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Measurement of the W boson mass at the LHC

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Abstract. We explore the ability of the Large Hadron Collider to measure the mass of the W boson. We believe that a precision better than ~ 15 MeV could be attained, based on a year of operation at low luminosity ($10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$). If this is true, this measurement will be the world's best determination of the W mass.

1 Introduction

The mass of the W boson, m_W, is one of the fundamental parameters of the Standard Model. As is well known [1], a precise measurement of m_W, along with other precision electroweak measurements, will lead, within the Standard Model, to a strong indirect constraint on the mass of the Higgs boson. Once the Higgs itself is found, this will provide a consistency test of the Standard Model and, perhaps, evidence for physics beyond. The precise measurement of m_W is therefore a priority of future colliders. LEP2 and Run II at Fermilab ($\int \mathcal{L}dt = 1\ \mathrm{fb}^{-1}$) are aiming for an uncertainty on m_W of about 40 MeV [2] and 35 MeV [3], respectively. An upgrade of the Tevatron [4], beyond Run II, might be possible, with a goal of an overall integrated luminosity of $\mathcal{O}(30\mathrm{fb}^{-1})$ and a precision on m_W of about 15 MeV. Clearly, hadron colliders have had and will continue to have a significant impact on the measurement of m_W. In this short paper [5] we investigate the potential to measure m_W at the Large Hadron Collider (LHC). The LHC will provide an extremely copious source of W bosons, thus allowing in principle for a statistically very precise measurement.

In Sect. 2 we consider the detector capabilities, in Sect. 3 the theoretical uncertainties, and in Sect. 4 the experimental uncertainties. We present our conclusions in Sect. 5.

2 Detector capabilities

A potential problem is that the general-purpose LHC detectors might not be able to trigger on leptons with sufficiently low transverse momentum (p_T) to record the W sample needed for a measurement of m_W. While this may be true at the full LHC luminosity ($10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) it does not appear to be the case at $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Based on a full GEANT simulation of the calorimeter, the CMS isolated electron/photon trigger [6] should provide an acceptable rate (< 5 kHz at level 1) for a threshold setting of $p_T^{e,\gamma} > 15$ GeV/c. This trigger will be fully efficient for electrons with $p_T^e > 20$ GeV/c. The CMS muon trigger [7] should also operate acceptably with a threshold of $p_T^\mu > 15 - 20$ GeV/c at $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. ATLAS should have similar capabilities. It is likely that the accelerator will operate for at least a year at this 'low' luminosity to allow for studies which require heavy quark tagging (e.g., B-physics). This should provide an integrated luminosity of the order of $10 fb^{-1}$.

The mean number of interactions per crossing, I_C, is about 2 at the low luminosity. This is actually lower than the number of interactions per crossing during the most recent run (IB) at the Fermilab Tevatron. In this relatively quiet environment it should be straightforward to reconstruct electron and muon tracks with good efficiency. Furthermore, both the ATLAS [8] and CMS [9] detectors offer advances over their counterparts at the Tevatron for lepton identification and measurement: they have precision electromagnetic calorimetry (liquid argon and $PbWO_4$ crystals, respectively) and precision muon measurement (air core toroids and high field solenoid, respectively).

The missing transverse energy will also be well measured thanks to the small number of interactions per crossing and the large pseudorapidity coverage ($|\eta| < 5$) of the hadronic calorimeters. The so-far standard transverse-mass technique for determining m_W should thus continue to be applicable. This is to be contrasted with the problem that the increase in I_C will create for Run II (and beyond) at the Tevatron. In [3], it was shown that it will substantially degrade the measurement of the missing transverse energy and therefore the measurement of m_W.

3 Theoretical uncertainties

Large theoretical uncertainties arising from substantial QCD corrections to W production at the LHC energy could deteriorate the possible measurement of M_W. In Fig. 3a, we present the leading order (LO) calculation and

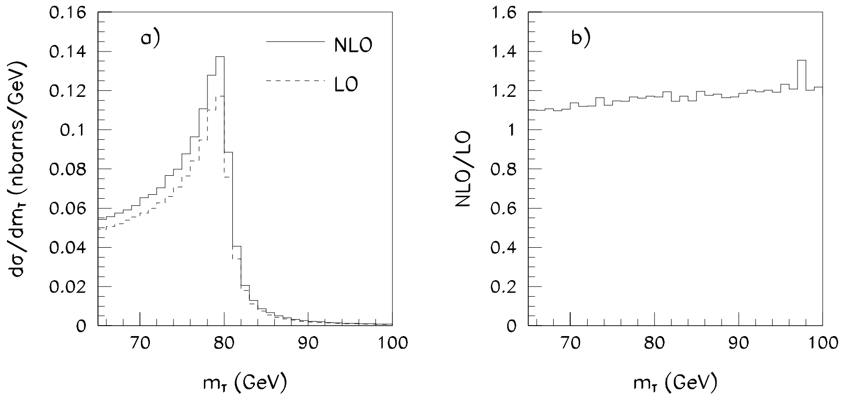

Fig. 1. **a** LO calculation (dashed line) and NLO QCD calculation (solid line) of the m_T distribution at the LHC. See text for the cuts, **b** Ratio of the NLO calculation over the LO calculation as a function of m_T

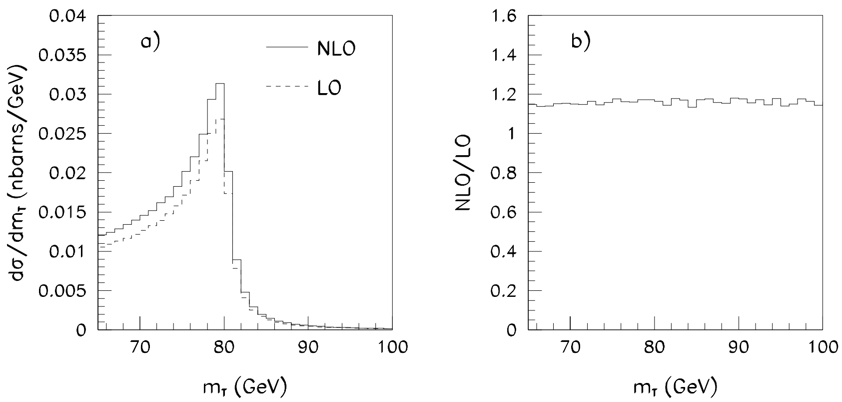

Fig. 2. Same as in Fig. 1 but for the Tevatron

next-to-leading order (NLO) QCD calculation [10] of the transverse mass distribution (m_T) at the LHC (14 TeV, pp collider) in the region of interest for the extraction of the mass. We used the MRSA [11] set of parton distribution functions, and imposed a charged lepton (electron or muon) rapidity cut of 1.2, as well as a charged lepton p_T and missing transverse energy cut of 20 GeV. We used m_W for the factorization and renormalization scales. No smearing effects due to the detector were included in our calculation. The uncertainty due to the QCD corrections can be gauged by considering the ratio of the NLO calculation over the LO calculation. This ratio is presented in Fig. 3b as a function of m_T. As can be seen, the corrections are not large and vary between 10% and 20%. For the extraction of m_W from the data, the important consideration is the change in the shape of the m_T-distribution. As can be seen from Fig. 3b, the corrections to the shape of the m_T-distribution are at the 10% level. Note that an increase in the charged lepton p_T cut has the effect of increasing the size of the shape change (it basically increases the slope of the NLO over LO ratio), such that for the theoretical uncertainty is is better to keep that cut as low as possible. For comparison, in Fig. 2 we present the same distributions as in Fig. 3 for the Tevatron energy (1.8 TeV, $p\bar{p}$ collider). The same cuts as for the LHC were applied. As can be seen the corrections are of the order of 20% and change the shape very little.

Currently, the estimated uncertainty on m_W associated with modelling the transverse momentum distribution of the W (*i.e.* due to QCD corrections) is of the order of 10 MeV at the Tevatron [12]. On the one hand, the larger QCD corrections at the LHC suggest that the uncertainty will also be larger. On the other hand, the p_T distribution of the W can be constrained by data (both W and Z) and the significant increase in statistics available, first at the upgraded Tevatron and then at the LHC, should keep the uncertainty under control. Note also that even though the shape change due to QCD corrections is undoubtedly larger at the LHC than at the Tevatron, in absolute terms it is still small and a next-to-next-to leading order calculation might be able to reduce the theoretical uncertainty to an acceptable level. Although such a calculation does not yet exist for the m_T-distribution, one may certainly imagine that it will be before any data become available at the LHC.

An alternative would be to use an observable with yet smaller QCD corrections. Recently [13], it was pointed out that the ratio of W to Z observables (properly scaled by the respective masses) are subject to smaller QCD corrections than the observables themselves. This is illustrated in Fig. 3 for the transverse mass. In Fig. 3a the ratio of NLO/LO calculations for the distribution of events as a function of the mass-scaled transverse mass X is presented; $X = m_T^W/m_W$ for the W and m_T^Z/m_Z for the Z. The cuts for the W case are as described before. The Z is required to have one lepton with $\eta < 1.2$ and the p_T cuts are scaled proportionally to the mass compared to the p_T cut in the W case[1]. Fig. 3b shows the factor NLO/LO

[1] This is done to avoid large corrections to the ratio of W to Z observables close to the cut

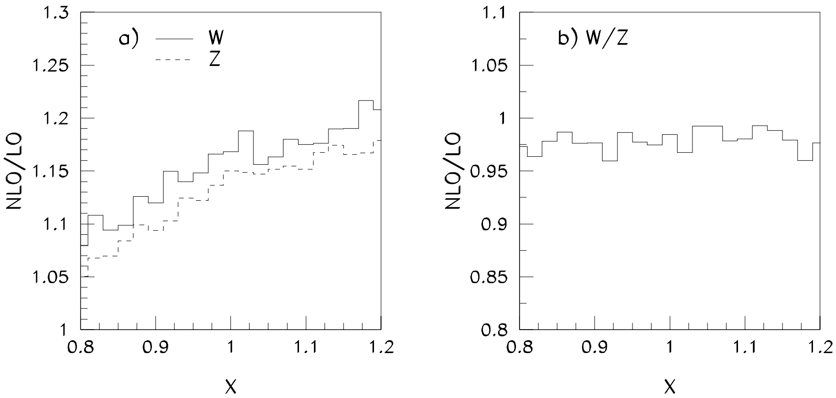

Fig. 3. **a** Ratio of NLO/LO calculations for the distribution of events as a function of the mass-scaled transverse mass X at the LHC energy. See text for the cuts. **b** NLO/LO for the quantity defined as the ratio of the number of W events to the number of Z events at a given X

for the quantity defined as the ratio of the number of W events to the number of Z events at a given X. As can be seen the NLO corrections to this quantity are much less dependent on X than the distribution themselves. Indeed, the corrections are similar for the W and Z mass-scaled distributions and therefore cancel in the ratio. This ratio could then be used to measure the W mass, with small theoretical uncertainty. Note that the measured mass and width of the Z are already used to calibrate the detectors [14] in current analysis [12]. Compared to the standard transverse-mass method, the ratio method will have a larger statistical uncertainty because it depends on the Z statistics, but a smaller systematic uncertainty because of the use of the ratio. This concept has now been verified in an experimental analysis [15]. Overall this ratio method might therefore be competitive if the systematic uncertainty dominates the overall uncertainty on m_W in the transverse-mass method. It is beyond the scope of this paper to study the sytematic uncertainties in detail; in what follows we shall benchmark these uncertainties using the demonstated CDF and D0 performance. The ratio method can also be used with other distributions, like the p_T-distribution of the charged lepton itself, see [13].

It is interesting to note that the average Bjorken-x of the partons producing the W at LHC with the cuts considered in this paper is $\sim 10^{-2}$, compared to $\sim 10^{-1}$ at the Tevatron. Without the rapidity cut, the range of x probed at the LHC is much larger, going from below 10^{-3} to above 10^{-1}. The uncertainty due to the parton distributions will thus be different at the LHC and Tevatron. Considering that this uncertainty might dominate in this very high precision measurement, complementary measurements at the Tevatron and LHC would be very valuable. It is not possible to quantify this statement considering the present status of PDF uncertainties [16].

At this time, it is obviously impossible to predict the overall theoretical uncertainty at the LHC. The present uncertainty of $\sim$ 30 MeV from the W production model [12] would already limit the precision of the mass measurement attainable in Run II at the Tevatron, so there is obviously great motivation to reduce such uncertainties. Part of our goal in writing this paper is to emphasize that such motivation also exists for the LHC, by demonstrating its potential for an extremely precise W mass measurement. In the rest of this paper we shall assume that the theoretical uncertainty at the LHC will be decreased to a value lower than the experimental uncertainty.

4 Experimental uncertainties

The single W production cross section at the LHC, for charged lepton $p_T > 20$ GeV/c and pseudorapidity $|\eta| < 1.2$, and transverse mass $65GeV \leq m_T \leq 100GeV$, is about 4 times larger than at the Tevatron with the same cuts[2]. Scaling from the latest high-statistics W mass measurement at D0 [12], where 2.8×10^4 $W \to e$ events were taken from an integrated luminosity of 82 pb^{-1}, we then expect at the LHC $\sim 1.5{\times}10^7$ reconstructed $W \to e$ events in one year at low luminosity (for $10 fb^{-1}$). Figure 4 shows that if the lepton rapidity coverage at the LHC were increased above the ± 1.2 assumed here, a large gain in signal statistics would be obtained, since the rapidity distribution is rather broad at the LHC energy. The configuration for which one Bjorken-x is very large and the other one very small is favored and creates the maxima at $|\eta| \sim 2.5$. The gain would be of order two if leptons were accepted out to $|\eta| < 2.5$, which is covered by the electromagnetic calorimetry of the ATLAS [8] and CMS [9] experiments, and as high as a factor of four for $|\eta| < 5$ which may be covered by other experiments [17].

As already noted, it is not straightforward to estimate the precision with which m_W can be determined because of the importance of systematic effects; even a full GEANT simulation of a detector is unlikely to include all of them. We have therefore based our estimate on a parametrization of the actual CDF and D0 m_W uncertainties developed in [3] in order to extrapolate to higher luminosity. The parametrization includes the effect of the number of interactions per crossing, I_C (which degrades the missing E_T resolution), and of those systematic effects which can be controlled using other data samples (such as Z bosons, J/ψ mesons, etc.) and which will therefore scale like $1/\sqrt{N}$. This behavior appears valid for the most important systematic uncertainties in the present measurement, such as the energy scale determination, underlying

[2] limiting the W transverse momentum to be less than 15 or 30 GeV does not significantly change this result

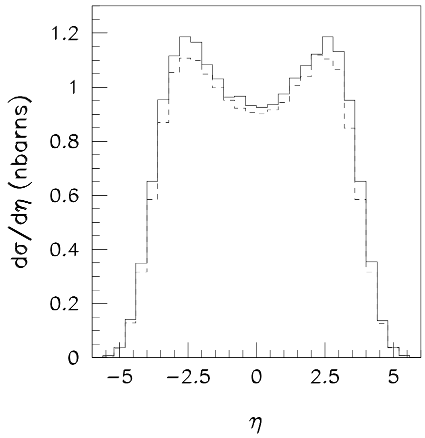

Fig. 4. Rapidity distribution of the charged lepton from single W production at the LHC. The histogram is for the NLO calculation and the dashed line for the LO. See text for the cuts

event effects, and the p_T distribution of the W. The use of these parametrizations, of course, explicitly does not take into account any of the detector improvements offered by the LHC detectors over their Tevatron counterparts which were described earlier.

The parametrized statistical and systematic uncertainties on m_W are given by:

$$\Delta m_W|_{stat} = 12.1\,\mathrm{GeV}\sqrt{\frac{I_C}{N}} \sim 4.4\,\mathrm{MeV}$$
$$\Delta m_W|_{sys} = 17.9\,\mathrm{GeV}\sqrt{\frac{I_C}{N}} \sim 6.5\,\mathrm{MeV} \qquad (1)$$

where N is the total number of events. Taken at face value these would suggest that $\Delta m_W \sim 8$ MeV could be reached. However, these parametrizations do not account for effects which do not scale as $1/\sqrt{N}$. Such systematic effects, which are not yet important in present data, will probably limit the attainable precision at the LHC. There is however an opportunity to measure the W mass to a precision of better than $\Delta m_W \sim 15$ MeV at the LHC.

It is worth noting that, while we have assumed that only one year of operation at low luminosity is required to collect the dataset, considerably longer would undoubtedly be required after the data are collected in order to understand the detector at the level needed to make such a precise measurement.

5 Conclusions

In conclusion, we see no serious problem with making a precise measurement of m_W at the LHC if the accelerator is operated at low luminosity ($10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) for at least a year. The cross section is large, triggering is possible, lepton identification and measurement straightforward, and the missing transverse energy should be well determined. The QCD corrections to the transverse mass distribution although larger than at the Tevatron, still appear reasonable. A precision better than $\Delta m_W \sim 15$ MeV could be reached, making this measurement the world's best determination of the W mass. We feel that it is well worth investigating this opportunity in more detail.

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