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W Boson Mass Working Group Report

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W Boson Mass Working Group Report

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II. INTRODUCTION

The W boson mass working group discussed the current status of the W boson mass measurement and the prospects for improving on LEP and Tevatron measurements at the LHC. The W boson mass is a very important parameter in the Standard Model. In the absence of radiative corrections, it is related to the mass of the Z boson by the relative coupling strengths of the $SU(2)_L$ and $U(1)_Y$ gauge interactions that mix under spontaneous symmetry breaking to form the photon and the massive weak bosons,

$$\frac{M_W}{M_Z} = \frac{g}{\sqrt{g^2+g'^2}}. \tag{1}$$

Of course, radiative corrections break this simple relation, but lead to a more complicated relation involving the masses of the Standard Model particles as well as the masses of any Beyond-the-Standard-Model particles that carry electroweak charge. The most important radiative corrections within the standard model involve the top quark, which are enhanced because of its large mass splitting with the b quark.

The Higgs boson mass is the most important unknown parameter involved, although the radiative corrections are only logarithmically dependent on its value. Nonetheless, measurements of the masses of the top quark and W boson constrain the mass of a Standard Model Higgs boson as

shown in Figure 1.

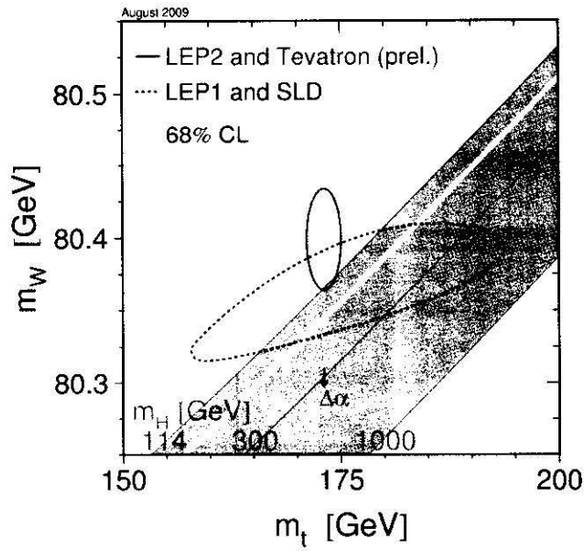

FIG. 1: Mass Constraint on a Standard Model Higgs boson from M_W and M_t.

At hadron colliders, the W boson mass is determined by making precise measurements of the observables of the leptonic (e or μ) decay modes, p_T^ℓ, p_T^ν, m_T^W, the transverse momentum of the charged lepton, the transverse momentum of the unobserved neutrino, and the transverse mass of the W boson respectively. The transverse momentum of the charged lepton is measured through a combination of tracking and calorimetry, the transverse momentum of the neutrino is inferred from the missing transverse momentum needed to balance the event and the transverse mass is built computed as $M_T^W = \sqrt{2 p_T^\ell p_T^\nu (1 - \cos\phi_{\ell\nu})}$.

The charged lepton spectrum is of course the best measured distribution, but it is subject to significant radiative corrections. The transverse mass is theoretically more stable, but relies upon the inferred values of p_T^ν and $\phi_{\ell\nu}$. The standard technique for determining the W boson mass at the Tevatron experiments is to measure the desired distributions for the Z boson, fit these measurements to the best available theoretical calculation, and then form templates at narrowly spaced mass intervals, of the expected shapes of the W boson distributions. The best-fitting template determines the W boson mass [1, 2].

The rates for W and Z production are known to next-to-next-to-leading order in QCD [3, 4], but the shapes of distributions are strongly affected by resummation effects. The Tevatron experiments therefore use the resummed next-to-leading order QCD calculation RESBOS [5, 6] to fit the Z boson distributions. In particular, they fit for non-perturbative shape functions that parametrize the Z boson transverse momentum distribution and then use those same shape coefficients to predict the W boson transverse momentum distribution and the resulting change in shape of the lepton distributions.

This procedure works quite well at the Tevatron and has led to the most precise measurements of the W boson mass, but is a procedure optimized for relatively low Z boson statistics. Fitting for the non-perturbative parameters makes efficient use of the Z sample, at the price of increasing the systematic uncertainty through the choice of more or less arbitrary fitting parameters.

At the LHC, the Z boson production rate will be quite large and it should be possible to leverage the high statistics measurement of the Zs to improve the W boson measurements. One suggestion for doing this is to use the "ratio method" [7]. The idea is to compute the lepton distributions for W and Z bosons, appropriately scaled by the masses, and use the ratio of the calculated distributions to scale the measured Z boson distributions into a prediction of the W boson distributions

$$\left(\frac{d\sigma^W}{dp_T^\ell}\right)_{\text{predicted}} = \left(\frac{d\sigma^W/dp_T^\ell}{d\sigma^Z/dp_T^\ell}\right)_{\text{theory}} \left(\frac{d\sigma^Z}{dp_T^\ell}\right)_{\text{measured}} \tag{2}$$

One of the advantages of this method is that one does not need resummed calculations to form the ratios. This fact stems from the universality of the leading infrared structure of gauge theories that allow one to even perform resummation. The general form of a cross section computed to nth order in perturbation theory is

$$\frac{d\sigma_V^{(n)}}{dp_T} = \frac{d\sigma_V^{(0)}}{dp_T} \sum_{l=1}^{n} \sum_{m=0}^{2l-1} a_{l,m}^V \alpha_s^l \log^m(p_T/\mu) + R_n(\alpha_s), \tag{3}$$

where $\sigma_V^{(0)}$ is the tree-level cross section. As $p_T \to 0$, the logarithms become large and the leading logarithmic terms dominate. These are the precisely the terms that get resummed. The universality of the leading infrared structure means that $a_{l,2l-1}^V$ is the same for any vector boson V, which in turn means that

$$\lim_{p_T \to 0} \frac{d\sigma_W^{(n)}/dp_T}{d\sigma_Z^{(n)}/dp_T} = \frac{d\sigma_W^{(0)}/dp_T}{d\sigma_Z^{(0)}/dp_T} \tag{4}$$

Even as $p_t \to 0$ and resummation effects become most pronounced, the ratio method, using unresummed calculations, becomes exact! This means that the ration method can take advantage of any fixed-order calculations, NLO QCD, NLO Electroweak, etc., as they become available.

The measurements at the Tevatron are already dominated by systematic uncertainties. The prospects for improving the precision of the W mass measurement at the LHC will depend upon reducing these systematic uncertainties [8, 9]. To achieve a precision of $20MeV$ or less, it will also be necessary to reduce the theoretical uncertainty of the analysis. Therefore, as the LHC begins operations, we feel that it is time to take a new look at the ratio method and to study how the inclusion of increasingly precise calculations will decrease the theoretical uncertainty in the determination of the W boson mass.

III. QUESTIONS

The questions that the working group hopes to address are:

- How well do we want to know the W boson mass? At what point does increased precision cease to constrain new physics?
- What is the current theoretical uncertainty on the W boson mass, and how far can it be reduced? Using the Ratio method, what level of precision is obtained as one includes increasingly precise theoretical input such as NLO QCD, NLO Electroweak, NNLO QCD, etc.

Beyond the immediate scope of the W boson mass measurement, the ratio method might prove useful for benchmarking expected signals for new physics. Therefore, we also consider the question

- Can we extend the ratio method to normalize gluon induced cross sections such as $pp \to t\bar{t}$ or $pp \to H$ from quark-gluon initiated processes like $pp \to Z$+jet?

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