PROCEEDINGS OF SCIENCE

Effect of flavor-dependent partonic transverse momentum on the determination of the W mass at hadron colliders

PoS(DIS2019)133

Marco Radici[*]
INFN-Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy
E-mail: marco.radici@pv.infn.it

Alessandro Bacchetta
Dipartimento di Fisica, Università di Pavia, and INFN-Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy
E-mail: alessandro.bacchetta@unipv.it

Giuseppe Bozzi
Dipartimento di Fisica, Università di Pavia, and INFN-Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy
E-mail: giuseppe.bozzi@unipv.it

Andrea Signori
Physics Division, Argonne National Laboratory, 9700 S. Cass Avenue, Lemont, IL 60439 USA
E-mail: asignori@anl.gov

We explore the impact of a flavor-dependent intrinsic transverse momentum of quarks on the production of $W^{\pm}$ bosons in proton-proton collisions at hadron colliders. We build a template fit to the transverse-mass and the lepton transverse-momentum distributions of the W decay products. We estimate the shift in the extracted value of the W mass induced by different choices of flavor-dependent parameters for the quark intrinsic transverse momentum, that all reproduce the same transverse-momentum distribution of the Z boson. Our findings call for more detailed investigations of nonperturbative effects, which might affect very precise determinations of some Standard Model parameters even at kinematics where these effects are expected to be small.

XXVII International Workshop on Deep-Inelastic Scattering and Related Subjects - DIS2019
8-12 April, 2019
Torino, Italy

---

[*] Speaker.

1. Introduction

Apart from the global electroweak fit of Ref. [1], the M_W has been extracted also from $p\bar{p}$ collisions at `D0` [2] and at `CDF` [3], and from pp collisions at `ATLAS` [4] with a total uncertainty of 23, 19, 19 MeV, respectively. The experimental analyses are based on a template-fit procedure on the differential distributions of the W-decay products, like the transverse momentum of the final lepton, $p_{T\ell}$, the transverse momentum of the neutrino $p_{T\nu}$ (only at the Tevatron), and the transverse mass m_T of the lepton pair (where $m_T = \sqrt{2\, p_{T\ell}\, p_{T\nu}\, (1 - \cos(\phi_\ell - \phi_\nu))}$, with $\phi_{\ell,\nu}$ being the azimuthal angles of the lepton and the neutrino, respectively). The free parameter M_W corresponding to the histogram best describing experimental data selects the measured value of the W boson mass. All the details of the theoretical calculations used to compute the template (choice of scales, parton distribution functions (PDFs), perturbative order, ...) enter the theoretical systematic error [5].

Using the template-fit procedure, it is possible to single out the contribution of each theoretical ingredient to the final uncertainty on M_W. Here, we are interested in the nonperturbative effects coming from modeling the intrinsic transverse momentum of the incoming partons participating in the hard scattering. These effects modify the spectrum of the W transverse momentum, q_T^W, subsequently inducing a non-negligible shift in the extracted value of M_W. The three experimental collaborations `CDF`, `D0`, and `ATLAS` obtain for the distributions in $(m_T, p_{T\ell}, p_{T\nu})$, respectively, the shifts δM_W = (3,9,4) MeV [3], δM_W = (2,5,2) MeV [2] and δM_W = (3,3) MeV [4] (the `ATLAS` analysis did not include $p_{T\nu}$ in the template fit). Except for `ATLAS` (because of the narrow range used for the $p_{T\ell}$ fit), the uncertainty δM_W propagating from the q_T^W spectrum via $p_{T\ell}$ turns out to be comparable in size to the uncertainty originating from the choice of PDFs.

At present, all the three experimental collaborations determine the nonperturbative parameters by fitting the transverse momentum distribution of Z boson production data. Assuming that these parameters are flavor-independent, they further predict the q_T^W distribution and estimate the corresponding δM_W. None of them includes information on the flavor dependence of these parameters, although Monte Carlo simulations show that the flavor content of the dominant channel in the hard scattering producing a Z boson $(u\bar{u} + d\bar{d})$ is different from the one for the W^+ boson production $(u\bar{d})$. Moreover, the template-fit procedure indicates that these measurements are in general very sensitive to the input: a distortion of the $p_{T\ell}$ distribution by a few per-mille produces a shift $\delta M_W \sim \mathscr{O}(10 \text{ MeV})$ [6].

Hence, if we want to determine the free parameters of the Standard Model, like M_W, with very high precision, we need to include nonperturbative effects like the flavor dependence of the intrinsic parton transverse momentum. In the following, we report on the study of this impact, illustrated in more detail in Ref. [7] (see also Ref. [8]).

2. Formalism and strategy

The factorization theorem and evolution equations in the transverse-momentum-dependent (TMD) framework have been extensively studied in the literature (see e.g. Refs. [9, 10, 11] and references therein). Recently, the unpolarized quark TMD parton distribution function (TMD PDF) was extracted for the first time from a global fit of data for semi-inclusive deep-inelastic scattering (SIDIS) and production of Drell-Yan lepton pairs and Z bosons [12].

Different implementations of the nonperturbative contributions to the quark Sudakov exponent in the TMD factorization formula have been presented in the literature (see e.g. Ref. [13] and references therein). In order to take into account possible differences between the valence and the sea quarks (and among different flavors in general), a flavor- and kinematic-dependent implementation of the nonperturbative quark Sudakov exponent has been suggested in Refs. [14, 15]. Here, we model this nonperturbative intrinsic dependence of the unpolarized TMD PDF by a simple Gaussian in the transverse momentum whose Fourier-conjugate expression reads $\exp[-g_{NP}^{a} b_T^2]$, where g_{NP}^{a} is a parameter related to the average intrinsic transverse momentum squared of a parton with flavor spanning the range $a = u_v, u_s, d_v, d_s, s, c, b, g$ (the subscripts referring to the valence and sea components, respectively). For simplicity, we assume $g_{NP}^{s} = g_{NP}^{c} = g_{NP}^{b} = g_{NP}^{g}$ so that each TMD PDF depends on five flavors. We also split g_{NP}^{a} into two contributions as $g_{NP}^{a} = g_{evo} \ln(Q^2/Q_0^2) + g_a$, where the first term in the right hand side is the nonperturbative flavor-independent correction due the TMD PDF evolution and g_a is the genuine flavor-dependent contribution [7]. Information on g_{evo} can be deduced from the global fit of Ref. [12]. In order to account for the uncertainties affecting the determination of g_{evo}, we choose to consider the interval $[0.2, 0.6]$ GeV^2 as a reasonable range and we vary g_a such that the g_{NP}^{a} values fall into this range [7]. Then, we generate random widths in the allowed range for the considered five flavors. We build 50 sets of flavor-dependent parameters together with a flavor-independent set where all the parameters are put equal to the central value of the variation range, defined as $\overline{g_{NP}^{a}} = 0.4$ GeV^2. Our analysis proceeds in two steps.

The first step consists in selecting “Z-equivalent" sets of parameters. For proton-proton collisions at $\sqrt{s} = 7$ TeV, we generate pseudodata for the q_T distribution of the Z boson (22 bins similar to the `ATLAS` ones [4]) using the flavor-independent set in the `DYqT` code [16, 17] at $\mathcal{O}(\alpha_s)$ and NLL accuracy. We do the same for proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV (72 bins similar to the `CDF` ones [3]). We assign to each of the q_T bins an uncertainty equal to the experimental one. We compute the q_T distribution of Z boson with the same code in the same conditions also for each of the 50 flavor-dependent sets. We calculate the χ^2 between each of these 50 distributions and the pseudodata generated by the flavor-independent set. We retain only those flavor-dependent sets that have a $\chi^2 < 80$ on the “`CDF`-like" bins (χ^2/d.o.f. < 1.1) and a $\chi^2 < 44$ on the “`ATLAS`-like" bins (χ^2/d.o.f. < 2). The first criterion selects 48 flavor-dependent sets out of 50; only 30 sets out of 50 match the second one, because the `ATLAS` data have smaller (experimental) uncertainties [7]. We keep those flavor-dependent sets that fullfil both criteria. When considering all the bins, these sets have a total $\chi^2 < 124$ on the pseudodata (χ^2/d.o.f. < 1.3). In practice, these selected flavor-dependent sets are equivalent to the flavor-independent one (with which the Z pseudodata are generated) at approximately 2σ level.

The second step of our strategy consists in performing a template fit to estimate the impact of our “Z-equivalent” flavor-dependent sets on the determination of M_W, following the scheme introduced in Refs. [18, 6]. In this step, we use the `DYRes` code [16, 19] because it provides the full kinematics of the vector boson and of its decay products, thus allowing one to apply arbitrary cuts on the final-state kinematical variables and to directly compare to experimental measurements. Importantly, we work at the same accuracy and kinematics as before, using the MSTW2008 NLO PDF set [20], setting central values for the renormalization, factorization and resummation scales $\mu_R = \mu_F = \mu_{res} = M_W$, and implementing `ATLAS` acceptance cuts on the final-state leptons [4]. We generate templates with very high statistics (750 M events) for the m_T, $p_{T\ell}$ distributions with different M_W masses in the range 80.370 GeV $\leq M_W \leq$ 80.400 GeV, using the flavor-independent set for the nonperturbative parameters. Then, for each "Z-equivalent" flavor-dependent set we generate pseudodata with lower statistics (135 M events) for the same leptonic observables with the fixed value $M_W = 80.385$ GeV. Finally, for each pseudodata set we compute the χ^2 of the various templates and we identify the template with minimum χ^2 in order to establish how large is the shift in M_W induced by a particular choice of flavor-dependent nonperturbative parameters. The statistical uncertainty of the template-fit procedure is estimated by considering statistically equivalent those templates for which $\Delta\chi^2 = (\chi^2 - \chi^2_{min}) \leq 1$. Consequently, we quote an uncertainty of 2.5 MeV for each of the obtained M_W shifts [7].

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27
6	0.40	0.52	0.46	0.54	0.21
7	0.22	0.21	0.40	0.46	0.49
8	0.53	0.31	0.59	0.54	0.33
9	0.46	0.46	0.58	0.40	0.28

	ΔM_{W^+}			ΔM_{W^-}		
Set	m_T	$p_{T\ell}$	$p_{T\nu}$	m_T	$p_{T\ell}$	$p_{T\nu}$
1	0	-1	-2	-2	3	-3
2	0	-6	0	-2	0	-5
3	-1	9	0	-2	-4	-10
4	0	0	-2	-2	-4	-10
5	0	4	1	-1	-3	-6
6	1	0	2	-1	4	-4
7	2	-1	2	-1	0	-8
8	0	2	8	1	7	8
9	0	4	-3	-1	0	7

	ΔM_{W^+}			ΔM_{W^-}		
Set	m_T	$p_{T\ell}$	$p_{T\nu}$	m_T	$p_{T\ell}$	$p_{T\nu}$
1	-1	-5	7	-1	-3	8
2	-1	-15	6	0	5	10
3	-1	1	8	-1	-7	5
4	-1	-15	6	0	-4	5
5	-1	-4	6	-1	-7	5
6	-1	-5	7	0	2	9
7	-1	-15	6	-1	-6	5
8	-1	0	8	0	3	10
9	-1	-7	7	0	4	10

Figure 1: Left panel: some selected values of the g_{NP}^a parameter for the flavors $a = u_v, d_v, u_s, d_s, s = c = b = g$; units are in GeV^2. Central panel: shifts in $M_{W^\pm}$ (in MeV) induced by the corresponding flavor-dependent parameters from the $m_T, p_{T\ell}, p_{T\nu}$ distributions at the `ATLAS` kinematics with $\sqrt{s} = 7$ TeV. Right panel: same at the `LHCb` kinematics at $\sqrt{s} = 13$ TeV.

3. Results

In Fig. 1, we show in the left panel some selected sets of the g_{NP}^a parameters (in GeV^2) for the flavor $a = u_v, d_v, u_s, d_s, s = c = b = g$, out of the 30 "Z-equivalent" sets. In the central panel, we show the corresponding shifts induced in $M_{W^\pm}$ (in MeV) when applying our analysis to the $m_T, p_{T\ell}, p_{T\nu}$ distributions of the final-state products at the `ATLAS` kinematics with $\sqrt{s} = 7$ TeV. The right panel contains the same information at the `LHCb` kinematics with $\sqrt{s} = 13$ TeV.

The shifts induced by the analysis performed on $p_{T\ell}$ are generally larger than for the m_T and $p_{T\nu}$ cases, since it is known that the former case is the most sensitive to q_T^W-modelling effects. In the $p_{T\ell}$ analysis at the `ATLAS` kinematics (central panel), the set 3 produces a shift on M_{W^+} of 9 MeV, namely with a size particularly large if compared to the corresponding uncertainty quoted by `ATLAS` (3 MeV). Taking also into account the statistical uncertainty of our analysis, the absolute value of the shifts induced in these conditions could exceed 10 MeV. At the `LHCb` kinematics (right panel), the sets 2, 4, 7 produce even larger shifts. On the contrary, for M_{W^-} the shifts are in general less significant and fall within a 2-σ interval around zero.

As a final comment, we can attempt to identify a systematic trend in the above results. In the kinematic conditions under consideration, W^+ bosons are dominantly produced by a $u\bar{d}$ partonic process, with the u coming from the valence region. Correspondingly, we observe that sets characterized by a larger value of the combination $g_{NP}^{u_v} + g_{NP}^{d_s}$ (sets 3 and 5) lead to positive shifts in the value of M_{W^+}, while sets with a smaller value of $g_{NP}^{u_v} + g_{NP}^{d_s}$ (set 2) lead to negative shifts. For W^- the situation is less clear.

4. Conclusions

We investigated the uncertainties on the determination of M_W at hadron colliders induced by a possible flavor dependence of the partonic intrinsic transverse momentum. From these outcomes (detailed in Ref. [7]), we point out that a "flavor-blind" data analysis may not be a sufficiently accurate option, especially when a total uncertainty lower than 10 MeV is expected for M_W at the LHC [21].

Future data from flavor-sensitive processes such as SIDIS (from the 12 GeV upgrade at Jefferson Lab [22], from the `COMPASS` collaboration [23], and from a future Electron-Ion Collider with both proton and deuteron beams [24, 25]) will shed new light on the flavor decomposition of the TMD functions.

All these data will improve our knowledge of the partonic structure of hadrons, and may help in reducing the uncertainties in precision measurements at high energies.

Acknowledgments

We are indebted to Mathias Ritzmann for his expertise and important contribution. This work is supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No. 647981, 3DSPIN). AS acknowledges support from the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, contract no. DE-AC02-06CH11357.

References

[1] **Gfitter Group** Collaboration, M. Baak, J. Cúth, J. Haller, A. Hoecker, R. Kogler, K. Monig, M. Schott, and J. Stelzer, *The global electroweak fit at NNLO and prospects for the LHC and ILC*, *Eur. Phys. J.* **C74** (2014) 3046, [`arXiv:1407.3792`].

[2] **D0** Collaboration, V. M. Abazov et al., *Measurement of the W boson mass with the D0 detector*, *Phys. Rev.* **D89** (2014), no. 1 012005, [`arXiv:1310.8628`].

[3] **CDF** Collaboration, T. A. Aaltonen et al., *Precise measurement of the W -boson mass with the Collider Detector at Fermilab*, *Phys. Rev.* **D89** (2014), no. 7 072003, [`arXiv:1311.0894`].

[4] **ATLAS** Collaboration, M. Aaboud et al., *Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Eur. Phys. J.* **C78** (2018), no. 2 110, [`arXiv:1701.0724`].

[5] C. M. Carloni Calame, M. Chiesa, H. Martinez, G. Montagna, O. Nicrosini, F. Piccinini, and A. Vicini, *Precision Measurement of the W-Boson Mass: Theoretical Contributions and Uncertainties*, *Phys. Rev.* **D96** (2017), no. 9 093005, [`arXiv:1612.0284`].

[6] G. Bozzi, J. Rojo, and A. Vicini, *The Impact of PDF uncertainties on the measurement of the W boson mass at the Tevatron and the LHC*, *Phys. Rev.* **D83** (2011) 113008, [`arXiv:1104.2056`].

[7] A. Bacchetta, G. Bozzi, M. Radici, M. Ritzmann, and A. Signori, *Effect of Flavor-Dependent Partonic Transverse Momentum on the Determination of the W Boson Mass in Hadronic Collisions*, *Phys. Lett.* **B788** (2019) 542–545, [`arXiv:1807.0210`].

[8] G. Bozzi and A. Signori, *Nonperturbative Uncertainties on the Transverse Momentum Distribution of Electroweak Bosons and on the Determination of the Boson Mass at the LHC*, *Adv. High Energy Phys.* **2019** (2019) 2526897, [`arXiv:1901.0116`].

[9] J. C. Collins, D. E. Soper, and G. F. Sterman, *Transverse Momentum Distribution in Drell-Yan Pair and W and Z Boson Production*, *Nucl. Phys.* **B250** (1985) 199–224.

[10] J. Collins, *Foundations of Perturbative QCD.* Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology. Cambridge University Press, 2011.

[11] M. G. Echevarria, A. Idilbi, and I. Scimemi, *Factorization Theorem For Drell-Yan At Low q_T And Transverse Momentum Distributions On-The-Light-Cone*, *JHEP* **1207** (2012) 002, [arXiv:1111.4996].

[12] A. Bacchetta, F. Delcarro, C. Pisano, M. Radici, and A. Signori, *Extraction of partonic transverse momentum distributions from semi-inclusive deep-inelastic scattering, Drell-Yan and Z-boson production*, *JHEP* **06** (2017) 081, [arXiv:1703.1015].

[13] I. Scimemi and A. Vladimirov, *Analysis of vector boson production within TMD factorization*, *Eur. Phys. J.* **C78** (2018), no. 2 89, [arXiv:1706.0147].

[14] A. Signori, A. Bacchetta, M. Radici, and G. Schnell, *Investigations into the flavor dependence of partonic transverse momentum*, *JHEP* **1311** (2013) 194, [arXiv:1309.3507].

[15] A. Bacchetta, M. G. Echevarria, P. J. G. Mulders, M. Radici, and A. Signori, *Effects of TMD evolution and partonic flavor on e^+ e annihilation into hadrons*, *JHEP* **11** (2015) 076, [arXiv:1508.0040].

[16] G. Bozzi, S. Catani, G. Ferrera, D. de Florian, and M. Grazzini, *Transverse-momentum resummation: A Perturbative study of Z production at the Tevatron*, *Nucl. Phys.* **B815** (2009) 174–197, [arXiv:0812.2862].

[17] G. Bozzi, S. Catani, G. Ferrera, D. de Florian, and M. Grazzini, *Production of Drell-Yan lepton pairs in hadron collisions: Transverse-momentum resummation at next-to-next-to-leading logarithmic accuracy*, *Phys. Lett.* **B696** (2011) 207–213, [arXiv:1007.2351].

[18] C. M. Carloni Calame, G. Montagna, O. Nicrosini, and M. Treccani, *Higher order QED corrections to W boson mass determination at hadron colliders*, *Phys. Rev.* **D69** (2004) 037301, [hep-ph/0303102].

[19] S. Catani, D. de Florian, G. Ferrera, and M. Grazzini, *Vector boson production at hadron colliders: transverse-momentum resummation and leptonic decay*, *JHEP* **12** (2015) 047, [arXiv:1507.0693].

[20] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, *Parton distributions for the LHC*, *Eur. Phys. J.* **C63** (2009) 189–285, [arXiv:0901.0002].

[21] *Studies of theoretical uncertainties on the measurement of the mass of the W boson at the LHC*, Tech. Rep. ATL-PHYS-PUB-2014-015, CERN, Geneva, Oct, 2014.

[22] J. Dudek et al., *Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab*, *Eur. Phys. J.* **A48** (2012) 187, [arXiv:1208.1244].

[23] **COMPASS** Collaboration, F. Gautheron et al., *COMPASS-II Proposal*, Tech. Rep. SPSC-P-340, CERN-SPSC-2010-014, 2010.

[24] D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang, et al., *Gluons and the quark sea at high energies: Distributions, polarization, tomography*, arXiv:1108.1713.

[25] A. Accardi et al., *Electron Ion Collider: The Next QCD Frontier*, *Eur. Phys. J.* **A52** (2016), no. 9 268, [arXiv:1212.1701].