Prospect for precision measurements of $\mathbf{M_{W^+} - M_{W^-}}$ & $\mathbf{M_W}$ at the LHC: Shortcuts revisited.

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The claim that the W boson mass might be measured at the LHC with a precision of $\mathcal{O}(10\,\mathrm{MeV})$ is critically reviewed. It is argued that such a precision cannot be achieved, unless a dedicated measurement program, specific to the LHC is pursued. We propose such a program. Its main target is to significantly improve the experimental control of the relative polarisation of the W^+, W^- and Z bosons. We propose to achieve this goal either by running dedicated isoscalar beams at the LHC or by running, in parallel to the standard pp collision program, a dedicated muon scattering "LHC-support-experiment" at the CERN SPS. One of these auxiliary measurements is necessary for the "precision measurement program" at the LHC, but not sufficient. It must be followed by dedicated measurement strategies which are robust with respect to both the systematic measurement uncertainties and to the perturbative and non-perturbative QCD effects. We propose such strategies and evaluate their precision. At the LHC, contrary to the Tevatron case, both the masses of the W^+ and of the W^- bosons must be measured with high precision. In this context, we propose and evaluate LHC dedicated strategies to measure the difference of the masses of the W^+ and W^- bosons and of the absolute mass of the W boson assuming both masses are equal. We show how one can overcome the obstacles in measuring the masses of W^+ and W^- to a precision of $10\,\mathrm{MeV}$. We present a detailed evaluation of the precision of the proposed methods based on the studies of a large, $\mathcal{O}(10^{11})$, sample of simulated W and Z production events.

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1. Introduction: the Tevatron results and the expectations for the LHC

In hadronic collisions, the properties of the W boson are extracted from its study in Drell–Yan like processes, *i.e.* $p\overset{(-)}{p} \to W + X \to l\,\nu_l + X$ with $l \equiv \{e, \mu\}$. The latest measurements of the mass of the W boson from the CDF and DØ experiments [1] are respectively $M_W = 80.413 \pm 0.048\,\text{GeV}$ and $M_W = 80.401 \pm 0.043\,\text{GeV}$. These precisions measurements are facilitated in $p\bar{p}$ collisions because the dynamics producing the W^+ and W^- bosons differ only by a *CP* transformation. This leads eventually to a perfect charge symmetry in the transverse kinematics of the leptons which are used in the extraction procedure of M_W. A perfect illustration of the benefits gained over this symmetry is shown when both charged states are considered separately, *i.e.* for the measurement of $M_{W^+} - M_{W^-}$. In this context, the last CDF result is $M_{W^+} - M_{W^-} \approx 0.26 \pm 0.15\,\text{GeV}$ [1].

Soon, the LHC should provide such important W boson data that physicists will be left with the task to reduce the Systematic Errors (SE) coming from the uncertainties of both phenomenological and apparatus models. Both ATLAS and CMS collaborations expect to control these two aspects well enough to measure M_W with a precision of $\mathcal{O}(10\,\text{MeV})$ [2] for an integrated luminosity of $L = 10\,\text{fb}^{-1}$. Nonetheless, the prospects that lead to such values did not explore the consequences of the LHC original context: in pp collisions, there is no *CP* symmetry between the dynamics of production of the W^+ and W^- bosons. Aware of this, we propose a program to measure the W boson mass charge asymmetry $M_{W^+} - M_{W^-}$ [3] and absolute mass M_W [4] through the study of the transverse momenta of the charged leptons l^+ and l^-.

In the rest, we briefly justify why, in our view, both $M_{W^+} - M_{W^-}$ and M_W measurements must be considered at the LHC for a relevant precision measurement of M_W. After that, we present a re-evaluation of the size of the main SE along with possible solutions to decrease them using, each time, dedicated systematic-robust strategies and observables. Below, the charge asymmetry of an observable x is defined as: $\text{Asym}^{(+,-)}(x) \equiv (d\sigma/dx_{l^+} - d\sigma/dx_{l^-})/(d\sigma/dx_{l^+} + d\sigma/dx_{l^-})$. Details of our work can be found in our published papers and, more exhaustively, in the Ph.D. dissertations of Florent Fayette [3] and Andrzej Siódmok [4].

2. Production of W^+ and W^- bosons at the LHC in Drell–Yan like processes

Here, like in our presentation [5], we review at the generator level and for both $p\bar{p}$ and pp collisions the behaviour of the most important kinematics entering in the extraction process of M_W.

At the level of the production, we focus on the transverse momenta distributions $p_{T,W}$ of the W^+ and W^- bosons. For $p\bar{p}$ collisions they are exactly the same, while for pp collisions charge asymmetries are observed. Because the W boson transverse motion has an important influence over the leptons transverse motion it appears vital for it to be well under control. For the W bosons leptonic decay, we study the charged leptons transverse momenta $p_{T,l}$. Again, for $p\bar{p}$ collisions there are no charge asymmetries at this theoretical level, while for pp collisions the charge asymmetries are larger than the one seen in the production. In a nutshell, these LHC-specific final state charge asymmetries result from the combination of the following effects: (1) the excess, through the valence quarks, of matter over anti-matter, (2) the transverse motion of the colliding quarks (hence of the W) and eventually (3) the $V - A$ coupling of fermions in electroweak interactions that magnifies the QCD initial state asymmetries from the items (1) and (2).

This loss of symmetry, with respect to the Tevatron, will open the door to large contributions to the error on M_W, in particular due to all the uncertainties tainting QCD. Then, two solutions are possible: (1) W^+ and W^- will have to be treated as distinct particles or (2), assuming $M_{W^+} = M_{W^-}$, the W mass can still be extracted by considering both charged lepton data in the analysis, *i.e.* $M_W = \frac{1}{2}(M_{W^+} + M_{W^-})$, but, parallel to that, it becomes mandatory to consider a precision measurement of $M_{W^+} - M_{W^-}$ as well. This second solution is the one we choose.

3. Expected systematic errors and strategies to reduce them

As a consequence of the previous development, we addressed, on top of the usual sources of SE, new ones specific to the LHC original context. For the apparatus we studied the impact from the miscalibration of the charged leptons absolute and relative Energy Scale (ES) and track parameters resolution. For the phenomenology, we considered the impact from the global uncertainties in the Parton Distributions Functions (PDFs) and from the parametrisation of the intrinsic transverse momenta of the partons k_T. In addition, we considered also new sources of SE coming from the uncertainties of specific sectors of the PDFs: (1) the $u^{(v)} - d^{(v)}$ valence (v) asymmetry, (2) the $s - c$ asymmetry and (3) the b flavour (for M_W only). In the rest, like in our talk [5], we focus on the ES, $u^{(v)} - d^{(v)}$ and $s - c$ asymmetries and choose only a few values to illustrate our discussion.

The study is realised by simulating with WINHAC and ZINHAC Monte Carlo [6] the expected statistic of $W \to e\,\nu_e$, $\mu\,\nu_\mu$ and $Z \to e^+e^-$, $\mu^+\mu^-$ events, for $L = 10\,\mathrm{fb}^{-1}$, with $\sqrt{s} = 14\,\mathrm{TeV}$ and by smearing these Monte Carlo events with the ATLAS tracker resolution. Cuts are performed upon the charged leptons transverse momenta and pseudo-rapidity distributions, respectively: $p_{T,l} > 20\,\mathrm{GeV}$ and $|\eta_l| < 2.5$. The W boson properties, and the impact of the biases upon them, are extracted by performing binned maximum likelihood fits to $p_{T,l}$-based observables.

Our first estimations of the size of the SE are obtained using the $\mathrm{Asym}^{(+,-)}(p_{T,l})$ observable for the extraction of $M_{W^+} - M_{W^-}$ and the ratio of W over Z events for the one of M_W. Considering errors of 0.5 % for the ES, we end up with SE on $M_{W^+} - M_{W^-}$ of $-550\,\mathrm{MeV}$ for charged-incoherent biases, and on M_W of $200\,\mathrm{MeV}$ for charged-coherent biases. For the $u^{(v)} - d^{(v)}$ and $s - c$ asymmetries we consider errors that would unlikely affect the Z rapidity distribution. Thus, in the valence sector, imposing $u^{(v)}_{\max} = 1.05\,u^{(v)}$ and $d^{(v)}_{\min} = d^{(v)} - 0.05\,u^{(v)}$ we observe SE of $130\,\mathrm{MeV}$ ($80\,\mathrm{MeV}$) for $M_{W^+} - M_{W^-}$ (M_W). For the $s - c$ sector, with $c_{\max} = 1.1\,c$ and $s_{\min} = s - 0.1\,c$ we observe SE of $-15\,\mathrm{MeV}$ ($-100\,\mathrm{MeV}$) for $M_{W^+} - M_{W^-}$ (M_W).

For the $M_{W^+} - M_{W^-}$ measurement, the errors from the absolute ES miscalibration could be reduced to $5\,\mathrm{MeV}$ by collecting half of the data with an inverted magnetic field in the tracker, so that both positive and negative tracks would be affected by the same biases. For PDFs, the influence of the valence quarks can be reduced by restraining the analysed data to a narrow-central bin in the W rapidity or, more realistic but less efficient, to the charged lepton pseudo-rapidity. These prescriptions shows visible reduction on the size of the errors but, the $u^{(v)} - d^{(v)}$ uncertainty still contribute to the SE with $70\,\mathrm{MeV}$. A perfect way to reduce greatly all those unknowns from the valence sector would be to collide isoscalar beams which, in our study, for deuterium beams, decreased the error to $4\,\mathrm{MeV}$. Still, some procedures invoked here are delicate and, if applicable, could be envisaged only in a more mature phase of the LHC program. For that matter, alternative strategies with softer constraints on the LHC and its detectors will be mentioned at the end.

For the M_W measurement, the first improvement in the analysis is to enhance the QCD resemblance between the W and the Z data. In an earlier work [4], we proposed to trick the W bosons to be produced by partons with the same Bjorken x as the one producing Z bosons. For that matter, a reduction of the nominal $\sqrt{s}$ by a factor $\frac{M_W}{M_Z}$ could be done when it would come to collect W data. In addition, a scaling of the magnetic field by a factor $\frac{M_W}{M_Z}$ would allow the charged leptons tracks from the W to suffer from the same biases that affect the leptons tracks from the Z bosons, and reduce potentially the impact of the relative ES miscalibration to 5 MeV. In a next step, to account for the fact that $M_W \neq M_Z$, a QCD correction factor was implemented and, although it lead to a reduction from the influence of k_T, it proved insufficient for the PDFs uncertainties.

To sum up, when the LHC data will be available we might face brick walls for a real enhancement of the precision on M_W due to two main difficulties: (1) the calibration of the relative ES and (2) the uncertainties in specific sectors of the PDFs. If we cannot free ourselves from these effects, we are left with the task to control them. First, for the relative ES calibration, the W^+ and W^- data, being no longer suitable, could be substituted by the "Z^+" and "Z^-" data defined respectively as the positively and negatively charged leptons from the Z boson decay. Eventually a precision could be met to have impacts of 10 MeV for the errors on $M_{W^+} - M_{W^-}$ and M_W. Second, for the PDFs, a dedicated muon deep inelastic scattering experiment at the SPS collider [7] could be used to decrease the uncertainties from these specific sectors that influence our measurements. If the uncertainty on the $u^{(v)}/d^{(v)}$ ratio can reach 1%, then the impact would be of 25 MeV (12 MeV) for $M_{W^+} - M_{W^-}$ (M_W). Finally, if the $s - c$ asymmetry is controlled for $M_{W^+} - M_{W^-}$ (M_W) at 2% (1%), the impact would be of 5 MeV (10 MeV).

4. Conclusion

Contrary to the earlier estimates, we conclude that one cannot reach a precision of $\mathcal{O}(10\,\text{MeV})$ for the measurement of the W mass at the LHC unless a dedicated measurement program *e.g.* the one proposed in this contribution is pursued.

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