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Towards the W-boson mass measurement with the CMS experiment

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Summary. — The mass of the W-boson, m_W, is a fundamental parameter of the Standard Model of particle physics. Its value is correlated with other observables of the theory and any deviation from the expectation would provide a striking hint of the possible existence of new physics. The measurement of m_W represents an outstanding experimental challenge, requiring a deep understanding of both the detector and the theoretical uncertainties. In a proton-proton collider, such as the LHC, the uncertainty is dominated by the parton distribution functions (PDFs). This paper describes the potential and prospects of an ancillary measurement that is being carried out by the CMS Collaboration to constrain the PDF uncertainty on m_W, namely the W-boson rapidity distribution as a function of its helicity state.

1. – Introduction

The W boson is one of the fundamental particles of the Standard Model (SM) of particle physics. Within the electroweak theory, its mass (m_W) is subject to higher-order corrections induced by the masses of heavy particles in the SM, such as the top quark and the Higgs boson. New heavy particles predicted by many theories beyond the SM would have a non-negligible effect on m_W as well. Therefore, the precise measurement of m_W represents an extraordinary handle to test the internal consistency of the SM and probe the possible existence of new physics.

The current experimental world average is $m_W = 80385 \pm 15\,\text{MeV}$ [1], dominated by the direct measurements at the Tevatron collider [2]. A global electroweak fit to SM parameters yields an indirect estimate of $m_W = 80358 \pm 8\,\text{MeV}$ [3]. The precision of the direct measurement is twice lower than the one of the global fit: this occurrence has

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motivated the need for an additional independent measurement, possibly with higher precision. The ATLAS experiment at the CERN Large Hadron Collider (LHC) has recently measured $m_W = 80370 \pm 19\,\mathrm{MeV}$ [4]. The CMS experiment at the LHC [5] has hitherto performed feasibility studies [6].

The measurement of m_W is traditionally performed using a sample of $W \to \mu\nu$ and $W \to e\nu$ events, due to the clean experimental signature offered by the charged lepton. However, the production of the undetected neutrino prevents the direct computation of the W-boson invariant mass. Indeed, in a hadronic collider, the longitudinal component of the total momentum in the initial state is not known due to the parton distribution functions (PDFs) of the colliding hadrons, which determine the momentum fraction carried by the hadron constituents that actively participate in the hard scattering process. As a consequence, the kinematics can only be closed in the transverse plane, orthogonal to the beam axis, where the total momentum is zero and the momentum of the neutrino can be estimated from the missing transverse energy of the event.

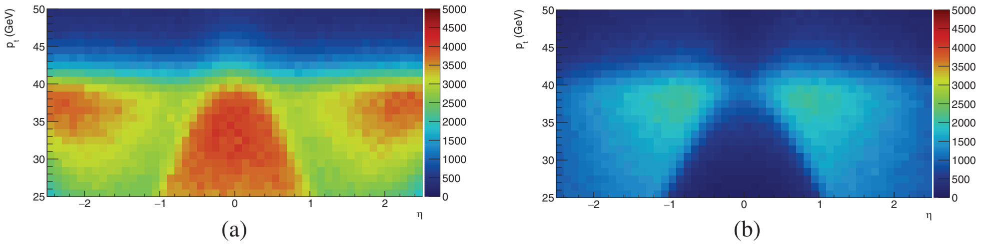
The m_W measurement is performed exploiting two observables defined in the transverse plane [2,4]: the charged lepton transverse momentum (p_T^l) and the W-boson transverse mass (m_T^W). They show a Jacobian peak at $m_W/2$ and m_W, respectively. For each observable, m_W is measured by comparing the measured distribution in data with several simulated templates for different mass hypotheses. For each template, a likelihood ratio is computed and the mass is evaluated as the value for which the distribution of the likelihood ratio reaches its minimum. This technique requires a deep understanding of both the performance of the detector and the theoretical uncertainties on the W-boson production and decay kinematics.

The dominant uncertainty on m_W at the LHC is the theoretical knowledge of the PDFs. Indeed, at tree level a W boson is produced from a quark-antiquark pair: at the Tevatron ($p\bar{p}$) the colliding partons are most often valence light quarks, while at the LHC (pp) the antiquark must originate from the sea and the contribution of heavy-flavour quarks is not negligible. The PDFs affect the W-boson rapidity (Y_W) and its transverse momentum (p_T^W), thus modifying the distribution of the observables. Reducing the PDF uncertainty on m_W (the ATLAS Collaboration quotes $9.2\,\mathrm{MeV}$ in [4]) is a key point to reach a precision of $10\,\mathrm{MeV}$ on m_W and probe the SM prediction. This goal can be achieved with *in situ* measurements of the W-boson properties, like its rapidity distribution.

2. – W-boson rapidity/helicity measurement

The method adopted by CMS to measure Y_W is based on the correlation of the W-boson production kinematics and the charged lepton in the decay, as described in [7]. The double-differential distribution of p_T^l and the lepton pseudorapidity (η^l) manifests characteristic patterns depending on the W-boson helicity state. This feature arises from the V-A coupling structure of the weak interactions, which correlates the spin of the W boson to the direction of motion of the lepton in the decay. Figure 1 shows the inclusive p_T^l *vs.* η^l distributions for the case of a W^+ with negative and positive helicity.

Fixing the W-boson helicity and rapidity, the lepton is emitted with $\eta^l = Y_W \pm \eta_0$, where the most probable value of η_0 is 0.5 and the sign depends on the W-boson charge and helicity. Therefore, one can split the simulated signal templates in fig. 1 into several bins of Y_W for each helicity state to obtain some characteristic p_T^l *vs.* η^l distributions. Eventually, Y_W is measured by fitting the measured p_T^l *vs.* η^l distribution in data with these signal templates and background processes as well. The fit extracts the cross



(a) (b)

Fig. 1. – Inclusive muon p_T^l *vs.* η^l distributions for a W^+ with negative helicity (a) and positive helicity (b), as obtained from Monte Carlo simulations (taken from [7]).

section of each signal component (one for each helicity state and Y_W bin), allowing to sample the Y_W distribution. The study presented in [7] demonstrates that this method can provide a measurement of Y_W with a lower uncertainty than the one that would be induced on Y_W by the PDFs. In other words, the framework can be recast into a fit of the PDFs, leading to a constraint of the associated uncertainty on m_W. Results in [7] are obtained using only generator-level information, neglecting the effect of backgrounds. CMS is expanding the analysis using full-simulation MC samples and comparing with data, featuring a careful estimation of backgrounds and other systematic uncertainties.

The Y_W measurement requires a dedicated tuning of the lepton reconstruction and identification efficiencies in simulations. Another key point is the accurate estimation of the main background induced by quantum chromodynamics (QCD) multi-jet processes. This background component originates primarily from the misidentification of hadrons as leptons or the production or real leptons from decays of heavy-flavour mesons. Simulations do not accurately reproduce the underlying processes, so the QCD background must be estimated from data. Other backgrounds consist of SM processes that produce real leptons such as Drell-Yan, $W \to \tau\nu$, diboson and top quark production, which are all fairly well described by simulations. Signal events are simulated at next-to-leading-order accuracy using `aMC@NLO` matched to `PYTHIA8`, with `NNPDF3.0` PDF set, while backgrounds are simulated using either `aMC@NLO` or leading-order MC such as `MADGRAPH`. The preliminary results of the CMS analysis already confirm that the target is being met.

3. – Prospects

The CMS experiment is currently working on the W-boson rapidity and helicity measurement using the dataset collected in 2016 at a center-of-mass energy of 13 TeV. Measuring Y_W is a preliminary step towards the m_W measurement and represents a fundamental ingredient to constrain the PDF uncertainty on m_W, which is expected to be the largest one. Moreover, Y_W is measured selecting events with low p_T^W, which is the relevant kinematic range for the m_W measurement: such measurement has never been performed so far at the LHC. The m_W measurement will also benefit from the ancillary direct measurement of the p_T^W distribution, which is quoted by ATLAS as the second largest source of uncertainty on m_W. This additional measurement will be carried out using a dedicated dataset collected by CMS in 2017 with special runs characterized by a low number of simultaneous proton-proton interactions, allowing for a better resolution on p_T^W.

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