PROCEEDINGS OF SCIENCE

Vector boson modeling for precision physics

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W- and Z- boson production are among of the most precisely analyzed processes at the LHC, enabling applications that range from precision determinations of couplings to parton distribution functions to particle masses. Direct measurements are meanwhile only limited by luminosity uncertainties of about 1%. On the other hand, the required theory predictions are pushing the boundaries of theoretical methods, with a level of sophistication reached that is setting the stage for the HL-LHC's demand for higher multiplicity processes at a similar level. In these proceedings we briefly summarize recent progress in the theoretical modeling of W- and Z-bosons.

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Experimental measurements. W and Z boson production are among the most important processes in LHC physics and constitute standard candles with a wide range of applications. Measurements at the level of 1% or better for both Z production [1–5] and W production by ATLAS, CMS and LHCb [5–9] [10–14] [15–19] demand the development of theoretical predictions to an unprecedented level. In the future this will be needed at a much broader scope for other processes to ensure a successful HL-LHC program. Only recently has the precision reached been limited by the measurement of the LHC luminosity to about 1%, improving upon earlier levels of 2-3% [20, 21]. Apart from direct kinematic measurements, the possibilities through this precision are manyfold, demonstrated for example by precision W-mass measurements [22–25], charge asymmetries [14, 26–29], parton distribution functions (PDFs) [9, 30–33], as well as the strong coupling α_s [34–36].

Theory predictions. However, these highly complex collider analyses have a strong dependence on the theoretical predictions for background suppression and subtraction as well as the signal process. Without equally precise predictions the statistically precise measurements cannot be fully interpreted. We are currently in a situation where theory predictions are behind, limiting this ability, with many individual uncertainties contributing at the percent level. This requires increasing the precision of individual components like fixed-order expansions in QCD, QED and electroweak couplings, higher-order resummation, parton showers, non-perturbative effects in PDFs and TMDs, possibly including higher power terms in (collinear) factorization, understanding phenomenological modeling and tuning, and even decreasing numerical precision and computational resource requirements. With uncertainties contributing at the per mill to percent level in all of these components, only the combination allows for comprehensive predictions aiming to match experimental precision.

First N^{3}LO QCD (α_s^3) predictions for W and Z boson production were calculated at a fully inclusive level for total cross-sections [37, 38] and rapidity distributions [39]. These calculations revealed unexpectedly large corrections of about -2.5% due to cancellations between partonic initial-state channels, but did not take into account effects from N^{3}LO PDFs. The current state-of-the-art in N^{3}LO QCD is at a fiducial and fully differential level [40–46], typically including the effect of transverse-momentum (q_T) resummation at a similar level in α_s. Generally the residual QCD truncation uncertainties at the level of α_s^3 are estimated to be at the level of $1-2\%$ inclusively, and at small transverse momenta $q_T \lesssim m_V$ due to the higher-order q_T resummation. Note that both fixed-order and resummed calculations require N^{3}LO PDFs for a consistent α_s^3 precision. The formal logarithmic accuracy of N^{4}LL (α_s^3) in particular relies on the four-loop DGLAP evolution.

Higher-order transverse-momentum resummation up the level of N^{3}LL' matched to α_s^2 fixed order predictions has also been studied in refs. [47–49]. Recent studies of threshold resummation in rapidity distributions were presented in refs. [50–53]. Transverse-momentum resummation is also considered with a focus on TMD fits in the literature, see e.g. refs. [54–57]. Attention will have to be paid in disentangling perturbative and non-perturbative contributions [58].

Currently, all of these fully differential calculations at α_s^3 rely on the idea of q_T slicing subtractions [59]. They are made possible through calculations of the corresponding three-loop beam-functions [60–62], complete three-loop hard function [63–67] and the existence of a NNLO calculation of V+jet production [68–72].

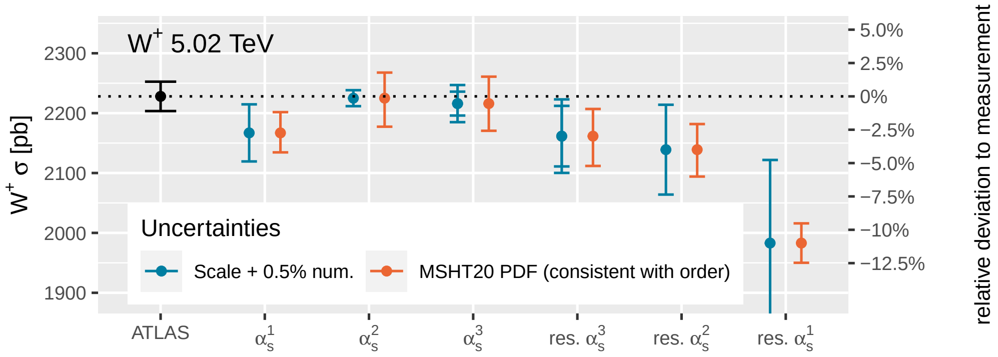

Figure 1: W^+ cross-sections at various perturbative orders in α_s, with and without q_T resummation, in comparison with the 5.02 TeV ATLAS measurement [5]. Error bars show uncertainties from scale variation and from the `MSHT20` PDF sets [86, 87] corresponding to the perturbative order. The α_s^3 results have an additional numerical and slicing cutoff uncertainty of 0.5% that was added linearly to the scale uncertainties for display. This figure is taken from ref. [41]

Recently there has been a shift from relying on fixed-order calculations for total fiducial cross-sections to resummed calculations. This is because convergence issues in the perturbative series due to fiducial cuts have been identified [73–75] that are resolved in resummation-improved perturbation theory without requiring modification of analysis cuts [74]. The difference between symmetric and product lepton cuts has been studied in ref. [43].

Apart from QCD effects, other Standard Model effects play a role at the level of 1% precision. Among these, mixed QCD⊗EW corrections were reported in refs. [76–78] for Z production and in refs. [79–83] for W production, and with an application to W-mass determinations in ref. [84]. QED-QCD transverse-momentum resummation has been considered in ref. [85]. Of particular importance are effects from PDFs, which currently dominate the uncertainty budget, see figs. 1, 2. They will require careful examination to resolve systematic issues and an extension towards N^{3}LO [86].

With W and Z-boson predictions entering crucially in W-mass analyses, there is a strong interest in how uncertainties propagate in W-mass analyses. A comprehensive review of how theoretical contributions and uncertainties impact the W-boson mass measurement was presented in ref. [88] (2016), while the impact of PDF [89] and higher-order [90] uncertainties have also been separately assessed more recently. An estimate for the impact of mixed QCD⊗EW corrections has since also been performed [84].

Due to the significance of this process and the complication of higher-order corrections, as well as the flexibility in approaches beyond fixed-order, it is important to compare different approaches, cross-check results, and allow for public and sustainable predictions [91, 92]. These aspects, especially public reproducibility, are increasingly important with very precise collider measurements that might indicate Standard Model tensions, see e.g. ref. [25].

Public codes for the calculation of W and Z production include RadISH+MATRIX at NNLO QCD

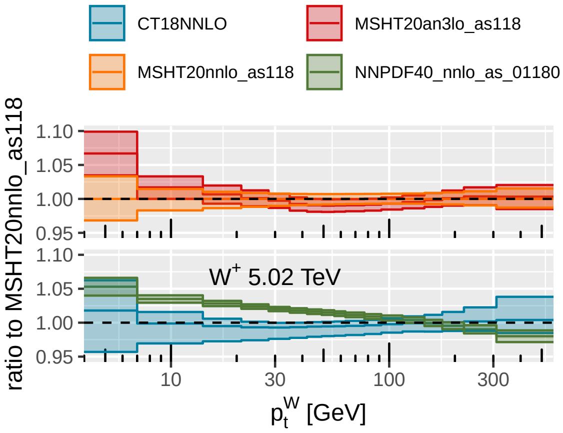

Figure 2: Relative PDF uncertainties of the W^+ transverse momentum distribution. Note that `MSHT20an3lo` includes uncertainties from missing higher orders, which are not included in the other sets. This figure is taken from ref. [41]

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including q_T resummtion and NLO EW [93–95], DYTurbo matching q_T-resummed predictions to NNLO QCD [45, 96, 97], CuTe-MCFM at N^{3}LO QCD including q_T resummation and NLO EW [40, 41, 98, 99], MiNNLO+PS+POWHEG NNLO QCD matched to parton shower [100], artemide [101] and Nanga Parbat [56] with resummed-only predictions focusing on transverse-momentum parton distribution functions, FEWZ [102, 103] at NNLO QCD using local subtractions, and Horace [104, 105] including NLO EW corrections with matching to QED parton shower. While fixed order NNLOjet predictions [69, 71] have been matched to RadISH resummation [106, 107] at the level of α_s^3, e.g. ref. [44], the code is not publicly available. Note that codes like DYTurbo can use NNLO V+jet results from MCFM [40, 41, 68, 70, 72] to also achieve full N^{3}LO accuracy.

Challenges and outlook. The experimental precision in W and Z-boson production demonstrates the LHC's capabilities for precision measurements, the success of modern data-analysis techniques, and showcases a level of precision that will be reached for a wider range of processes at the HL-LHC. Matching the precision in theoretical predictions is a future challenge, requiring not just higher perturbative orders in individual components and more precise non-perturbative inputs like PDFs, but the combination of a multitude of effects that contribute at the percent level. Overcoming these challenges will require an unprecedented community effort in novel developments and open collaboration. Ultimately this will ensure that we maximize the return on investment of the LHC in our goal of describing the fundamental laws on nature.

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