Hadron structure and parton branching beyond collinear approximations

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We briefly illustrate recent developments in the parton branching formulation of TMD evolution and their impact on precision measurements in high-energy hadronic collisions.

The impact of hadron structure on precision studies of fundamental interactions and searches for new physics plays an essential role at high-energy colliders of the present and next generation. The QCD theoretical framework based on collinear parton distribution functions (PDFs) and parton showers, in particular, is extremely successful in describing a wealth of collider data.

However, PDFs are the result of a strong reduction of information and tell us only about the longitudinal momentum of partons in a fast moving hadron. This restriction is lifted in the transverse momentum dependent (TMD) parton distribution functions — more general distributions which provide “3-dimensional imaging” of hadron structure. Such distributions are needed to obtain QCD factorization formulas for collider observables in “extreme” kinematic regions characterized by multiple momentum scales. These will be relevant both for experiments at the high-energy frontier and for exploring the region of the highest masses accessible at the high-luminosity frontier.

A large body of knowledge has been built about collinear PDFs over the last three decades from the analysis of high-energy experimental data in hadronic collisions, greatly aided by the development of realistic Monte Carlo (MC) event simulations for the parton cascades associated with PDF evolution. TMDs, on the other hand, are much less known. Hadronic 3D imaging, with its implications for high-energy physics, will constitute the subject of intensive studies in the forthcoming decade. The construction of MC event generators incorporating TMDs and 3D hadron structure effects is thus a central objective of physics programs for future hadron colliders (HL-LHC, LHeC, EIC, FCC). Steps toward TMD MCs have recently been taken in the works, in which a parton branching formalism is proposed for TMD evolution, and applications to deep inelastic scattering (DIS) and Drell-Yan (DY) processes are presented. In the following we give a brief account of these studies.

The parton branching (PB) approach gives TMD evolution equations of the

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schematic form

\[ A_a(x, k, \mu^2) = \Delta_a(\mu^2, \mu_0^2) A_a(x, k, \mu_0^2) + \sum_b \int \frac{d^2 \mu'}{\pi \mu'^2} \int dz K_{ab}(x, k, \mu^2; z, z_M, \mu'^2) A_b\left(x/z, k + a(z) \mu', \mu'^2\right), \]

where \( A_a(x, k, \mu^2) \) is the TMD distribution of flavor \( a \), carrying the longitudinal momentum fraction \( x \) of the hadron’s momentum and transverse momentum \( k \) at the evolution scale \( \mu \); \( z \) and \( \mu' \) are the branching variables, with \( z \) being the longitudinal momentum transfer at the branching, and \( \mu' = \sqrt{\mu'^2} \) the momentum scale at which the branching occurs; \( z_M \) is the soft-gluon resolution scale; the function \( a(z) \) specifies the ordering condition in the branching; \( K_{ab} \) are evolution kernels, computable in terms of Sudakov form factors, real-emission splitting functions and phase-space constraints. The initial evolution scale is denoted by \( \mu_0 \); the distribution \( A_a(x, k, \mu_0^2) \) at scale \( \mu_0 \) in the first term on the right hand side of Eq. (1) is the intrinsic \( k_T \) distribution.

The PB evolution equations are designed to be applicable over a wide kinematic range from low to high energies and implementable in MC generators. By taking the ordering function \( a(z) \), soft-gluon resolution scale \( z_M \) and strong coupling \( \alpha_s \) of the form prescribed by angular ordering, Eq. (1) gives, once it is integrated over transverse momenta, the CMW coherent-branching equation. On the other hand, for soft-gluon resolution \( z_M \rightarrow 1 \) and strong coupling \( \alpha_s \rightarrow \alpha_s(\mu'^2) \), integrating Eq. (1) over transverse momenta gives collinear PDFs satisfying DGLAP evolution equations. The convergence to DGLAP at leading order (LO) and next-to-leading order (NLO) has been verified numerically against the evolution program at the level of better than 1% over a range of five orders of magnitude both in \( x \) and in \( \mu \). Besides the collinear limits, Eq. (1) can be used at unintegrated level for event simulation of TMD physics effects.

In Figs. 1 and 2 we give examples of PB-TMD applications to DIS and DY processes. Fig. 1 shows results for TMDs from PB fits at NLO to the HERA high-precision inclusive DIS data performed using the fitting platform \( \text{xFitter} \) and the numerical techniques developed to treat the transverse momentum dependence in the fitting procedure. In two fitted TMD sets are presented, differing by the treatment of the momentum scale in the coupling \( \alpha_s \), so that one can compare the effects of \( \alpha_s \) evaluated at the transverse momentum scale prescribed by the angular-ordered branching with \( \alpha_s \) evaluated at the evolution scale. The TMDs are extracted including a determination of experimental and theoretical uncertainties. The lower panels in Fig. 1 show these uncertainties for \( \bar{u} \) and gluon distributions, at fixed values of \( x \) and \( \mu \), as a function of transverse momentum.

The \( k_T \) dependence in Fig. 1 results from intrinsic transverse momentum and evolution. The intrinsic \( k_T \) in Fig. 1 is taken for simplicity to be described by a gaussian at \( \mu_0 \sim \mathcal{O}(1 \text{ GeV}) \) with (flavor-independent and \( x \)-independent) width \( \sigma = k_0/\sqrt{2}, k_0 = 0.5 \text{ GeV} \). This is to be compared with higher values of intrinsic
$k_T \sim 2$ GeV obtained from tuning in shower MC event generators (see e.g.\cite{20}).

\begin{align*}
\mu, t \quad & x_A(x, k_T) \quad -10^6 \quad -10^5 \quad -10^4 \quad -10^3 \quad -10^2 \quad -10^1 \quad -10^1 \quad = 100 \text{ GeV} \\
\mu_{\text{anti-up}}, \quad x = 0.01, \quad \text{PB-NLO-HERAI+II-2018-set1} \\
\mu_{\text{gluon}}, \quad x = 0.01, \quad \text{PB-NLO-HERAI+II-2018-set2}
\end{align*}

\begin{align*}
\text{full uncertainties} & \quad \mu, t \\
\text{full uncertainties} & \quad \mu, t
\end{align*}

In Fig. 1 the PB TMDs are combined with the NLO calculation of DY $Z$-boson production to determine predictions for the lepton-pair transverse momentum $p_T$ spectrum. These are compared with LHC measurements\cite{21}. The computation in Fig. 2 requires addressing issues of matching\cite{22} analogous to those that arise in the case of parton showers. The matching is accomplished in the aMC@NLO framework\cite{23}. The calculations are performed via CASCADE\cite{24} to read LHETAG files, perform TMD evolution,\cite{25} produce output files, and RIVET\cite{26} to analyze the outputs.

The behaviors in the DY spectrum in Fig. 2 can be understood in terms of the $k_T$ distributions in Fig. 1. The uncertainties on the DY predictions come from TMD uncertainties and scale variations, with the latter dominating the overall uncertainty. We see from the left panel in Fig. 2 that the spectrum at low $p_T$ is sensitive to the angular ordering effects embodied in the different treatment of $\alpha_s$ in the PB Set 1 and Set 2. The bump in the $p_T$ distribution for intermediate $p_T$ is an effect of the matching and choice of the matching scale\cite{21,23} — a similar effect is seen when using parton showers instead of PB TMD. The deviation in the spectrum at higher $p_T$ is due to including only $O(\alpha_s)$ corrections but missing higher orders. We see from the right panel of Fig. 2 that the contribution from DY + 1 jet at NLO plays an important role at larger $p_T$. The merging of higher jet multiplicities\cite{27} in the PB TMD framework is one of the ongoing developments needed for MC event generators including 3D hadron structure effects.

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Fig. 2. Transverse momentum $p_T$ spectrum of Z-bosons as measured by\textsuperscript{21} at $\sqrt{s} = 8$ TeV compared to the prediction\textsuperscript{18} using aMC@NLO and NLO PB-TMD. Left: uncertainties from the PB-TMD and from changing the width of the intrinsic gaussian distribution by a factor of two. Right: with uncertainties from the TMDs and scale variation combined.

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