) and \(x\bar{D} = xd + x\bar{s}\) at
the starting scale.
In summary, our parametrisation is:
\[
\begin{align*}
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1 - x)^{C_{u_v}} \left(1 + E_{u_v} x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1 - x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1 - x)^{C_{\bar{U}}} \left(1 + D_{\bar{U}} x\right), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1 - x)^{C_{\bar{D}}}, \\
xg(x) &= A_g x^{B_g} (1 - x)^{C_g} - \widehat{A}_g x^{B_g} (1 - x)^{C_g}. \quad (13)
\end{align*}
\]

In the above equations, to ensure the same behavior of
the \(x\bar{u}\) and \(xd\) as \(x \to 0\), one can impose the addi-
tional constraints \(B_{\bar{U}} = B_{\bar{D}}\) and \(A_{\bar{U}} = A_{\bar{D}} (1 - f_s)\) [71].
In this analysis, we fixed the \(D_{\bar{g}}\) parameter after the first
minimization because, in the presence of IC contribu-
tion, the selected DIS data set does not constrain the
\(D_{\bar{g}}\) well enough. The strange-quark distribution is expres-
sed as an \(x\)-independent function, \(f_s\), of the \(d\)-type sea,
\(x\bar{s} = f_s x\bar{D}\), at \(Q_0^2\). The value \(f_s = 0.31\) was chosen in
the strange quark density as suggested in Ref. [92]. For the
gluon PDF, \(C_{\bar{g}}\) is fixed to \(C_{\bar{g}} = 25\) to ensure a positive
 gluon density at large \(x\), as suggested in Ref. [96].
The normalization parameters for gluon and valence
distributions, \(A_g, A_u, A_d\) are constrained by the
fermion number and momentum sum rules,
\[
\int_0^1 ududx = 2, \quad \int_0^1 ddxdx = 1, \quad (14)
\]
\[
\int_0^1 [xg + \sum_i (q_i + \bar{q}_i)] + c_{ext} + c_{ext} + c_{int} + \bar{c}_{int}]dxdx = 1. \quad (15)
\]

In fact, in the above sum rule the total intrinsic charm
momentum fraction is
\[
\int_0^1 x(c_{int} + \bar{c}_{int})dxdx \equiv< x > = \varepsilon. \quad (16)
\]

Notice that in Eq. (13) we can fix the \(P_{\varepsilon\varepsilon}\) value with 1\%,
which is only included in the intrinsic part of above equa-
tion, or can be considered as a free parameter. It should
be noted that the extrinsic charm generated perturba-
tively using the DGLAP evaluation equation and the in-
trinsic charm evolve by a non-singlet evaluation equation
[64].

In this analysis, we use the nuclear correction on the
EMC data because these data come from a nuclear target.
This correction creates a connection between the parton
distributions in the nucleus \(A\) and parton distribution in
the proton which we model as:
\[
f_i^A(x, Q^2) = R_i(x, A, Z) f_i(x, Q^2), \quad (17)
\]
where \(f_i^A(x, Q^2)\) is the parton distribution with type \(i\)
in the nucleus and \(f_i(x, Q^2)\) is the corresponding parton
distribution in the proton. \(A\) and \(Z\) are the mass num-
ber and atomic number, respectively. To study the impact
of the EMC data on the PDFs behavior considering IC
contributions, we apply the nuclear correction factor from
Ref. [17] on EMC data.

By comparing the theoretical and experimental mea-
surements of various physical observables, we determine
the unknown PDFs parameters by minimizing the \(\chi^2\)
function taking into account the correlated and uncor-
related measurement uncertainties. The \(\chi^2\) function
is minimized using the MINUIT package [98], and is de-
defined as [61, 99]
\[
\chi^2 = \sum_{i,j}(t_i - d_i)(C^{-1})_{i,j}(t_j - d_j), \quad (18)
\]
where $C_{ij}^{-1}$ is the covariance matrix. If the full correlated uncertainties of the experimental data are available, the $\chi^2$ function is as follows

$$\chi^2 = \sum_i \left( \frac{d_i - t_i(1 - \sum_j \beta_j s_j)}{\delta_{i,unc}^2 t_i^2 + \delta_{i,stat}^2 t_i} \right)^2 + \sum_j s_j^2 , \quad (19)$$

where $t_i$ is the theoretical prediction, $d_i$ is the measured value of the $i$-th data point, $(Q^2, x, s)$, and $\delta_{i,unc}$ and $\delta_{i,stat}$ are the relative statistical and uncorrelated systematic uncertainties. In the above, $\beta_j$ are the corresponding systematic uncertainties, in which case $s_j$ are the nuisance parameters associated with the correlated systematic error. Here $j$ labels the sources of correlated systematic uncertainties, and in the Hessian method the $s_j$ are not fixed. If the $s_j$ are fixed to zero, the correlated systematic errors are ignored.

The Hessian matrix is defined as $C_{H}^{−1}$ where $\delta$ uncertainties of the experimental data are available, the

$$\text{where} \ C \ \text{is the covariance matrix. If the full correlated uncertainties of the experimental data are available, the} \ \chi^2 \ \text{function is as follows}$$

$$\chi^2 = \sum_i \left( \frac{d_i - t_i(1 - \sum_j \beta_j s_j)}{\delta_{i,unc}^2 t_i^2 + \delta_{i,stat}^2 t_i} \right)^2 + \sum_j s_j^2 , \quad (19)$$

where $t_i$ is the theoretical prediction, $d_i$ is the measured value of the $i$-th data point, $(Q^2, x, s)$, and $\delta_{i,unc}$ and $\delta_{i,stat}$ are the relative statistical and uncorrelated systematic uncertainties. In the above, $\beta_j$ are the corresponding systematic uncertainties, in which case $s_j$ are the nuisance parameters associated with the correlated systematic error. Here $j$ labels the sources of correlated systematic uncertainties, and in the Hessian method the $s_j$ are not fixed. If the $s_j$ are fixed to zero, the correlated systematic errors are ignored.

The Hessian method for the PDF uncertainties are obtained from $\Delta \chi^2 = T^2$. A tolerance parameter $T$ is selected such that the criterion $\Delta \chi^2 = T^2$ ensures that each data set is described within the desired confidence level. The correlated statistical error on any given quantity $q$ is then obtained from the standard error propagation:

$$\langle \sigma_q \rangle^2 = \Delta \chi^2 \left( \sum_{\alpha,\beta} \frac{\partial q}{\partial p_{\alpha}} C_{\alpha,\beta} \frac{\partial q}{\partial p_{\beta}} \right) . \quad (20)$$

The Hessian matrix is defined as $H_{\alpha,\beta} = \frac{1}{2} \frac{\partial^2 \chi^2}{\partial p_{\alpha} \partial p_{\beta}}$, and thus the covariance matrix $C = H^{-1}$ is the inverse of the Hessian matrix evaluated at the $\chi^2$ minimum. In order to be able to calculate the fully correlated 1σ error bands for the valence PDFs, one can choose $T = 1$ in the xFitter package.

Indeed, we have 13 unknown PDFs parameters in addition to free parameters $\alpha_s$ and $P_{c/p}$ which are obtained from the fit.

V. FIT RESULTS

The main goal of this paper is the simultaneous determination of the intrinsic charm probability $P_{c/p}$ and strong coupling $\alpha_s$. This allows us to study the interaction of these two quantities as well as the influence on the PDFs in the presence of IC contributions.

For fit analysis, we will include the DIS reduced cross section and differential cross section data from HERA I+II, the charm combined cross sections data from H1 and ZEUS, and the proton structure function data from BCDMS, SLAC, and EMC. The detailed information and references, number of data points, and their kinematic range of $x$ and $Q^2$ for each data set are summarized in Table I.

To investigate the effect of the EMC data in the present analysis with and without IC contributions, we will divide our QCD analysis into four fits:

- **Base**: We include all the data sets of Table I with exception of the EMC experimental data, this totals 1519 data points. In the Base fit we consider zero IC contribution, i.e., $P_{c/p} \equiv 0$. We fixed $\alpha_s(M_Z^2) = 0.1182$ considering to the world average data as a first step.

- **Fit A**: We include all the data from the Base fit in addition to the EMC $F_Z$ data and this gives us 1535 data point. This fit also assumes zero IC contribution and we use a fixed $\alpha_s(M_Z^2) = 0.1182$.

- **Fit B**: We use all the data sets of the Table II and we use a fix $\alpha_s(M_Z^2) = 0.1182$ parameter and include an intrinsic charm probability $P_{c/p}$ value as a free parameter.

- **Fit C**: This is all same as Fit B, except now use a free $\alpha_s(M_Z^2)$.

The $\chi^2$/number for each data set after cuts, the total $\chi^2$, and $\chi^2$/dof for all fits are summarized in Table I. According to Table I and without taking into account IC contribution in Base fit, as a first step, the total $\chi^2$/dof value is 1872/1506 = 1.243. There are 13 unknown parameters for PDFs only.

As a second step and the same as Base fit, we have 13 unknown parameters for PDFs in Fit. A. In this case and according to Table I, we obtain 2047/1522 = 1.345 for the total $\chi^2$/dof for Fit A.

For a more complete discussion, the investigation of necessity to include a non-zero $P_{c/p}$ in the present QCD analysis and also the effect of including the EMC data would be important. In Fit B, as a third step, we obtain 1959/1521 = 1.289 for the total of $\chi^2$/dof for Fit B. There are 13 unknown parameters for PDFs and an unknown parameter for intrinsic charm probability, therefore the total number of unknown parameters is 14.

Our motivation to present Base, Fit A and Fit B results is to show that an IC component is unnecessary as long as the EMC data remains excluded.

Finally, in Fit C we consider the intrinsic charm probability $P_{c/p}$ and $\alpha_s(M_Z^2)$ as free parameters in our QCD analysis, so there are 13 unknown parameters for PDFs and two unknown parameters for strong coupling constant and intrinsic charm probability. In Fit C, the total number of unknown parameters is 15, which should be obtained by the QCD fit on experimental data. In this fit, we obtain 1957/1520 = 1.287 for the total $\chi^2$/dof with considering intrinsic charm probability $P_{c/p}$ and $\alpha_s(M_Z^2)$, as the free parameters.

It should be noted that, in the present analysis and for Fit A, B, and C, the nuclear effects are considered. Although the Fit C contains the complete analysis, the comparison of this fit with other above cases with each other would be interested.

Obviously, in comparison Fit A with Fits B and C, there are almost 4% improvements for $\chi^2$ values and the fit quality.
TABLE I. The list of observable and experimental data with detailed information which we used in our QCD analysis. For each data sets, we indicate the number of data points and their x and Q^2 kinematic ranges.

| Observable | Experiment | Ref. | # Data | x | Q^2  [GeV^2] |
|------------|------------|------|--------|---|------------|
| DIS σ     | HERA1+2 CC e^+p | [71] | 39 | $[8.0 \times 10^{-4}]$-0.4 | [300-300000] |
| DIS σ     | HERA1+2 CC e^-p | [71] | 42 | $[8.0 \times 10^{-4}]$-0.65 | [300-300000] |
| DIS σ     | HERA1+2 NC e^+p | [71] | 159 | $[8.0 \times 10^{-5}]$-0.65 | [60-50000] |
| DIS σ     | HERA1+2 NC e^-p 460 | [71] | 200 | $[3.4 \times 10^{-5}]$-0.65 | [1.5-800] |
| DIS σ     | HERA1+2 NC e^-p 575 | [71] | 249 | $[3.4 \times 10^{-5}]$-0.65 | [1.5-800] |
| DIS σ     | HERA1+2 NC e^-p 820 | [71] | 68 | $[6.21 \times 10^{-7}]$-0.4 | [0.045-30000] |
| DIS σ     | HERA1+2 NC e^-p 920 | [71] | 363 | $[5.02 \times 10^{-6}]$-0.6 | [1.5-30000] |

| DIS F_2^P | BCDMS F_2^P 100 GeV | [72] | 83 | $[0.07-0.75]$ | [7.5-75] |
| DIS F_2^P | BCDMS F_2^P 120 GeV | [72] | 91 | $[0.07-0.75]$ | [8.75-99] |
| DIS F_2^P | BCDMS F_2^P 200 GeV | [72] | 79 | $[0.07-0.75]$ | [17-137.5] |
| DIS F_2^P | BCDMS F_2^P 280 GeV | [72] | 75 | $[0.1-0.75]$ | [32.5-230] |
| DIS F_2^P | SLAC F_2^P | [72] | 24 | $[0.07-0.85]$ | [0.59-29.2] |

| DIS σ^{cc} | Charm cross section H1-ZEUS combined | [74] | 47 | $[1.8 \times 10^{-4}]$-0.025 | [5.0-120] |
| DIS F_2^P | EMC F_2^P | [73] | 16 | $[0.0075-0.421]$ | [2.47-78.1] |

TABLE II. The results for the χ^2/number of points, correlated χ^2, and the total χ^2/ degree of freedom (dof) values of each data sets, for different Base, and Fits A, B, C. The nuclear effects are considered for Fits A, B and C and the intrinsic charm contribution is included for Fits B and C.

| Experiment | Base | Fit A | Fit B | Fit C |
|------------|------|-------|-------|-------|
| HERA1+2 CC e^+p | 69 / 39 | 56 / 39 | 56 / 39 | |
| HERA1+2 CC e^-p | 55 / 42 | 55 / 42 | 55 / 42 | |
| HERA1+2 NC e^+p | 236 / 159 | 239 / 159 | 239 / 159 | |
| HERA1+2 NC e^-p 460 | 213 / 200 | 213 / 200 | 213 / 200 | |
| HERA1+2 NC e^-p 575 | 225 / 249 | 221 / 249 | 220 / 249 | |
| HERA1+2 NC e^-p 820 | 72 / 68 | 72 / 68 | 72 / 68 | |
| HERA1+2 NC e^-p 920 | 482 / 363 | 474 / 363 | 476 / 363 | |
| BCDMS F_2^P 100 GeV | 113 / 83 | 95 / 83 | 95 / 83 | |
| BCDMS F_2^P 120 GeV | 73 / 91 | 73 / 91 | 73 / 91 | |
| BCDMS F_2^P 200 GeV | 105 / 79 | 96 / 79 | 95 / 79 | |
| BCDMS F_2^P 280 GeV | 74 / 75 | 71 / 75 | 72 / 75 | |
| SLAC F_2^P | 41 / 24 | 59 / 24 | 59 / 24 | |
| Charm cross section H1-ZEUS combined | 44 / 47 | 44 / 47 | 44 / 47 | |
| EMC F_2^P | 102 / 16 | 74 / 16 | 70 / 16 | |

In Ref. 27, 100, the NNPDF collaboration studied the influence of the EMC data in their analyses with and without the IC contribution. They found χ^2 per point = 7.3 for the EMC data if the charm PDF was generated perturbatively, and χ^2 per point = 4.8 when the IC contribution was included and the EMC data was rescaled. They improved the fit quality of the EMC data by imposing an additional cut of x > 0.1 when the charm PDF was fitted.

According to Table III, we note that the χ^2 per point for the EMC data are 6.37, 4.56 and 4.37 in Fits A, B and C, respectively. When the IC includes in Fits B and C, we find an improvement in the χ^2 per point for the EMC data of 28% and 31%, respectively in comparison with Fit A.

To investigate the specific impact of the EMC data with and without IC contribution at NLO, we need to compare our results for our individual fits: Base, Fits A, B, and C. In Fig. III, we display some samples of our theoretical predictions for all fits in comparison to fixed target DIS data from HERA1+II [71], H1-ZEUS combined charm cross section [74] (Fig IIIa), BCDMS [72], SLAC [73] and EMC [43] measurements (Fig IIIb) and their uncertainties at NLO as a function of x for different values of Q^2. According to Fig. III(b), the data description turns out to be better including the IC component in comparison with the Fit A results. In fact, we find that in general, it is necessary to include a non-zero P_{c\bar{c}}/p to have a better description of the EMC data.

In Table III, the numerical QCD fit results for the PDFs parametrization according to Eq. (13), α_s value and the intrinsic charm probability P_{c\bar{c}}/p are summarized in four separate cases.

It is obvious that the P_{c\bar{c}}/p value has significant sensitivity to the α_s value. The simultaneous determination of P_{c\bar{c}}/p and α_s, as shown in Table III, gives a somewhat lower IC probability and an α_s which is more or less in agreement with the world average value of α_s(M_Z^2) = 0.1182 ± 0.0011 [101]. This is a very reasonable result based on the fact that IC is a non-perturbative phenomenon.

According to Tables II and III, the increase of 8% of χ^2/dof in Fit A with respect to our Base fit, and ~ 4% improvement of χ^2/dof in Fit B and Fit C...
with respect to Fit A, is obtained. Conversely, we observed the significant changes in both, the PDFs parameters and their uncertainties. Using the definition of \( \Delta P_{c\bar{c}/p} = P_{c\bar{c}/p}^{\text{Fit C}} - P_{c\bar{c}/p}^{\text{Fit B}} \), we find a change of \( \sim 7.6\% \) on \( \Delta P_{c\bar{c}/p}/P_{c\bar{c}/p}^{\text{Fit B}} \). It is clear that a simultaneous determination of \( P_{c\bar{c}/p} \) and \( \alpha_s \) in the present analysis can impact the central value of the intrinsic charm probability.

Fig. 2 illustrates the NLO QCD fit results for valence, sea and gluon PDFs as a function of \( x \) at the initial scale of \( Q_0^2 = 1.9 \text{ GeV}^2 \). Although there are no significant changes in the valence and sea PDFs in all fits, significant changes in the gluon PDFs are observed (left panels). To clarify the difference between our four fits, we present the relative uncertainties \( \delta xQ(x, Q^2)/xQ(x, Q^2) \) with respect to the Base fit. According to this figure, the changes of the central values of the PDFs, their uncertainties, or both are observed (right panels).

In Fig. 3 we present our results for the extrinsic charm PDF based on our four fits as a function of \( x \) for \( Q^2 = 10 \text{ GeV}^2 \) and \( Q^2 = 100 \text{ GeV}^2 \) at NLO (left panels). The relative uncertainties \( \delta xc(x, Q^2)/xc(x, Q^2) \) are also shown (right panels).

Since our analysis fixed the charm mass to 1.5 GeV, we are interested in study the impact of the charm mass value on \( P_{c\bar{c}/p} \). Basically, the charm mass impact in our analysis has led us to recalculate the simultaneous fit of \( P_{c\bar{c}/p} \) and \( \alpha_s \) for different values of charm mass. Here, we choose Fit C, as a reference point to study the impact of charm mass on PDFs behavior and the extraction \( P_{c\bar{c}/p} \) and \( \alpha_s \) values.

As mentioned above, to compute the perturbative part of structure-function, we utilize the GM-VFN scheme, which assumes that the charm distribution is generated perturbatively by gluon and light quark splittings. The detail of this is sensitive to the charm quark mass, which is not precisely known. We are going to use the RT-opt heavy quark scheme and we are going to vary the charm mass 1.2 GeV to 1.8 GeV and we will scan the \( \chi^2 \) to determine the optimal value \( m_c \). In the present paper, we consider the initial value of \( Q_0^2 \) for the evolution to be below the charm threshold \( m_c \).

The \( \chi^2(m_c) \) value is calculated for each fits and the optimal values of \( m_c^{\text{opt}} \) parameter is determined in a given scheme from a parabolic fit to the \( \chi^2(m_c) \) values as

\[
\chi^2(m_c) = \chi^2_{\text{min}} + \left( \frac{m_c - m_c^{\text{opt}}}{\sigma(m_c^{\text{opt}})} \right)^2,
\]

where \( \chi^2_{\text{min}} \) is the \( \chi^2 \) value at the minimum and \( \sigma(m_c^{\text{opt}}) \) is the fitted experimental uncertainty on \( m_c^{\text{opt}} \). The procedure of the \( \chi^2 \)-scan is illustrated in Fig. 4 for the optimal RT (RT-opt) scheme by fitting the experimental data. According to this figure, we find the minimum of \( \chi^2 \) value for the charm mass of 1.50 GeV. This was our motivation to choose \( m_c = 1.50 \text{ GeV} \) in the presence of IC.

In Table \ref{tab:charm_mass}, we summarize the influence of the charm mass for the determination of \( P_{c\bar{c}/p} \) and the strong coupling constant using Fit B and Fit C. According to this table and for Fit B, \( P_{c\bar{c}/p} \) goes from 0.78% to 1.4% as increases \( m_c \) from 1.39 to 1.6 GeV. For Fit C, we found \( P_{c\bar{c}/p} \) changes from 0.97% to 0.88% as \( m_c \) changes and we also find the \( \alpha_s(M_Z^2) \) increase from 0.1152 to 0.1225 with the similar uncertainties.

As expected, we show the intrinsic charm probability and the strong coupling constant values depend on the charm mass value. The stronger dependence of \( P_{c\bar{c}/p} \) and charm mass is due to the fact that the heavier \( m_c \) makes it harder to create \( c\bar{c} \) pairs to obtain 5-particle Fock states.

In Fig. 5 we present the valence, sea and gluon PDFs with their uncertainties for different values of \( m_c \) are presented as a function of \( x \) at the input scale of \( Q_0^2 = 1.9 \text{ GeV}^2 \) based on our results for Fit C. Although there are no significant changes in the valence and sea PDFs when comparing different charm mass values, significant changes in the gluon PDFs are observed (left panels). Also we present the relative uncertainty ratios \( xQ(x, Q^2)/xQ(x, Q^2)_{\text{ref}} \) with respect to \( m_c = 1.5 \text{ GeV} \). According to this figure, the changes of the central values of the PDFs and their uncertainties for different values of the charm mass are especially observed for the gluon PDFs (right panels).

Since the gluon PDF plays an important role in the total cross section of the top quark production, we used the results of Fit C with different charm quark masses and Fit B with fix \( m_c = 1.5 \) to calculate the top quark cross section at the LHC using the HATHOR package.

According to Fig. 6 the gluon densities show significant variation for the different cases with varying charm mass values for Fit C, as a complete fit to study the impact of charm mass. We obtain the total top quark cross section as 804.7±6.6, 828.7±8.0 and 855.7±7.8, using different values of charm mass \( m_c = 1.43, 1.5 \) and 1.55, respectively. Also, we find the total top quark cross section to be 817.8±6.4 using Fit B when \( m_c = 1.5 \). These results are in agreement with the recent CMS top quark cross section measurements 834±25 (stat.) ±118 (syst.) ±23 (lumi.) at the LHC for 13 TeV.

Fig. 4 shows the NLO extrinsic charm PDF extracted from Fit C with different charm quark mass values for range of \( Q^2 \) as a function of \( x \), for different values of \( Q^2 = 10, 100 \text{ GeV}^2 \) (left panels). The relative uncertainty ratios \( xc(x, Q^2)/xc(x, Q^2)_{\text{ref}} \) in respect to \( m_c = 1.5 \text{ GeV} \) (right panels) are shown.

In Table \ref{tab:charm_mass} we present the intrinsic charm probability values extracted from Fit C with the present analysis for different values of charm mass and compare with other predictions from the literature. The extracted value of intrinsic charm probability is in good agreement with the other predictions of the models.

In Table \ref{tab:charm_mass} we present the momentum fraction of the IC distribution \( < x >_e \) at the input scale \( x \) according to Eq. \ref{eq:charm_mass} and \( < x >_{e+\bar{e}} \) at the full charm momentum fraction, \( < x >_{e+\bar{e}} < x >_e \) extracted in Fit C, and compared to the NNPDF3IC and CT14-IC at \( Q^2 = 4 \text{ GeV}^2 \). Our results
TABLE III. The fit results for parameter values in Eq. (13), and the intrinsic charm probability $P_{c\bar{c}/p}(\%)$ and their uncertainties at the initial scale $Q_0^2=1.9$ GeV$^2$ at NLO, for Base, Fit A, Fit B and Fit C.

| Parameter | Base | Fit A | Fit B | Fit C |
|-----------|------|------|------|------|
| $B_{sv}$  | 0.834 ± 0.018 | 0.753 ± 0.028 | 0.804 ± 0.020 | 0.819 ± 0.021 |
| $C_{sv}$  | 3.964 ± 0.056 | 4.142 ± 0.042 | 4.054 ± 0.047 | 4.022 ± 0.049 |
| $E_{sv}$  | 2.84 ± 0.40 | 4.84 ± 0.57 | 3.63 ± 0.44 | 3.40 ± 0.46 |
| $B_{sg}$  | 1.152 ± 0.070 | 0.958 ± 0.064 | 1.075 ± 0.062 | 1.092 ± 0.064 |
| $C_{q}$  | 5.43 ± 0.33 | 5.21 ± 0.28 | 5.27 ± 0.29 | 5.23 ± 0.29 |
| $C_{C}$  | 4.44 ± 0.63 | 3.56 ± 0.83 | 4.4 ± 1.2 | 4.6 ± 1.2 |
| $D_{q}$  | -0.34 (Fixed) | -0.65 (Fixed) | -0.4 (Fixed) | -0.4 (Fixed) |
| $A_{p}$  | 0.201 ± 0.011 | 0.210 ± 0.014 | 0.209 ± 0.012 | 0.212 ± 0.013 |
| $B_{p}$  | -0.1460 ± 0.0074 | -0.1376 ± 0.0081 | -0.1406 ± 0.0075 | -0.1398 ± 0.0078 |
| $C_{p}$  | 11.9 ± 2.3 | 19.3 ± 2.0 | 16.1 ± 1.9 | 15.3 ± 1.8 |
| $B_{p}$  | -0.235 ± 0.073 | -0.107 ± 0.026 | -0.359 ± 0.066 | -0.377 ± 0.061 |
| $C_{q}$  | 11.1 ± 1.4 | 2.55 ± 0.26 | 5.10 ± 0.45 | 4.72 ± 0.44 |
| $A_{q}$  | 15 ± 12 | -54 ± 13 | 0.90 ± 0.11 | 0.86 ± 0.11 |
| $B_{q}$  | 0.43 ± 0.15 | 0.888 ± 0.072 | -0.405 ± 0.054 | -0.416 ± 0.051 |
| $C_{q}$  | 25.0 (Fixed) | 25.0 (Fixed) | 25.0 (Fixed) | 25.0 (Fixed) |
| $f_{x}$  | 0.31 (Fixed) | 0.31 (Fixed) | 0.31 (Fixed) | 0.31 (Fixed) |
| $\alpha_s(M_Z^2)$ | 0.1182 (Fixed) | 0.1182 (Fixed) | 0.1182 (Fixed) | 0.1191 ± 0.0008 |
| $P_{c\bar{c}/p}(\%)$ | 0 | 0 | 1.017 ± 0.20 | 0.94 ± 0.20 |

TABLE IV. The extracted values of the intrinsic charm probability $P_{c\bar{c}/p}$, from Fit B and Fit C, and strong coupling constant $\alpha_s(M_Z^2)$, for different values of charm mass.

| $m_c$ (GeV) | Fit B $P_{c\bar{c}/p}(\%)$ | $\alpha_s(M_Z^2)$ |
|-------------|-----------------|-----------------|
| 1.39        | 0.78 ± 0.18     | 0.1192 (Fixed)  |
| 1.43        | 0.86 ± 0.19     | 0.1182 (Fixed)  |
| 1.50        | 1.02 ± 0.20     | 0.1182 (Fixed)  |
| 1.55        | 1.24 ± 0.22     | 0.1182 (Fixed)  |
| 1.60        | 1.40 ± 0.24     | 0.1182 (Fixed)  |

for $<x>_{c+\bar{c}}$ and $<x>_{c+\bar{c}}$ are obtained using $P_{c\bar{c}/p}(\%)=0.94 ± 0.20$. The momentum fraction of the IC distribution and the total momentum fraction of the charm PDF are in good agreement with other models. Note that in the CT analysis several models for IC are studied whilst NNPDF3IC assumed a specific parameterisation of the charm PDF which is fitted simultaneously to light quarks and gluons.

In Fig. 4 we show the intrinsic charm distribution $x_{c\bar{c}}(x,Q^2)$ with its uncertainty as a function of $x$ at different values of $Q^2$ with $P_{c\bar{c}/p} = 0.94 ± 0.2\%$. In Fig. 5 we display the intrinsic charm $x_{c\bar{c}}$, extrinsic charm $x_{cext}$ and the total charm $x_{c\bar{c}}+x_{cext}$ distributions with their uncertainties with $P_{c\bar{c}/p} = 0.94 ± 0.2\%$, as a function of $x$ and $Q^2$.

In Fig. 6 we display the valence, sea and gluon PDFs extracted in our QCD Fit C for selected $Q^2$ values as a function of $x$, and compared them with the results obtained by HERAPDF2 [71] and NNPDF3IC [38]. Note that the NNPDF collaboration used a different methodology to parametrize the PDFs, and chose different input scales and the cut values.

Finally, in Fig. 10 we present our results for the extrinsic charm PDF (top panels) with its uncertainty and the relative charm PDF uncertainty $\delta x_{c}/x_{c}$ (bottom panels) as a function of $x$ at varied scale of $Q^2$, and also compared with HERAPDF2 [71] and NNPDF3IC [38].

TABLE V. The predictions of intrinsic charm probability $P_{c\bar{c}/p}$ in the different approaches.

| Reference (Approach) | $P_{c\bar{c}/p}(\%)$ |
|-----------------------|---------------------|
| BHPS model (Light-cone) [4] | <1.93 |
| Brodsky et al (Light-cone with LHC data) [58] | 0.86 |
| Harris et al (PGF NLO) [45] | 0.31 |
| Hofmann and Moore (PGF NLO) [44] | 0.86 |
| Steffens et al (Meson cloud) [103] | 0.86 |
| Dujat et al (PQCD-NNLO) [55] | <2 |
| Jimenez-Delgado (PDF) [109] | 0.3-0.4; <1.0 |

Our results (PDF + Light-cone "Fit C")

| $m_c$ (GeV) | $P_{c\bar{c}/p}(\%)$ |
|-------------|---------------------|
| 1.43 GeV   | 0.96 ± 0.20 |
| 1.5 GeV    | 0.94 ± 0.20 |
| 1.55 GeV   | 0.92 ± 0.20 |

TABLE VI. The intrinsic charm moment fraction $<x>_{c+\bar{c}}$ according to Eq. (15) and total charm momentum fraction, $<x>_{c+\bar{c}}<x>_{c+\bar{c}}$ compared to the NNPDF3IC and CT14-IC at $Q^2 = 4$ GeV$^2$.

| Reference Approach | $<x>_{c+\bar{c}}(\%)$ | $<x>_{c+\bar{c}}(\%)$ |
|--------------------|---------------------|---------------------|
| NNPDF3IC [38]      | Valence Like        | 0.5                | 1.2 |
| CT14-BHPS [68]      | Valence Like        | 0.6                | 1.64 |
| CT14-SEA1 [38]      | Sea Like            | 0.6                | 1.61 |

This Fit($m_c=1.5$GeV$^2$) Valence Like 0.48 ± 0.1 1.06 ± 0.6 |

VI. DISCUSSION AND CONCLUSION

We performed a QCD analysis using fixed target DIS data from HERA-I+II [71], H1-ZEUS combined charm cross section [74], BCDMS [72], SLAC [73] and EMC [43] considering IC contribution at NLO. We determined
PDFs with their corresponding uncertainties and also the intrinsic charm probability and strong coupling constant using the xFitter package [52, 53].

To investigate the effect of the EMC data in the present analysis and to clarify the results, we divided our QCD analysis into four steps. As a first step, we performed a fit with all data sets of Table I with the exception of the EMC experimental data. We used a fixed $\alpha_s(M_Z^2)$ value of 0.1182 taken from the world average [10] for the Base fit.

We then include all the data from the Base fit in addition to the EMC $F_2^\prime$ data with assuming zero IC contribution in Fit A.

Taking into account the IC contribution and considering $P_{c/\bar{c}/p}$ as a free parameter, we performed our QCD analysis for two separate Fit B and Fit C. In Fit B, we used all data sets which used in Fit A and we fixed strong coupling $\alpha_s(M_Z^2)$. In this case we consider the intrinsic charm probability $P_{c/\bar{c}/p}$ as a free parameter. We found that $P_{c/\bar{c}/p}$ depends on the $\alpha_s$ value, so the simultaneous determination of these parameters in the QCD analysis, taking into account IC is important. In Fit C, we considered $P_{c/\bar{c}/p}$ and $\alpha_s(M_Z^2)$ as free parameters.

The extracted value of the strong coupling constant $\alpha_s(M_Z^2) = 0.1191 \pm 0.0008$ at NLO in Fit C, is in good agreement with the world average value of $\alpha_s(M_Z^2) = 0.1182 \pm 0.0011$ [10]. This extracted value is also consistent with our recent reported results of $\alpha_s(M_Z^2) = 0.1199 \pm 0.0031$, based on charged current neutrino-nucleon DIS data at NLO [64]. For $P_{c/\bar{c}/p}$, we extracted 1.017 $\pm$ 0.2 for Fit B and 0.94 $\pm$ 0.2 for Fit C. We found 7.6% difference between Fit B and Fit C on $P_{c/\bar{c}/p}$ values by comparing these fits.

The Q^2-evolution of intrinsic charm PDF using $P_{c/\bar{c}/p} = 0.94 \pm 0.2$% in the proton which extracted in the present analysis, are presented. The extracted value of $P_{c/\bar{c}/p}$ in the present QCD analysis is consistent with the recent reported upper limit of 1.93% of Ref. [68], which is obtained for the first time from LHC measurements [57].

To find the impact of the charm mass in the present analysis, we study the influence on the extraction of $P_{c/\bar{c}/p}$. For Fit B, $P_{c/\bar{c}/p}$ goes from 0.78% to 1.4% as increases $m_c$ from 1.39 to 1.6 GeV. For Fit C, we also find $P_{c/\bar{c}/p}$ changes from 0.97% to 0.88% as $m_c$ changes and the $\alpha_s(M_Z^2)$ increase from 0.1152 to 0.1225.

Since the gluon PDF plays an important role in the total cross section of top quark production, we find a total top quark cross section of $817.5 \pm 6.4$ using by Fit B when $m_c = 1.5$. In Fit C, we find the cross section of $804.7 \pm 6.6$, $828.7 \pm 8.0$ and $855.7 \pm 7.8$ for $m_c = 1.43$, $m_c = 1.5$ and $m_c = 1.55$, respectively.

The parabolic fit to $\chi^2$ as a function of $m_c$ is used to find the optimal value of $m_c$. In this analysis, we choose the value of $m_c$ equal to 1.50 GeV. We performed our QCD analysis based on this value of $m_c$ in presence of IC.

In the comparison of our PDFs to others in the literature, the valence, sea, gluon and charm PDFs and their uncertainties are in good agreement with other theoretical models. This agreement is despite of different phenomenology and differences in the parametrization and choose of the data sets.

In our previous results, we have shown the differential cross section of $\gamma + c$-jet is sensitive to intrinsic charm contribution [54]. In the near future, we will investigate the role of IC contributions in other processes, such as $\gamma + c/b$, and $Z/W + c/b$ production cross section measurements in pp collisions at the LHC.

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(a) HERA I+II and combined H1 and ZEUS charm cross sections
FIG. 1. Our theoretical predictions of the reduced cross section and proton structure function which are obtained from the QCD fits as a function of the momentum fraction $x$ at different values of $Q^2$ for our Base, Fits A, B and C. We compare to the experimental data from HERA I+II [71], the charm cross section from the combined the H1 and ZEUS [74] (Fig 1a), the proton structure function from SLAC [73] and BCDMS [72], and the charm structure function from EMC data [43] (Fig 1b).
FIG. 2. The NLO PDFs of our Base, Fits A, B and C results for $xu_v$, $xd_v$, $x\Sigma$ and $xg$ at the initial scale of $Q_0^2 = 1.9$ GeV$^2$ as a function of $x$, with $m_c = 1.50$ GeV (left panels). The relative uncertainties $\delta xq(x, Q^2)/xq(x, Q^2)$ are displayed (right panels) and the Fits B and C have IC contribution.
FIG. 3. The NLO extrinsic charm PDF from the Base and Fits A, B, and C as a function of $x$ for $Q^2 = 10$ GeV$^2$ and $Q^2 = 100$ GeV$^2$ (left panels) and the relative uncertainties $\frac{\delta x_c(x,Q^2)}{x_c(x,Q^2)}$ (right panels) are shown.

FIG. 4. The parabolic fit to the QCD $\chi^2$ values as a function of charm mass in the RT-opt scheme.
FIG. 5. The NLO PDFs from Fit C (This Fit) for different charm mass values $m_c = 1.43, 1.5$ and $1.55$ GeV at the initial scale of $Q^2 = 1.9$ GeV$^2$ as a function of $x$ (left panels). This fit uses the IC contribution. The relative uncertainty ratios $xq(x, Q^2)/xq(x, Q^2)_{\text{ref}}$ with respect to $m_c = 1.5$ GeV (right panels) are shown.
FIG. 6. The NLO extrinsic charm PDF extracted from Fit C (This Fit) with different charm mass values $m_c = 1.43$, 1.5 and 1.55 GeV for $Q^2 = 10$ GeV$^2$ and $Q^2 = 100$ GeV$^2$ as a function of $x$ (left panels). This fit include the IC contribution. The relative uncertainty ratios $x c(x, Q^2)/x c(x, Q^2)_{ref}$ with respect to $m_c = 1.5$ GeV (right panels) are shown.
FIG. 7. The intrinsic charm distribution as a function of \( x \) and its uncertainties at \( Q^2 = 4, 10 \) and 100 GeV\(^2\) with \( P_{c\bar{c}/p} = 0.94 \pm 0.2\% \).

FIG. 8. The comparison of the intrinsic charm \( xc_{\text{int}}(x, Q^2) \), extrinsic charm \( xc_{\text{ext}}(x, Q^2) \), and total charm distribution \( xc(x, Q^2) = (xc_{\text{int}} + xc_{\text{ext}})(x, Q^2) \), extracted from Fit C as a function of \( x \) for \( Q^2 = 4 \) and 100 GeV\(^2\) with \( P_{c\bar{c}/p} = 0.94 \pm 0.2\% \).
FIG. 9. The comparison of our NLO results for $xu$, $xd$, $x\Sigma$ and $xg$ PDFs in presence of IC from Fit C (This Fit). We compare with HERAPDF2 [71] and NNPDF3IC [38] results, for $Q^2 = 10$ GeV$^2$ and $Q^2 = 100$ GeV$^2$ as a function of $x$. 
FIG. 10. The extrinsic charm PDFs from Fit C (left panels) and the relative uncertainties $\delta xq(x, Q^2)/xq(x, Q^2)$ (right panels) for the selected scales $Q^2 = 4$, 10, 100, 8317 GeV$^2$, as a function of $x$, and compared with HERAPDF2 [71] and NNPDF3IC [38].