Recent theoretical and experimental results on top quark mass measurements

Roberto Franceschini
CERN, 1211 Geneve 23, Switzerland

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-04/317

In this contribution I will review recent experimental results on the measurement of the top quark mass. I will also review recent proposals about new methods proposed for the extraction of the top quark mass. Finally I will comment on recent detailed studies of the theoretical uncertainties in measurements based on templates fitting.

1 Introduction

The top quark mass is a key parameter of the Standard Model of particle physics. Indeed it is one of the free parameters of the theory that needs to be measured to fully define it. The top quark mass is also an input of many precision predictions of the Standard Model that are needed to assess its validity up to higher energy scales, possibly up to the Planck scale.

The great importance of the top quark mass for Standard Model and Beyond the Standard Model physics is motivation for the large efforts that the experimental community has put in its measurement. Remarkably, the LHC and TeVatron experiments have recently combined their results and obtained a combined measurement $173.34 \pm 0.27(stat) \pm 0.71(syst)$ GeV [1]. The uncertainty is dominated by systematic errors, in particular the measurement of hadornic jets, and is likely to not improve much when more data will be added to the analyses. The dominance of systematic errors in the current measurement is certainly a great motivation to think about new methods to mesure the top quark mass. At the end of Run-2 of the LHC it is foreseen to have few 1/ab of integrated luminosity, which would yield some *1 billion top pairs* produced at the LHC. The prospect to have such large sample of top quarks makes possible to consider measurement of the top quark mass that exploit very special final states (such as for instance J/ψ states or other exclusive decays) or exploit features of kinematic distributions that are not hugely populated (such as for instance end-point regions and tails). The hope is that among these alternative approaches to the top quark mass measurement one can find methods that are based on experimentally clean quantities and that exploit observables which are well under theoretical control. The balance of these two needs will be a key issue for the methods that will provide a reliable *precision* determination of the top quark mass.

The measurement of top quark mass through the measurement of the total inclusive $pp \to t\bar{t}$ cross-section is one instance of theoretically clean quantity, as it can be computed to high order in QCD, but, unfortunately, suffers of large uncertainties on the experimental side. The issue here has to do with the fact that the experiments measure the cross-section in the region of phase space accessible to their acceptance, not the total cross-section. The total cross-section is obtained using MonteCarlo simulations to extrapolate from a fiducial region of phase-space to the total phase-space. Such extrapolation suffers of uncertainties that at the moment make impossible to measure the top quark mass better than a few GeV [2]. On the other hand the measurements that are more under control on the experimental side, and that has been possible to carry out with the current top quark sample, tend to be difficult to reliably interpret on a theory standpoint. One issue above all that can be mentioned is that the currently most precise measurement do require the construction of templates, whose matching with data, determines the top quark mass and its uncertainty. These templates can only be built from samples of exclusive events, that necessarily come from event generators. The accuracy of these events generators is often questioned when measurements at less than 1% are quoted; furthermore even the theoretical definition of the quantity that is measured with current template procedures might be not understood at this level of accuracy [3]. For these reasons it is useful to think about new quantities that can be used to measure the top quark mass having in mind from the very beginning the possibility to both compute and measure them *accurately*.

2 A portrait from different angles

One recent effort in the direction of measuring the top quark mass using a theoretically robust quantity is the measurement of the end-point of the invariant mass distribution of the lepton and the b-jet from the top decay [4]. The accuracy of this mass measurement is expected to reach a quite interesting sub-GeV level [5, 6]. Furthermore, by the end of the run of the LHC, with a luminosity of order 1/ab, other measurements are foreseen to become useful and to attain a similar level of accuracy [5, 6] thanks to the high statistics, reduced systematic errors and the improved theoretical calculations that will be available by then.

The fact that several new top quark mass measurement will be feasible with the large LHC top quark data set is extremely welcome. In fact to measure this mass with a precision well below the 1% level, one needs to carefully assess several delicate effects, most of which are particularly tough to control theoretically due to the nature of strong interactions and hadronic physics. The hope is that, by obtaining several independent measurements, each based on different experimental objects and possibly suffering of different theoretical uncertainties, we can obtain a *global* picture for the top quark mass measurement. In this picture it is likely that each single measurement will have a set of assumptions that can hardly be tested in the measurement itself or in other available data. For instance each measurement will have to deal in its own way with the many issues that exist in our *description* of hadronic physics: effect of higher order corrections, the estimation of theory uncertainties from scale variations and possible functional dependence of the scale on the kinematics, effect of finite width of unstable particles and radiation in the decay of resonances, effect of hadronization of partons and color neutralization. Each measurement will have different sensitivity to these effects and its interpretation will depend on our choice about how to address each of these issues. In the end the best knowledge of the top quark mass will emerge from the *combination* of truly independent, possibly uncorrelated, measurements. The variety of angles under which we will be able to observe the top quark will be the biggest strength of its mas measurement.

3 Issues with resonance reconstruction and templates

A very important issue with the top mass measurement has to do with the reconstruction of a resonance in the events that are used to measure the mass. Intuitively we expect that the most straightforward way to measure a resonance mass is to measure all its decay products and to compute the mass of the total four-vector. For instance for a Z boson one might want to look at $Z \to \mu^+\mu^-$ events and compute $\left(p_{\mu^+} + p_{\mu^-}\right)^2$. This procedure will definitively be good enough for most uses of the measured mass, however issues arise when one seeks *precision* and radiative corrections are added to this picture. In fact one has to remember that charged leptons come with an associated spectrum of emitted radiation that in reality makes the decay $Z \to \mu^+\mu^- +$ photons. The existence of these corrections to the naive (leading order) picture requires to move away from the simple picture outlined above and motivates complementary approaches to the mass measurement. In fact one can attempt to derive the Z boson mass from properties of just a subset of its decay products, even from just one of the leptons. This is a possibility actually very meaningful to entertain because it avoids to have to specify how the Z boson is reconstructed. This is even more true for the measurement of masses of particles where the final state is partly invisible, such as W bosons decaying leptonically and, as a consequence, top quarks. Furthermore, not having to reconstruct a resonance it is possible to measure the mass using more inclusive final states, which is a bonus for the accuracy of theory calculations. A recent attempt to obtain a mass measurement from inclusive single lepton distribution has been discussed in Ref. [7], which finds that the theory uncertainty on the top quark mass from such observable could be as low as 0.8 GeV.

Another interesting result from Ref. [7] has to do with the inherent uncertainties that should be evaluated when templates are used to extract the top quark mass. The fact is that templates are only as good as the approximation to real hadronic physics that has been put in the calculation or event generator used to obtain the templates. Therefore it is very important to scrutiny the effect on the measurement that arises from the several choices that one has to do in the making of the templates. For instance one needs to study the impact of the measurement of the presence of parton shower corrections, spin correlations treatment, and even the precise relation between the event kinematics and the choice of scales that are introduced in the calculation. Some of these effects my be not so relevant in other aspects of top quark physics, still, due to the differential nature of the information that is used in the top quark mass extraction, they might have a significant impact when one tries to extract the top quark mass better than 1% accuracy that is interesting nowadays. Ref. [7] discusses a few examples of leptonic observables that suffer from these *theory biases* and in particular highlights how in some cases even a higher order calculation seems to not help much to cure these largely unpredictable biases.

4 Phenomenological Lorentz invariants

The last issue discussed above motivates to consider observables that are as much as possible insensitive to the effects that are difficult to incorporate in the calculations used to produced the templates. In this respect observables that are invariant under Lorentz transformations are naturally interesting to look at. The reason is that many details about the events that produce the top quarks become irrelevant. In fact all the effects that amount to change the boost distribution of the top quark in the given production environment are not important.

One can simply compute these observables in the top quark rest frame and, by virtue of the invariance, carry the prediction to the laboratory frame. The example of the mass of the muon pair above perfectly displays the utility of Lorentz invariants. However, from the discussion above we also know that it is crucial to observe *all* the products of the decay, including the cloud of real photons (that can be energetic in some cases) that accompany the charged leptons.

A possible solution to this problem is to retrieve Lorentz invariant quantities from information encoded in the laboratory frame *distribution* of suitable Lorentz-variant quantities. The key idea is that distributions do retain the full information on the kinematics in the top quark rest frame and that, in suitable experimental conditions, one can reliably extract the top quark rest frame quantities from these distributions. Observables that have been considered so far are: a specially weighted median of the inclusive lepton energy distribution [8] and the position of the peak of the inclusive energy distribution of the b-jet [9]. The extraction of Lorentz invariants from the distribution of Lorentz-variants is potentially advantageous because can be carried out from the observation of a *single particle* among all the decay products of the top. This simplifies the issue of adding radiative corrections as one can base the top quark mass extraction on the study of a single distribution that is fully inclusive with respect to the presence of extra radiation. The further consequence of dealing with a single particle measurement is that there is no need to proceed to a resonance reconstruction. Furthermore a single particle observable avoids all the issues connected to the identification of the correct pair of particles to be combined to reconstruct a resonance from its invariant mass. The study of NLO corrections to the energy distribution of leptons and b-jets for the top mass measurement is currently underway.

5 Conclusions

The determination of the top quark mass with uncertainty below 1 GeV is a very challenging task both theoretically and experimentally. After the epoch of measurements based on a limited sample of top quarks, the LHC will make possible a variety of mass measurements that need large statistics. The combination of these measurement will provide a *global* assessment of the top mass, whose consistency will make us confident that the small error of these measurements is actually backed up by a solid *precision* understanding of QCD in top quark physics.

References

[1] ATLAS, CDF, CMS and D0 Collaborations. First combination of Tevatron and LHC measurements of the top quark mass. *ArXiv:1403.4427.*

[2] CMS Collaboration. Determination of the top quark pole mass and strong coupling constant from the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV. *Phys.Lett.*, B728:496–517(2013).

[3] A. H. Hoang and I. W. Stewart. Top Mass Measurements from Jets and the Tevatron Top-Quark Mass. *Nucl. Phys. B Proc. Supp.*, 185:220–226(2008).

[4] CMS Collaboration. Measurement of masses in the $t\bar{t}$ system by kinematic endpoints in pp collisions at $\sqrt{s}$ = 7 TeV. *Eur.Phys.J.*, C73:2494(2013).

[5] Juste et al. Determination of m_{top} circa 2013: methods, subtleties, perspectives. *ArXiv:1310.0799.*

[6] CMS Collaboration. Projected improvement of the accuracy of top quark mass measurements at the upgraded LHC. CMS-PAS-FTR-13-017

[7] S. Frixione and A. Mitov. Determination of the top quark mass from leptonic observables. *ArXiv:1407.2763.*

[8] Kawabataa et al. Weight function method for precise determination of m_{top} at the LHC. *ArXiv:1405.2395.*

[9] Agashe et al. A simple, yet subtle 'invariance' of two-body decay kinematics. *Phys. Rev. D*, 88(5):057701