PROCEEDINGS OF SCIENCE

TMD gluon density determination including uncertainties

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We discuss fits to the combined HERA structure function measurements based on transverse momentum dependent (TMD) QCD factorization and CCFM evolution, and present determinations of the TMD gluon density including experimental and theoretical uncertainties.

XXI International Workshop on Deep Inelastic Scattering and Related Subjects
April 22-26, 2013
Marseille, France

PoS(DIS 2013)053

The combined measurements of proton's structure functions in deeply inelastic scattering (DIS) at the HERA collider [1] provide high-precision data capable of constraining parton density functions (pdfs) over a wide range of the kinematic variables. These data have been used for determinations of the collinear pdfs and related studies at the LHC [2, 3].

On the other hand, QCD applications to complex final state observables typically require improved formulations of factorization [4] involving transverse-momentum dependent (TMD), or unintegrated, parton density functions [5]. In processes with multiple hard scales TMD pdfs serve to describe appropriately nonperturbative physics and to control perturbative large logarithms to higher orders of perturbation theory [6].

The purpose of our work [7] is to use the high-precision DIS data [1] for determination of TMD pdfs. A general program for TMD pdfs phenomenology has been proposed in [5]. Our work has a more limited scope than this program as we limit ourselves to considering DIS data in the small-x kinematic region. On the other hand, from the point of view of TMD pdfs this region is interesting because a well-defined form of TMD factorization holds at high energy [8], which has been applied to sum small-x logarithmic corrections to DIS to all orders in α_s at leading and next-to-leading $\ln x$ level [9]. Furthermore, given the high precision of the combined data [1], this analysis provides a compelling test of the TMD approach and of the limitations of the logarithmic approximations used at small x. This is to be contrasted with earlier analyses based on older and much less precise structure function measurements [10, 11].

The high-energy factorization [8] expresses the DIS structure functions in terms of the TMD gluon density via well-prescribed, calculable perturbative coefficients. Phenomenological applications of this approach require combining small-x contributions with contributions from medium and large x [9, 12, 13, 14, 15]. To this end we use the CCFM evolution equation [16] implemented in the parton branching Monte Carlo [17]. The TMD gluon distribution at the initial scale Q_0 of the evolution is determined from fits to DIS data.

We here present results from fits to the F_2 structure function data [1] in the range $x < 0.005$ and $Q^2 > 5$ GeV, based on high-energy factorization, CCFM evolution and inclusion of two-loop running coupling, finite-x gluon splitting and energy-momentum consistency constraint as described in [7, 18]. In addition to the gluon-induced process $\gamma^* g^* \to q\bar{q}$ the contribution from valence quarks is included via $\gamma^* q \to q$ [7] by using CCFM evolution of valence quarks according to the method [19]. The results presented here are obtained with the `herafitter` package by treating the correlated systematic uncertainties separately from the uncorrelated statistical and systematic uncertainties.

To obtain a reasonable fit to the structure function data, the starting scale Q_0 as well as Λ_{QCD} have been varied. The best fit gives $\chi^2/ndf \sim 1.2$ for $Q_0 = 1.8$ GeV and $\Lambda_{\text{QCD}} = 0.17$ GeV at $n_f = 4$ flavours. The precise value depends on the number of parameters in the starting gluon distribution $\mathscr{A}_0$. It has been checked that the χ^2/ndf does not change significantly when using 3 instead of 4 parameters for the initial starting distribution $\mathscr{A}_0$. In Fig. 1 we show the unintegrated TMD gluon density (JH-set1) resulting from the fit to F_2 data. The distribution is plotted as a function of x and k_t^2 for given value of p^2, and compared with the previous set A0 [20] and with the result obtained from the derivative of the ordinary (integrated) gluon distribution.

In [7] we study experimental and theoretical uncertainties of the TMD parton distributions. Results are shown in Figs. 2 and 3.

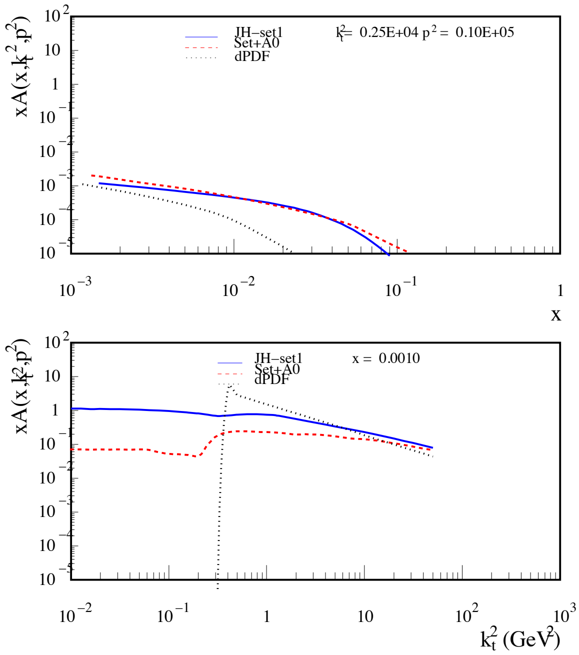

Figure 1: Unintegrated TMD gluon density JH-set1 as a function of x for different values of k_t^2 and as a function of k_t^2 for different values of x. The result is compared to set A0 [20].

Experimental uncertainties are obtained within the `herafitter` package from a variation of the individual parameter uncertainties, following the procedure described in [21] applying $\Delta\chi^2 = 1$. These result in 10 to 20 percent gluon uncertainty for medium and large x. The experimental uncertainties on the gluon at small x are small (much smaller than those obtained in standard fits based on integrated pdfs), since only the gluon density is fitted. The uncertainty bands for the gluon density are shown in Fig. 2. Theoretical uncertainties are modeled from variation of factorization and renormalization scales. Fig. 3 shows results from these variations separately. The curves correspond to variations by factor 2.

It is worth stressing that, although the fits are performed in the restricted kinematic range in x and Q^2 given above, the high precision of the data provides a highly nontrivial test, to an accuracy never reached before, of the approach based on TMD factorization and CCFM evolution.

This approach differs from finite-order perturbative QCD fits, e.g. at the NLO level, because it takes into account corrections to the collinear ordering in the initial state evolution to all orders in α_s. It also differs from BFKL evolution because it takes into account, for any x, color coherence associated with soft multi-gluon emission.

Within the framework [14, 17] it is possible to study quantitatively the significance of these contributions by imposing transverse momentum ordering and taking the one-loop approximation to the evolution kernel in the CCFM equation. Then we find [7] that the quality of the fit rapidly worsens, signaling the onset of contributions which, in the one-loop, strong-ordering approximation mode, are to be attributed to quark evolution. First results, in the one-loop CCFM mode, including both gluon and (perturbatively generated) quarks at TMD level are presented in [7].

It will be of interest to investigate whether the approach of this work can be extended into the

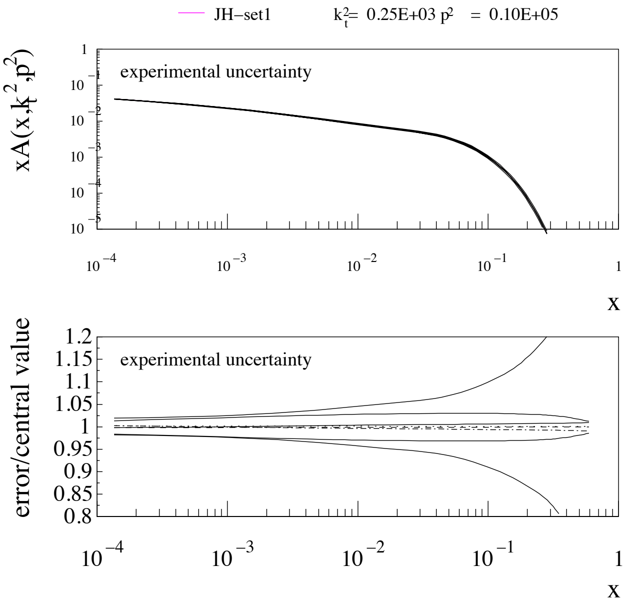

Figure 2: Experimental uncertainties of the unintegrated TMD gluon density at $p^2 = 25$ GeV^2.

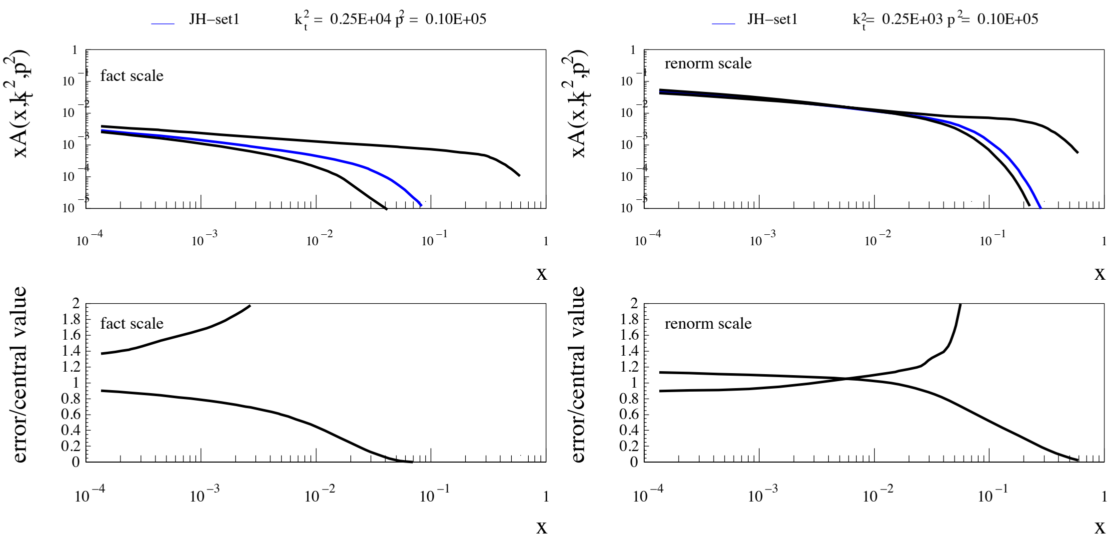

Figure 3: Uncertainties of the unintegrated TMD gluon density obtained from variation of (left) factorization scale and (right) renormalization scale.

low Q^2 region, where precise measurements of F_2 are also available [1], and whether the low x kinematic cut can be relaxed, leading to the inclusion of higher Q^2.

TMD pdfs determined from high-precision DIS data, including uncertainties, can be used to make predictions for hadron-hadron collider processes and to give uncertainty bands on the predictions. Work in this direction is underway.

Acknowledgments. Many thanks to the workshop organizers for the opportunity to present this

work and for putting up a very interesting conference.

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