Determination of the TMD gluon density in a proton using recent LHC data

N.A.Abdulov, H.Jung, A.V.Lipatov, G.I.Lykasov, M.A.Malyshev

September 20, 2018

Phys. Rev. D 98, 054010

- A theoretical description of a number of processes at high energies and large momentum transfer containing multiple hard scales requires *unintegrated*, or *transverse momentum dependent* (TMD) parton density functions, which encode nonperturbative information on a proton structure, including transverse momentum and polarization degrees of freedom.
- In the high-energy factorization, the production cross sections at low transverse momenta are governed by the nonperturbative input to the TMD parton density functions. The latter, being used as an initial condition for the subsequent QCD evolution, could play an important role in phenomenological applications.

E. Avsar, Int. J. Mod. Phys. Conf. Ser. 04, 74 (2011); arXiv:1203.1916.
S. M. Aybat and T. C. Rogers, Phys. Rev. D 83, 114042 (2011).
B. I. Ermolaev, M. Greco, and S. I. Troyan, Eur. Phys. J. C 71, 1750 (2011); 72, 1953 (2012).
P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, and A. Van Hameren, J. High Energy Phys. 09 (2015) 106.

At present, several approaches to determine the TMD gluon density in a proton are known in the literature:

- In the Kimber–Martin–Ryskin (KMR) scheme developed at leading order (LO) and next-to-leading order (NLO), the TMD quark and gluon densities are derived from the conventional parton distribution functions.

  M. A. Kimber, A. D. Martin, and M. G. Ryskin, Phys. Rev. D 63, 114027 (2001); G. Watt, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. C 31, 73 (2003)

  A. D. Martin, M. G. Ryskin, and G. Watt, Eur. Phys. J. C 66, 163 (2010)

- The TMD quark and gluon densities in a proton were determined from fits to precision measurements of deep inelastic scattering cross sections at HERA and evolved by the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) evolution with NLO splitting functions using the parton branching method.

  F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik, Phys. Lett. B 772, 446 (2017)

  F. Hautmann, H. Jung, A. Lelek, and V. Radescu, J. High Energy Phys. 01, 070 (2018)

- The parameters of the initial TMD gluon distribution were fitted from the precision HERA data on proton structure function $F_2(x, Q^2)$ in the range $x < 5 \times 10^{-3}$, $Q^2 > 5$ GeV^2, and $F_2^c(x, Q^2)$ at $Q^2 > 2.5$ GeV^2 assuming the Gaussian-like dependence on the intrinsic gluon transverse momentum at $k_T \leq \mu_0 \sim 2$ GeV.
  The approach based on the Catani–Ciafaloni–Fiorani–Marchesini (CCFM) gluon evolution equation was used to determine the TMD gluon distribution in all kinematic region.

  F. Hautmann and H. Jung, Nucl. Phys. B883, 1 (2014).
  M. Ciafaloni, Nucl. Phys. B296, 49 (1988);
  S. Catani, F. Fiorani, and G. Marchesini, Phys. Lett. B 234, 339 (1990); Nucl. Phys. B336, 18 (1990);

  G. Marchesini, Nucl. Phys. B445, 49 (1995)

- In papers

  A. A. Grinyuk, A. V. Lipatov, G. I. Lykasov, and N. P. Zotov, Phys. Rev. D 93, 014035 (2016).
  A. V. Lipatov, G. I. Lykasov, and N. P. Zotov, Phys. Rev. D 89, 014001 (2014).
  A. A. Grinyuk, A. V. Lipatov, G. I. Lykasov, and N. P. Zotov, Phys. Rev. D 87, 074017 (2013)

  the initial TMD gluon density was derived in the framework of the soft quark-gluon string model by taking into account gluon saturation effects at low Q^2. The essential parameters were obtained from the best description of the inclusive spectra of hadrons produced in pp collisions at LHC energies in the midrapidity region at low transverse momenta $p_T \leq 4.5$ GeV.

- Being used with the CCFM evolution, the predictions based on the proposed TMD gluon density describe well the HERA measurements of the proton structure functions $F_2^c(x, Q^2)$, $F_2^b(x, Q^2)$, and $F_L(x, Q^2)$. Thereby, the connection between soft LHC processes and small-x physics at HERA in a wide kinematical region was established.
- An important advantage of the approaches

  A. V. Lipatov, G. I. Lykasov, and N. P. Zotov, Phys. Rev. D 89, 014001 (2014).
  A. A. Grinyuk, A. V. Lipatov, G. I. Lykasov, and N. P. Zotov, Phys. Rev. D 87, 074017 (2013)

  F. Hautmann and H. Jung, Nucl. Phys. B883, 1 (2014).

  is that one can rather easily take into account a large piece of higher-order corrections, namely, part of $NLO + NNLO + \ldots$ terms containing leading $\log 1/x$ enhancement of cross sections due to real initial state parton emissions absorbed into the CCFM evolution.

Objectives of the study

- Here we continue previous studies and refine its large-x behavior using the latest LHC data on the inclusive top quark pair production at $\sqrt{s} = 13$ TeV. Moreover, we test the parameters of the initial TMD gluon density using the recent NA61, LHC, and RHIC data for soft hadron production in pp and AA collisions obtained in a wide energy range.
- We extend the updated TMD gluon distribution to the whole range of the longitudinal momentum fraction x, transverse momentum $\mathbf{k}_T^2$, and hard scale μ^2 numerically using the UPDFEVOLV package, which is the CCFM evolution code for TMD parton densities. The CCFM equation is the most suitable tool for our study since it smoothly interpolates between the small-x Balitsky–Fadin–Kuraev–Lipatov (BFKL) gluon dynamics and the conventional DGLAP one.

- Then, we supply the obtained TMD gluon density with the corresponding TMD valence and sea quark distributions calculated in the approximation, where the sea quarks occur in the last gluon splitting.
- Finally, we present several phenomenological applications of the proposed TMD parton densities to hard LHC processes sensitive to the quark and gluon content of the proton:

  — Proton structure functions F_2^c and F_2^b

  — Single top production at the LHC

  — Inclusive Higgs boson production at the LHC

- The determination of the parameters of the initial TMD gluon density in a proton can be split into the two almost independent pieces referring to the regions of small and large x.
- We consider first the small-x region and start from the simple analytical expression for the starting TMD gluon distribution function at some fixed scale $\mu_0 \sim 1 - 2$ GeV.

$$f_g^{(0)}(x, \mathbf{k}_T^2, \mu_0^2) = \tilde{f}_g^{(0)}(x, \mathbf{k}_T^2, \mu_0^2) + \lambda(x, \mathbf{k}_T^2, \mu_0^2) f_g(x, \mathbf{k}_T^2)$$

where x and $\mathbf{k}_T$ are the proton longitudinal momentum fraction and two-dimensional gluon transverse momentum, respectively.

$\tilde{f}_g^{(0)}(x, \boldsymbol{k}_T^2, \mu_0^2)$ was calculated within the soft QCD model:

$$\tilde{f}_g^{(0)}(x, \boldsymbol{k}_T^2, \mu_0^2) = c_0 c_1 (1-x)^b \left[R_0^2(x)\boldsymbol{k}_T^2 + c_2 (R_0^2(x)\boldsymbol{k}_T^2)^{a/2} \right] \times \\ \times \exp\left(-\sqrt{R_0^2(x)\boldsymbol{k}_T^2} - d[R_0^2(x)\boldsymbol{k}_T^2]^{3/2} \right),$$

where $R_0^2(x) = (x/x_0)^\lambda/\mu_0^2$, $c_0 = 3\sigma_0/4\pi^2\alpha_s$.

The parameters $\sigma_0 = 29.12$ mb, $\lambda = 0.22$, $x_0 = 4.21 \times 10^{-5}$, $\alpha_s = 0.2$ come from the Golec–Biernat–Wüsthoff (GBW) saturation model, while the other parameters a, b, c_1 , c_2 and d were fitted from LHC data on inclusive spectra of charged hadrons.

The gluon density $\tilde{f}_g^{(0)}(x, \boldsymbol{k}_T^2, \mu_0^2)$ differs from the one obtained in the GBW model at $|\mathbf{k}_T| < 1$ GeV and coincides with the GBW gluon at larger $|\mathbf{k}_T| > 1.5$ GeV

The second term $f_g(x, \mathbf{k}_T^2)$ represents the analytical solution of the linear BFKL equation at low x weighted with a matching function $\lambda(x, \mathbf{k}_T^2, \mu_0^2)$

$$f_g(x, \mathbf{k}_T^2) = \alpha_s^2 x^{-\Delta} t^{-1/2} \frac{1}{v} \exp[-\frac{\pi \ln^2 v}{t}],$$

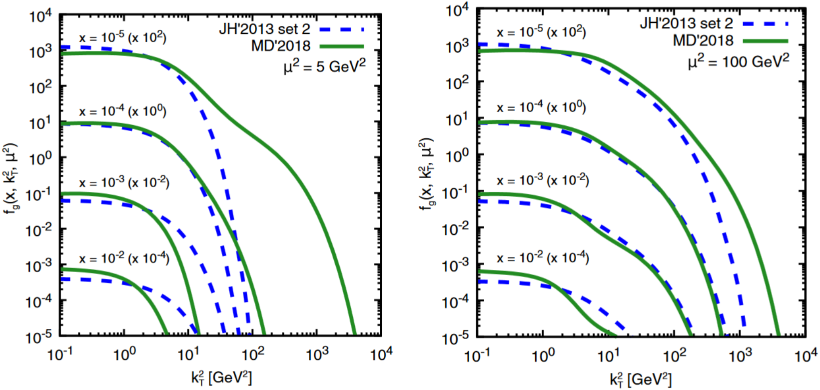
$$\lambda(x, \mathbf{k}_T^2, \mu_0^2) = c_0 (\frac{x}{x_0})^{0.81} \exp[-k_0^2 \frac{R_0(x)}{|\mathbf{k}_T|}],$$

where $t = 14\alpha_s N_c \zeta(3) \ln(1/x)$, $\Delta = 4\alpha_s N_c \ln 2/\pi$, $v = |\mathbf{k}_T|/\Lambda_{QCD}$, $k_0 = 1$ GeV.

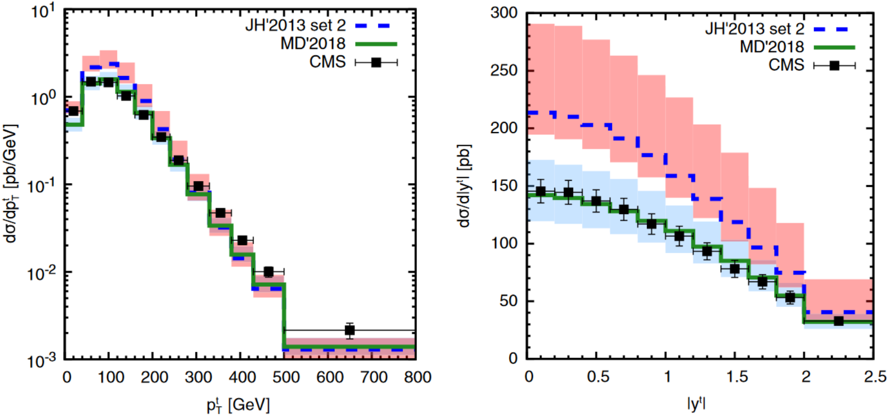
This term allows one to describe LHC measurements of inclusive charged hadrons up to $p_T \leq 4.5$ GeV. It is important that the contribution from $f_g(x, \mathbf{k}_T^2)$ is only nonzero at $|\mathbf{k}_T| \ll \Lambda_{QCD}(1/x)^{\delta}$ with $\delta = \alpha_s N_c$, resulting in an average generated gluon transverse momentum of $\langle |\mathbf{k}_T| \rangle \sim 1.9$ GeV.

The latter value is close to the nonperturbative QCD regime that allows one to treat the TMD gluon density above as a starting one for the CCFM evolution.

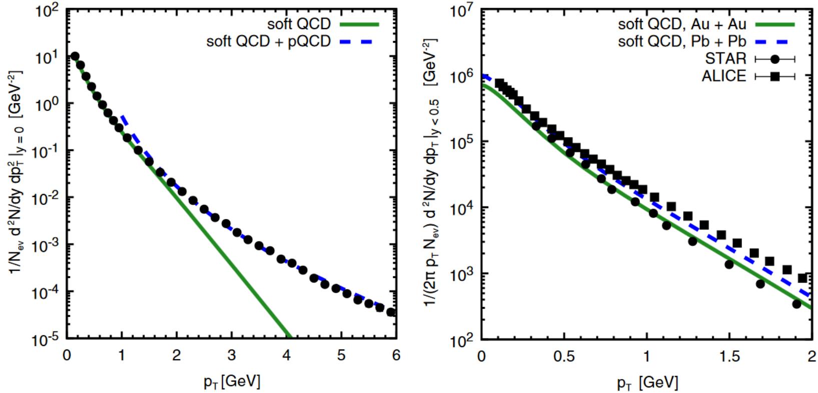
- We find that $b = 10$ and $d = 0.4$ are more preferable to describe the distributions on the rapidity and transverse momentum of top quark pairs. The latter leads, in addition, to a different value of overall normalization $N = 0.27$, which was determined using the CMS data on inclusive b-jet production.
- The obtained gluon density is labeled as Moscow-Dubna 2018, or MD'2018.



- Then, we refine some of these parameters essential in the large-x region using recent experimental data on inclusive $t\bar{t}$ production at $\sqrt{s} = 13$ TeV. These data refer to $x \sim 2m_t/\sqrt{s} \sim 3 \times 10^{-2}$(with a top mass $m_t \sim 170$ GeV) and are reported at the parton level in the full phase space, allowing us to avoid the numerical simulation of top quark decays.



- These parameters do not contradict our calculations and the experimental data on the pion transverse mass distribution in Au + Au and Pb + Pb collisions taken by the STAR Collaboration at the RHIC and the ALICE Collaboration at the LHC.



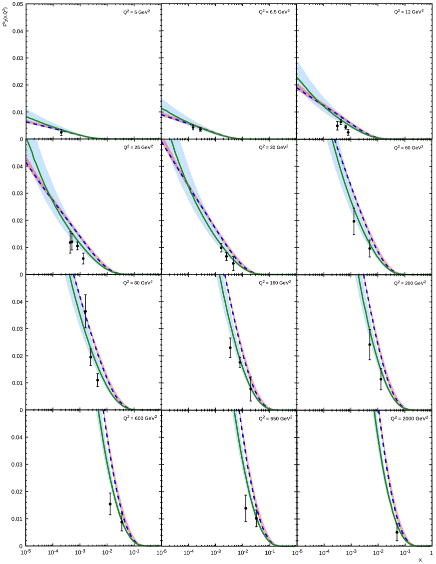
Now we can apply the MD'2018 gluon density to several hard processes studied at hadron colliders. We use the k_T–factorization approach, where the production cross section of any process under consideration can be written as

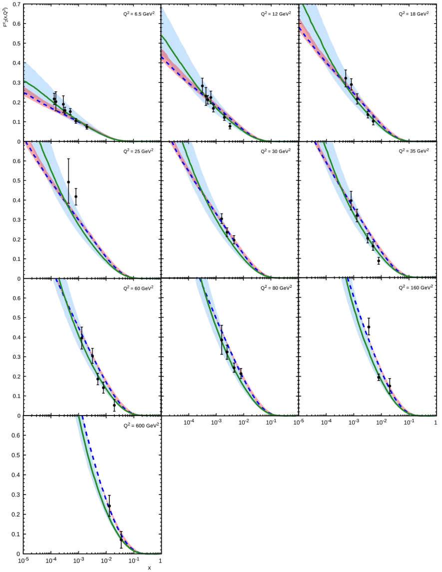
$$\sigma = \sum_{i,j} \int dx_1 dx_2 \int d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 f_{i/h_1}(x_1, \mathbf{k}_{1T}^2, \mu^2) f_{j/h_2}(x_2, \mathbf{k}_{2T}^2, \mu^2) \times$$
$$\times\, d\hat{\sigma}_{ij}(x_1, x_2, \mathbf{k}_{1T}^2, \mathbf{k}_{2T}^2, \mu^2),$$

where i,j denote the partons inside colliding particles $h_{1,2}$ (protons or heavy ions), and $\hat{\sigma}_{ij}(x_1, x_2, \mathbf{k}_{1T}^2, \mathbf{k}_{2T}^2, \mu^2)$ is the corresponding off-shell (depending on the transverse momenta of incoming particles) partonic cross section.

The multidimensional integration was performed by the Monte Carlo technique, using the routine VEGAS.

Proton structure functions F_2^b and F_2^c





Single top production at the LHC

- To calculate the total and differential production cross sections, we employ the four-flavor scheme so that the leading contribution comes from the $2 \to 3$ off-shell (reggeized) quark-gluon interaction subprocess:

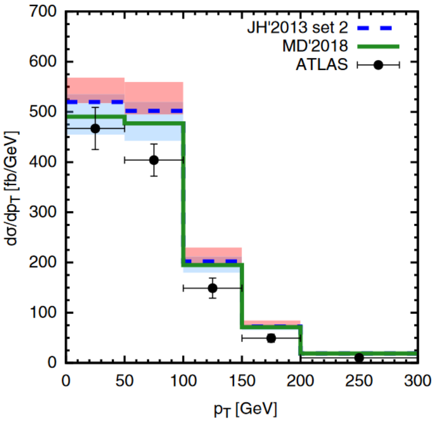
$$q^*(k_1) + g^*(k_2) \to q'(p_1) + \bar{b}(p_2) + t(p)$$

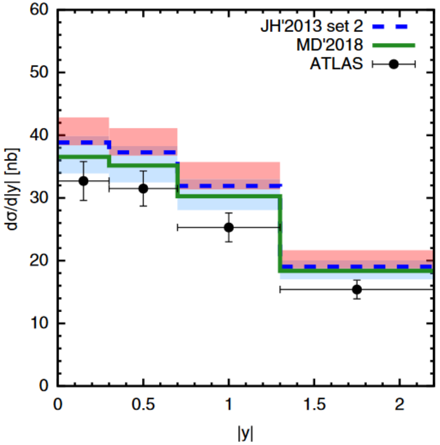
- The diagrams were calculated for the first time, using the effective vertex that ensures the gauge invariance of the amplitude despite the off-shell initial partons

  L. N. Lipatov and M. I. Vyazovsky, Nucl. Phys. B 597, 399 (2001).

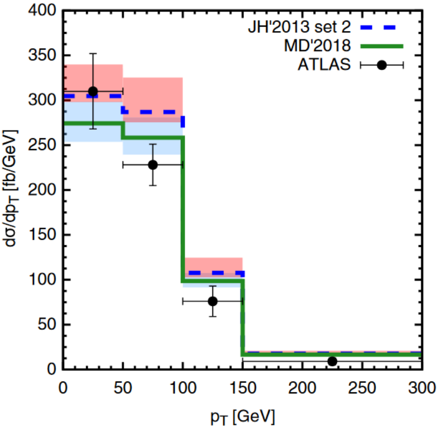
  A. V. Bogdan and V. S. Fadin, Nucl. Phys. B 740, 36 (2006)

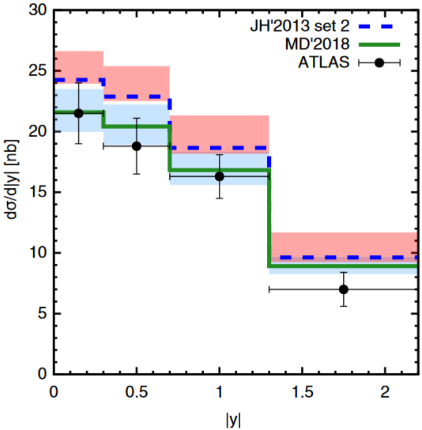
The differential cross sections of inclusive t-channel single top production at $\sqrt{s} = 8$ TeV





The differential cross sections of inclusive t-channel single antitop production at $\sqrt{s} = 8$ TeV





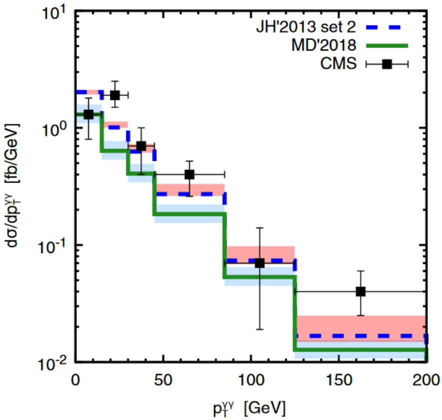
Inclusive Higgs boson production at the LHC

- The measurements of the total and differential cross sections of inclusive Higgs boson production obtained in different Higgs decay channels can be used to investigate the gluon dynamics in a proton since the dominant mechanism of the inclusive Higgs production at the LHC is a gluon-gluon fusion.
- Here, to calculate the total and differential cross sections of Higgs boson production, we strictly follow our previous consideration

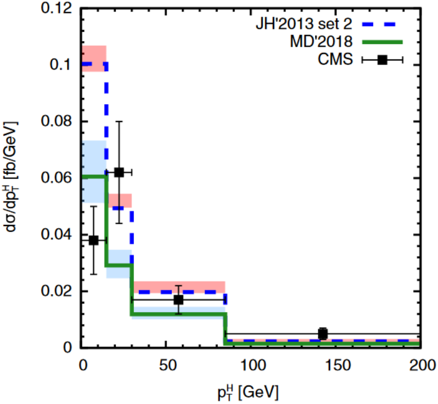
  N. A. Abdulov, A. V. Lipatov, and M. A. Malyshev, Phys.Rev. D97, 054017 (2018).

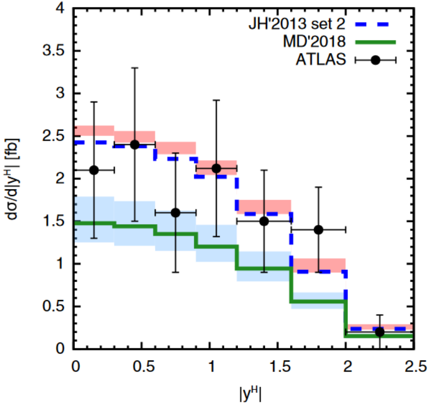
  The latter is based on the off-shell amplitude of the gluon-gluon fusion subprocess $g^* g^* \to H$ calculated using the effective Lagrangian for the Higgs coupling to gluons and extended recently to the subsequent $H \to \gamma\gamma$, $H \to W^+W^- \to e^\pm \mu^\mp \nu\bar{\nu}$, and $H \to ZZ^* \to 4l$ decays.
  J. R. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B106, 292 (1976).
  M. A. Shifman, A. I. Vainstein, M. B. Voloshin, and V. I. Zakharov, Sov. J. Nucl. Phys. 30, 711 (1979).

The differential cross sections of inclusive Higgs boson production (in the diphoton decay mode) at $\sqrt{s} = 13$ TeV



The differential cross sections of inclusive Higgs boson production (in the $H \to ZZ^* \to 4l$ decay mode) at $\sqrt{s} = 13$ TeV





Conclusion

- We have refined a fit of the experimental data on the inclusive spectra of the charged particles produced in the central pp and AA collisions at the RHIC and the LHC to determine the TMD gluon density in a proton at the starting scale. The parameters of this fit do not depend on the initial energy in a wide energy interval.
- Using a numerical solution of the CCFM gluon evolution equation, we extended the derived TMD gluon density (denoted as Moscow-Dubna 2018 or MD'2018 set) to a whole kinematical region and supplied it with the relevant TMD valence and sea quark distributions. The latter was calculated in the approximation where the gluon-to-quark splitting occurred at the last evolution step using the TMD gluon-to-quark splitting function.

- We achieved a good description of various data from HERA, RHIC, and LHC using the same set of parameters that confirms the link between soft processes at the LHC and low-x physics at HERA.
- We demonstrated a significant influence of the initial nonperturbative gluon distribution on the description of the LHC data, which is important to further precise determination of the TMD quark and gluon densities in a proton.

Thank you for attention!

Next, we extend the obtained TMD gluon density to a higher scale μ^2 using the CCFM evolution equation. This equation resums large logarithms $\alpha_s^n \ln^n 1/x$ and $\alpha_s^n \ln^n 1/(1-x)$ and is valid at both small and large x. In the leading logarithmic approximation, the CCFM equation with respect to the evolution scale μ^2 can be written as

$$f_g(x, \boldsymbol{k}_T^2, \mu^2) = f_g^{(0)}(x, \boldsymbol{k}_T^2, \mu_0^2)\Delta_s(\mu^2, \mu_0^2) + \\ + \int \frac{dz}{z} \int \frac{dq^2}{q^2} \theta(\mu - zq)\Delta_s(\mu^2, z^2q^2)P_{gg}(z, q^2, \mathbf{k}_T^2)f_g(x/z, \mathbf{k'}_T^2, q^2),$$

where $\mathbf{k'}_T = \mathbf{q}(1-z) + \mathbf{k}_T$. The exact analytical expressions for the Sudakov form factor $\Delta_s(p^2, q^2)$ and gluon splitting functions $P_{gg}(z, q^2, \mathbf{k}_T^2)$ can be found in

F. Hautmann, H. Jung, and S. Taheri Monfared, Eur. Phys. J. C 74, 3082 (2014).

The CCFM equation with the starting TMD gluon density $f_g^{(0)}(x, \boldsymbol{k}_T^2, \mu_0^2)$ was solved numerically using the UPDFEVOLV package.

To produce the TMD valence and sea quark distributions, we apply the approach of

F. Hautmann, M. Hentschinski, and H. Jung, Nucl. Phys. B865, 54 (2012).

The TMD sea quark density was calculated in the approximation where the sea quarks occur in the last gluon splitting:

$$f_q^{(s)}(x, \boldsymbol{k}_T^2, \mu^2) = \int_x^1 \frac{dz}{z} \int d\mathbf{q}_T^2 \frac{1}{\boldsymbol{\Delta}^2} \frac{\alpha_s}{2\pi} P_{qg}(z, \mathbf{q}_T^2, \boldsymbol{\Delta}^2) f_g(x/z, \mathbf{q}_T^2, \bar{\mu}^2),$$

where z is the fraction of the gluon light-cone momentum carried by the quark and $\boldsymbol{\Delta} = \mathbf{k}_T - z\mathbf{q}_T$.
The hard scale $\bar{\mu}^2$ was defined from the angular ordering condition which is natural from the CCFM point of view:

$$\bar{\mu}^2 = \boldsymbol{\Delta}^2/(1-z)^2 + \mathbf{q}_T^2/(1-z).$$

The off-shell gluon-to-quark splitting function $P_{qg}(z, \mathbf{q}_T^2, \boldsymbol{\Delta}^2)$ was calculated in

S. Catani and F. Hautmann, Nucl. Phys. B427, 475 (1994); Phys. Lett. B 315, 157 (1993).

- The main contribution to the amplitude comes from the diagram, which corresponds to initial gluon splitting to a $b\bar{b}$ pair with subsequent exchange of the W boson between the b and the light quark and it reads:

$$A = -g \frac{e^2}{8\sin^2\theta_w} V_{qq'} V_{tb} \bar{u}_{s_1}(p_1)\Gamma^{\mu}_{(+)}(k_1, -p_1)(1-\gamma^5)u_{s_2}(x_1 l_1)\times$$

$$\times\, \bar{u}_{s_3}(p)\gamma_\mu(1-\gamma^5)\frac{\hat{k}_2 - \hat{p}_2 + m_b}{(k_2-p_2)^2 - m_b^2}\hat{\epsilon}(k_2)v_{s_4}(p_2)\times$$

$$\times\, t^a \frac{1}{(p_1-k_1)^2 - m_w^2 + i m_w \Gamma_w},$$

where g and e are the strong and electric charges, respectively, θ_w is the weak Weinberg mixing angle, $V_{q_a q_b}$ are the Cabibbo–Kobayashi–Maskawa matrix elements, m_b and m_w are the b–quark and W–boson masses, a is the eightfold color index, and Γ_w is the W–boson full decay width.

- The effective vertex $\Gamma^{\mu}_{(+)}(k, q)$ that ensures gauge invariance of the amplitude despite the off-shell initial partons

$$\Gamma^{\mu}_{(+)}(k, q) = \gamma^{\mu} - \hat{k}\frac{l_1^{\mu}}{l_1 \cdot q}$$

where l_1 is the proton four-momentum ($k_1 = x_1 l_1 + k_{1T}$ and $k_2 = x_2 l_2 + k_{2T}$).

- The polarization sum for the off-shell gluon is taken in the BFKL form

$$\sum \epsilon^{\mu}(k)\epsilon^{\nu}(k) = \frac{k_T^{\mu} k_T^{\nu}}{k_T^2}$$

- In all other aspects, the calculation is straightforward and follows standard Feynman rules. The evaluation oftraces was performed using the algebraic manipulation system FORM