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MEASURING THE MASS OF THE W AT THE LHC ¹

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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 ($10^{33} \text{ cm}^{-2} \text{ s}^{-1}$). If this is true, this measurement will be the world's best determination of the W mass. We feel this interesting opportunity warrants investigation in more detail.

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Measuring the mass of the W 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} cm⁻² s⁻¹). If this is true, this measurement will be the world's best determination of the W mass. We feel this interesting opportunity warrants investigation in more detail.

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. The precise measurement of m_W is therefore a priority of future colliders. LEP2 and Run II at Fermilab ($\int \mathcal{L} dt = 1$ fb⁻¹) are aiming for an uncertainty on m_W of about 40 MeV [2] and 35 MeV [3], respectively. A recent study [4] has shown that an upgrade of the Tevatron, beyond Run II, might be possible, with a goal of an overall integrated luminosity of $\mathcal{O}(30\text{fb}^{-1})$ and a precision on m_W of about 15 MeV. In this short contribution we take a very first look at the potential to measure m_W at the Large Hadron Collider (LHC).

It has often been claimed that LHC detectors will not be able to trigger on lepton 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} cm⁻² s⁻¹) it does not appear to be the case at 10^{33} cm⁻² s⁻¹. Based on a full GEANT simulation of the calorimeter, the CMS isolated electron/photon trigger [5] 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 [6] should also operate acceptably with a threshold of $p_T^\mu > 15 - 20$ GeV/c at 10^{33} cm⁻² s⁻¹. 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 10fb^{-1} and therefore an ample dataset for a measurement of m_W .

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 and CMS de-

tectors offer advances over their counterparts at the Tevatron for lepton identification and measurement: they have precision electromagnetic calorimetry (liquid argon and PbWO₄ 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 detectors. 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 at the Tevatron. In Ref. [3], it was shown that it will substantially degrade the measurement of the missing transverse energy and therefore the measurement of m_W .

It has also been asserted that there are large theoretical uncertainties arising from substantial QCD corrections to W production at the LHC energy. In Fig. 1a., we present the leading order (LO) calculation and next-to-leading order (NLO) QCD calculation [8] 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 [7] 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 detector effects 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. 1b. 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. 1b, 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 better to keep that cut as low as possible. For comparison, in Fig. 2 we present the same distributions as in Fig. 1 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. Although the shape change due to QCD corrections is undoubtedly larger at the LHC than at the Tevatron, this does not appear to be a serious problem considering the size of the corrections. A next-to-next-to leading order or eventually an appropriate resummed calculation should be able to bring the theoretical uncertainty down to an acceptable level. Although the next-to-next-to-leading order calculation doesn't yet exist for the m_T -distribution, one may certainly imagine that it will be done before any data become available at the

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smaller QCD corrections. Recently [9], it was pointed out that the ratio of W over Z observables (properly normalized with the mass) are subject to smaller QCD corrections than the observables themselves. Indeed, the corrections are similar for the W and Z observables and therefore cancel in the ratio. The ratio of the transverse mass could be used to measure the mass, with small theoretical uncertainty. Compared to the standard transverse-mass method, this 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. Overall this ratio method might therefore be competitive.

It is interesting to note that the average Bjorken- x of the partons producing the W at LHC is $\sim 6 \times 10^{-3}$ ($\sim m_W/\text{energy}$ of the collider), compared to $\sim 4 \times 10^{-2}$ at the Tevatron. The uncertainty due to the parton distributions will thus be different at the LHC and Tevatron as different region of Bjorken- x are probed. Considering that the uncertainty due to the parton distribution functions might dominate in this very high precision measurement, complementary measurements at the Tevatron and LHC would be very valuable.

The production cross section at the LHC, with the cuts already mentioned and $65\text{GeV} \leq m_T \leq 100\text{GeV}$, is about 4 times larger than at the Tevatron. Scaling from the 9×10^3 W events measured at the Tevatron with an integrated luminosity of 20pb^{-1} [10] (one detector), we then expect at the LHC $\sim 1.8 \times 10^7$ reconstructed W events in one year at low luminosity (for 10fb^{-1}). (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.)

As a first estimate of the precision with which m_W can be determined we have simply taken the formula which were developed by the TeV2000 study [3] to include the effect of I_C :

$$\begin{aligned} \Delta m_W|_{stat} &= 12.1 \text{ GeV} \sqrt{\frac{I_C}{N}} \sim 4 \text{ MeV} \\ \Delta m_W|_{sys} &= 17.9 \text{ GeV} \sqrt{\frac{I_C}{N}} \sim 6 \text{ MeV} \end{aligned} \quad (1)$$

where N is the total number of events. Taken at face value these would suggest that $\Delta m_W \sim 7 \text{ MeV}$ could be reached. Systematic effects which are not yet important in present data could limit the attainable precision; but we feel that it should be possible to measure the W mass to a precision of better than $\Delta m_W \sim 15 \text{ MeV}$ 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.

In conclusion, while this is a very first study of this question, we see no serious problem with making a precise measurement of m_W at the LHC if the accelerator is operated at low luminosity ($10^{33} \text{ cm}^{-2} \text{ s}^{-1}$) 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

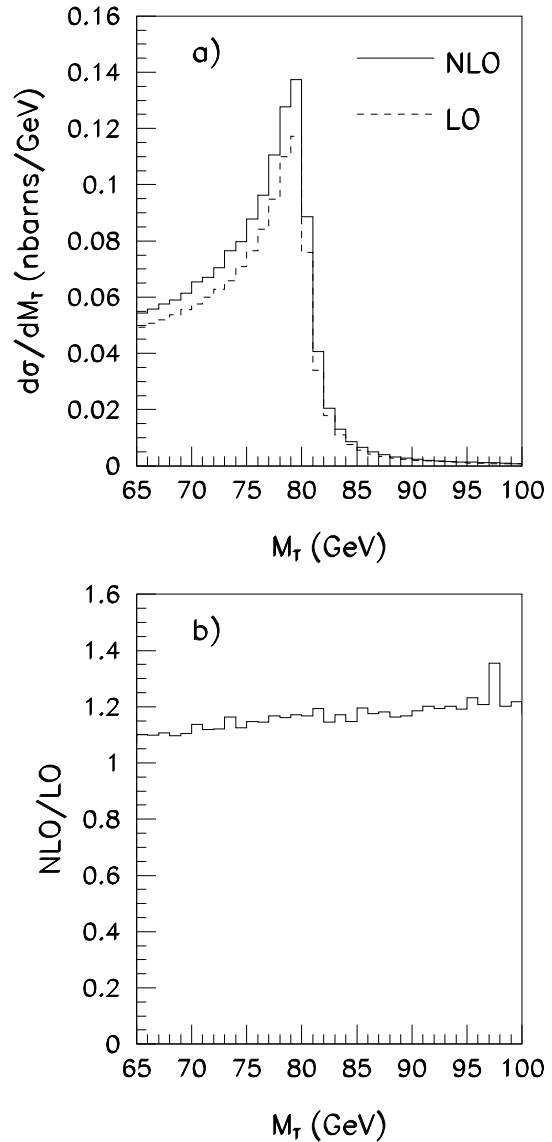


Figure 1: a) LO calculation (dashed line) and NLO QCD calculation (solid line) of the m_T distribution at the LHC. See text for the cuts. b) ratio of the NLO calculation over the LO calculation as a function of m_T .

transverse mass distribution although larger than at the Tevatron, still appear reasonable. We imagine that a precision better than $\Delta m_W \sim 15 \text{ MeV}$ 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 details.

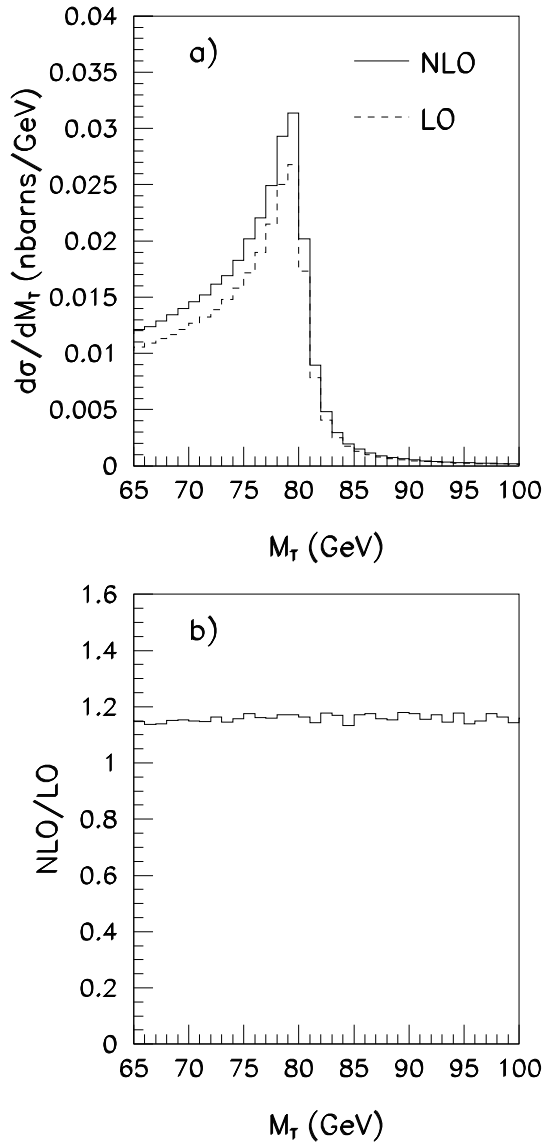


Figure 2: Same as in Fig. 1 but for the Tevatron.

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