

## Flavor-dependent $b$ -profiles from Drell-Yan spectra at low transverse momenta

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We discuss our recent study of the impact of collinear PDFs and their uncertainties on the determination of transverse momentum dependent (TMD) distributions and the description of Drell-Yan (DY) production measurements at low transverse momenta. Using QCD factorization and evolution in transverse coordinate  $b$  space, this study takes into account for the first time flavor-dependent non-perturbative  $b$ -profiles. It illustrates that collinear PDF uncertainties and non-perturbative TMD flavor dependence are both essential to obtain reliable TMD determinations.

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Transverse momentum spectra in Drell-Yan (DY) vector boson production constitute one of the key areas of precision strong-interaction physics at hadron colliders. The QCD factorization formula for the DY differential cross section in the vector boson transverse momentum  $q_T$  [1] at  $q_T \ll Q$ , where  $Q$  is the vector boson invariant mass, enables one to explore perturbative dynamics, embodied in logarithmic resummations to all orders in the strong coupling  $\alpha_s$ , as well as non-perturbative dynamics, embodied in transverse momentum dependent (TMD) parton distributions [2]. Phenomenological studies of DY  $q_T$  spectra and their impact on precision electroweak measurements [3] are carried out at present with a variety of computational approaches, from the classic RESBOS platform [4] to the recent tools [5–10] to the global TMD fits [11, 12].

According to the factorization formula, the DY  $q_T$  differential cross section may be written schematically, up to power corrections in  $q_T/Q$  and  $\Lambda_{\text{QCD}}/Q$ , as

$$\frac{d\sigma}{dq_T^2} = \sum_{i,j} \int d^2b e^{ib \cdot q_T} \sigma_{ij}^{(0)} f_i(x_1, b; \mu, \zeta_1) f_j(x_2, b; \mu, \zeta_2) , \quad (1)$$

where the indices  $i, j$  run over quark and antiquark flavors,  $b$  is the transverse distance Fourier conjugate to  $q_T$ ,  $\sigma_{ij}^{(0)}$  are perturbatively calculable hard-scattering functions, and  $f_i$  and  $f_j$  are TMD parton distributions, evolving with the mass and rapidity scales  $\mu$  and  $\zeta$  according to well-prescribed evolution equations. Eq. (1) is the basis for the phenomenological program advocated in [13], which consists in determining TMD distributions, via the factorization and evolution framework, from fits to experimental data, in a manner analogous to (but independent of) the case of ordinary, collinear parton distribution functions (PDFs).

In practice, many current studies employ, besides the factorization and evolution formulas, the operator product expansion (OPE) of TMD distributions in terms of PDFs. This is valid at small distances  $b$ , up to power corrections in  $b\Lambda_{\text{QCD}}$ , and reads

$$f_i(x, b; \mu, \zeta) = \sum_j \int_x^1 (dy/y) C_{ij}(y, b; \mu, \zeta) q_j(x/y, \mu) + \mathcal{O}(b\Lambda_{\text{QCD}})^2 , \quad (2)$$

where  $q_j(x, \mu)$  are the PDFs, and  $C_{ij}$  are perturbatively calculable coefficient functions.

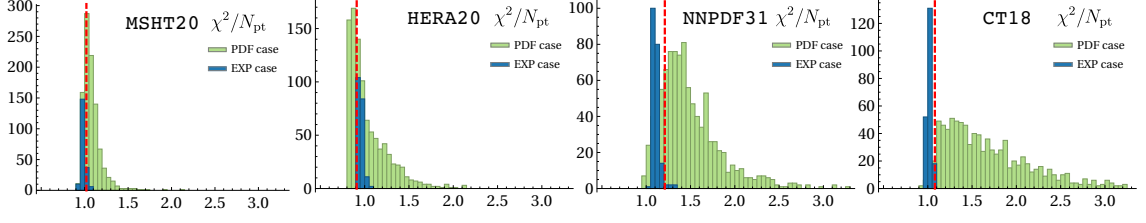
In particular, to carry out TMD fits an ansatz is made for the non-perturbative (NP) TMD distributions at large  $b$ , where the power corrections to Eq. (2) become sizeable, of the form

$$f_i(x, b; \mu, \zeta) = \sum_j \int_x^1 (dy/y) C_{ij}(y, b; \mu, \zeta) q_j(x/y, \mu) f_{\text{NP}}^i(x, b) . \quad (3)$$

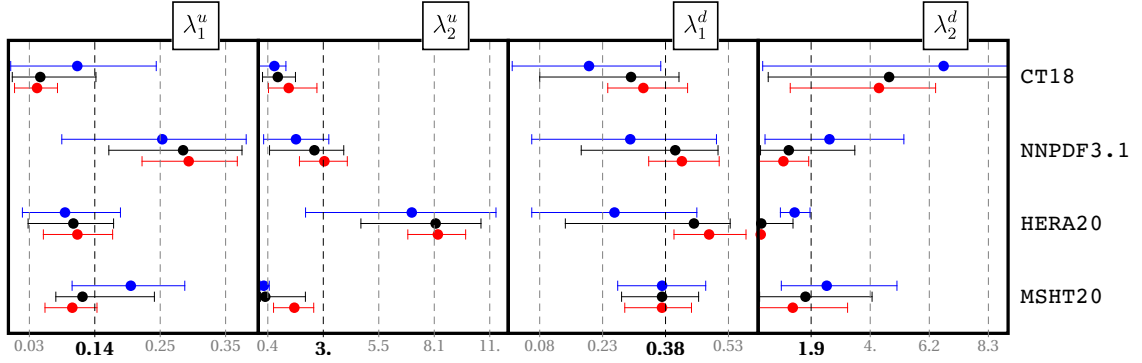
Here the distributions  $f_{\text{NP}}^i$  behave as  $f_{\text{NP}}^i(x, b) \sim 1 + \mathcal{O}(b\Lambda_{\text{QCD}})^2$  for  $b \rightarrow 0$ , thus matching the OPE (2), and are to be determined from experimental data, once a choice is made for the collinear PDF in Eq. (3).

While earlier studies have assumed flavor-independent  $f_{\text{NP}}$ , Ref. [14] explores for the first time the flavor dependence in the non-perturbative  $f_{\text{NP}}$   $b$ -profiles. The implications of propagating uncertainties from the PDF  $q_j$  in the ansatz (3) to the extracted NP TMD  $f_{\text{NP}}$  via Eq. (1) have also not been addressed in the literature before, and are explored for the first time in Ref. [14].

For the study [14] we use the implementation of TMD factorization and evolution at the next-to-next-to-leading-logarithmic level as in [15] (NNLL' according to the terminology adopted in [3]);



**Figure 1:** Distribution of  $\chi^2$  values for **PDF** and **EXP** cases. The position of the final  $\chi^2$  is indicated by the red line.



**Figure 2:** Fitted NP TMD parameters: (blue) value from the fit of the **PDF** case; (red) value from the fit of the **EXP** case; (black) final result.

we perform the analysis for the PDF sets MSHT20 [16], CT18 [17], NNPDF3.1 [18], HERA20 [19], taken as representatives of different methodological approaches at next-to-next-to-leading order (NNLO); we carry out fits of experimental data for low- $q_T$  DY production at fixed-target [20–22], RHIC [23], Tevatron [24, 25] and LHC [26–28] experiments. Unlike previous TMD determinations in which TMD uncertainties are obtained from experimental uncertainties, in the analysis [14] TMD uncertainties result from both experiment (EXP) and PDF. The two sources of uncertainties are taken into account through a Bayesian approach, in which PDFs are represented as Monte Carlo ensembles, and uncertainties are obtained by fitting each member of the input ensemble. The bootstrap method [29] is used to address the issue of combining EXP and PDF sources. The key findings are as follows.

(i) An overall reasonable description of the data is obtained for all PDF sets, with total  $\chi^2$  values of the fits and individual  $\chi^2$  values for each experiment given in Table 1. The  $\chi^2$  distribution among PDF and EXP replicas is shown in Fig. 1. In all cases the PDF uncertainty is found to be larger than the EXP uncertainty. If flavor-independent  $b$ -profiles are assumed, as e.g. in [12], the spread of  $\chi^2$  values is found to be much larger than in Fig. 1.

(ii) Flavor-dependent TMD parameters in  $f_{\text{NP}}^i$  are extracted from the fits. An example is given in Fig. 2, where  $f_{\text{NP}}^i(x, b)$  are parameterized through a combination of exponential and gaussian  $b$ -profiles with flavor-dependent  $\lambda$  coefficients (while the NP contribution to the evolution kernel is parameterized through a linear behavior at large  $b$  — see [15] for discussion of alternative parameterizations, including a constant large- $b$  behavior in the spirit of the picture [30]).

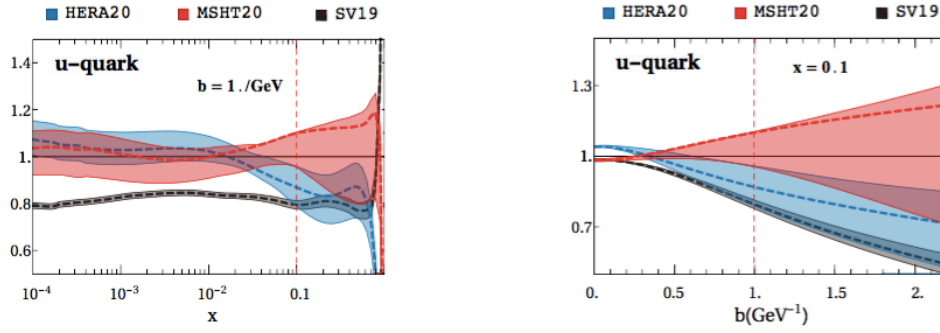
Data set	$N_{pt}$	MSHT20	HERA20	NNPDF31	CT18
		$\chi^2/N_{pt}$	$\chi^2/N_{pt}$	$\chi^2/N_{pt}$	$\chi^2/N_{pt}$
CDF run1	33	0.78	0.61	0.72	0.75
CDF run2	39	1.70	1.42	1.68	1.79
D0 run1	16	0.71	0.81	0.79	0.79
D0 run2	8	1.95	1.39	1.92	2.00
D0 run2 ( $\mu$ )	3	0.50	0.59	0.55	0.52
ATLAS 7TeV 0.0< y <1.0	5	4.06	1.94	2.12	4.21
ATLAS 7TeV 1.0< y <2.0	5	7.78	4.83	4.52	6.12
ATLAS 7TeV 2.0< y <2.4	5	2.57	2.18	3.65	2.39
ATLAS 8TeV 0.0< y <0.4	5	2.98	3.66	2.12	3.23
ATLAS 8TeV 0.4< y <0.8	5	2.00	1.53	4.52	3.21
ATLAS 8TeV 0.8< y <1.2	5	1.00	0.50	2.75	1.89
ATLAS 8TeV 1.2< y <1.6	5	2.25	1.61	2.49	2.72
ATLAS 8TeV 1.6< y <2.0	5	1.92	1.68	2.86	1.96
ATLAS 8TeV 2.0< y <2.4	5	1.35	1.14	1.47	1.06
ATLAS 8TeV 46<Q<66GeV	3	0.59	1.86	0.23	0.05
ATLAS 8TeV 116<Q<150GeV	7	0.61	1.03	0.85	0.70
CMS 7TeV	8	1.22	1.19	1.30	1.25
CMS 8TeV	8	0.78	0.77	0.75	0.78
CMS 13TeV 0.0< y <0.4	8	3.52	1.93	2.13	3.73
CMS 13TeV 0.4< y <0.8	8	1.06	0.53	0.71	1.65
CMS 13TeV 0.8< y <1.2	10	0.48	0.14	0.33	0.88
CMS 13TeV 1.2< y <1.6	11	0.62	0.33	0.47	0.86
CMS 13TeV 1.6< y <2.4	13	0.46	0.32	0.39	0.57
LHCb 7TeV	8	1.79	1.00	1.62	1.16
LHCb 8TeV	7	1.38	1.29	1.63	0.83
LHCb 13TeV	9	1.28	0.84	1.07	0.93
PHE200	3	0.29	0.42	0.38	0.29
E288-200	43	0.43	0.36	0.57	0.43
E288-300 $Q < 9\text{GeV}$	43	0.77	0.56	0.89	0.55
E288-300 $Q > 11\text{GeV}$	10	0.29	0.37	0.45	0.44
E288-400 $Q < 9\text{GeV}$	34	2.19	1.15	1.49	1.34
E288-400 $Q > 11\text{GeV}$	42	0.25	0.61	0.44	0.40
E772	35	1.14	1.37	1.79	1.11
E605 $Q < 9\text{GeV}$	21	0.52	0.47	0.47	0.61
E605 $Q > 11\text{GeV}$	32	0.47	0.73	1.34	0.52
<b>Total</b>	<b>507</b>	<b>1.12</b>	<b>0.91</b>	<b>1.21</b>	<b>1.08</b>

**Table 1:** The  $\chi^2$  values for the central replica over the TMD data set for different PDF input.

(iii) With the analysis including collinear PDF effects and flavor-dependent  $b$ -profiles, TMD error bands are significantly increased compared to earlier OPE-based fits. The bands are illustrated in Fig. 3 versus  $x$  and versus  $b$ . A comparison with the bands from the earlier fit [12] is also shown.

We conclude by noting that variations in PDF replicas are found to affect not only the normalization but also the  $q_T$  shape of TMD predictions. This causes the observed spread in  $\chi^2$  values among replicas. It is due to the OPE coupling the  $b$  and  $x$  dependences. Also, TMD uncertainty contributions from PDFs are comparable in size to theoretical uncertainties from perturbative scale variations for low- $q_T$  DY observables, pointing to the relevance of joined TMD and PDF fits.

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**Figure 3:** TMD uncertainty bands as functions of  $x$  and  $b$ . The plot is weighted with the central TMD value averaged over different PDF sets. For comparison the result SV19 [12] is also shown.

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